AGN in early Universe

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Active galaxies at different scales and wavelengths, Nizhny Arkhyz, Russia, October 14-17, 2024

Outline

- Background of this theme
    - Importance of AGN in early Universe
    - Latest advances and progress
- Detailed expansion of selected topics
    - Rapid growth of first-generation SMBHs via super-Eddington accretion
    - Dwarf Galaxies as Fossils of Early Seed BHs ?
    - Evolution of AGN cross comics eras
- Open questions and Perspectives

Important role of AGN in early Universe

- Unveiling Early Cosmic Structure Formation (SMBH, galaxy)
- Explaining Rapid Growth of Supermassive Black Hole
- Exploring Black hole - Galaxy Co-evolution and Feedback
- Probing Cosmic Reionization
- Chemical Enrichment of the Early Universe
- Cosmological Probes and Testing Comological Models
- More …

Detection Methods and Challenges for High-Redshift AGNs

Key Detection Methods:

1. Multi-Wavelength Approach: X-ray, optical/NIR spectroscopy, sub-mm detections.
2. JWST NIRSpec Contributions: Detects high-ionization lines (NIV, CIV), broad emission lines (Hβ), and Lyman-alpha break.

Challenges:

- Dust Obscuration: Optically faint AGNs.
- Redshift Uncertainty: ±0.2 offsets in estimates.
- AGN vs Star Formation: Difficulty separating contributions.

Complement Methods:

- Gravitational Lensing: Detects $z > 9$ AGNs.
- X-ray/Radio(eg. ALMA): Complements JWST in dusty/obscured AGN detections.

Typical Characteristics of z>5 Quasars

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High Luminosity:

- Lbol> 10^46 erg/s, more luminous than low-z

High Black Hole Mass in high-z quasars:

- SMBHs, often >10^9 M☉, challenging early growth models.

High Accretion Rate:

- sometimes exceeding the Eddington limit.

High Metallicity:

- Near or super-solar metallicy despite young age.

Powerful Outflows:

- Broad absorption lines and blueshifted emission indicate powerful outflows.

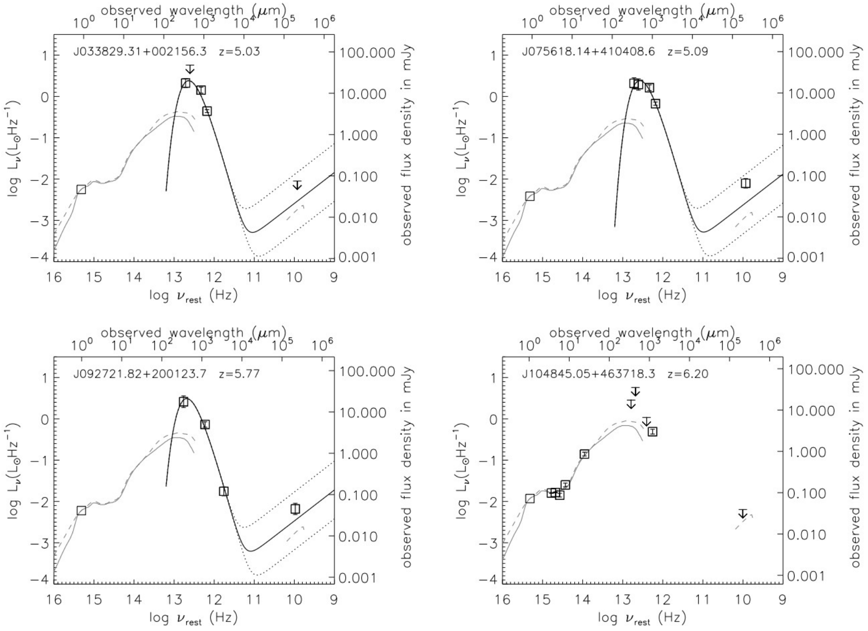
Comparison with Low-Redshift quasars:

- Emission Lines: Stronger Lyα, weaker C IV.
- Radio-Loud Fraction: Decreases at high redshift.
- Host Galaxies: Often unresolved in high-z AGNs.
- Environment: Found in overdense regions.
- Variability: May be less variable than low-z counterparts. But some with larger amplitudes

https://arxiv.org/pdf/0712.1612

SHARC-II Observations of z≥5 Quasars

- Detected FIR emission in 3 out of 4 quasars at z≥5.
- FIR luminosities of ~10^13 Lsun (**10^46 erg/s**), with dust temperatures of 39-52 K and dust masses ≥10^8 Msun.
- Emission suggests large amounts of warm dust in quasar host galaxies by z~6.
- FIR-to-radio SEDs point to star formation-driven processes.
- Rapid dust formation mechanisms are required to explain the significant dust mass at such early epochs (~1 Gyr after the Big Bang).

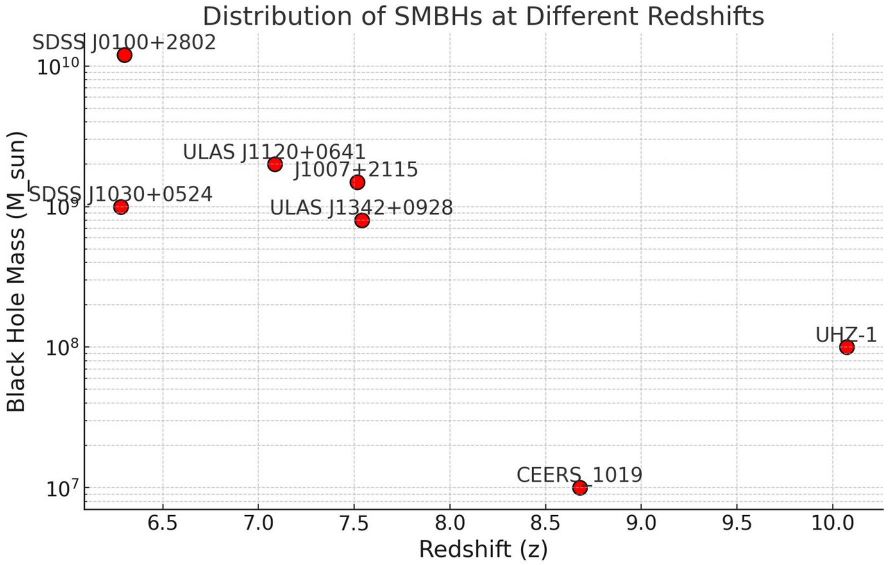


optical-to-radio SEDs of the four quasars, three show FIR excess, compared to local quasar templates (Wang Ran et al. 2008)

Rapid growth of early SMBHs
via super-Eddington accretion

High-Redshift Quasar Discoveries

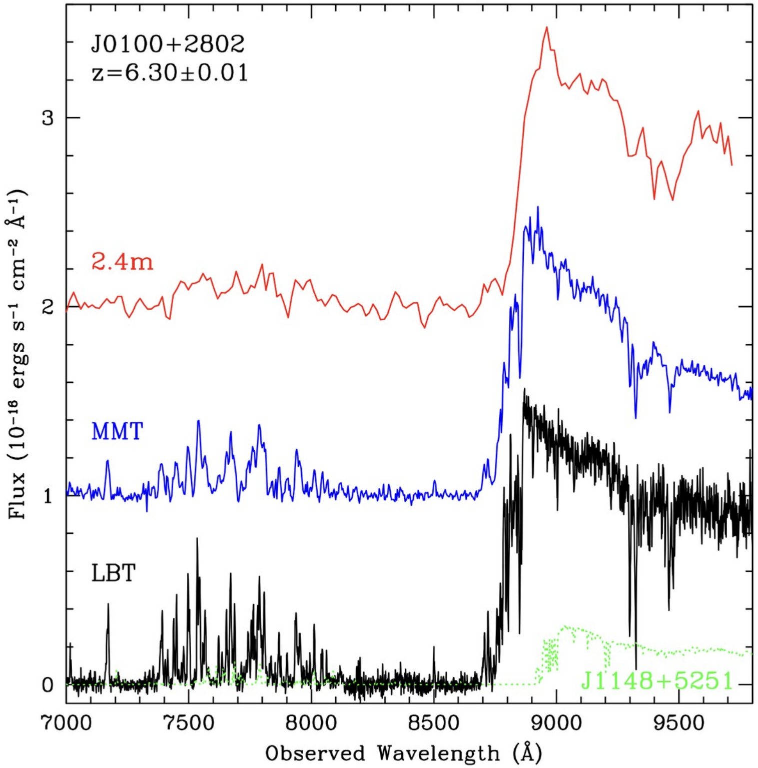
- ***UHZ-1 (z = 10.073)***: Earliest SMBH (~500 Myr post-BB). 10^7–10^8 M☉; M_BH/M⋆ ratio 2-3 orders above local values.
- ***CEERS_1019 (z = 8.679)***: M_BH ~ 10^7 M_☉. 1.2× Eddington; high star formation.
- ***~50 AGN candidates at z > 6.*** Broad-line AGN found by JWST
- ***ULAS J1342+0928***: BH ~8 × 10^8 M_☉ at z=7.54 (690 Myr old universe) [Bañados et al., 2018].
- ***J1007+2115***: BH ~1.5 × 10^9 M_☉ at z=7.515 [Yang et al., 2020].
- ***ULAS J1120+0641***: Black hole ~2 × 10^9 M_☉ at z=7.085 (770 Myr after Big Bang) [Mortlock et al., 2011].
- ***SDSS J0100+2802***: Black hole ~1.2 × **10^10** M_☉ at z=6.30 [Wu et al., 2015].
- ***SDSS J1030+0524:*** Early quasar at z=6.28 with ~10^9 M_☉ [Fan et al., 2001].



- **SMBH Formation and Rapid Growth Mechanisms (z = 6–10)**
- **Turnover of Mass Distribution at z~6? and Why?**

SDSS J0100+2802: An Extreme High-Redshift Quasar

- Discovery: Wu et al. (2015), Nature, 518, 512
- Extreme Properties: z = 6.30, M_BH ~ 10^10 M_⊙. Most massive/ luminous quasar known at z>6
- Growth Challenges: Implies massive seeds or sustained super-Eddington growth.
- Lensing Debate: Evidence against significant lensing: X-ray, Lyα zone, and JWST observations.
- Environment: Found in a large-scale overdensity of galaxies.
- Its existence and properties continue to **challenge our understanding of black hole formation and growth in the first Gyr after the Big Bang.**



Initial Black Hole Seeds:

- Core-collapse of Massive Stars:
  - Collapse of stars >30M☉ forms stellar BH seeds, but growth is often limited by feedback from stellar radiation.
- Dynamical Evolution of Star Clusters:
  - Runaway collisions form intermediate-mass black hole seeds (~10^3-10^4 M☉), though efficiency is limited by disruptive dynamics.
- Direct Collapse of Metal-Free Gas Clouds:
  - Primordial gas collapses into massive black holes (10^4-10^6 M☉), though fragmentation often inhibits direct collapse into massive seeds.

Formation Mechanisms for High-z SMBHs: pathways for growth

- Rapid Accretion:
  - Gas-rich environments enable super-Edd accretion, esp in dense galactic nuclei.
- Black Hole Mergers:
  - Mergers between galaxies also lead to black hole mergers, boosting SMBH mass.
- Gas Dynamics in Overdense Regions:
  - Overdense, high-redshift environments favor rapid gas inflow, aiding SMBH growth through the interplay of accretion and mergers.

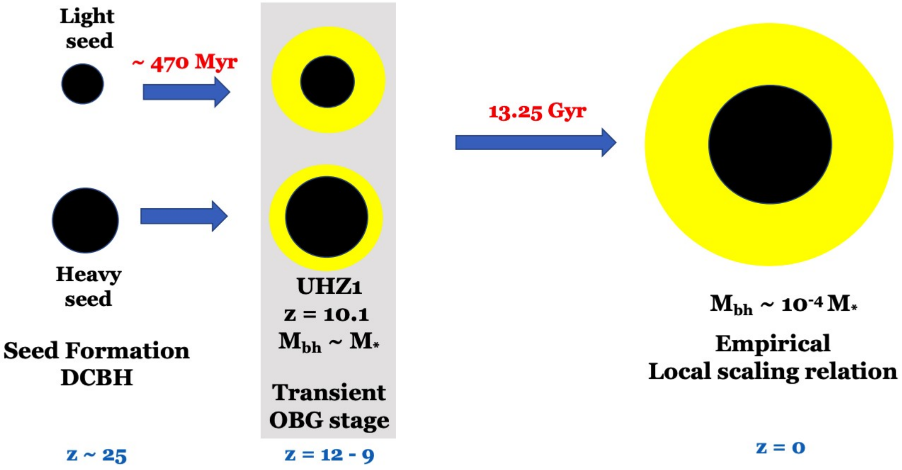
UHZ-1: A High-Redshift Overmassive Black Hole Galaxy

Detected at z ~ 10.3 (~450 Myr post-Big Bang).

Black hole mass ~4 × 10^7 M_☉; bolometric luminosity ~5 × 10^45 erg/s.

Classified as an Overmassive Black Hole Galaxy, likely formed by direct collapse of heavy BH seeds.

X-ray to IR flux ratios, redshift, and SED match OBG characteristics.



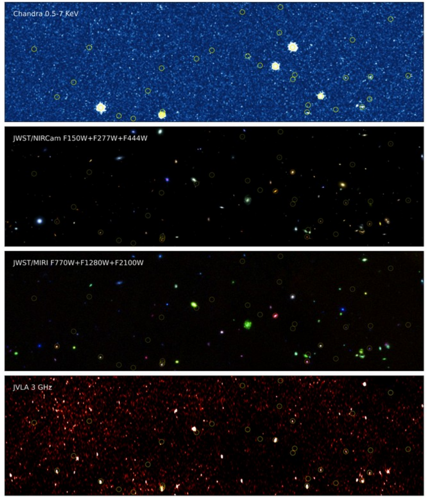
https://arxiv.org/abs/2308.02654

Super-Eddington Accretion and High-Redshift SMBH Growth

- Theoretical Support:
  - Super-Eddington accretion aids rapid SMBH growth, with episodes lasting tens of Myr, leading to $\sim 10^9$-$10^{10}\ M_\odot$ SMBHs.
  - Reduces need for heavy SMBH seeds.
- Observational Evidence:
  - Presence of $\sim 10^9\ M_\odot$ black holes at $z \sim 7.5$ and $\sim 10^{10}\ M_\odot$ at $z \sim 6.3$ indicates rapid growth, likely involving super-Eddington phases.
  - JWST: SMBHs at $z \geq 6$ are significantly more massive than expected compared to the local M_{BH}-stellar mass relation, suggesting very rapid accretion.
  - Observed characteristics (e.g., absence of X-ray emission) match super-Eddington accretion.
- Challenges:
  - Difficult to sustain over long periods. Typically brief growth phases.
  - Feedback mechanisms and jets regulate growth, limiting super-Eddington rates to ~2-3 times Eddington
- Conclusion:
  - Strong observational support, but sustaining conditions remain a challenge.

JWST Discovery: Faint Dusty AGNs at High Redshifts

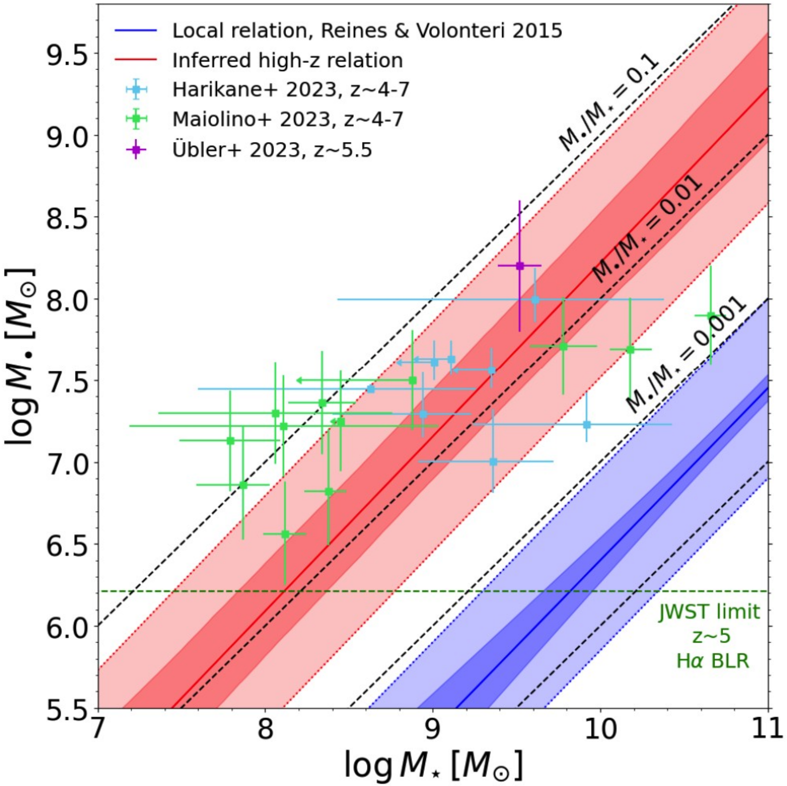
- JWST's SMILES survey (MIRI) identified 217 AGN candidates, including 20 at z~4-8.4. 80% are new
- Compact, point-like sources, with bimodal SED and faint magnitudes; Mostly obscured, increasing obscuration with z
- Implications for Early Black Hole Growth:
  - Accreting black holes with masses of ~10^6-8 M☉.
  - Growth is consistent with super-Edd accretion models.
  - Potentially descendants of heavy black hole seeds.



https://arxiv.org/pdf/2310.12330 Systematic Mid-infrared Instrument Legacy Extragalactic Survey (SMILES).
https://arxiv.org/abs/2305.14418 Extremely red galaxies at z=5−9 with MIRI and NIRSpec: dusty galaxies or obscured AGNs?
https://arxiv.org/abs/2409.07805 Extremely Dense Gas around Little Red Dots and High-redshift AGNs: A Non-stellar Origin of the Balmer Break and Absorption Features
https://arxiv.org/abs/2305.12504 Are we surprised to find SMBHs with JWST at z > 9?
https://arxiv.org/abs/2409.07805 Extremely Dense Gas around Little Red Dots and High-redshift AGNs: A Non-stellar Origin of the Balmer Break and Absorption Features

High-Redshift BH-Galaxy Mass Relations: Insights from JWST

- Significantly different M•-M relation at z=4-7 vs. local universe.*
- High-z black holes are 10-100 times more massive than predicted by local galaxy mass relations.
- **Suggests rapid black hole growth relative to host galaxies in the early universe.**
- Predicts an abundance of low/intermediate-mass black holes at high z.



https://arxiv.org/pdf/2308.12331

LID-568: A Super-Eddington Accreting BH at High Redshift

- Extreme Growth: 7.2 × 10^6 M_☉ black hole at z~4, accreting at 4000% Eddington.
- AGN Outflows: -600 km/s H-alpha emission indicates strong AGN-driven feedback.
- Unique AGN Population: Faint, dusty AGN at high-z; bright in X-rays.
- Distinct SED: Extremely red IR slope, unlike current AGN templates.
- Implications: Supports rapid black hole growth, new constraints on seeding models, unexplored accretion regime.

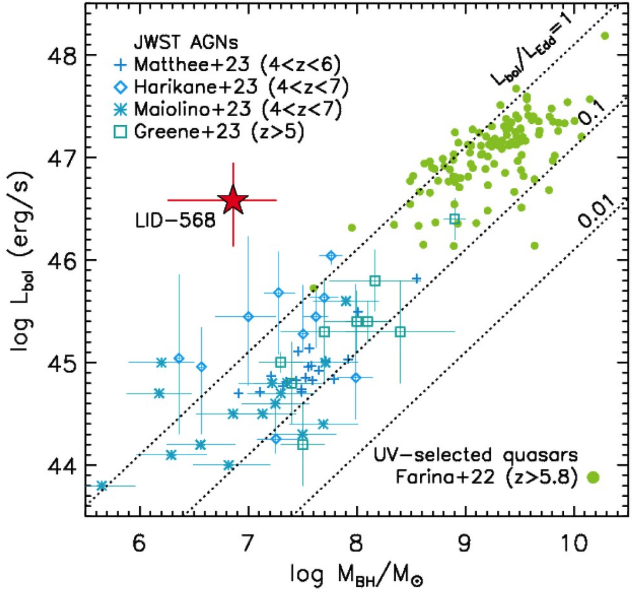


Figure 2. AGN bolometric luminosity (L_{bol}) versus black hole mass (M_{BH}) of AGNs at high redshift. LID-568, with super-Eddington accretion (L_{bol}/L_{Edd}~41.5) at z~4, is shown as a red filled star. Its X-ray-derived bolometric luminosity is approximately a factor of ~100 higher than that of faint AGNs at z~4-7 with low-mass black holes[2,3,5,6] recently found by JWST observations. For reference, we also show the UV-selected quasars at z>5.8[12].

https://arxiv.org/pdf/2405.05333

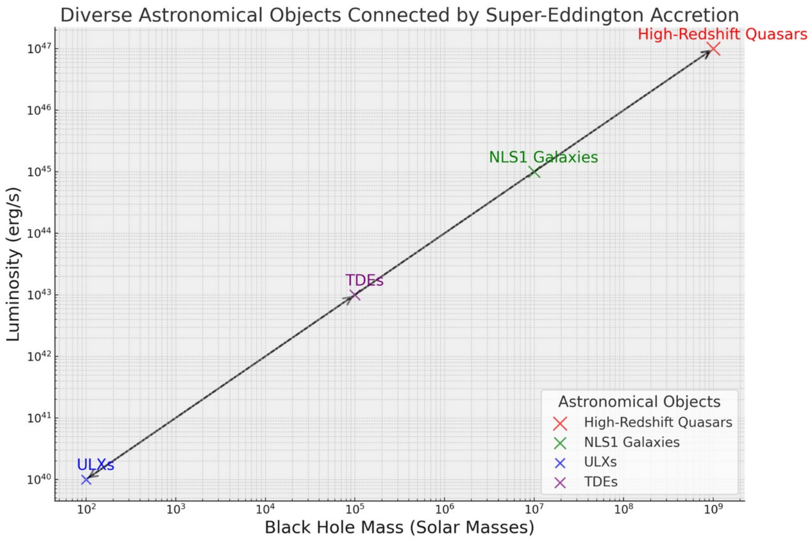
Super-Edd Accretion Across Diverse Astronomical Objects

High-Redshift Quasars: Early cosmic growth of SMBHs (~10^9 M_☉) through rapid, super-Eddington accretion.

NLS1 Galaxies: Low-mass BHs (~10^6-10^8 M_☉) with high accretion rates, e.g., RX J0134.2-4258 at 20× Eddington limit.

Tidal Disruption Events (TDEs): Stars disrupted by BHs, leading to short-term super-Eddington accretion phases.

Ultraluminous X-ray Sources (ULXs): Stellar-mass BHs with super-Eddington luminosities; anisotropic emission complicates mass estimates.



Connecting Masses and Luminosities:

- BH masses range from stellar (~10^2 M☉) to supermassive (~10^9 M☉).
- Super-Eddington systems exhibit extreme luminosities due to rapid mass growth and anisotropic effects.

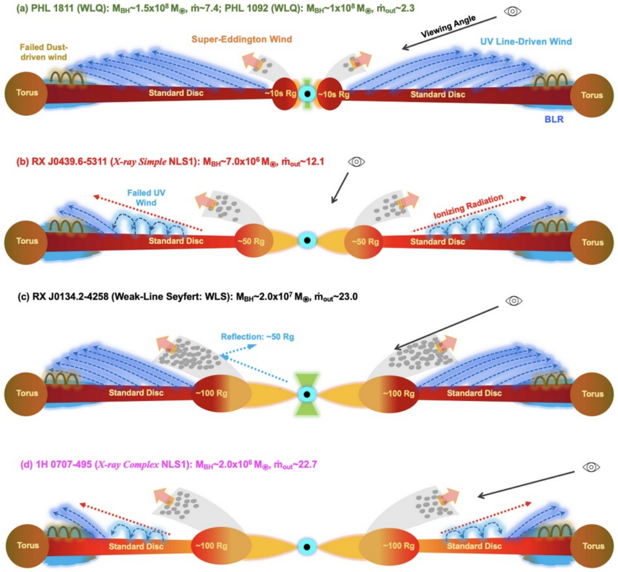
Super-Eddington Accretion in NLS1 Galaxies

Accretion Rates: ~20xEddington limit, observed luminosity ratio of Lbol/LEdd ~ 6

Black Hole Growth: Low-mass black holes 10^6-7Msun, with growth limited by mass supply, not the Eddington limit.

Luminosity: Saturation suggests Kerr (rotating) black holes are involved.

Others: weak emission lines; Low Temperature, Optically Thick Coronae; Drastic X-ray Variability; multi-phase outflows on parsec scales; reduced radiative efficiency; associated with late-stage galaxy mergers



Extreme Super-Eddington NLS1 RX J0134.2-4258 (Jin et al. 2022)

Role of Radio Studies in NLS1 Galaxies

- **Jet Properties**: Radio observations reveal jet formation in super-Eddington systems, challenging traditional jet models.
- **Radio Loudness**: Helps classify NLS1s and explore the link between accretion rate and jet formation.
- **Multi-Wavelength Campaigns**: Radio data contribute to broadband SEDs and studies on super-Eddington energetics.
- **Outflows & Feedback**: Reveals outflows impacting the efficiency of accretion processes.

Key findings:

- **Radio Morphology**: 50% show core-jet structures, others compact cores with kpc-scale jets.
- **Spectral Characteristics**: Diverse, with flat/inverted or steep spectra; gamma-ray NLS1s show more variability.
- **Brightness Temperatures**: 10^8.4-11.4 K, lower than blazars, indicating non-thermal jet emission.
- **Radio Loudness**: Some highly radio-loud (R > 100), with varying jet properties.
- Mildly to moderate relativistic jets in high accretion systems
- **Host Galaxy Interaction**: Star formation may contribute to radio emission.

Radio Observations of Narrow-Line Seyfert 1 (NLS1) Galaxies

Radio Morphology: NLS1s show diverse structures—50% with compact cores, others with core-jet structures, some even have kpc-scale jets.

Radio Loudness: 7% of NLS1s are radio-loud, with extreme cases having R > 100.

Spectral Characteristics: Radio-quiet NLS1s have steep spectra, while radio-loud ones show flat or inverted spectra.

Jet Properties: Some NLS1s exhibit relativistic jets, with speeds > 10c, indicating blazar-like activity.

Accretion: Jet power scales with both black hole mass and accretion rate, challenging traditional models.

Host galaxy interactions: SF may contribute to radio emission in lower luminosity NLS1s

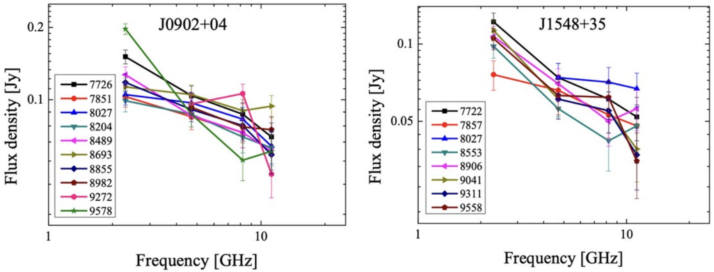


Figure 1: Radio spectrum evolution of two NLS1s not emitting γ-rays: J0902+04 (left) and J1548+35 (right).

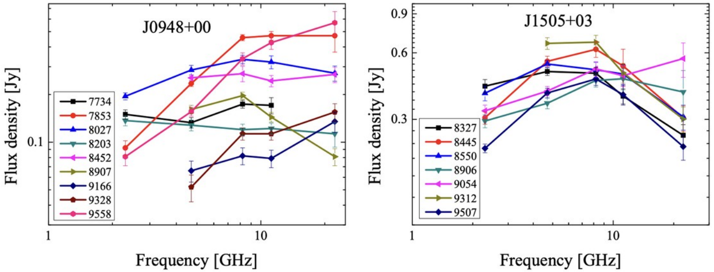
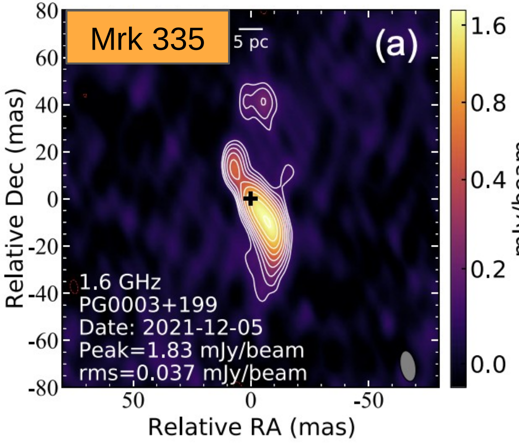


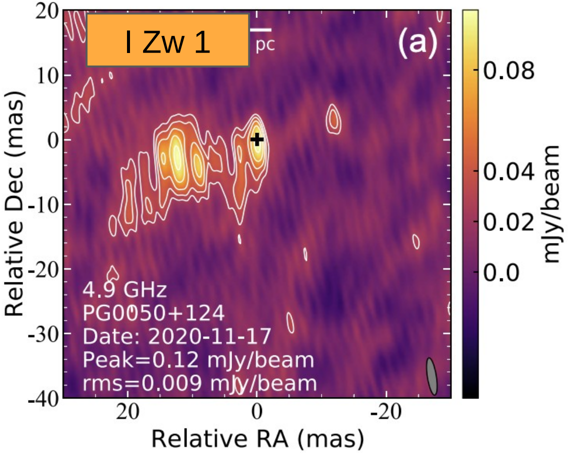
Figure 2: Radio spectrum evolution of two γ-ray emitting NLS1s: J0948+00 (left) and J1505+03 (right).

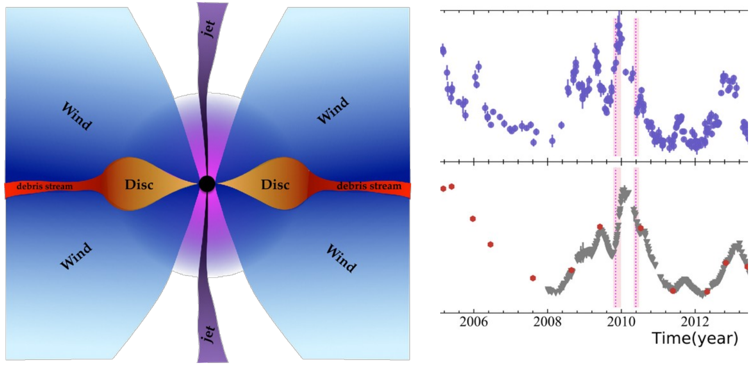
Study of the radio spectra evolution of Narrow-line Seyfert 1 galaxies with **RATAN-600** **A. Mikhailov**, **Y. Sotnikova**, **T. Mufakharov**, **M. Mingaliev**, **T. Semenova**

VLBI Observations of two radio-quiet NLS1s Mrk 335 and I Zw 1

- **Mildly Relativistic Jets**: Radio-quiet NLS1s harbor weaker, less aligned jets compared to radio-loud counterparts.
- **Jet dominance:** radio morphology, steep spectra indicate extended jets as the primary source of VLBI structure.
- **Distinct AGN Class**: High accretion rates with lower BH masses suggest NLS1s form a unique AGN category.
- **Jet Formation**: Relativistic jets in some NLS1s provide crucial data on jet formation under super-Eddington accretion conditions.
- I Zw 1 study suggests that super-Eddington accretion may drive powerful outflows, leading to jet instabilities and complex interactions between the disk, wind, and jets, influencing the overall jet properties (see III Zw 2).







Wang, An et al. 2023c: jet-disk wind Interactions in a nearby radio intermediate quasar III Zw 2

Wang, An, et al. 2023a, b; Yao et al. 2021; Alhosani et al. 2022; Chen et al. 2023

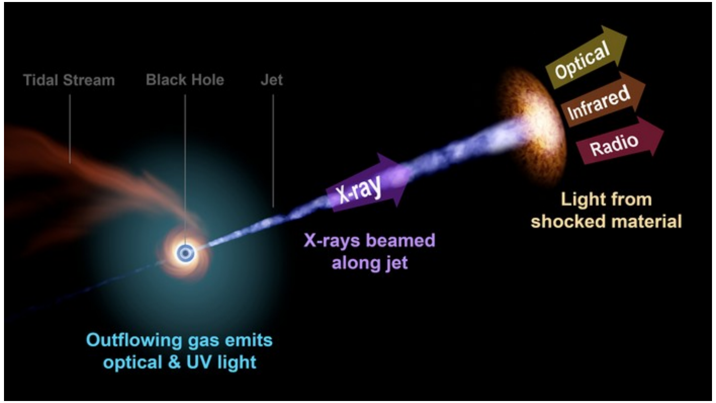
Super-Eddington Accretion in TDEs

Super-Eddington Accretion: >20x Edd limit, L~>10^44 erg/s

Outflows and jets: Strong outflows 0.1-0.3c and relativistic jets are common, with speeds up to 0.7c.

Spectral Features: Dominated by thermal X-ray emission; some show ionized absorbers or disk reflection.

Cosmological Relevance: May explain rapid, episodic SMBH growth in the early universe, observed in high-z SMBHs by JWST.



Radio observations of TDEs

Late-Time Emission: ~40% of optical TDEs show radio brightening hundreds to thousands of days post-discovery, with luminosities (10^37-39 erg/s) much lower than relativistic TDEs like Sw J1644+571.

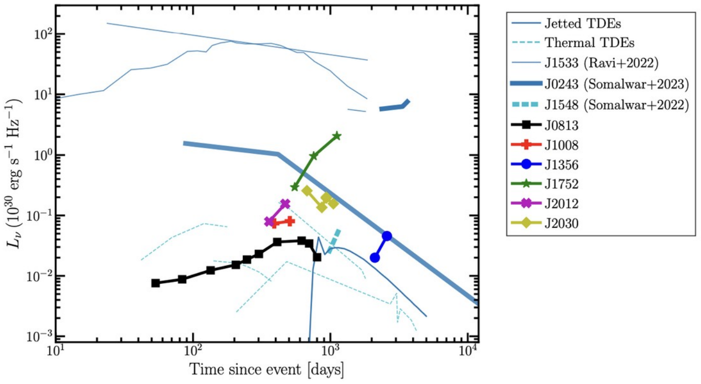
Outflows: Delayed, non-relativistic outflows with velocities 0.02c-0.15c and kinetic energies up to 10^49 erg are common. rule out off-axis relativistic jets as late-time radio emission

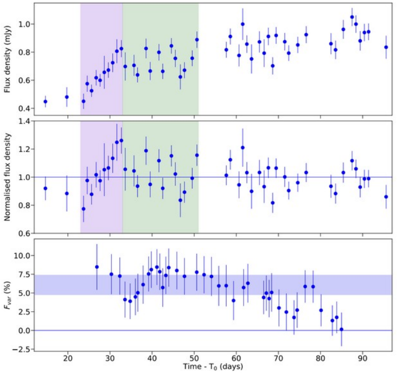
Circumnuclear Medium: Dense environments can enhance radio emission in distant TDEs.

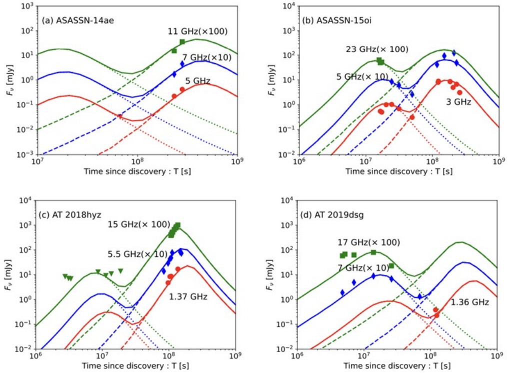
Radio-selected TDEs: more energetic, larger radio emittin regions, faint and cool optical flares, lower BH mass -> Super Edd accretion and enhanced circumN environments

Jet Models: Some TDEs show late-time rebrightening due to axis two-component jets.

Rate of radio-emitting TDEs $\gtrsim$ 10 Gpc^{-3} yr^{-1} (0.1%-1% of all)

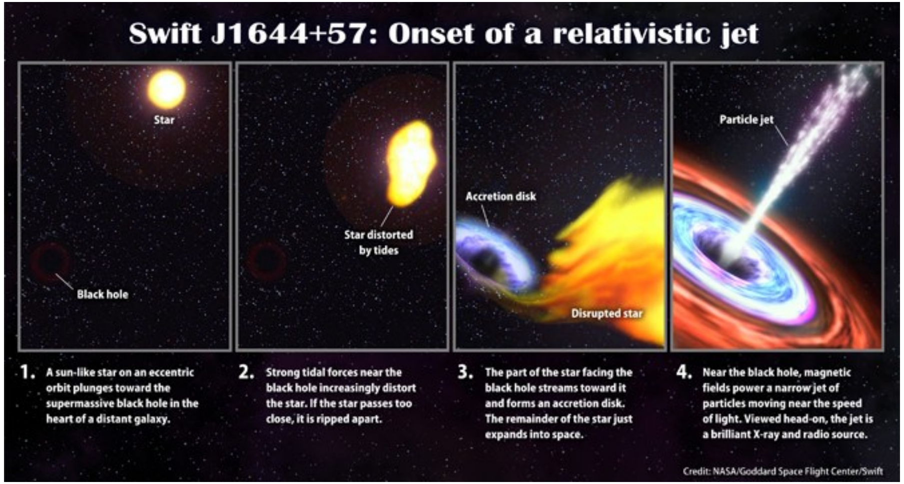






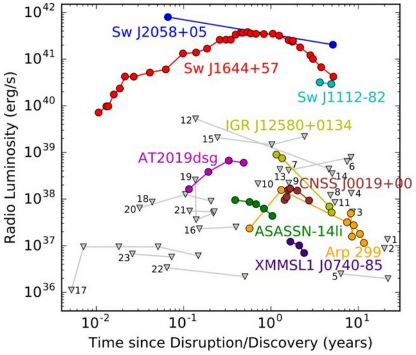
Diversity of radio TDEs

Radio emission: jets, disk winds, delayed outflows
Relativistic jetted: Sw J1644+57
Resolved relativistic jet: Arp299-B AT1
Non-relativistic jet: AT2019dsg; (wind-cloud)
Relativistic outflow: AT2022mc
Only a small fraction of TDEs launch relativistic jets, likely influenced by black hole spin.

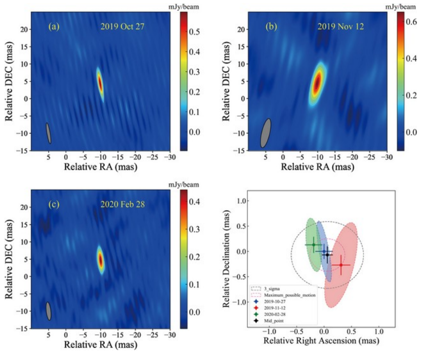


1. A sun-like star on an eccentric orbit plunges toward the supermassive black hole in the heart of a distant galaxy.
2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.
3. The part of the star facing the black hole streams toward it and forms an accretion disk. The remainder of the star just expands into space.
4. Near the black hole, magnetic fields power a narrow jet of particles moving near the speed of light. Viewed head-on, the jet is a brilliant X-ray and radio source.

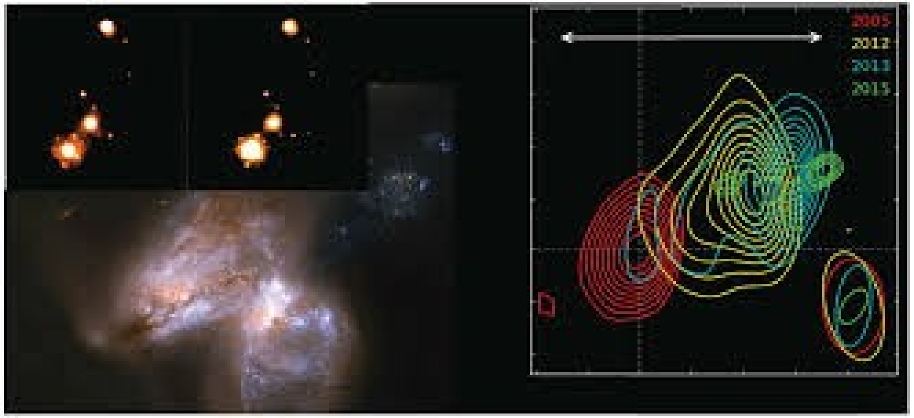
Credit: NASA/Goddard Space Flight Center/Swift



Alexander et al. 2020



Mohan, An, Yang, 2020



; Mattila et al. 2018

Ultra-Luminous X-ray Sources (ULXs)

Definition: extreme sources with X-ray luminosities >10^{39} erg/s, exceeding the Eddington limit for stellar-mass black holes.

Nature: Powered by **super-Eddington accretion** onto stellar-mass black holes or neutron stars. Other interpretations.

Super-Eddington Features:

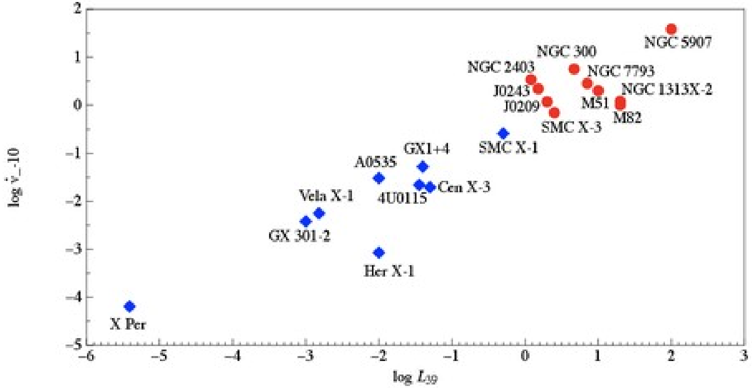
- **Disk Structure**: Radiation-dominated, quasi-spherical inner disk.
- **Relativistic winds** (0.1-0.3 c) affect accretion and feedback.
- **Spectral States**: Hard UL, Soft UL, and Super-Soft UL states.

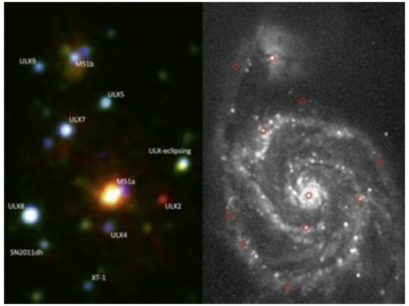
Compact Object Types:

- **Black Holes**: Masses range from ~20 M⊙ to ~100 M⊙.
- **Neutron Stars**: Discovery of pulsations challenges traditional accretion physics.

Observational Characteristics:

- X-ray luminosities can exceed 10^{41} erg/s.
- Associated with ~100 pc superbubbles, formed by powerful outflows.





Radio observations of Ultra-Luminous X-ray Sources (ULXs)

Challenges in radio (low detection rate):

- **Faint Radio Flux density**: 0.01mJy theoretical prediction
- **Variability**: Some ULXs show transient behavior, complicating studies.

Key Findings:

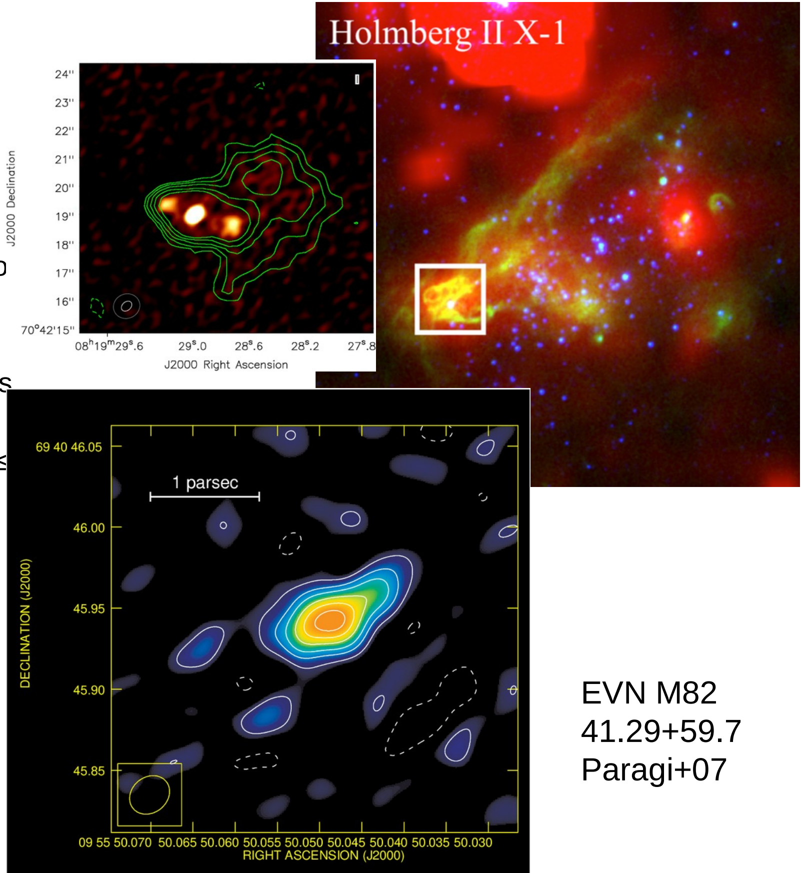
- **Extended Emission**: Some show radio structures like bubbles or jets.
- **Core Emission**: Compact radio cores have been detected
- **Transient Behavior**: Observed in some ULXs, indicating variable accretio or jet activity.

Implications for Models and challenges:

- **Microblazar Hypothesis**: however lack of detected radio flares constrains models involving relativistic jets.
- **Intermediate-Mass BH Limits**: Radio observations suggest BH masses ≤ 10^3 M_☉ in some ULXs. e.g. M82 X-1
- **Jet-Disk Coupling**: VLBI observations reveal jets aligned with X-ray polarization.

Future Prospects with SKA:

- **Enhanced Sensitivity**: SKA will improve detection of faint ULXs.
- **Population Studies**: Large-scale surveys may identify new ULXs
- **Multi-Wavelength Campaigns**: SKA data combined with X-ray observations for comprehensive studies.



EVN M82
41.29+59.7
Paragi+07

Dwarf Galaxies:

Connecting the Early Universe to the Local

Characteristics and Importance of Dwarf Galaxies

Key Characteristics:

- **Stellar Mass**: Typically < 10^9 solar masses.
- **Dark Matter**: High mass-to-light ratios, making them essential for dark matter research.
- **Gas Content**: gas-rich (e.g., dwarf irregulars) and gas-poor (e.g., dwarf spheroidals).

Scientific Insights:

- **Metallicity**: Generally low, providing clues on early universe chemical enrichment.
- **Star Formation**: Ranges from active in gas-rich galaxies to dormant in gas-poor ones.
- **Dark Matter Detection**: Prime targets for indirect detection via gamma-ray observations.

Scientific Importance:

- **Galaxy Formation**: Relics from the early universe, offering insights into star formation.
- **Cosmological Probes**: Test dark matter models and cosmological theories.
- **Reionization Studies**: likely among the first structures formed

Dwarf Galaxies—AGN in the Early Universe

- **Early Black Holes**: Dwarf galaxies may host seed black holes (10^2 - 10^5 M☉), crucial for understanding SMBH evolution (direct collapse mechanisms in the dense primordial gas clouds; rapid growth wrt host galaxies).
- **AGN Activity**: Dwarf galaxies exhibit AGN activity up to redshift z~3, impacting their star formation and evolution.
- **Feedback Mechanisms**: AGN-driven outflows regulate gas and star formation, influencing galaxy growth.
- **Seed Black Hole Formation**: Observations of IMBHs (remnants of the early universe's BH population,) support the theory of direct-collapse black holes in the early universe.

Recent Observations of Dwarf Galaxies

- **ALFALFA Survey**: Discovered gas-rich, optically faint "Almost-Dark" galaxies using blind H I surveys.
- **MaNGA AGN dwarf galaxies (MAD):** spatially-resolved emission-line diagnostics, 664 AGN-hosting dwarf galaxies higher AGN fraction (~20% of 3459) than previous studies
- **Molecular Gas Content**: Low-metallicity dwarf galaxies lack CO emission despite star formation, revealing complex gas structures.
- **X-Ray Properties**: XMM observations suggest potential IMBH candidates in low-metallicity dwarfs.
- **Morphological Studies**: AGN-host dwarf galaxies often show (pseudo)bulges, contrasting with pure disk non-AGN hosts.
- **Euclid Observations**: Over 1,100 new dwarf galaxy candidates identified in the Perseus cluster, many classified as dwarf ellipticals.

Role of Radio Observations in Dwarf Galaxies

- **Role of Radio Observations**
  - Detect **star formation** via synchrotron emissions.
  - Identify **AGN activity** in dwarf galaxies hosting low-luminosity AGNs and IMBHs.
  - Study **cosmic evolution** as dwarf galaxies are relics of the early universe.
- **Key Findings**
  - Compact radio sources found via LOFAR linked to **FRBs** and IMBHs.
  - IMBHs in dwarf AGNs show **jet activity** comparable to larger galaxies.
  - Radio studies reveal insights into **star formation rates**.
- **Future Plans**
  - **Expanded surveys** with SKA.
  - **Deep VLBI imaging** for jet structures.
  - **Multi-wavelength approaches** integrating optical, infrared, and X-ray data.

Searching for Compact Radio Sources in Dwarf Galaxies

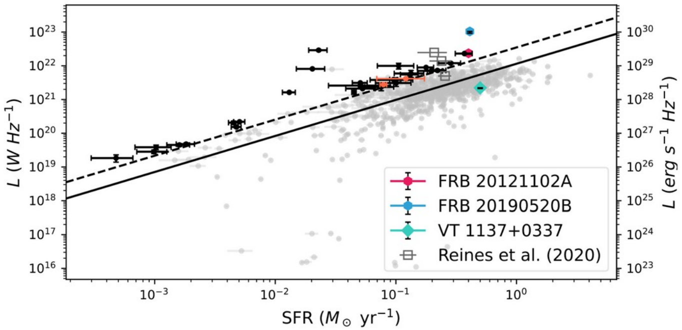


Fig. 2. Candidate selection via the L–SFR relation. Gray-filled markers indicate compact radio sources matched to dwarf galaxies matched. Black filled circles correspond to our final selection of OCRs matched to a dwarf galaxy with luminosity exceeding 3σ (dashed line) on the L–SFR relation by Gürkan et al. (2018, and the solid line) shows those with validated redshift. The uncertainty on luminosity is below the marker size. Orange markers are sources within the AGN region in Fig. 1. As a reference, we show PRS luminosity and the SFR of the host for both FRB 20121102A (Tendulkar et al. 2021; Law et al. 2022) and FRB 20190520B (Niu et al. 2022), with luminosity measurements scaled to 144 MHz using α from Resmi et al. (2021, evaluated between 2 MHz and 10 GHz,) and from Niu et al. (2022, evaluated between 1.5 and 5.5 GHz), respectively. We also show the transient source VT 1137+0337 using values from Dong & Hallinan (2023). Finally, we show Reines et al. (2020) galaxies (J0909+5655, J1136+2643, J1220+3020) matched in CLU for which SFR information is available, with luminosity scaled to 144 MHz using α values fitted between 1.4 GHz and 9 GHz by Eftekhari et al. (2020). The large scatter in luminosity is discussed in Sect. 2.3 and Appendix A.

LOFAR dwarf galaxies https://arxiv.org/abs/2303.12598

Persistent Radio Sources (PRSs): Linked to FRBs and potential IMBHs in dwarf galaxies.

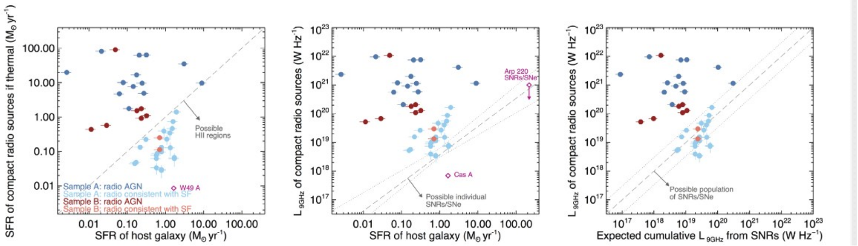
Study Results: 29 over-luminous compact radio sources (OCRs) identified using LOFAR/CLU, with radio luminosities comparable to PRSs.

Origin: Optical diagnostics suggest star formation for most OCRs, but higher-resolution radio data needed for confirmation.

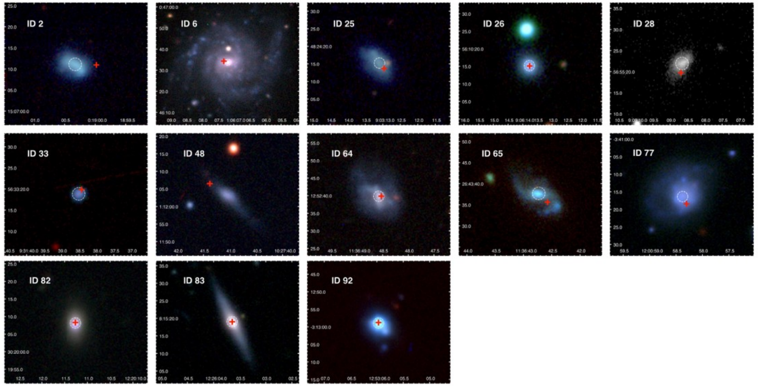
Future Work: Strategies to differentiate FRB hosts from black hole origins, expanding understanding of low-mass galaxy phenomena. Evolution of dwarf galaxies, their radio properties, and their significance in the broader context of galaxy formation and cosmic history.

VLA observations of dwarf galaxies

- Observed 111 dwarf galaxies (M* < 3×10⁹ M☉) using the VLA.
- Detected compact radio sources in 39 galaxies.
- 13 of these almost certainly host active massive black holes, with many being off-nuclear.
- Offsets and signs of interactions suggest "wandering" black holes, consistent with simulation predictions.
- Indicates that black hole populations in dwarf galaxies may be more complex, involving non-nuclear growth.
- Radio-based technique complements optical and X-ray methods for identifying black holes in dwarf galaxies.



Radio emission possible origins

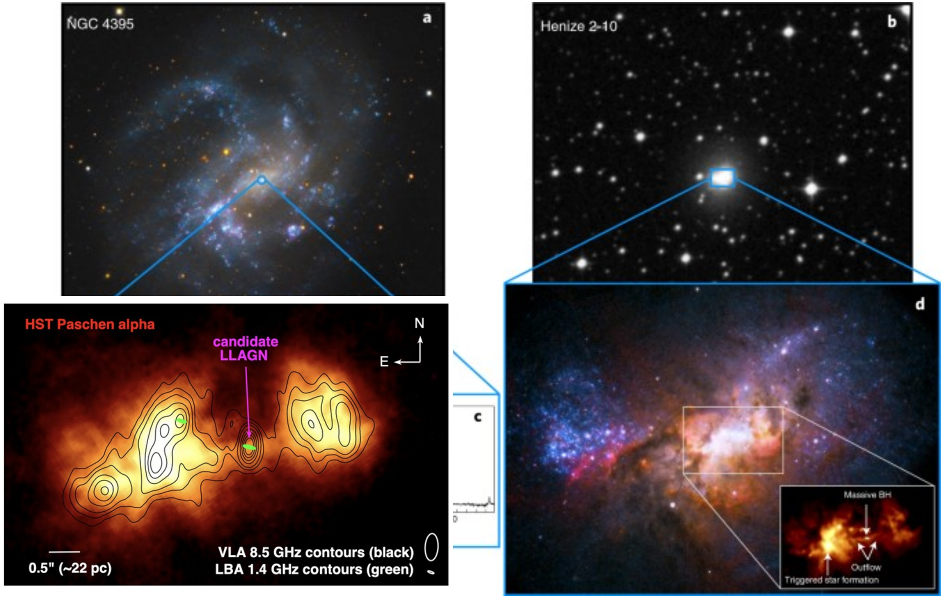


Radio - red cross, SDSS - white circle

Reines et al. 2020 https://arxiv.org/pdf/1909.04670

Radio VLBI Detection of Compact Components in Off-Nucleus Dwarf Galaxies: Henize 2-10

- **Massive BH Discovery**: M_BH ~ 10^6 M☉ found in the dwarf starburst galaxy He 2-10, offering insight into early-universe-like black holes.
- **LBA VLBI Observations** at 1.4 GHz: a compact radio source with physical size < 3pc×1pc at the AGN location.
- **Non-Thermal Emission of LLAGN**: Brightness temperature>3×10^5 K confirms not from supernova remnants.
- **Off-Nuclear Source**: Likely a supernova remnant in a super star cluster.
- BH drives a bipolar outflow triggering SF in the central region of the galaxy.

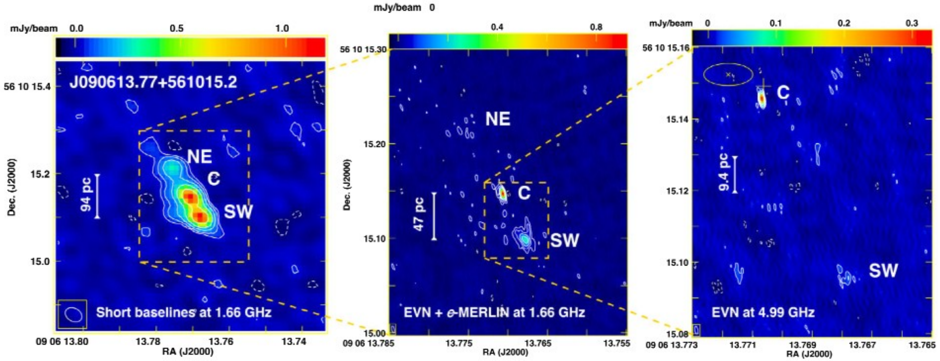


https://www.nature.com/articles/s41550-021-01556-0

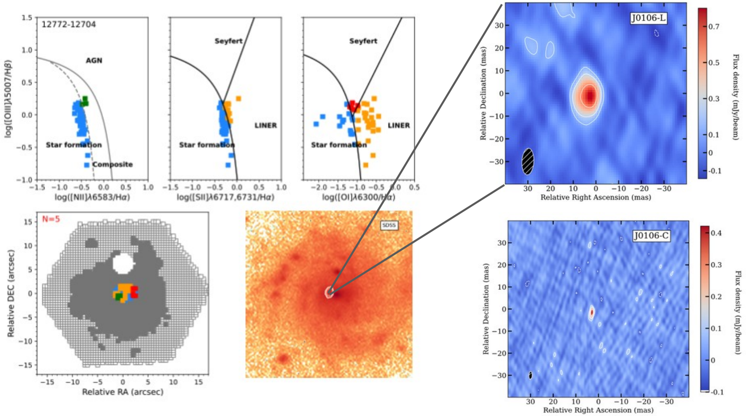
Examples of radio observations of dwarf galaxies

SDSS J090613.77+ 561015.2
EVN network 1.66 and 4.99 GHz
 two-sided jet morphology with a size up to about 150 mas (projected length ∼140 pc) demonstrates the existence of **powerful IMBH jet activity** in dwarf AGNs

12772-12704 （MaNGA plateifu）
VLBA detected at 1.5 and 5 GHz
High Tb, spectral index –0.5
Special: off-nuclei, 2 arcsec separation
No strong AGN in optical criteria
Identify wandering BH with VLBI



Yang et al. 2023
https://ui.adsabs.harvard.edu/abs/2023MNRAS.520.5964Y/abstract



AGNs in cosmic noon

Radio Study of High-Redshift (z>3) Radio-Loud AGNs

Scientific Significance:

- Probing SMBH growth and feedback effects on host galaxies.
- Tracing large-scale structures and cold gas distribution during reionization.

Research Methods:

- Multi-wavelength observations (radio, mm, IR, optical, X-ray).
- High-res imaging (VLBI), molecular gas studies (ALMA).
- SED fitting and environmental analysis.

Important Impacts:

- Discovery of AGN feedback, early AGN-triggering environments.
- Observing Lyα nebulae, identifying early radio-loud AGNs.
- Insights into cosmic evolution of AGNs and SMBH formation.

RATAN-600 monitoring z>=3 AGN

Study Overview: 101 quasars, monitored (2017-2020) at 2.3-22.3 GHz using RATAN-600.

Detection Rates: 100% at 4.7 GHz, 89% at 11.2 GHz.

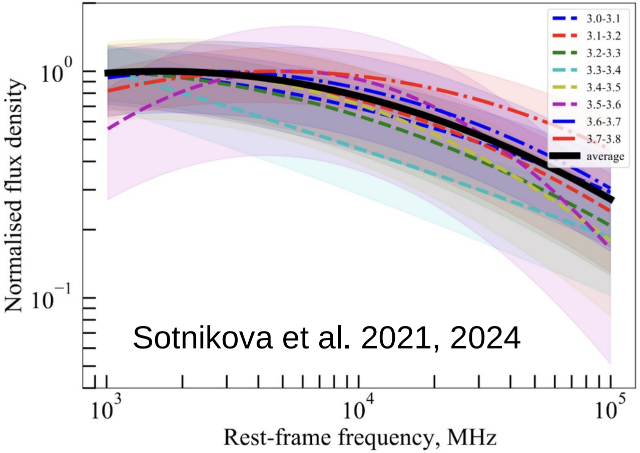
Spectral Classification: 46% peaked-spectrum, 24% flat.

Radio Loudness: Median log R = 3.5 (high radio-loudness).

Variability: ~50% show significant variability (25-50%), higher at 22.3 GHz, suggesting core dominance.

Implication: Peaked spectra suggest compact core dominance and distinguish high-z blazars from low-z counterparts.

No significant correlation found between z and spectral index α.



Sotnikova et al. 2021, 2024

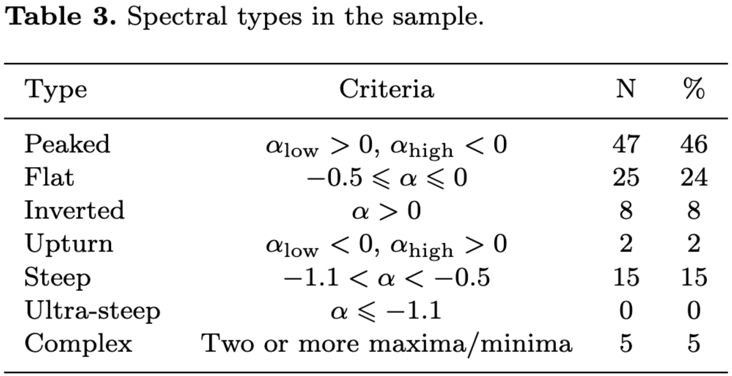


Table 3. Spectral types in the sample.

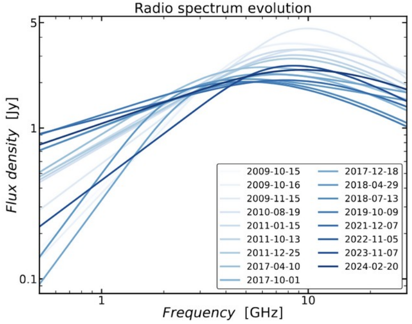
Type	Criteria	N	%
Peaked	$\alpha_{\rm low} > 0$, $\alpha_{\rm high} < 0$	47	46
Flat	$-0.5 \leqslant \alpha \leqslant 0$	25	24
Inverted	$\alpha > 0$	8	8
Upturn	$\alpha_{\rm low} < 0$, $\alpha_{\rm high} > 0$	2	2
Steep	$-1.1 < \alpha < -0.5$	15	15
Ultra-steep	$\alpha \leqslant -1.1$	0	0
Complex	Two or more maxima/minima	5	5

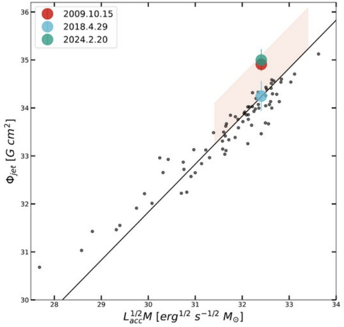
Magnetically Driven Jet in OH 471 z=3.4 Blazar

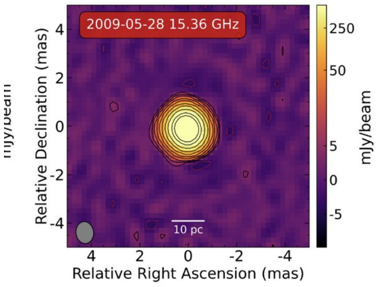
- Evidence for magnetically arrested disk (MAD) powering a relativistic jet in OH 471.
- Multi-frequency RATAN-600 monitoring and VLBI imaging over 30 years.
- Magnetic flux in jet supports efficient black hole energy extraction via MAD.
- Provides key insights into early SMBH accretion and jet formation.

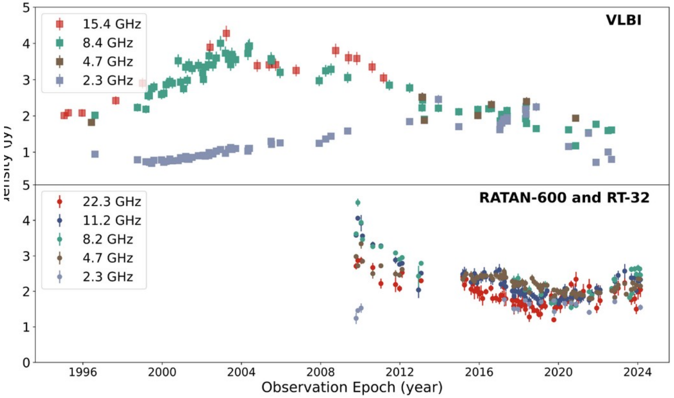
Magnetically Driven Relativistic Jet in the High-Redshift Blazar OH 471

S. Guo[1, 2, 3], T. An[1, 2, 3,★], Y. Liu[1], Y. Sotnikova[4], A. Volvach[5], T. Mufakharov[4, 6], L. Chen[1], L. Cui[7], A. Wang[1, 2], Z. Xu[1], Y. Zhang[1], W. Xu[2, 7], Y. A. Kovalev[8], Y.Y. Kovalev[9], M. Kharinov[10], A. Erkenov[4], T. Semenova[4], and L. Volvach[5]









Summary: Open questions in high-redshift AGN

- **SMBH Growth**: How did the first SMBHs grow so rapidly in the early universe?
- **AGN Feedback**: How do AGN feedback processes impact SF and galaxy growth?
- **AGN Lifetimes**: What is the typical lifetime of AGNs at $z > 6$, and how do their duty cycles affect cosmic evolution?
- **Black Hole Seeding**: What are the dominant black hole seeding mechanisms—stellar remnants or direct collapse?
- **Radiative Efficiency**: How does radiative efficiency evolve in super-Eddington accreting AGNs?
- **AGN Abundance**: What is the true abundance of AGNs at high redshifts, considering obscuration?

Open questions in high-redshift AGN - how to address

- **SMBH Growth**:
    - *JWST/NIRSpec*: Detect early SMBHs and their accretion rates via emission line observations.
    - *SKA/ngVLA*: Map AGN radio jets and explore the role of feedback in black hole growth.
- **AGN Feedback**:
    - *SKA/ngVLA*: Measure gas outflows and star formation suppression due to AGN feedback.
    - *Future X-ray telescopes*: Study X-ray winds and AGN-driven outflows.
- **AGN Lifetimes**:
    - *JWST/ALMA*: Track AGN duty cycles via deep surveys and spectral energy distribution (SED) modeling.
    - *SKA/ngVLA*: Detect jet activity over time to estimate lifetimes.
- **Black Hole Seeding**:
    - *JWST*: Probe black hole seeds by detecting faint AGNs.
    - *SKA/ngVLA*: Identify radio signatures of direct collapse black holes.
- **Radiative Efficiency**:
    - *Future X-ray/gamma-ray telescopes*: Measure high-energy emissions in super-Eddington accreting AGNs.
- **AGN Abundance**:
    - *JWST*: Deep field surveys to discover obscured AGNs.
    - *SKA/ngVLA*: Conduct deep radio surveys to reveal hidden AGN populations.

Thanks !

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