The Origin of Supermassive Black Holes in the Early Universe

Jasbir Singh

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

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Introduction
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• 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 ($z \sim 7.5$).
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• 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 $10^5 \, M_\odot$. 
Methods
Methods

• To test this seeding mechanism, we used PINOCCHIO to generate catalogs of dark matter halos in cosmological volumes (Monaco, Theuns & Taffoni 2002, Munari et al. 2017).

• The code outputs catalogs of minihalos at different redshifts, which includes information such as the mass, position, velocity, and more, of all the minihalos.

• Also generates a file containing the record of the merger history of all the halos, including the appearing and merging redshifts.
Results
Number density

Singh et al., to be submitted
Number density

Singh et al., to be submitted
Occupation fraction

$\text{Singh et al., to be submitted}$
Clustering

$d_{iso} = 50$ kpc

$d_{iso} = 100$ kpc

$d_{iso} = 200$ kpc

$\xi_{hh}(r)$

$r$ [Mpc]

Seeded halos only
All halos
HMT model
Randoms mirroring seeded

Singh et al., to be submitted
Synthetic ultra deep field

\[ z \in [5, 6), z \in [6, 7), z \in [7, 8), z \in [8, 9), z \in [9, 10), z \in [5, 10) \]

- \( d_{50} = 50 \text{ kpc} \)
- \( d_{50} = 100 \text{ kpc} \)
- \( m_{th} = 7.1 \times 10^{10} M_\odot \)

Singh et al., to be submitted
SMBH merger events

Singh et al., 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 the tendency of the most massive halos to be always occupied by SMBHs.

• We also showed how we can compare among different seeding mechanisms by calculating the number density of AGNs at high redshifts.

• Future work involves doing extended black hole merger analysis to make predictions for the Pulsar Timing Array experiments and the upcoming LISA.
Thank you for listening!
References

Extra material
WIMP DM conditions

• Since the WIMP DM annihilation rates scale as $\rho_\chi^2$, 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).