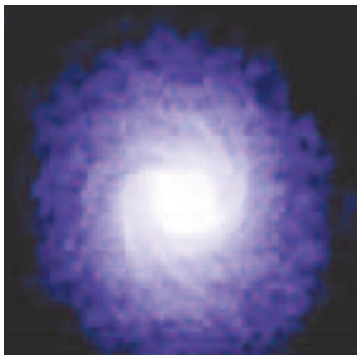
Synergy with ALMA beyond 2020

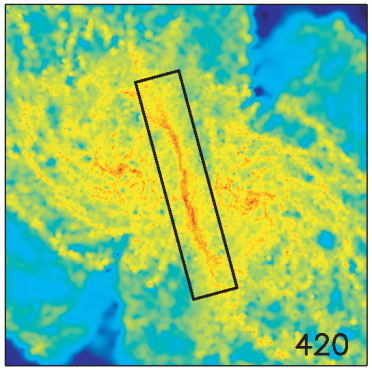
Daisuke Iono
(NAOJ, Chile Observatory)

Major Merger Evolution

Saitoh et al. (2009)



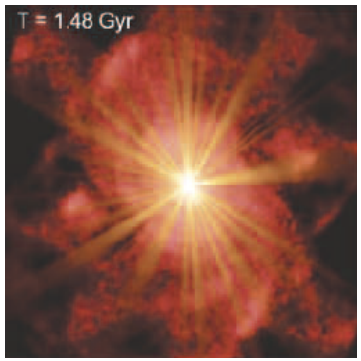
Galaxy Collision
(early stage)



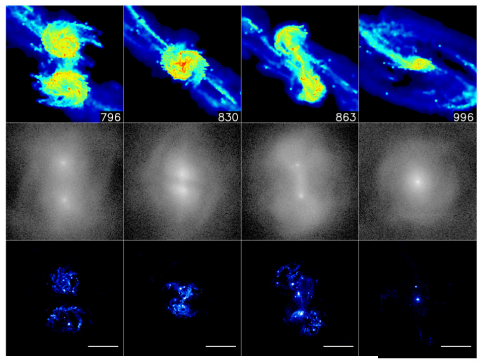
Merging
(merger remnant)

Formation
&
Evolution

Active Star Formation
(intermediate stage)



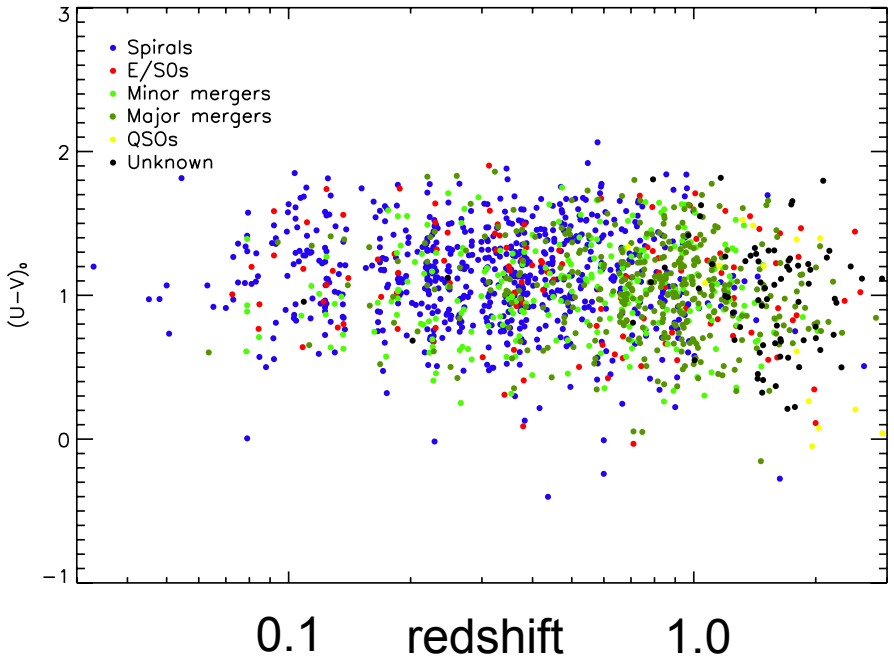
Growth of Black Hole
(late stage)

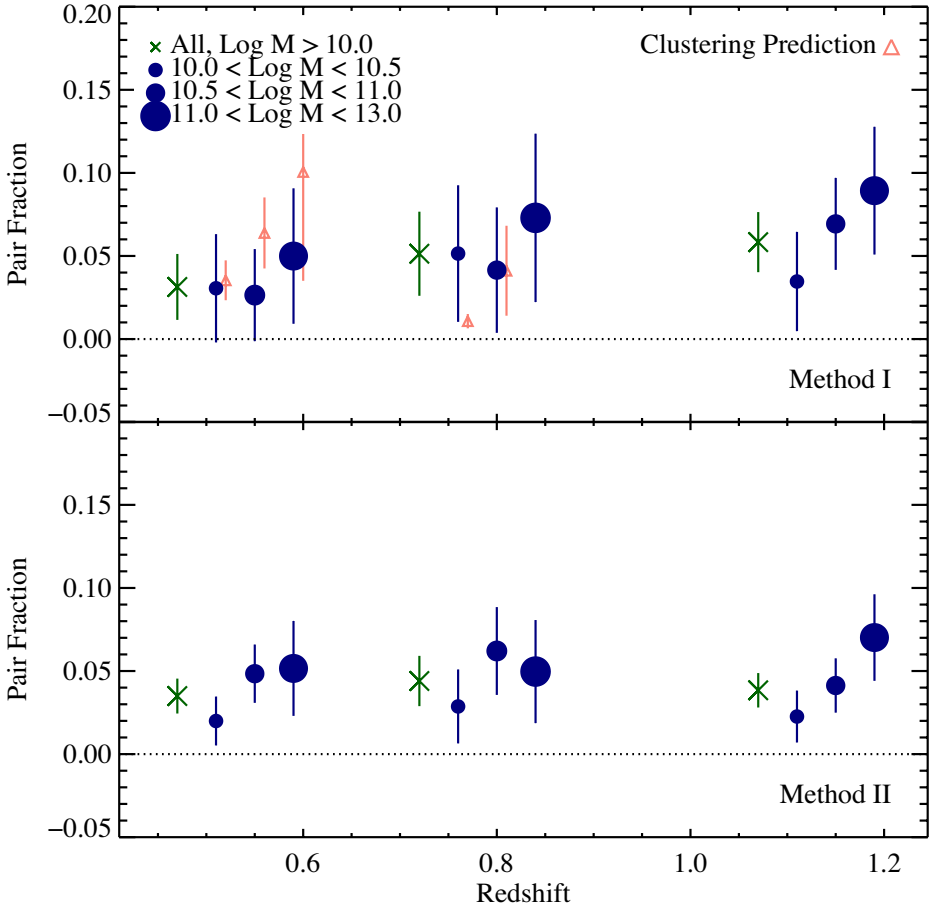


Hopkins et al. (2006)

Matsui et al. (2012)

Role of mergers in galaxy evolution

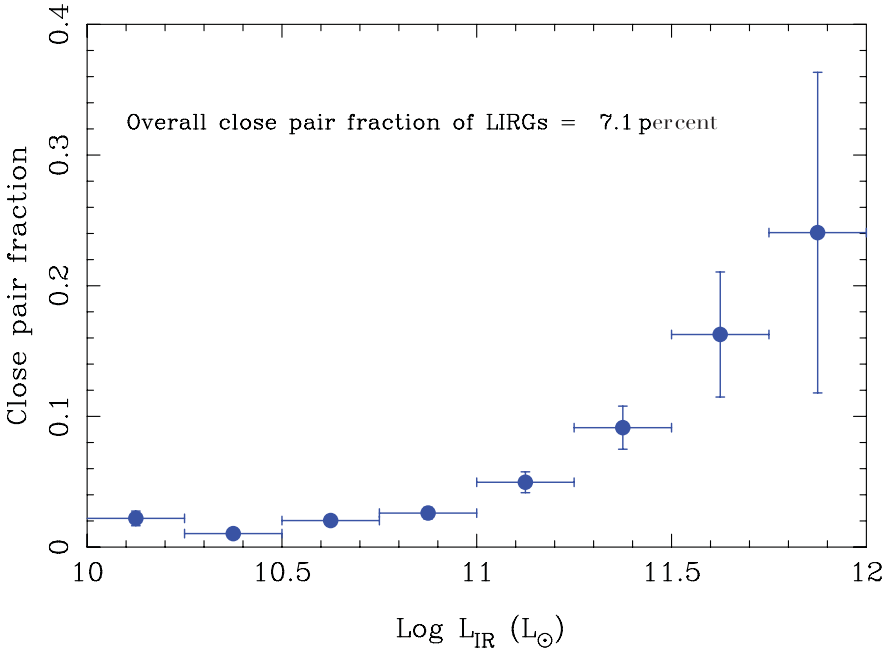




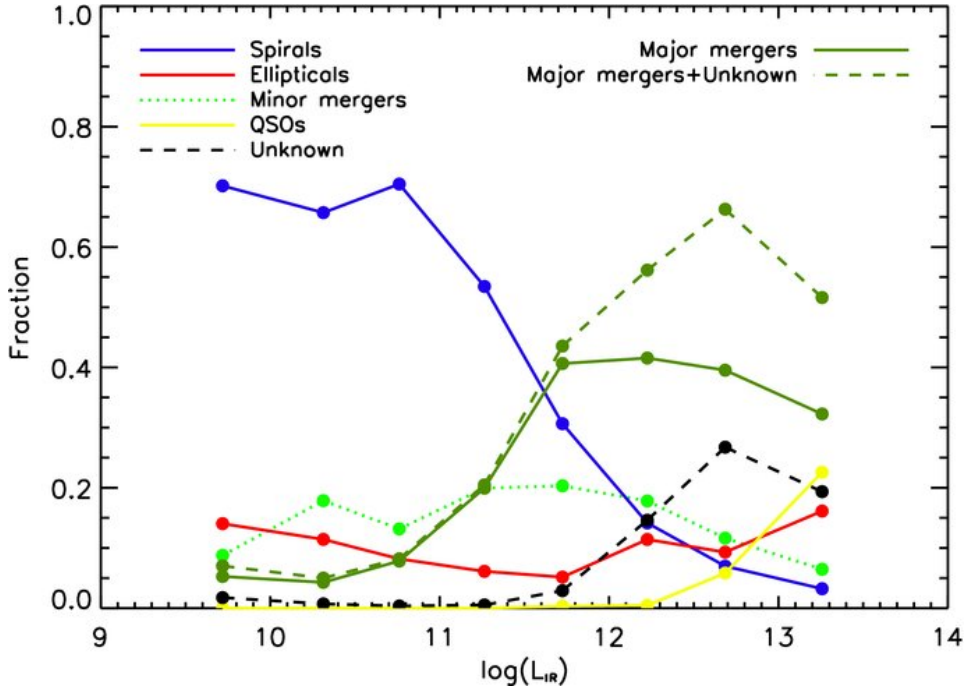
1503, 70 micron selected galaxies in the 0.01 < z < 3.5 universe using COSMOS Kartaltepe et al. (2010)

Subaru MOIRCS Bundy et al. (2009)

Mergers produce bright galaxies



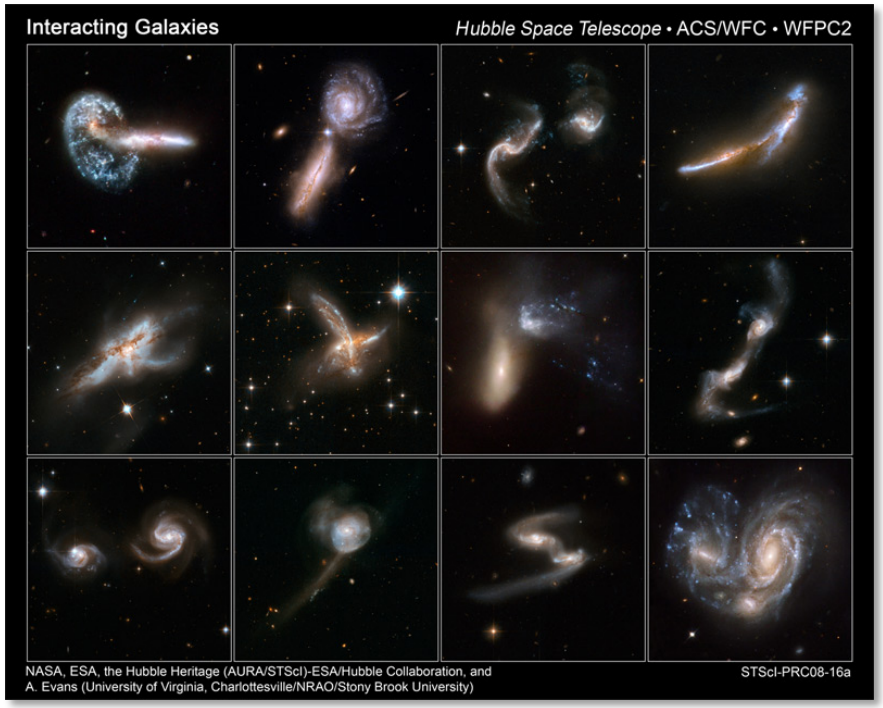
9397 galaxies in the z < 0.1 universe using SDSS
Ellison et al. (2013)



Kartaltepe et al. (2010)

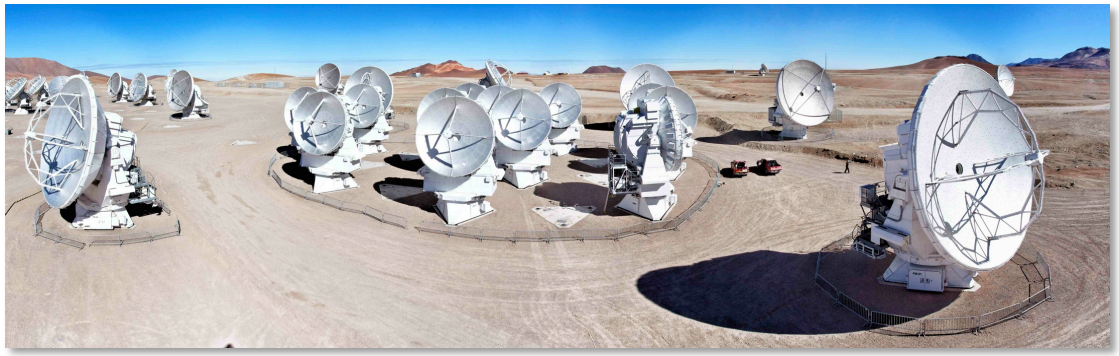
Local Merging Galaxies

- Stellar morphology, gas mass fraction, etc may be different between low and high-z.
- z = 0 merging U/LIRGs are the only sources that we can study in detail in order to understand interaction triggered SB and AGN activity.



ALMA Studies of Colliding Galaxies

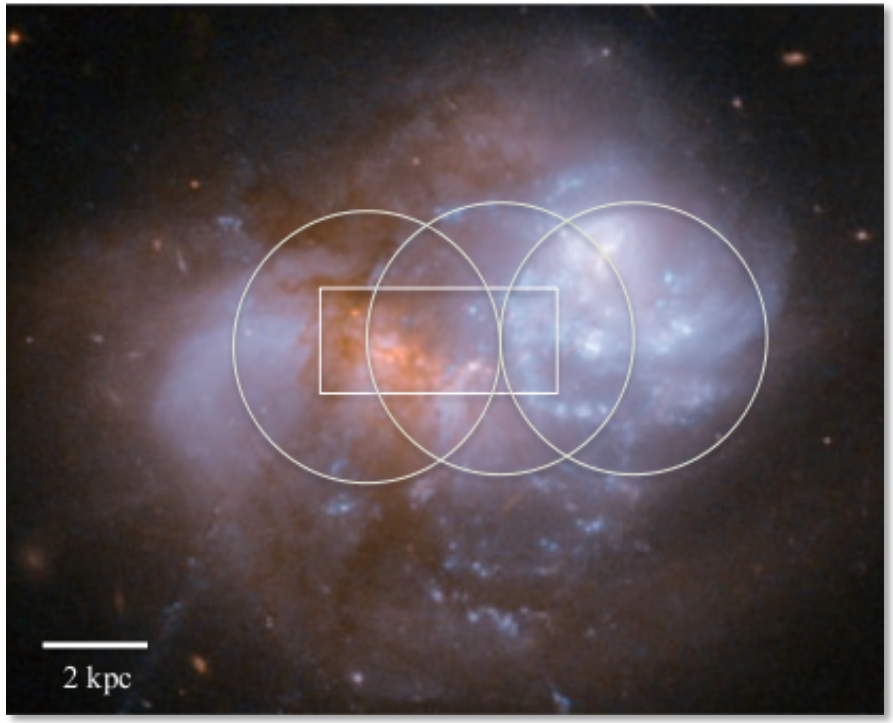
1. Case Study – VV114
2. What is the end product of a major merger?



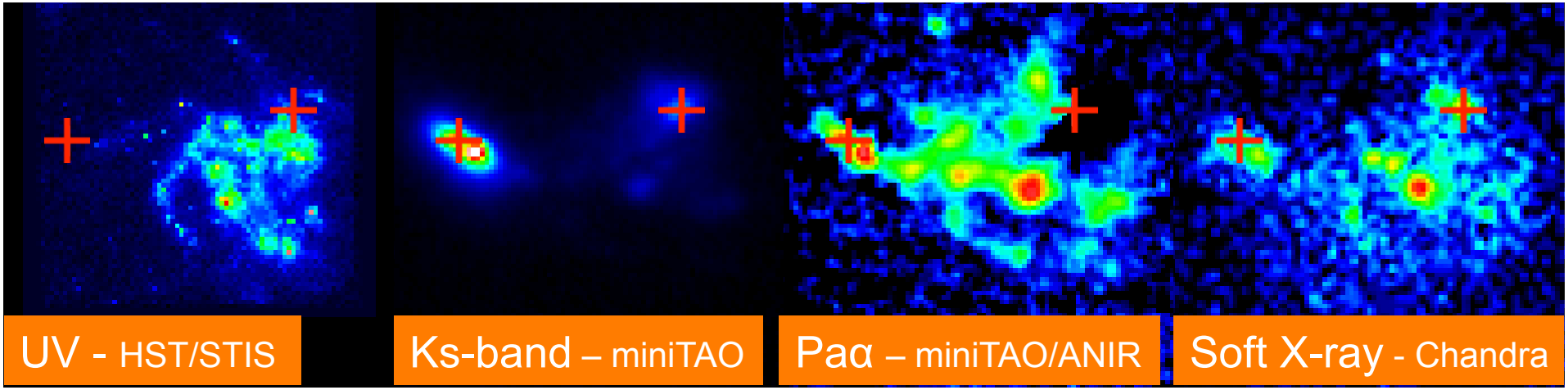
ALMA Observations of VV114

- $L_{FIR} = 4.1 \times 10^{11} L_{sun}$
- D = 77 Mpc
- projected nuclear separation ~ 6 kpc

- Iono, Saito et al. (2013)
- Saito, Iono et al. in prep



VV114 seen in different wavelengths



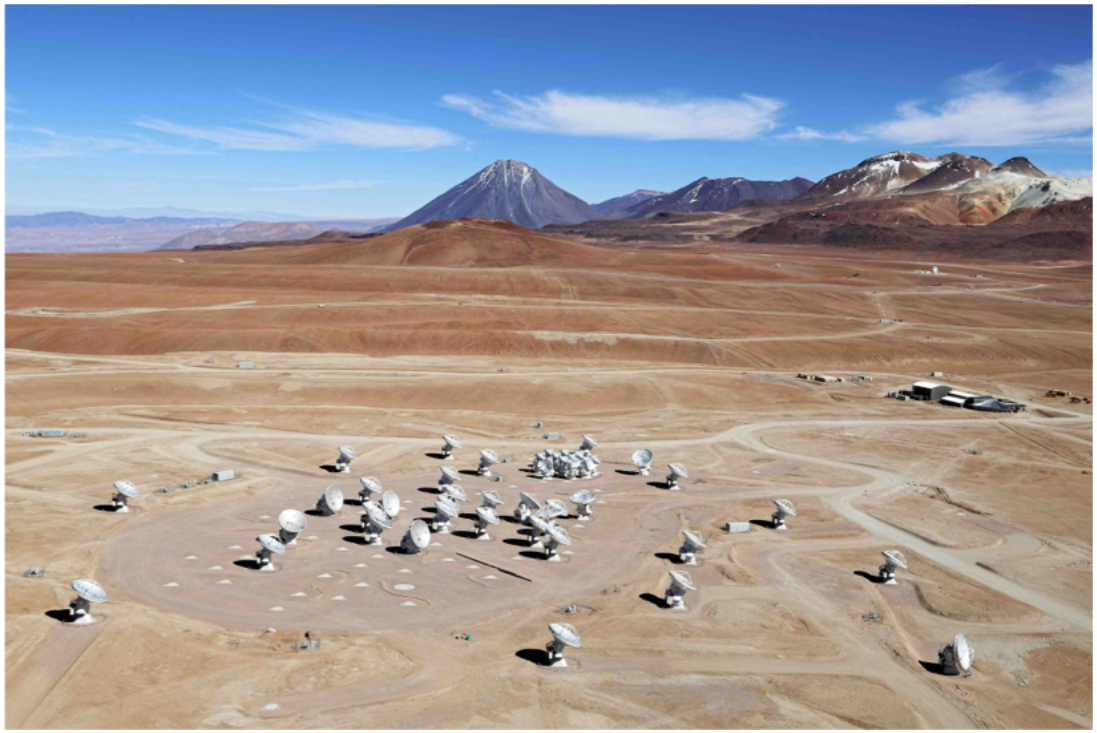
Grimes+ 2006, Le Floc'h+ 2002, Alonso+ 2002, Tateuchi+ 2012

VV114E	VV114W
A compact starburst (mid-IR) and/or **highly obscured AGN (X-ray)**	**Diffuse starburst (mid-IR)**

Global $SFR_{Pa\alpha}$ ~ 45 M_{sun}/year

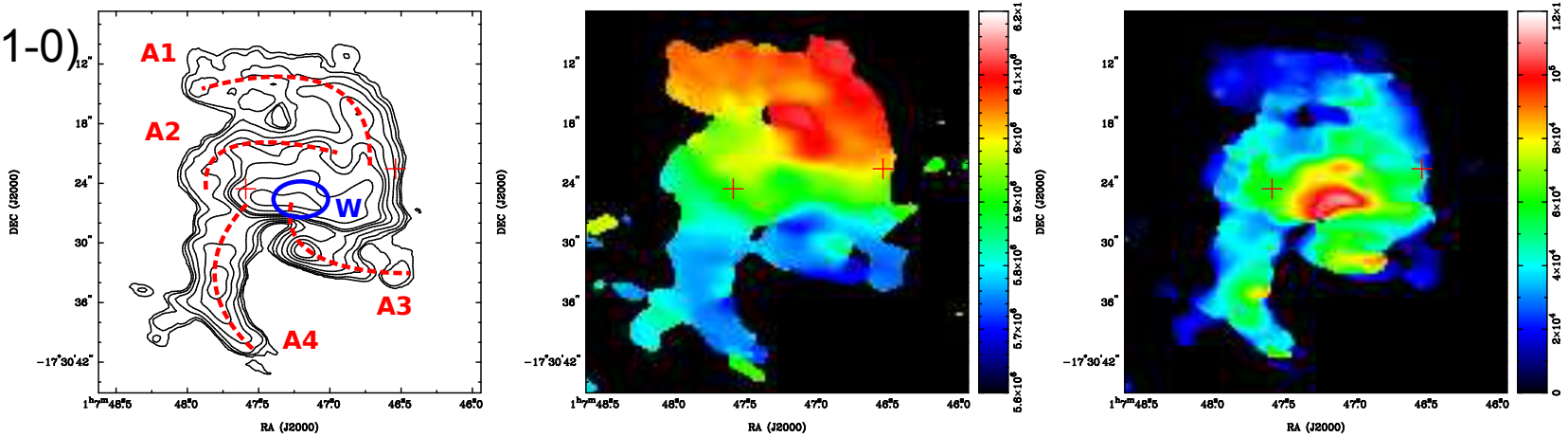
ALMA Observations

- CO(1-0), (3-2) – cold gas tracer
- HCN (4-3), HCO+(4-3) – dense gas tracer

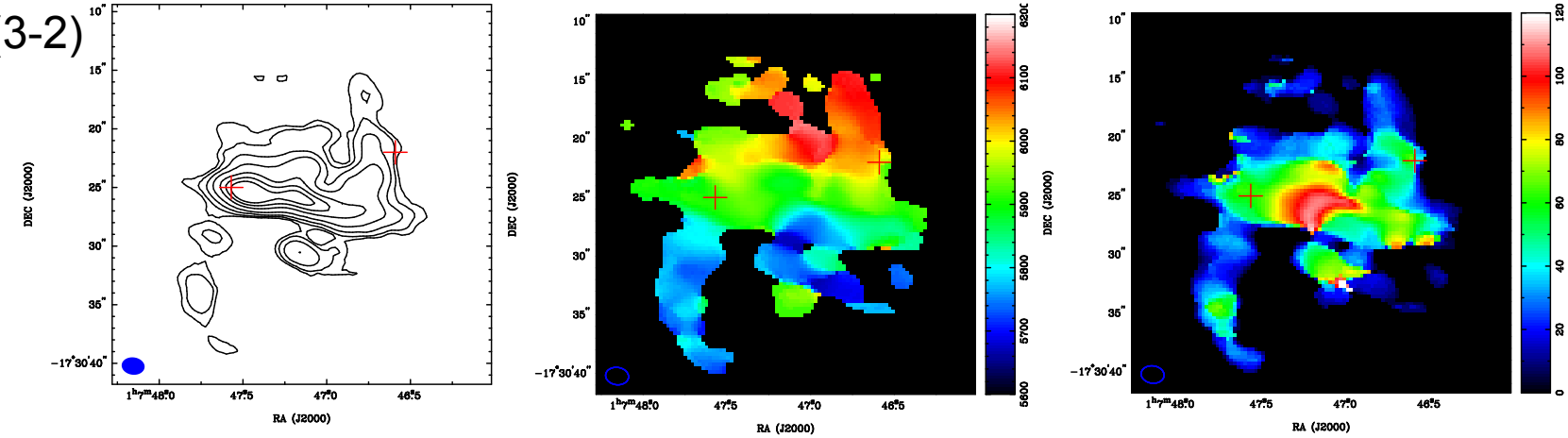


CO(1-0), CO(3-2)

CO(1-0)



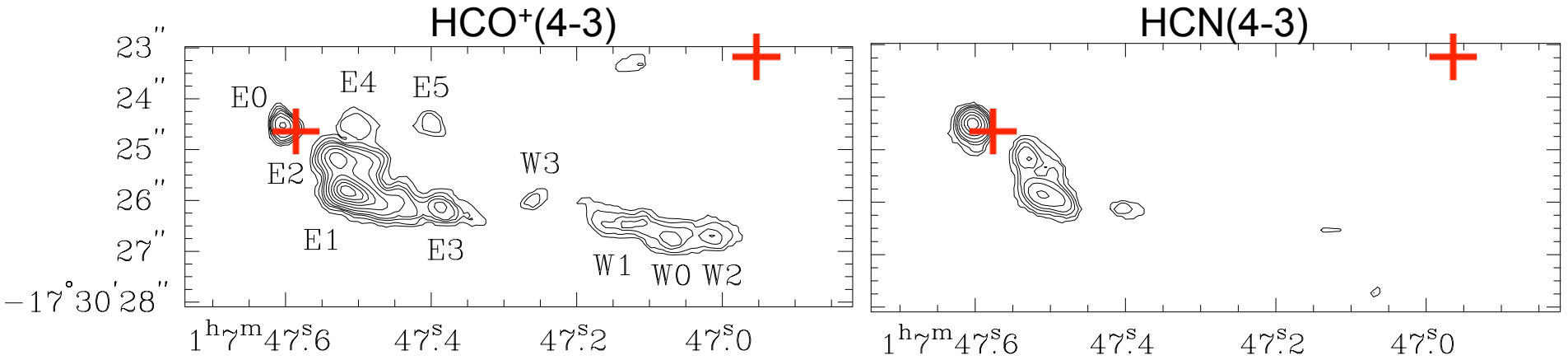
CO(3-2)



Saito, Iono et al. in prep

ALMA HCN and HCO maps

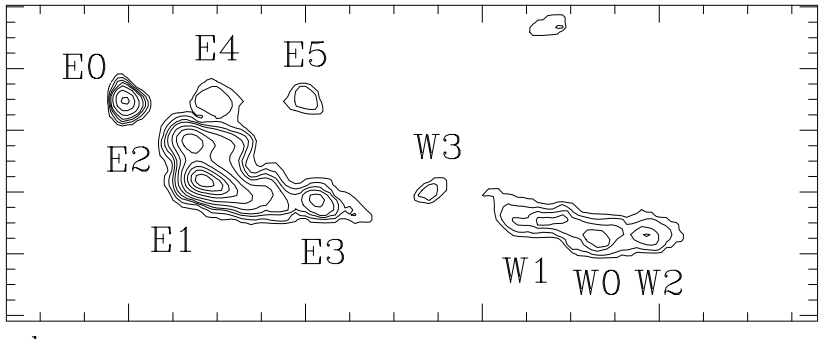
- HCN(4-3) & HCO^+(4-3)
  - Compact unresolved source (E0)
  - Extended filamentary structure with massive dense gas clumps (~230 pc, ~10^6 M_{sun})

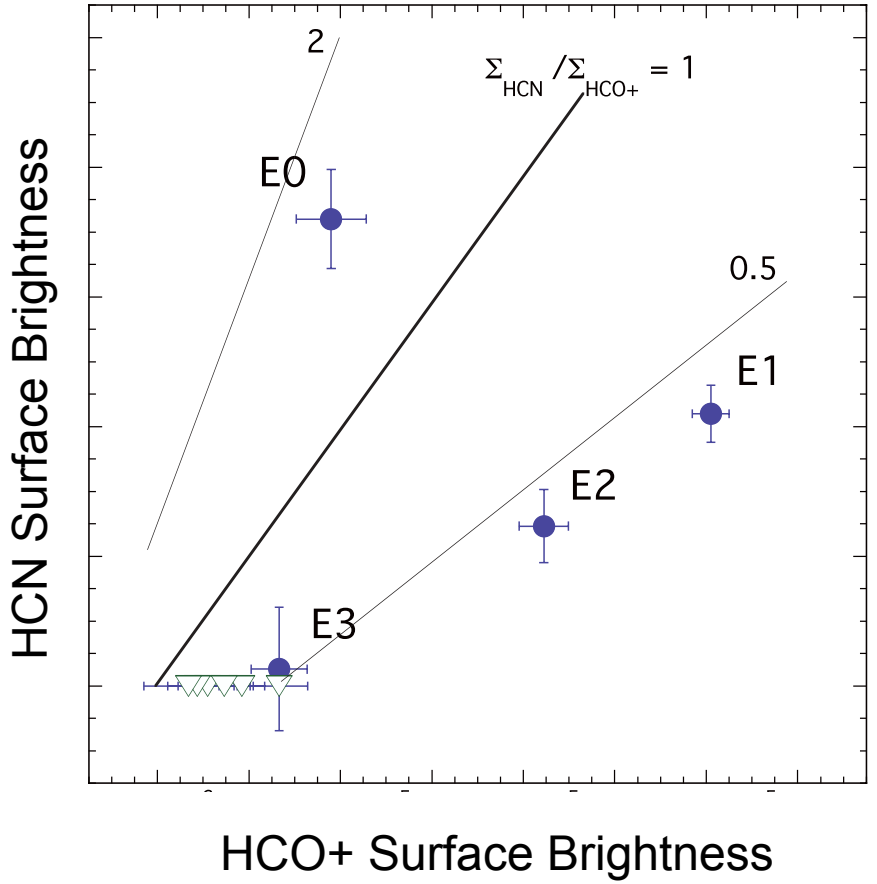


Buried AGN?

- Unresolved with 200 pc beam
- Broad linewidth (FWZI ~ 290 km/s)
- E0 has HCN/HCO > 1
- Observational evidence that such high HCN/HCO suggests AGN (e.g. Kohno et al. 2001)

Mass < 8.1 x 10^6 M_{sun} AGN triggered by the merger?





Iono, Saito et al. (2013).

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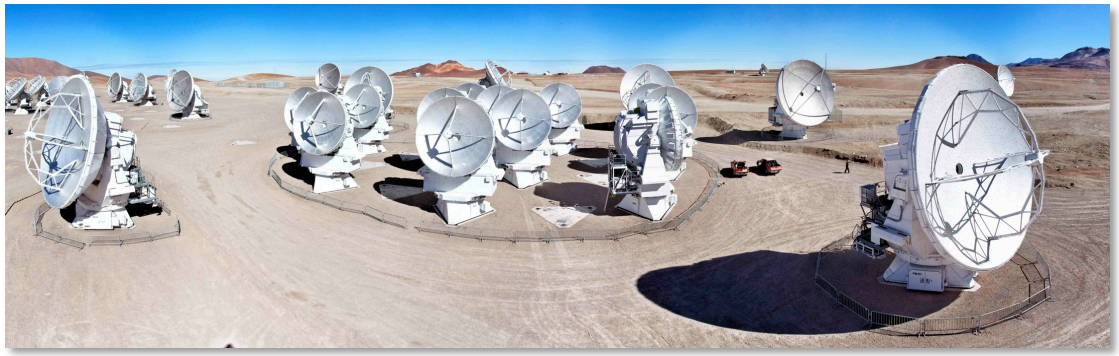
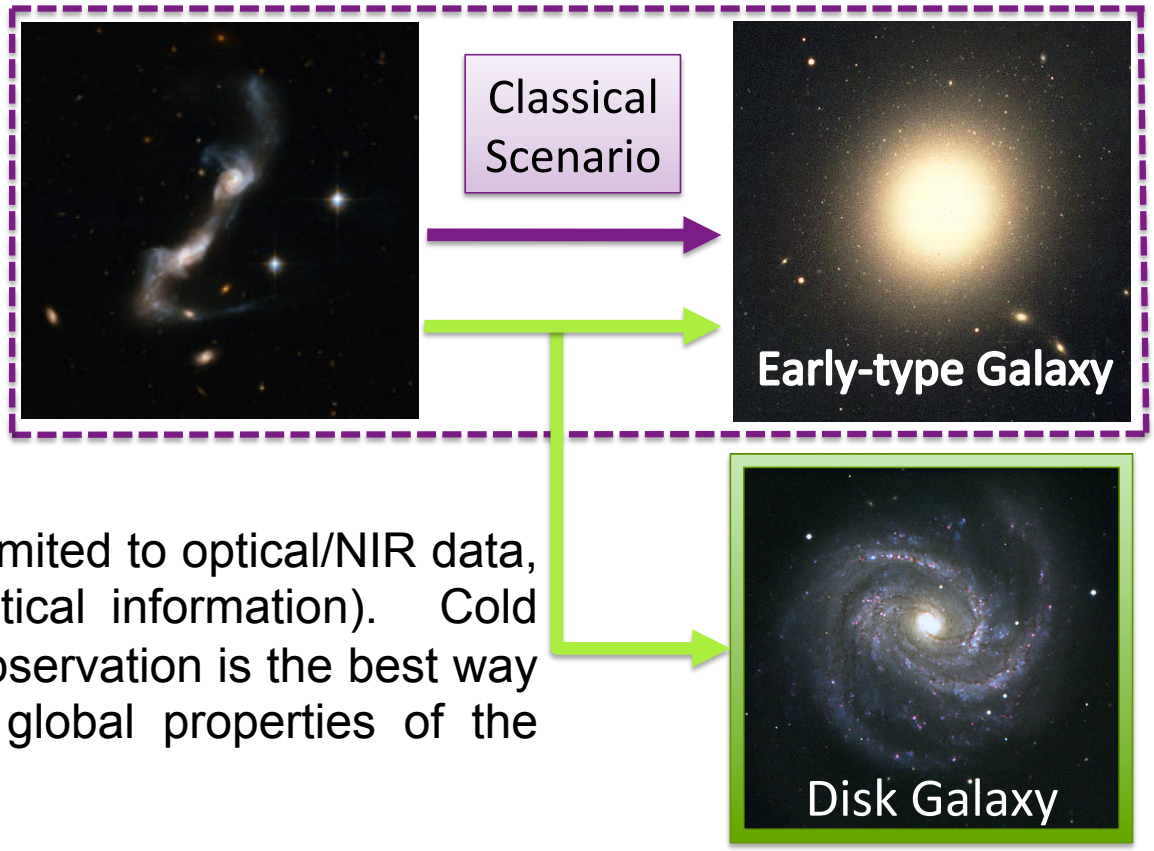


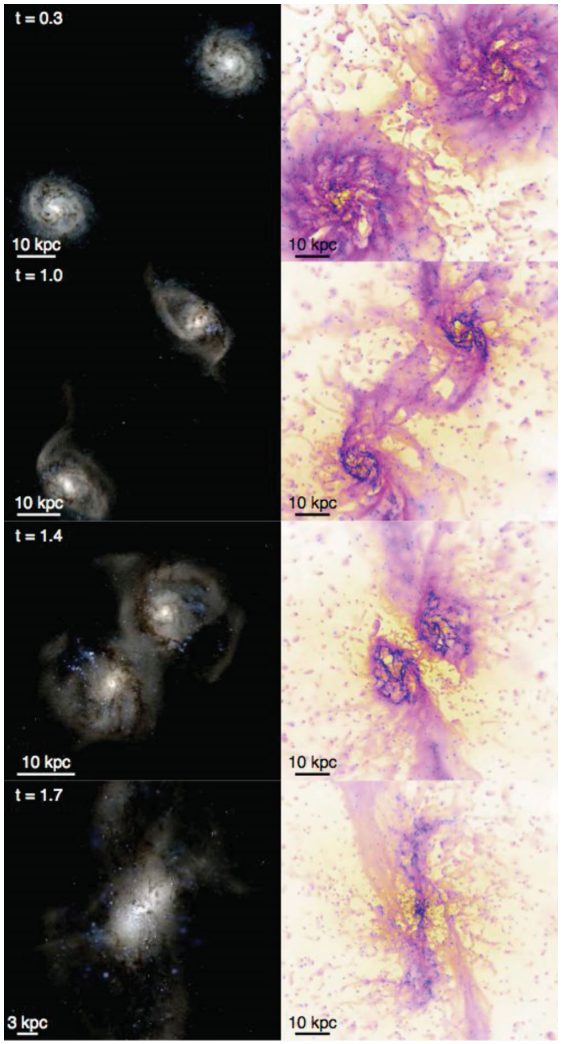
What is the end product of a major merger?

Junko Ueda (U. Tokyo) et at. in prep

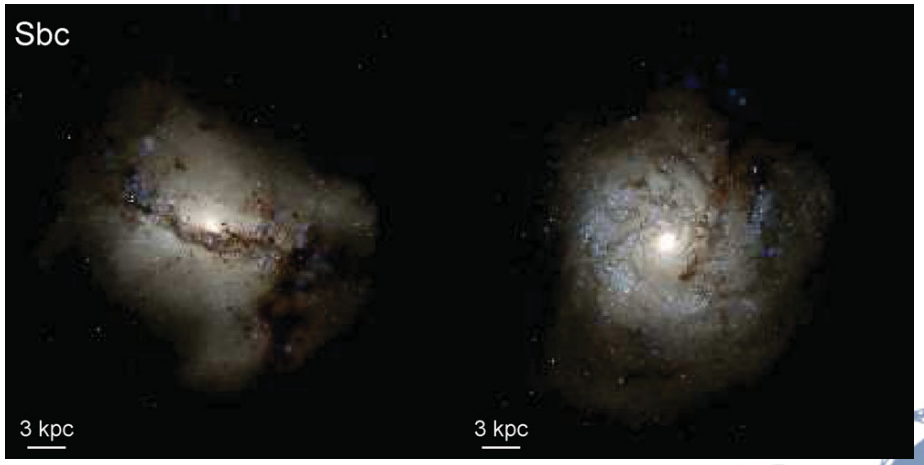


Past studies were limited to optical/NIR data, (i.e. limited kinematical information). Cold gas traced in CO observation is the best way to understand the global properties of the end product.

Disk survival

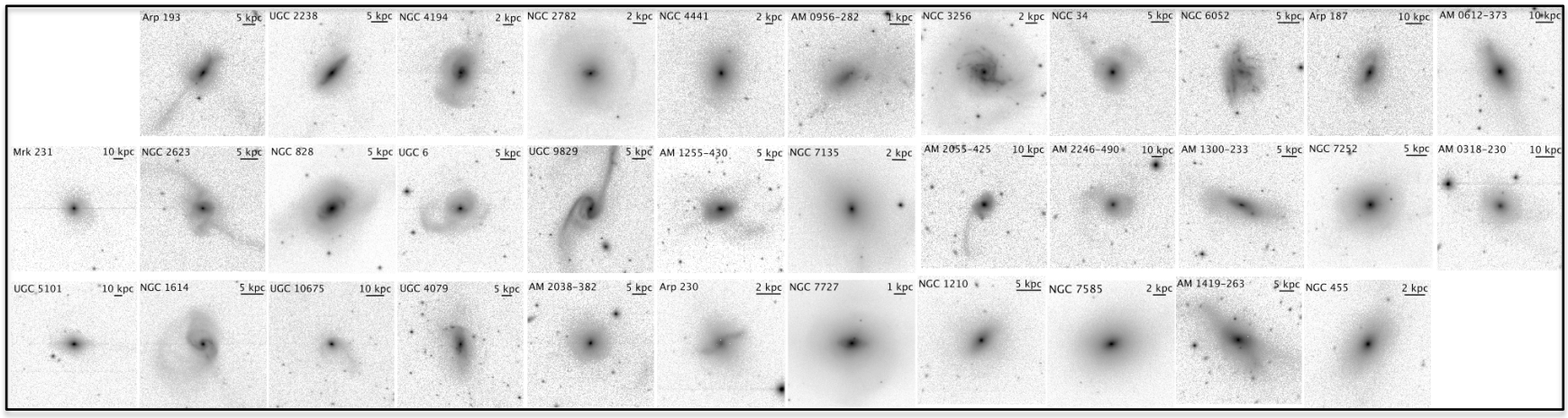


- Initial parameters, gas mass fraction can be the important parameter for disk survival. (Hopkins et al. 2006, 2013)
- AGN can also play a key role in the evolution of disks (Okamoto et al. 2008)

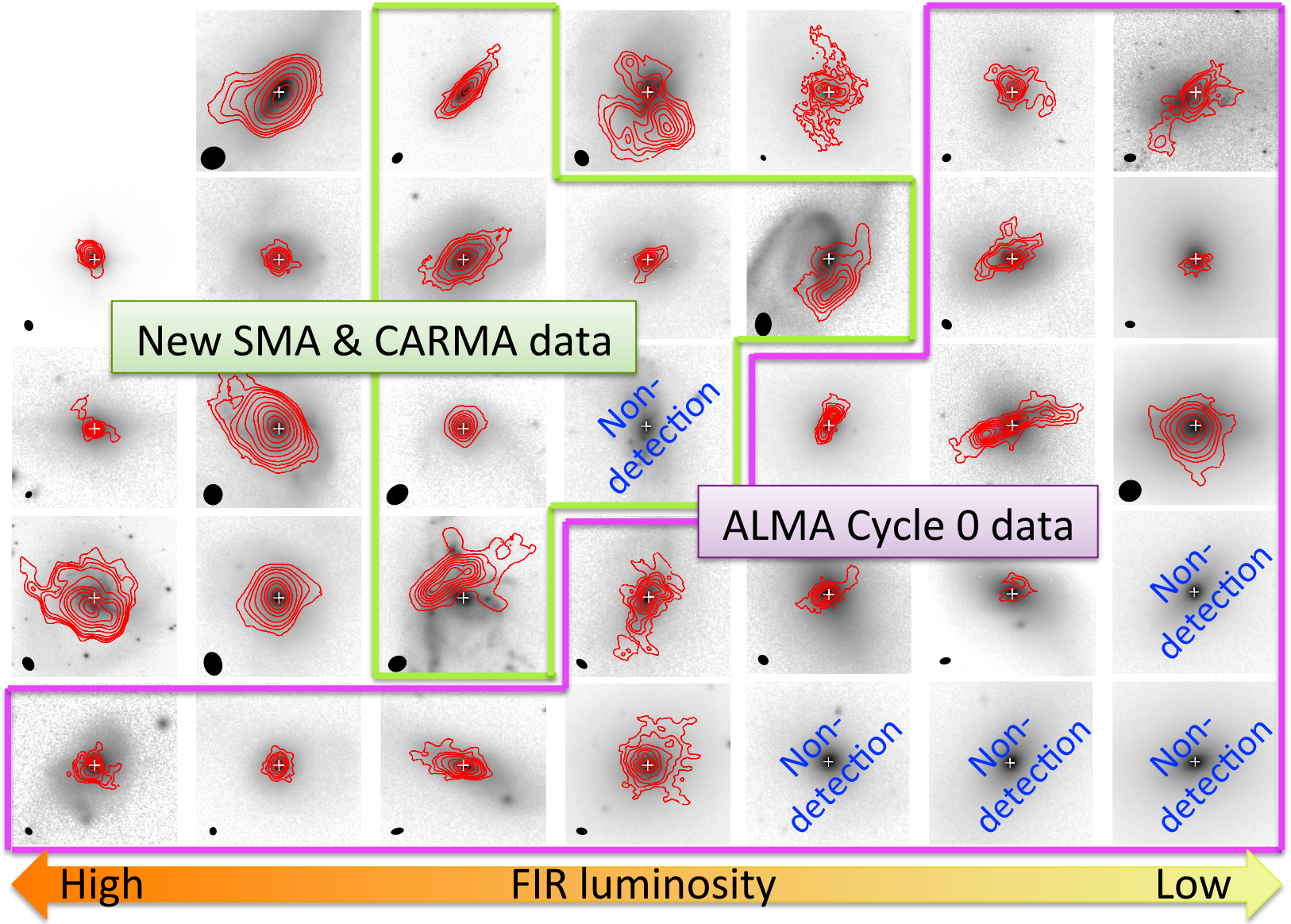


Merger Remnant Sample

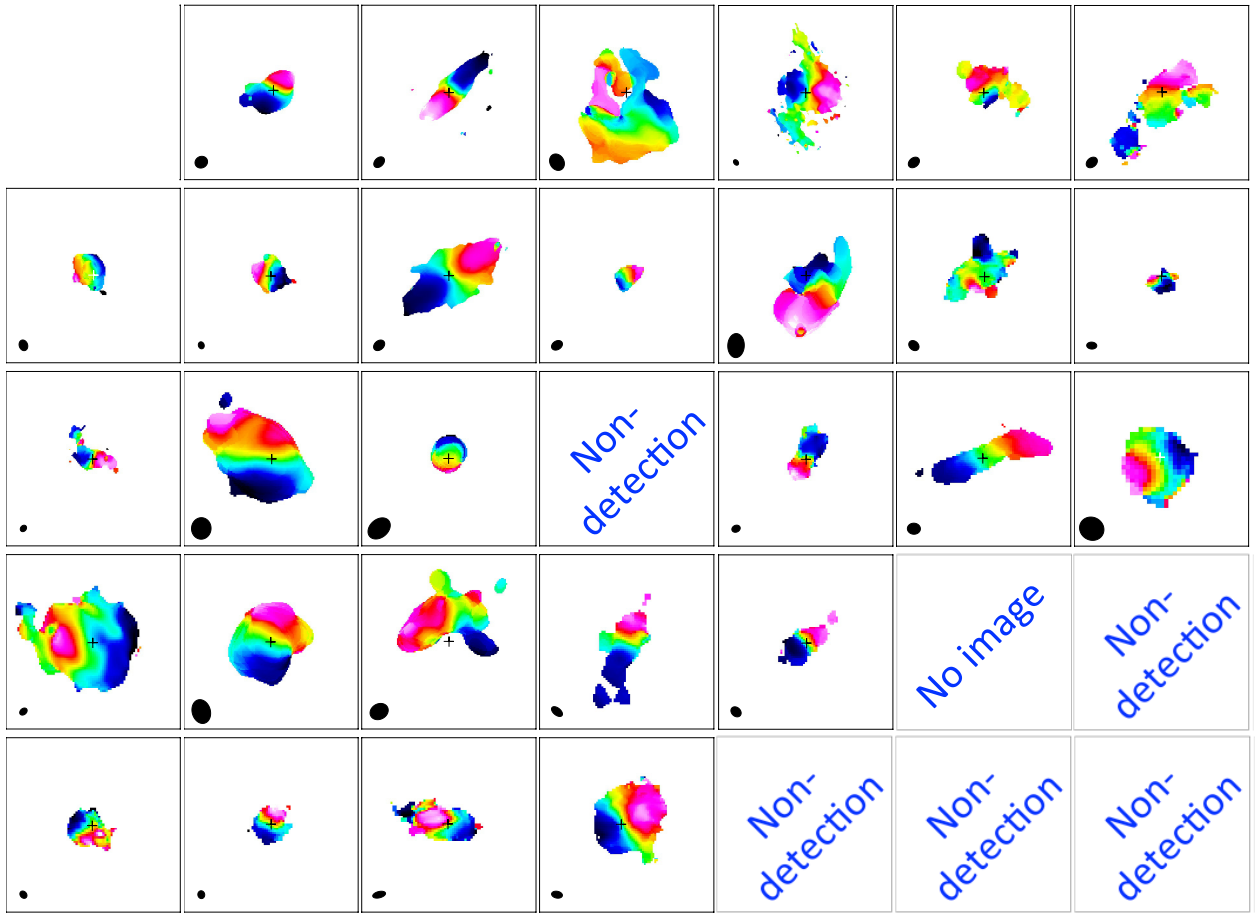
- 37 galaxies out of Rotheberg & Joseph (2004) catalog
- Rotheberg & Joseph (2004) is a catalog of 51 merger remnants compiled from 4 catalogs of peculiar galaxies (e.g., Arp, VV,..), and then selected based on K-band
    1. Optical morphology (tidal tails, loops)
    2. Single nucleus + No nearby companion



CO observations of merger remnants

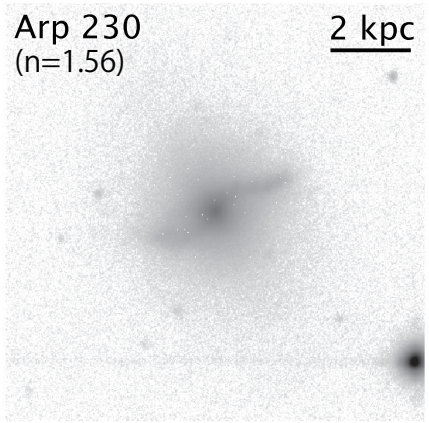


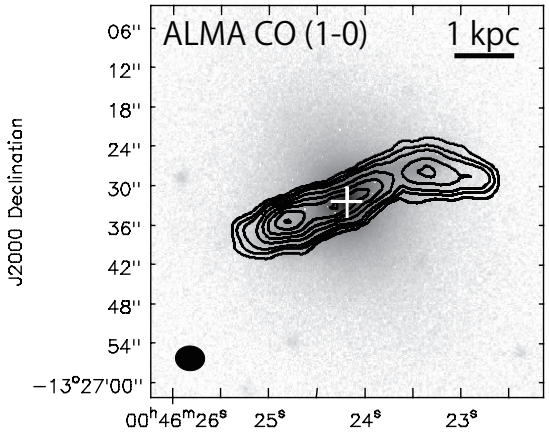
Kinematics

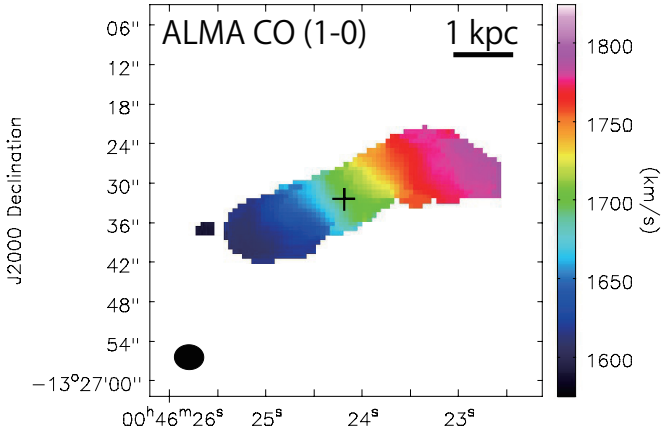


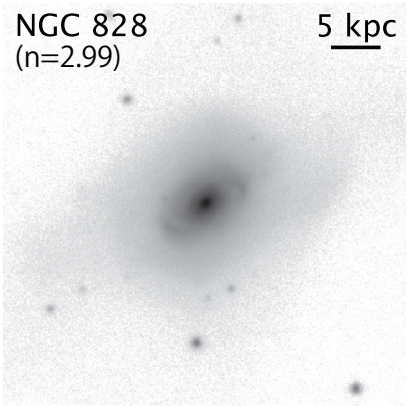
High FIR luminosity Low

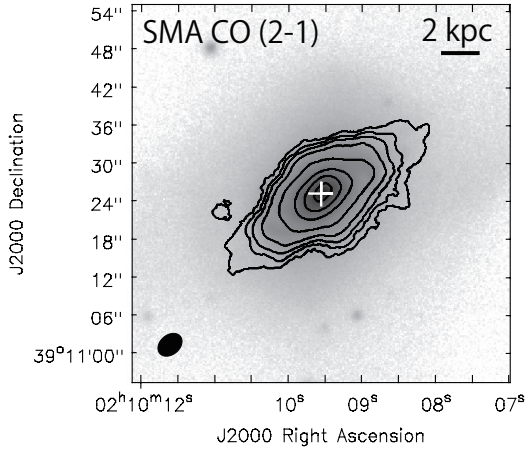
Large disks

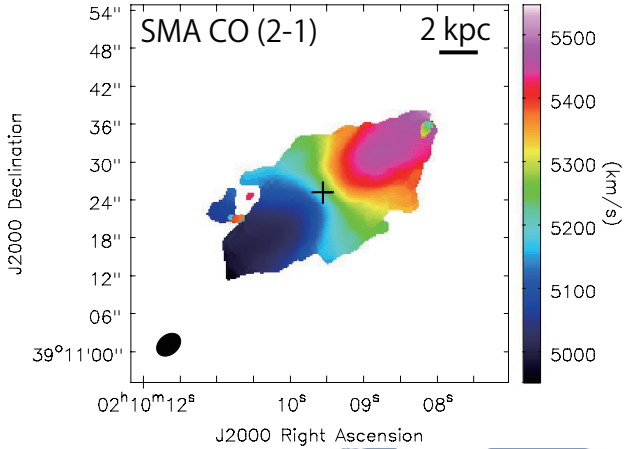

Arp 230
(n=1.56)
2 kpc


ALMA CO (1-0)
1 kpc
J2000 Declination
06''
12''
18''
24''
30''
36''
42''
48''
54''
−13°27'00''
00h46m26s
25s
24s
23s

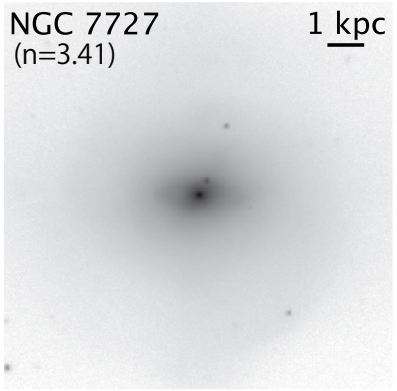

ALMA CO (1-0)
1 kpc
J2000 Declination
1800
1750
1700
1650
1600
(km/s)

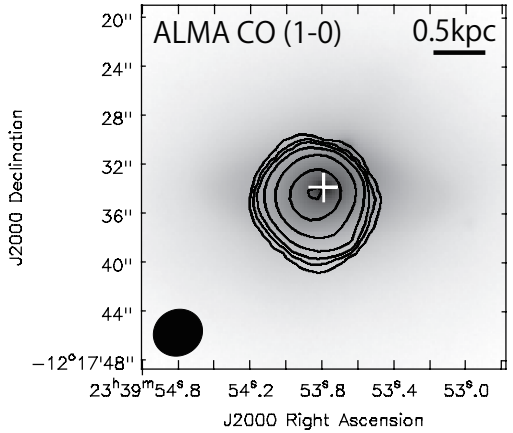

NGC 828
(n=2.99)
5 kpc

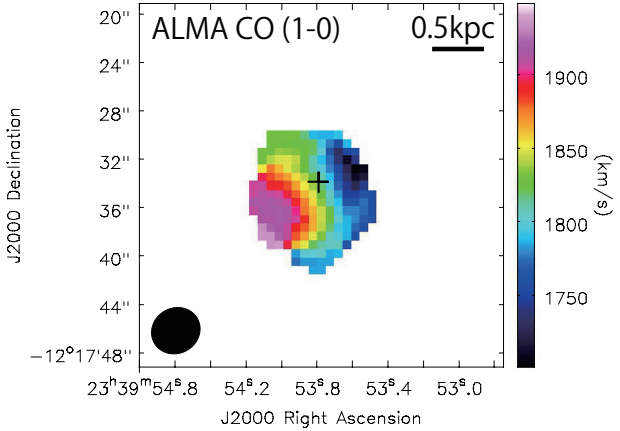

SMA CO (2-1)
2 kpc
J2000 Declination
54''
48''
42''
36''
30''
24''
18''
12''
06''
39°11'00''
02h10m12s
10s
09s
08s
07s
J2000 Right Ascension

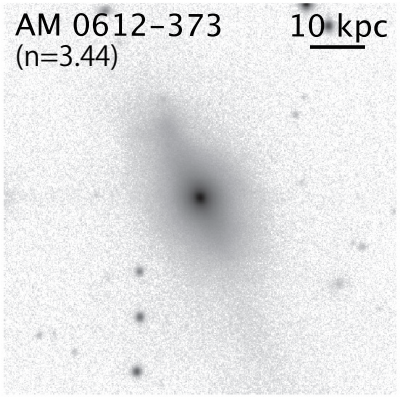

SMA CO (2-1)
2 kpc
J2000 Declination
5500
5400
5300
5200
5100
5000
(km/s)
J2000 Right Ascension

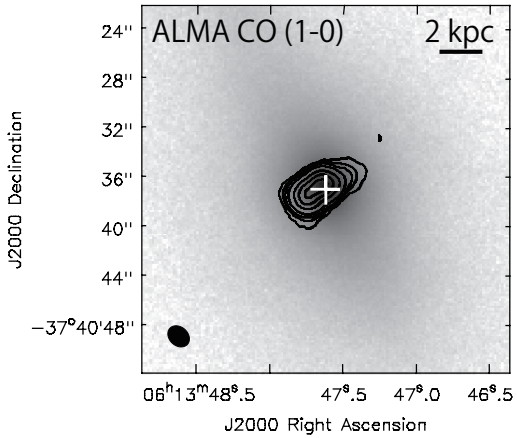
Small disks

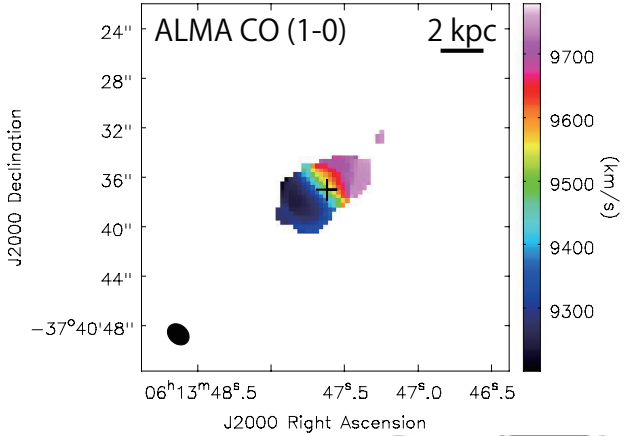

NGC 7727
(n=3.41)
1 kpc


ALMA CO (1-0)
0.5kpc
J2000 Declination
J2000 Right Ascension

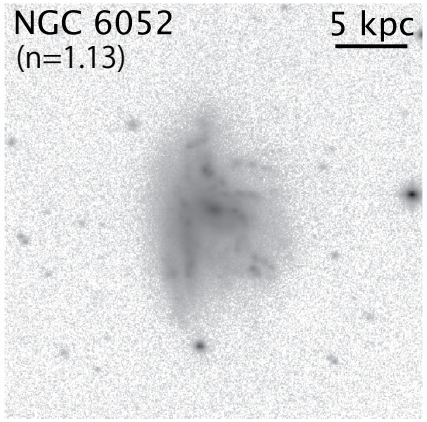

ALMA CO (1-0)
0.5kpc
J2000 Declination
J2000 Right Ascension
(km/s)

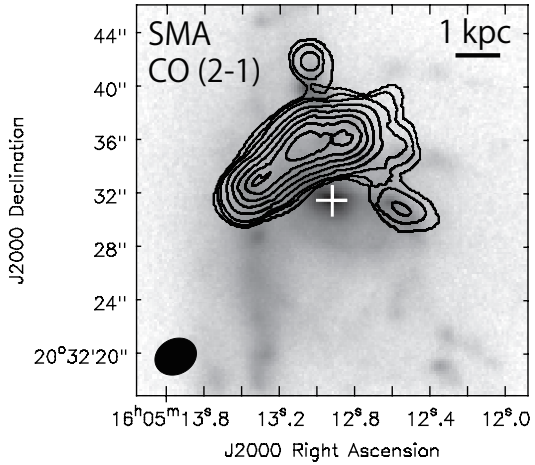

AM 0612-373
(n=3.44)
10 kpc

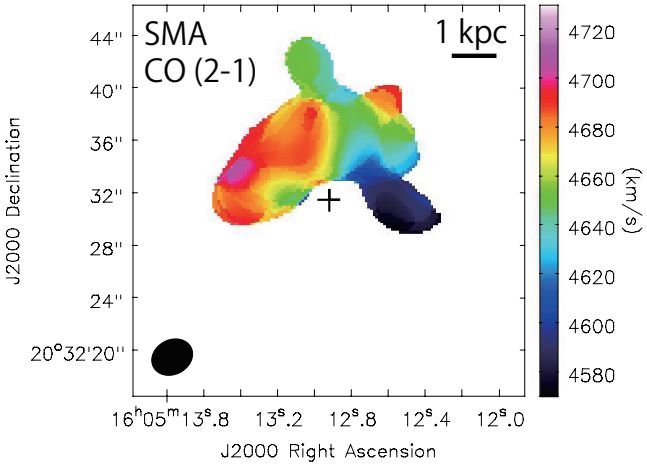

ALMA CO (1-0)
2 kpc
J2000 Declination
J2000 Right Ascension

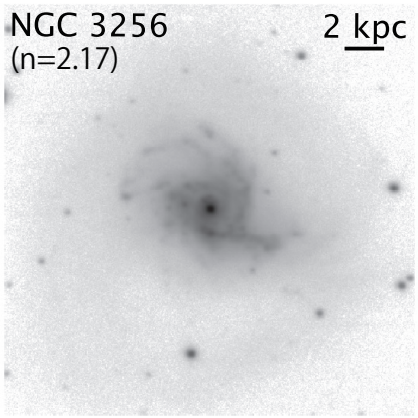

ALMA CO (1-0)
2 kpc
J2000 Declination
J2000 Right Ascension
(km/s)

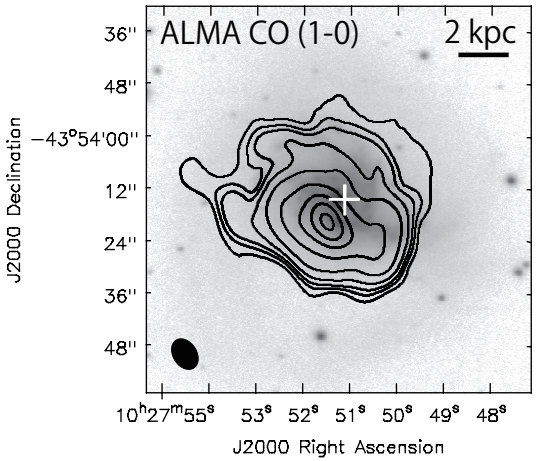
Clumpy distribution

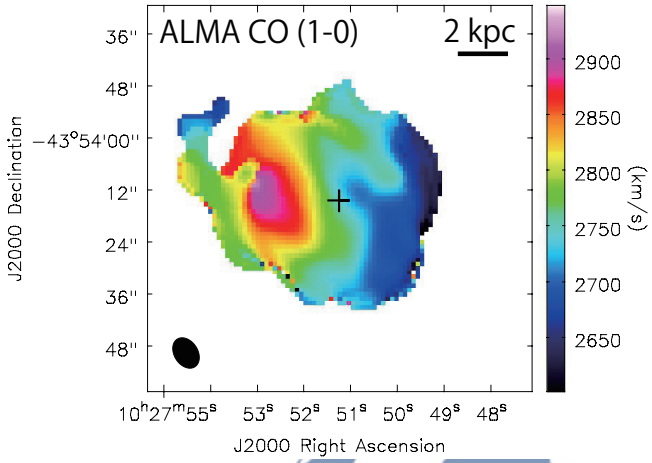






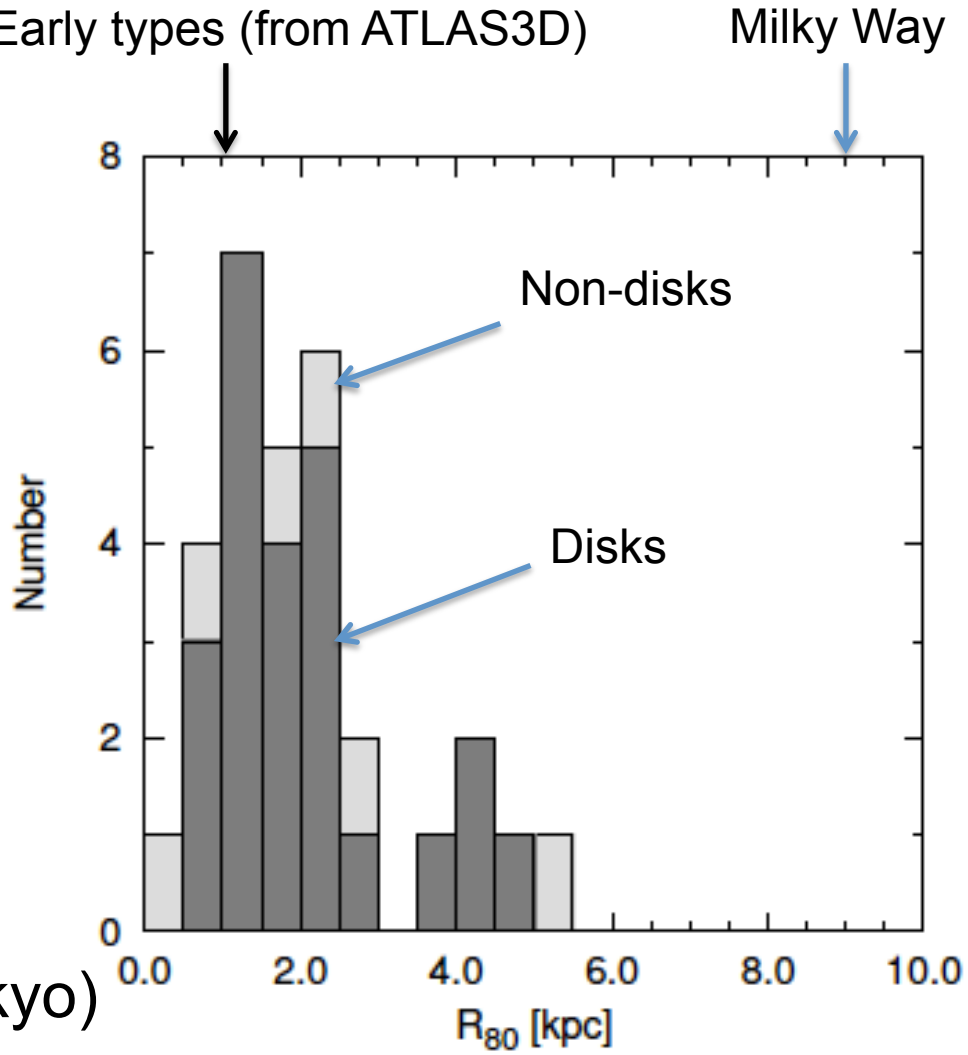




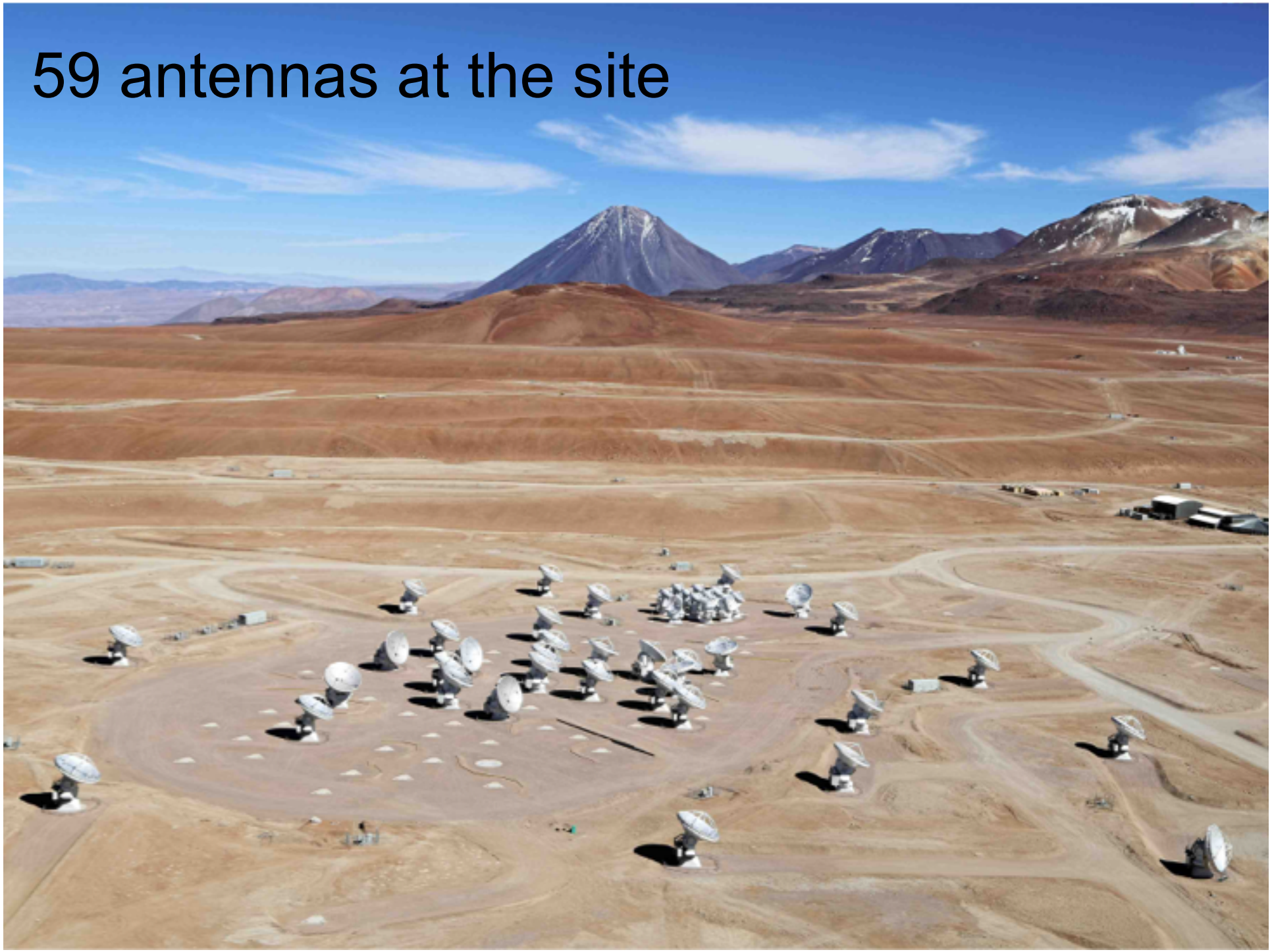


Size of the CO disks

Median (Merger remnants)
= 1.7 +/- 1.2 kpc
Median (Early types)
= 1.1 +/- 0.6 kpc



Ongoing work by J. Ueda (Tokyo)

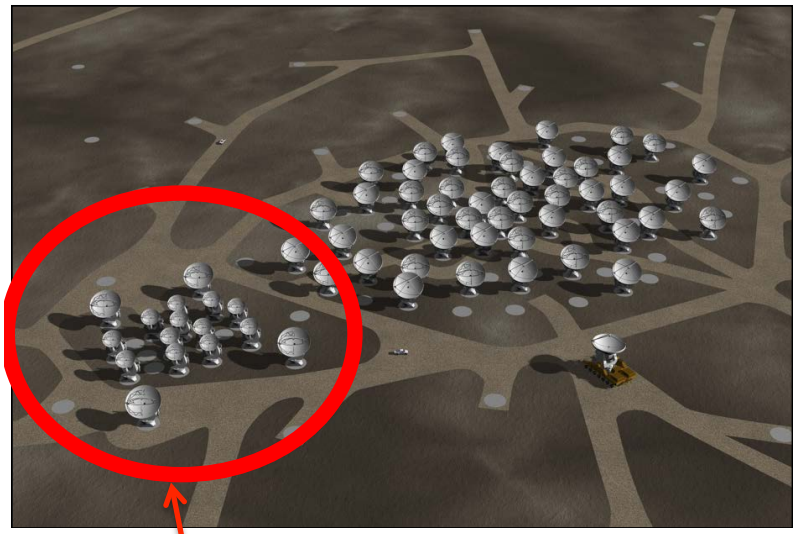

59 antennas at the site

ALMA Overview

- An international project
  - 20 countries and regions (Japan, Taiwan, U.S., Canada, 15 EU nations, Chile)
- 4 regions
  - East Asia (NAOJ)
  - North America (AUI/NRAO)
  - Europe (ESO)
  - Chile
    - Joint ALMA Observatory (JAO)

ALMA Performance

- Number of antennas
  - 12m main array: 50 x 12m
  - Atacama Compact Array (ACA): 4 x 12m + 12 x 7m
- Angular resolution
  - 0.01” (x10 of HST)
- Sensitivity
  - 30 – 100 times better than existing radio telescopes



ACA (Japanese Contribution)

ALMA Status

ALMA operation

Operations Support Facility

Array Operations Site

ALMA Inauguration (March)

6 presentations at the OSF
(2900 m site)

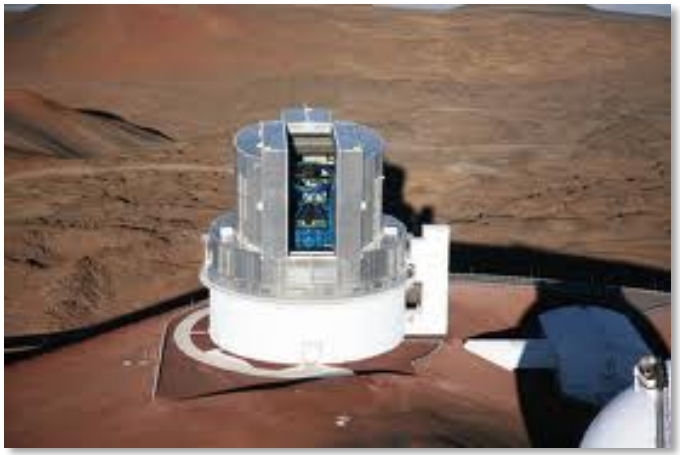
Vice Minister of MEXT Fukui

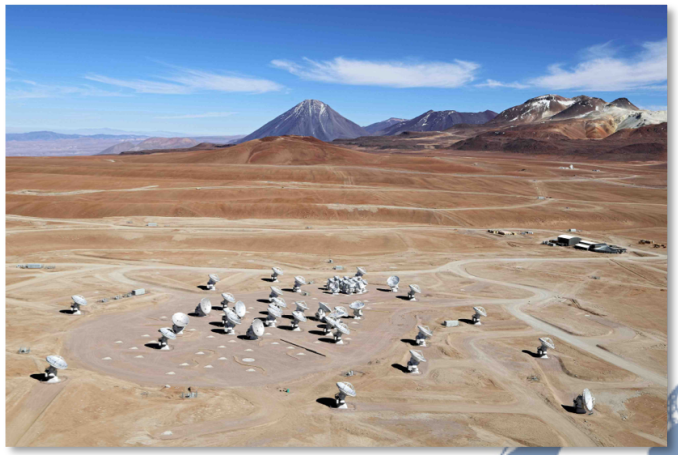
President Pinera

ALMA Chief Scientist Ryohei Kawabe

Subaru-ALMA Synergy

- Cycle 0 (2011-2012), Cycle 1 (2013)
- ~30% of ALMA cycle 0/1 accepted proposals in East Asia are based on Subaru data
- Subaru – stellar distribution, mass, (kinematics)
- ALMA – gas distribution, mass, kinematics





Strengths and weaknesses of ALMA

Strengths

- High resolution
- High sensitivity and dynamic range
- Observable during daytime
- Covers the entire mm/ smm atmospheric window

Weaknesses

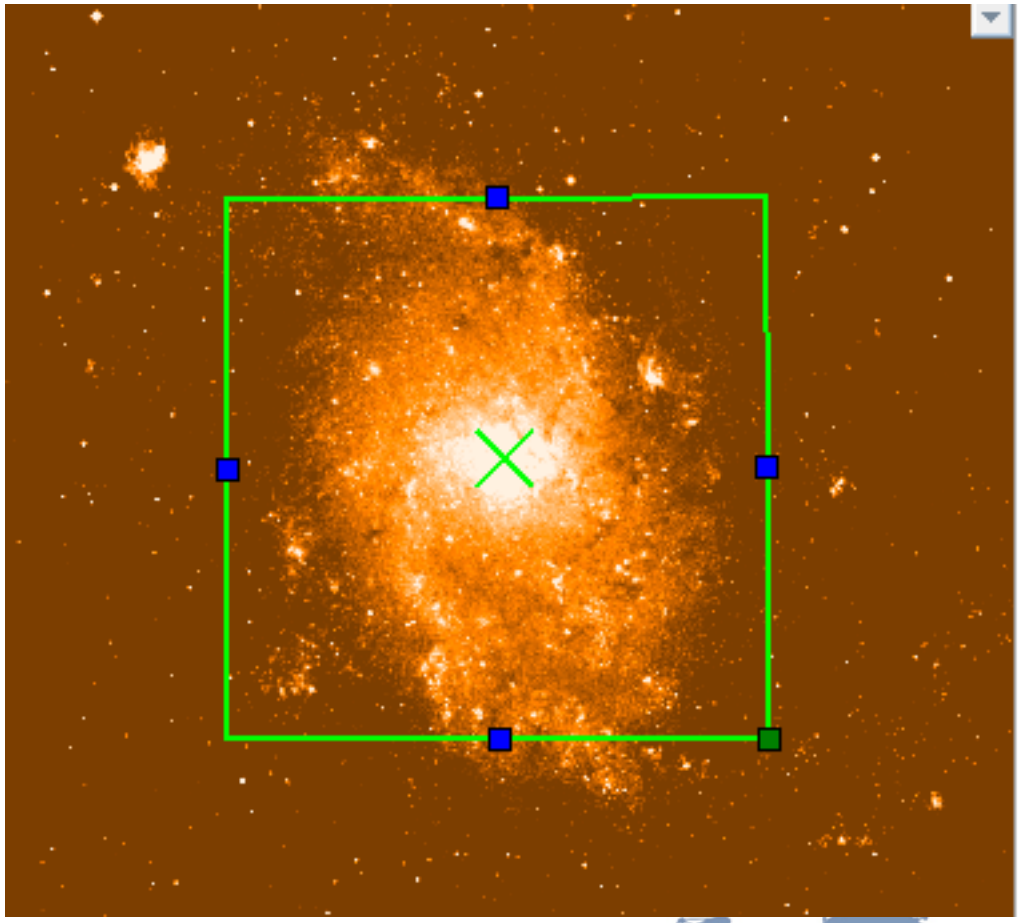
- Small FOV
  - 18” at 850 micron
- Narrow Bandwidth
  - 8 GHz per IF

.

ALMA pointing

- 880 pointings (Nyquist@100GHz) to cover 14 x 14 arcmin (GLAO FOV)

M33



Future Developments

- Near (~5 year) future (before 2020)
  - Band 1, 2, 5 (Baseline bands)
  - VLBI capabilities
- >10 years ahead (> 2020)
  - Band 11 (THz: high-J CO, [NII])?
  - Multi-beam receiver (~10-100 pixels)?
  - Wide bandwidth (10-100 GHz?)?
  - Longer baselines (expanded ALMA)?
- Workshop on future development (July 8-9) "EA ALMA Development Workshop"

Questions

- Which instrument is important?
  - Proposed wide-field instruments important for ALMA synergy (particularly for ALMA follow-up)
  - Spectroscopic capabilities will allow direct comparison with ALMA cold gas observations.
    (But targeted AO may be sufficient for merger studies: TMT?)
- Synergy?
  - Complementary: ALMA will possibly seek wide field capabilities for 2020 and beyond