Chasing wandering supermassive black holes in the COSMOS

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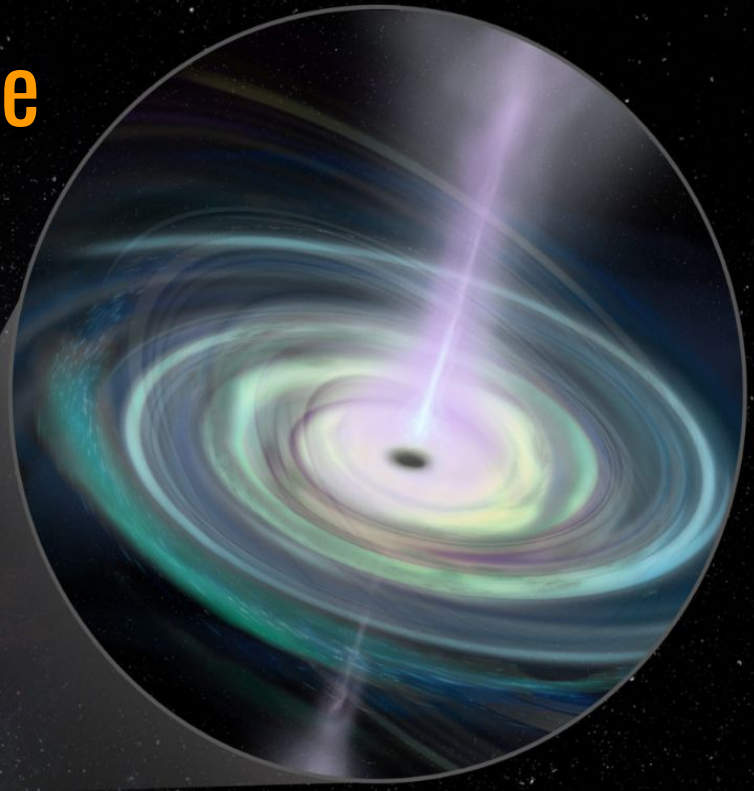

In collaboration with:
R. Bhatawdekar, D. Izquierdo-Villalba, M. Dotti, A. Sesana, P. Severgnini, S. Belli, E. Daddi, B. Kalita, G. Peluso, M. Perna, J. Singh, V. Smolcic, C. Spingola, F. Ubertosi, I. Prandoni, M. Gitti, A. Traina, G. Zamorani, A. Zanella and the COSMOS-Web team

Credit: Sophia Dagnello, NRAO/AUI/NSF

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Based on a ESA Archival Research Visitor Programme
next deadline: 31/10/2025 —> https://www.cosmos.esa.int/web/esdc/visitor-programme

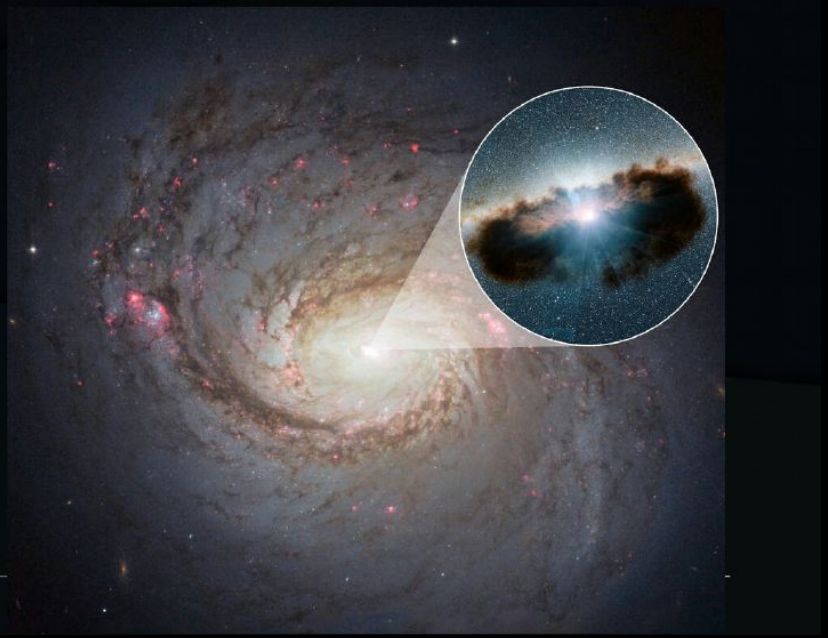
Credit: Sophia Dagnello, NRAO/AUI/NSF

“Stellar” black holes

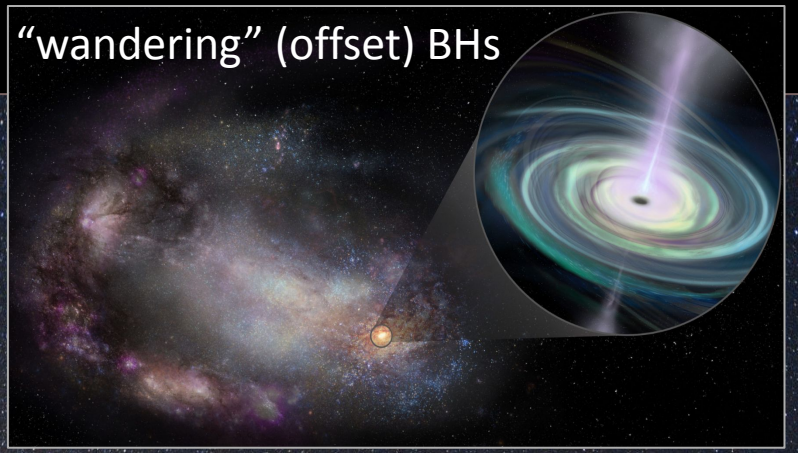
$M_{BH} \sim 1\text{-}100\ M_{sol}$

“Supermassive” black holes

$M_{BH} \sim 10^{6}\text{-}10^{10}\ M_{sol}$



Our own laboratory: the Milky Way

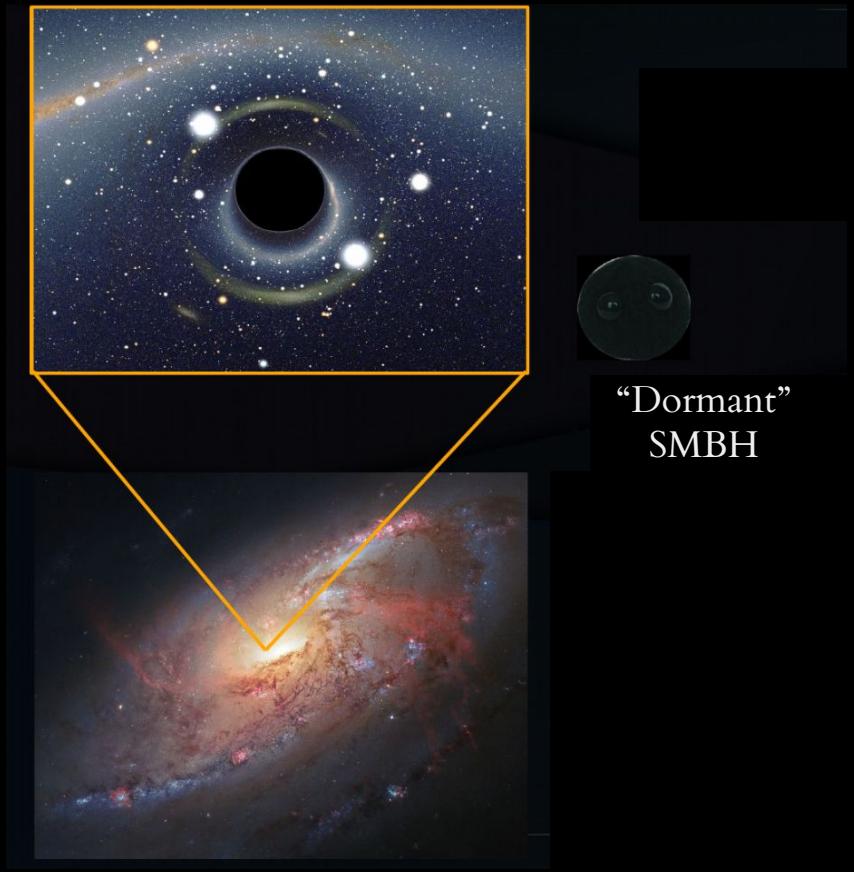


Sagittarius A*
(EHT)

M_{BH} = 4 million M_{sol}

Very Large Telescope (VLT)

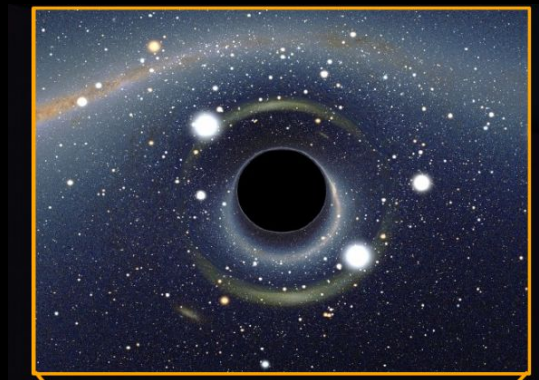
Growing supermassive black holes



"Dormant" SMBH

NGC 4258. Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), and R. Gendler (for the Hubble Heritage Team). J. GaBany

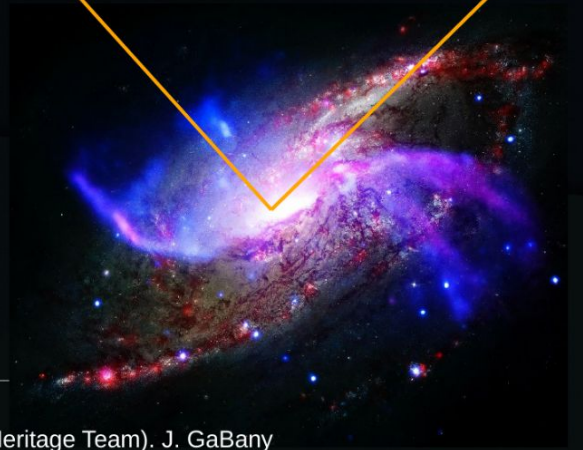
Growing supermassive black holes: Active Galactic Nuclei (AGN)



gas accretion

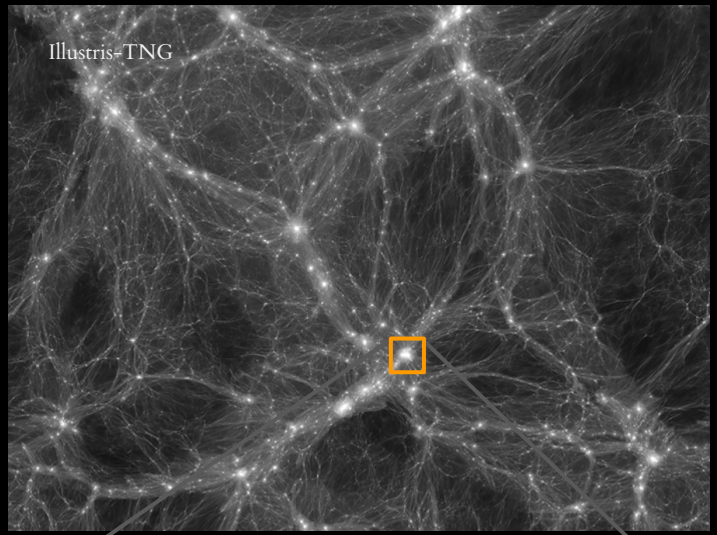
"Dormant" SMBH

AGN

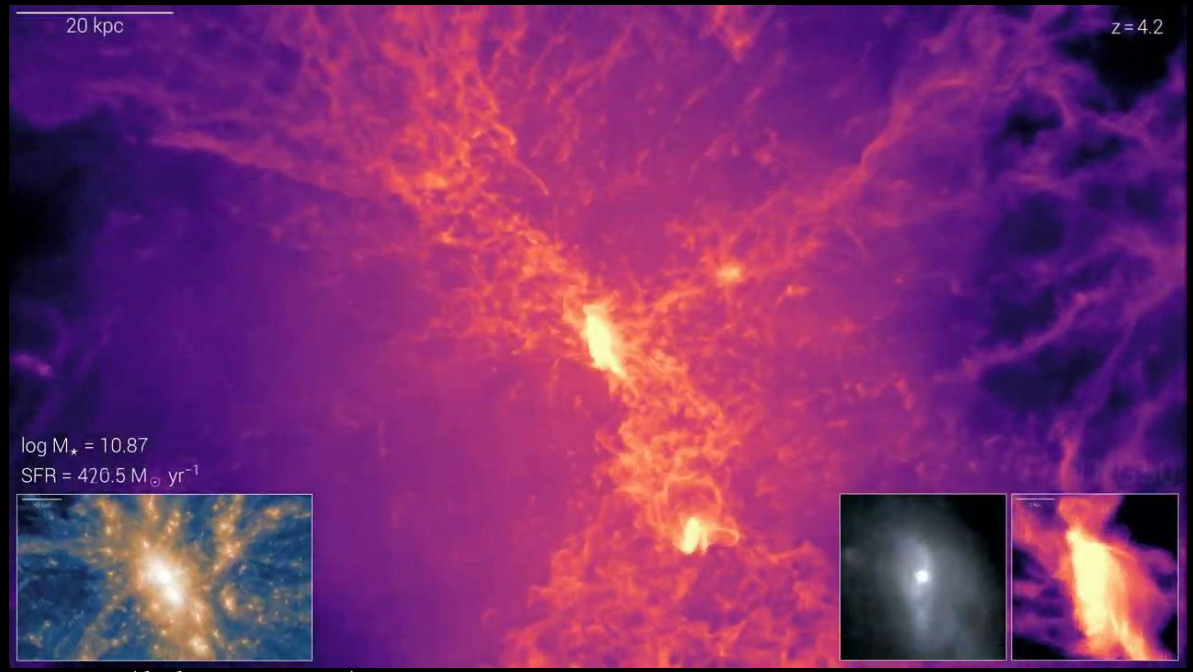


NGC 4258. Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), and R. Gendler (for the Hubble Heritage Team). J. GaBany

Hierarchical galaxy growth through merging



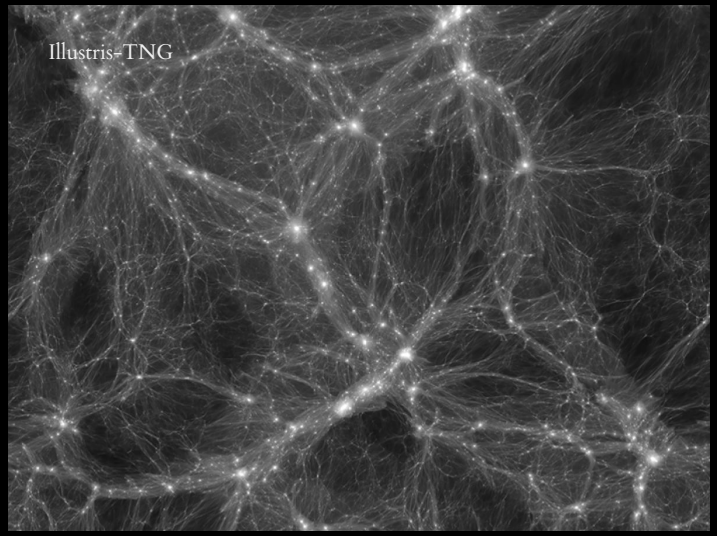
Galaxies grow in the cosmic web, which fuels and sustains star formation (and AGN activity) through gas streams and mergers



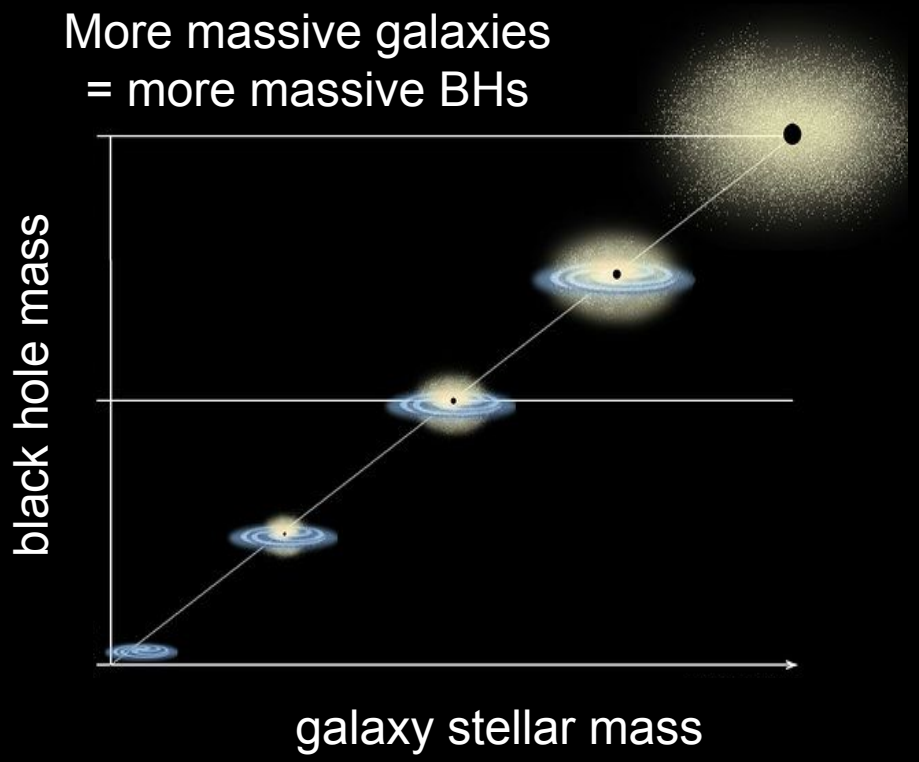
zoom-out (dark matter + gas) stars gas

Illustris TNG (Pillepich et al. 2018)

Galaxy growth ⟺ SMBH growth



More massive galaxies
= more massive BHs

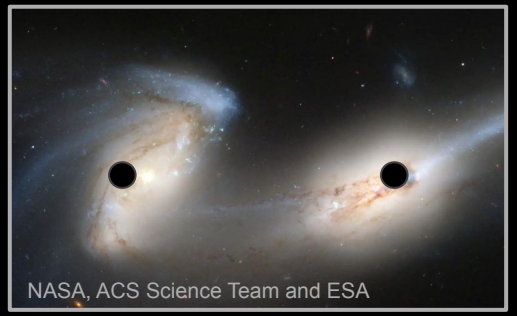


Kormendy+2013

On the way to merging: three stages

separation

10 - 100 kpc



Pre-merger

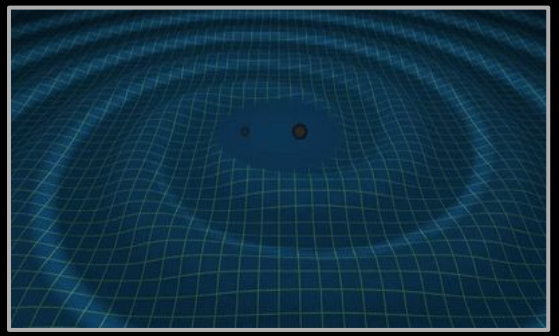
(e.g. Blecha+2013: Kaviraj+2019; Silverman+2020; Reines+2020; Severgnini+2021; De Rosa+2022; Inaba+2022; Pfeifle+2023, Perna+2023,24; Tanaka+2023; Ishikawa+2024; Mezcua+2024 etc)

100 pc - 10 kpc

Post-merger

(e.g. Hwang+2020; Shen+2021; Chen+2022; Mannucci+2022; 2023; Ciurlo+2023; Scialpi+2024; Übler+2024)

<< 100 pc



SMBH binaries

Kharb+2017; Rodriguez+2006 (VLBI); Sillanpaa+96; Papovic+2012; Graham+2015; Charisi+2016; Vaughan+2015; Severgnini+2018; Xi+2020; Serafinelli+2020; Zhu+2020; Komossa+2023; Rigamonti+2025 etc

Wandering (i.e. off-centre) BHs

Dynamical friction drives angular momentum losses: **merging can take several Gyrs**

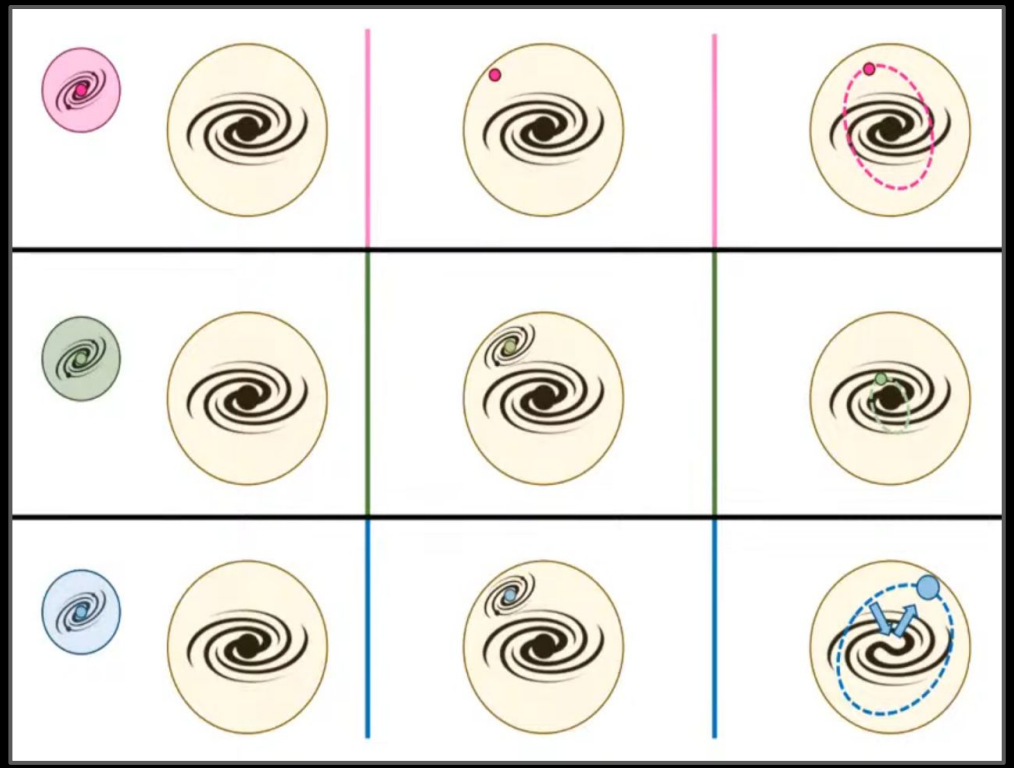
Formation channels of wandering BHs

Three main formation channels (Izquierdo-Villalba+2020; Ricarte+2021):

Disrupted (orphan) BHs

Pairing BHs

Ejected/ recoiling BHs



time

d > 10 kpc
falling inward

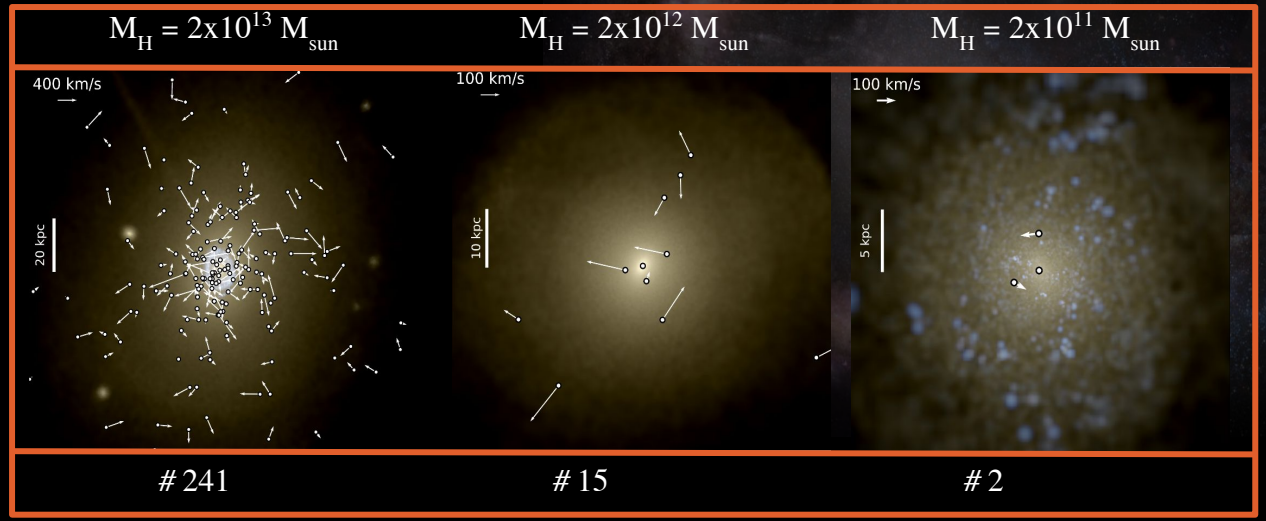
d < 10 kpc
falling inward

d > 10 kpc
recoiling outward

How many wandering BHs do models predict?

Cosmological simulations (ROMULUS, Tremmel+2016; Ricarte+2021 a,b) predict:

- Wandering BHs are prevalent in **more massive galaxies/halos and at higher *z***
- At *z*=0, **~10%** of SMBH mass is locked in wanderers, while it increases to **>50% at *z*>3**



Incidence of wandering BHs

⇕

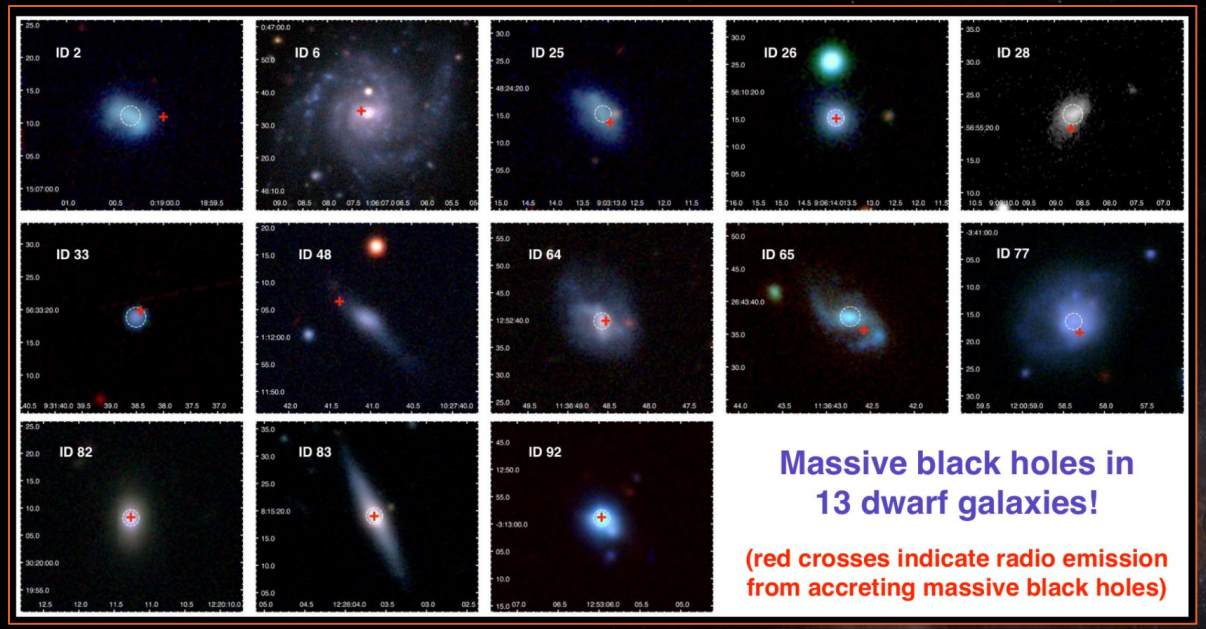
merger rate and SMBH mass assembly

Ricarte+2021a

Wandering BHs in local dwarf galaxies

Reines+2020 (high-resolution VLA, 0.25", z<0.055)

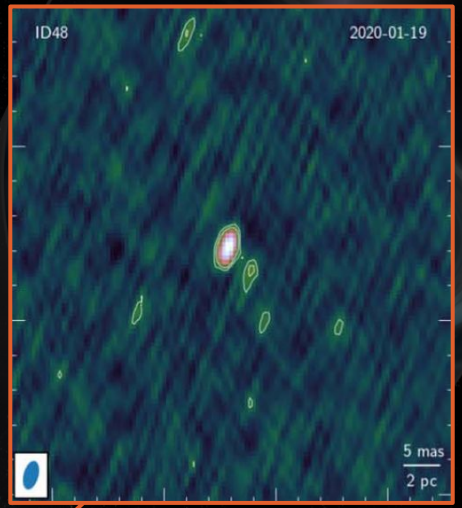
See also e.g. Yao+2025



- A few of them are offset: wandering BH candidates

but…

(Sargent+2022, VLBI follow-up)

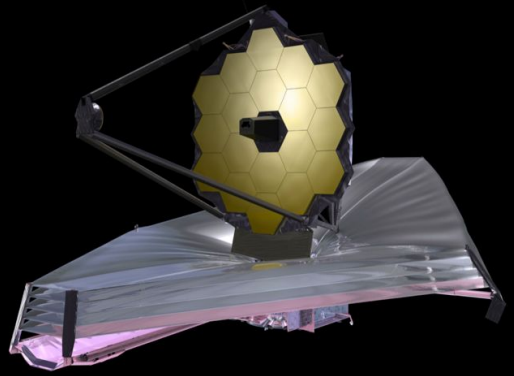


- **CAVEAT**: chance alignments between background AGN & foreground galaxy

JWST & VLBA team up for chasing distant wandering BHs

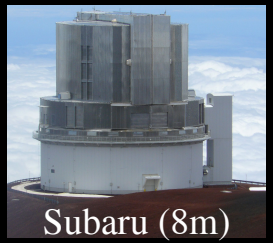
Searching for wandering BHs via spatial offset between galaxy and AGN positions

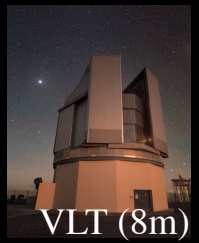
James Webb Space Telescope (JWST)

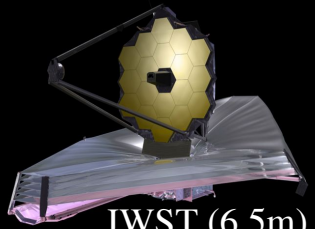


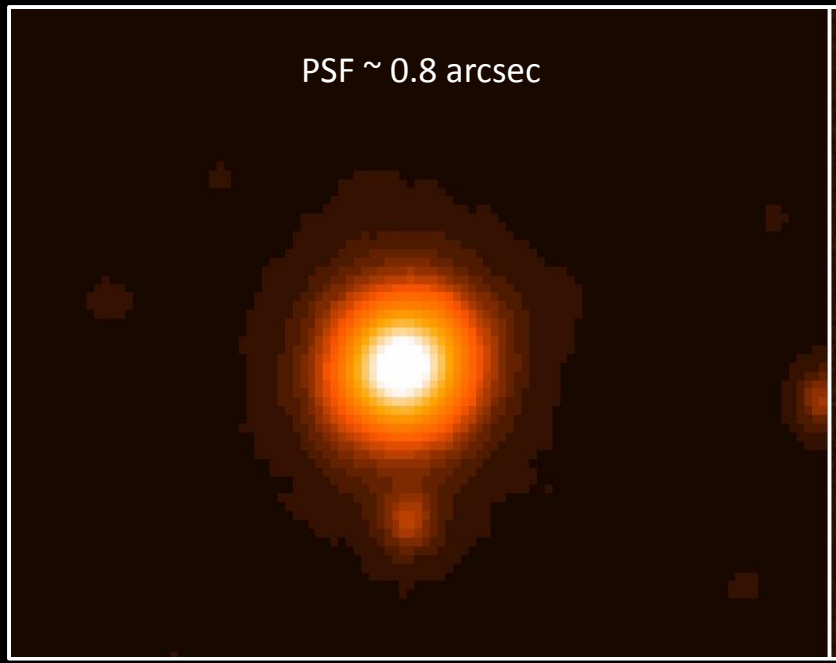
Very Long Baseline Array (VLBA)

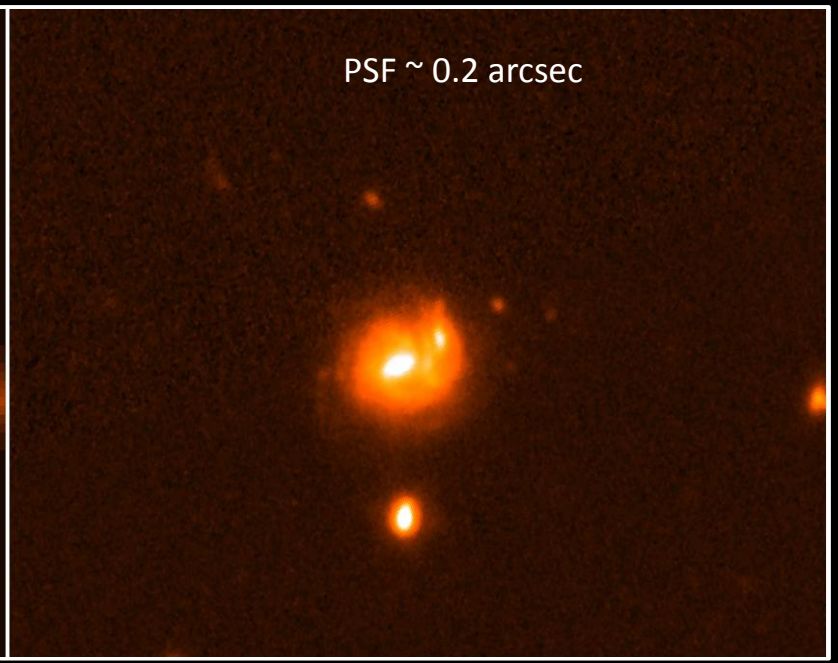
Why the JWST?


Subaru (8m)

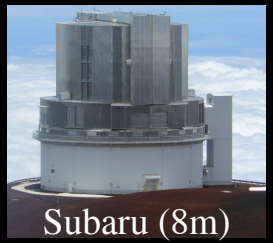

VLT (8m)

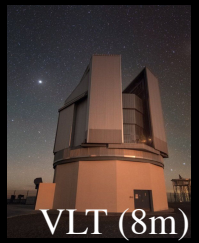

JWST (6.5m)

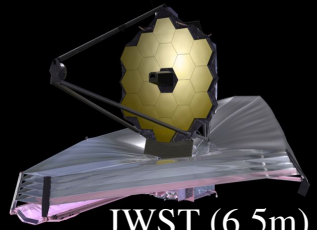


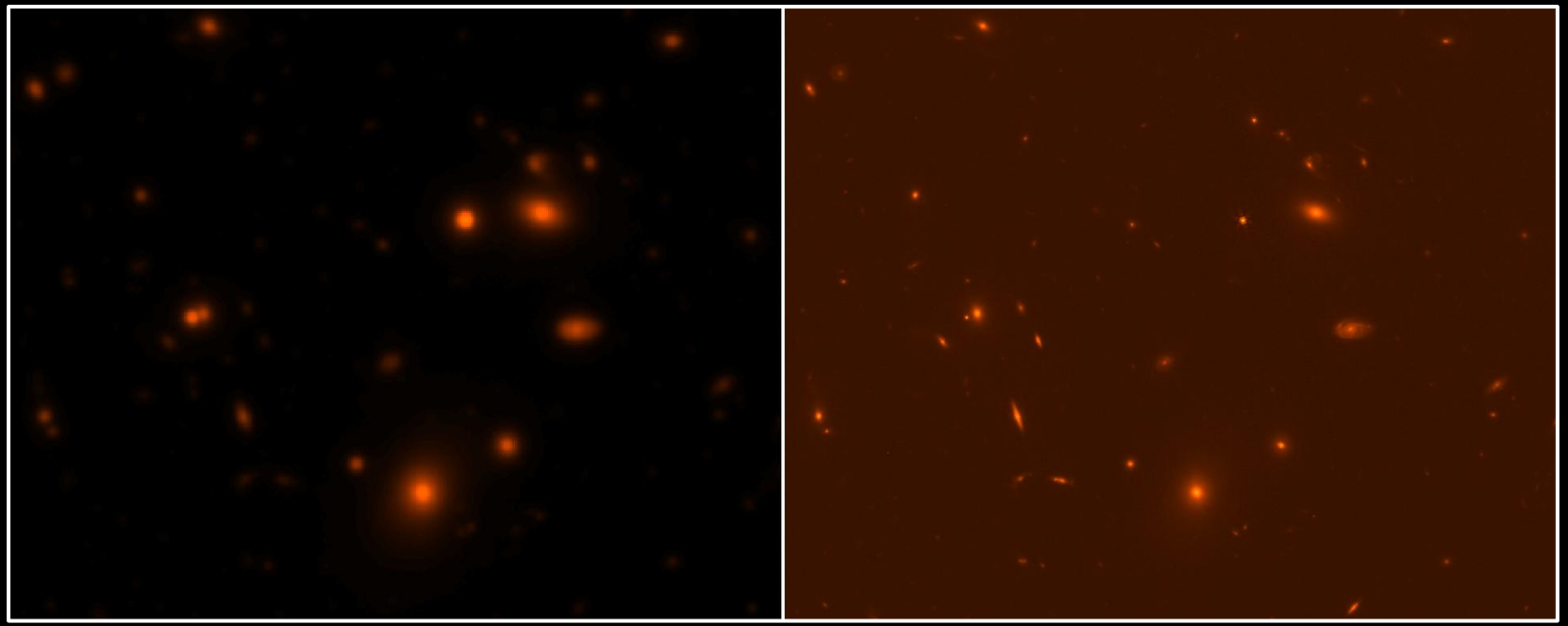


Why the JWST?

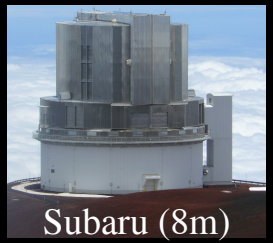

Subaru (8m)

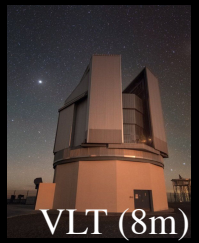

VLT (8m)

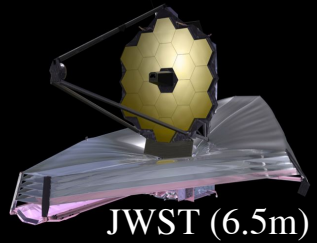

JWST (6.5m)

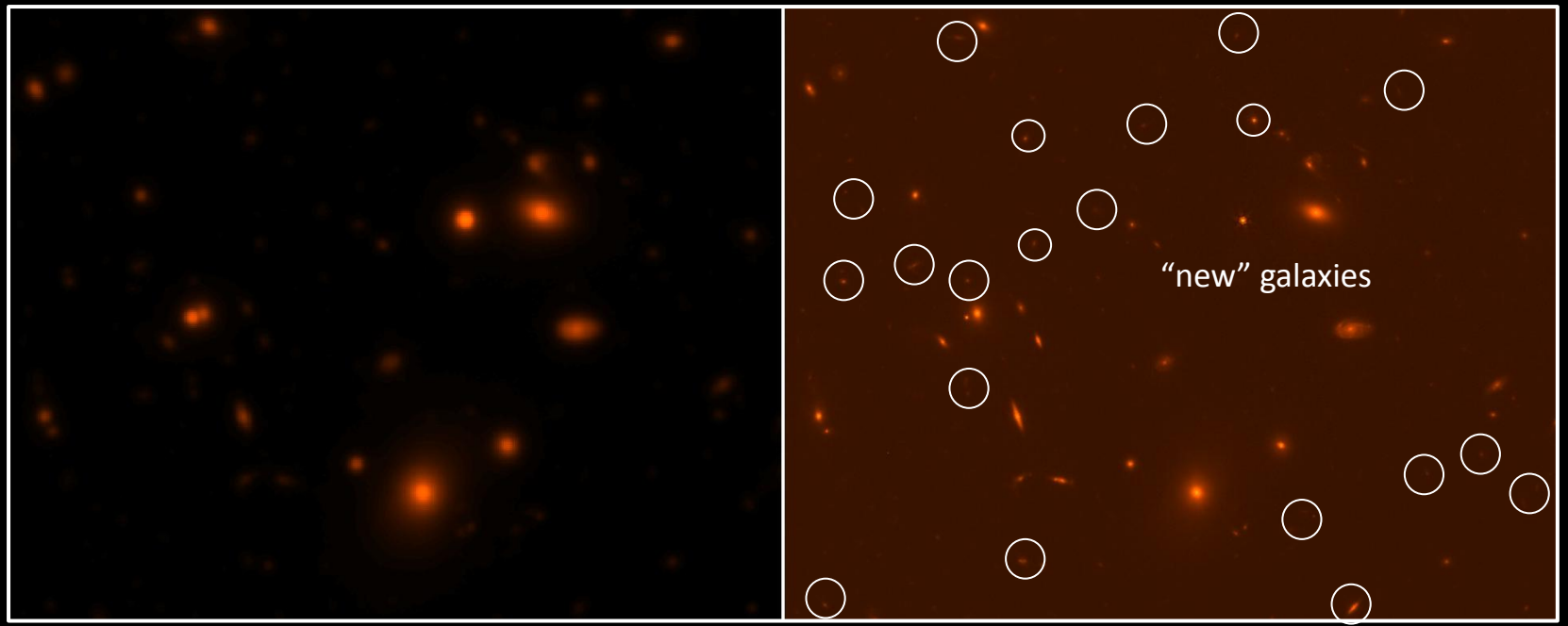


Why the JWST?

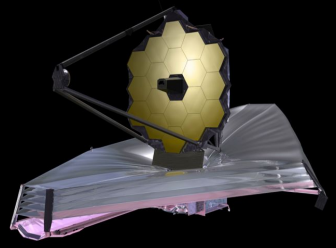

Subaru (8m)


VLT (8m)

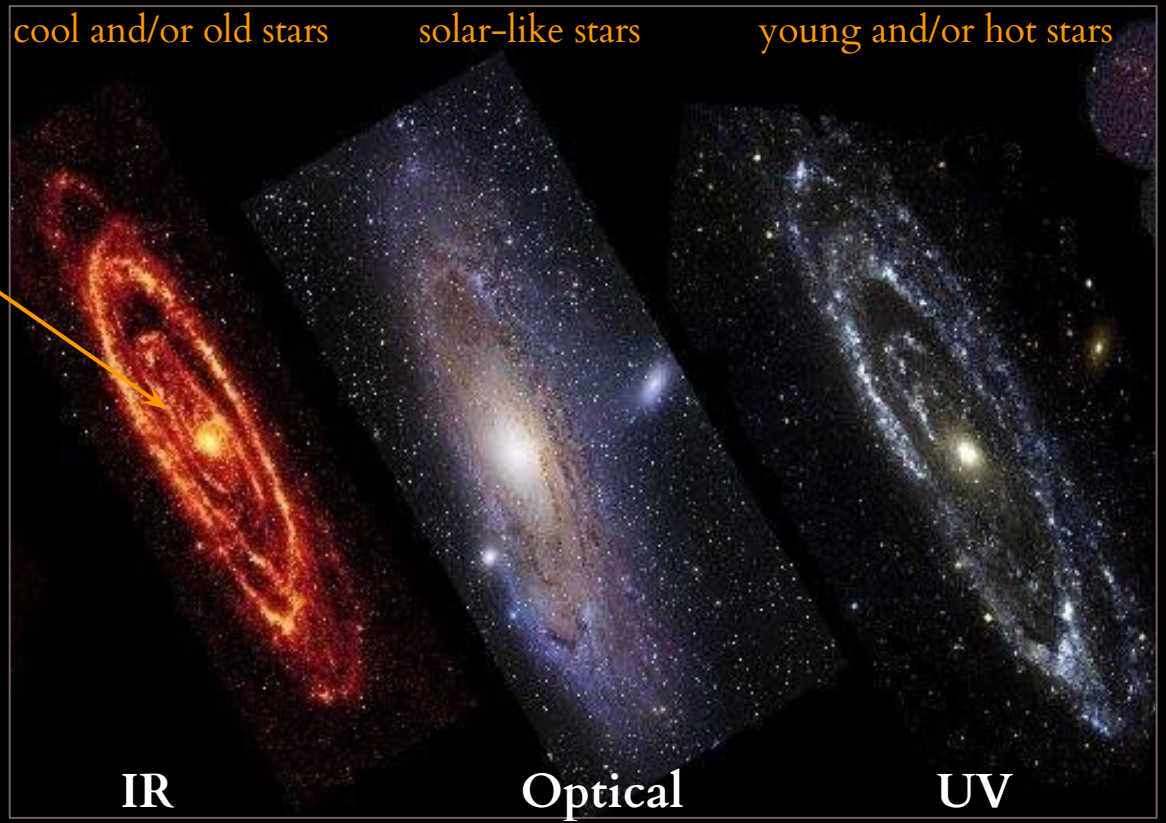

JWST (6.5m)



Why the JWST?



JWST traces the bulk of the galaxy stellar mass (and its center of mass)



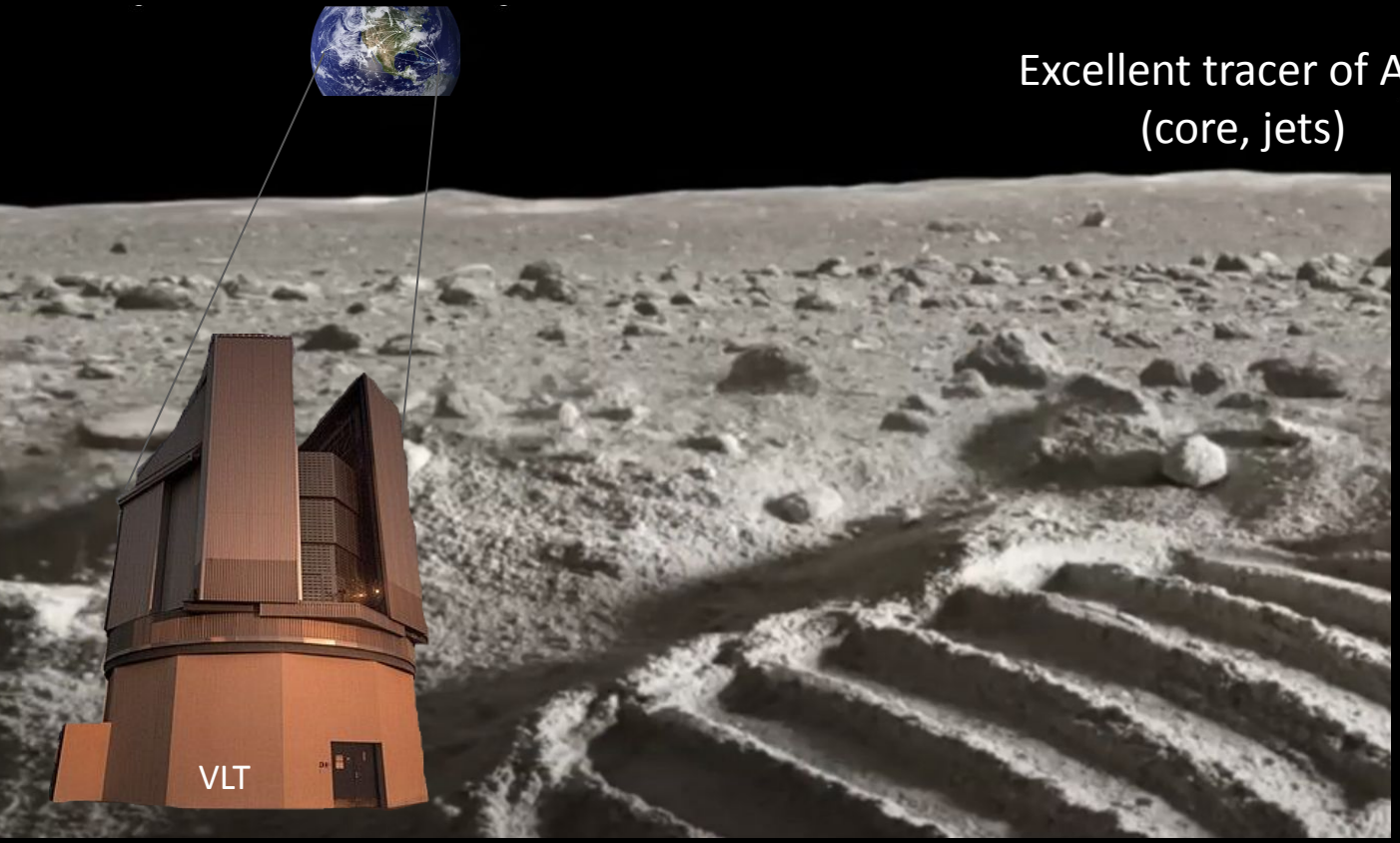
frequency

Why the Very Long Baseline Array (VLBA)?

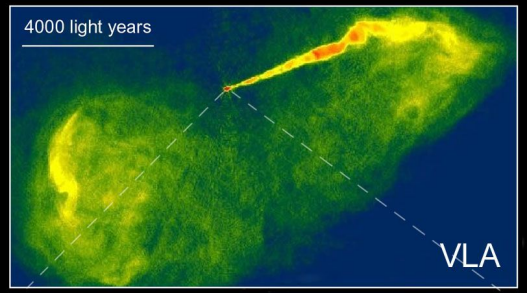
- 10 identical antennas (25m) in the US
- Resolution power of a single 9000 km-sized dish!

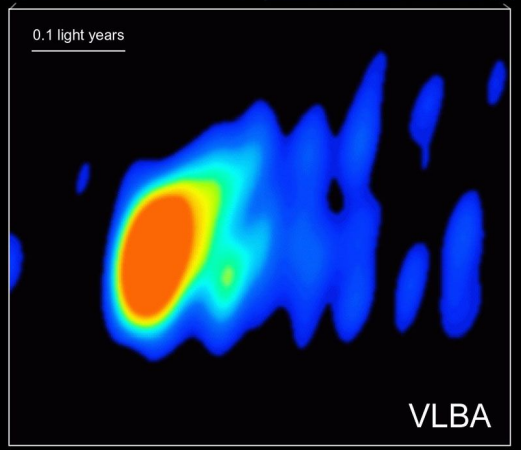
Why the Very Long Baseline Array (VLBA)?

Angular resolution <10 milli-arcsec

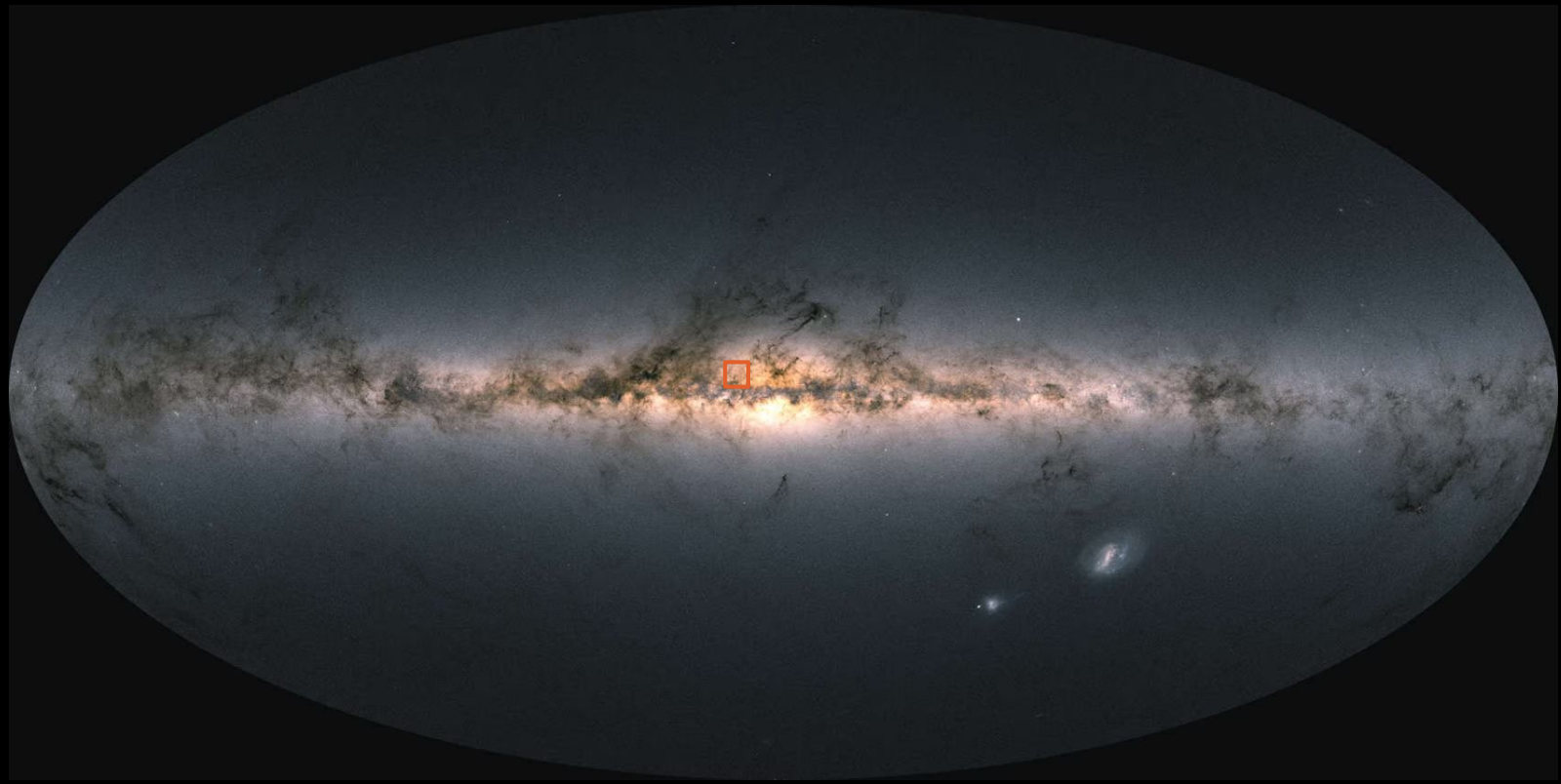


Excellent tracer of AGN
(core, jets)

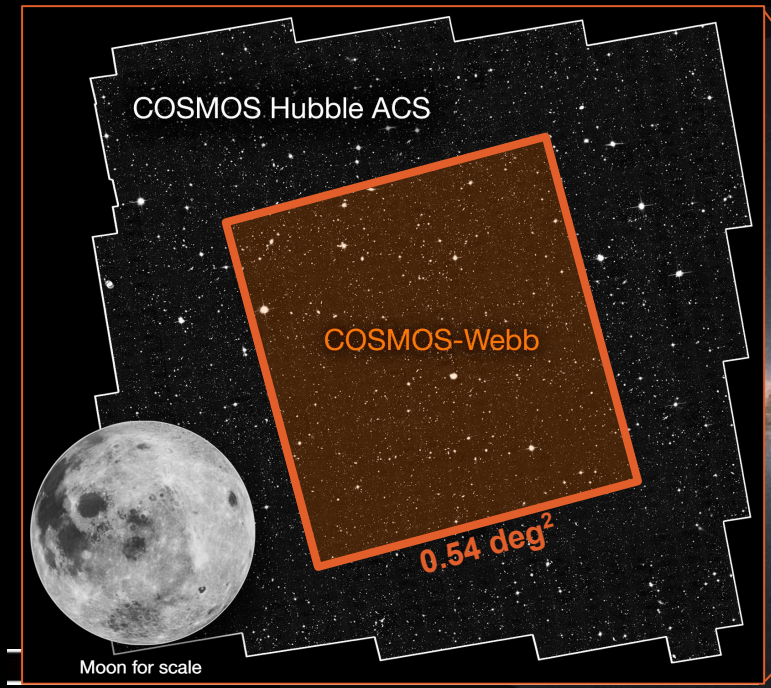


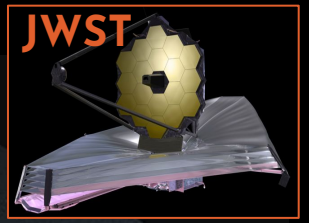


JWST & VLBA team up for chasing high-z wandering BHs



JWST & VLBA team up for chasing high-z wandering BHs

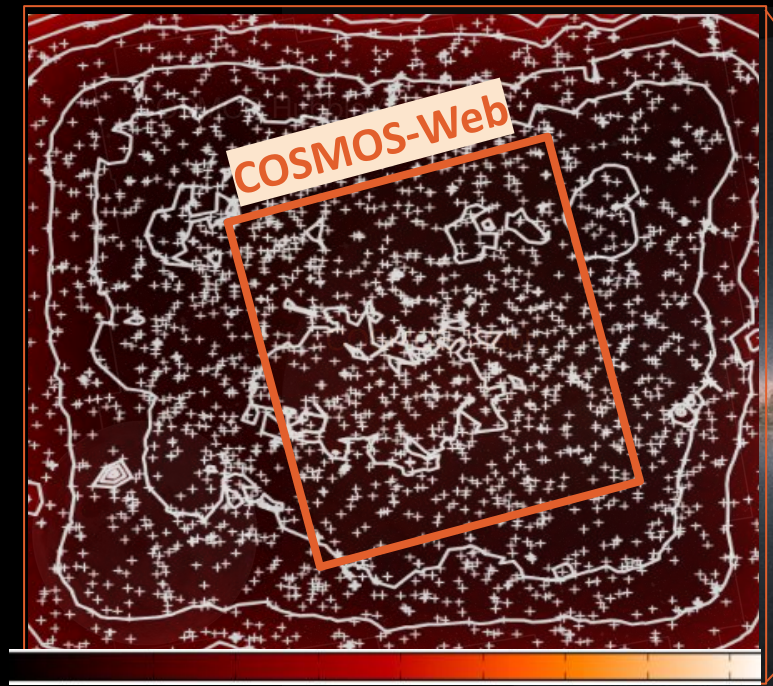


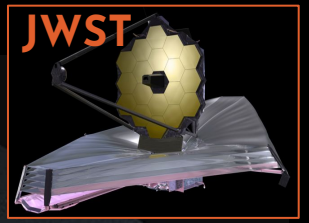


- NIRCam filters: **F115W, F150W, F277W, F444W**
- Sensitive to galaxy stellar mass distribution (rest 1.6μm)
- Astrometry with <0.05" accuracy (tied to GAIA DR3)

Casey+2023; Franco+ in prep.

JWST & VLBA team up for chasing high-z wandering BHs





- NIRCam filters: **F115W, F150W, F277W, F444W**
- Sensitive to galaxy stellar mass distribution (rest 1.6μm)
- Astrometry with <0.05” accuracy (tied to GAIA DR3)

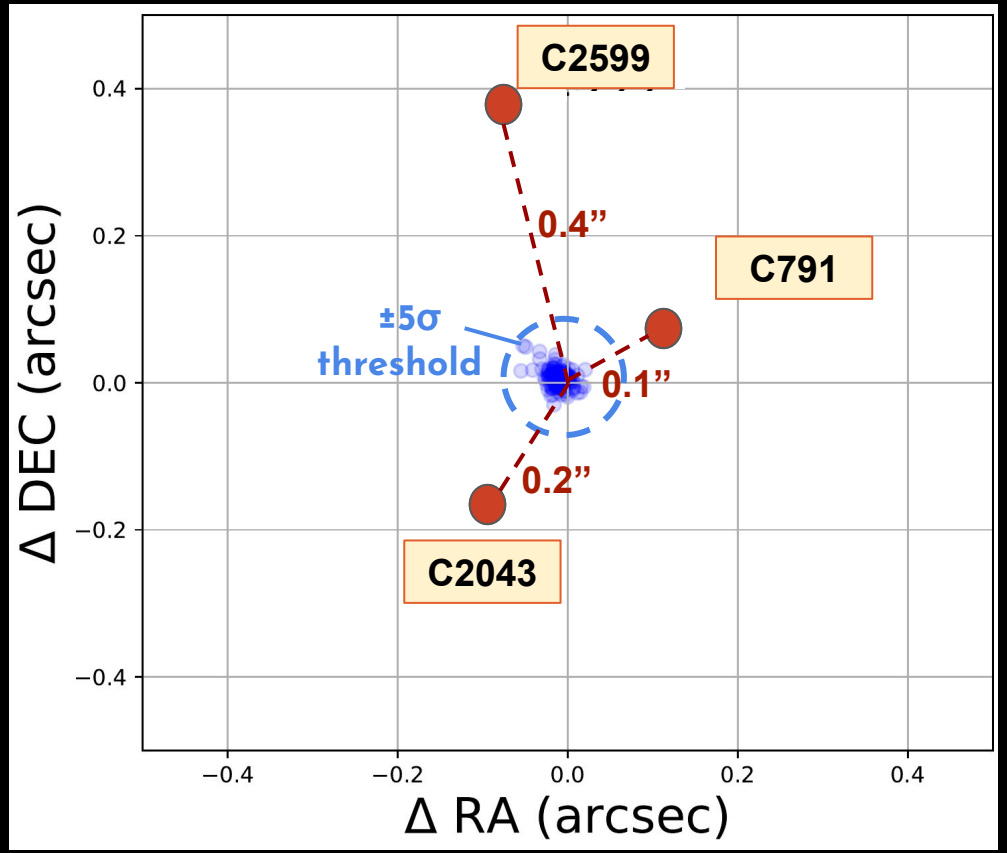
- **170** VLBA AGN at **0.1<z<4** within COSMOS-Web
- Pure tracer of AGN emission
- Excellent astrometric accuracy (~ 1 milli-arcsec)

Herrera Ruiz+2017, 2018
ID+2025

VLBA + JWST cross-match

- Scatter (σ) ~ 0.01 arcsec
- 5σ threshold ~ 0.05 arcsec (0.4 kpc at z=1)

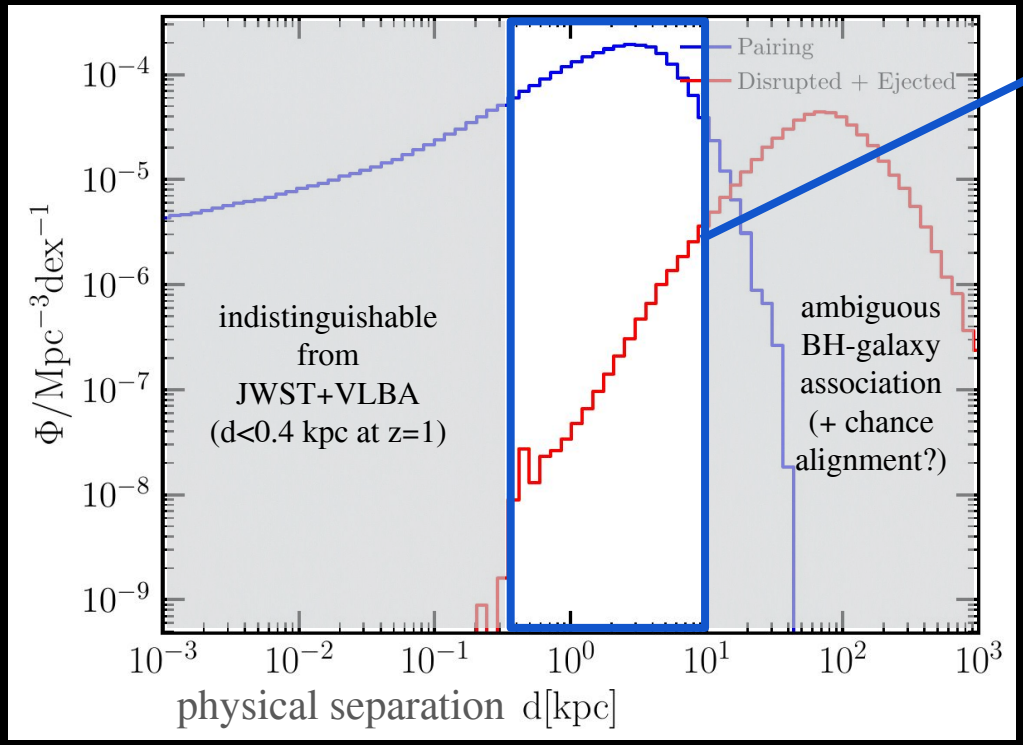
3 wandering AGN candidates



How many wandering BHs did we expect?

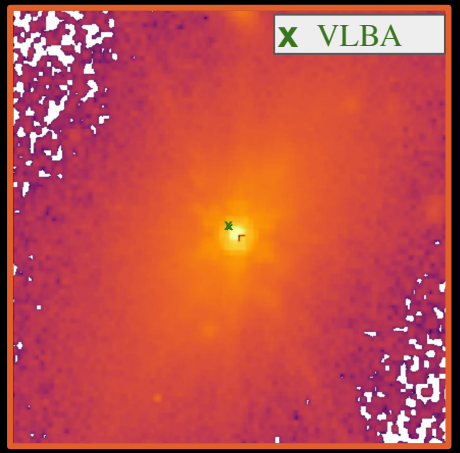
L-Galaxies (Henriquez+2016;2020; Izquierdo-Villalba+2022,23,24):

- ❏ Matched in galaxy mass, z, AGN properties
- ❏ Matched in area (within COSMOS-Web)



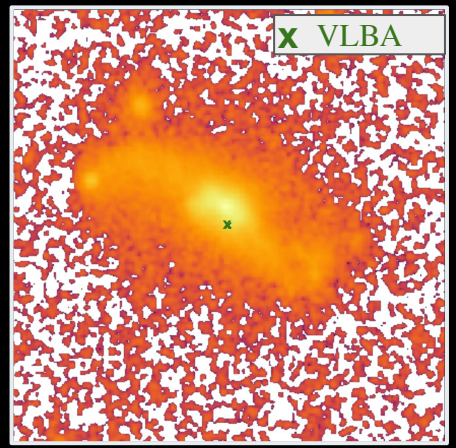
4.3 expected wBHs (mostly pairing)

VLBA + JWST: three wandering BH candidates



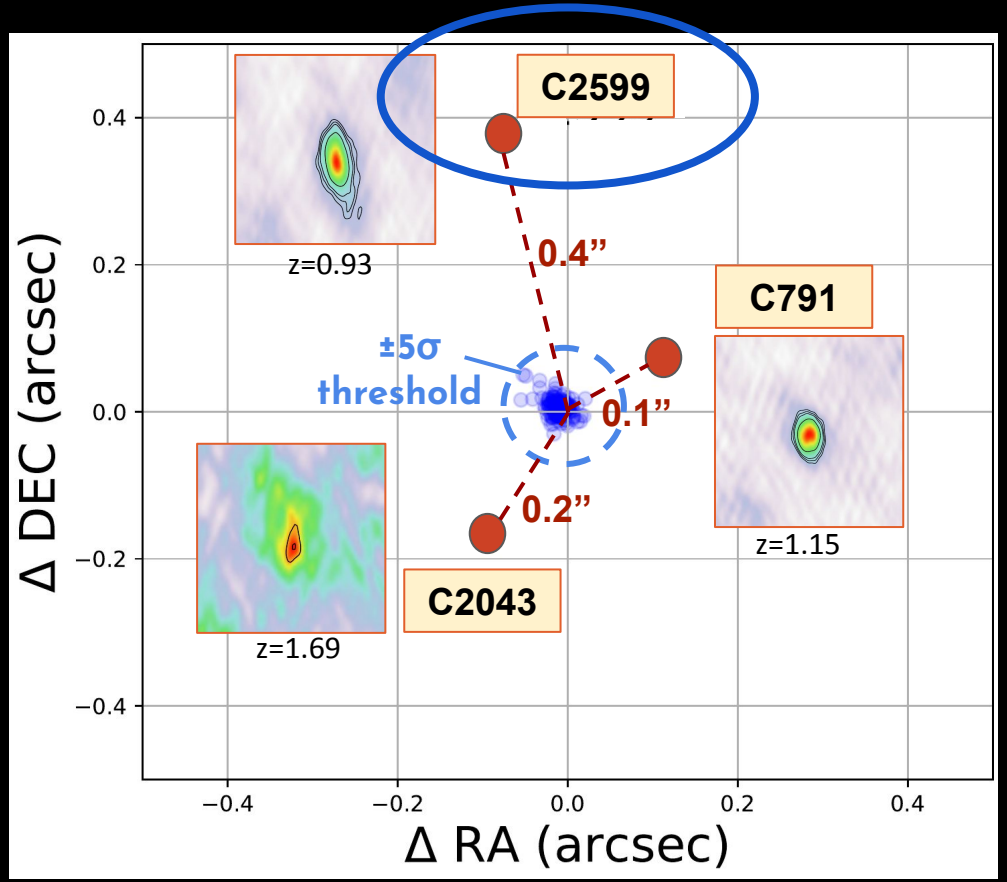
C791 (z=1.15)

- offset ~ 0.1 arcsec
- Spectroscopic confirmation is challenging

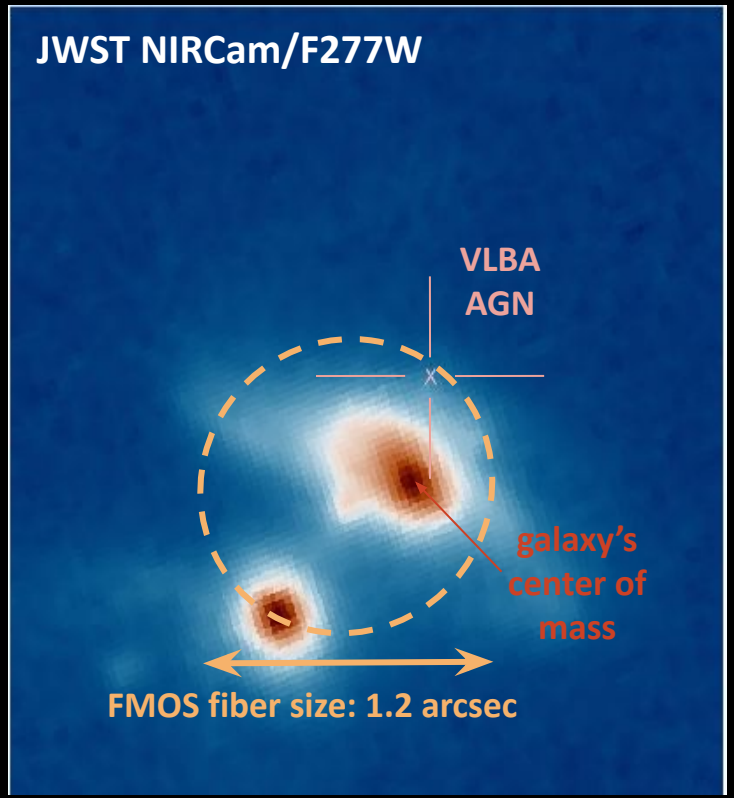


C2043 (z=1.69)

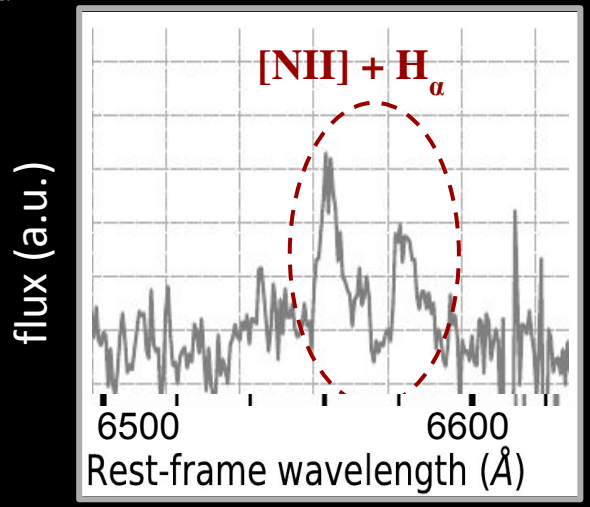
- offset ~ 0.2 arcsec
- Only photometric redshift



C2599: the best wandering AGN candidate in COSMOS-Web

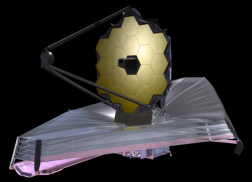


- F277W image as proxy for stellar mass distribution
- VLBA AGN lies 0.4" (= 3kpc) away from the primary galaxy's center of mass: P(chance) < 0.0015
- Merging system at z=0.93 (spectroscopic)
- Robust spec-z but blended (1.2" diameter), with "ambiguous" [NII]/H_α line ratio

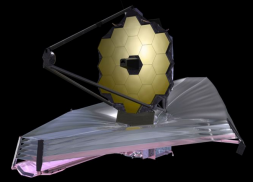


C2599: the best wandering AGN candidate in COSMOS-Web

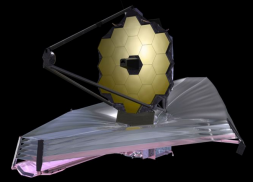
HST/F814W



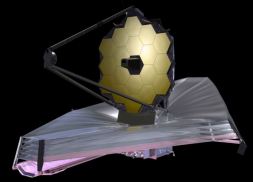
NIRCam/F115W



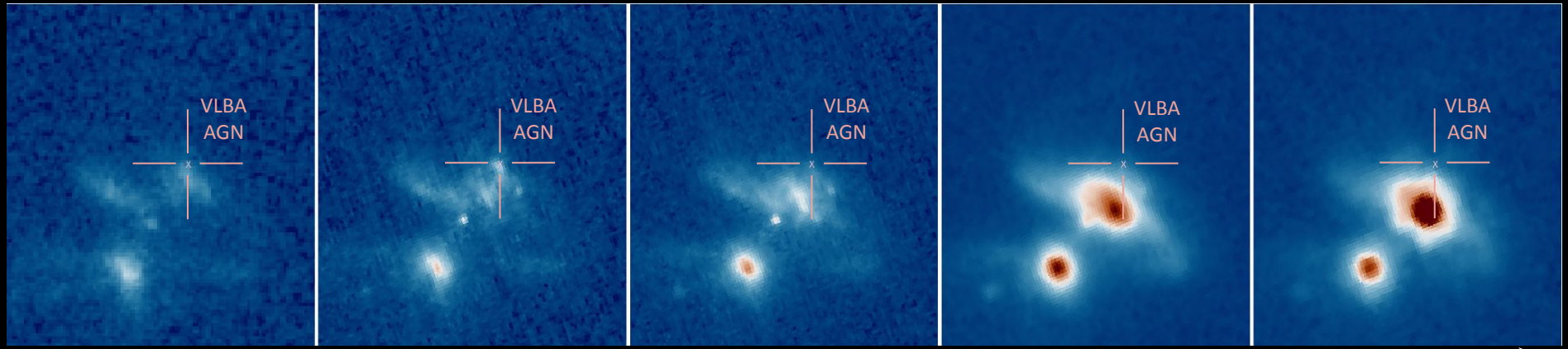
NIRCam/F150W



NIRCam/F277W



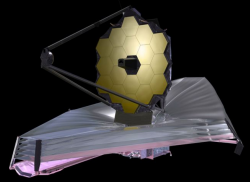
NIRCam/F444W



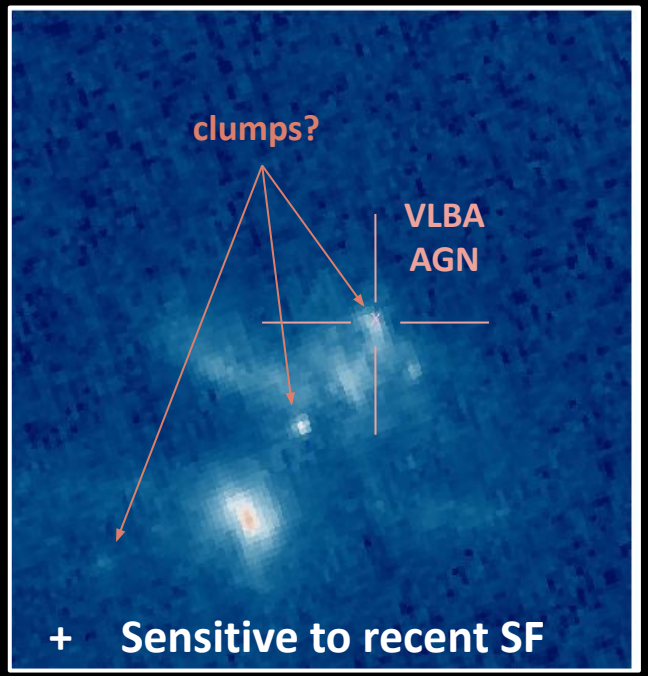
\+ sensitive to recent star formation

\+ sensitive to stellar mass

C2599: the best wandering AGN candidate in COSMOS-Web

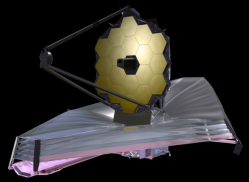


NIRCam/F115W

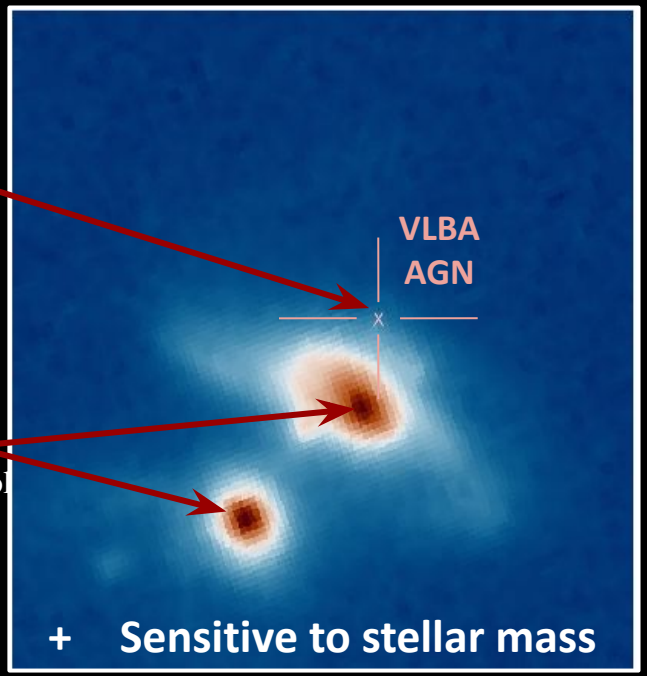


$M\star_{CLUMP} < 3x10^{7}\ M_{sol}$

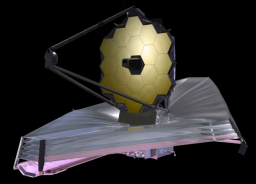
$M\star_{GALAXY} \sim 3x10^{10}\ M_{sol}$



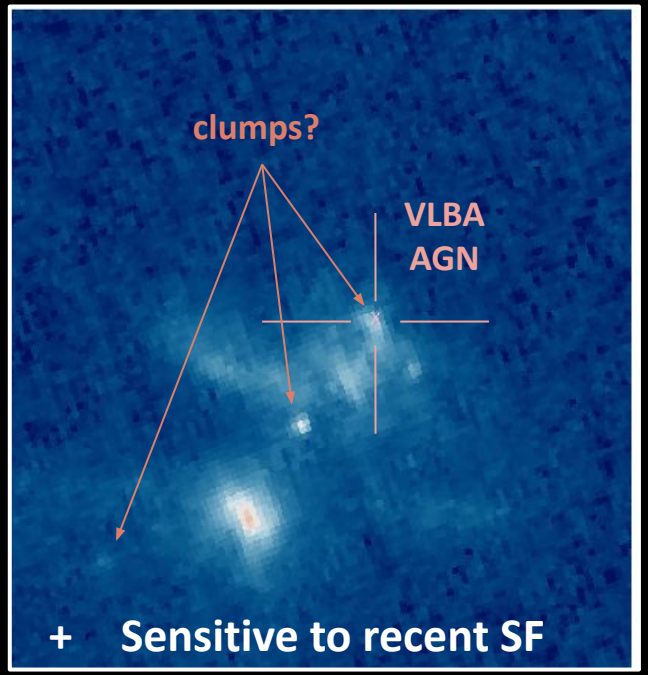
NIRCam/F277W



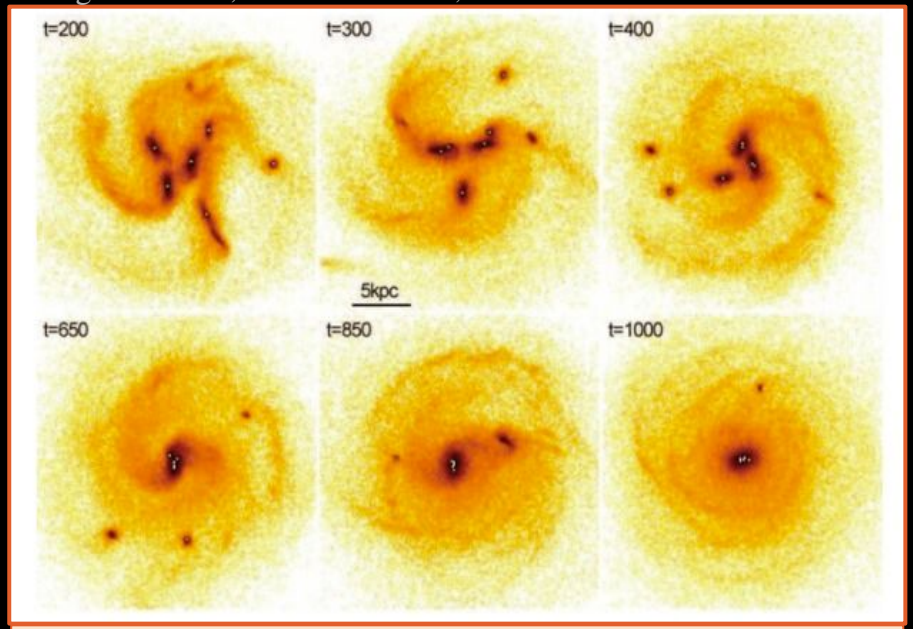
C2599: the best wandering AGN candidate in COSMOS-Web



NIRCam/F115W



Elmegreen+2008; Bournaud+2011, etc



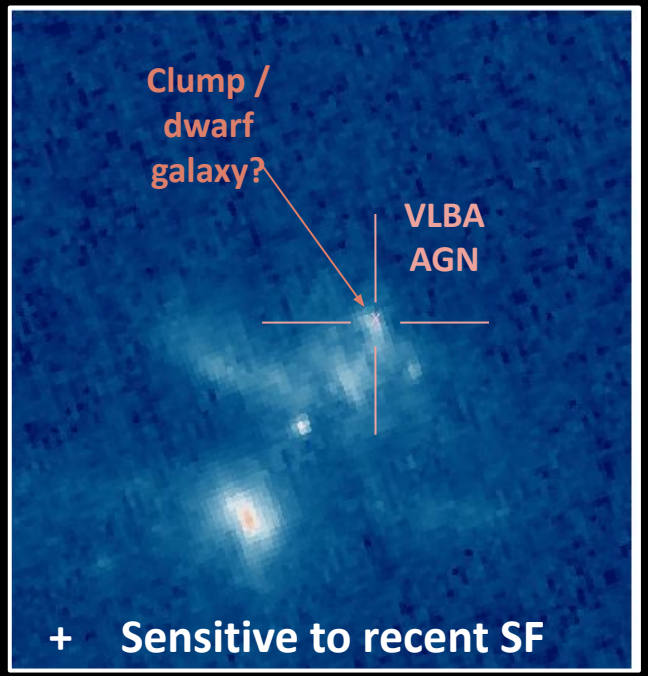
AGN in *clumps* have been predicted but never confirmed

+ Sensitive to stellar mass

C2599: the best wandering AGN candidate in COSMOS-Web

1st Scenario: wandering AGN in a *clump* of the primary galaxy

2nd Scenario: central AGN in a dwarf/satellite galaxy being accreted onto the primary



$M\star_{CLUMP} < 3x10^{7}\ M_{sol}$

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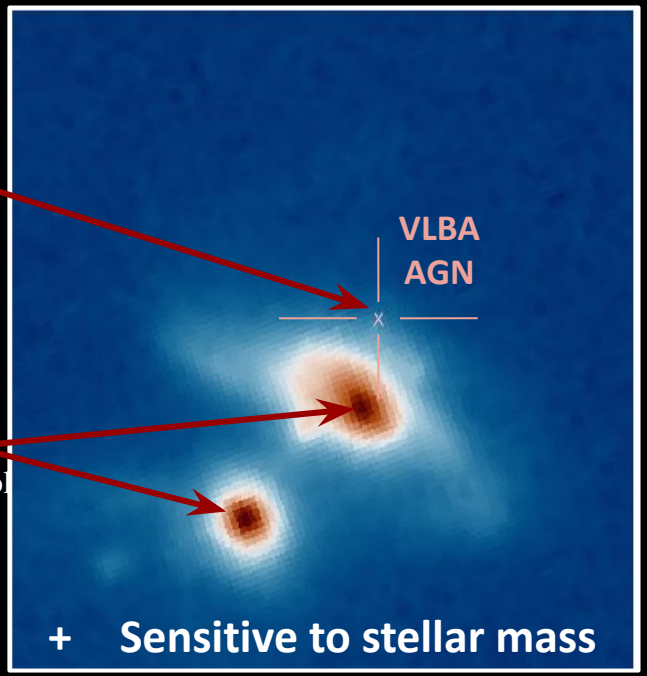

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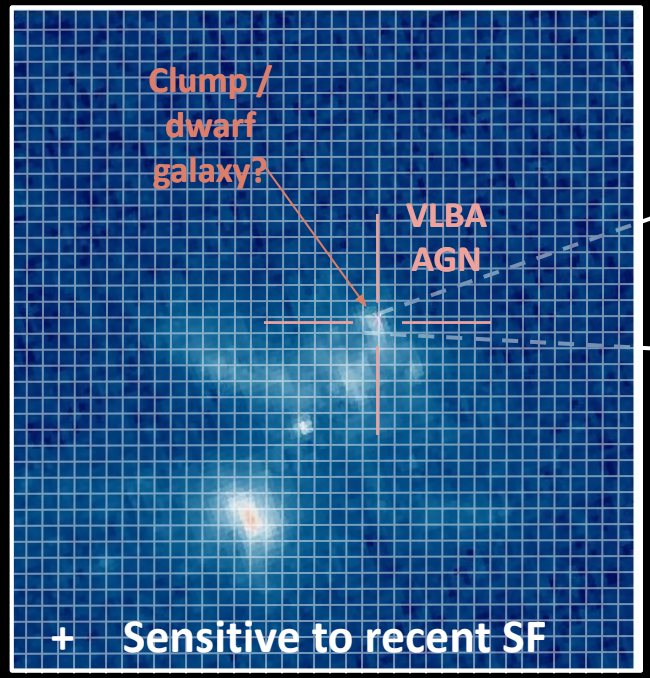
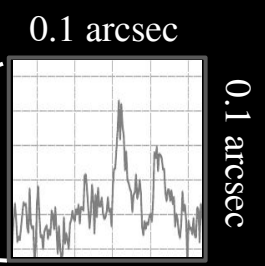
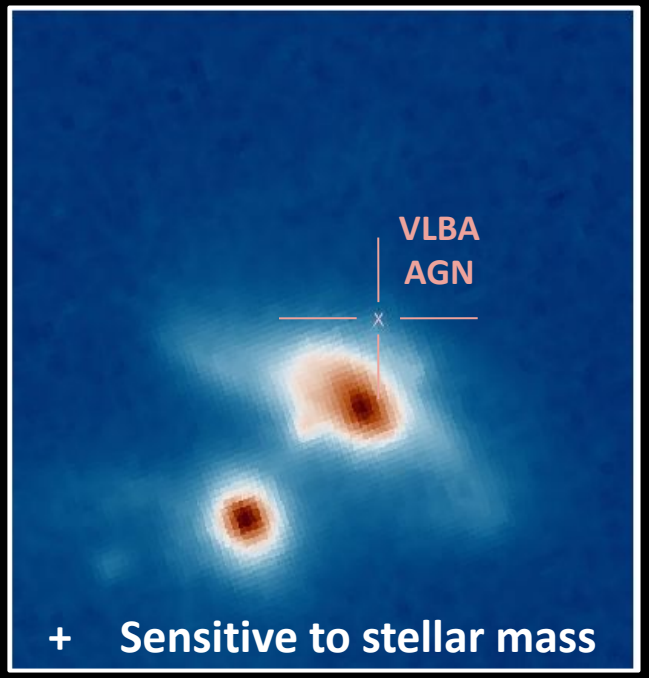




Approved
JWST/NIRSpec
Cycle4 GO program
(#8325: PI: Delvecchio)



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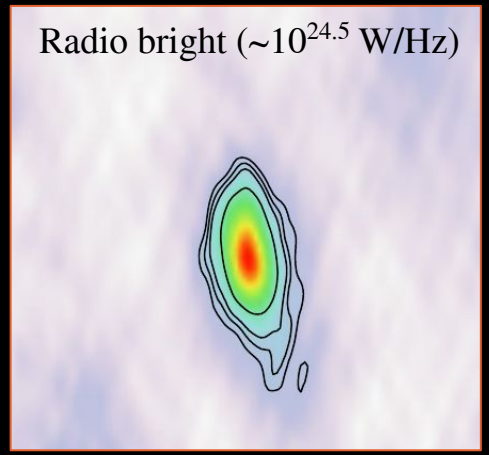
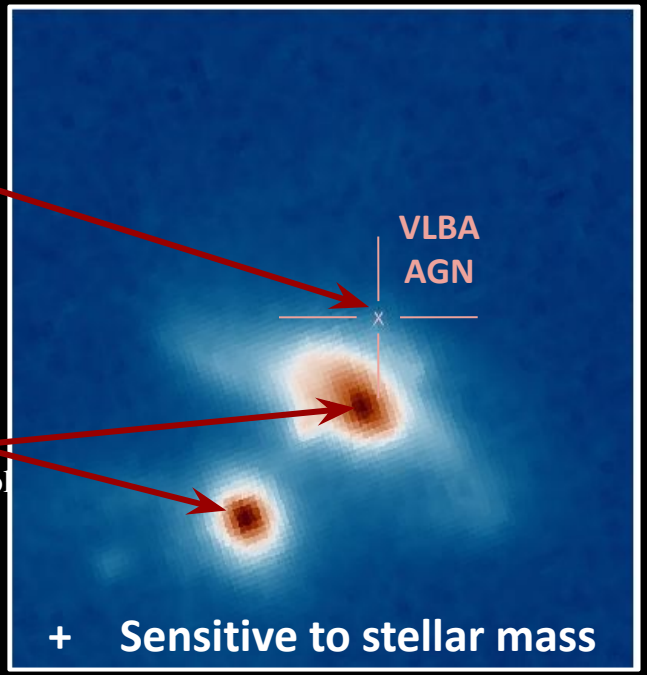
F277W



M_{BH} ~ 8x10^8 M_{sun}
(radio-M_{BH} relation:
Merloni+2003)

$M\star_{CLUMP} < 3x10^7\ M_{sol}$

$M\star_{GALAXY} \sim 3x10^{10}\ M_{sol}$



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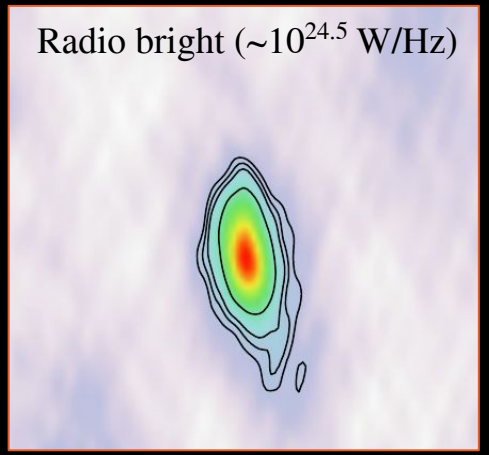
F277W



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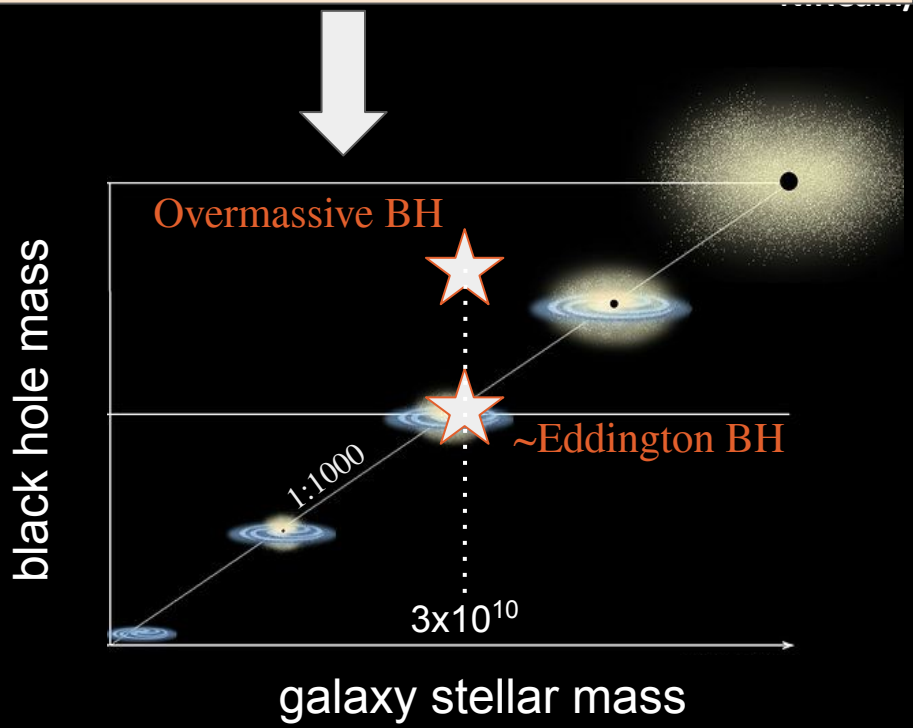
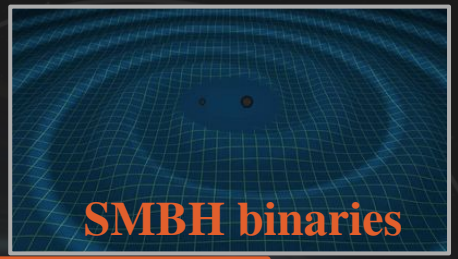
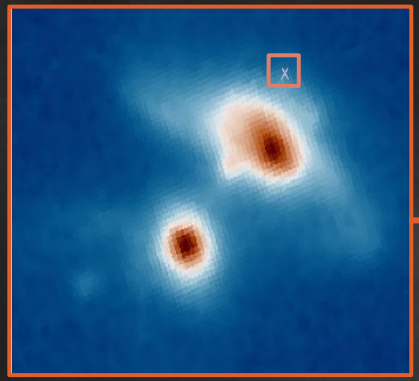


Take away points:

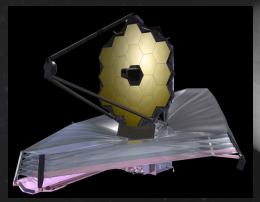


Wandering BHs hold clues on the merging history of galaxies and their BHs



Good agreement with models, but spectroscopic confirmations are needed: stay tuned!

JWST + VLBA could open a systematic search for wandering BHs in the distant Universe



JWST

VLBA

Thanks!