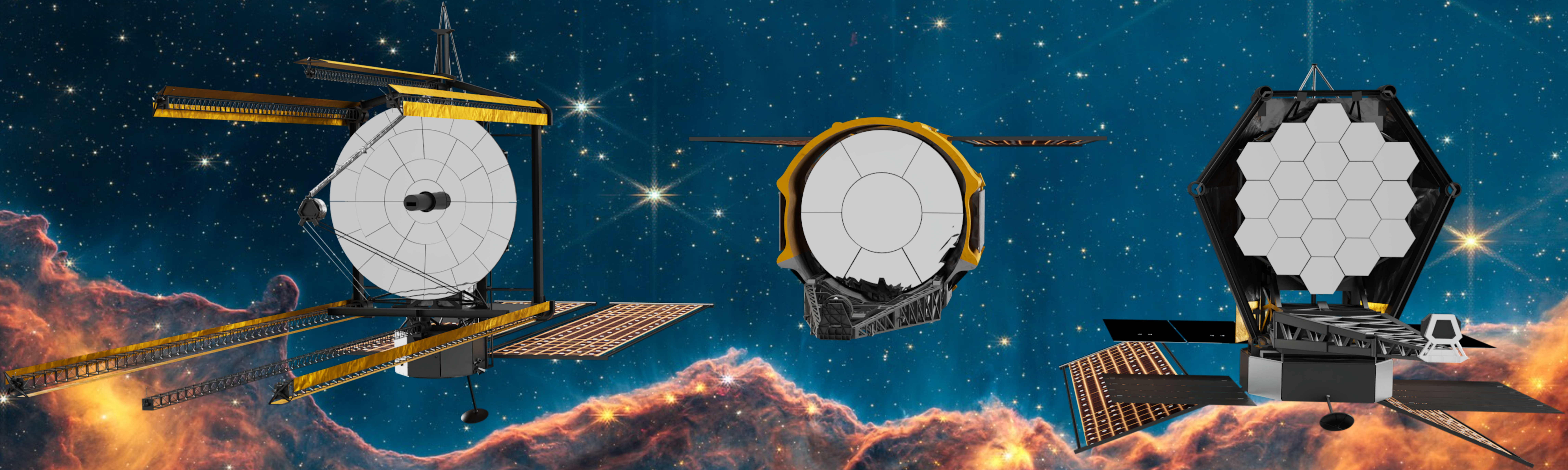

AGN and Galaxy Evolution: Exploring the Final Frontier with HWO

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Aim of this talk

- Which AGN research topics will be “hot” in the 2040s?
- What capabilities must Habitable Worlds Observatory have to address these topics?

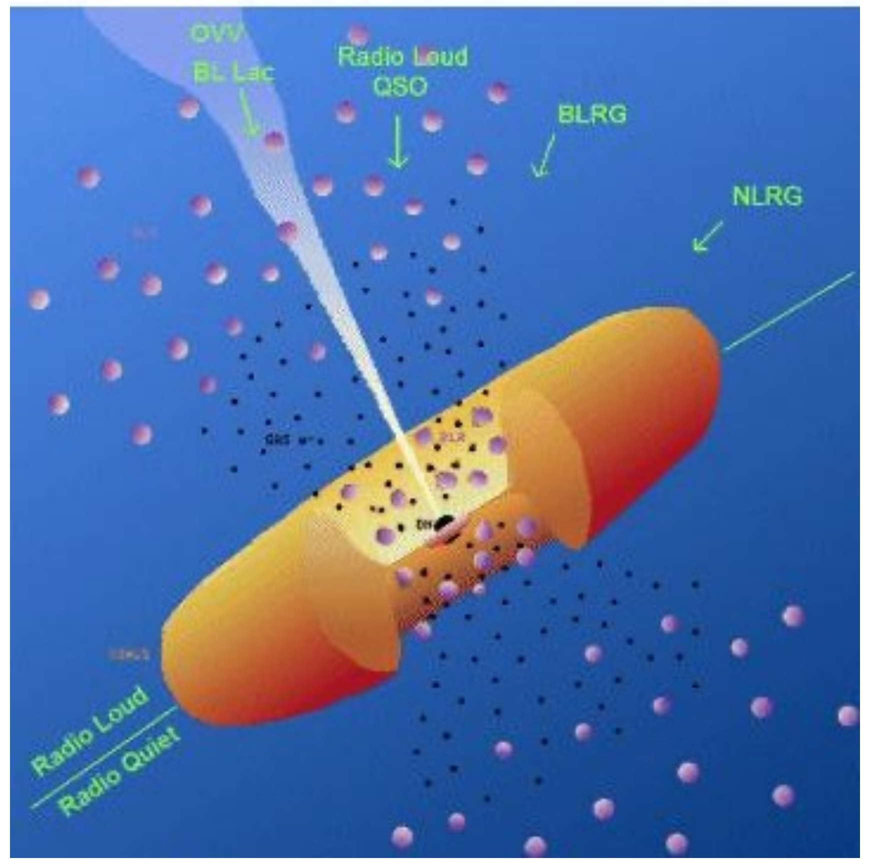
Outline

- The current landscape: from AGN as "light bulbs" to breakthroughs in the last ~10 years and the role of JWST
- Future landscape & Synergies with HWO: expected key AGN/galaxy research topics in ~20 years from now
- Possible science cases, HWO current concept and missing instrumental capabilities

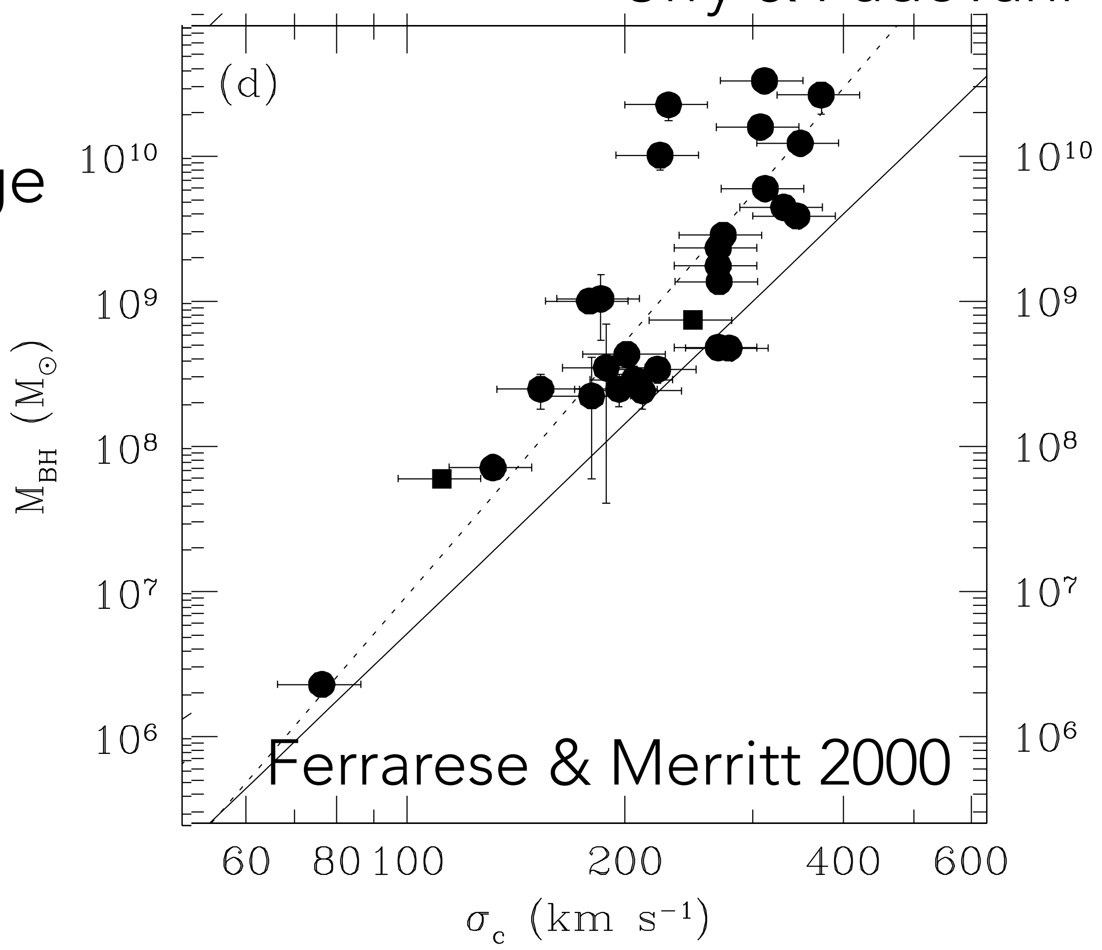
AGN & Galaxies in the 1990s → early 2000s

AGN treated as isolated "light bulbs"; AGN & galaxy-evolution communities mostly separate

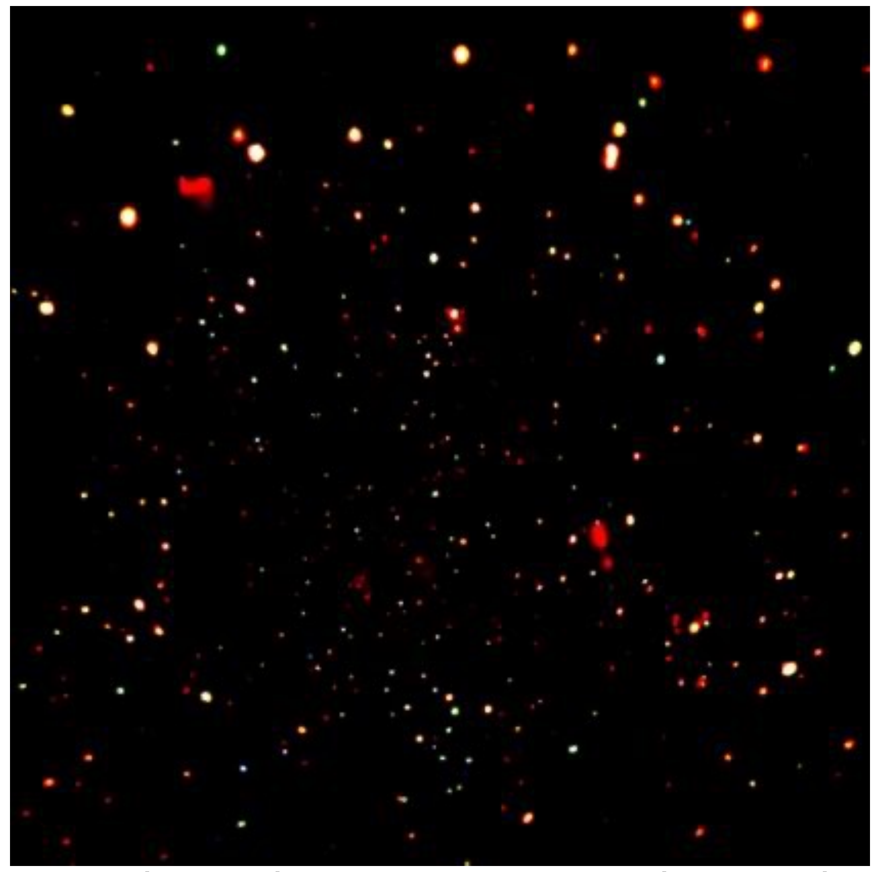
- First direct **BH mass measurements with HST** gas/stellar dynamics (e.g. NGC 4258 Miyoshi+1995, M87 Macchetto, AM+1997)
- Discovery of **BH–bulge scaling relations** – M_{BH}–σ, M_{BH} – M_{bulge} (Magorrian+1998; Ferrarese & Merritt 2000; Gebhardt+2000)
- Birth of the **AGN-feedback hypothesis** to explain those relations (e.g., King 2003)
- **Wide-field optical/NIR surveys** (2MASS, SDSS) allow AGN demographics
- **X-ray deep fields** (Chandra, XMM) uncover large population of obscured AGN and their evolution → idea of BH relics (Ueda+ 2003)
- Emerging picture of **anti-hierarchical ("downsizing") growth** also for AGN: massive BHs form early (Hasinger+ 2005)



Urry & Padovani 1995



Ferrarese & Merritt 2000

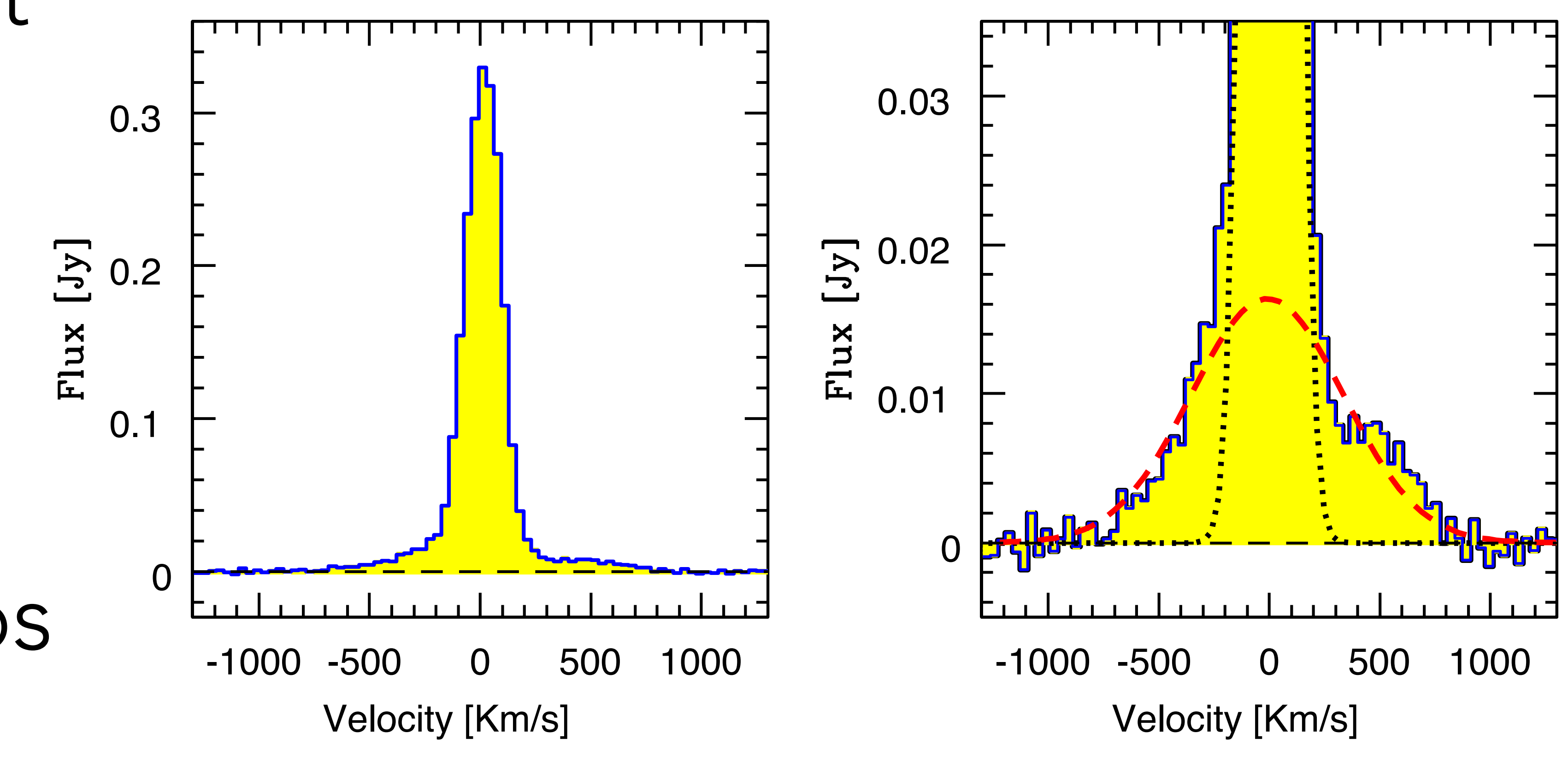


Chandra Deep Field South

First Feedback Clues & Cosmic Evolution (2000–2015)

Molecular / ionised outflows detected in local quasars → first direct feedback evidence

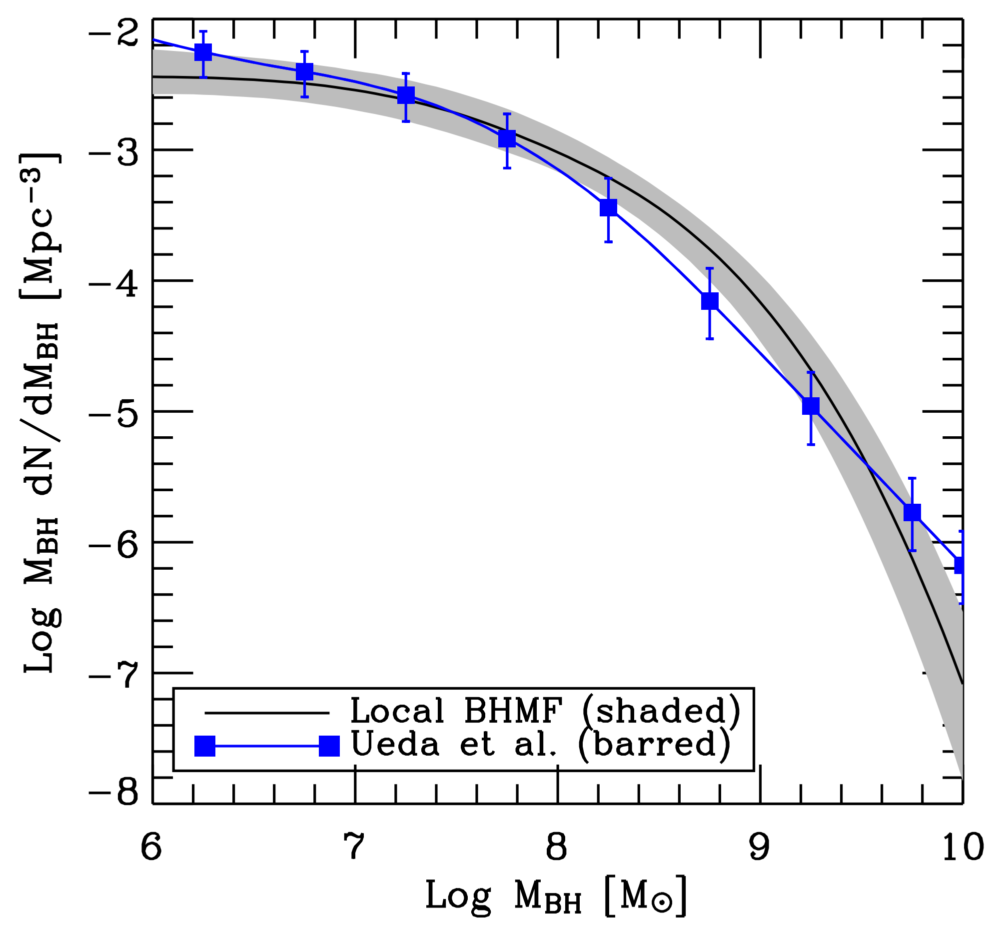
- Mrk 231 CO & OH outflows – IRAM 30 m (Feruglio+ 2010), Herschel-PACS (Sturm+ 2011)
- 8 m-class IFU spectroscopy (VLT/SINFONI, Keck/OSIRIS) maps kpc-scale AGN winds



Mrk 231: Feruglio+ 2010

Cosmic AGN "downsizing" quantified: luminous AGN peak at z ≈ 2, low-luminosity peak later

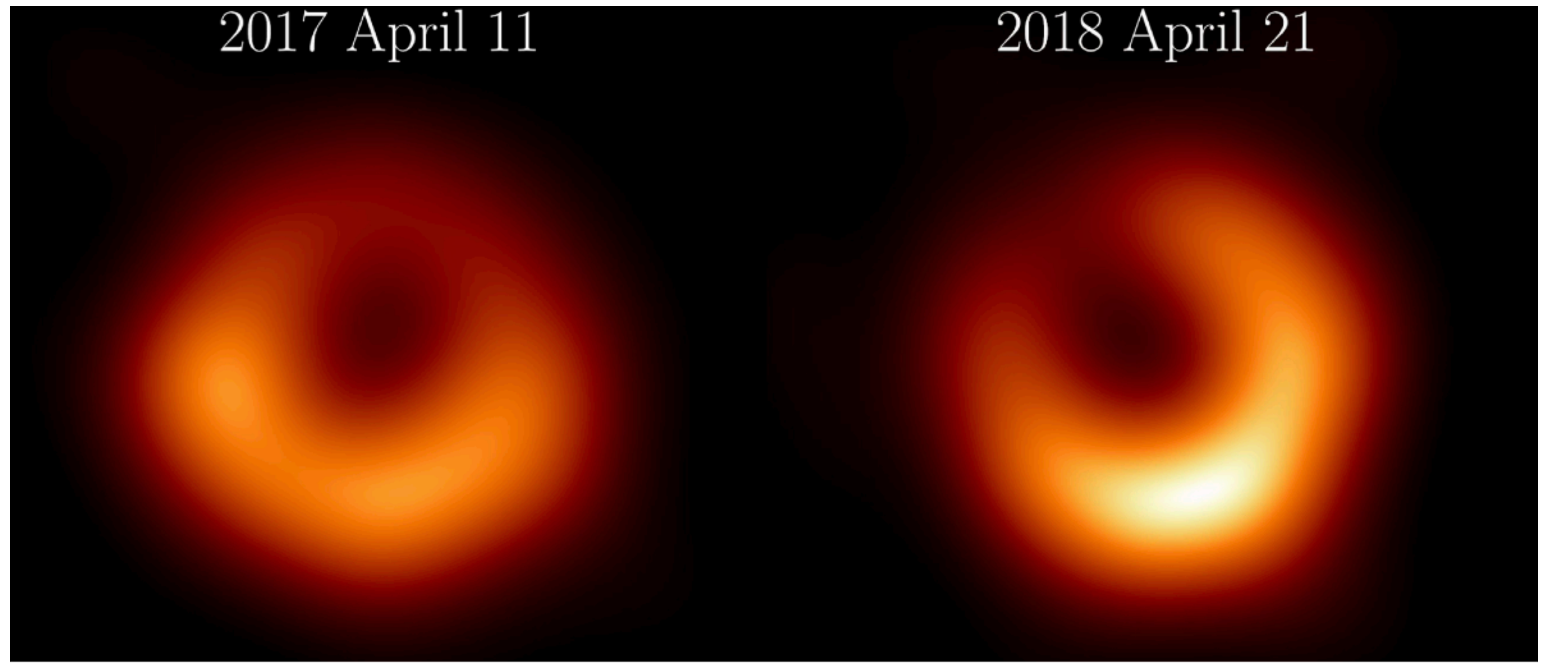
- Soltan argument refined – local dormant BH mass density matches integrated quasar light (Marconi+ 2004, Shankar+ 2004)
- Growing evidence that most massive BHs formed early & rapidly



Marconi+2004

Seeds of **multi-wavelength synergy:** Spitzer mid-IR (2003-2009/2020), ALMA submm (2009–), Herschel far-IR (2009-2013), Fermi γ-ray (2008-), together with Chandra & XMM provide multiwavelength AGN census & studies

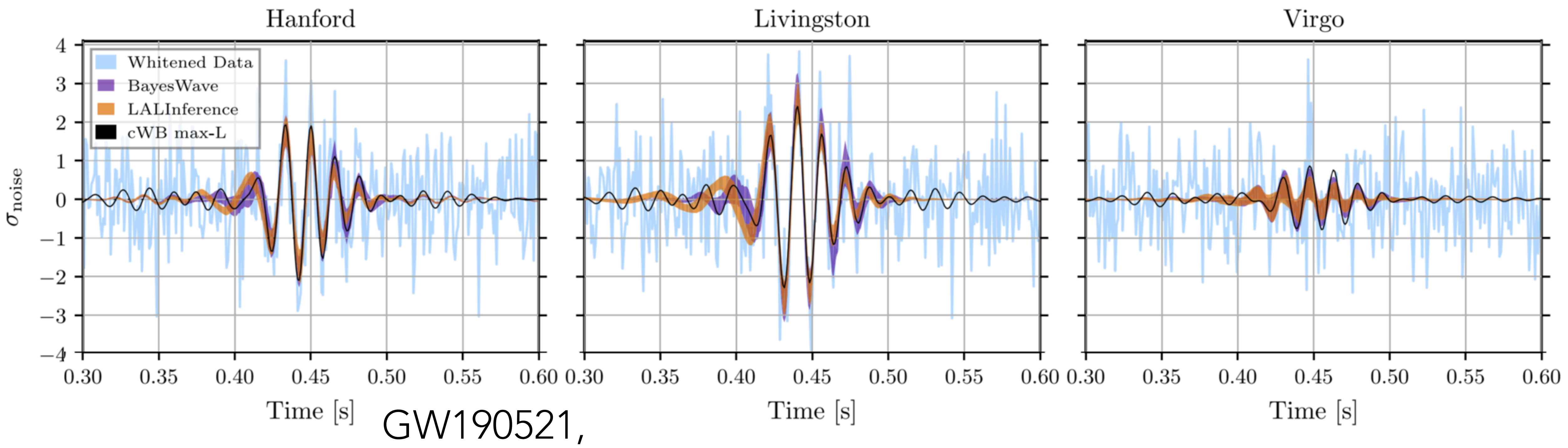
A Decade of Breakthroughs (2015–2025)



2017-2018
EHT Collaboration

Event Horizon Telescope (2017–2022)

- First-ever images of M87* and Sgr A* event horizons
- Confirmed GR predictions in strong gravity
- Magnetic-field structure driving relativistic jets



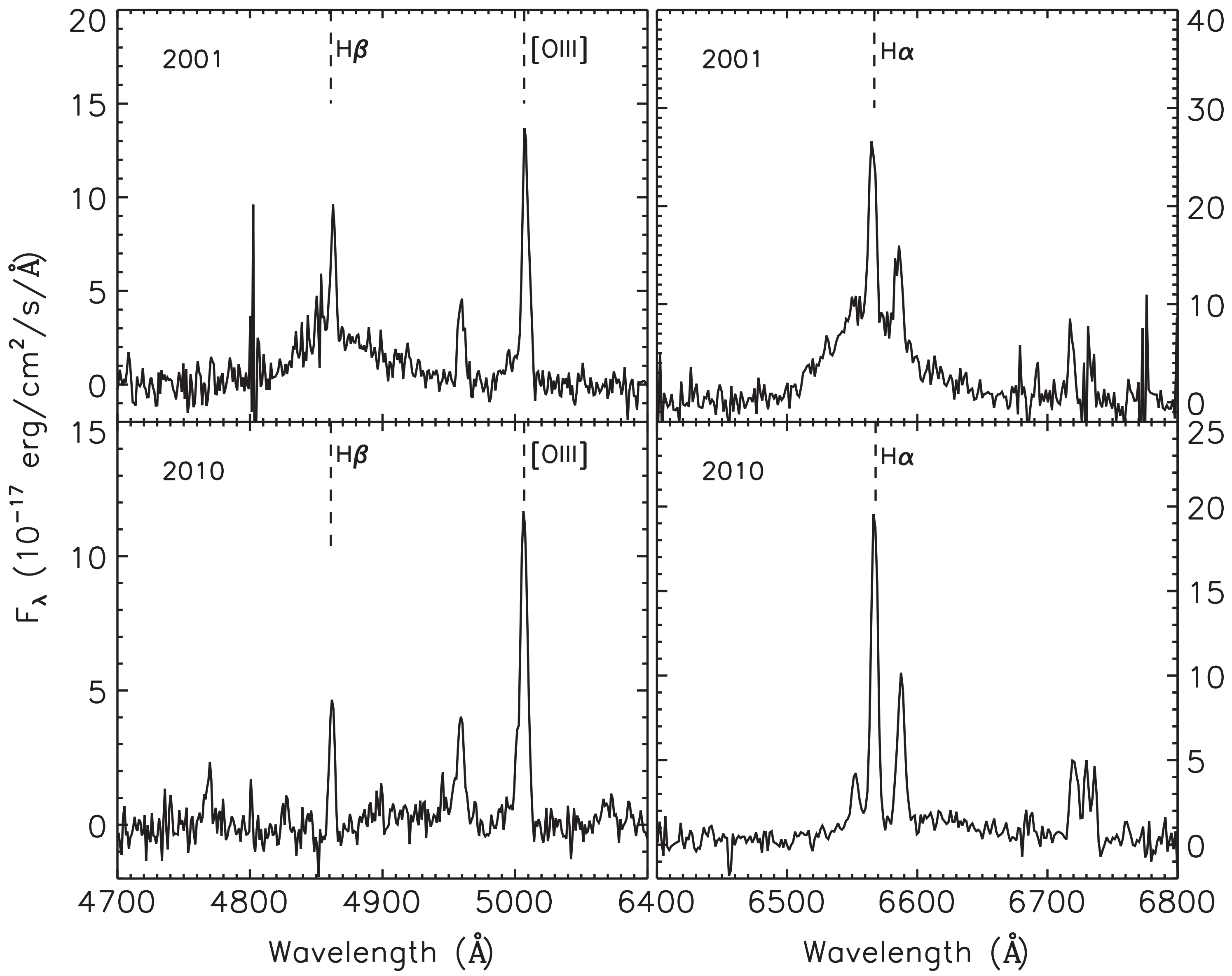
GW190521,
Abbott+2020

Era of Gravitational-Wave Astronomy (2015–)

- LIGO/Virgo detect frequent stellar-mass BH mergers
- GW190521 hints at ~IMBH merger ($85 - 65\,M_\odot$ Abbot+2020)
- Opens path to multi-messenger AGN environments

Time-Domain AGN Science

- Zwicky Transient Facility and the All-Sky Automated Survey for Supernovae: Thousands of tidal disruption events (TDEs)
- Changing-look AGN flip type on timescales of months-years (LaMassa+2015)
- Machine-learning analyses applied to large time series (2020-)



LaMassa+2015

The JWST revolution (2022 -)

SMBHs at Cosmic Dawn

- BH masses $\gtrsim 10^8 - 10^9\,\mathrm{M_\odot}$ detected at $z \gtrsim 10$
- Challenges seeding & growth models (< 500 Myr after Big Bang)

"Little Red Dots" & Over-massive BHs

- LRDs: compact, IR-bright sources at z ≈ 6–10, likely AGN
- Confirms BH/stellar-mass ratios up to 10× local at high z → early BH-dominated growth

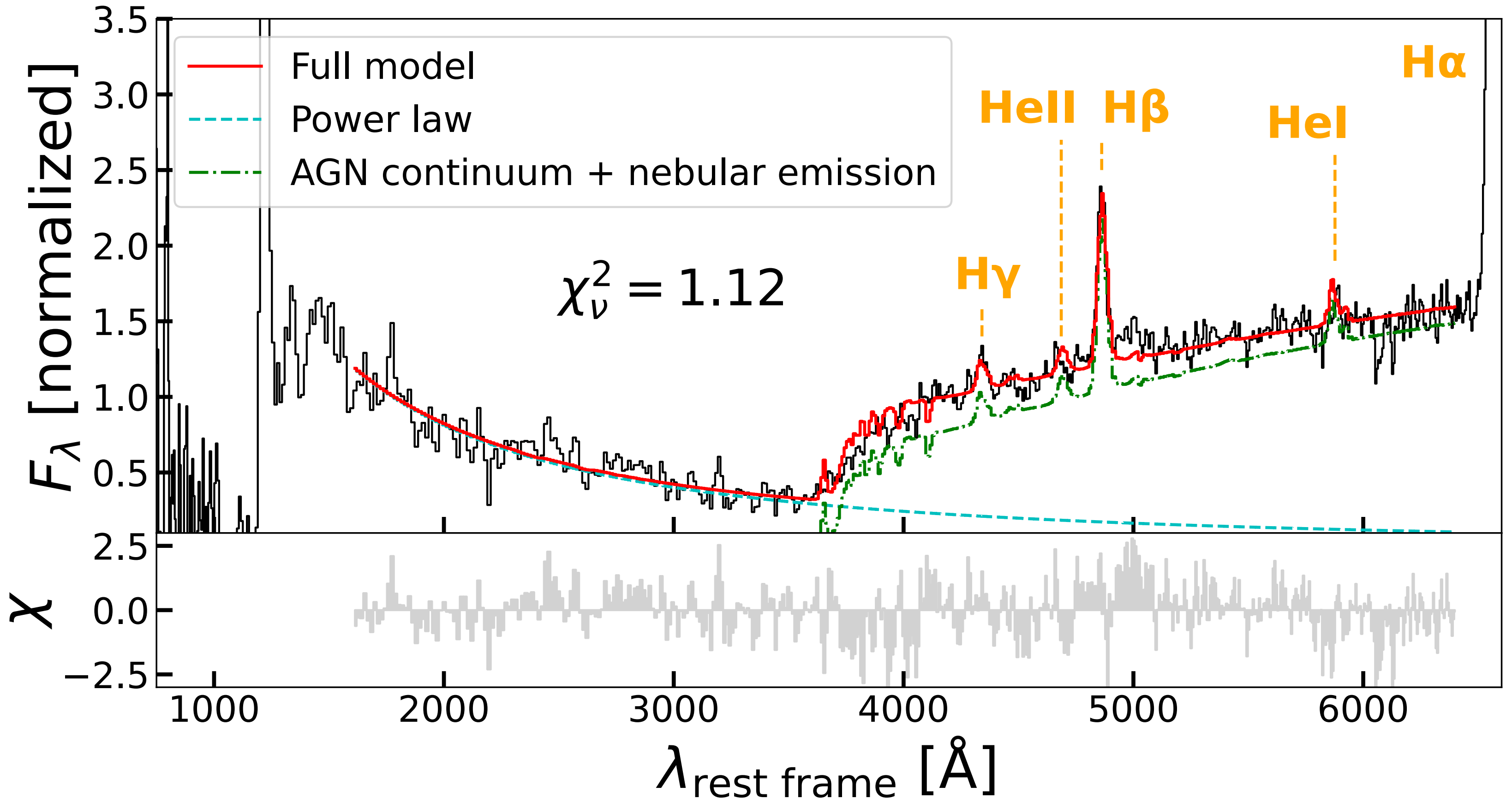
Dust-Obscured AGN Census

- NIRSpec spectra reveal hidden AGN missed in UV/optical
- Revisions to high-z AGN luminosity function

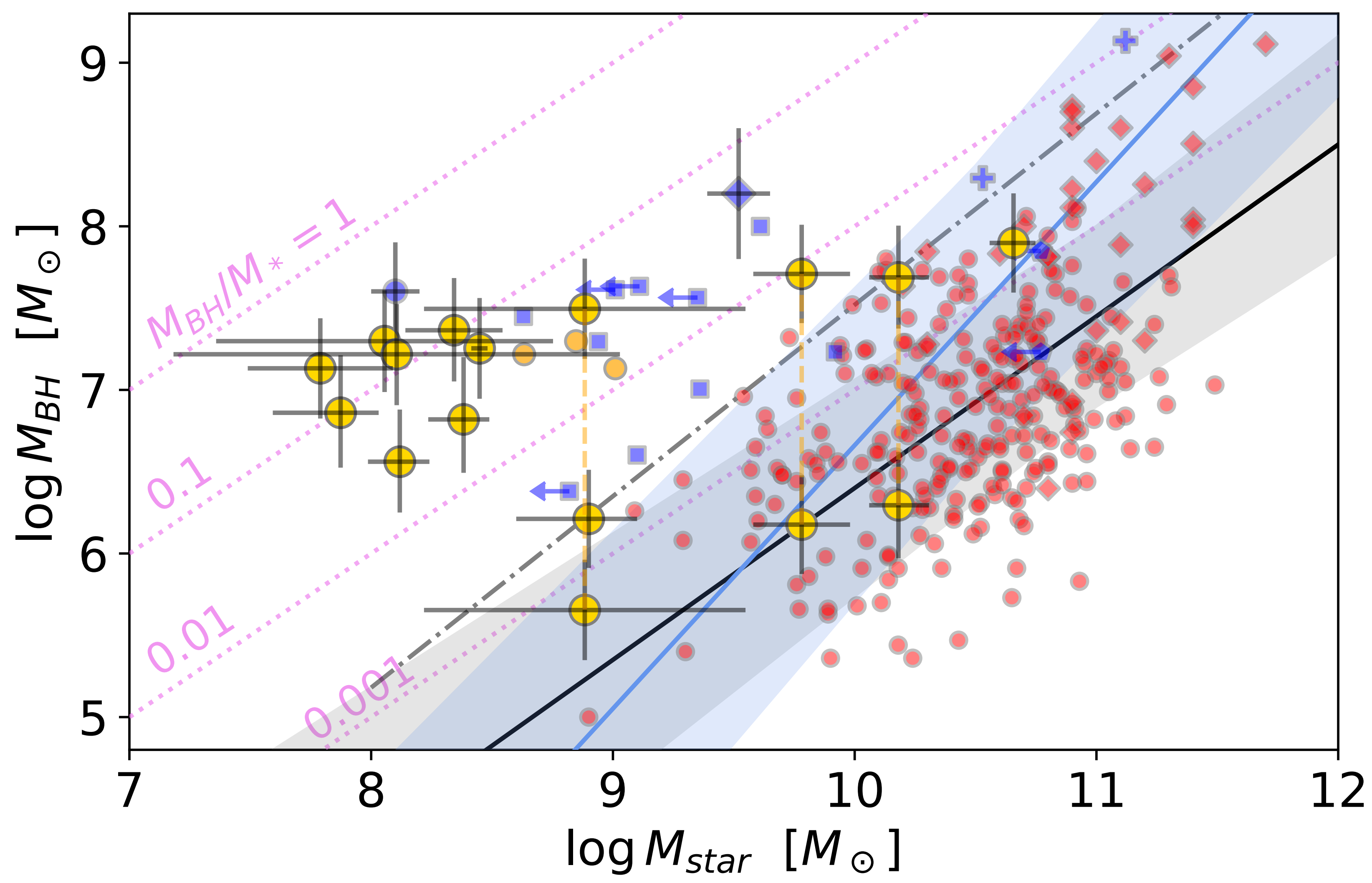
Resolved Feedback in Action

- IFU maps show kpc-scale ionised & molecular outflows
- First direct look at AGN regulating star formation beyond the local universe

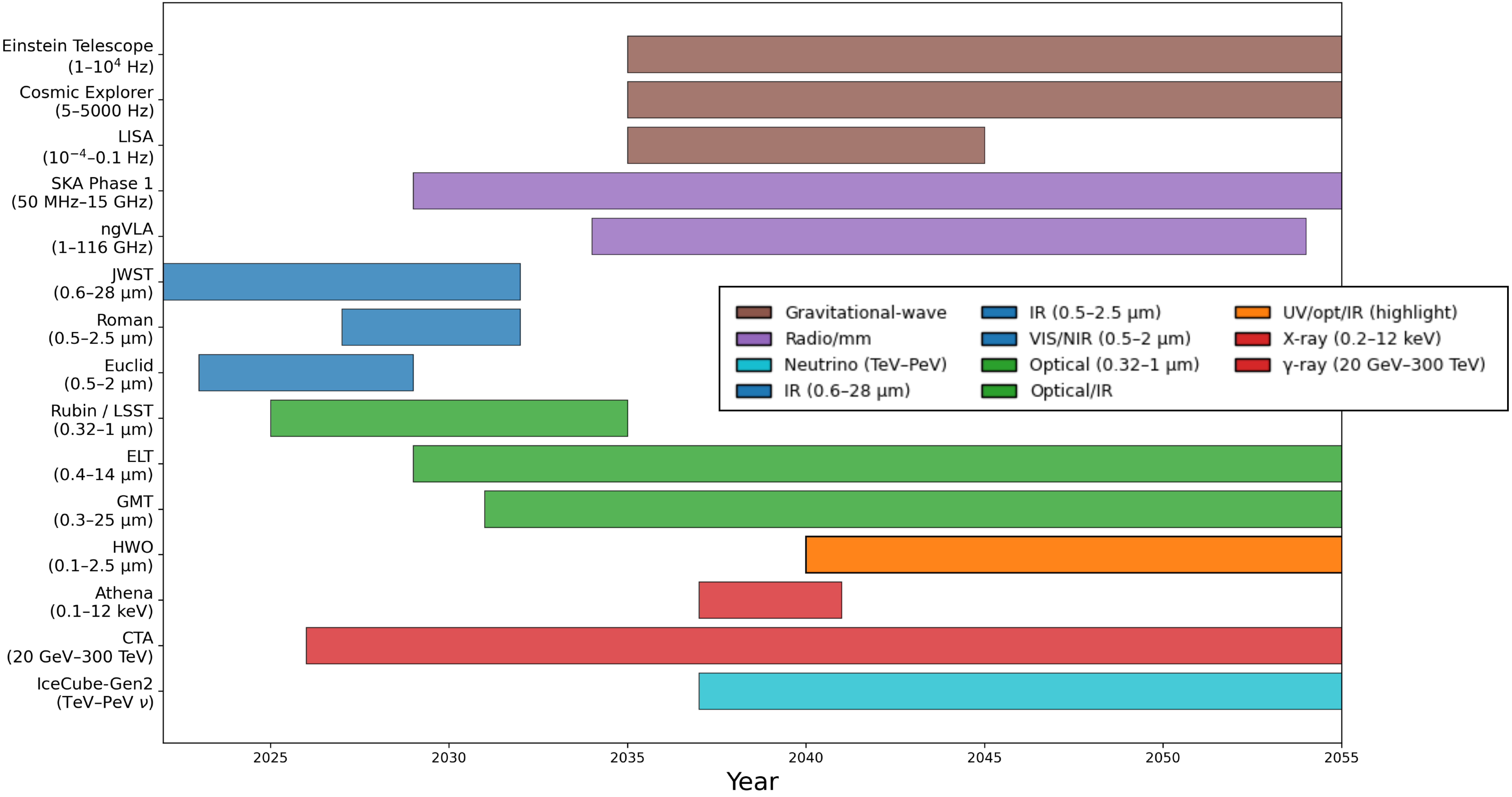
Little Red Dot, Ji+25



Overmassive BHs, Maiolino+23



The era of multi-messenger astrophysics, 2025 → 2045



What We'll Know by the 2040's: Observational Landscape

Complete AGN Census

Rubin variability + Roman/Euclid + Radio-quiet & heavily obscured AGN found by SKA/ngVLA + Athena + JWST → $10^7 - 10^8$ AGN across $0 < z < 15$

Resolved Feedback at All Scales

ELT-class IFUs: 50-100 pc scale outflows at $z \approx 1 - 4$ (*quasar mode feedback*)

Athena (X-ray from hot halos and ICM) + SKA (radio lobes of jets) trace multi-phase energy injection (*radio mode feedback*)

BH Mergers in Real Time

LISA provides masses, spins, merger rates of $10^4 - 10^7\,\mathrm{M}_\odot$ binaries out to $z \approx 10$

ET / Cosmic Explorer give IMBH merger demographics to cosmic dawn

Multi-messenger "routine" observations

AGN flares tied to GW or neutrino triggers; coordinated AI-driven (?) alert network schedules follow-up within minutes

What We'll Know by the 2040's: new analysis tools

Integrated Photo-ionisation + Kinematic Fitting

Next generation photoionization (e.g. HOMERUN, Marconi+24) & kinematical/dynamical models (e.g. MOKA3D, Marconcini+24) fitted jointly to IFU cubes to infer physical properties of NLR

Distances and velocities for individual BLR lines (from photoioniz. models?) → type-1 BH mass accuracies ≤ 0.1 dex

AI-Driven Simulation Emulators

Neural networks trained on ~10^3 full hydro / radtran sims → millisecond prediction of spectra & kinematics

Bayesian inference can deliver posterior PDFs on physical parameters straight from datacubes

Sub-parsec GRMHD + RadTran Coupling

Real-time SED & polarisation outputs from MHD+GR accretion simulations used in spectral fits

Direct link between EHT-scale physics and galaxy-scale feedback via nested simulations

IMBH & Seed-BH Physics

Zoom-ins (≤ 1 pc) in next-gen cosmological simulations track direct-collapse seeds and Pop III remnants & subsequent mergers; predictions tested with LISA rates and VLT/JWST/ELT detections

SC1 The BH Engine: Feeding & Feedback on Sub-parsec Scales

Map the pc-scale accretion zone in nearby Seyferts & Quasars

- Directly image UV/optical wind base (C IV, N V, O VI) on ≲1-10 pc scales in nearby AGN.

Resolve multi-phase outflows & shocks

- Measure launch radii, mass-loading, and magnetic geometry of outflows; e.g., test magnetically arrested disks (MAD) vs. radiative driving.

Link jet base to galaxy-scale impact

- Link EHT horizon data (jet axis) to kpc-scale feedback mapped with ELT IFUs.

Benchmark AGN feedback models

- compare HWO wind velocity–ionisation profiles with predictions from Next Gen Simulations

Capability	Science Requirements	Why We Need It
Wavelengths	0.10 – 0.55 µm (rest-UV lines C IV, N V, O VI)	Wind diagnostics & BLR physics
Angular resolution	0.01″ in the UV (≈ 1 pc at 20 Mpc)	Resolve launch region & jet base
Spectral resolution	R ≥ 10000 (≈ 30 km s^{-1})	Separate narrow wind components
High-contrast imaging	Contrast ≲ 10^{-8} at 0.01″	See faint sub-pc structures next to bright nucleus
Polarimetry	Linear polarisation accuracy ≈ 0.1 %	Distinguish magnetically-arrested vs. radiative winds
Cadence	Daily/weekly repeats for a few months	Reverberation & variability mapping

Instrument idea: UV–optical integral-field spectro-polarimeter that can work behind the coronagraph.

SC2 Co-evolution at Cosmic Dawn: First Black Holes & Their Host Galaxies

Detect 10^5–10^6 M⊙ seed BHs and measure BH/stellar-mass ratios in first galaxies.

Map Ly α / C IV outflows and inflows on kiloparsec scales (~200 pc resolution at z = 10).

Provide rapid UV-NIR spectroscopy for LISA massive-BH mergers and early TDEs.

Trace first-galaxy metal enrichment and its coupling to BH growth.

Capability	Science Requirements	Why We Need It
Wavelengths	0.12 – 2.5 μm (rest-UV lines redshift to 1–2 μm)	Detect seed BHs & host stars
Angular resolution	≤ 0.03″ at 1 μm (≈ 200 pc at z = 10)	Resolve kpc-scale outflows & host morphologies
Spectral resolution	R ≈ 5000 – 10000	Measure line IDs & outflow speeds (~30–60 km s^{-1})
Sensitivity	Point sources AB ≈ 31 (10 nJy) in ~10 h	Detect emission lines from 10^5–10^6 M⊙ seeds
Rapid follow-up	Slew to new target within ≲ 2 h	Followup LISA BH-merger afterglows & early TDEs
FoV	Few-arcmin imager + few-arcsec IFU	Capture host context and kpc-scale gas

Instrument idea: broad-band UV–NIR IFU/imager with a built-in “target-of-opportunity” mode.

SC3 Metal-Enriching Black Holes: AGN Production & Host-Galaxy Impact

Derive BLR and NLR metallicities (N V/C IV, O III], Fe II) out to z ≈ 10.

- First direct metallicities for JWST "little-red-dots"

Map radial metallicity gradients (~100 pc) and quantify metal mass-loading in AGN-driven winds.

- Quantify metal dilution vs. AGN-driven inflows/outflows
- Test whether AGN eject more metals than supernovae in massive hosts

Compare metal budgets with Next Gen. Simulations predictions and Athena/SKA halo measurements.

Capability	Science Requirements	Why We Need It
Wavelengths	0.10 – 0.75 µm	Key metallicity ratios (N V/C IV, O III], Fe II)
Angular resolution	0.03″ at 250 nm (≈ 300 pc at z ≈ 1)	Map metal gradients out to kpc
Spectral resolution	R ≥ 10000	Measure weak lines to 0.1 dex accuracy
Signal-to-noise	S/N ≥ 50 per resolution element on µ ≈ 26 mag arcsec^2	Reliable abundance diagnostics
IFU FoV	≥ 2″ × 2″	Cover extended narrow-line region / outflows

Instrument idea: deep-UV high-resolution IFU

Current baseline vs desiderata

Current Baseline	SC 1 – Feeding & Feedback	SC 2 – Cosmic-Dawn Co-evolution	SC 3 – Metal Enriching BHs
Telescope • 6–10 m segmented • 0.1–2.5 µm • diff-limited @ 0.5 µm	✓ Aperture and UV coverage meet spatial-resolution target	✓ Aperture and NIR reach allow detection of seed BHs at z ≈ 10	✓ Collecting area sufficient for S/N≥50 on faint UV metallicity lines
High-contrast Coronagraph • Contrast < 10^{-10} • Vis R ≈ 140 • NIR R ≈ 70 / 200	✗ Lacks required high-dispersion (R ≥ 10000) feed and polarimetry for wind kinematics	(Not critical—seed BHs unresolved) baseline acceptable	(Not required for metallicity mapping)
High-resolution Imager • 3′×2′ FoV • 0.2–2.5 µm	✗ Needs ≤5 mas pixels in UV to Nyquist-sample 0.01″ core	✓ Large FoV + 0.03″ sampling at 1 µm will separate host and nucleus at z ≈ 10	✗ Require ≤30 mas pixels in NUV to resolve 100 pc gradients at z ≈ 1
UV MOS • 0.1–1.0 µm • R 500 – 50 000 • ~840 x 420 apertures in 2′×2′ FoV	✗ Replace with 0.01″ integral-field slicer for sub-pc mapping	✗ Extend wavelength to 2.5 µm to capture C IV/N V at z ≈ 10	✓ Resolving power adequate, but high sensitivity at R~10000 needed
Fourth Instrument (TBD) • NUV coronagraph • FUV IFS • UV spectropolarimeter	Ideal instrument: **UV–optical IFU + spectro-polarimeter, R ≈ 10000, 0.01″ spaxels**	Ideal instrument: **0.12–2.5 µm IFU, R ≈ 5000-10000, rapid ToO mode**	Ideal instrument: **deep-UV high-resolution IFU, R ≥ 10 000, ≥2″ × 2″ FoV**

What is needed: IFU capability with at least R~10,000 and at least 0.1-1 µm range (ideally up to 2.5 µm), ~0.01" spaxels i.e. a NIRSPEC like instrument (with IFU and MOS) but which includes the UV. Modify the UV MOS instrument to UV MOS+IFU?

Conclusions

AGN breakthroughs with JWST were NIRSpec-driven

- Hidden quasars at $z > 10$, early metallicity, and outflow kinematics all came from the dual MOS + IFU modes.

HWO's flagship AGN program demands the same architecture

A NIRSpec-class spectrograph shifted to 0.1–1.0 (possibly up to 2.5) μm for HWO

- Multi-object (≥ 1000 micro-shutters) for high-z surveys
- Integral-field unit ($R \approx 10000$, FoV ≥ 2″ × 2″, ~0.01″ spaxels) for detailed physics
- Optional (spectro)polarimetric capability for sub-parsec winds and accretion disk physical properties

No other planned facility provides space-based UV–opt–NIR spectroscopy with both MOS and IFU.

Take home message: A NIRSpec-like spectrograph expanded to UV–optical, equipped with IFU, MOS, and optionally (spectro)polarimetry, is the single critical addition that will allow groundbreaking AGN science for HWO in the 2040s