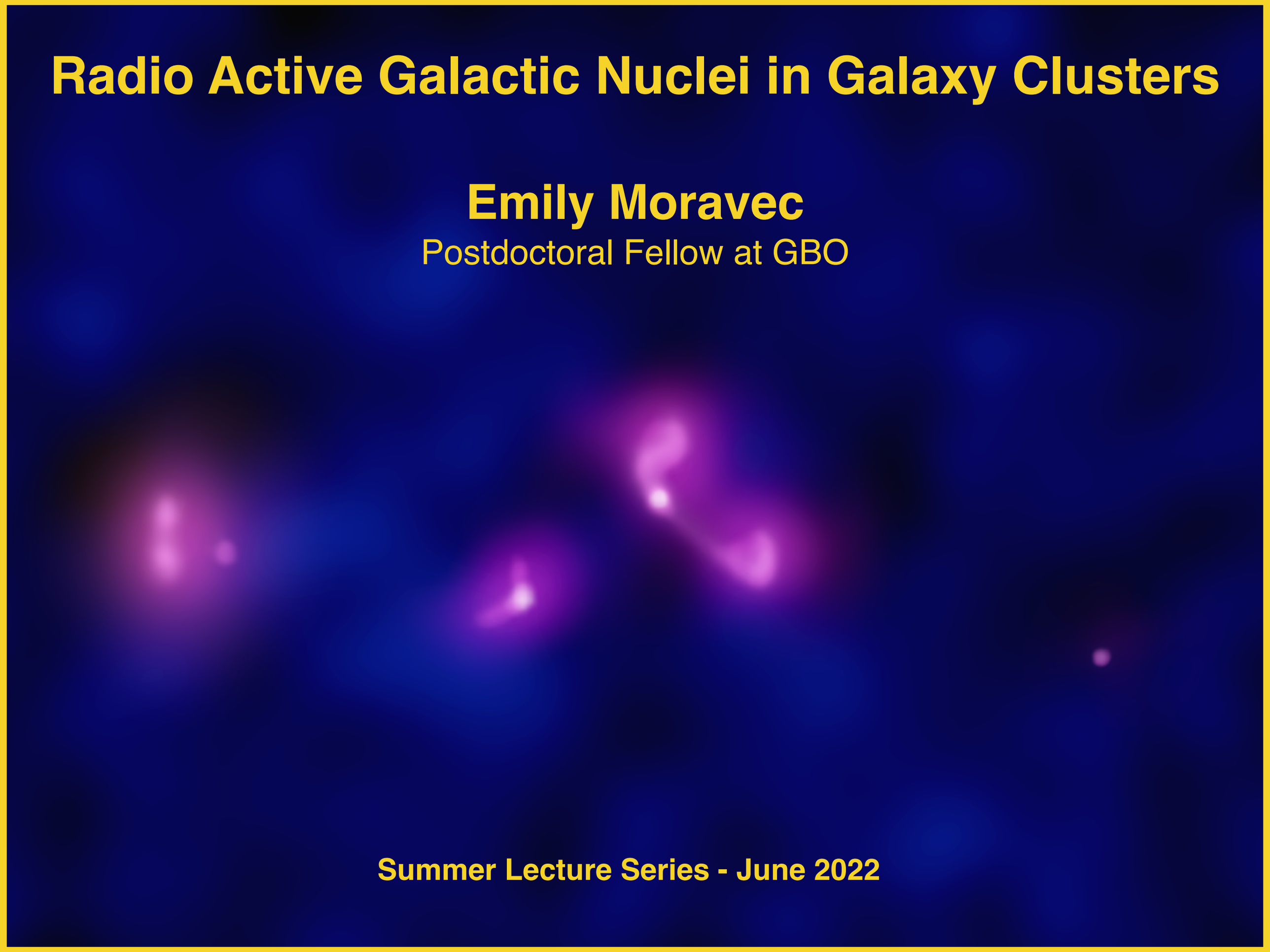
Radio Active Galactic Nuclei in Galaxy Clusters

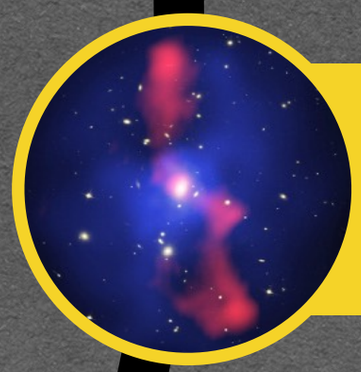
Emily Moravec
Postdoctoral Fellow at GBO



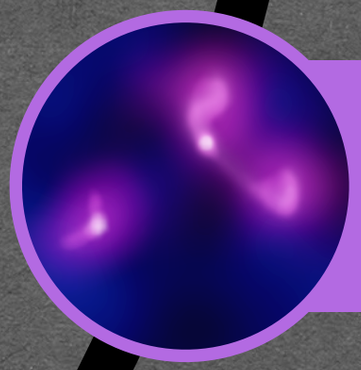
Summer Lecture Series - June 2022

Galaxy Clusters

AGN & AGN in Clusters



Radio-AGN in Galaxy Clusters

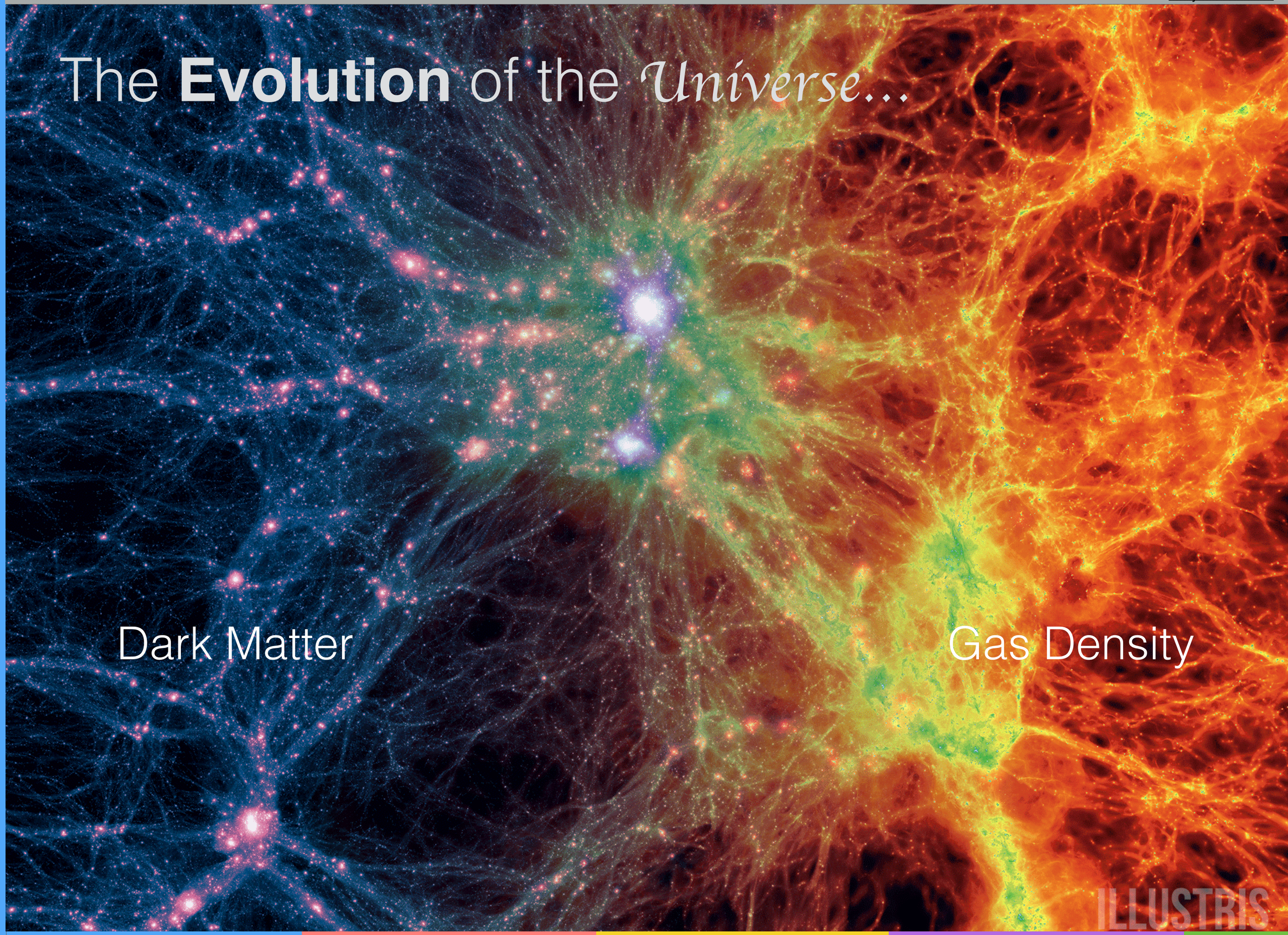


My work: Radio-AGN in Clusters

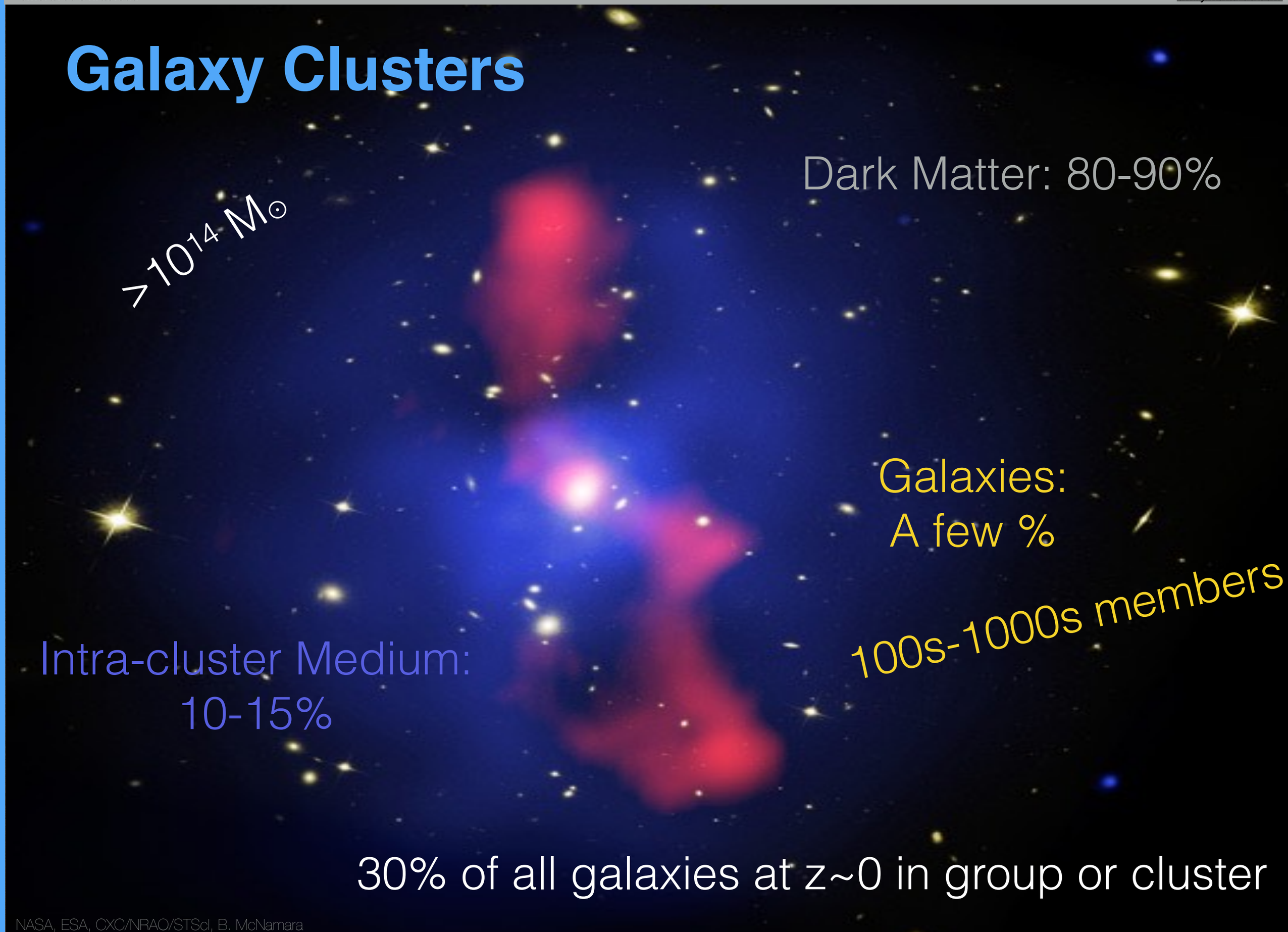
Galaxy Clusters

Image Credit: NASA/JPL-Caltech/Gemini/CARMA

The **Evolution** of the *Universe…*



Galaxy Clusters



30% of all galaxies at z~0 in group or cluster

NASA, ESA, CXC/NRAO/STScI, B. McNamara

	Groups	Clusters
# members	< 50	100s-1000s
Mass	$\sim 10^{13}\ M_\odot$	$> 10^{14}\ M_\odot$
Size	1-2 Mpc	several Mpc
Components	no ICM	ICM

Intracluster Medium (ICM)

Superheated plasma — 10^7 - 10^8 K

Gravitational PE -> KE (shocks)

Bremsstrahlung radiation

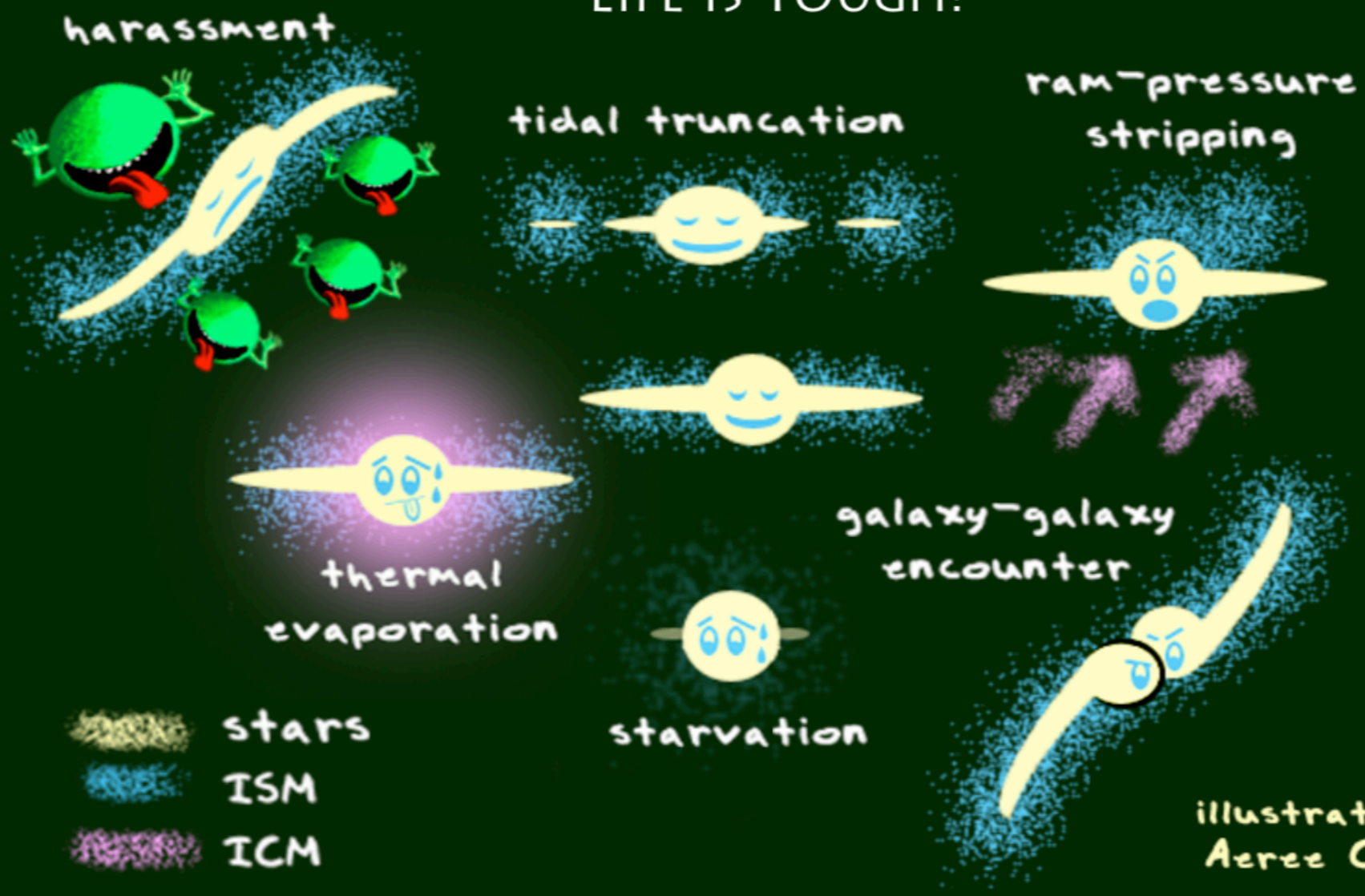
Diffuse but majority of baryonic mass

Origin: debated — primordial or ejected

Gonzalez+15

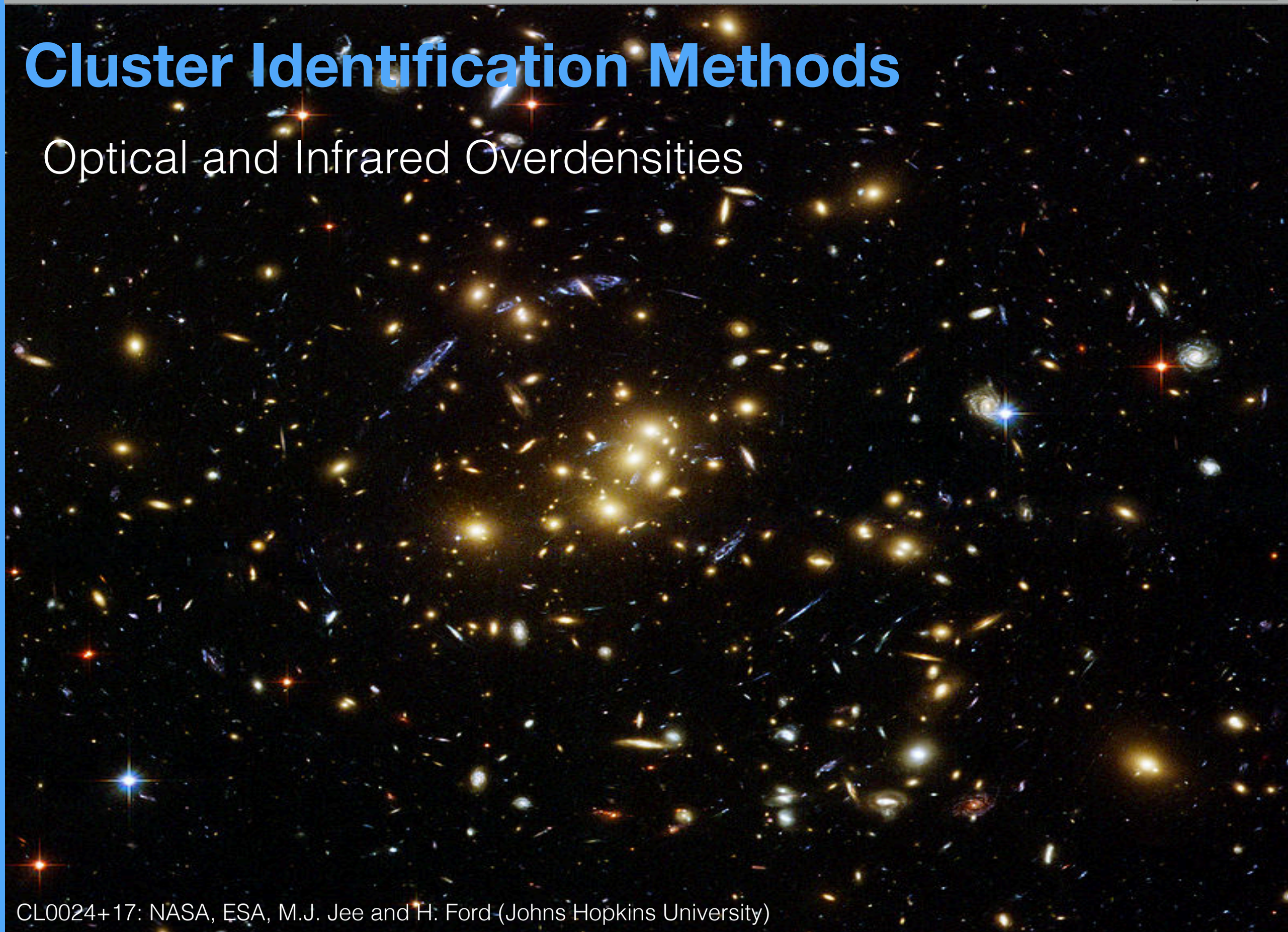
Galaxies can go through...

Life is Tough!

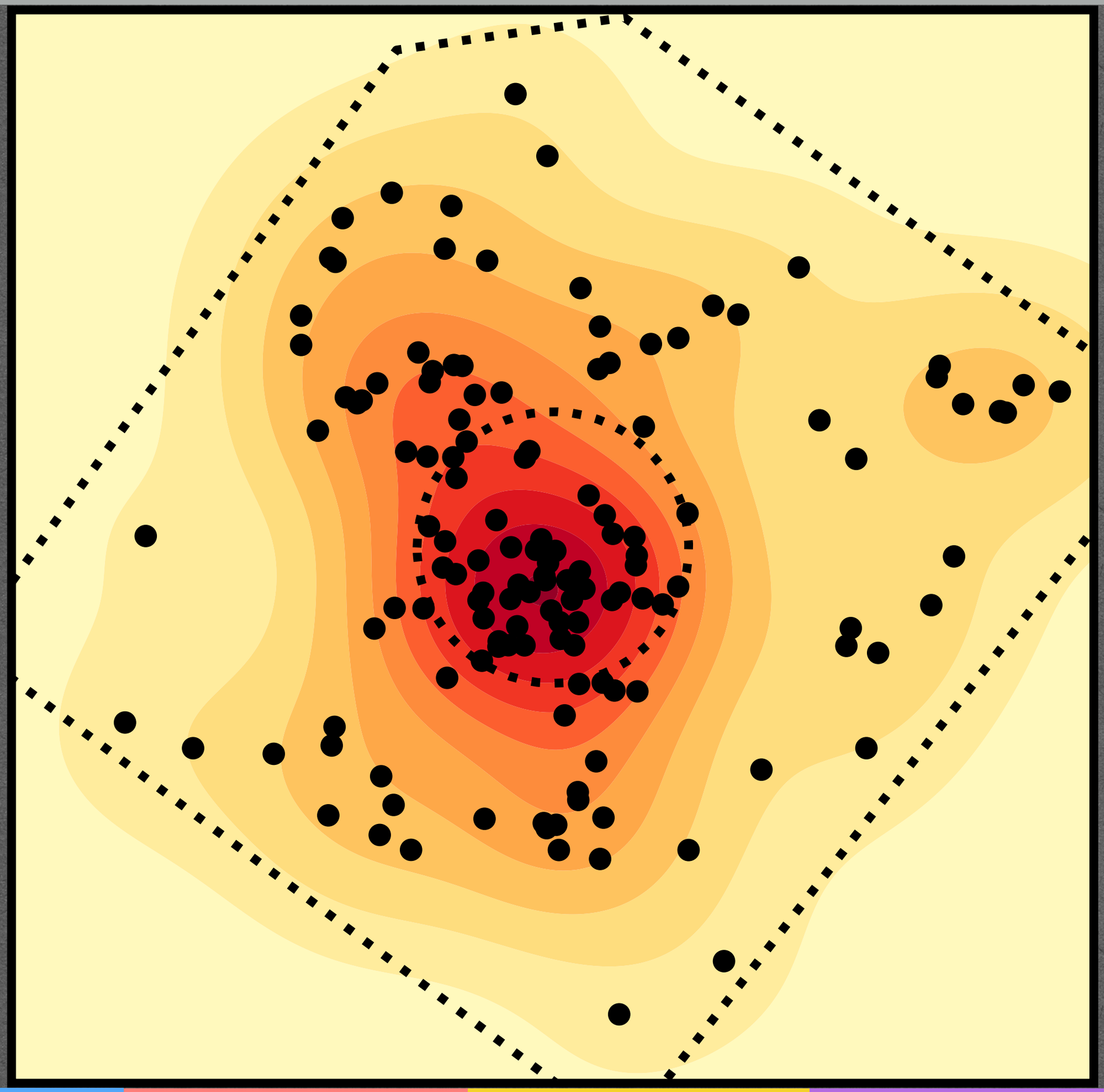


Cluster Identification Methods

Optical and Infrared Overdensities



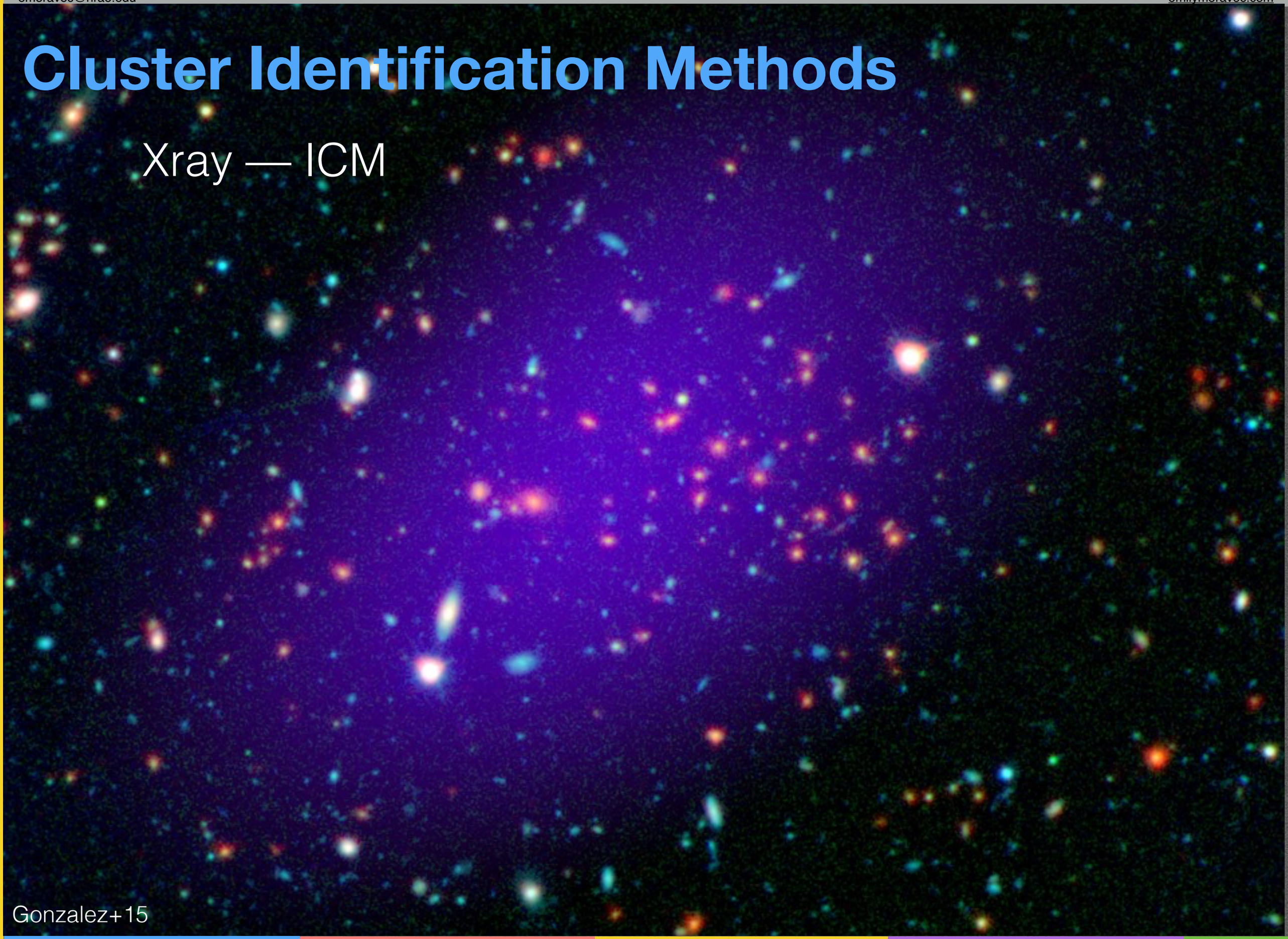
CL0024+17: NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)



Moravec+20b

Cluster Identification Methods

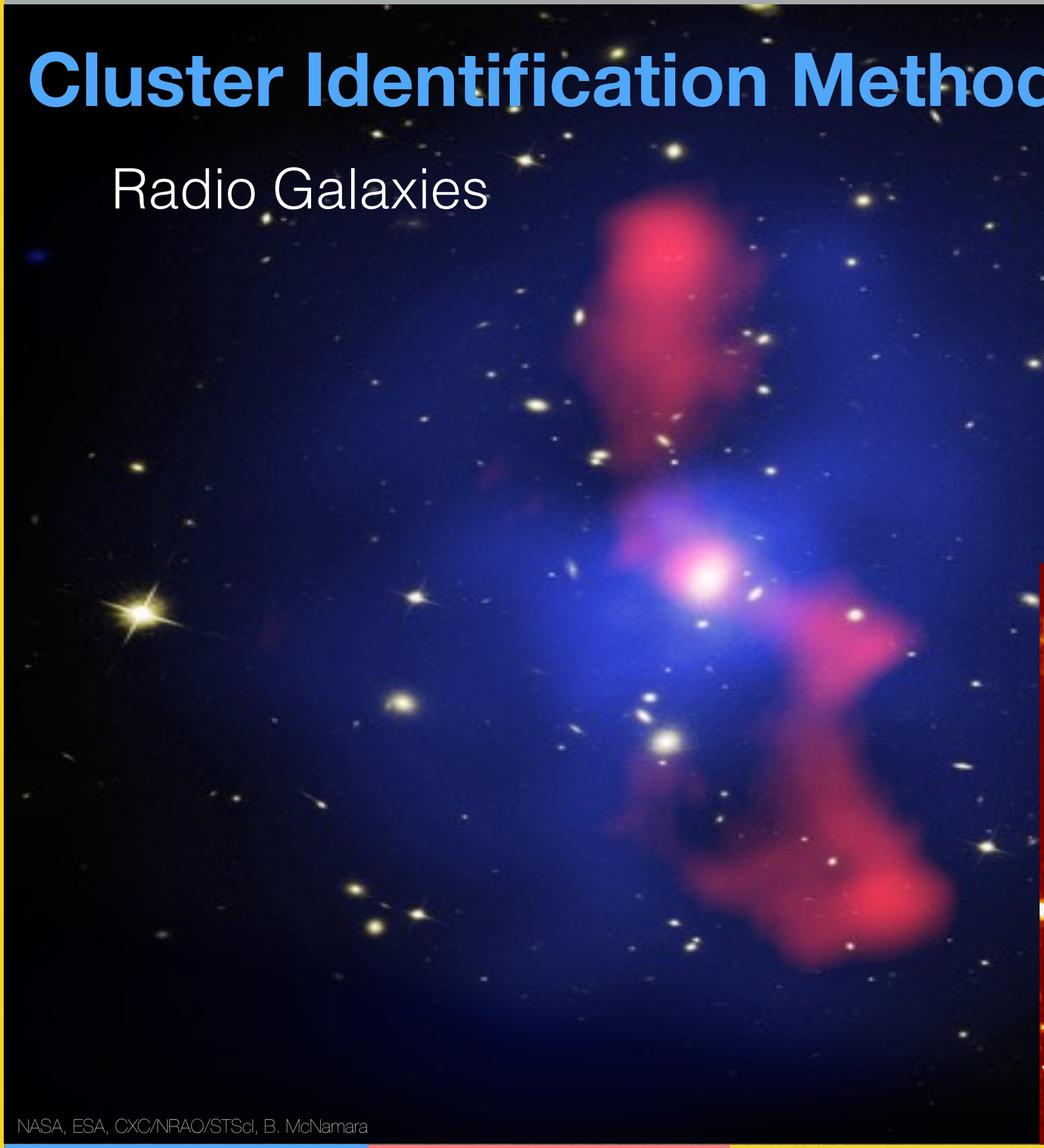
Xray — ICM



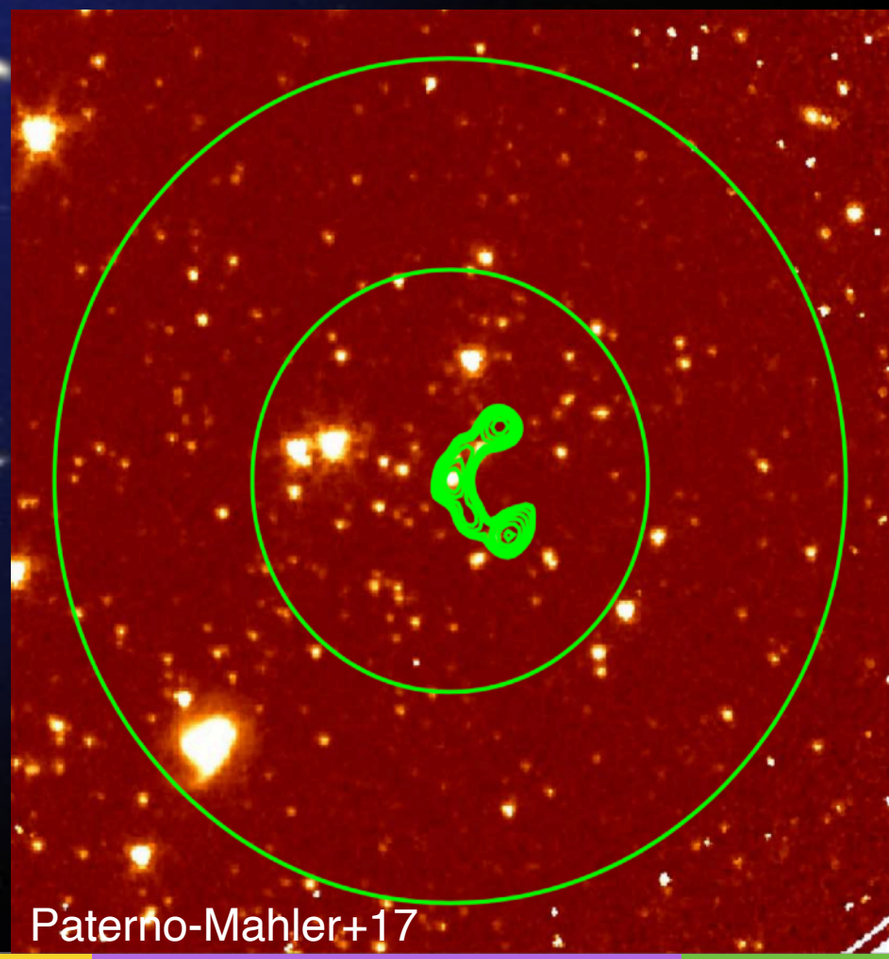
Gonzalez+15

Cluster Identification Methods

Radio Galaxies



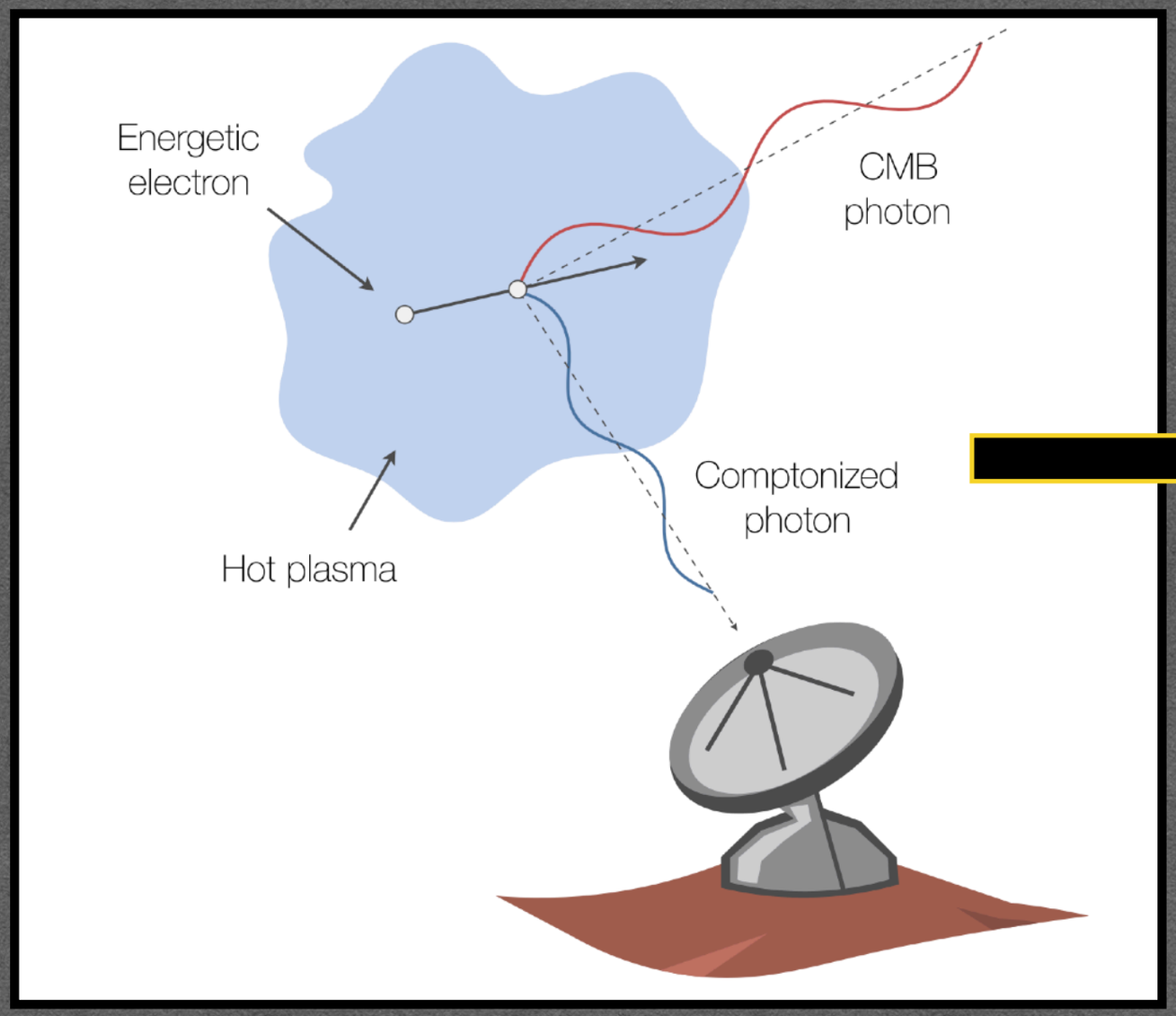
NASA, ESA, CXC/NRAO/STScI, B. McNamara



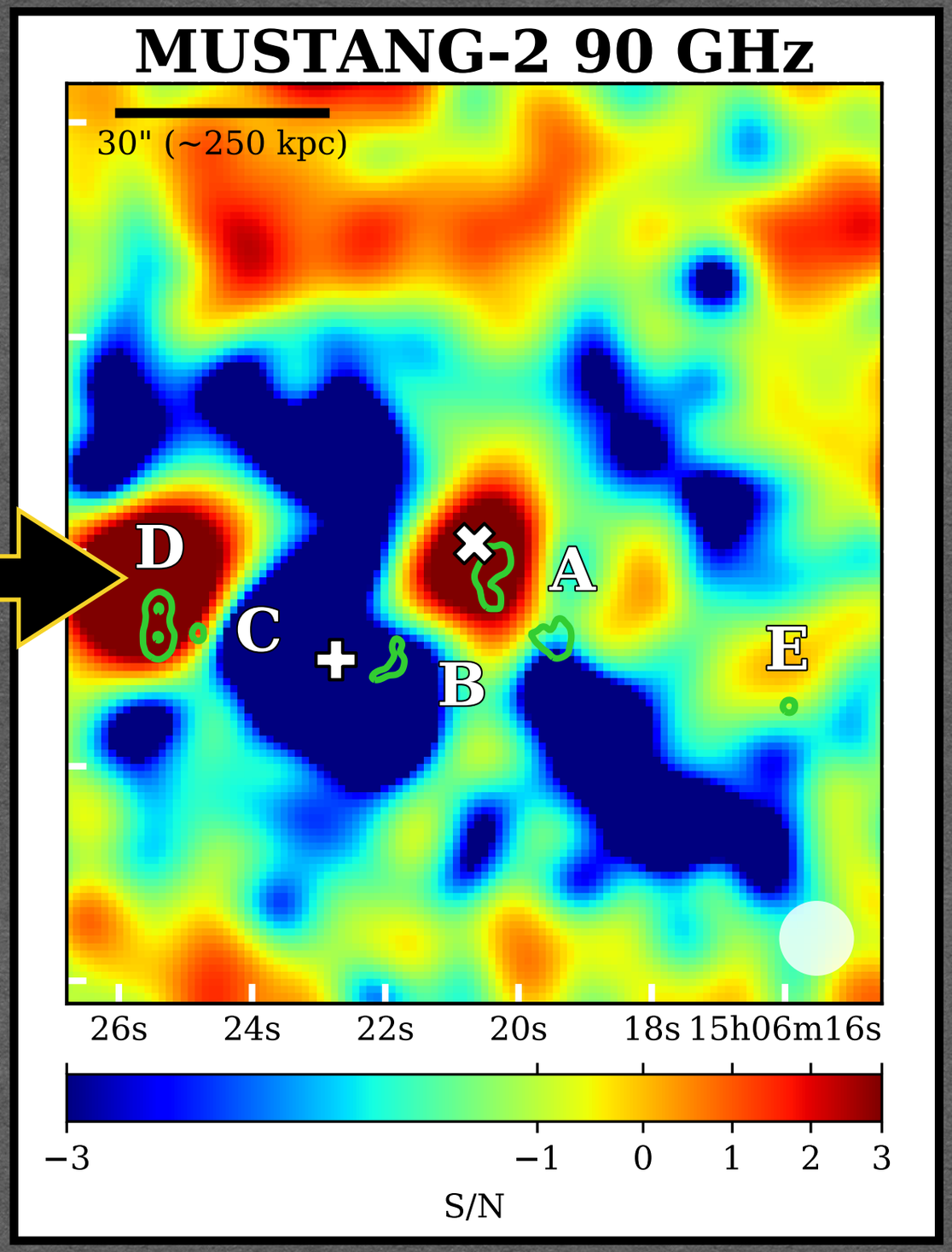
Paterno-Mahler+17

Cluster Identification Methods

Sunyaev-Zeldovich (SZ) Effect

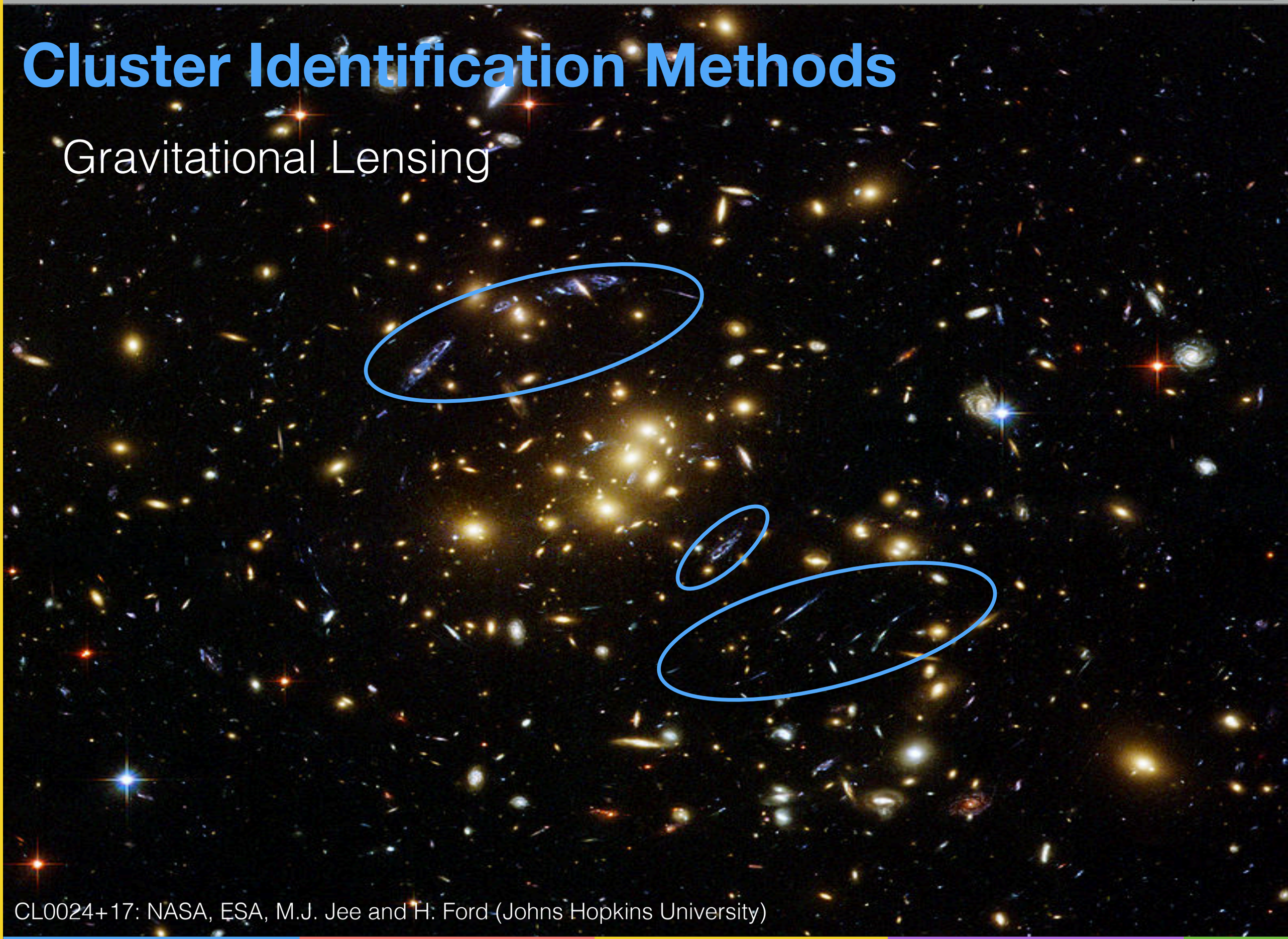


Mroczkowski+19



Cluster Identification Methods

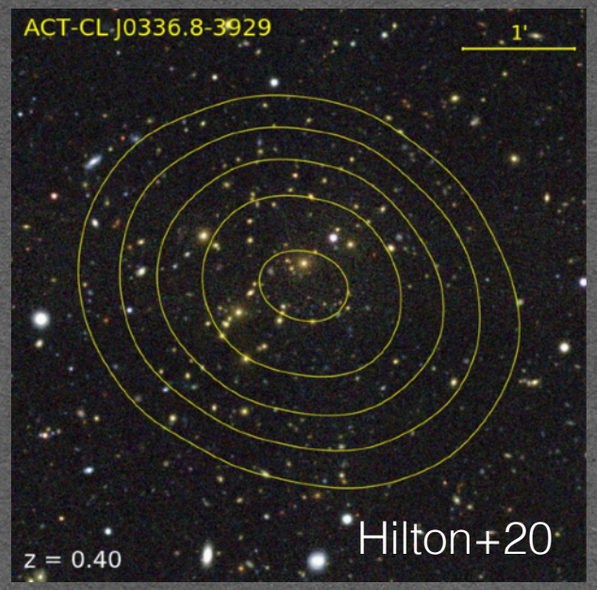
Gravitational Lensing



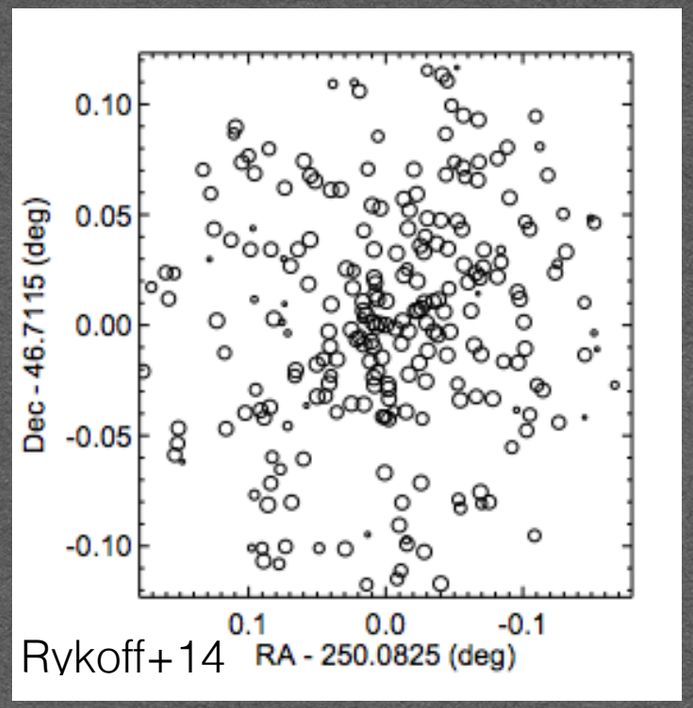
CL0024+17: NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

Massive and Distant Clusters of WISE Survey (MaDCoWS)
~2300 at z~1 (Opt + IR)

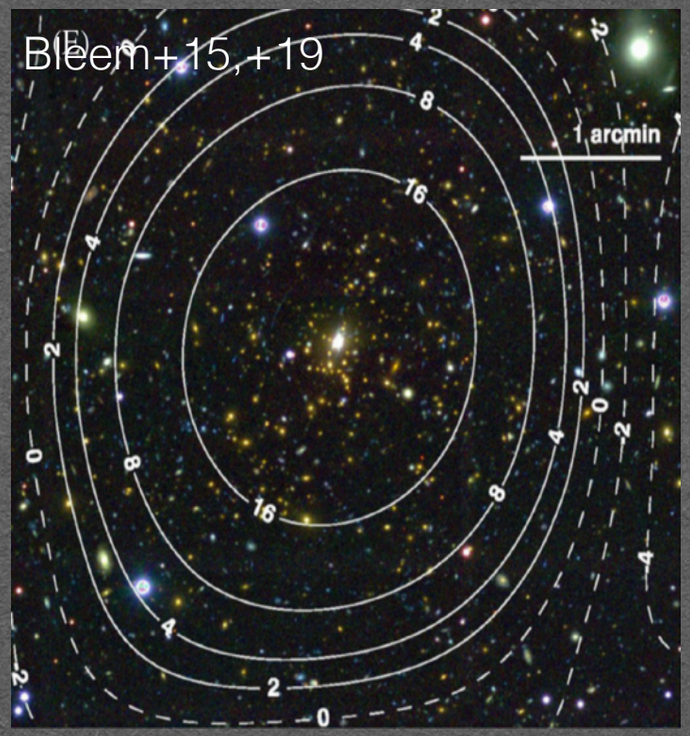
Atacama Cosmology Telescope (ACT)
~4200 at 0.05 < z < 1.9 (SZ)



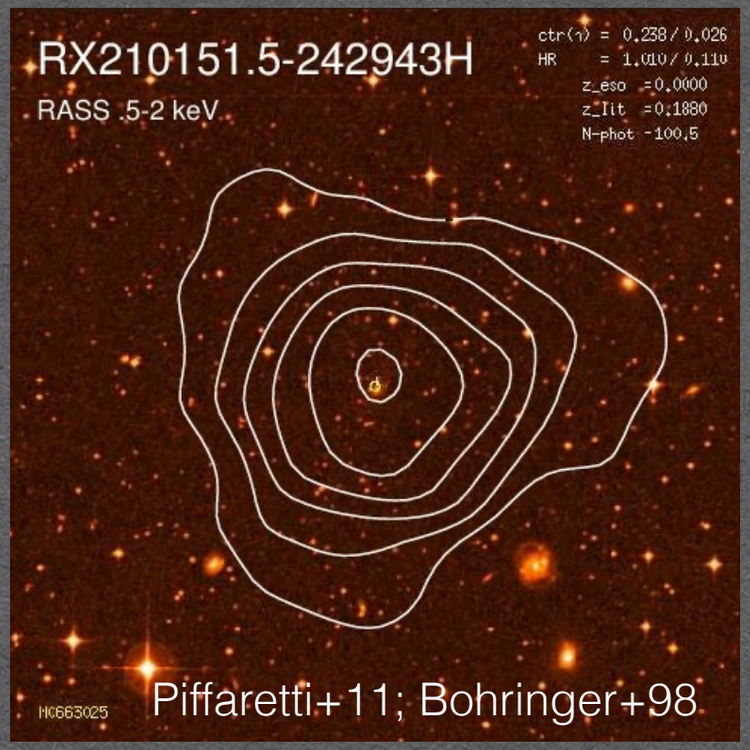
redMaPPer (SDSS)
~25,000 at z < 0.55 (optical)



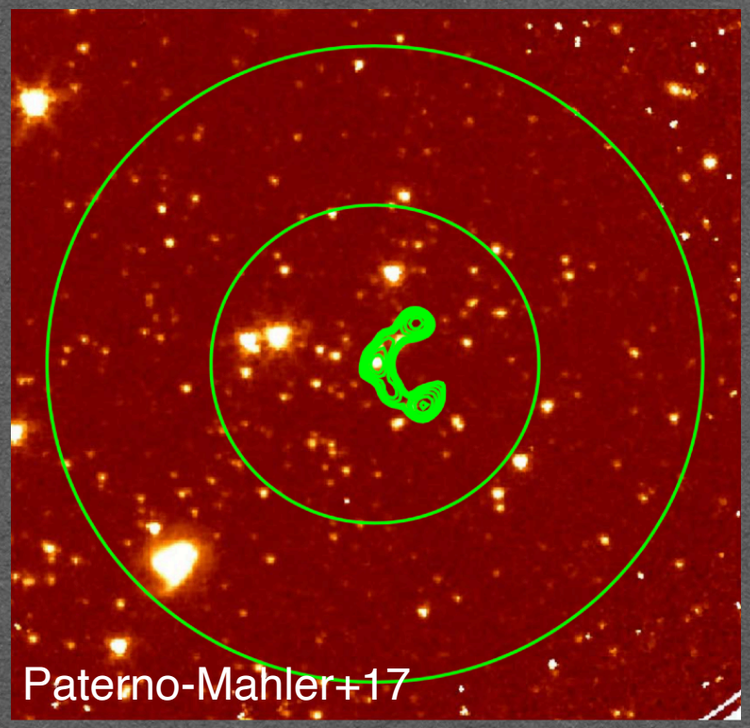
South Pole Telescope (SPT)
~few hundred at z < 1.5 (SZ)



MCXC (ROSAT)
~1800 (X-ray)



COBRA
~200 at z < 3 (RGs)



AGN in Galaxy Clusters

NASA, ESA, CXC/NRAO/STScI, B. McNamara

Active Galactic Nuclei (AGN)

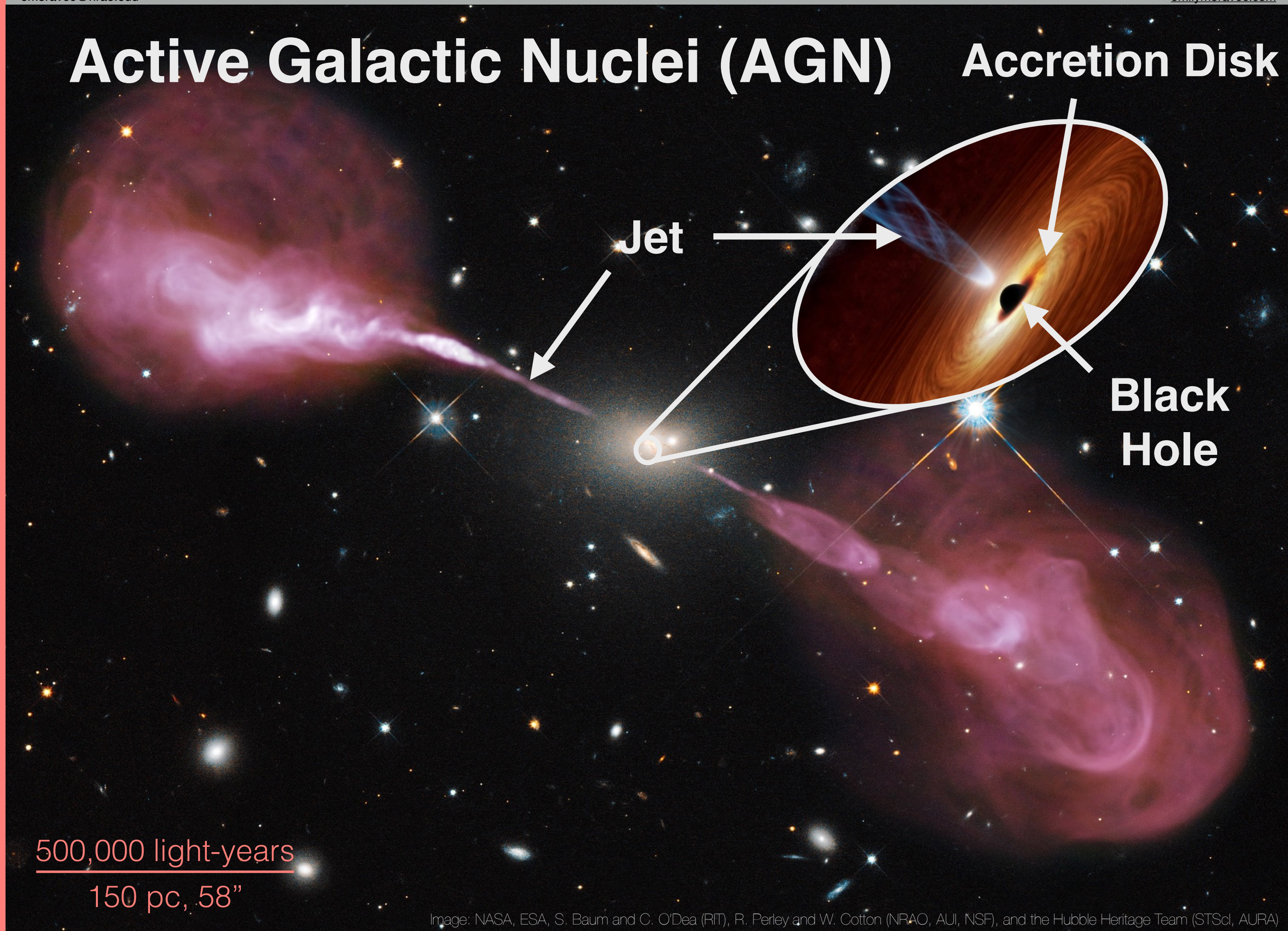
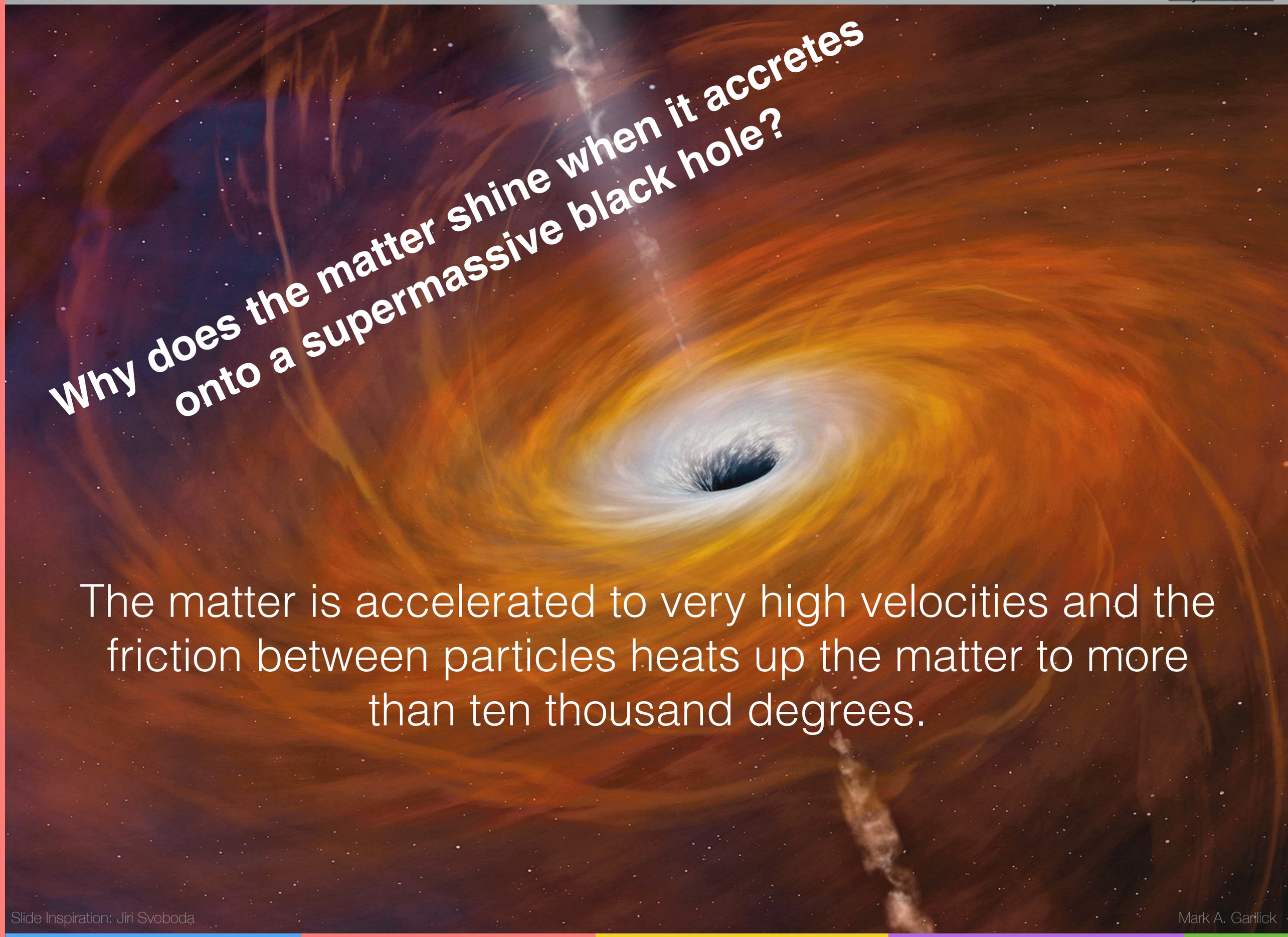


Image: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO, AUI, NSF), and the Hubble Heritage Team (STScI, AURA)



Why does the matter shine when it accretes onto a supermassive black hole?

The matter is accelerated to very high velocities and the friction between particles heats up the matter to more than ten thousand degrees.

Slide Inspiration: Jiri Svoboda

Mark A. Garlick

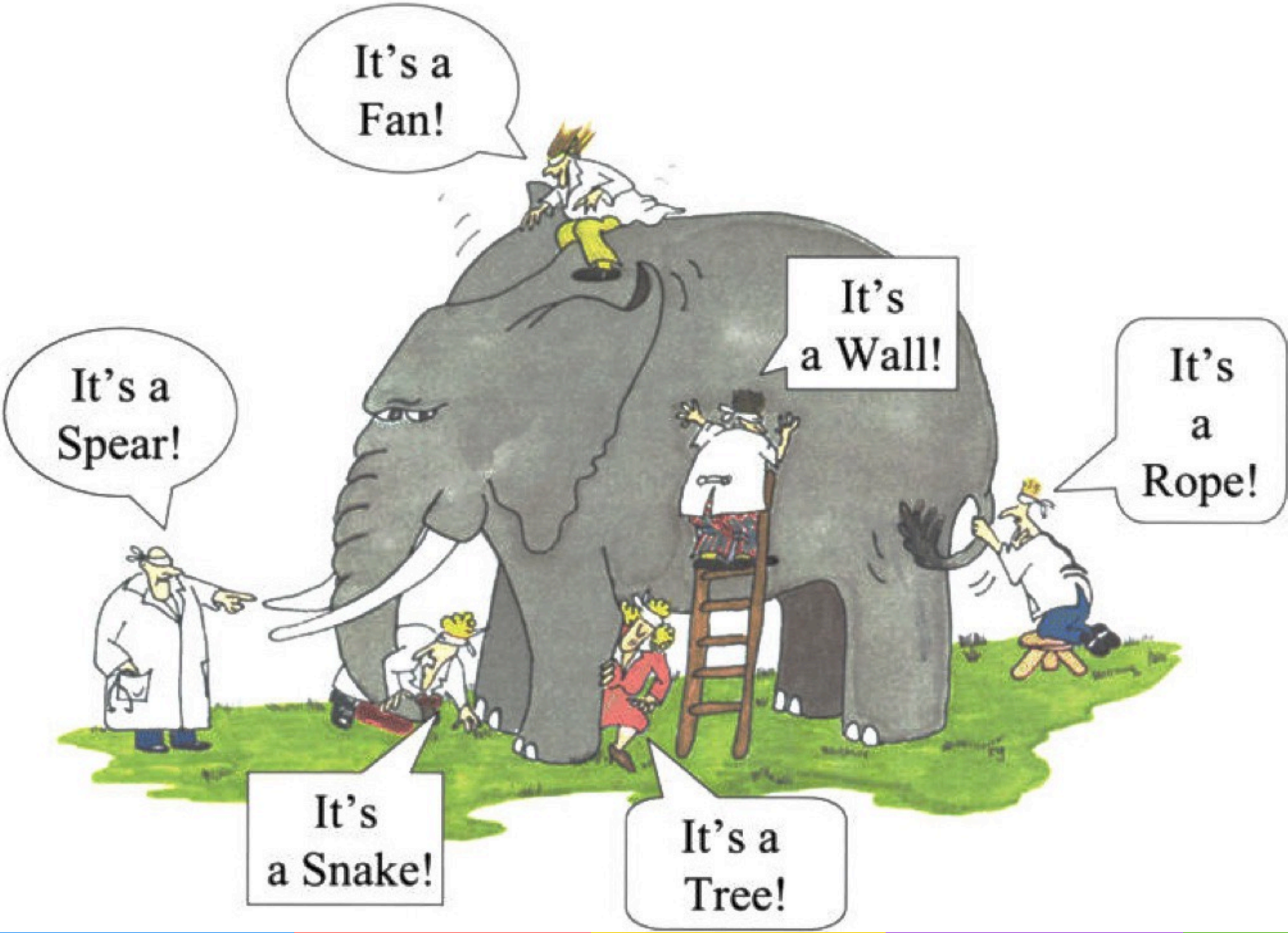
Why does the matter shine when it accretes onto a supermassive black hole?
Why are some galaxies active and others are not?
There must also be sufficient amount of matter that accretes onto the black hole to ignite AGN.
Slide Inspiration: Jiri Svoboda
Mark A. Garlick

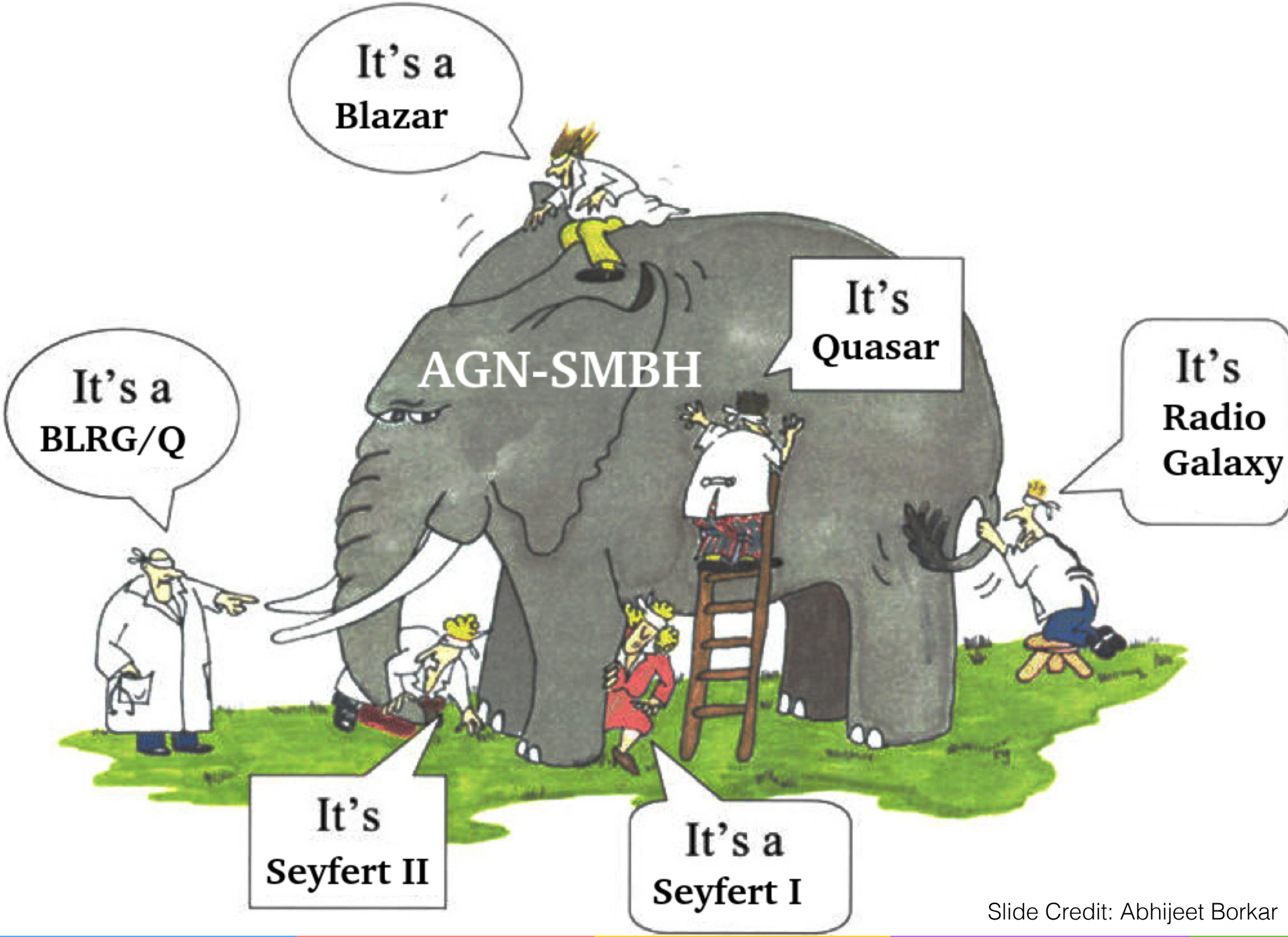
AGN Types

- Seyfert 1, Seyfert 2, and Compton-thick AGN
  - Optical and X-ray - Effect of obscuration/Orientation on optical and X-ray spectra
- 'Changing-look' AGN
  - Optical: Type 1 <-> Type 2
    - Type 1 - nucleus is visible (the spectra has both narrow and broad emission lines)
    - Type 2 - the broad line region (BLR) is obscured and the lines are very narrow
- LINERs
  - Optical - Weakly accreting local AGN
- Broad absorption line quasars
  - Optical - Driving a wind
- FR-Is, FR-IIs, FSRQs, and BL Lacs
  - Radio - jets, environment, and orientation

Slide Credit: Daniel Kynoch

Resource: https://astrobites.org/guides/galaxy-and-agn-types/

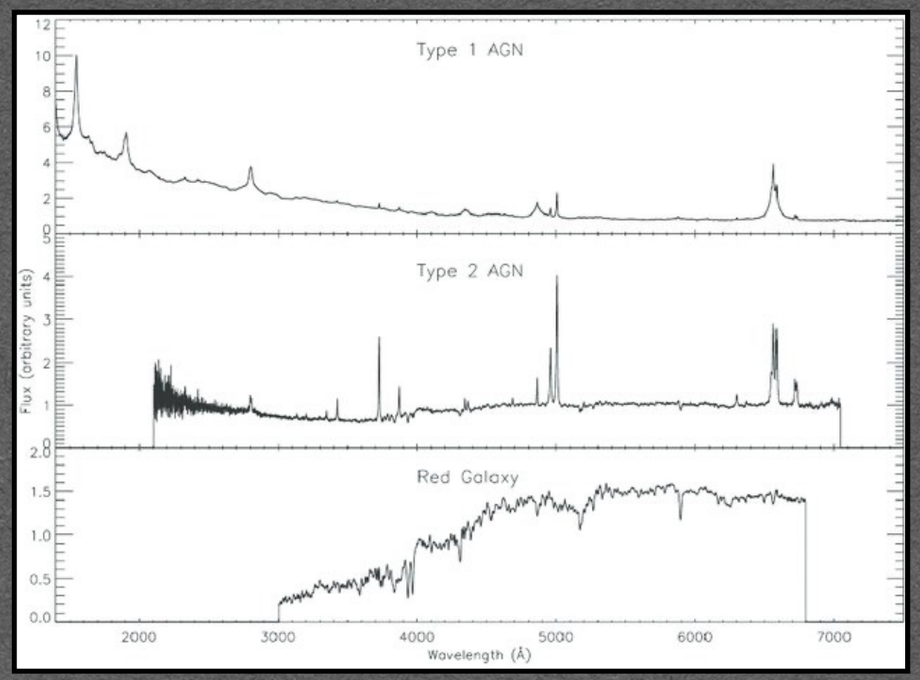

It's a Fan!
It's a Wall!
It's a Spear!
It's a Rope!
It's a Snake!
It's a Tree!



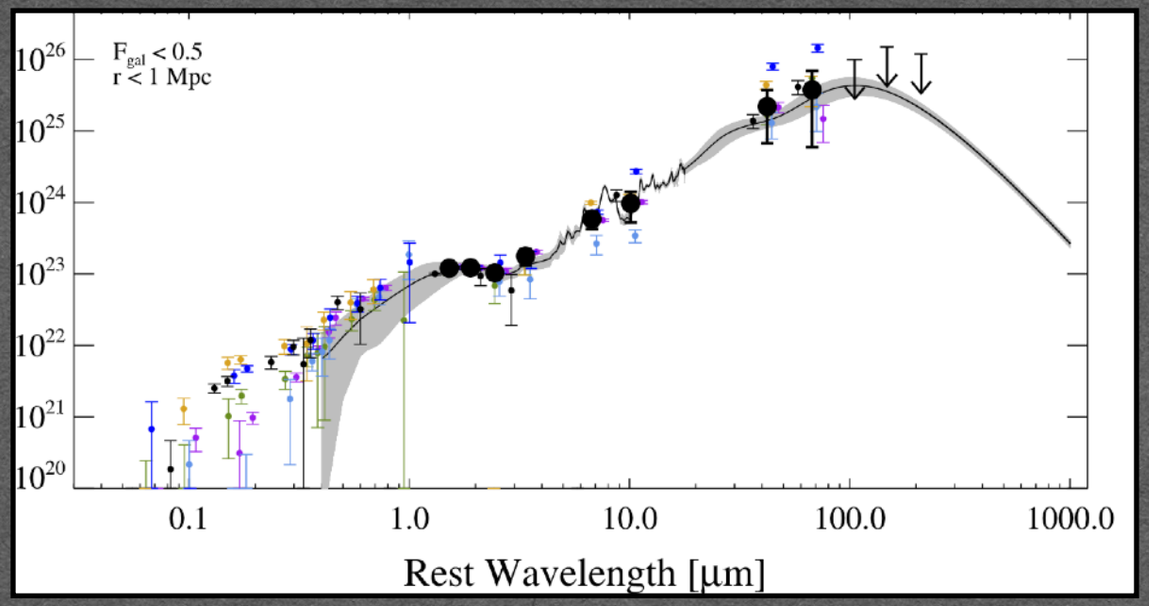
Slide Credit: Abhijeet Borkar

AGN Identification

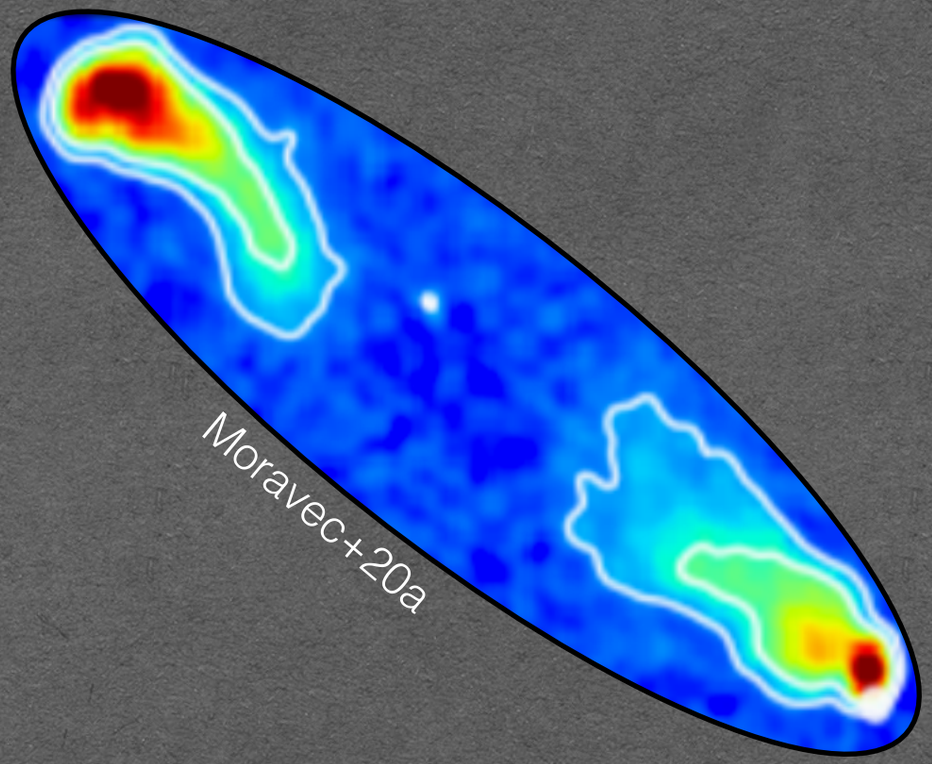
- Optical lines, magnitude, or color
- Infrared color or luminosity
- X-ray luminosity
- Radio luminosity and morphology
- Combination of above
- SED analysis
- Many more



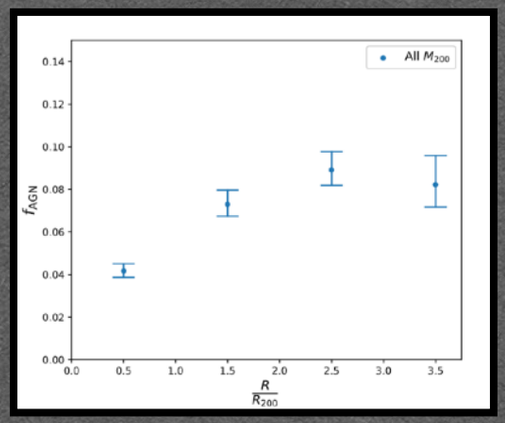
Mickaelian+15

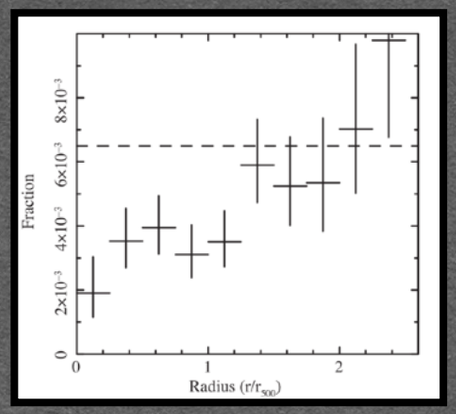


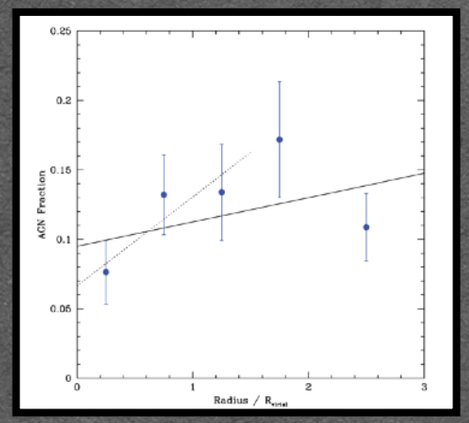
Alberts+16

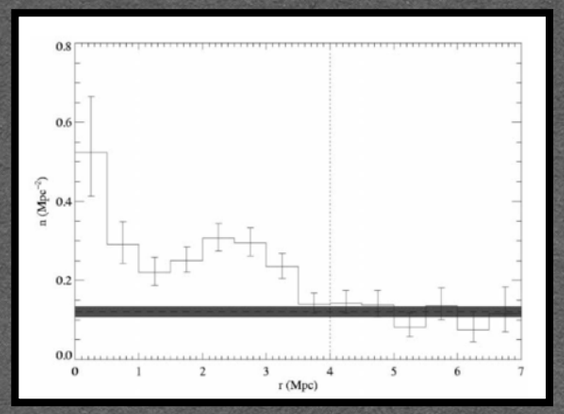


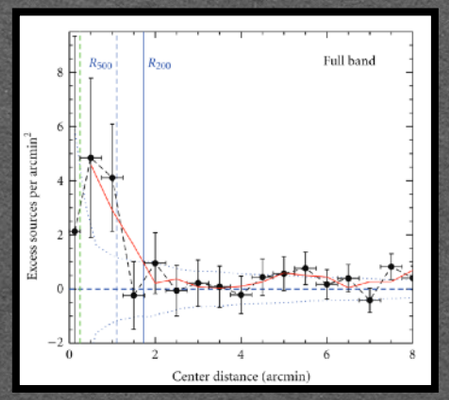
Moravec+20a



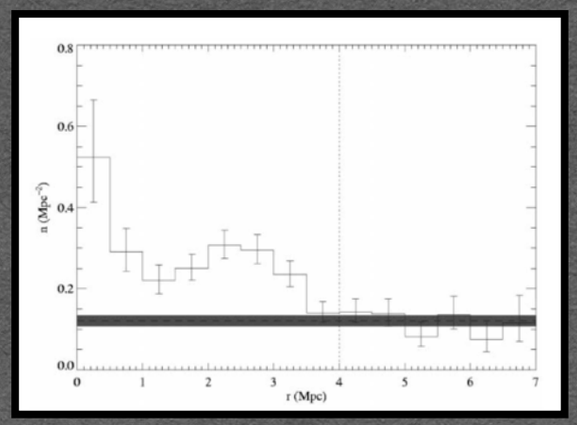


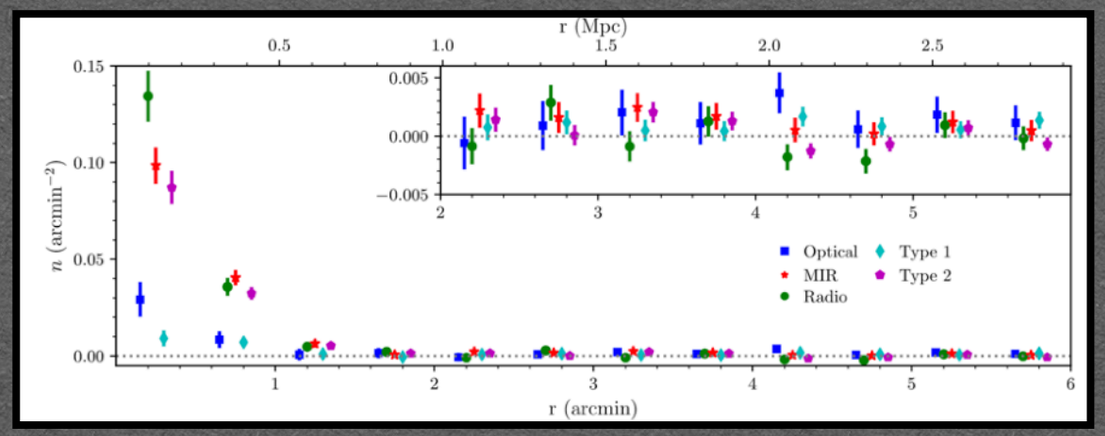


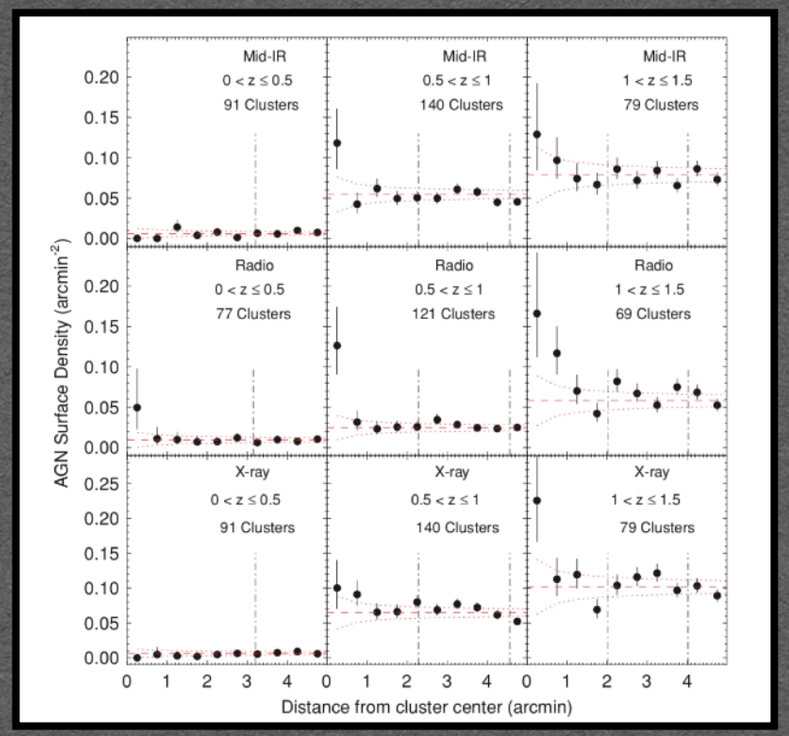




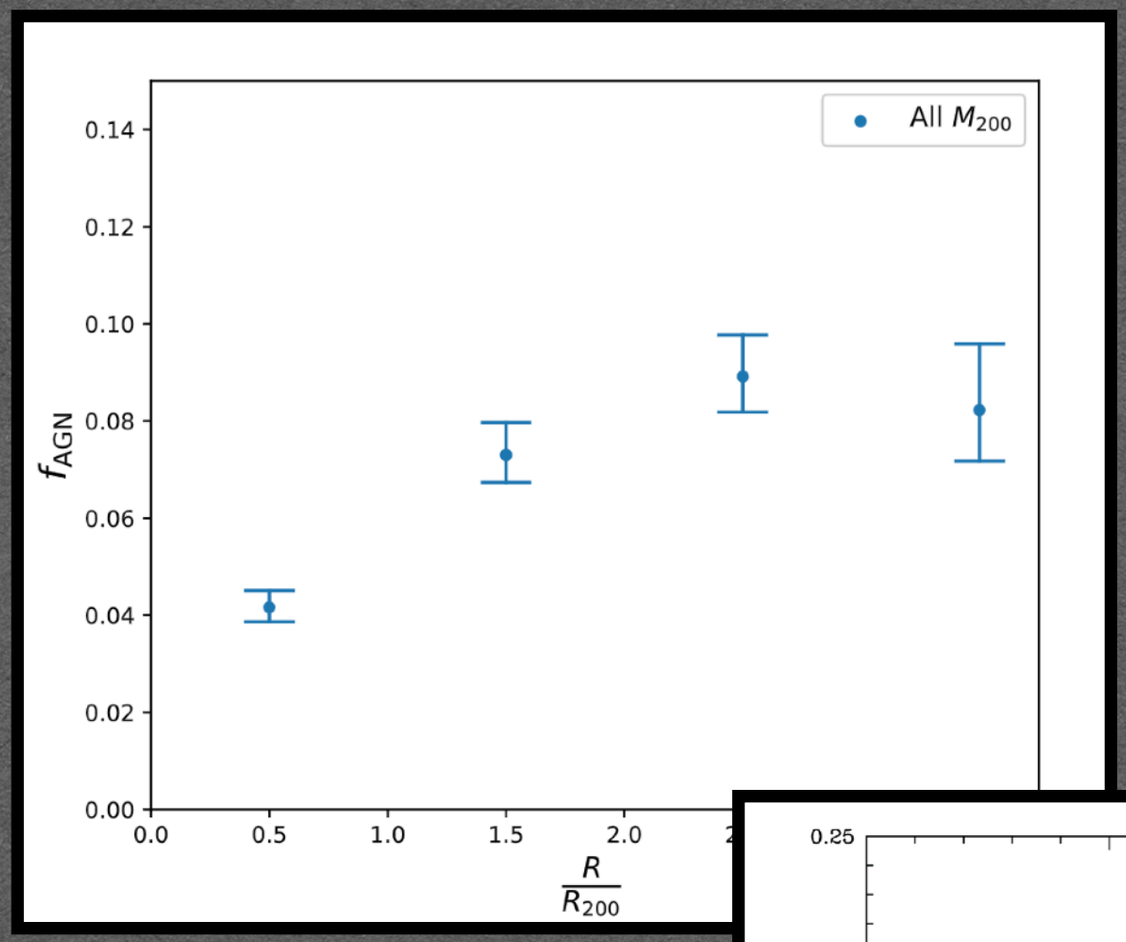
WARNING: Many, Many Plots



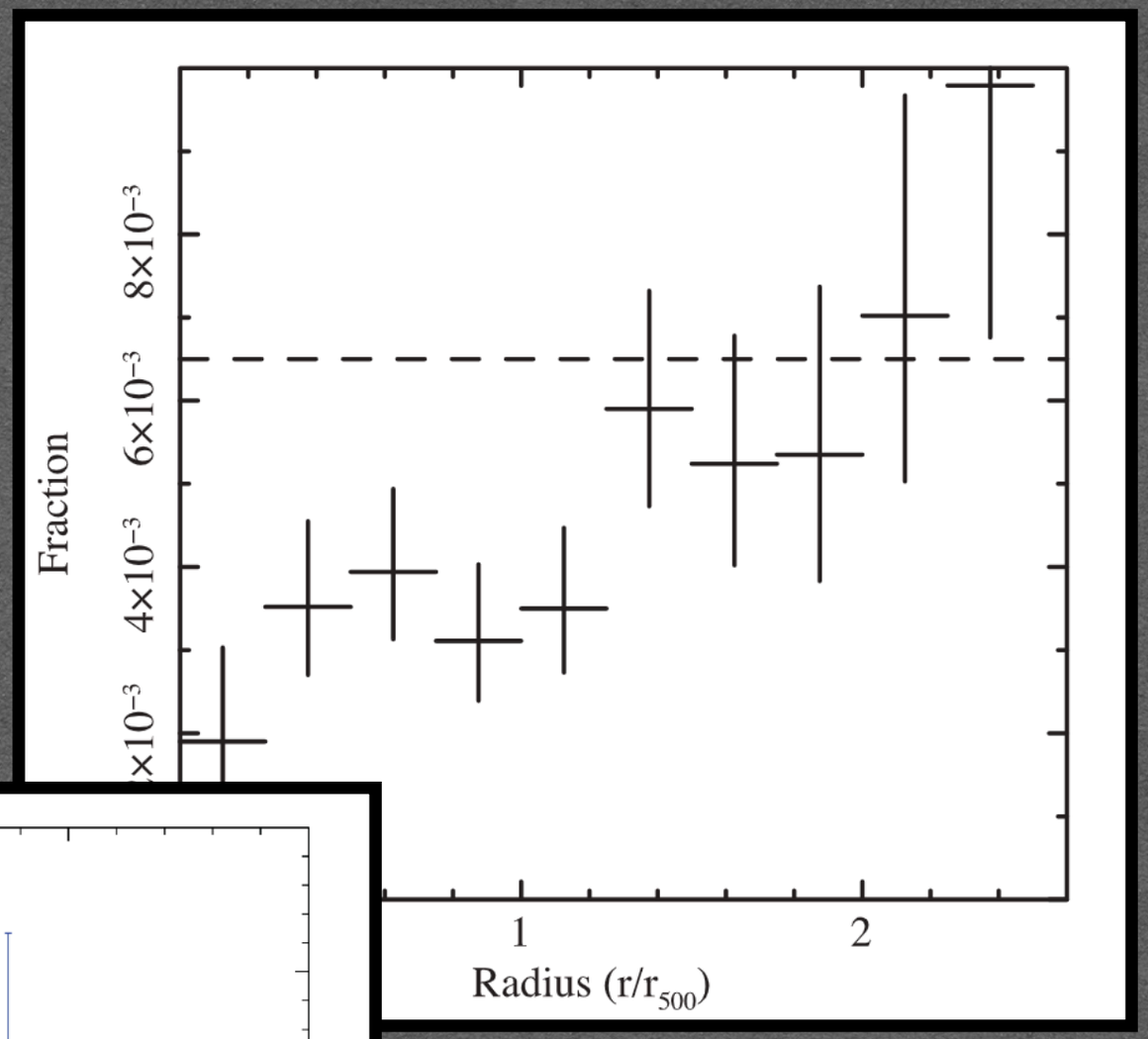




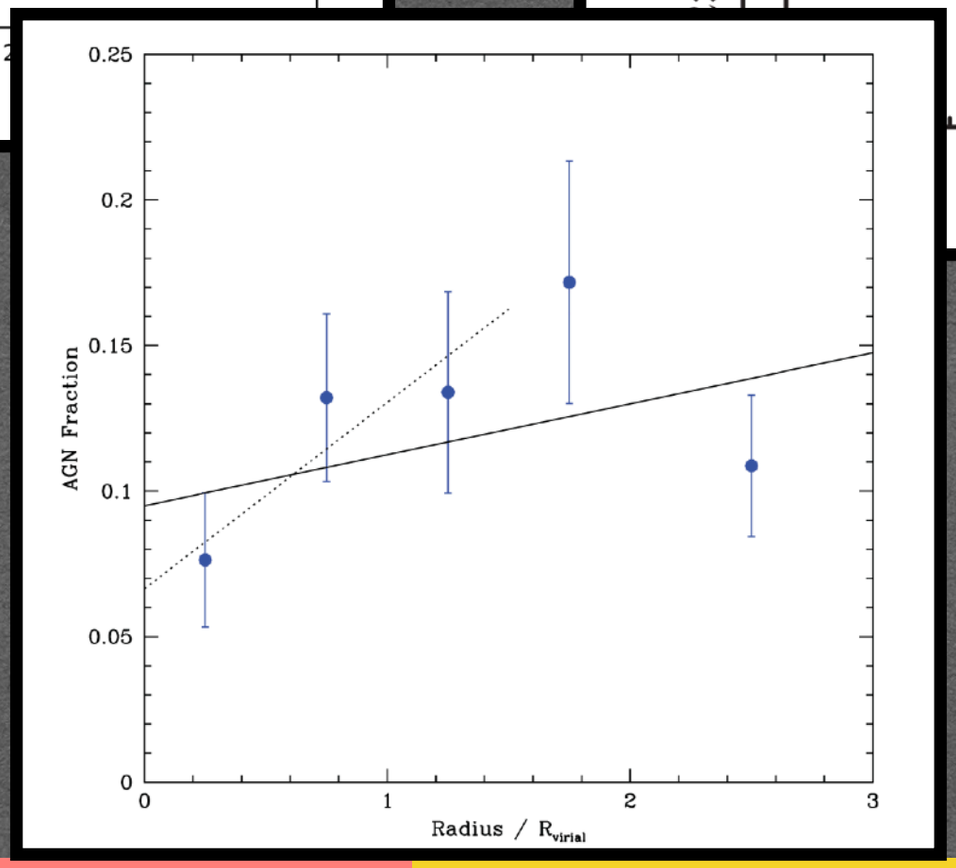
Low-z Clusters Prominent Deficit of AGN in Centre



Gordon+18
z<0.15
optical



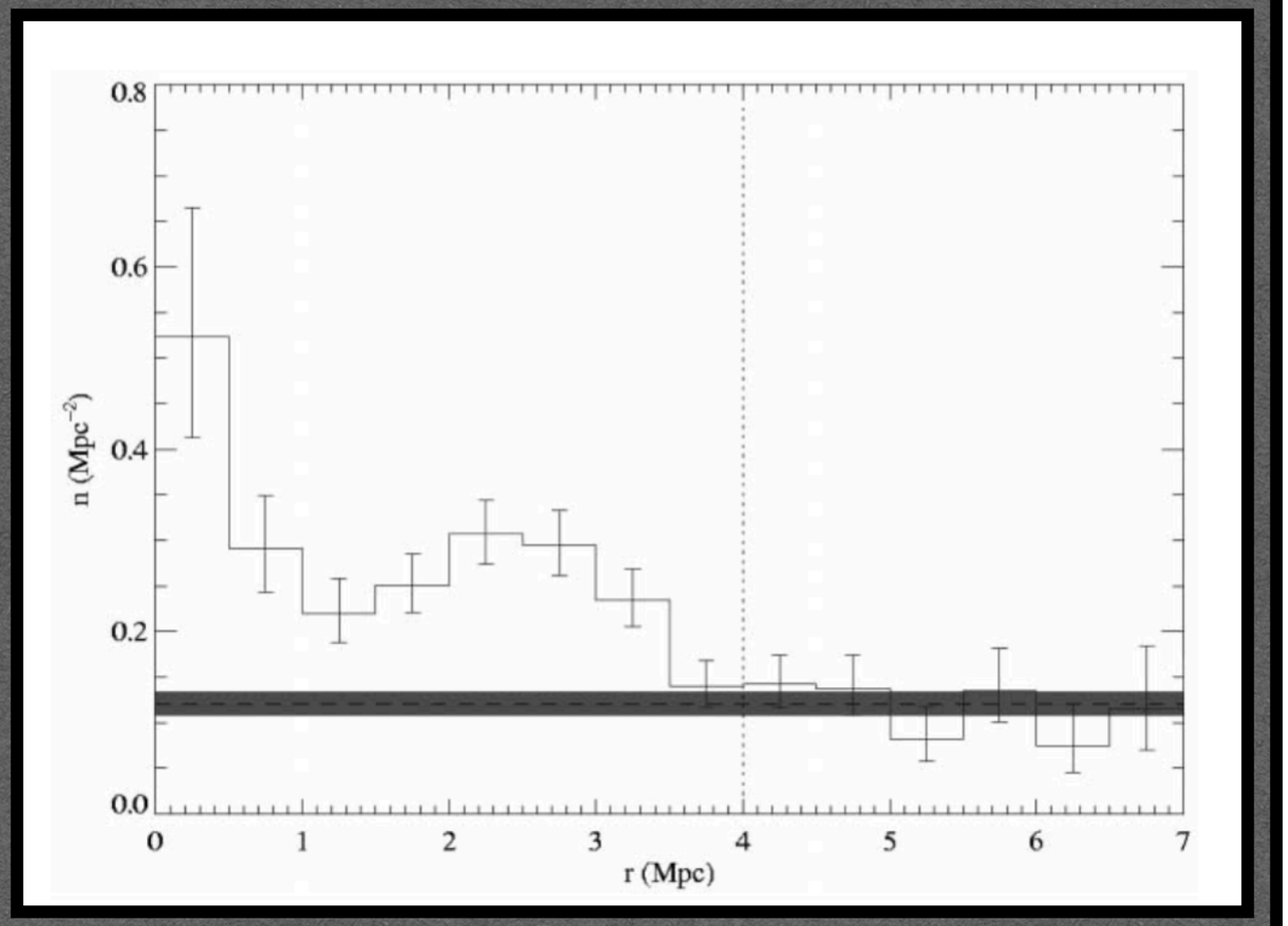
Ehlert+14
0.2 < z < 0.7
X-ray



Pimbblet+13
z ~ 0.07
optical

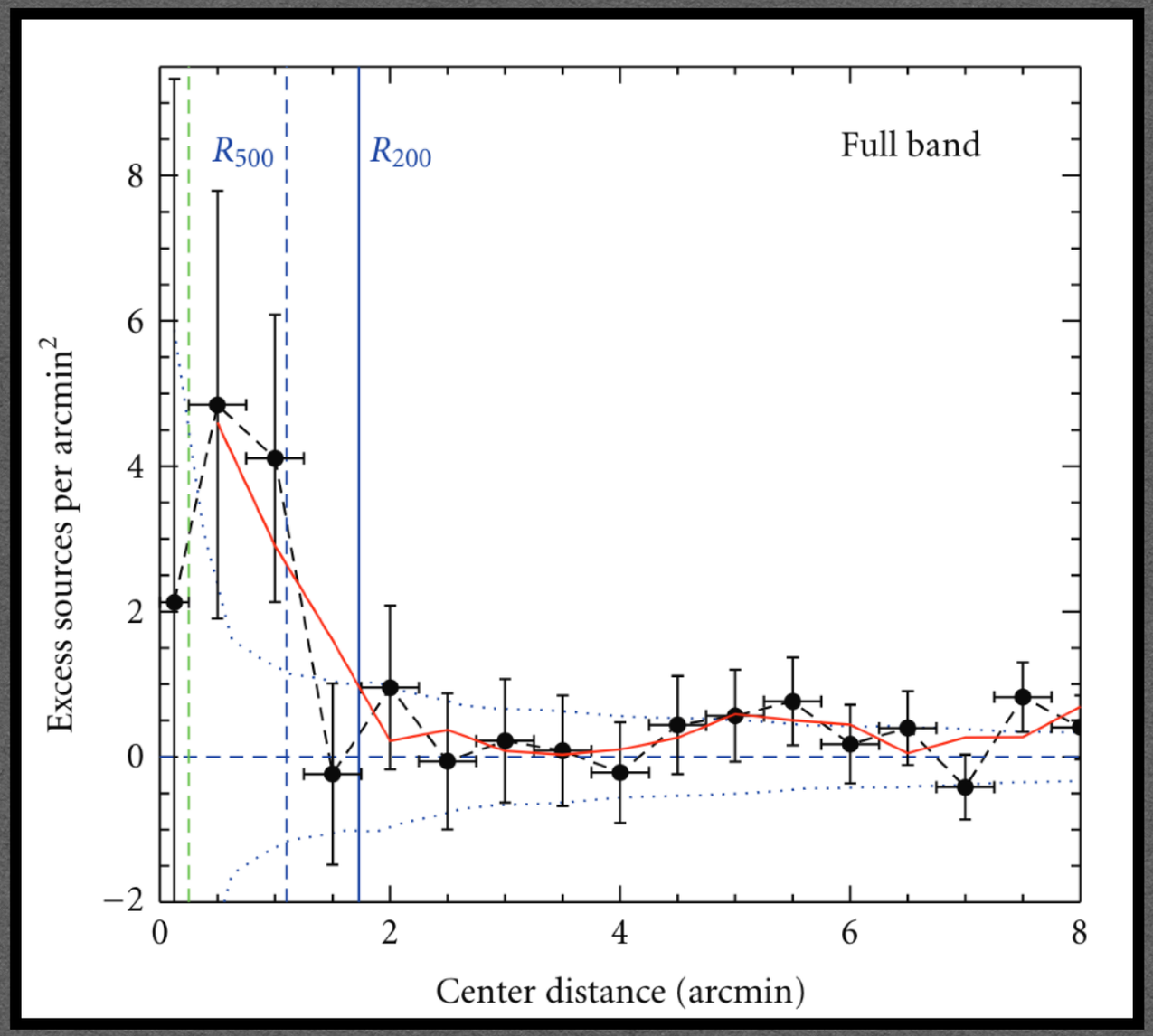
Excess of X-ray Sources/AGN in Clusters at z > 0.5

0.3 < z < 0.7



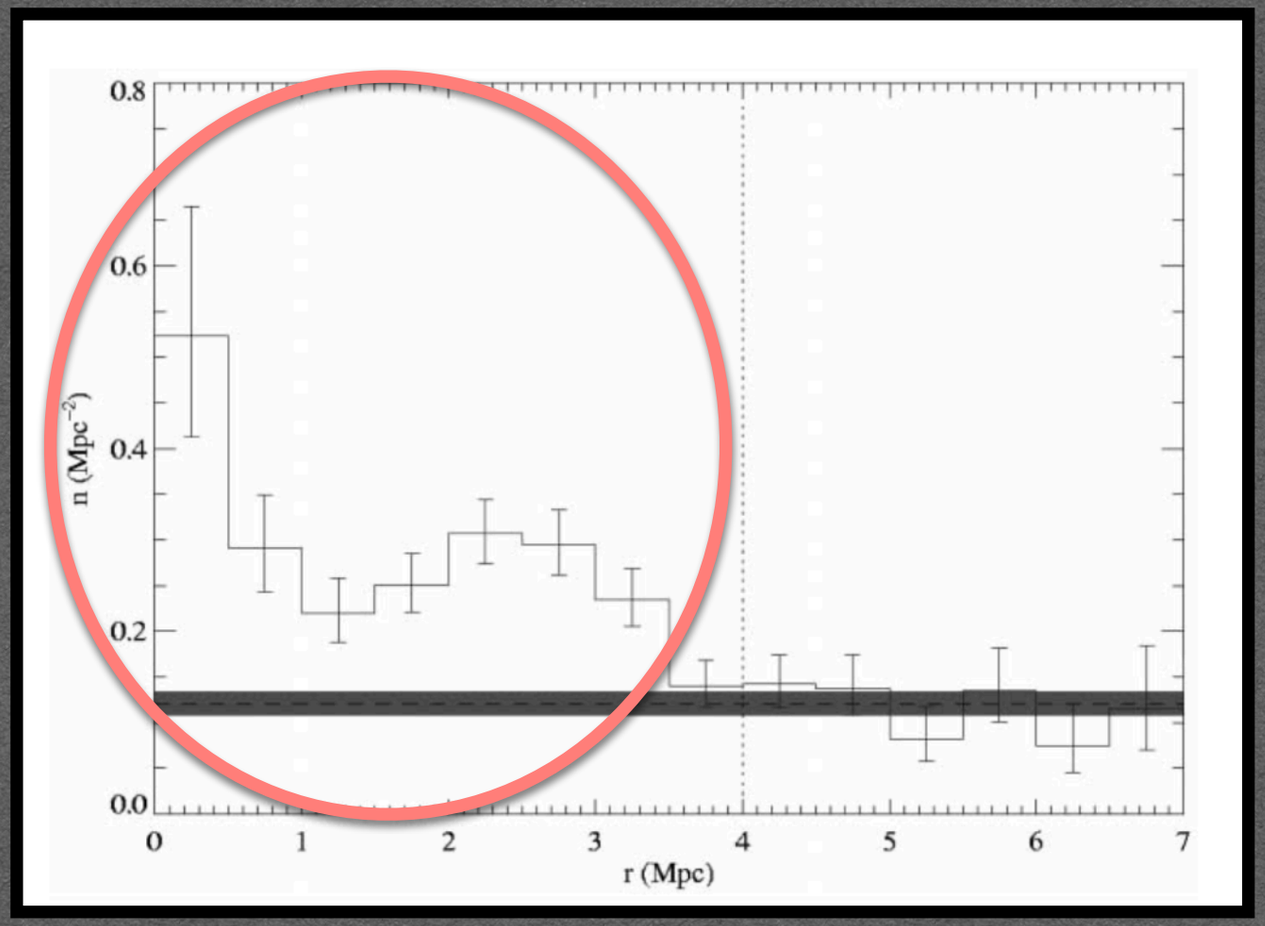
Ruderman+05

0.9 < z < 1.6



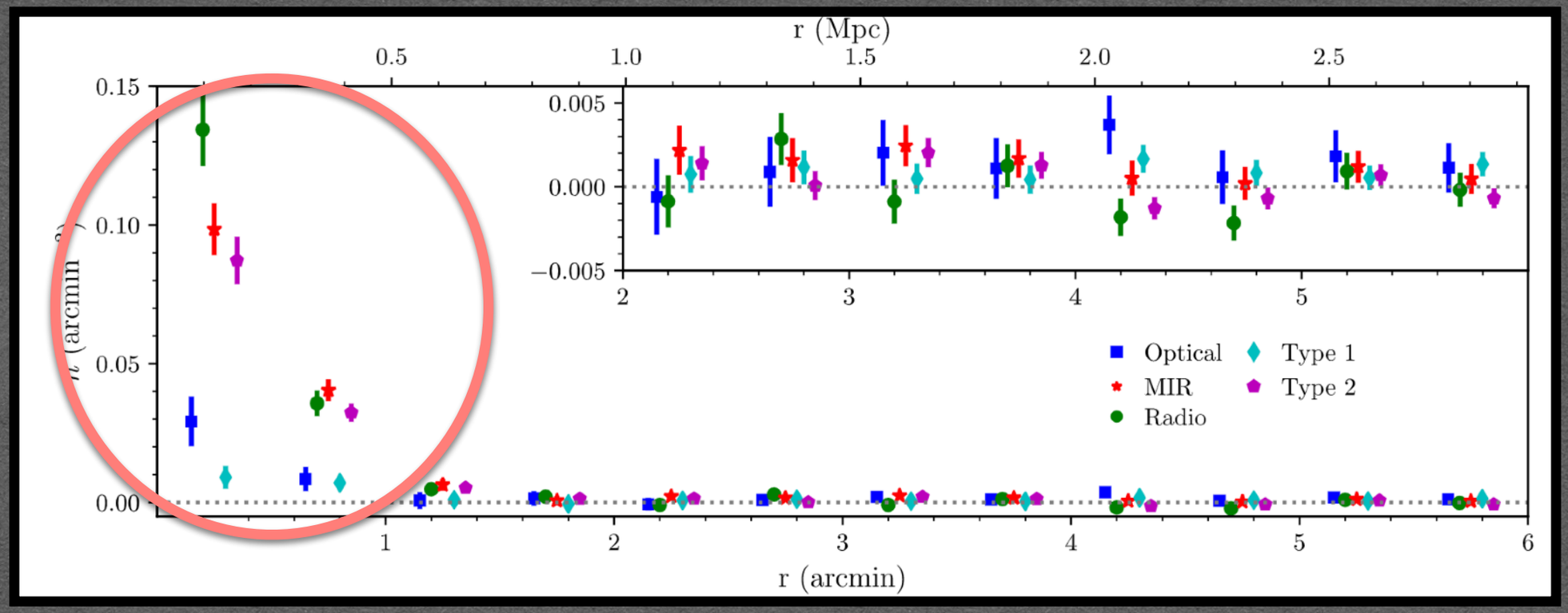
Fassbender+12

Ruderman+05
0.3 < z < 0.7

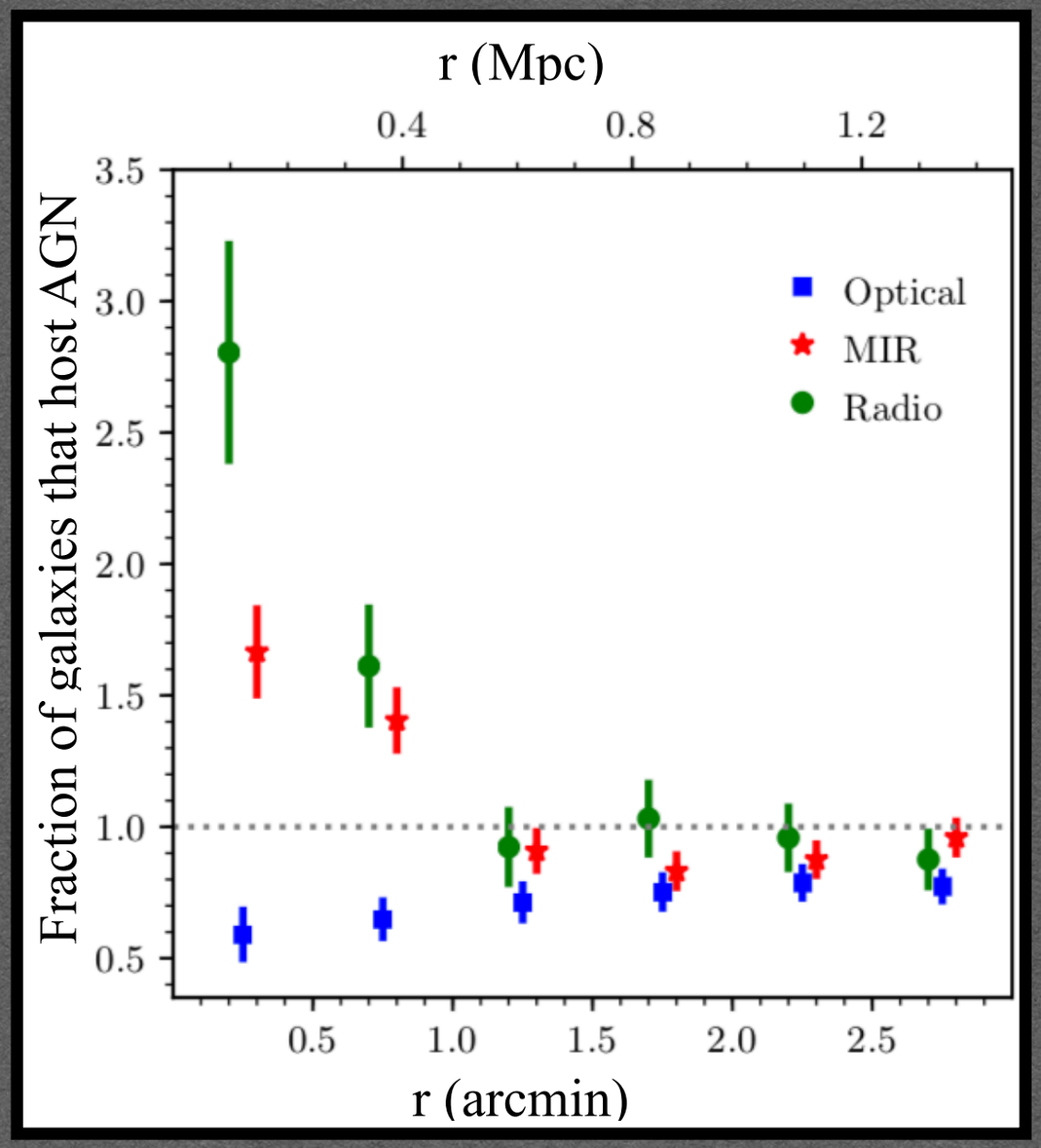


Intermediate to High z (z>0.5) Excess Radio, IR, X-ray AGN in Cluster Centre

Mo+18
z~1

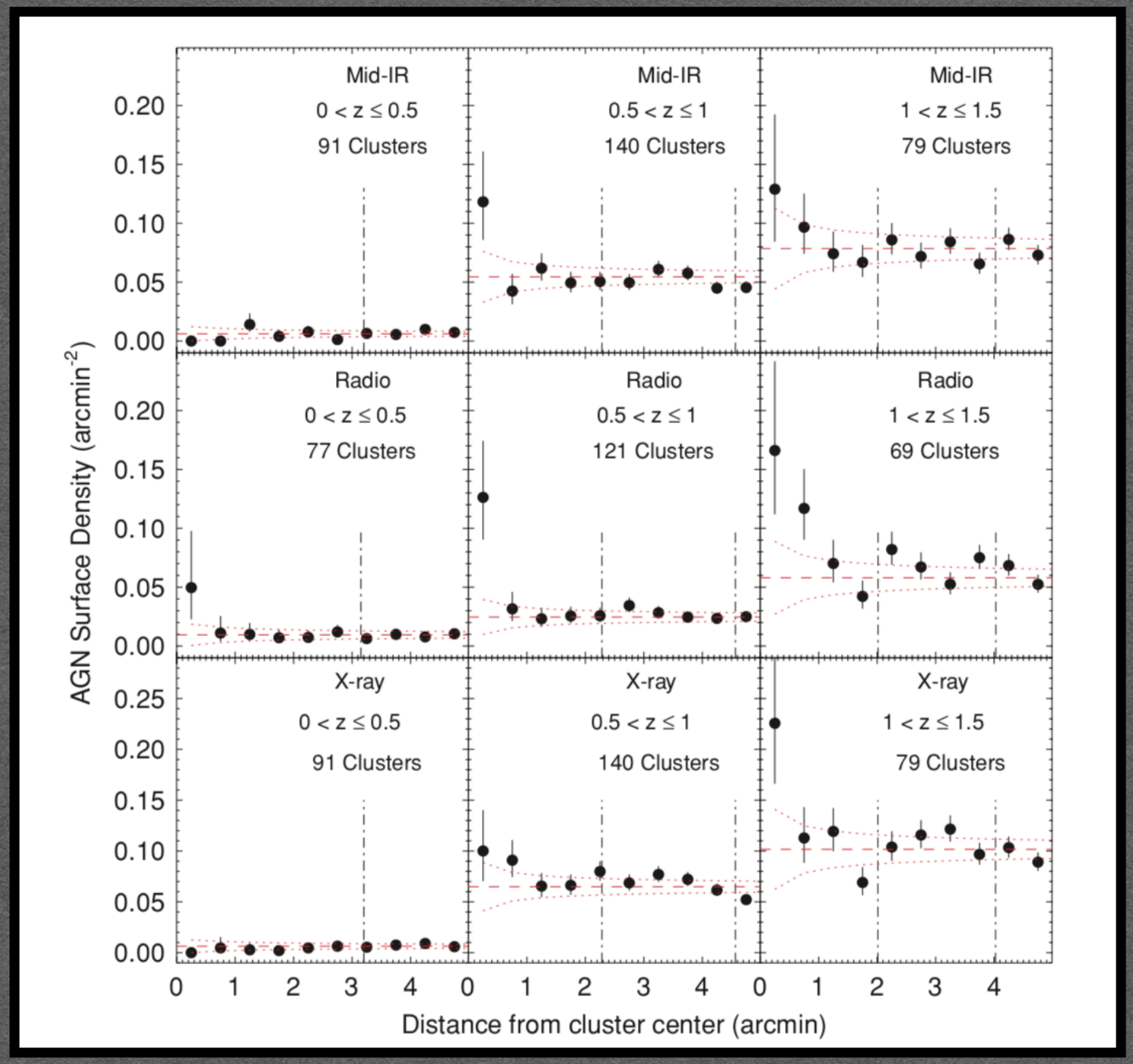


Equal or Excess of X-ray, IR, Radio Selected AGN in High-z Clusters

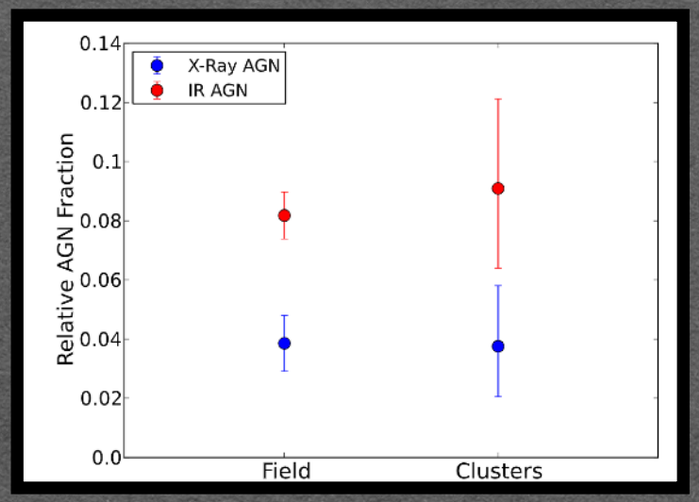


Mo+18
z~1

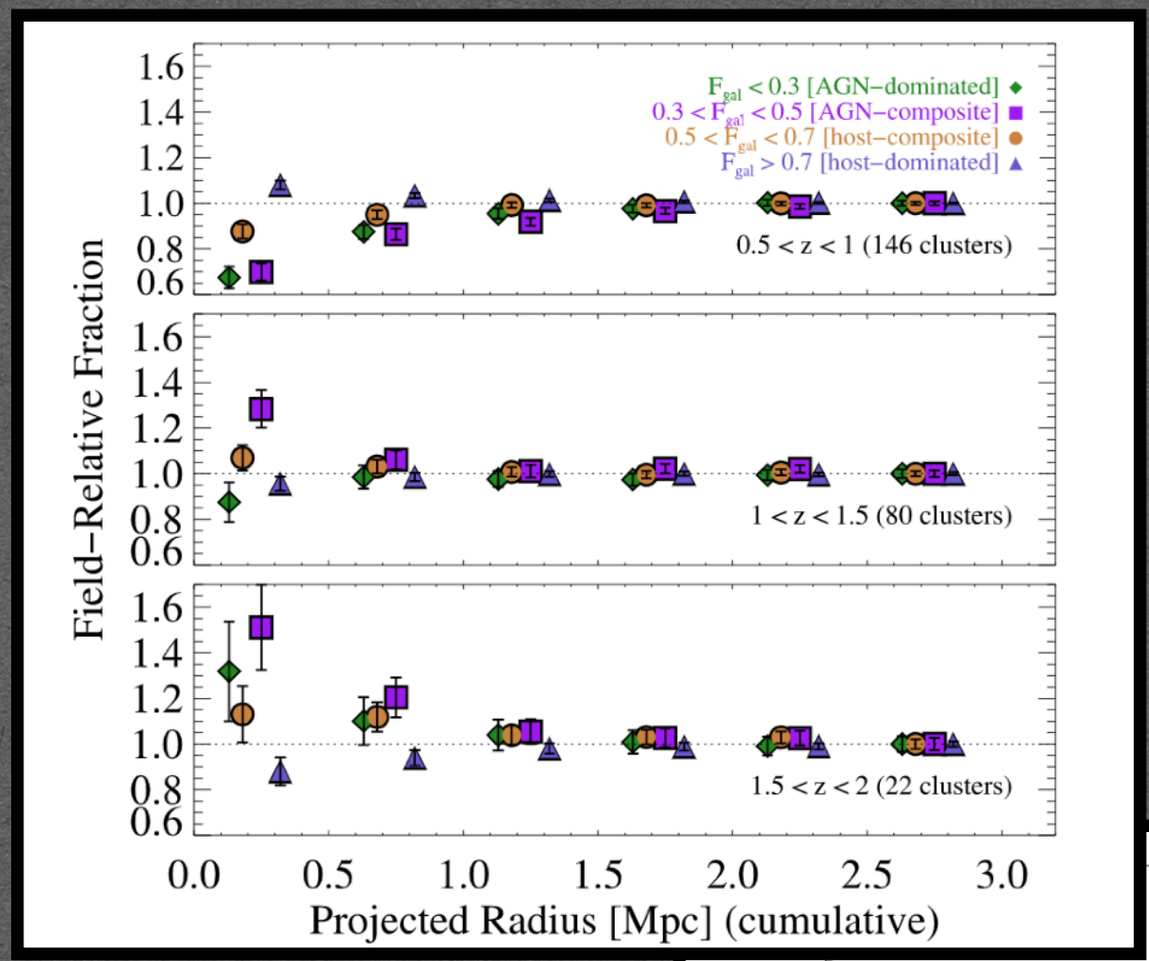
Galametz+09



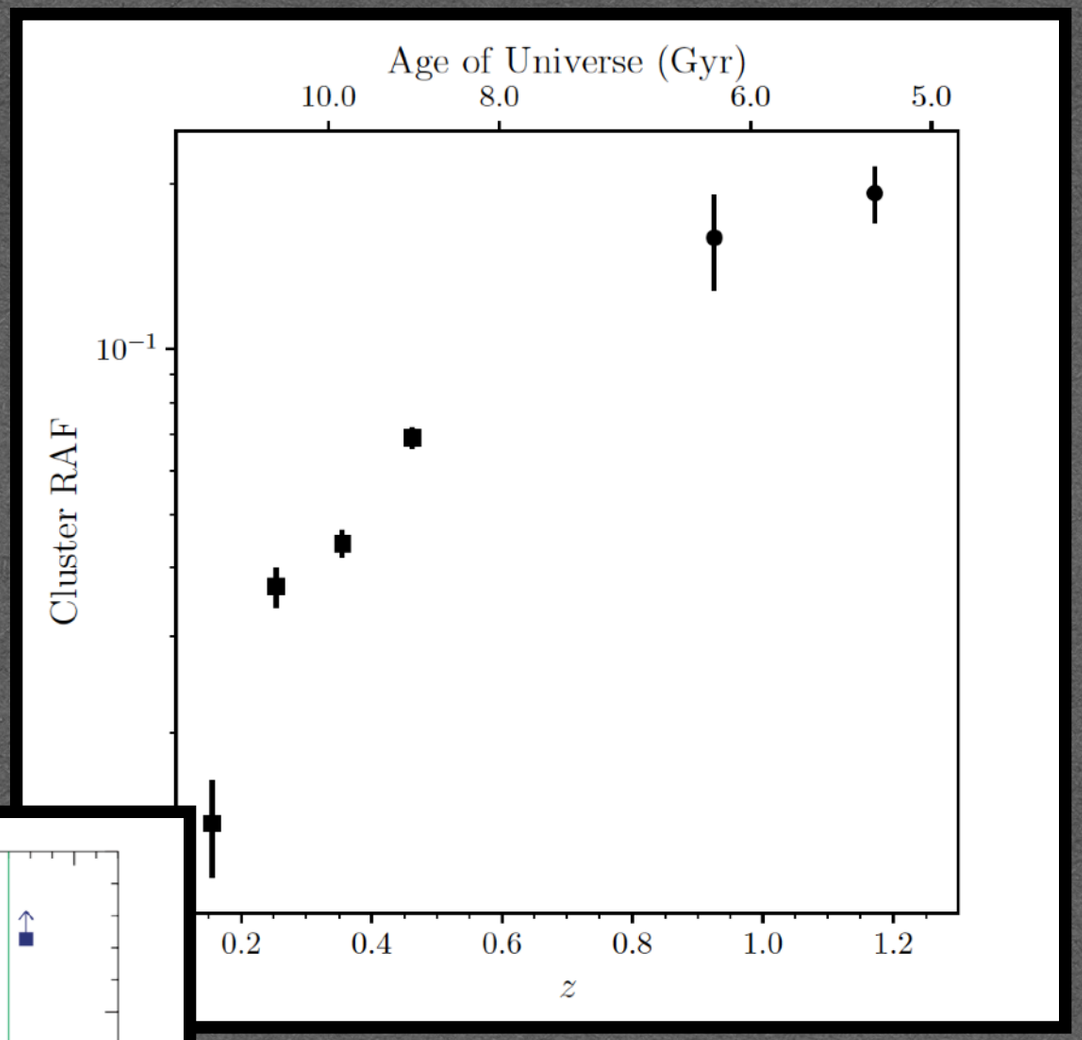
Martini+13
1 < z < 1.5



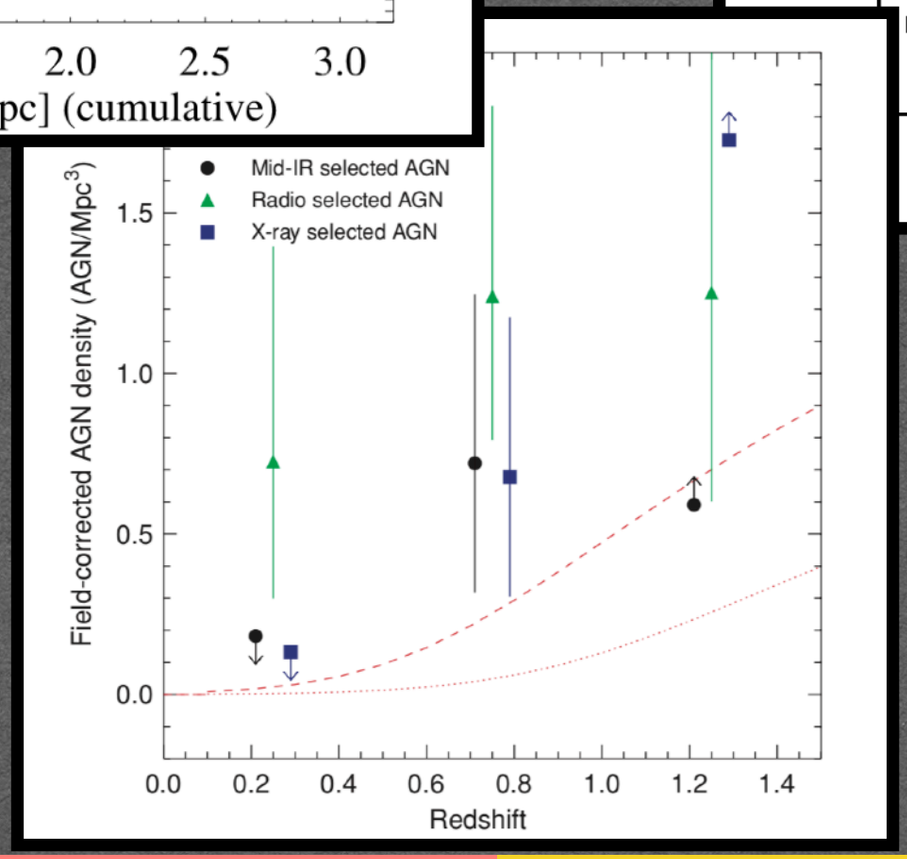
AGN Fraction Increases with Increasing z



Alberts+16



Mo+20



Galametz+09

What do we know? What does it mean?

1. Number X-ray, IR, and Radio identified AGN in clusters are either equal or in excess compared to field at intermediate and high redshifts ($z > 0.5$)

2. More X-ray, IR, and Radio identified AGN in cluster center at intermediate and high redshifts ($z > 0.5$)

3. Deficit of optically and X-ray identified AGN in cluster center at low redshift ($z < 0.5$)

4. Fraction of AGN in clusters increases with increasing redshift — deficit, equal, excess compared to field

What do we know? What does it mean?

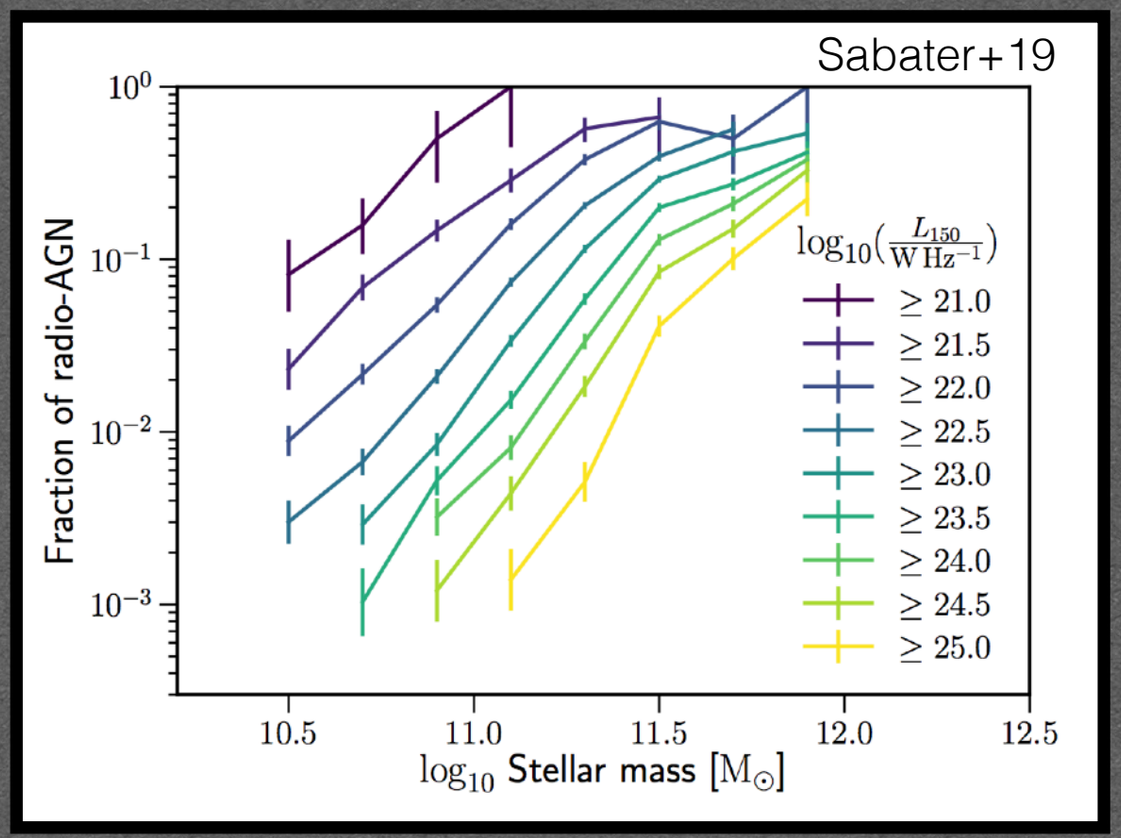
1. **High-z:** clusters still forming = more interactions and gas supply

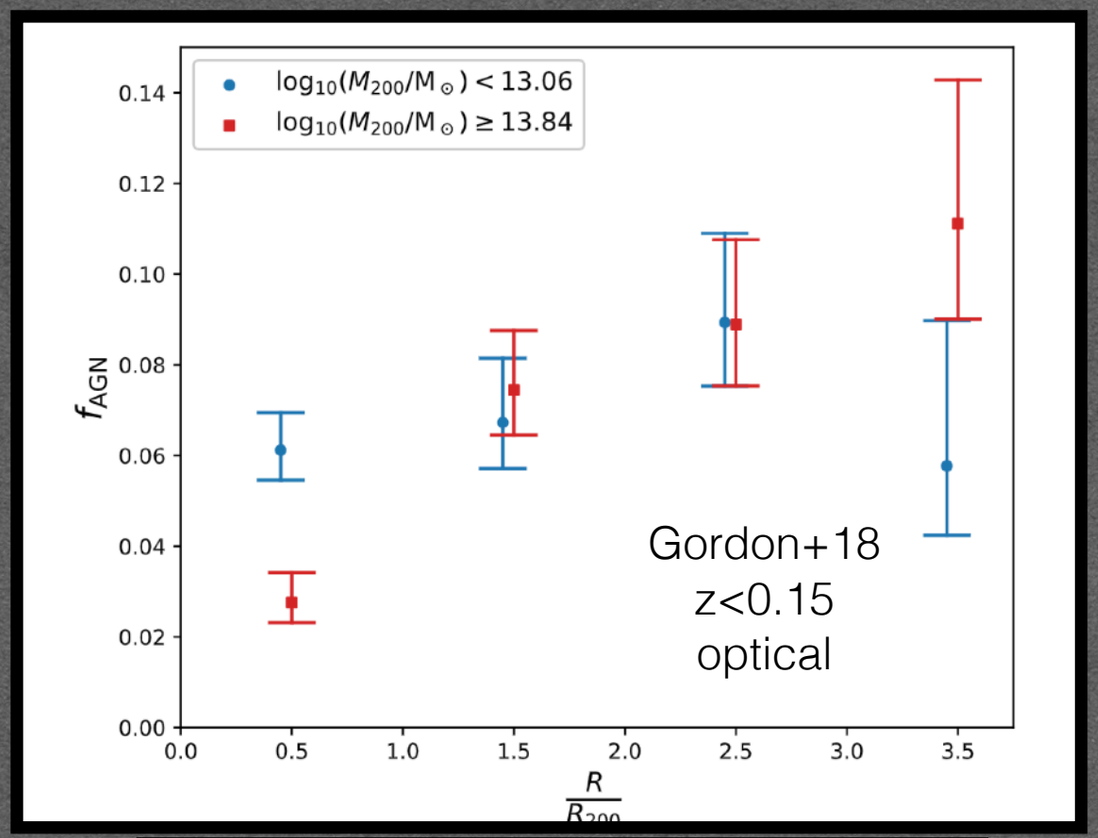
2. **Low-z:** clusters more formed and relaxed
   - a. **core** = higher velocity dispersion = less interactions, gas supply in galaxies in core is depleted due to interactions with ICM
   - b. **infalling population** = lower velocities = more interactions, infalling population has gas supply

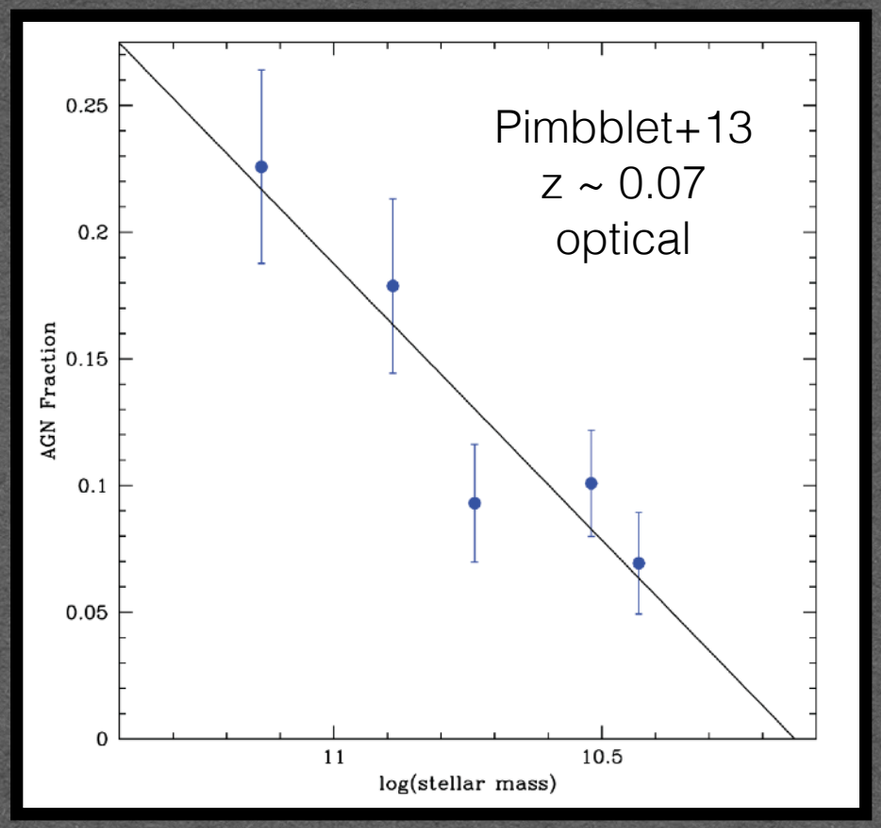
3. Mirrors SF activity evolution in clusters

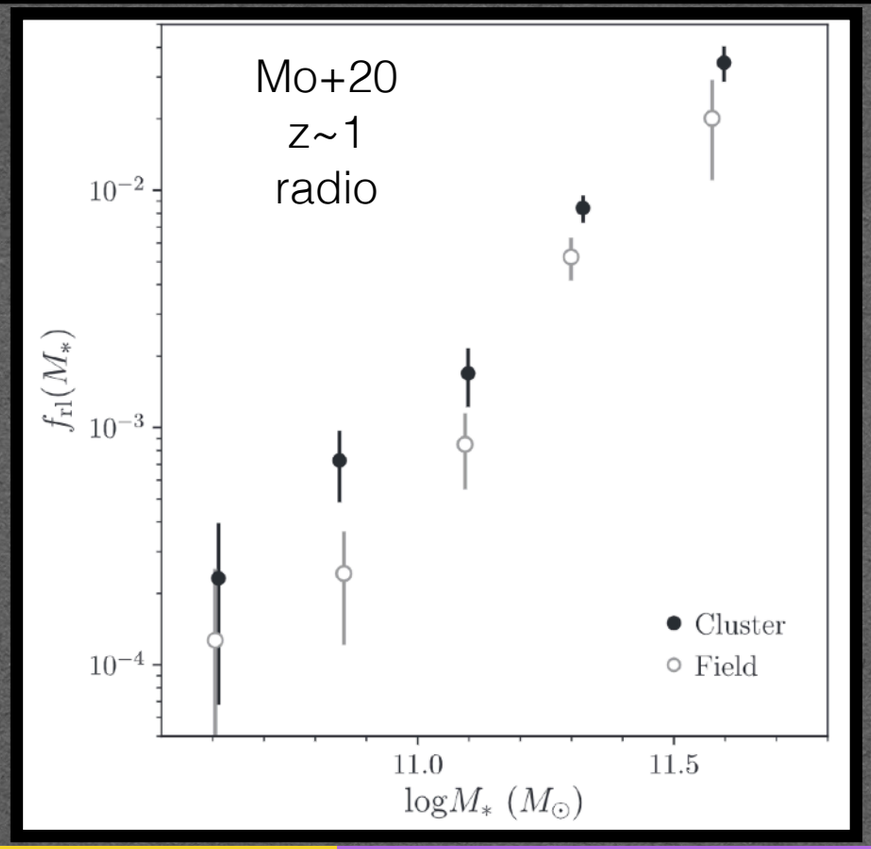
Haines+12, Martini+13, Ehlert+14, Alberts+16, Gordon+18

Complications: stellar mass, galaxy type, redshift

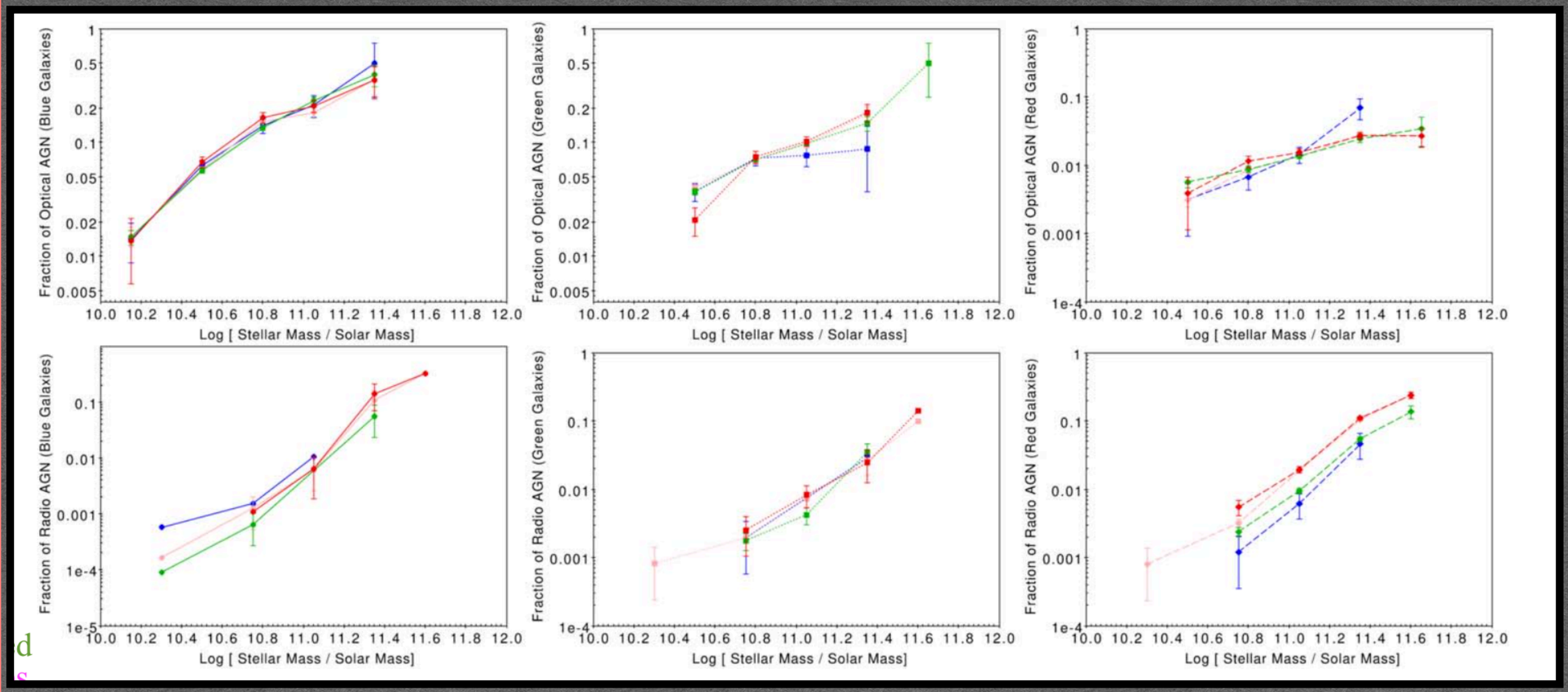








Complications: stellar mass, galaxy type, redshift



Miraghaei+20

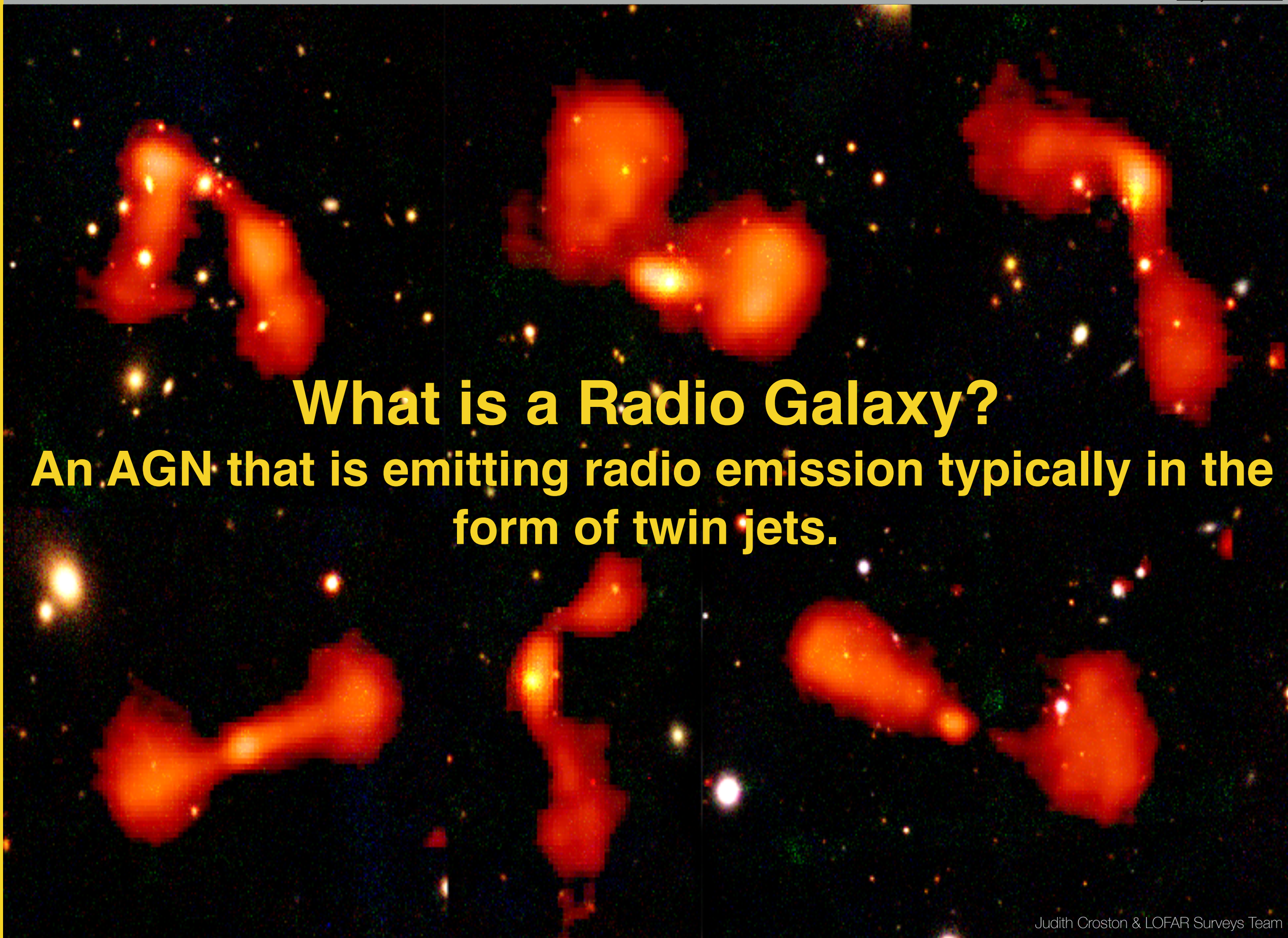
Complications: stellar mass, galaxy type, redshift

Difficult to disentangle cause and effect due to stellar mass, galaxy type, AGN selection method, redshift, black hole mass, luminosity, location within cluster, and cluster richness effects

NASA, ESA, CXC/NRAO/STScI, B. McNamara

Radio-AGN in Galaxy Clusters

Moravec+20b



What is a Radio Galaxy?

An AGN that is emitting radio emission typically in the form of twin jets.

Judith Croston & LOFAR Surveys Team

What are we seeing when we observe AGN in the radio wavelengths?

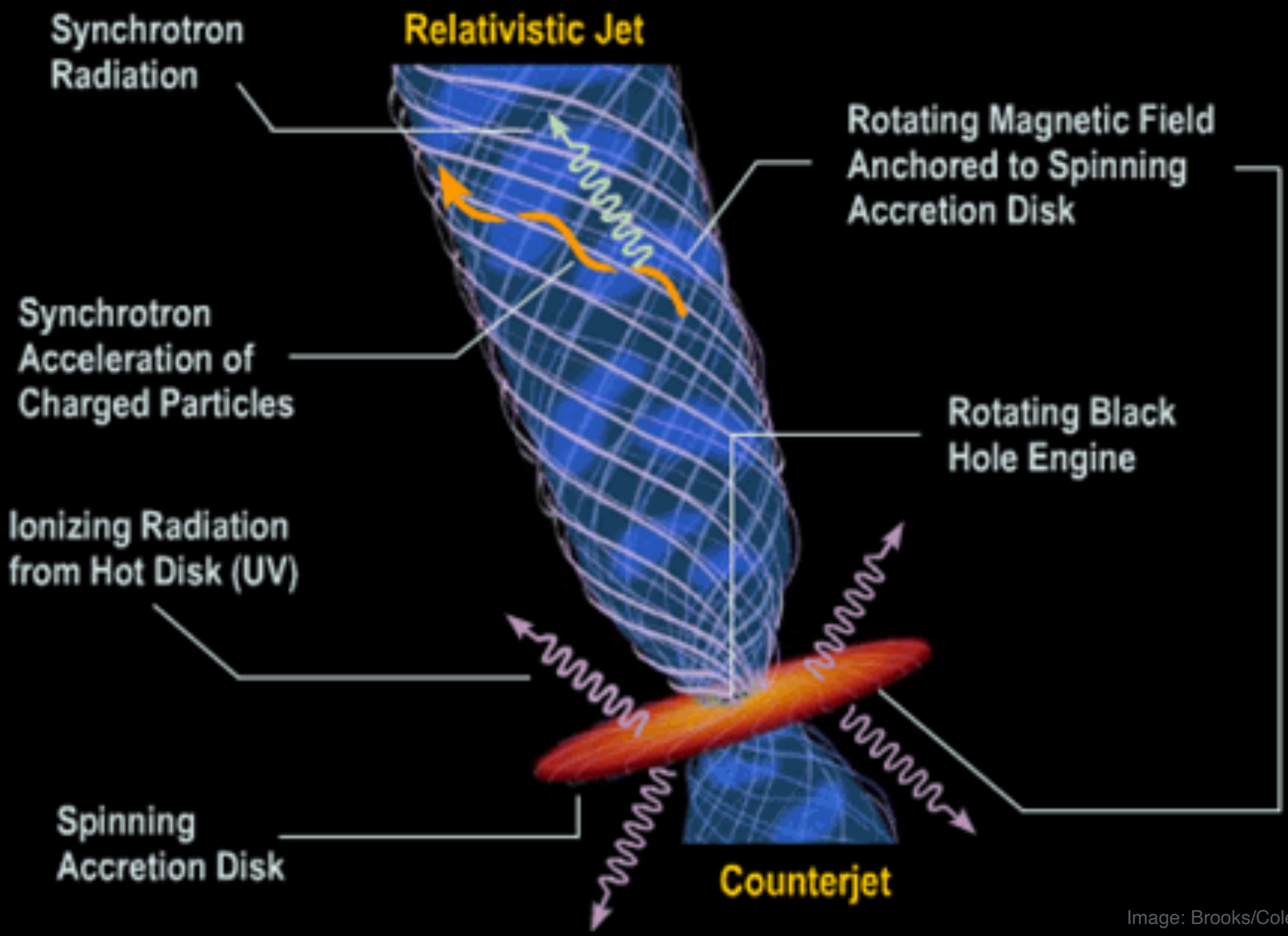
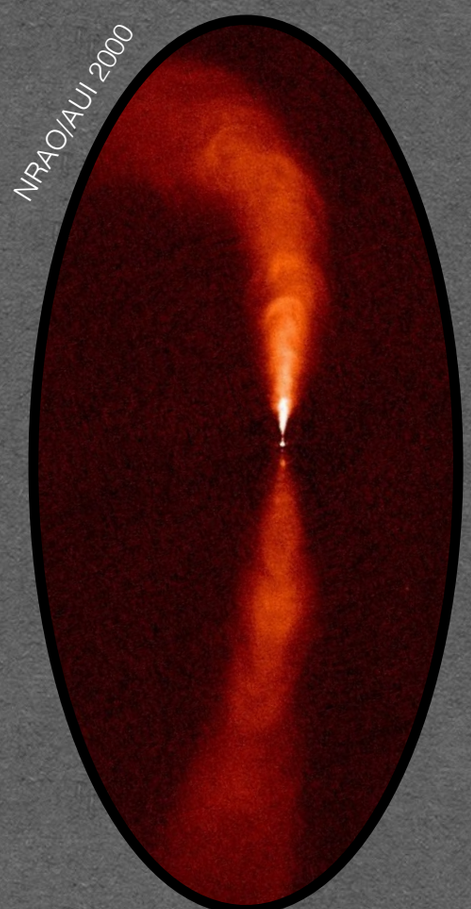
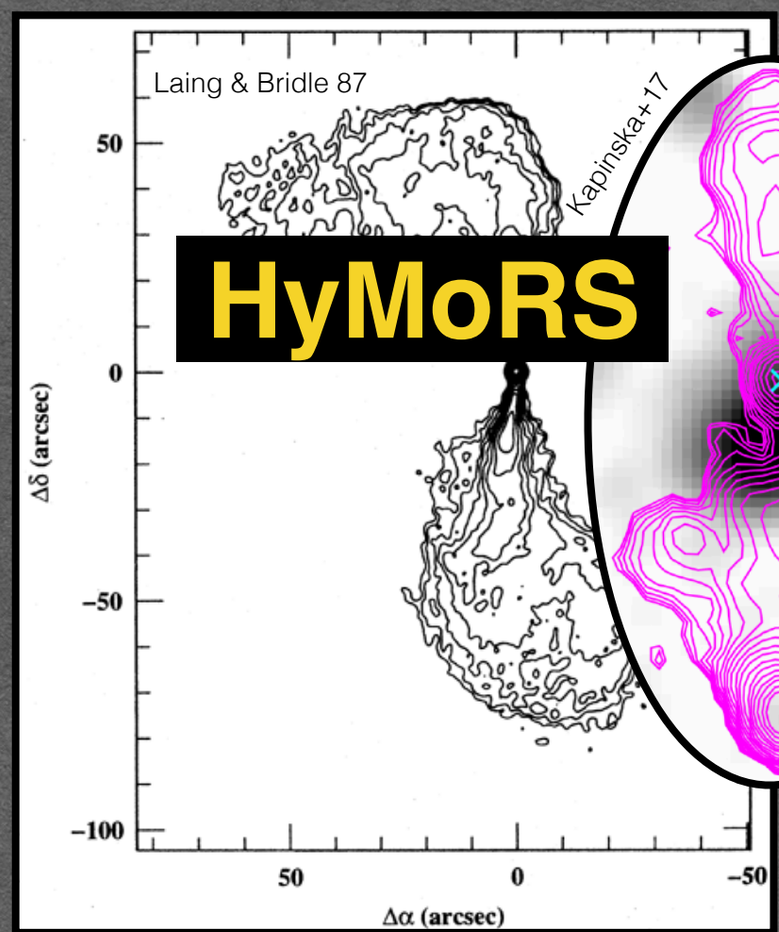


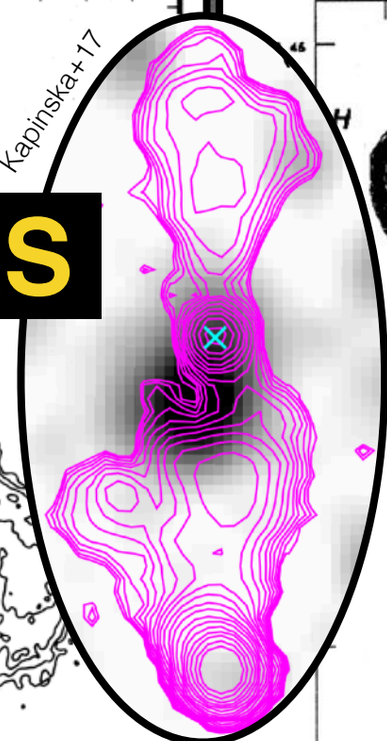
Image: Brooks/Cole Thomson Learning

Radio Galaxy Morphologies

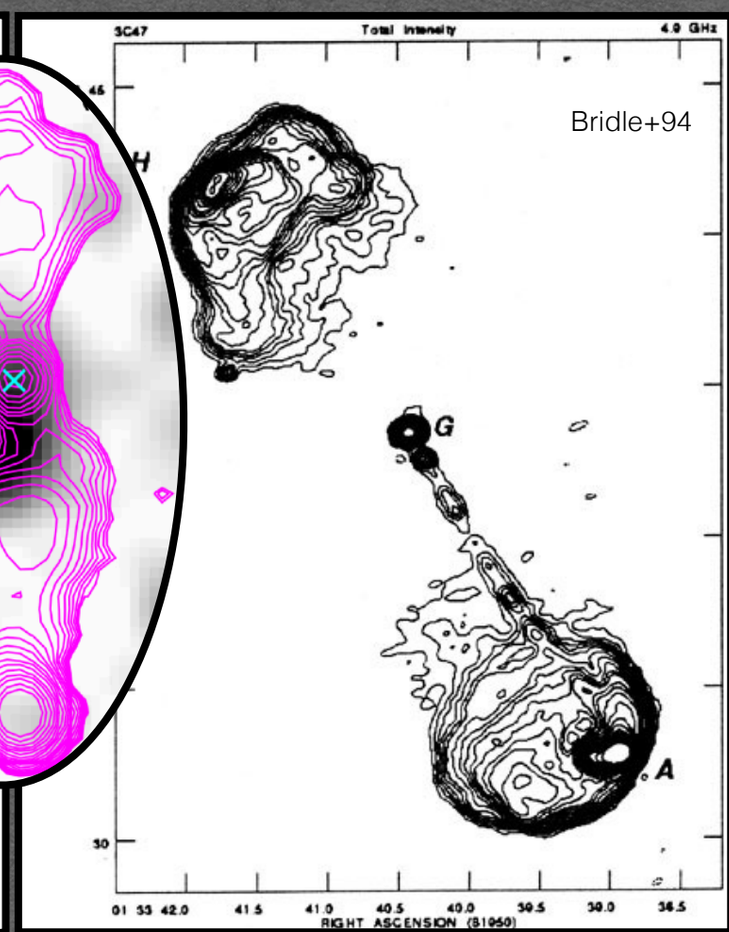
FR I **FR II**

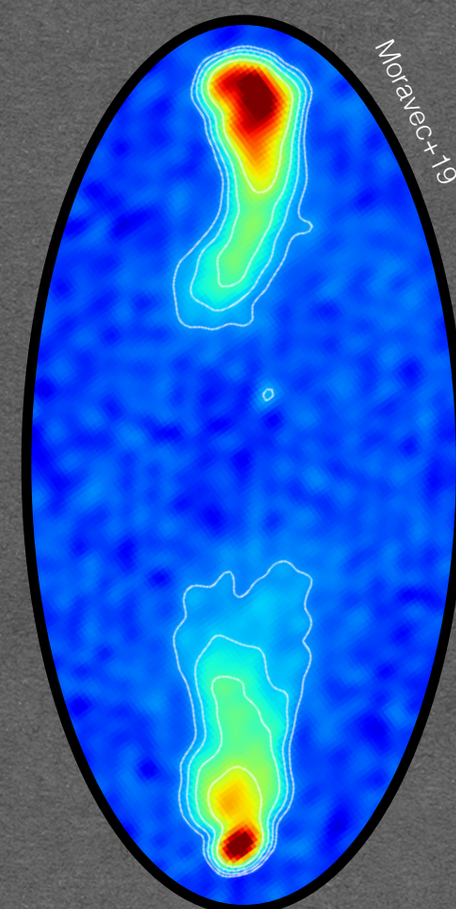




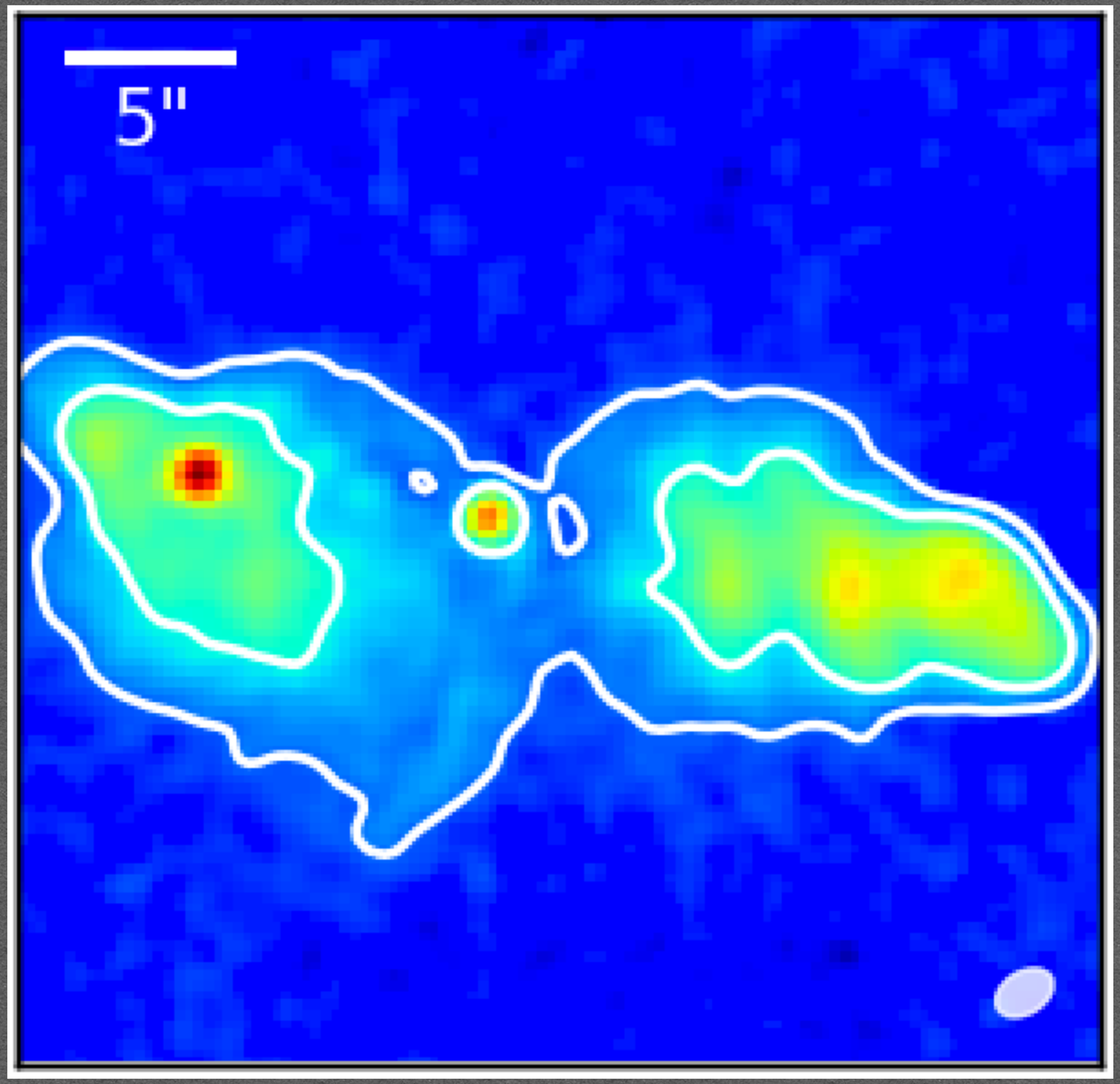


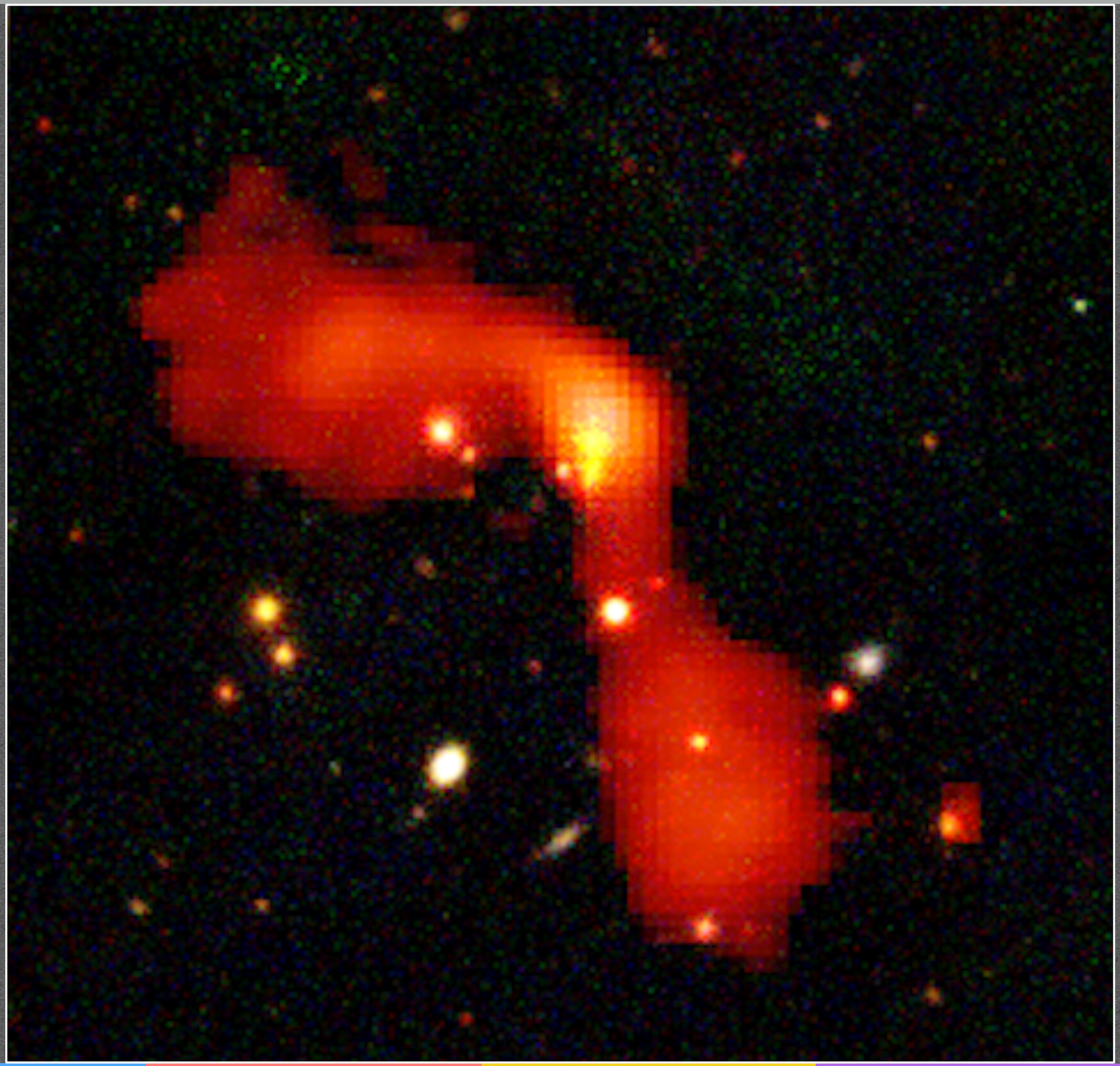
HyMoRS

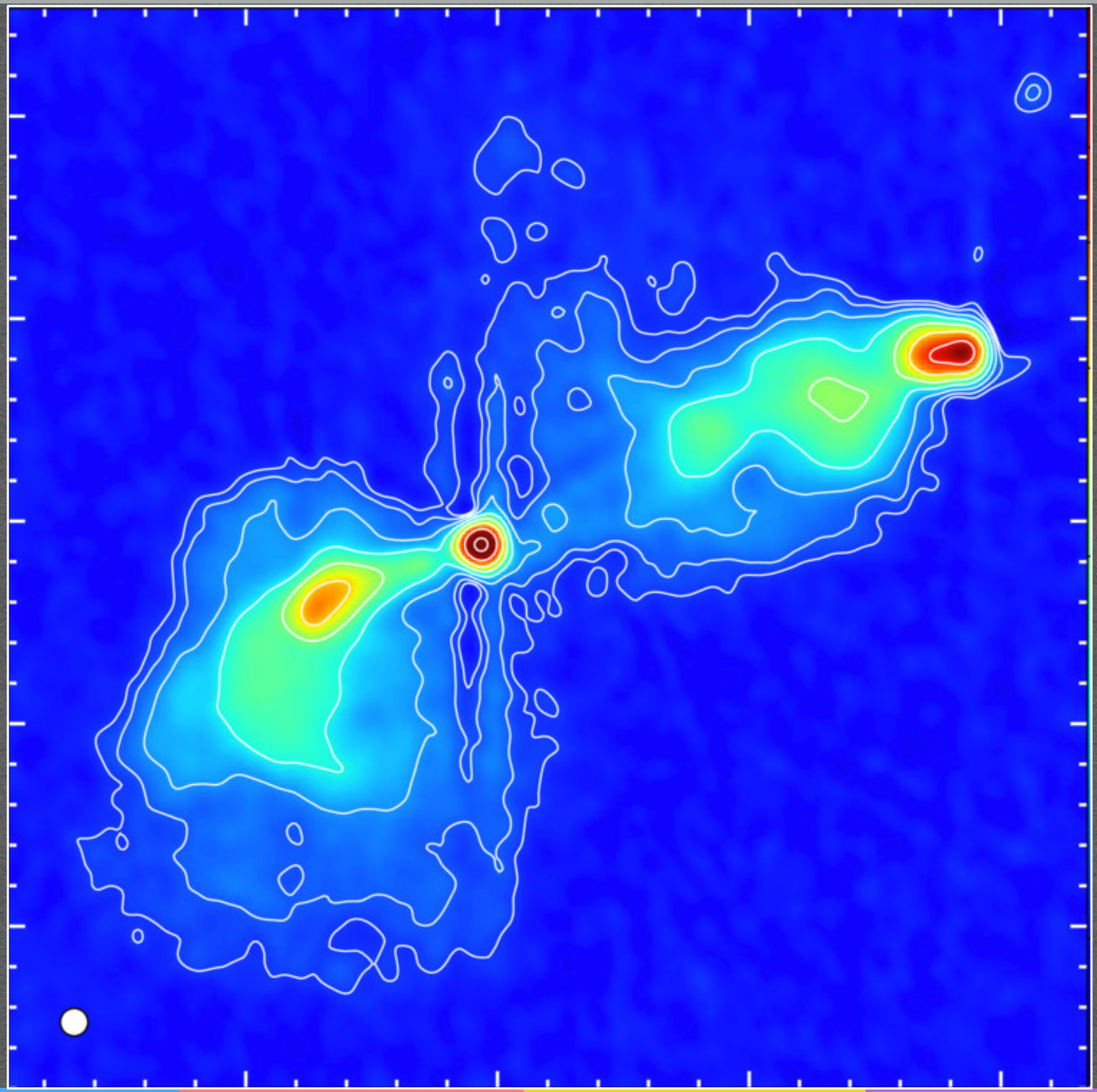


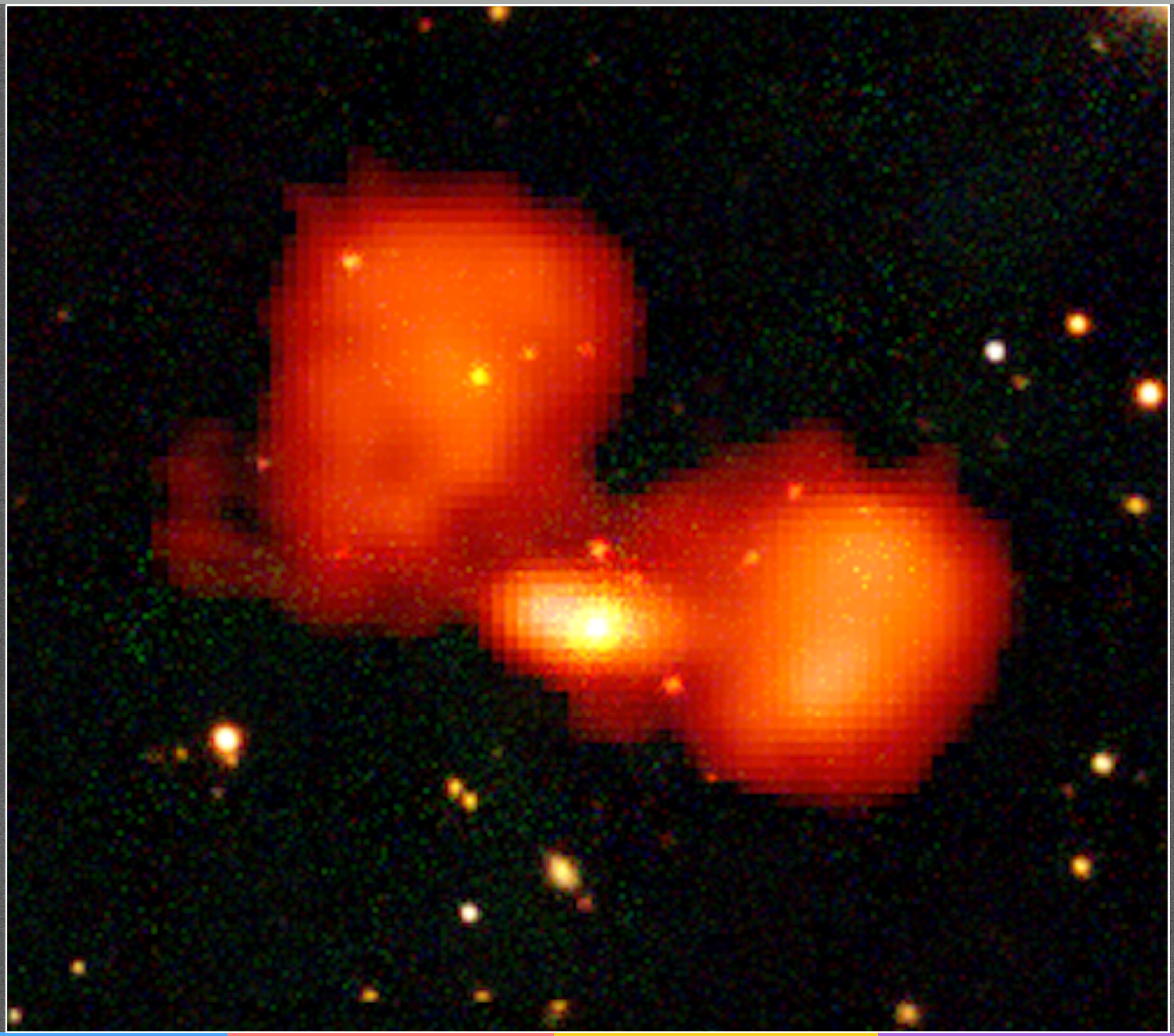


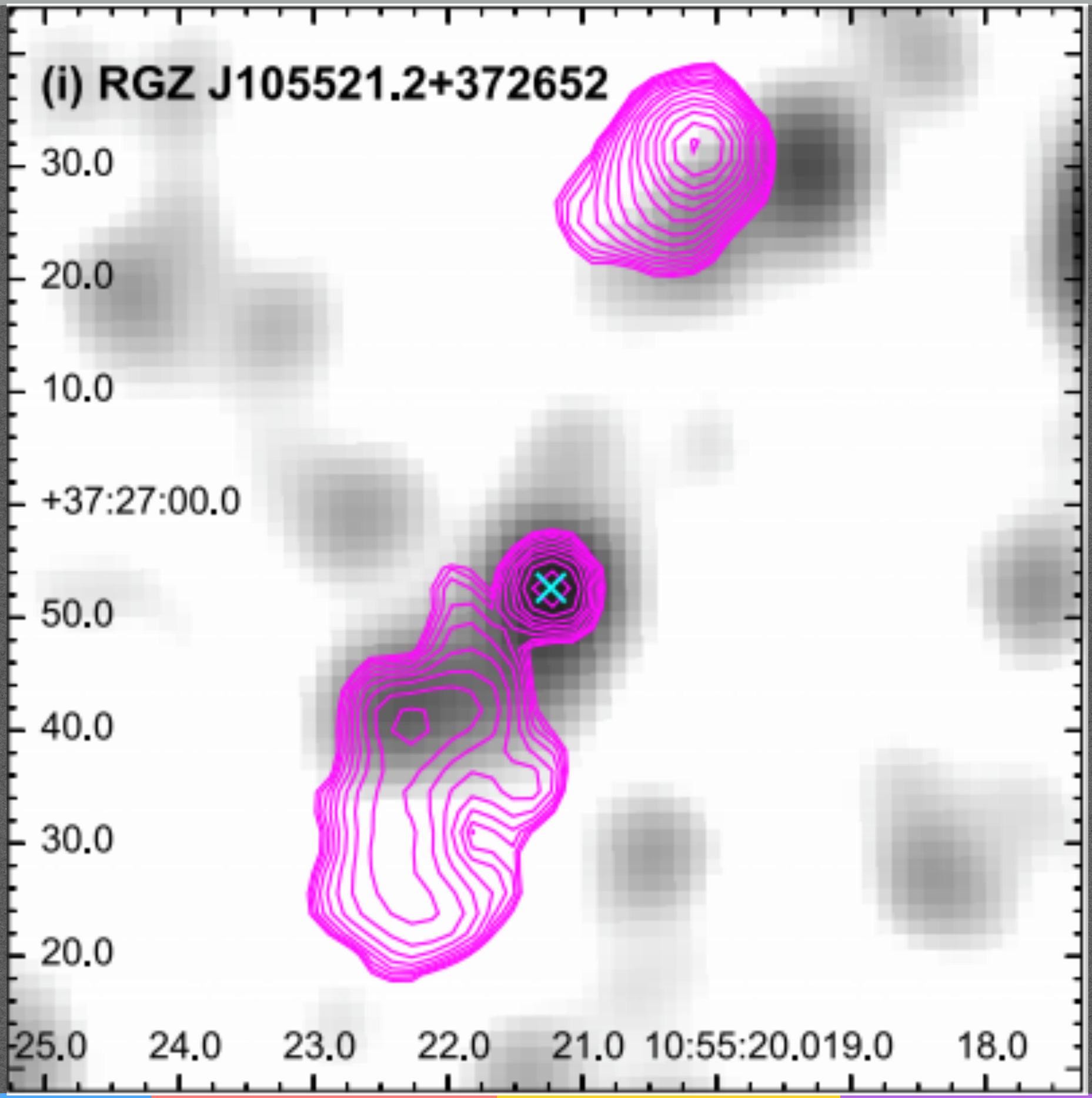
Your Turn! FR I, FR II, or Hybrid?










(i) RGZ J105521.2+372652
30.0
20.0
10.0
+37:27:00.0
50.0
40.0
30.0
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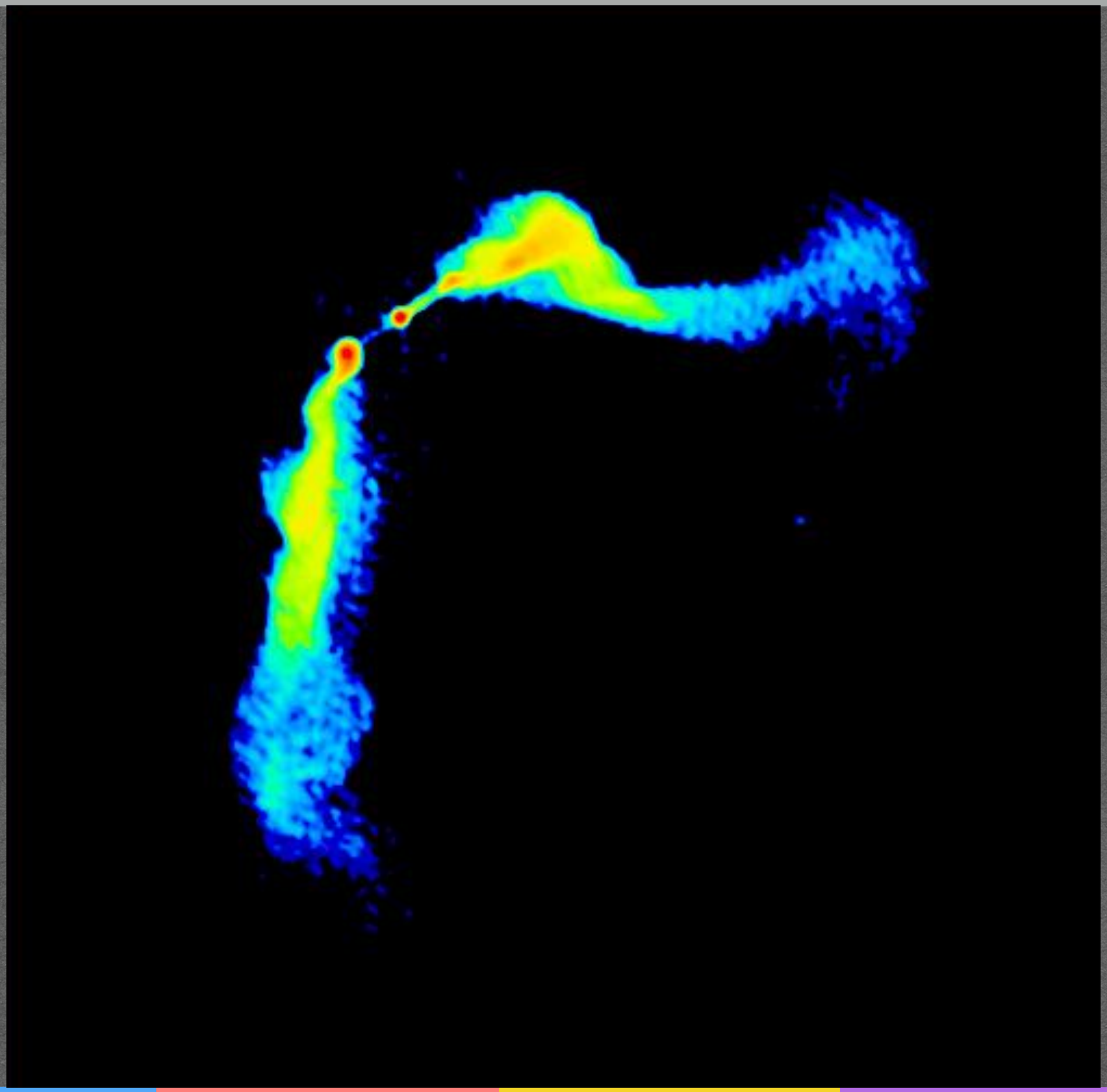
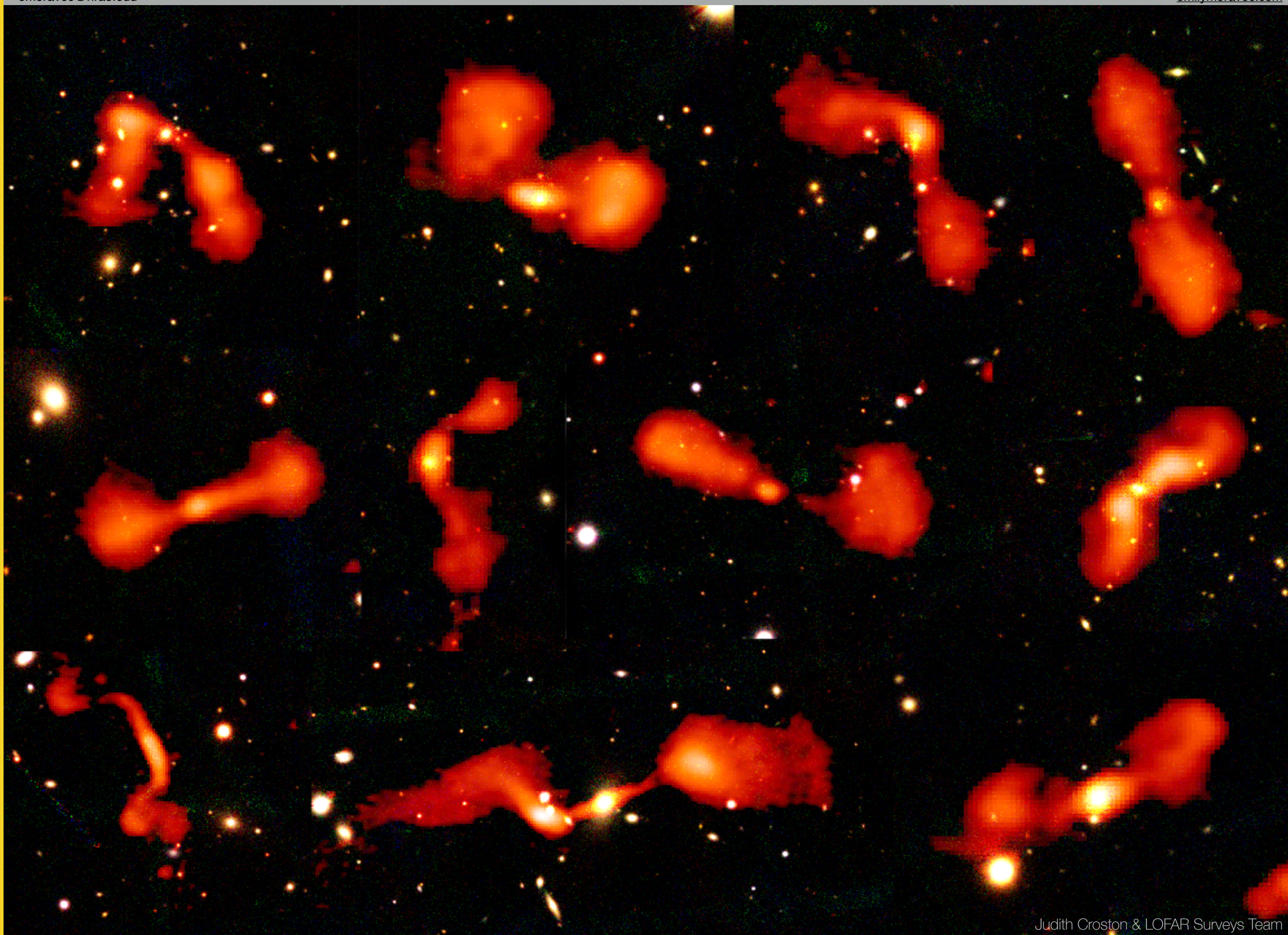
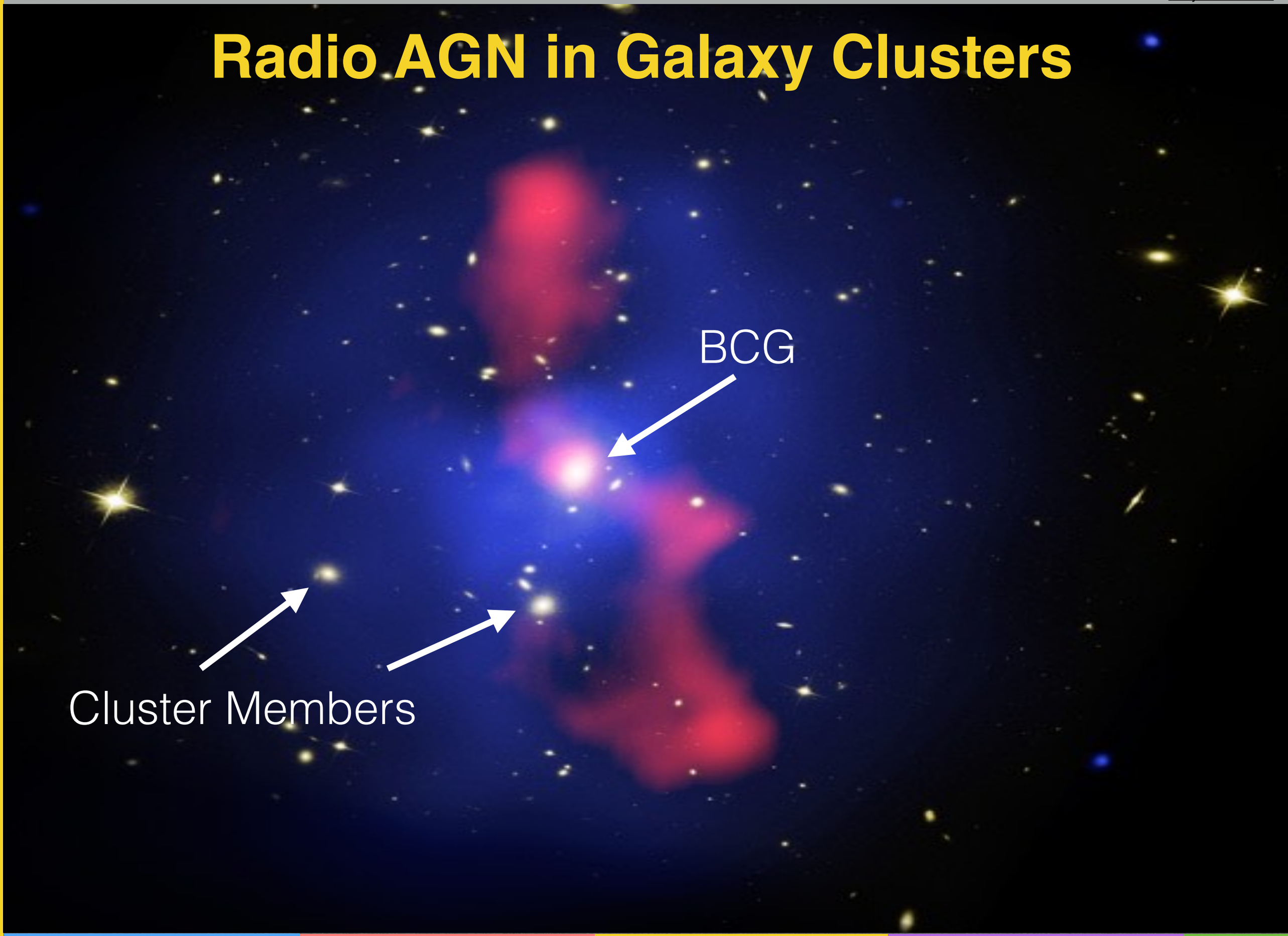
19.0
18.0

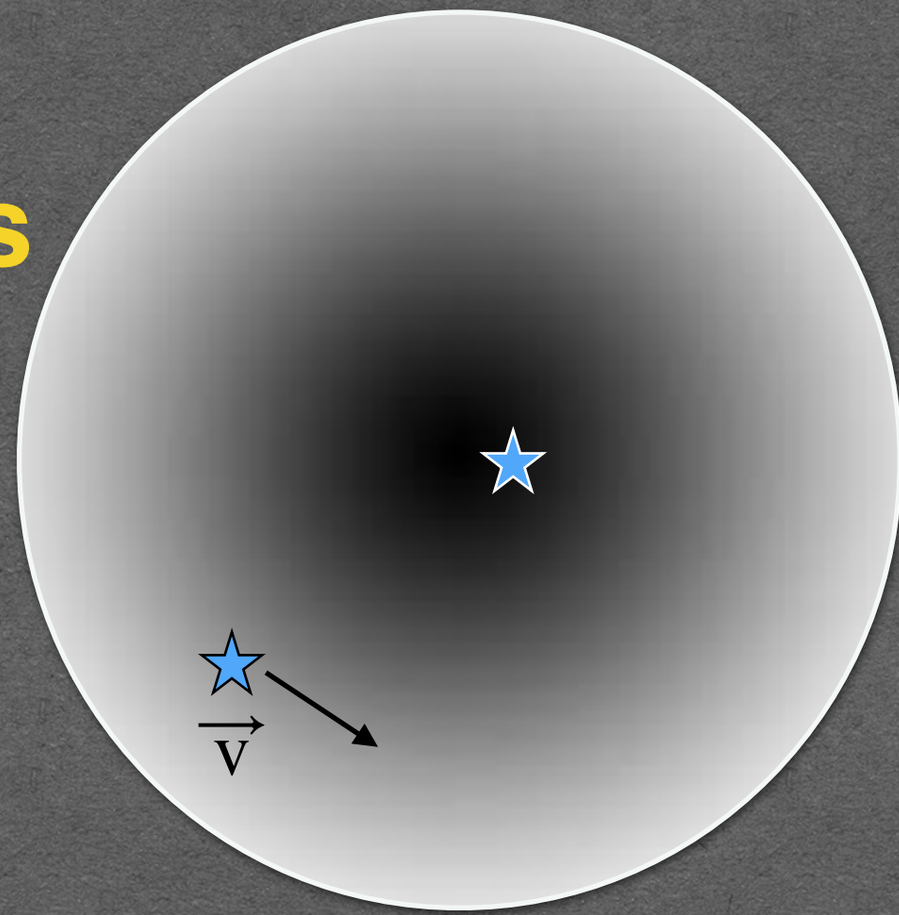



Judith Croston & LOFAR Surveys Team

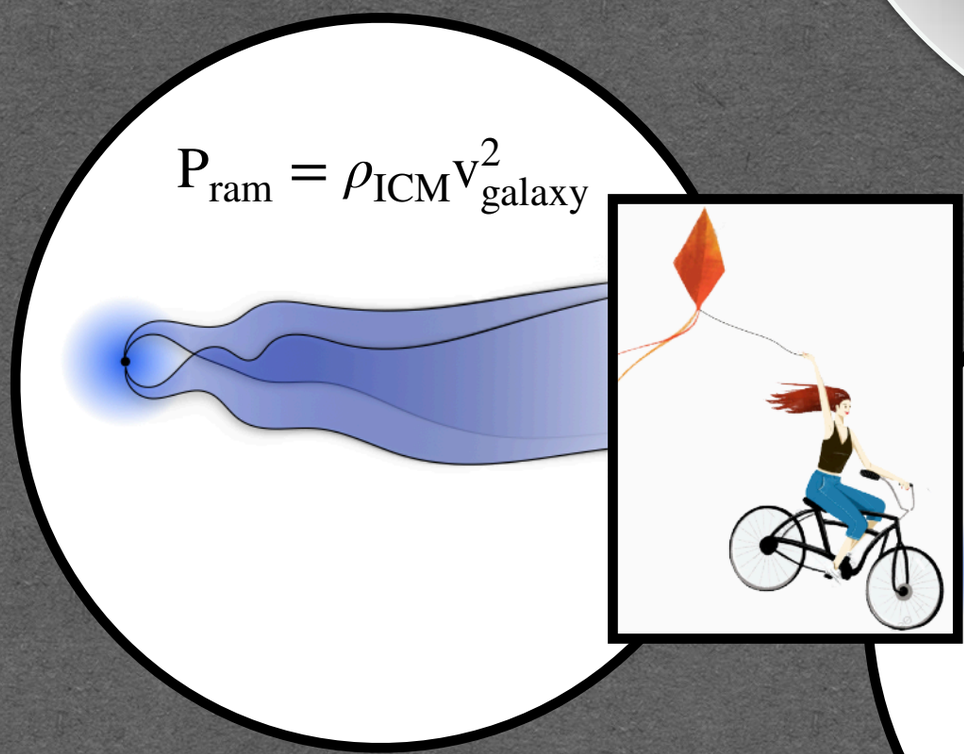
Radio AGN in Galaxy Clusters



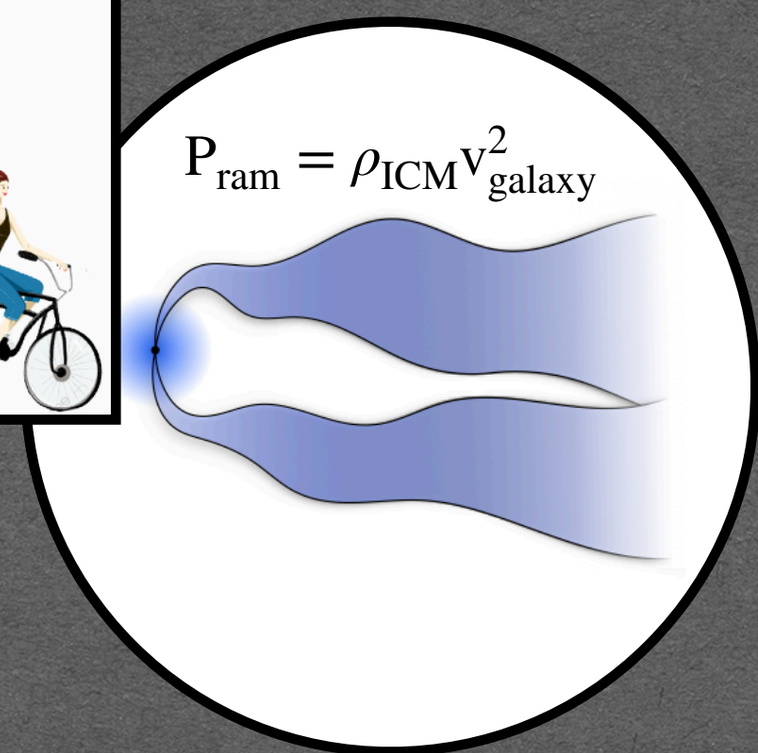
Bent Tail Radio Galaxies



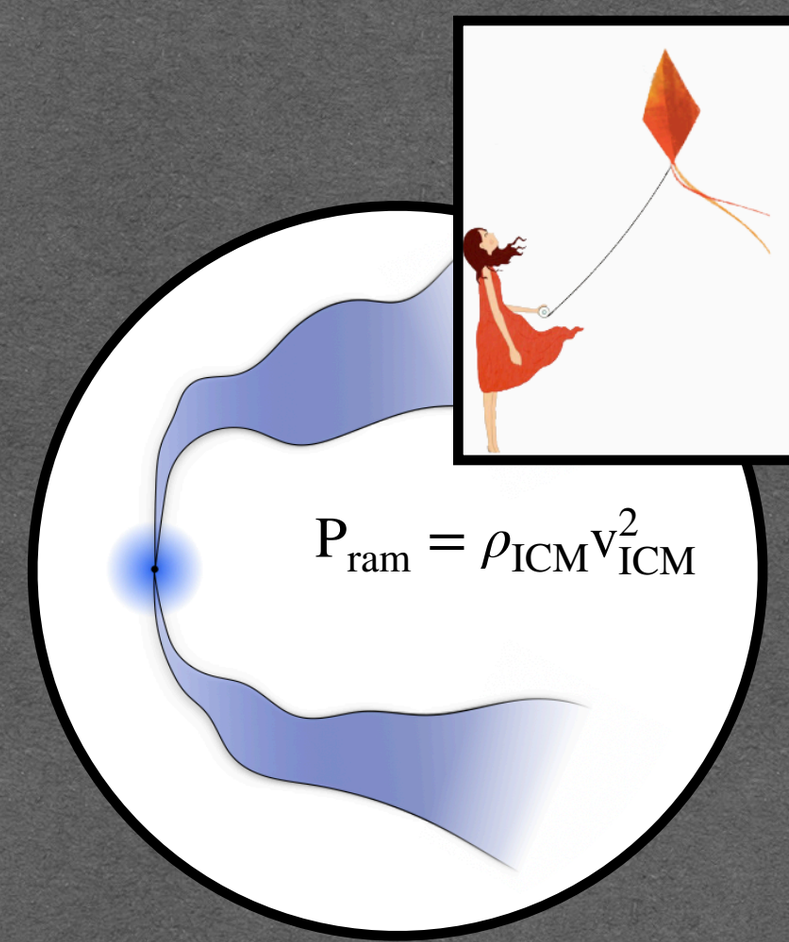
$$P_{ram} = \rho_{ICM} v^2$$



Head-Tail (HT)

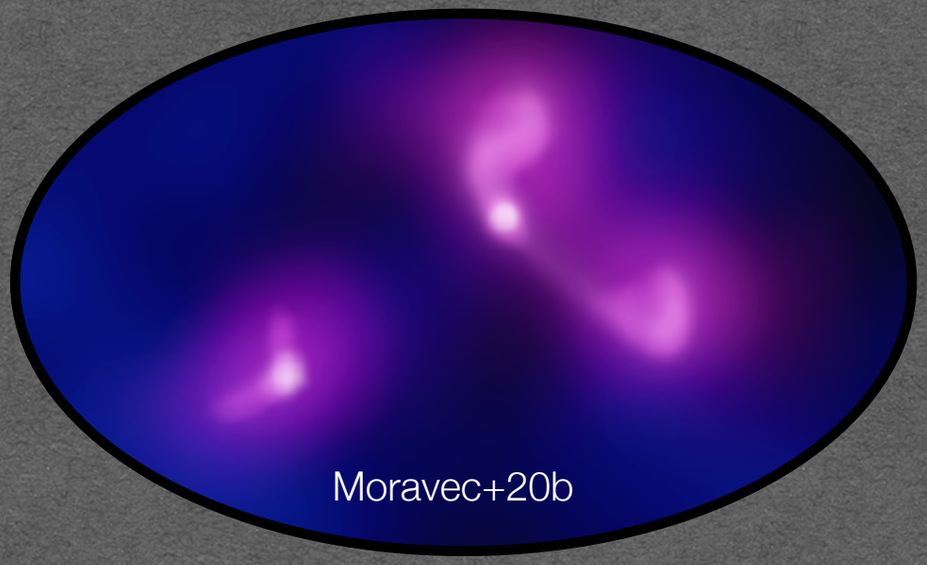


Narrow-Angle Tail (NAT)

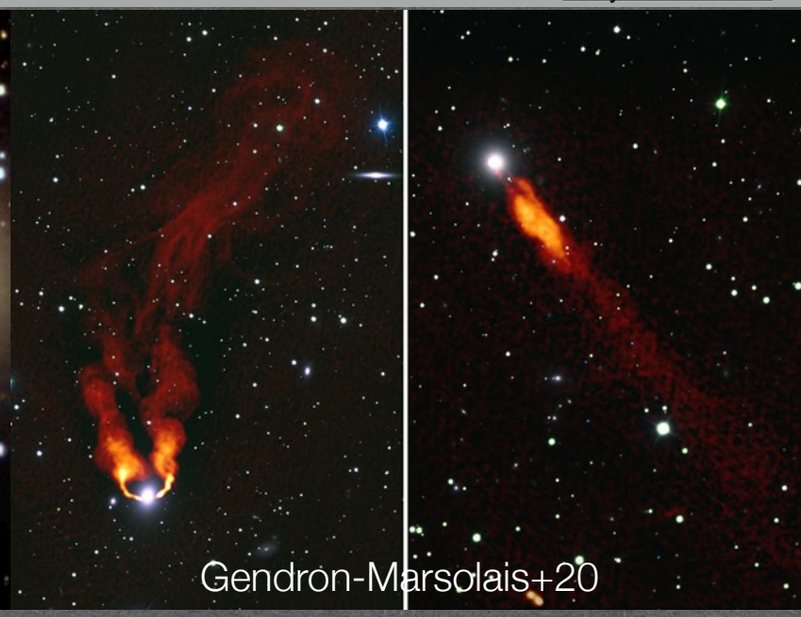


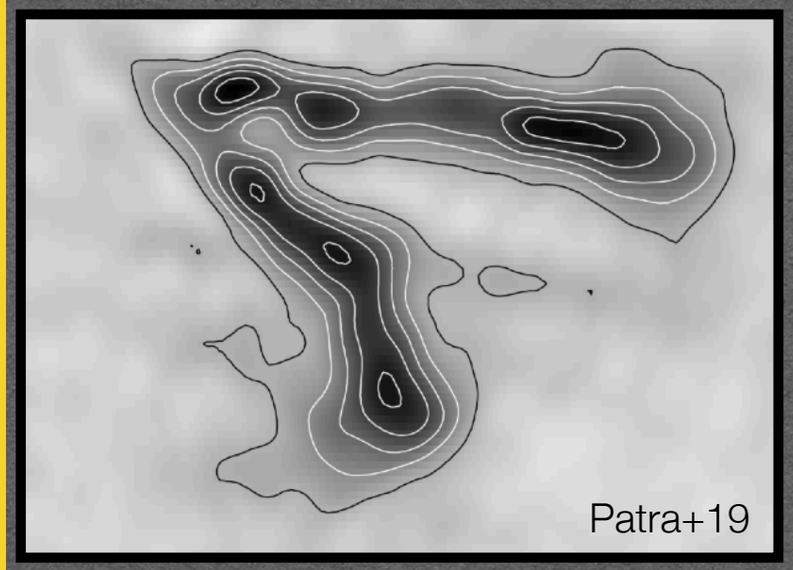
Wide-Angle Tail (WAT)

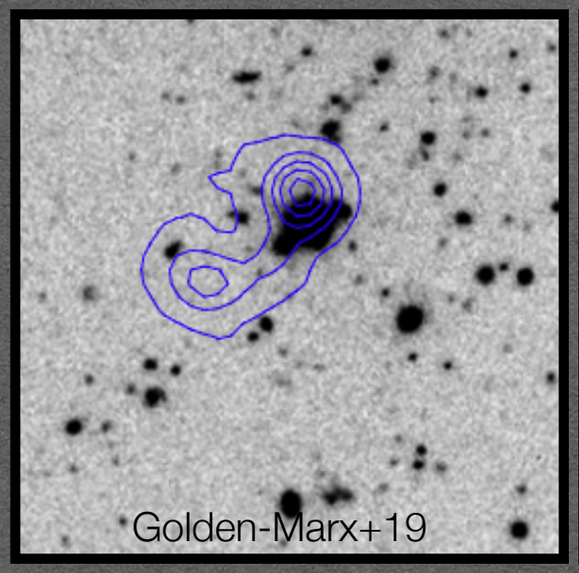
Cartoons courtesy of Marie-Lou Gendron-Marsolais

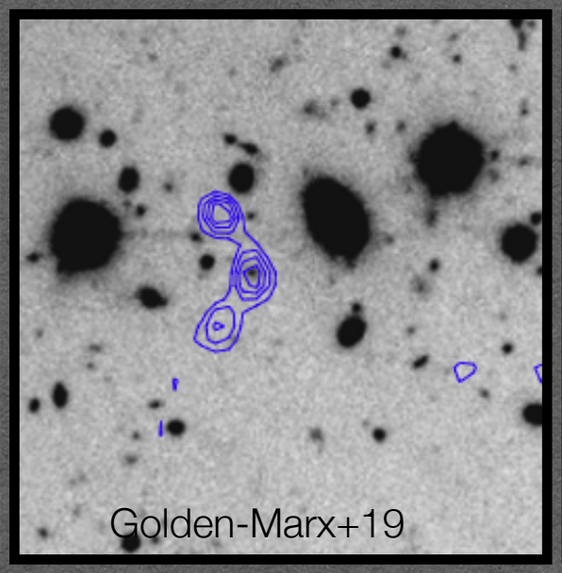

Moravec+20b

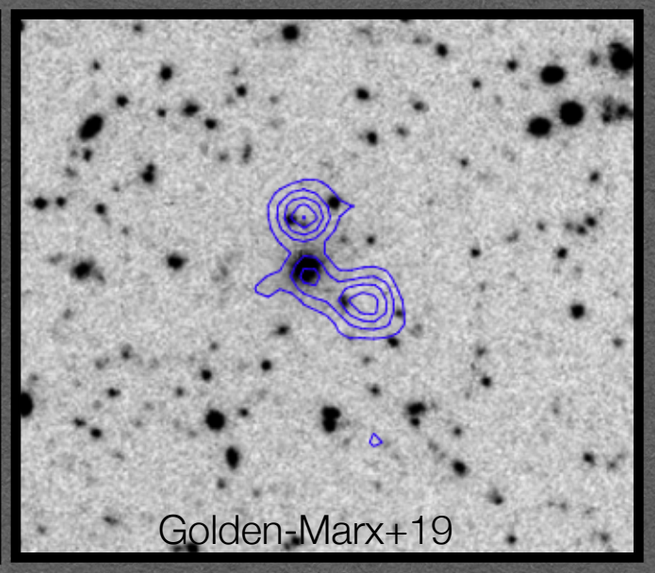
Gendron-Marsolais+21

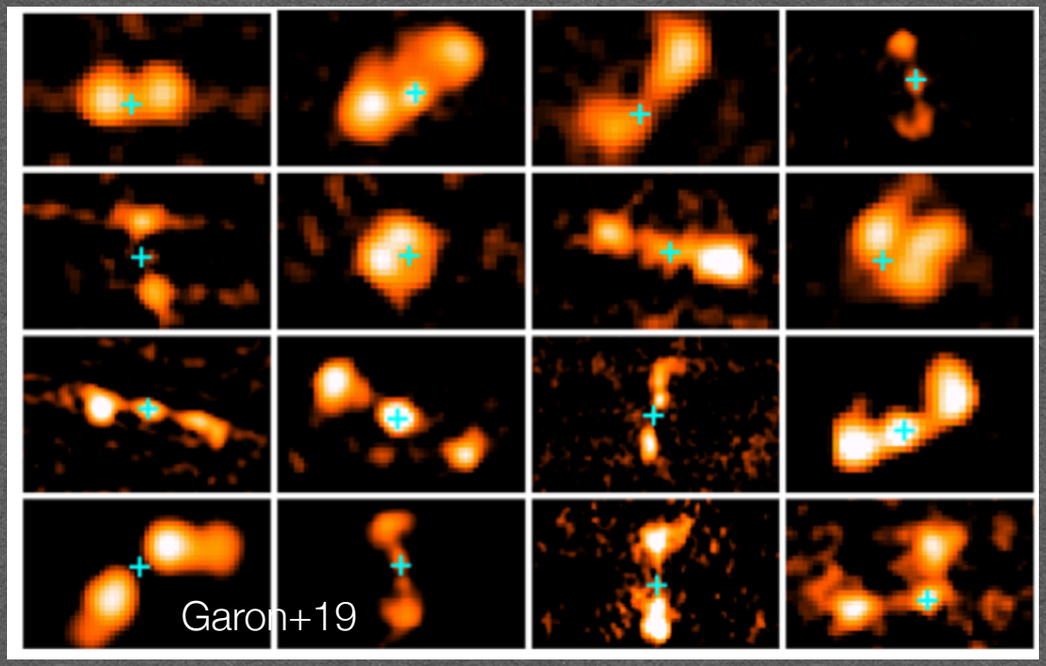

Gendron-Marsolais+20


Patra+19

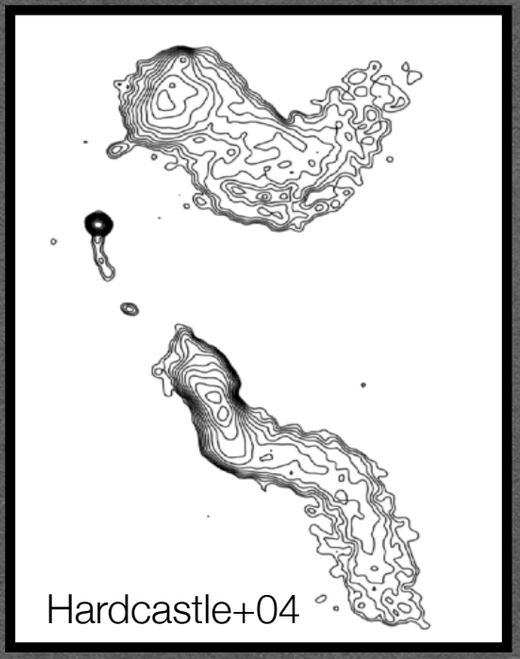

Golden-Marx+19


Golden-Marx+19


Golden-Marx+19


Garon+19

Cyril Tasse and the LOFAR surveys team


Hardcastle+04

Animation of Bent Tail Radio Galaxies

https://astronomynow.com/2016/06/14/citizen-scientists-discover-huge-matorny-terentev-galaxy-cluster/

Radio-AGN and Galaxy Clusters

Rigby+14
26 RGs at 2 < z < 4
In overdense environ.

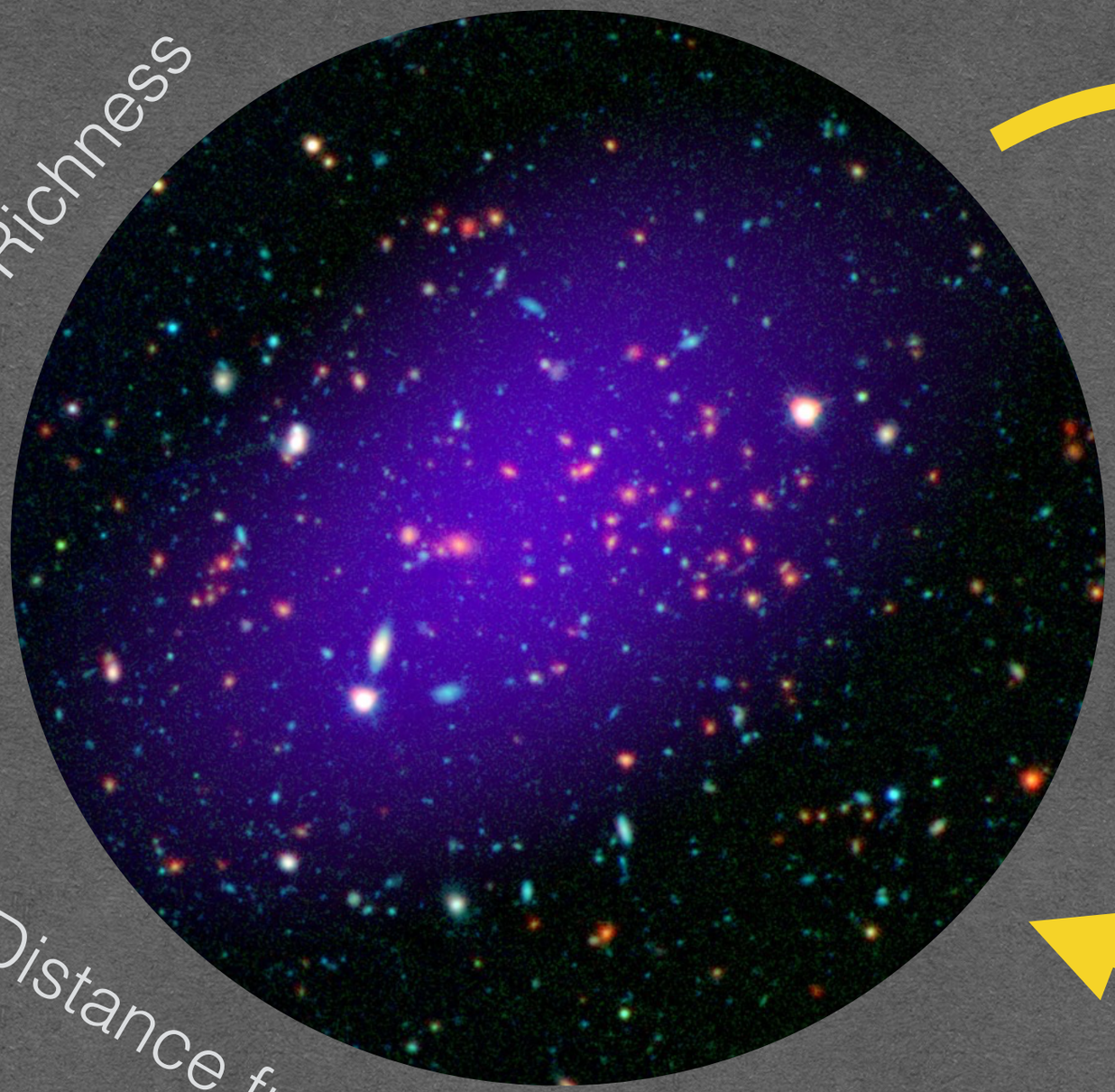
Clusters Occupied by Bent Radio AGN (COBRA)
~200 at 1.2 < z < 3.2 (RGs)
Paterno-Mahler+17

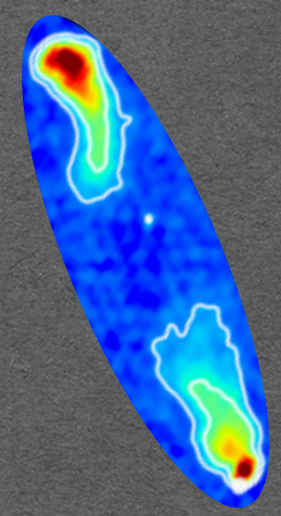
Clusters Around Radio Loud AGN (CARLA)
~150 at z < 3 (RGs)
Wylezalek+13,+14

Castignani+14
32 FRIs at 1 < z < 2
70 % FRIs are in overdense environ.

NASA, ESA, CXC/NRAO/STScI, B. McNamara

Environment ⟷ Radio Source



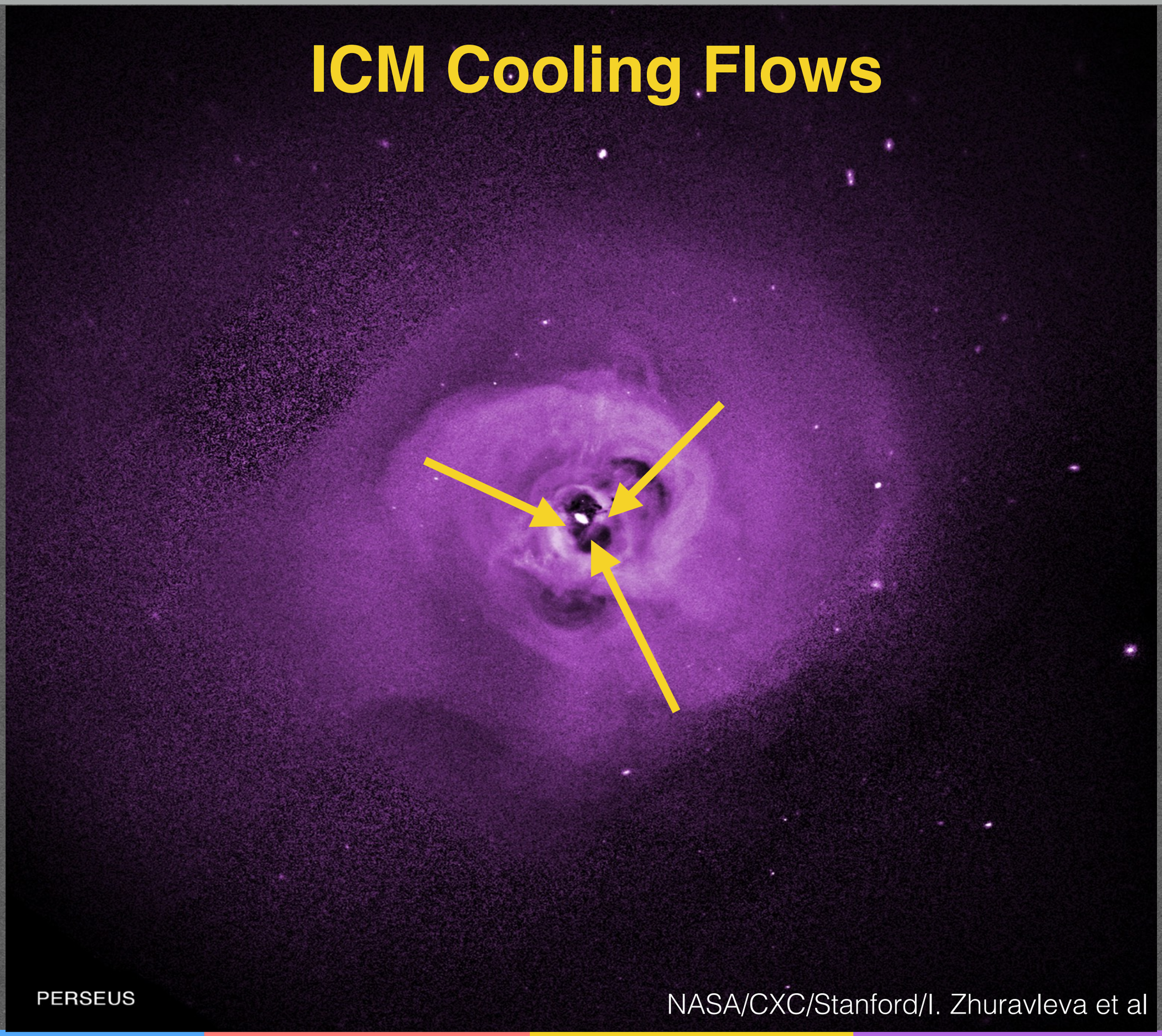


Stellar Mass

Radio Size

Radio Luminosity

ICM Cooling Flows



Radio-AGN Inject Energy into ICM

Radio-AGN ↔ Intracluster Medium (ICM)

NASA, ESA, CXC/NRAO/STScI, B. McNamara — MS 0735.6+7421

Radio AGN in Galaxy Clusters

Radio AGN creating cavities in ICM (Hydra A, Abell 2199, Centaurus, M87, etc.)

FR Is in more dense environments than FR IIs (Longair+79, Prestage+88, Ledlow+96, Miller+99, Wing+11, Gendre+13)

Power and size of AGN increases with cluster richness (Ineson+15, Croston+19)

Radio galaxy bent morphology depends on distance from cluster center (Garon+19)

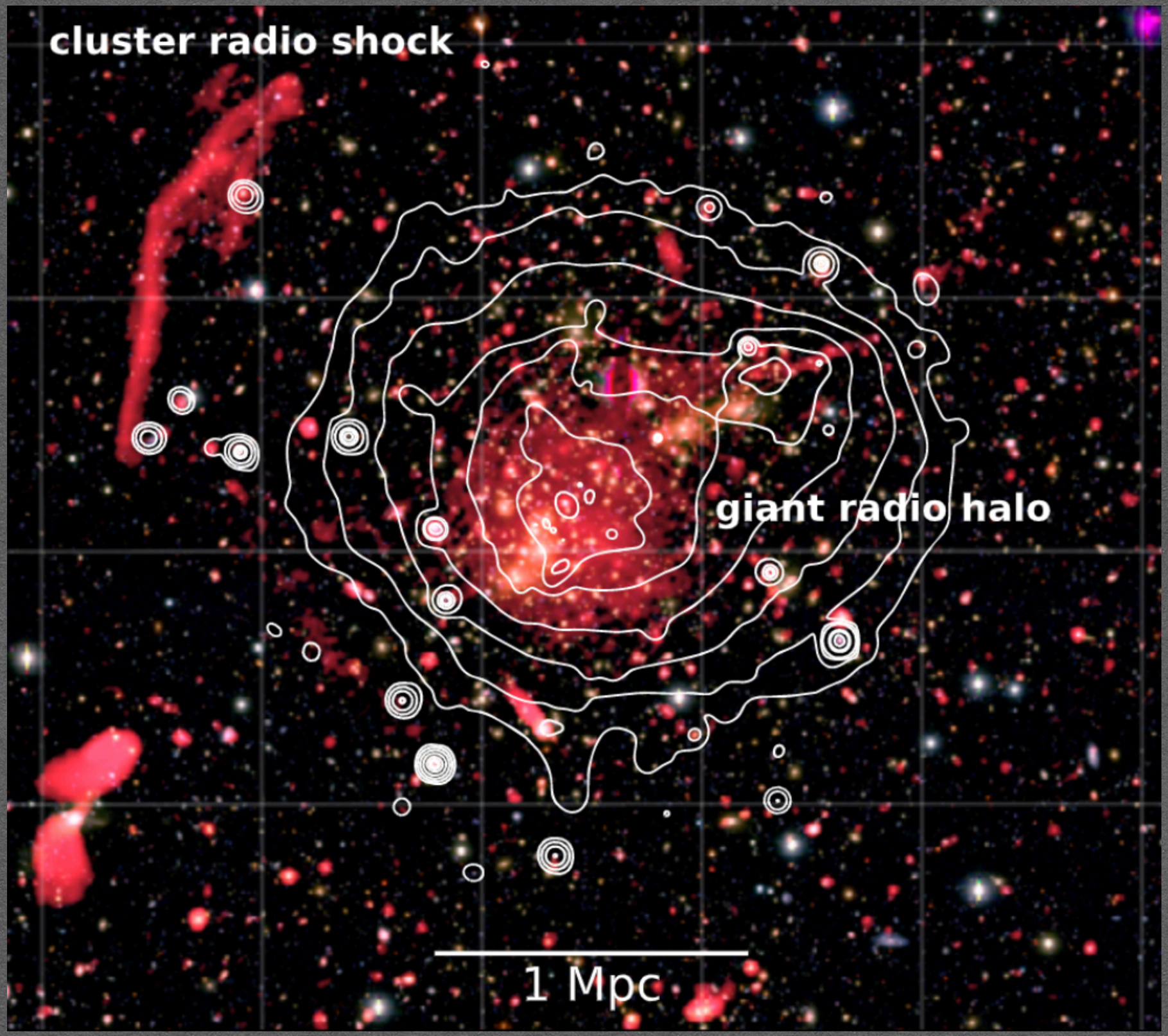
Radio galaxy luminosity decreases with cluster-centric distance (Croston+19)

2.5 times more radio AGN in cluster than field at z~1 (Mo+18)

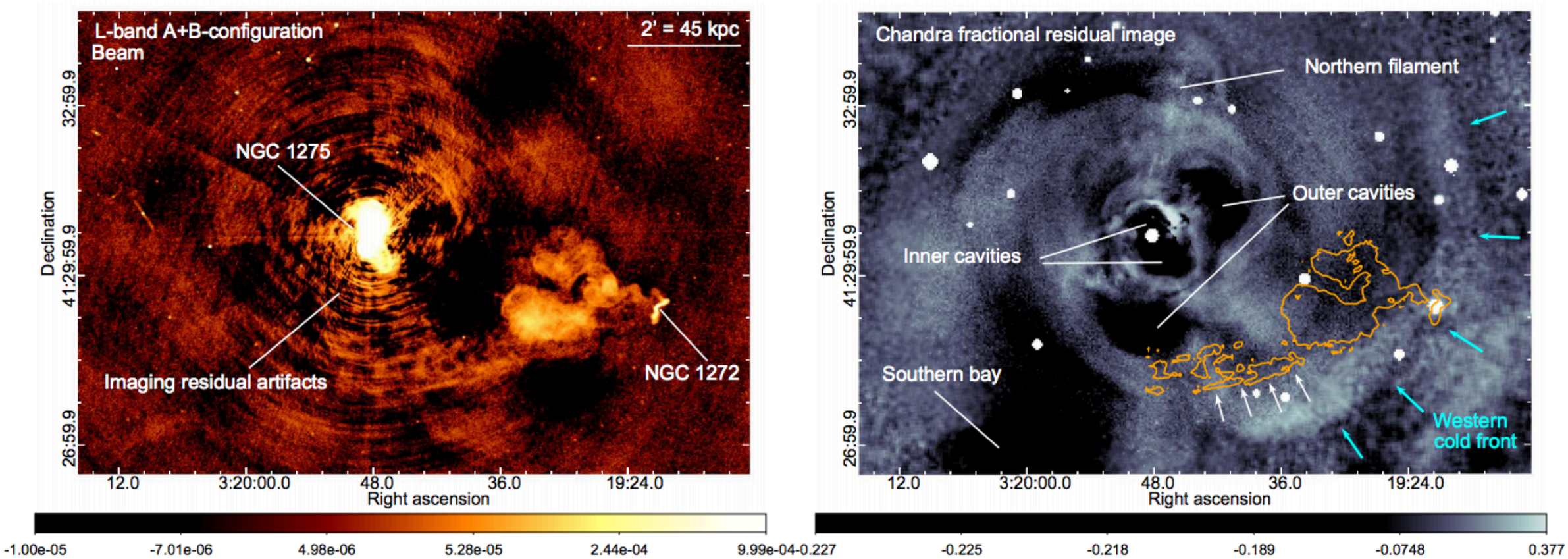
Radio galaxies used to successively find galaxy clusters (surveys: CARLA, COBRA, HzRGs)

NASA, ESA, CXC/NRAO/STScI, B. McNamara

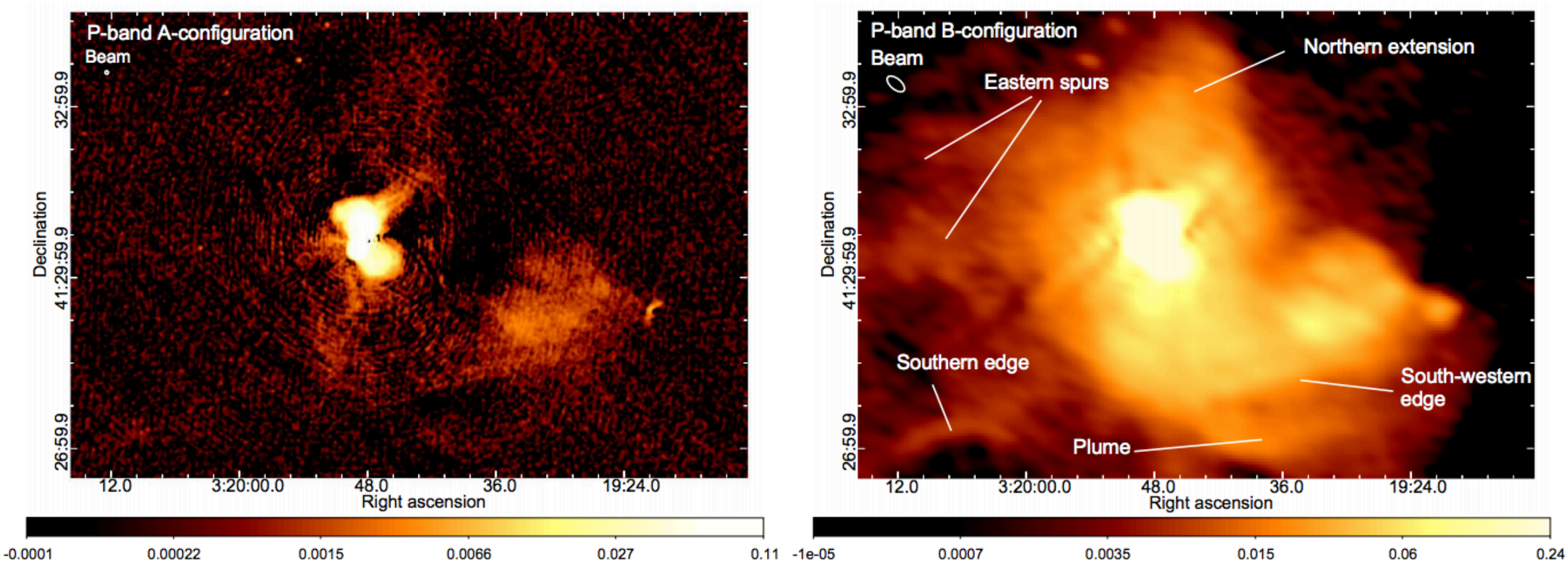
Radio-AGN and Radio Halo Connection?



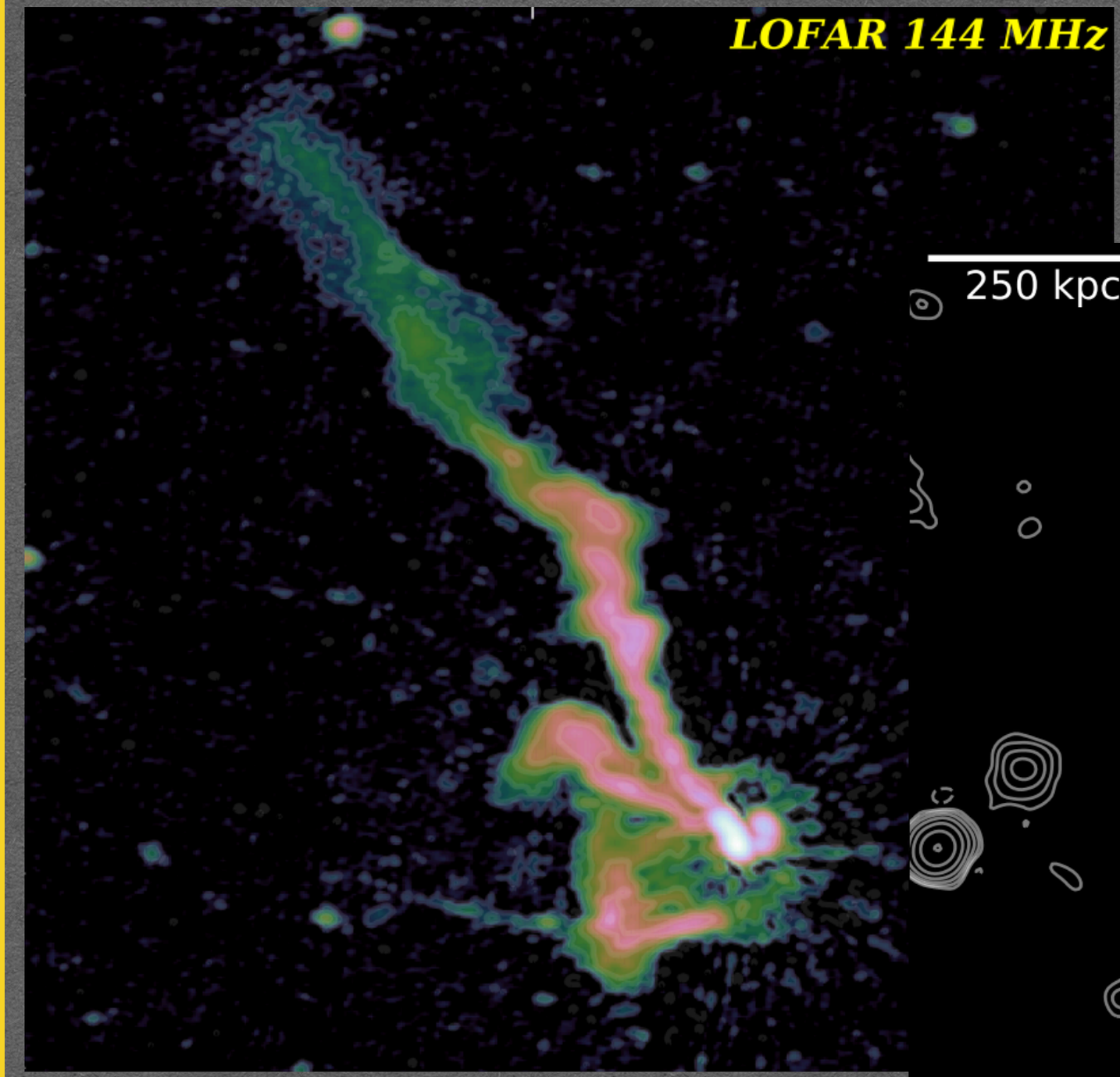
van Weeren+19

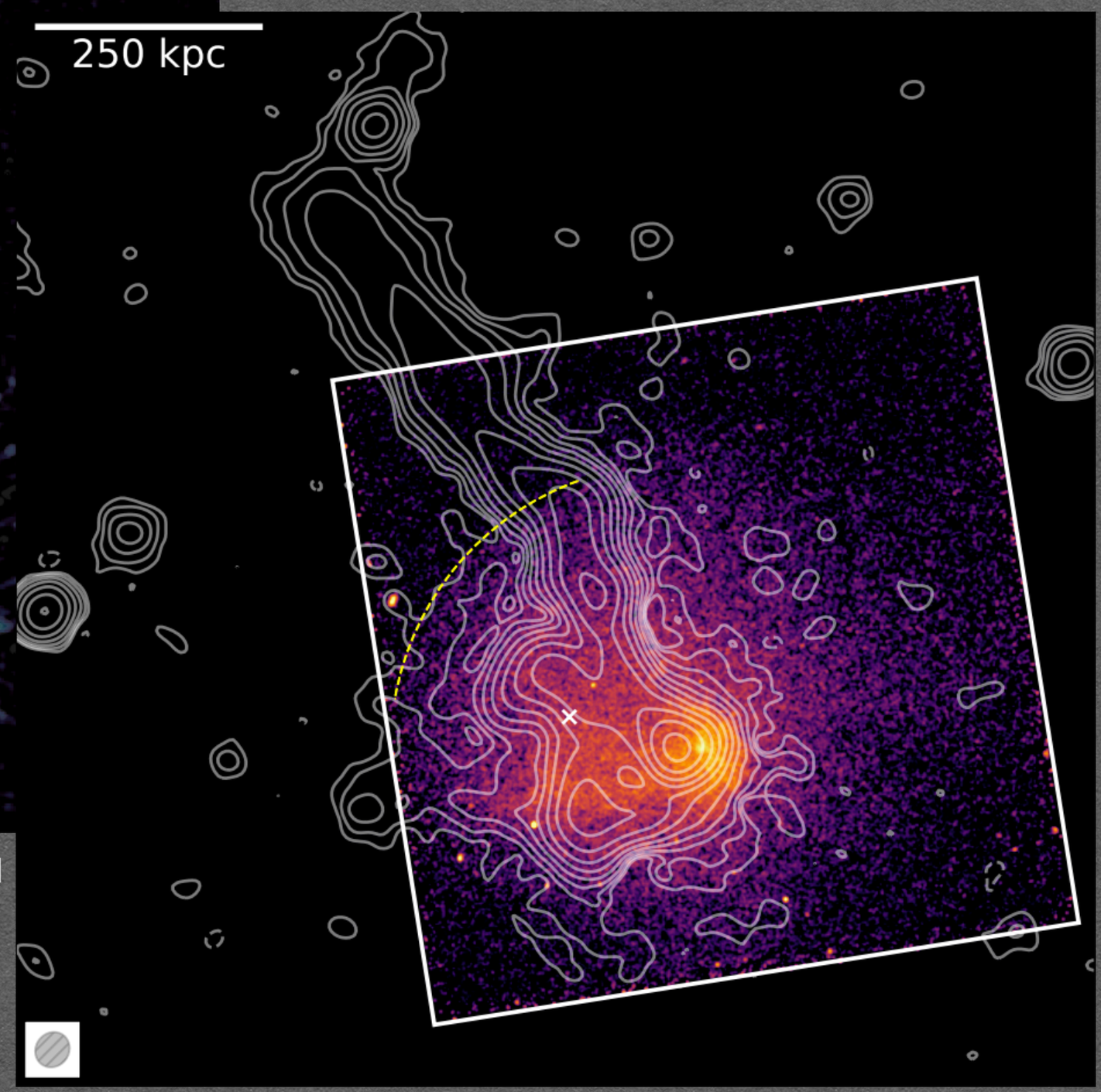


Perseus: Gendron-Marsolais+21



Abell 1775

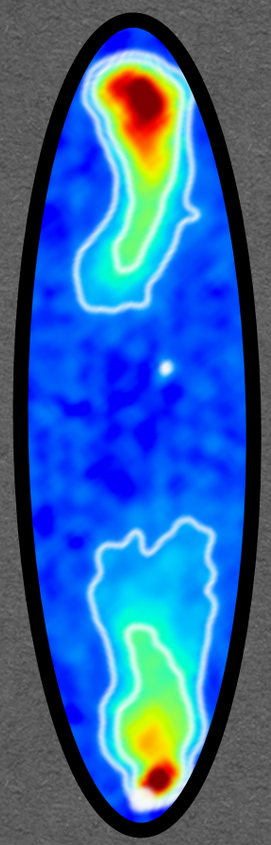


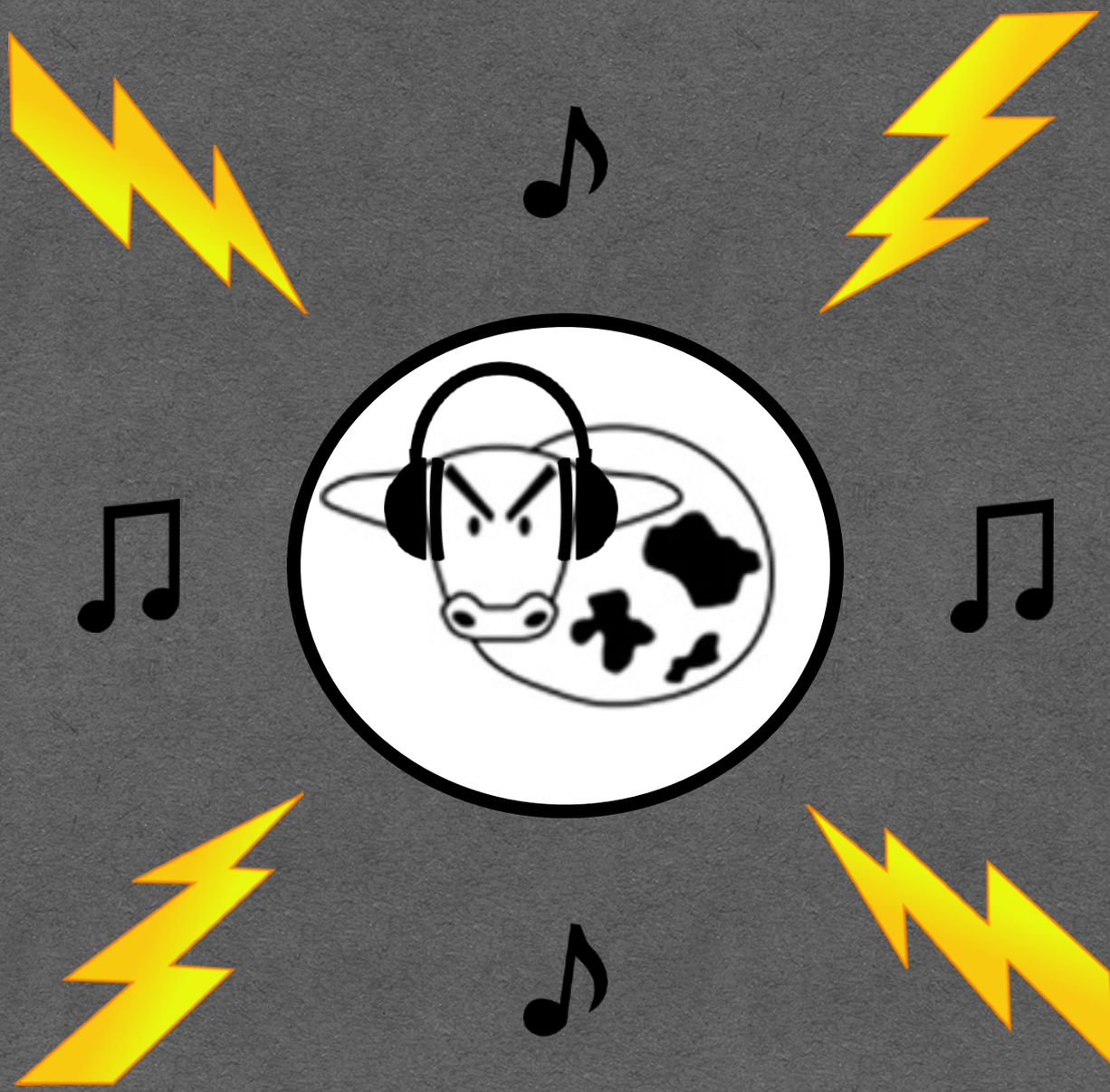


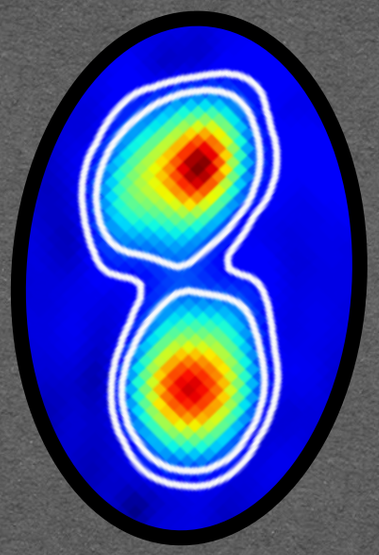
Botteon+21

Animation of Shocks in Clusters

https://vimeo.com/464248944/3fc17a5b8b

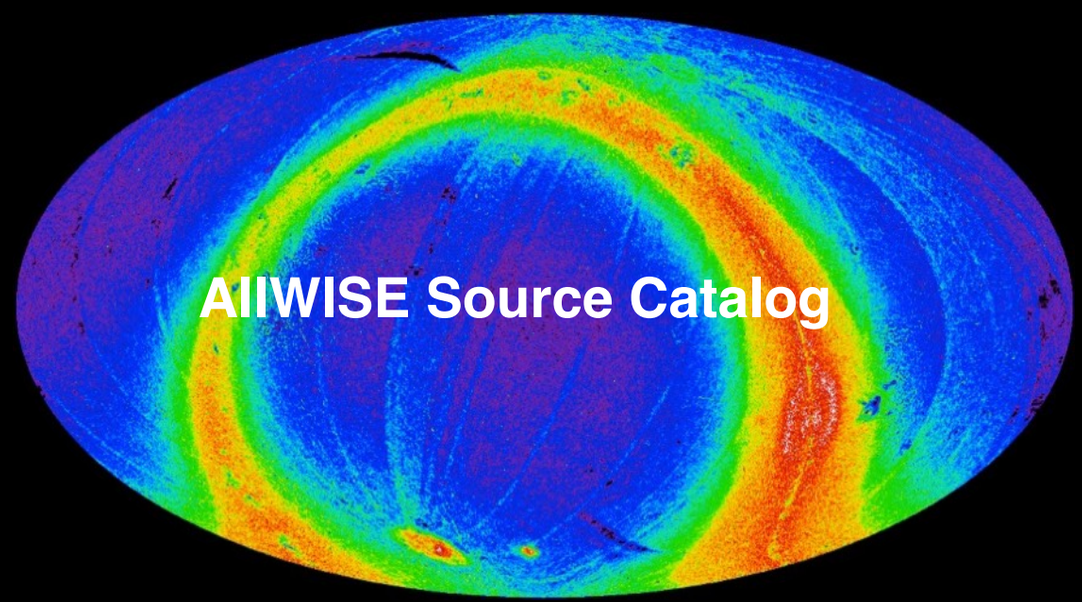






Radio-Active CoWS: Probing the relationship between radio-AGN and their environment

The Massive and Distant Clusters of WISE Survey (MaDCoWS)



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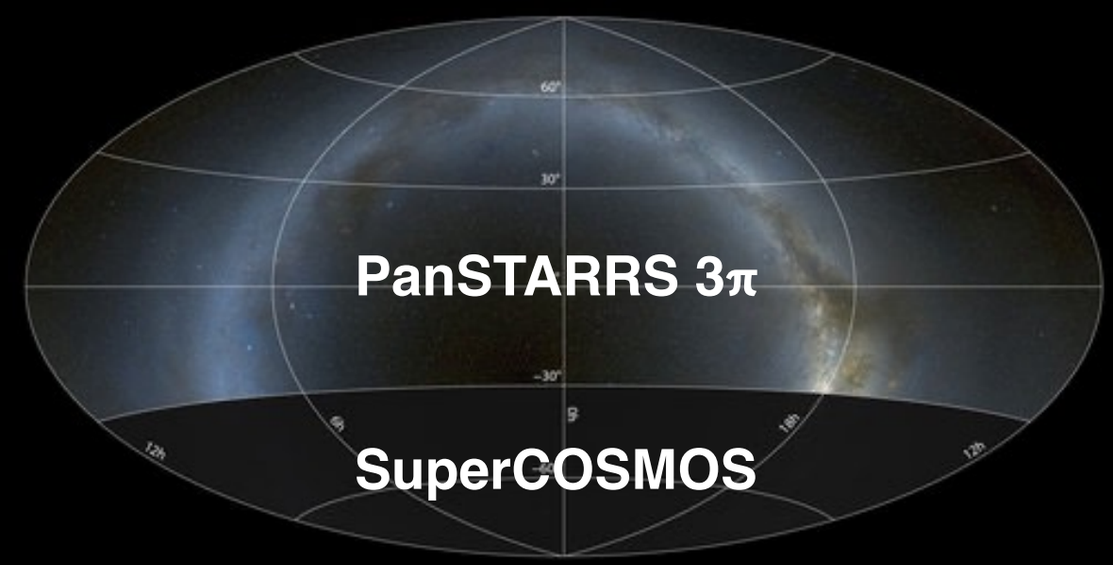

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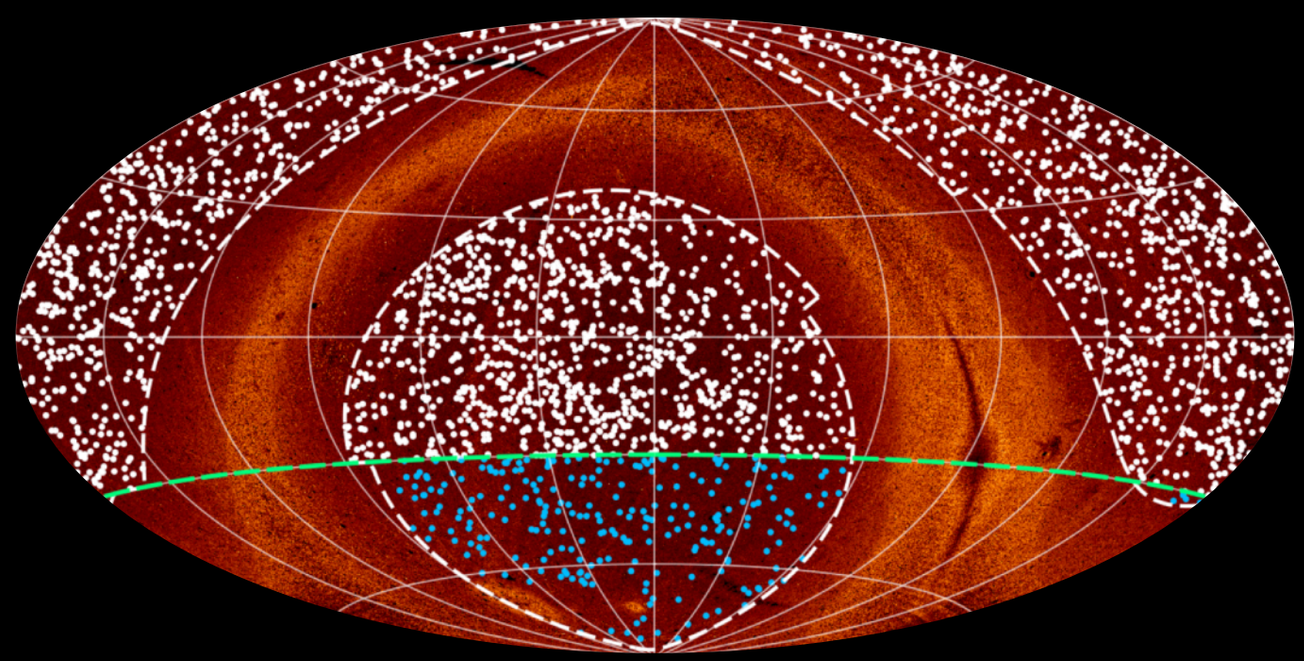
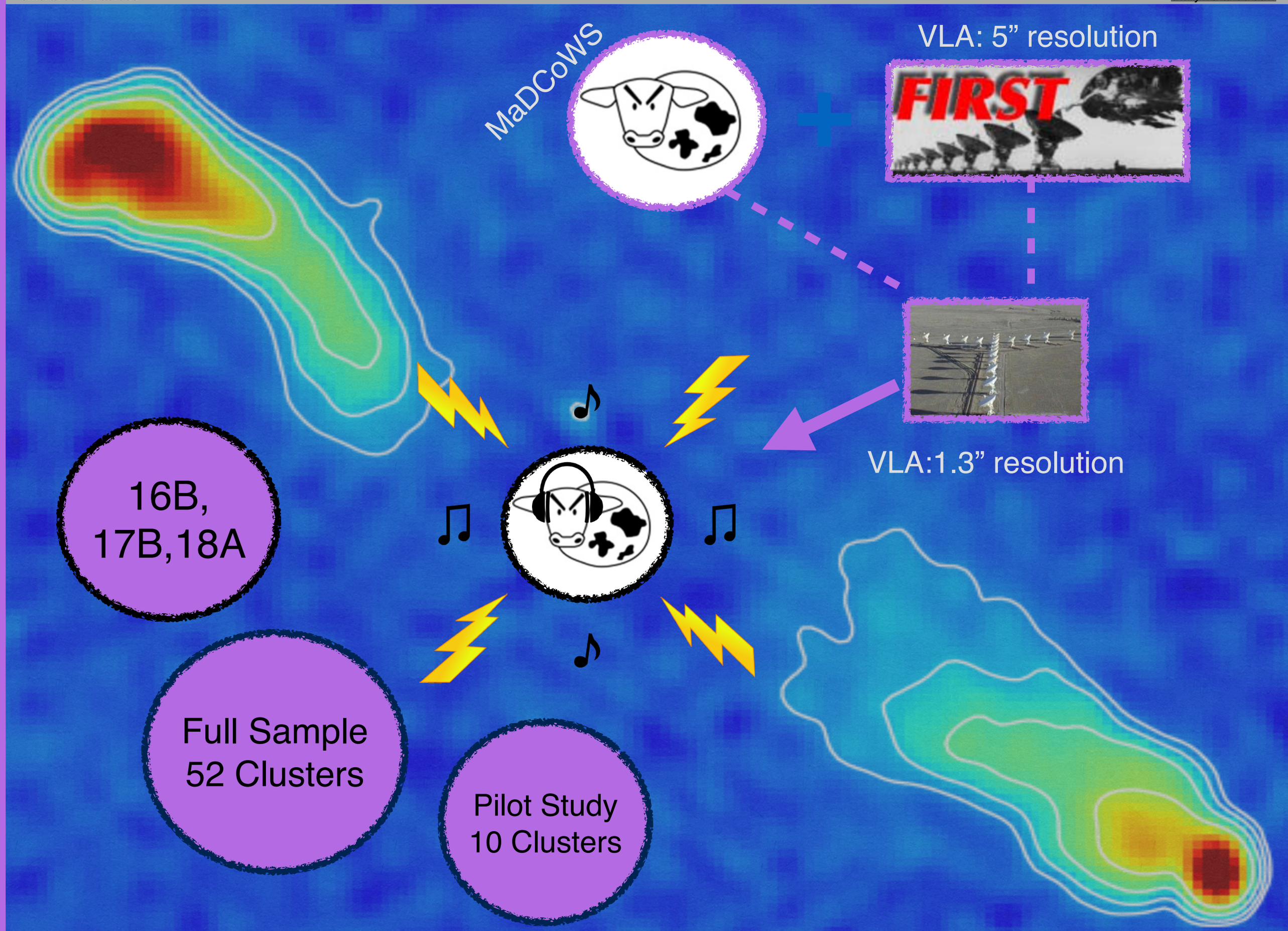
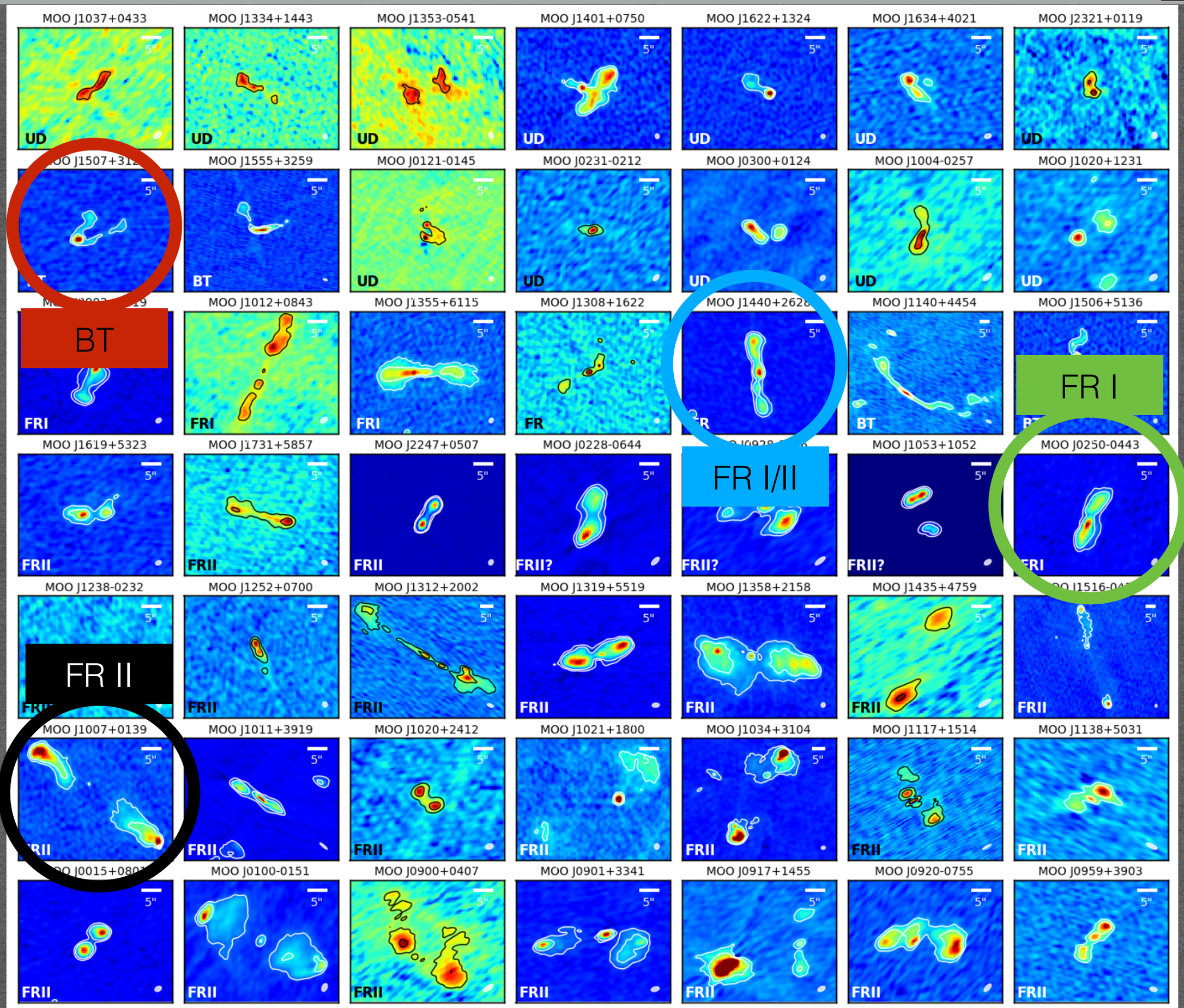


~2700

~2700 massive clusters at 0.7< z < 1.5 over the full extragalactic sky

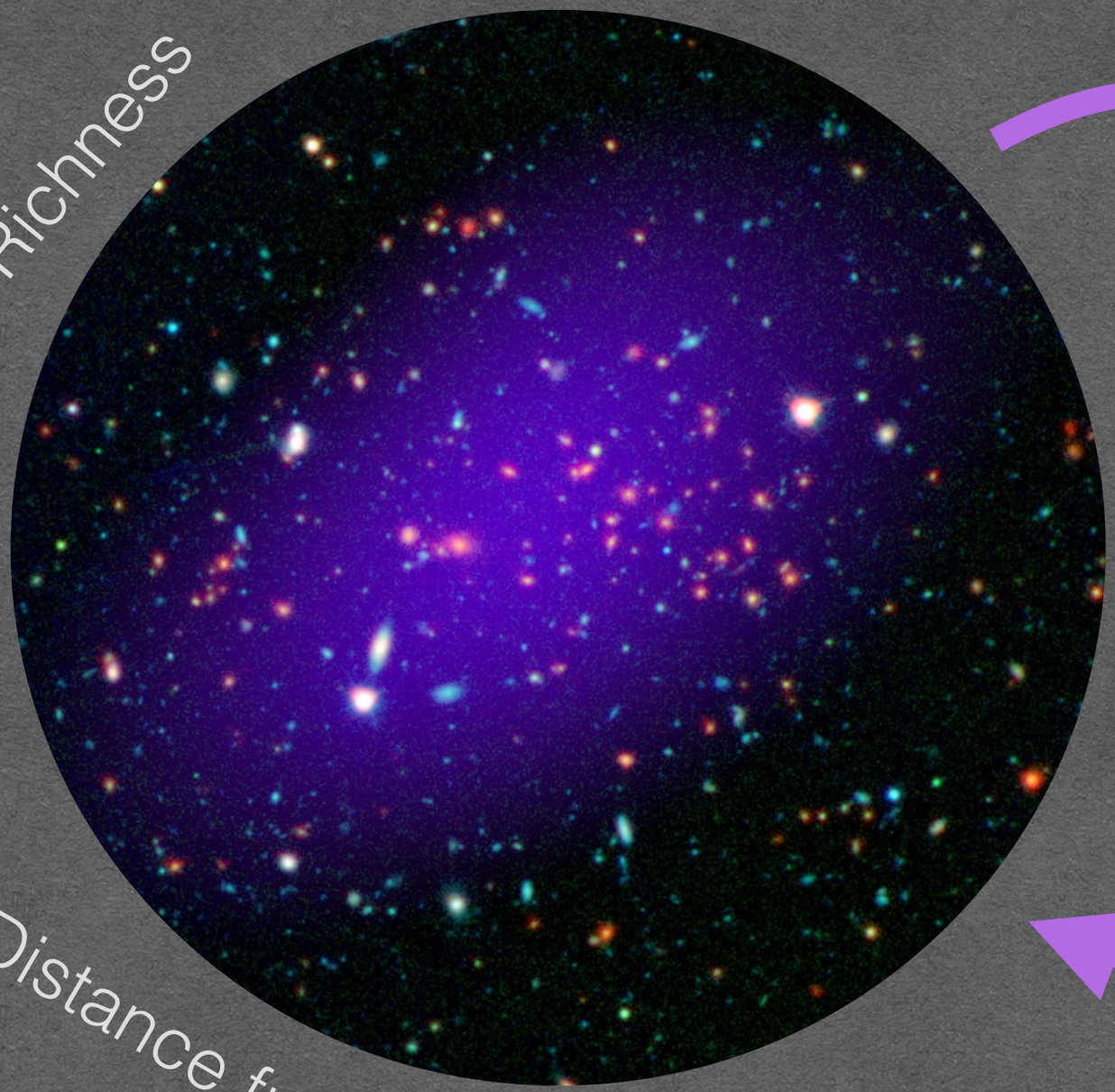

MaDCoWS
VLA: 5” resolution
FIRST
VLA:1.3” resolution
16B,
17B,18A
Full Sample
52 Clusters
Pilot Study
10 Clusters

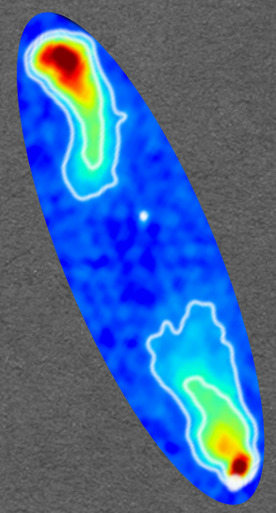
Radio-Active Cows



Moravec+20

Environment ⟷ Evolution of Source

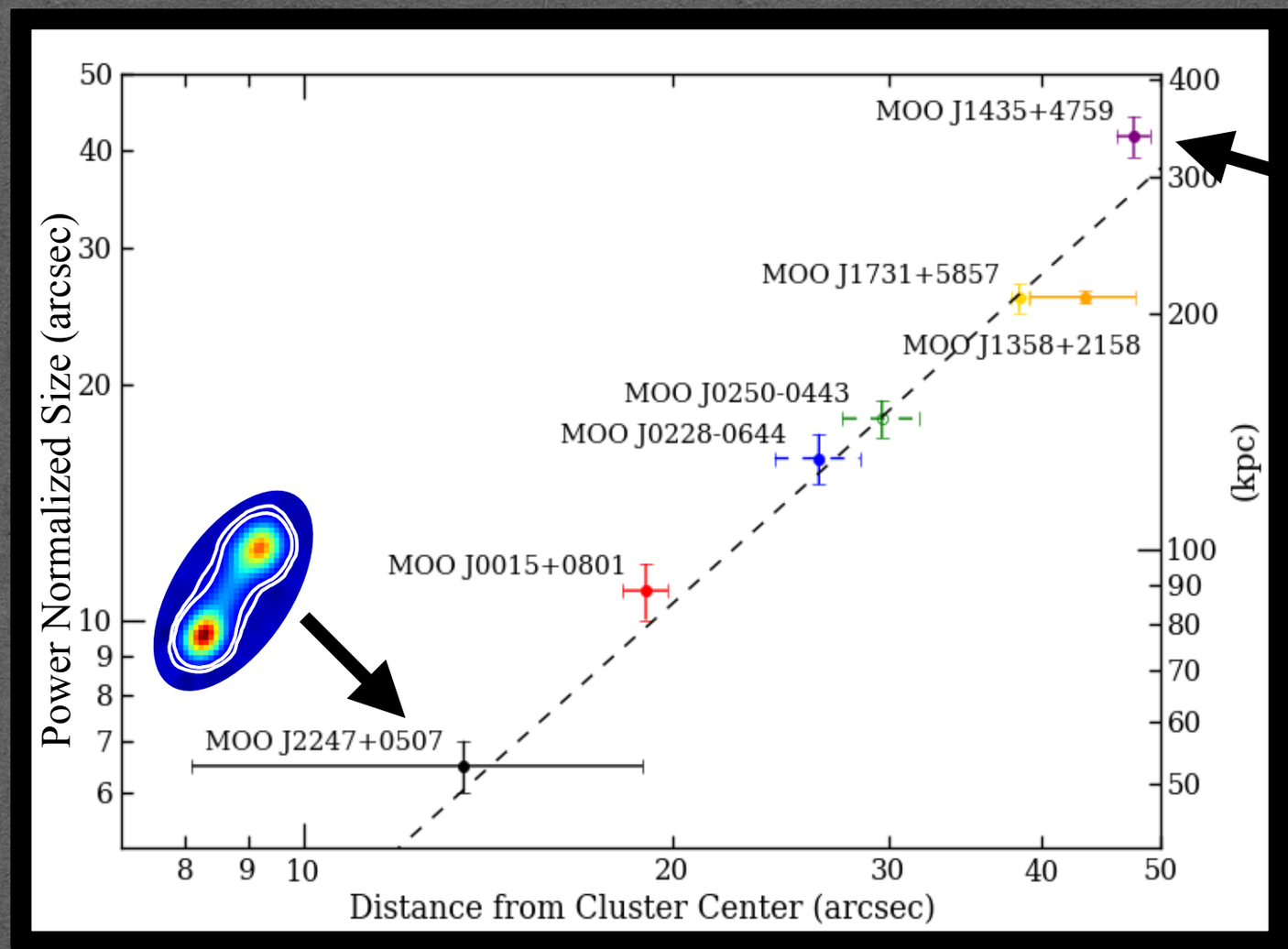


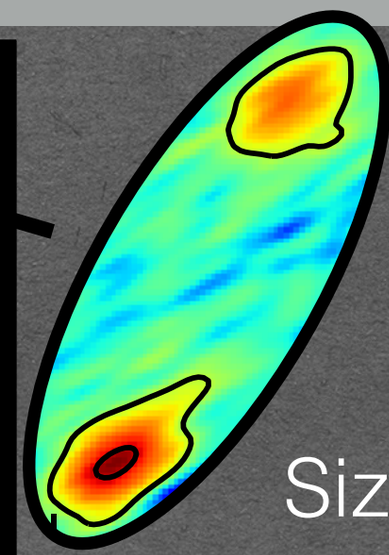


Stellar Mass

Radio Size

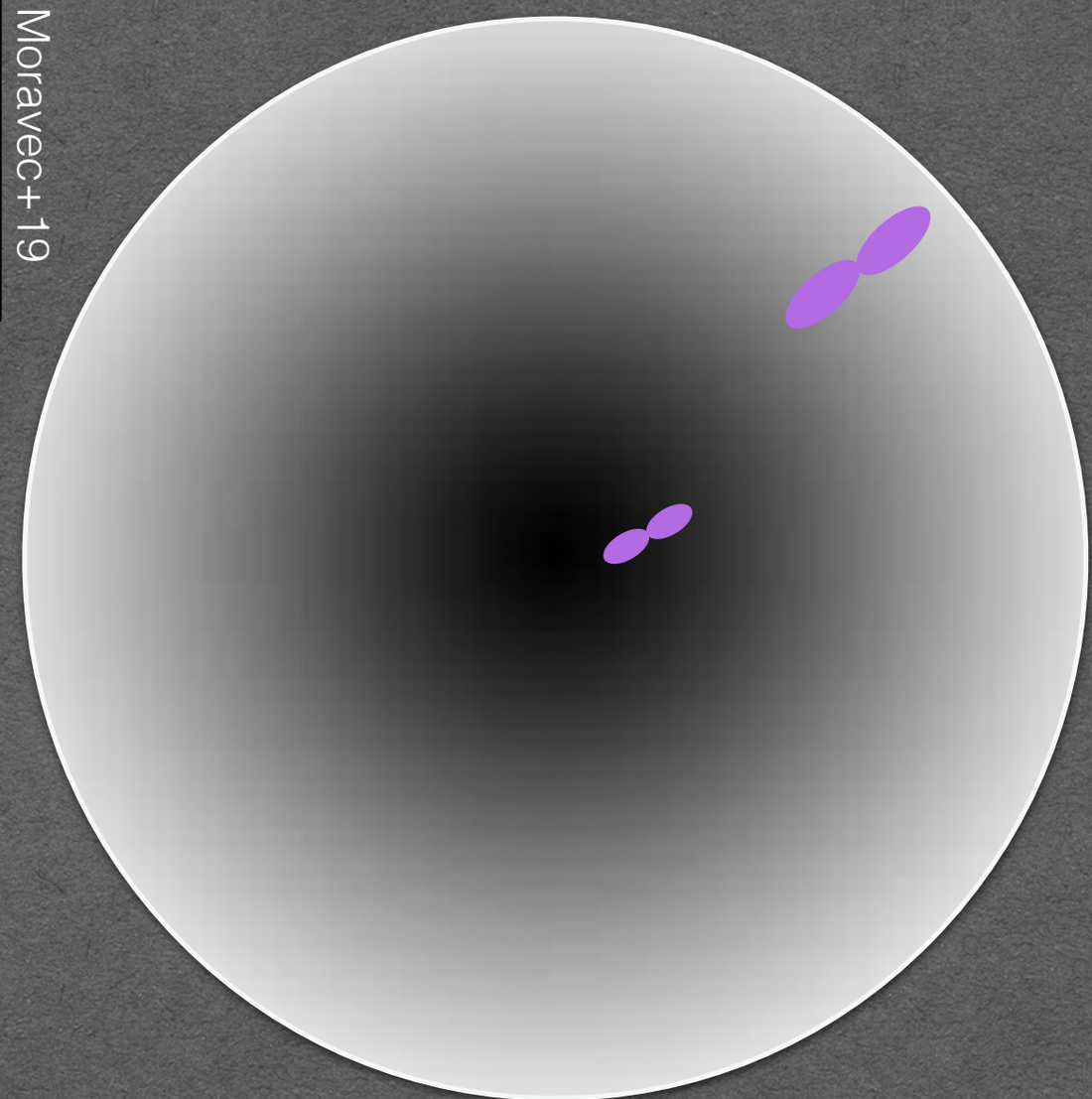
Radio Luminosity



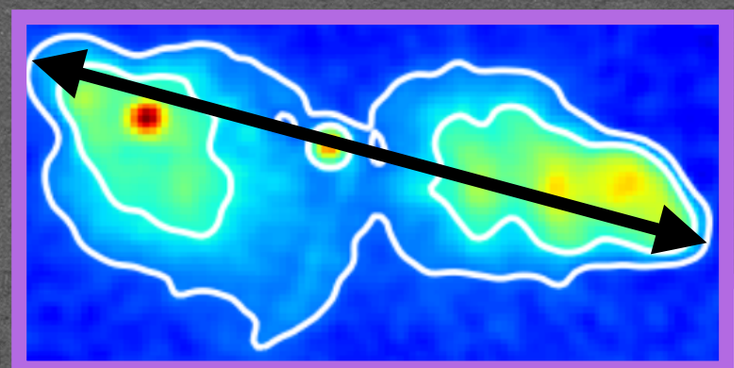


Size correlated with radial distance

Moravec+19

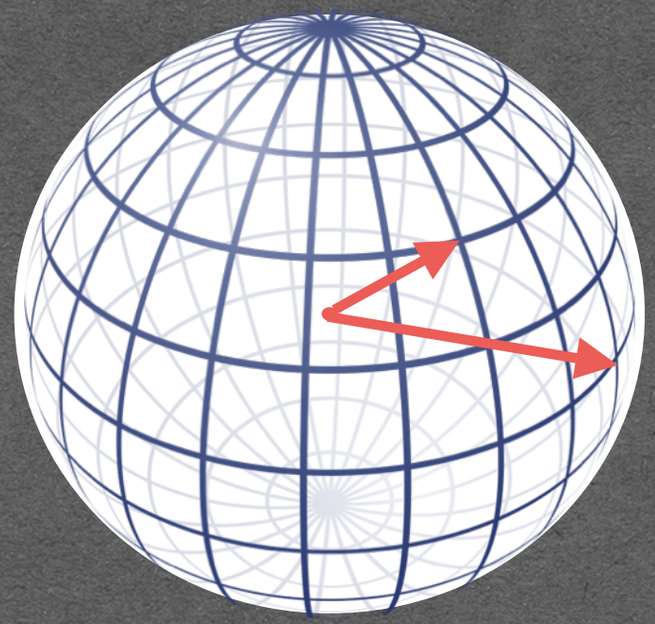


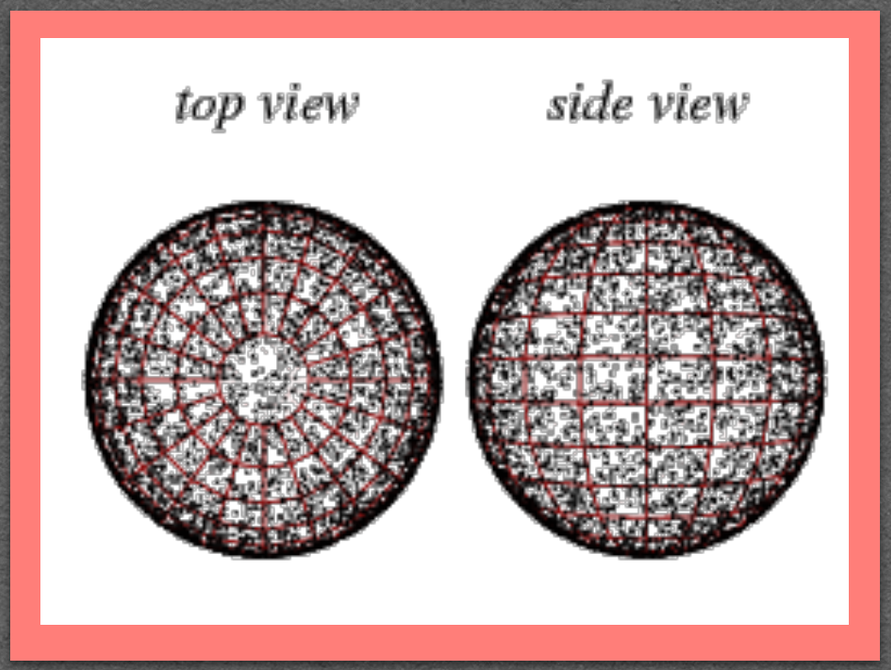
L_j = Largest Angular Size

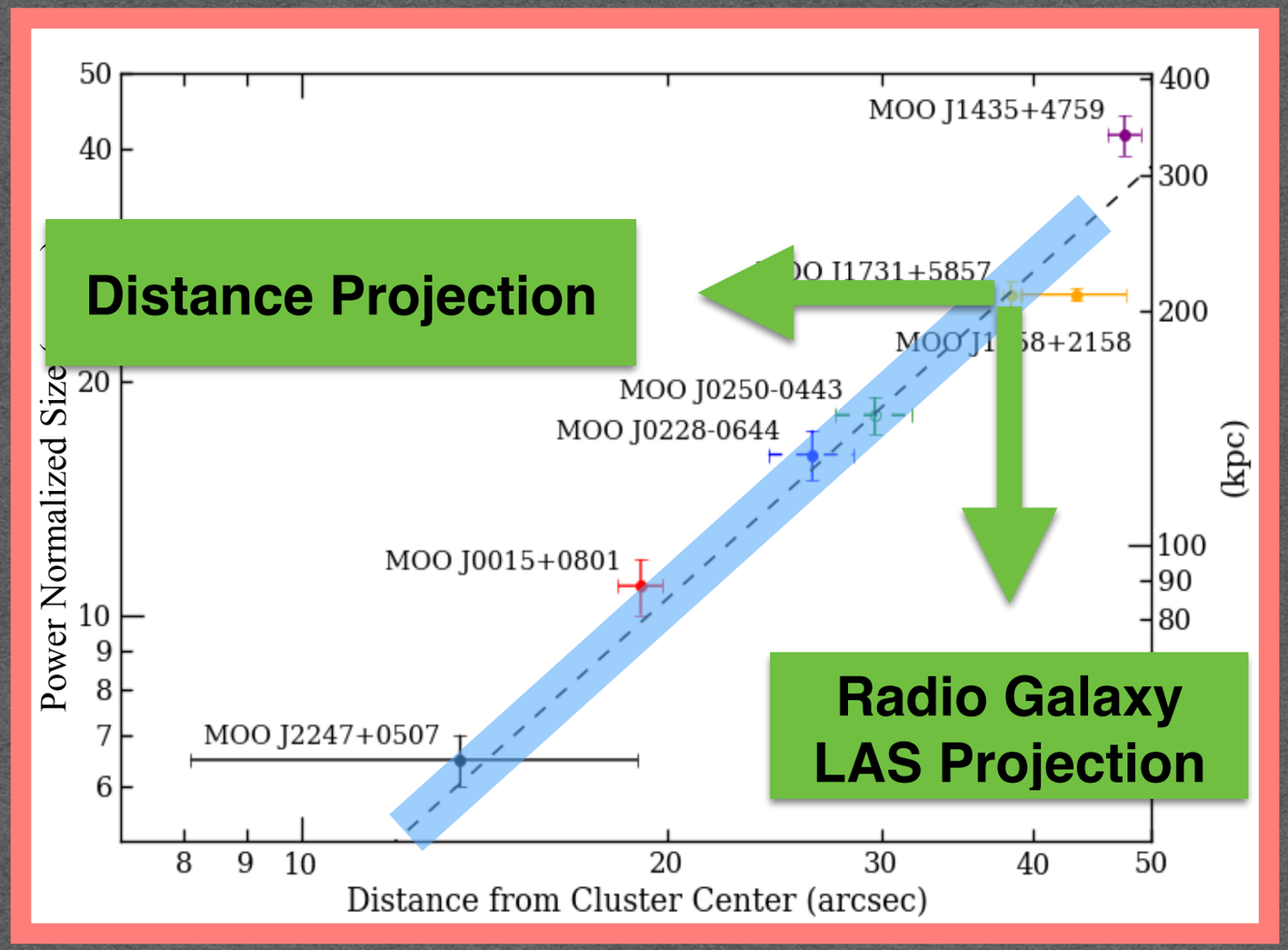


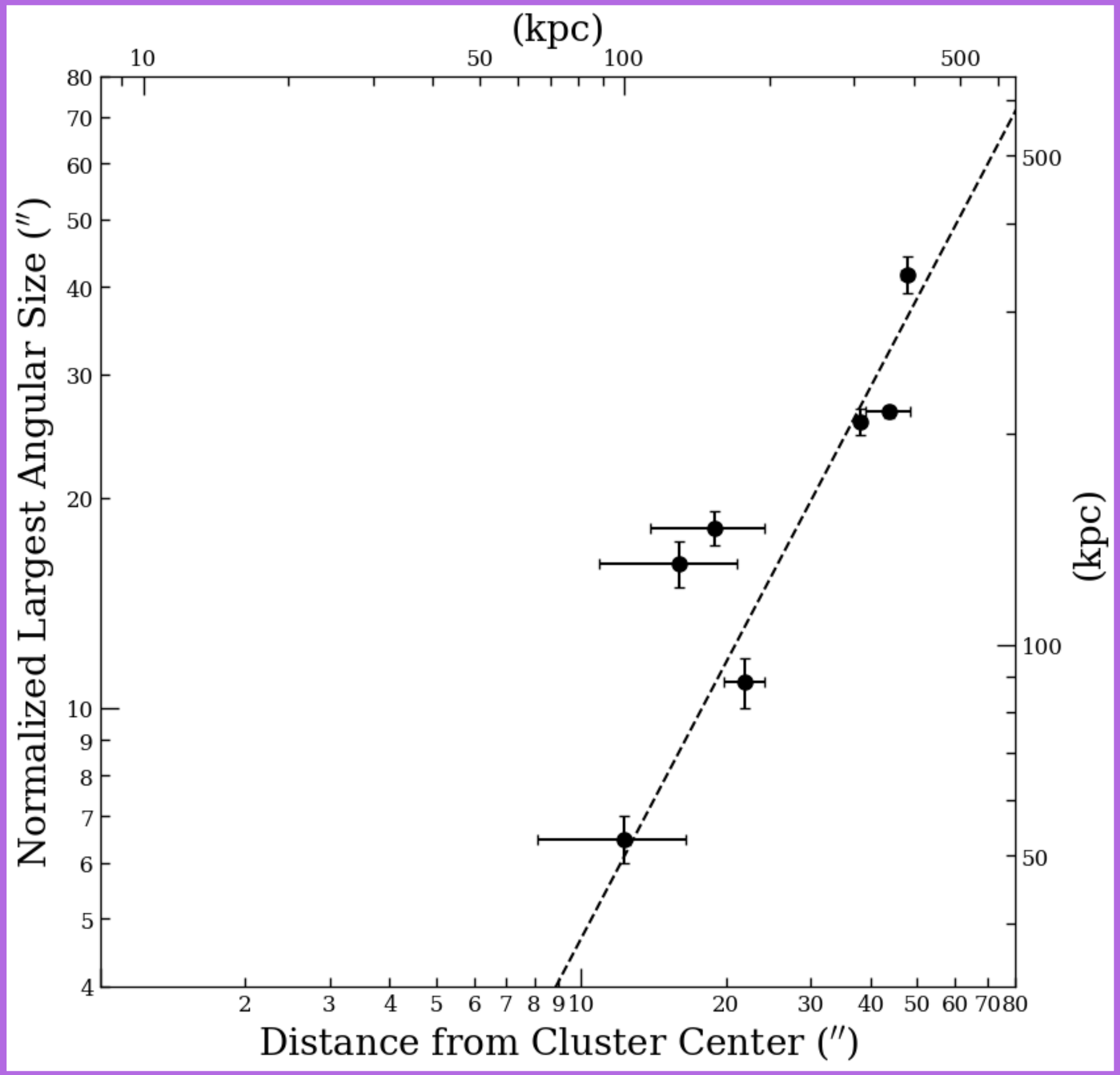
$$L_j = \left(\frac{P}{\rho}\right)^{1/5} t^{3/5}$$

Projection Effects



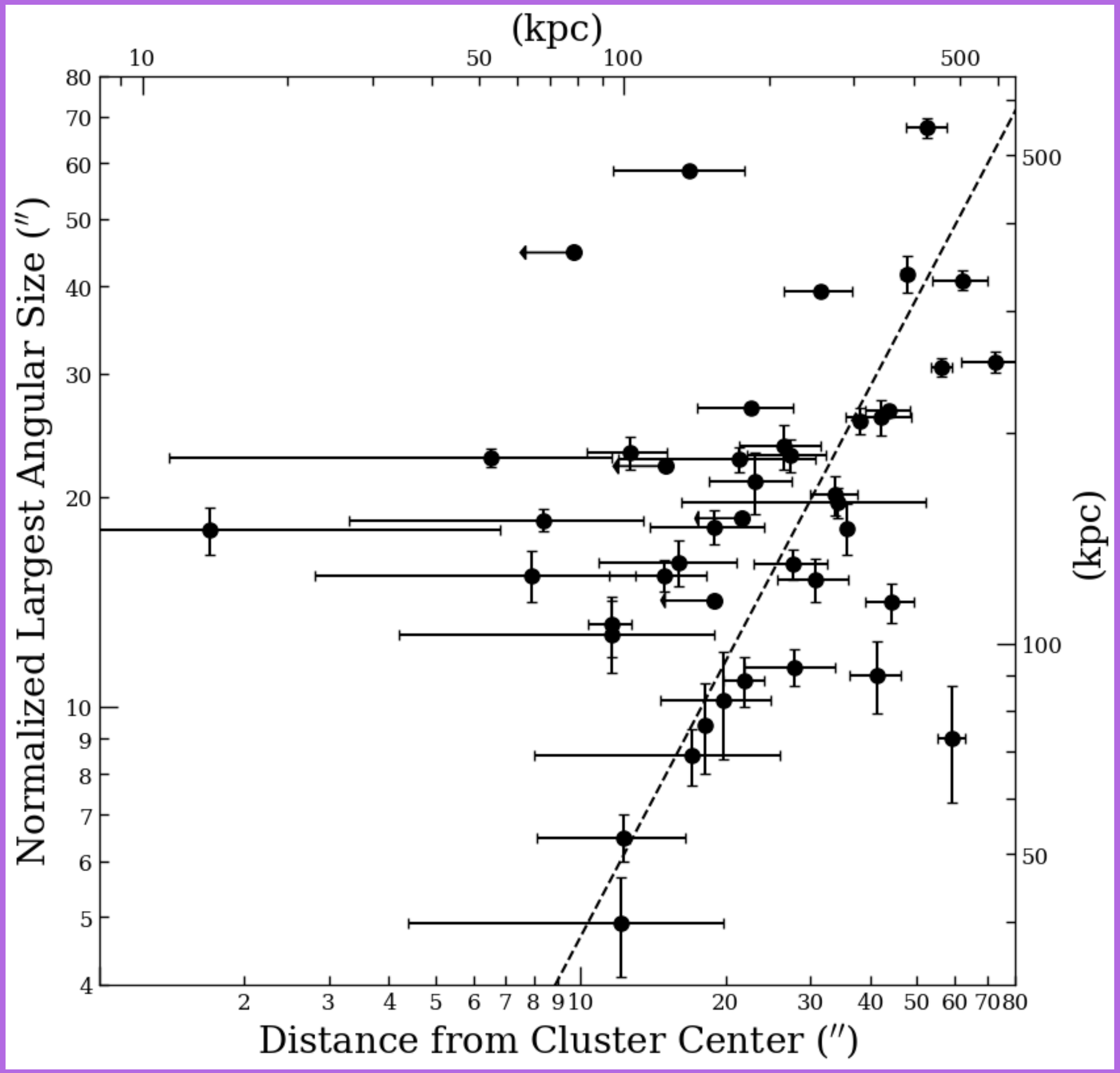






Pilot

$$L_j = \left(\frac{P}{\rho}\right)^{1/5} t^{3/5}$$

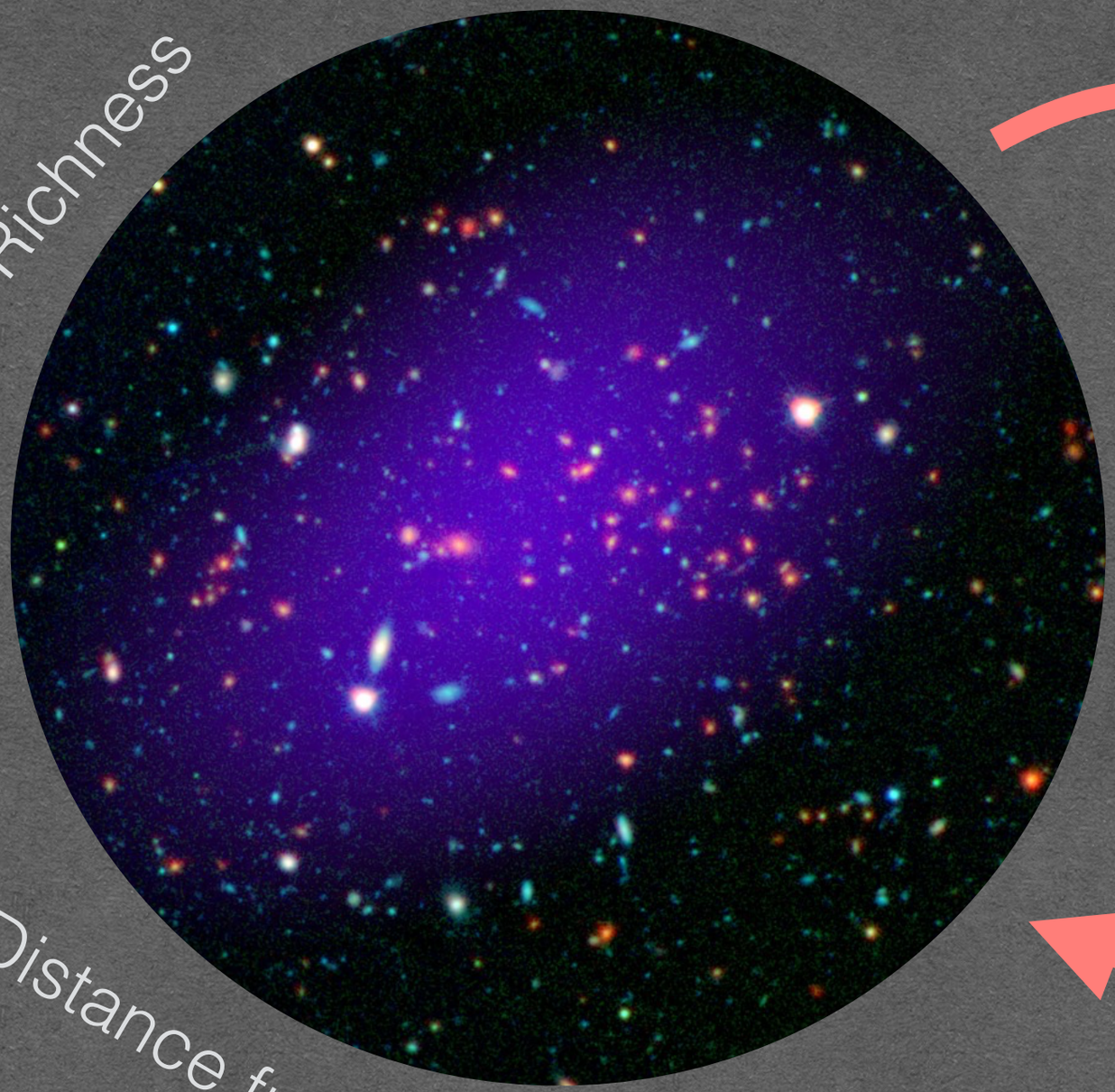


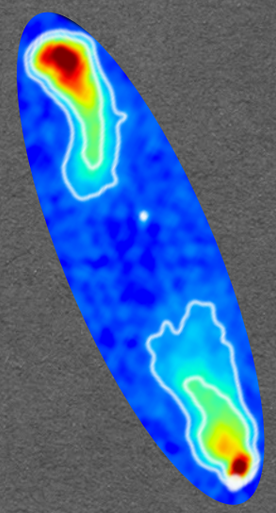
Full

$$L_j = \left(\frac{P}{\rho}\right)^{1/5} t^{3/5}$$

Projection effects account for the majority spread of points

Environment ⟷ Evolution of Source





Stellar Mass

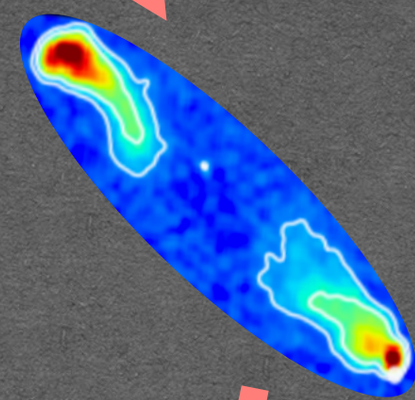
Radio Size

Radio Luminosity

✗ Luminosity vs. Cluster-Centric Distance

✗ Richness vs. Luminosity

✓ 40% of radio galaxies are BCGs



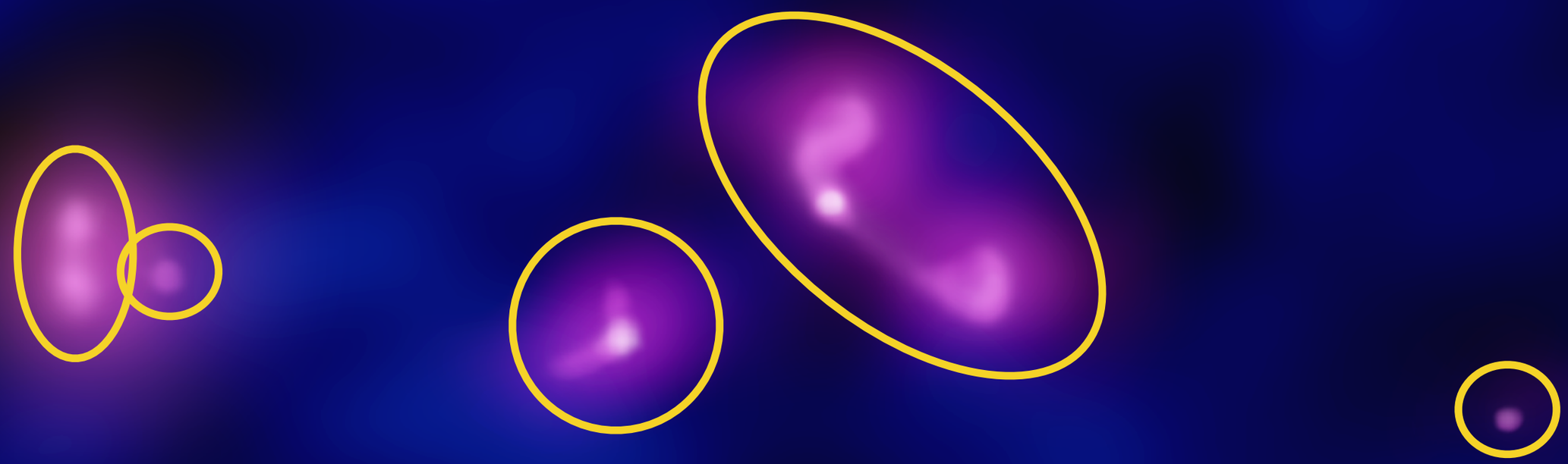
✗ Richness vs. Size

✓ Size vs. Cluster-Centric Distance

✓ Highest stellar mass objects confined to center and host compact jets

Cluster environment fosters radio activity, especially for massive galaxies near the center, but is not the sole driver of the evolution of the rest of the population

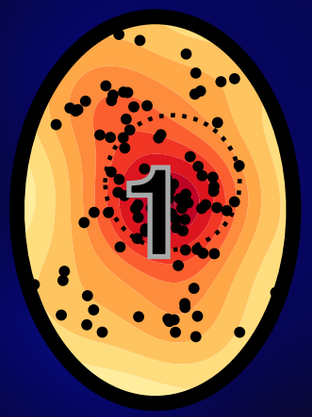
The Curious Case of MOO J1506+5137

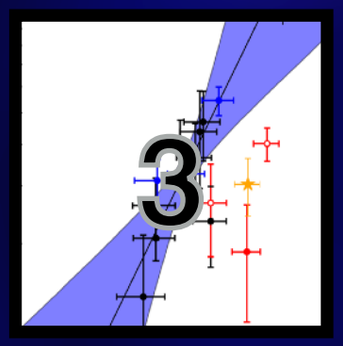


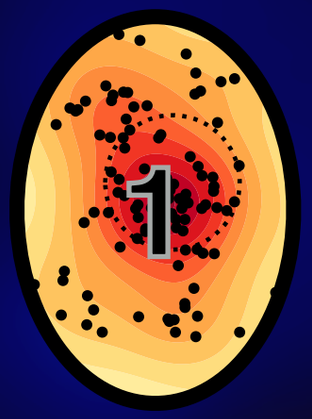
Why does this cluster have high radio activity?

Large-scale OR Small-scale

MOO 1506+5137 is a merging system

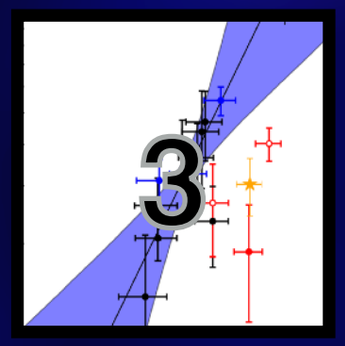






Spatial distribution of galaxies

Radio morphology of AGN jets



Mass-richness relation

Interpretation: Dynamical state affects radio activity

Current Work: Radio-AGN in Merging Clusters

Is enhanced radio-AGN activity ubiquitous in merging systems?

200 merging clusters at $0 < z \lesssim 1.5$

Merging Cluster Collaboration

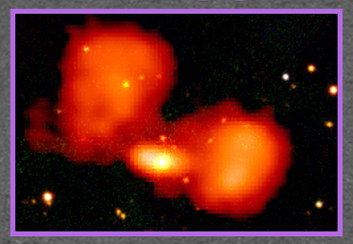
ACT DR5

MaDCoWS

COBRA

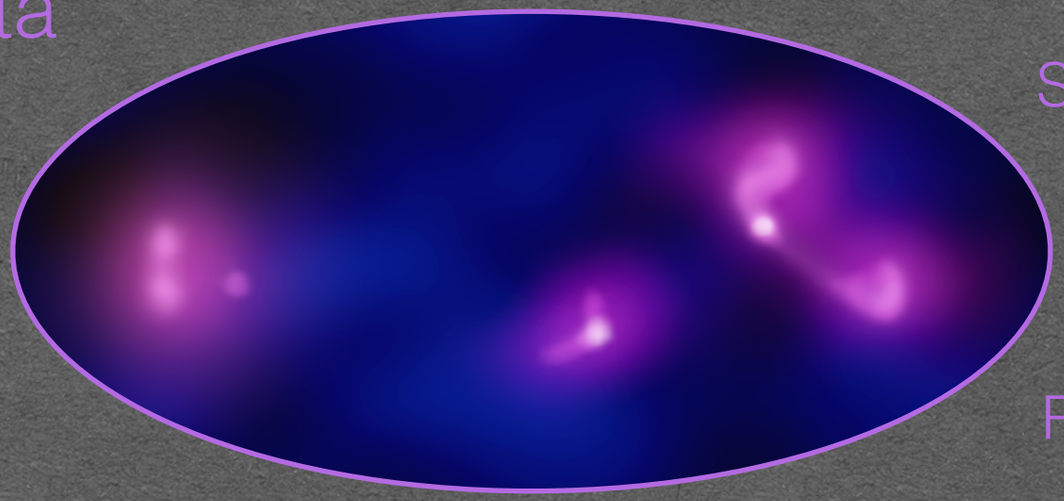
Survey Data

LoTSS



VLASS

VLA SKY SURVEY



Spatial Distribution

Fraction that are RL

Radio Morphology

Comparing Radio-AGN of Merging and Relaxed Clusters at Low-z

Mary Rickel

Bilton+20: 25 Relaxed and 8 Merging

NGC 1265

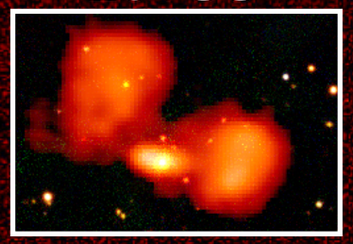
NGC 1275

CR 15

IC 310

Survey Data

LoTSS



VLASS

FIRST

Spatial Distribution

Radio Morphology

Perseus Cluster: VLA 300 MHz - Gendron-Marsollais+20

VLA Program

12 merging + 7 relaxed
at z~1

Radio Morphology

Compare radio-activity

21B

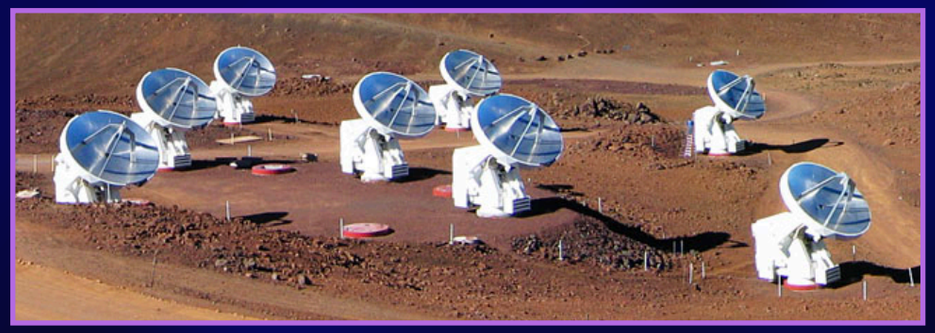
GBT Program

ICM Structure

ICM - AGN

22B

SMA Program: 21B



https://www.eso.org/public/ukraine/images/eso1229e/?lang

2 merging clusters at z~1
with central radio-AGN

Molecular gas content

SEDs of radio-AGN

Radio-AGN in Galaxy Clusters

1. Galaxy clusters are largest gravitationally bound objects in Universe and are interesting laboratories to study AGN evolution

2. Evolution of number of AGN in clusters with redshift

3. Radio-AGN and cluster environment affect one another in many many ways

4. I am investigating how the merging cluster environment affects the triggering and evolution of radio-AGN