DID BH-JETS ENHANCED THE FORMATION OF POP-III STARS?

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- **~300 SMBHs of ~10^9 $M_\odot$ in QSOs at 5 < z < 8 have been detected**

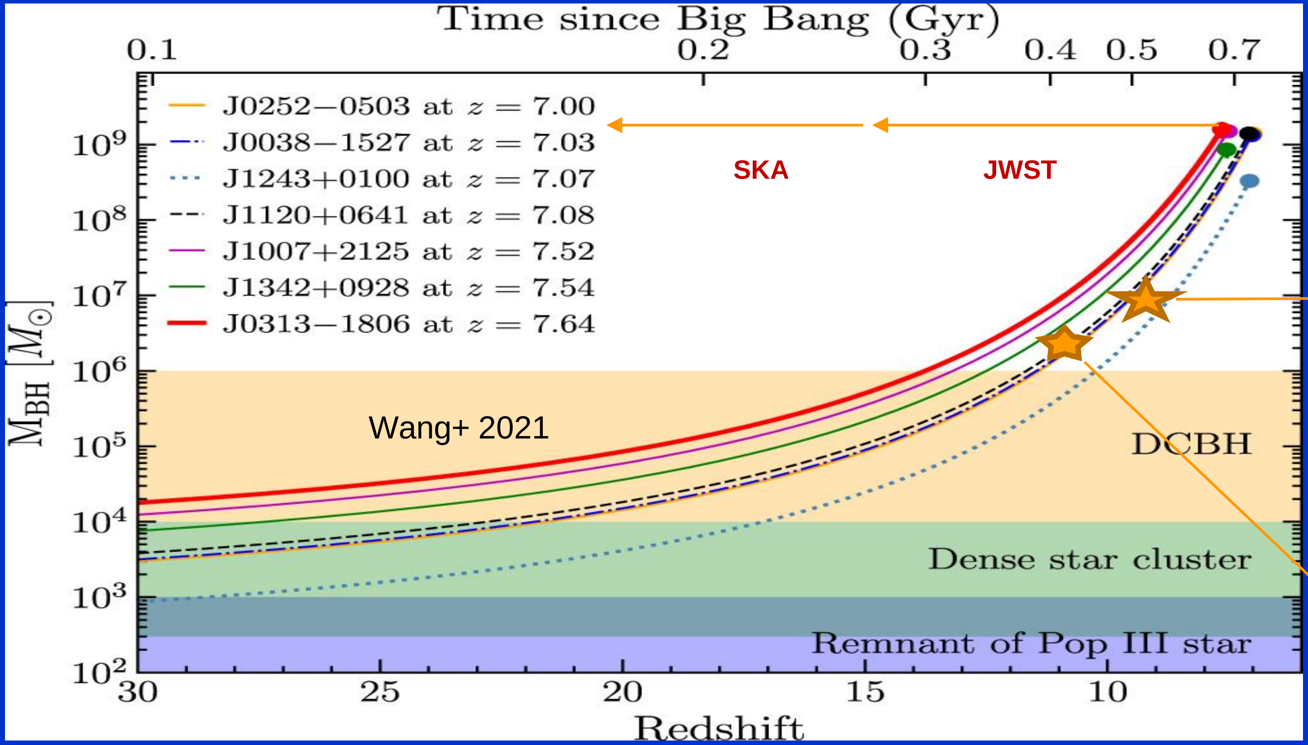
It is believed these SMBHs are the tip of a BH iceberg and could be related to

- **JWST Ultra-compact galaxies at z > 10 with stellar masses of ~10^8 $M_\odot$**

Puzzle: How SMBHs were formed & grown so fast to become so massive?
Inayoshi+ ARAA 58, 27 (2020) & Mirabel & Rodríguez in New Astron Reviews 92, 101642 (2022)

HOW SMBHs CAN GROW UP TO ~10^9 $M_\odot$ WHEN THE UNIVERSE WAS LESS THAN 700 Myr OLD?

Assuming they grow at Eddington limit with radiative efficiency of 10% from seeds >10^3 $M_\odot$ at z = 30



New high-z MBHs with JWST

BH at z = 8.679

M_{BH} = 8.9 x 10^6 $M_\odot$

Larson+ (2023)

AGN in GN-z11?

at z = 10.6

Bunker+ (2023)

log M_{BH} = 6.2 $M_\odot$

Maiolino+ (2023)

SUCH RAPID BH GROWTH IS POSSIBLE BECAUSE THE GLOBAL COSMIC GAS DENSITY EVOLVES WITH Z AS

$$\rho \propto (1 + z)^3$$

At z = 30 the mean global gas density would be $10^{4\text{-}5}$ times the mean local global gas density

What are the current astrophysical models on the formation of these SMBH seeds?

MODELS ON THE FORMATION OF SMBH SEEDS

- **Primordial** (Zel'dovich & Novikov 1967; Carr & Hawking 1974; Blinnikov+ 2016)
- **In the context of WDM Cosmologies SMBH seeds are formed by gravitational collapse of fermionic dark matter cores** (Argüelles+ 2023).
- **In the context of CDM Cosmologies, turbulent cold flows give birth to SMBH seeds** (Latif+ Nature 2022). Halos of 4 x 10^5 $M_\odot$ at z = 35 in the rare convergence of strong, cold accretion flows, create by direct collapse at z = 25 massive BH seeds of few times10^4 $M_\odot$. **Star formation is prevented by the high turbulence of cold flows. Could MBH seeds be formed before Pop-III stars?**

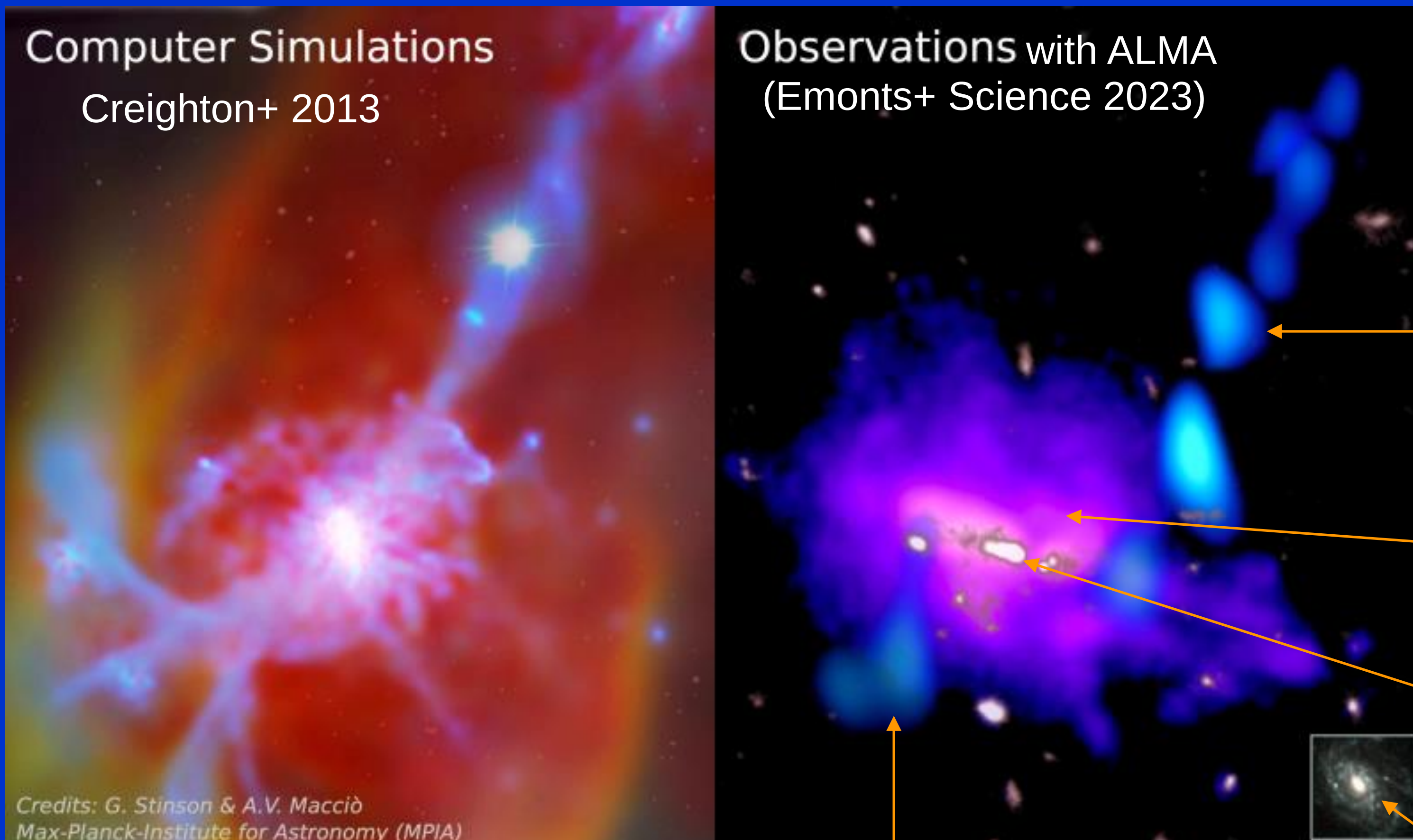
These channels for the formation of SMBH seeds in the high-z Universe are not associated with and could precede the first generation of Pop-III stars

&

WOULD CHANGE THE PARADIGM OF POP-III STARS & SMBHs FORMATION

Are there observations of converging turbulent cold flows in massive DM halos?

Intergalactic cold gas streams feeding the SMBH in 4C 41.17 at a proto-cluster of MGs at cosmic noon (cosmic age ~ 1.7 Gyr)



Cold gas in [C1]

Warm gas in **Lyα**

Radio Galaxy

Cold gas in [C1]

MW galaxy

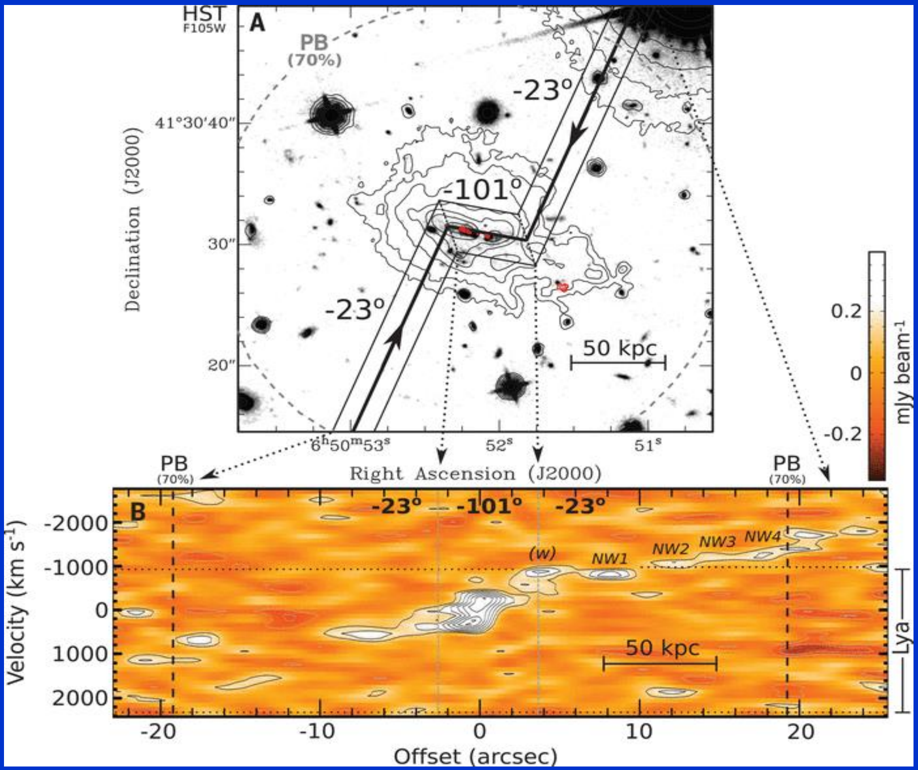
Cold gas streams merge in a massive dark matter halo inducing high turbulence in the accreted gas

Emonts+ (Science 2023)

ALMA observations of [C ı] in the rest-frame λ609 μm (492 GHz). [C ı] has an upper energy level of 23.6 K, a critical density of n_{crit}~ 500 cm^{-3} … traces H_2

Stream $M_{H2} \sim 7 \times 10^{10}\ M_\odot$
Central $M_{H2} \sim 1.4 \times 10^{11}\ M_\odot$
Macc-rate ~ 450 ± 180 $M_\odot$/yr
SFR $\gtrsim$ 250 $M_\odot$/yr for the last 10^9 yrs

The NW & SE streams converge at a relative velocity of ~1500 km/s



Turbulent cold flows at z > 20 may give birth to SMBH seeds by direct collapse preventing star formation. In this context, the seeds of SMBHs may be formed before the bulk of Pop-III stars as proposed by Latif+ (2022).

Could the jets/outflows of rapidly growing BH seeds induce the formation of Pop III stars?

FEEDBACK FROM BH-JETS/OUTFLOWS MAY BE NEGATIVE (QUENCH) OR POSITIVE (ENHANCE) STAR FORMATION

- **BH-jets/outflows at high gas column densities compact the gas…**
- **& BH-jets/outflows imprint mechanical energy & gas turbulence**…

(…Gaibler 2014; Bieri+ 2016; Fragile+ 2017; Nesvadba+ 2021…)

DEEP SURVEYS OF RADIO GALAXIES HAVE SHOWN

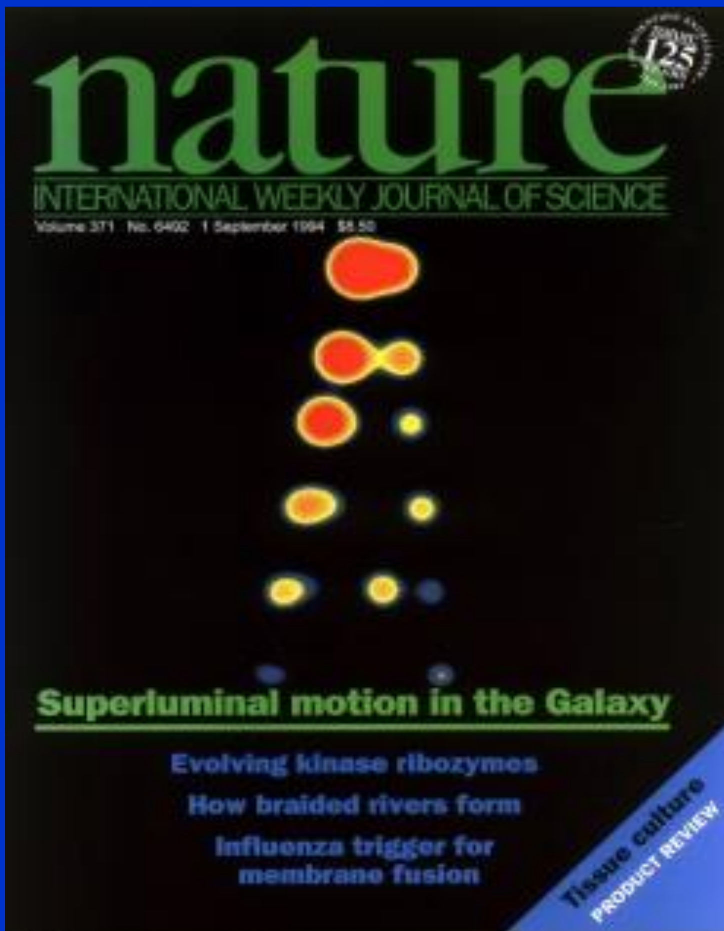
- **A decrease of the length of BH-jets with increasing redshift z**
  due to mean gas density evolution $\delta \propto (1 + z)^3$
- **Hα & Lα emission from massive stars aligned with the BH-jets**
  due to jet induced star formation
- **Extreme SFRs in high-z radio galaxies are commonly observed**

therefore

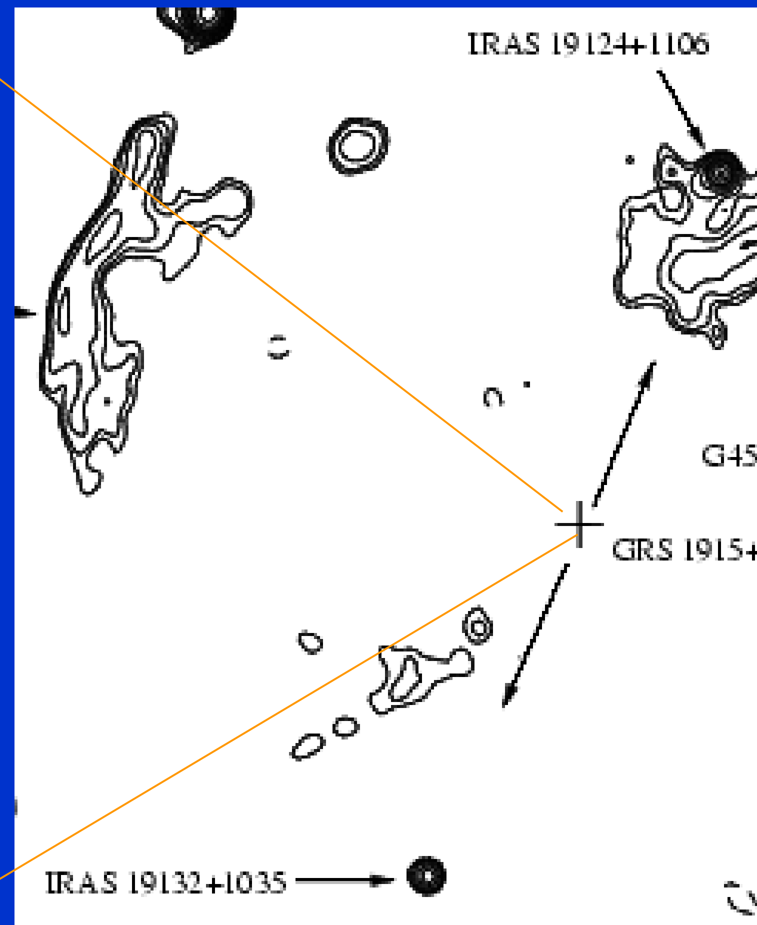
Positive jet feedback is expected to prevail at increasing redshifts

MASSIVE STAR FORMATION IN THE MILKY WAY INDUCED BY RELATIVISTIC JETS FROM A STELLAR BH

Mirabel & Rodríguez (1994)



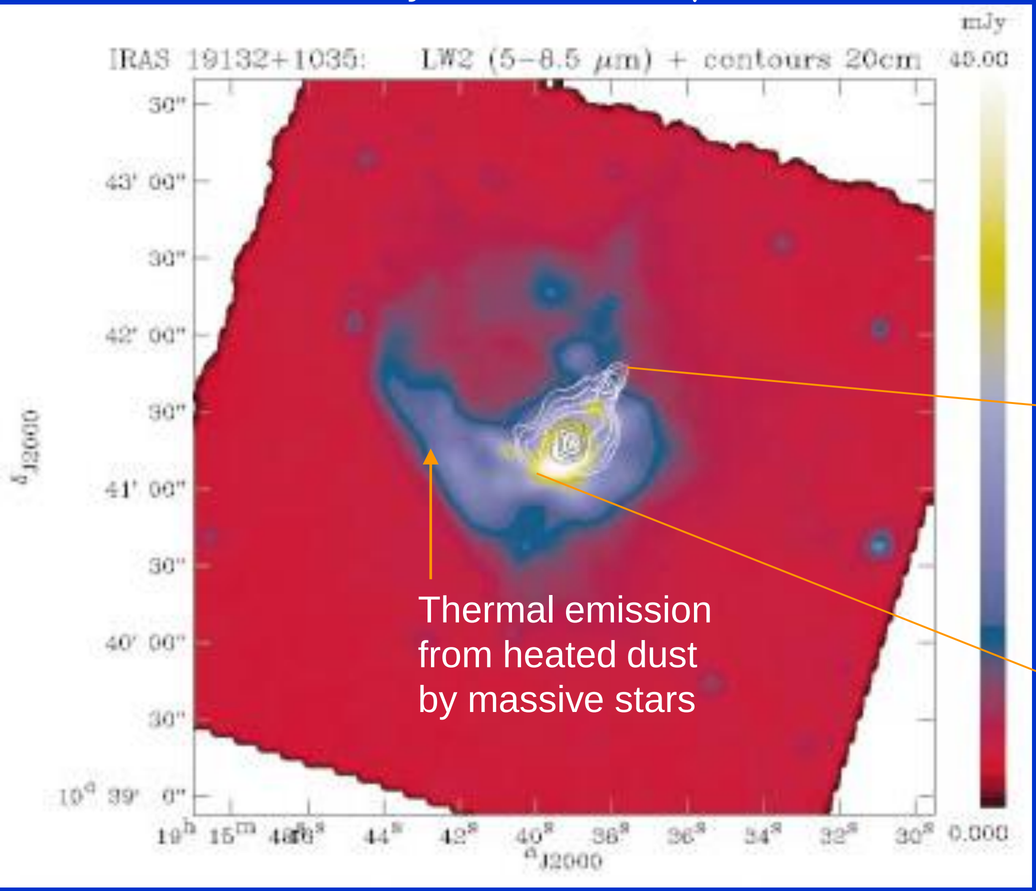
Rodríguez & Mirabel (1998)



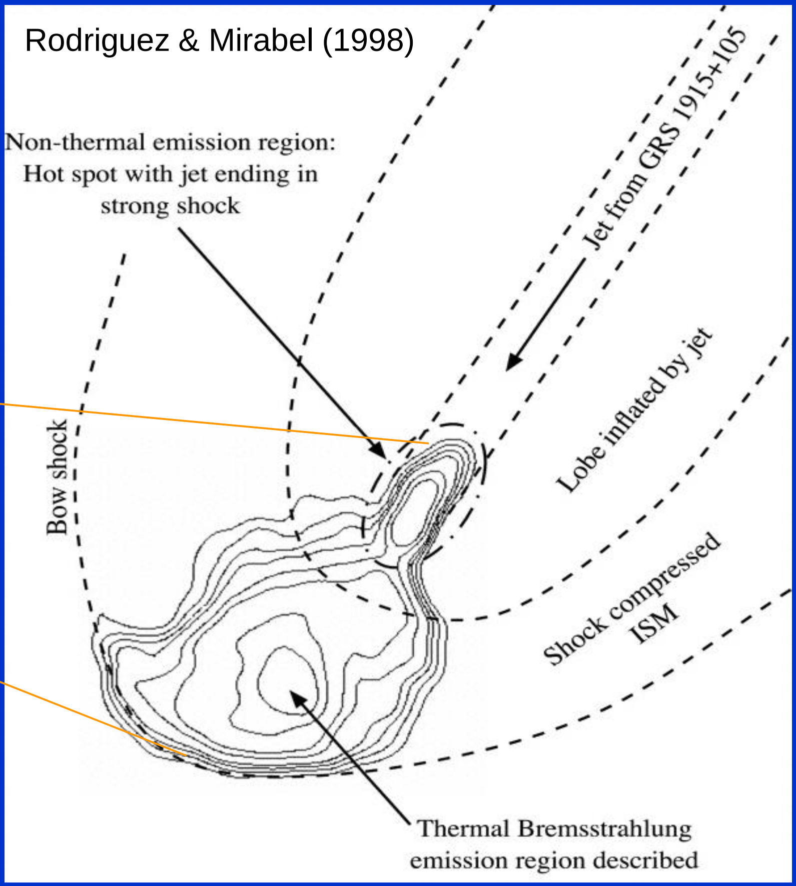
The radio-parallax of the μQSQ (8.6±1.8 kpc) has shown that the BH-jet source and the IRAS sources are spatially related (Reid+ 2014)

Evidence for interaction of the μQSO outflow with the star formation region

Chaty+ 2001: ISO 7μm



Kaiser+ 2004

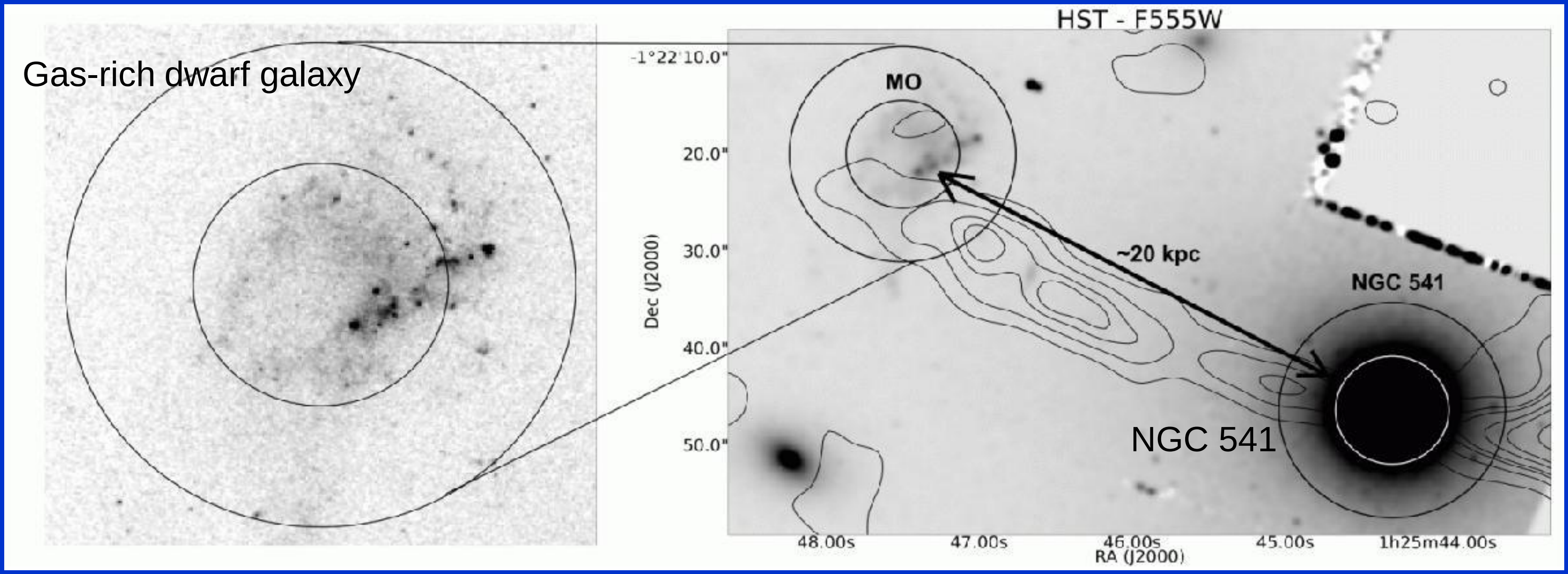


- **This bow shock resembles the lobes observed in radio galaxies** (Kaiser+ 2004)

Positive feedback by BH-jets depends on jet properties: jet power, duty cycle, precession, & local environment: gas density, composition, other sources of feedback. (Tetarenko+ 2018)

AGN Jets enhance star formation in a dwarf galaxy
(Minkowski's Object)

Salomé+ (2015)

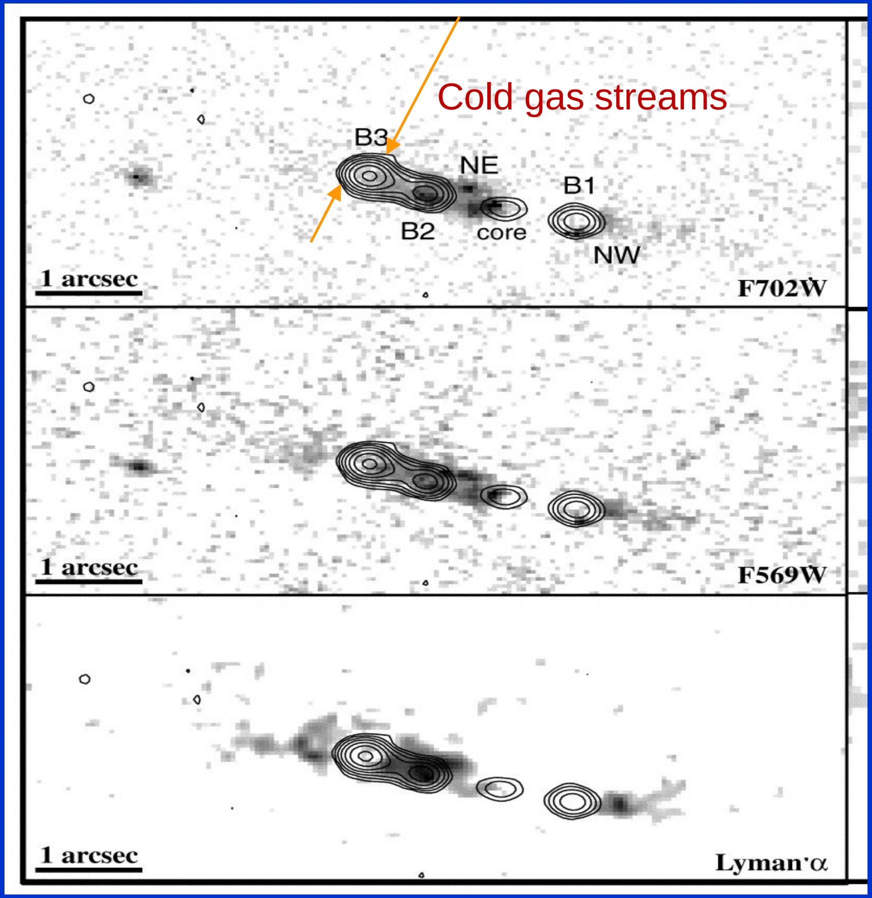


VLA λ21 cm overlaid on a stellar continuum image. Details of Minkowski's Object are on the left.

Massive star formation is enhanced in the region where the jets impact the gas-rich dwarf galaxy

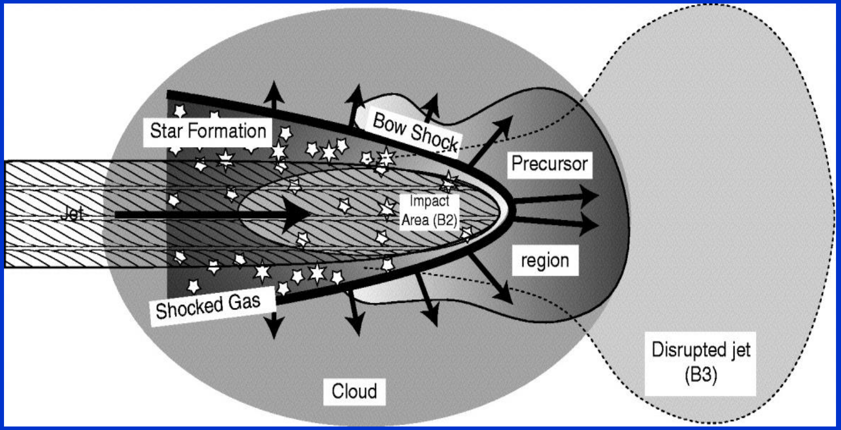
Jet & outflow of the Radio Galaxy 4C 41.17 induce massive star formation in a proto-cluster at z = 3.8

Bicknel+ 2000



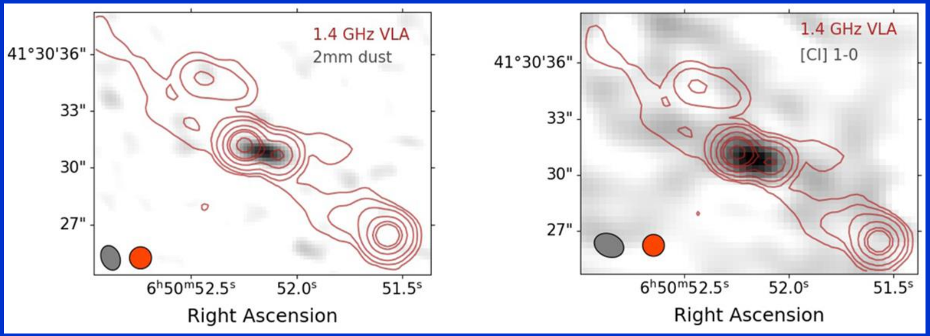
HST images with F702W (λrest ~ 1430 Å), F569W & Lyα Lyα filters. Contours are 8 - 12 GHz radio images.

Bicknell+ 2000



Suggested morphology of a jet-cloud interaction

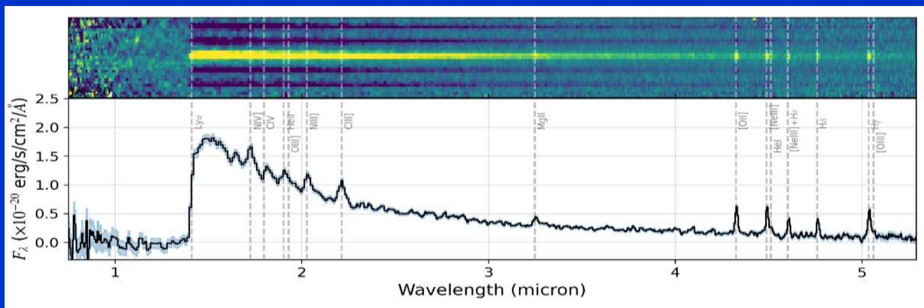
Nesvadba+ 2020



Dust & Neutral Carbon gas aligned with the BH-jets

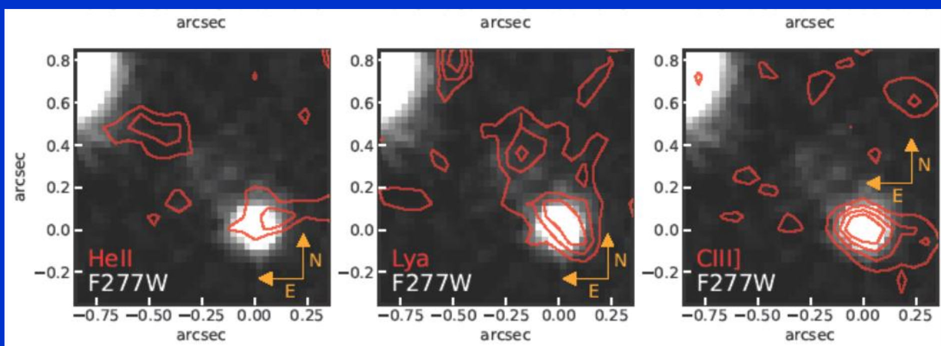
Could evidence of this BH-Jet-Star-formation mechanism be found at even higher Zs?

Do jets & outflows from GN-z11 induce as in 4C 41.17 massive star formation in a proto-cluster at z = 10.6?



« GN-z11 hosts an AGN of type 1 »

[NeIV]λ2423 and nebular lines tracing gas densities $>10^{10}$cm^{-3}, typical of type I AGN, and a blueshifted CIVλ1549 absorption trough, from an outflow with a velocity of ~900km/s (Bunker+; Maiolino+ 2023a)

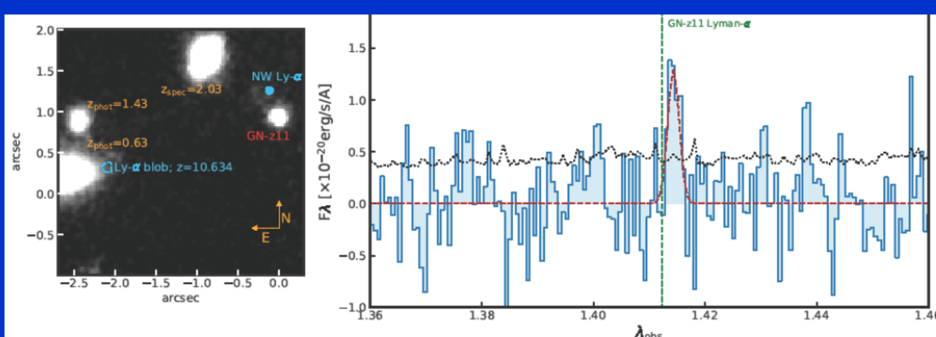


"Population III stars in the halo of GN-z11"

HeIIλ1640 emission & no metals consistent with photoionisation by PopIII stars with top-heavy IMF.

There is a Lyα halo stemming out of GN-z11 and extending out to ~2 kpc (Maiolino+2023b).

Is synchrotron radio emission associated with the stemming out Lyα halo?



"GN-z11 is a candidate proto-cluster core"

forming 400 Myr after the Big Bang, because 3 other emission line candidates are found at the same redshift. The dark matter halo mass of this structure would be Mh ~ 3 ×10^{10}M$_\odot$ (Scholtz+ 2023)

CONCLUSION

- **Relativistic jets from rapidly growing compact seeds of SMBHs observed in quasars at z > 6, must have enhanced the formation of massive Pop-III stars at cosmic dawn.**

- **How the jet-induced star formation mechanism compares with other mechanisms of star formation in the early universe is an open question that deserves further exploration.**

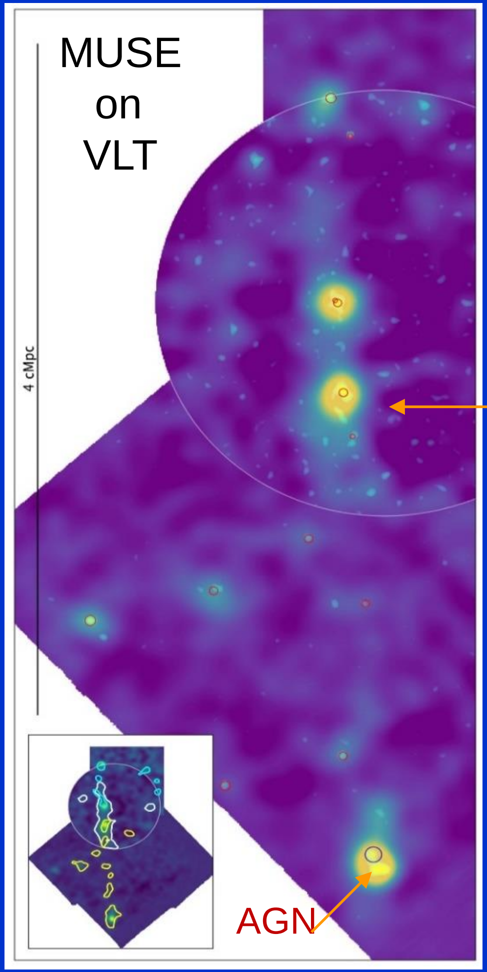
Concerning the exploration of cosmic dawn by radio astronomy

- **HERA result is consistent with X-ray heating (Dilon+) by large populations of low metallicity HMXBs at cosmic dawn proposed (Mirabel+ 2011)**

- **SKA will be able to detect in the radio continuum the early MBH seeds, as the individual sources of HI 21cm line absorptions at z > 13. HI absorption may be detectable in the case of proto-groups of galaxies with centrally growing BHs, and even individually in case of being cosmic dawn blazars, or amplified by intervening gravitational lens sources** (Mirabel & Rodríguez. New Astron Reviews 2022)

SMBHs & MGs in Cosmic Web filaments by Lyα emission at z ~ 3

A z = 3.07 typical over-density in 4.6 cMpc x 191 ckpc (Bacon+ 2021)



UVB is needed for Lyα fluorescence

from

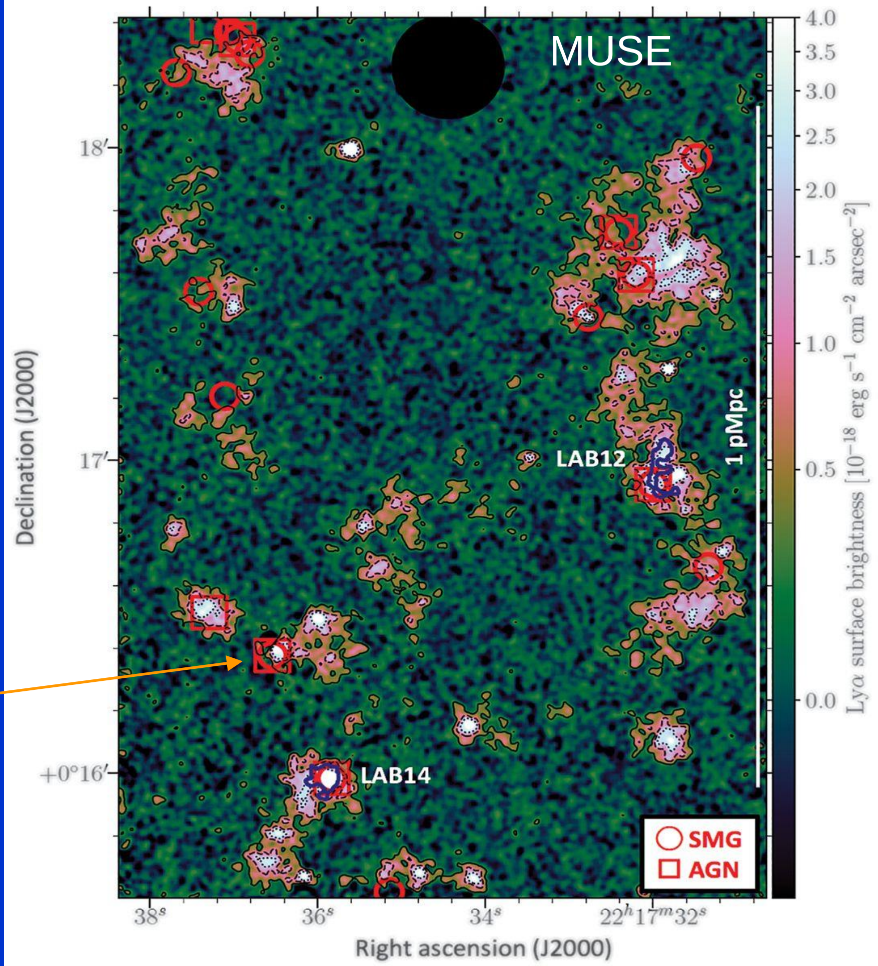
Ultra-low luminosity Lyα sources

In a proto-cluster

MGs & AGN

But Lyα emission traces gas of T > 10^4 K

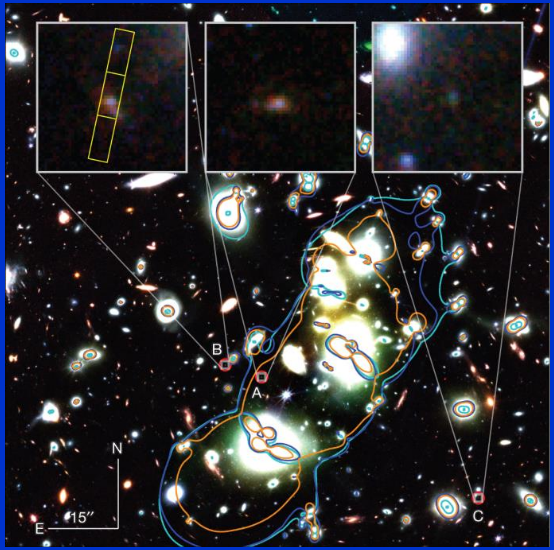
A protocluster at z = 3.1. Total gas mass ~$10^{12} M_\odot$ with mean N_H~$2 \times 10^{21} \cdot cm^{-2}$ (Umehata+ 2019)

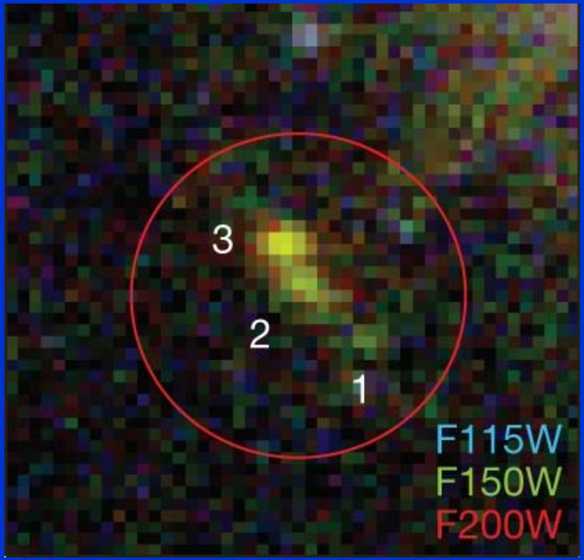


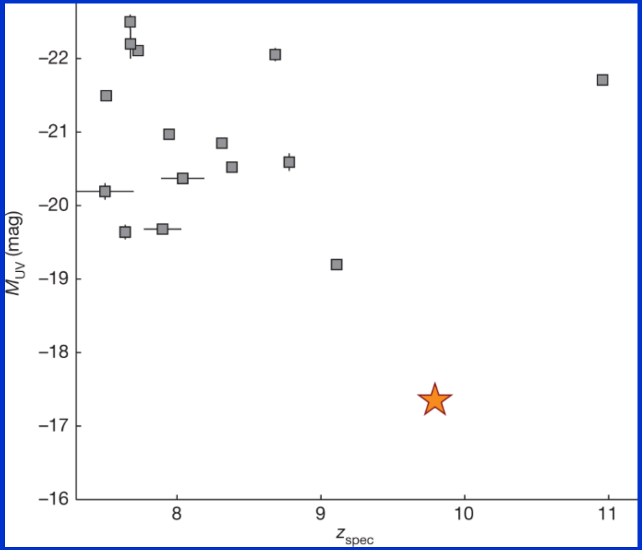
Have cold gas streams along filaments of the Cosmic Web been observed feeding MBHs & MGs?

An ultra-faint galaxy at z ~ 10 observed with JWST

Roberts-Borsani (2023)



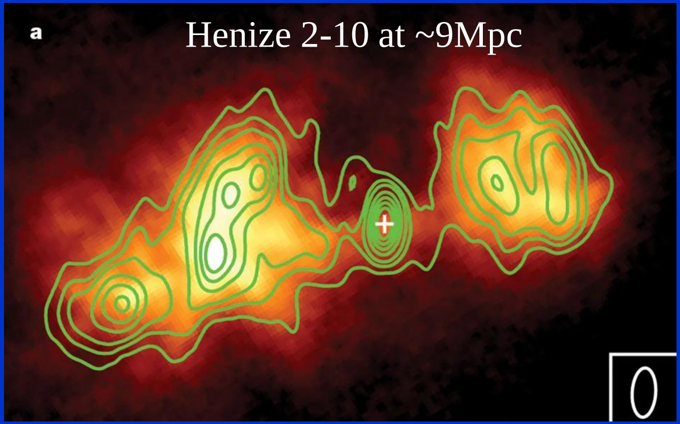




- Faint galaxies should dominate the photon budget needed for reionization
- JD1 is a triply-imaged galaxy with a gravitational magnification factor of 13
- JD1 is at $z = 9.79$, observed 480 Myr after the Big Bang
- It has a stellar mass of $10^{7.2}\,M_\odot$ and sizes of the nuclei and extended components of 18–30 pc and 100 ± 25 pc, respectively.

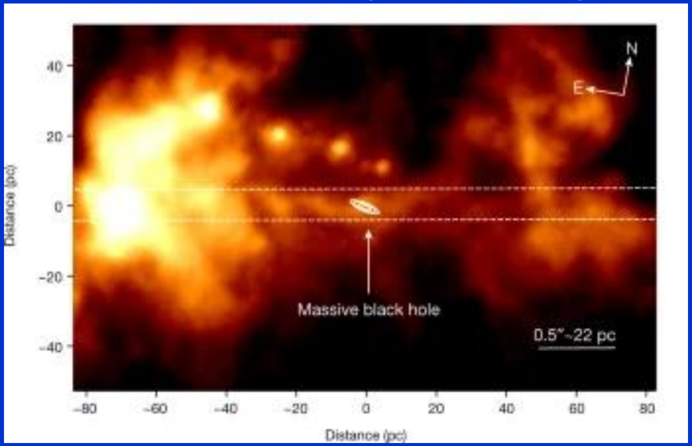
A local analogue of high-z MBHs with no stellar bulge

Amy Reines+ (Nature 2011)



Paα recombination line of hydrogen at 1.87 μm & VLA 8.5 GHz.

Schutte & Reines (Nature 2022)

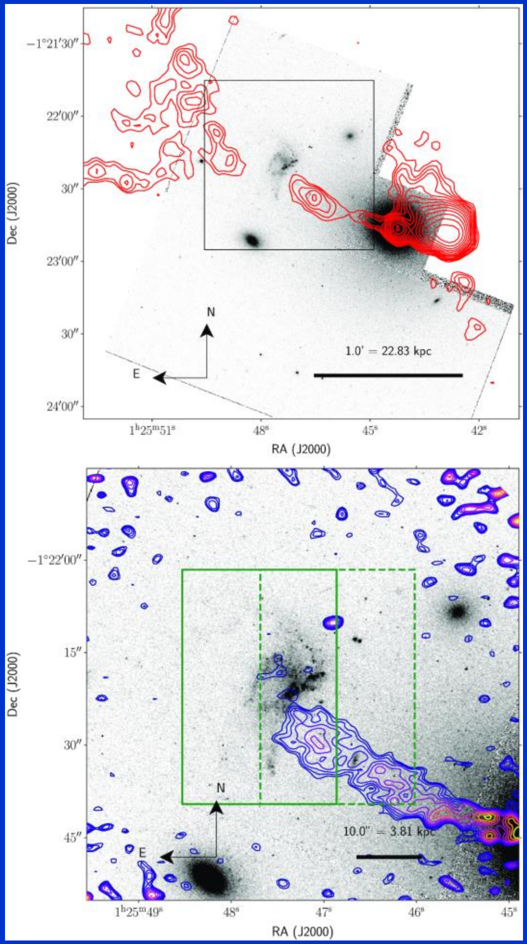


Hα+continuum with HST & VLBA radio emission from BH compact jet

- **The absence of a stellar spheroid suggests that the massive BH of ~10^6 $M_\odot$ is formed before a stellar bulge.**
- **BH-jets inject mechanical energy in the high density gas triggering star formation at a distance of ~70pc.**

Are there other evidences of BH-jets triggering star formation in the local & distant Universe?

Zovaro+ (2020)



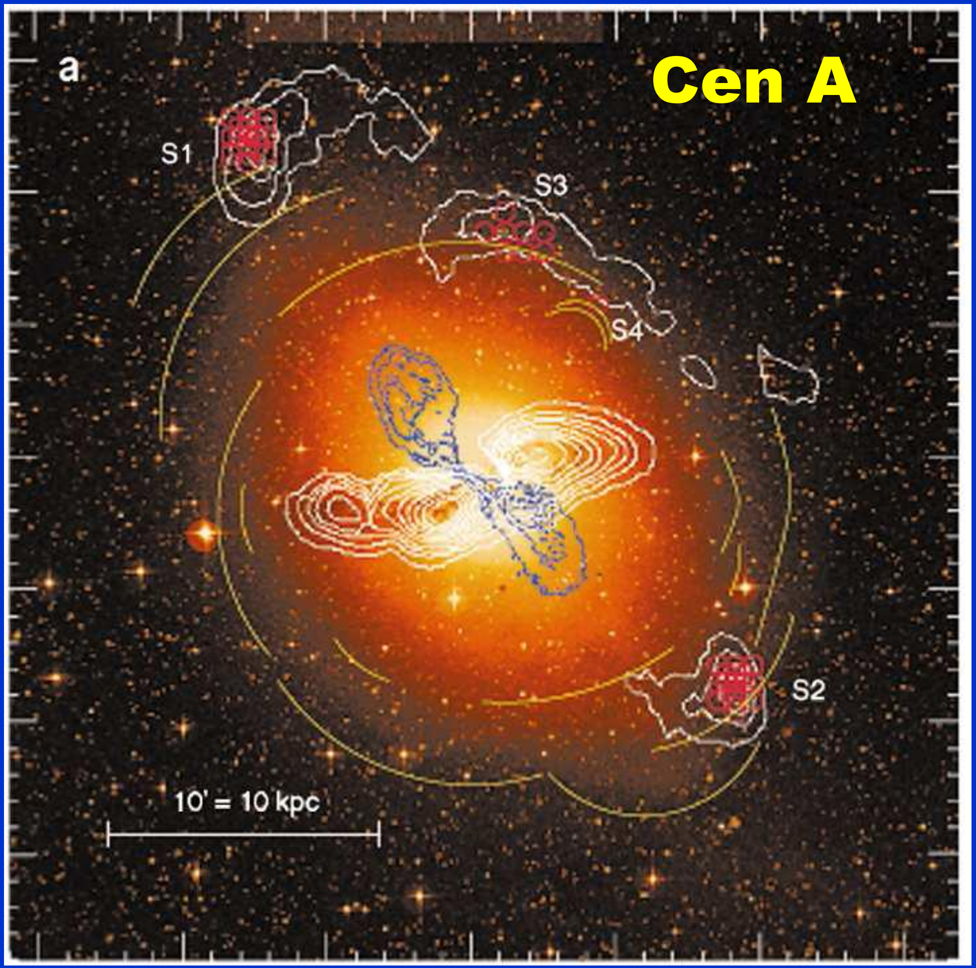
- Top: archival HST WFPC2 F555W image overlaid with contours showing the 1.4 GHz continuum flux from VLA/FIRST indicating the path of the radio jet from NGC 541.

- Bottom: a magnified view of the region outlined by the black square in the top panel, overlaid with contours showing the ALMA 106 GHz continuum from the jet. The green solid and dashed boxes indicate the two base pointings of our WiFeS integral field spectroscopy observations.

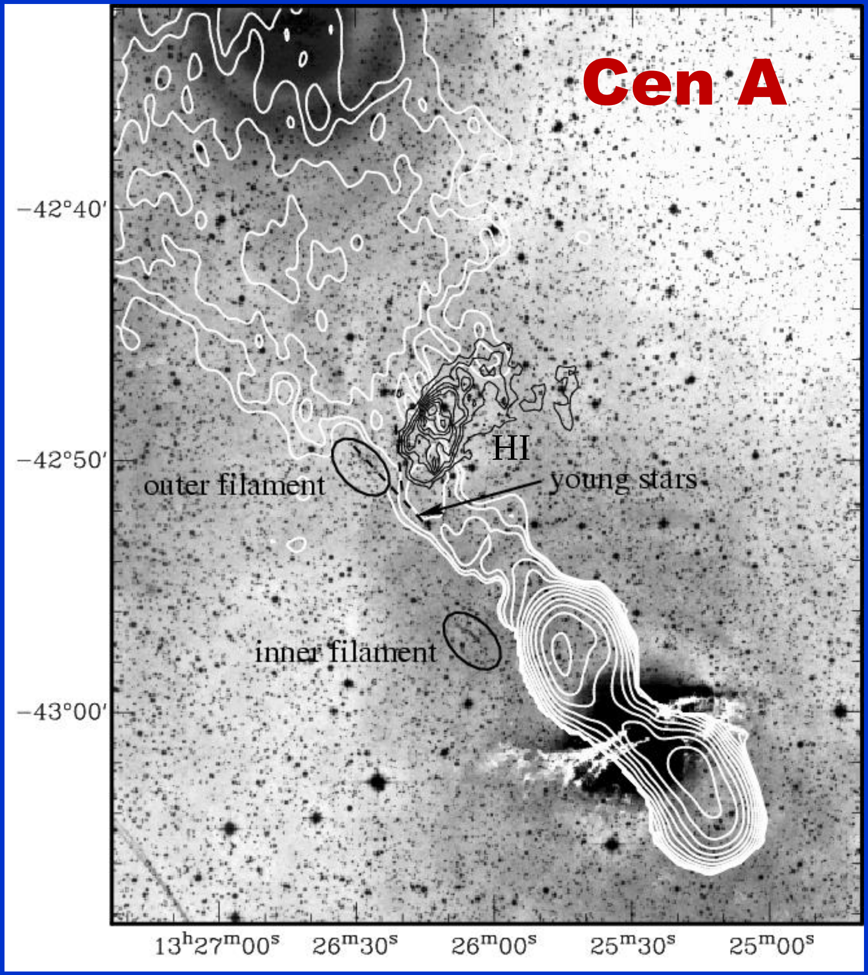
MO is embedded in a cloud of neutral gas with an estimated mass MHI=4.9×108M⊙ which is located along the path of the jet, extending downstream of MO. Molecular gas has been detected in four distinct clumps with intervening diffuse emission with a total mass MH2=3.0×107M⊙ assuming a standard Milky Way (MW) CO-to-H2 conversion factor αCO, or MH2=1.8×108M⊙

SMBH-JETS INDUCE THE FORMATION OF MOLECULAR GAS & STARS ALONG THE JETS

Molecular gas (CO): Charmandaris+ 2000



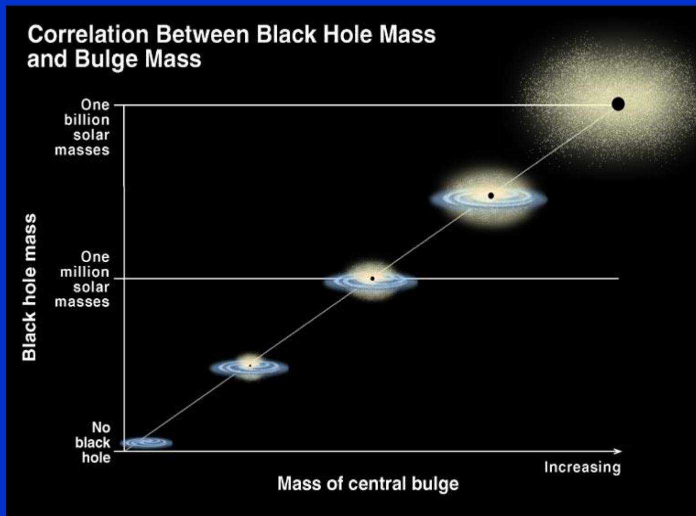
Blanco+1975; Oosterloo & Morganti, 2005



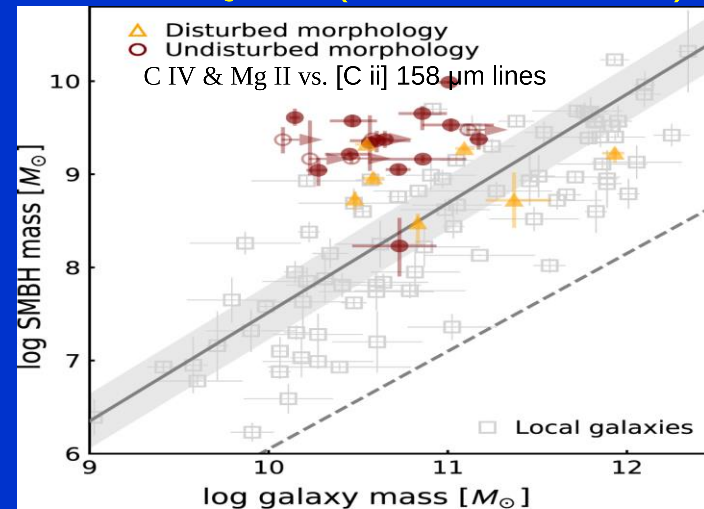
Molecular gas in hi shells at 15 kpc from SMBH aligned with jets

DID BH FORMATION PRECEDED STAR FORMATION AT COSMIC DAWN?

In the Local Universe



In z>6 QSOs (Neeleman+ 2021)



Central Bulge

- **SMBH/STELLAR MASS RATIOS AT z > 6 SEEM TO BE LARGER THAN LOCALLY**
- At high z BHs are ~ seven times more massive respect to galaxy hosts (Kormendi & Ho, ARAA 2013).
- **But may be selection effects in the sample of z>6 QSOs**: 1) Fainter QSOs may be missing. 2) It is difficult to disentangle emission from BHs and stellar bulges (e.g. GN-z11 at z = 10.6).

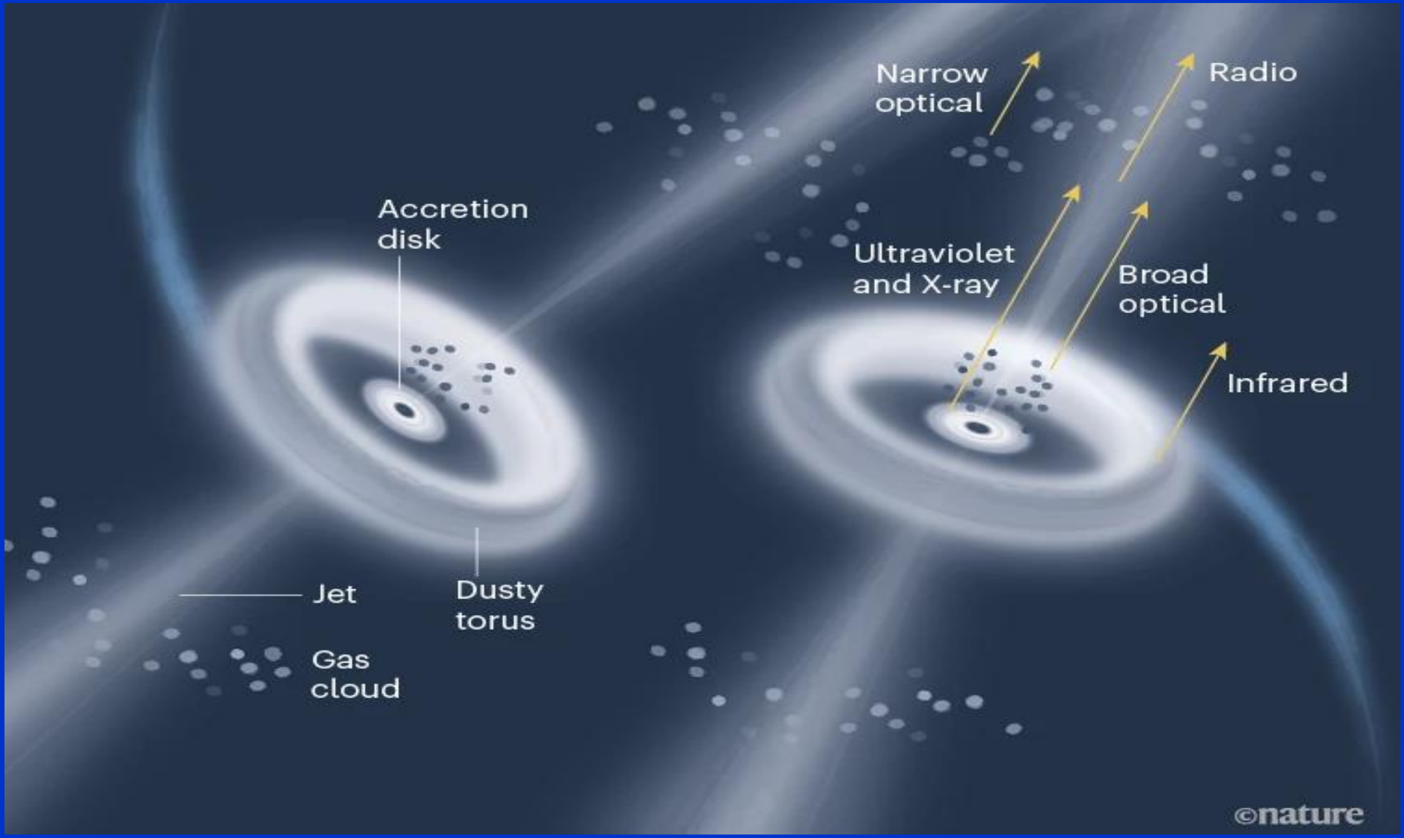
Trinity I & Trinity II (Zhang+ 2023a,b): An empirical model that infers the statistical connections between dark matter haloes, galaxies, and SMBHs, constrained by galaxy observables from 0 < z < 10

This question had conflicting answers, but at least some SMBHs have formed & grown before stellar bulges

AN EXAMPLE OF SMBHs WITH NO STELLAR BULGES

Binary quasars in merger galaxies with massive disks but no star bulges at z = 2.17 (~3 Gyr), before the cosmic peak of star formation and QSO activity

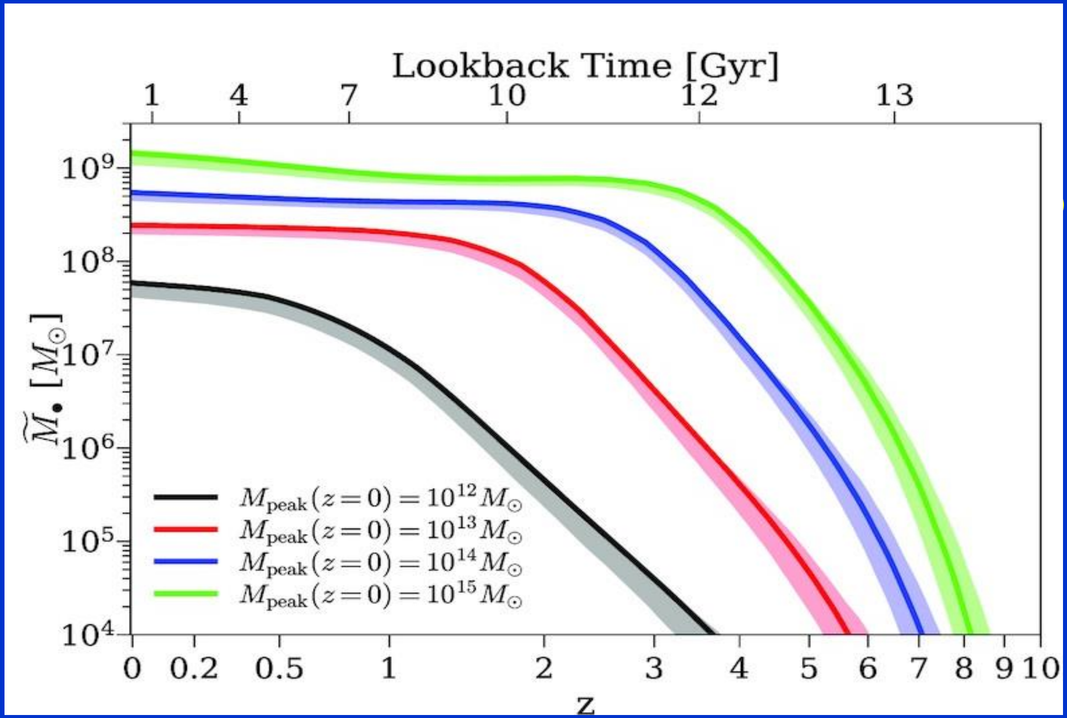
Chen+ in Nature, April 2023 (figure from News & Views)



Are stellar bulges formed later by disk instabilities, accretion of dwarfs & galaxy mergers?

AGN downsizing: Eddington ratios start to decrease earlier for more massive SMBHs

Trinity I (Zhang+ 2023)

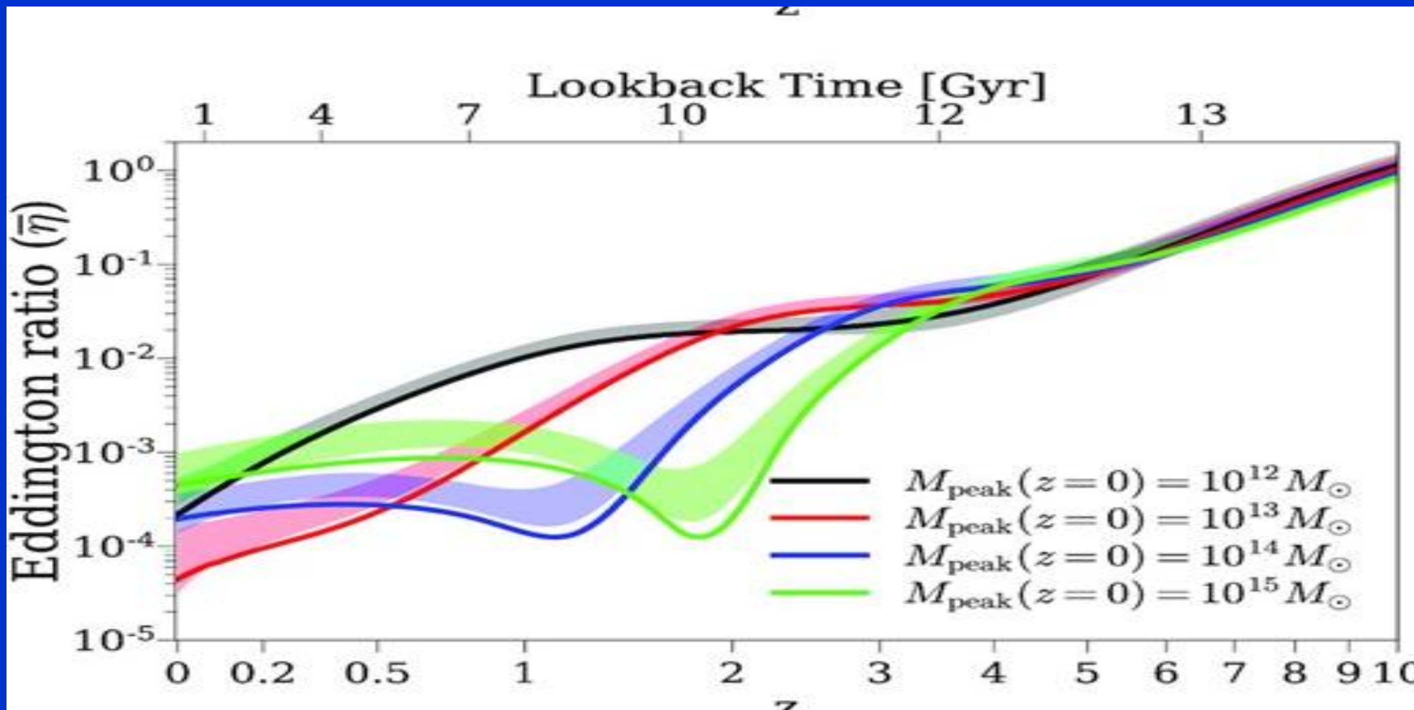


BH histories as a function of halo mass at z = 0. At all halo masses, SMBH growth is very fast in the early universe, and slows down towards lower redshifts (this may be do to cosmic decreasing gas density and depletion as a function of cosmic age). However, the fast-growth phase ends earlier for more massive black holes. This is consistent with the phenomenon called ‘AGN downsizing’ .

average SMBH *total* (i.e. radiative+kinetic) Eddington ratio (η¯¯�¯) as a function of M_{peak} and *z*

Average BH accretion rates and Eddington ratios

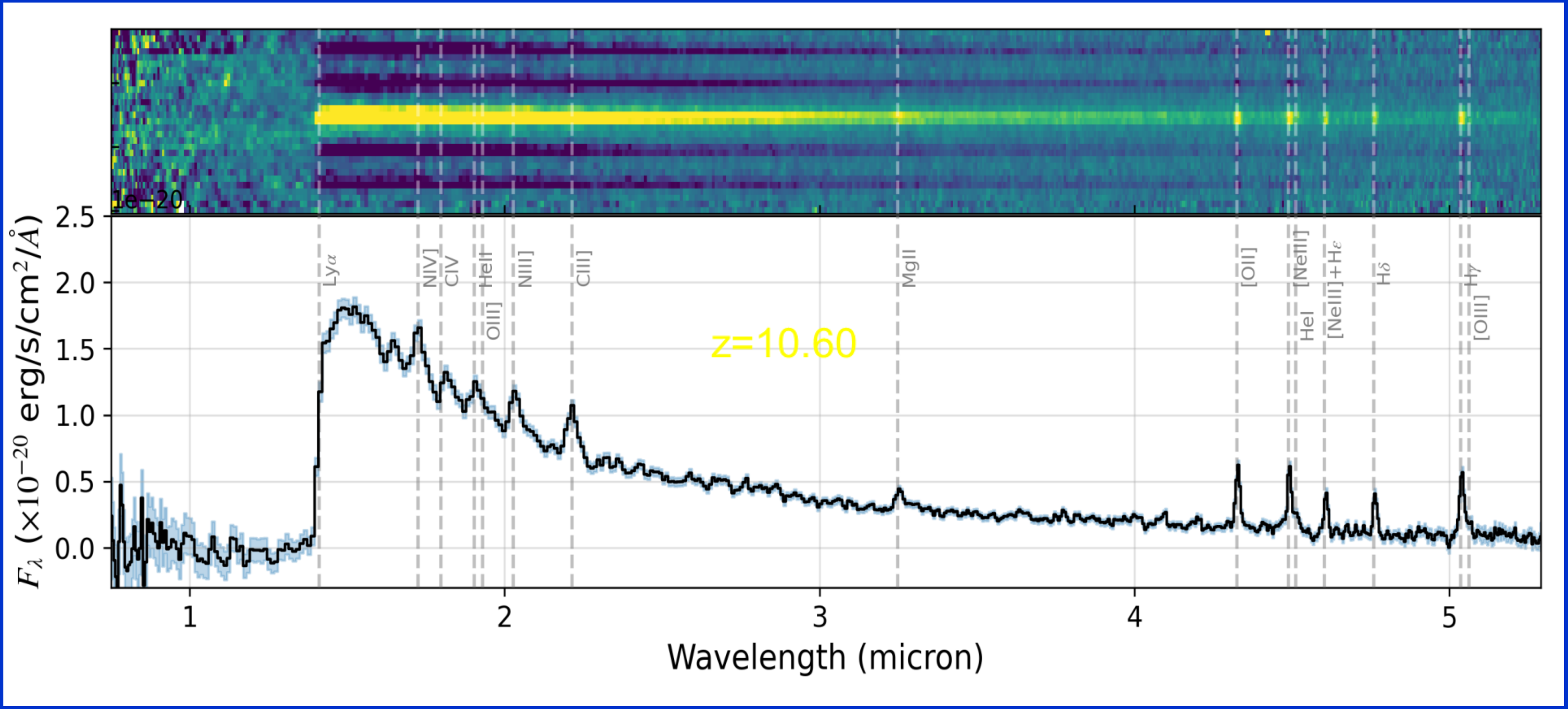
Trinity I (Zhang+ 2023)



Average SMBH total (i.e. radiative+kinetic) Eddington ratio (η) as a function of Mpeak and z. At high redshifts, SMBHs of different masses accrete at similar Eddington ratios. Below z ~ 3, the activity level among more massive BHs starts to decline earlier. Consequently, we see that η decreases towards higher mass B Hs.

AGN in a luminous, compact galaxy at z = 10.60?

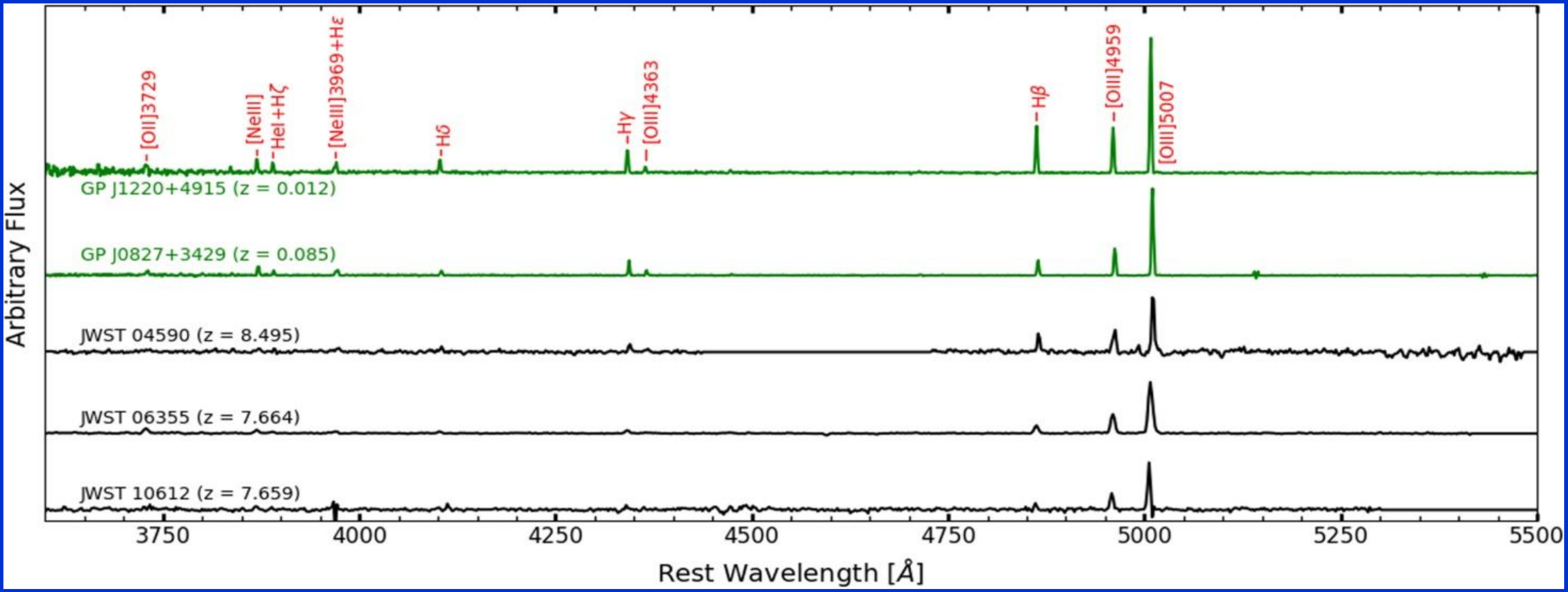
(Bunker+ 2023)



JWST-NIRSpec of GN-z11: Lα emission and possible AGN enhance NIII, NIV, & CIII abundances in a luminous ~60pc galaxy (Maiolino 2023)

PEAS IN THE EARLY UNIVERSE WITH JWST

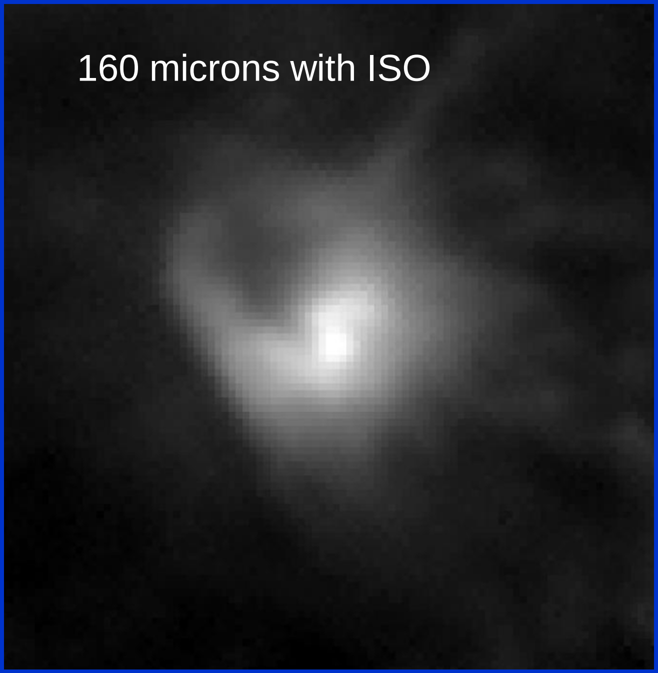
Compact Lyman-alpha emitting galaxies of very low metallicity (Rhoads 2023)



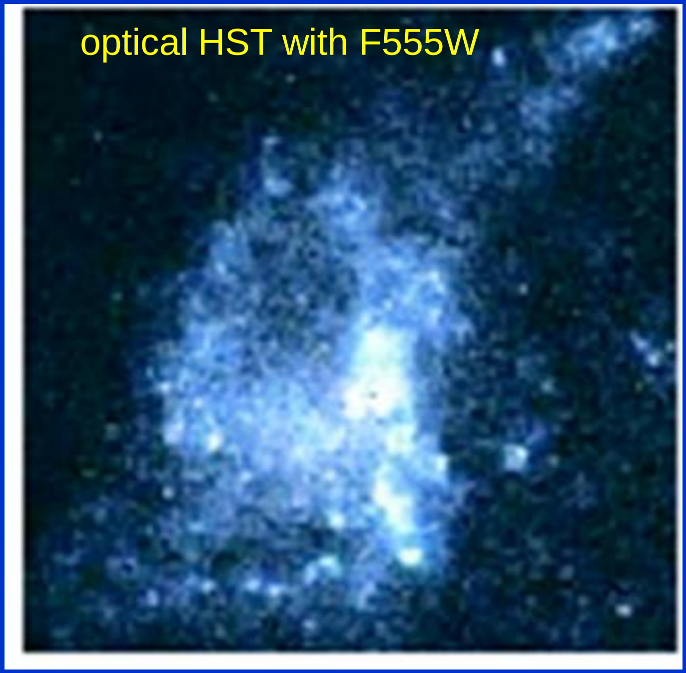
Comparison of the rest-optical spectra of local & EoR Green Pea galaxies.
Evidence of AGNs in high-z GPs found using WISE-MIR (Harish+ 2023)

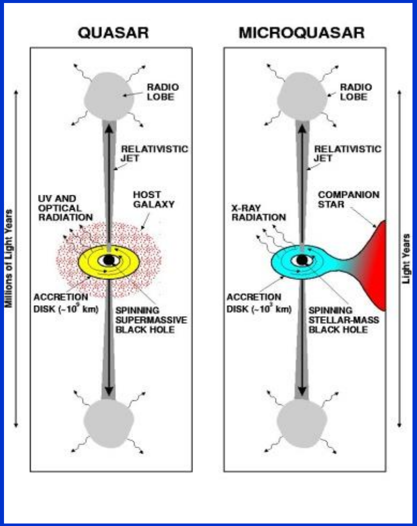
MORPHOLOGIES IN BOW SHOCKS OF μQSOs & AGN JETS

IRAS 19132+1035 (Mirabel+ 2014)



Minkowski object (van Breugel+ 1985)



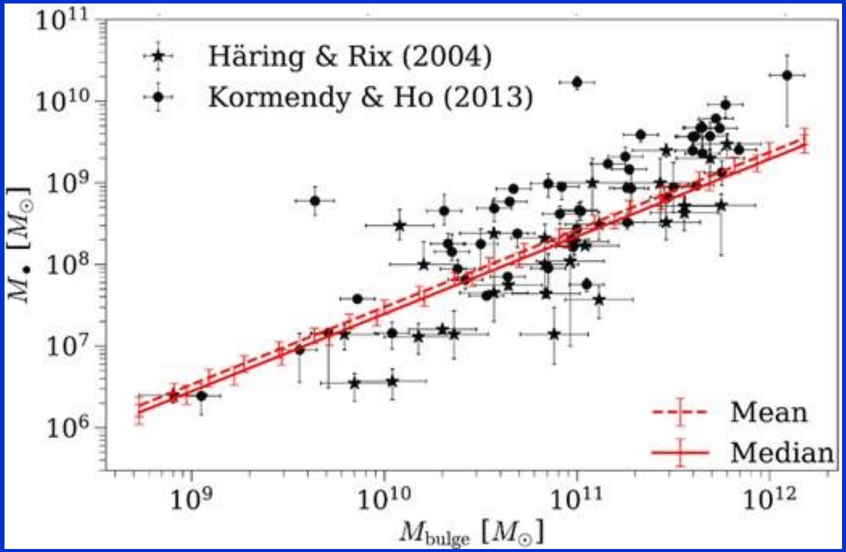


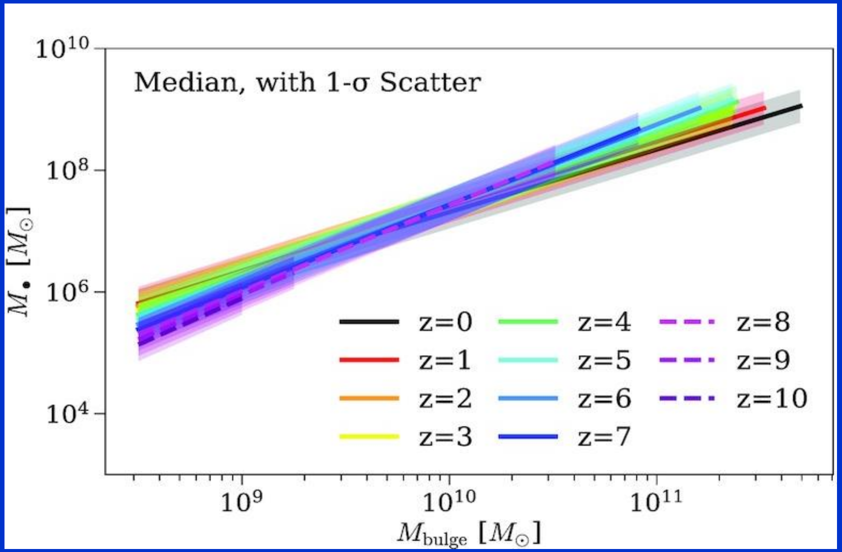
Analogy of μQSOs with QSOs?

Mirabel & Rodriguez (Nature 1998)

The M_{BH}–M_{bulge} relation for z = 0 to z = 10

TRINITY I: an empirical model that infers the statistical connections between dark matter haloes, galaxies, and SMBHs, constrained by galaxy observables from 0 < z < 10
Zhang+ 2023a





"The slope of the SMBH mass–bulge mass relation increases mildly from z=0 to z= 10"

TRINITY II: "However, to accurately measure the intrinsic M_{BH} - M_{stars} relation, it is essential to include fainter quasars with $L_{bol} \lesssim 10^{45}$ erg/sec" (Zhang+ 2023b)

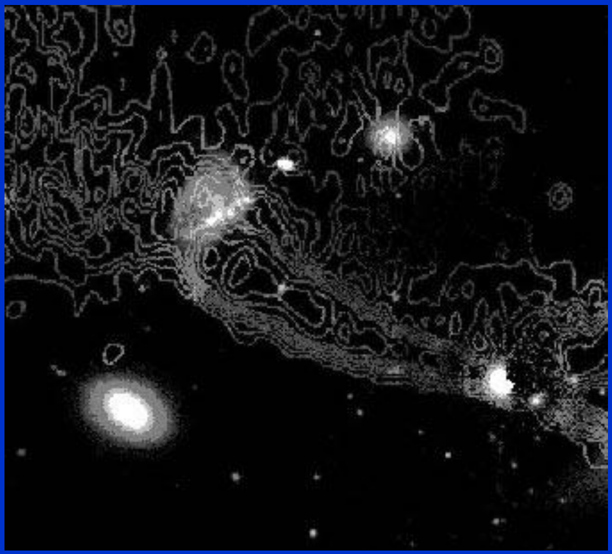
But it is observed that at least some SMBHs have formed & grown before stellar bulges

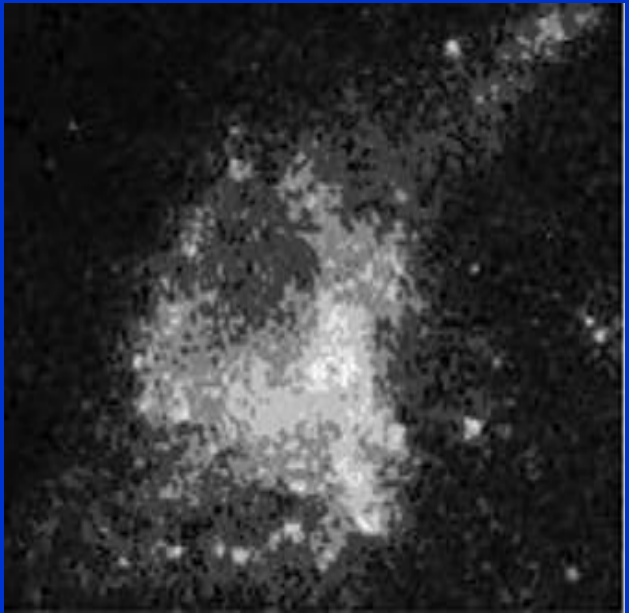
STAR FORMATION IS OBSERVED

- At relative low rates in galactic disks (e.g. Milky Way)
- At high rates in gas-rich galaxy mergers
  (Luminous & Ultra-luminous IR galaxies: e.g. Arp 220)
- At high rates in the early universe where cold gas streams merge along cosmic web filaments in massive dark matter halos (e.g. 4C 41.17)

Minkowski's Object in NGC 541

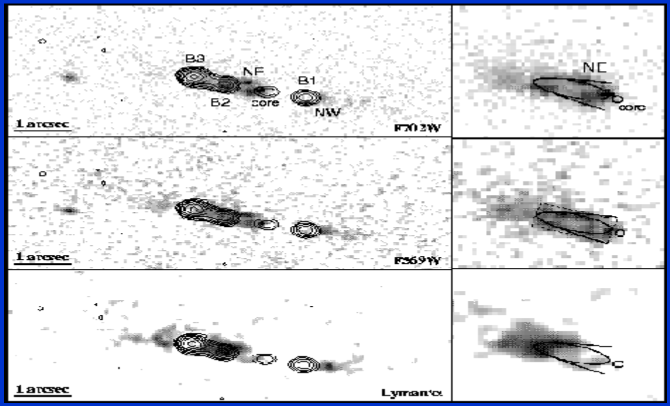
van Breugel + *1985-2004*



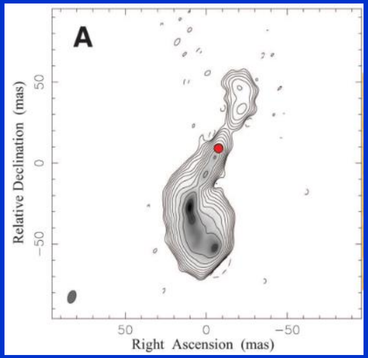


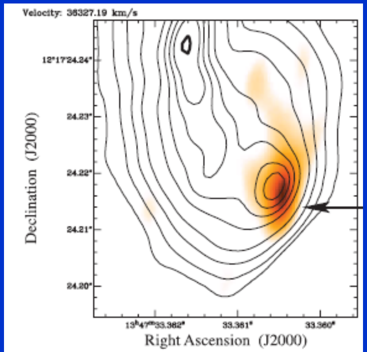
4C41.17 @ z=3.8

Bicknell + 2000



Morganti+ 2013



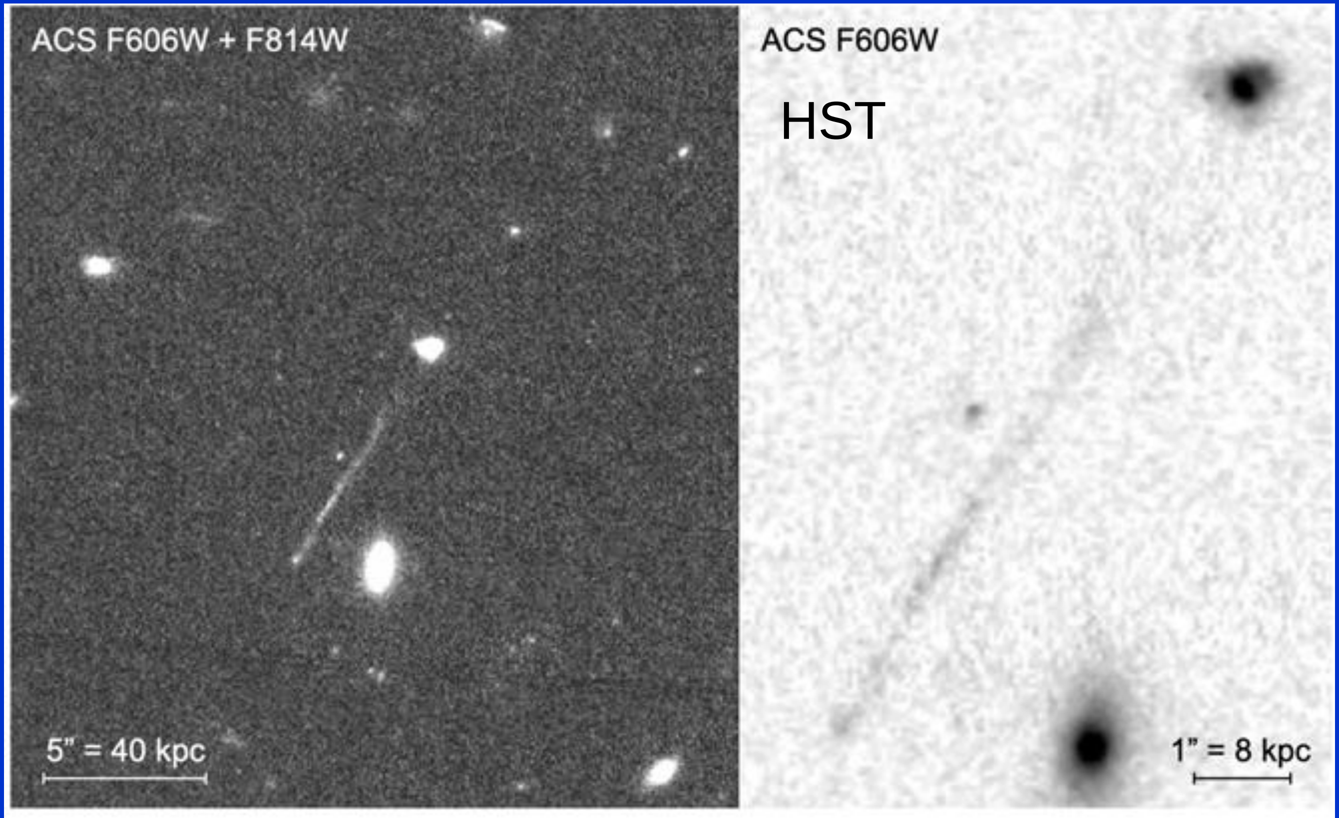


STATISTICAL STUDIES HAVE SHOWN

- **Alignment of Hα with radio galaxy jets due to induced star formation**
- **Size of jets decrease with redshift z due to increase of gas density**

A Runaway SMBH Identified by Shocks and Star Formation in its Wake?

van Dokkum+ (2023)

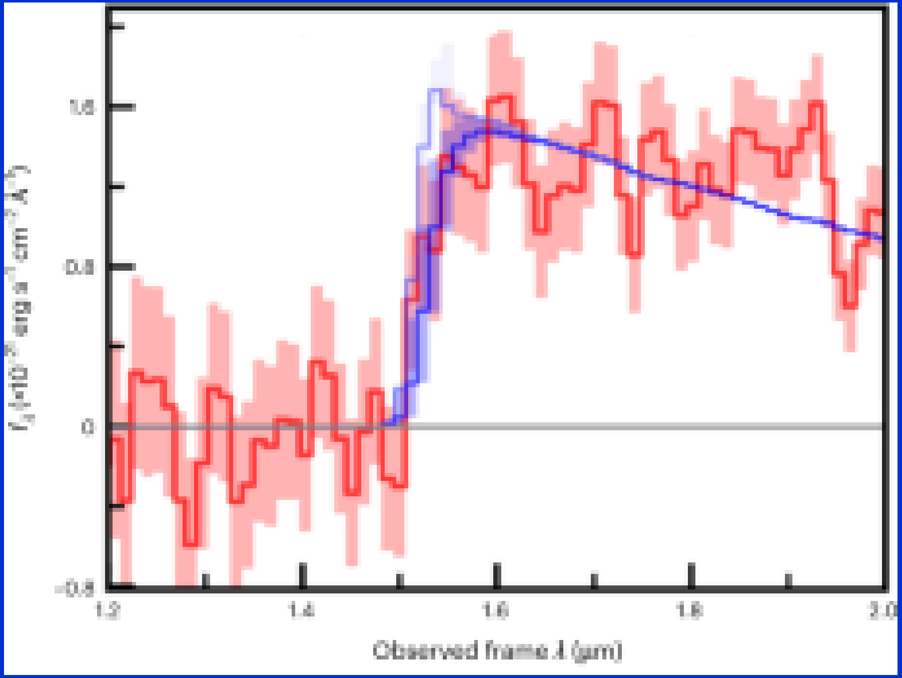


- Star Formation galay & wake at z = 0.964 imply l_{wake} = 62 kpc
- [O III]/Hβ ratio indicates star formation & fast shocks
- Stellar continuum colors indicate increasing age with the distance from the tip.
- Time since ejection is ~39 Myr, and the BH velocity is $v_{BH} \sim 1600$ km s^{-1}.
- Opposite the wake is a short feature, only in [O III] and rest-frame far-UV.

Previous research's: Burbidge+1971; Arp 1972; Saslaw & de Young 1972; Rees & Saslaw 1975)

Could BH-jets trigger the rapid emergence of the first generation of galaxies?

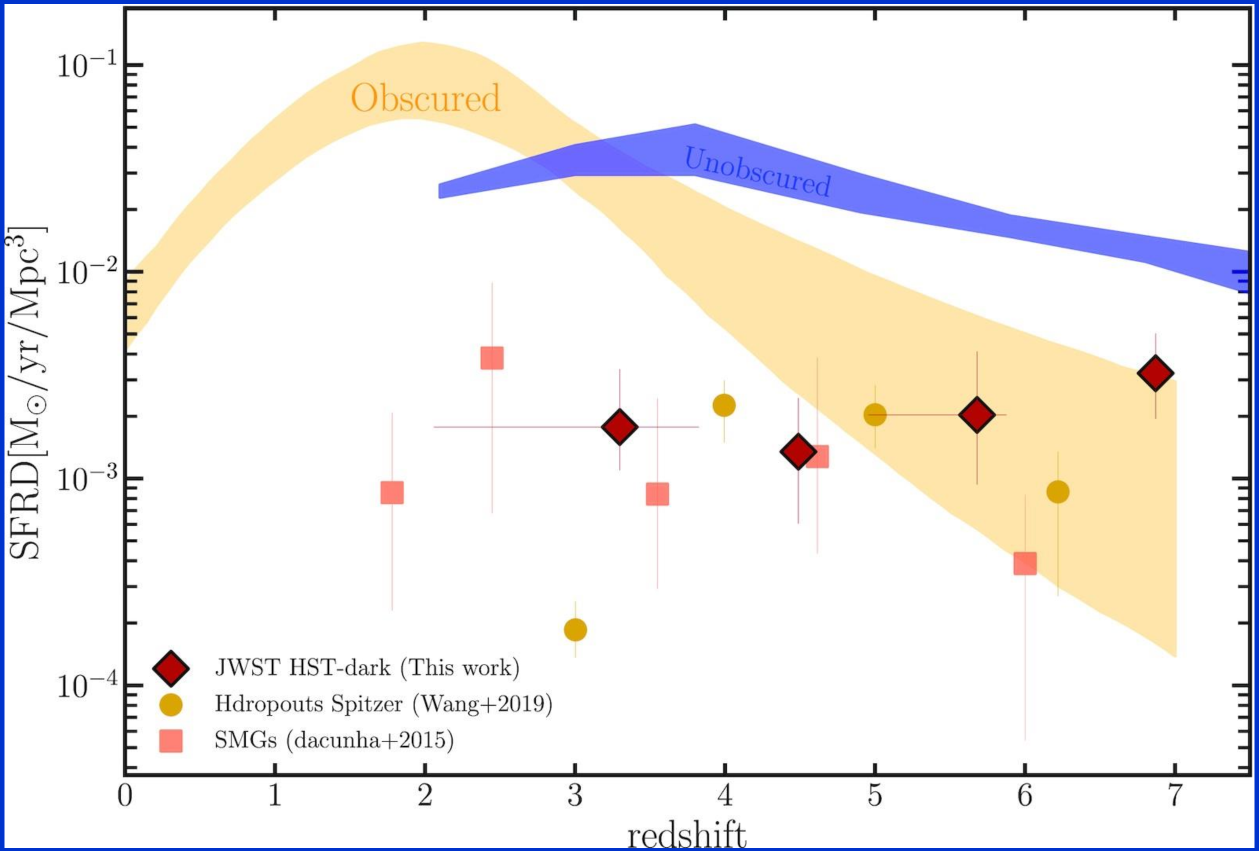
Metal poor compact galaxies of 10^7 – 10^8 solar masses at 10.3 < z < 13.2 less than 450 Myr after the Big Bang (Curtis-Lake+ April 2023)



Spectral break fit region and the derived constraints on neutral hydrogen in the IGM for JADES-GS-z11-0.

infrared bright, optically dark galaxies with early JWST data

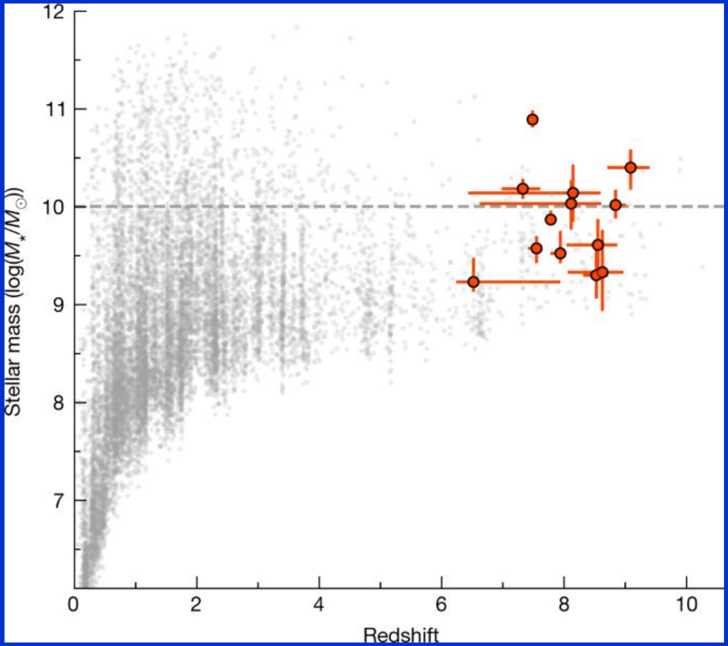
Barrufet+ (2023)



SFRD against redshift for the *HST*-dark galaxies (red diamonds) compared to a compilation of previous studies. The orange area represents the dust-obscured SFH from semiempirical models presented in Zavala et al. (2021), whereas the blue area shows the unobscured star formation (Bouwens et al. 2022). The contribution of our *HST*-dark galaxies remains almost constant from redshift 3.5 $< z < 6$. The *HST*-dark contribution is similar to SMGs at $z \sim 5$–6 (orange squares; da Cunha et al. 2015). Our SFRD is in agreement with previous *HST*-dark studies at $z \sim 4$–6 (orange dots; Wang et al. 2019), but we extend the result to $z \sim 7$.
Our analysis shows an *HST*-da

A population of red candidate massive galaxies ~600 Myr after the Big Bang
Labbé+ (Nature 2023)

intrinsically red galaxies in the first roughly 750 million years of cosmic history. In the survey area, we fnd six candidate massive galaxies (stellar mass more than 1010 solar masses) at 7.4 ≤ z ≤ 9.1, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of roughly 1011 solar masses.

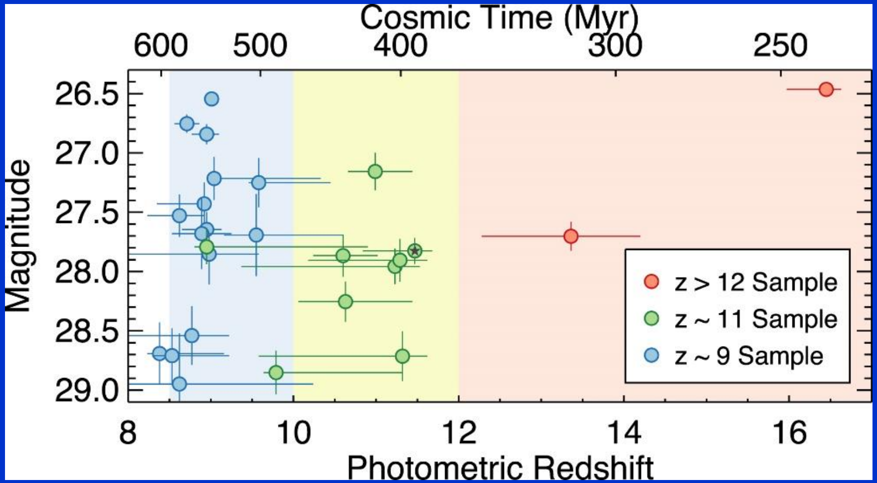


Redshifts and tentative stellar masses of double-break selected galaxies.

Larson's BH = 8.9x10^6 solar masses and galaxy 3,2x10^9 at *z* = 8.679

A combination of either super-Eddington accretion from stellar seeds or Eddington accretion from very massive black hole seeds is required to form this object by the observed epoch.

The Galaxy/BH mass = 360



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PLAN OF THE TALK

• First I will mention two recent models in the context of dark matter cosmologies where it is proposed that the compact seeds of the SMBHs at redshifts z > 6 were formed by direct collapse in dark matter haloes.

• Then, I will show that recent high-z observations of the gas with ALMA & VLT, and of BHs with the JWST, are consistent with astrophysical hypotheses in those models.

•Finally, based on those recent theoretical and observational contexts, and on the extensive observations of the environments of BH-jets in the local and distant universe, I conclude that jets from rapidly growing BHs must have enhanced the formation of Pop-III stars at cosmic dawn.