Efficient Exploration of the Cosmic Reionization

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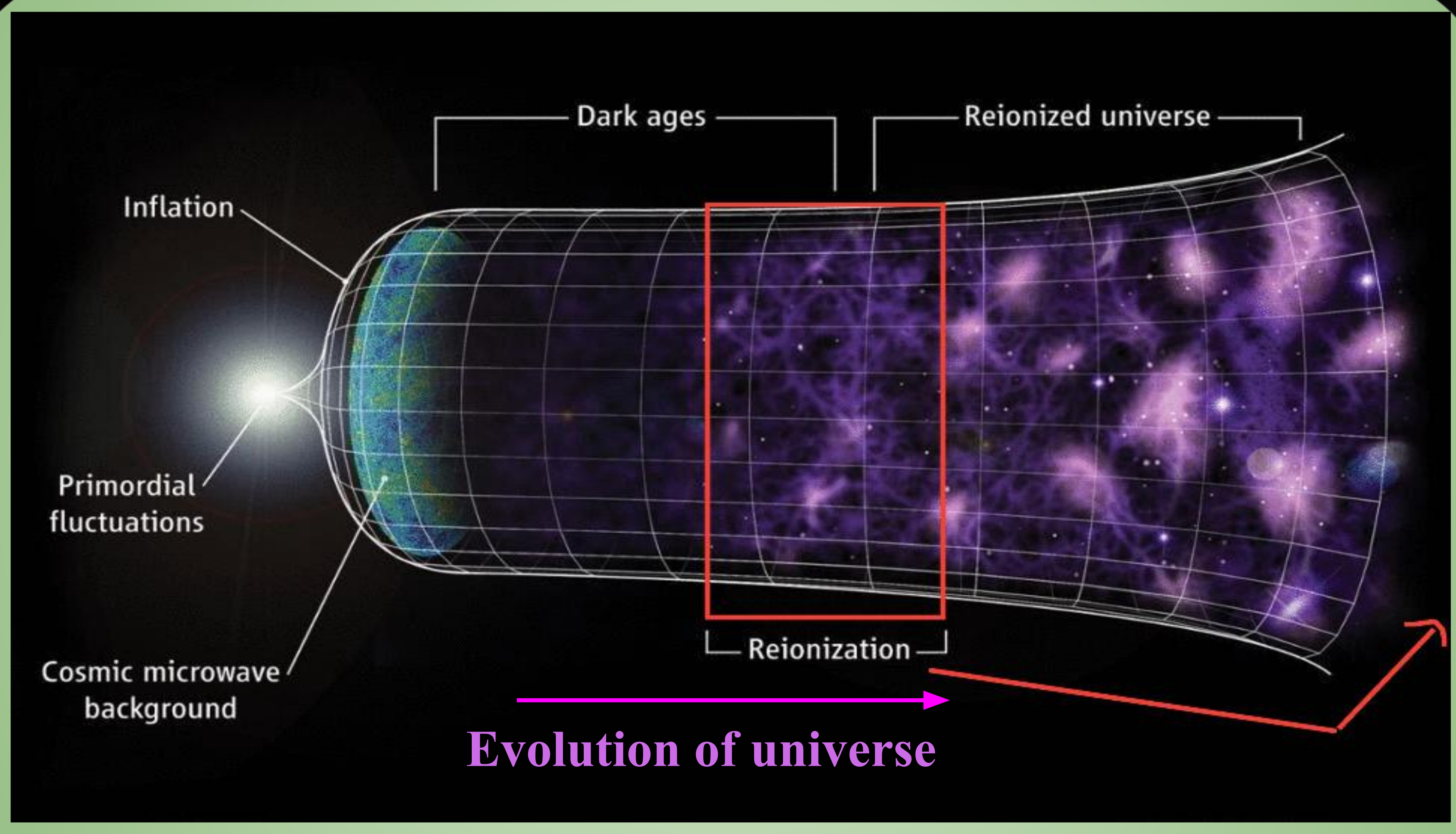


Courtesy: *C. Faucher-Giguere, A. Lidz, and L. Hernquist, Science 319, 5859 (47)*

Reionization:

Ionization of neutral hydrogen (small amount of helium) atoms via the photons coming from the very first luminous sources in the universe. It is one of the least understood phases in the evolution history of the universe. This also belongs to the *final frontiers in modern cosmology.*

Motivations behind the work:

- *The precise end and the duration of the reionization era are not completely known. The different astrophysical processes during reionization are yet to be fully understood.*
- *The observational prospects are very bright. The era can be explored with multiple wavelength bands using available and upcoming facilities (like JWST, SKA, TMT, etc).*
- *Efficient and accurate theoretical modelling is needed to correctly interpret the observational data and gain insights about different uncertain physical parameters.*

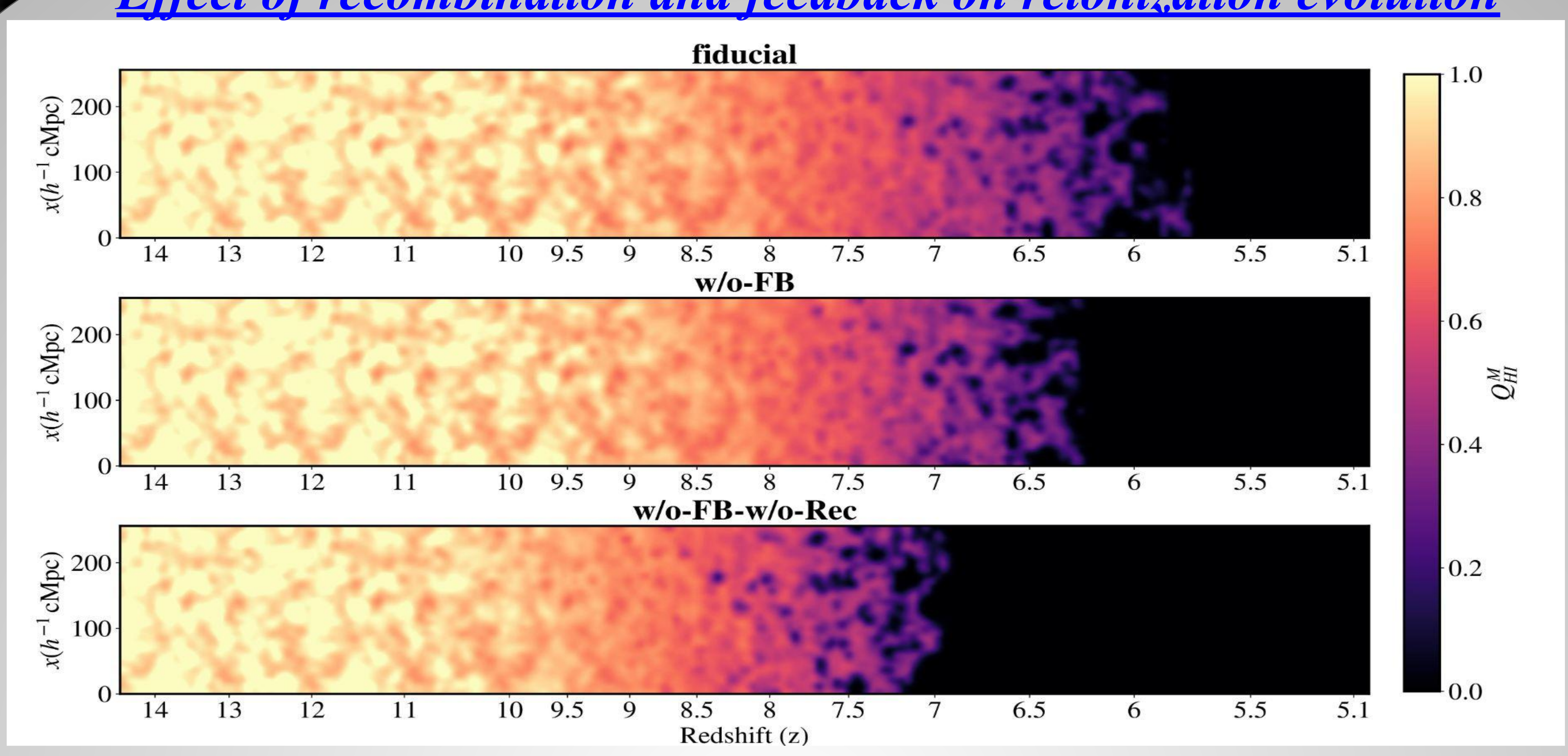
SCRIPT *(The Exploration Tool)*: Semi Numerical Code for ReIonization with PhoTon Conservation

Physically, one expects that there should not be any net gain or loss in photon numbers during the reionization process which is obeyed in the photon conserving criterion. SCRIPT solves the problem of photon number non-conservation associated with the traditional semi-numerical models based on the Excursion Set approach (for details, see Choudhury & Paranjape, MNRAS, 2018**).**

This work:

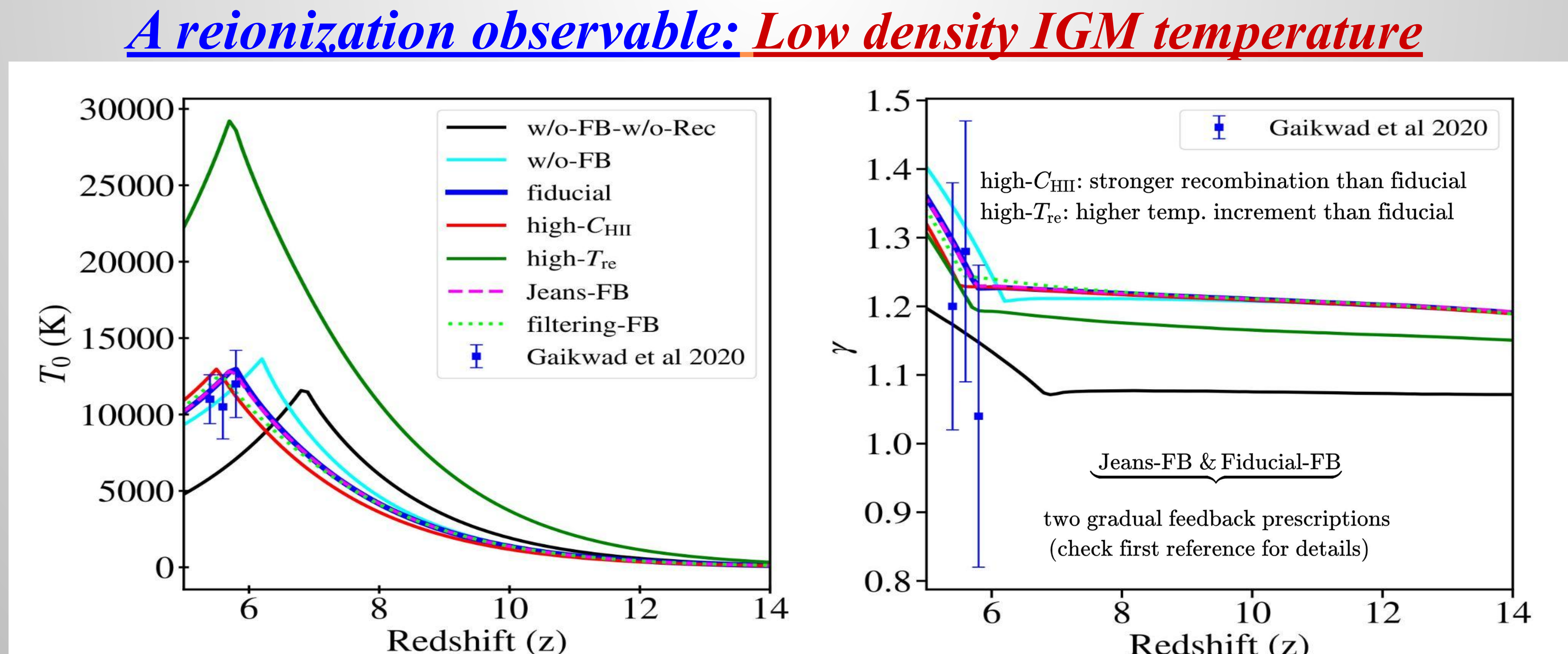
- **We model various physical processes during the reionization using SCRIPT and study their effects on a variety of observables. These processes include** ***1. Thermal evolution of Intergalactic Medium (IGM) during reionization which carries the imprint of reionization process; 2. Inhomogeneous recombination which acts as an opposite effect of ionization; 3. Radiative feedback on reionizing sources (a consequence of reionization heating) by which the star formation at lower mass halos are suppressed.***
- **We use these realistic, efficient models (including various inhomogeneous physical processes) and available observational data (CMB scattering optical depth, UV luminosity functions, low density IGM temperature, model independent limits on ionization fraction) to constrain reionization parameters via Bayesian approach. We also assume that reionization is ended by redshift z~5.3.**
- **We also check the prospects of 21 cm power spectra as a tracer of reionization parameters using realistic mocks (assuming 1000 hrs of SKA like observation) exploiting our photon conserving model.**

Effect of recombination and feedback on reionization evolution



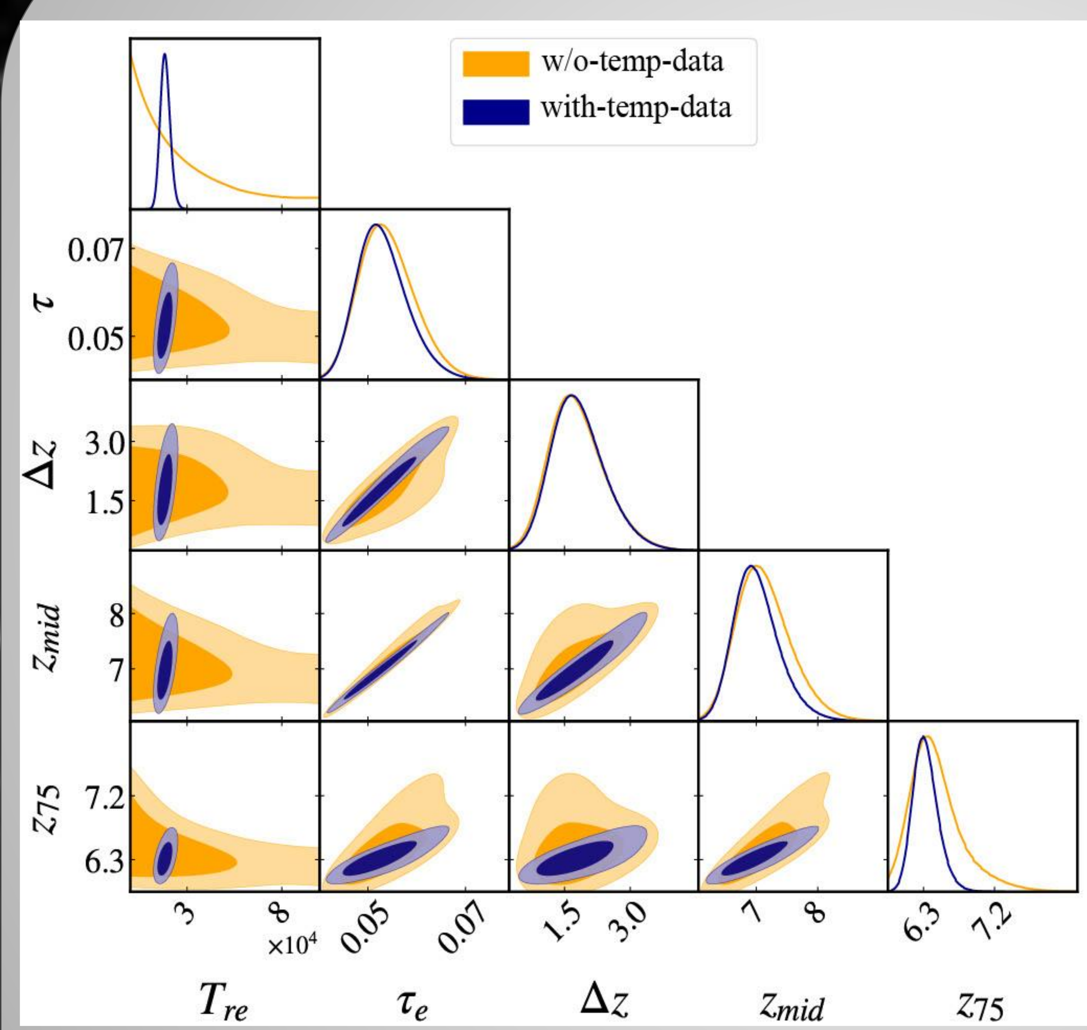
Takeaway: **The colorbar shows the neutral hydrogen fraction of the universe, i.e. reionization proceeds from left to right. The 'fiducial' model contains both recombination and feedback effects (assuming a step like suppression in star formation) whereas the 'w/o-FB' doesn't have feedback and the 'w/o-FB-w/o-Rec' has neither feedback nor recombination. Clearly, both the effects delay the reionization end by shifting it towards lower redshift.**

A reionization observable: Low density IGM temperature



Takeaway: **The low-density IGM temperature follows a power-law relation with the overdensity (known from full hydro-simulations). This can be a potential probe as reionization is associated with the heating of IGM. The left panel shows the redshift evolution of temperature at unit overdensity and the right panel gives the evolution of the power-law index. It can be seen that the model with a very high temperature (i.e green line) is not favored by the already available observational constraints. This in turn put constraints on the strength of feedback during reionization.**

Constraining Reionization parameters using real data (an example)



Free parameter

Temperature increment (T_{re})
(other parameters include ionizing efficiency and escape fraction of photons)

Derived parameters

CMB scattering optical depth (τ_e)

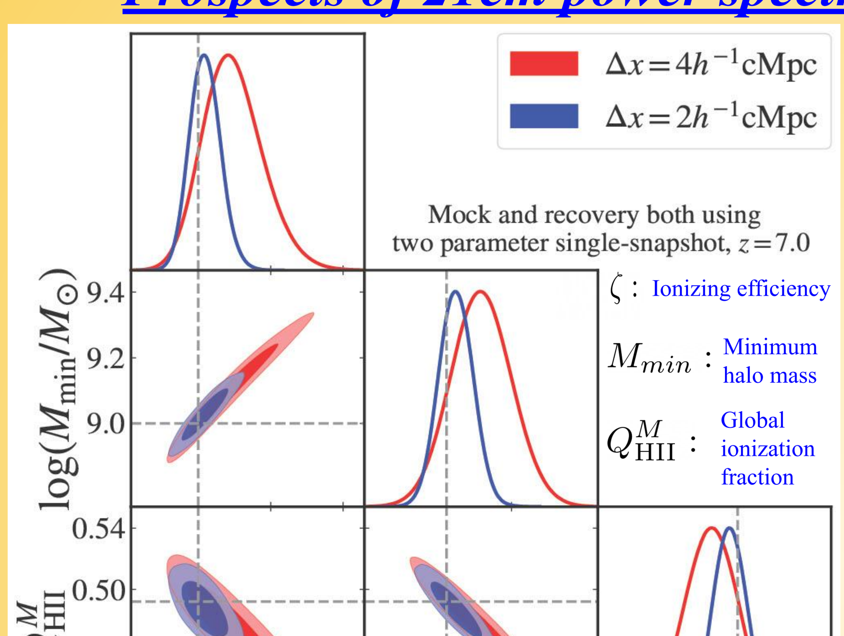
Reionization interval (25% -75% ionization) (Δz)

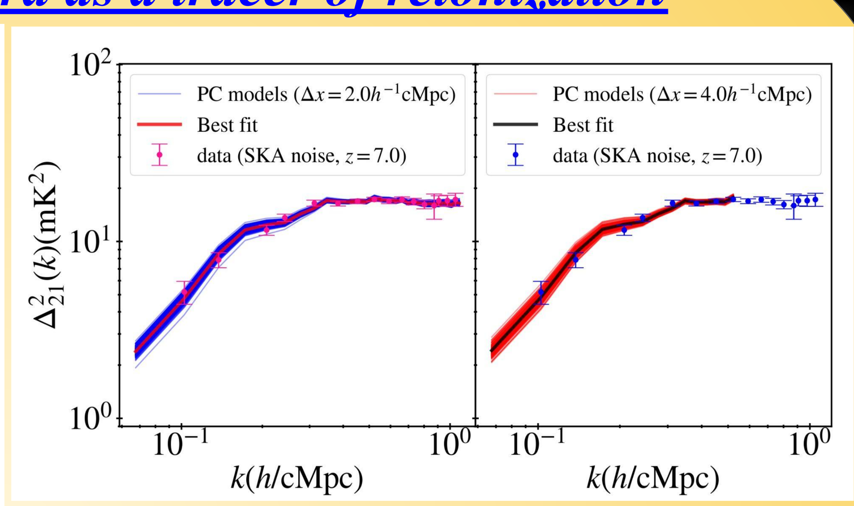
Reionization midpoint (z_{mid})

75% ionization redshift (z_{75})

Takeaway: **The diagonal panels are showing the 1D marginalized posteriors on different parameters and off-diagonal panels are the joint 2D posterior distributions for any couple of parameters. The plots are shown for two cases (i.e with and without including low density IGM temperature data) The inclusion of low density IGM temperature data significantly tightens the parameter spaces.**

Prospects of 21cm power spectra as a tracer of reionization





Takeaway: **Here is an example of parameter recovery with two parameter simple photon conserving model without any recombination / feedback effect. The left figure shows the parameter recoveries and the upper figure shows the 200 random samples from the posterior space along with the mock data. The free parameters are ionizing efficiency and minimum threshold halo mass for star formation. The dashed lines show the input values used for mock generation.**

The goal is to recover the input parameters from the realistic 21 cm mock power spectra (including noise, assuming ~1000 hrs observation of SKA). The input mock is generated using the finer resolution (2 cMpc/h) while the recovery has been made with an initial seed different from the one used for mock generation for two resolutions. The data take into account the contribution from both thermal noise and cosmic variance.

It can be observed that the input parameters (including the globally averaged ionization fraction, which is derived quantity) are reasonably well recovered from the mock 21 cm power spectra for both the resolutions. This result is consistent what we expect from the large scale convergence of the power spectra produced by the photon conserving models.

Conclusions:

- **Inhomogeneous recombination and radiative feedback play crucial roles during reionization which can substantially affect the inferences drawn from observational data.**
- **The low density IGM temperature estimates can be an extremely promising probe of reionization which has not been explored much in the past. This can significantly tighten the parameter space.**
- **We check the prospects of parameter recoveries from 21 cm mocks (including realistic noise) and find that our photon conserving model can provide unbiased estimates (w.r.t resolution) of ionization state of the universe .**

References:

- Maity & Choudhury, MNRAS, 2022a
- Maity & Choudhury, MNRAS, 2022b
- Choudhury & Paranjape, MNRAS, 2018
- Maity & Choudhury, MNRAS, 2023

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