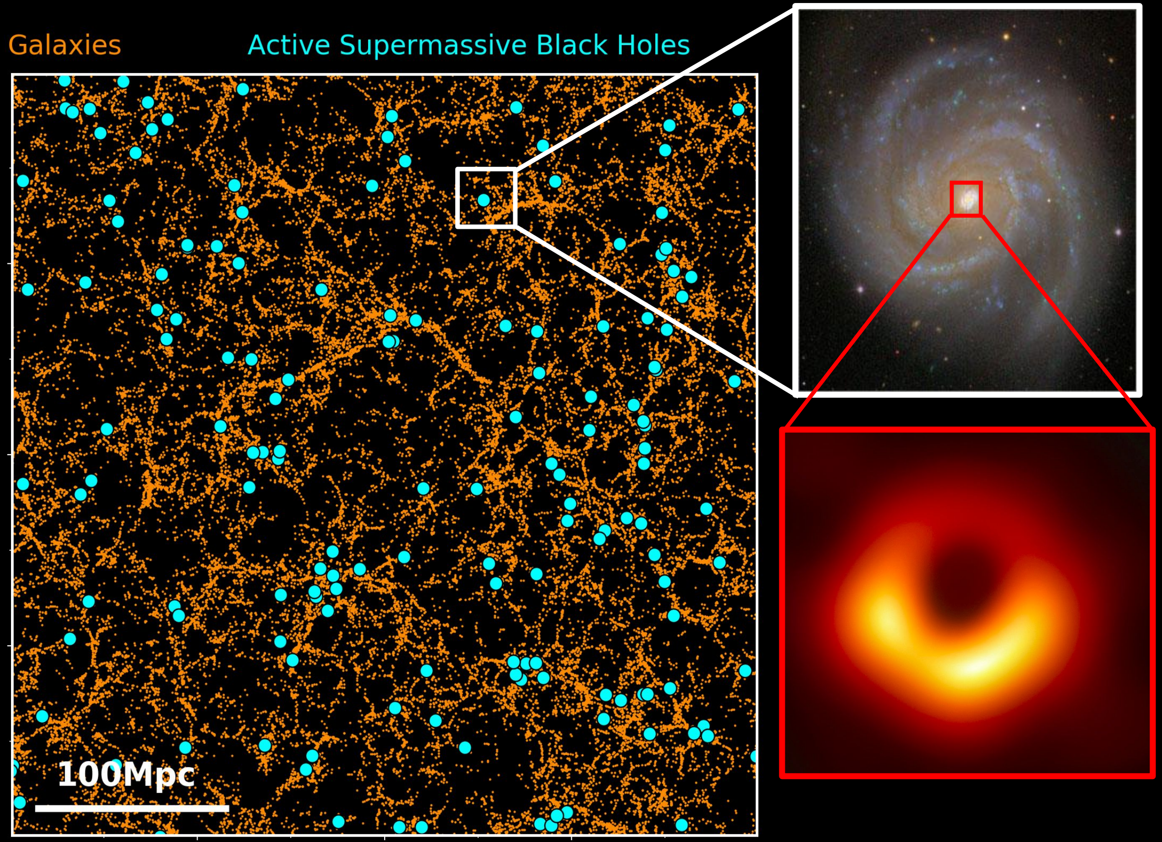
Forward Modelling the Energetic Universe



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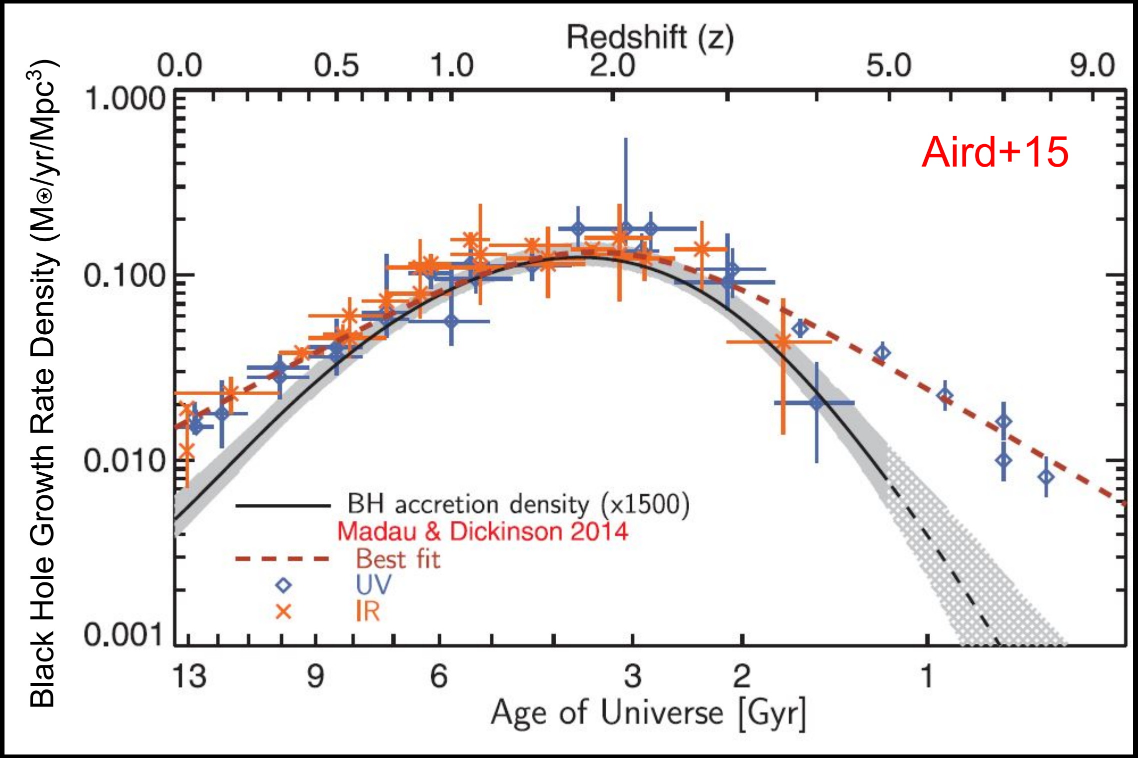
Motivation

What are the physical conditions that promote the growth of supermassive black holes at the centres of galaxies?

- Multi-parametric studies of AGN host galaxies (e.g. star-formation, morphology, star-formation rate)
- Semi-empirical forward modelling approach is well-suited to interpret the observations.
- Demonstration for the role of environment in activating the black-holes of galaxies.

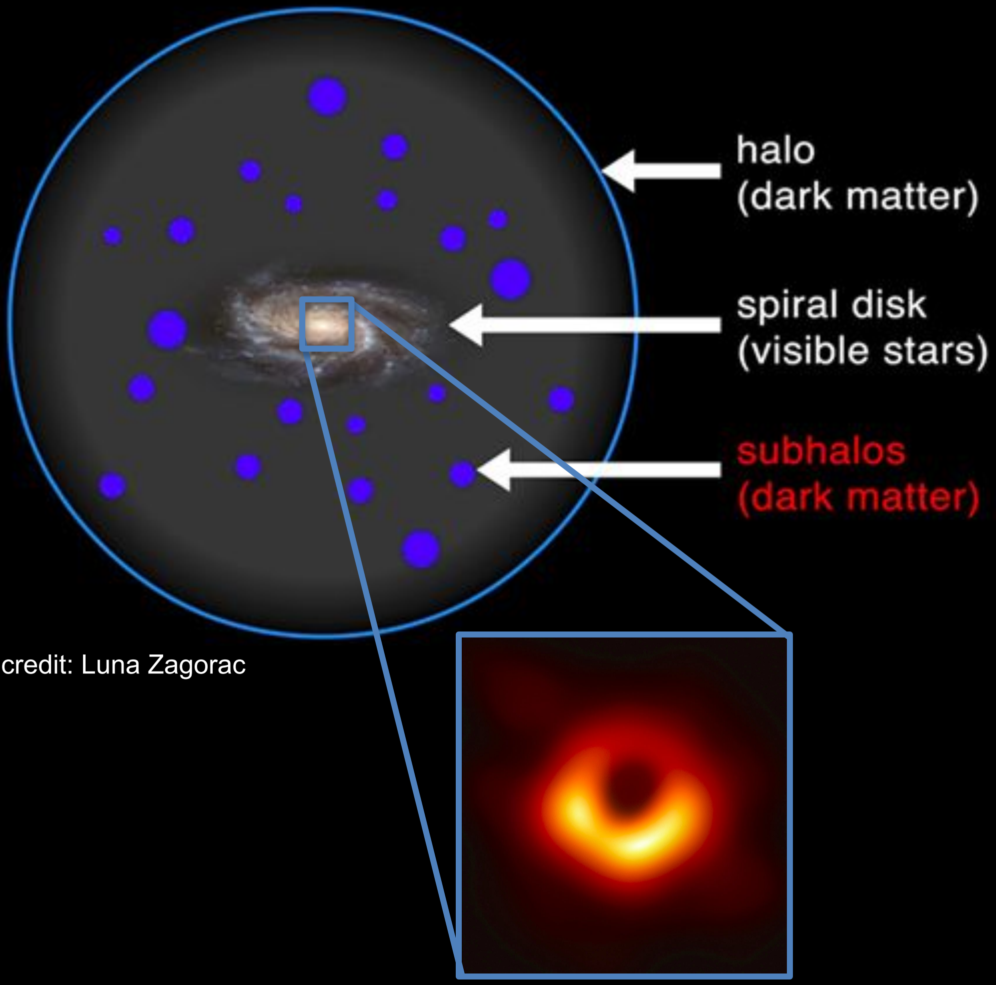
Growth of Black Holes across cosmic time



- Use observations to count AGN as a function of cosmic time (demographics)
- Strong evolution of the AGN population from the local Universe to earlier times
- What is driving this evolution?

Miyaji+01, Ueda+03, Hasinger+05, Akylas+06, Aird+10, Ueda+14, Aird+15, Buchner+15, Miyaji+15, Vito+14, Georgakakis+15, Vito+16

Formation of baryonic matter



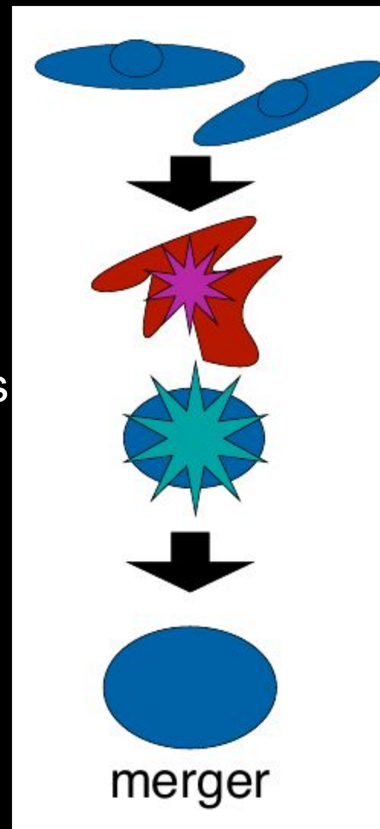
credit: Luna Zagorac

- Dark Matter Halos: sites where galaxies form and evolve
- Baryonic processes:
  - gas cooling / heating
  - gas inflows
  - formation of stars
  - feedback processes

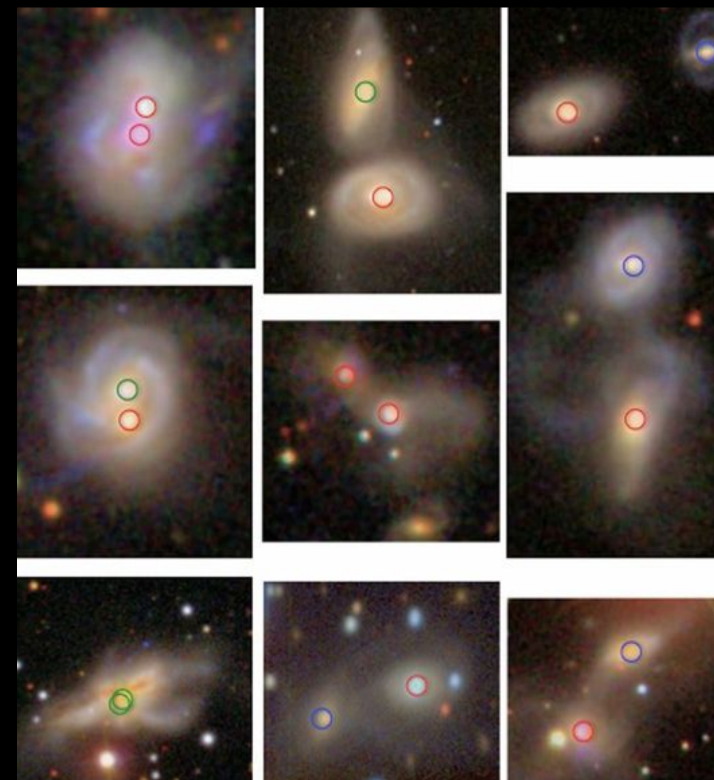
- Most massive galaxies host at their nuclear regions supermassive black holes

AGN population studies: probe physics of black hole accretion flows

- Multi-parametric studies of AGN host galaxies, e.g. star-formation, morphology, environment, gas content.
- Identify regions of the parameter space that are conducive to accretion events
- Example: AGN-merger connection.



Alexander & Hickox 2012



Koss+11: Swift-BAT AGN

Grogin+05; Gabor+09; Georgakakis+09; Cisternas+11; Ellison+11; Koss+11, +12; Kocevski+12; Schawinski+12;Sabater+15; Mechtley+16; Goulding+18; Marian+19; Ellison+19

AGN population studies: probe physics of black hole accretion flows

Caveat:

- covariances between parameters of interest + observational selection effects introduce hidden biases and may lead to erroneous interpretations.

Mitigation strategies:

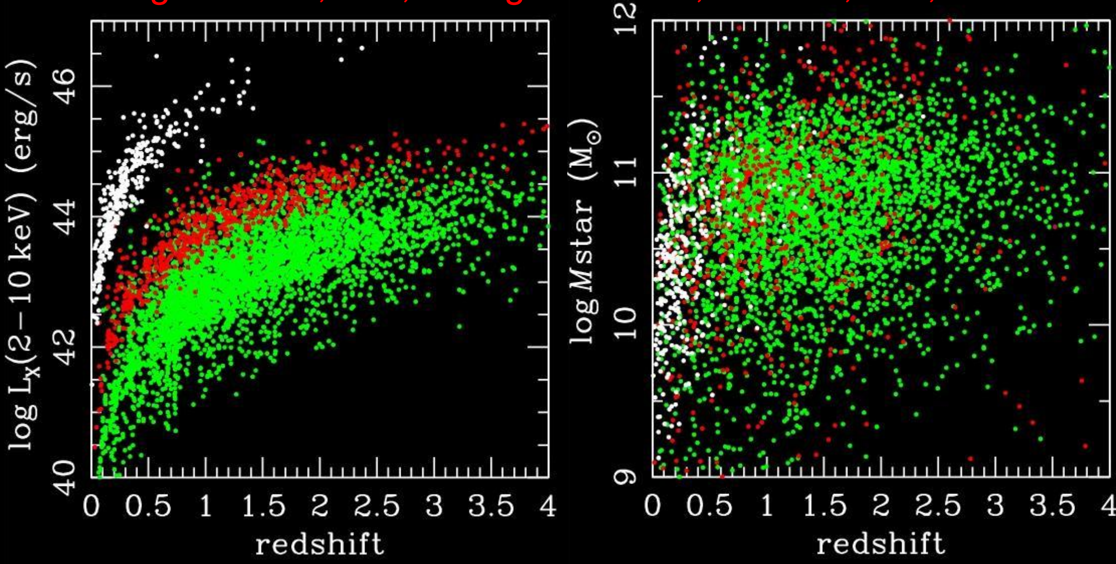
- define “control” samples of non-AGN
- forward modelling

Forward Modelling AGN and galaxies in a cosmological volume

- Produce a realistic (empirical) model of AGN and galaxies in the Universe under certain hypotheses.
- Use the model to replicate real observations by adding all the characteristics of the observational data (e.g. noise, flux limits, field-of-view).
- Compare mock with real observations to test the model hypotheses

Multi-wavelength extragalactic survey fields

Bongiorno+12, +16, Georgakakis+17, Aird+12, +18,+19

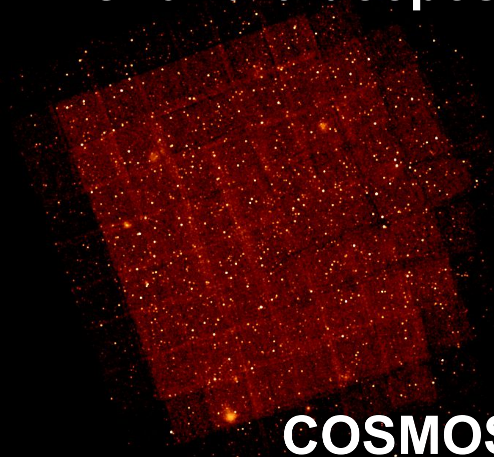


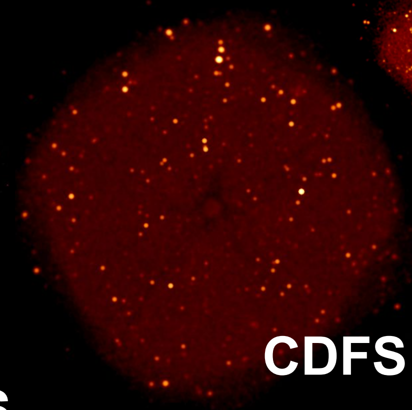
Specific accretion rates of AGN samples:

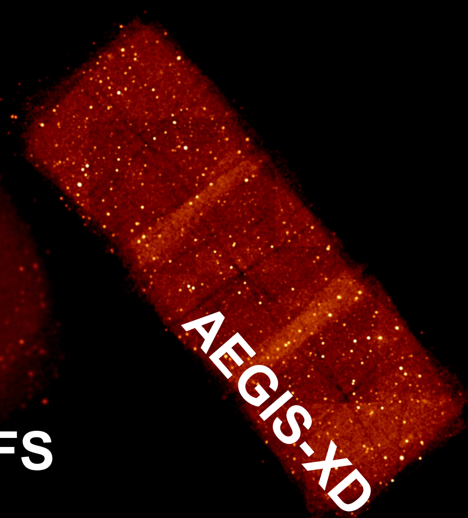
$$\lambda \propto L_X / M_{star}$$

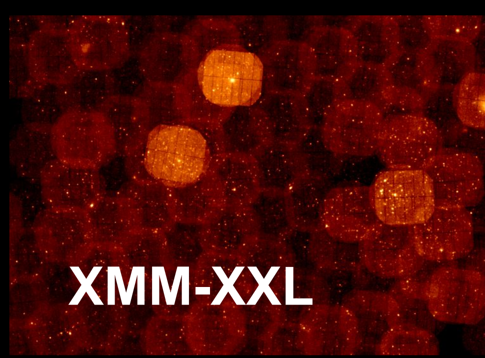
Chandra deepest fields

XMM widest fields



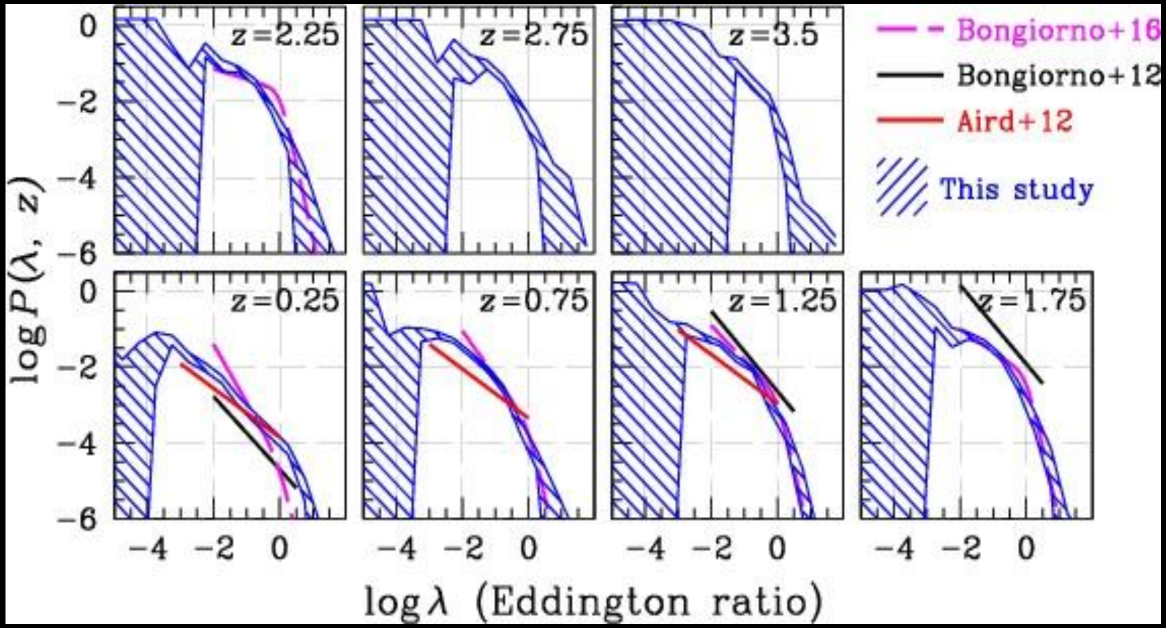






Incidence of AGN in galaxies: specific accretion rate distributions

Georgakakis+17, Aird+12, +19, Bongiorno+12, +16



- $P(\lambda,z)$ is the probability of a galaxy hosting an active black hole with specific accretion rate $\lambda \propto L_X/M_{star}$.
- $P(\lambda,z)$ provides information on how AGN occupy galaxies.

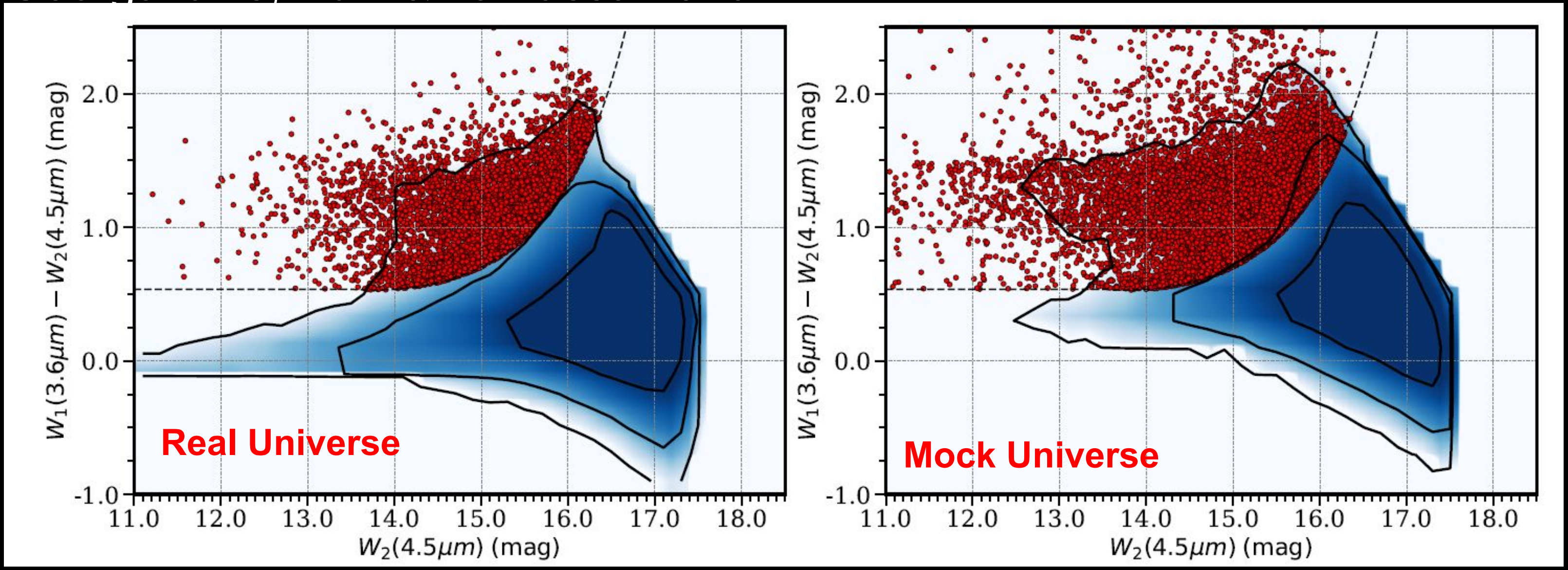
Building empirical models of AGN in cosmological volumes

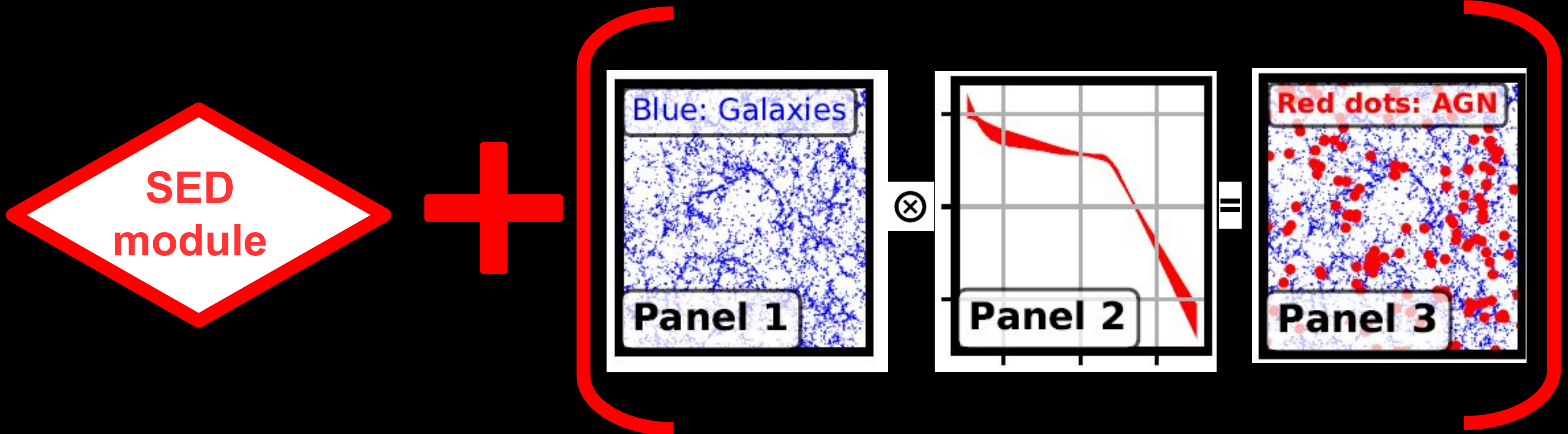
Empirical model consistent with:

- AGN Luminosity Function
- X-ray AGN host stellar mass function

Specific accretion rate distributions: multiwavelength AGN demographics

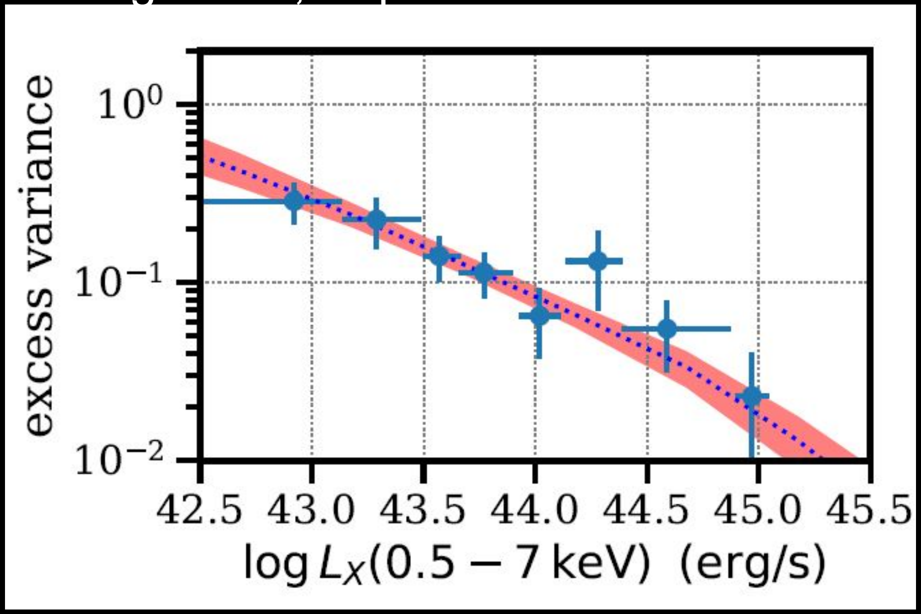
Georgakakis, Ruiz & LaMassa 2020



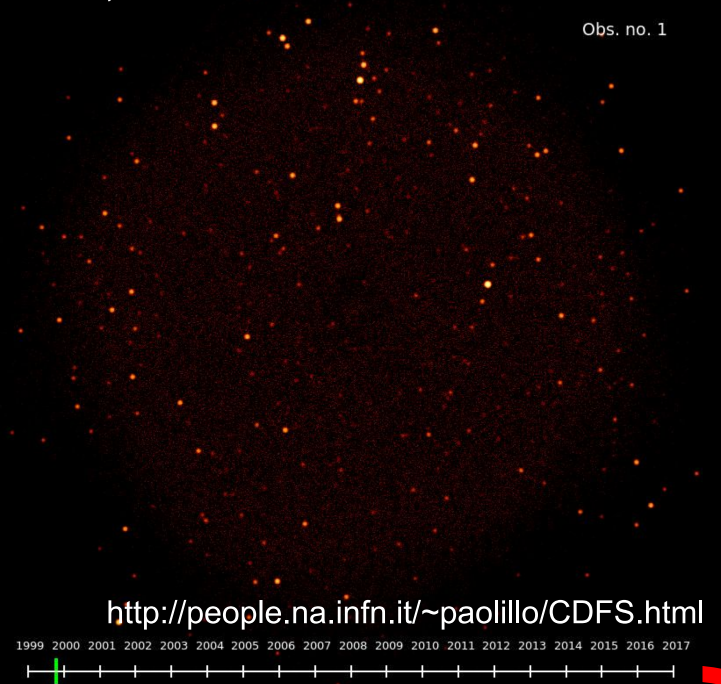


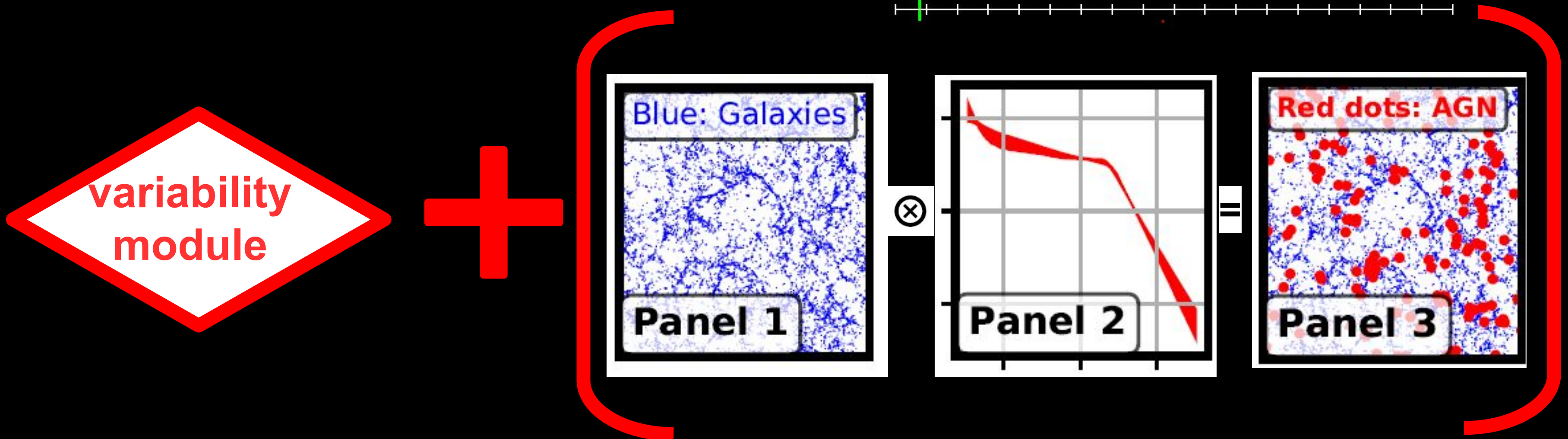
Specific accretion rate distributions: AGN flickering

Georgakakis, Papadakis & Paolillo 2021

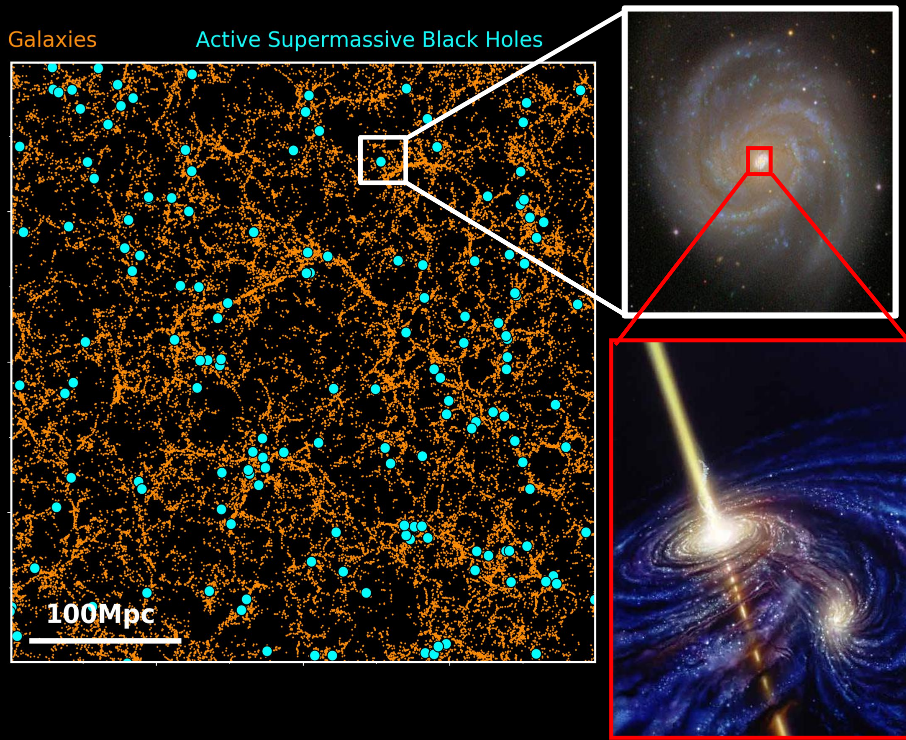


AGN flickering in the Chandra Deep Field South, Paolillo+17



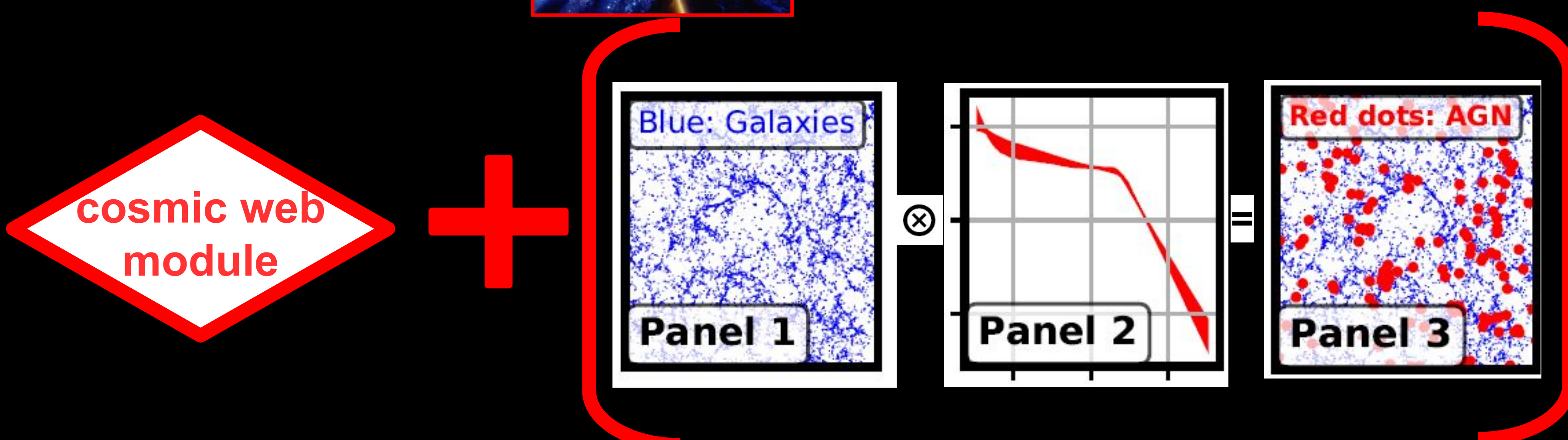


Specific accretion rate distributions: AGN environment

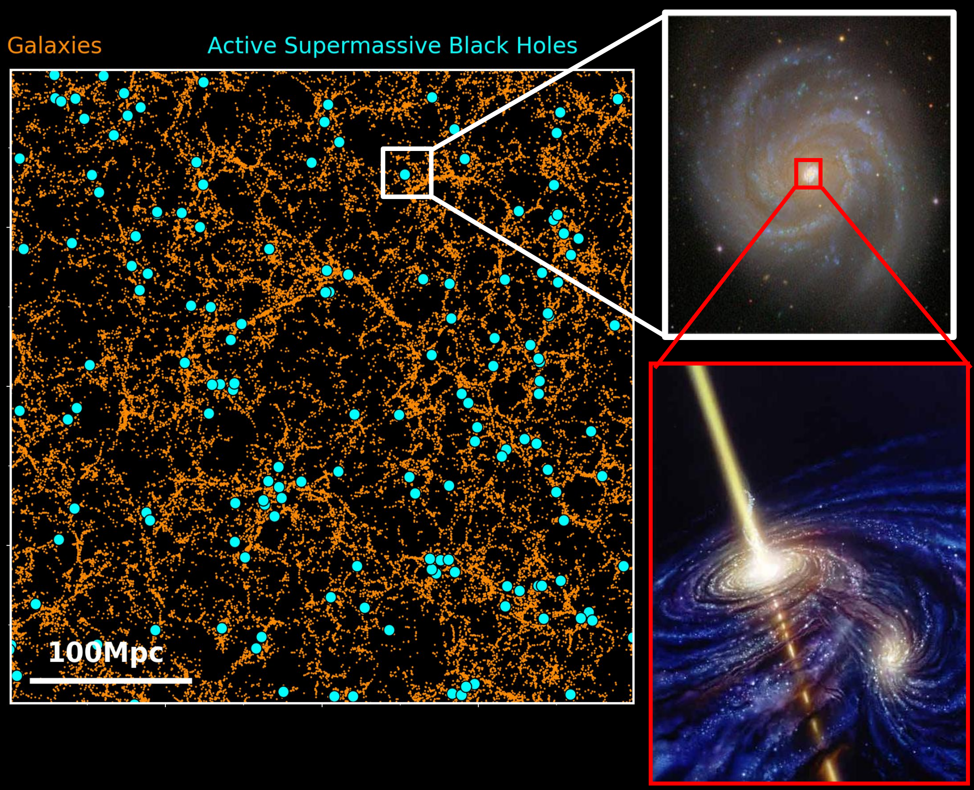


Does the environment regulate the activation of black holes in galaxies?

Georgakakis+19; Comparat+19; Aird+21; Muñoz-Rodríguez, AG+22

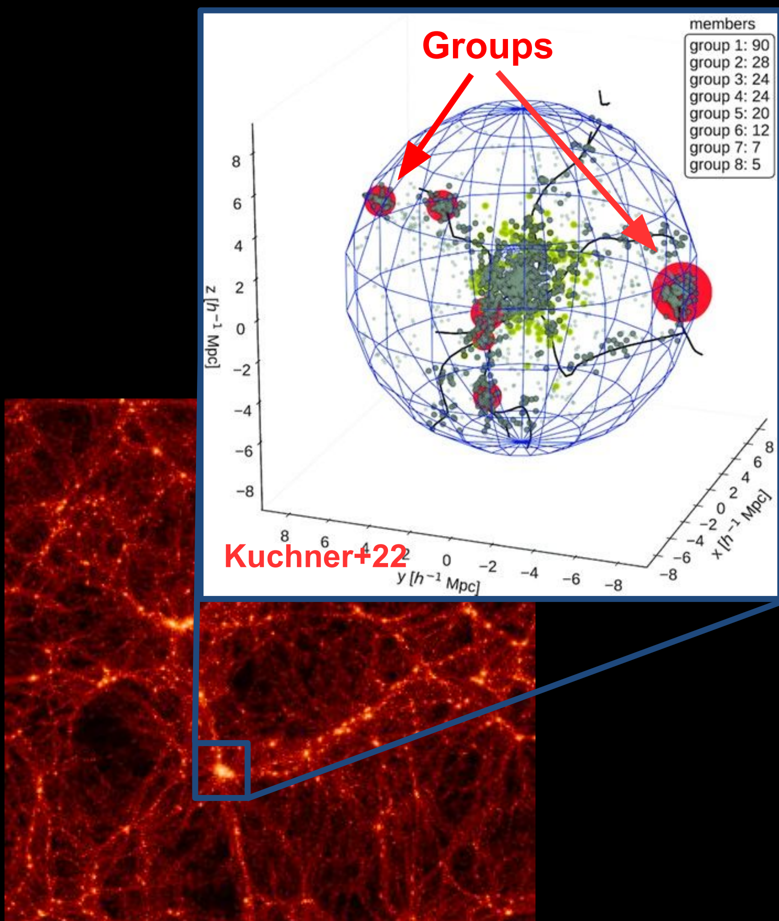


Environment: Definitions



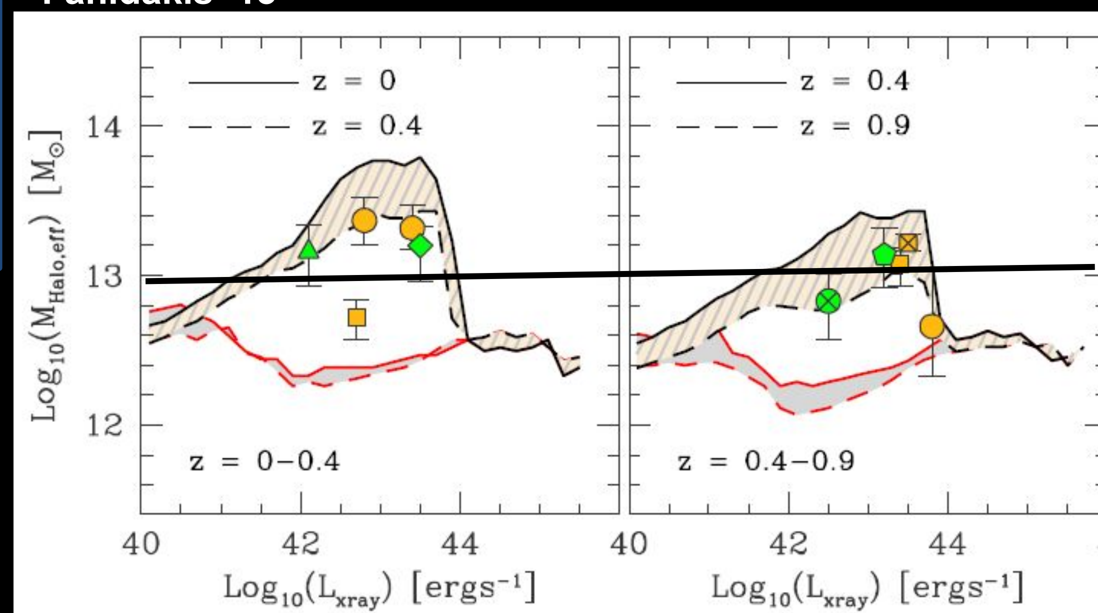
- Environment = local density of matter
- Environment = Clusters, Groups, Filaments, Voids
- Environment of galaxies/AGN = mass of the dark matter halo (M_{DMH}) in which the live
- Groups: M_{DMH}~$10^{13}M_{sun}$; clusters: M_{DMH}>$10^{14}M_{sun}$

The environment of active supermassive black holes



- Observations suggest that AGN live in groups
- Mean halo masses 10^{13}-10^{14} solar.
- Galaxy collisions are expected to be frequent in groups

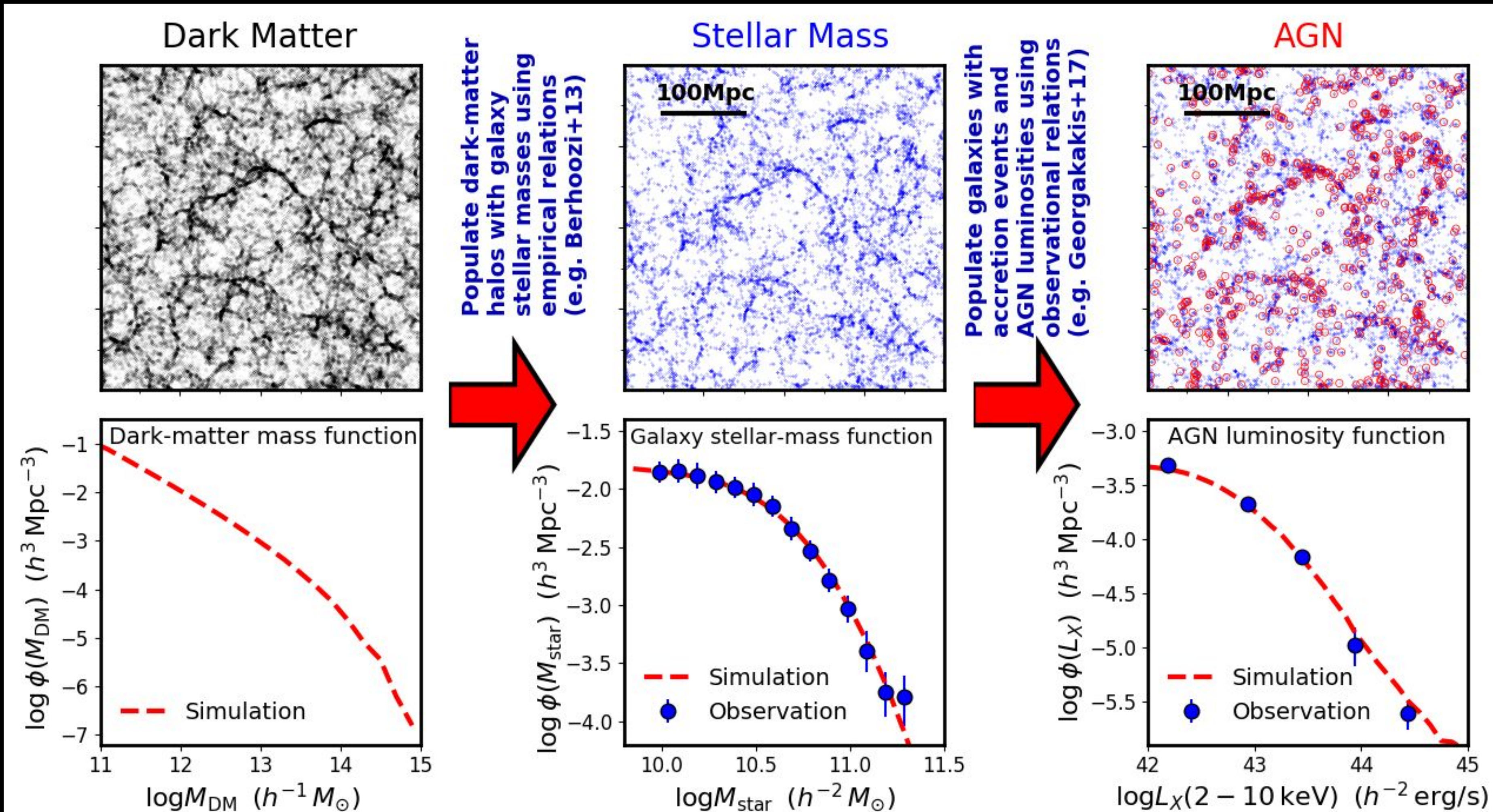
Fanidakis+13



Hypothesis testing: Do accretion events onto supermassive black-holes depend on environment?

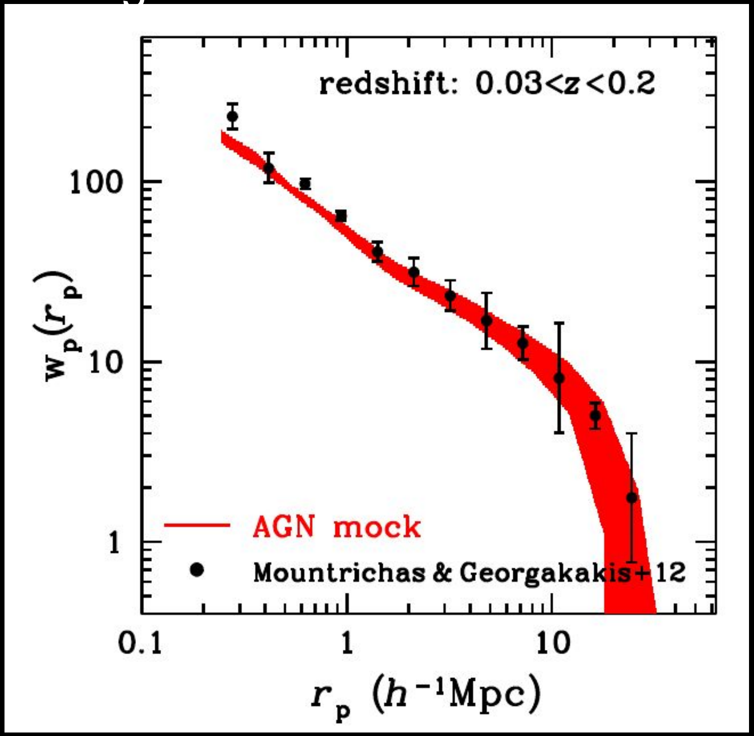
1) Costruct AGN mocks assuming that the black-hole accretion is a stochastic process, i.e. independent of environment.
2) Infer the large scale distribution (clustering) of AGN in mocks.
3) Compare with measurements of clustering in real observations to test assumption in (1).

Recipe for simulating AGN on the cosmic web



The environment of active supermassive black holes

Georgakakis+19



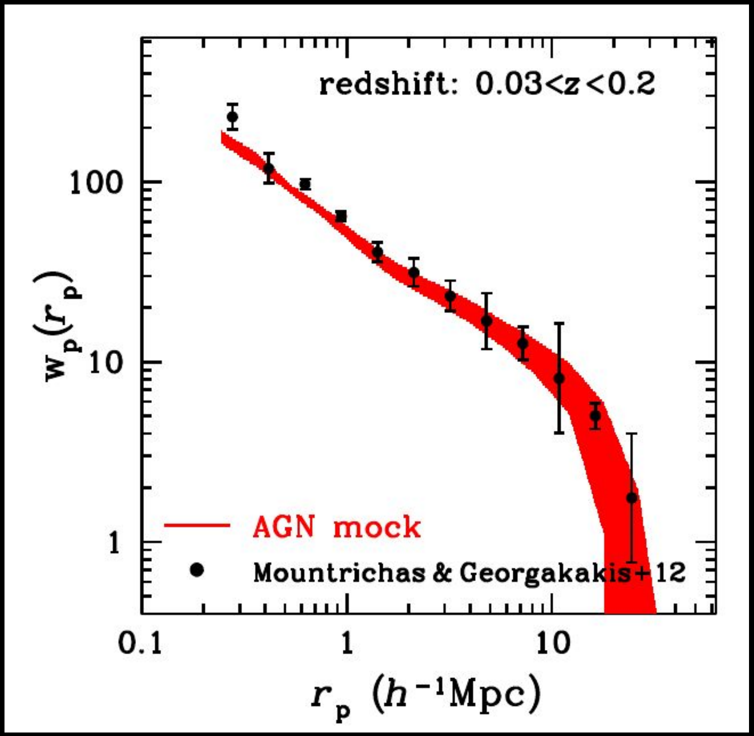
Correlation Function w_p

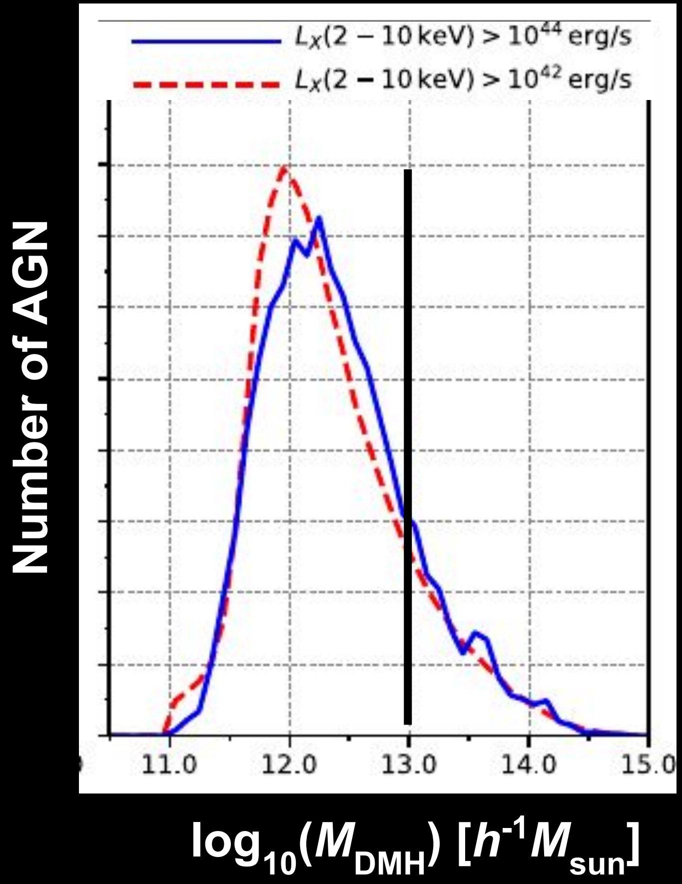
Separation r_p (Mpc)

- Recent evidence: AGN do NOT live preferentially in group environments
- Observations can be reproduced by models in which accretion events occur stochastically in all galaxies independent of environment

The environment of active supermassive black holes

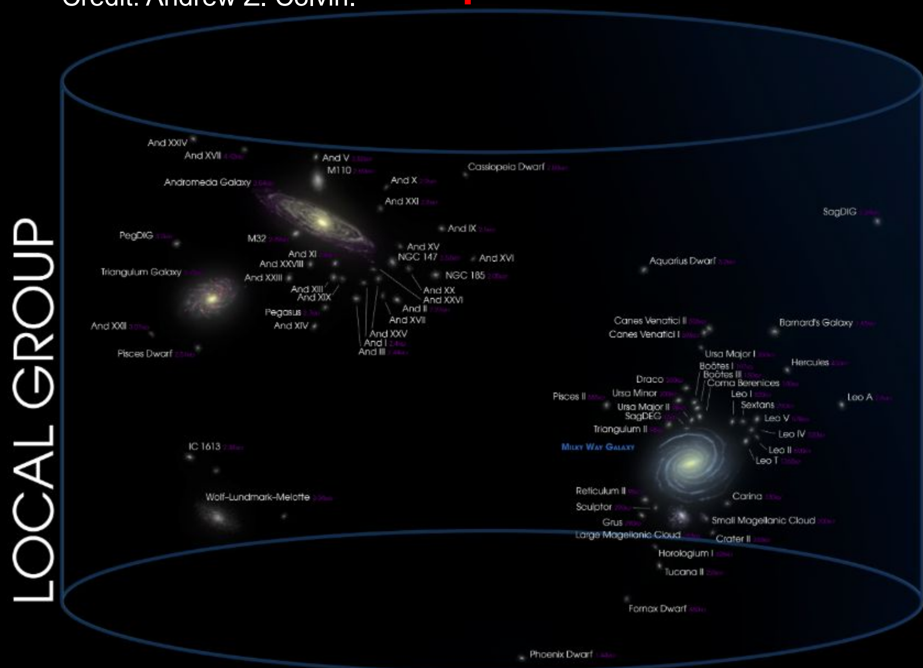
Georgakakis+19

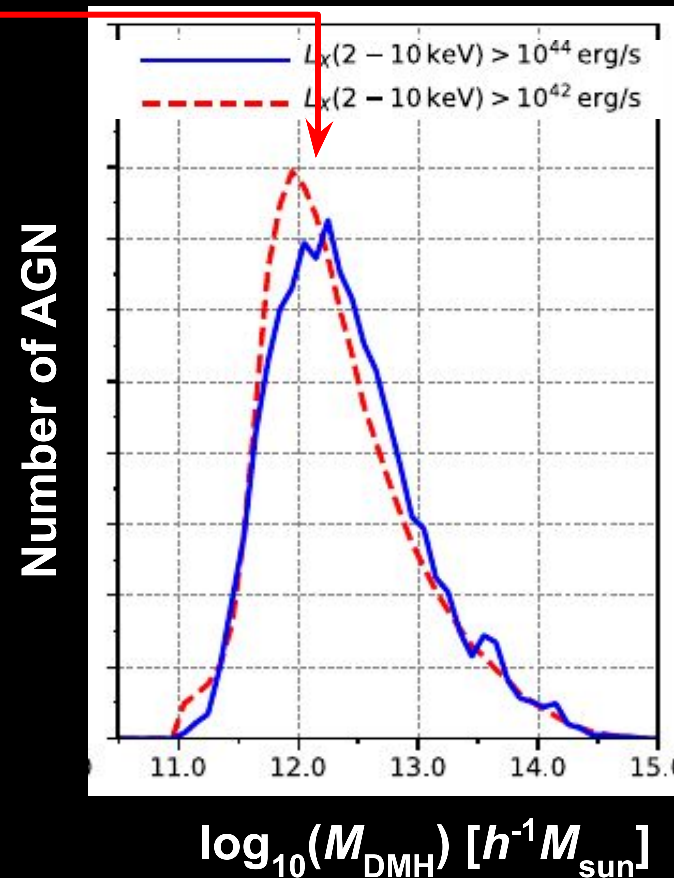




The environment of active supermassive black holes

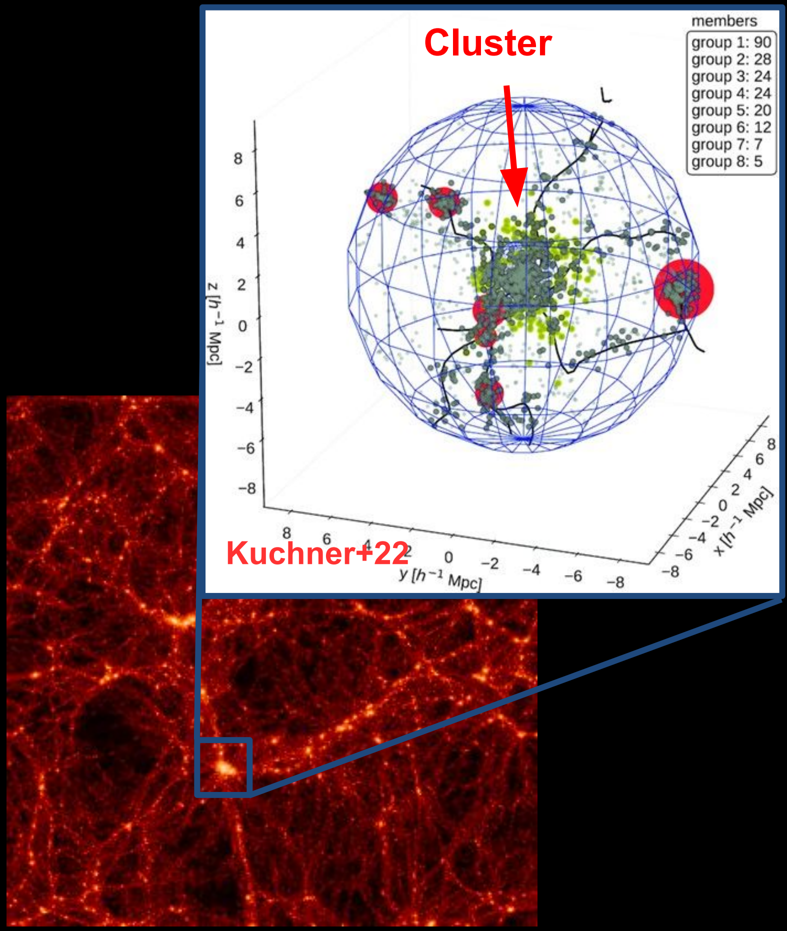
Credit: Andrew Z. Colvin.





AGN live in environments similar to Milky Way ~3×10^{12}solar (Benisty+22)

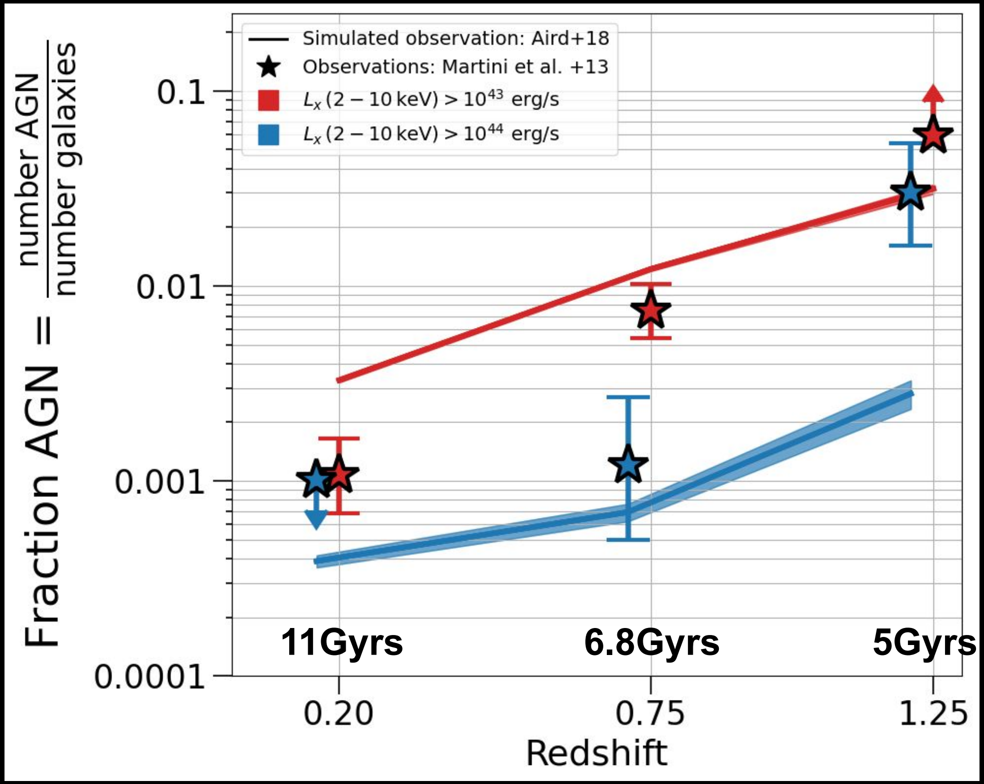
Active supermassive black holes in the most extreme environments



- Massive Clusters of Galaxies, >10^{14} solar
- Galaxy lifecycle in such dense environments is very different:
  - ram pressure
  - strangulation
  - harassment
- Is black-hole growth also affected?

Active supermassive black holes in the most extreme environments

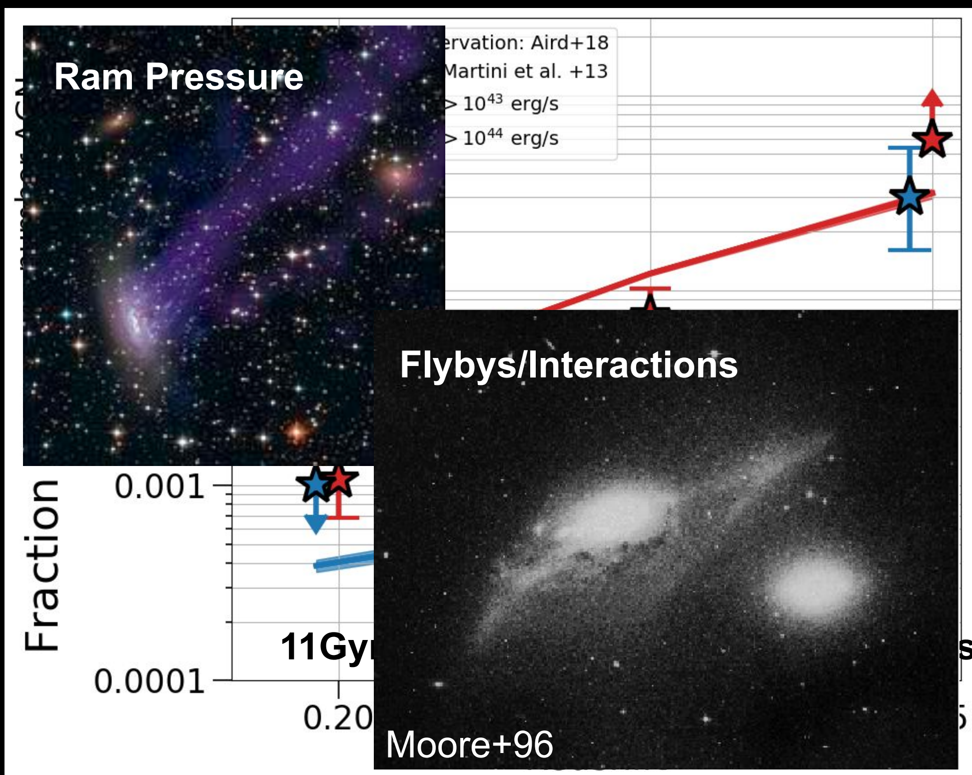
Muñoz Rodríguez, AG, et al., 2022



- Fraction of AGN in massive clusters as a function of cosmic time
- Model AGN in the Universe assuming no environmental dependence: Fails to reproduce the observations
- Massive Clusters of Galaxies at earlier times promote black-hole growth:
  - ram pressure at infall
  - interactions during infall

Active supermassive black holes in the most extreme environments

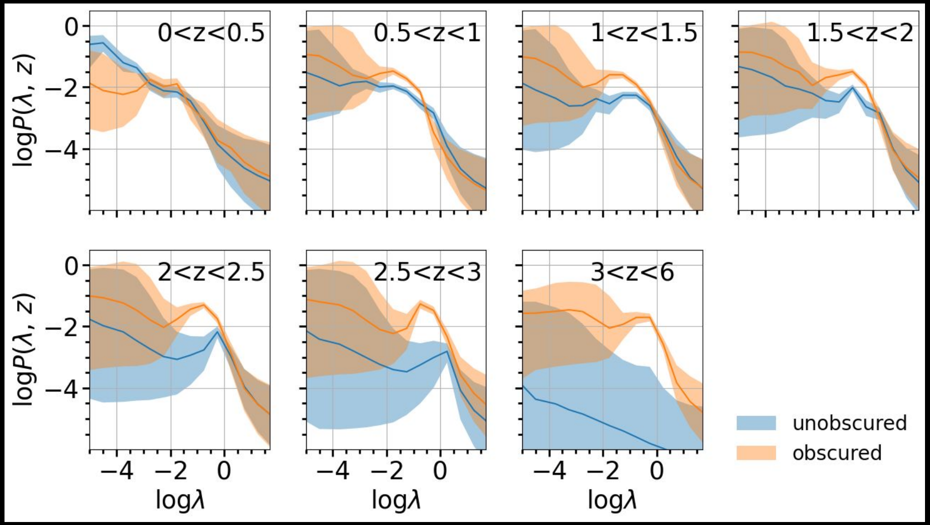
Muñoz Rodríguez, AG, et al., 2022



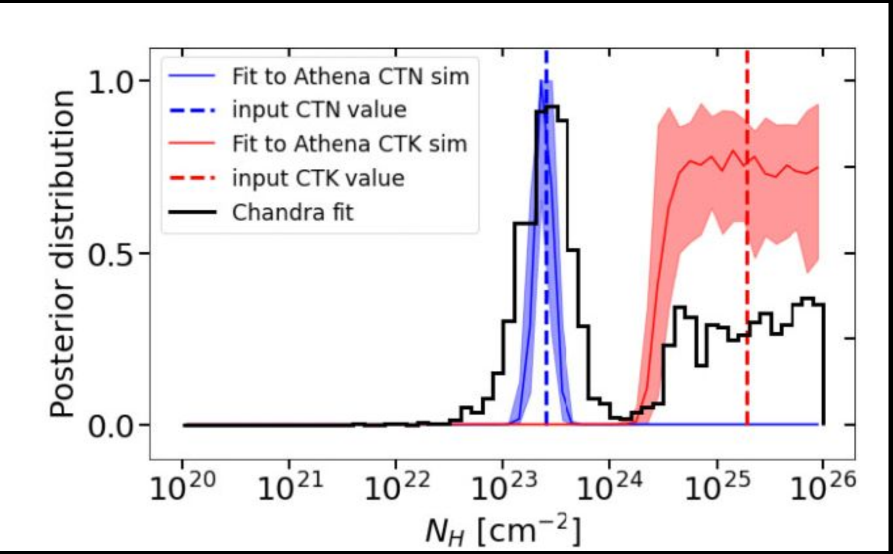
- Fraction of AGN in massive clusters as a function of cosmic time
- Model AGN in the Universe assuming no environmental dependence: Fails to reproduce the observations
- Massive Clusters of Galaxies at earlier times promote black-hole growth:
  - ram pressure at infall (Ricarte+20; Peluso+22)
  - interactions during infall

Outlook for the (new) Athena X-ray observatory

Measure accurate specific accretion rate distributions taking into account obscured AGN: more realistic mocks



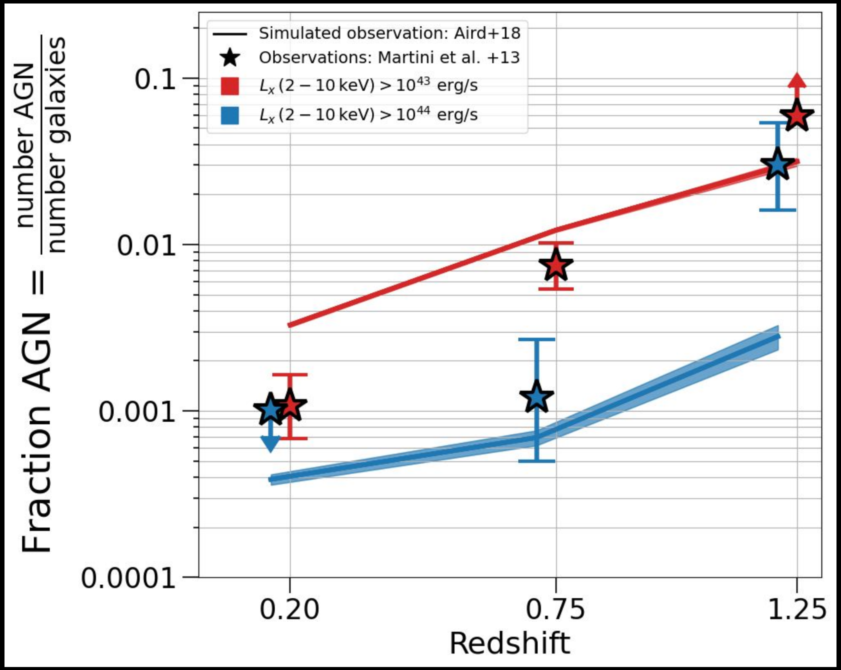
Laloux, AG, et al. in prep: First attempt to characterise the specific accretion-rate distribution of obscured and unobscured AGN to high redshift.

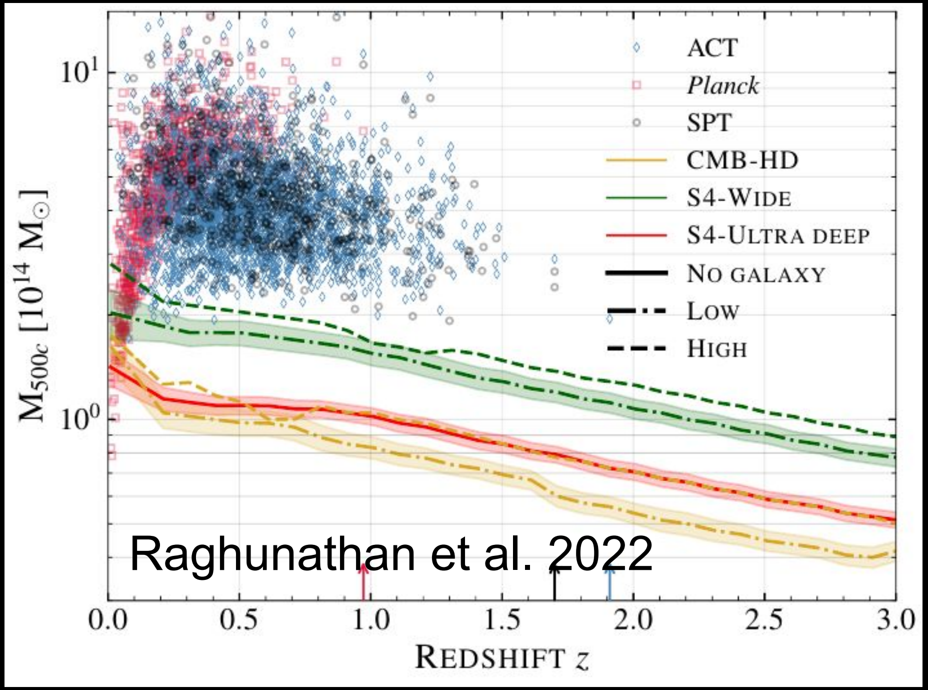


Laloux, AG, et al. 2022: Athena can discover heavily obscured AGN out to high redshift (*z*~3-4).

Outlook for the (new) Athena X-ray observatory

Measure the incidence of AGN in clusters of galaxies to z~1 and beyond.





Cluster/Group catalogues in the 2030s: eROSITA, NewAthena (X-rays), CMB-S4/-HD, AtLAST (SZ)

Summary & conclusions

- Population studies provide information on AGN triggering mechanisms
- Semi-Empirical Forward-Modelling provide a powerful tool for interpreting observations and hypothesis testing:
    - Active black holes are mostly found in low density environments similar to our Local Group
    - Massive Clusters of Galaxies promote black-hole growth at early times. In contrast at present time very dense regions are suppressing AGN.
- The new Athena mission will provide improve semi-empirical AGN models and provide large samples for multi-parametric AGN population studies.