Science with radio continuum surveys

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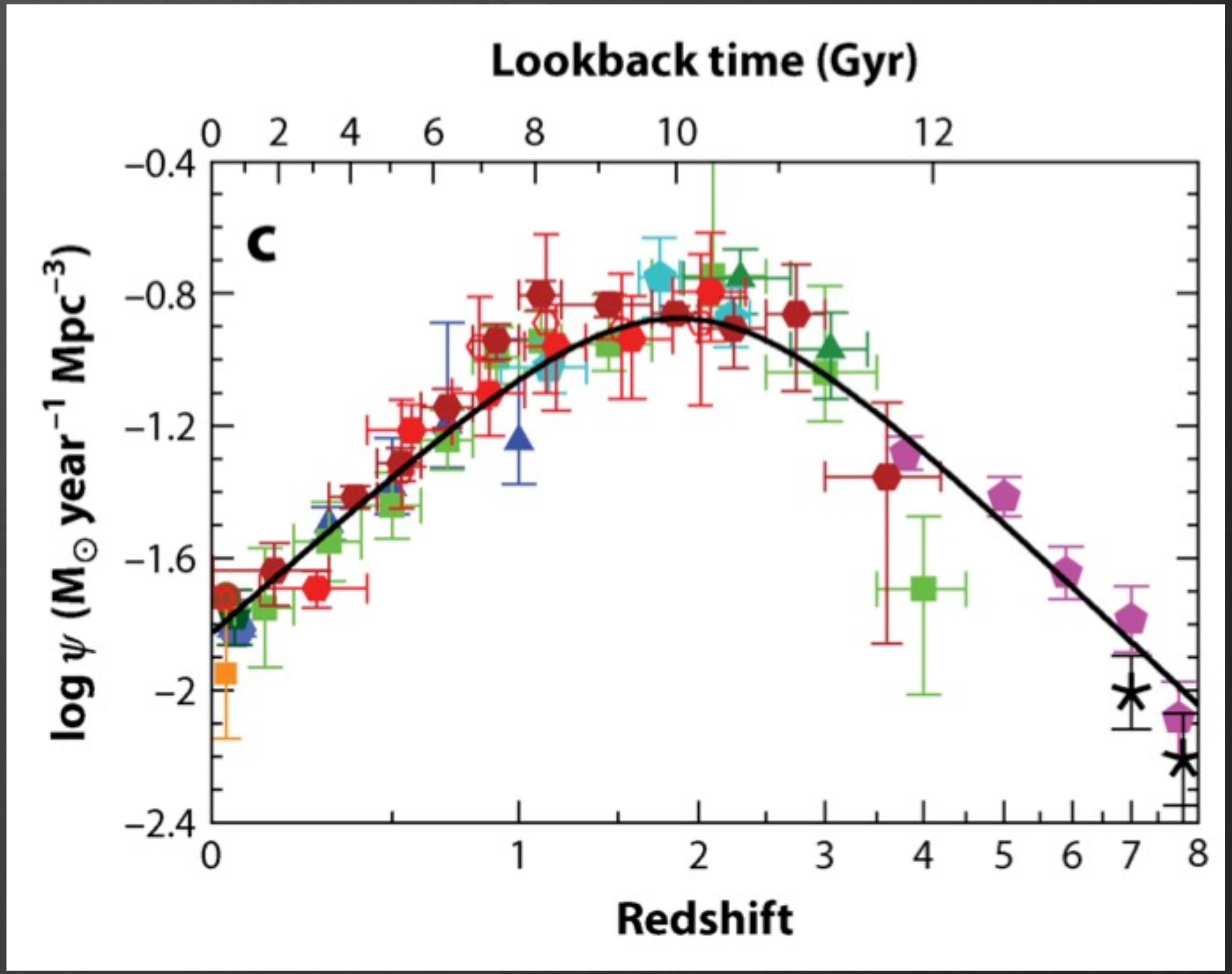
Thanks to: Catherine Hale, Ian Heywood, Imogen Whittam, Leah Morabito, Matt Prescott, Jacinta Delhaize & the MIGHTEE team

Science goals of radio continuum surveys

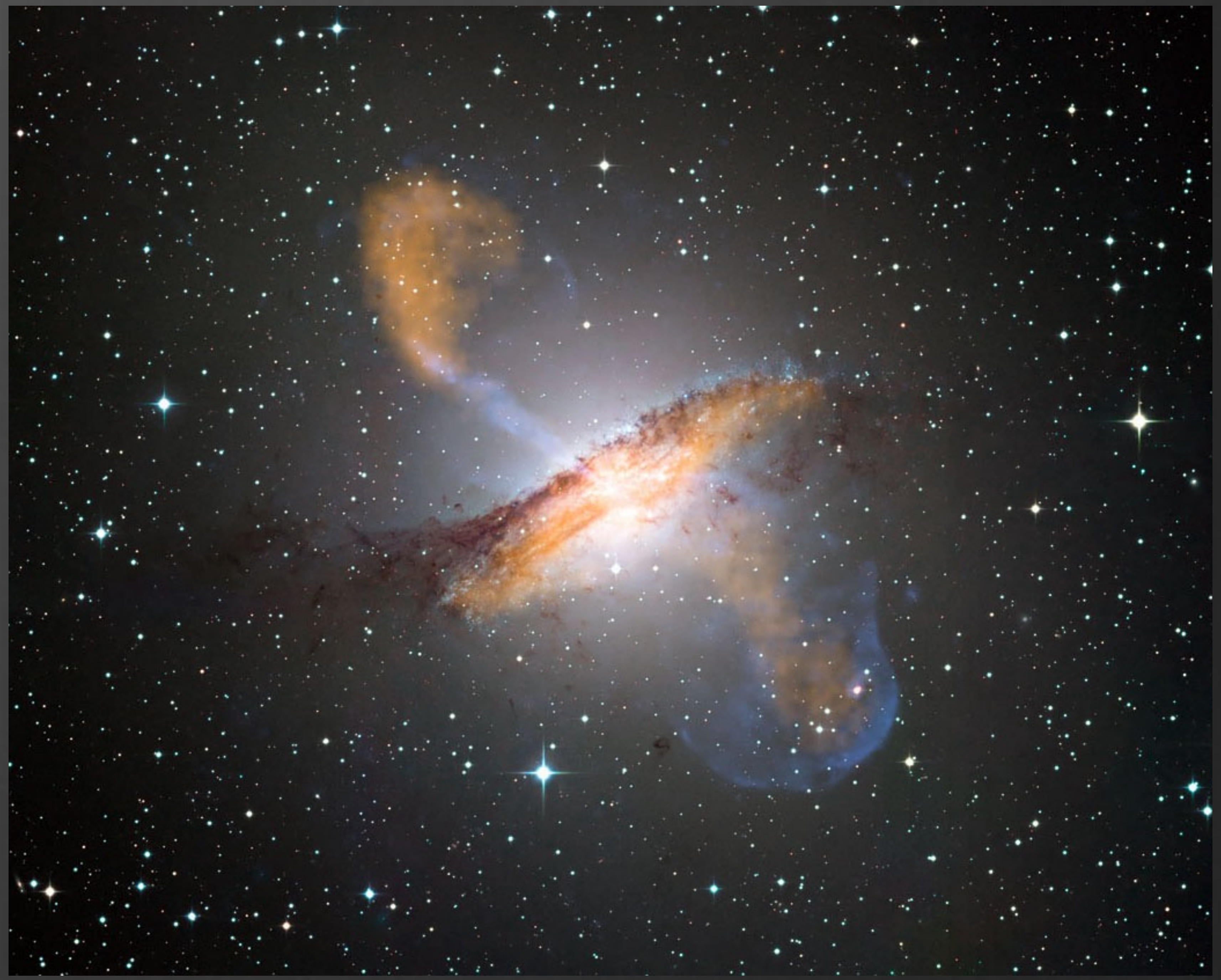
★ How, when and why of star formation out to z~4 – dust free.



Madau & Dickinson (2014)

Science goals of radio continuum surveys

- ★ The cosmic history of star formation out to z~4 — dust free
- ★ How are black holes fuelled and how does accretion onto black holes affect the evolution of galaxies?



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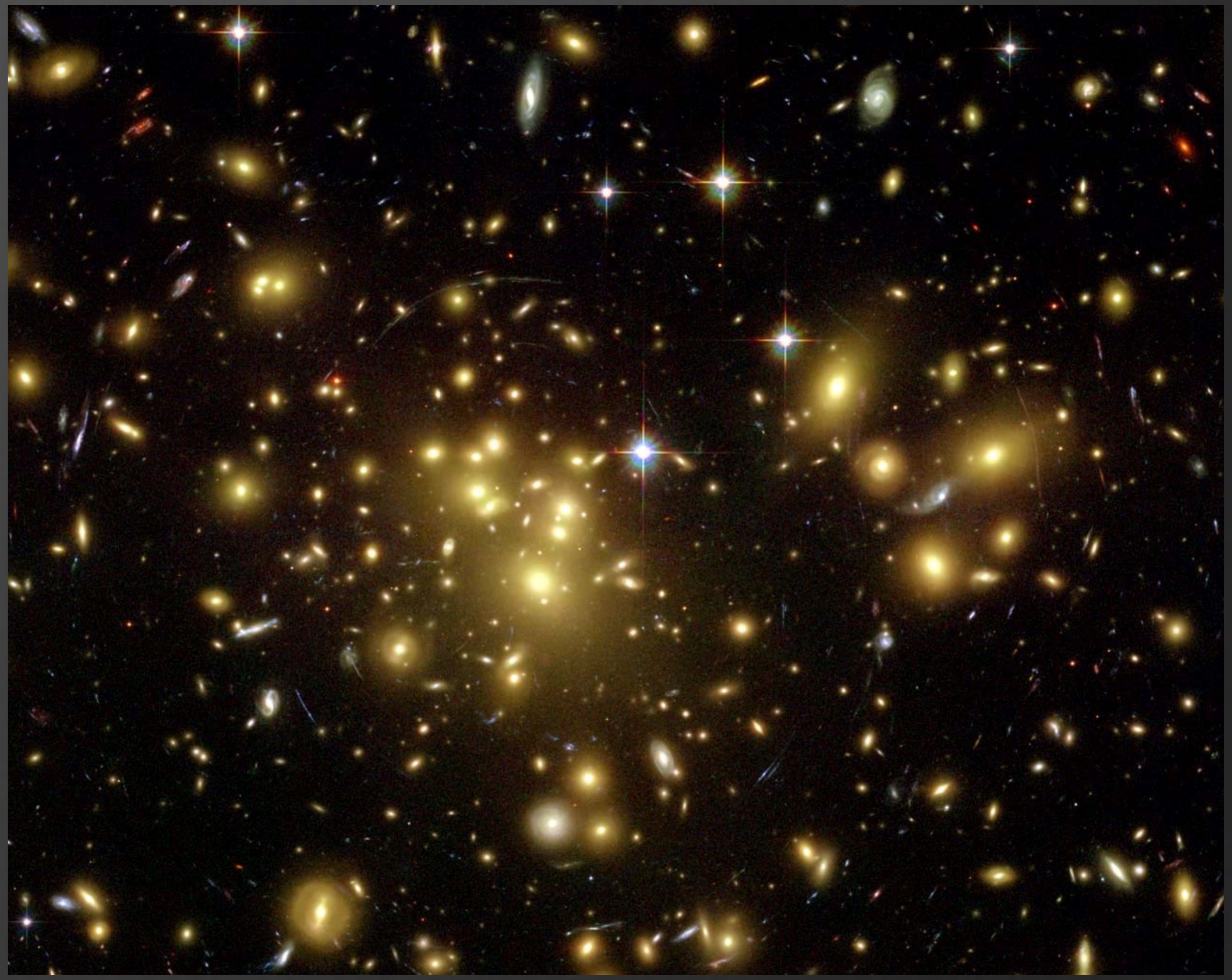

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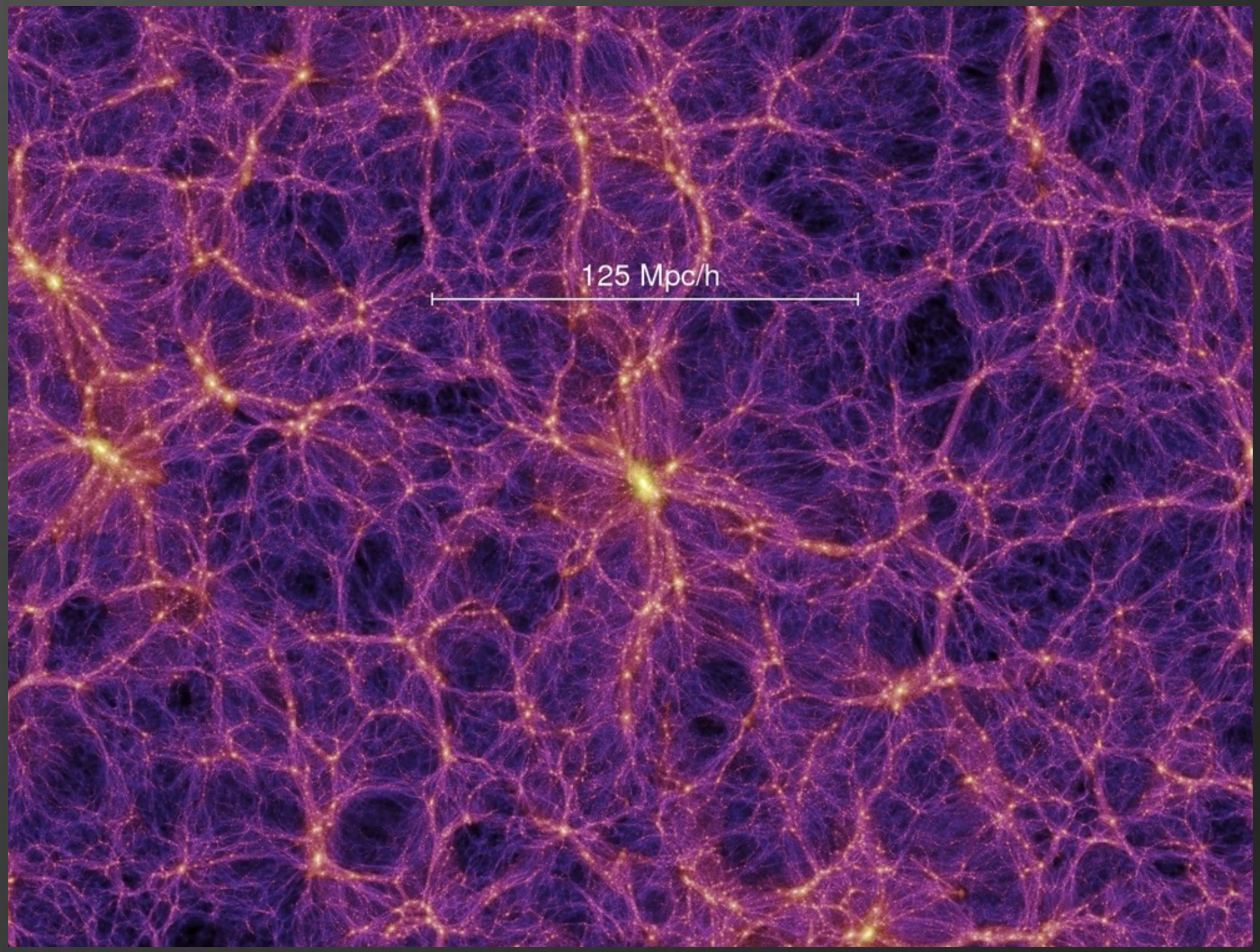
- ★ How do baryons trace the underlying dark-matter distribution?



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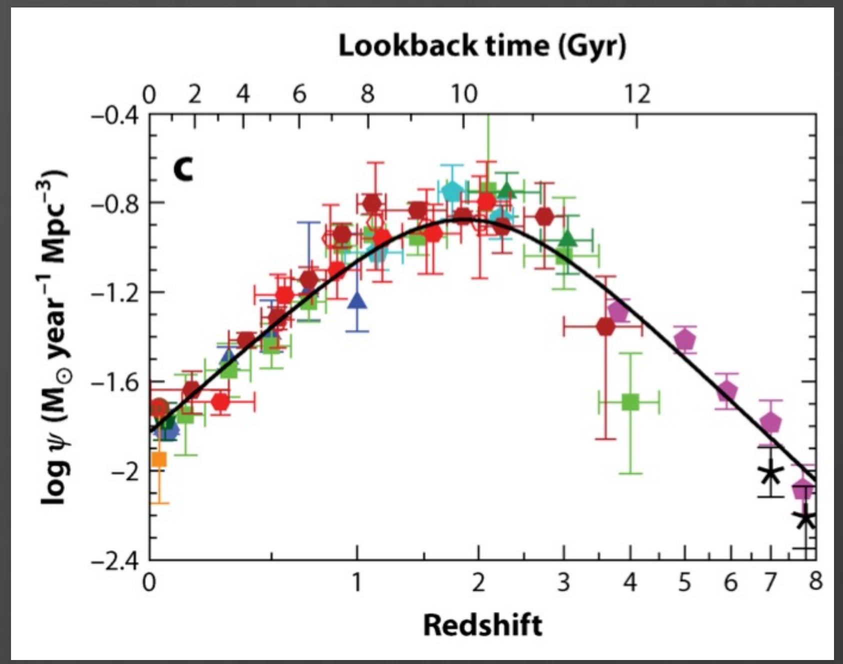
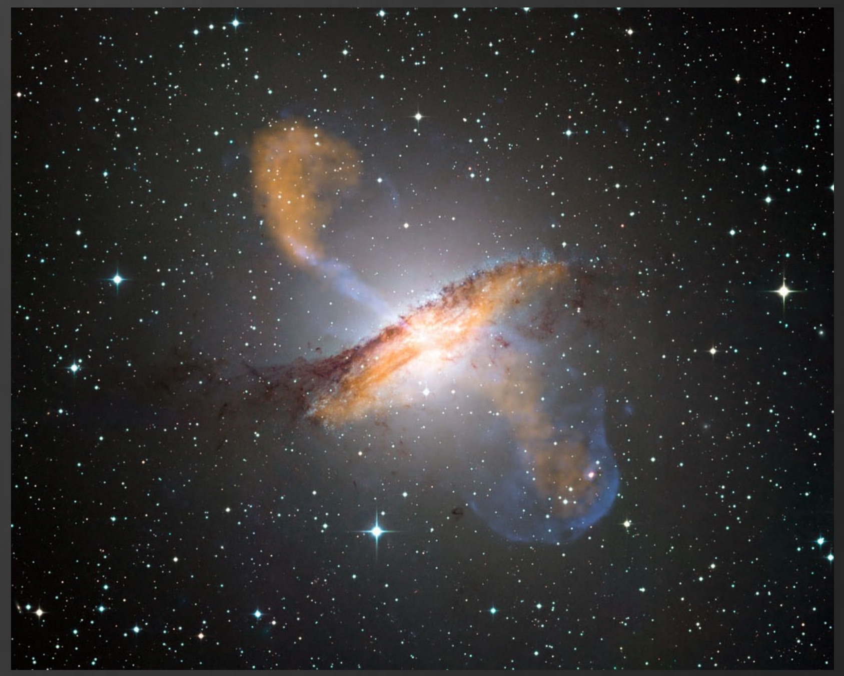
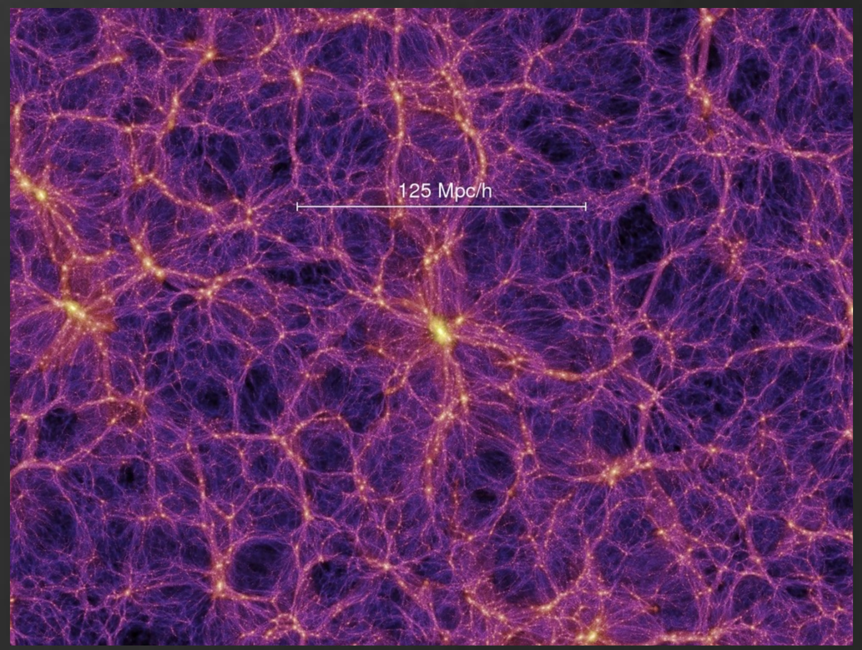
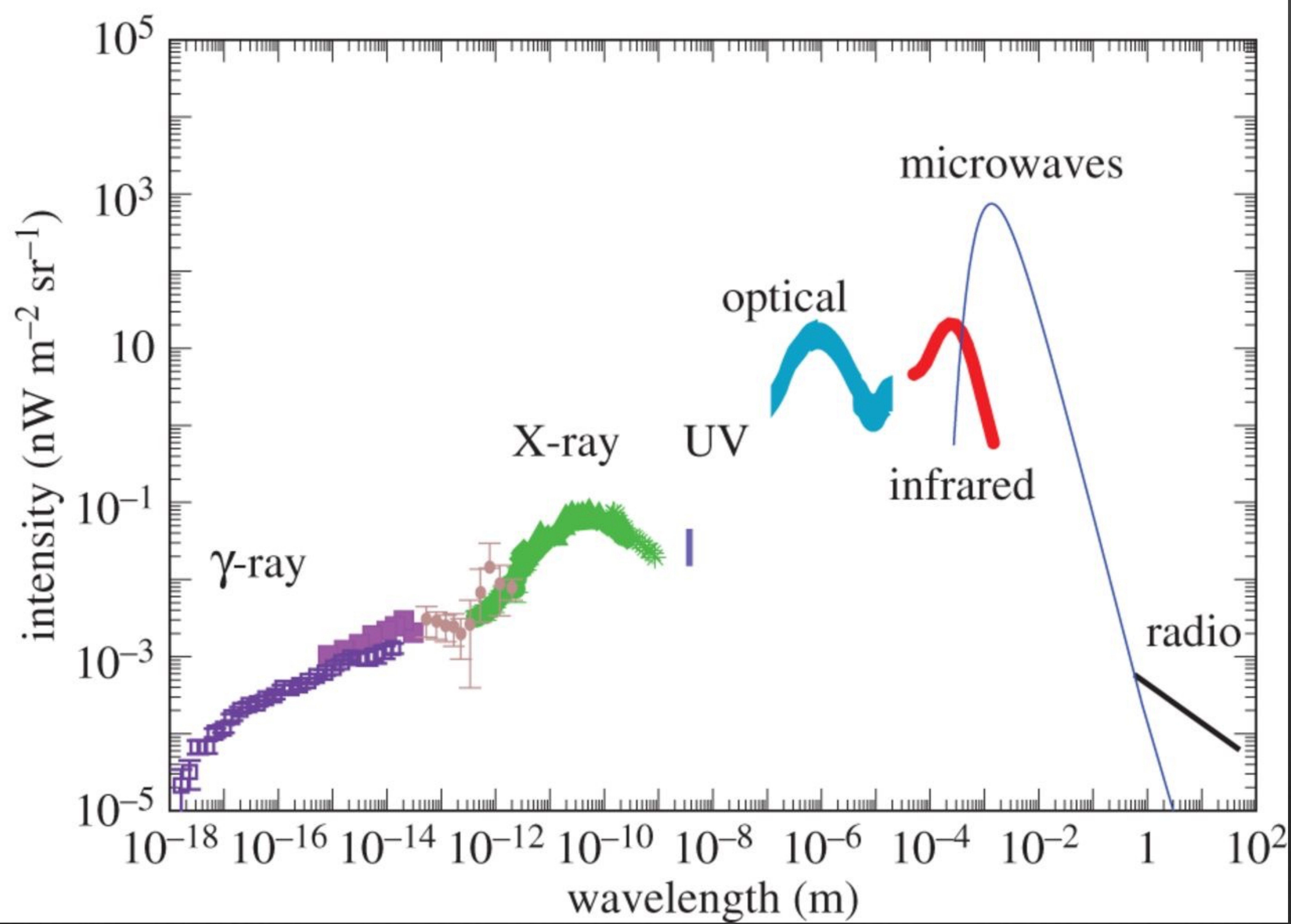
- ★ How do baryons trace the underlying dark-matter distribution?
- ★ Clusters





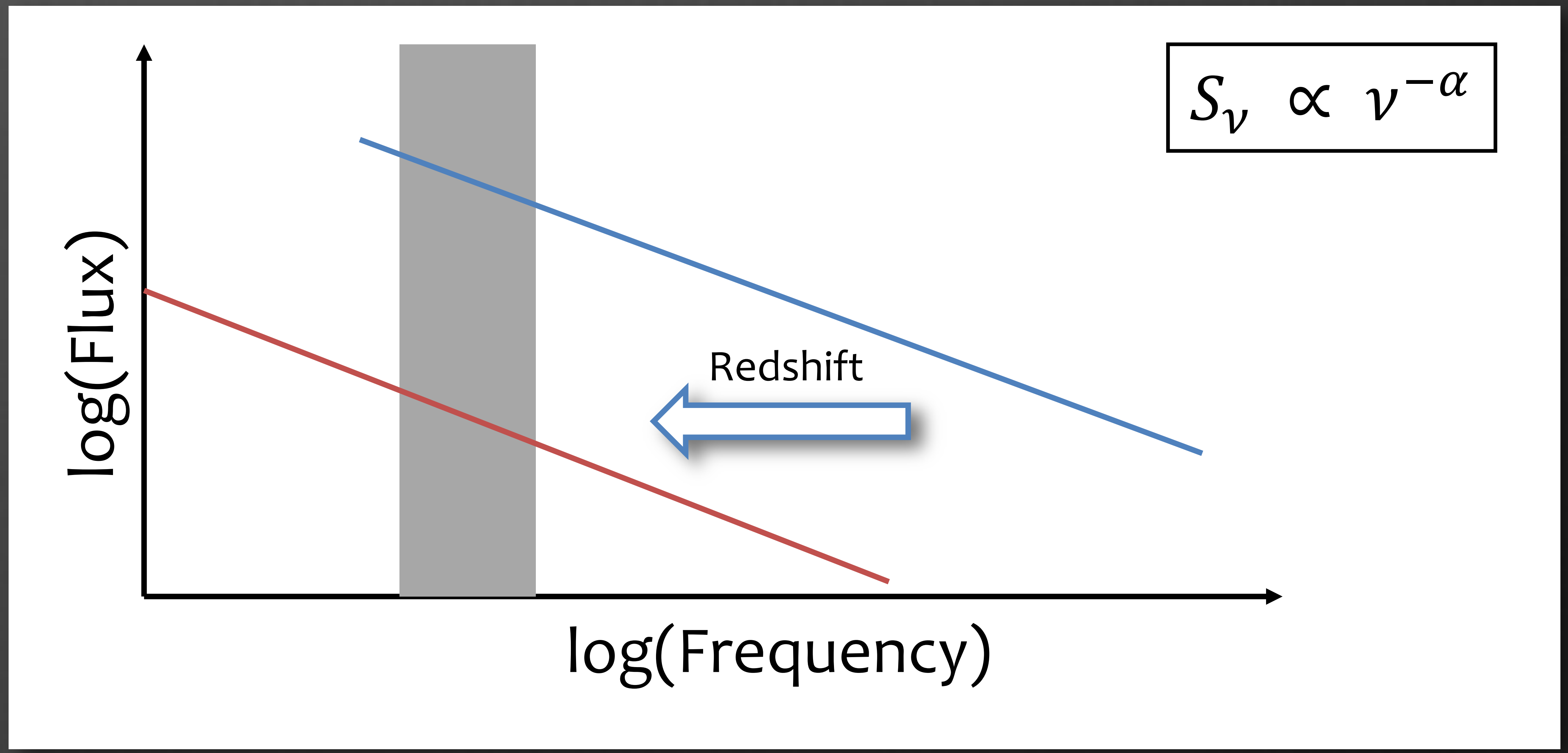


Extragalactic background light intensity



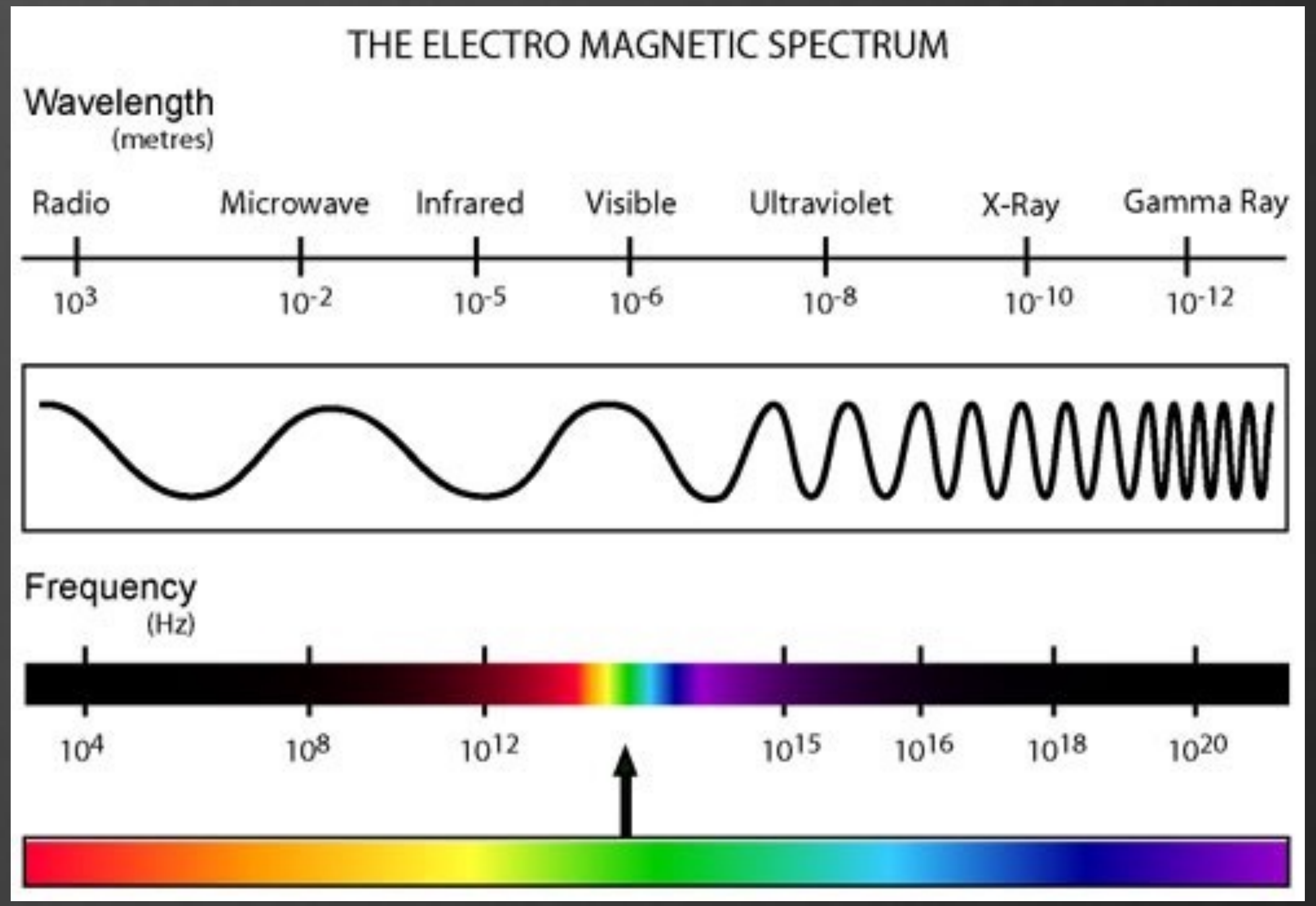
Why are multi-wavelength data important?

- Radio spectra are typically power laws – not much information.
- Data at other wavelengths required for:
  - Redshift
  - Separation of star-forming galaxies from AGN.
  - Information about host galaxy e.g. star-formation rate, stellar mass.

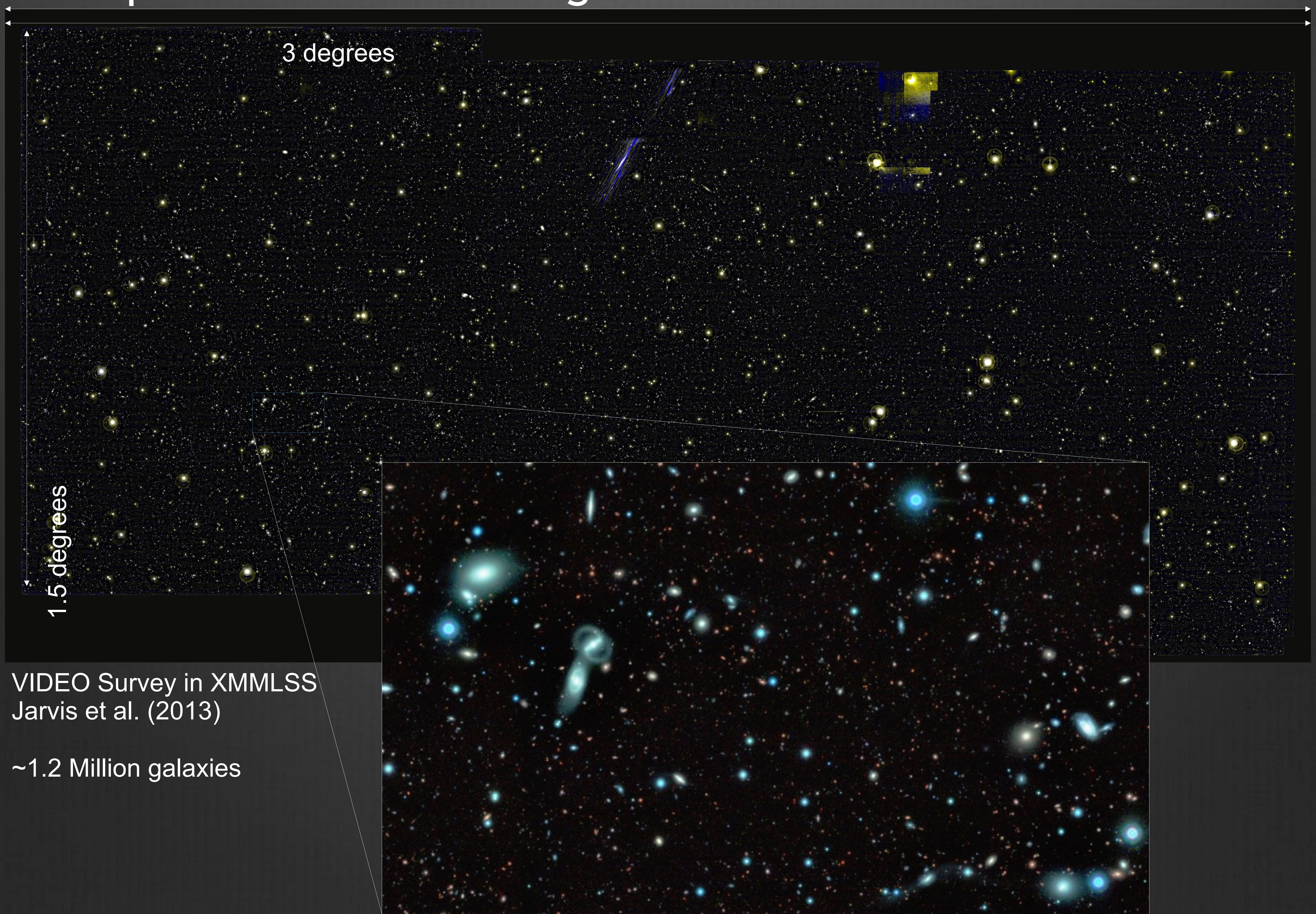


Multi-wavelength data

- ★ Fields chosen because they have excellent multi-wavelength data available.
- ★ Wide range of current and future surveys covering the full range of the electromagnetic spectrum.

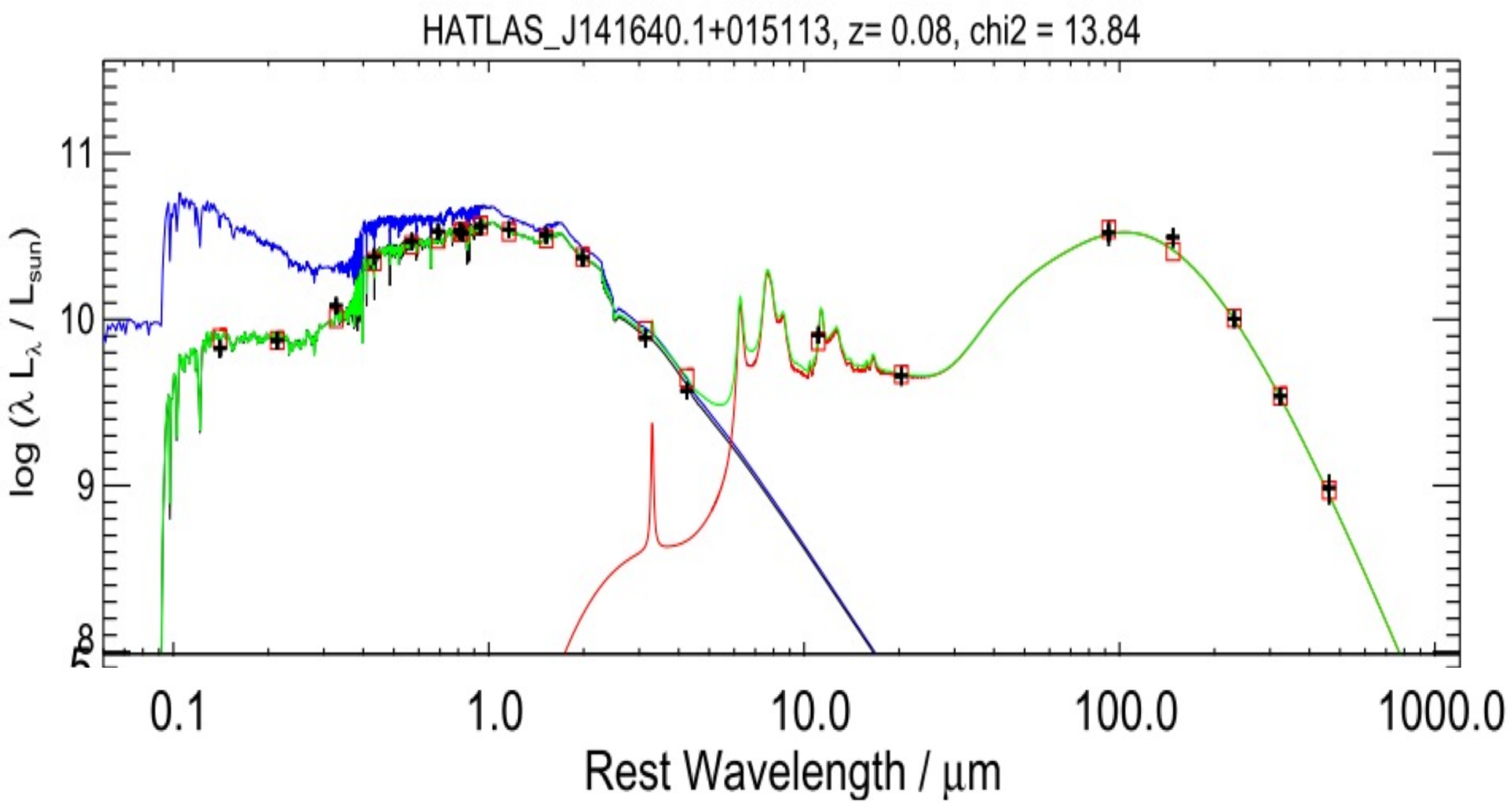


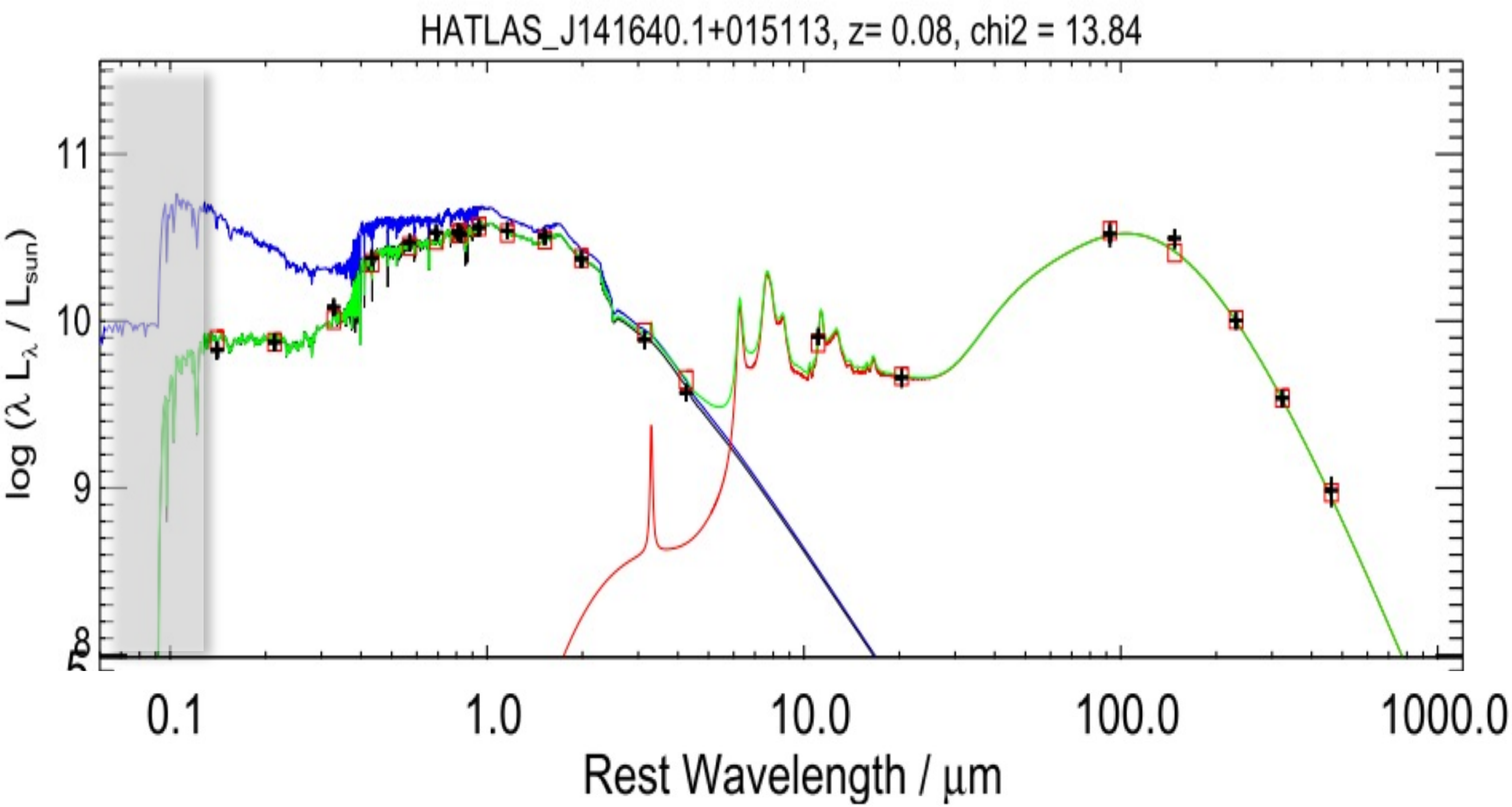
Example of multi-wavelength data: VIDEO near-infrared survey



VIDEO Survey in XMMLSS
Jarvis et al. (2013)

~1.2 Million galaxies


HATLAS_J141640.1+015113, z= 0.08, chi2 = 13.84
log (λ L_λ / L_sun)
11
10
9
8
0.1
1.0
10.0
100.0
1000.0
Rest Wavelength / μm

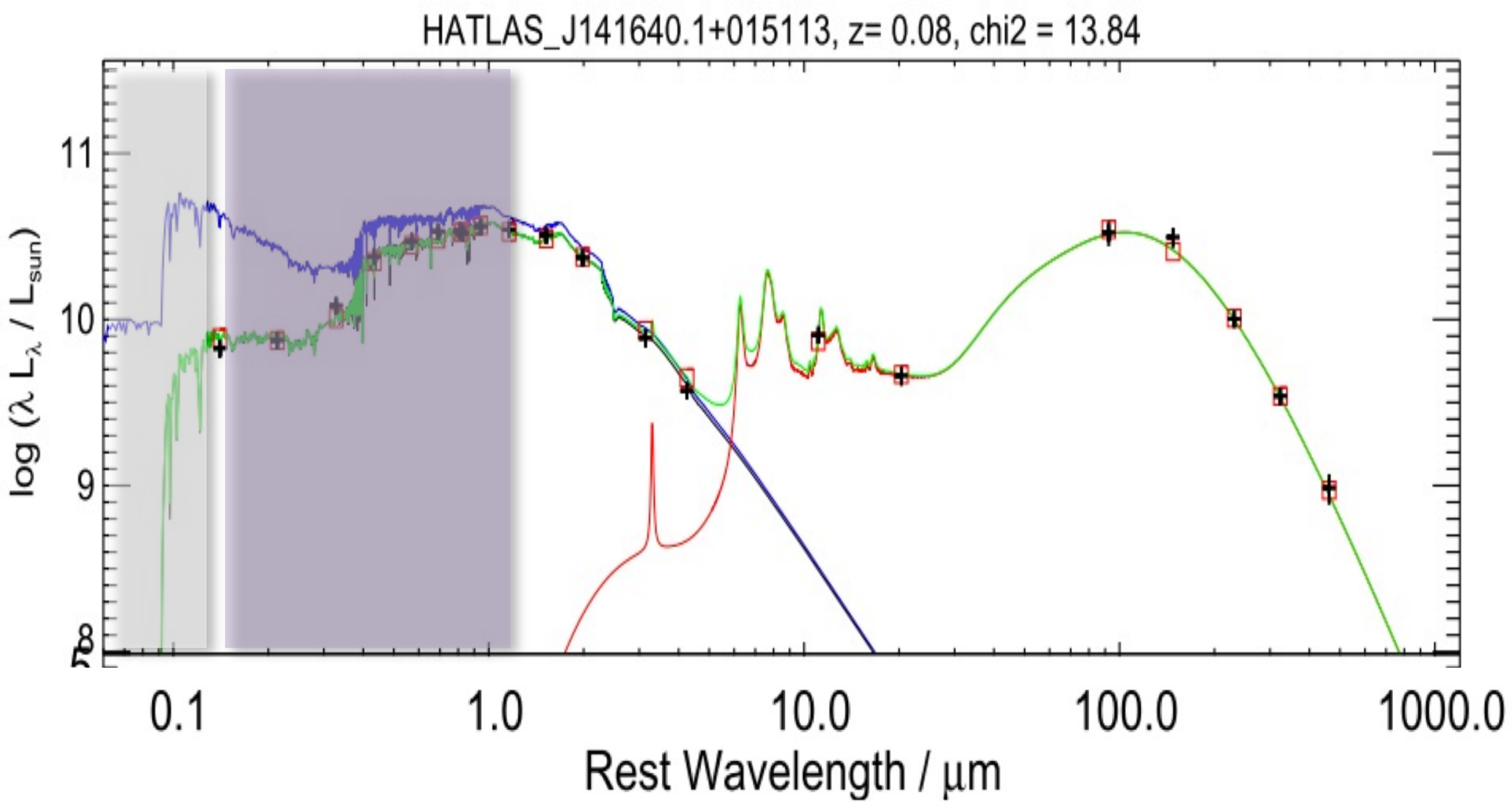


UV

Hot massive young stars

Thermal radiation from accretion disks around Black Holes

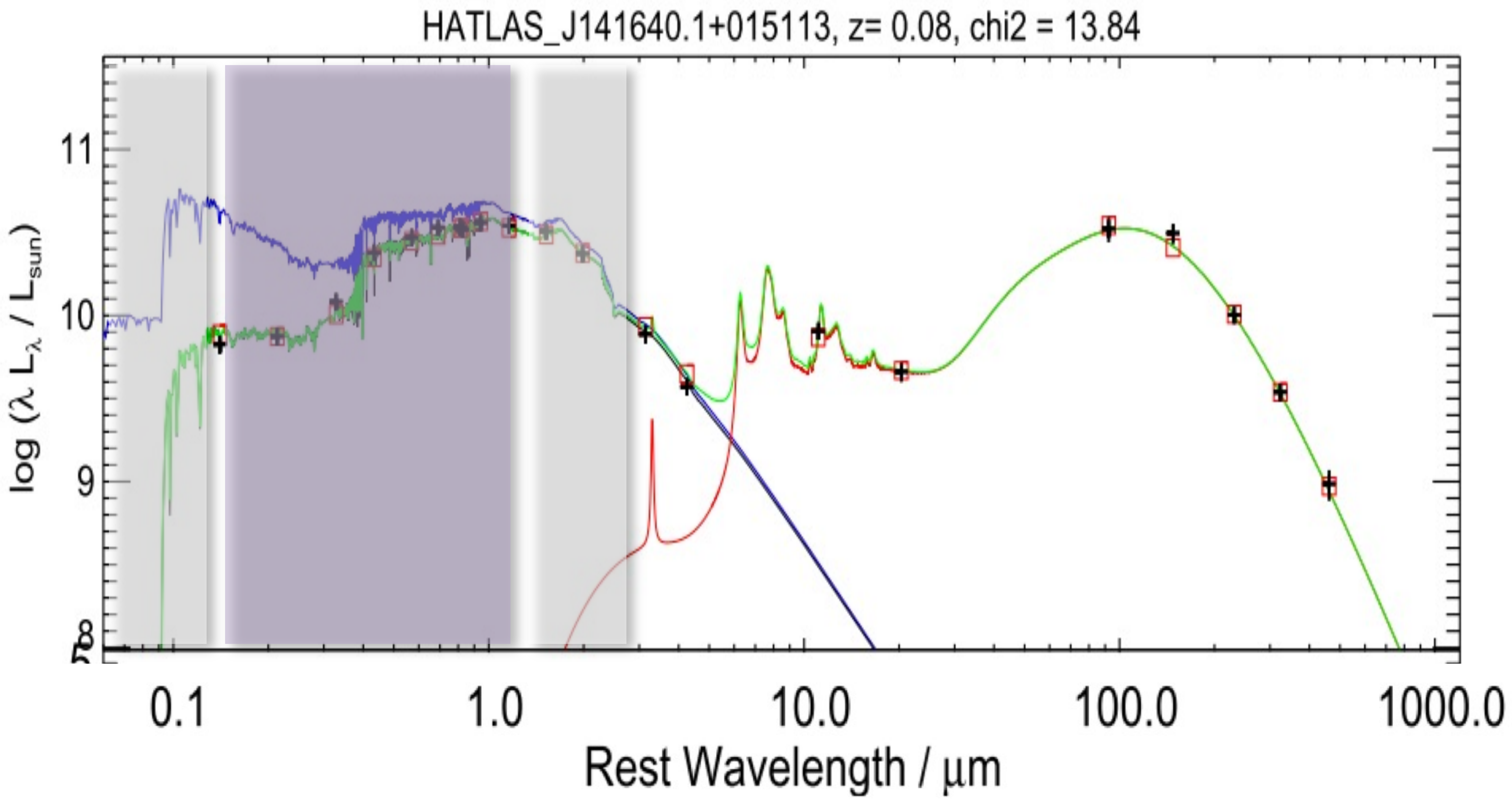
Telescopes: GALEX, HST



Visible

Young & Moderate age stellar populations through to old populations (>4000A)
Thermal radiation from accretion disks around Black Holes

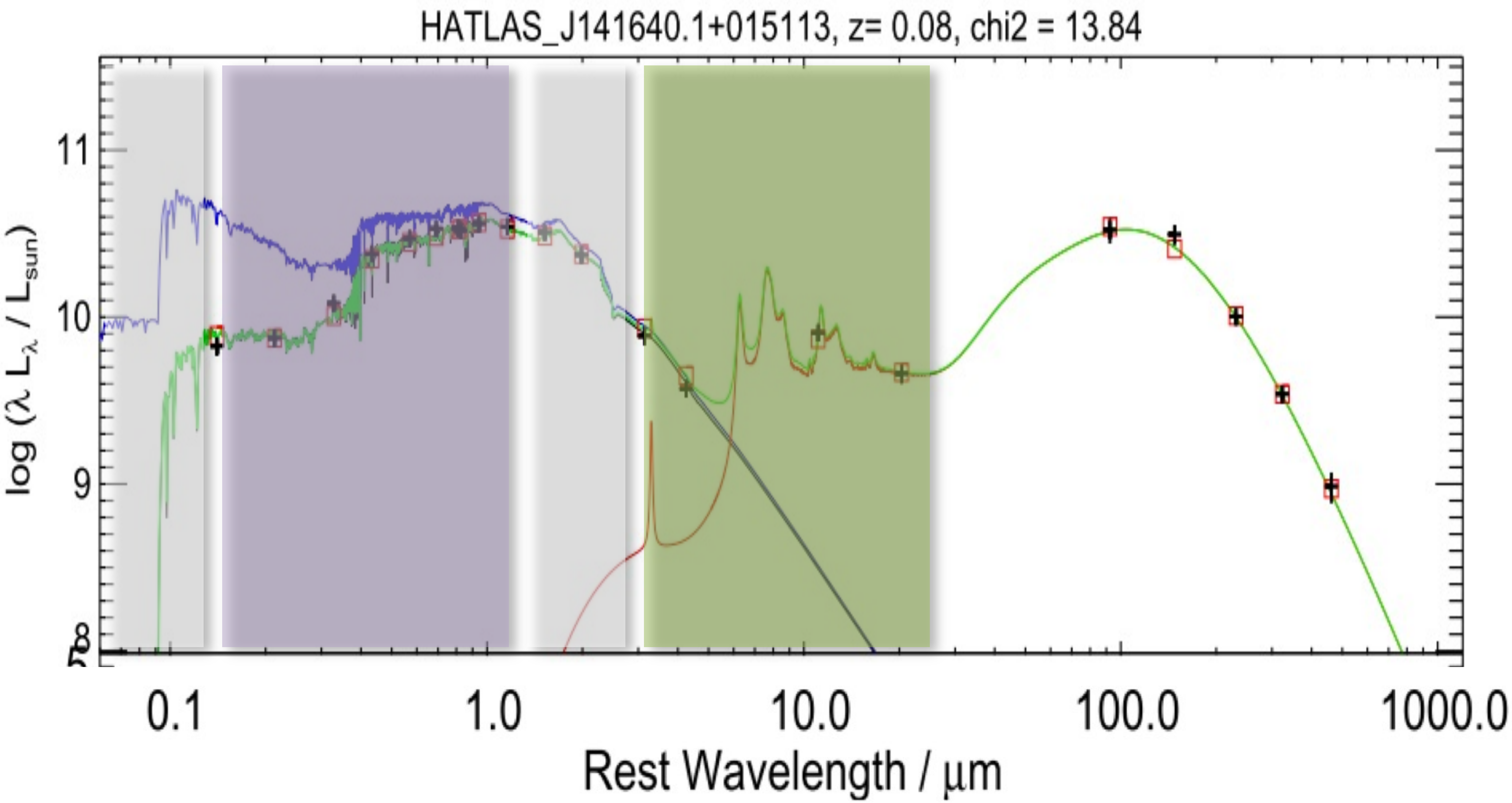
Telescopes: SALT,VLT,Gemini,Subaru, WHT etc etc



NearIR

Emission from evolved stars, generally dominate the stellar mass in galaxies
Very hot thermal dust emission ~1000K

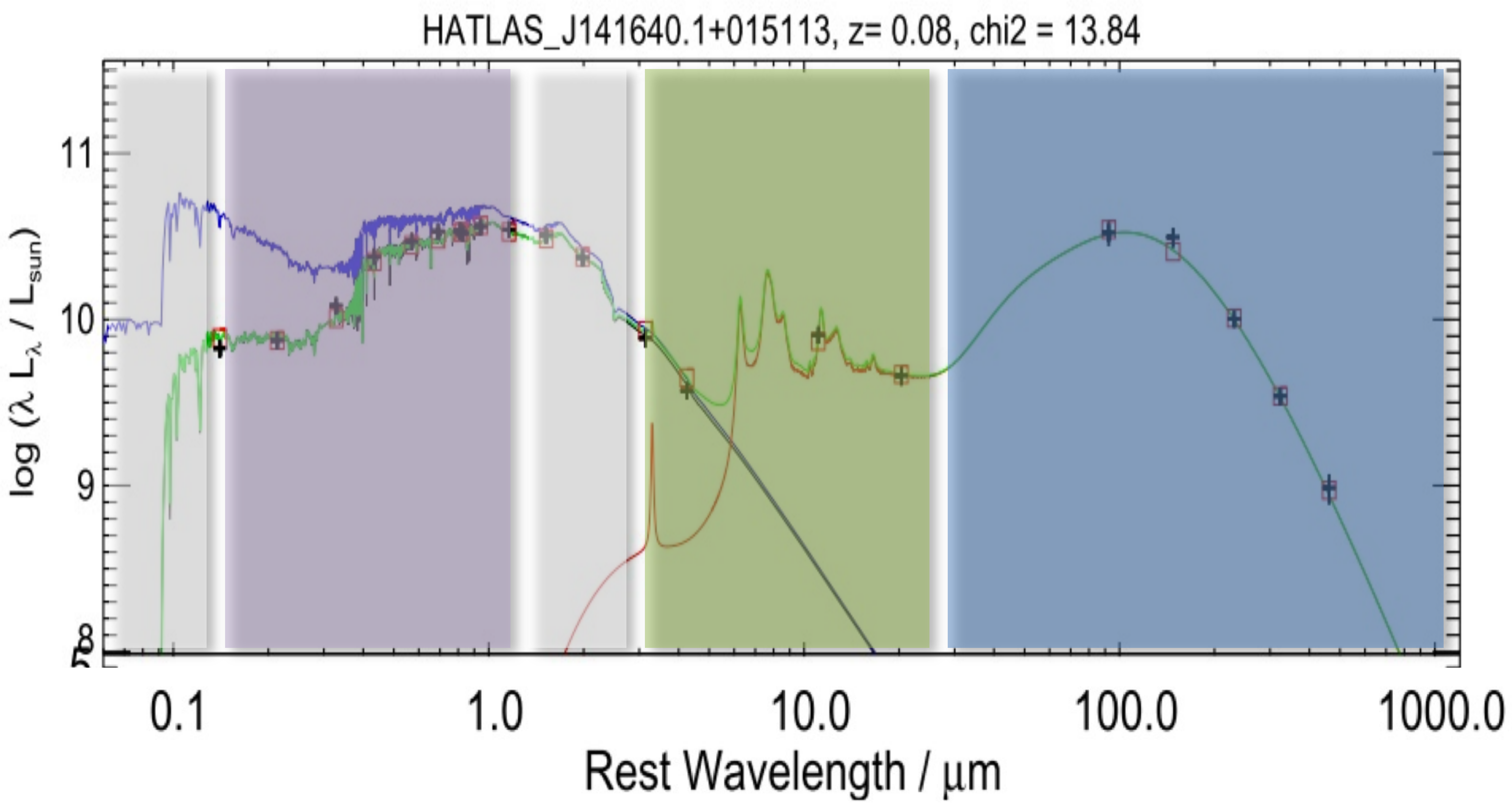
Telescopes: VLT, Gemini, Subaru, UKIRT, VISTA etc etc



MidIR

Hot dust heated by ongoing star formation and AGN
PAH features

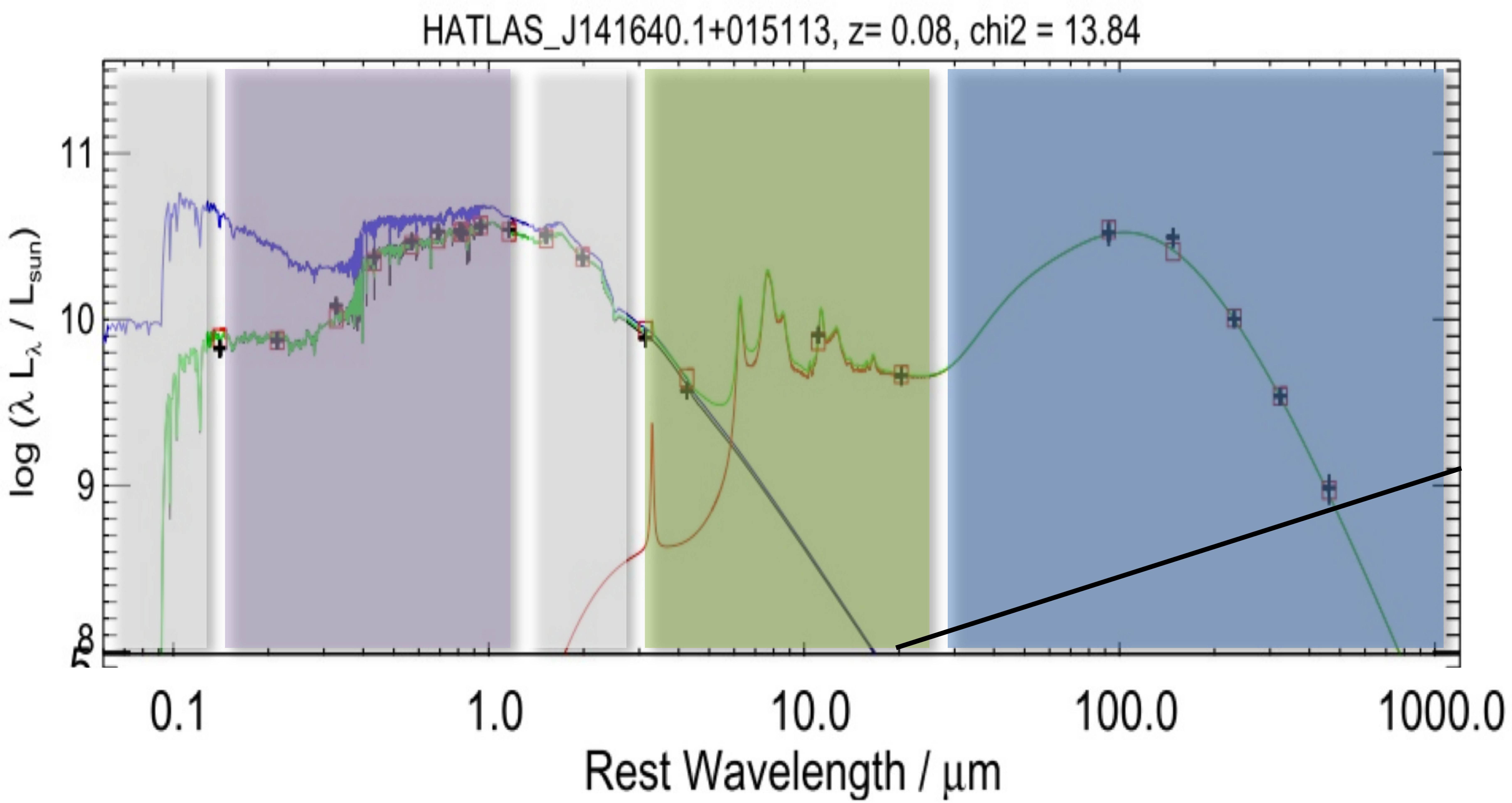
Telescopes: Spitzer, WISE, AKARI…



FarIR

Cold dust (~25K) heated by SF, AGN and old stars

Telescopes: Herschel, SCUBA2, ALMA

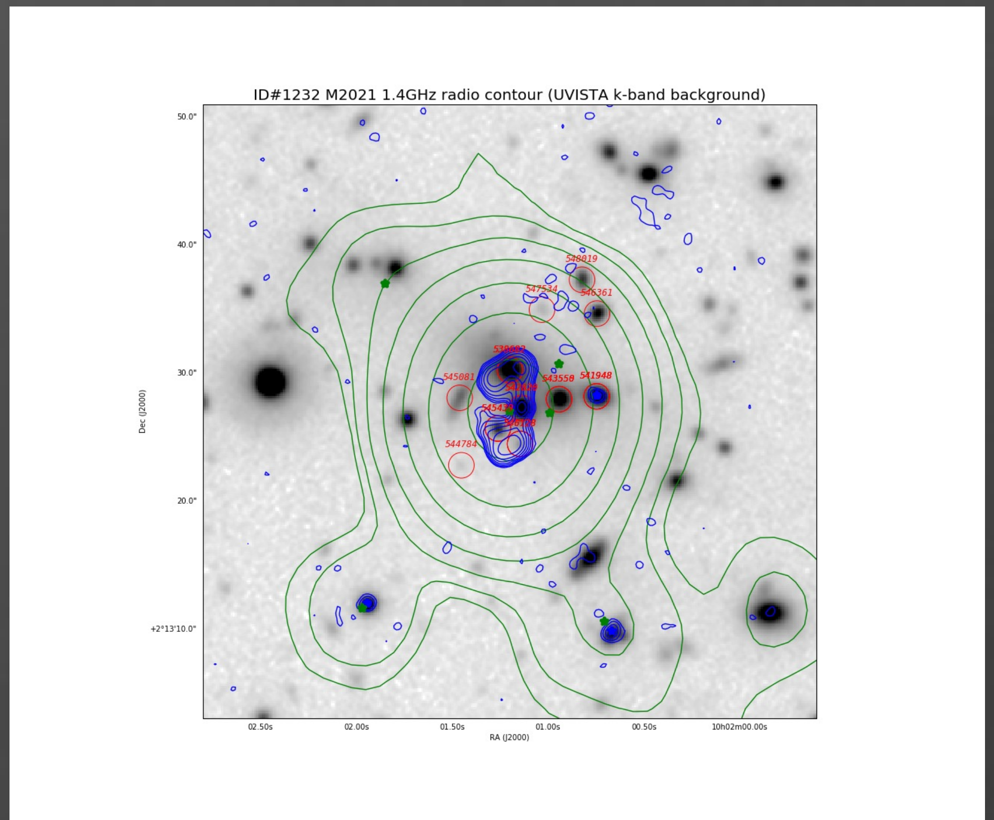


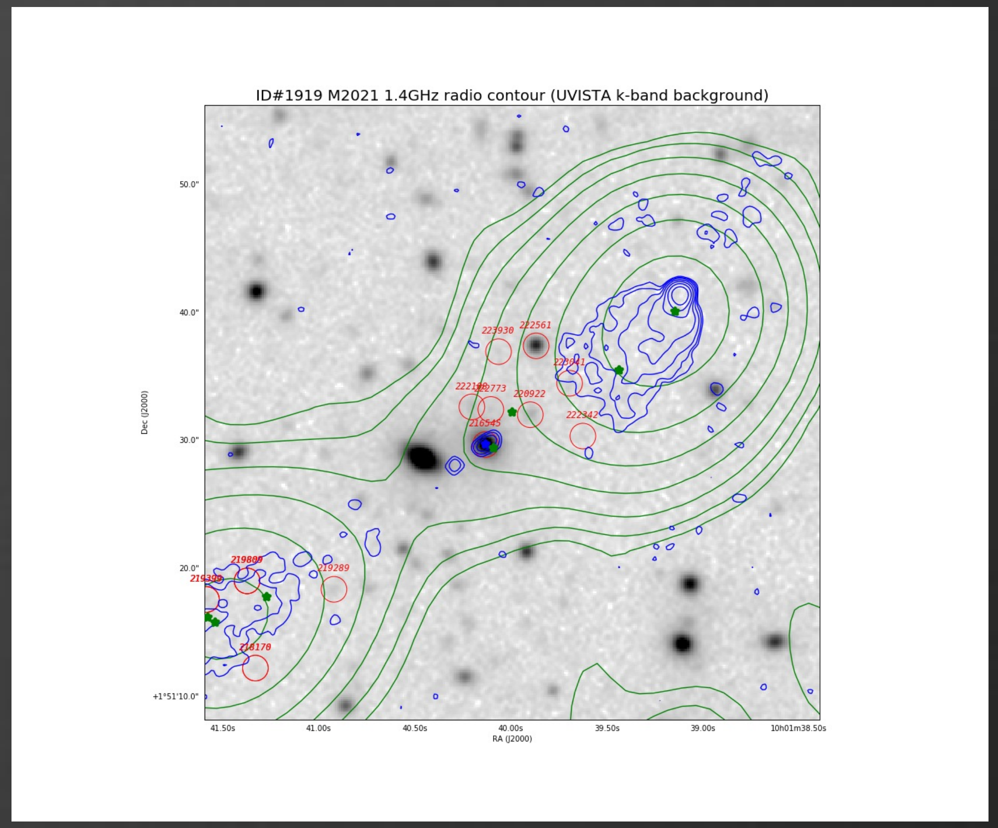
FarIR

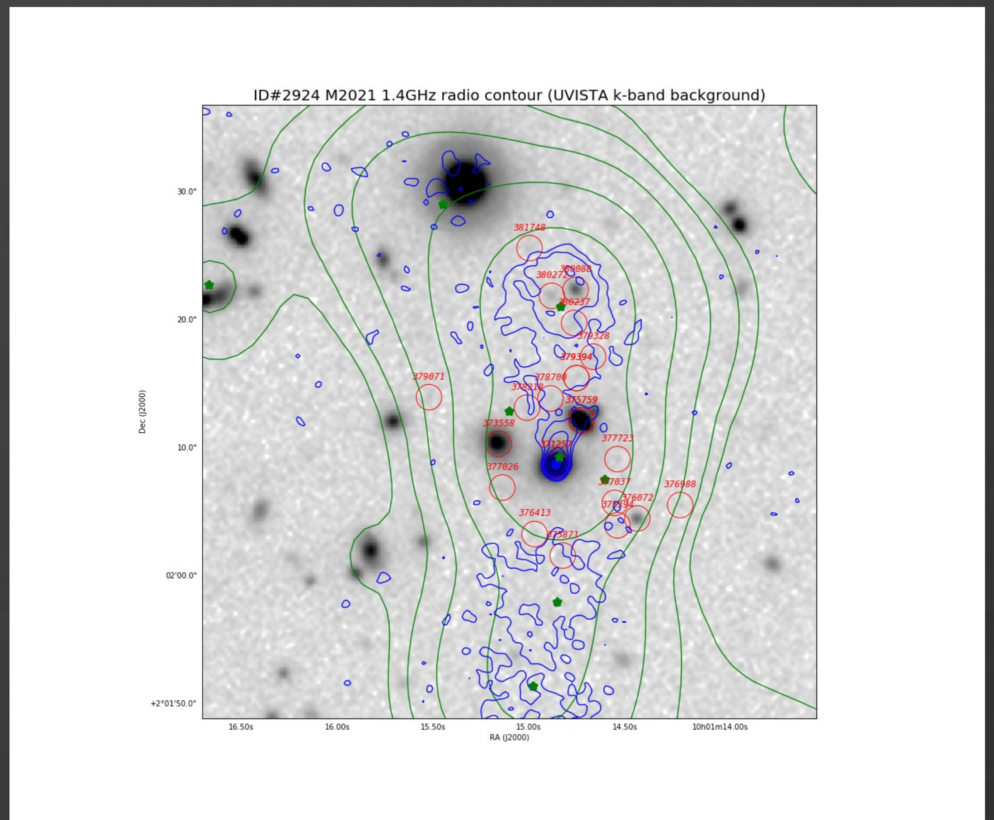
Can be contaminated by Synchrotron emission, which dominates the radio

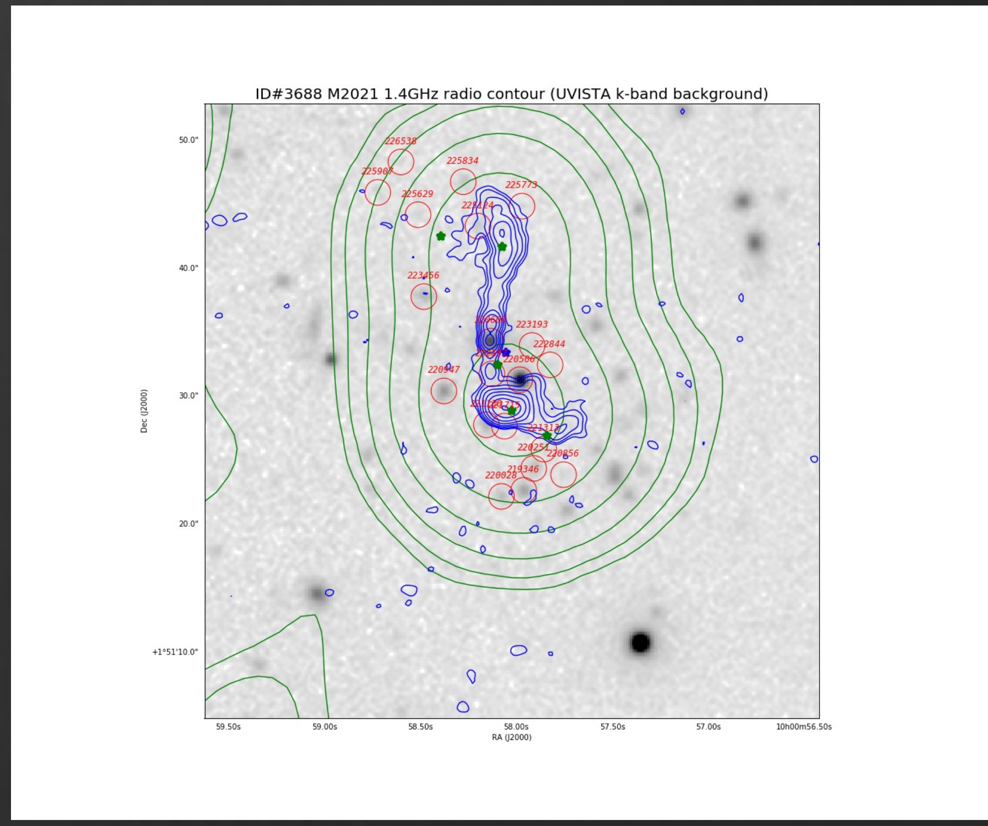
Cross-matching radio and multi-wavelength data

- ★ Cross-matched ~1 deg^2 in COSMOS field by eye.
- ★ Visual inspection GUI in a jupyter notebook created by Matt Prescott.
- ★ 6000 sources, each was classified by 3 people.
- ★ 95% have an optical counterpart.
- ★ Using to test strategy for rest of the survey - combination of Likelihood Ratio and visual matching for complicated sources.



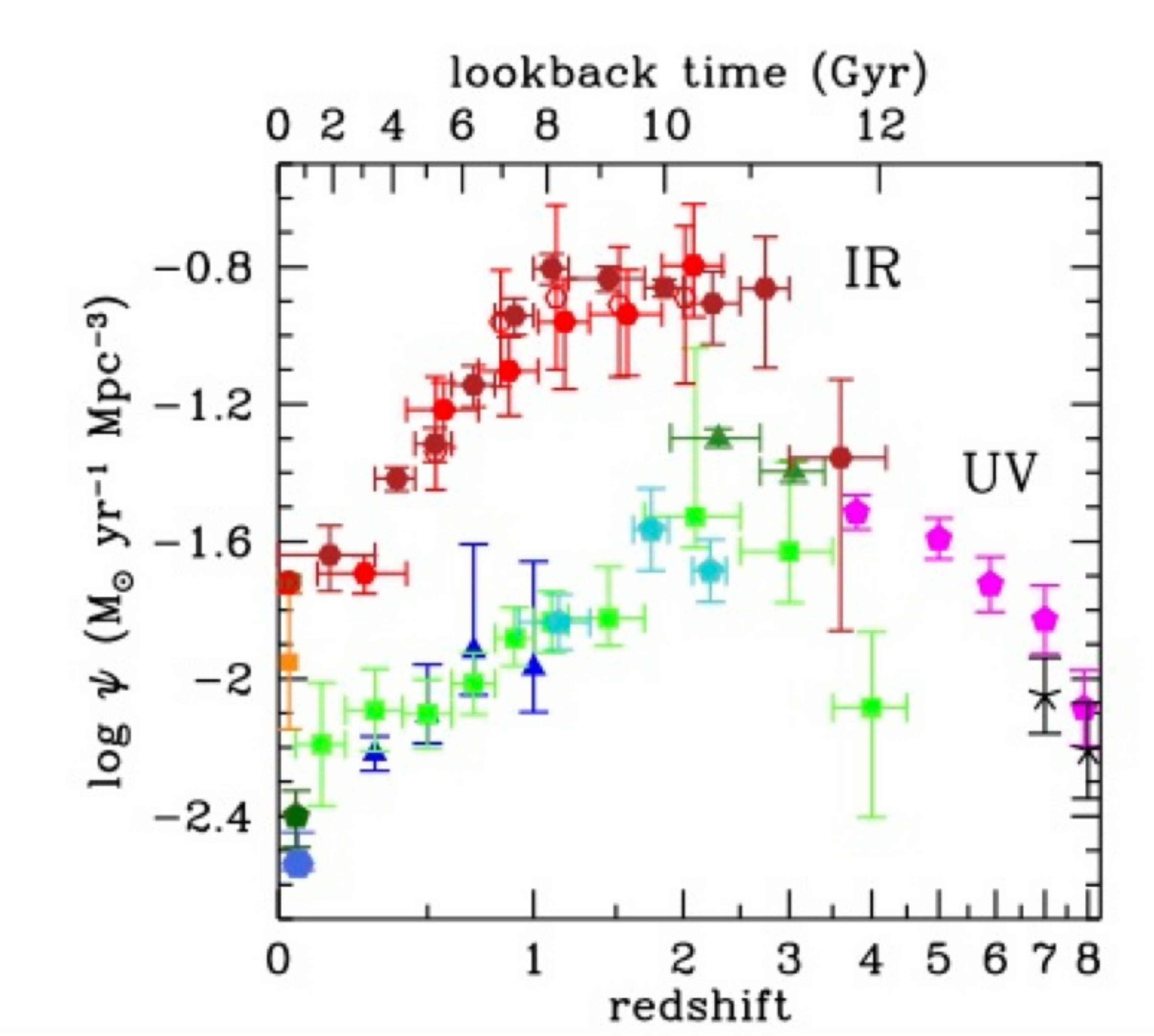




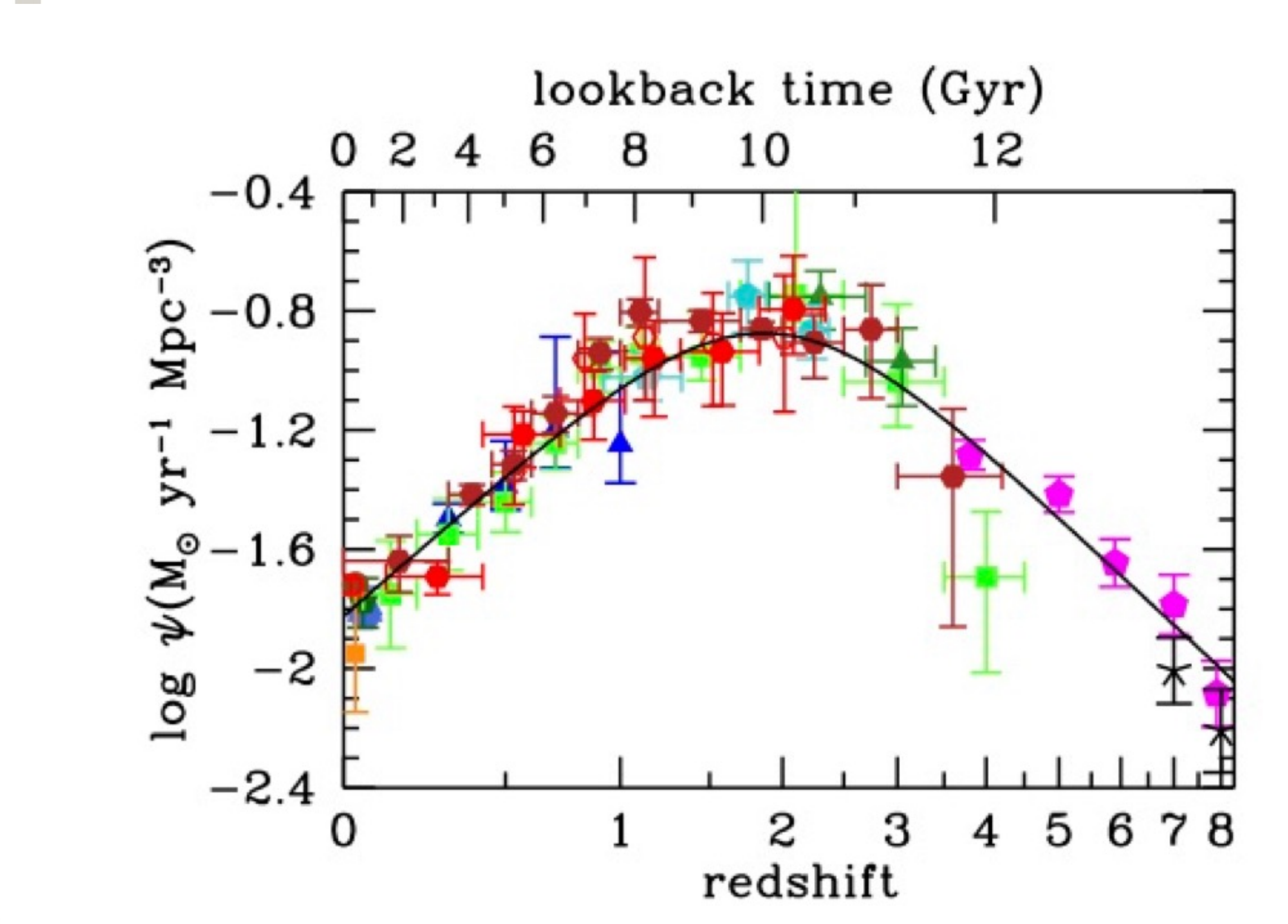


The cosmic history of star formation

Dust Uncorrected



Dust Corrected



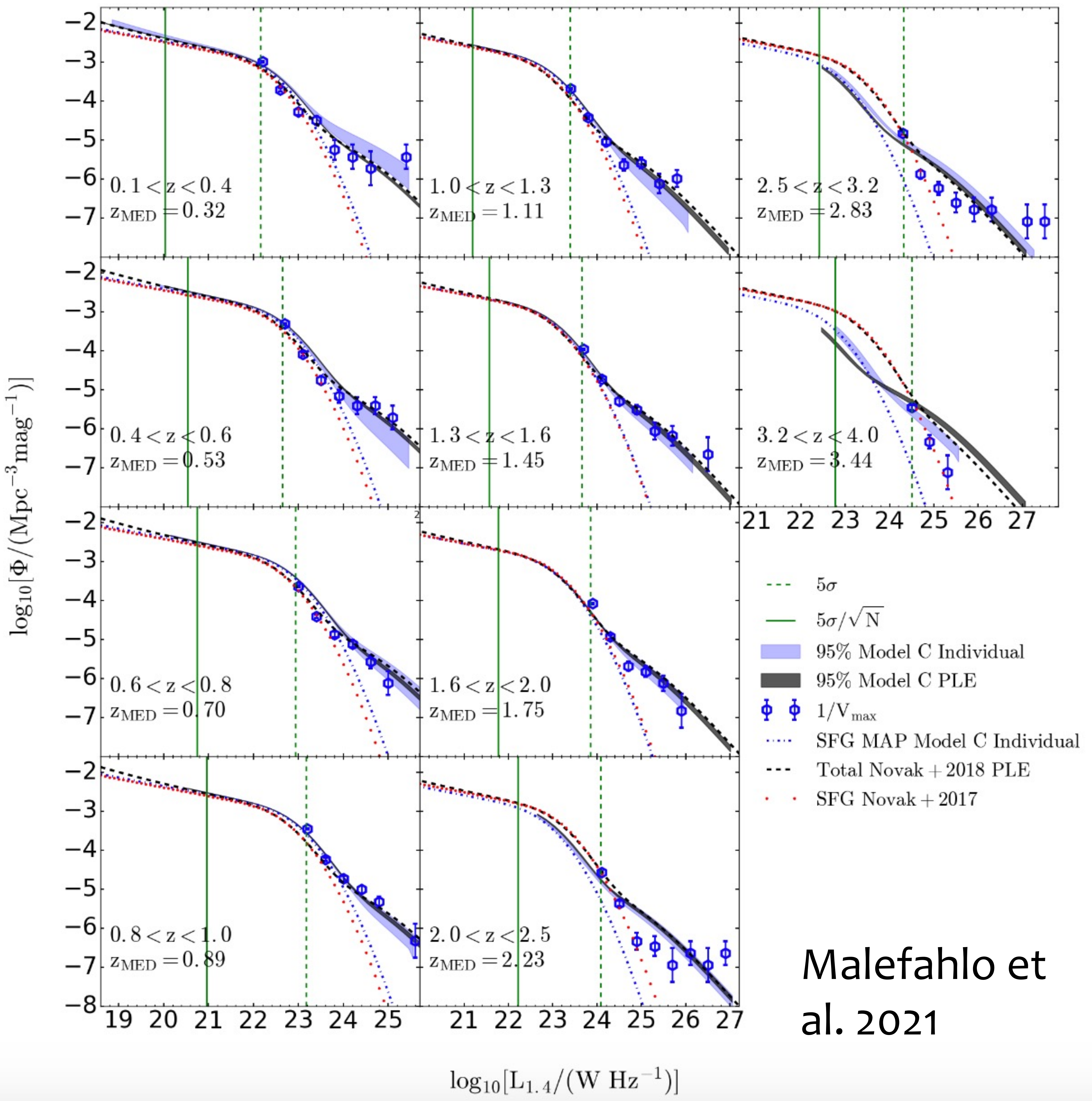
Madau & Dickinson 2014

SFR density uncertain due to dust

Radio continuum observations provide a dust-free probe of SF history to z~4

Given good ancillary data can do this as a function of stellar mass, halo mass and proximity to AGN

The cosmic history of star formation



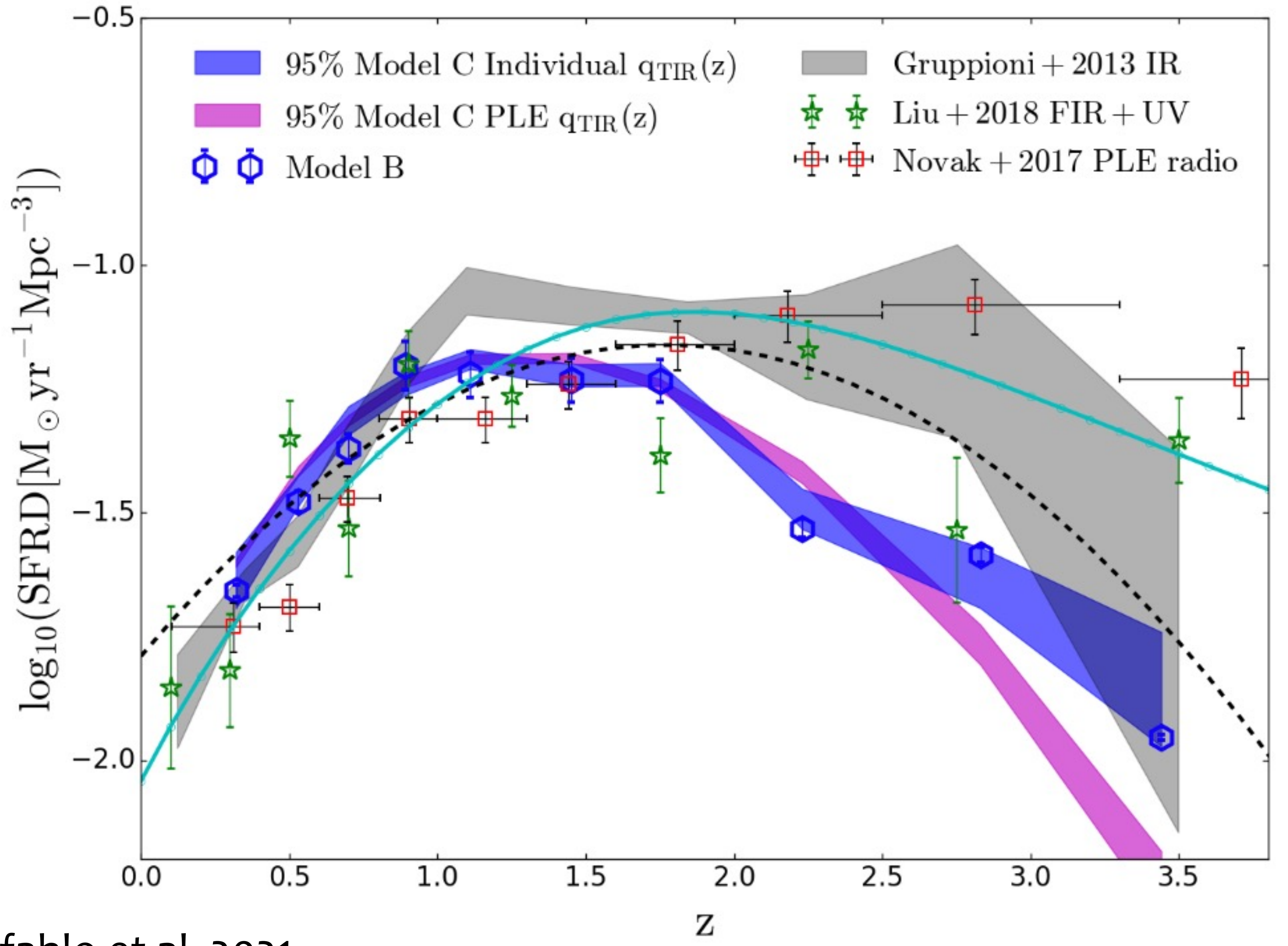
Malefahlo et al. 2021

How do you measure it?

First you have to measure the radio luminosity function across all redshifts

Then integrate under the luminosity function and convert from radio luminosity to star-formation rate

The cosmic history of star formation



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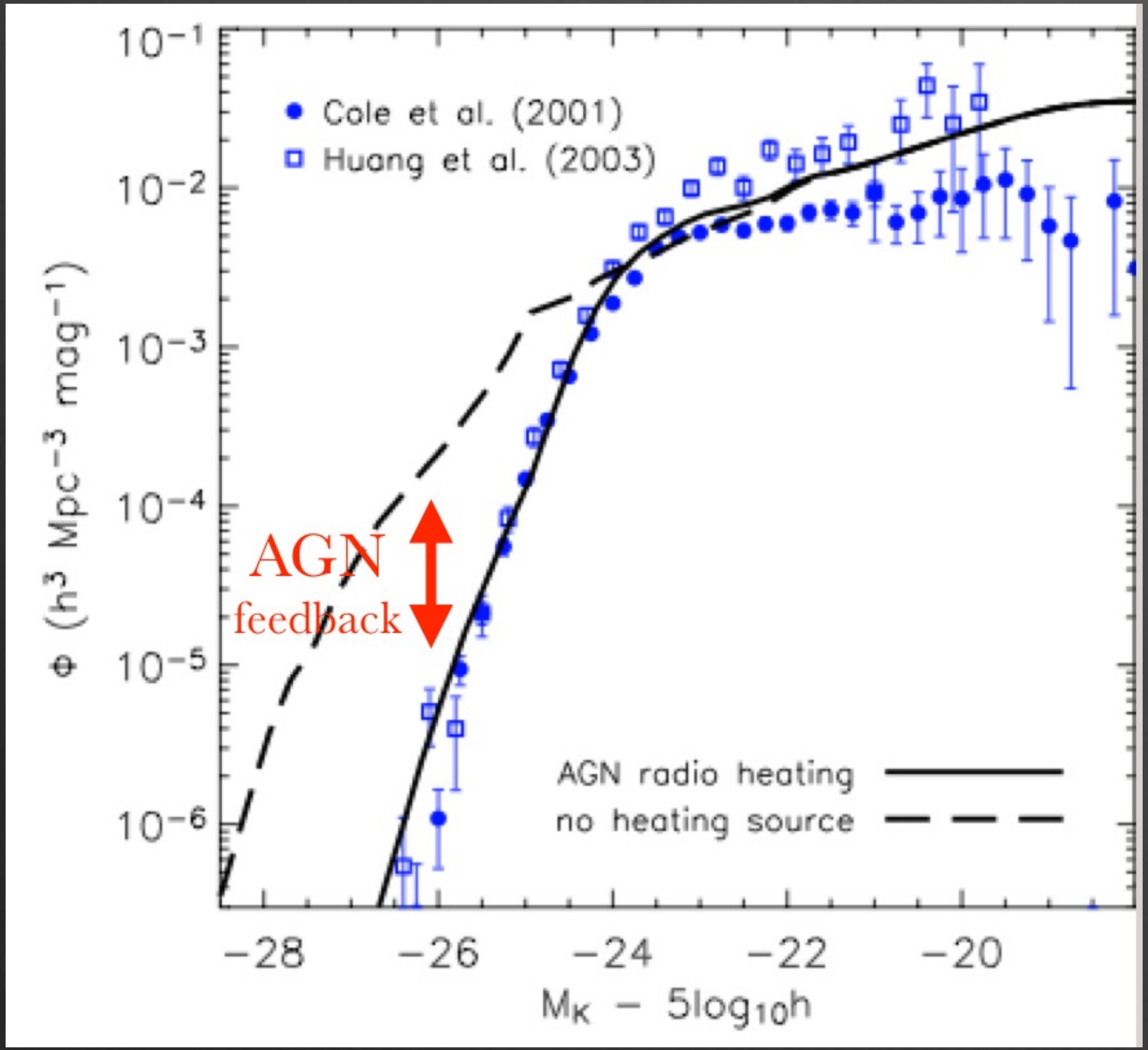
AGN evolution and Feedback



Exponential cut-off at the bright end of the luminosity function

Radio galaxies

Radio galaxy = AGN with significant radio emission

Accretion onto the central supermassive black hole powers jets of relativistic electrons.

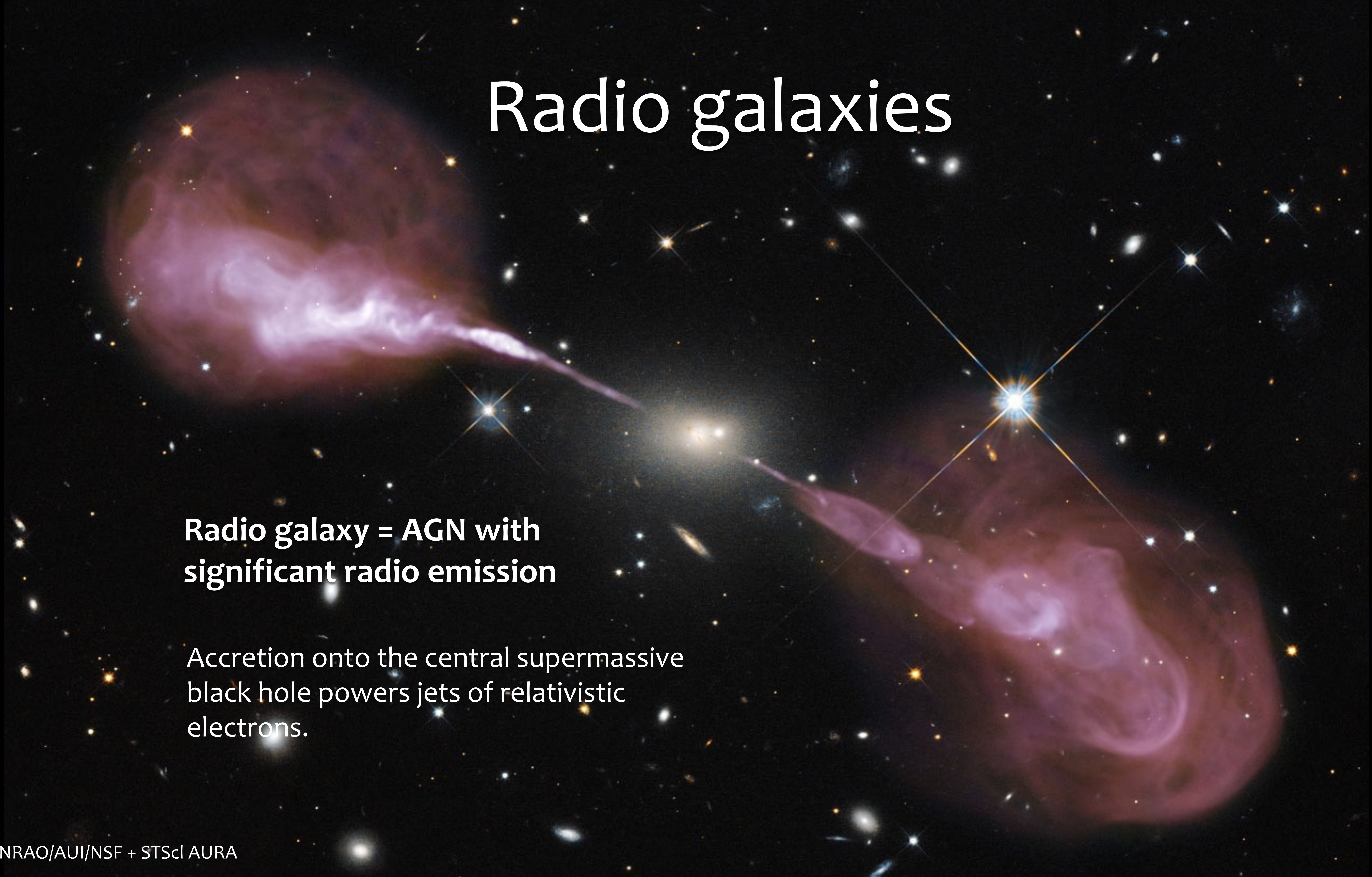
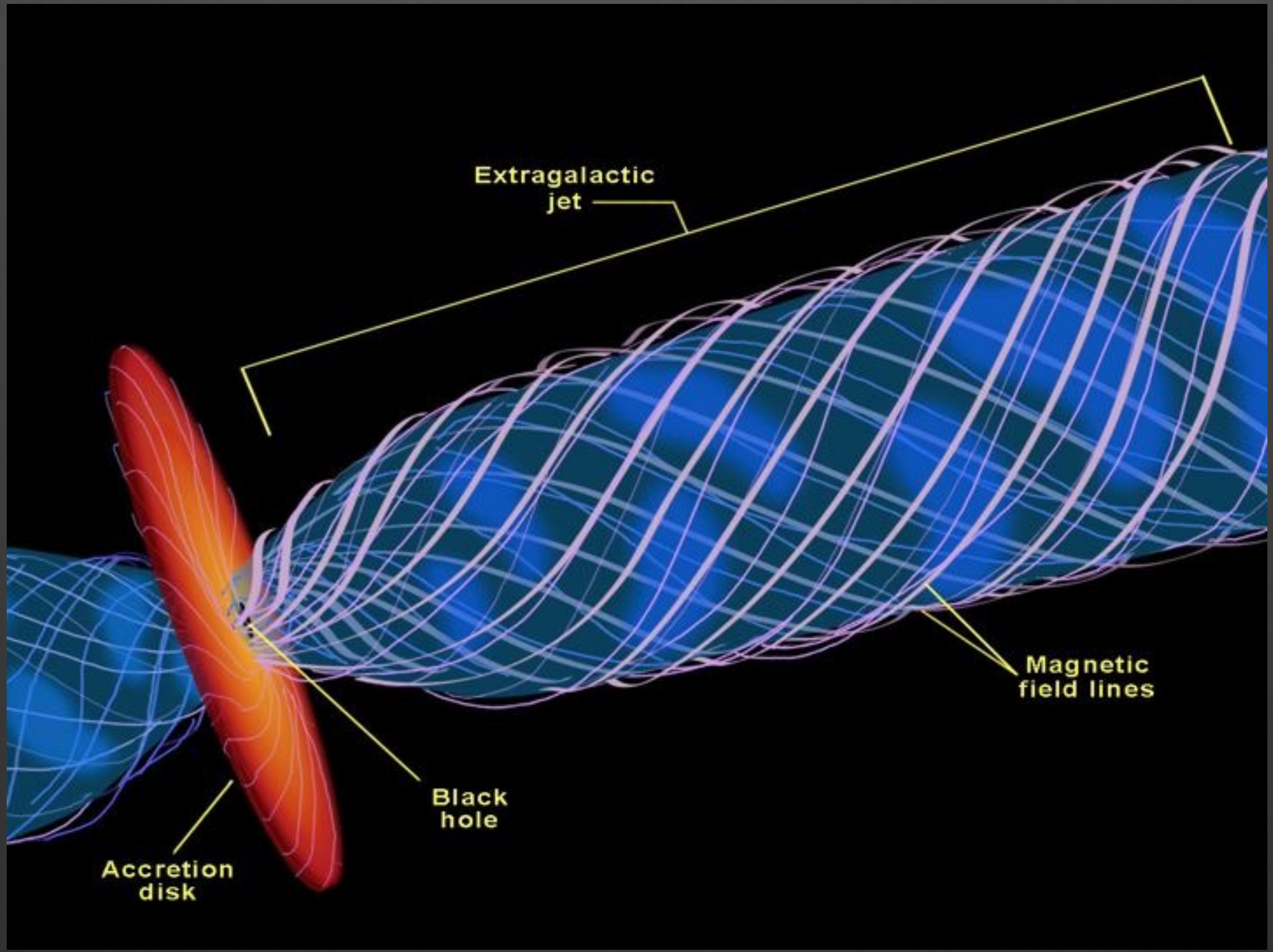


Image: NRAO/AUI/NSF + STScl AURA

Radio galaxy jets



Credit: SRON Netherlands Institute for Space Research

Why are radio galaxies important?

- ★ Radio galaxies perform a key role in galaxy evolution, regulating star-formation in massive galaxies.
- ★ Mechanisms are not well understood.

Image: South African Radio Astronomy Observatory (SARAO)

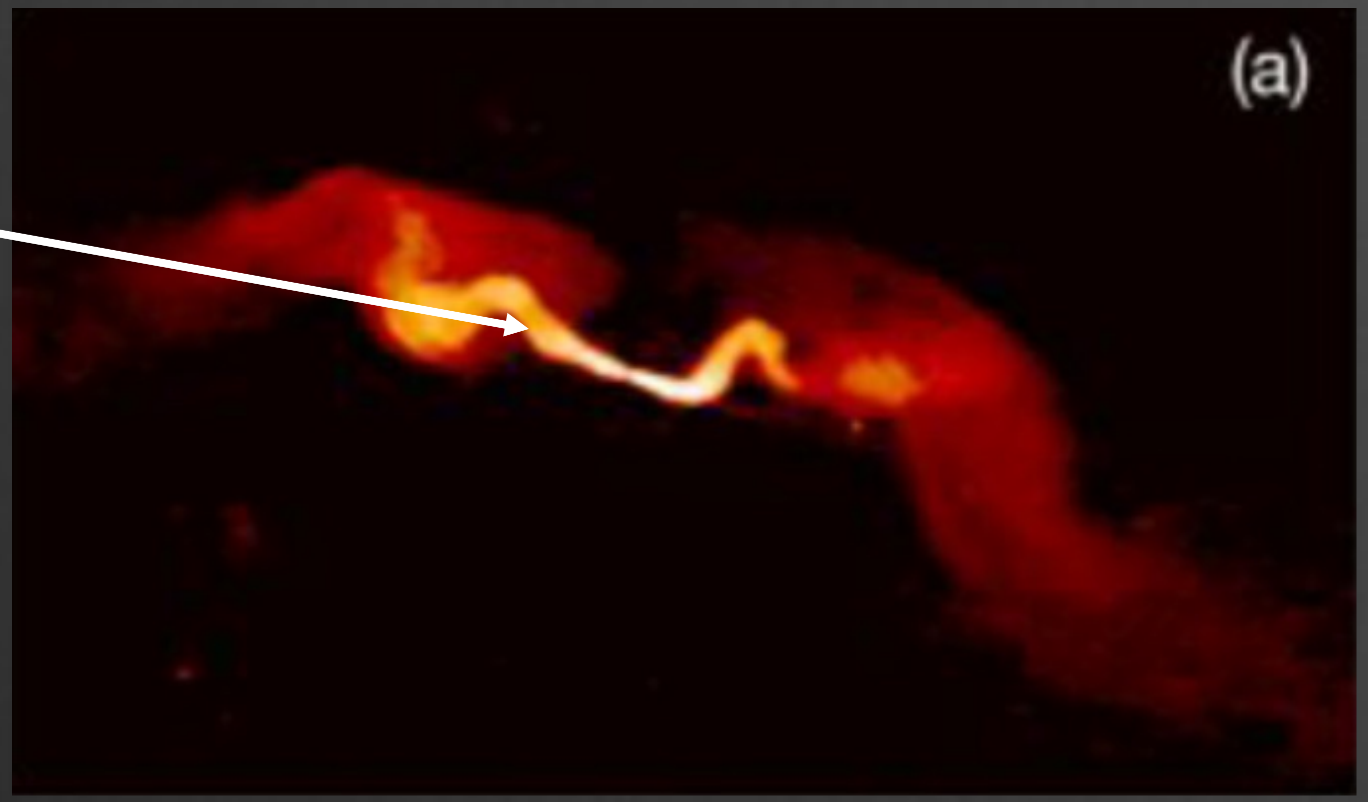
Fanaroff & Riley (1974)

Types of radio galaxy

Fanaroff and Riley classes - morphological classification

FRI

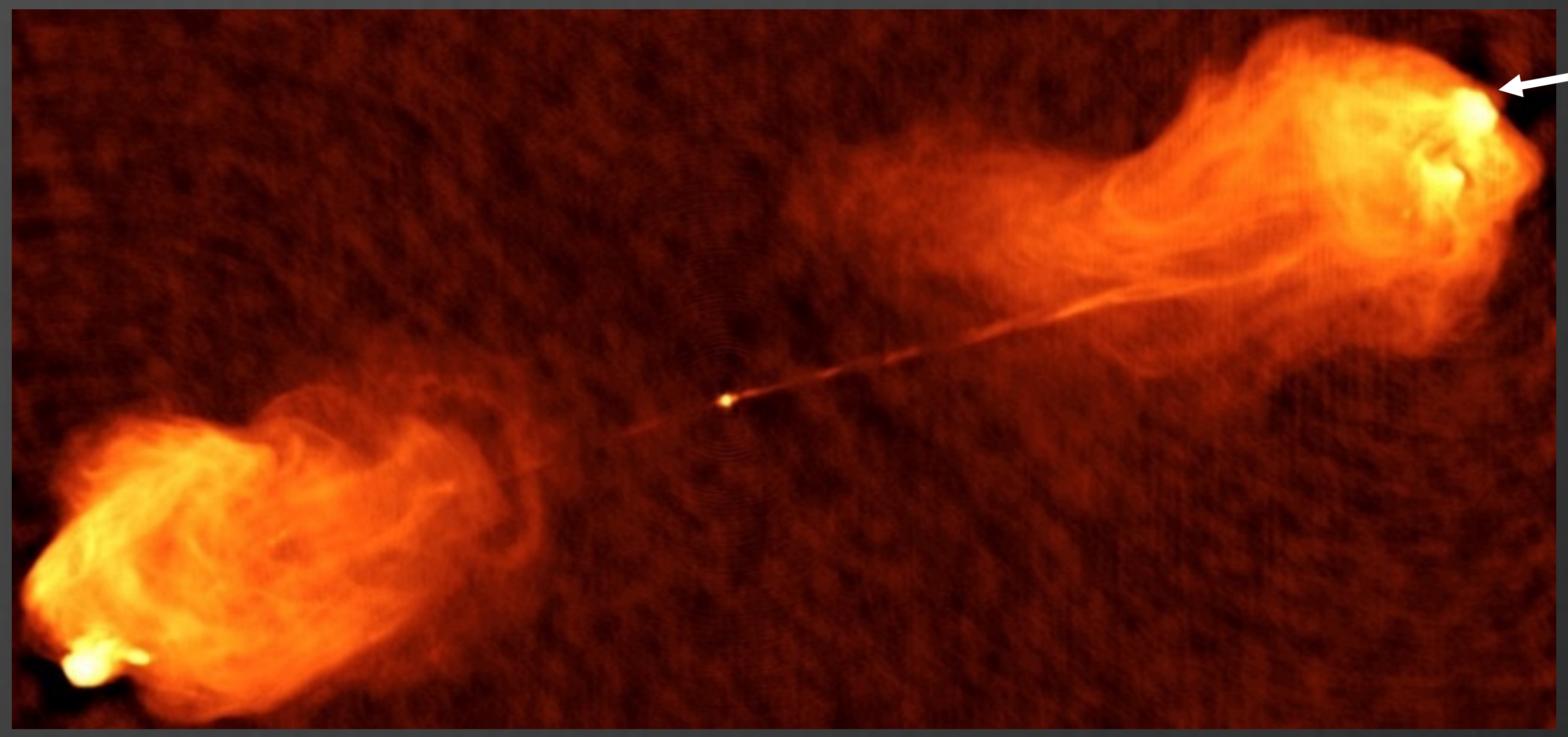
Brightest emission near the centre.



Lower radio power

$L_{1.4\ \mathrm{GHz}} < 10^{24.5}$ W / Hz

FRII



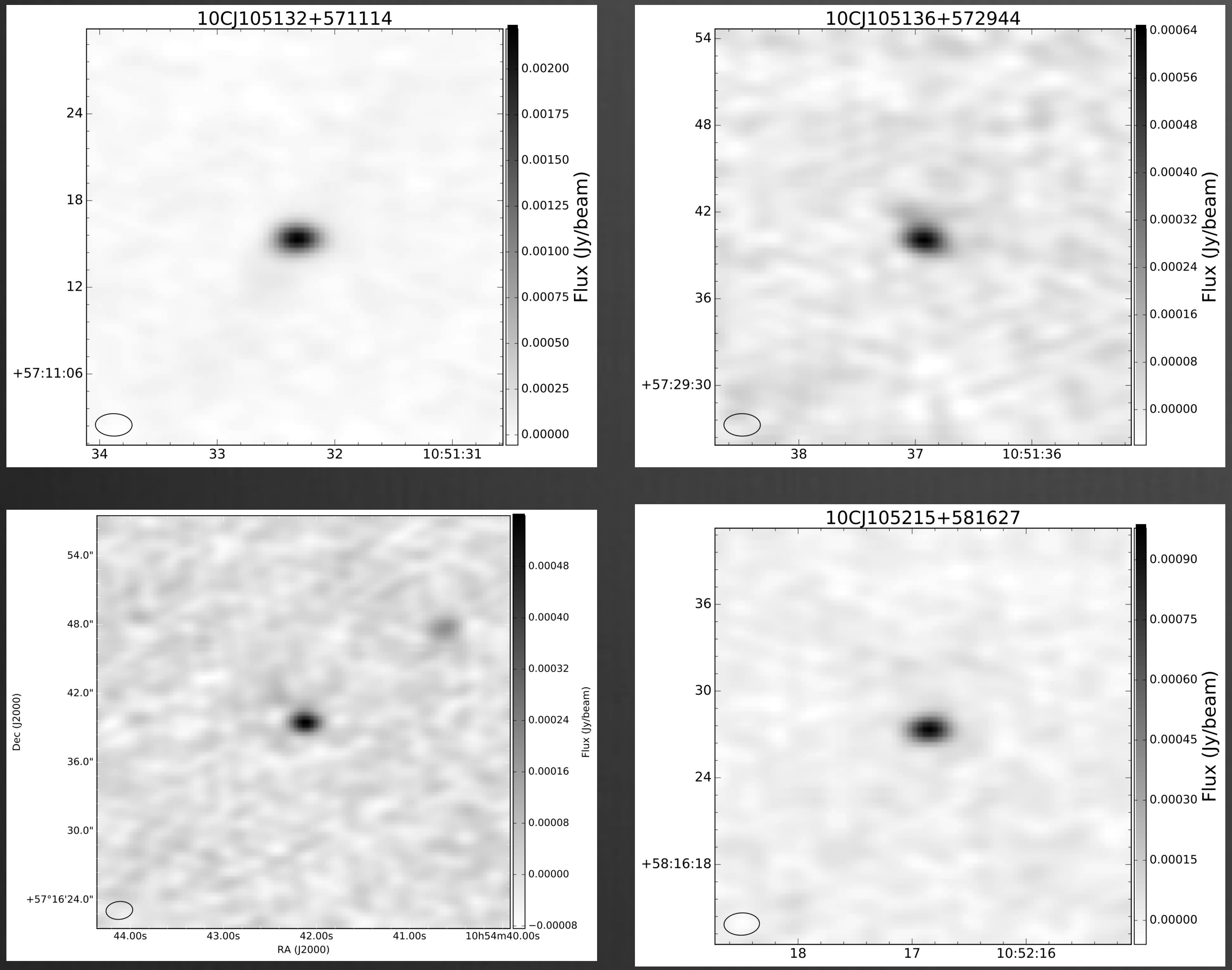
Hotspots at edge of lobes

Higher radio power

$L_{1.4\ \mathrm{GHz}} > 10^{24.5}$ W / Hz

Images: NRAO/AUI

Compact radio galaxies

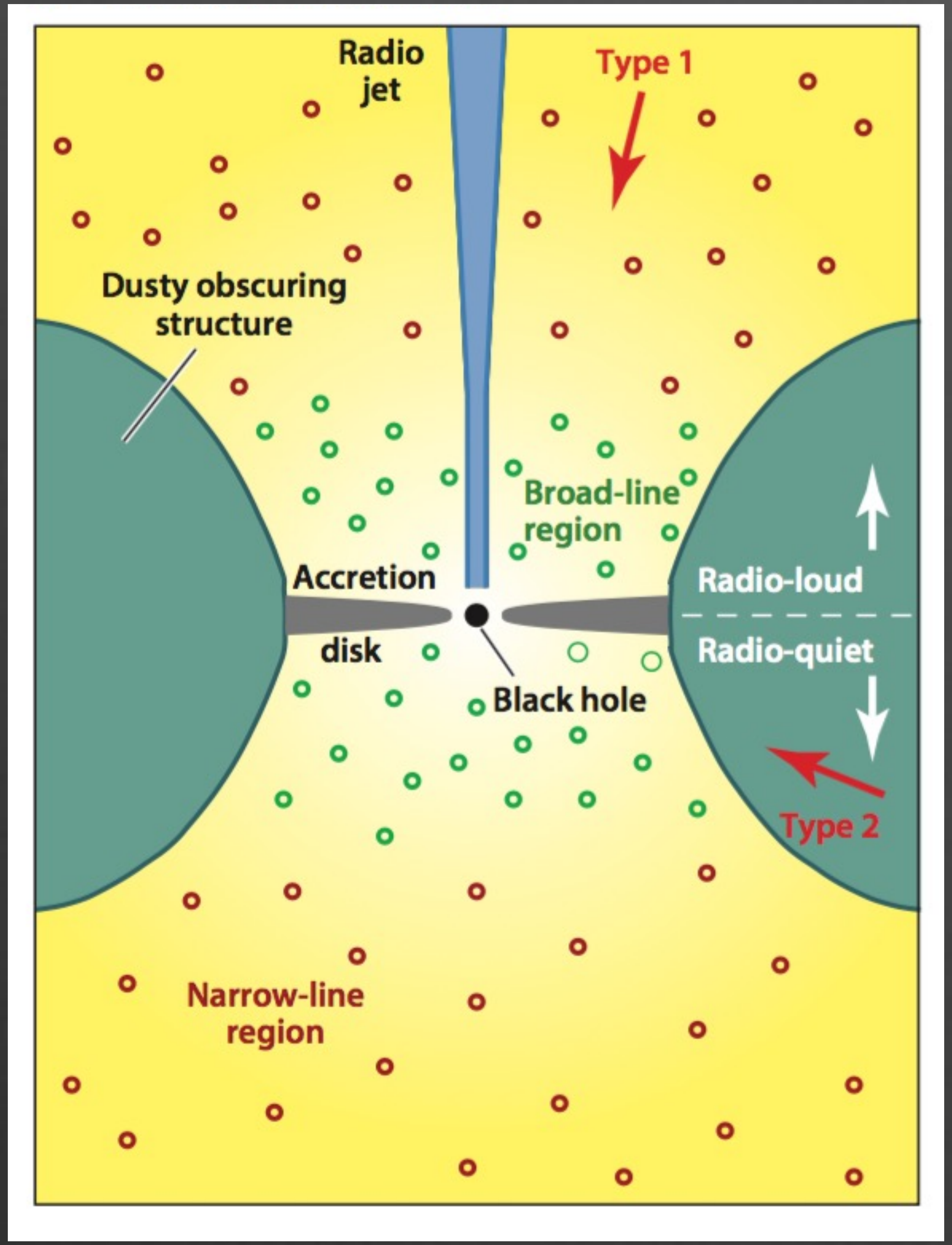


Whittam et al. (2020)

★ Majority of radio galaxies are actually compact.
(Baldi et al. 2015, Sadler et al. 2014, Whittam et al. 2013).

★ Mixed population - far too numerous to all be young radio galaxies.

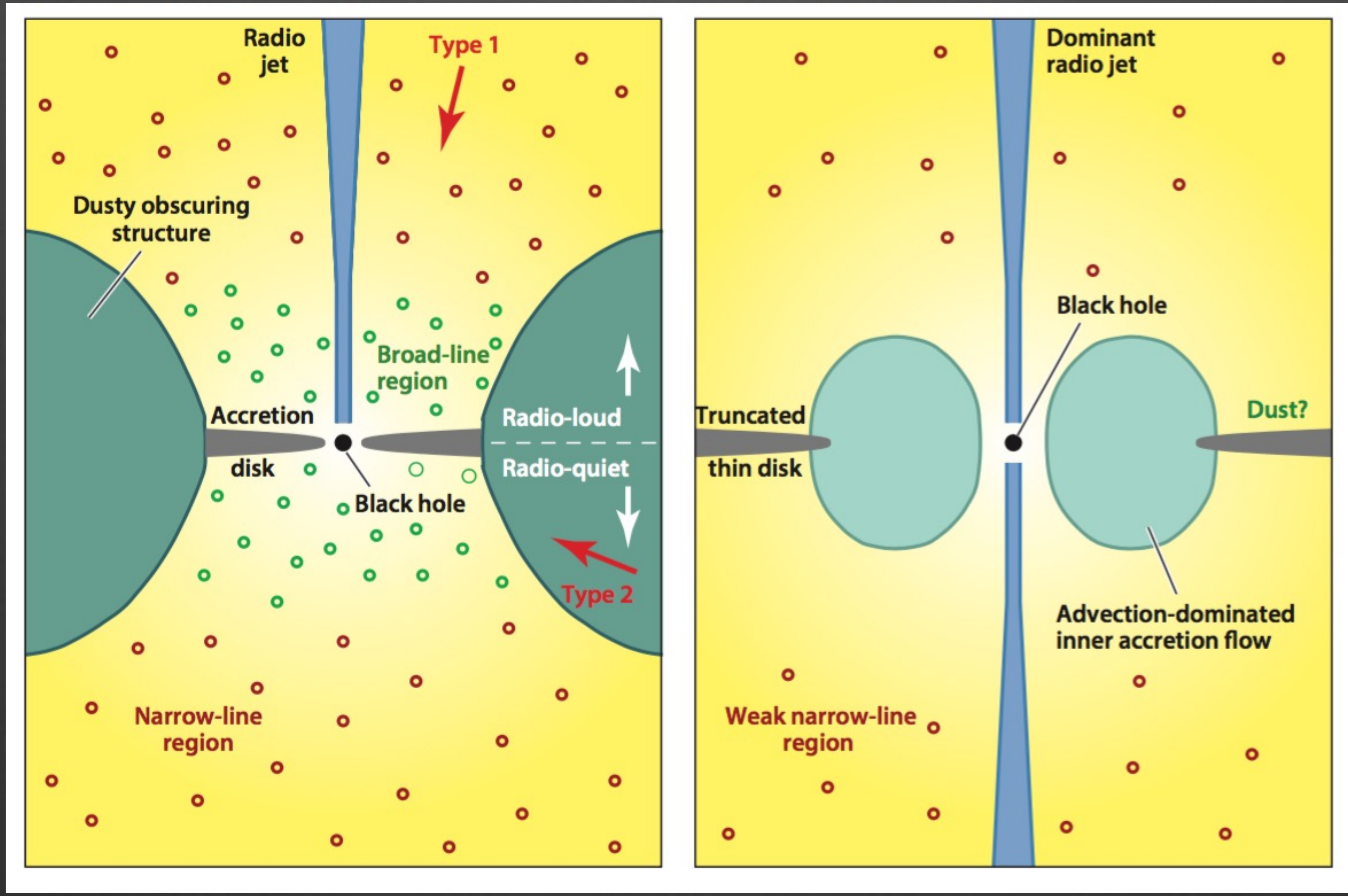
Radio galaxy accretion modes



Heckman & Best (2014)

High Excitation Radio Galaxies/ cold mode/ quasar mode/ radiative mode/ radiatively efficient

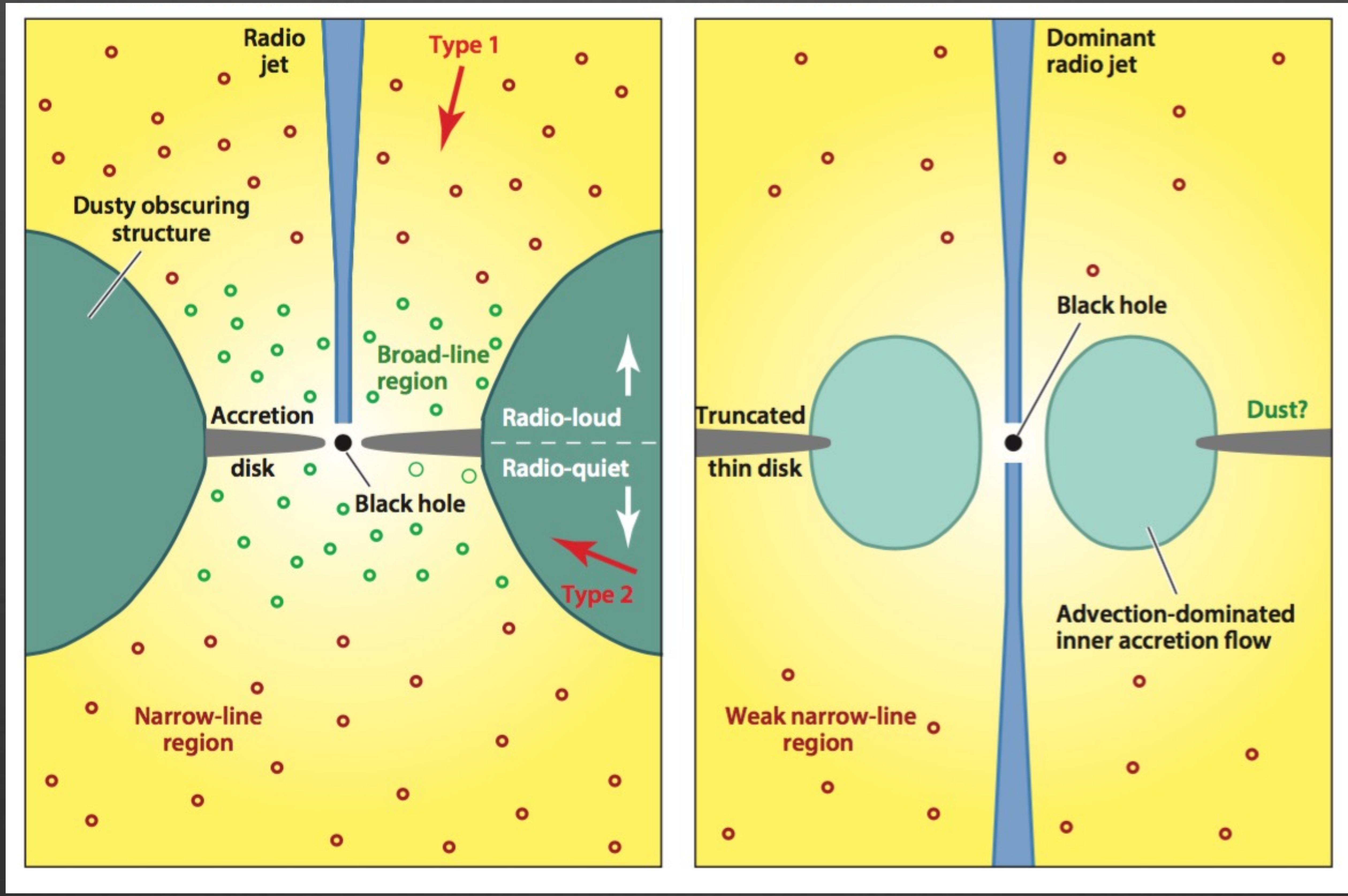
Low Excitation Radio Galaxies/ hot mode/ radio mode / jet mode / radiatively inefficient



Heckman & Best (2014)

See Best et al. (2005), Hardcastle et al. (2007),
Best & Heckman (2012), Whittam et al. (2016),
Whittam et al. (2018),
Hardcastle & Croston (2020).

HERG | LERG



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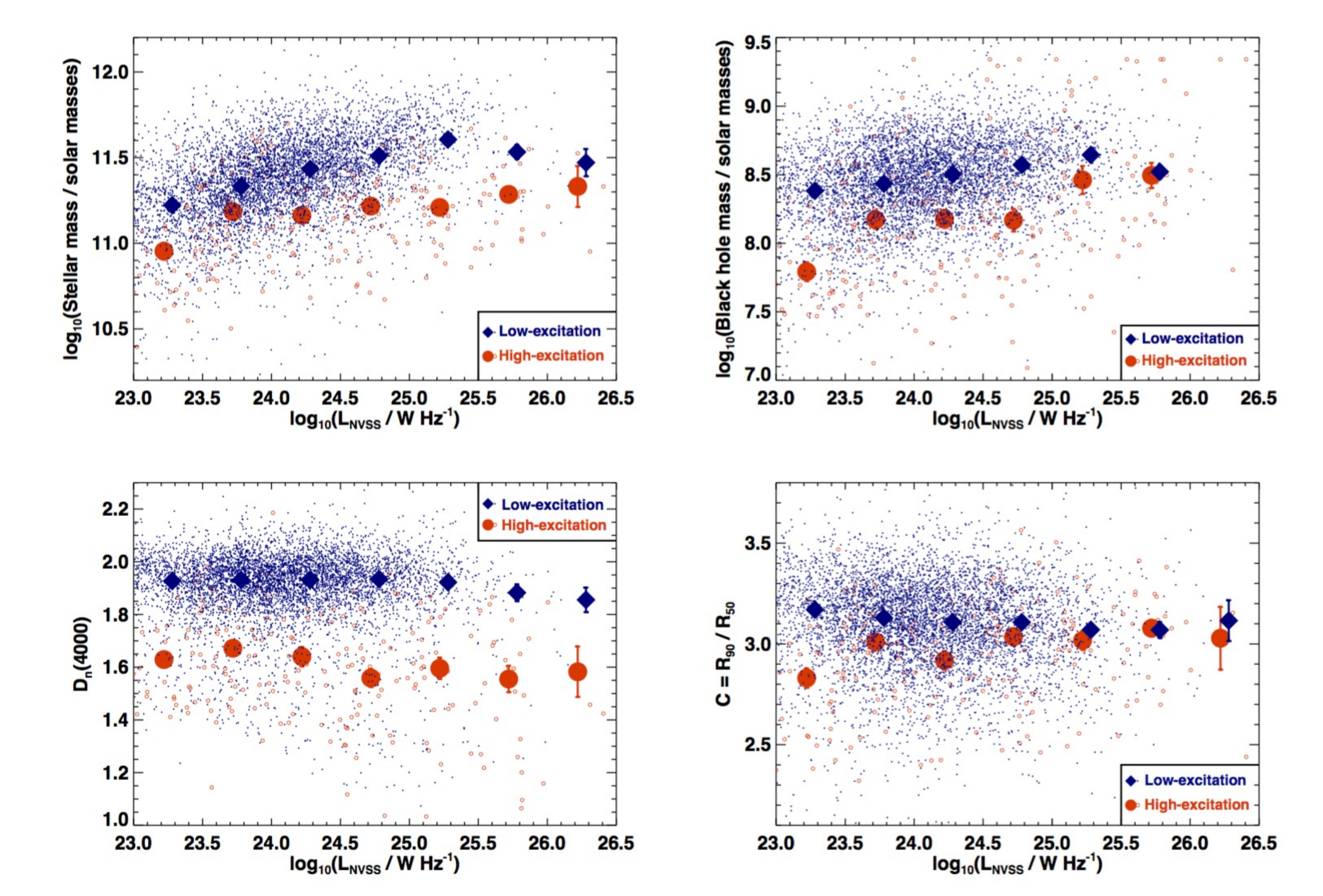
Host galaxies



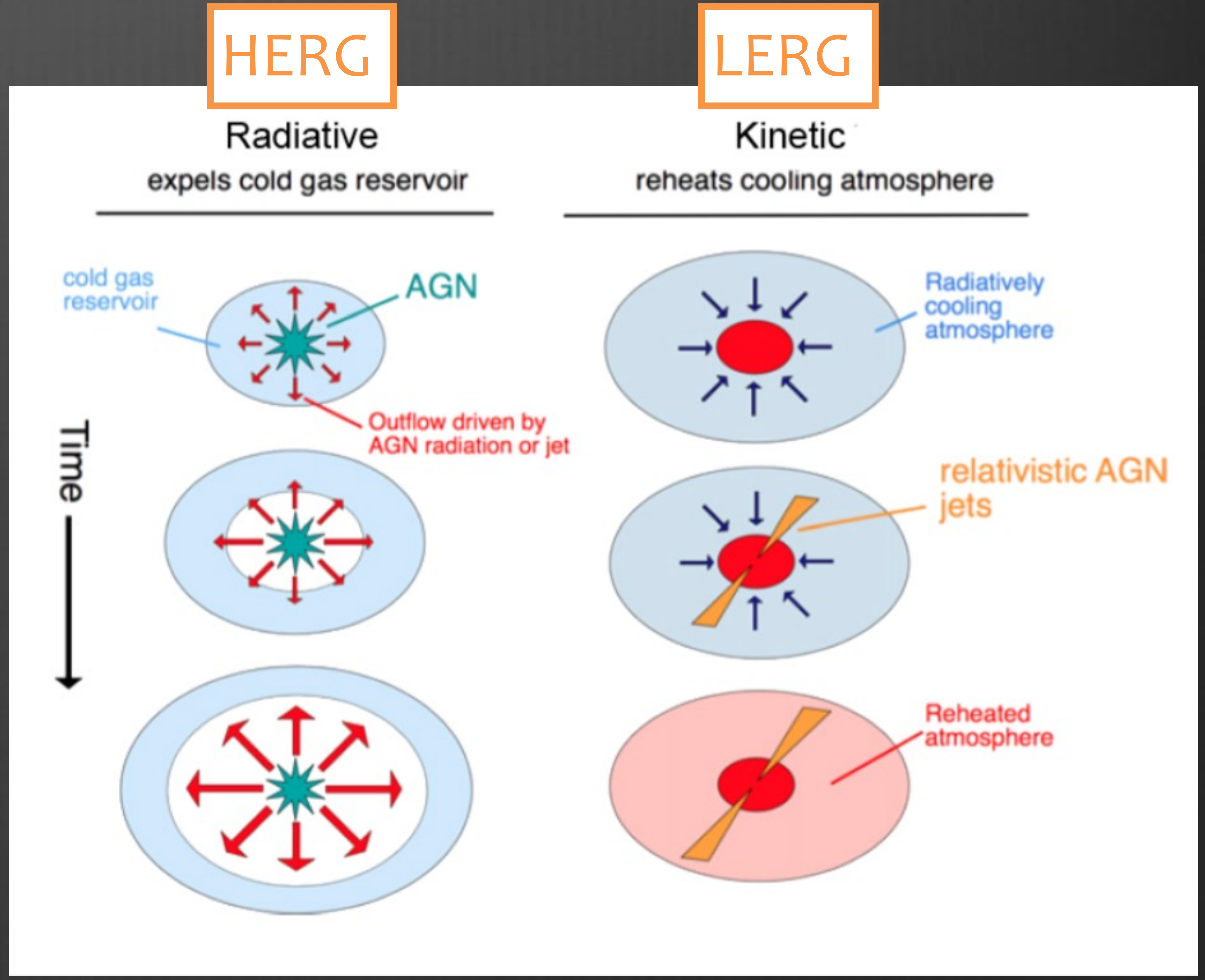
HERG hosts are less massive, younger and more concentrated.

Best and Heckman (2012)

How does AGN activity affect galaxy evolution?

★ AGN feedback is a key component of hydro sims - required to quench SF in massive galaxies.

★ Some sims (Horizon-AGN, Illustris) implement quasar and radio mode feedback separately, others (EAGLE, MUFASA) do not.



Alexander and Hickox (2010)

Un-answered questions

- ★ How does radio activity relate to host galaxy properties? (star-formation rate, type…)
- ★ Is there a dichotomy between HERGs and LERGs?
- ★ How do radio structures evolve?
- ★ What happens when a jet turns off?
- ★ Why do some radio galaxies not produce powerful jets?
- ★ How does environment influence this?
- ★ How does all of this depend on radio power, redshift...?

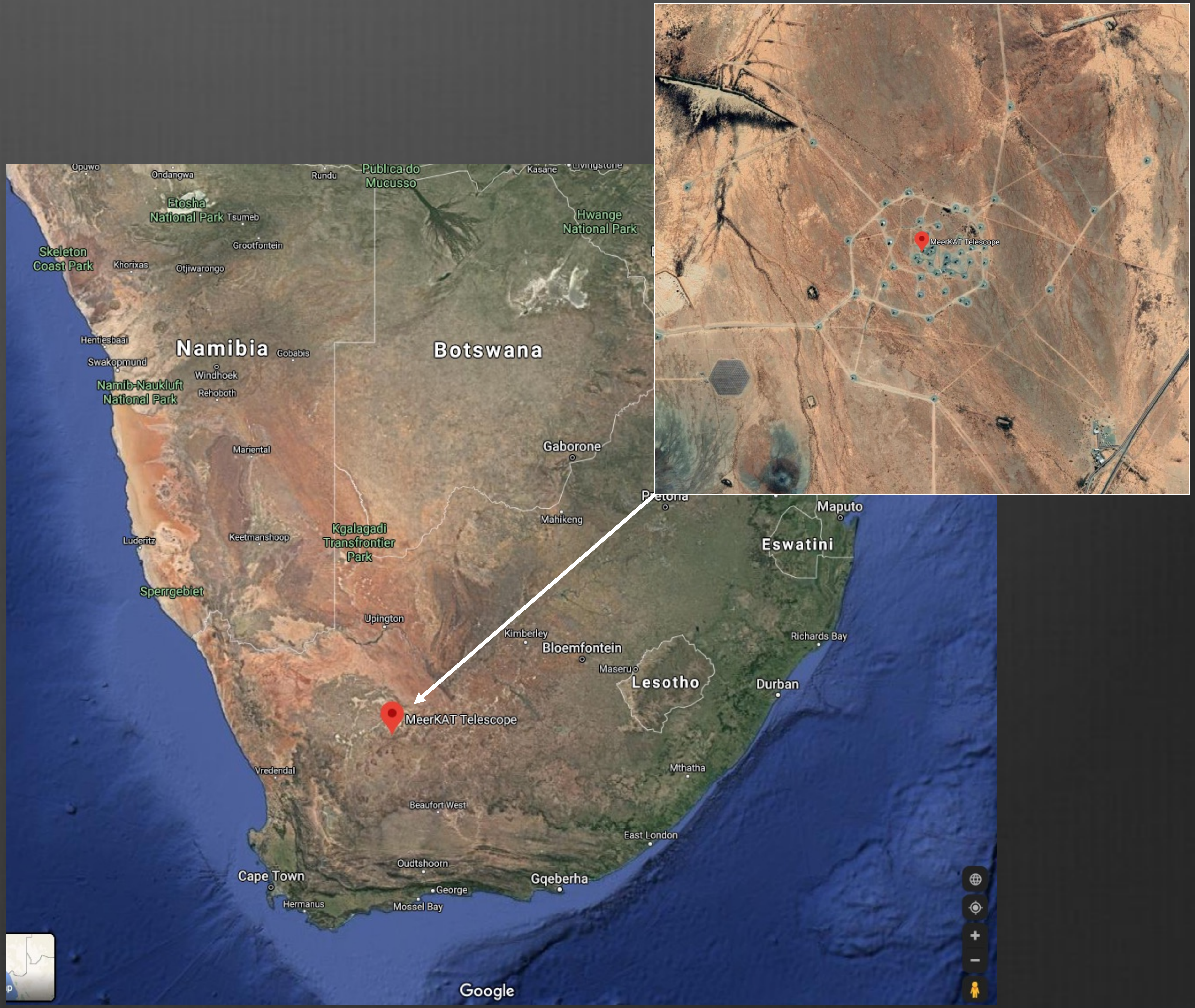
The MeerKAT telescope

- ★ World-leading radio telescope in the Northern Cape, RSA.
- ★ Consists of 64 dishes, each 13.5m across.
- ★ Max baseline = 8km
- ★ Operates from 850 - 3500 MHz. (UHF, L and S bands).
- ★ Precursor for Square Kilometre Array (SKA).

National Research Foundation
SARAO South African Radio Astronomy Observatory

Why the Karoo?

- ★ Away from people (= sources of RFI!)
- ★ Dry and lots of space.



MeerKAT

South African Radio Astronomy Observatory (SARAO)

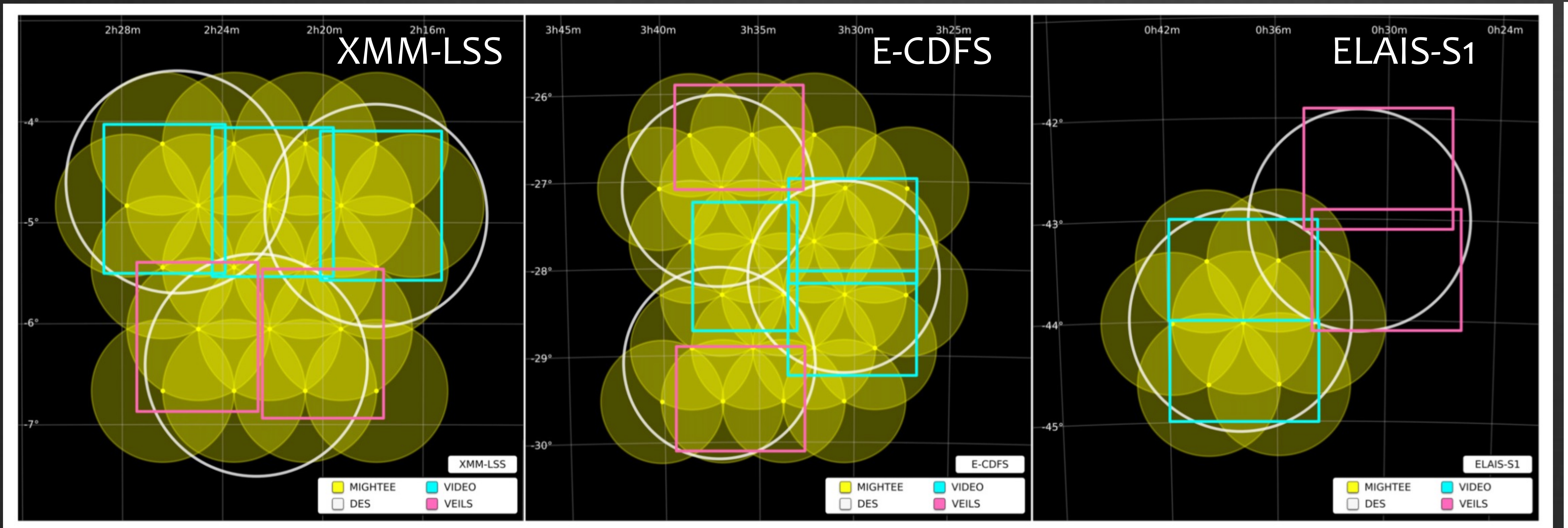
MeerKAT

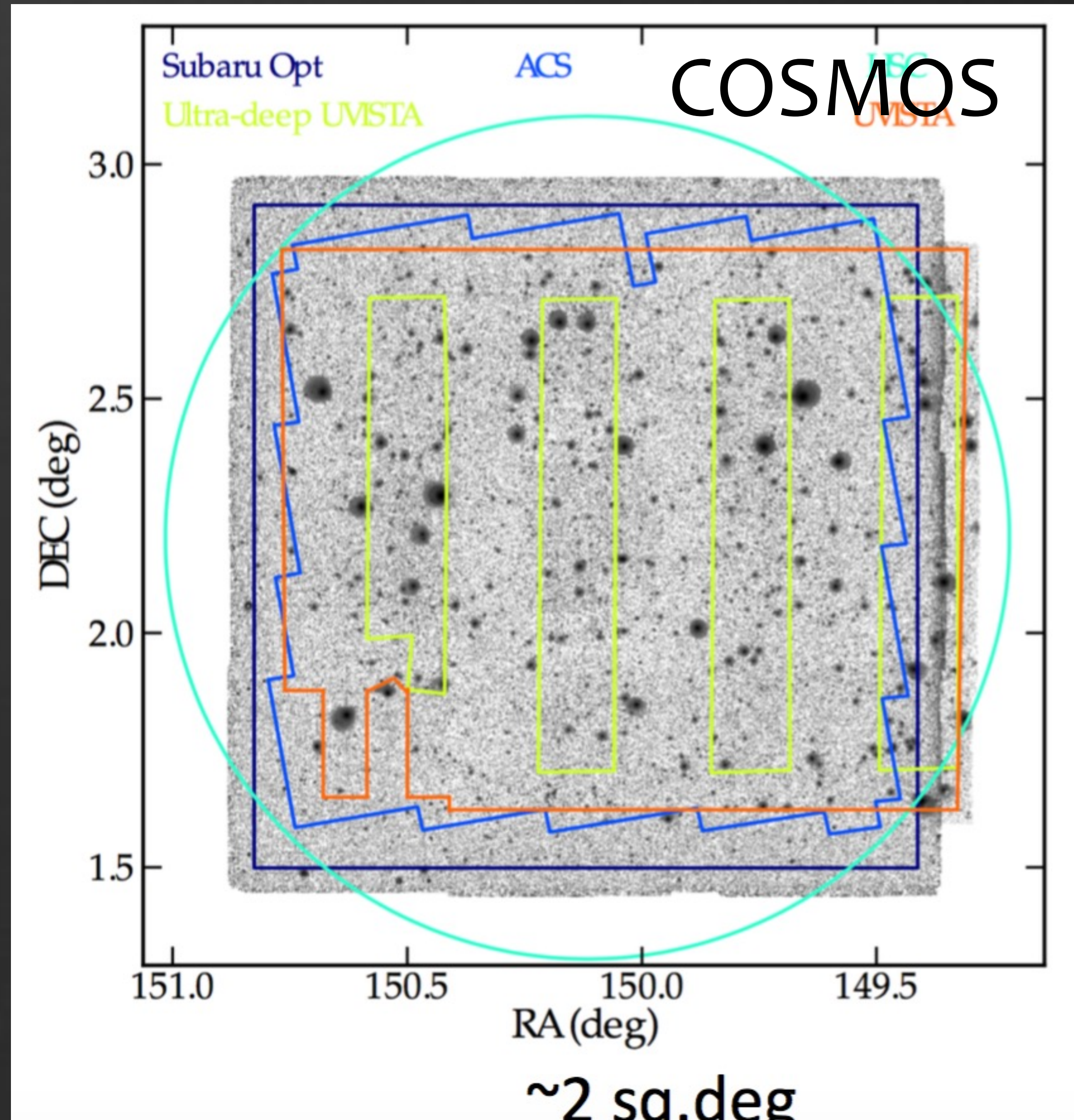
Image: South African Radio Astronomy Observatory (SARAO)

The MIGHTEE survey

- ★ Extragalactic radio survey with MeerKAT (one of 8 approved large survey projects).
- ★ Covers 20 deg^2 in 4 different fields.
- ★ L-band (900-1600 MHz), reaching ~1 μJy/beam rms.
- ★ ~2000 hours of observing time.

PIs: Matt Jarvis and Russ Taylor
Jarvis et al. arxiv.1709.01901

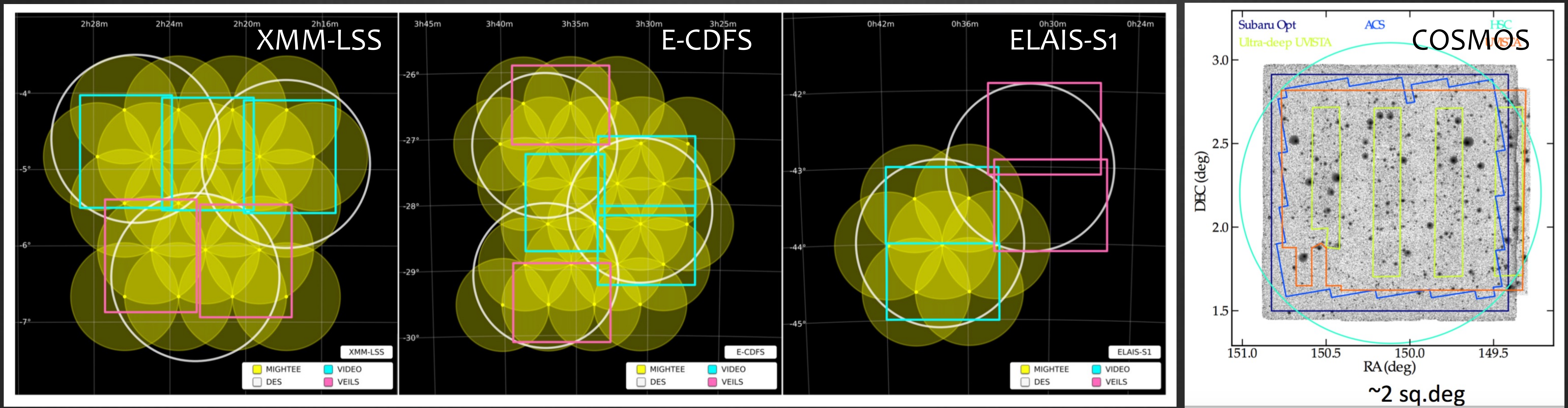




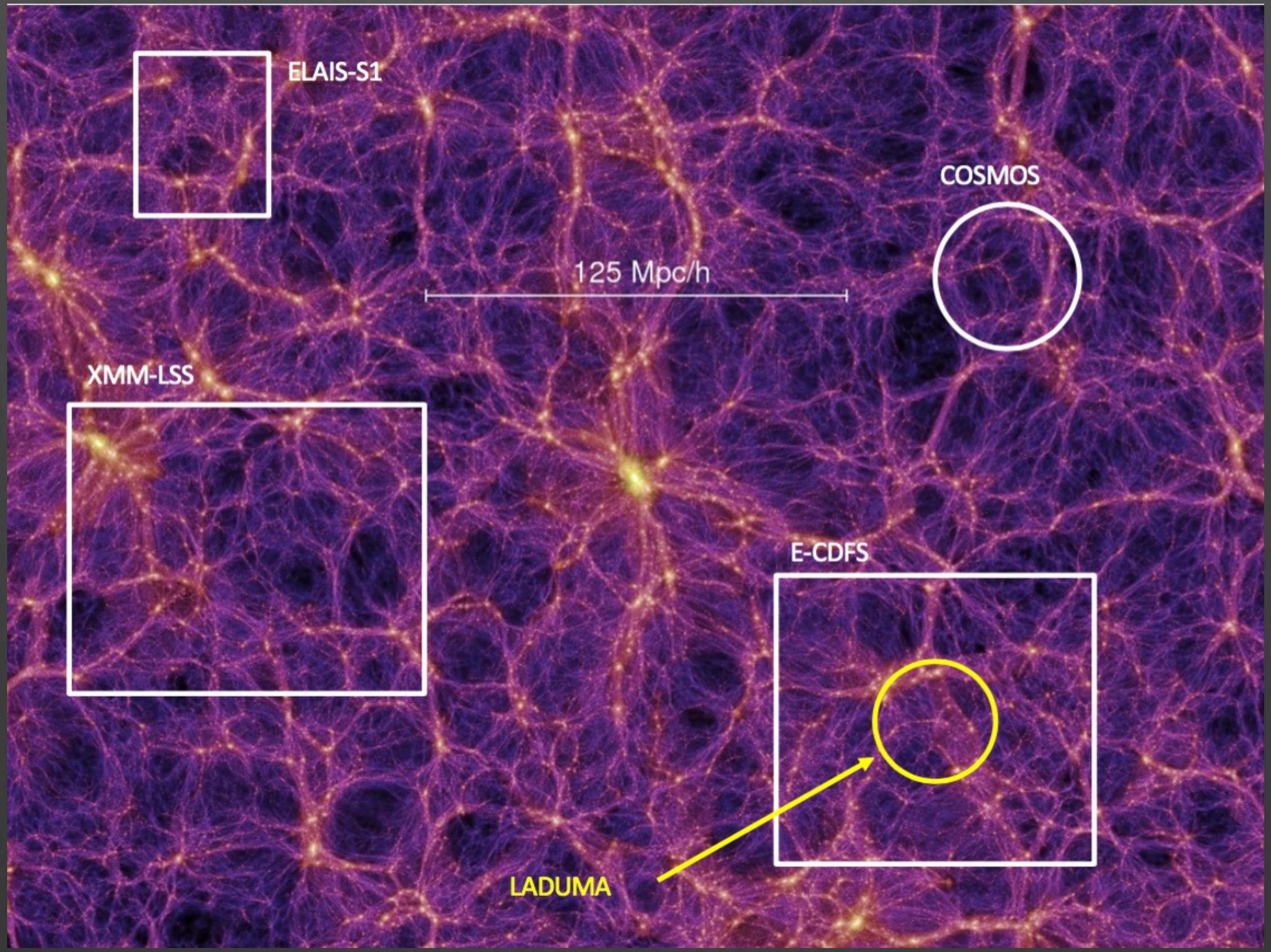
The MIGHTEE survey

★ There are three main data products:

1. Continuum images
2. Spectral line cubes – HI emission and absorption
3. Polarisation



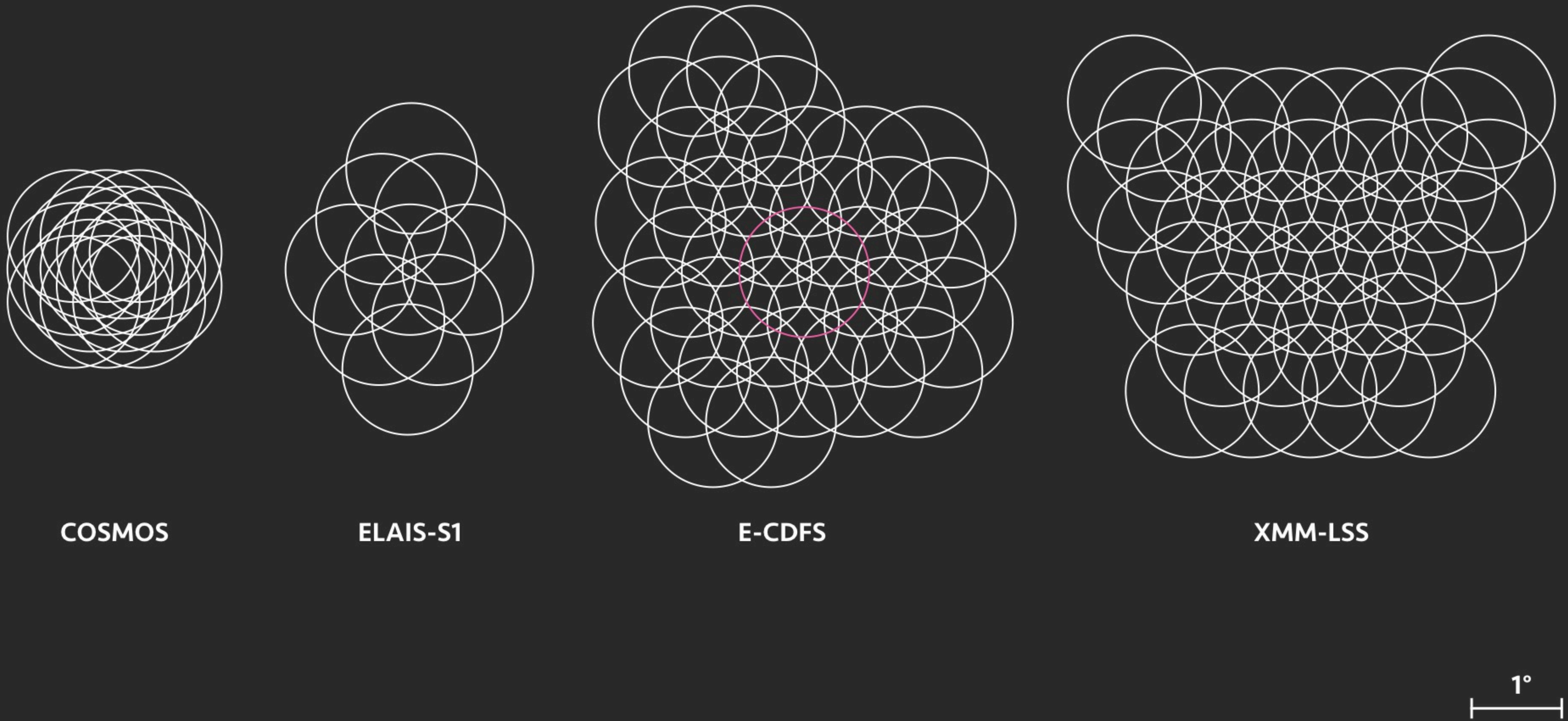
Why is MIGHTEE mighty?



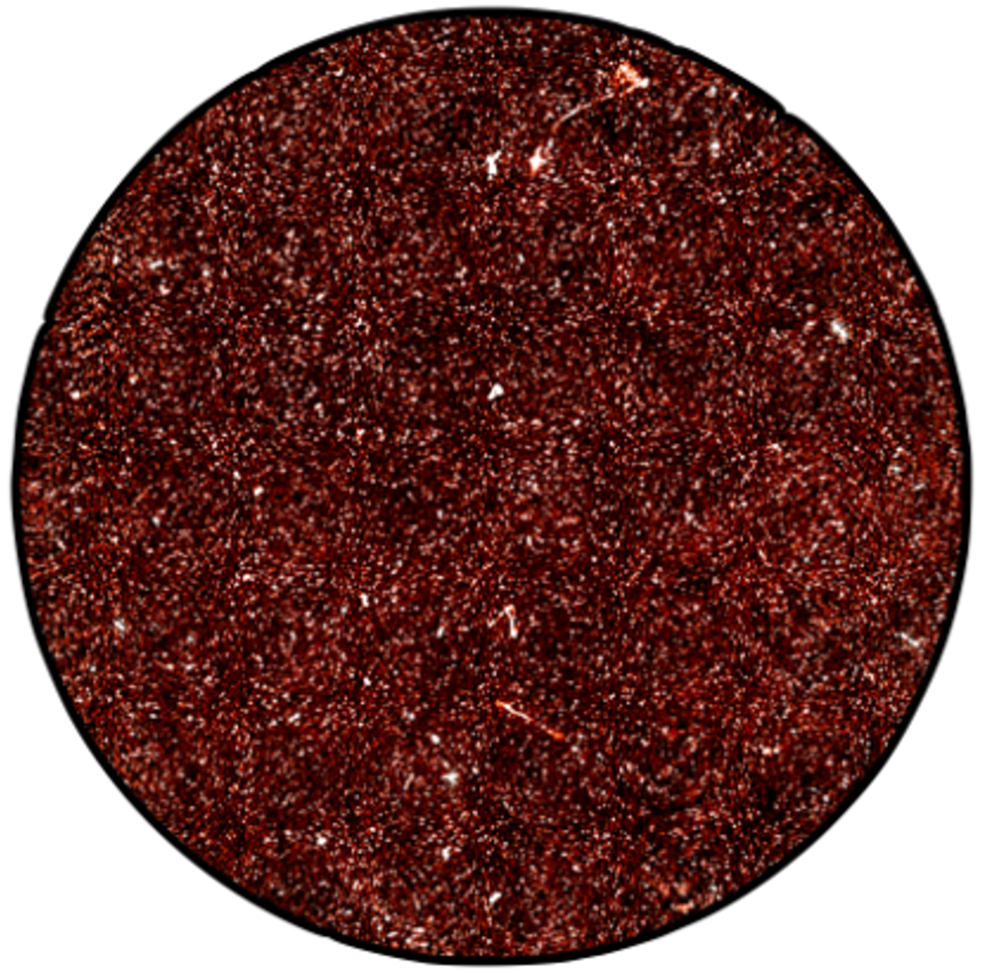
- ★ Unique combination of depth and area.
- ★ Excellent multi-wavelength data.

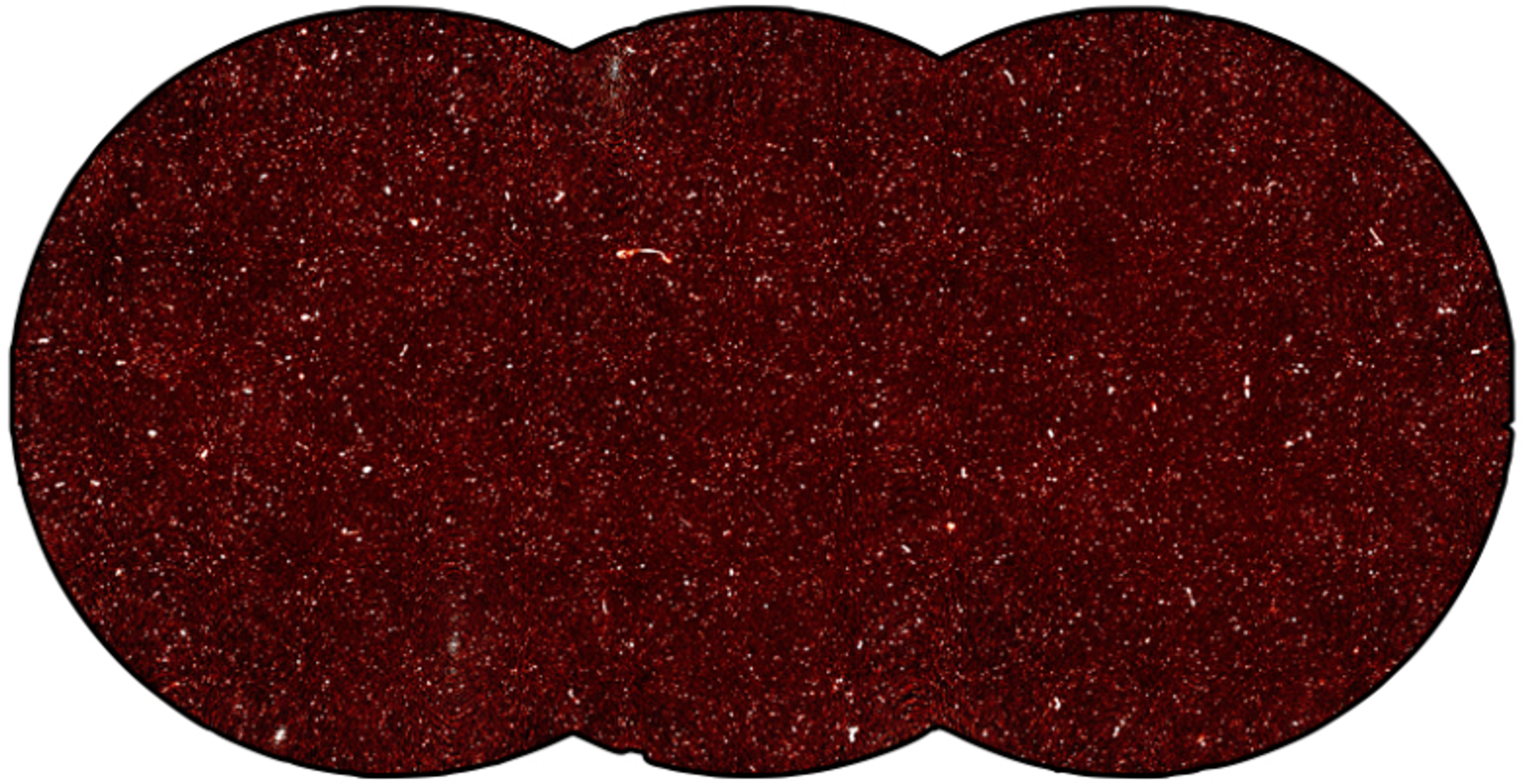
MIGHTEE observations are underway

- ★ Observations and data processing in progress (lead by Ian Heywood).
- ★ The total observing time to date is ~420 hours out of a total allocated ~2000 hours.
- ★ Science-ready images in COSMOS and XMM-LSS.
- ★ Early science underway.


COSMOS
ELAIS-S1
E-CDFS
XMM-LSS
1°

Early Science Data (now public – see Heywood et al. 2021)





COSMOS
19.5 h / 1.6 deg^2

XMM-LSS
37 h / 3.5 deg^2

Continuum Early Science data

Data processed soon to be released to the collaboration

COSMOS
140 h / 4.3 deg²

XMM-LSS
300 h / 14.4 deg²

Full survey data


CDFS (ultra)deep (MIGHTEE / LADUMA)
63.4 hours, single pointing centre, ten tracks, L-band
Traditional direction-independent selfcal (2GC)
Performance is limited by sidelobes from PKS 0326-288 and DDEs around brighter sources


CDFS (ultra)deep (MIGHTEE / LADUMA)
63.4 hours, single pointing centre, ten tracks, L-band
PKS 0326−288 peeled, followed by facet-based DDE corrections (3GC)
Noise is improved by 20%, thermal is 0.8 μJy / beam, further improvements pending

How can MIGHTEE help us understand radio galaxies?

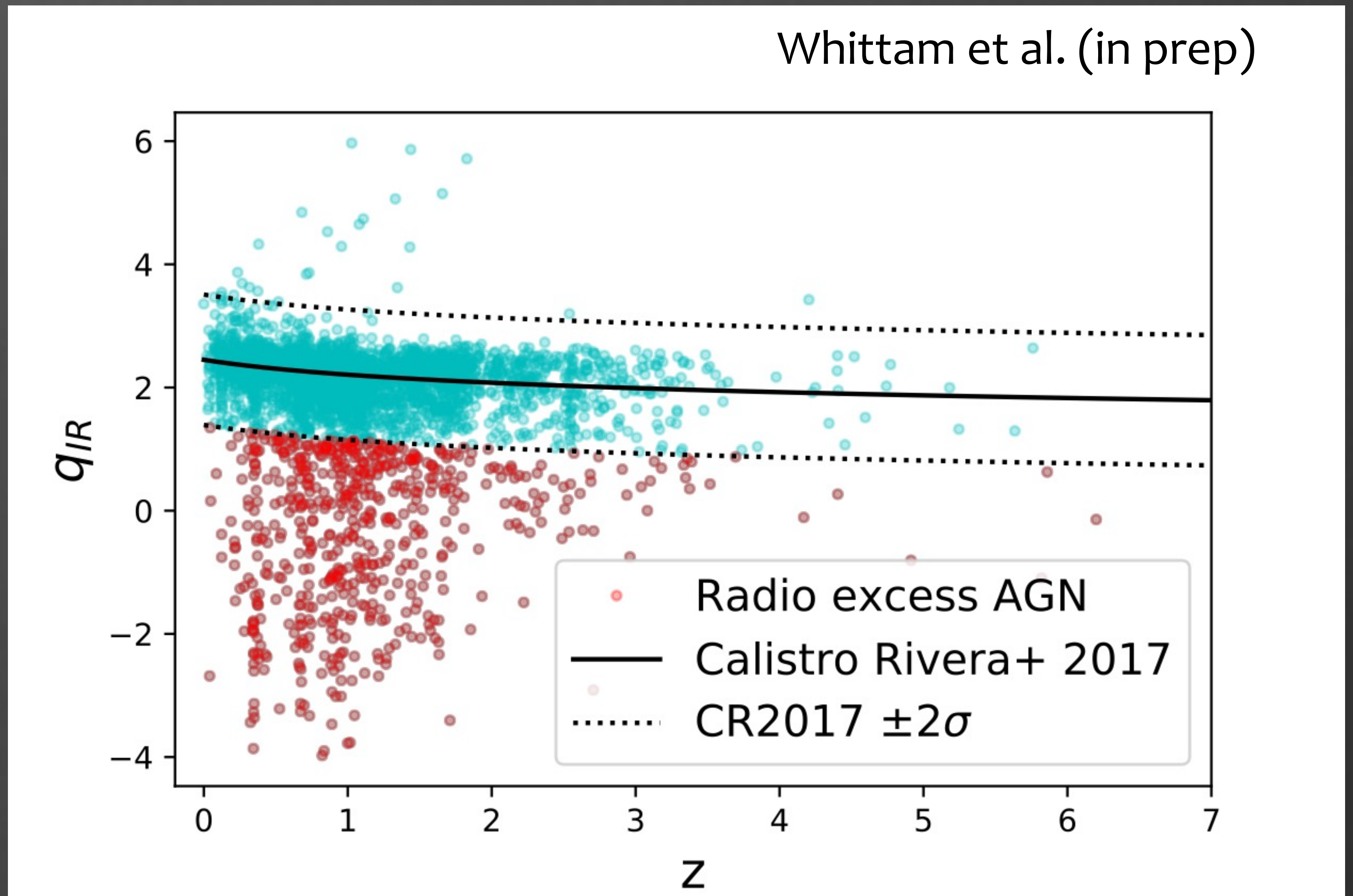
- ★ Detect a large number of radio galaxies out to z~6 – statistical studies.
- ★ Cover a wide range of radio powers ($10^{20} < L_{1.4\ GHz}$ / W $Hz^{-1} < 10^{27}$)
- ★ Probe different environments.
- ★ Excellent multi-wavelength data – redshifts, trace processes in host galaxy.

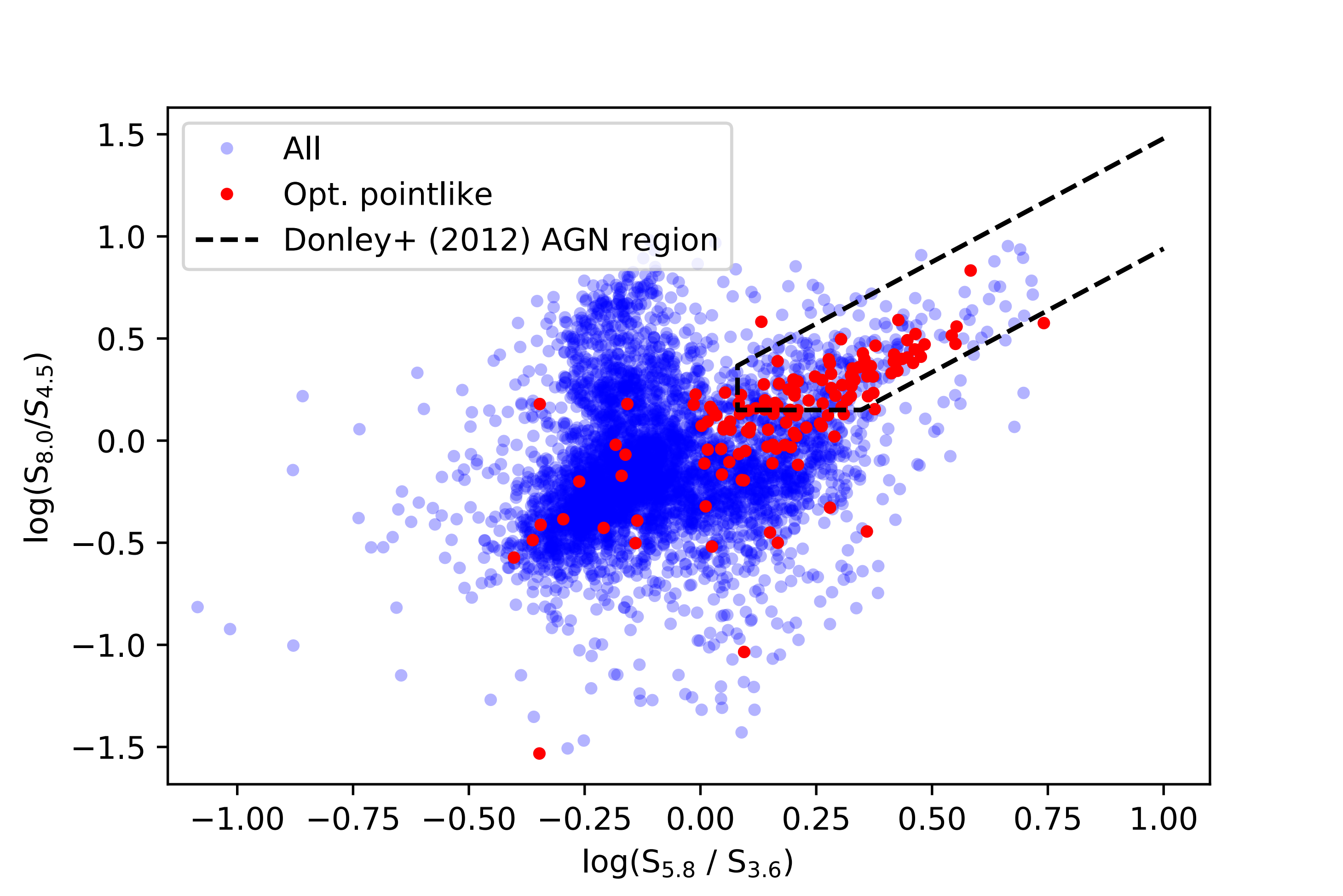
MIGHTEE radio galaxies

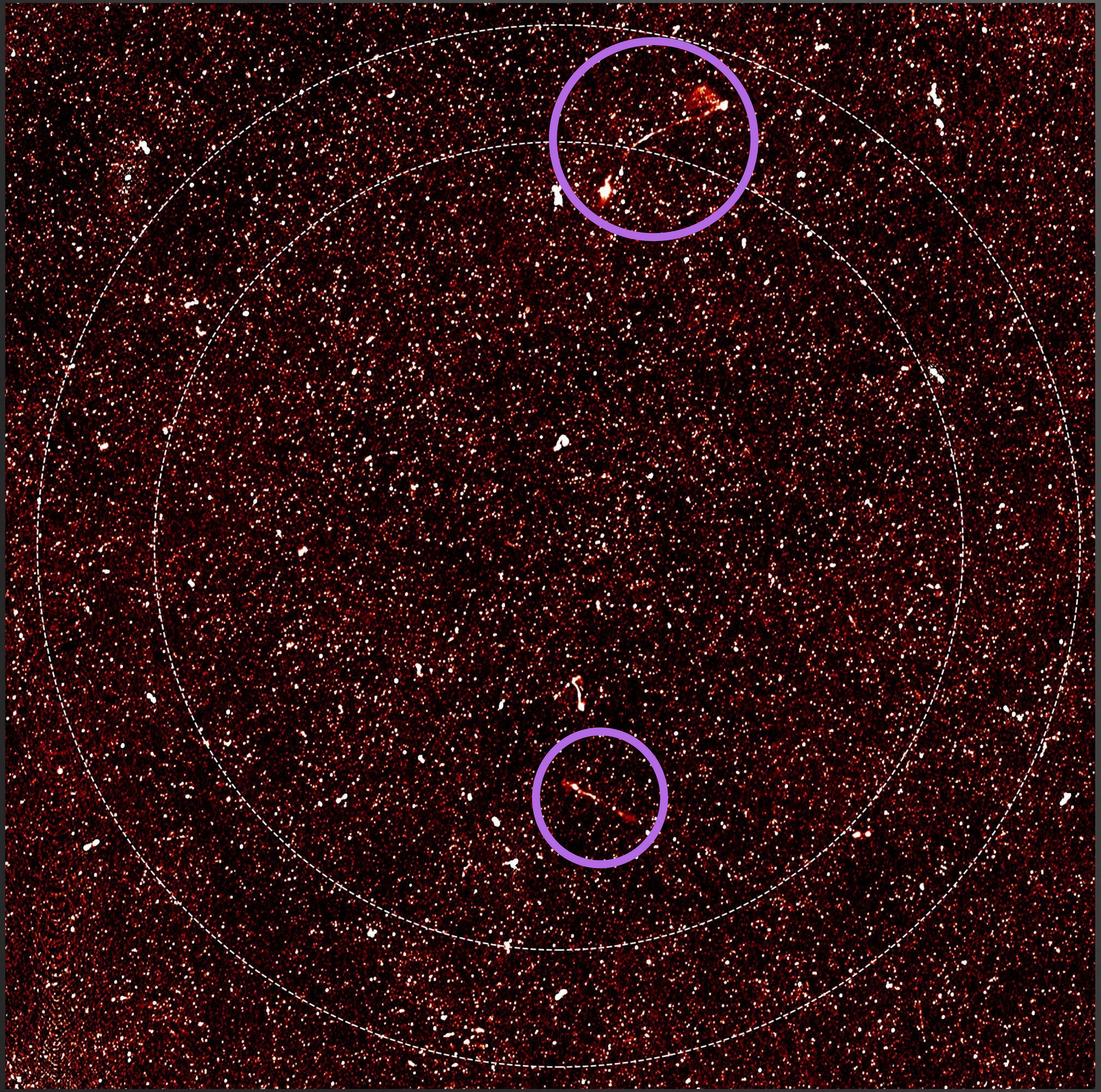
★ Sample of 1500 radio galaxies selected from MIGHTEE Early Science data.

★ SFG/AGN classification is based on four criteria:

1. **Radio Excess** - AGN if radio emission is >2sigma above infrared-radio correlation.
2. **X-ray** - AGN if $L_X > 10^{42}$ erg/s
3. **Mid-infrared AGN – Donley+ (2012) AGN selection region.**
4. **Optical AGN** - AGN if point-like in ACS I-band data.







Giant radio galaxies in MIGHTEE

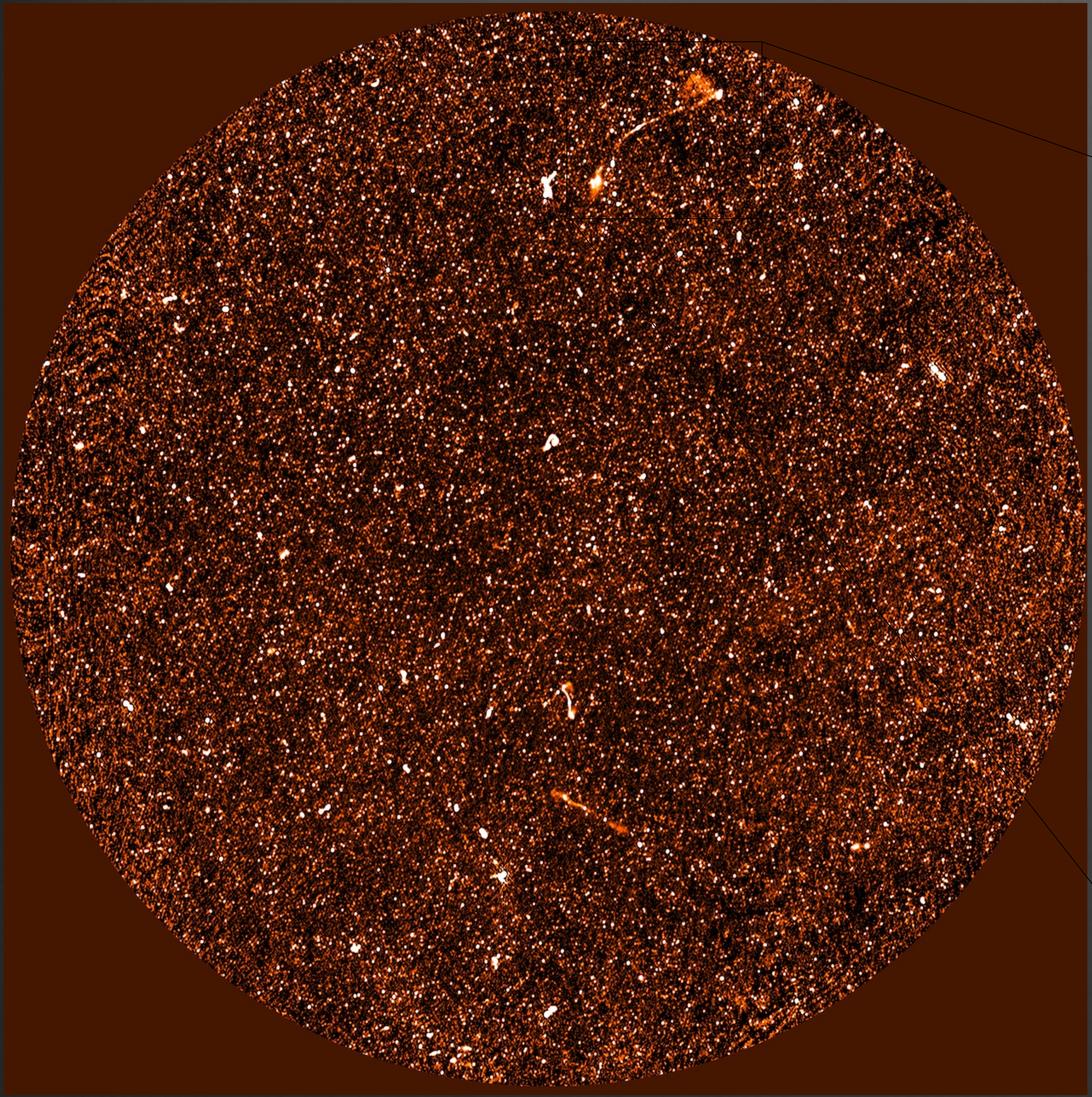
★ Project led by Jacinta Delhaize (University of Cape Town).

★ Giant radio galaxy = radio galaxy larger than 0.7 Mpc.

★ Found 2 GRGs in ~1 square degree of MIGHTEE early science data (COSMOS field).

arxiv:2012.05759

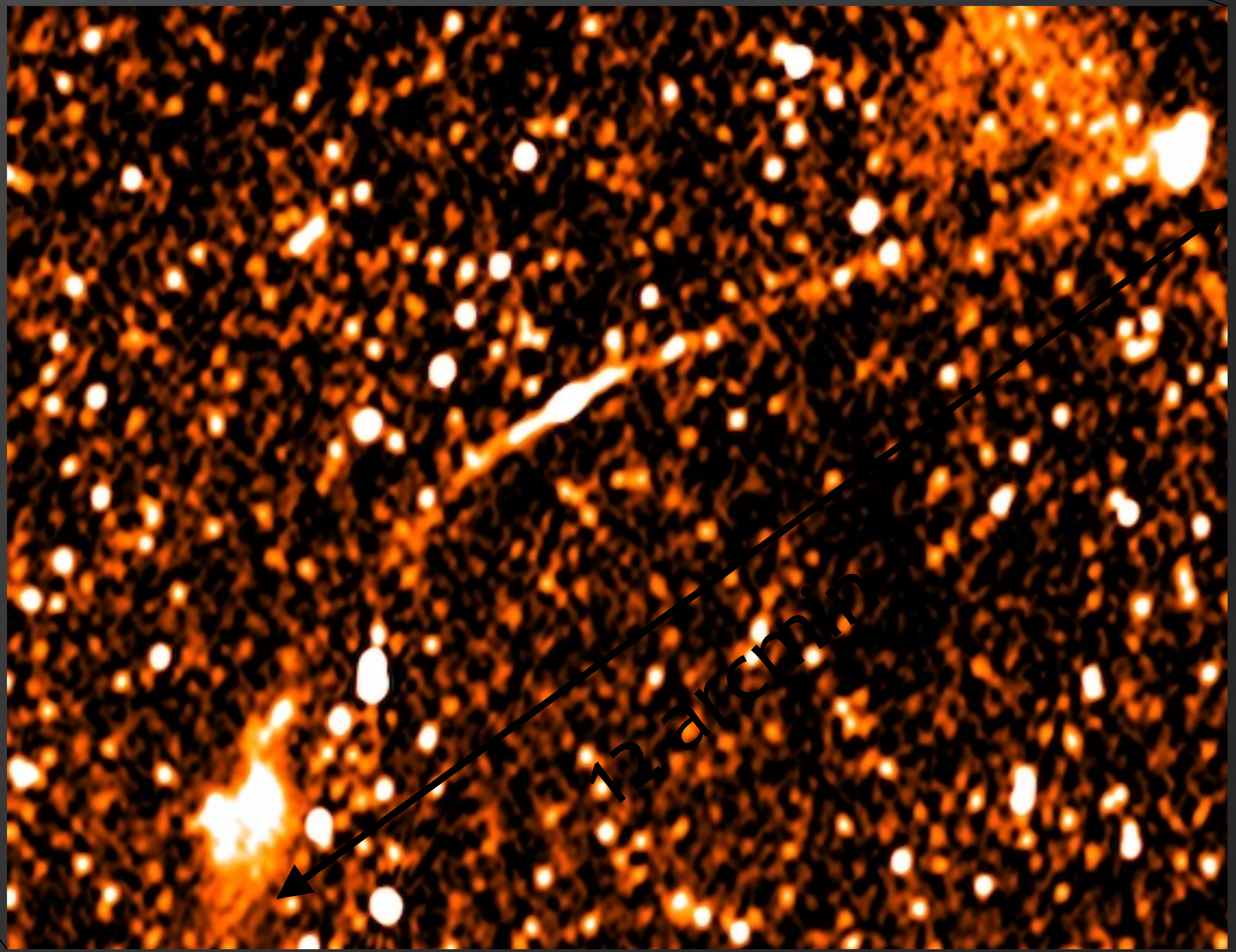
Giant diffuse radio galaxies in COSMOS (>2Mpc)



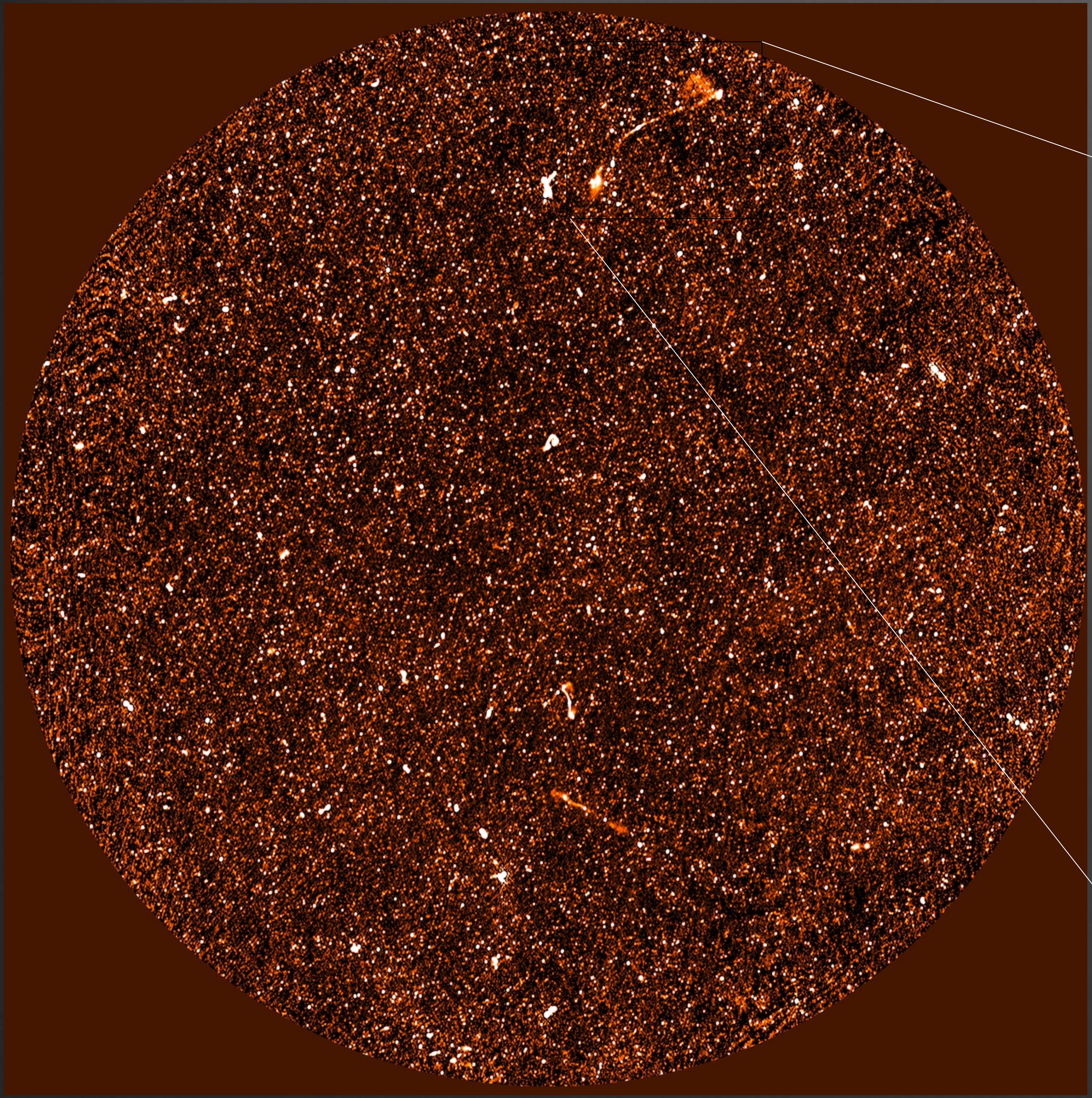
Delhaize et al 2021

A good example of what MeerKAT can do that the JVLA finds difficult

MIGHTEE (Heywood et al. 2021)



Giant diffuse radio galaxies in COSMOS (>2Mpc)



Delhaize et al 2021

A good example of what MeerKAT can do that the JVLA finds difficult

JVLA 3GHz (Smolcic et al. 2017)

Giant radio galaxies in MIGHTEE

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MIGHTEE: are giant radio galaxies more common than we thought?

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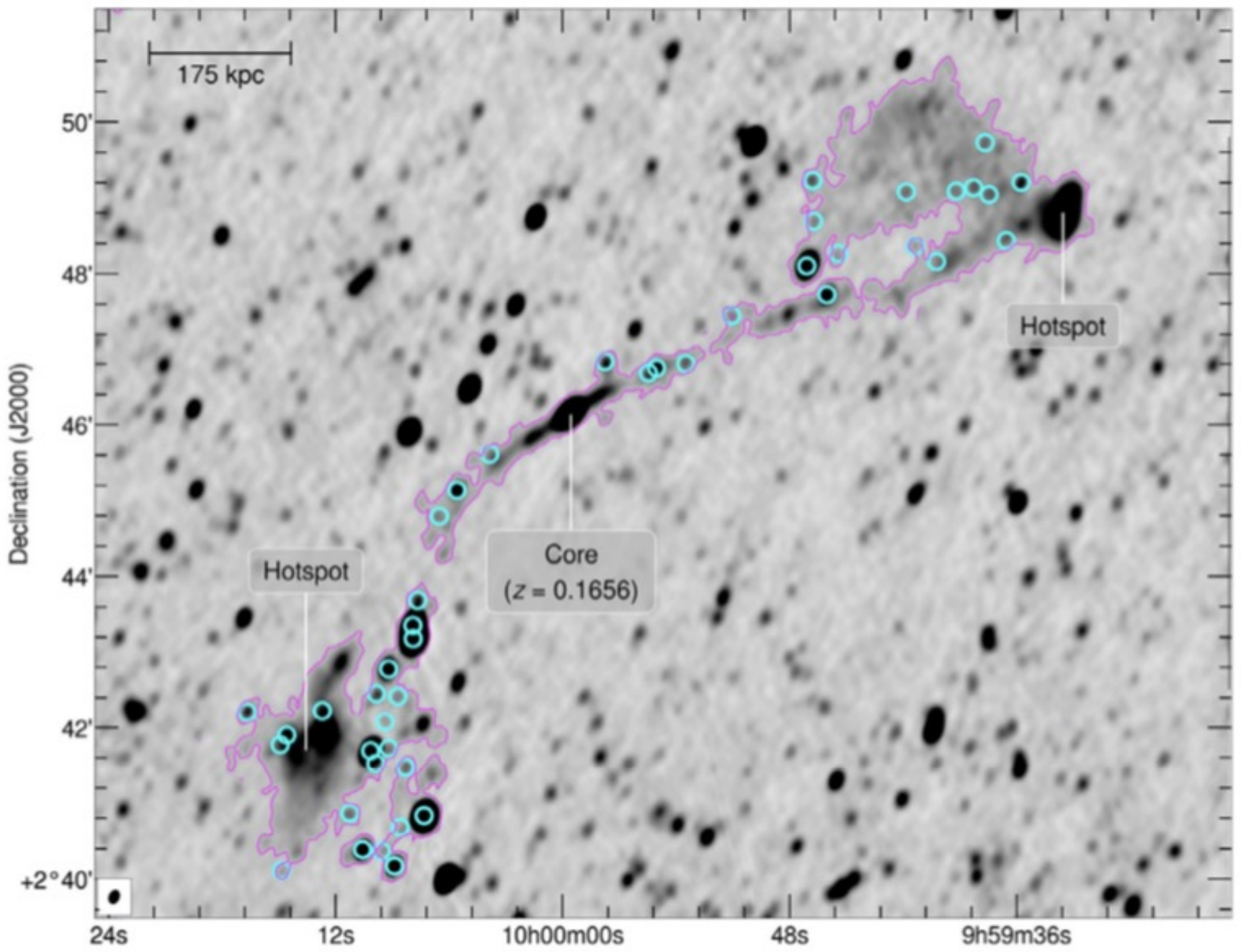
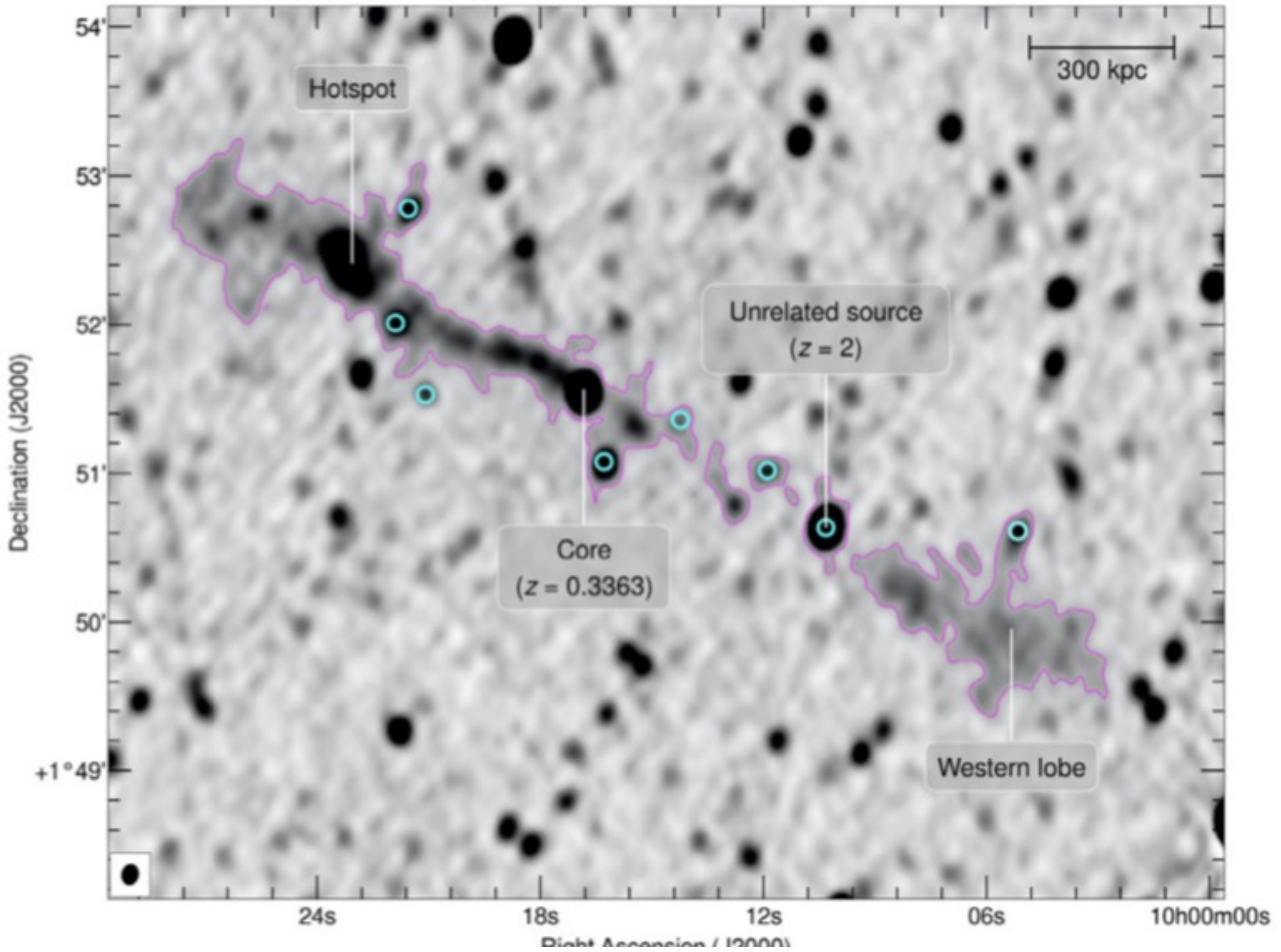


z = 0.166, 2.42 Mpc in size!



z = 0.336, 2.02 Mpc in size!

- ★ Project led by Jacinta Delhaize (University of Cape Town).
- ★ Based on LOFAR sky density estimates, probability of finding two GRGs in this field is 2.7e-6.
- ★ Suggests GRGs are more common that previously thought!

arxiv:2012.05759

Conclusions

- ★ Radio continuum surveys of the extragalactic sky provide key information about the formation and evolution of galaxies
- ★ They trace the star formation by measuring the synchrotron emission from supernovae
- ★ They trace Black Hole accretion activity through detecting the synchrotron emission from jets and winds
- ★ However, the most insights are gained when combined with data at other wavelengths, giving a complete overview of all the key phases in a galaxy's life

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NRF National Research Foundation

SARAO South African Radio Astronomy Observatory