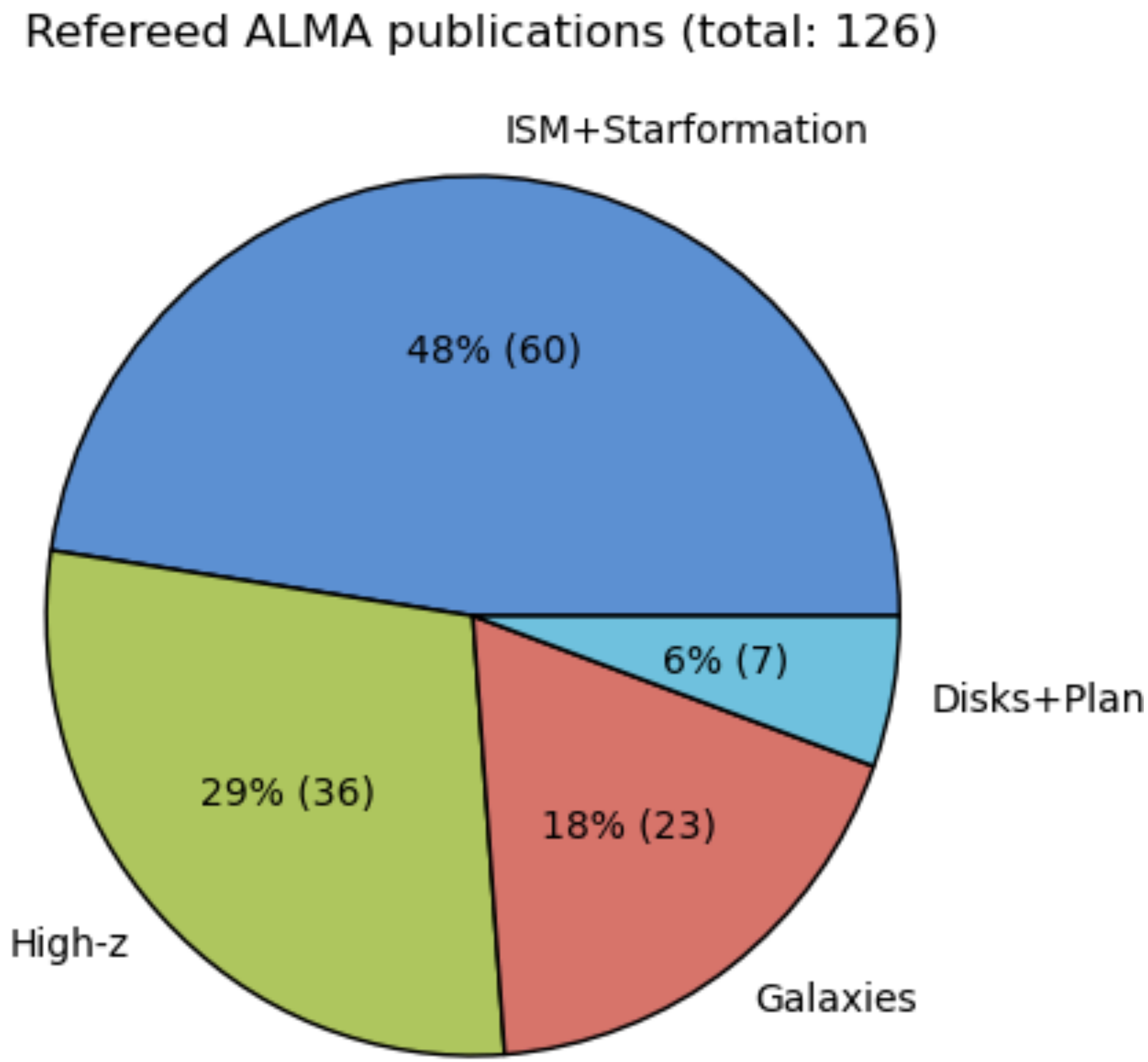
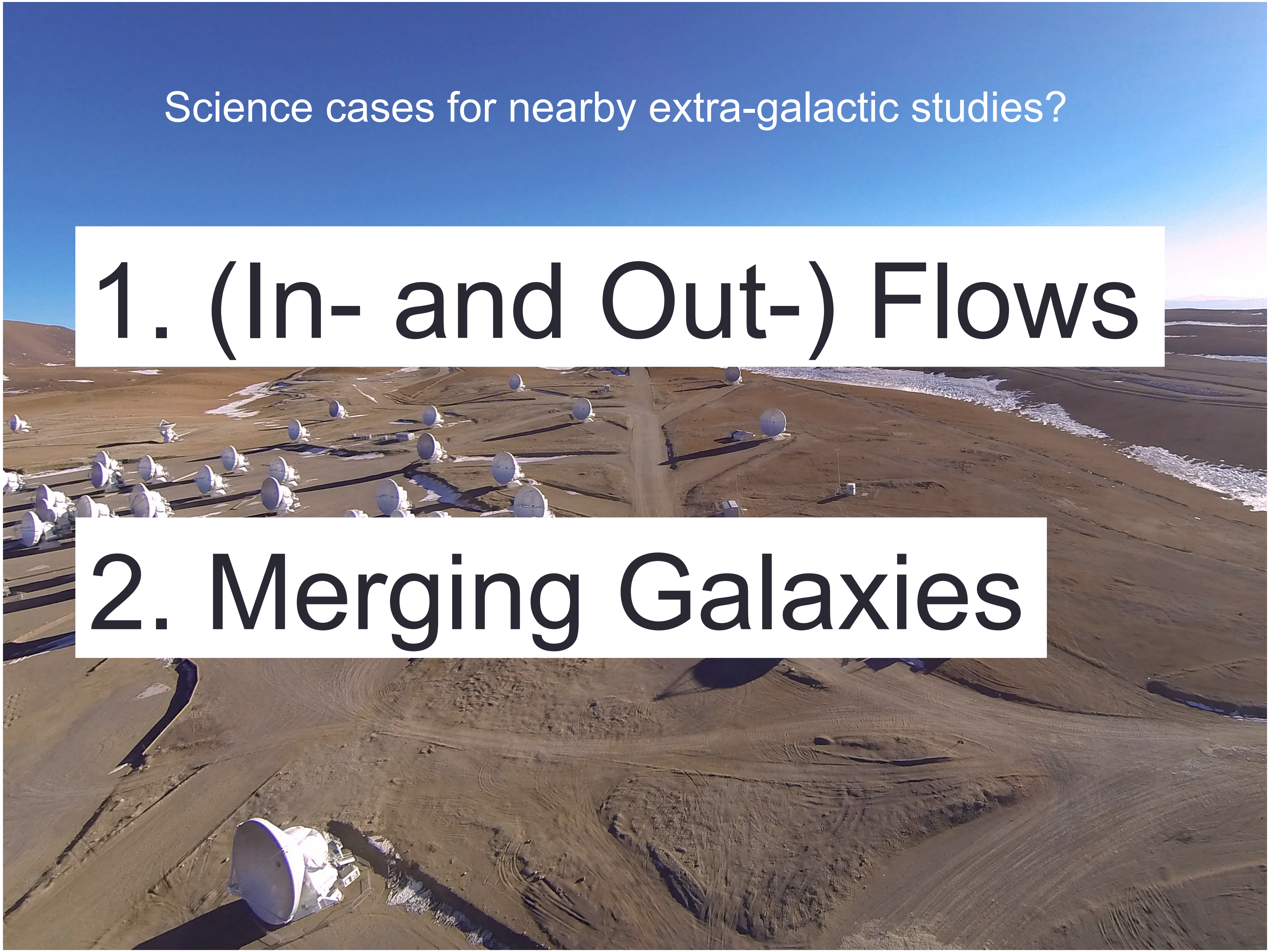
NEARBY GALAXY OBSERVATIONS -- SYNERGIES WITH ALMA --

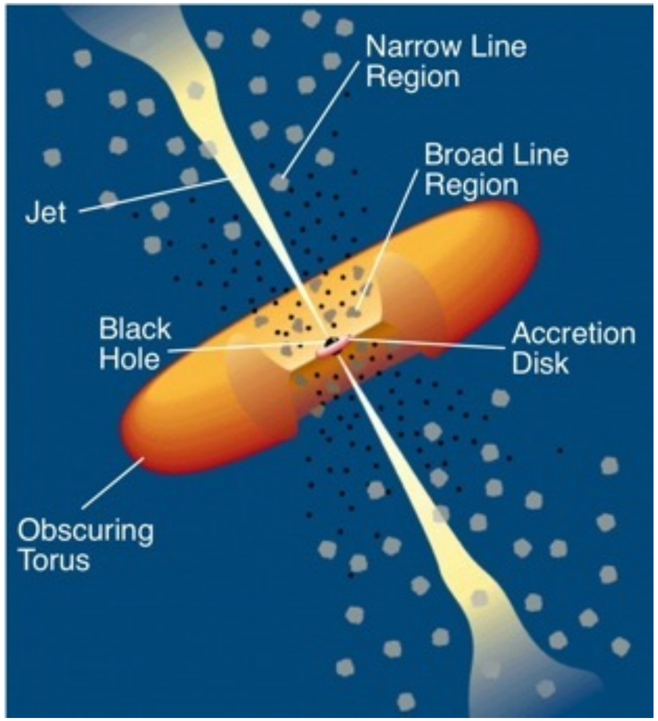
Daisuke Iono (NAOJ)


Refereed ALMA publications (total: 126)
ISM+Starformation
48% (60)
6% (7)
Disks+Plan
29% (36)
18% (23)
High-z
Galaxies


Science cases for nearby extra-galactic studies?
1. (In- and Out-) Flows
2. Merging Galaxies

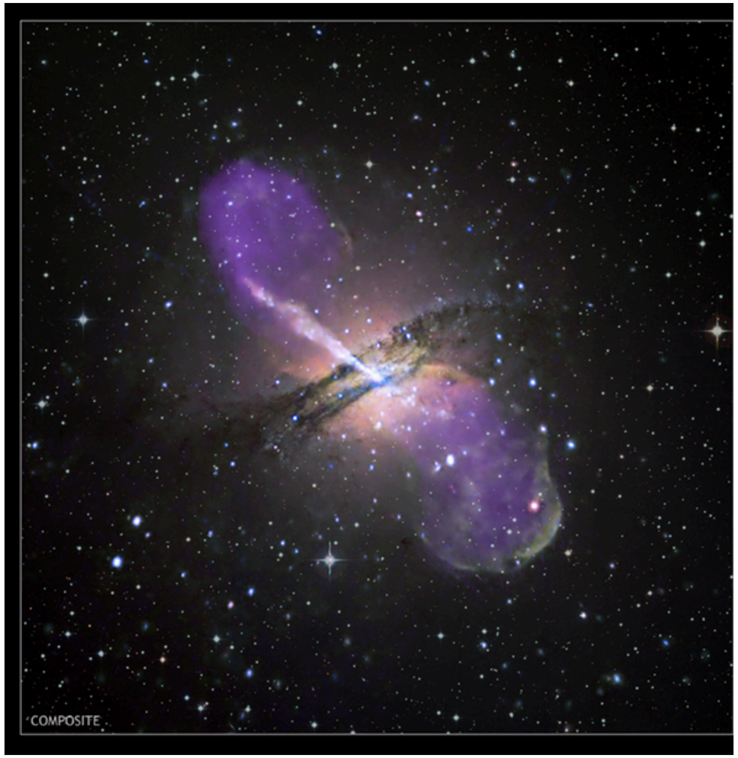
AGN in/out-flows

<u>Gas inflow:</u>
Feeing the AGN



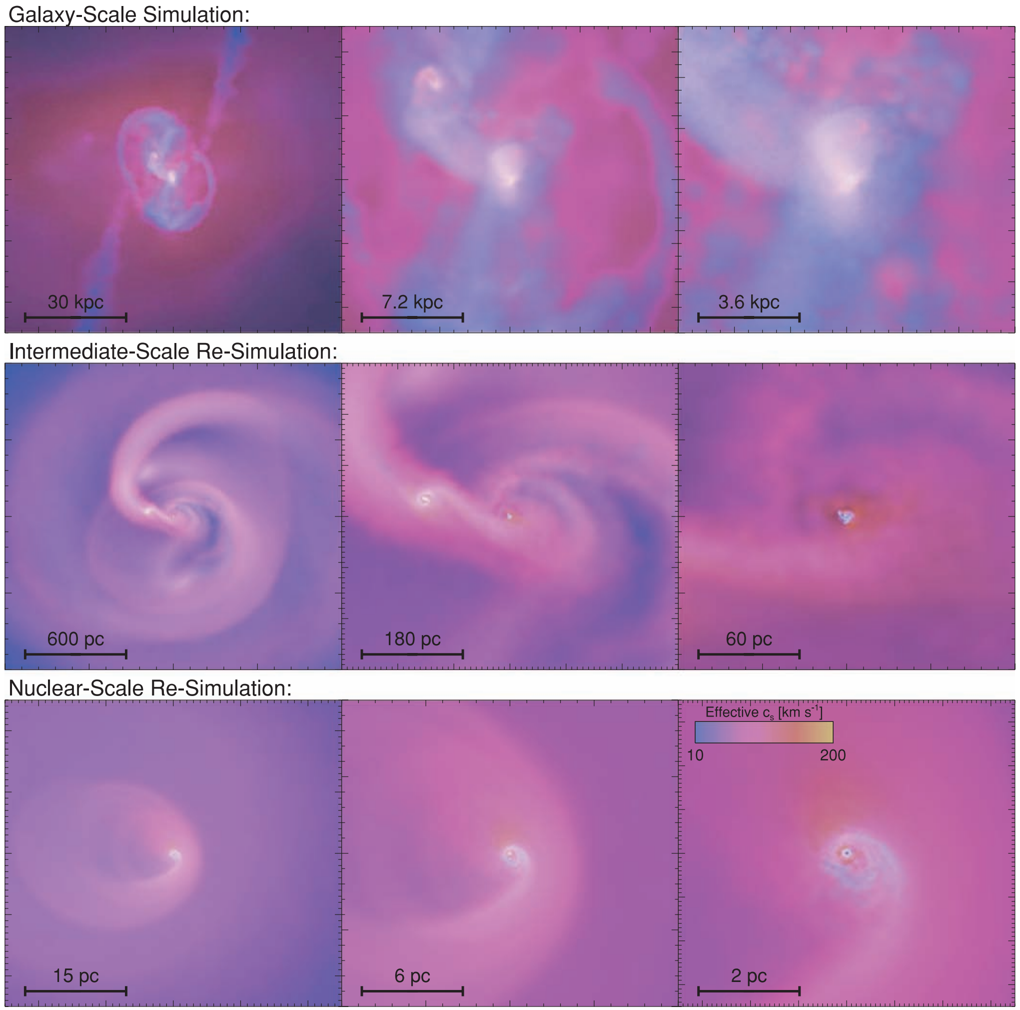
Circum-Nuclear Disk ~ < 0.1 – 1 pc scale
Torus ~ pc scale

<u>Gas outflow:</u>
Expelling material and provide feedback



Jets ~ > kpc scale

Mass accretion onto the black hole



Hopkins & Quataert (2010, MN, 407, 1529)

Large (> kpc) scales

- Mergers
- Bars in isolated galaxies

10 – 1000 pc scales

- Gas inflow due to nested bars
- Resonances

1- 10 pc scales

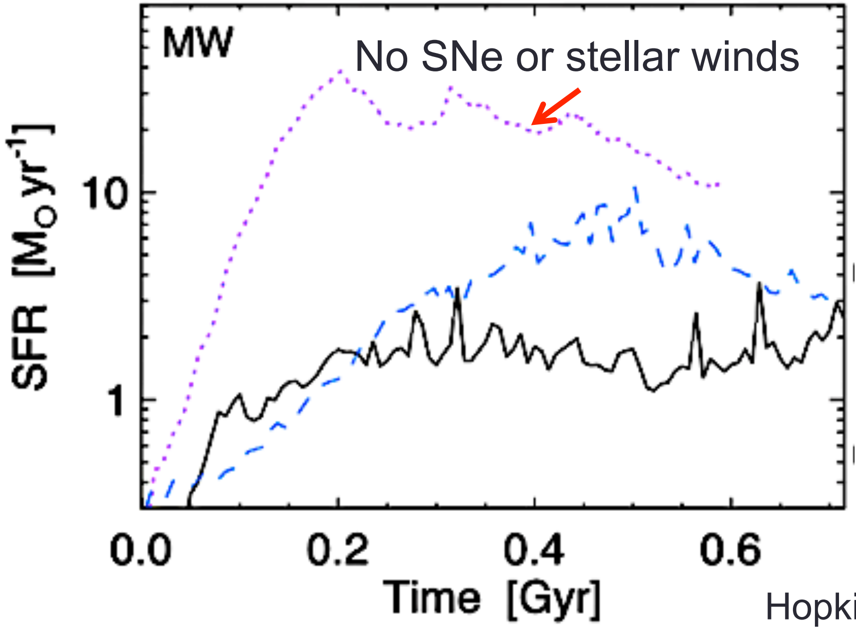
- Potential dominated by BH
- Forming m = 1 type spiral mode
- Inflow rate of 1- 10 M_{sun}/yr

Starburst winds/outflows

M82
(Smithsonian Institution/Chandra X-ray Observatory)

- Ubiquitous in SB galaxies with ~ 0.1 $M_{sun}/yr/kpc^2$
- Expansion along minor axis
- Multi-phase: hot (x-ray), ionized (H alpha) and cold (molecular)

Mass loss and feedback (quenching star formation)

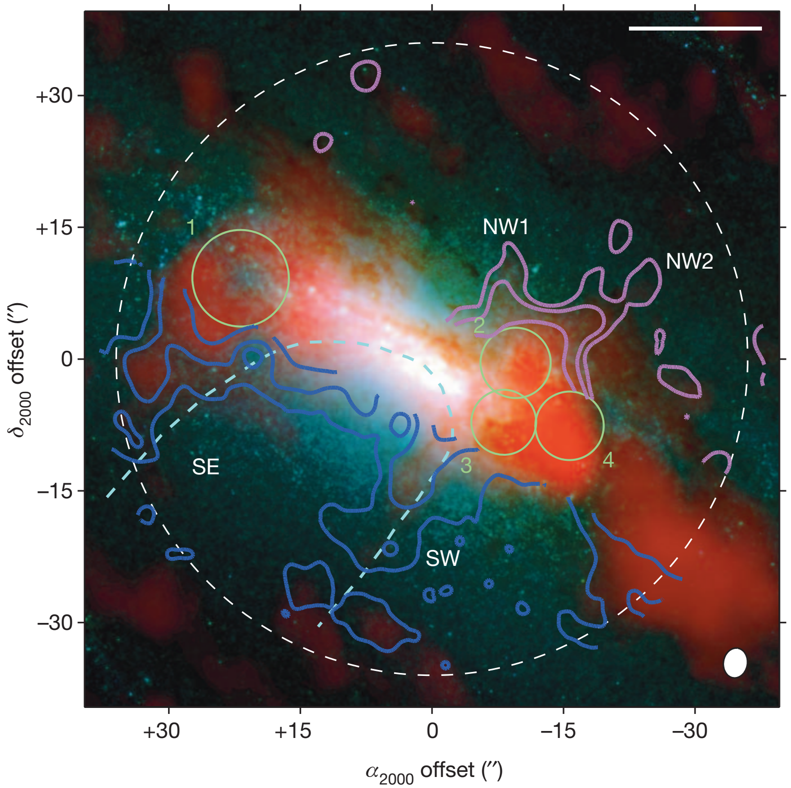


Hopkins et al.

NGC 253 – evidence of outflow

Starburst galaxy with outflows seen in ionized gas (low luminosity BH is not the dominant source).

The CO(1-0) (beam=3.2”) outflow coincides with the Hα outflow.



Outflow mass: ~ 6.6 x 10^6 M_{sun}
Outflow rate: 9 M_{sun}/yr
SFR : ~ 3 M_{sun}/yr

Outflow rate > SFR

Starburst driven wind is limiting the star formation activity

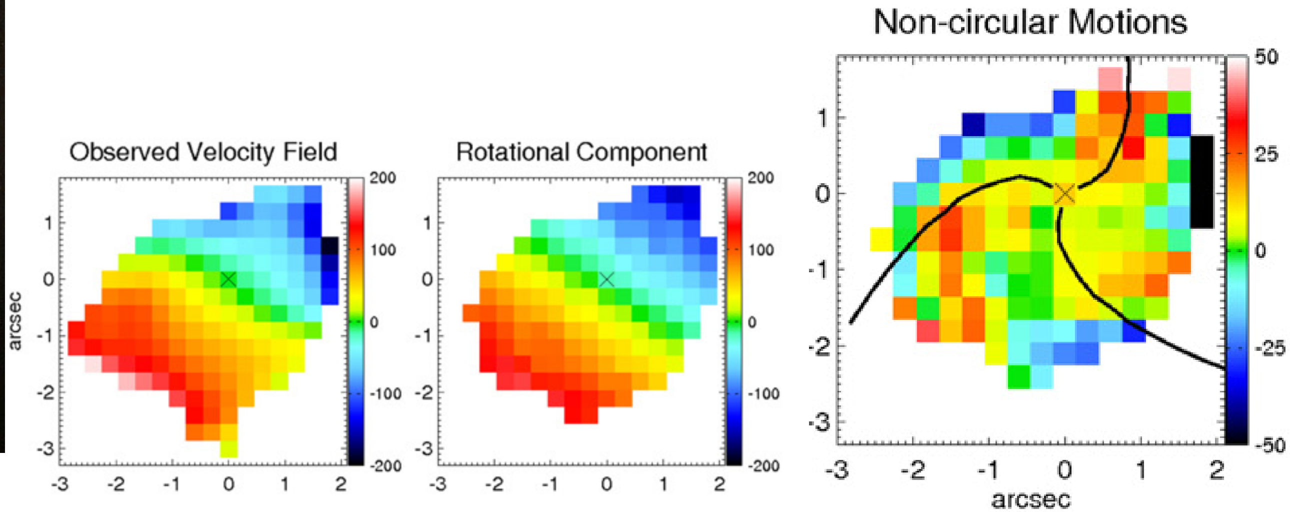
Bolatto et al. 2013

NGC 1097 – evidence of inflow

Used HCN(4-3) velocity field to model the gas kinematics associated with the AGN. Found non-circular motion with gas mass inflow of 0.1 – 0.6 M_{sun}/yr, feeding the central blackhole.

AGN and SB ring

HST



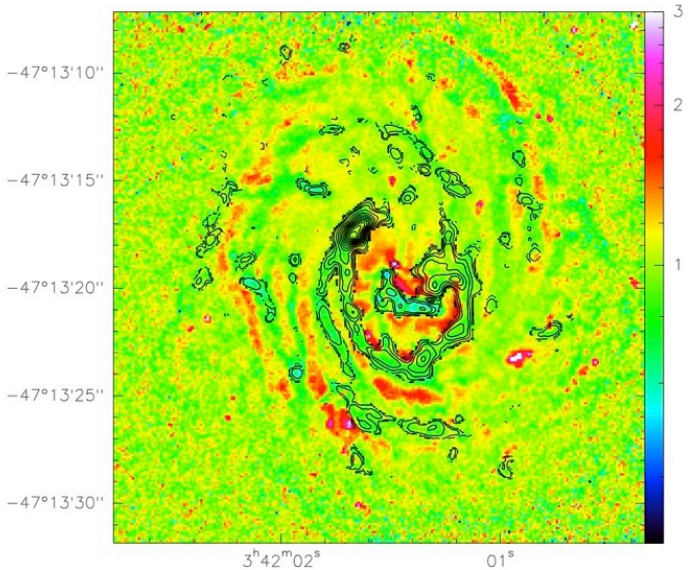
Fathi et al. 2013

NGC 1433 – evidence of outflow

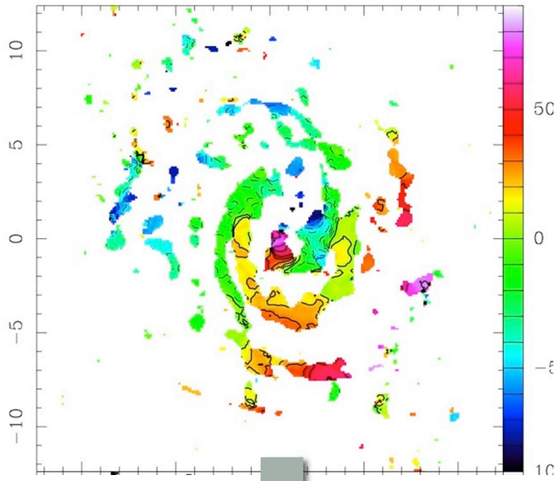
Combes et al. 2014

Barred spiral galaxy with a Seyfert 2 nucleus

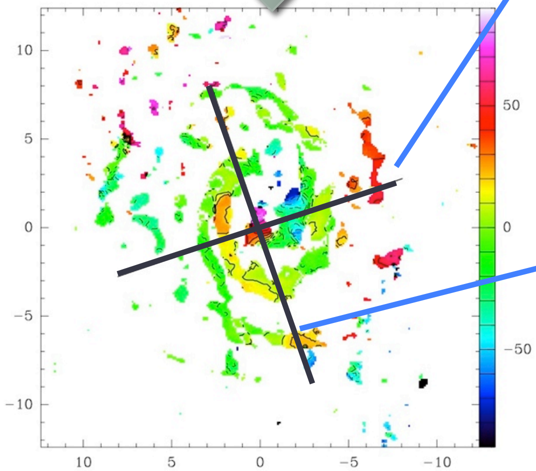
CO(3-2) on HST

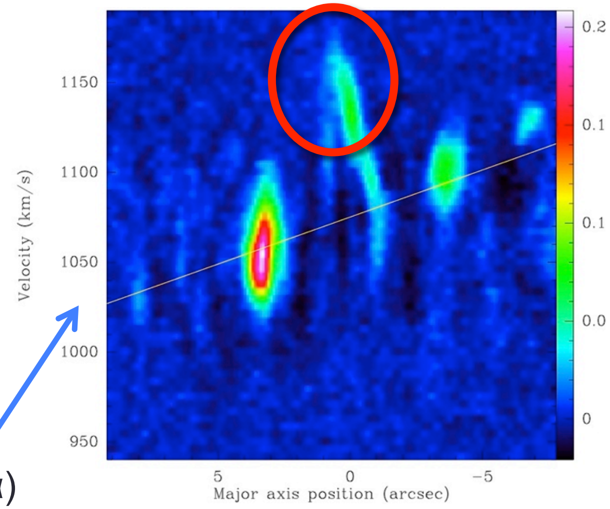


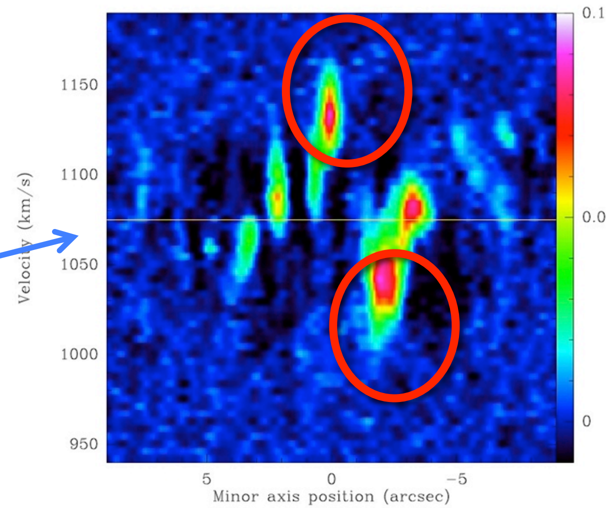
Molecular outflow
M ~ 3.6 x 10^6 M_{sun}
Rate ~ 7 M_{sun}/yr



Subtraction of the rotation (from Hα)



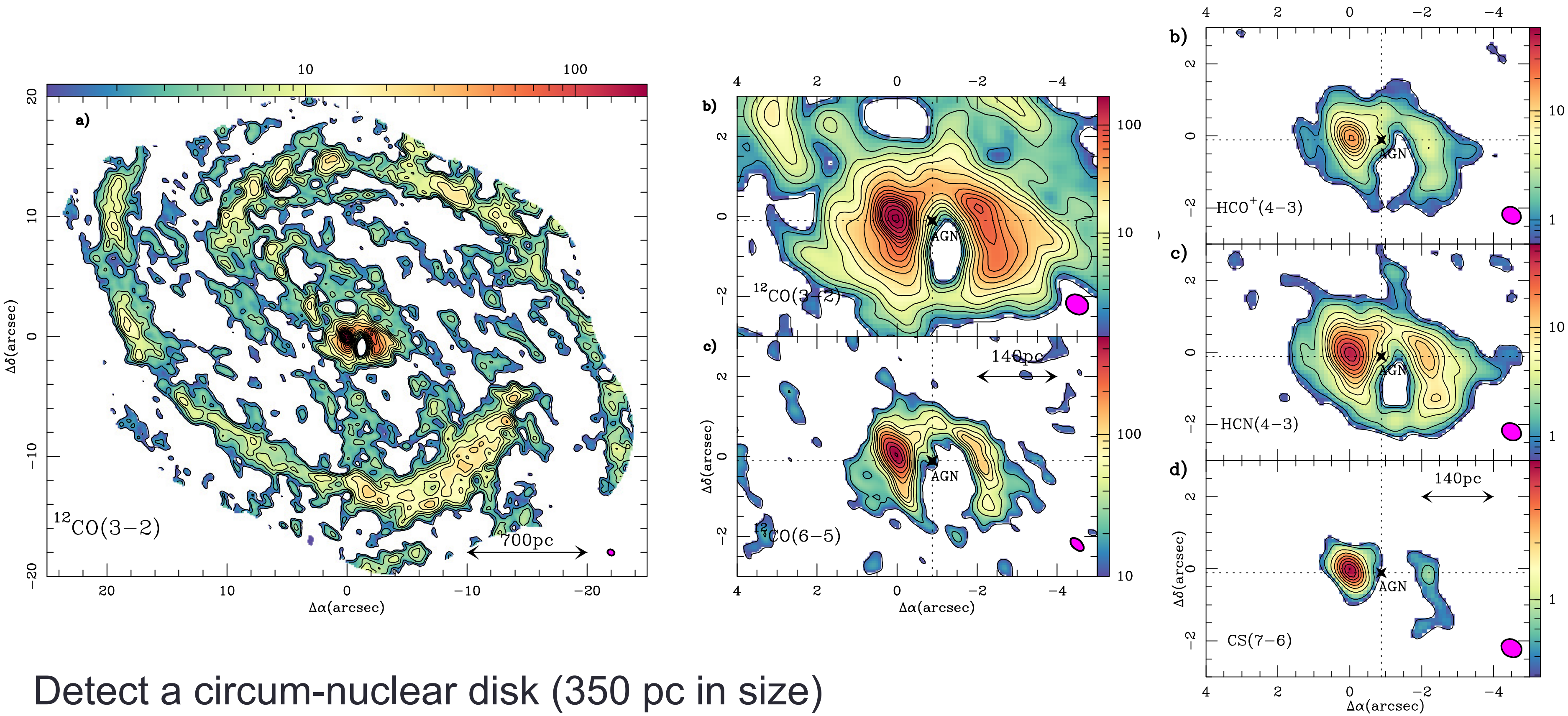




NGC 1068 – inflow(?) and outflow

- 14.4 Mpc (1” = 72 pc)
- AGN (Seyfert 2) + Starburst ring (diameter = 30”)

NGC 1068 – inflow(?) and outflow



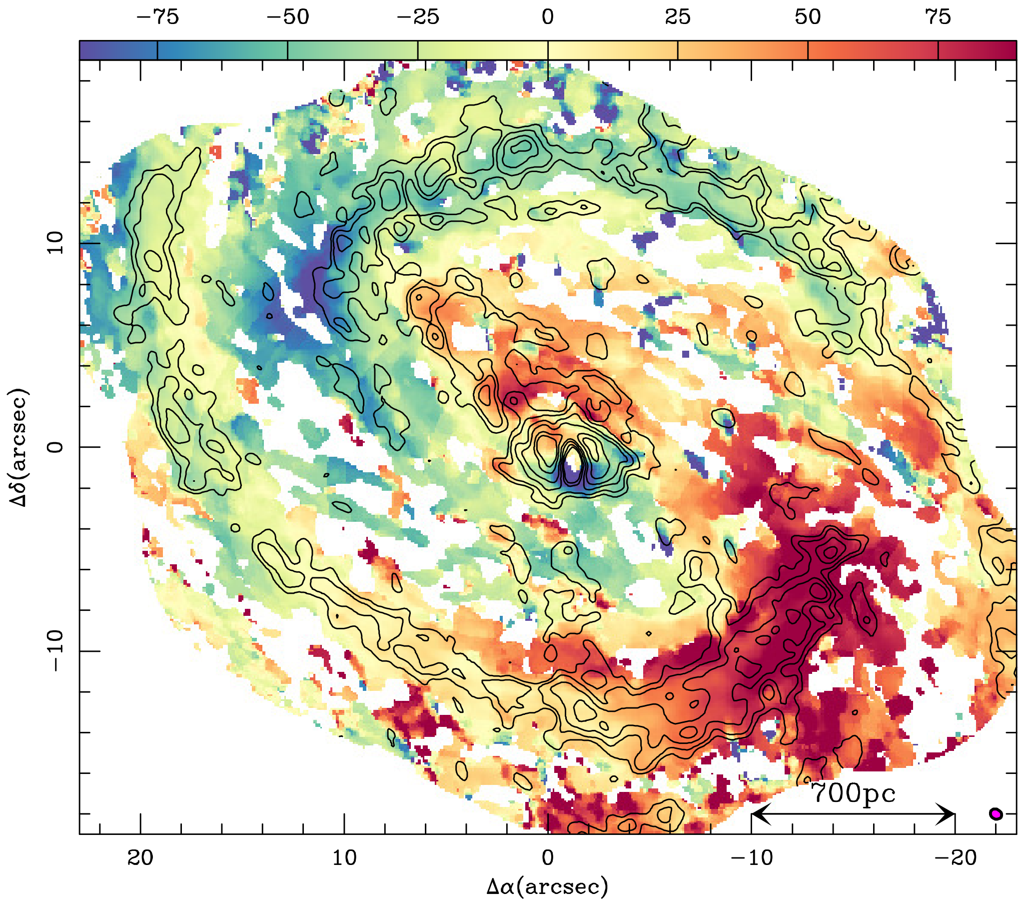
Detect a circum-nuclear disk (350 pc in size)

CO(3-2) is abundant, tracing the extended/ring SF, whereas dense gas tracers such as CO(6-5), HCN(4-3), HCO+(4-3), CS(7-6) are only detected in the nuclear disk.

Garcia-Burillo et al. (2014)

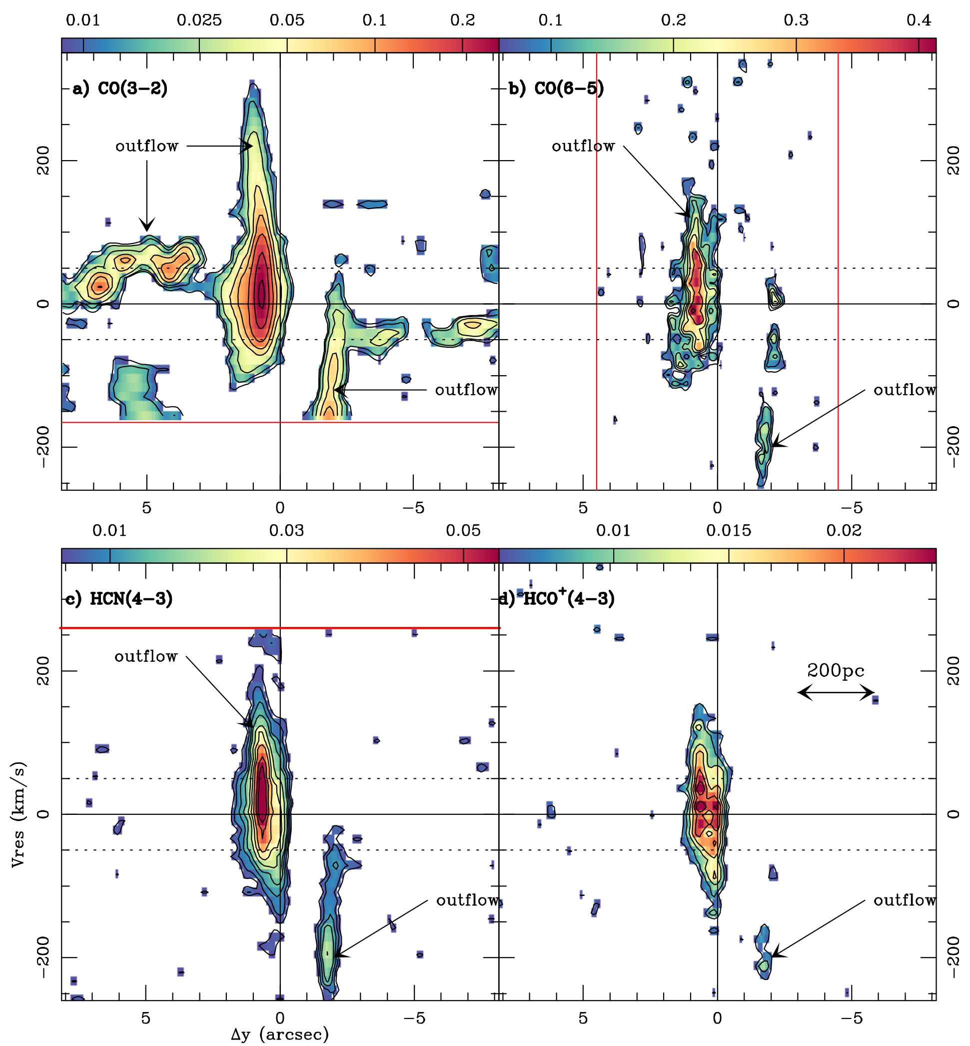
NGC 1068 – inflow(?) and outflow

Residual velocity after subtracting the best fit rotation model.



Significant non-circular motion is present -> which may be caused by the bar

NGC 1068 – inflow(?) and outflow



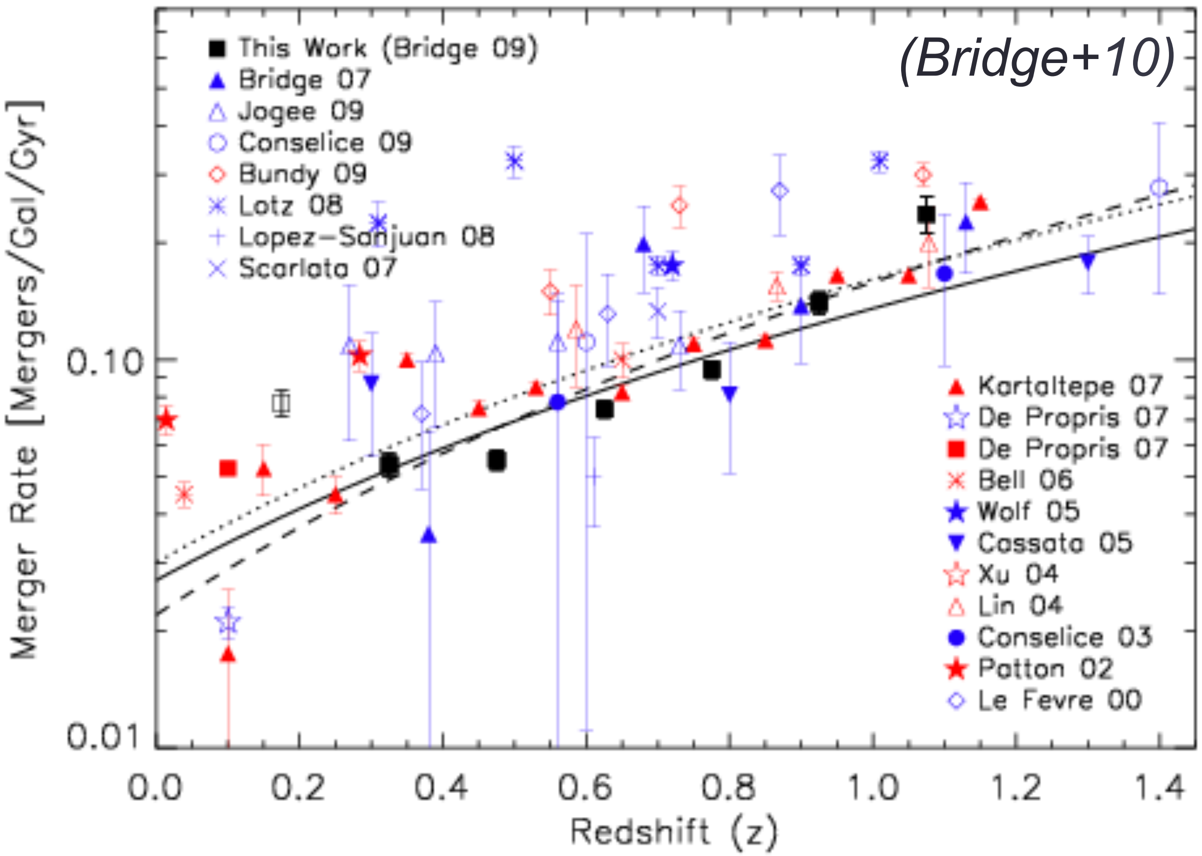
High velocity component seen at small (~100 pc) scales

Signature of outflow

Galaxy Mergers

1. Gas outflow
2. K-S Law and mergers
3. Morphological evolution

Galaxy Interactions and Mergers

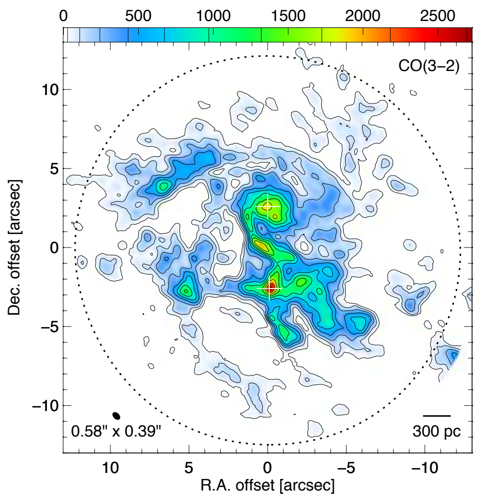


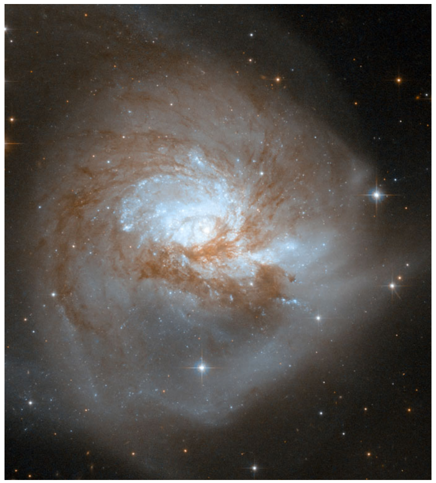
Galaxy mergers play important roles in the formation and evolution of galaxies, as illustrated by the increasing galaxy merger rate at higher redshifts *(e.g., Lin+04, Bundy+09)*.

NGC 3256 – mergers and outflows

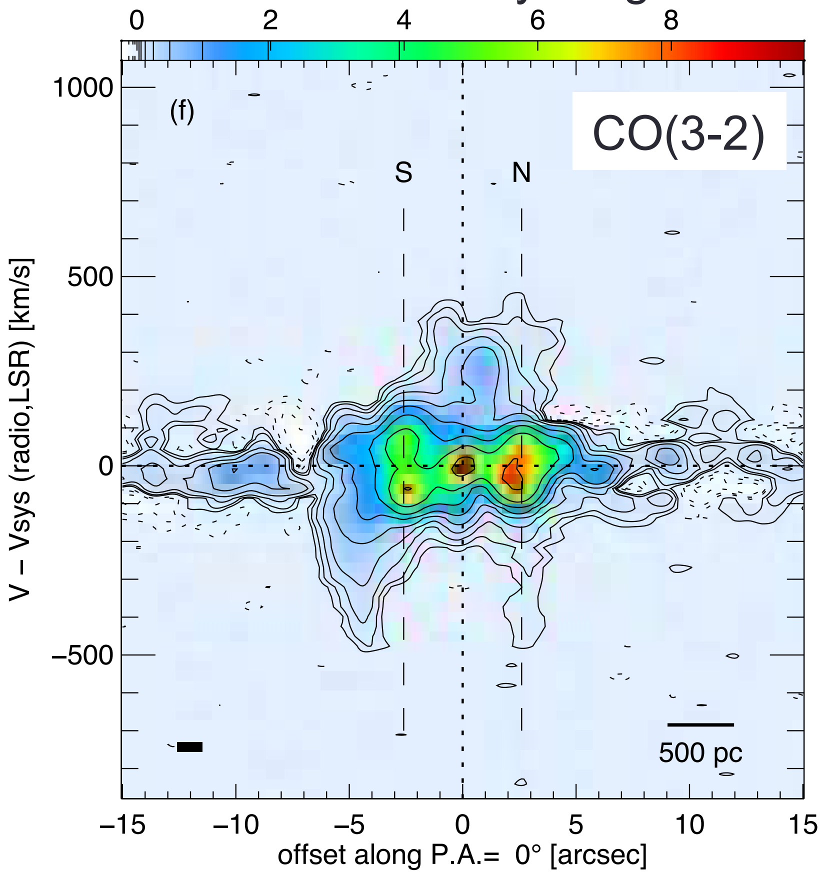
Sakamoto et al. (2014)

CO(3-2) integrated intensity





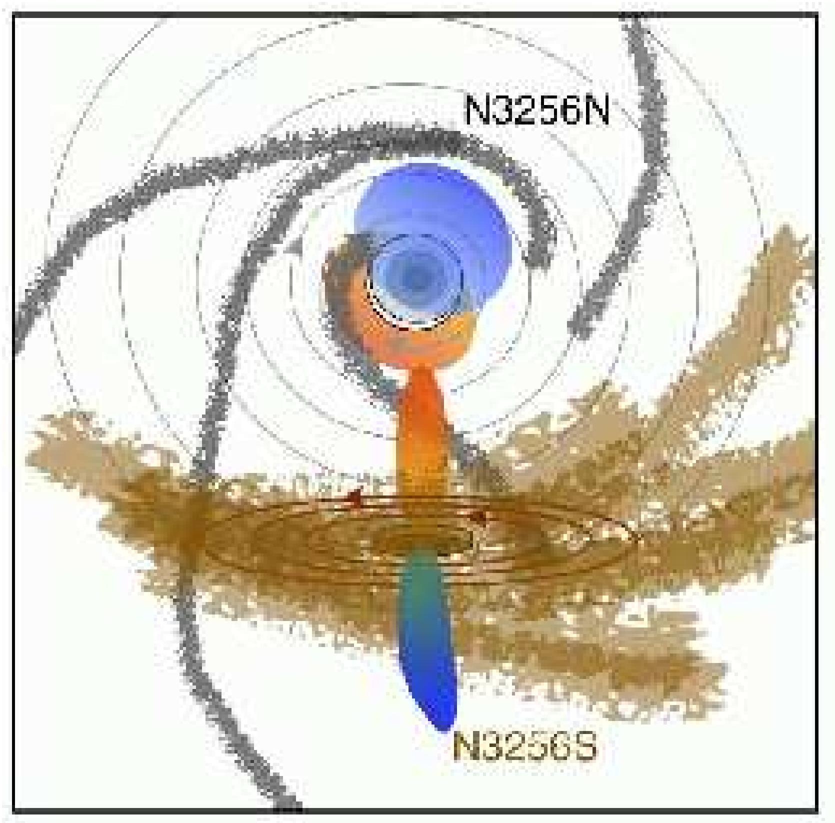
Position Velocity Diagram



Bipolar outflow from both galaxies

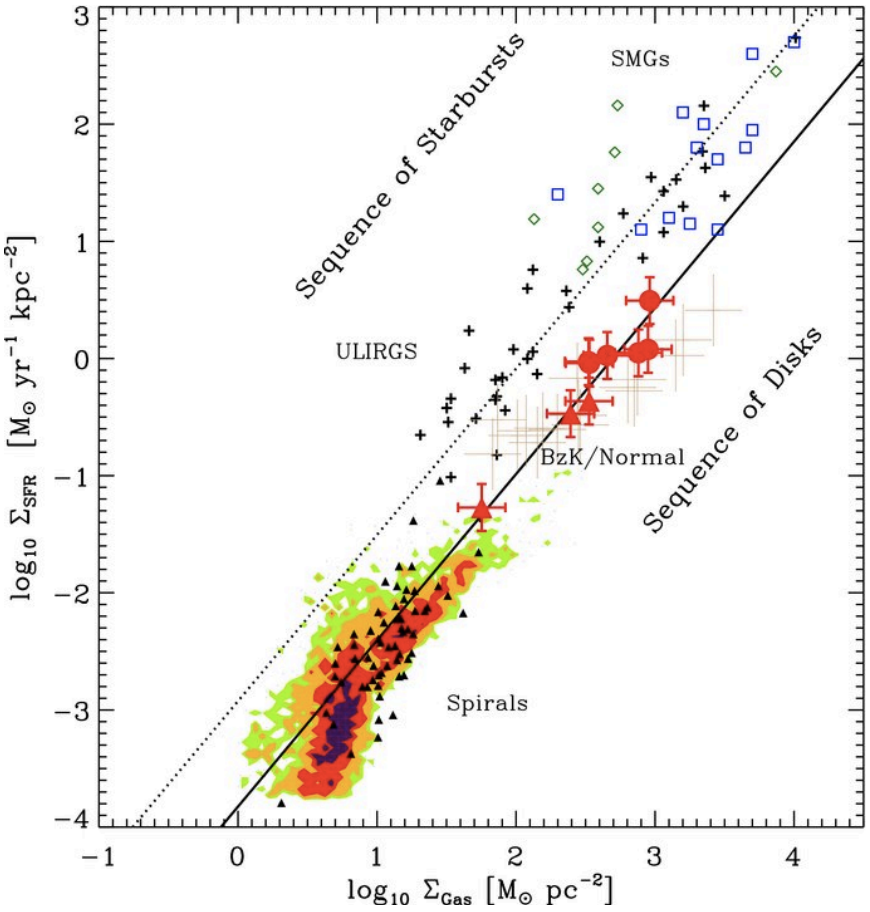
Both > 50 – 60 M_{sun}/yr

NGC 3256 – mergers and outflows

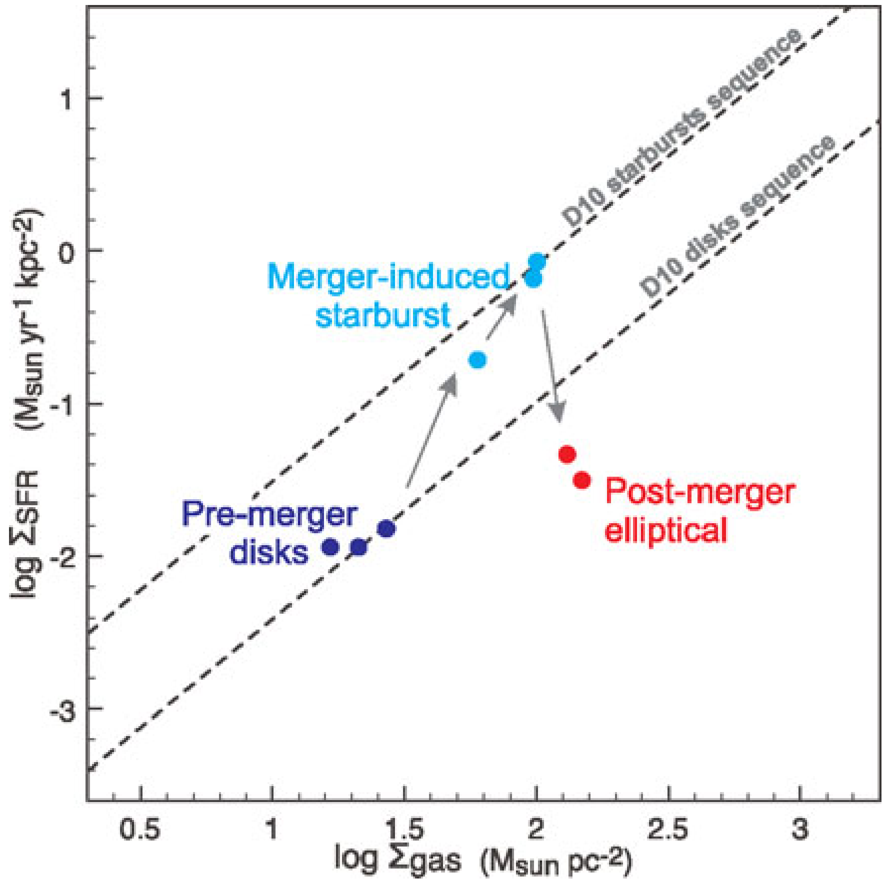


Sakamoto et al. (2014)

K-S Law and Merging Galaxies



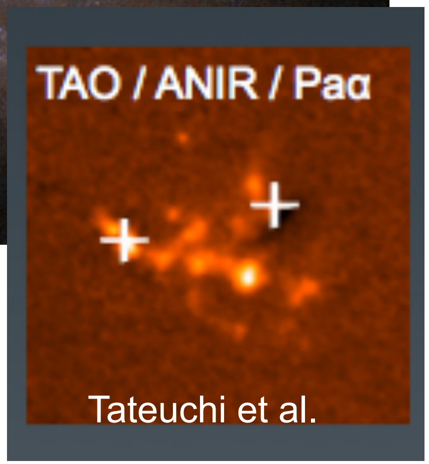
Daddi et al. (2010)

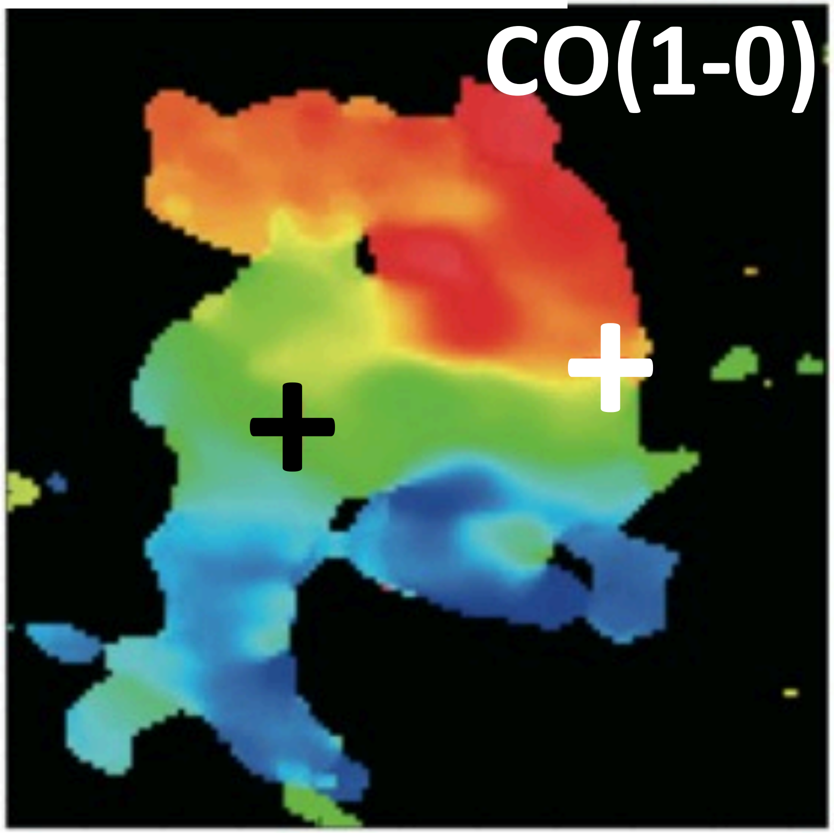


Bournaud et al. (2011)

ALMA observation of a merging LIRG VV114

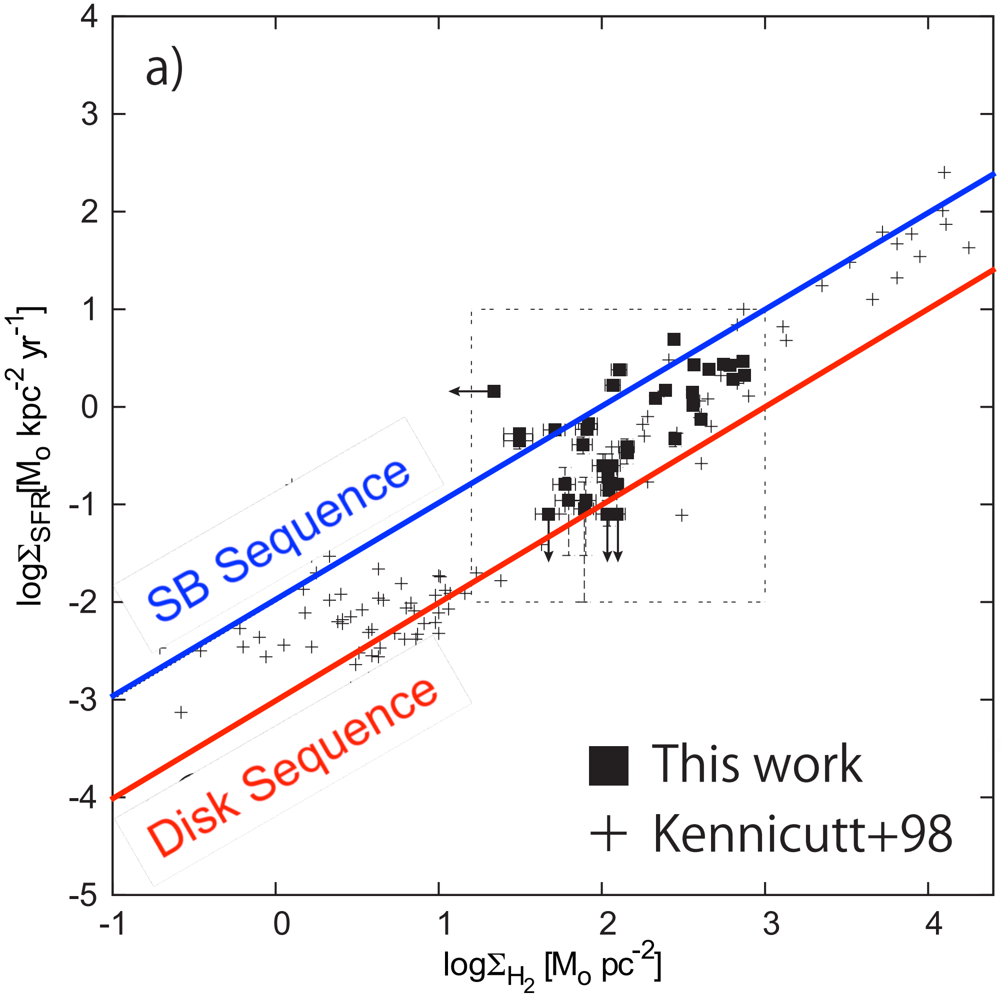
HST



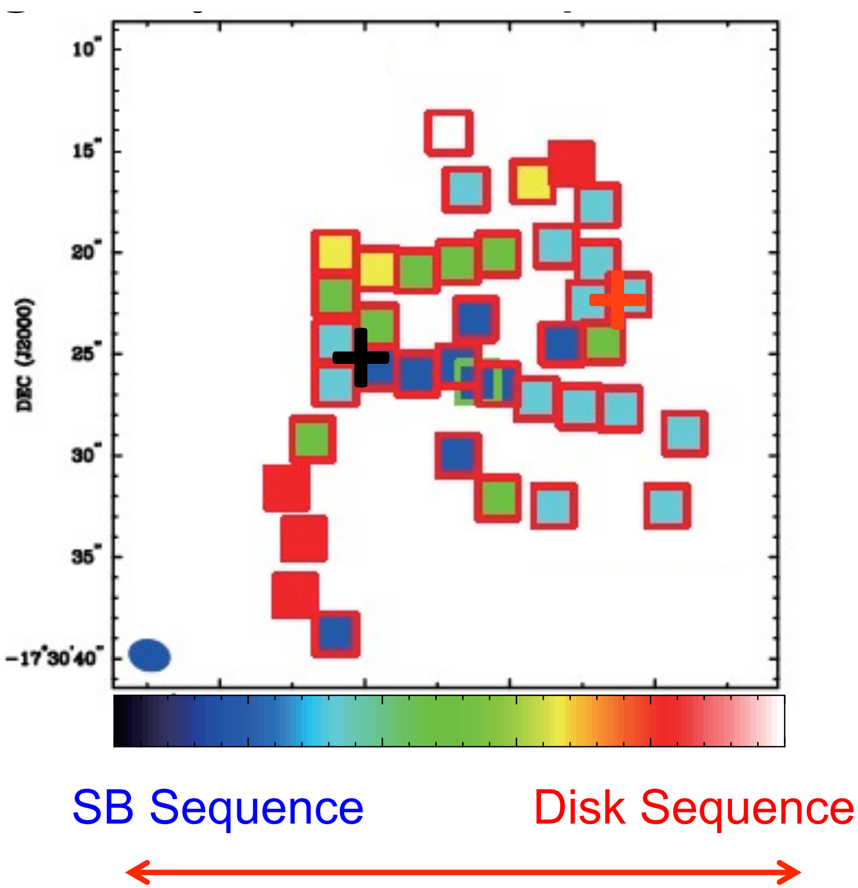


ALMA CO(1-0); Saito et al. in prep

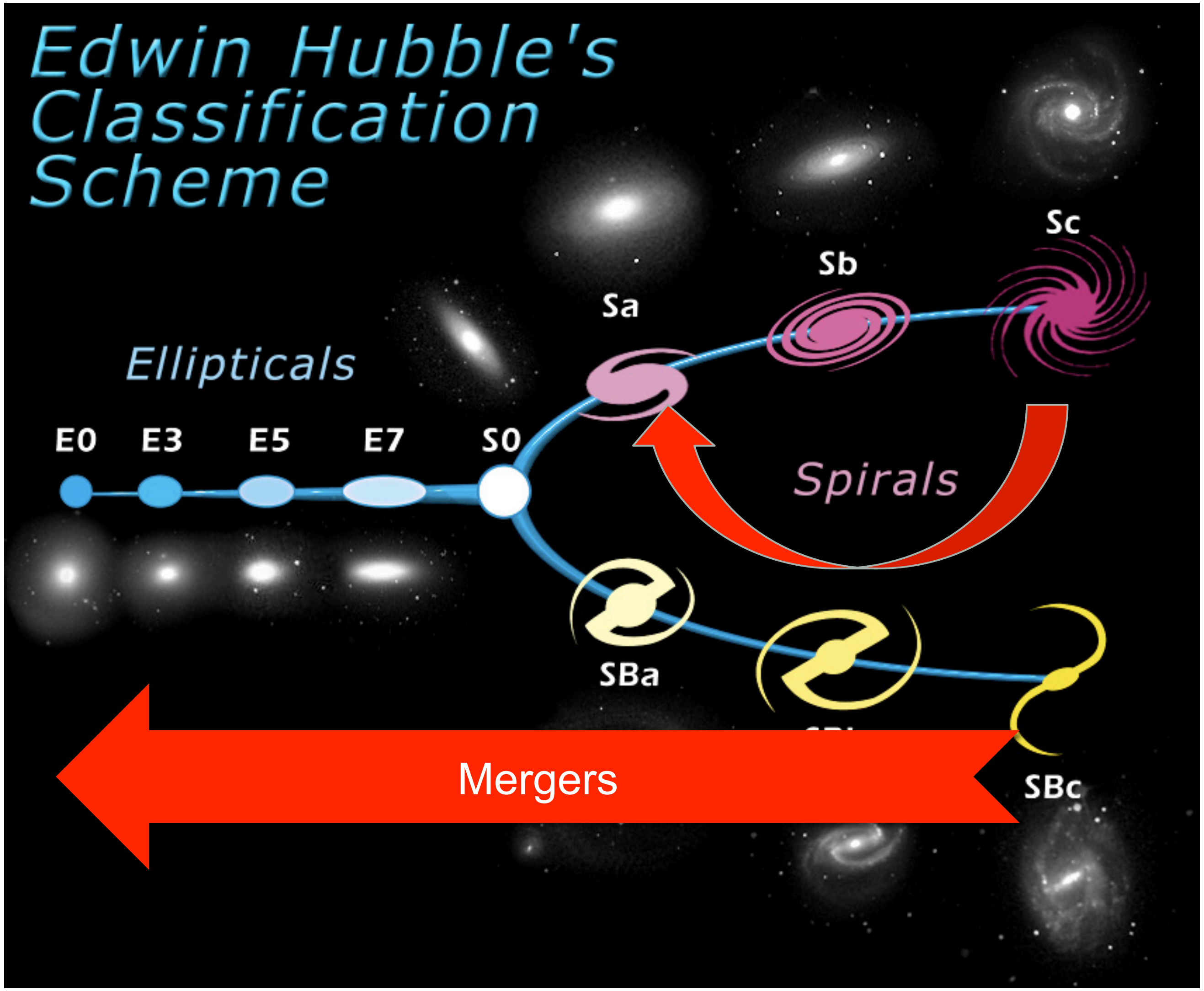
Spatially Resolved K-S Law



Saito et al. in prep

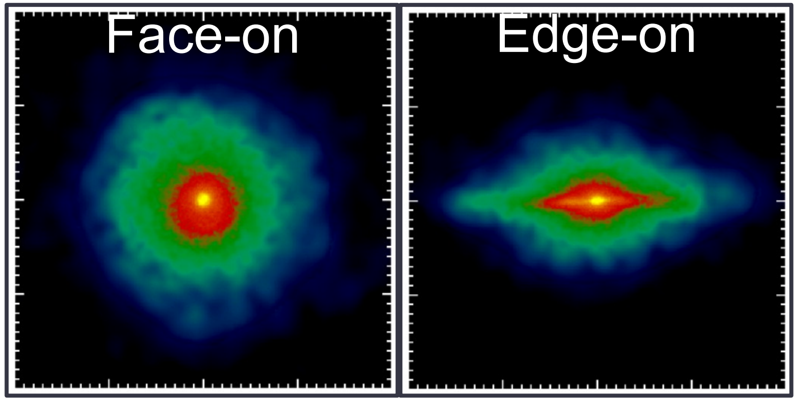


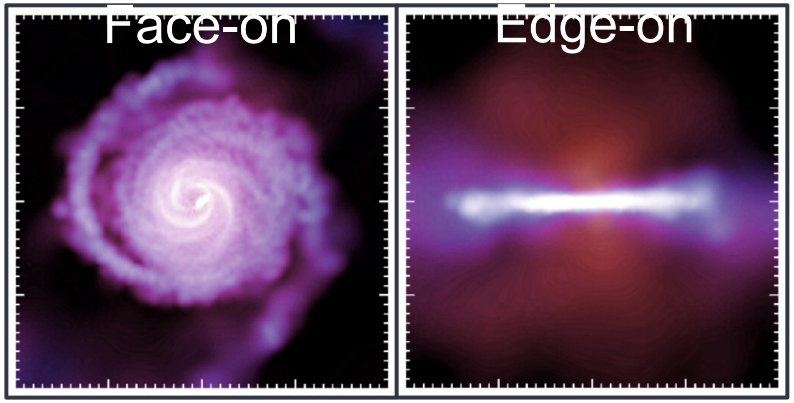
Morphological Evolution



Formation of an extended gas disk

- Stars: Violent relaxation -> Spheroidal component
- Gas: Nuclear/Extended star formation

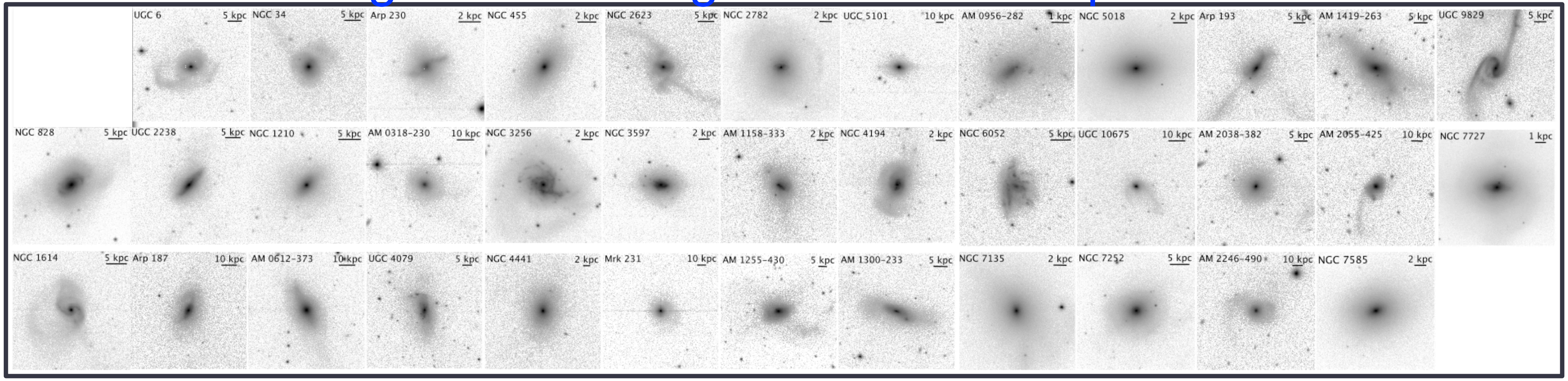




The distribution of stars vs. gas in a merger remnant
(*Springel & Hernquist+05)*

Sample of Merger Remnants

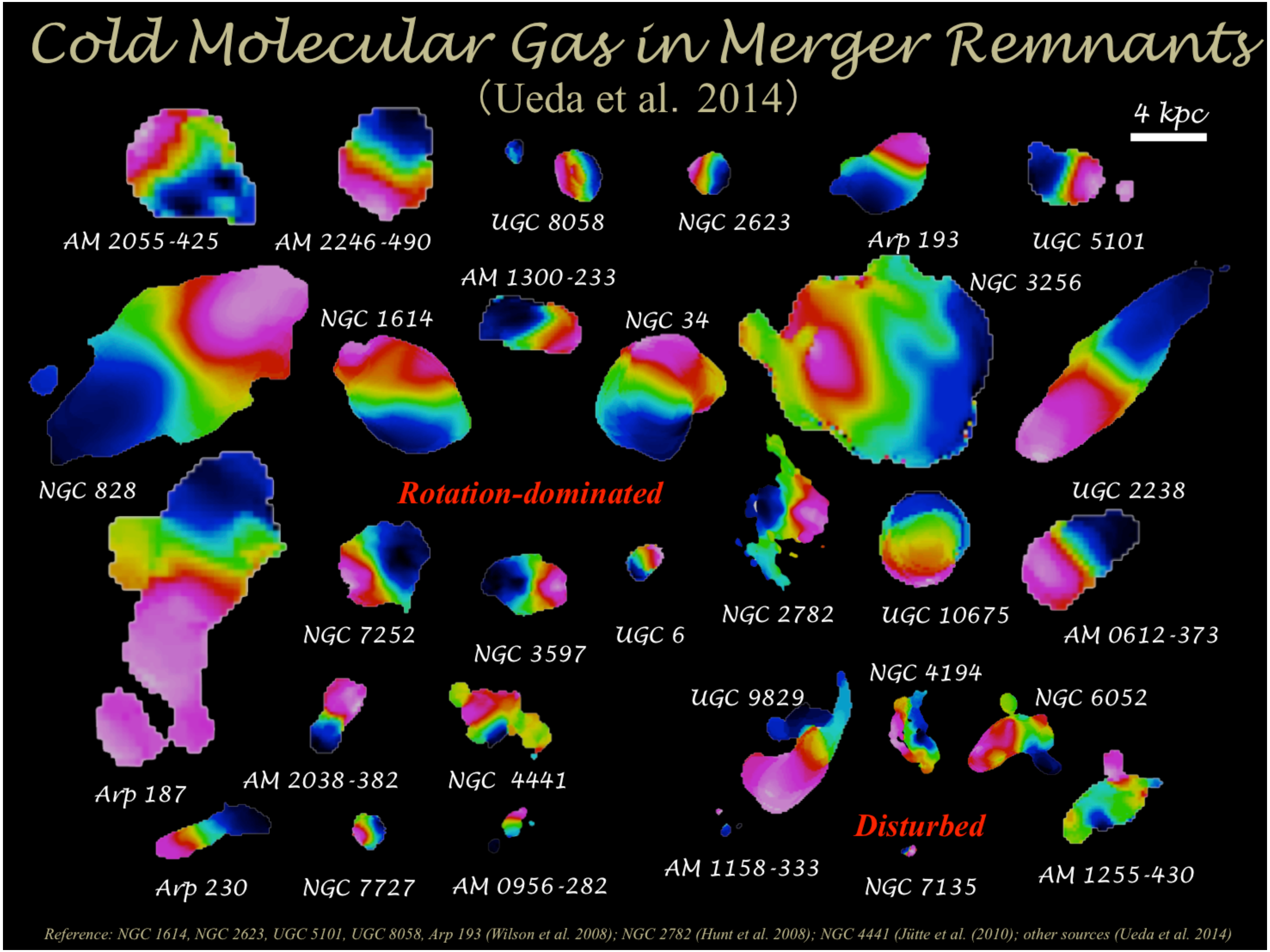
K-band images of 37 merger remnant sample



(Images: Rothberg & Joseph 2004)

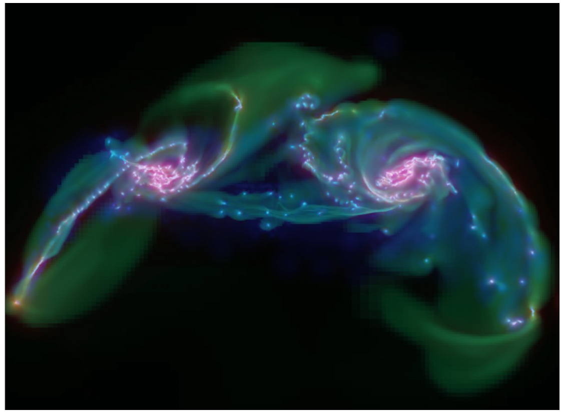
Our sample is drawn from the ***optically-selected*** merger remnant sample (Rothberg & Joseph 2004) according to the following criteria:

1. Optical morphology (tidal tails, loops, and shells)
2. Single nucleus
3. The absence of nearby companion

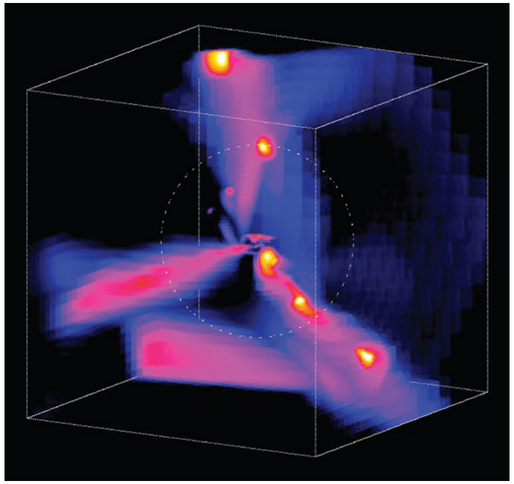

Cold Molecular Gas in Merger Remnants
(Ueda et al. 2014)
4 kpc
AM 2055-425
AM 2246-490
UGC 8058
NGC 2623
Arp 193
UGC 5101
AM 1300-233
NGC 3256
NGC 1614
NGC 34
NGC 828
Rotation-dominated
UGC 2238
NGC 7252
NGC 3597
UGC 6
NGC 2782
UGC 10675
AM 0612-373
NGC 4194
UGC 9829
NGC 6052
Arp 187
AM 2038-382
NGC 4441
Disturbed
Arp 230
NGC 7727
AM 0956-282
AM 1158-333
NGC 7135
AM 1255-430
Reference: NGC 1614, NGC 2623, UGC 5101, UGC 8058, Arp 193 (Wilson et al. 2008); NGC 2782 (Hunt et al. 2008); NGC 4441 (Jütte et al. (2010); other sources (Ueda et al. 2014)

Results and Implications

- 54% of the sources have smaller gas disks than the K-band effective radius
  - **Candidates for early type galaxy**
- 46% of the sources have larger gas disks than the K-band effective radius
  - **Candidates for late type galaxy with stellar bulge**



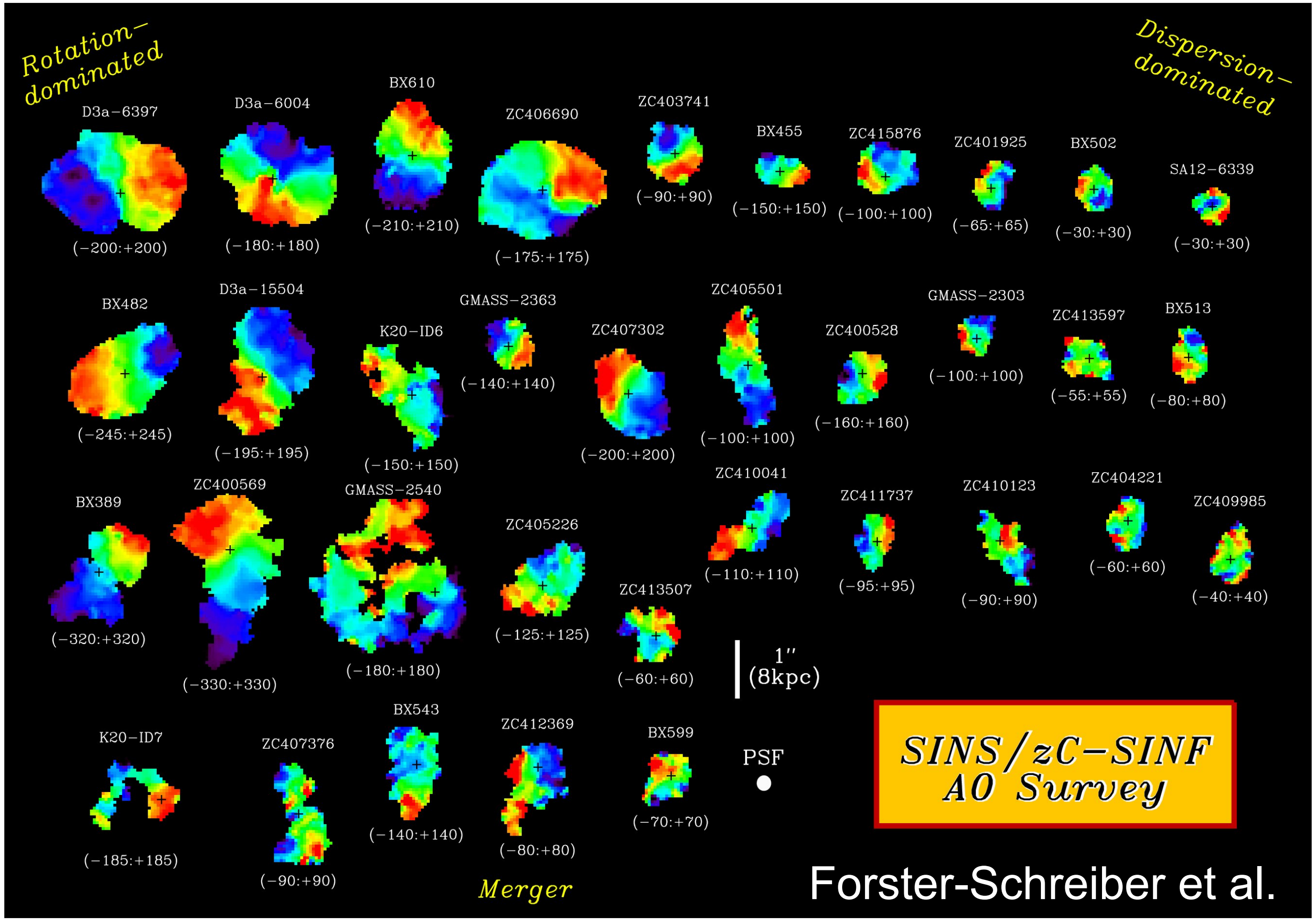
Teyssier et al. (2010)



Dekel et al. (2009)

Results and Implications

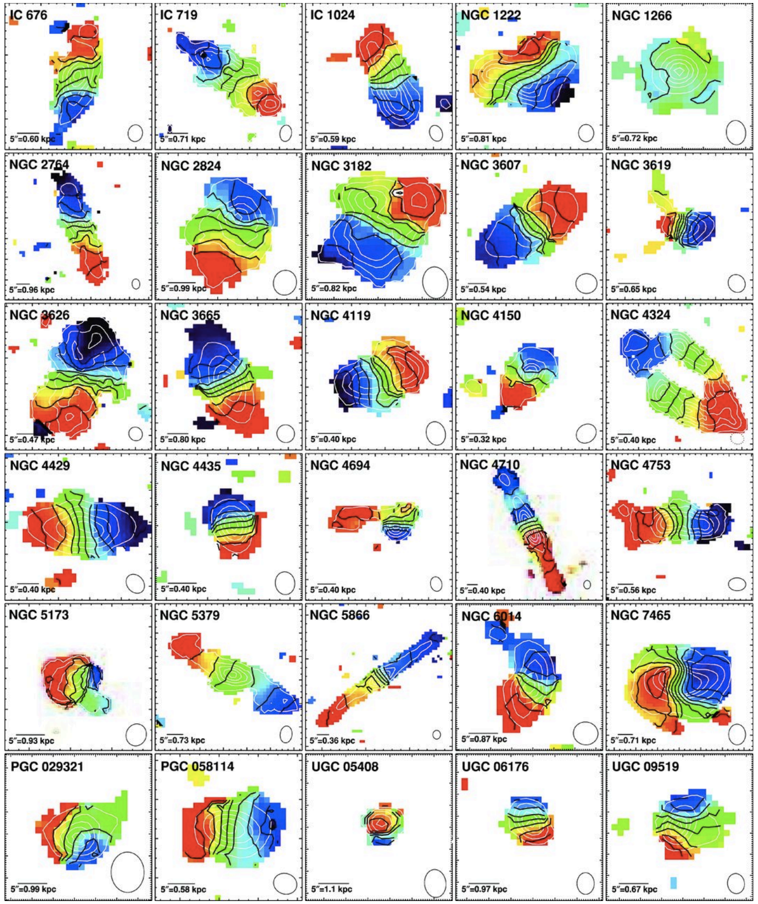
Kinematics alone is not sufficient to tell if these high-z galaxies are **quiescent disks (favoring cold accretion)** or **mergers**.



Future of ALMA and Synergies with Subaru in the 2020's

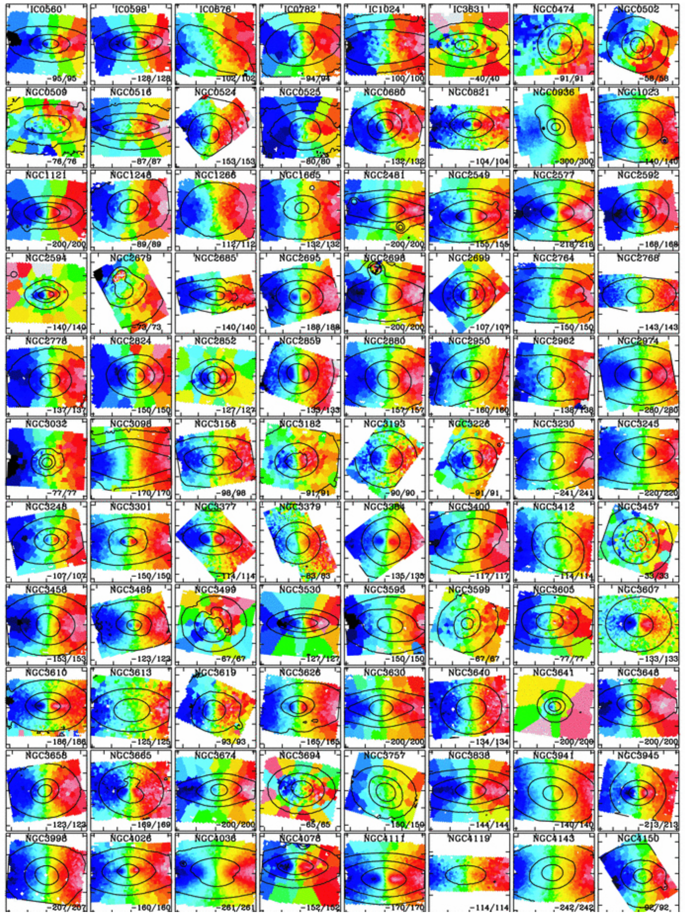
Subaru – ALMA Synergy

Cold molecular gas



Alatalo et al. (2013)

Warm/ionized gas



Krajnović et al. (2011)

Results from ATLAS3D

ALMA in 2020 and beyond

- 0.01″ resolution realized (currently ~0.1″)
- Point source sensitivity improved by 50% (with Full ALMA)
- (almost) all frequency bands available from 35 GHz – 900 GHz
- VLBI and solar observations
- Future development (2020-2030)
  - Multi-beam receiver (Increase the FOV)
  - Longer baselines (even higher angular resolution)
  - Better correlator
  - Wider bandwidth

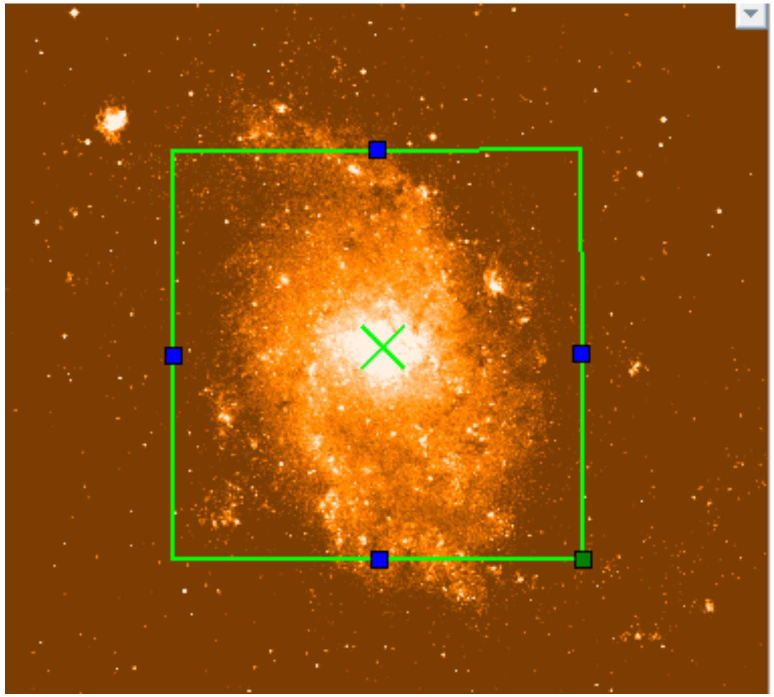
ALMA FOV

Band	Frequency [GHz]	Wavelength [mm]	FOV [arcsec]
3	84 - 116	2.6 – 3.6	~52”
4	125 - 163	1.8 – 2.4	~32”
6	211 – 275	1.1 – 2.4	~21”
7	275 – 373	0.80 – 1.09	~17”
8	385 – 500	0.60 – 0.78	~11”
9	602 – 720	0.42 – 0.50	~8”
10	787 – 950	0.32 – 0.38	~6”

Requirements for IFU

- Nearby galaxies are very large (1-10s of arcmin)
- 880 ALMA pointings (Nyquist @ 100GHz) to cover 14 x 14 arcmin
- Both ALMA and Subaru/IFU will not be ideal for a large scale kinematical mapping of large galaxies

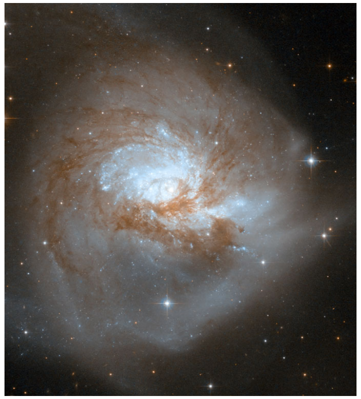
M33

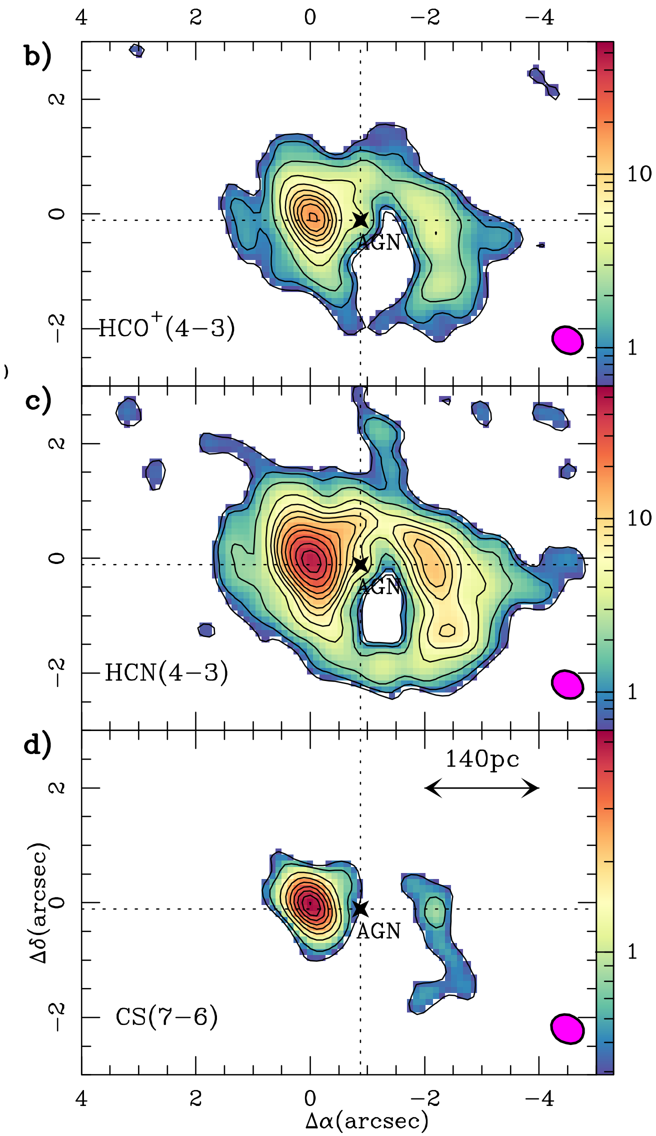


Requirements for IFU

- Focus on nuclear regions of nearby galaxies (1 – 10" scale) or compact U/LIRGs (~< 60" scales)
- Nuclear inflow/outflow kinematics of cold gas (ALMA) and ionized/warm gas (Subaru)
- Comparable FOV (6 – 11") at high frequency ALMA bands (> 400 GHz).

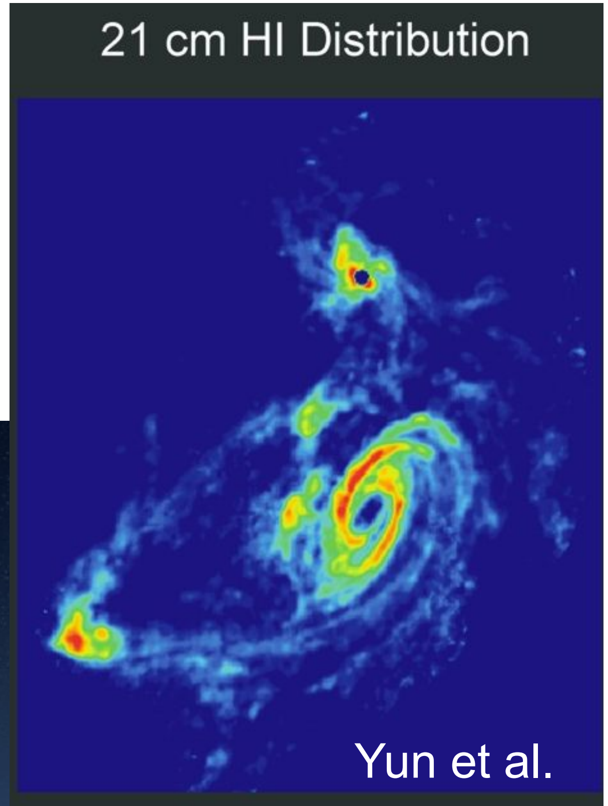

VV114

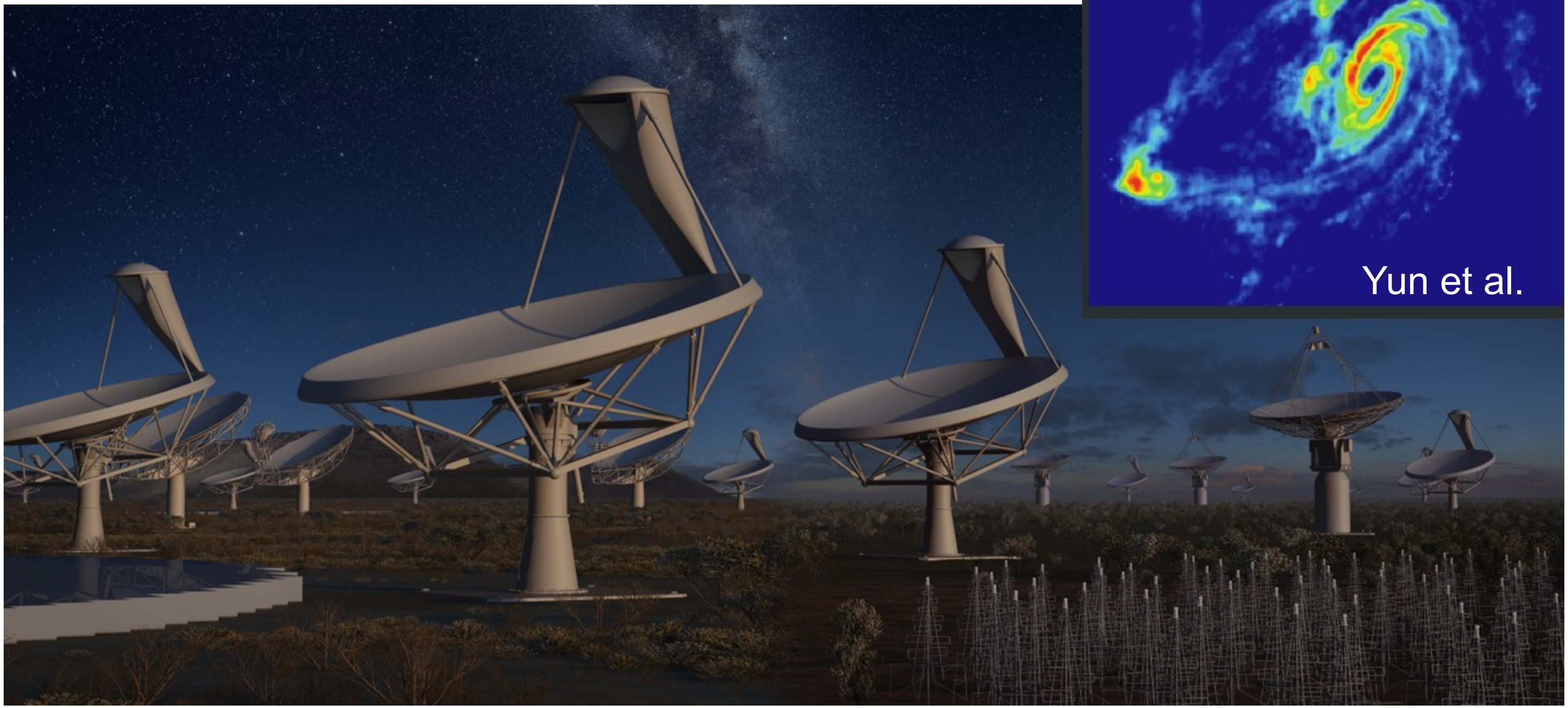

NGC3256



NGC1068

HI kinematics with SKA (2020 -)





Summary

- ALMA producing new results
  - Inflow, outflows in SB and AGNs
  - Merging galaxies (K-S law, Morphology, outflows)
  - and a lot more!
- ALMA in the 2020s
  - 0.01” resolution
  - All frequency bands (cold gas to warm/dense gas)
  - FOV will still be a problem unless we implement a multi-beam receiver
- Subaru-ALMA synergies in the 2020s
  - Kinematics of cold and warm/ionized gas
  - FOV of Subaru/IFU and high frequency ALMA bands are comparable
  - Wide area IFU will be complementary to future development of ALMA