Mystery of Relativistic Jets in Spiral Galaxies

Exploring new AGN science with SKA

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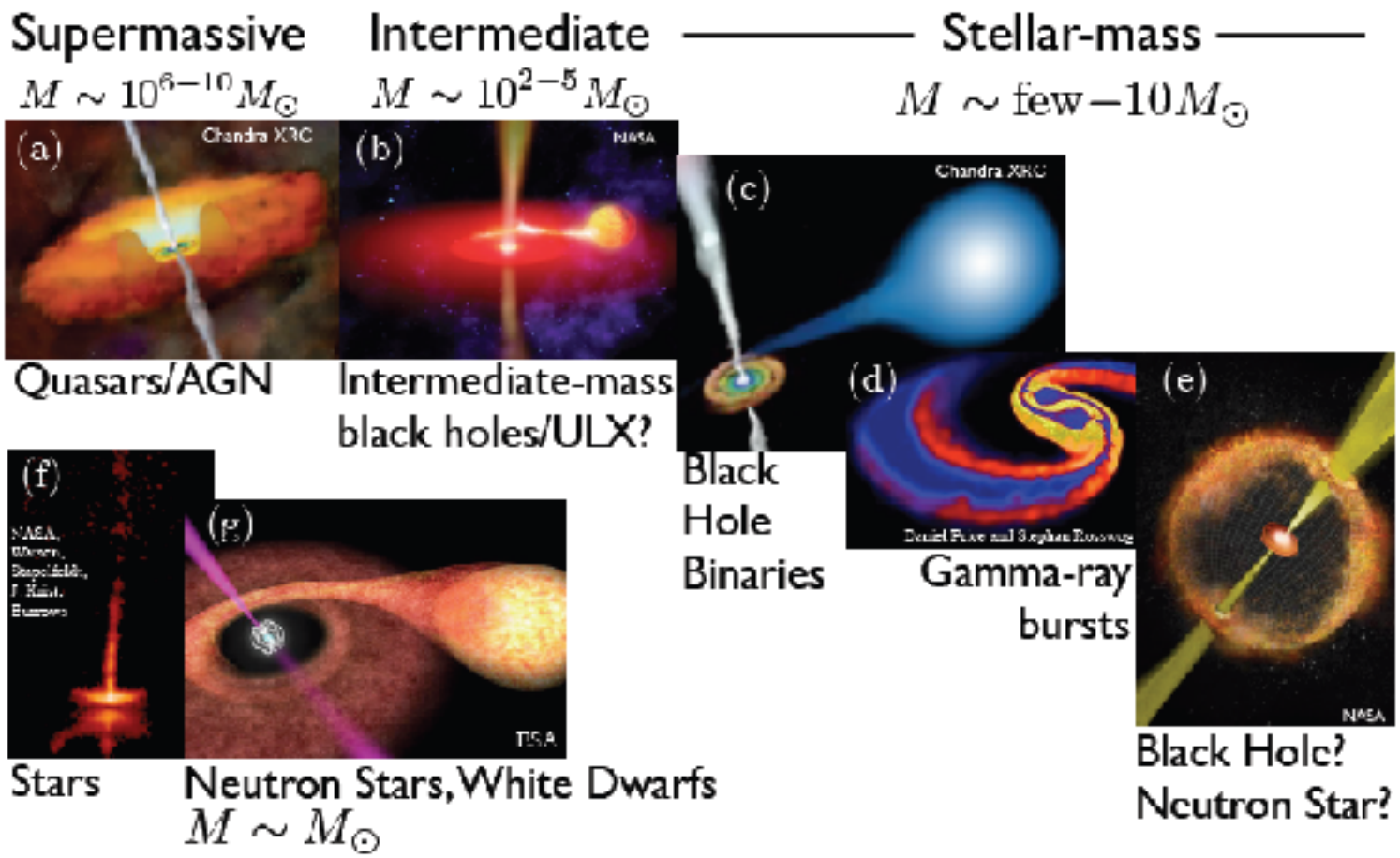
Radio Jets are Everywhere: Usually Found Near Mass Accreting Black Holes or Compact Stars in Binary Systems



The BH mass spans an enormous range ~ few 10 to >10^{10} Solar Mass

The Fundamental Quest is: Why there are radio jets? How they are launched and how they may effect their host galaxies and the surroundings?

Second Question: Why Almost always powerful radio jets are hosted by elliptical Galaxies?

With SKA, LOFAR, GMRT etc. we intend to answer this long standing major mystery of AGN phenomenon !

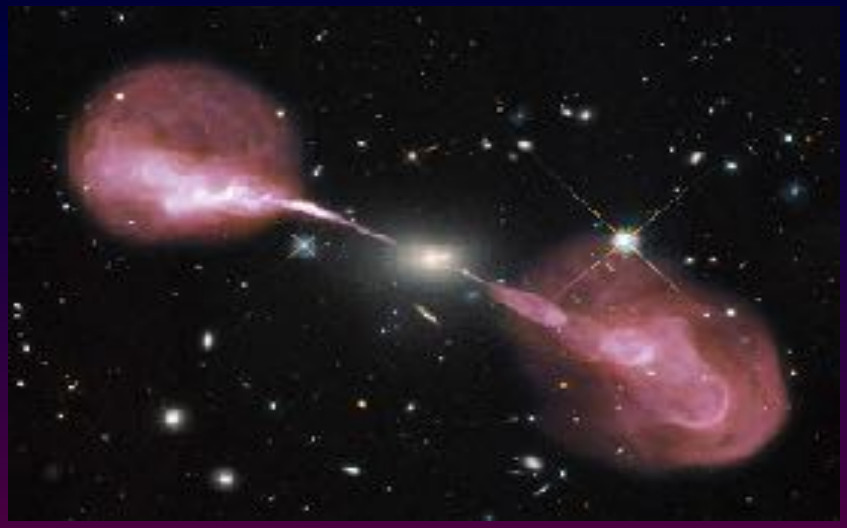
The "central" mystery :

✓ 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_{radio} (spirals) $< 10^{3} - 10^{4}$ L_{radio} (ellipticals) !



Big Radio jets are always made in elliptical hosts

A Possible Reason?: Jet launching from AGN may require extremely specific and necessary physical conditions near the central super massive BHs (why only in ellipticals ??)

BH Mass, Accretion rate

Poloidal B-field strength at BH

Spin (Prograde vs. Retrograde ?)

'Spin 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 (Check!)
✓Mostly disk + small/no bulge
Low spin of black hole (?)
High accretion rate (?)
Cold (quasar) mode accretion (?)

Radio quiet ??

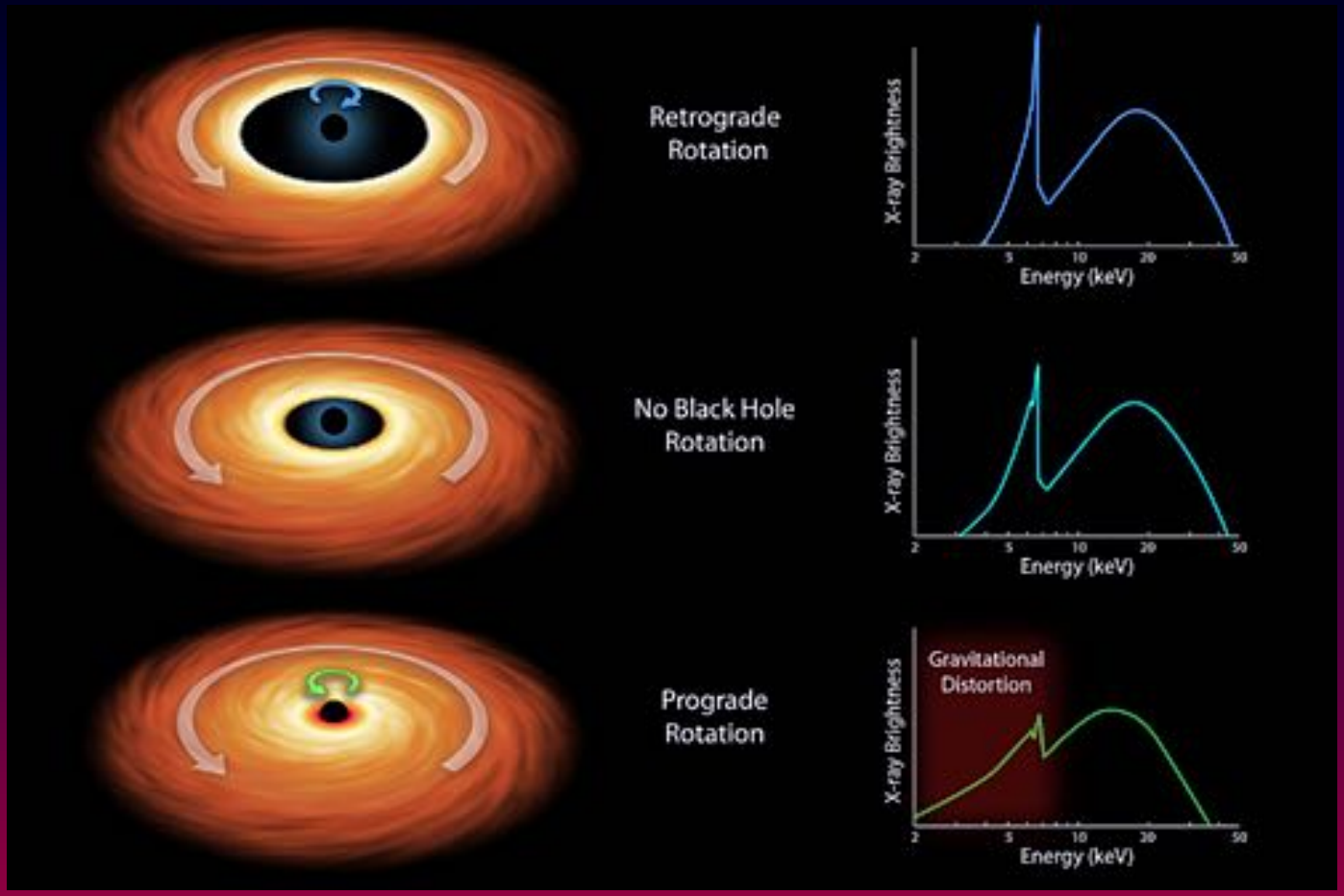
Radio loud

Elliptical Galaxy

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

How Important is Spin of BH?

To Spin or Not to Spin => Does it mean to be a Jet or not to be a Jet??



R (isco) = 9 x Rg

a = -1

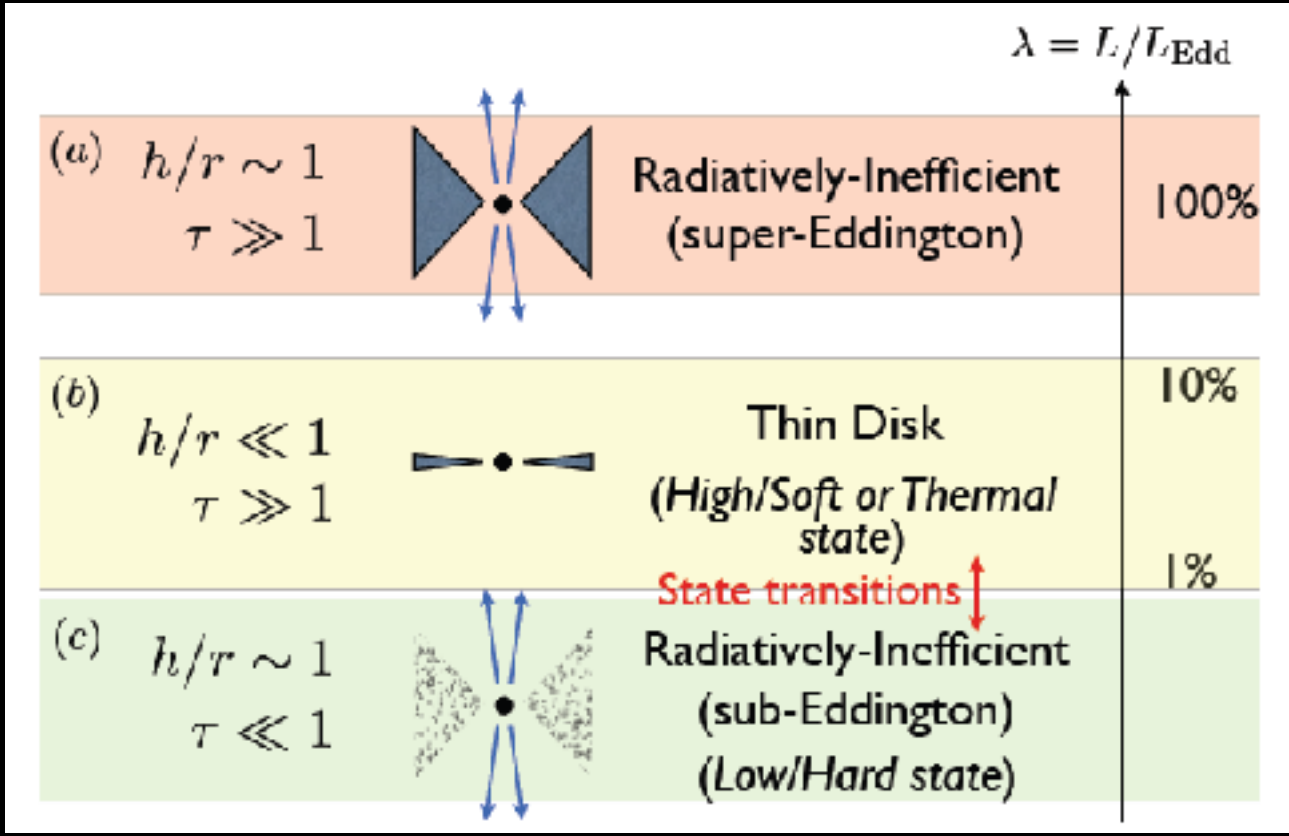
R (isco) = 6 x Rg

a = 0

R (isco) = Rg

a = +1

A major unsolved question in the study of AGN is what are the key parameters that drive radio loudness (e.g., Wilson & Colbert 1995, Best et al. 2005, Capetti & Balmaverde 2006, Sikora et al. 2007, Bagchi et al. 2014……..)



Observationally it is seen that jet production is strongly connected to the spectral-state of the accretion disk (FP of black hole activity)

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 Mpc radio jets found in some extraordinary radio loud spiral galaxies

At black hole accretion rates above a critical value

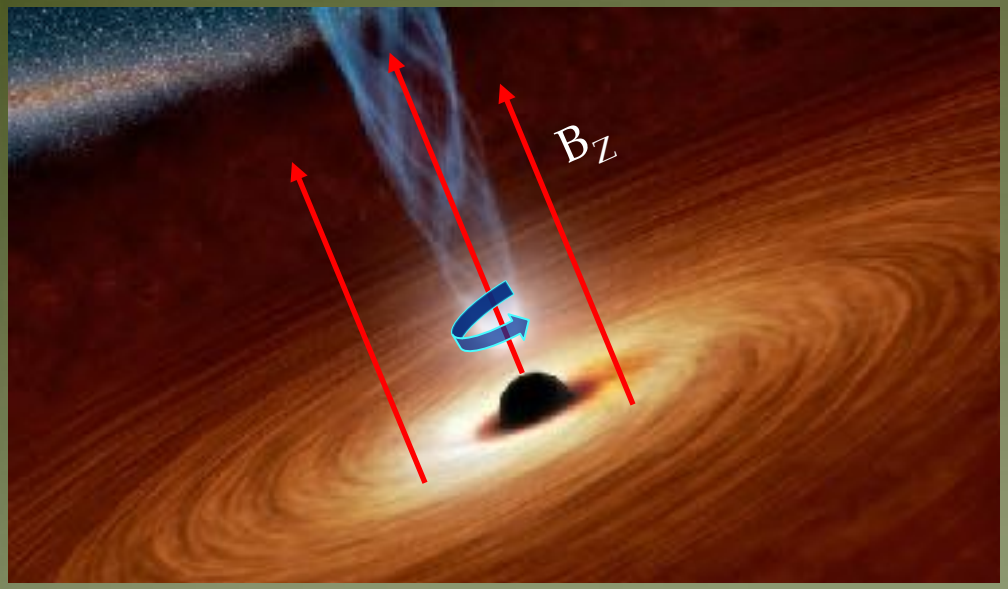
$$\lambda_{crit} \sim 10^{-2} - 10^{-3}, \text{ where } \lambda = [dm/dt] / [dm/dt]_{Edd}$$

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.

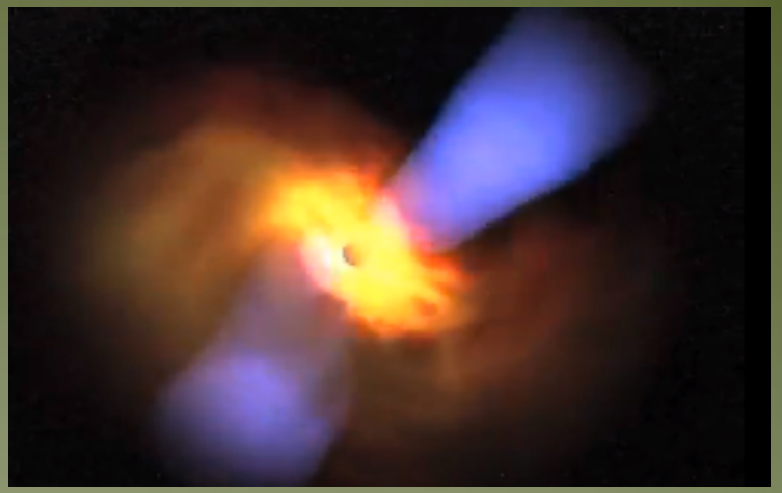
Narayan & Yi (1994, 1995), Abramowicz, Chen, Kato, Lasota & Regev (1995) etc.

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

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

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

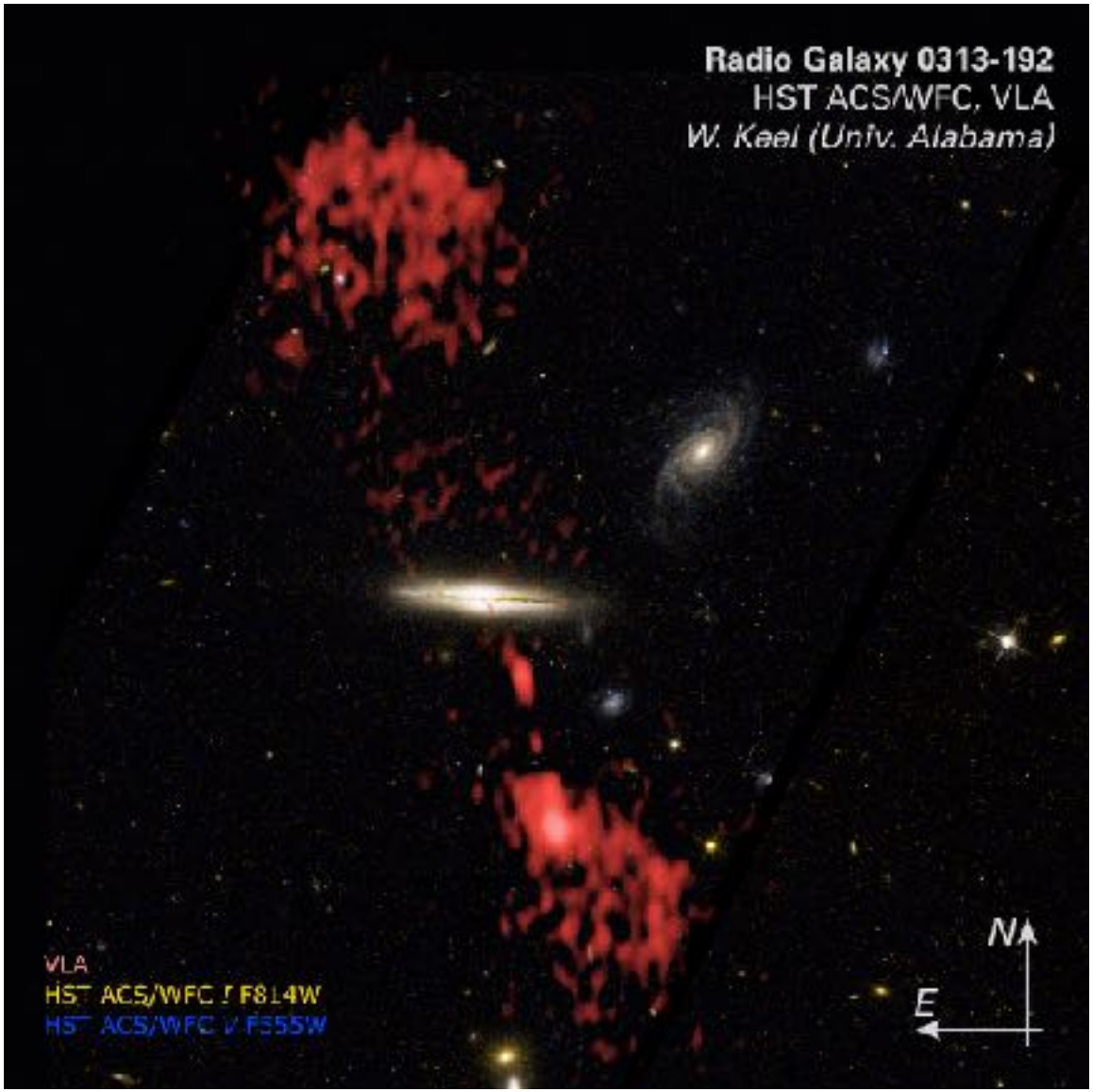
The answer is still hazy (as only a very few confirmed examples known) - **exceptionally rare event ! p < 1 in 1,00000 !**

Probably we have two important clues here:

Seyfert Galaxies : small ~ kiloparsec scale jets (almost there)

Extremely massive spirals : large Mpc

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



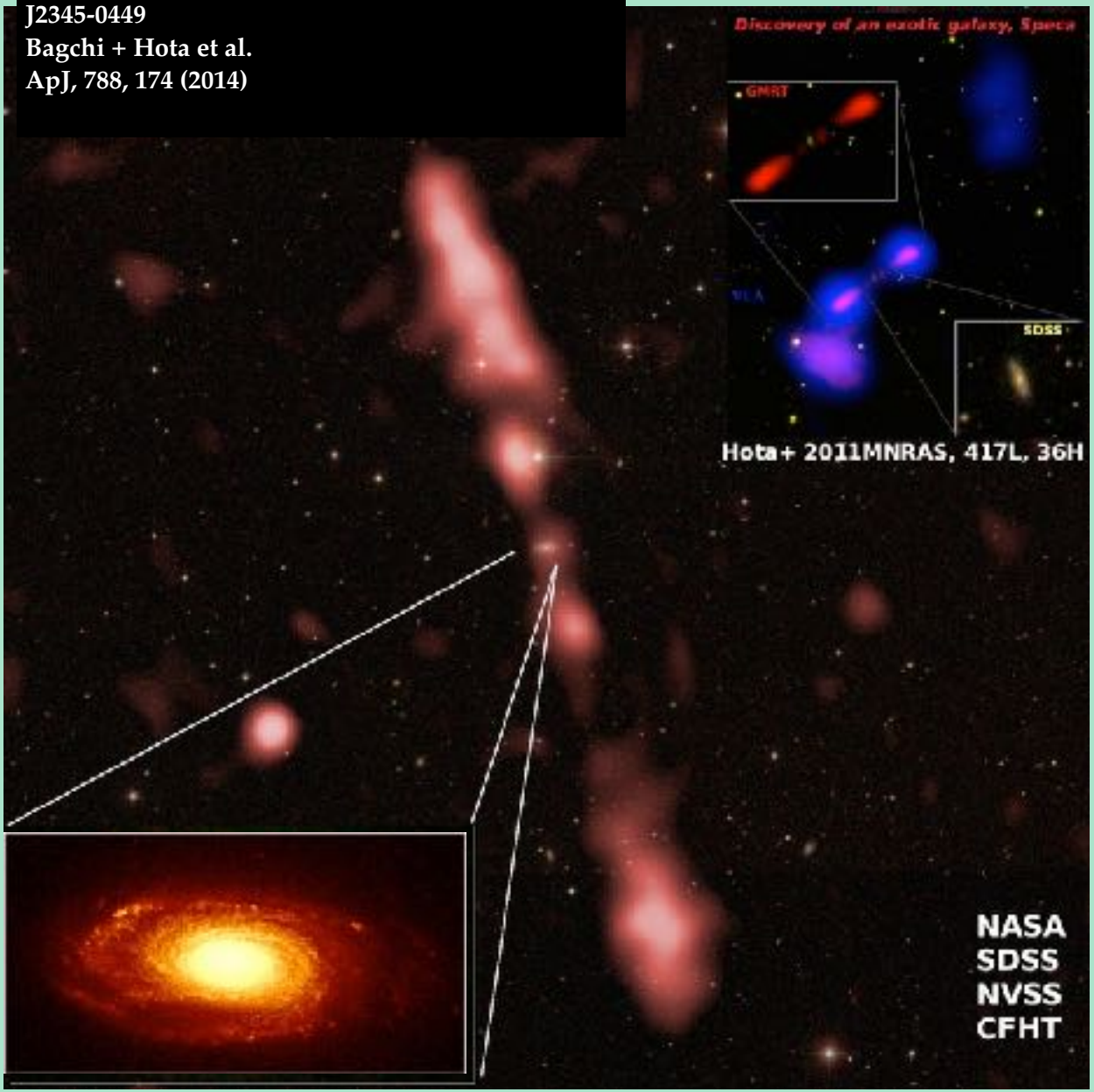
Ledlow, Owen & Keel (ApJ)

Recently, due to pioneering efforts of several Indian researchers, some extraordinary discoveries of > 100 kpc to ~2 Mpc scale highly relativistic jets in spiral galaxies have been reported for the first time in the history of radio astronomy !

These extraordinary sources may 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 giant ellipticals with bulges

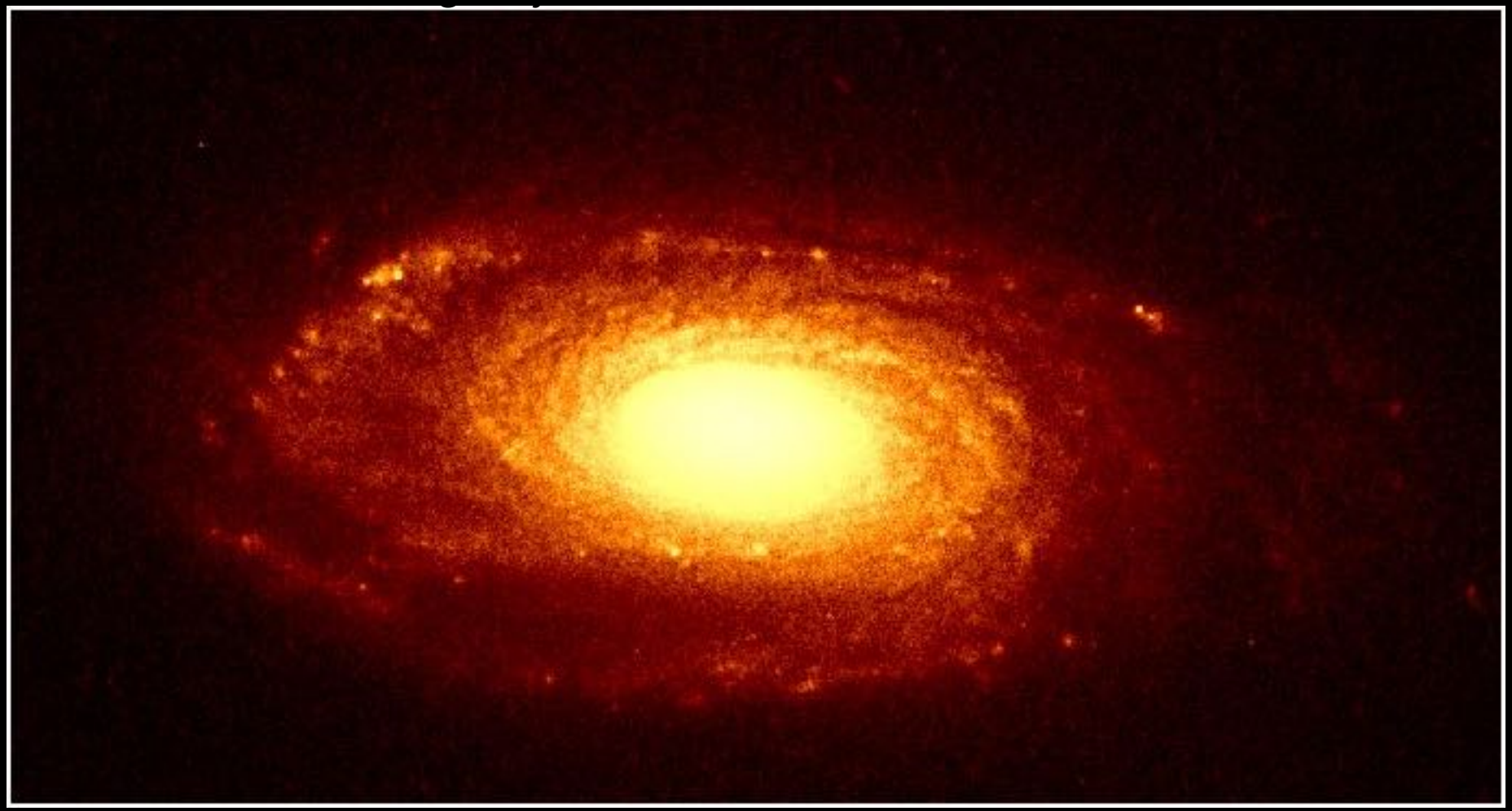
Ananda Hota et al. (2011), Joydeep Bagchi etal. (2014), Veeresh Sihgh et al. (2015), Preeti Kharb et al. (2014,..), Kaviraj (2013,2015).....

First clear examples of Mega parsec scale radio jets in a spiral host



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

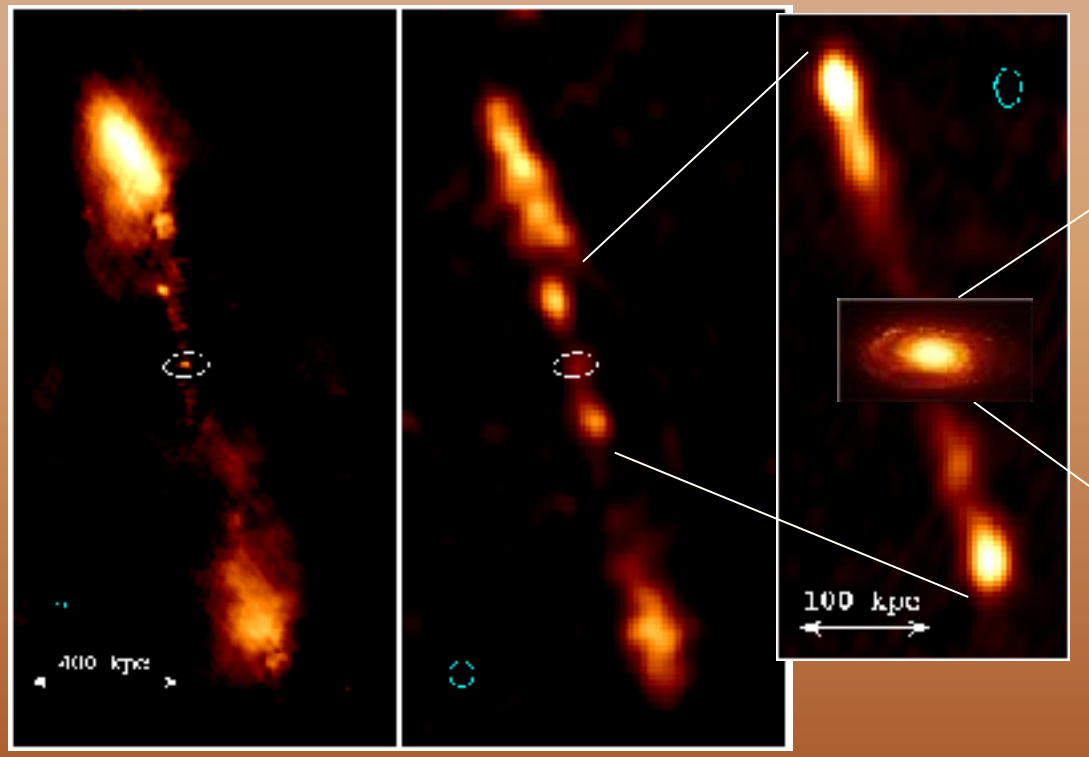
The low frequency imaging sensitivity of GMRT was essential !



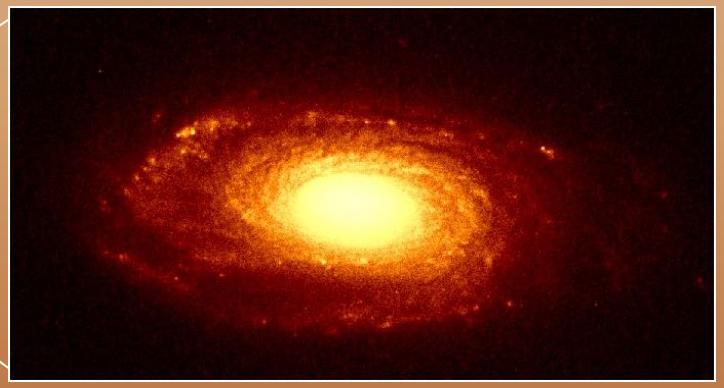
J. Bagchi et al., Astrophysical Journal, 788, pp 174 (2014)

Surprising 'double-double' radio-jets launched from an extreme spiral !

GMRT 325 MHz VLA 1.4 GHz VLA 4.8 GHz HST deep near-IR image

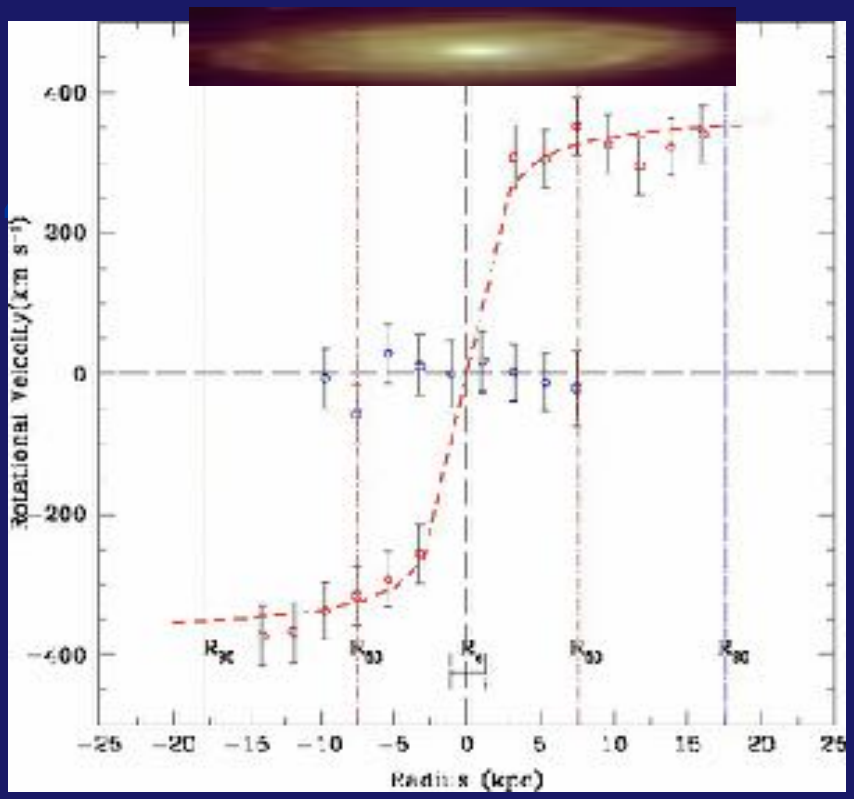


Redshift z = 0.075

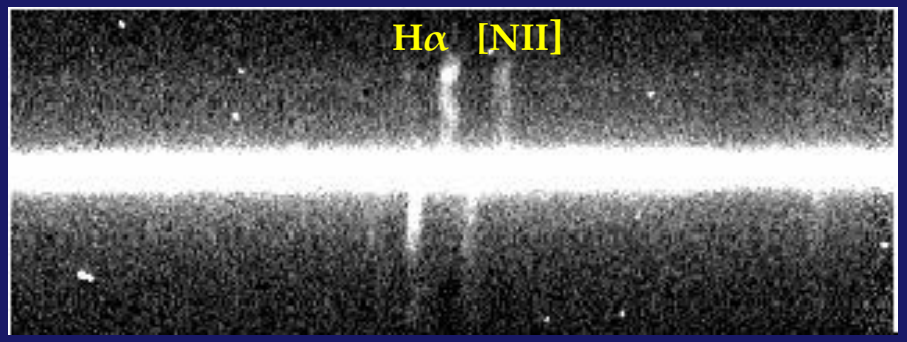


- Extremely rare occurrence of 1.6 Mpc scale relativistic jets emerging in a spiral galaxy - Twice! May be more? Challenges standard paradigms!
- A huge `double-double` structure two episodes of black hole jet activity
- Host spiral shows very fast flat rotation speed ~ 430 km/sec !
- Its central velocity dispersion is uncommonly large σ ~ 300 km/sec !

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



Tully-Fisher Relation



Long slit spectrum taken with IFOSC on IUCAA 2m telescope

An extremely massive galaxy is implied

$M_{dyn} \sim V^2 G / r$

$\sim$ **few x 10^{12} M_{sun}**

even at r < 20 kpc !

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 disk accretion in its formative stages ?

The central velocity dispersion σ ~ 350 km/sec is unusually high for a spiral galaxy and one <u>without a classical central bulge</u> !

⇨ **Huge central mass concentration**

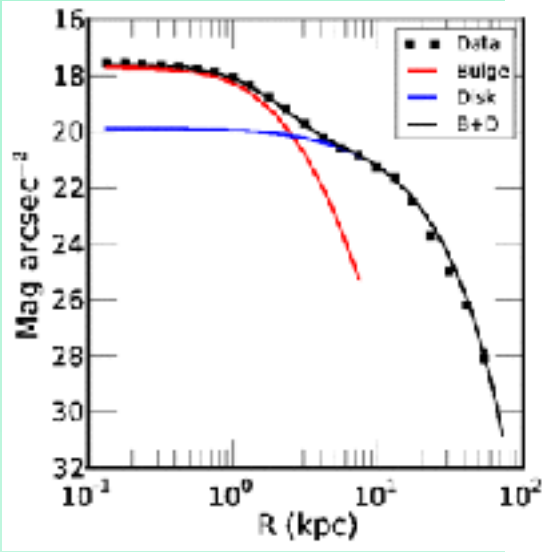
M_{Bulge} ~ 10^{11} M_{sun} ! How much of it is in a SMBH ??

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

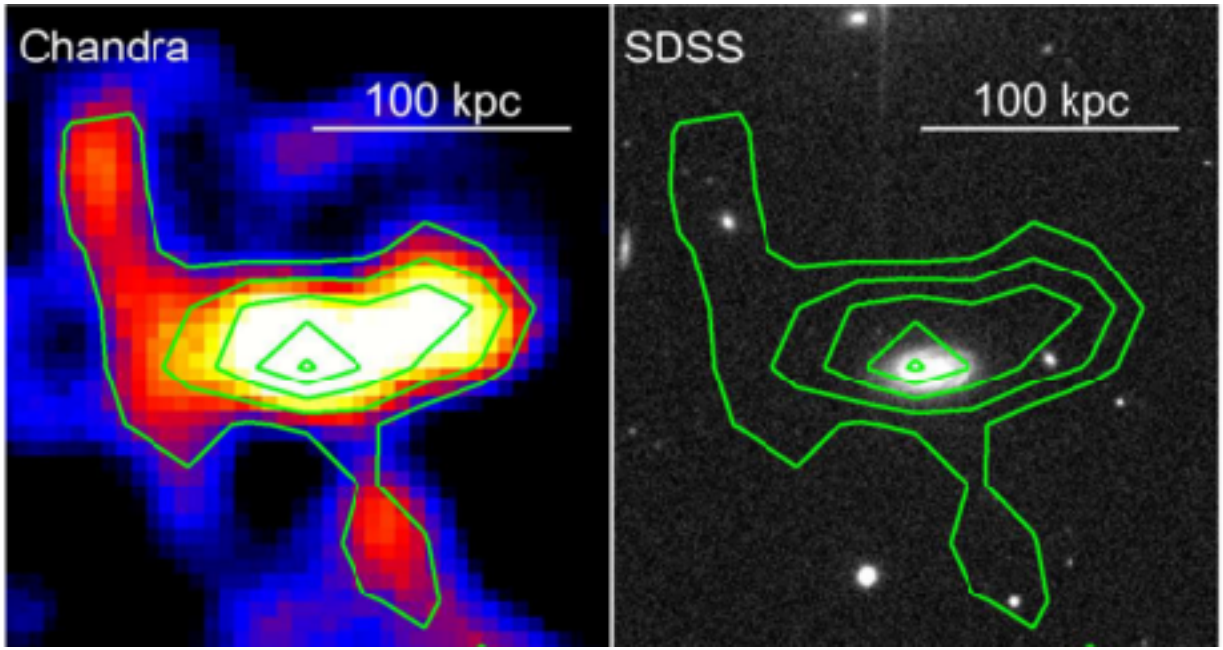
M_{BH} Vs σ^* Correlation

Bulge – disk modeling of host spiral shows

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

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

A faint, hot halo of 'missing' baryonic matter is detected around the massive spiral disk ! Very rarely it is seen.



Walker, Bagchi & Fabian

MNRAS, 449, 3527 (2015)

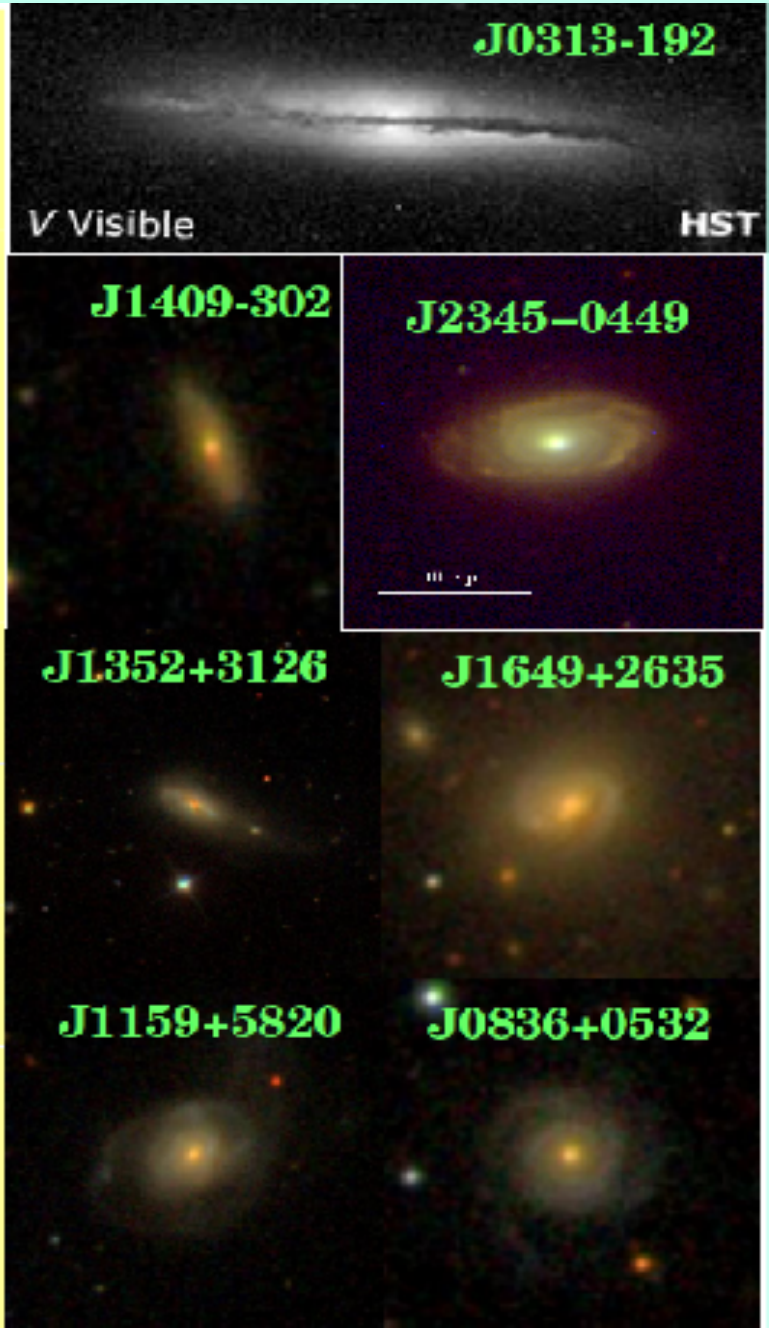
Such Xray halos are difficult to detect but expected from the formation scenarios of extremely massive galaxies

Provides information about the baryon budget and a clue to the rarefied "Working Surface" needed for radio lobe formation at Mpc distance. Possibly AGN is fuelled via hot-mode accretion as in RL Ellipticals ?

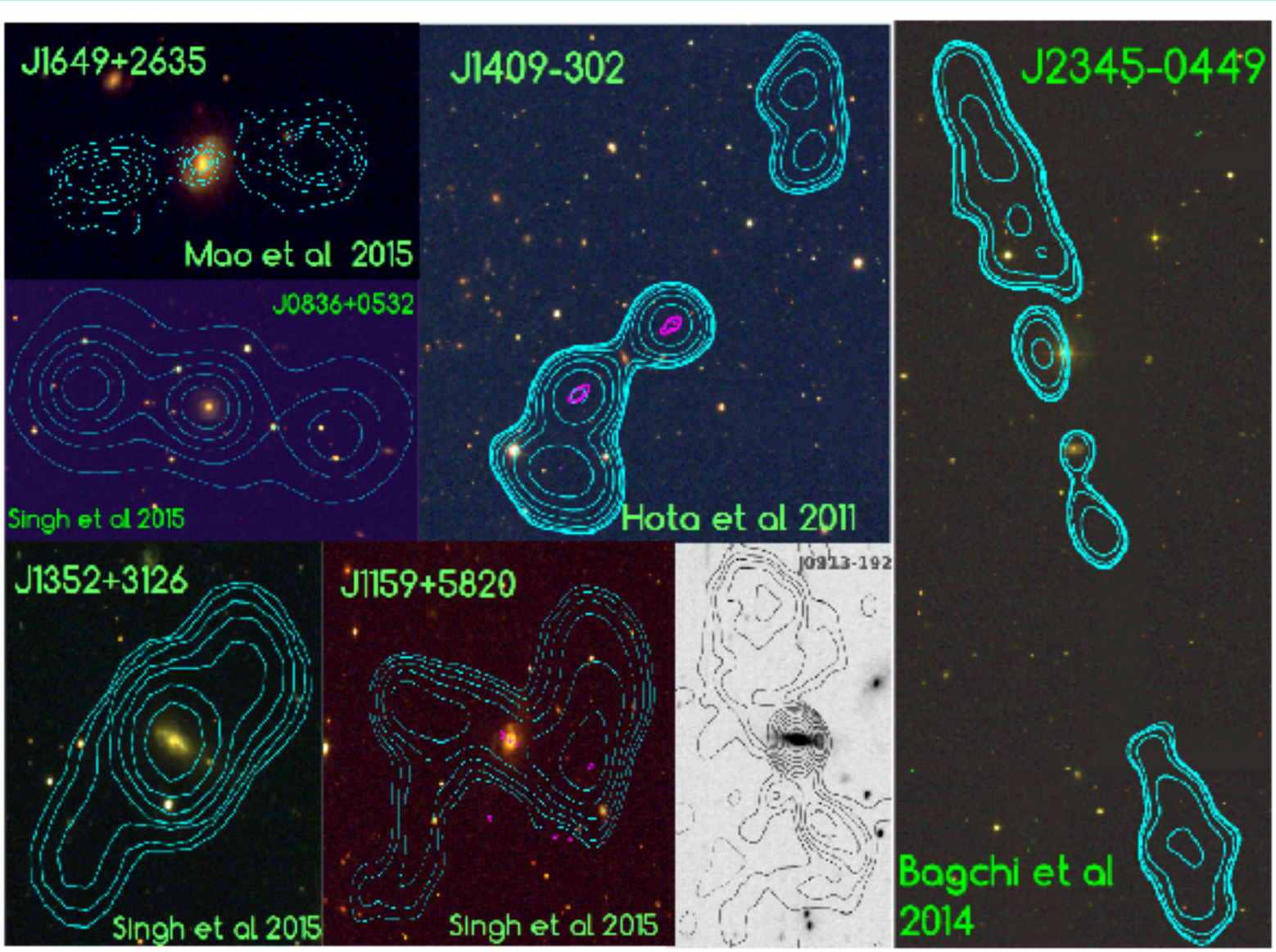
More detailed study are planned in UV (Astrosat) and X-rays (XMM-Newton). HST will observe this galaxy in September 2016

SPIRAL GALAXIES SHOWING LARGE-SCALE (> 100 kpc) RADIO JETS

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	"



Spiral galaxy with big jets: Rouges Gallery of 'Outlaws' (only 7 + 1 caught so far!)



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

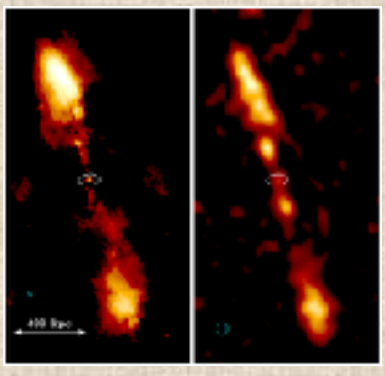
So far we have only two clear examples of spiral galaxies showing radio emission on > 1 Mpc scale !

& 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

Proposed SKA, LOFAR studies for jet-launching exotic spiral galaxies

A deep imaging search at low frequencies is necessary to find many more such Galaxies. What is the parent population? Are we only picking extreme objects so far? (Use wide-field optical surveys too)

Look for >100 kpc – Mpc scale jet – lobed double radio structures

Finding more double-double giant radio galaxies will be very interesting

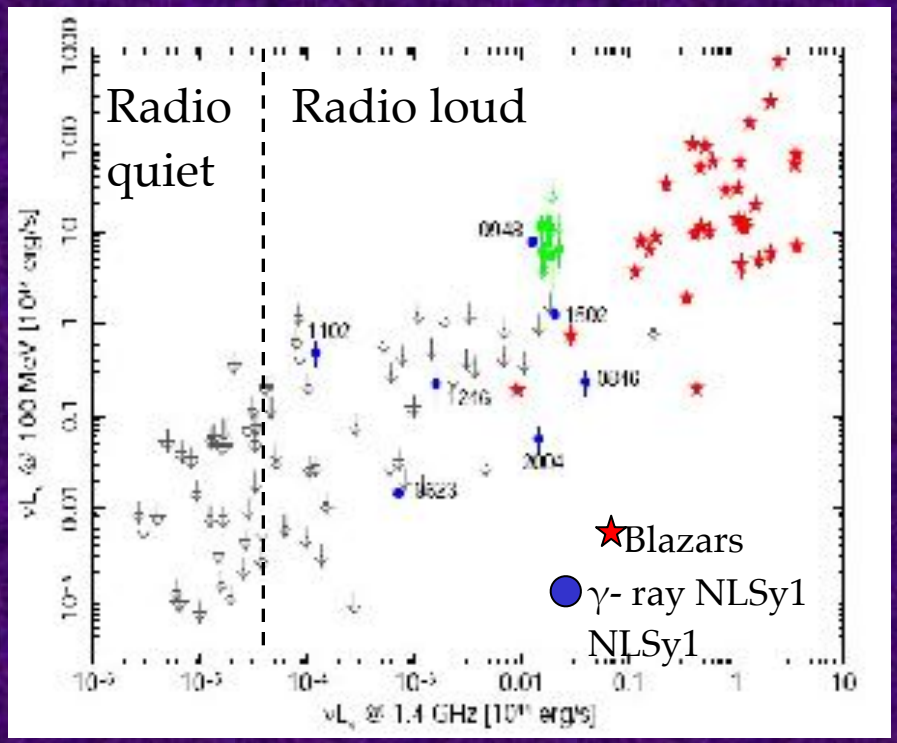
Construct a Radio Luminosity Function and compare with RLF of Normal radio loud galaxies associated with ellipticals

If we extend our search to higher redshift universe, do we find more Radio loud spiral galaxies? Go to $0.5 < z < 2$ or more

Are the low redshift spirals of extreme nature, 'Surviving Fossils' of once common activity? What is the reason that they are still active and show large scale radio jets, while at present most spiral galaxies are radio quiet or show no large scale jets?

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

However they are never emitters of > 100 kpc scale radio jets. Why? It's still a major 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, IR, 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 small mass 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, IR

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

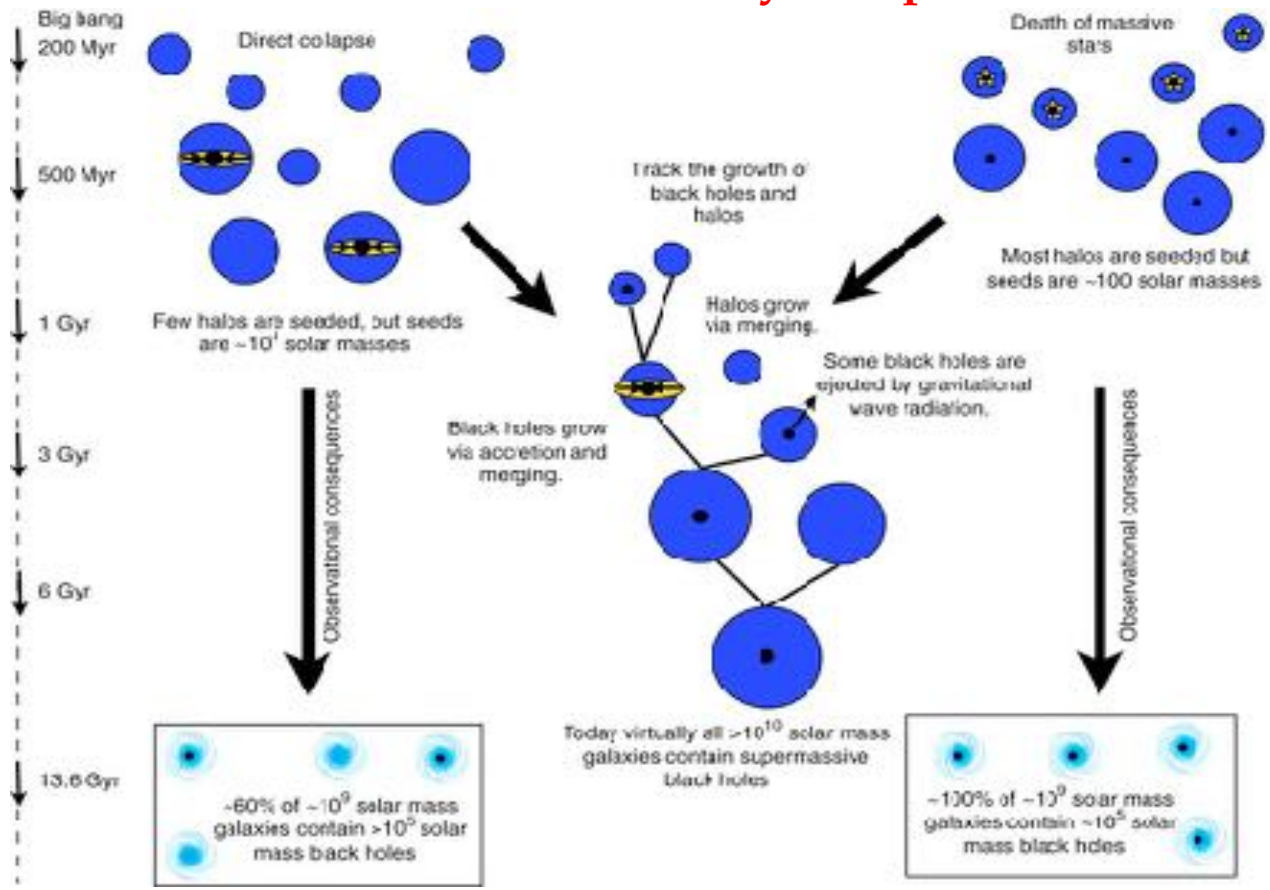
FR-II relativistic jets present

Possibly Pseudo-bulge host with super massive black hole ?

Black hole accreting at low Eddington rate ?

Do Spiral Galaxies Hosting Large-scale Radio Jets Host Unusually Massive BHs?

Evolution of seed black holes may take place via two major routes



Volonteri M., Lodato G., Natarajan P.

"The evolution of massive black hole seeds. "
Mon. Not. R. Astron. Soc. **383**, 1079–1088 (2008).

★ **Present Spiral Galaxies are believed to host only less Massive BHs (~10^{4-6} solar mass) BH mass in Milky Way Galaxy ~ 4 million solar mass**

★ **However all known radio-loud spirals (with >100 kpc jets) show BHs of masses > 10^{8-9} solar mass ! This is a very important fact which could have major implications if confirmed with more data! Are the low-mass spiral host radio-loud galaxies yet to be discovered? Need SKA/LOFAR/GMRT Observations**

Next Generation Wide-area radio surveys such as the

2011

2011

Why study of radio - AGN in spiral galaxies is desirable ?

Not just because they are there and 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 ~ 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 relativistic jets, and living 'fossils' of some sort

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. SPECA is peculiar too.

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.

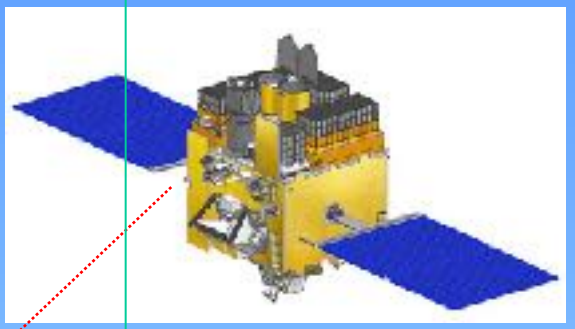
How did these spiral galaxy evolve to acquire these extraordinary range of properties? Need far better observations and simulations to find the answer.

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

"We dance round in a ring and suppose

But the secret sits in the middle and knows"

- Robert Frost



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