university of groningen / faculty of science and engineering / kapteyn astronomical institute

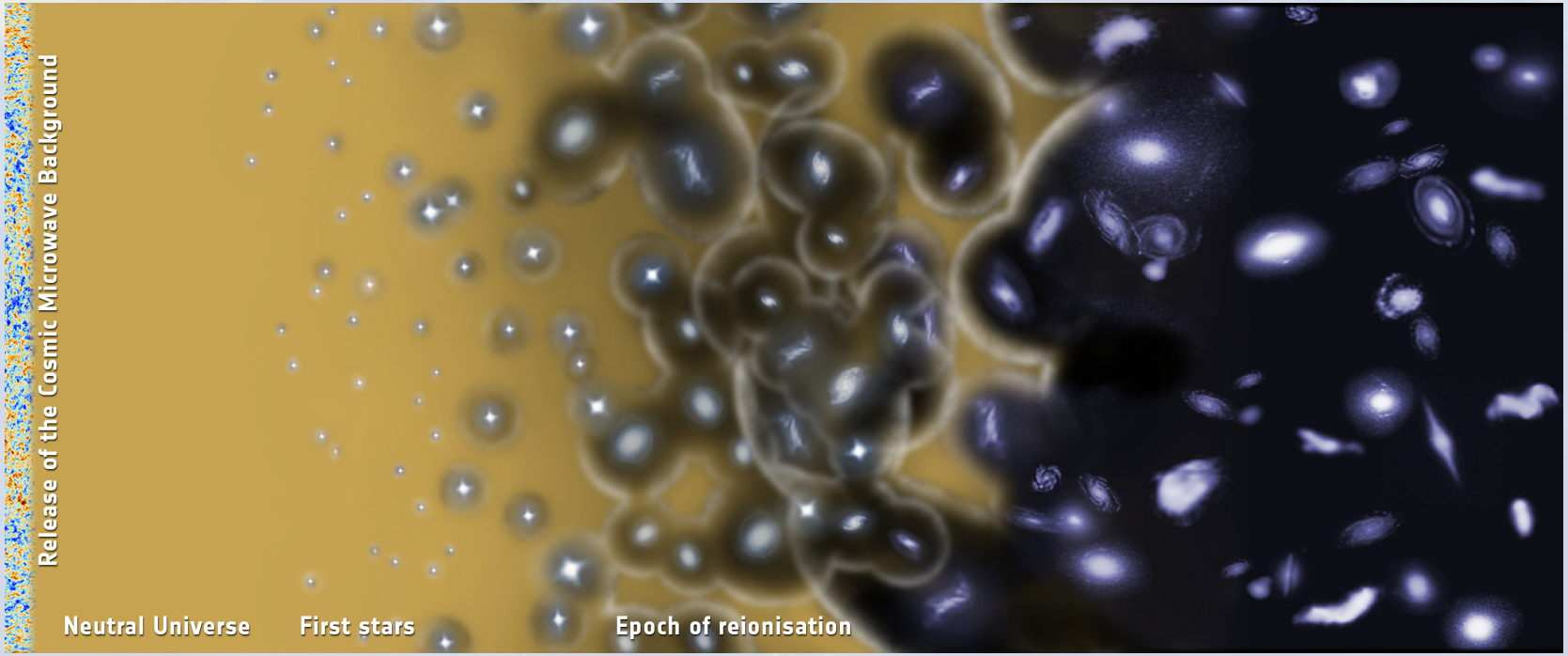
Modelling the contribution of AGN to reionisation

Maxime Trebitsch – Kapteyn Astronomical Institute

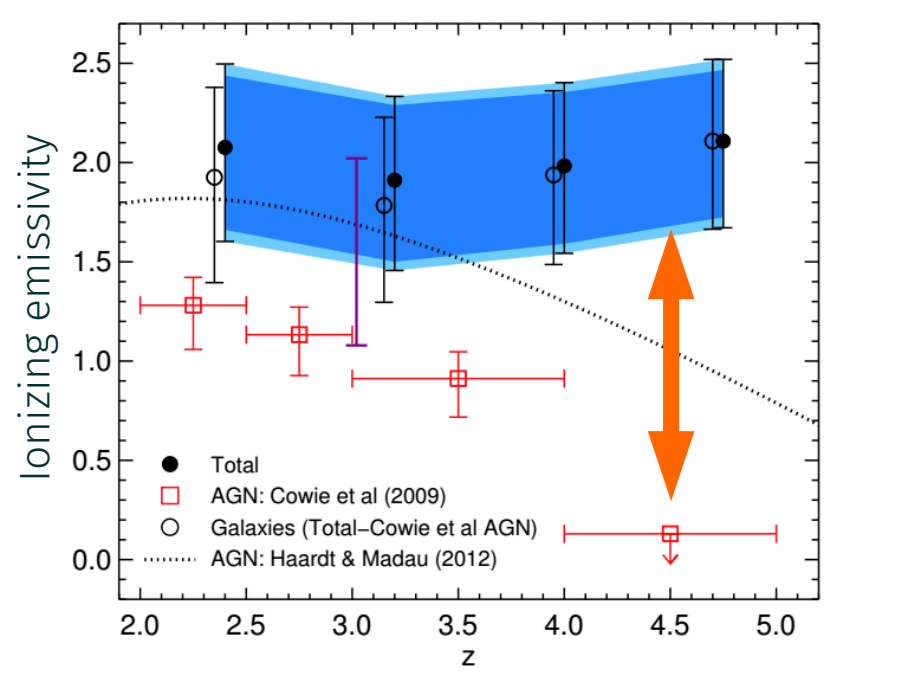
*in collaboration with Y. **Dubois**, M. **Volonteri**, P. **Dayal**, A. **Hutter**, H. Pfister, C. Cadiou, H. Katz, J. Rosdahl, T. Kimm, C. Pichon, R. Beckmann, J. Devriendt and A. Slyz*

April 21st, 2023

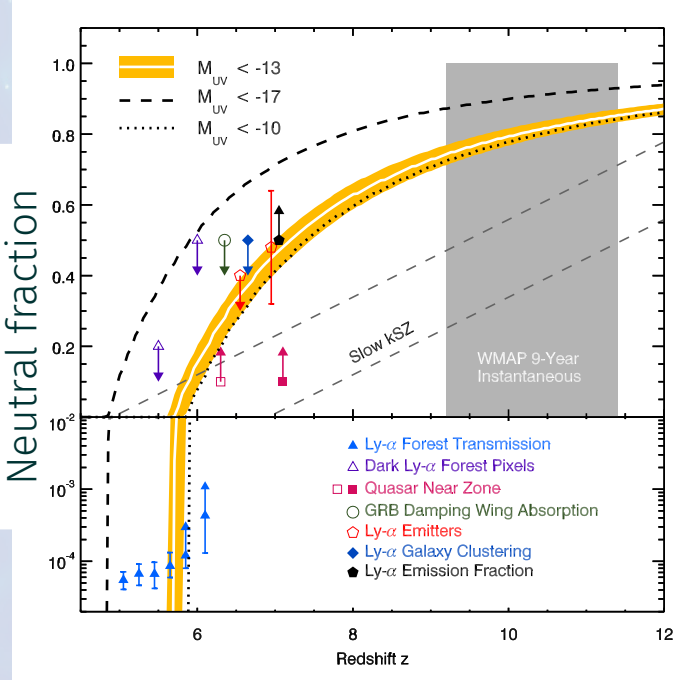
A different view of reionisation



Classical picture: quasars are too rare to contribute significantly



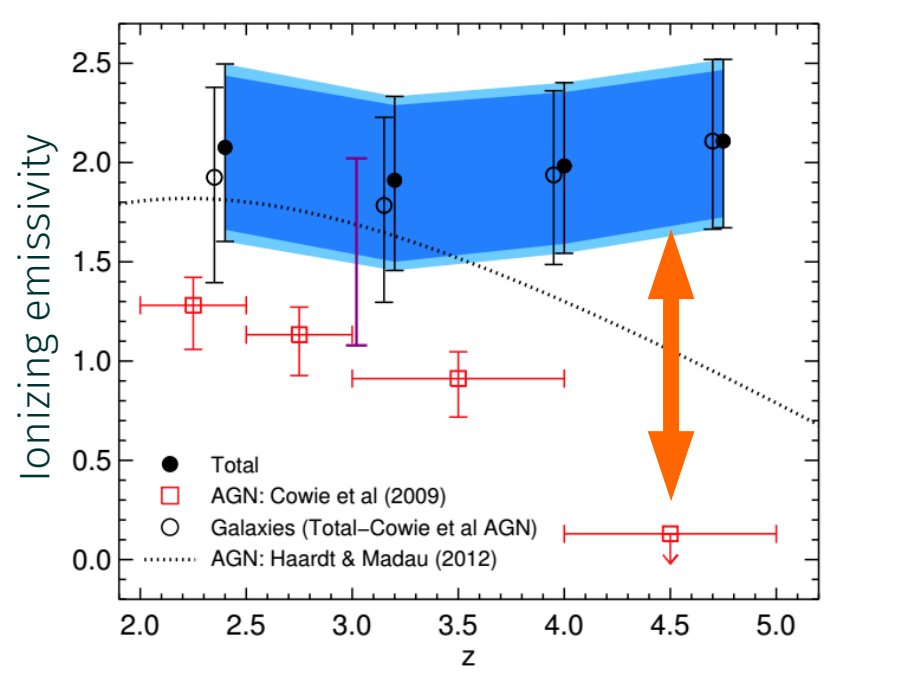
Becker & Bolton 2013



Robertson+2015

- Bright quasars are **too rare** at high-z to reionize the Universe alone
- **Faint galaxies ($M_{UV} \leq 13$) could provide the bulk of the ionizing budget**

Classical picture: quasars are too rare to contribute significantly



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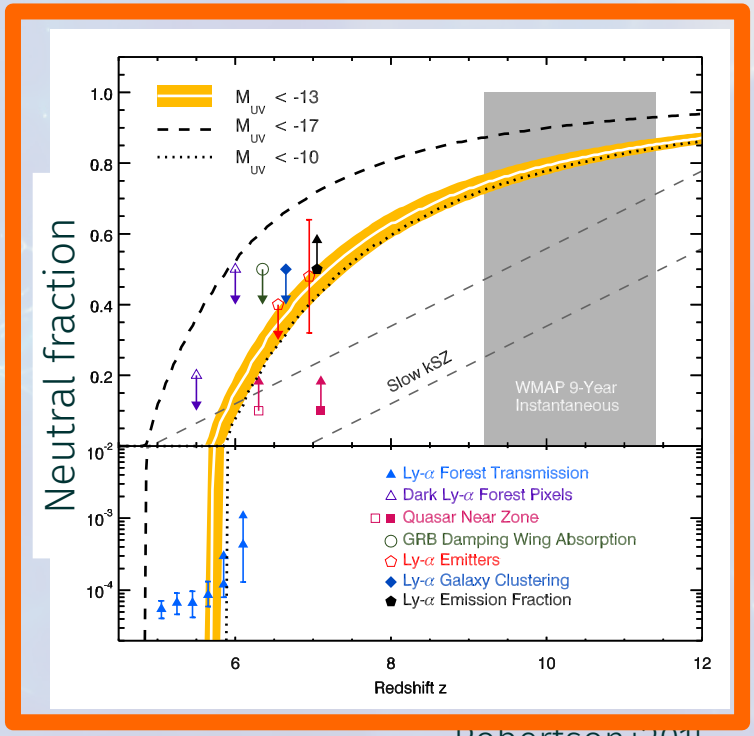

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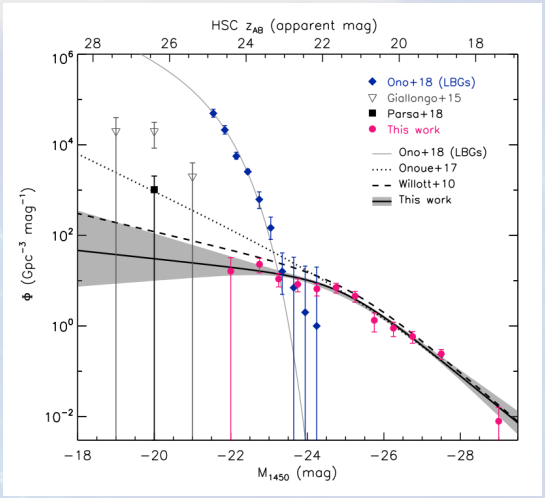
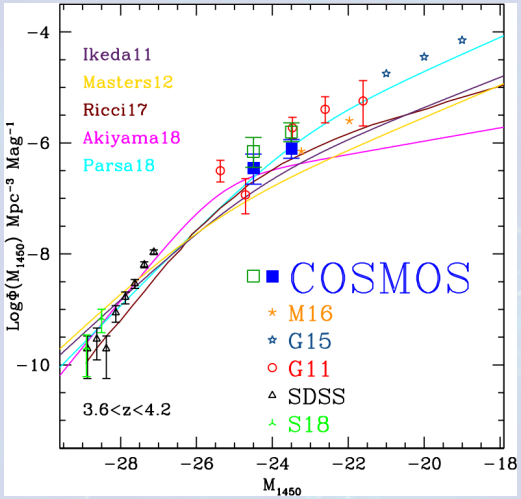
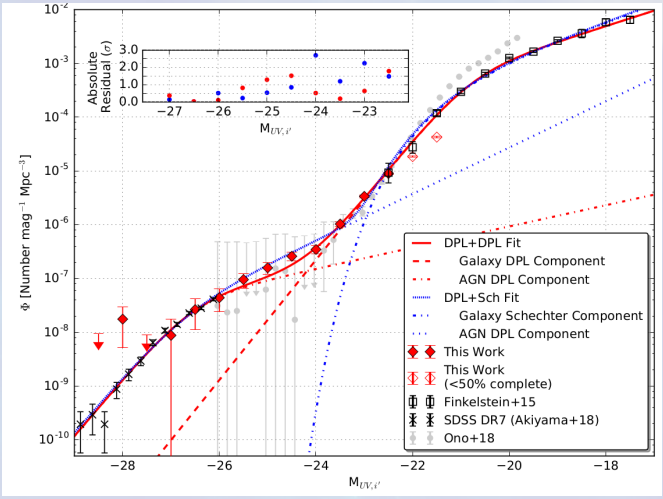
Difficult measurements of the high-z AGN LF

Matsuoka+2018



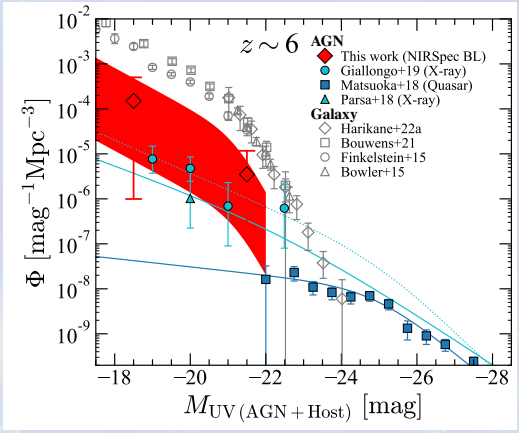


Boutsia+2018

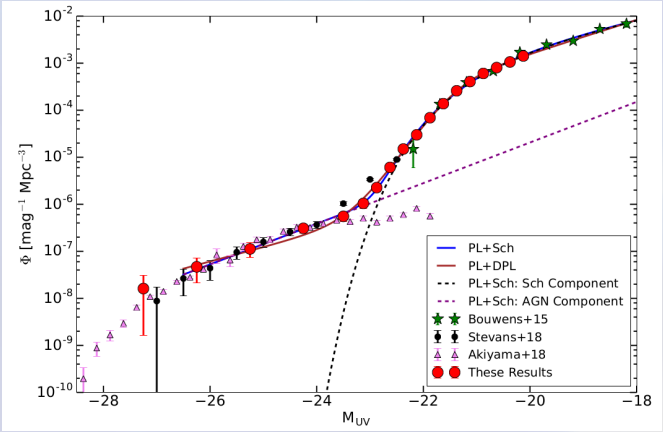


Stevans+2018

Harikane+2023

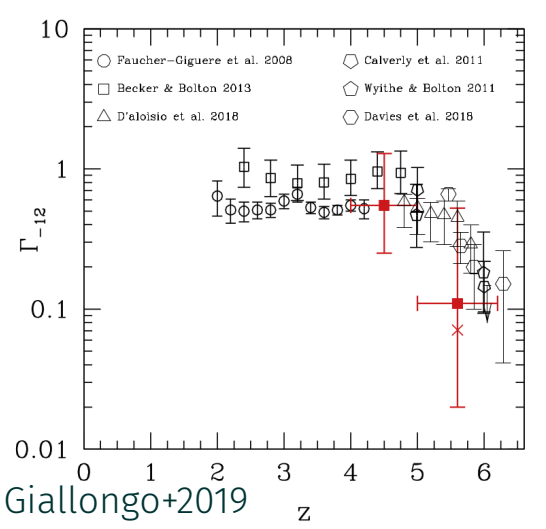


- Large effort to constrain the number of faint AGN
- Difficult to identify AGN and remove the contribution from the host galaxy

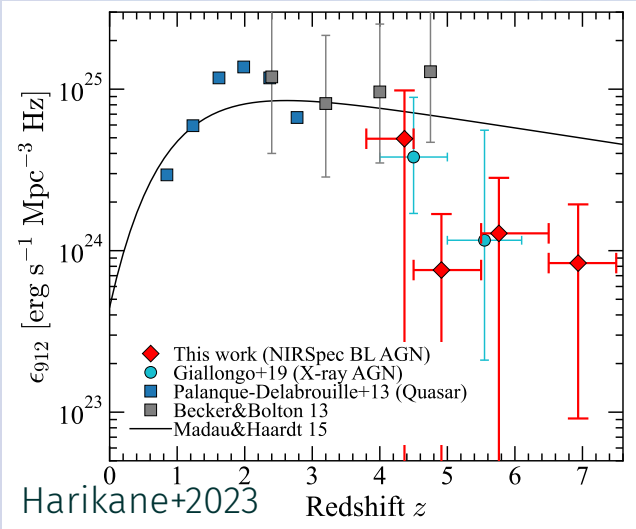


Adams+2019

Uncertainty on the AGN LF = uncertainty on the contribution to the UV background



Giallongo+2019



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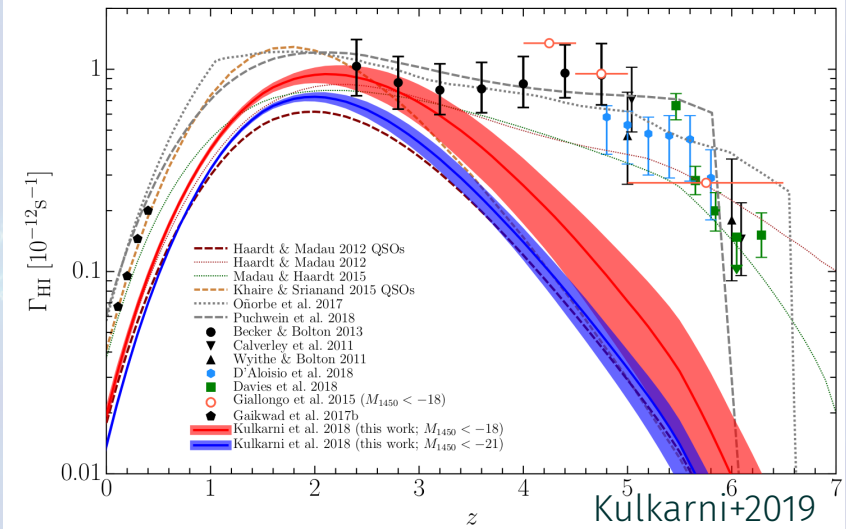


Kulkarni+2019

- Search for high-z faint AGN suggests that they could boost the contribution of AGN to reionization up to ~ 30%
- **But** this assumes a high f_{esc} for the AGN, and little contribution from the host galaxy

Simulating reionization

“Wishlist” for the ideal simulation

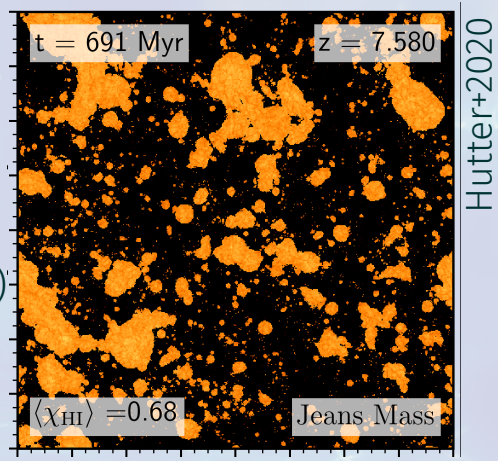
- *High-resolution*: we want to resolve the structure of the ISM
- *Radiation-hydrodynamics*: we want to follow the radiation self-consistently
- *Large cosmological volume*: we want to capture rare objects + the IGM

Problem: this is way too expensive

→ choose one (or two) of these...

Simulating reionization

- Post-processing a large cosmological volume (hydro or DM-only)
  - This is good to study the **reionization process** itself and test assumption on the sources, but says very little about the galaxies
  - Only way to access >> 100 Mpc scales so far (eg for **21-cm science**)



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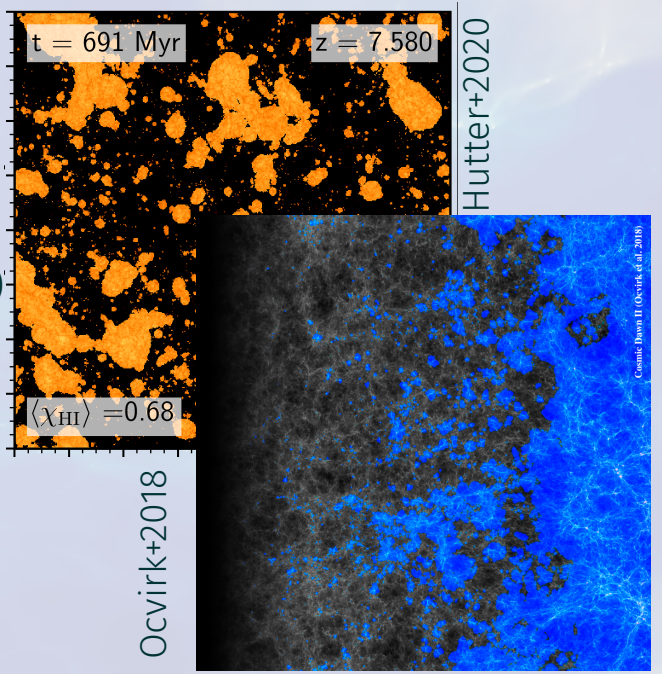
  - Good to study the **gas response to reionization**, but requires calibrating the sources
  - Eg: CoDa, CROC, Technicolor, AURORA, THESAN



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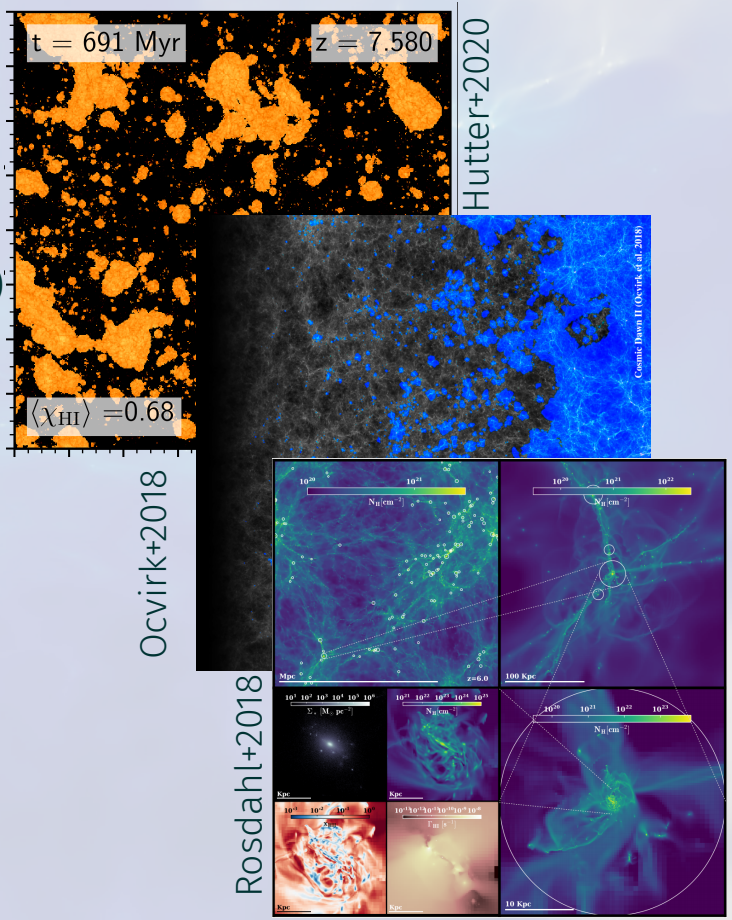
  - Can access the emissivity of galaxies and **study the sources**, but harder to generalize (because size or environment)
  - Eg: SPHINX, Renaissance, Obelisk



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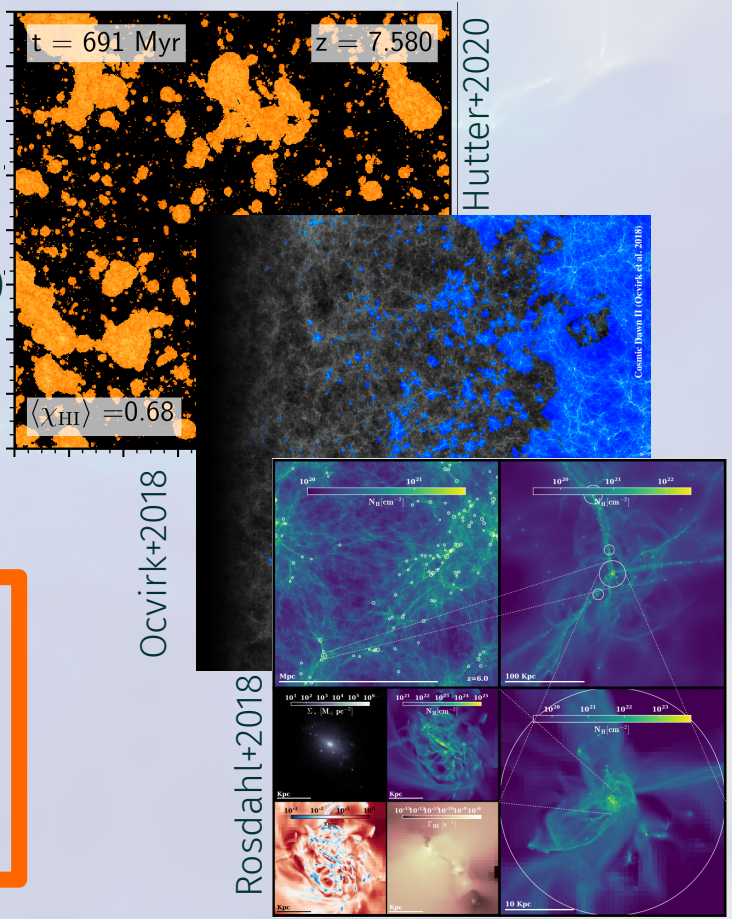
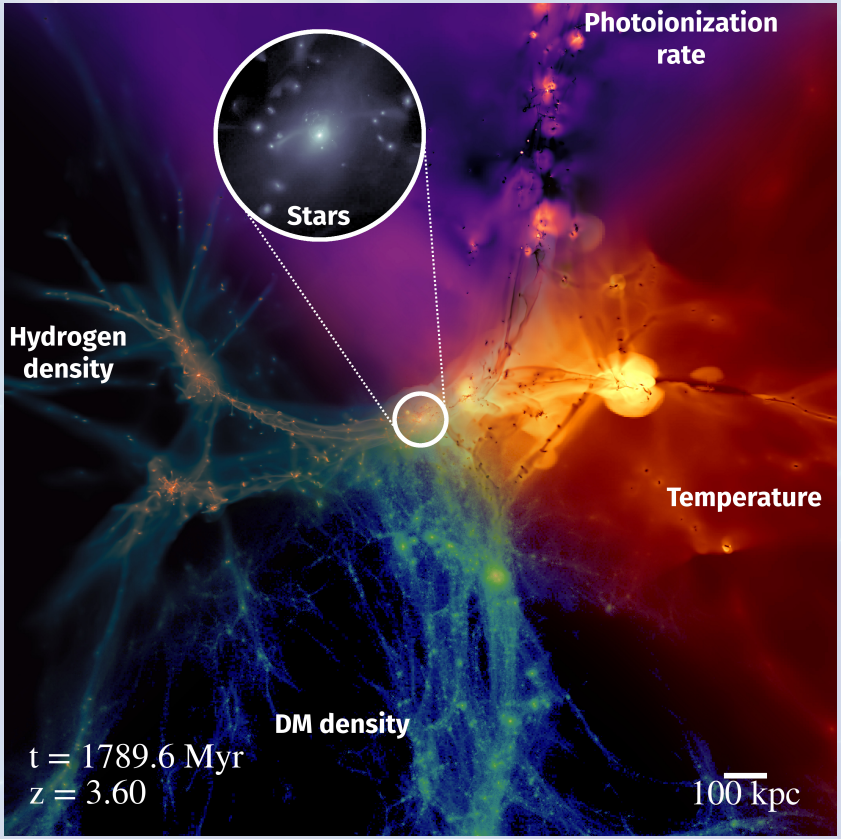


Introducing *Obelisk*: zooming on a proto-cluster environment



- Zoom on a **proto-cluster** region (V ~ 10^4 cMpc^3), currently at z~3.5
- **RHD simulation** with Variable Speed of Light Approximation
- **High resolution**
  - Δx = 35 pc
  - $M_{DM} = 10^6\ M_\odot$
  - Snapshots every 15 Myr
- Stellar physics
  - Turbulent star formation
  - Mechanical SN feedback
  - BPASS model for radiation
- Black-hole physics
  - Eddington-limited Bondi accretion
  - Thermal + jet AGN feedback
  - Spin evolution of the BH
  - Radiation following the BH properties
- **Traces source of radiation (stars or AGN)**
- Twin simulation: hydro, but with tracer particles
- Subgrid model for dust (purely passive)

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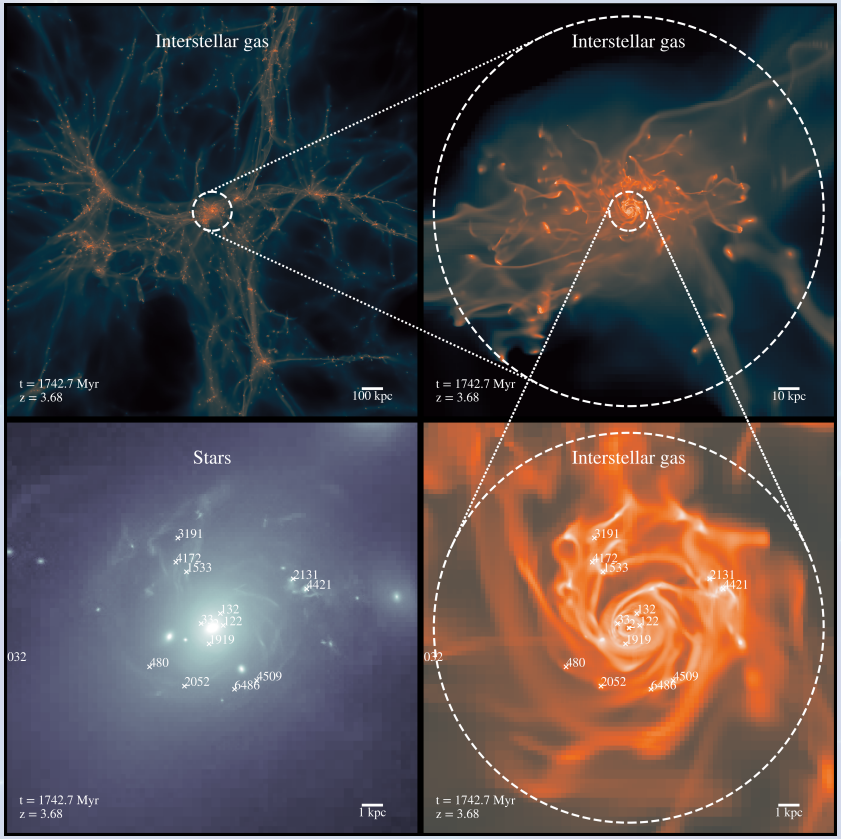

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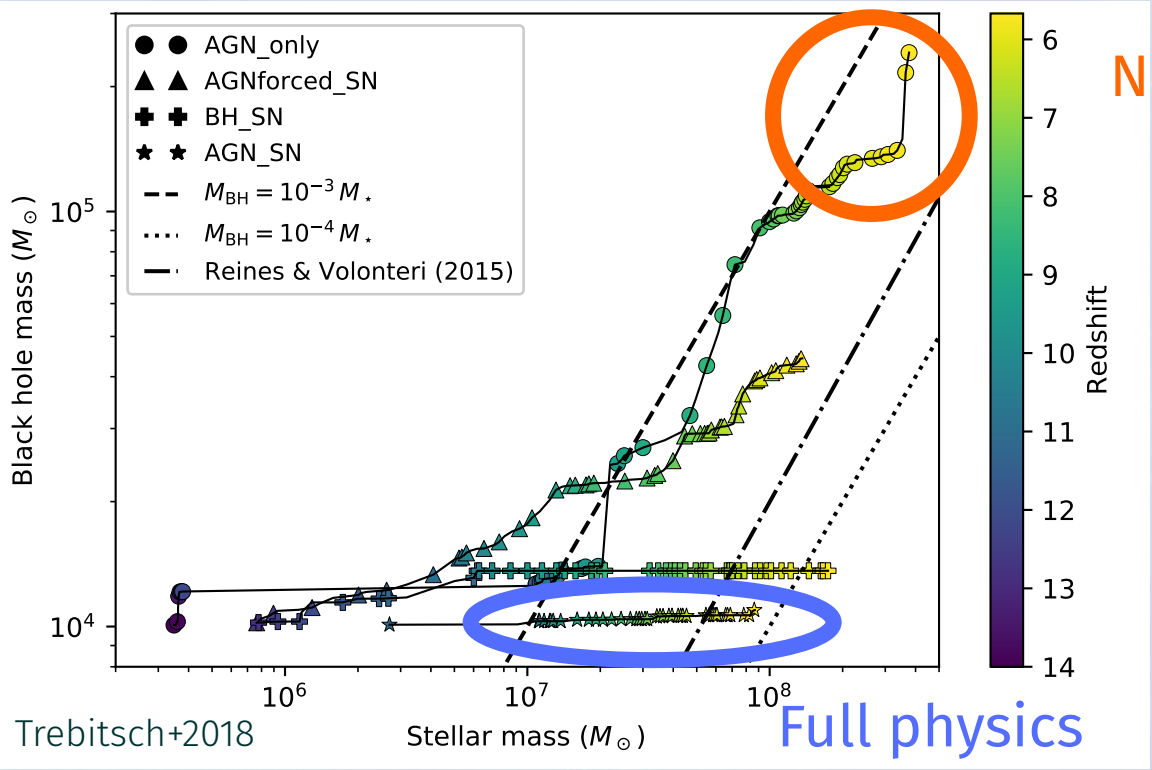
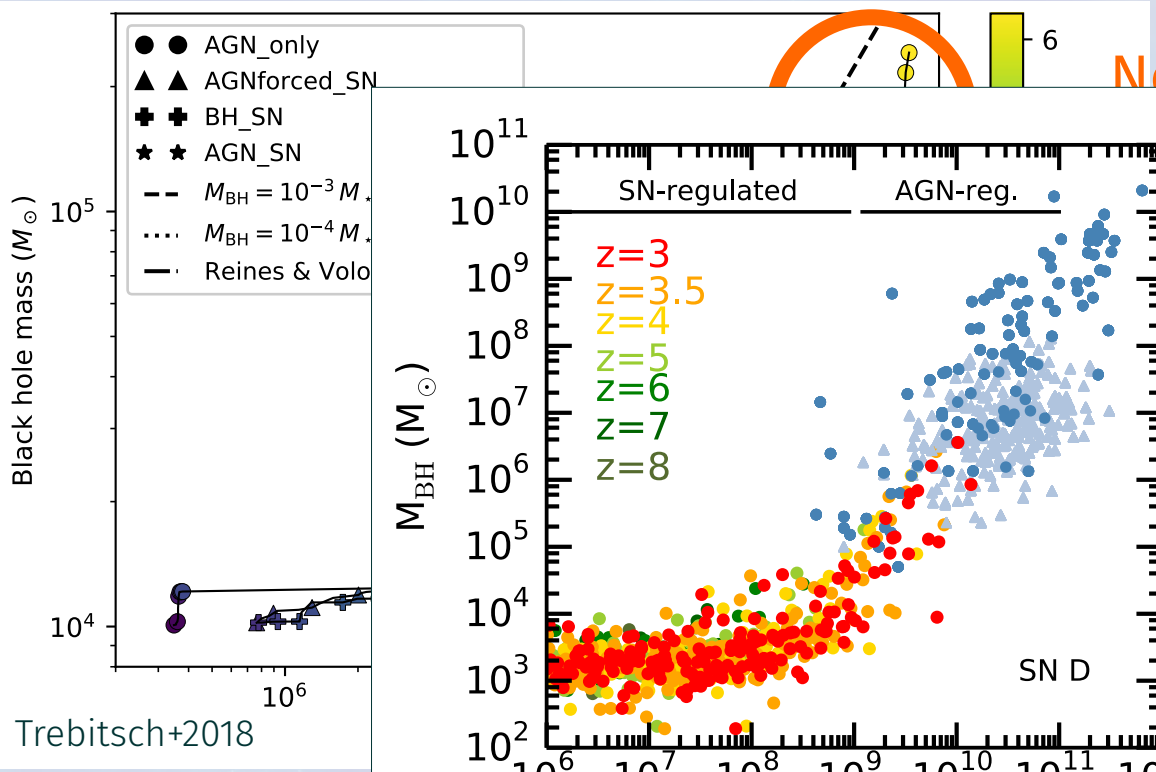
Major challenge: modelling SMBH growth

Growing BH in low-mass galaxies



SN feedback prevents BH growth in low mass galaxies

Growing BH in low-mass galaxies

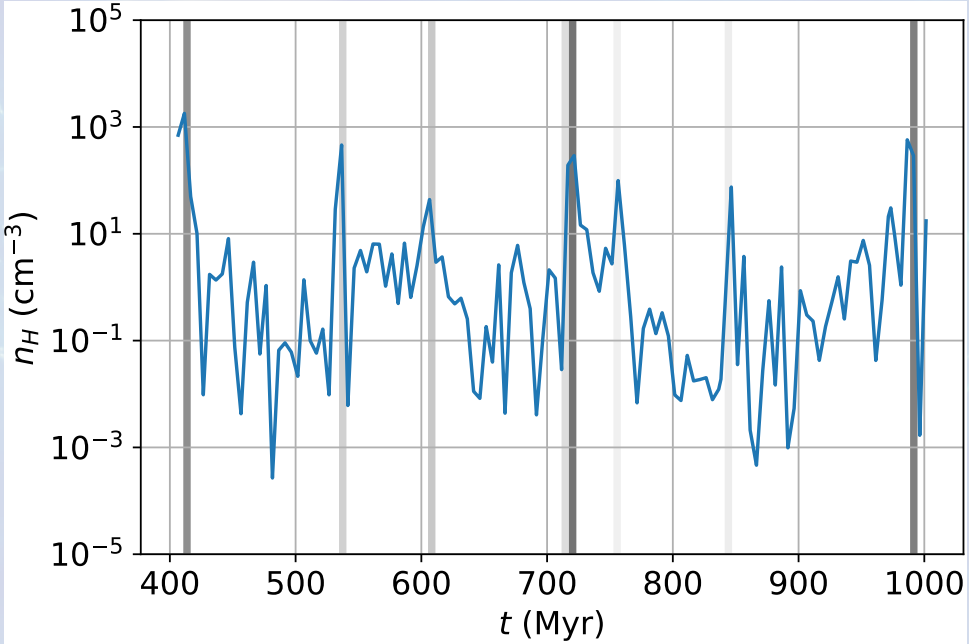


No supernova

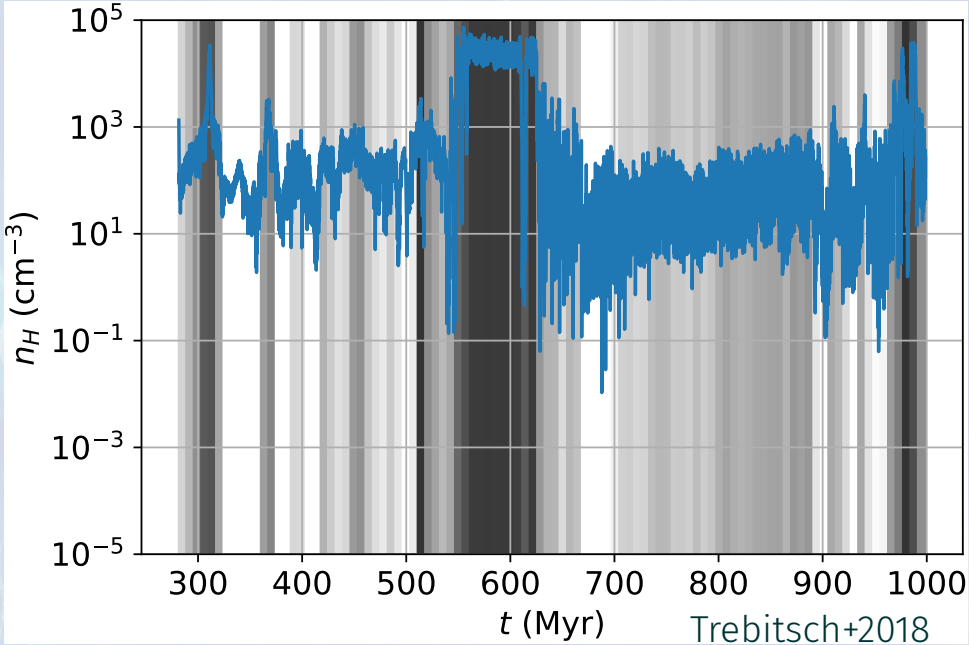
SN feedback prevents BH growth in low mass galaxies

Growing BH in low-mass galaxies: feeding

SN feedback = low density



No supernovae = high density



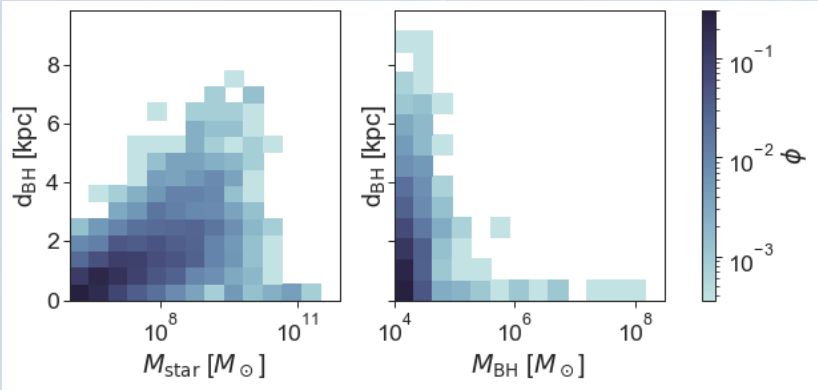
SN feedback prevents BH growth in high-z dwarf galaxies

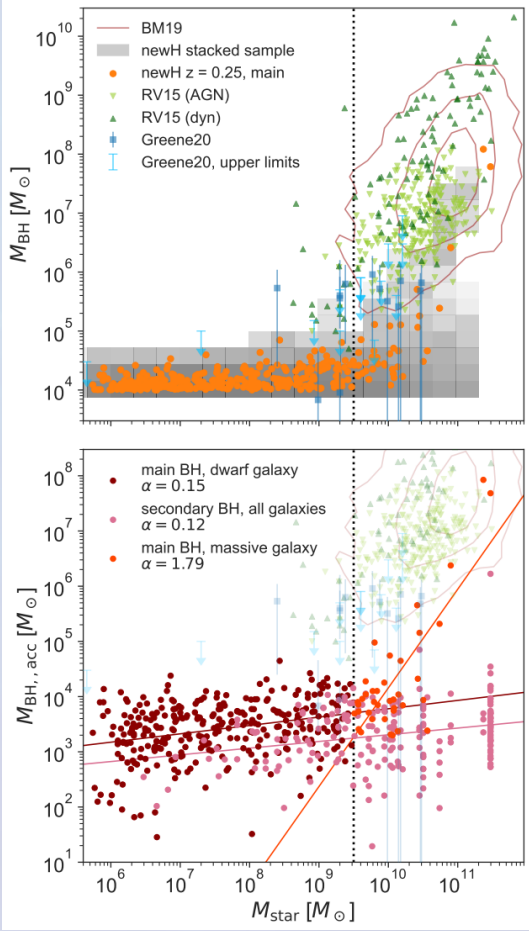
(Although see e.g. Koudmani+2022)

Growing BH in low-mass galaxies: dynamics

- Low-mass galaxies have a shallow potential well
- Recent simulations attempt to track the dynamics of SMBH, but this is a hard problem
- When done right, it seems that low-mass galaxies can have wandering SMBH…

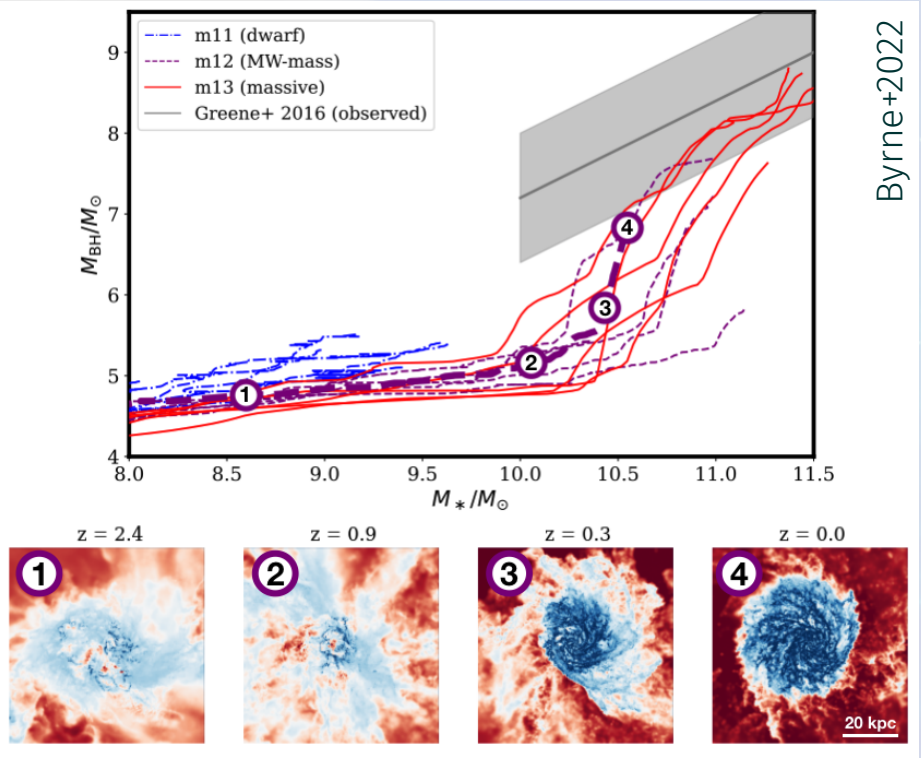
(see also: Bellovary+2021, Sharma+2022)

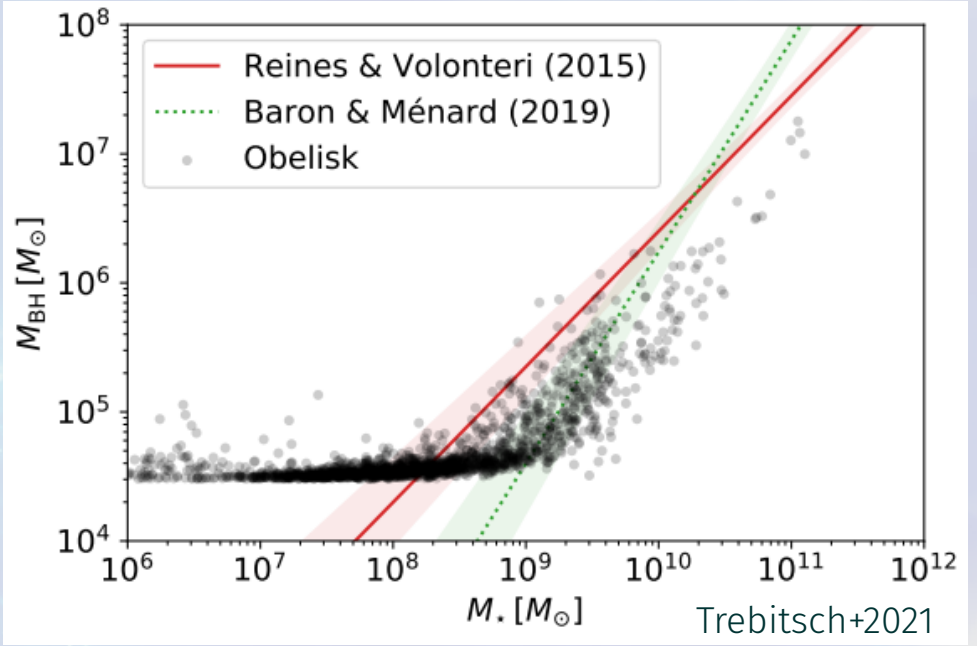




Beckmann, …, MT+2022

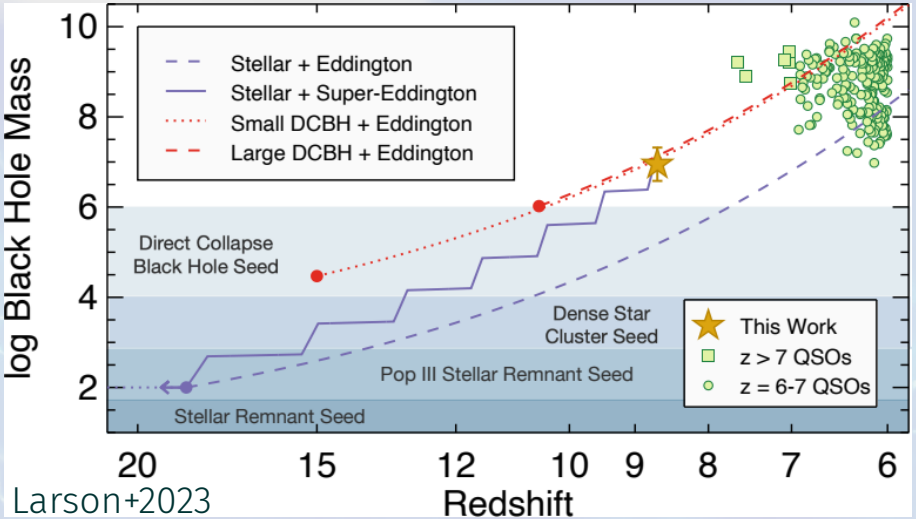
Growing BH in low-mass galaxies: critical mass





- Above a critical mass, SMBH grow much more efficiently
- This mass is uncertain, but around log(Mstar) ~ 9.5 - 10.5

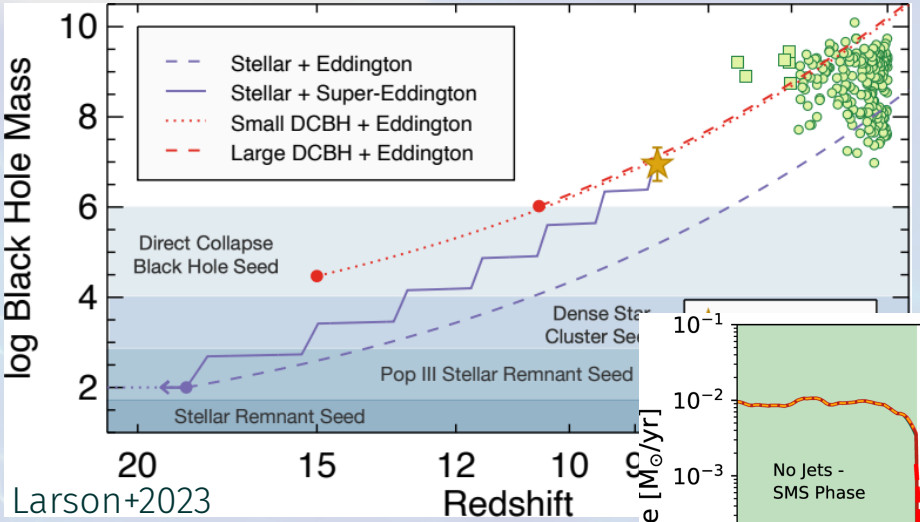
Super-Eddington growth? Probably not the universal solution



Larson+2023

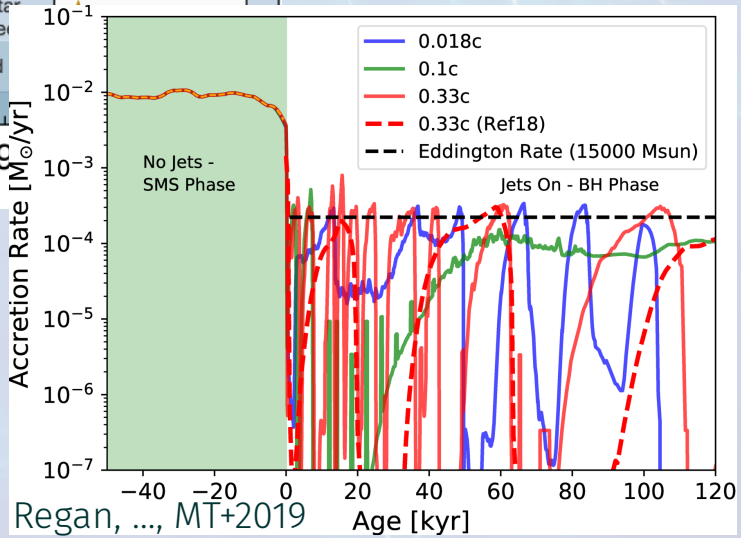
- Super-Eddington accretion has been suggested to boost SMBH growth

Super-Eddington growth? Probably not the universal solution

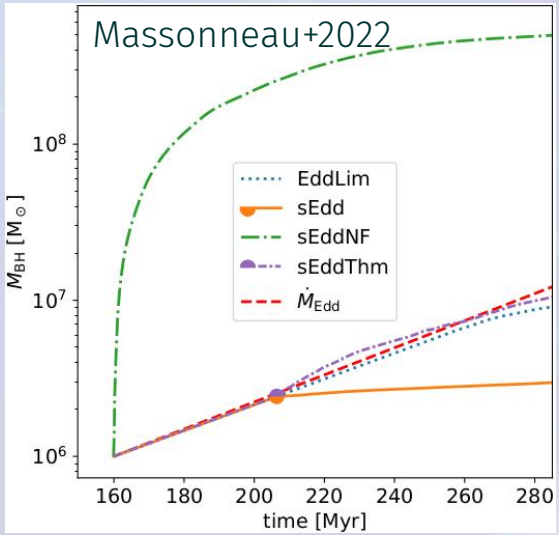


Larson+2023

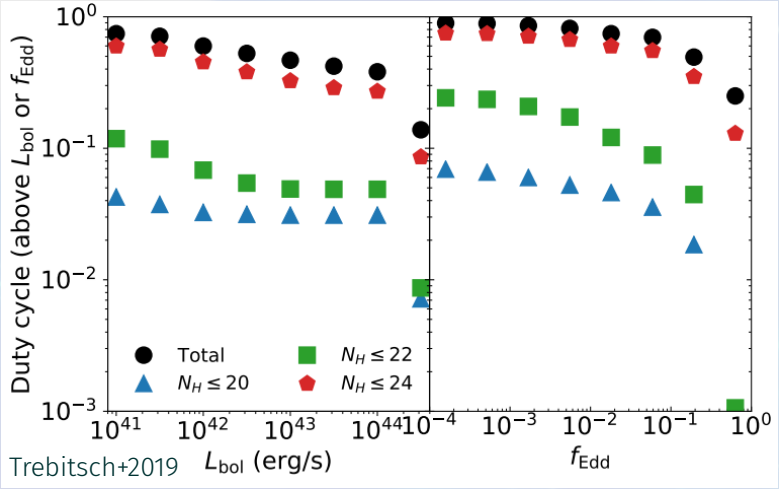
- Super-Eddington accretion has been suggested to boost SMBH growth
- However, models including AGN feedback are severely Eddington limited



Regan, ..., MT+2019

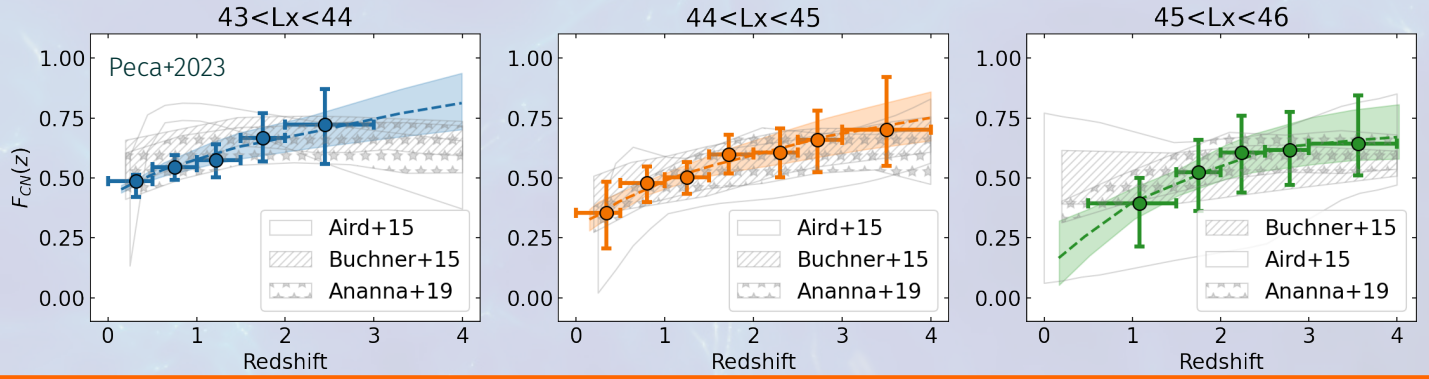


Side issue: how obscured are these AGN?



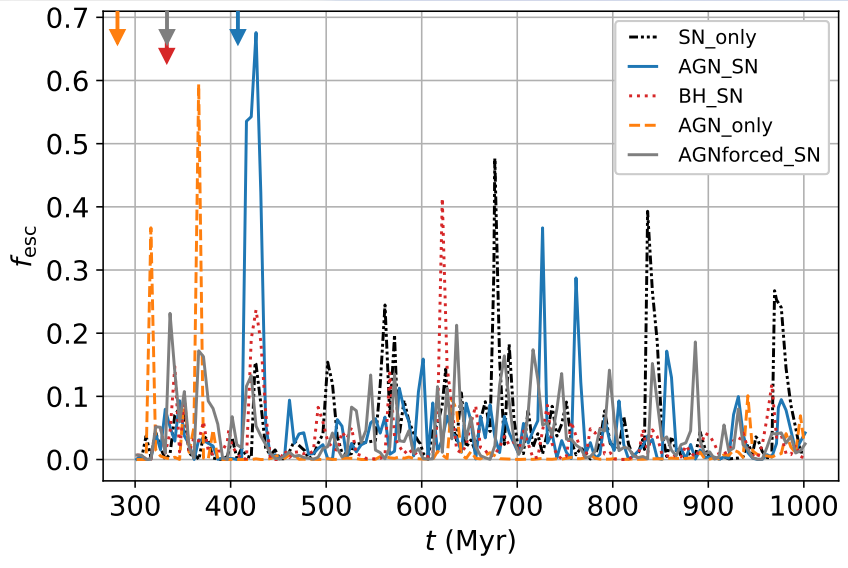
Trebitsch+2019

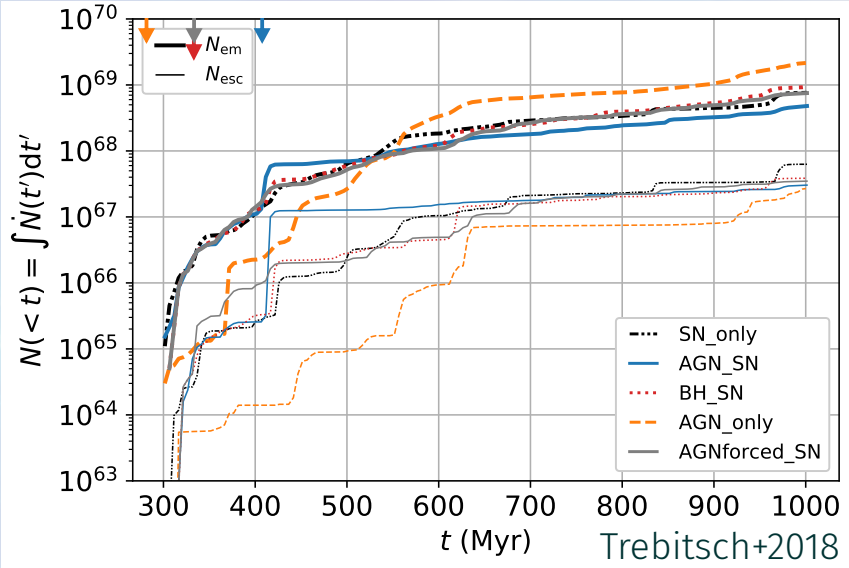
- Simulation find a lot of obscured growth
  - → growing BH requires gas
  - → gas will obscure the AGN
  - → LyC radiation will not escape
- Observations do find that high-z AGN are highly obscured…
  (e.g. Vito+2018, Vijarnwannaluk+2022, Peca+2023, Yang+2023)



What does this mean for the sources of reionisation?

Escape of ionising photons from a high-z dwarf galaxy

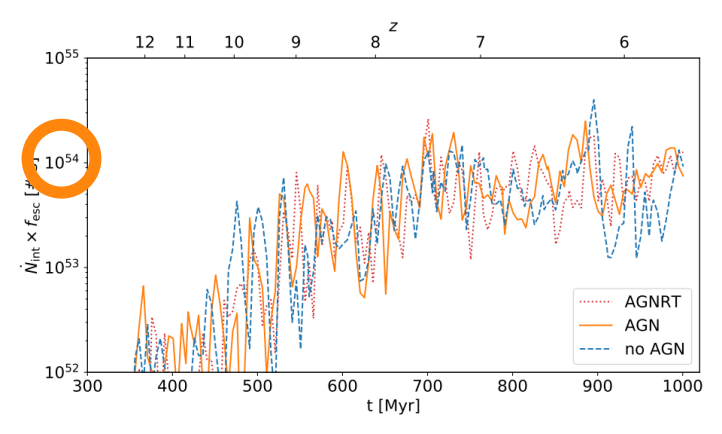


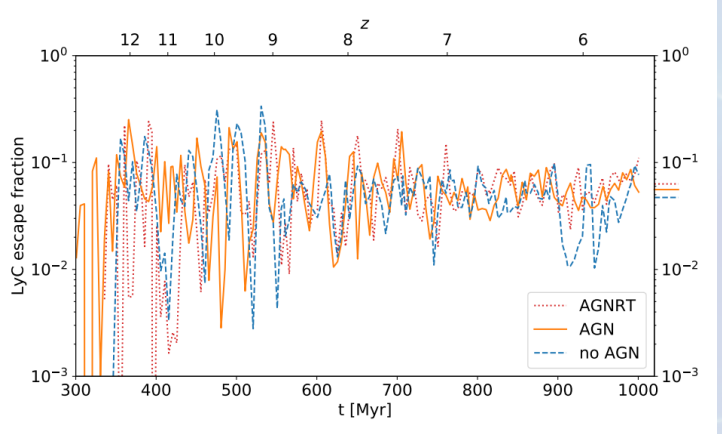


- AGN feedback in dwarf galaxies does not change how much radiation escapes
- It does not change the galactic ionising luminosity either
- However, the absence of SN feedback strongly decreases the escape fraction

Faint AGN in a bright galaxy: ionising photons

Stellar ionising radiation

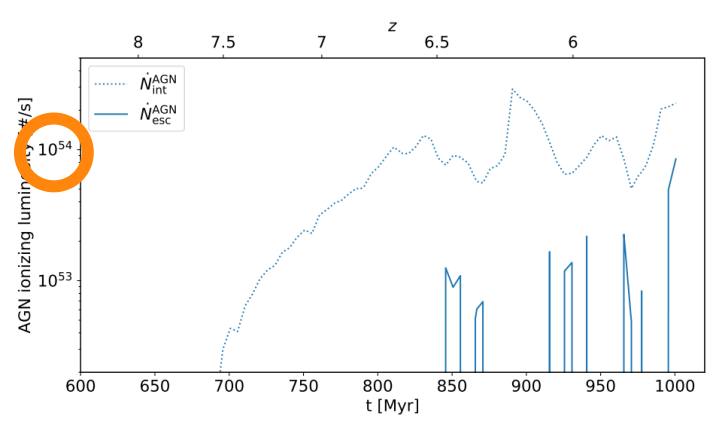




Trebitsch+2020

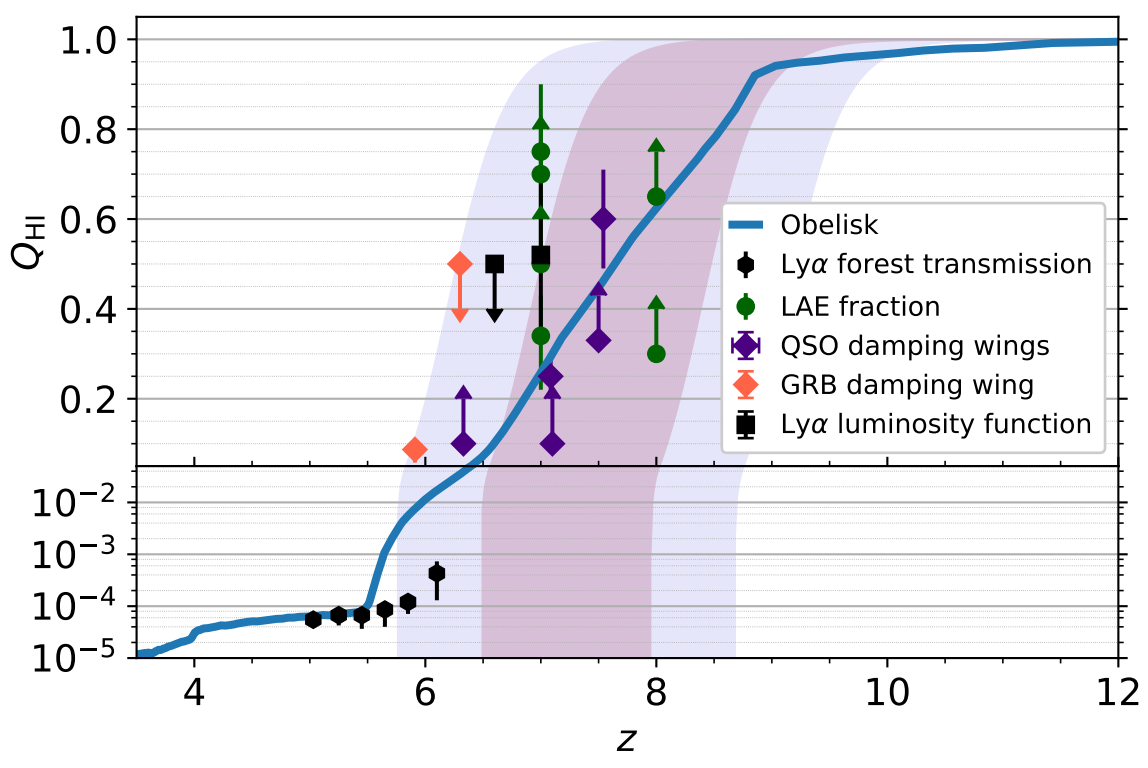
Stellar escape fraction

AGN ionising radiation



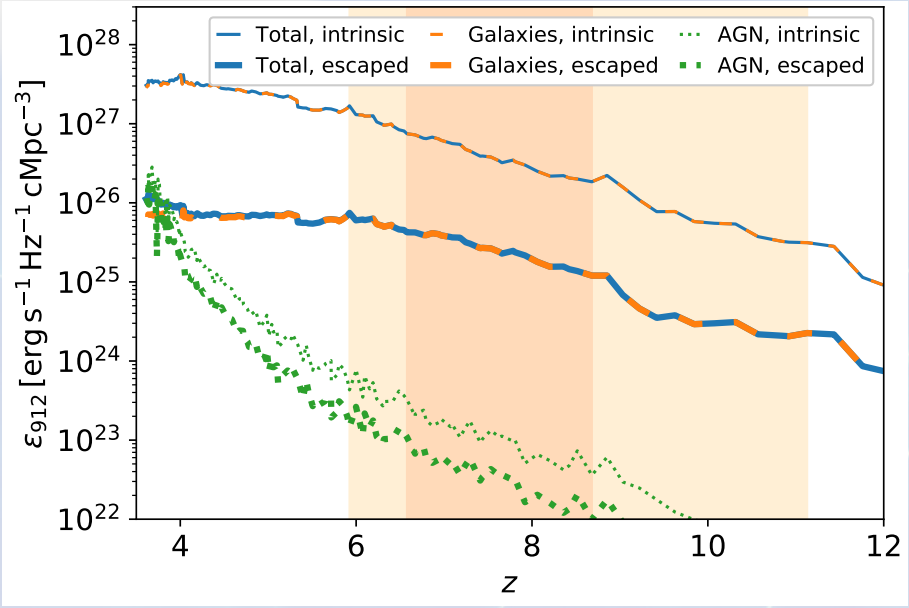
- The stars contribute many more ionising photons than the AGN
- On average, f_{esc} ~ 5-8 % for that galaxy
- This is insensitive to the details of the AGN feedback

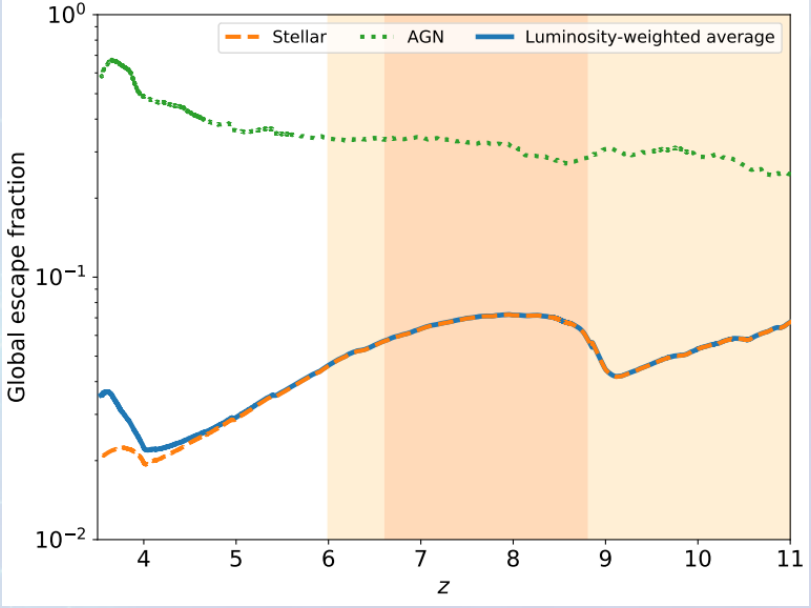
Reionization history of the *Obelisk* volume



- Overall, the reionization history matches observational constraints
- The post-reionization neutral fraction is reasonably well recovered
- We should not expect a perfect match: *Obelisk* is a biased environment

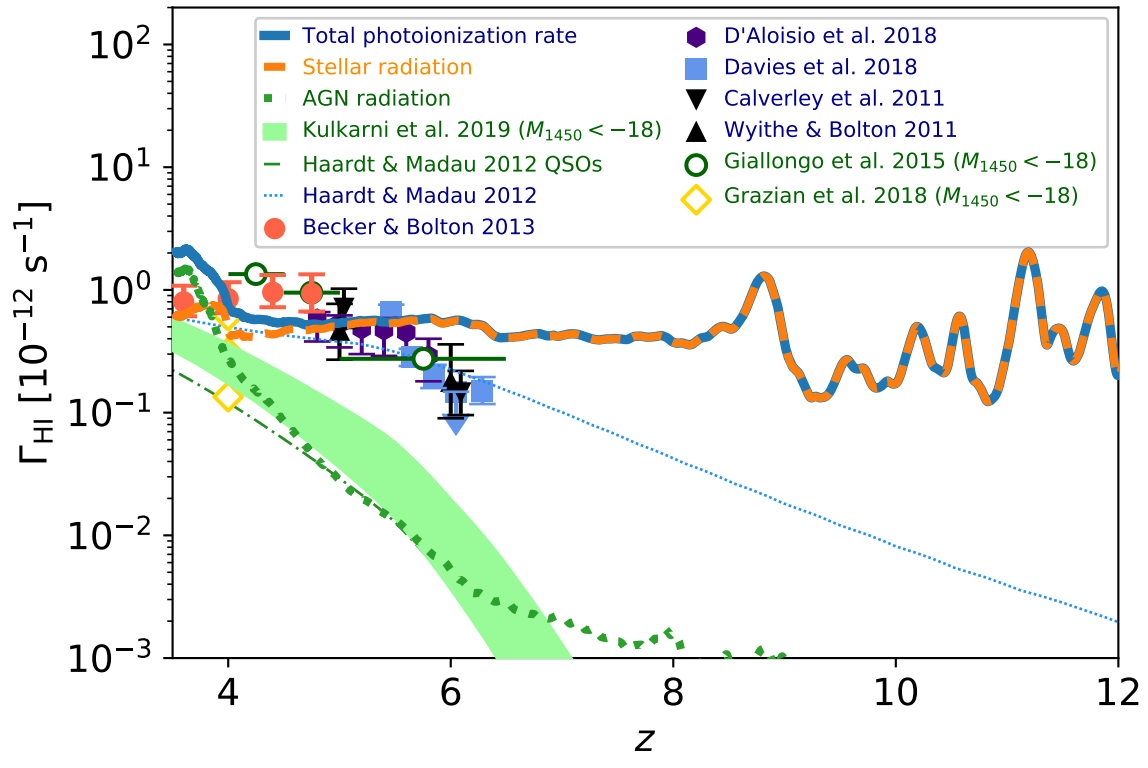
In *Obelisk*, galaxies are responsible for reionisation





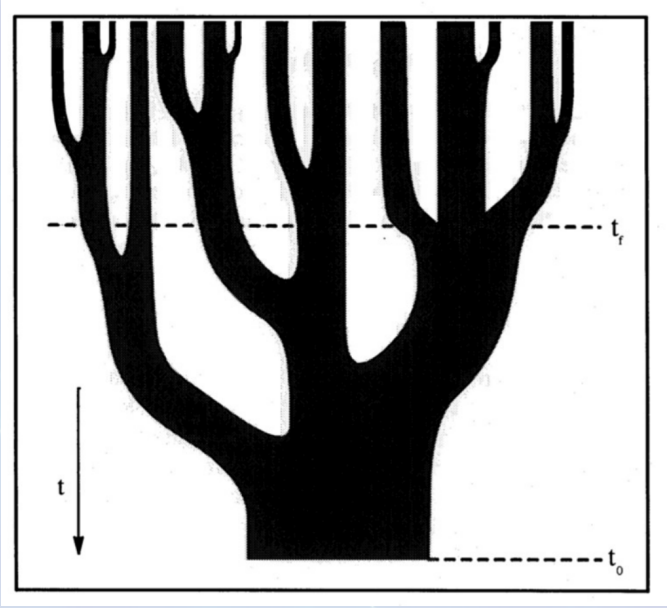
- The ionising emissivity is largely dominated by stellar populations at $z > 4$
- Overall, radiation escapes easily from bright AGN, but they are not numerous enough

Ionizing UV background in the *Obelisk* volume

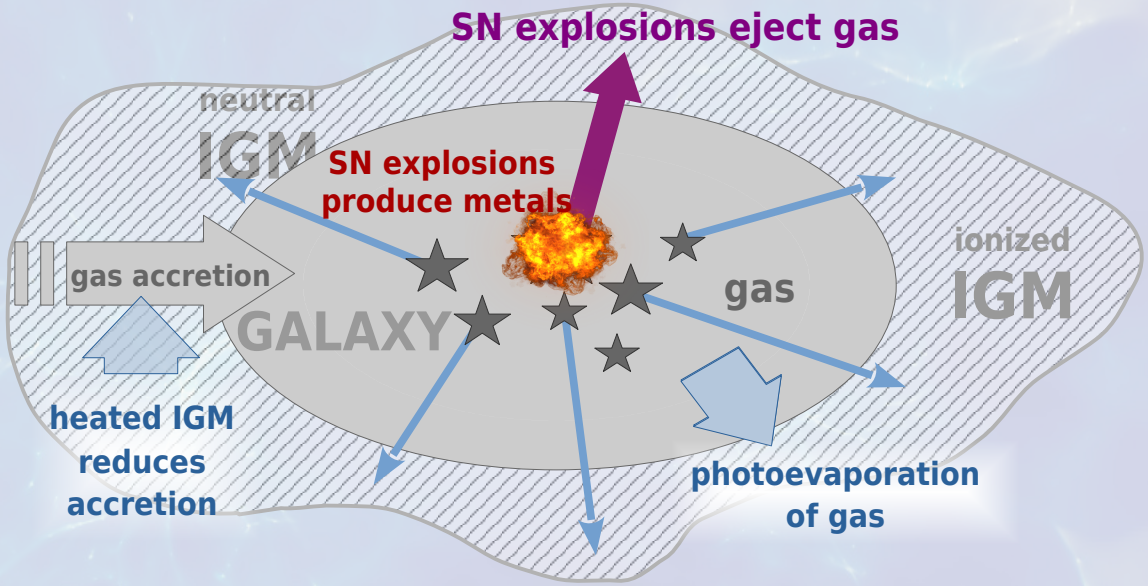


- We get sensible values for the total HI photoionisation rate
- During the Reionisation era, stellar populations completely dominate the ionising UV background
- At $z \leq 5$, AGN start to take over and ultimately dominate

Semi-analytical reionisation models



Lacey & Cole 1993

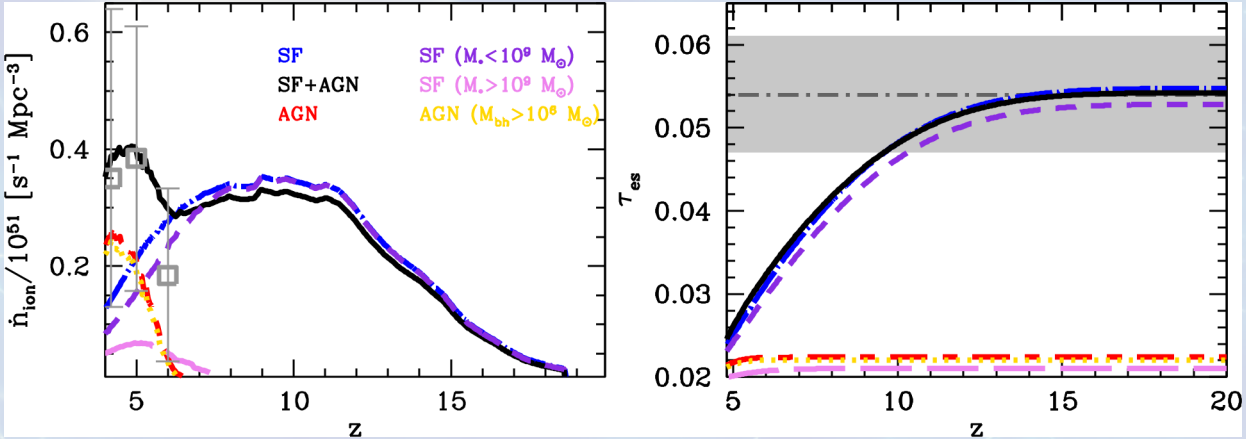


A. Hutter

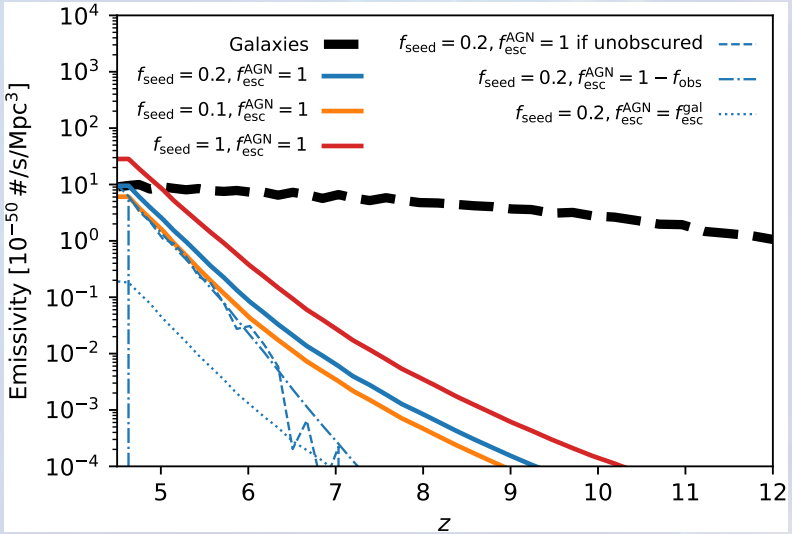
Semi-analytical approach: DM merger tree + galaxy evolution + reionization model

→ Delphi (Dayal+2014), Astraeus (Hutter+2020)

Semi-analytical reionisation models



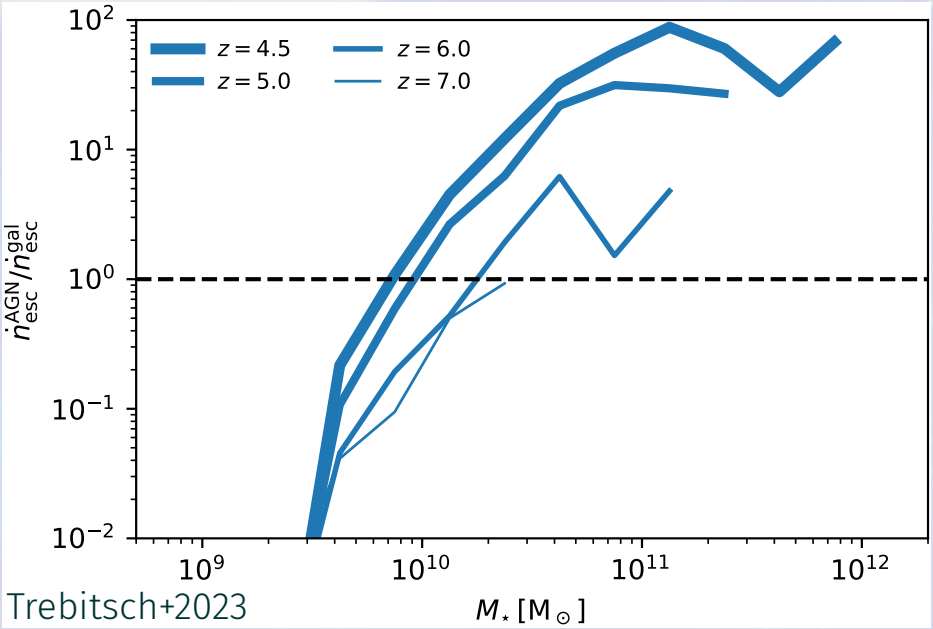
Dayal, ..., MT+2020

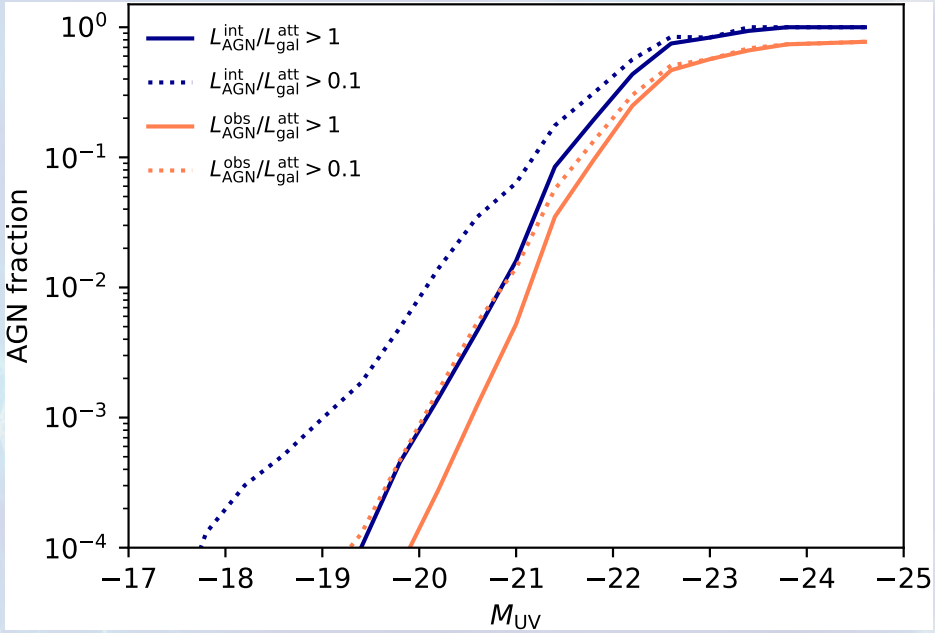


Trebitsch+2023

- Semi-analytical models make it easy to explore the model space
- More idealised, but also more direct way to test trends
- All explored models lead to a **subdominant contribution of AGN to reionization**

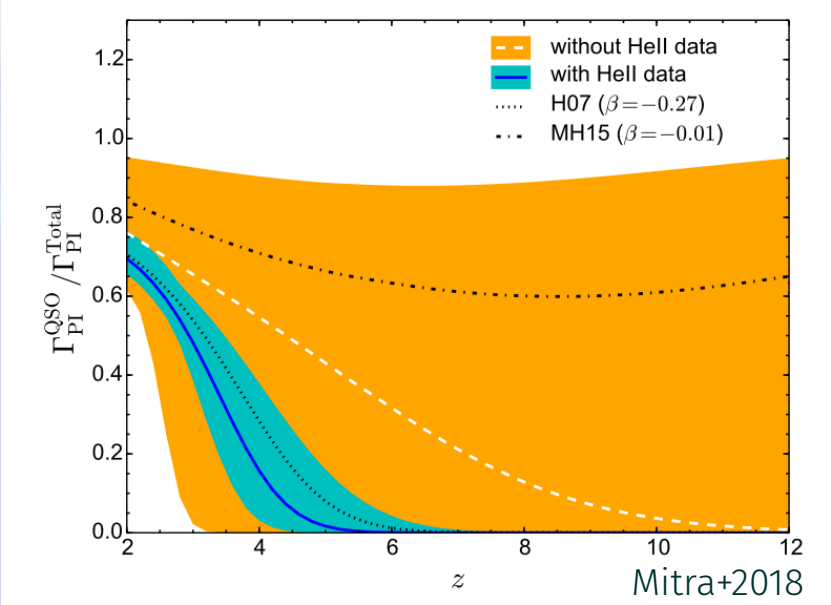
AGN vs galaxy luminosities in Astraeus

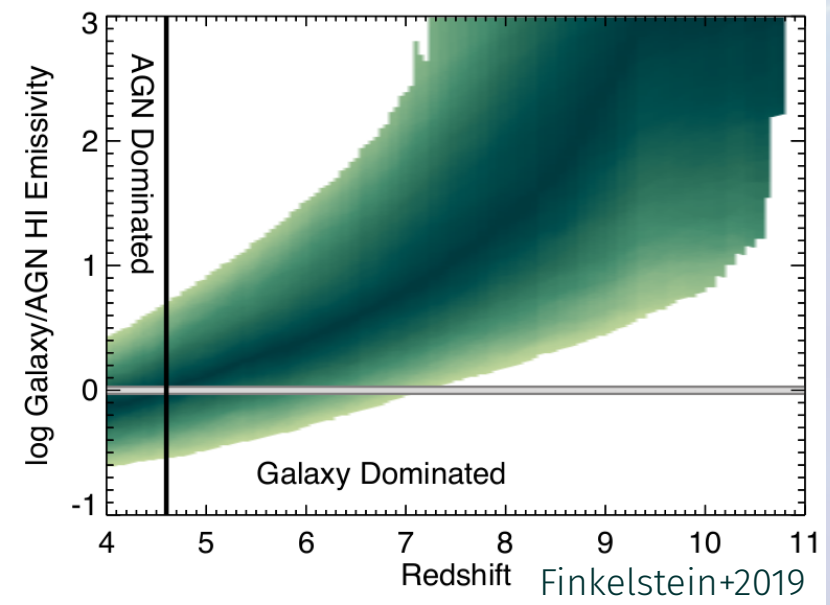




- AGN are dominating over their hosts ionizing luminosity in high-mass galaxies
- They dominate in the UV at M_{UV} brighter than -22 to -23

Empirical models





Direct simulations, semi-analytical models, and empirical approaches all seem to agree

(See also results from Qin+2017, Eide+2020, Yung+2021, for example)

Summary

https://obelisk-simulation.github.io/

SMBH in low-mass galaxies have a hard time growing

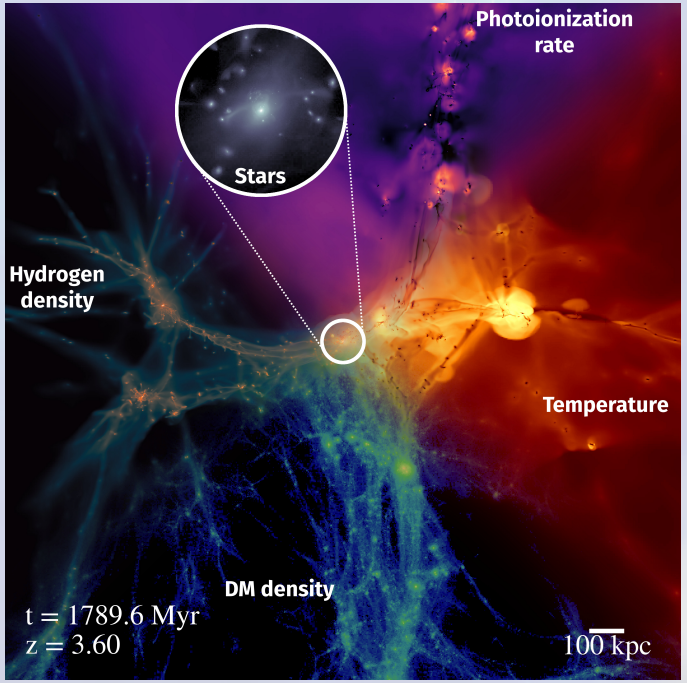
- There seems to be a critical host mass for BH growth
- This is a combination of complex dynamics + feeding

  ... still room for improvement (BH seeding?)
- Most of the growth tends to be obscured anyway

  → Overall, expect low contribution from AGN

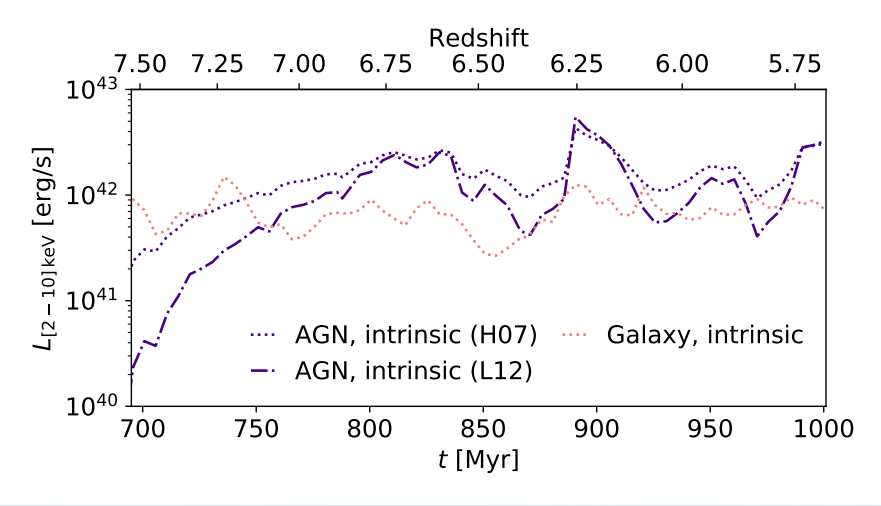
Galaxies dominate the EoR ionizing background

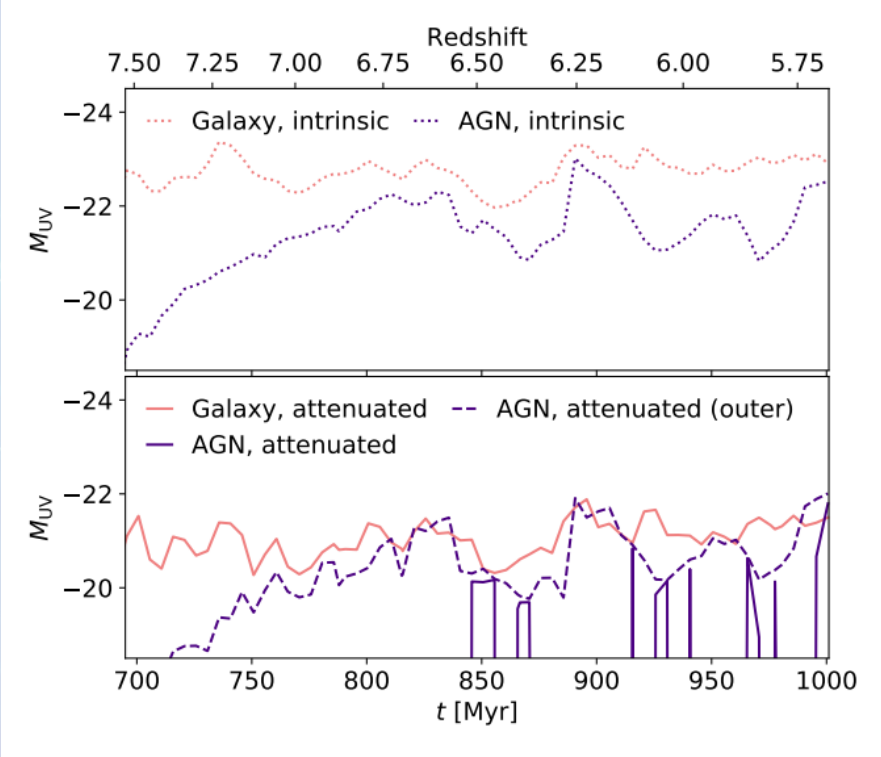
- Galaxies seems to provide enough photons to reionize the Universe by $z \sim 6$
- AGN most likely play a sub-dominant role
- **Robust** to very different modelling typese



Backup slides

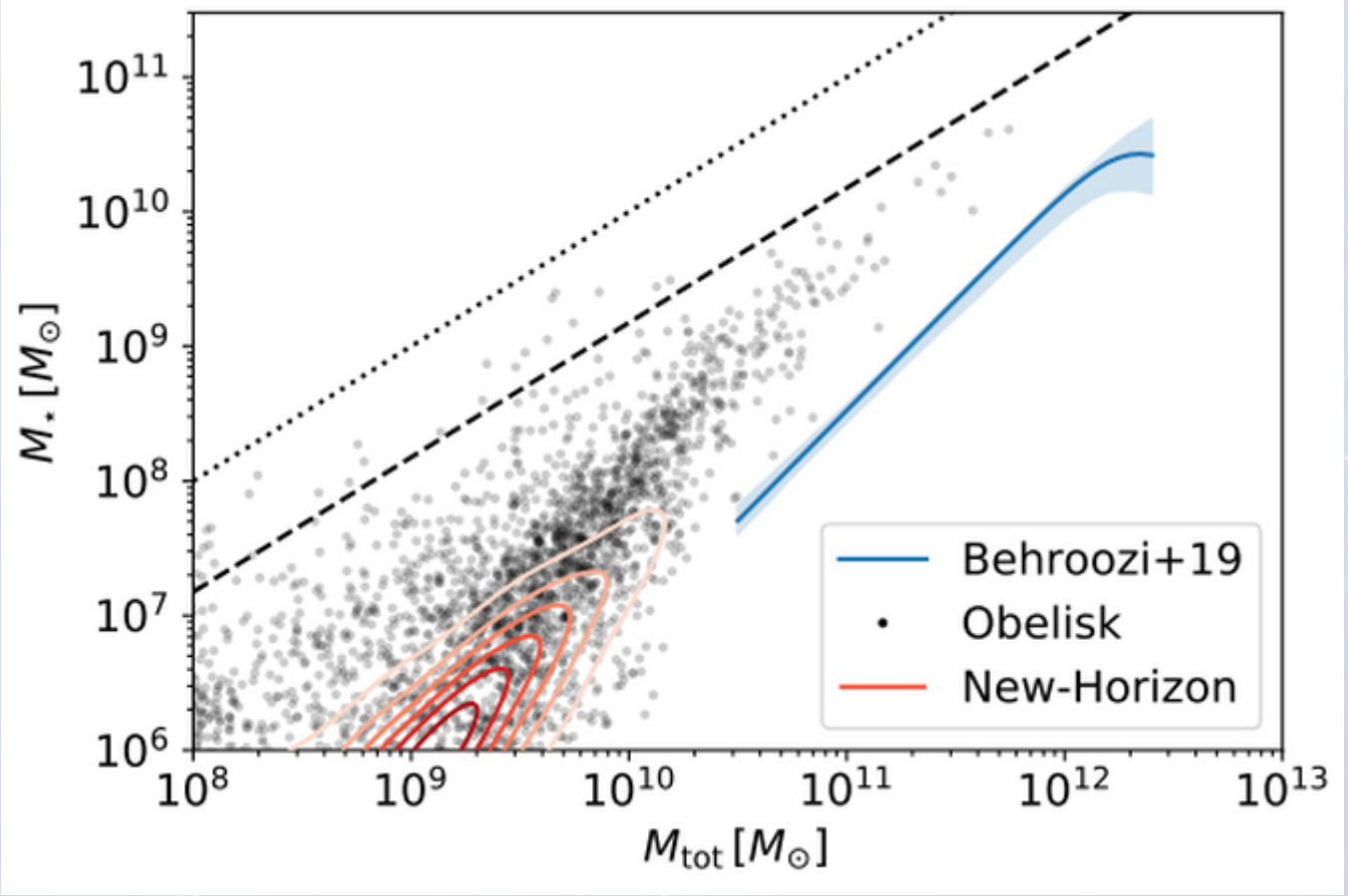
Bright galaxy, faint AGN: observability



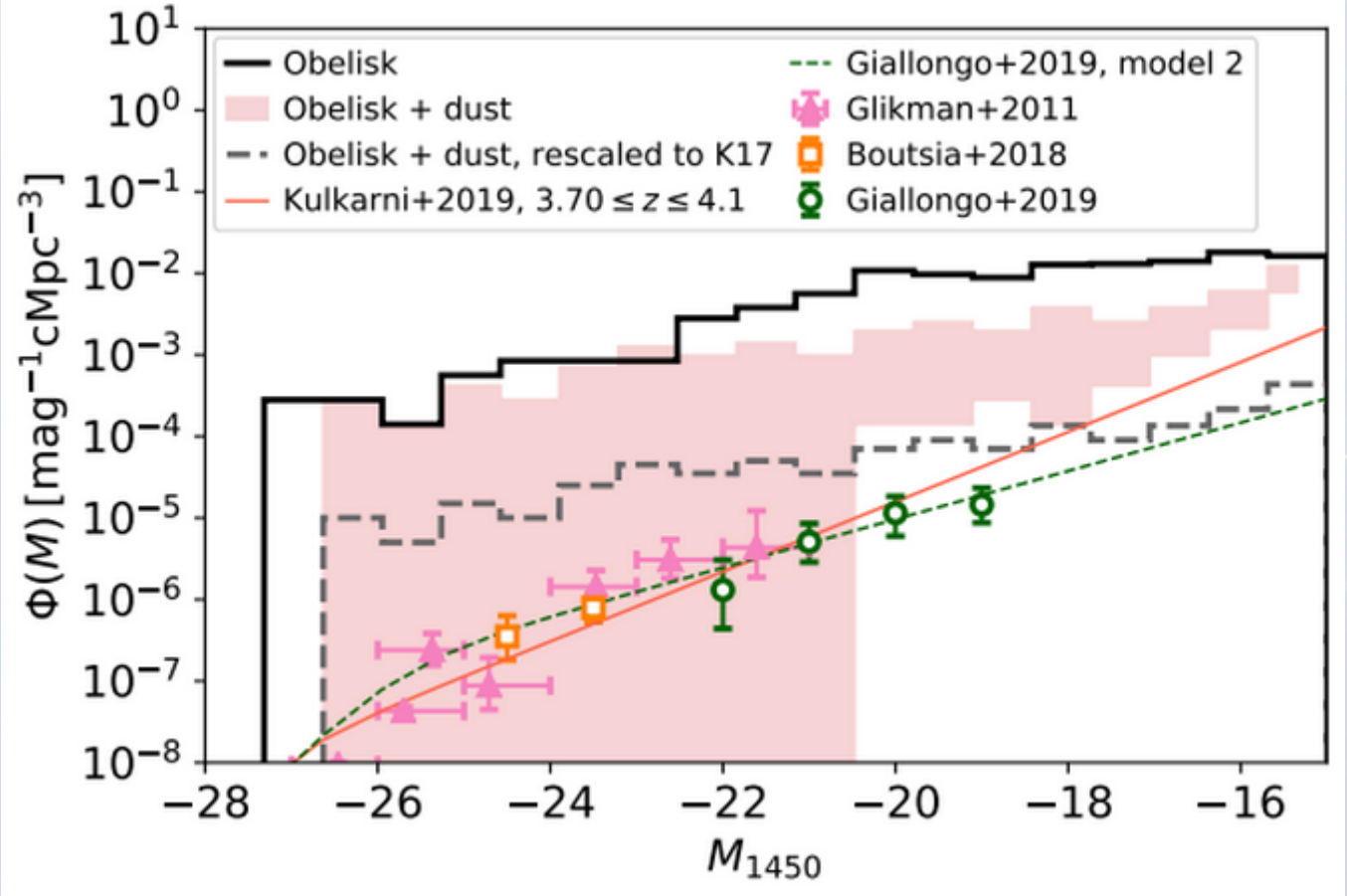


- Most of the time, the AGN dominates the X-ray emission
- However, the UV is often dominated by the host
- This means that converting the UV to LyC from the AGN can overestimate their contribution

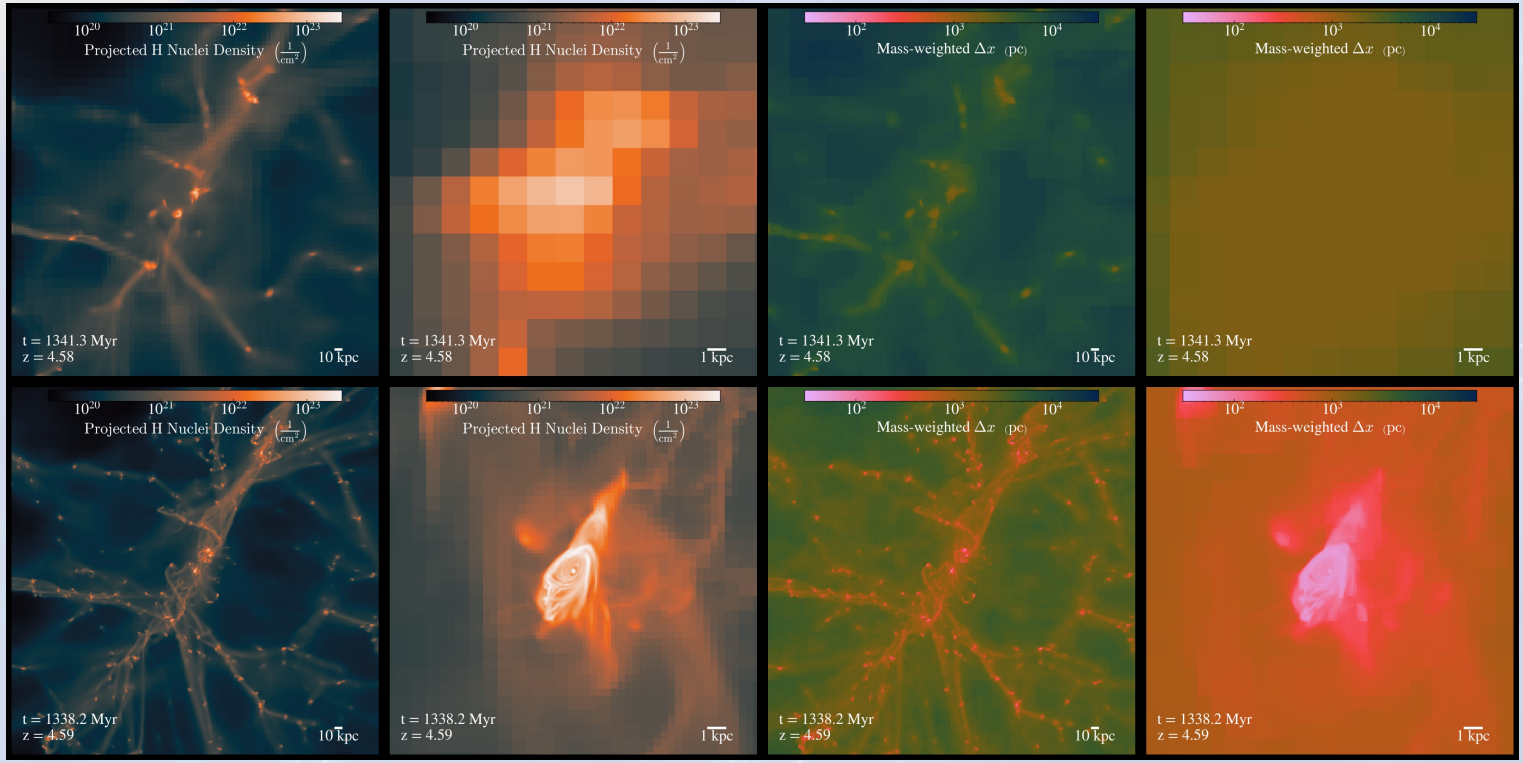
Obelisk: Stellar to halo mass relation



Obelisk: AGN UV LF



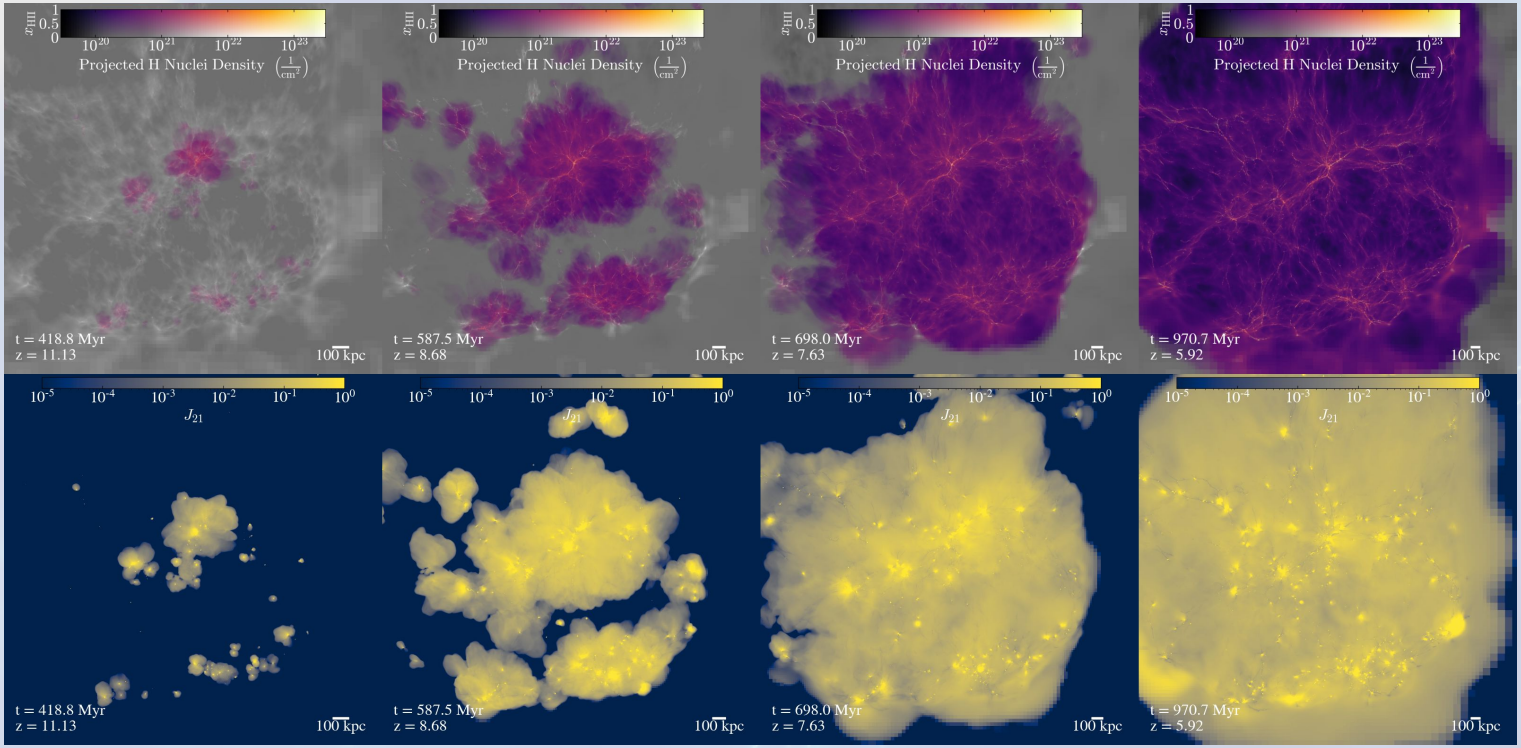
Resolution matters



Evolution of (most of) the high-resolution region

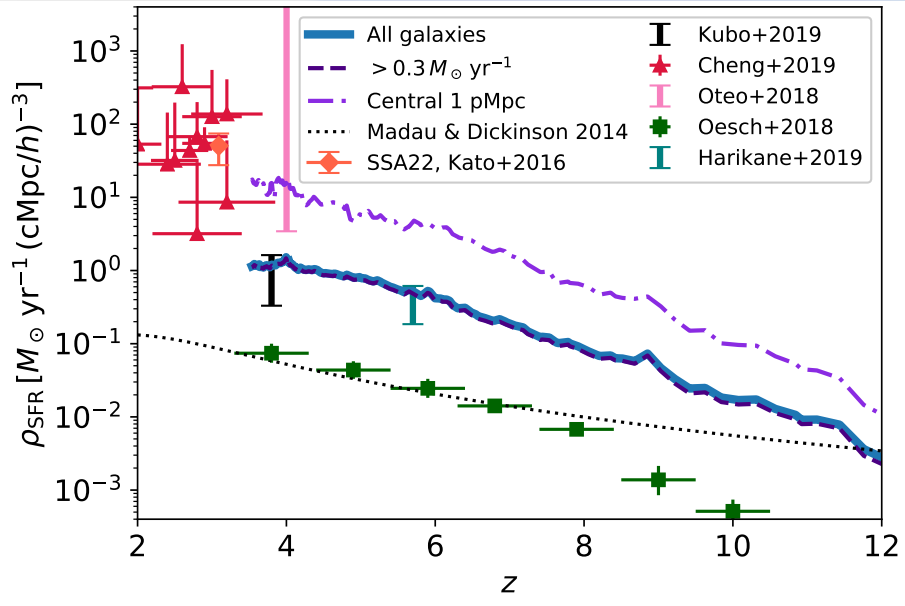
x_{HI} (color)
density

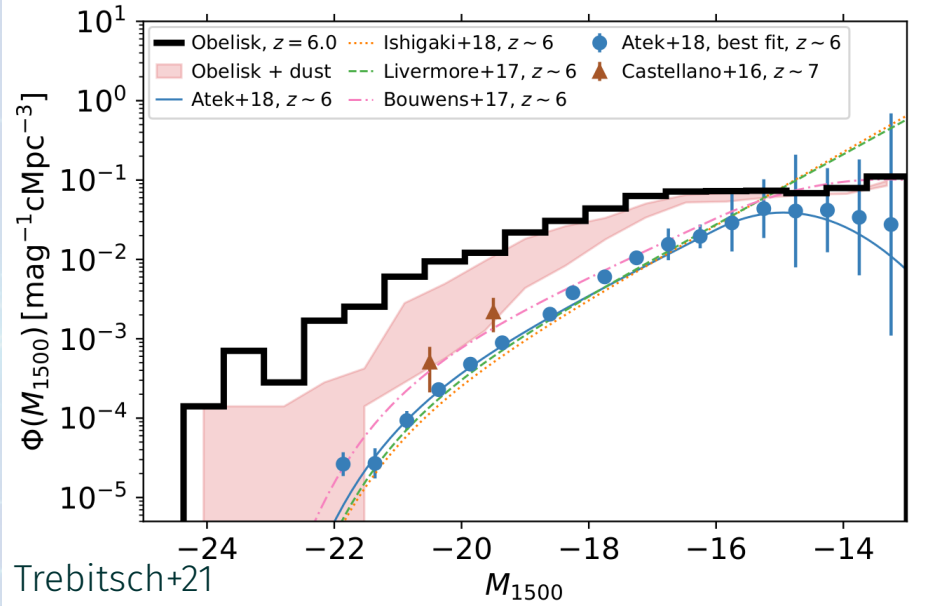
J_{21}



$\langle x_{HI} \rangle$ = 1 % $\langle x_{HI} \rangle$ = 10 % $\langle x_{HI} \rangle$ = 50 % $\langle x_{HI} \rangle$ = 99 %

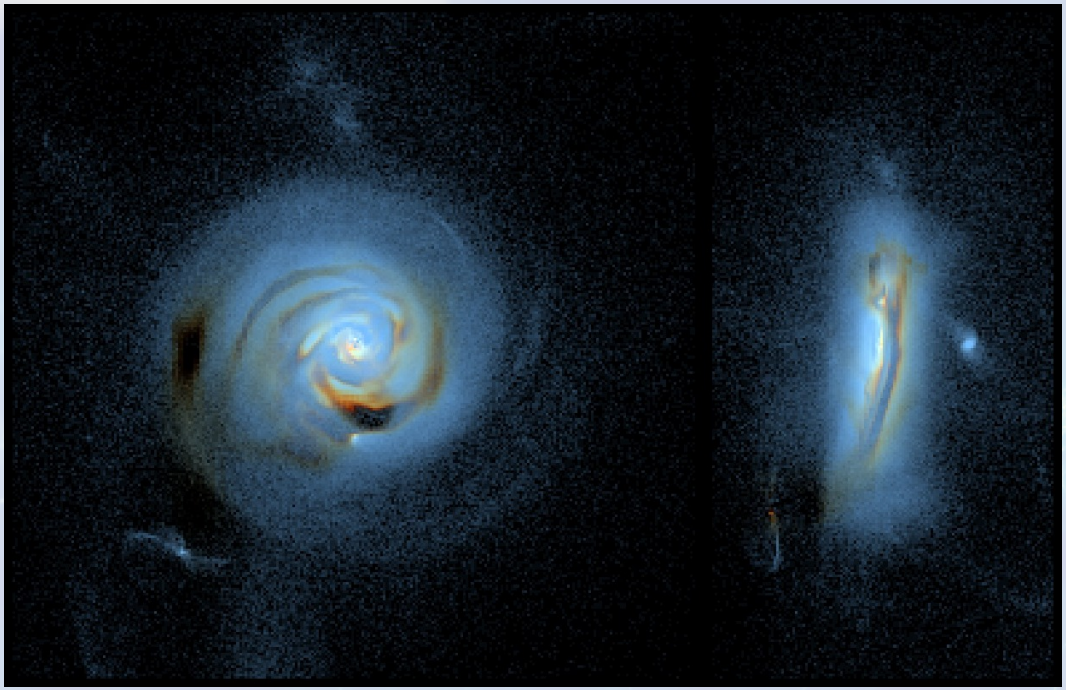
Assembly of a protocluster: enhanced star formation

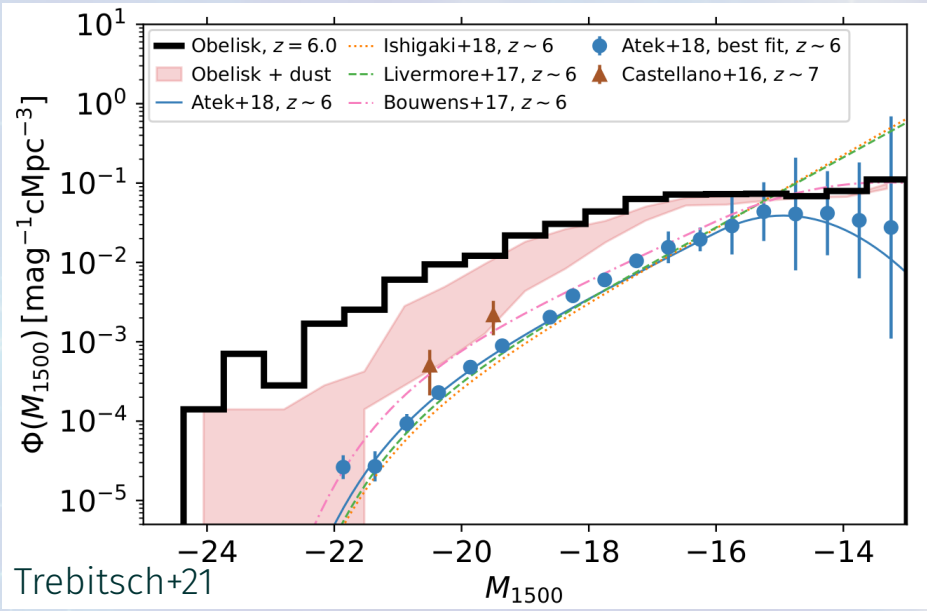




- Obelisk is a proto-cluster: it contains a larger number of massive galaxies than the field
- Once dust is taken into account, the UV LF in Obelisk is comparable to observed overdensities

Assembly of a protocluster: enhanced star formation





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