Supermassive black holes from Pop III.1 stars with dark matter self-annihilation and their gravitational wave background

Jasbir Singh

Supervisors: Prof. Pierluigi Monaco (University of Trieste) and Prof. Jonathan Tan (Chalmers University of Technology, Gothenburg, Sweden)

Cosmology 2023 in Miramare
1 September 2023

Contents

Credits: NASA, ESA, CSA, and STScI

Introduction

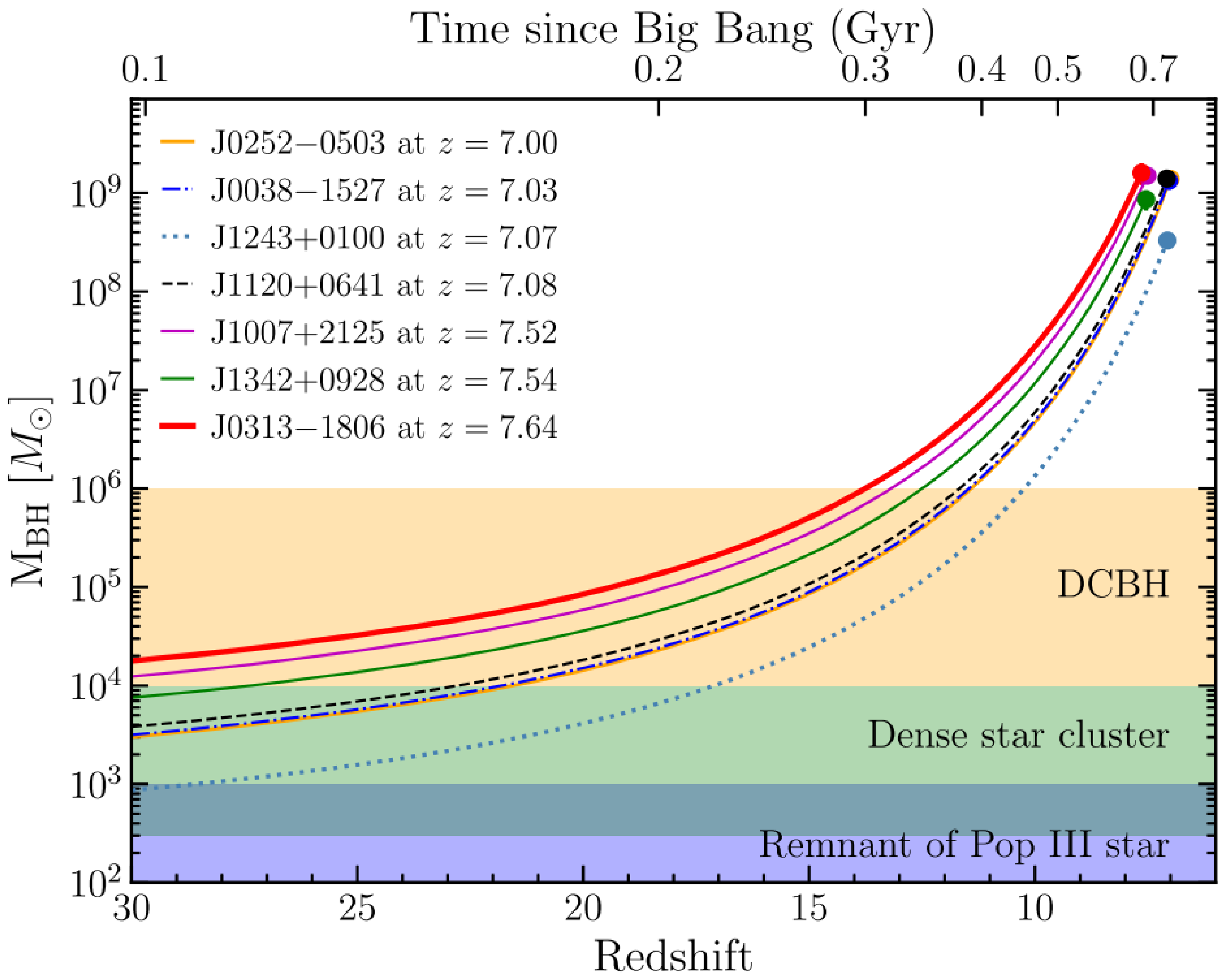

Credits: NASA, ESA, CSA, and STScI

Introduction

- The formation of stellar mass black holes is well understood, whereas there is still no consensus on the formation of supermassive black holes (SMBHs).

- Their masses are of the order of $\geq 10^5 M_{\odot}$ and they are present in most of the large galaxies.

- The problem is explaining the high masses ($\gtrsim 10^9 M_{\odot}$) at high redshifts (z~7.5).



Wang F., et al., 2021

Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
    - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.

Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
  - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.

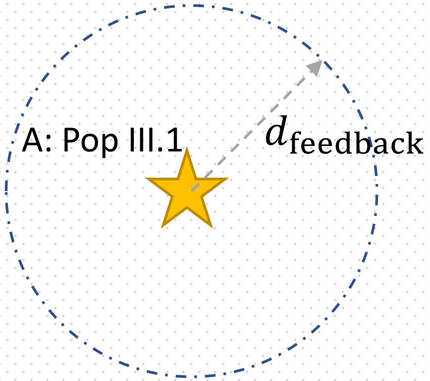
Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
    - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.

A: Pop III.1

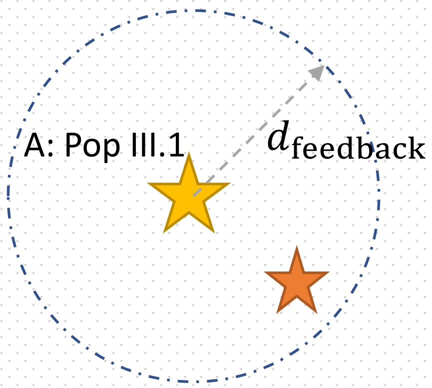
Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
  - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.



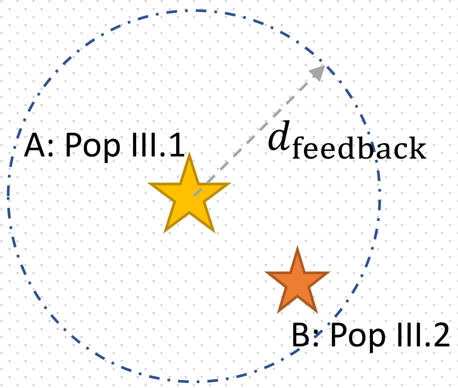
Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
  - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.



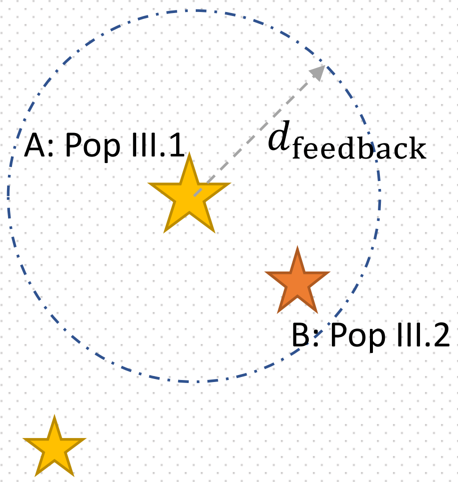
Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
    - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.



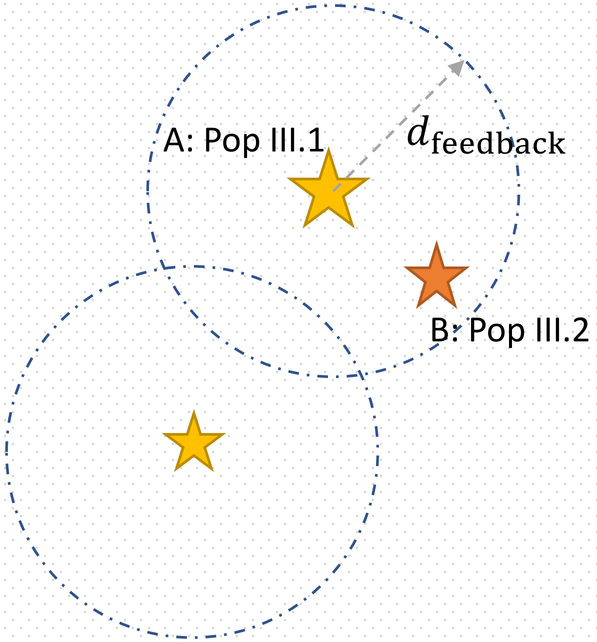
Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
  - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.



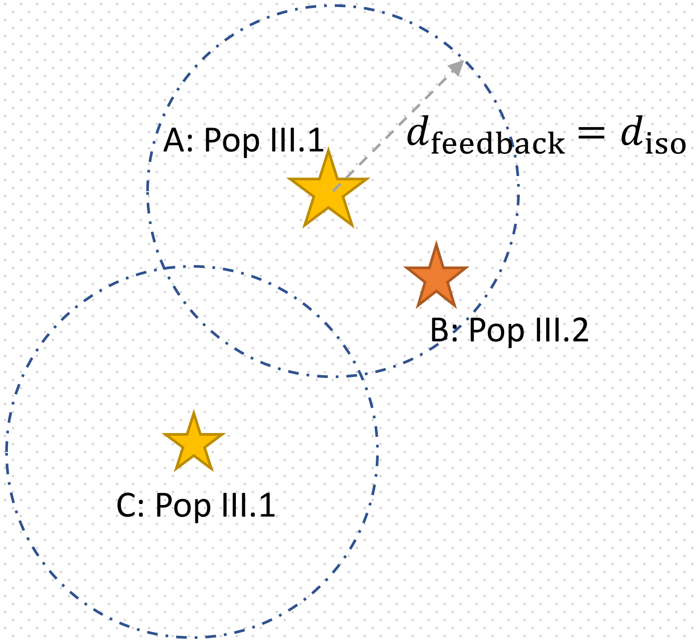
Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
  - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.



Introduction

- Another method to explain the origin of these black holes is by considering Population III.1 stars (McKee & Tan, 2008).
    - These are the stars of primordial composition and are formed in relative isolation from other stars and/or feedback sources.



Introduction

- Tan, Smith & O’Shea (2010) showed that for varied accretion rates, the initial mass function peaks at around$\sim 100\ M_{\odot}$, with a tail extending to $\sim 10^{3}\ M_{\odot}$.

- To achieve even higher masses for Pop III.1 stars, one can consider the energy input from WIMP dark matter self annihilation inside the protostar (Spolyar, Freese & Gondolo 2008; Natarajan, Tan & O’Shea 2009).

- With this energy injection, the protostar can become large, but stay relatively cool so that the ionizing feedback is minimum.

- This allows the protostar to accrete most of the baryonic content in its natal minihalo, i.e., around $10^{5}\ M_{\odot}$.

Pinocchio

https://github.com/pigimonaco/Pinocchio

Credits: NASA, ESA, CSA, and STScI

PINOCCHIO

PINpointing Orbit Crossing Collapsed Hierarchical Objects

Uses Lagrangian Perturbation Theory to evolve the overdensities in a matter dominated universe (Monaco, Theuns & Taffoni 2002, Munari et al. 2017).

```
pinocchio
```

```
catalogs(z)
```

```
[('name', numpy.int64),
 ('Mass', numpy.float32),
 ('pos', numpy.float32, 3),
 ('vel', numpy.float32, 3),
 ('posin', numpy.float32, 3)]
```

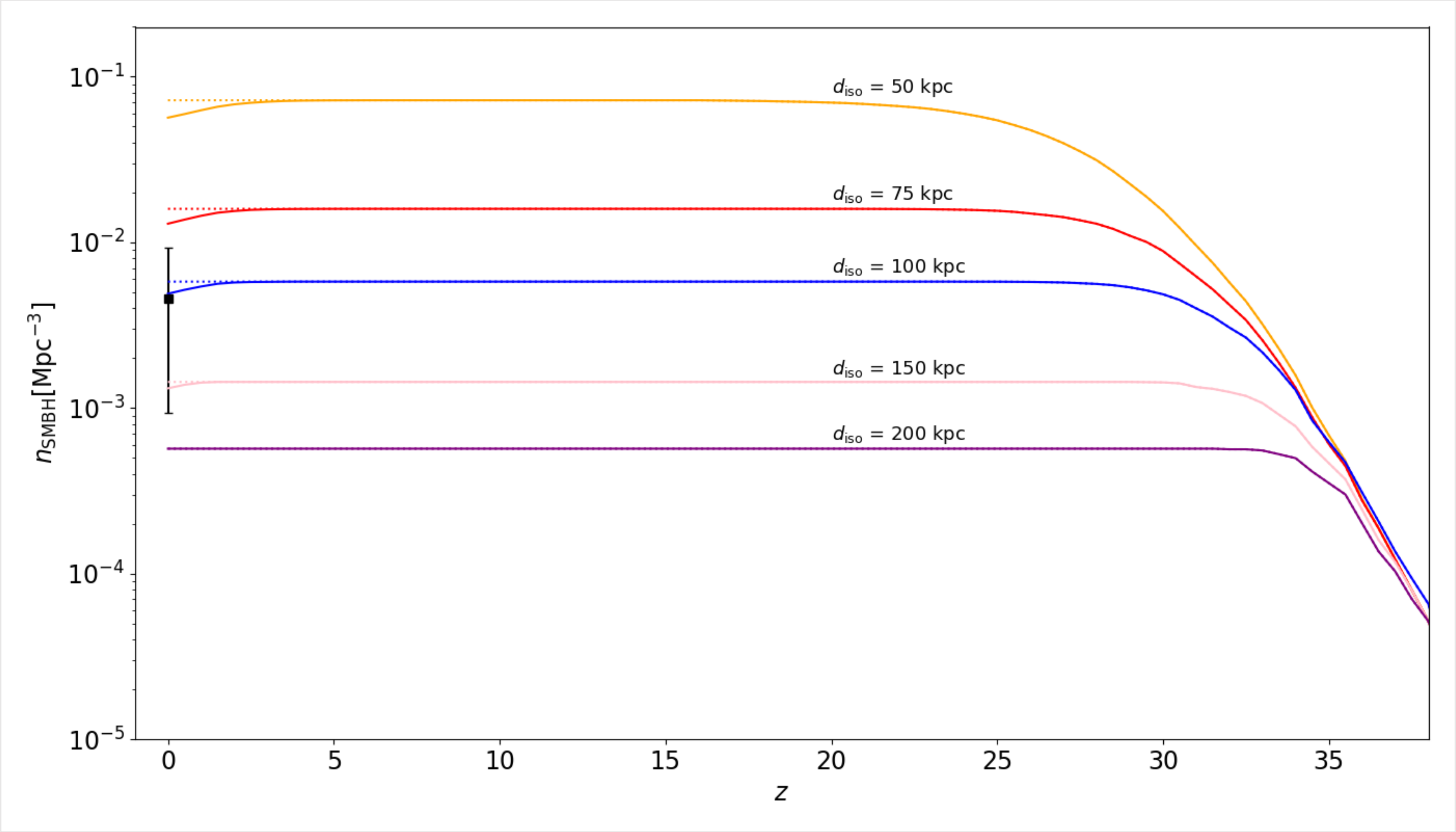
```
histories
```

```
[('name', numpy.uint64),
 ('nickname', numpy.int32),
 ('link', numpy.int32),
 ('merged_with', numpy.int32),
 ('mass_at_merger', numpy.int32),
 ('mass_of_main', numpy.int32),
 ('z_merging', numpy.float32),
 ('z_peak', numpy.float32),
 ('z_appear', numpy.float32)]
```

Results

Credits: NASA, ESA, CSA, and STScI

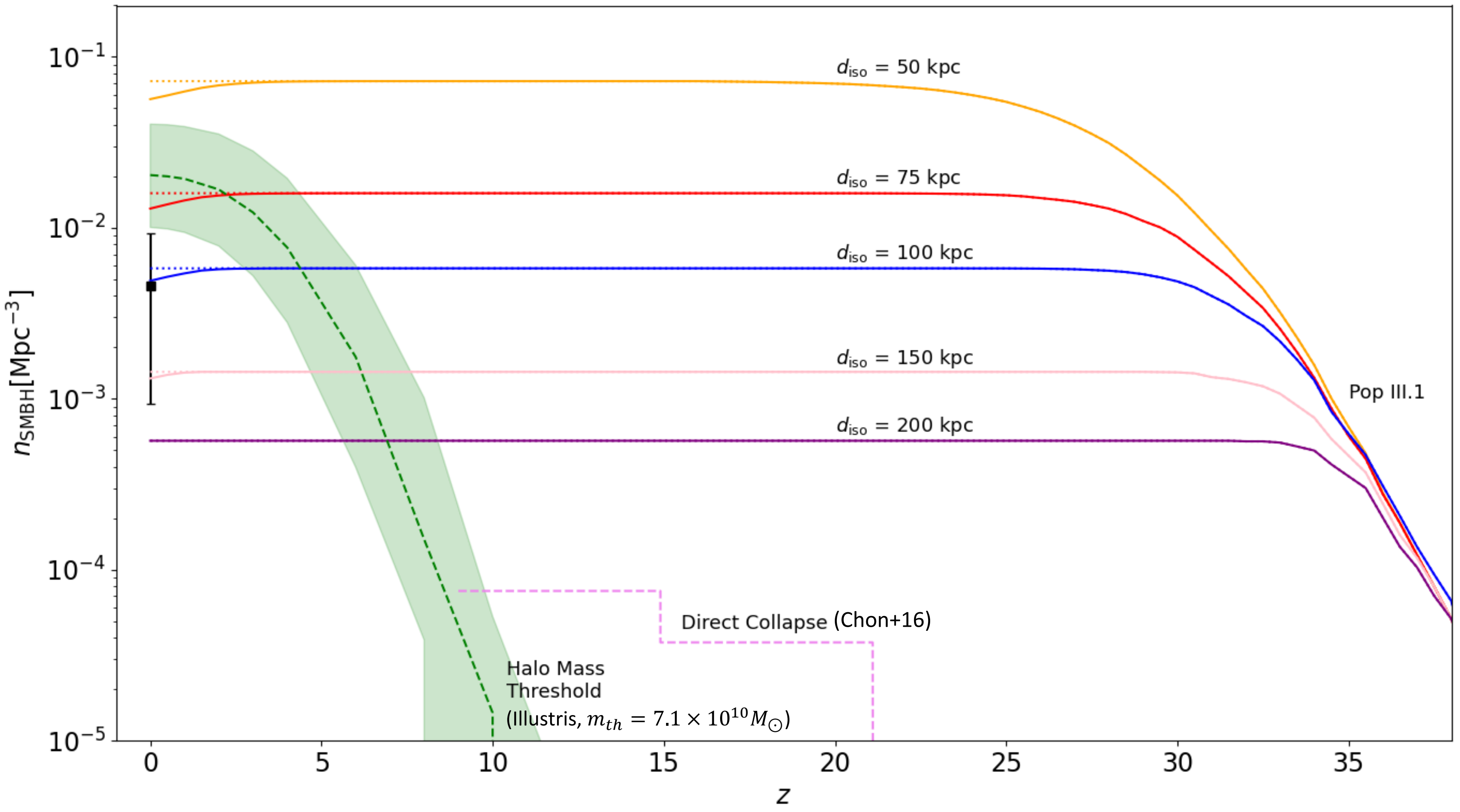
Number density



arXiv:2301.11464

JS, Monaco and Tan 2023

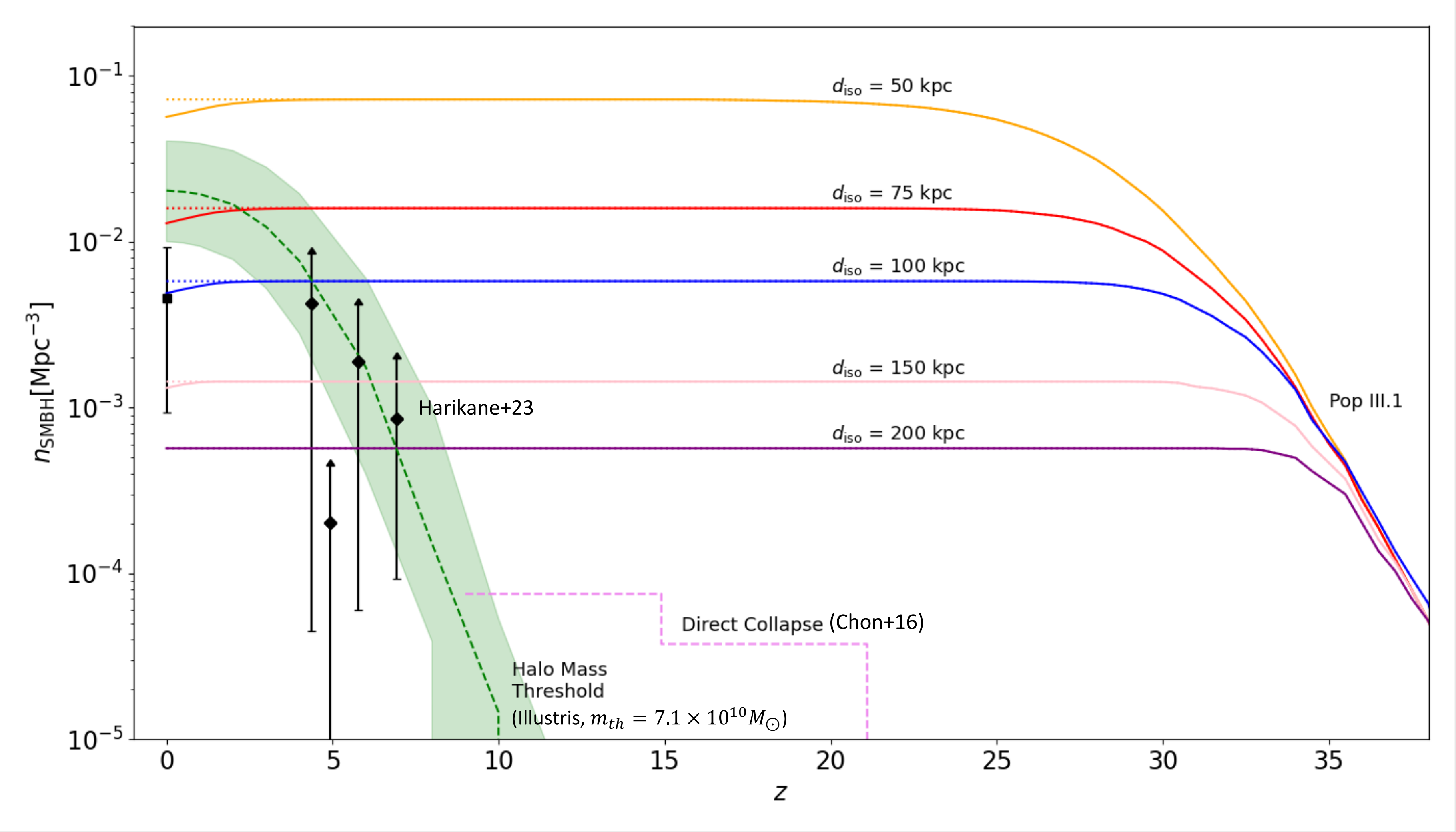
Number density



arXiv:2301.11464

JS, Monaco and Tan 2023

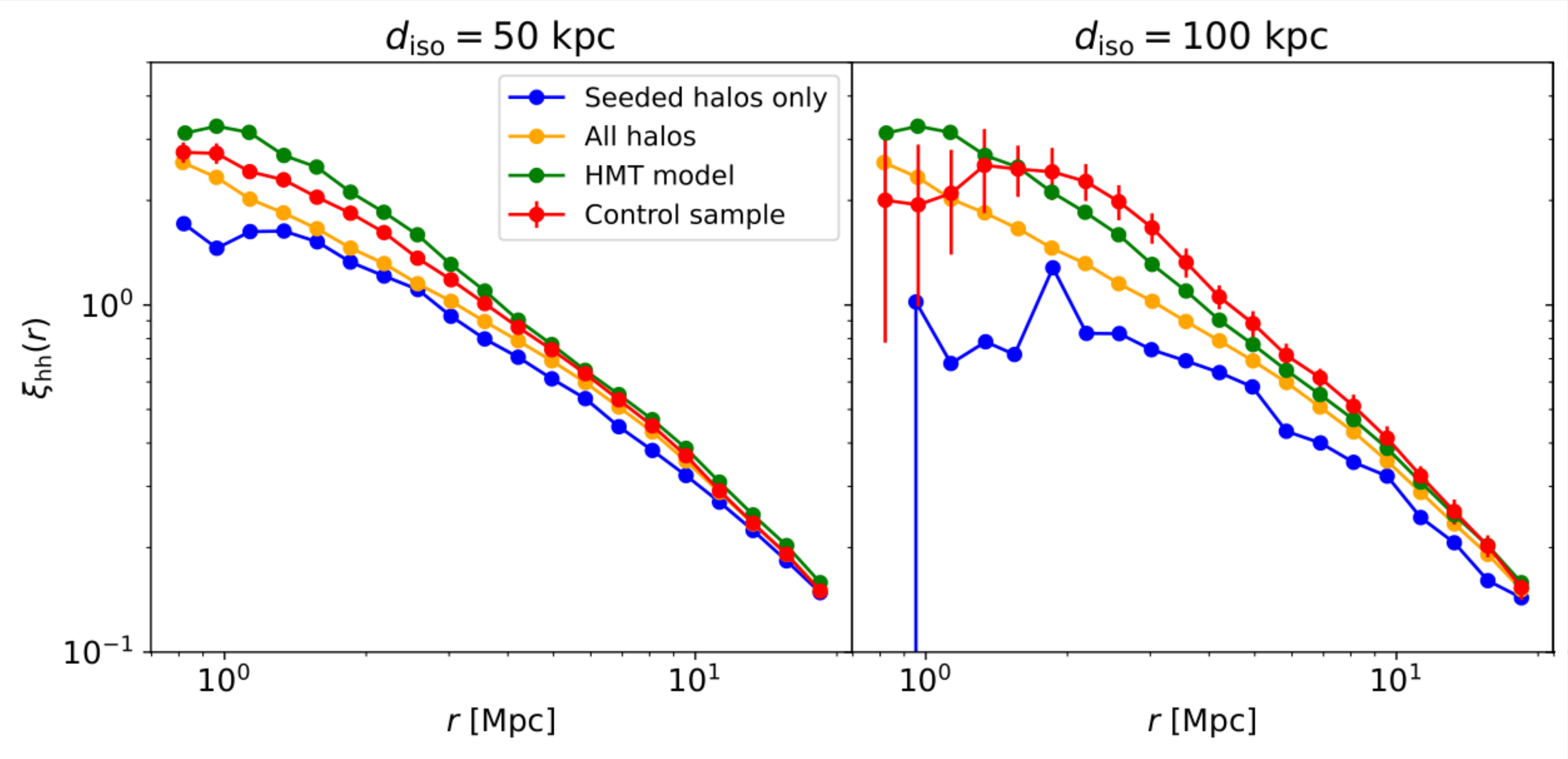
Number density



arXiv:2301.11464

JS, Monaco and Tan 2023

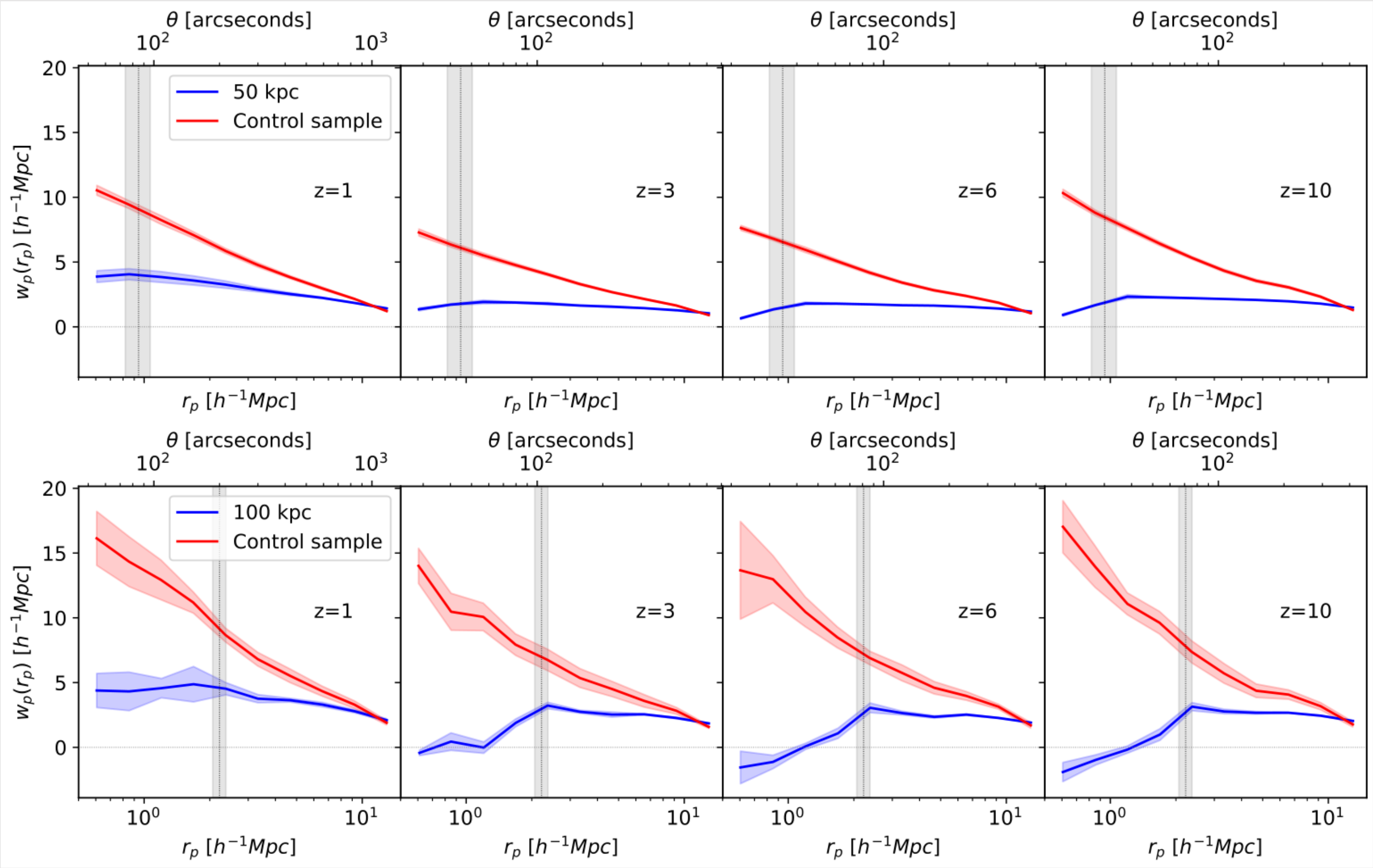
Clustering



JS, Monaco and Tan 2023

arXiv:2301.11464

Clustering evolution

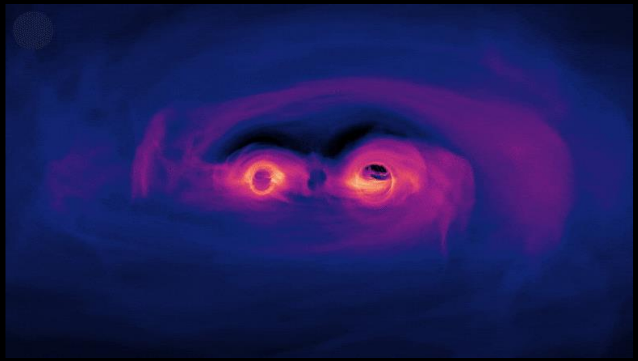


arXiv:2301.11464

JS, Monaco and Tan 2023

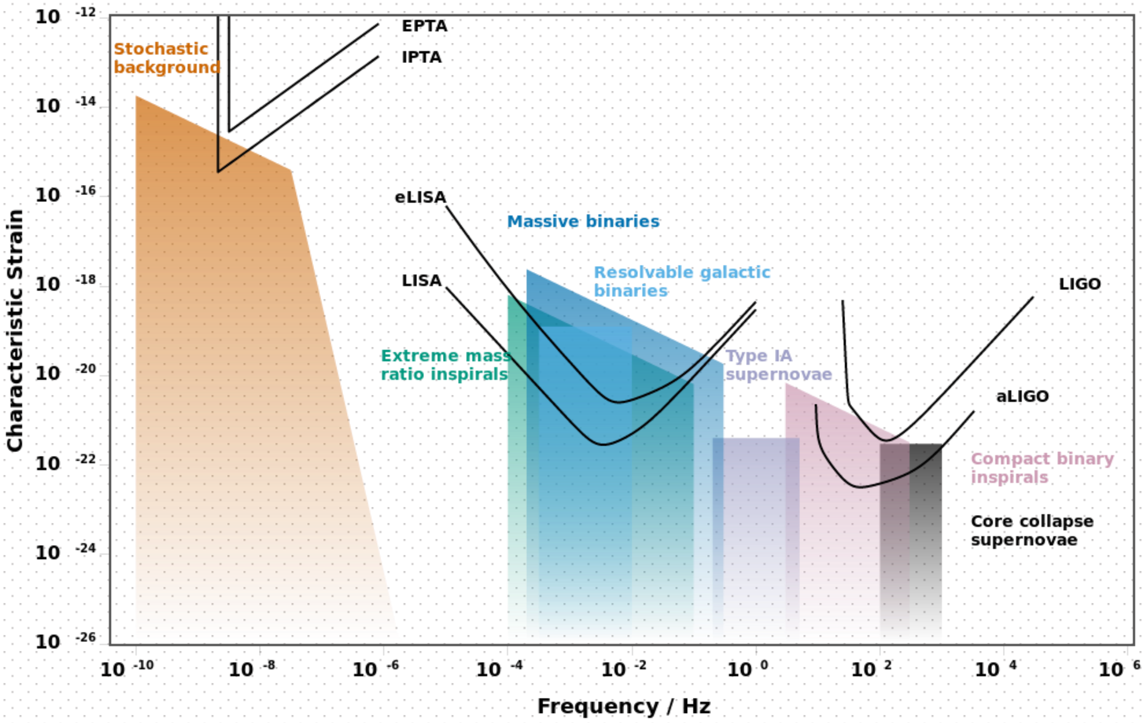
Credits: NASA, ESA, CSA, and STScI

Gravitational Wave Background

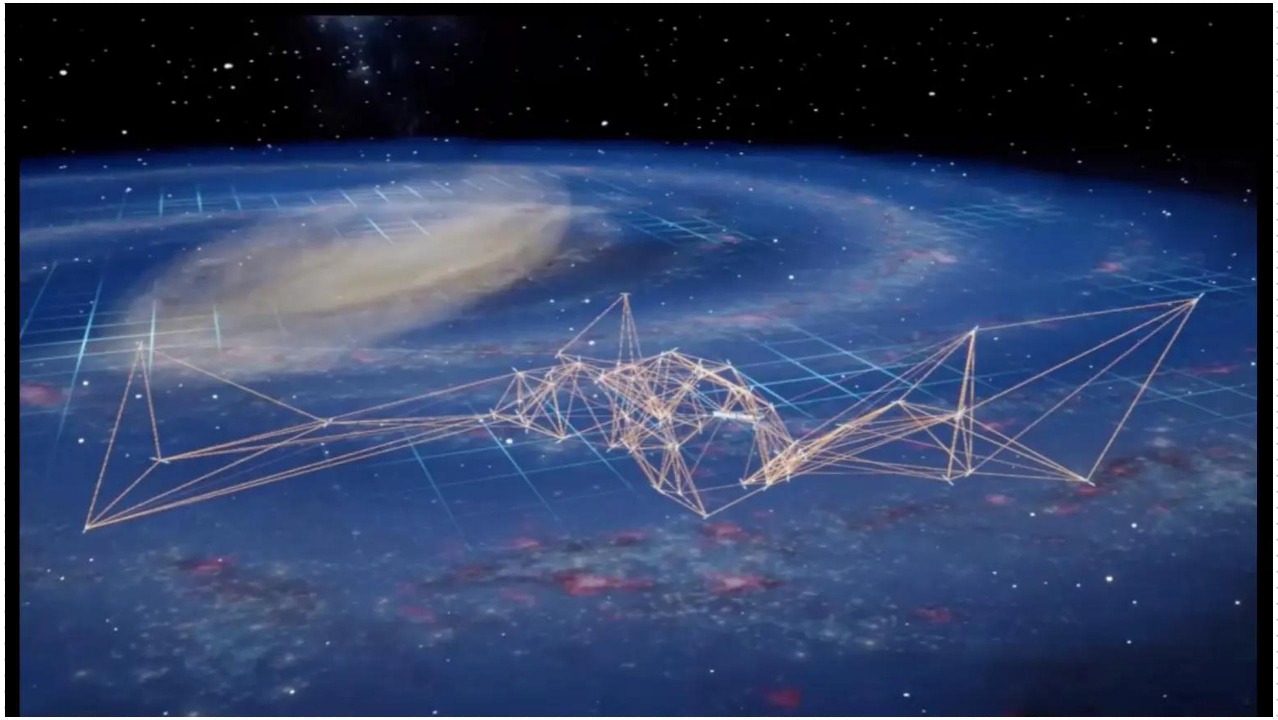


Credit: NASA

Pulsar Timing Arrays

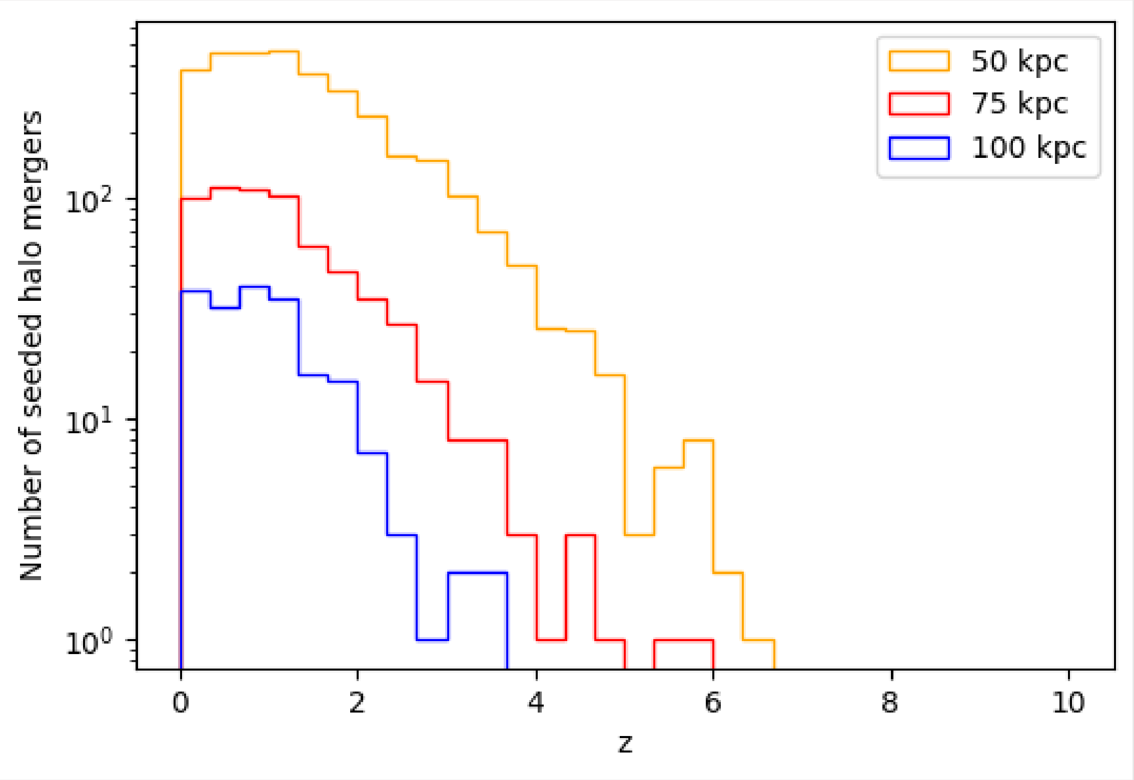


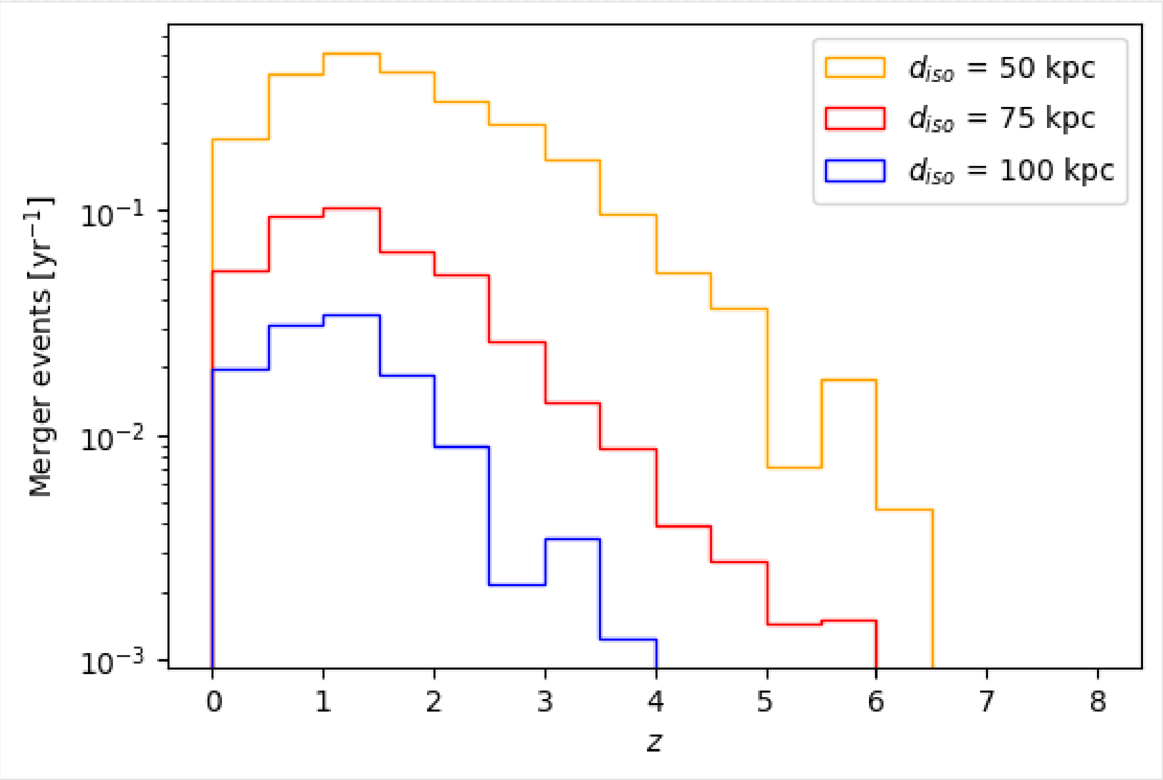
Credit: Christopher Moore, Robert Cole and Christopher Berry - http://rhcole.com/apps/GWplotter/, CC BY-SA 1.0, https://commons.wikimedia.org/w/index.php?curid=32227462



NANOGrav Collaboration

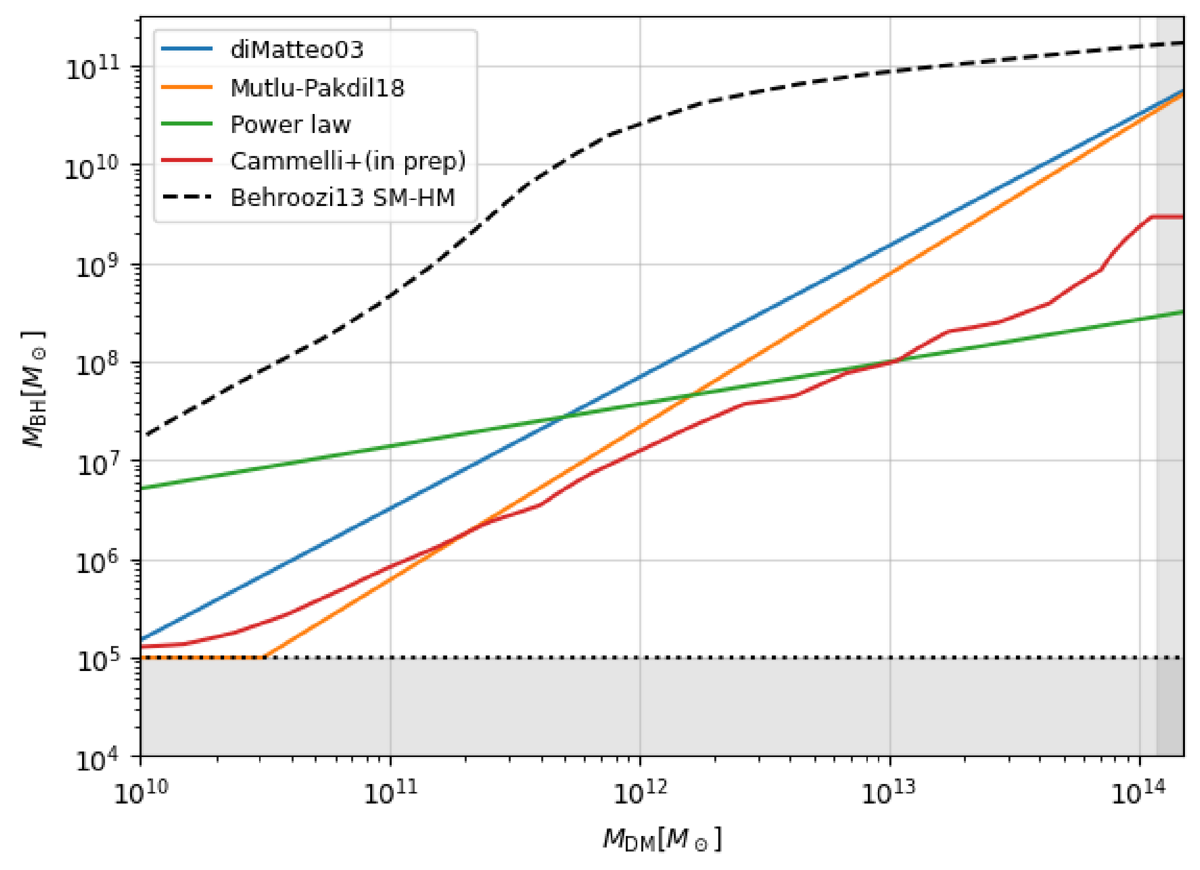
SMBH merger events



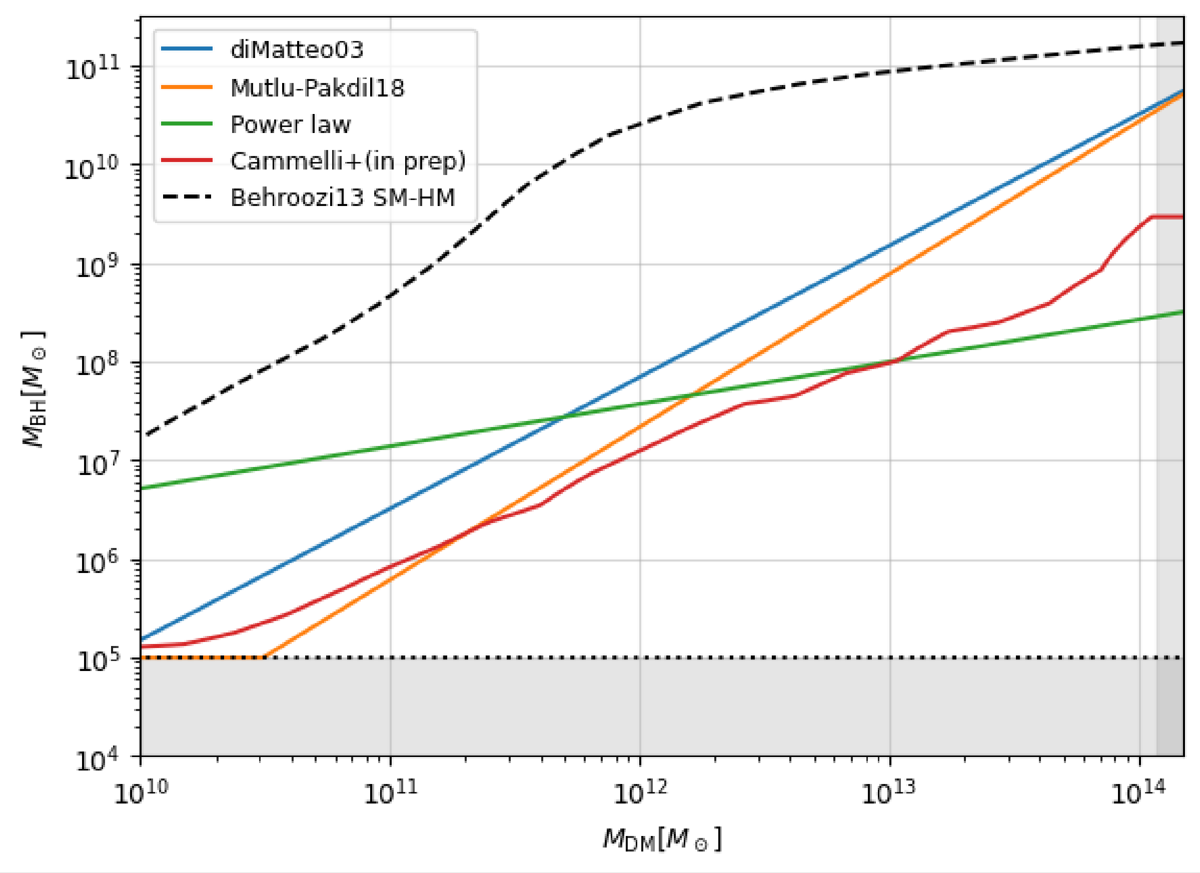


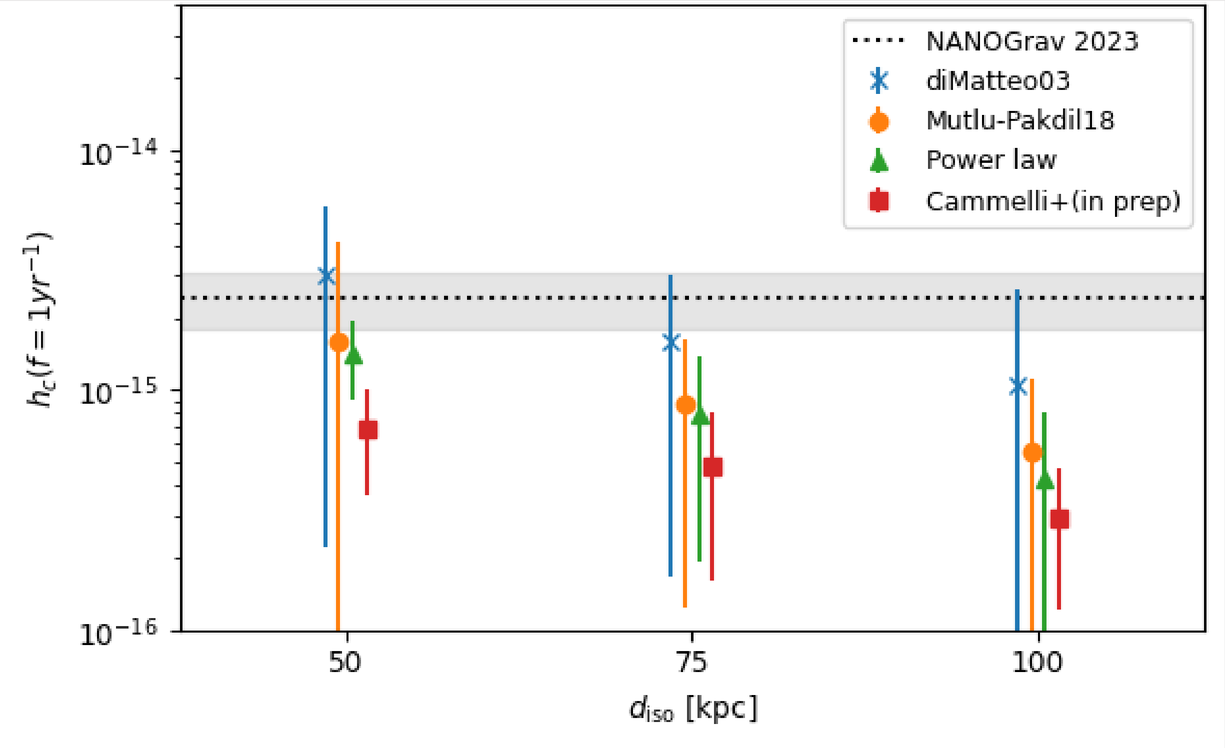
JS+, in prep

GWB from Pop III.1 model



GWB from Pop III.1 model





JS+, in prep

Summary and Conclusions

- Seeds forming from Pop III.1 stars with WIMP dark matter self annihilation can reach up to $10^5 M_\odot$ before collapsing.
- Using dark matter catalogs from PINOCCHIO, we can identify the seeded halos and follow their evolution.
- The model is able to explain the current observed number density and predict a clear clustering signal.
- By assuming a simple black hole mass – halo mass relation, the model is able to explain the observed GWB.
- Future work involves using a more physical growth model of black holes using semi analytical models to improve predictions for the GWB.

Thank you for your attention!

jasbir.singh@inaf.it

References

- Abel T., Bryan G. L., Norman M. L., 2002, **Science**, 295, 93
- Bromm V., Loeb A., 2003, **ApJ**, 596, 34
- Bromm V., Coppi P. S., Larson R. B., 2002, **ApJ**, 564, 23
- Freese K., Ilie C., Spolyar D., Valluri M., Bodenheimer P., 2010, **ApJ**, 716, 1397
- McKee C. F., Tan J. C., 2008, **ApJ**, 681, 771
- Monaco P., Theuns T., Taffoni G., 2002, **MNRAS**, 331, 587
- Munari E. et al., 2017, **MNRAS**, 465, 4658
- Natarajan A., Tan J. C., O'Shea B. W., 2009, **ApJ**, 692, 574
- Rindler-Daller T., Montgomery M. H., Freese K., Winget D. E., Paxton B., 2015, **ApJ**, 799, 210
- Singh J., Tan J. C., Monaco P., **arXiv:2301.11464**
- Spolyar D., Freese K., Gondolo P., 2008, **Phys. Rev. Lett**., 100, 051101
- Tan J. C., Smith B. D., O'Shea B. W., 2010, AIP Conf. Proc. Vol. 1294, Am. Inst. Phys., New York. p. 34
- Zehavi I. et al., 2011, **ApJ**, 736, 59

Extra material

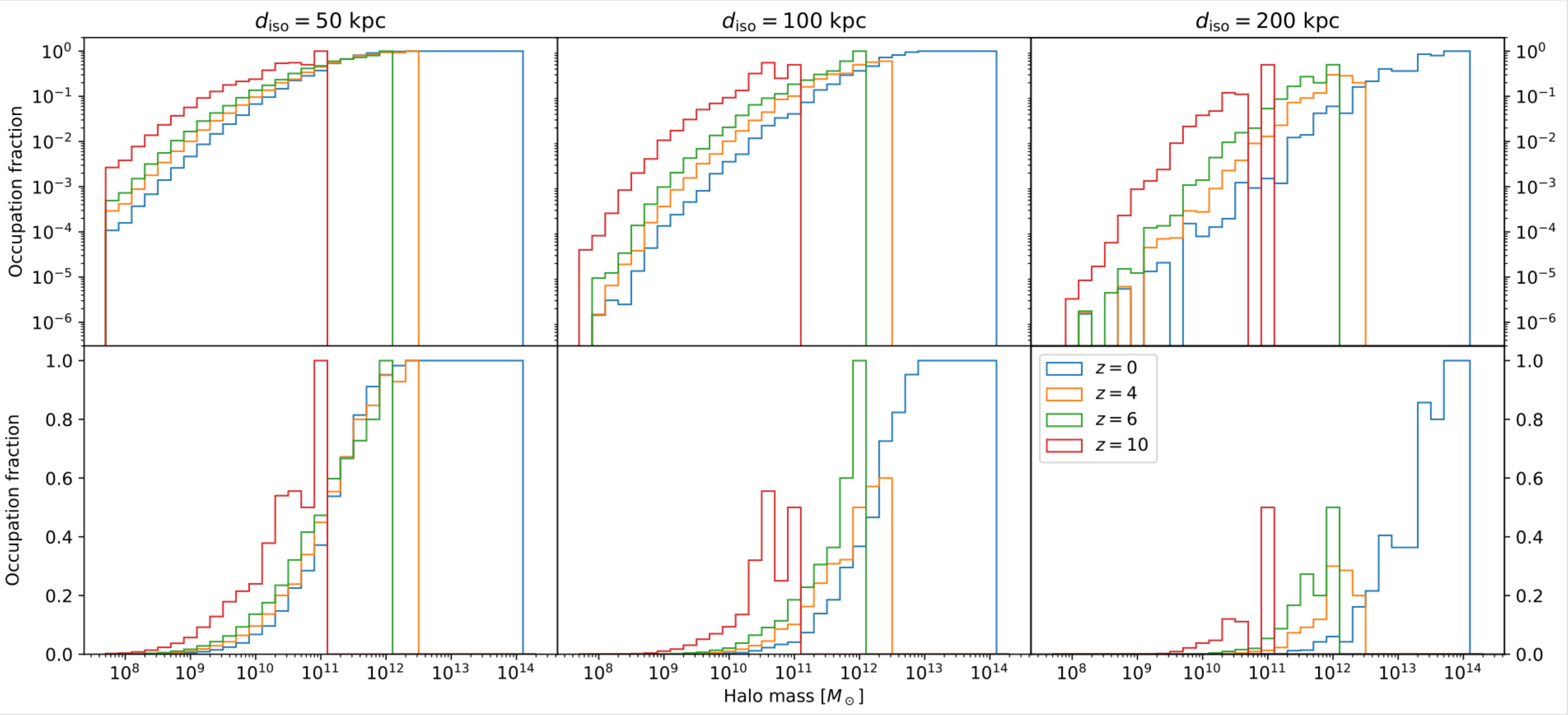
Credits: NASA, ESA, CSA, and STScI

WIMP DM conditions

- Since the WIMP DM annihilation rates scale as ρ_χ^2, this effect is most prominent if the protostar is located at the center of the minihalo, where the density of DM particles is maximum.

- Protostars powered by this mechanism have been shown to grow up to $\gtrsim 10^5\ M_\odot$, starting from an initial mass of 2 to 5 $M_\odot$(Fresse *et al.* 2012; Rindler-Daller *et al.* 2015).

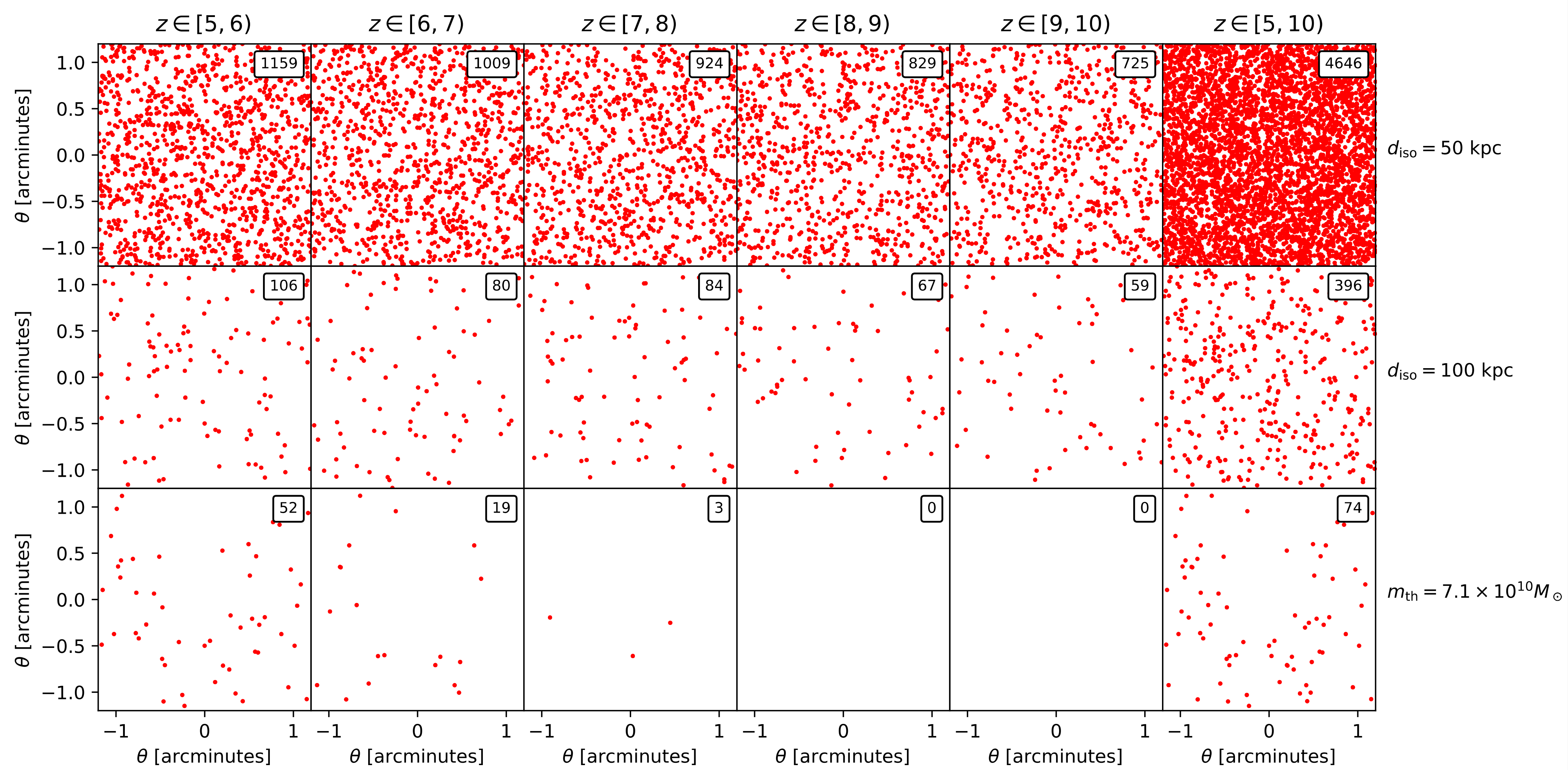
Occupation fraction



JS, Monaco and Tan 2023

arXiv:2301.11464

Synthetic ultra deep field



arXiv:2301.11464

JS, Monaco and Tan 2023