Constraining the origin of Super-Massive Black Holes

and modelling their growth in a cosmological context

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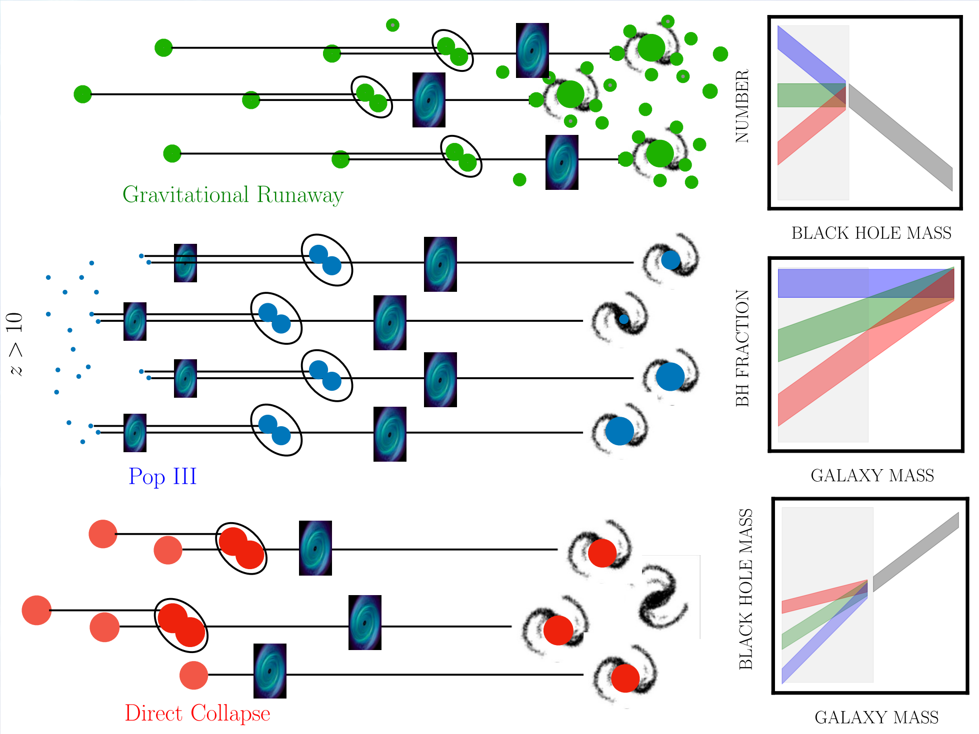
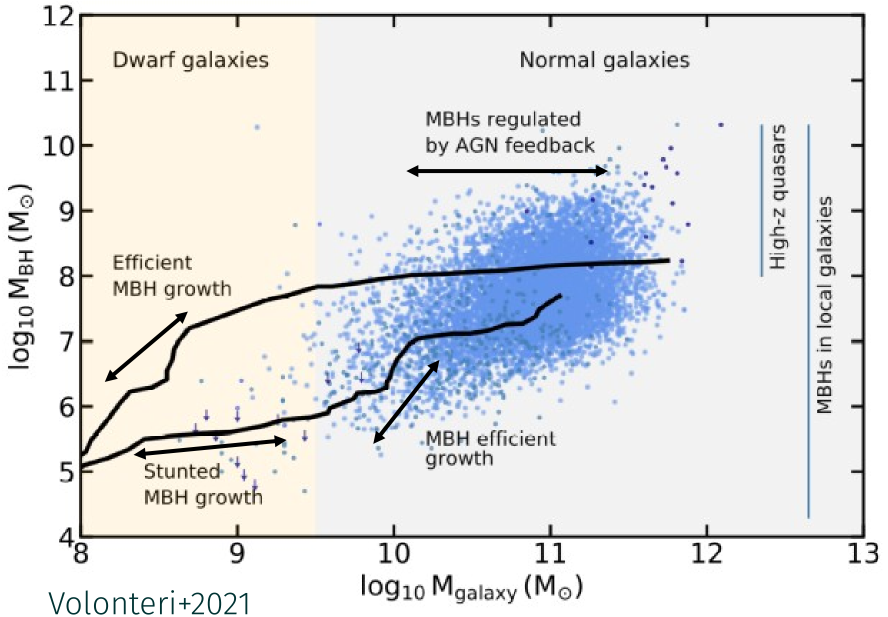
Massive Black Holes formation scenarios

- Depending on how they **form**, the population of SMBH can vary:
  - Number density
  - Occupation fraction
  - BH-to-stellar mass ratio
- In massive, low-redshift SMBH, the seeding signatures tend to be washed away by > 10 Gyr of evolution
- Progress requires either:
  - (very) high-z SMBH
  - (very) faint sources



Greene+2020

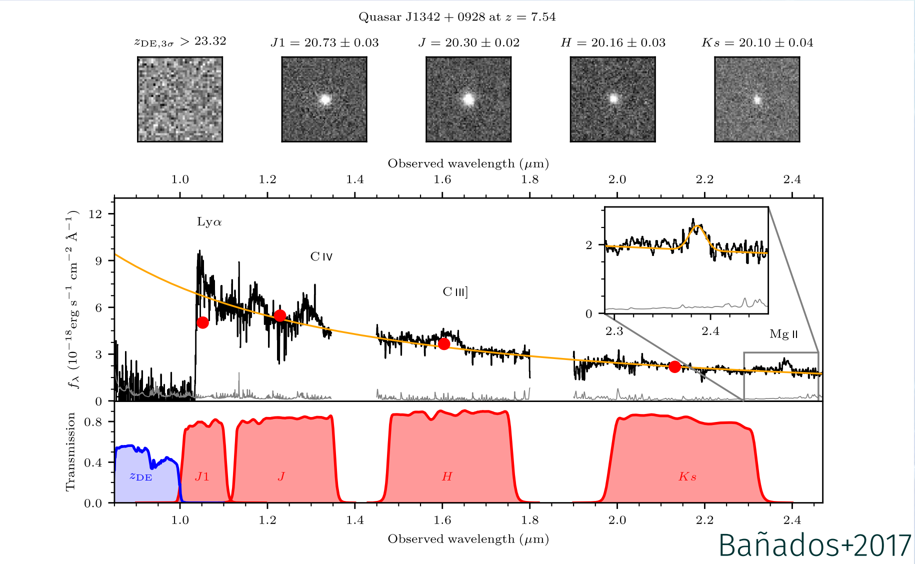
Massive Black Holes growth scenarios



Volonteri+2021

- The **growth** scenarios of SMBH (at high-redshift) are also uncertain
- The interplay between galaxy formation physics and BH growth should leave patterns in the BH-to-mass ratio
- Progress on this requires :
  - Measuring BH masses and stellar masses at different redshift
  - Probing a large range of BH masses and stellar masses
  - Good control of selection effects (more on this later)

High-redshift SMBH prior to JWST



Bañados+2017

- Prior to JWST, most of the (very) high-z observational effort was driven by individual quasars
- Mostly limited to bright sources, and reaching z~7 (with heroic effort)

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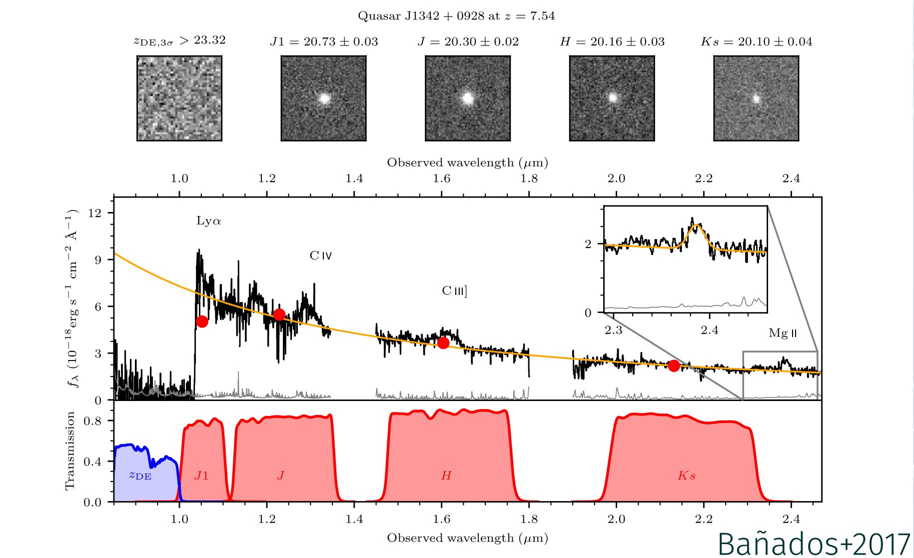

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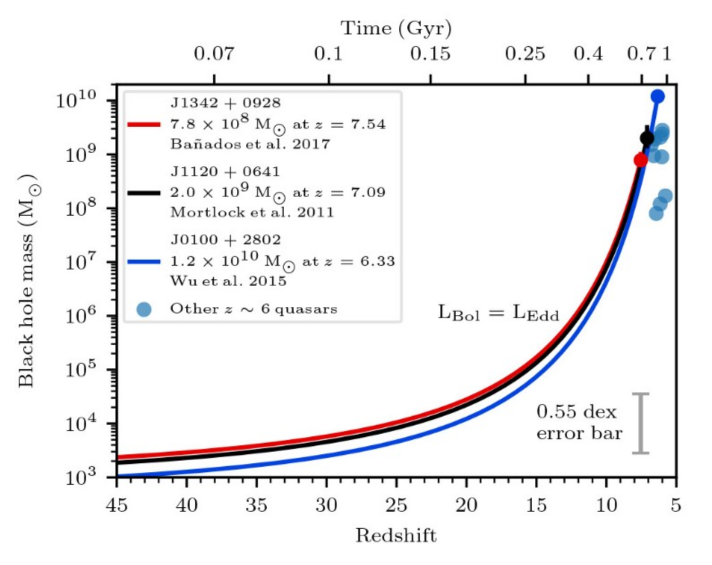
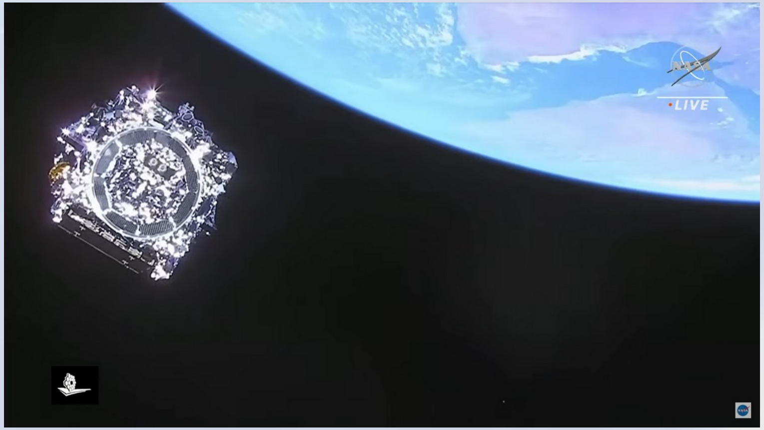
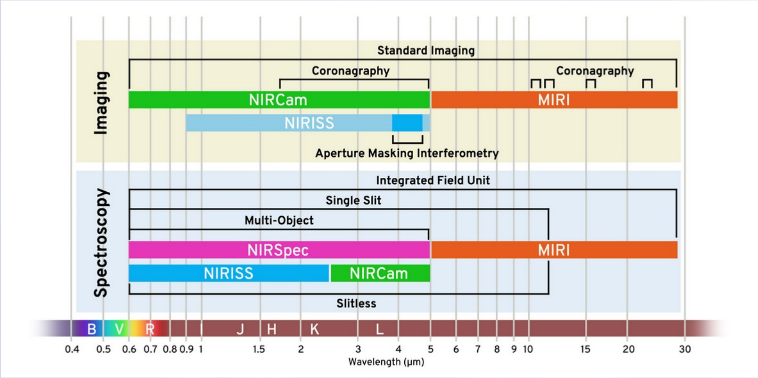


- Prior to JWST, most of the (very) high-z observational effort was driven by individual quasars
- Mostly limited to bright sources, and reaching z~7 (with heroic effort)
- Testing “BH formation scenarios” relied on extrapolating BH growth at $z \gg 6$

Enters JWST: new era for high-z AGN

- On December 25th 2021, launch of the JWST
- 6.4 m mirror, designed to work in the near/mid IR
- Four main instruments :
  - NIRCam (Near-IR imaging)
  - NIRSpec (Near-IR spectroscopy)
  - NIRISS (Near-IR slitless spectroscopy)
  - MIRI (Mid-IR imaging + spectroscopy)
- All of these modes have been used (very) successfully for SMBH-related studies

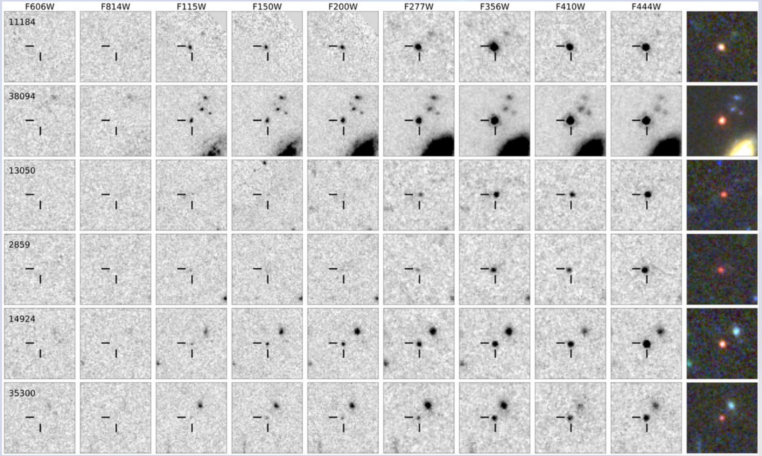




High-z SMBH in the JWST era

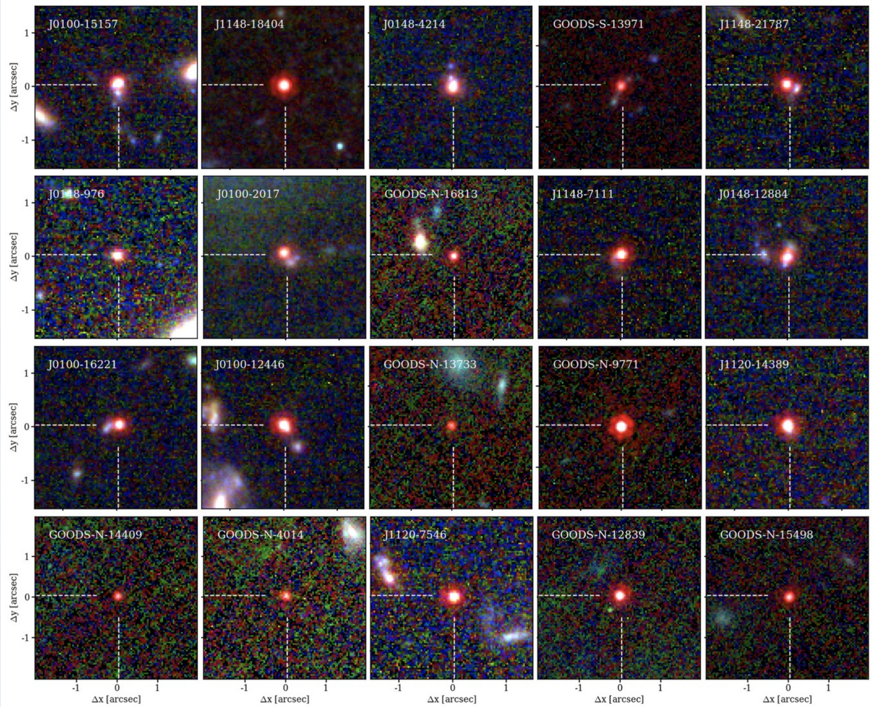
Early JWST results

- Some of the first results from JWST have revealed a puzzling population of sources :
  - All very “red”
  - All very compact
- If these were standard galaxies, then the inferred stellar masses would be “break ΛCDM”
- However, other possibilities :
  - Calibration issues
  - “Odd” stellar populations
  - Non-stellar emission = AGN contribution



Labbé+2022

Small high-z sources : “Little Red Dots”



Matthee+2023

- Over a few months, large effort of the community to try and understand these sources

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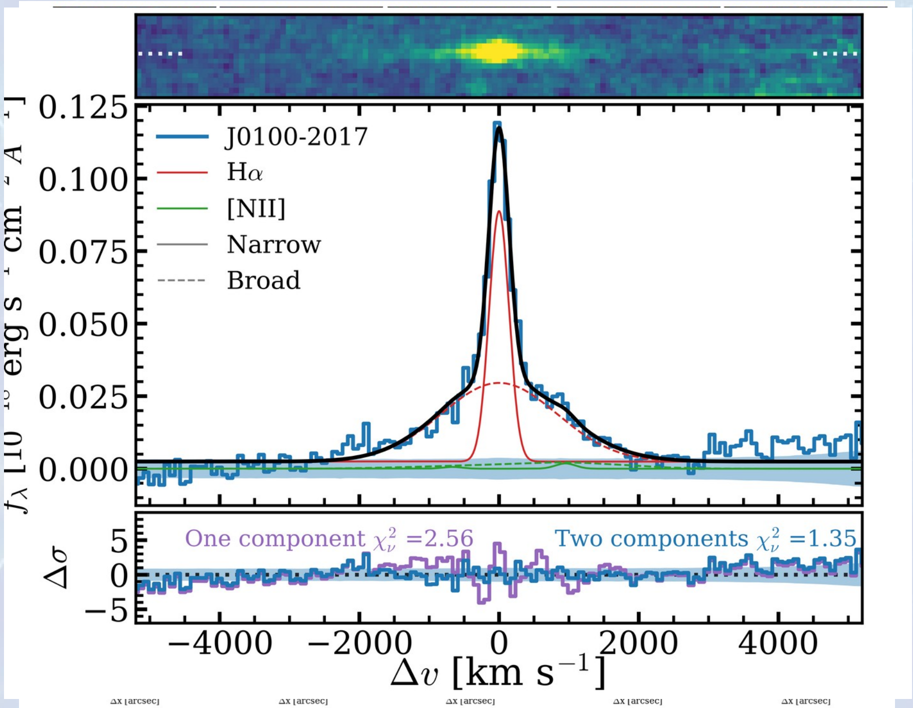
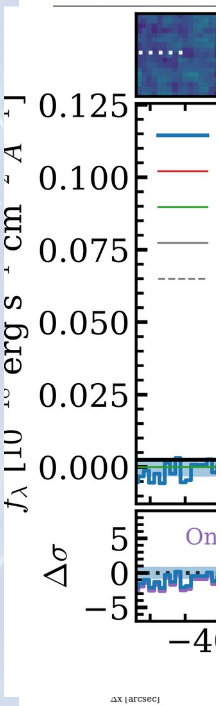
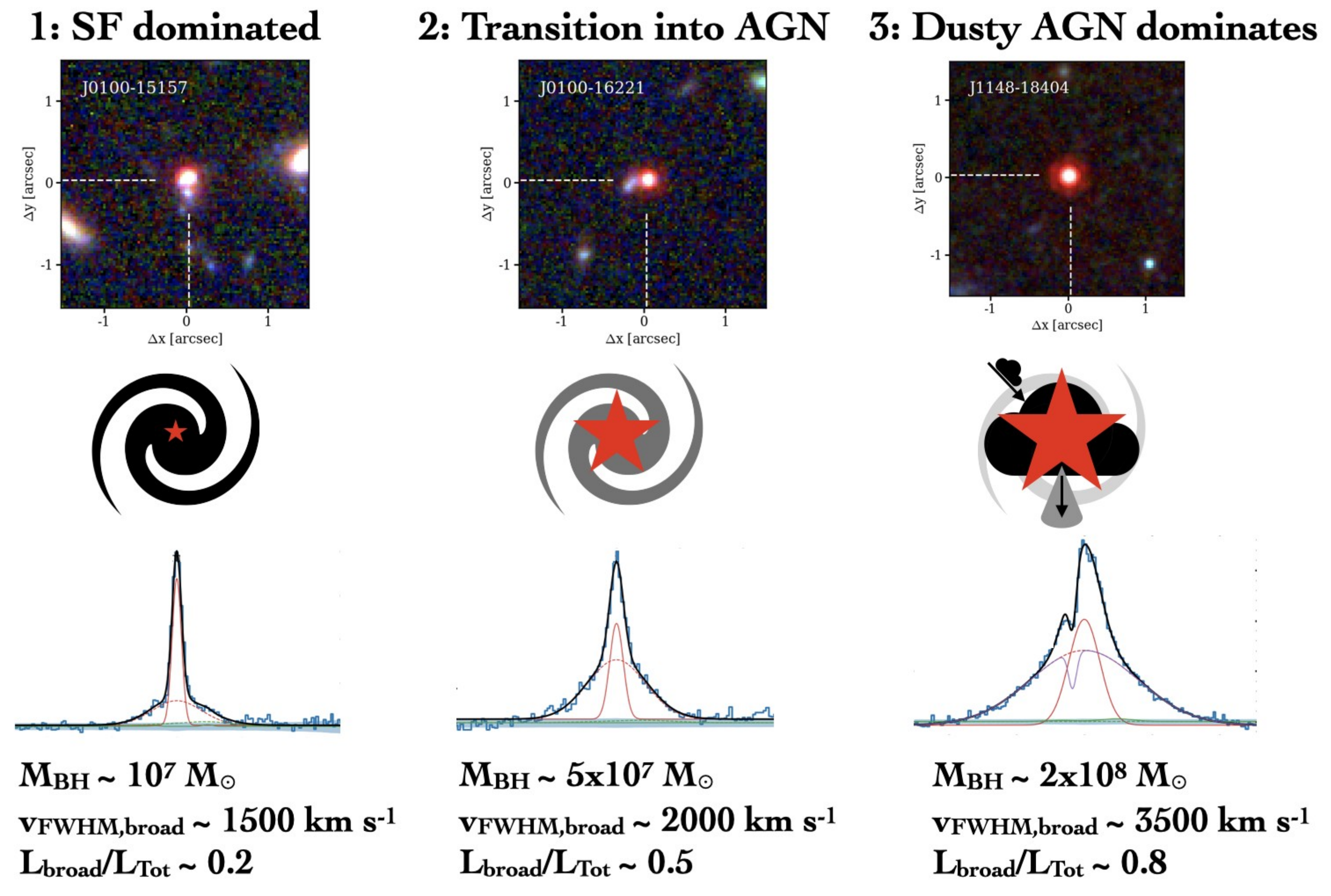


Matthee+2023

- Over a few months, large effort of the community to try and understand these sources
- Using NIRCam slitless spectroscopy, Matthee+2023 discovered a population of **red**, **compact** sources all presenting **broad** emission lines
- This was interpreted as the presence of AGN emission in all these sources

Small high





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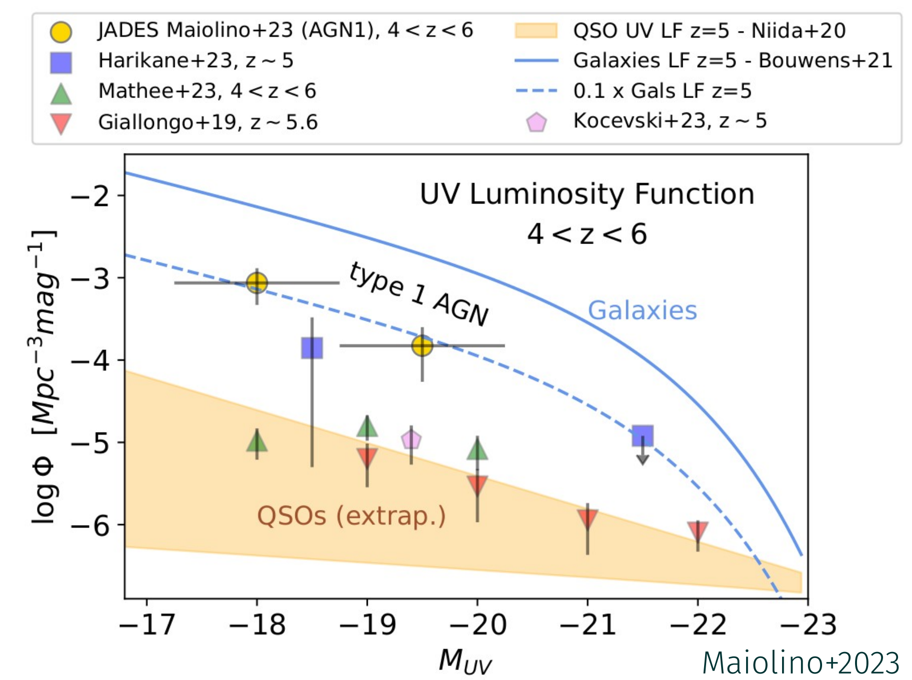
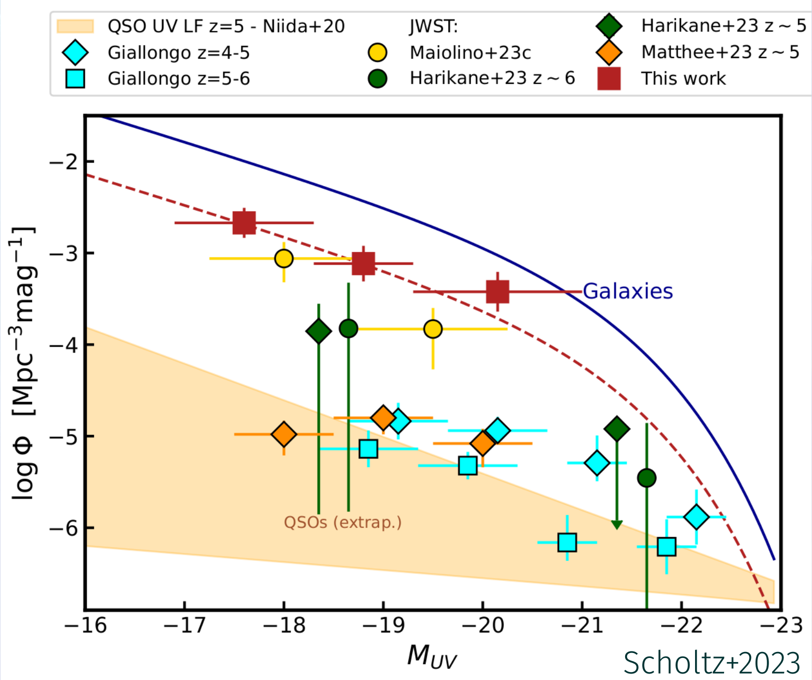
First conclusion: number density of high-z AGN





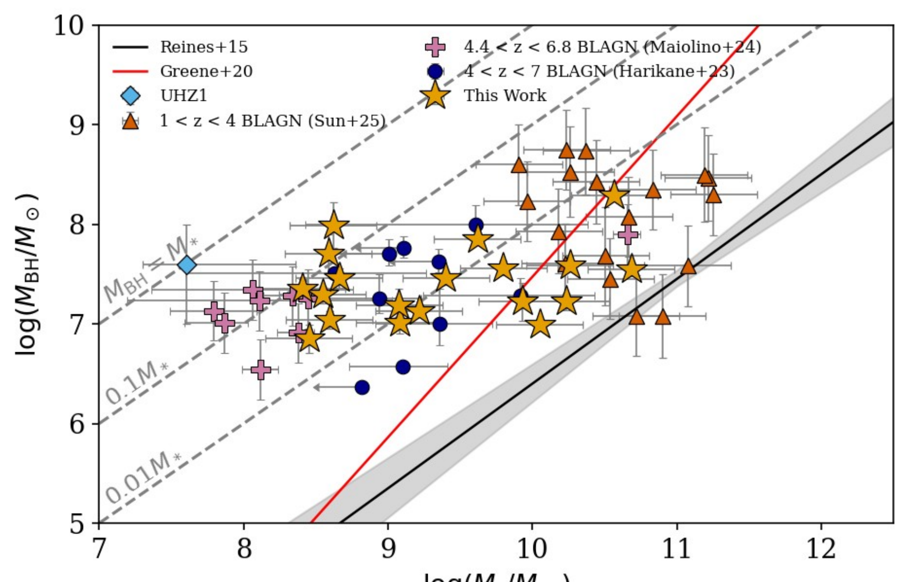
- JWST surveys indicate that **AGN are more frequent at high-z** than extrapolation suggested
- One caveat: disentangling host galaxy and AGN can be tricky

Masses of high-z SMBH

- Most of the sources have been detected through their broad lines
- We can deduce an estimate for the SMBH mass from the broad line
- SED fitting techniques can estimate a stellar mass for all these objects

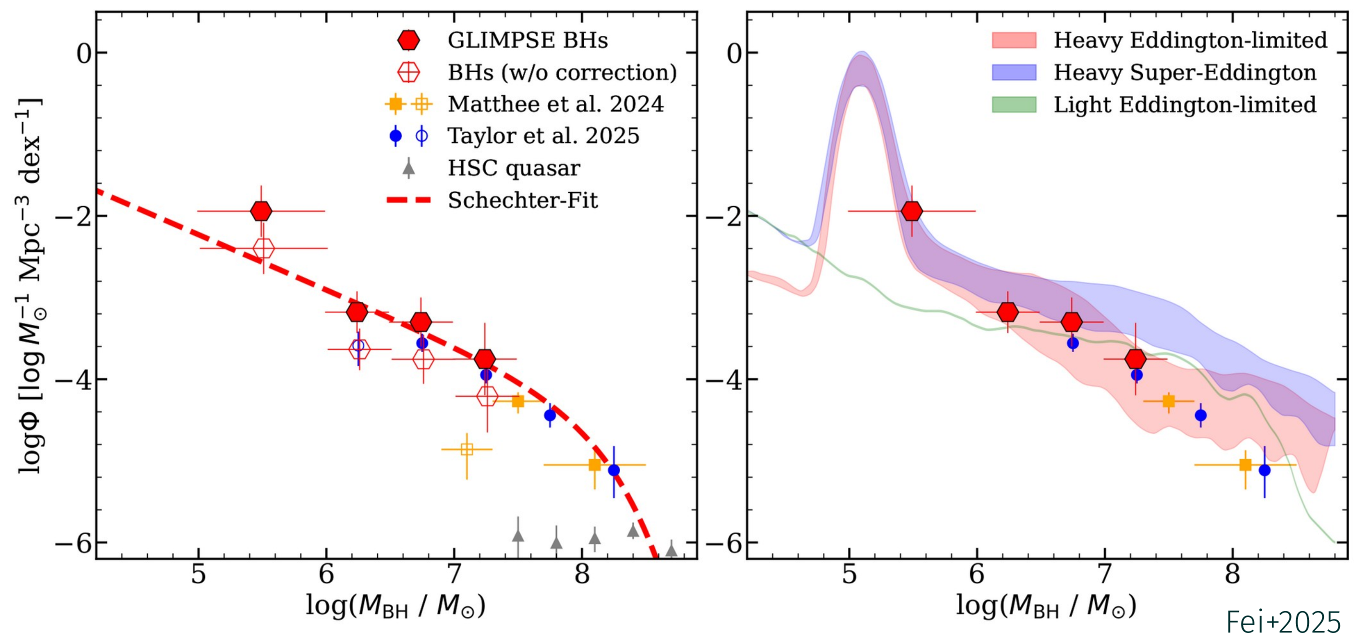
→ **BH-to-stellar mass** measurements!

- Most studies tend to find "overmassive BH"



Zhang+2025

Extending BH mass measurements to the IMBH regime

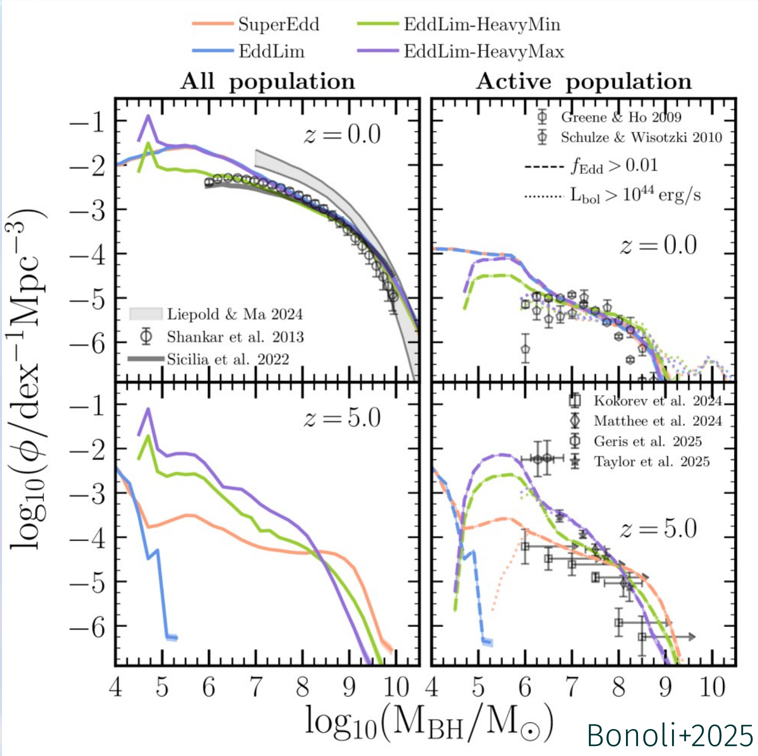


- Using extremely deep imaging + spectroscopy, we can now detect BH at very high-z **and** in the very low-mass regime
- This regime starts to probe formation scenarios (if the masses are robust)

Models struggle to reproduce the abundance of early SMBH

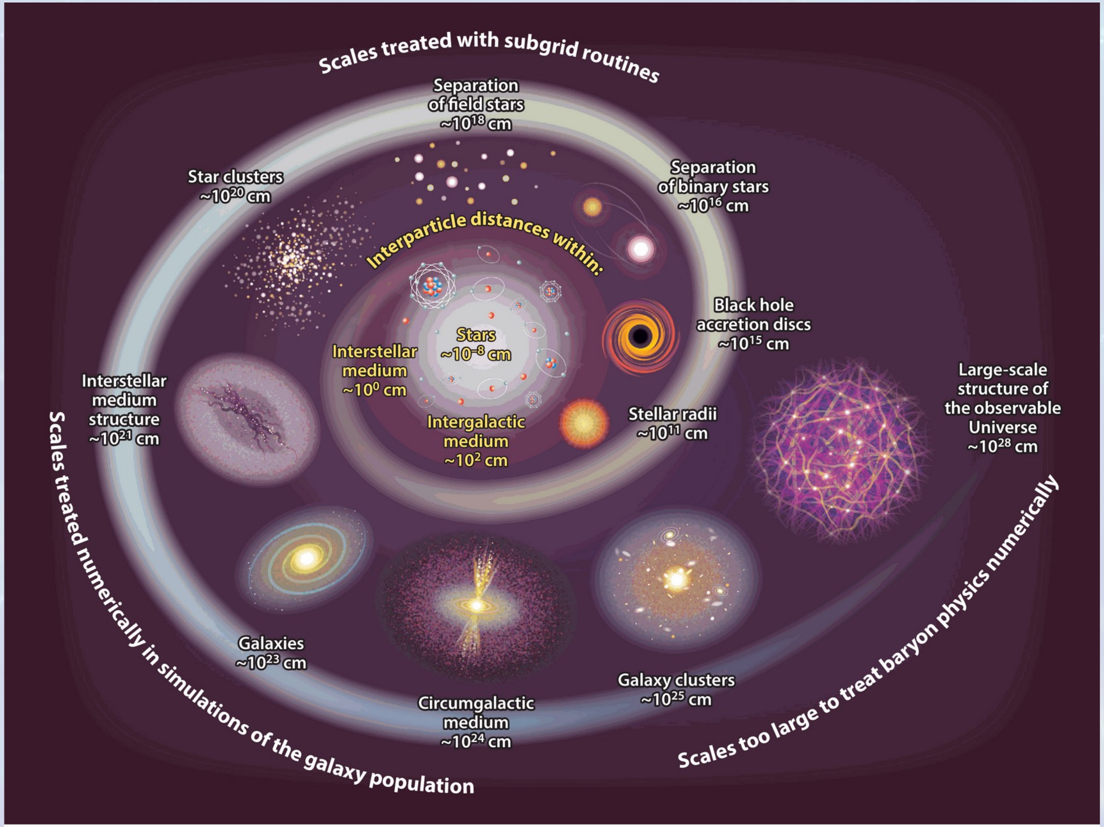
- Galaxy formation models are usually calibrated on pre-JWST data
- Usual models tend to under-estimate the number of high-z SMBH and AGN
- This is true both of hydrodynamical simulations and semi-analytical models

- This can be partly alleviated by allowing **super-Eddington accretion** to happen



What do models actually do?

Supermassive black holes, super small scales



Crain RA, van de Voort F. 2023
Annu. Rev. Astron. Astrophys. 61:473–515

- Major issue: scale problem
  - IGM: ~10s Mpc
  - Galaxies: ~1-10s kpc
  - ISM: ~ 1-300 pc
  - …
  - Accretion disc: 0.001 pc
  - $r_{Schwarzschild}$ ~ 10^{-6} pc

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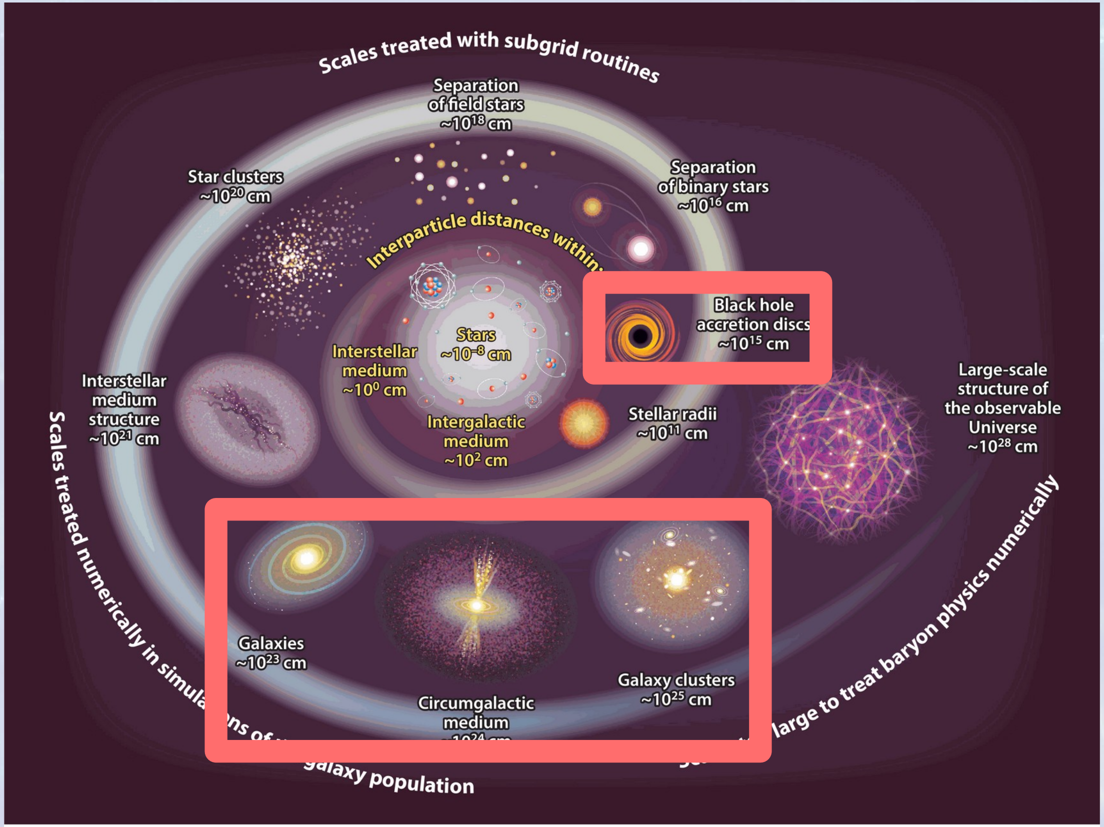

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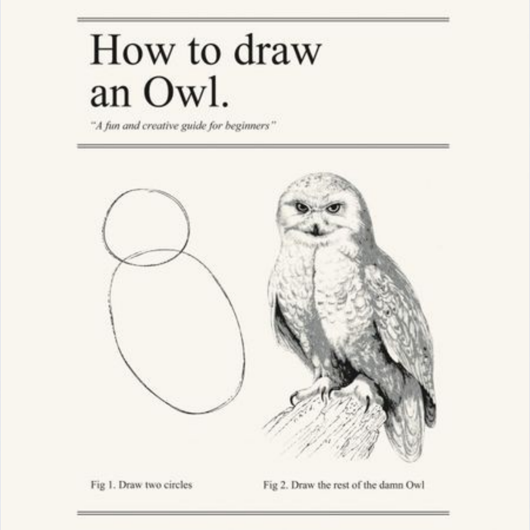
  - Accretion disc: 0.001 pc
  - $r_{Schwarzschild}$ ~ 10^{-6} pc
- Simulations **have to** rely on sub-resolution modelling across (many) orders of magnitude

So how do we model black holes in galaxies?

- Put a BH particle in a galaxy
- Let it accrete gas
- Maybe do feedback
- Hope for the best



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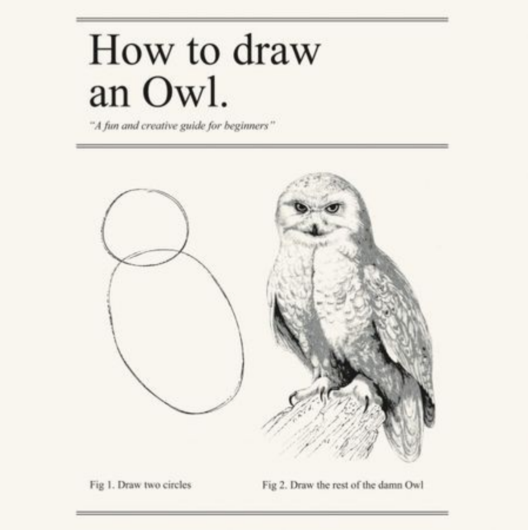

Many subtle details

- *Where* and *when* do we put the BH, exactly?
- *How* do we accrete the gas?
- Do we let the BH just move freely?
- How do we do feedback?
- Also, what about BH mergers?

NB: All of these topics could be a ~~talk~~ conference

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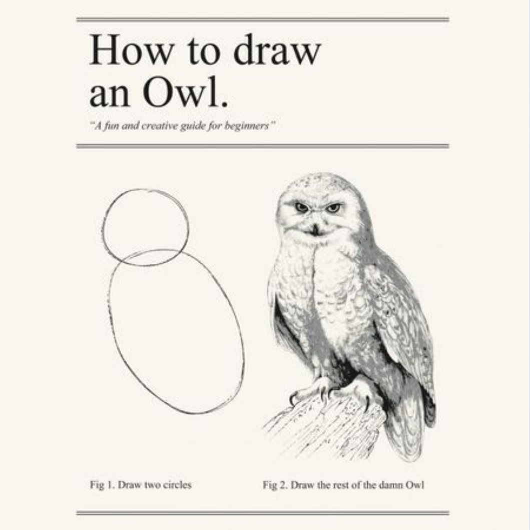

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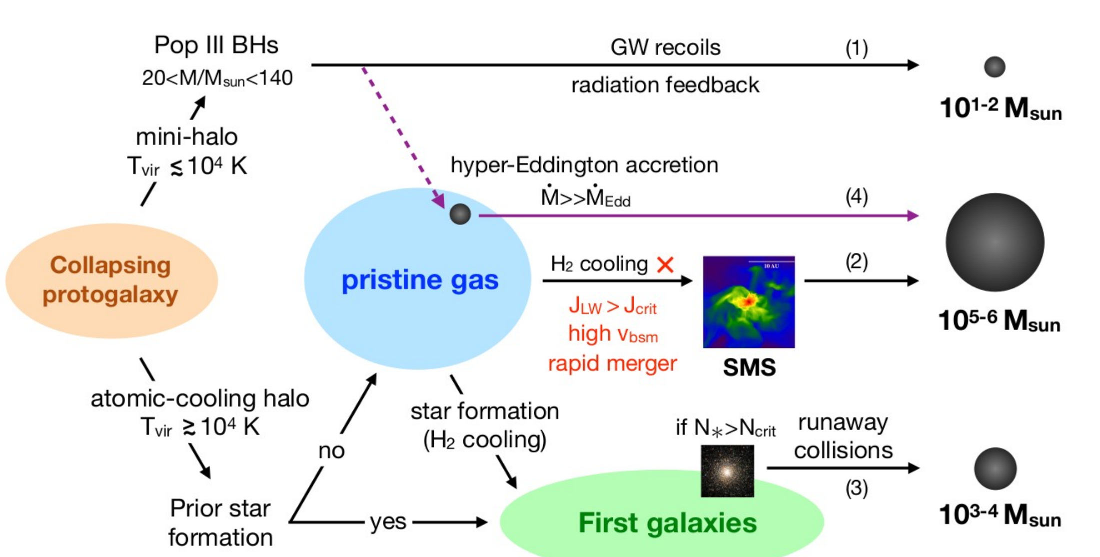
How do we "seed" black holes (in galaxies)?

- Several processes can seed BHs
- In practice: we put a BH "where we want it to be"
  - This can be in the centre of a halo
  - Based on matter overdensity
- Seed mass is usually chosen for **numerical** reasons (~10^5 - 10^6 $M_\odot$)
- In reality, fairly agnostic on the underlying physical model



Inayoshi+2020

How do we model BH growth?

- In the simplest approach, assume that the BH is
  - embedded in an homogeneous medium
  - moving without disturbing the flow too much
  - accreting spherically

  → This is the "Bondi-Hoyle-Lyttleton" prescription

- Only a fraction $(1-\varepsilon_r)$ of the accreted gas grows the BH
- Quantities like ρ, c_s, v_{rel} are estimated **at infinity**!
- This strongly depends on the BH mass, as well as on the relative velocity v_{rel}!

THE EFFECT OF INTERSTELLAR MATTER ON CLIMATIC VARIATION

By F. HOYLE and R. A. LYTTLETON

Received 19 April 1939

ON SPHERICALLY SYMMETRICAL ACCRETION

H. Bondi

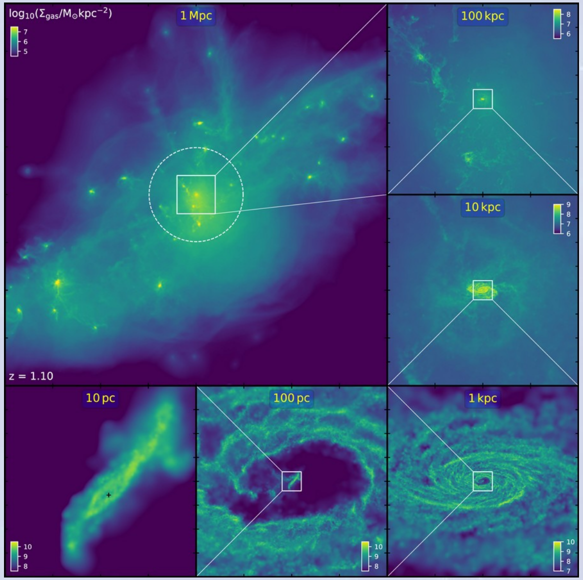
(Received 1951 October 3)

Summary

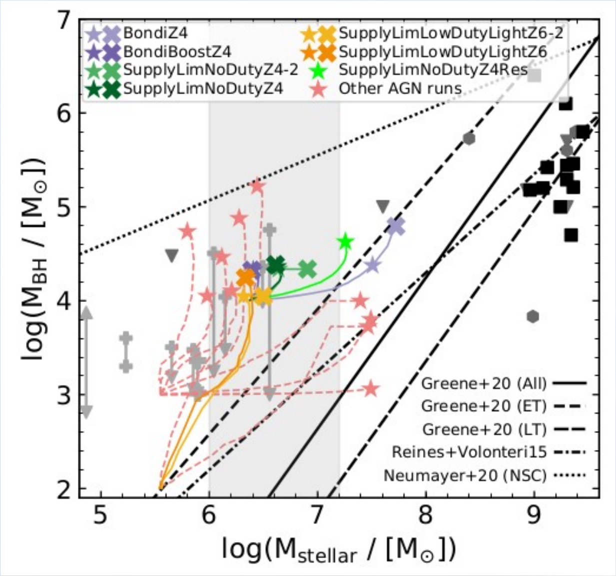
The special accretion problem is investigated in which the motion is steady and spherically symmetrical, the gas being at rest at infinity. The pressure is taken to be proportional to a power of the density. It is found that the accretion rate is proportional to the square of the mass of the star and to the density of the gas at infinity, and varies inversely with the cube of the velocity of sound in the gas at infinity. The factor of proportionality is not determined by the steady-state equations, though it is confined within certain limits. Arguments are given suggesting that the case physically most likely to occur is that with the maximum rate of accretion.

High-resolution simulations break all Bondi assumptions

- The ISM is **not** homogeneous at < 100 pc scales
- Some simulations try to resolve "all the way down", but this is extremely expensive



Angles-Alcazar+2021

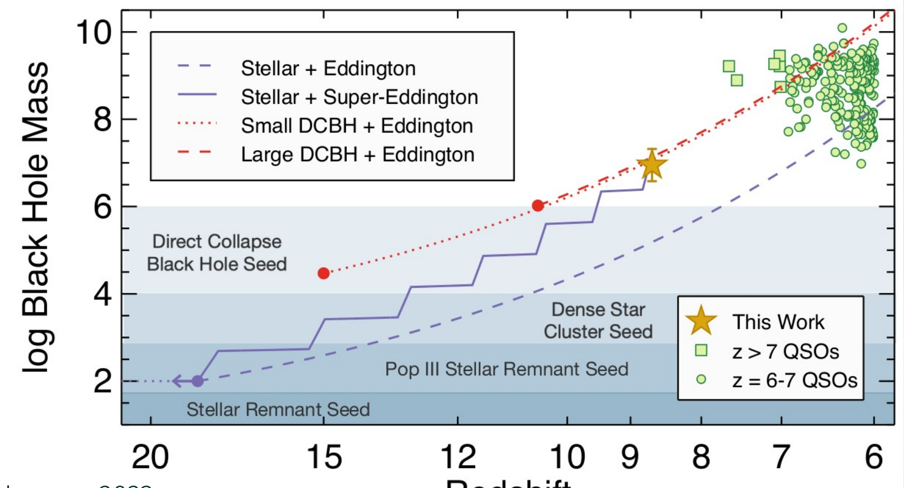


Koudmani+2022

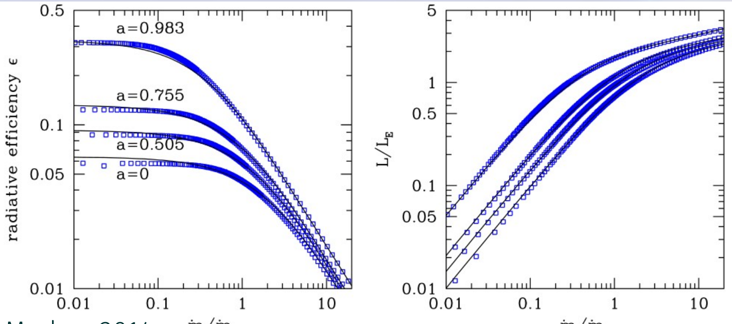
- Changing the accretion model **STRONGLY** changes the growth of BH in dwarf galaxies
- Definitely room to improve models!
- NB: adding radiation might limit BH growth again…

Growing BH really fast: breaking the Eddington limit?

- Super-Eddington growth is often invoked to "solve" BH growth issues
- In principle, accretion is not spherical, so great idea!
- Super-Eddington "exists"
  - Found in ULX
  - GRAVITY+ finds $\lambda_{Edd} > 1$ in PDS 456 (arXiv: 2401.07676)
- However, can simulations make it work?
  - Affects the feedback model
  - Different radiative efficency
  - Depends on BH spin…

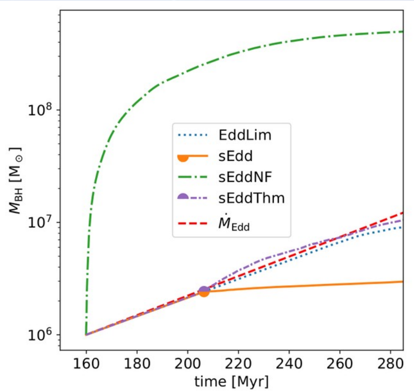


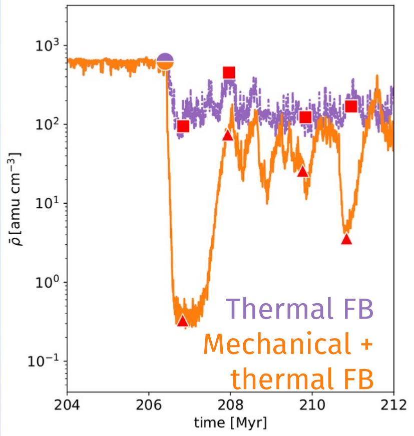
Larson+2023



Madau+2014

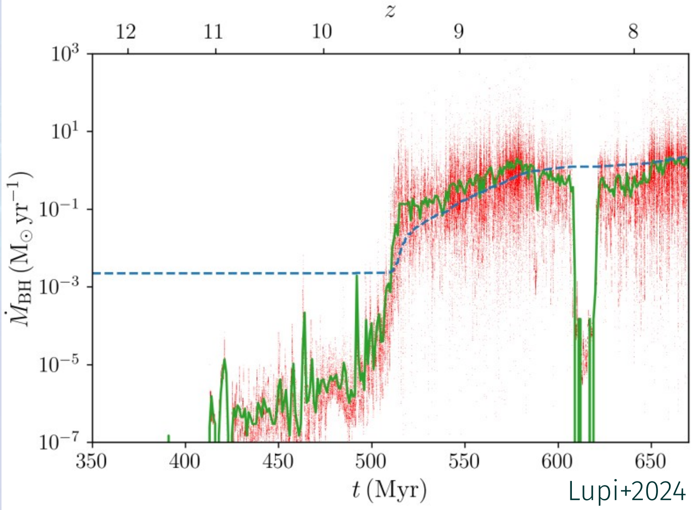
Growing BH really fast: breaking the Eddington limit?





Massonneau+2023

- Different simulations have attempted this
- Results are not converged yet
  - Massonneau+2022,2023 find that with efficient feedback, super-Eddington growth is actually reducing BH growth
  - Lupi+2024 find that sustained Super-Eddington accretion can happen



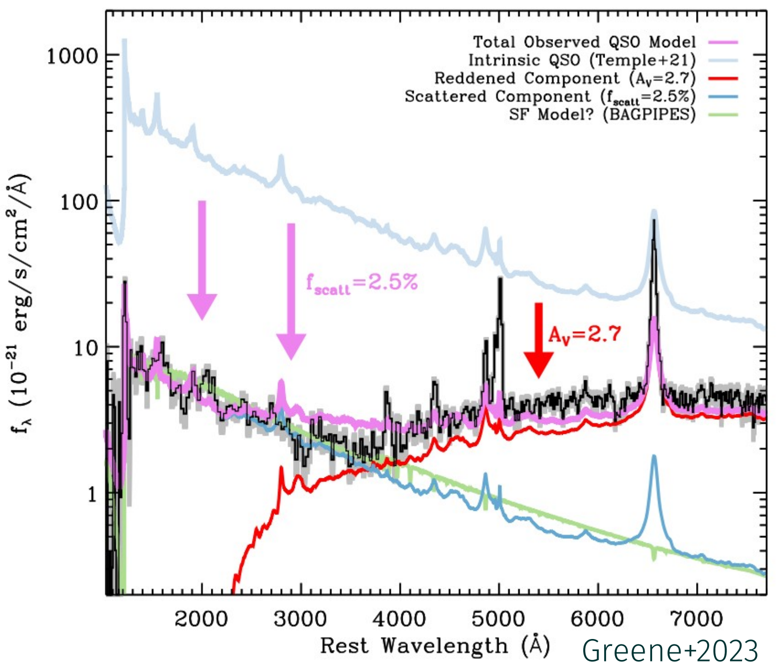
- This will require more investigation
- We (at least, I) don't understand systematics and numerical effects yet

Back to observations

-

LRDs : a strange sub-population

LRD selection



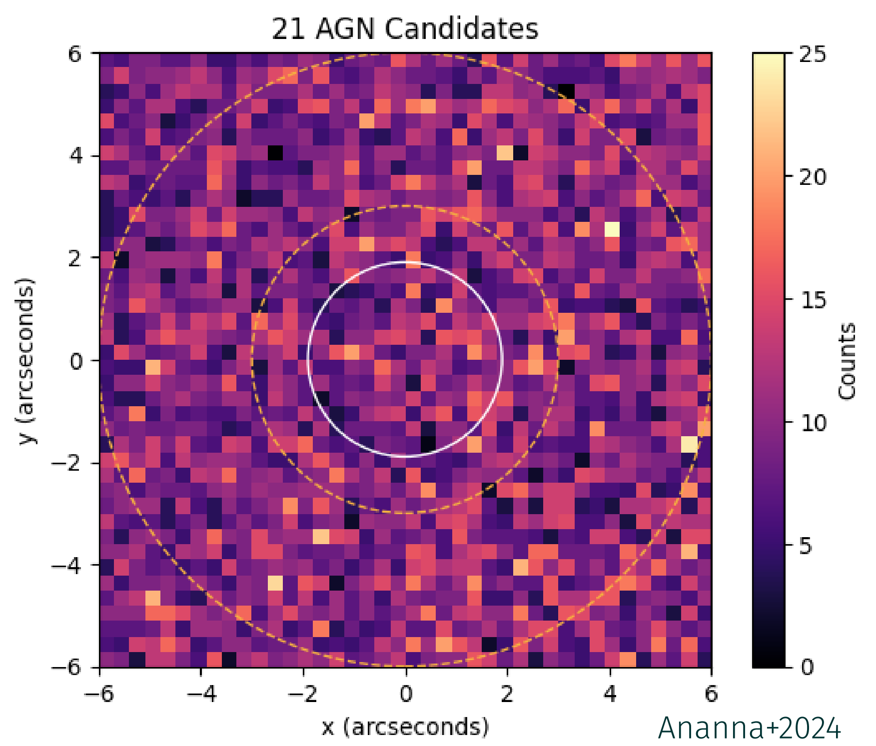
Greene+2023

- Even if Little Red Dots were defined from spectroscopy, they have a **peculiar V-shaped SED**

  → Efficient way of selecting AGN candidates from photometry !

- Greene+2023 found that this is indeed a robust selection method
- However, the origin of this V-shaped SED is very unclear

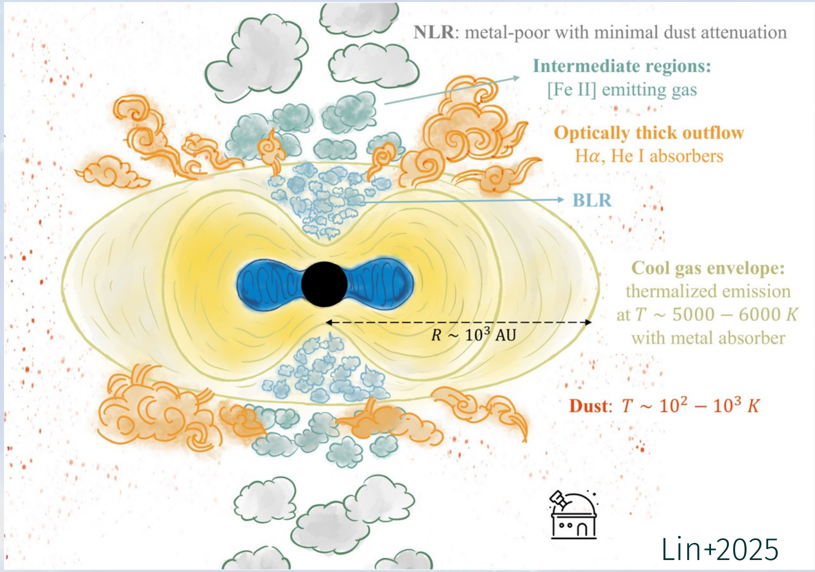
Puzzling spectral shape of LRDs

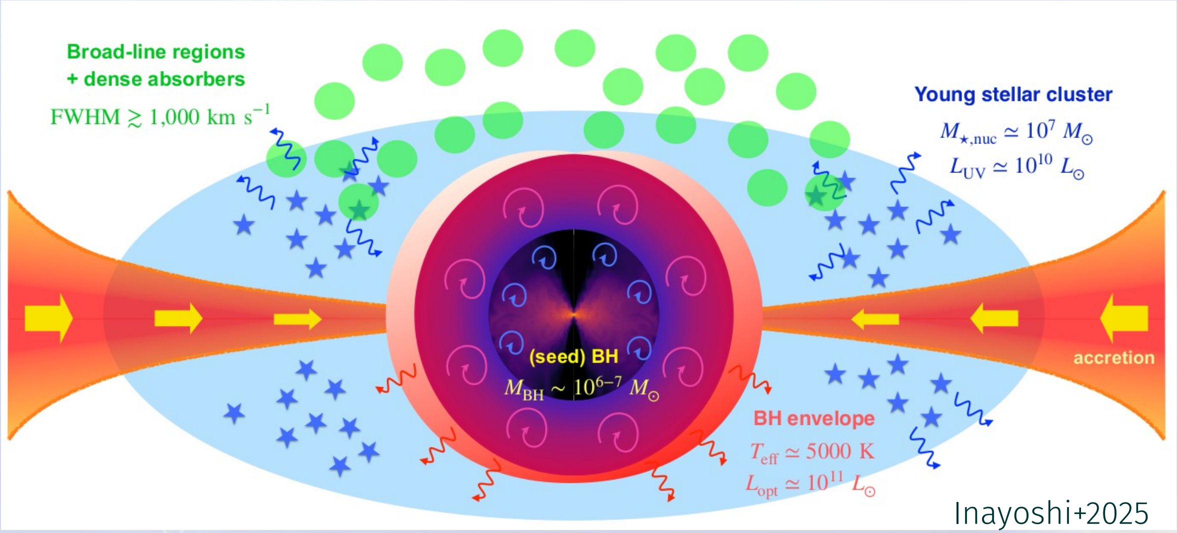


Ananna+2024

- Multiple scenarios have been proposed to explain the spectra of LRDs:
  - Galaxy + obscured AGN
  - Dust-obscured galaxy + blue AGN
  - Non-standard accretion disc
  - TDEs in clusters
- Main puzzles for the LRDs:
  - Origin of the two continuum slopes
  - Presence of a “Balmer break”
  - Lack of X-ray
  - Lack of (cold) dust

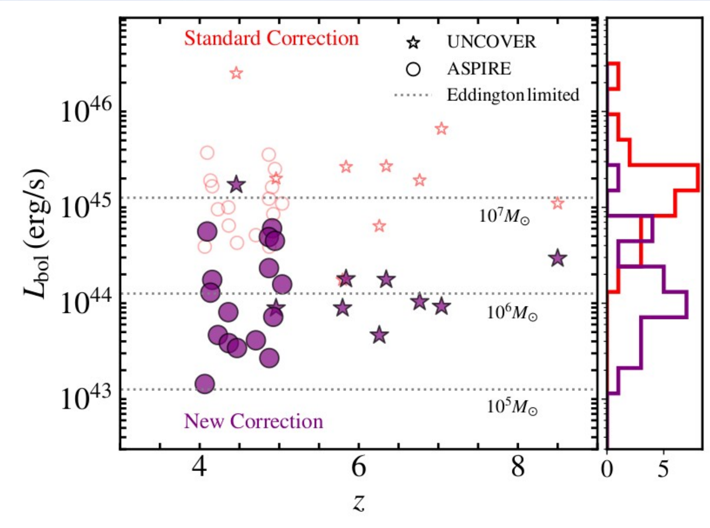
Towards a partially consistent of LRDs: dense gas in the centre

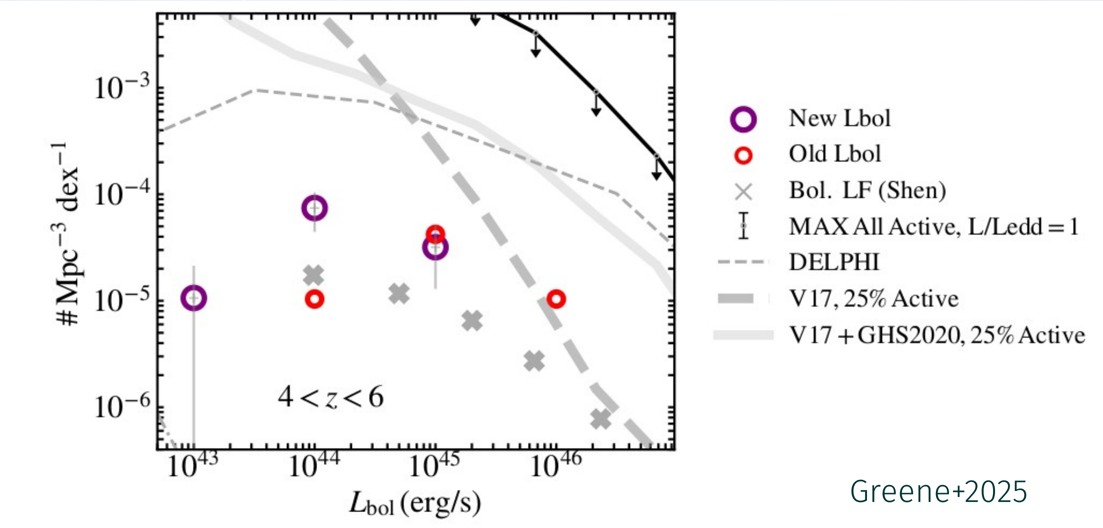




- More and more studies seem to point to a “peculiar” physical origin of LRDs:
  - Relatively low-mass, actively growing black hole
  - Surrounded by dense gas (dust and metals still TBD)
- This suggests that LRDs could be a “phase” of early SMBH growth

Cautionary tale: these are still the early days





Greene+2025

- Updates on the knowledge on the spectra of LRDs can dramatically alter our understanding
- For example, updates on the full spectra of 2 sources suggests LRDs could host much less massive MBHs than previously thought
- This means that the BH population at high-z can still considerably change

Conclusions

Conclusions

- JWST has opened a **new window on the “first” SMBH** :
  - We now “routinely” observe SMBH at $z > 6$
  - We have samples of AGN at $z > 8$
  - We can start probing low-mass SMBH in the high-z Universe
  - The population of early SMBH appears more complex than “light seeds” vs “heavy seeds”
- We are still facing **significant challenges** (eg measuring BH masses robustly)
- Overall, there is still (a lot of) **work for modellers** :
  - Simulations struggle to reproduce the high-z SMBH population
  - Little Red Dots in particular present very peculiar properties
  - The **more physics** we add (so far), **the harder this gets**: recoil kicks, newer feedback, etc