Large and Small Scale Radio Jets From Spiral Galaxies

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ALMOST ALWAYS POWERFUL RADIO JETS ARE HOSTED BY ELLIPTICALS ?

Here we address a long standing major mystery of AGN phenomenon

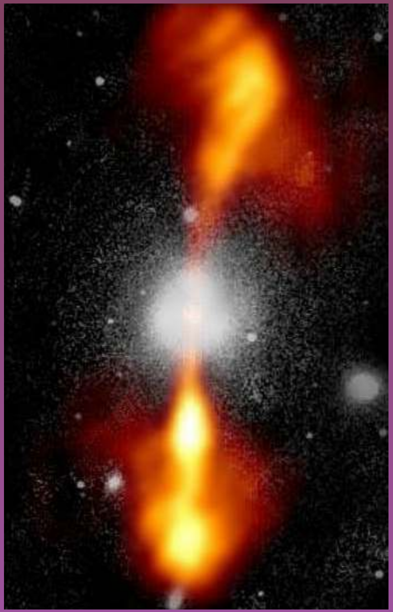
The "central" mystery is :

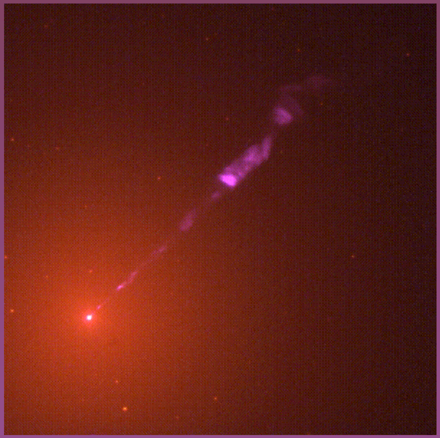
✓ Why spiral galaxies never produce large-scale radio jets (jet size > 100 kpc) ?

✓ Why powerful radio galaxies and radio-loud quasars/blazars all originate in (bulge dominated) Elliptical galaxies ?

✓ Why spirals are so unusually radio quiet? (Although they may show a very bright Seyfert /Quasar like AGN) ?

L_R (spirals) < $10^3 - 10^4$ L_R (ellipticals) !





Big Radio jets always made in elliptical hosts

Some Conjecture: Radio jet launching from AGN may require extremely specicial fundamental physical conditions near the central super massive BH (why only in ellipticals ??)

Mass

Accretion rate

and Spin

The 'Spin – Mass Paradigm'

Sikora et al. (2007), Wilson & Colbert (1995), Narayan & Yi (1995)....etc.

Spiral Galaxy

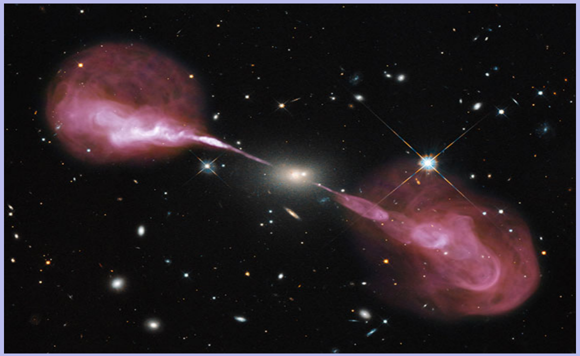
✓Faint radio luminosity
✓No large scale radio jets
✓Small black hole mass
Low spin of black hole (?)
High accretion rate (?)

Elliptical Galaxy

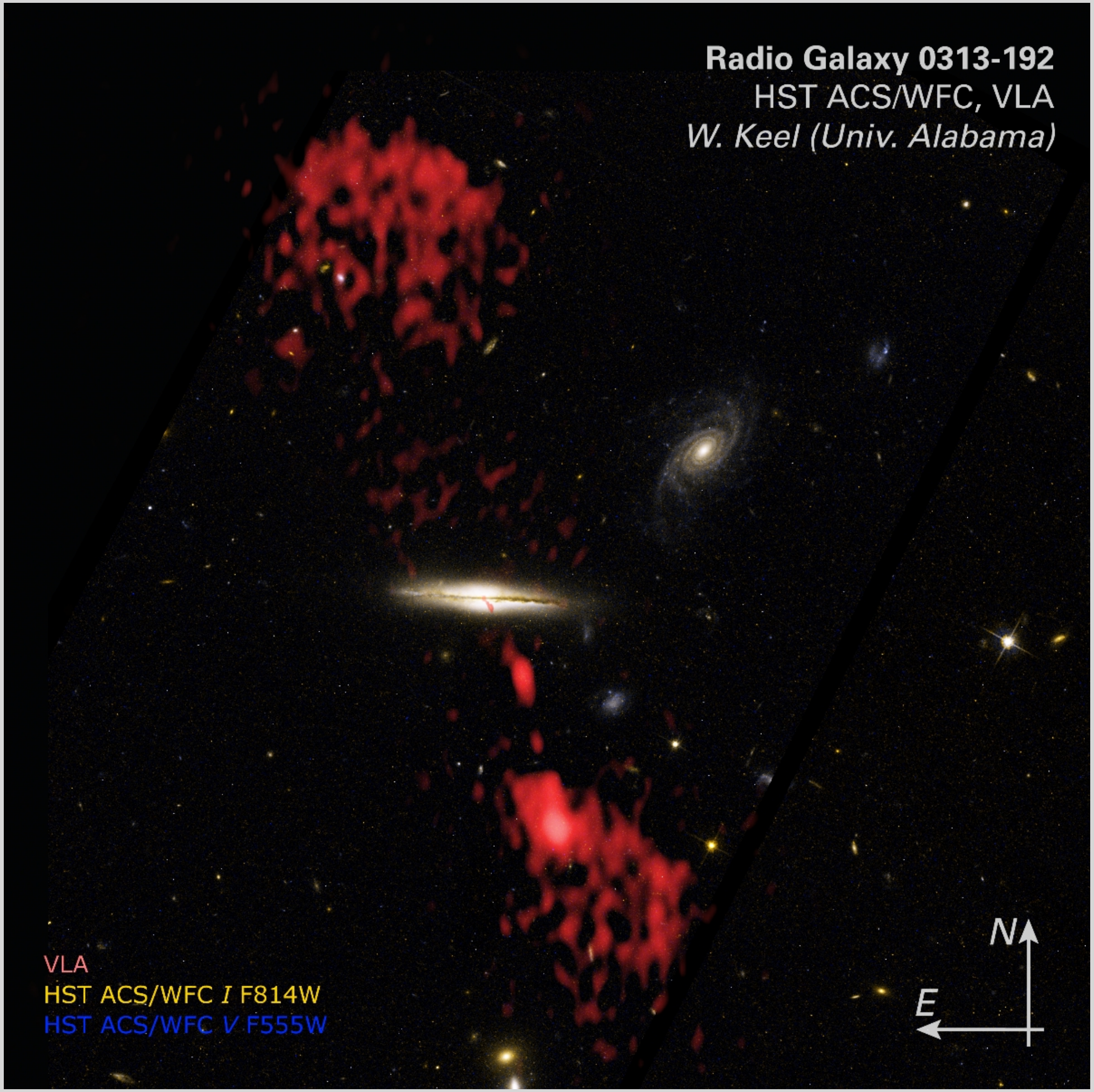
✓ High radio luminosity
✓ Large scale radio jets
✓ Large black hole mass
High spin of black hole (?)
Low accretion rate (?)

Radio quiet ←

Radio loud →



First Example of ~ 100 kpc Radio Jets from a Spiral Galaxy was found in 1998



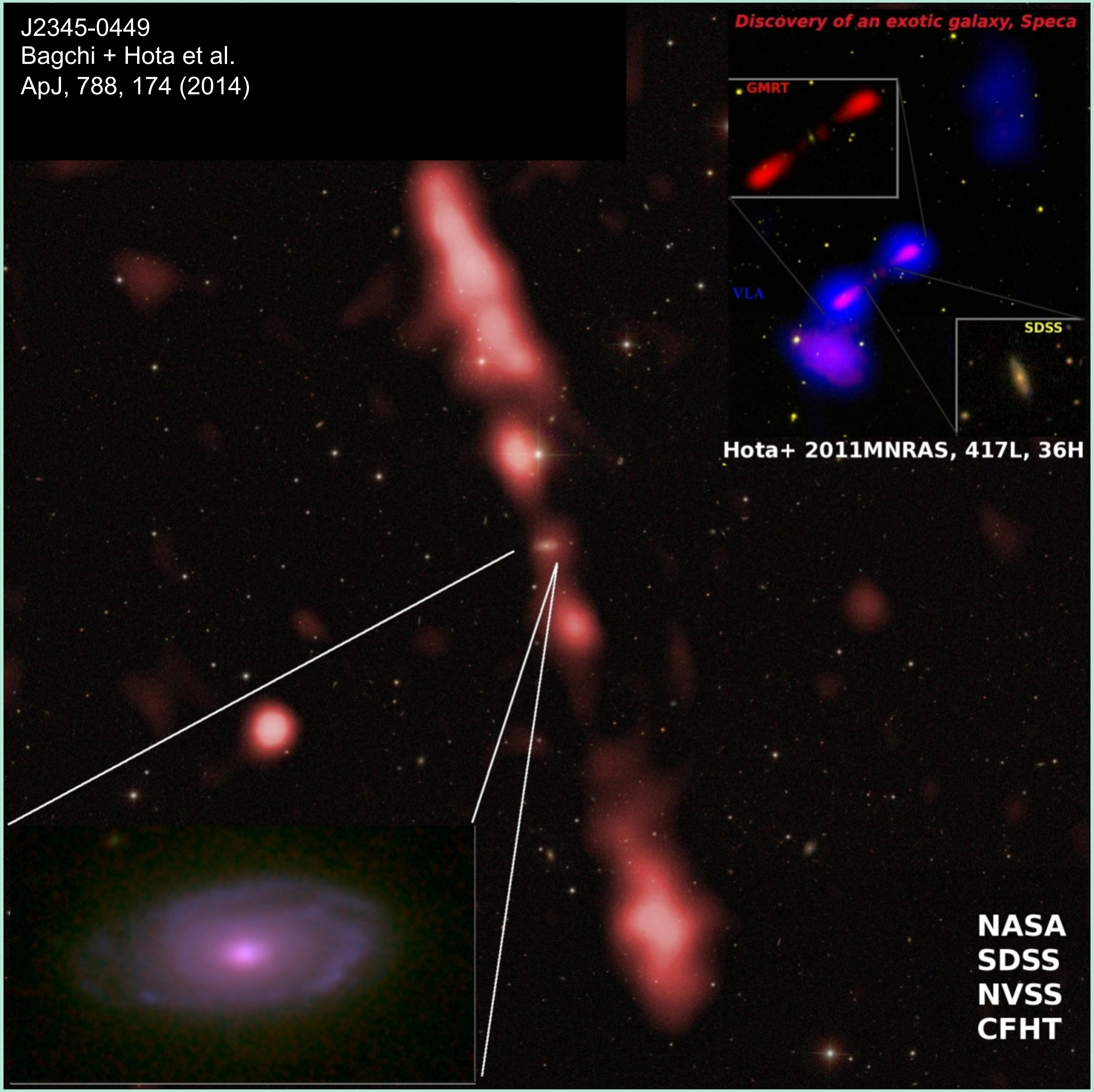
Ledlow, Owen & Keel

However, recently, due to pioneering efforts of several Indian researchers, some extraordinary discoveries of > 100 kpc to 1 Mpc scale highly relativistic jets in spiral galaxies have been reported for the first time in the history of radio astronomy !

These amazing sources contain major astrophysical clues for radio jet formation and perhaps an answer to the long standing puzzle of why large scale jets are almost never made in flat spiral galaxies but only in big ellipticals with bulges

Anand Hota et al. (2011), Joydeep Bagchi etal. (2014), Veeresh Sihgh et al. (2015), Preeti Kharb et al. (2014,..), Kaviraj (2013,2015).....

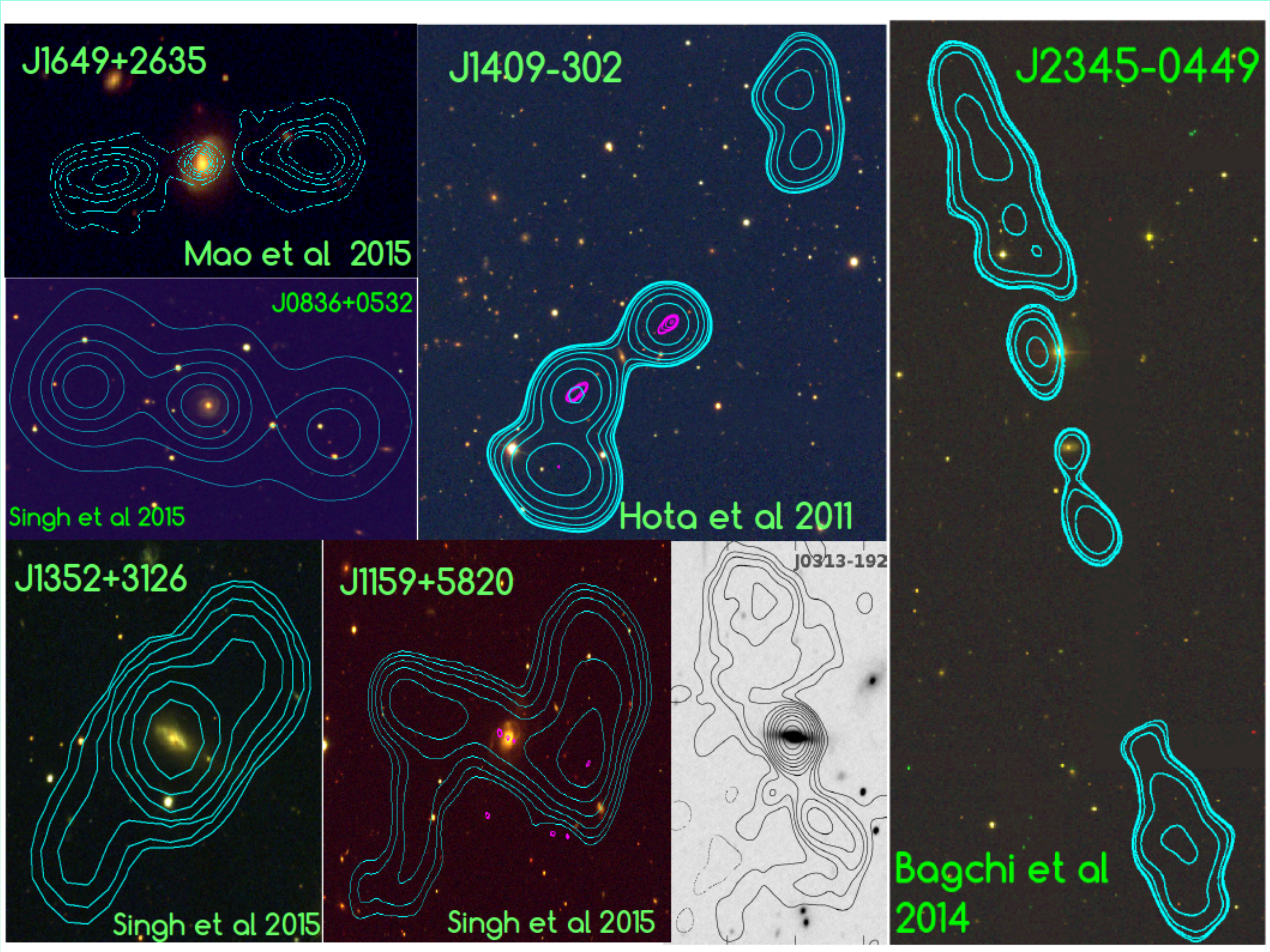
First clear examples of Mega parsec scale radio jets in spiral hosts



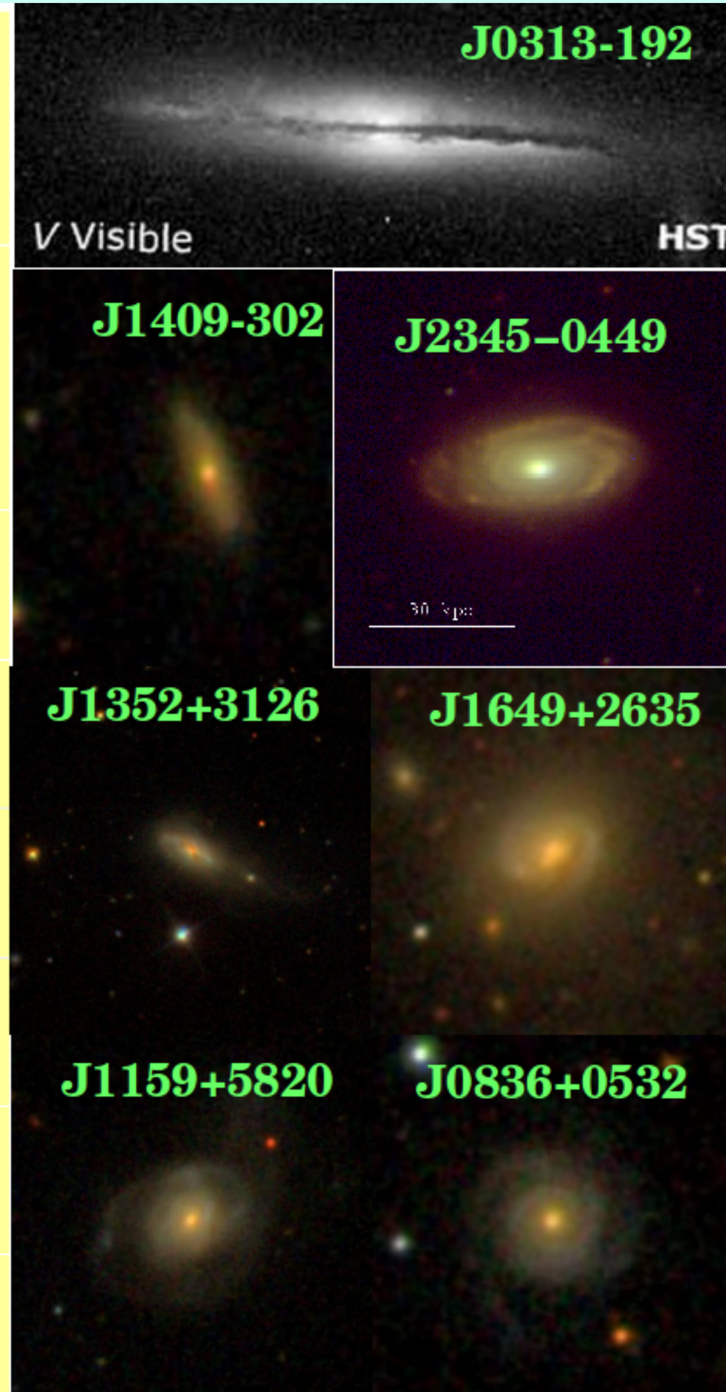
GMRT played a major role in highlighting these extremely important astrophysical sources

The low frequency imaging sensitivity of GMRT was essential !

Spiral galaxy with big jets: Rouges Gallery of 'Outlaws' (only 7 caught so far!)



Sr.No	Object Name	Z	Size (Kpc)	Authors
1	J0313-192	0.067	200	Ledlow , Owen & Keel (1998)
2	J1409-302	0.138	1300	Hota et al. (2011)
3	J2345–0449	0.076	1600	Bagchi et al. (2014)
4	J1649+2635	0.055	100	Mao et al. (2015)
5	J0836+0532	0.099	420	V.Singh et al. (2015)
6	J1159+5820	0.054	494	"
7	J1352+3126	0.045	335	"



What kind of spirals would eject huge (> 100 kpc) relativistic jets?

The answer is still unclear (only a few confirmed examples known) - **exceptionally rare !**

Probably we have two important clues here:

Seyfert Galaxies : small < kiloparsec scale jets

Extremely massive spirals : large Mpc jets

Why study of radio AGN in spiral galaxies is desirable ?

Not just because they are so rare !

They may hold major clues to the behaviour of radio jets in disc environments.

While this is uncommon at low redshifts, the bulk of the stellar and black-hole mass in Universe was created at $z \sim 2$ (e.g. Madau et al. 1998; Hopkins & Beacom 2006), epoch when both star formation (e.g. Kaviraj et al. 2013) and black-hole growth (e.g. Kocevski et al. 2012; Schawinski et al. 2012) were predominantly hosted by late type galaxies.

Connection between the black hole and a disc-like host system was common around the epoch of peak cosmic star formation era, making radio AGN in nearby disk galaxies useful laboratories for exploring this connection

We have a feeling that perhaps extreme spirals are very important as drivers of Mpc scale jets

Kiloparsec radio jets in SEYFERT Galaxies

Seyferts are mainly spirals with compact AGN core bright in from IR to UV light

Optical spectrum may show both narrow and broad lines and weak stellar absorption lines (Sy1 , Sy2 and intermediates)

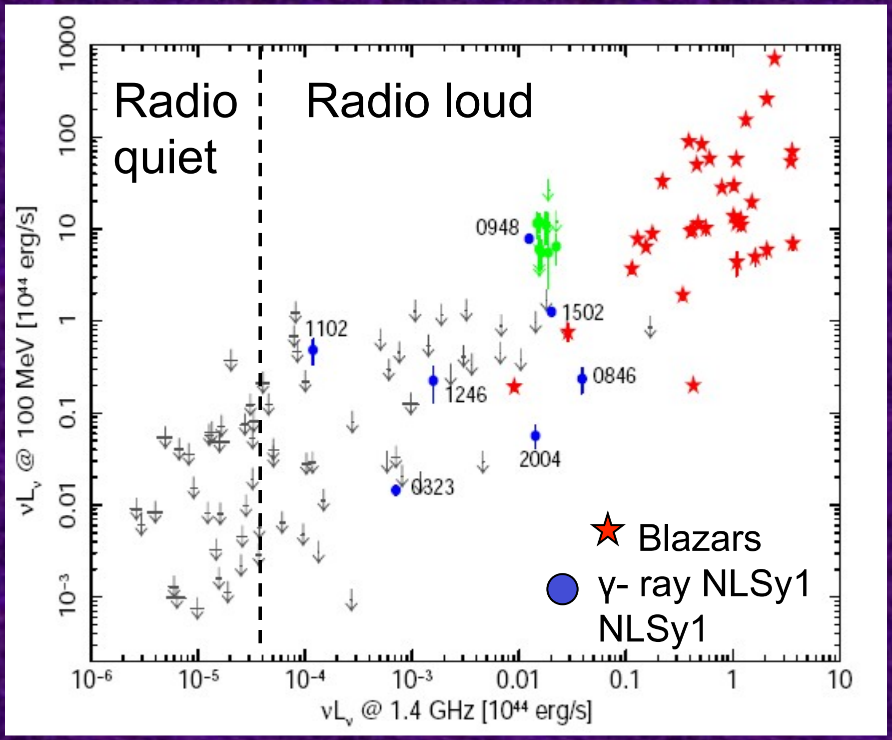
Several Radio studies find a few Seyferts may have extended radio structures on ~kpc scale but almost never exceeding > 10 kpc (e.g. Veeresh Singh et al. 2015)

They are classified as radio-quiet AGNs with radio loudness parameter R << below radio galaxies or Quasars

It is still a huge mystery why Seyfert galaxies are unable to launch ~ 100 kpc - Mpc scale relativistic jets ?? Narrow line Sy1s may have powerful relativistic iets !

A few Narrow Line Seyfert 1 (NLSy1) are also strong gamma ray emitters and are invariably very radio loud, suggesting that highly relativistic jets are present

However they are never emitters of kpc scale radio jets. Why? It's still a mystery !



Foschini 2011

Some Possibilities:

Pole-On view along a highly beamed jet (a Blazar like AGN?)

Small mass (spin?) of the black hole does not allow a powerful big jet to form

As yet unknown physics of Disk – Jet coupling in spiral Galaxies with AGN

Narrow line Seyfert-1 Galaxies

Extremely mysterious objects

Extremely active spirals with an AGN bright in radio, UV, optical, Xray

Compact, core- dominated or small radio jets (< 1 kpc)

In some γ- ray emission implies relativistic jets (FERMI) !

Possibly Pseudo-bulge host with less massive black hole

Black hole accreting at high Eddington rate?

Extremely massive spiral Galaxies

Extremely mysterious objects

Sometimes active with AGN bright in Xray, UV, optical

Two are known to launch Mpc Scale Radio jets (rare !)

FR-II relativistic jets present

Possibly Pseudo-bulge host with super massive black hole ?

Black hole accreting at low Eddington rate?

Huge Jets in Spirals: Are Mega parsec Scale Jets Launched Mainly in Extremely Massive Spirals?

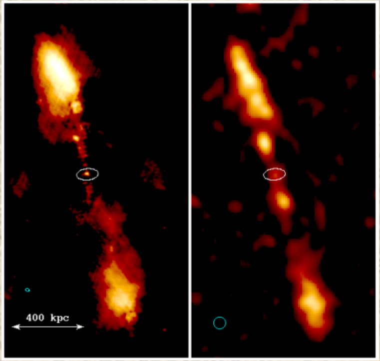
So far we have only two clear examples of spiral galaxies showing radio emission on > 1 Mpc scale

& Both are extremely massive fast rotating spirals! Why??

J1409-302 ('SPECA')
1.3 Mpc scale FR-II
V_{rot} ~ 350 km/sec !

Hota et al., MNRAS, 2011

J2345-0449
1.6 Mpc scale FR-II
V_{rot} ~ 430 km/sec !



Bagchi et al., ApJ, 2014

Mpc Scale Relativistic Jets Launched from an Accreting Super Massive Black Hole in an Extreme Spiral Galaxy

Astrophysical Journal, 788, pp 174 (2014)

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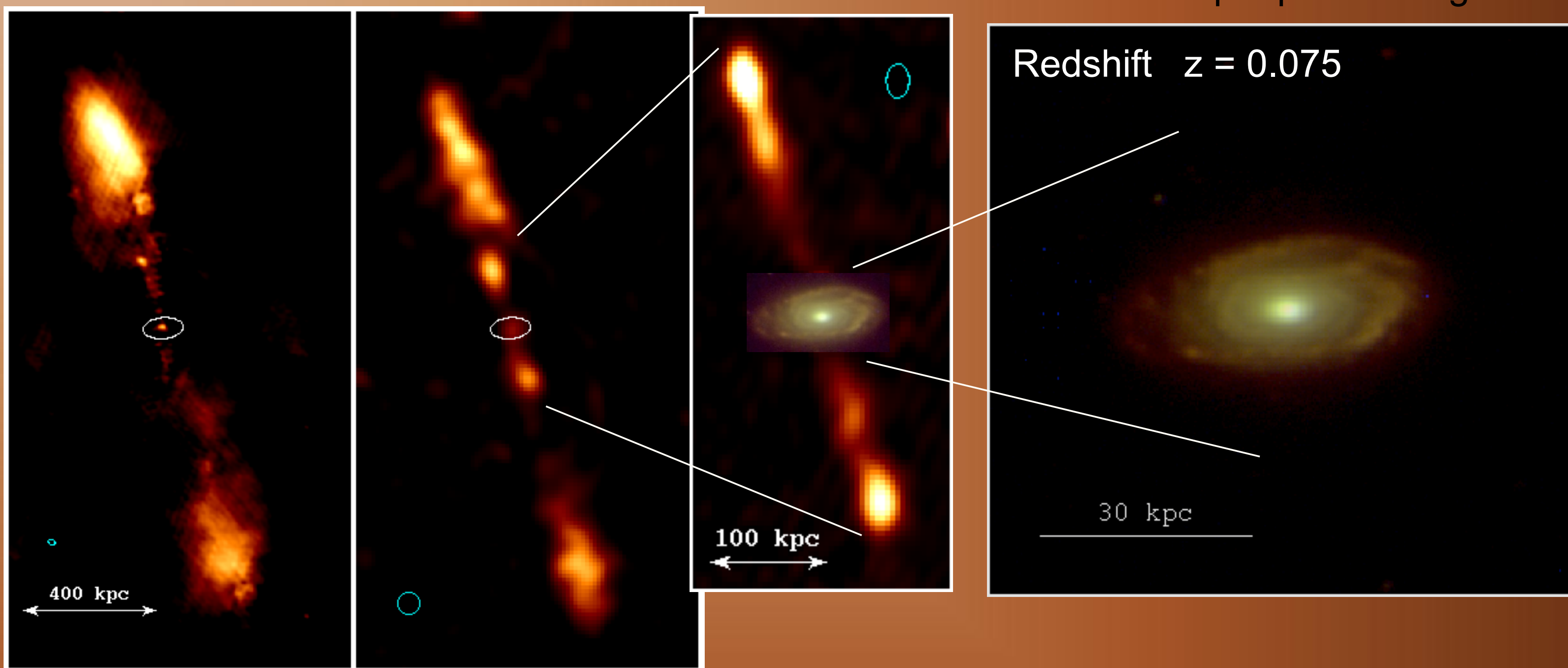
Surprising ‘double-double’ radio-jets launched from an extreme spiral !

GMRT 325 MHz　VLA 1.4 GHz　VLA 4.8 GHz　CFHT deep optical image

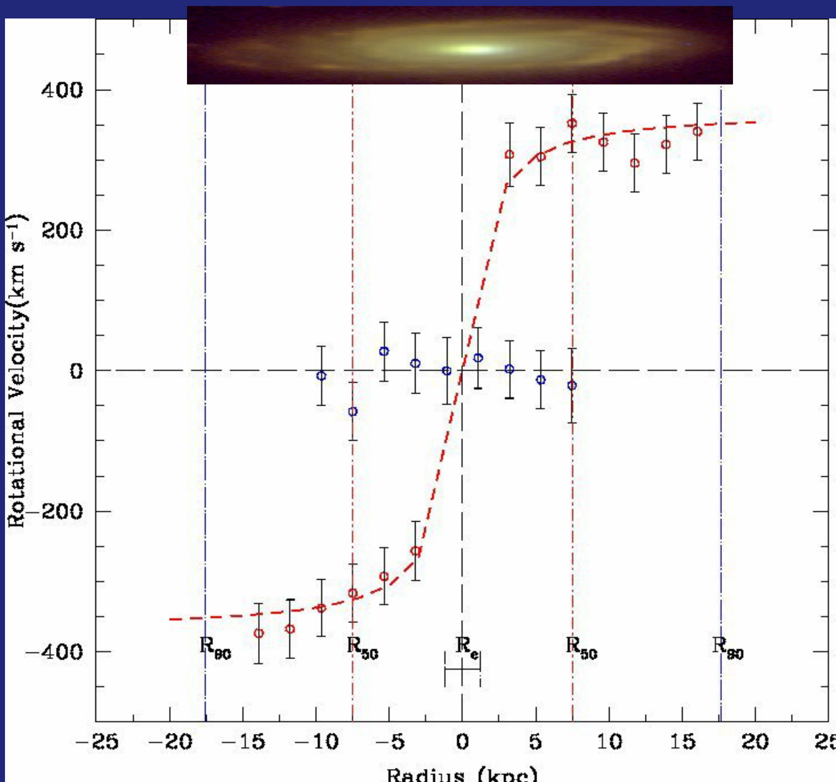


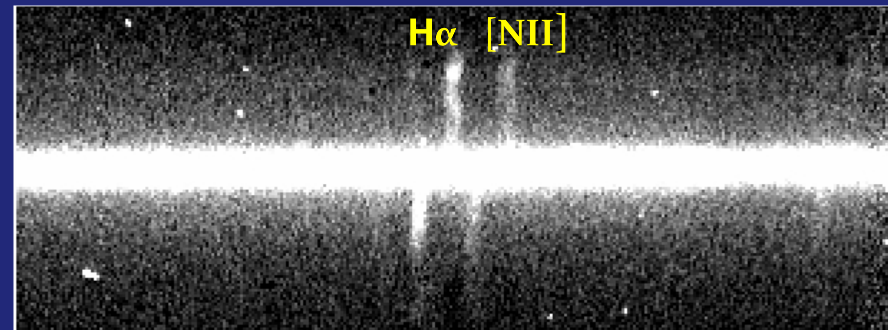
- **Extremely rare occurrence** of Mpc scale relativistic jets emergin in a spiral galaxy - Twice! May be more?

Challenges standard paradigms!

- A huge `double-double` structure two episodes of black hole jet activity
- Host spiral shows very fast flat rotation speed ~ 430 km/sec !
- Its central velocity dispersion is uncommonly large σ ~ 300 km/sec !
- ***Such an extreme galactic phenomenon is observed for the first time***

Host spiral is very bright and shows very fast flat rotation speed touching V ~ **430** km/sec at **20 kpc and beyond** !





Long slit spectrum taken with IFOSC on IUCAA 2m telescope

An extremely massive galaxy is implied

M_{dyn} ~ V^2 G / r

~ **few x 10^{12} M_{sun}**

even at r < 20 kpc !

Tully-Fisher Relation

About 7 times the mass of Milky Way!

Virial mass $M_{200} \approx 10^{13}$ M_{sun}

This spiral disk has acquired a huge mass & angular momentum ! How? When?♪

Via Tidal Torques or Coplanar accretion in its formative stages ?

The central velocity dispersion σ ~ 300 km/sec is unusually high for a spiral galaxy and one <u>without a classical central bulge</u> !

⇨ **Huge central mass concentration**

M_{Bulge} ~ 10^{11} M_{sun} ! How much of it is in a SMBH ??

Mass/light ratio ~ **5 - 10** within **1.25** kpc !

Estimations of Black Hole mass:

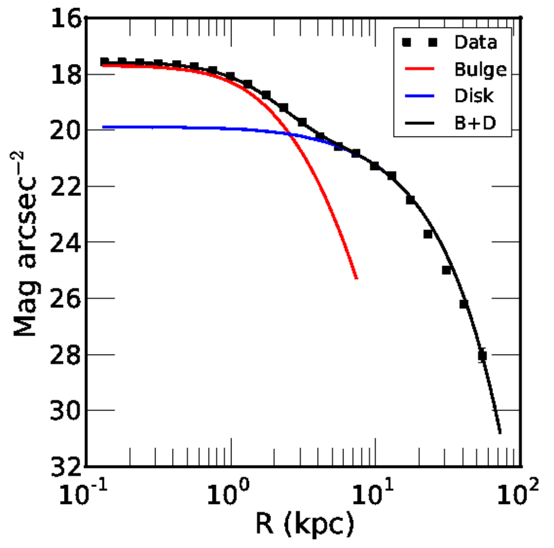
M_{BH} = 2.7 (± 0.4) x 10^8 M_{sun} from
M_{BH} Vs M_{bulge} Correlation

M_{BH} = 3.8 (± 0.4) x 10^9 M_{sun} from
M_{BH} Vs σ Correlation

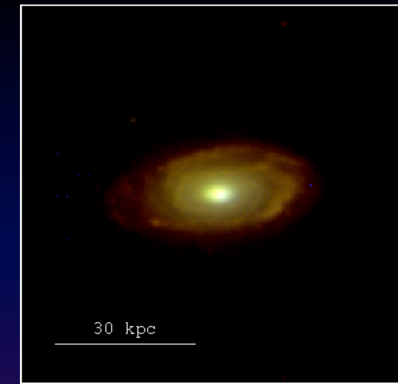
Bulge – disk modeling of host spiral shows

A `pseudo bulge' center n_{sersic} ~ 1

No classical bulge (n_{sersic} ≠ 2 to 6)



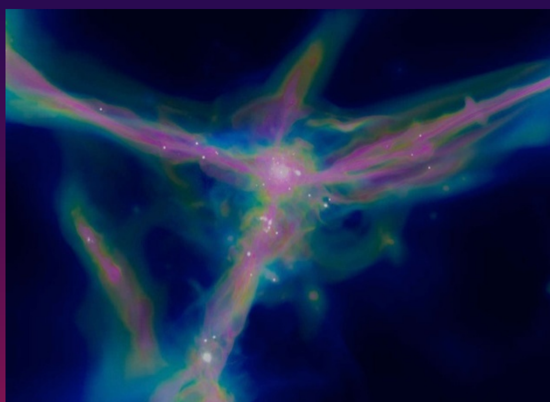
A Clue to the Formation Scenario



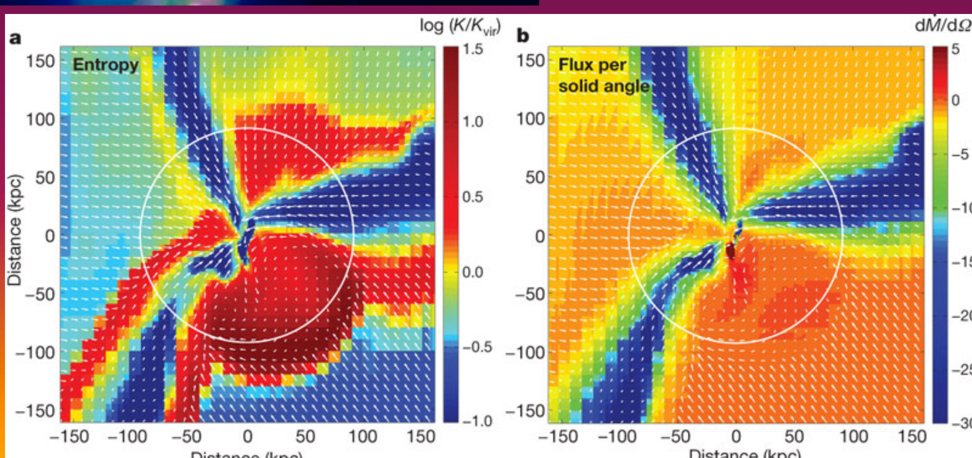
How This Rare Bulge-less Spiral Acquired its

Large Mass ? M_{dyn} ~ few x 10^{12} M_{sun} at r < 25 kpc

Huge Angular Momentum ? V_{Rot} ~ 430 km/sec



Numerical simulation: Dekel et al., Nature (2008)



Formation might involve `secular' (isolated) processes

Violent galaxy merger route not favored

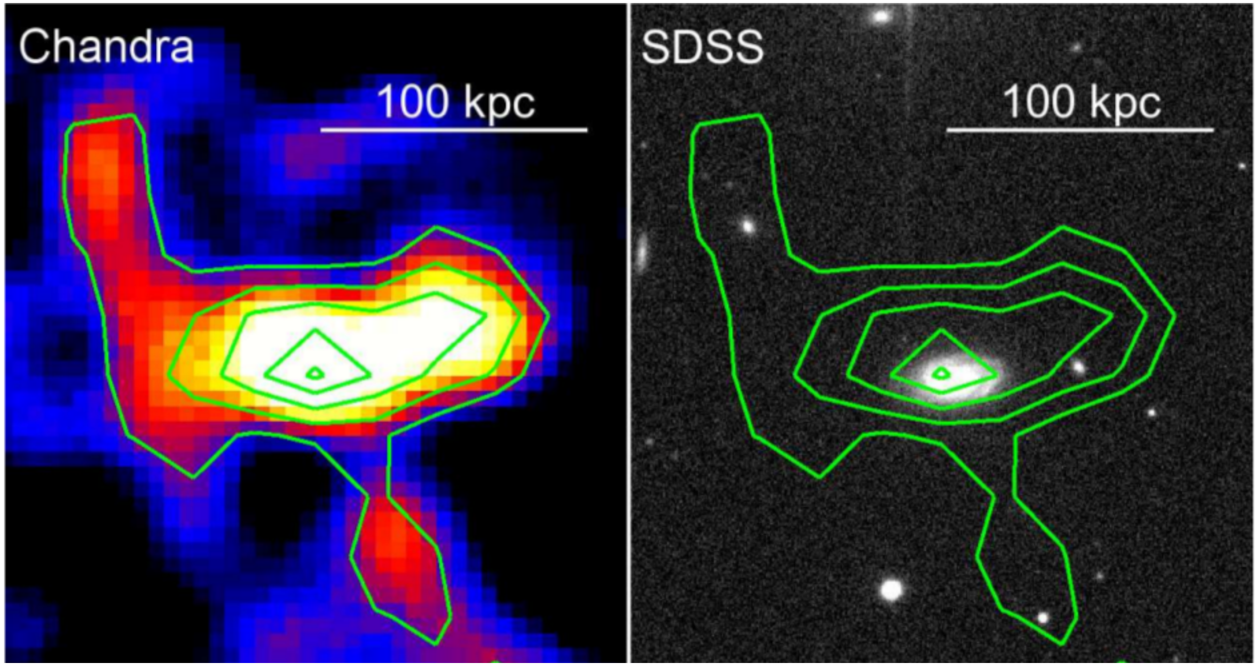
In its pancake stage (z ~ 4) mass assembly happened via

Dominant Coplanar 'cold streams' feeding a massive halo

Spin of galaxy disk grows via angular momentum transfer

Disk driven processes created a pseudo-bulge and not a real bulge

A faint, hot halo of 'missing' baryonic matter is detected around the massive spiral disk



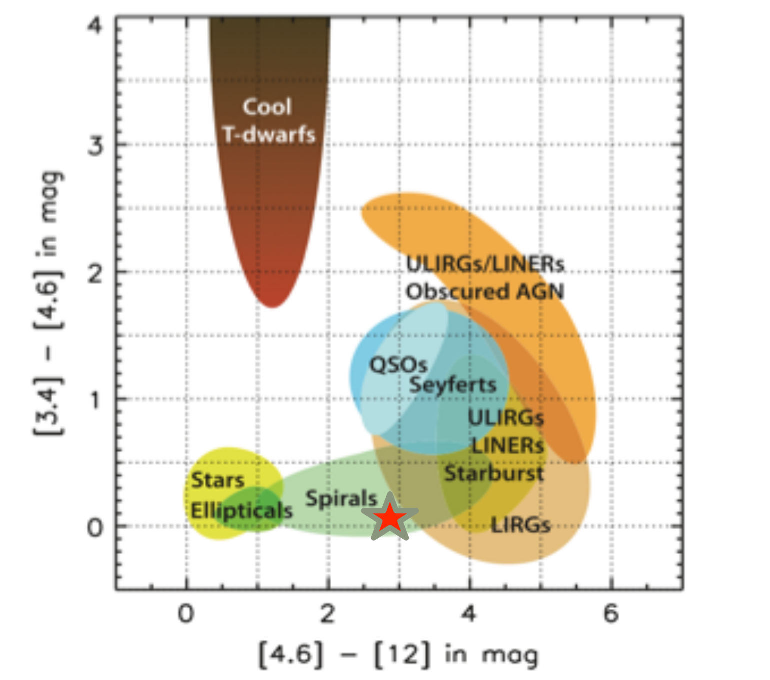
Walker, Bagchi & Fabian

MNRAS, 449, 3527 (2015)

Such Xray halos are difficult to detect but expected from the formation scenarios of extremely massive galaxies

Provides information about the baryon budget and a clue to the rarefied "Working Surface" needed for radio lobe formation at Mpc distance

More detailed study are planned in UV (Astrosat) and X-rays (XMM-Newton)

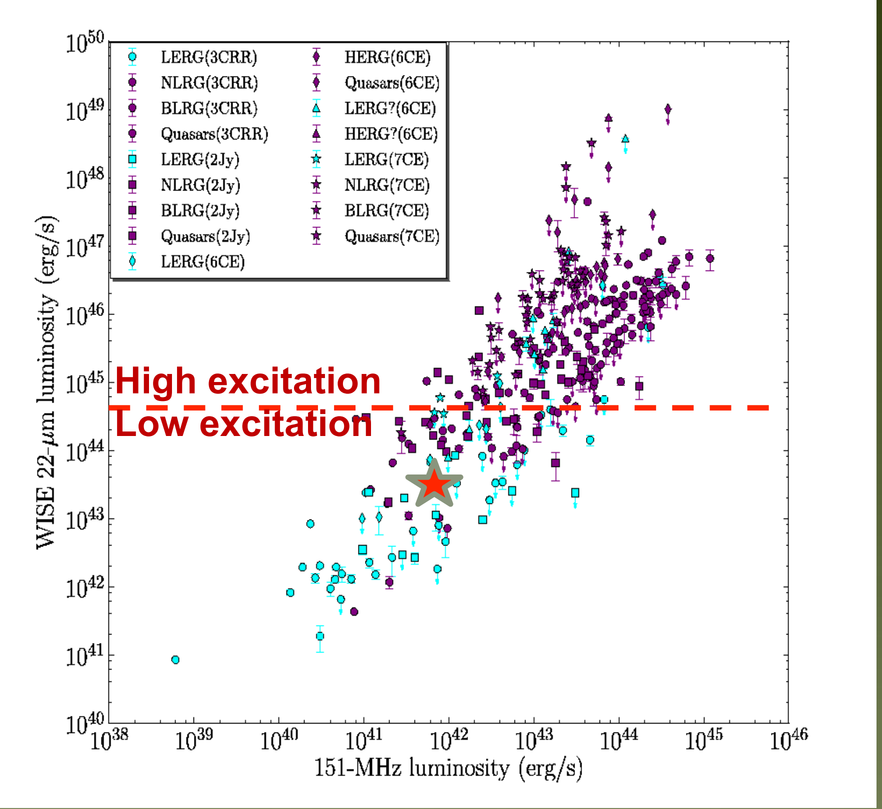


WISE **mid-IR color-color plot**

WISE mid-IR color-color plot proves it is a spiral galaxy of low excitation AGN

✓No broad lines in AGN spectrum
✓Hα Luminosity of AGN faint
✓Only weak narrow lines present

Gurkan, Hardcastle & Jarvis (2013)



WISE **mid-IR (22 μm) – radio (151 MHz) correlation of radio AGN**

WISE ***mid-IR vs Radio plot also proves this is a*** **low excitation AGN**

➡ <u>The extreme spiral is a low excitation radio galaxy, the BH possibly in low Eddington rate accretion state, possibly ADAF</u>.

Advection Dominated Accretion Flow (ADAF) and Jet Formation

A strong link between radio jet formation and accretion rate has been suggested in literature, which is of great interest in view of the giant radio jets found in this unusual spiral galaxy

At black hole accretion rates above a critical value

$$\lambda_{crit} \sim 10^{-2} - 10^{-3}, \text{ where } \lambda = [dm/dt] / [dm/dt]_{Edd}$$

the accretion disk structure is a standard Shakura and Sunyaev (1974), radiatively efficient, geometrically thin disk, whereas at very low accretion rates ($\lambda << \lambda_{crit}$) transition to an Advection-dominated accretion flow (ADAF) state results, fuelled by hot gas from a large-scale spherical halo.

Narayan & Yi (1994, 1995), Abramowicz, Chen, Kato, Lasota & Regev (1995) etc.

Our Proposed Scenario :

- **The unusual radio jet activity** of extreme spiral galaxy is possibly caused by BH accretion state switching from

Previous high accretion rate $\boldsymbol{\lambda \approx \lambda_{crit} \sim 10^{-2} - 10^{-3}}$,

where $\boldsymbol{\lambda = [dm / dt] / [dm / dt]_{Edd}}$

To the present low accretion rate $\boldsymbol{\lambda << \lambda_{crit}}$

- Thus driving the 'central engine' toward ADAF state and launch of high powered radio jets

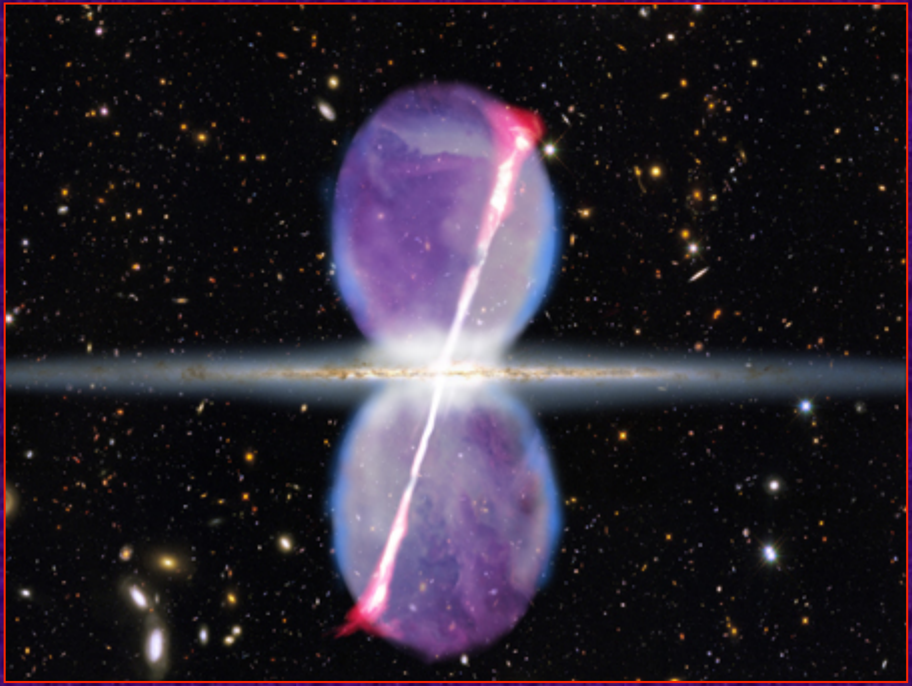
- This change may be brought about due to unusual growth of an overmassive Black hole itself, possibly also spinning rapidly , in a pure disk galaxy

- Such an unusual black hole growth in a bulge-less galaxy can happen only via a previous very rapid disk driven growth phase at very high accretion rates

- In this phase of growth in the early universe the galaxy might have shone like a luminous quasar

- The above must be an extremely rare event and thus do not happen in most other spiral galaxies

Future Deep Searches May Find Ghostly Bubbles of Black Hole Jet Activity in Spiral Galaxies



FERMI gamma Ray bubbles seen in our Milky Way Spiral

FERMI also saw faint gamma ray jets (?) within bubbles!

Bubble also seen in microwaves By PLANCK and WMAP

Giant ghostly bubbles are visible in Milky Way in Radio, Xray and Gamma Rays

Could These be relics of past AGN jet activity of central black hole ?

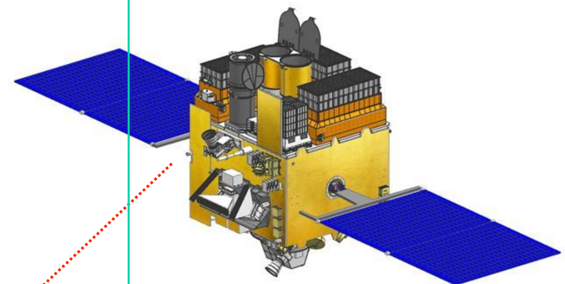
Or these high energy bubbles are tracers of galactic wind blown by intense star formation activity in the past?

A GMRT/LOFAR /SKA deep low frequency survey (50 – 200 MHz) of massive spirals may reveal faint 'Ghost Radio Bubbles" of past AGN activity

"We dance round in a ring and suppose

But the secret sits in the middle and knows"

- Robert Frost



Summary:

A handful of extraordinary spiral galaxies with > 100 kpc jets are found

The extreme large scale Mpc jets are found in extremely massive spirals

We discovered an extremely rare and clear example of 1.6 Mpc `episodic' radio jets in a spiral galaxy. This is the largest ever seen.

The spiral shows extreme properties: Very bright, very fast disk rotation, huge central mass, no classical bulge and no (recent) merger signs

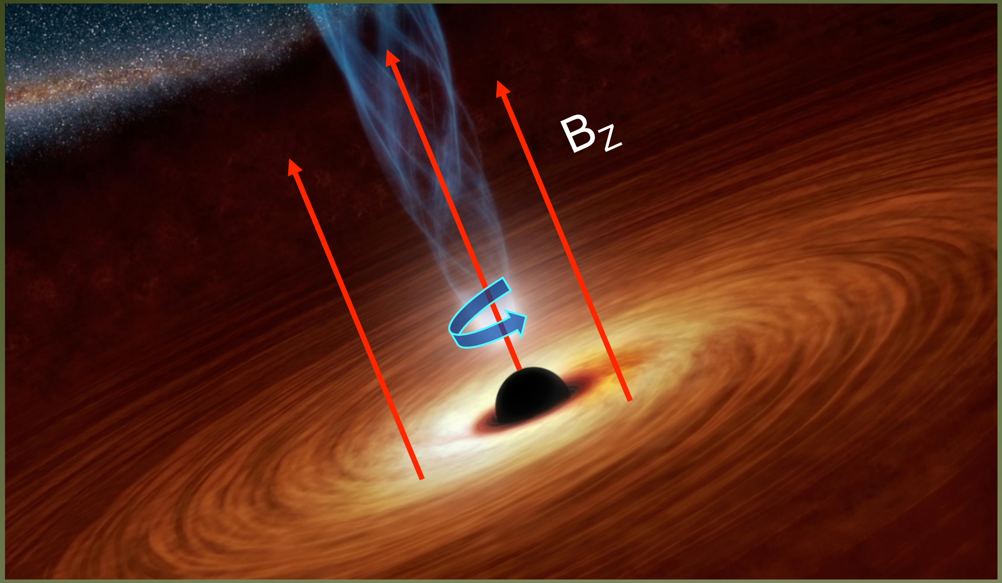
Possibly the central black hole is abnormally massive and spinning very rapidly (need to confirm). Need to resolve the central 100 pc to get the BH mass.

How did this spiral galaxy evolve to acquire these extraordinary range of properties? Need far better observations and simulations to find the answer.

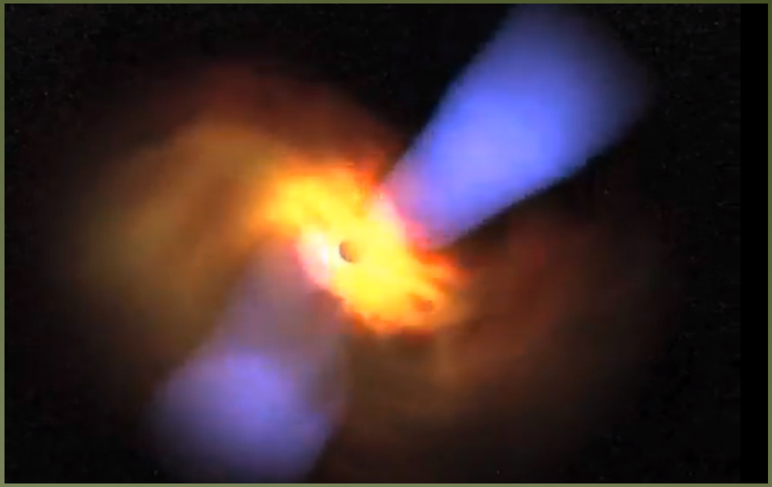
These very interesting galaxies are ideal targets for LOFAR, SKA, VLBA, ALMA and Hubble, Chandra, XMM, NuSTAR, ASTROSAT observations.

Blandford – Znajek mechanism offers very efficient extraction of huge spin energy of mass accreting, spinning BHs in Active Galactic Nuclei (AGN)

MHD Jet efficiency = (Q_J / accretion luminosity) ≈ 30 -- 140 % for a = 0 -- 1



Blandford – Znajek Jet Simulation



'Science' Jan. 2013: J. McKinney et al.

Black Hole spin parameter a = J_{BH}/J_{max} , 0 < a < 1

For a Kerr BH largest possible spin J_{max} = G M^2 / C

Typical Jet luminosity **$L_j \sim \kappa\, [\, a\, M_9\, B_4\,]^2 \sim 10^{45}$ erg/sec**

for $M \sim 10^9 M_{sun}$ a ~ 1 and $B \sim 10^4$ G

Compare L_{Edd} **~ 10^{46} erg/sec for same BH of** $M \sim 10^9 M_{sun}$