High-Energy Neutrino Production in Clusters of Galaxies

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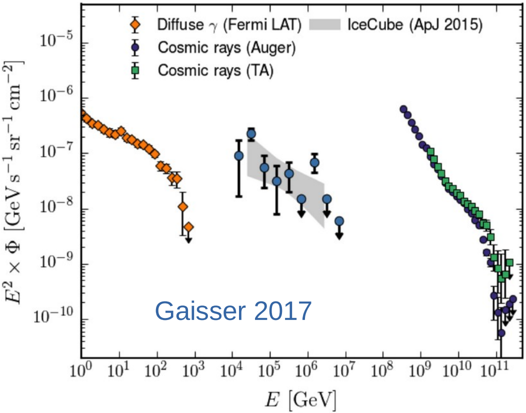
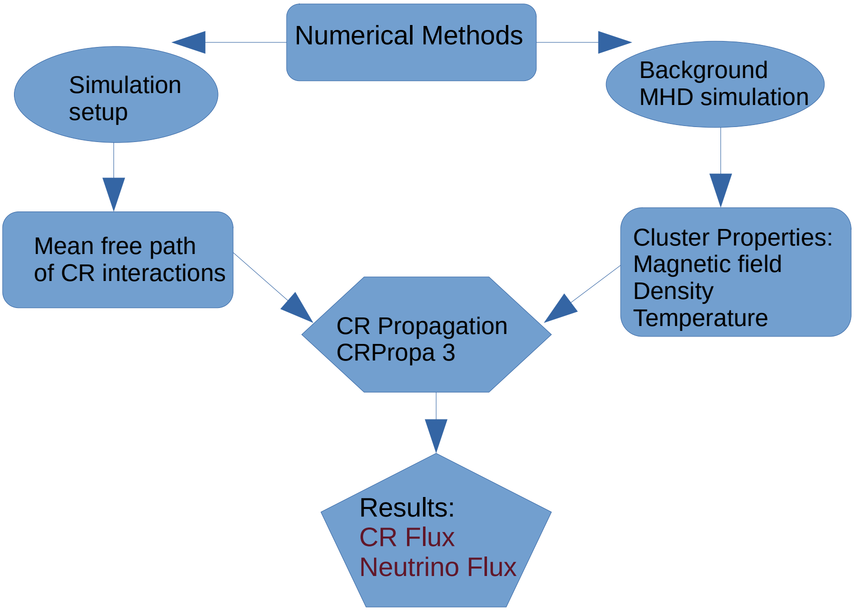
Cosmic-rays, High-Energy Neutrinos and Gamma-rays Connections

- The observed fluxes of High-energy multi-messengers are all comparable
- CRs interactions in ICM can produce them

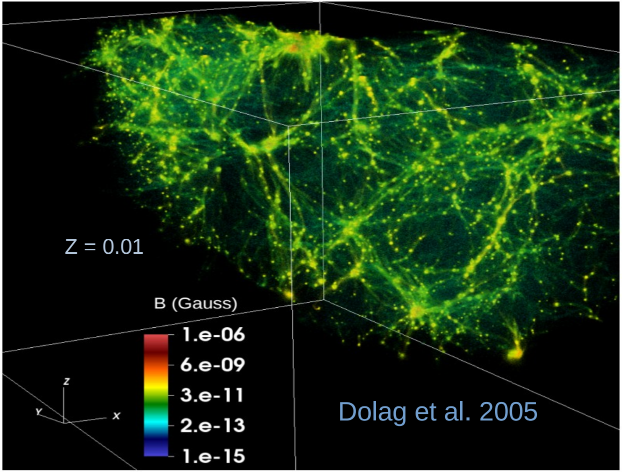


Our Main Goal: **Derive the Contribution of Clusters to the Flux of High-Energy Neutrinos**

Methodology

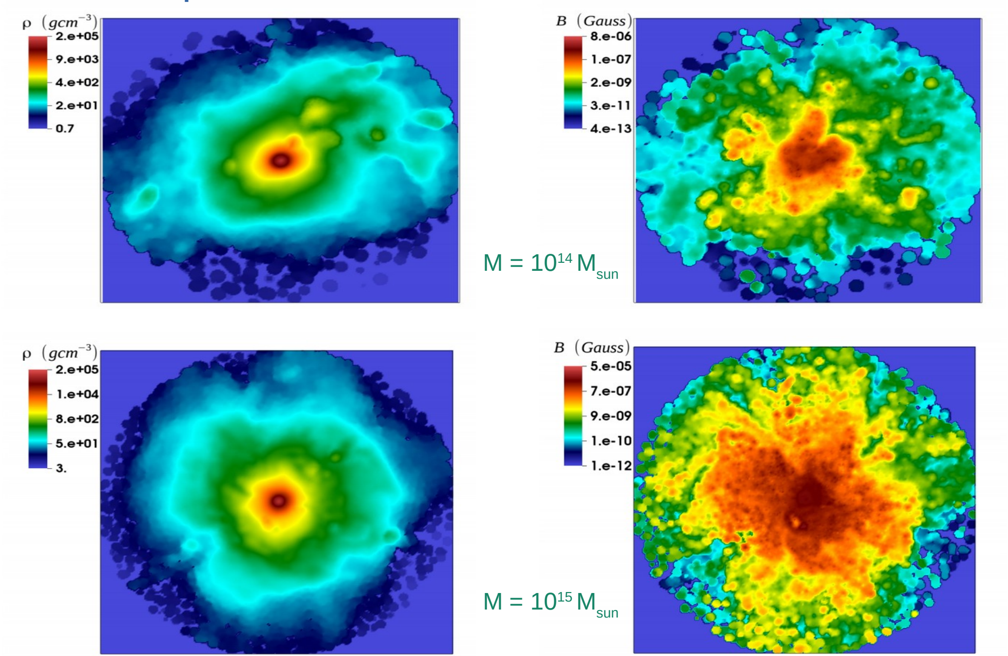


Cosmological MHD Simulations of Cluster of Galaxies



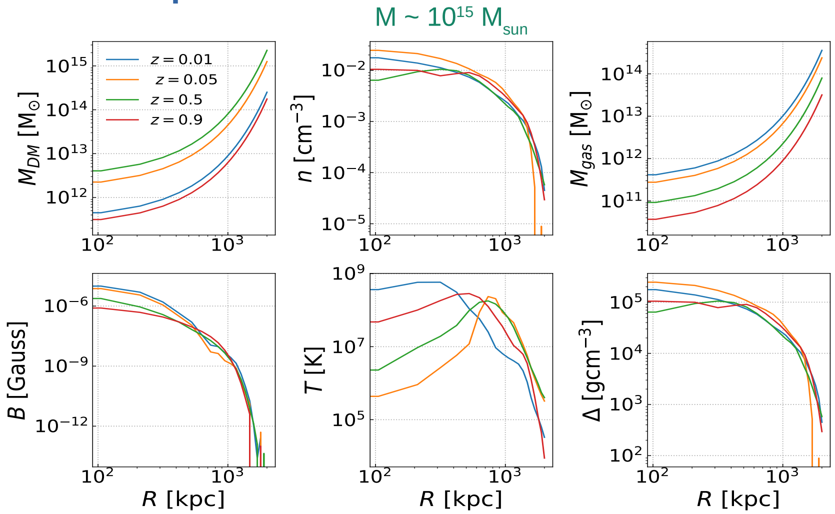
- Large-scale structure of matter, including clusters and filaments
- 1/8 of total volume (= 240 Mpc^3)
- Snapshots: z = 0.01; 0.05; 0.2; 0.5; 0.9; 1.5; 5.0

Cluster Maps



Clusters are not spherically symmetric

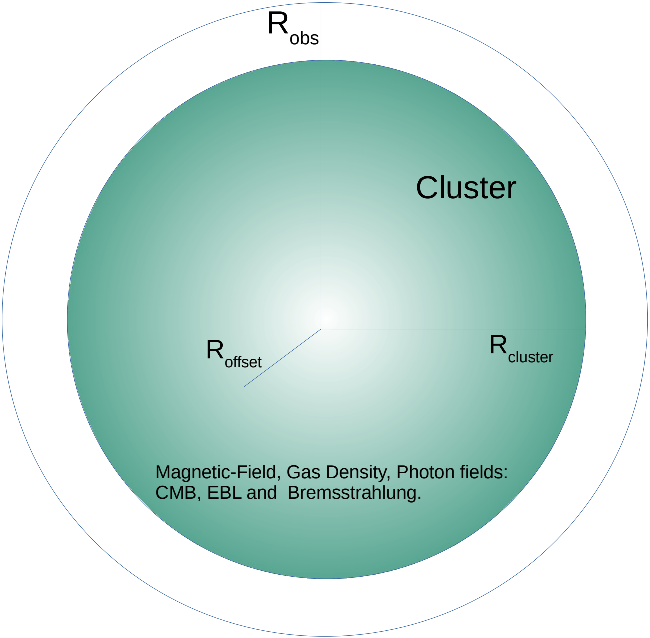
Cluster Properties



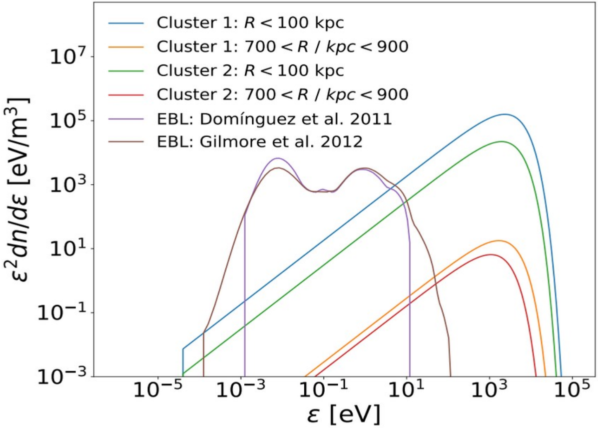
- Profiles of different quantities
- Temperature (T) fluctuations are indicative of the presence of shocks

Hussain et al., MNRAS 2021

Schematic Diagram of CR Simulation



Comparison of Photon Fields

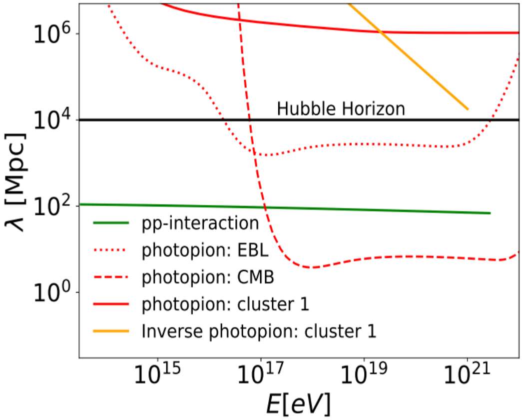


- Bremsstrahlung photon field is dominant at X-rays
- EBL dominates at infrared and optical wavelengths

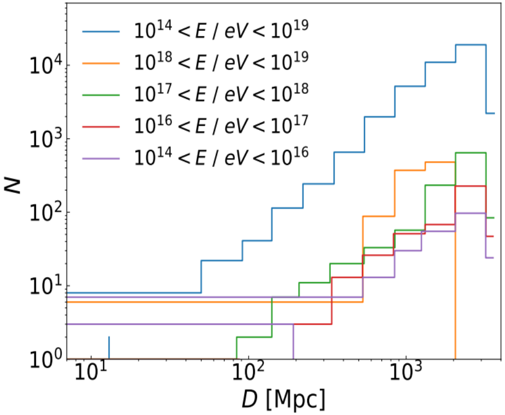
Hussain et al. MNRAS 2021

Mean Free Paths and Trajectory Length

Mean free path of CRs for neutrinos



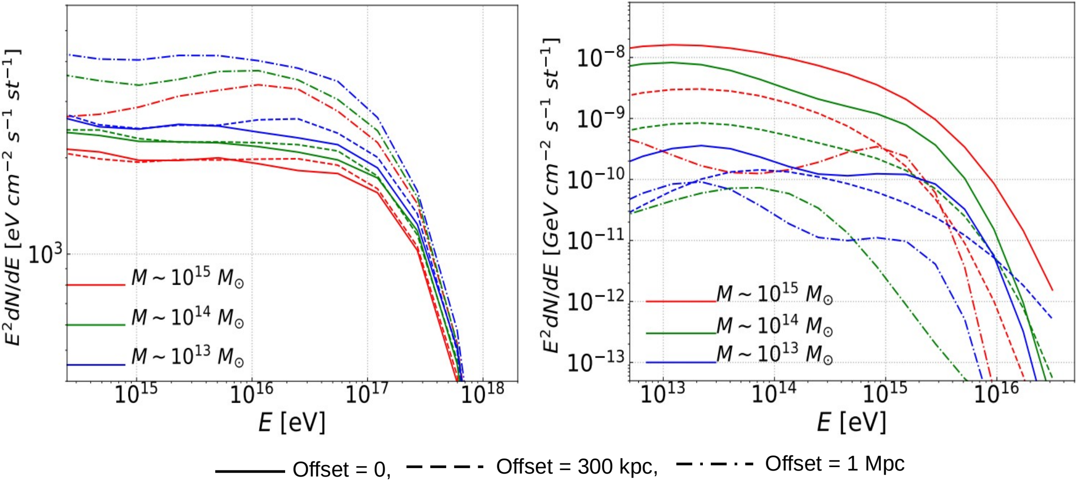
Trajectories length of CRs inside clusters



Mean free path and trajectories length are comparable

Hussain et al., MNRAS 2021

Flux of CRs and Neutrinos: dependence on cluster mass

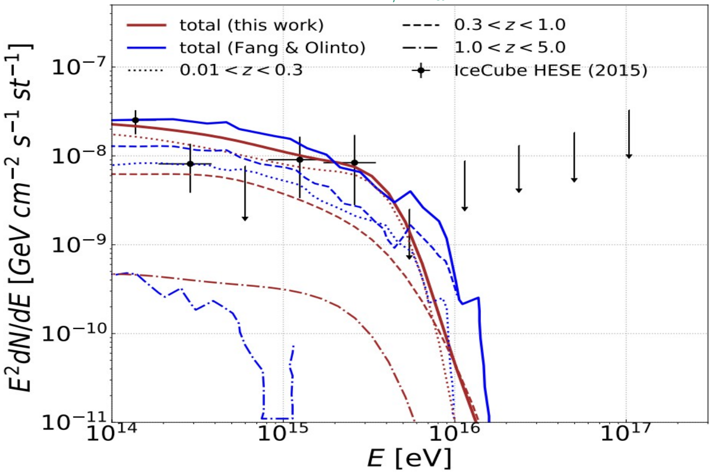


High-energy CRs are more trapped in massive clusters and produce more neutrinos there than in less massive

Hussain et al., MNRAS 2021

Total Flux of Neutrinos: dependence on redshift

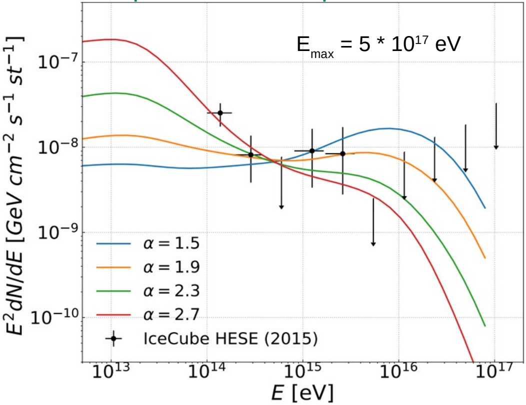
Spectral Index $E^{-1.5}$, $E_{max} = 5 \times 10^{16}$ eV



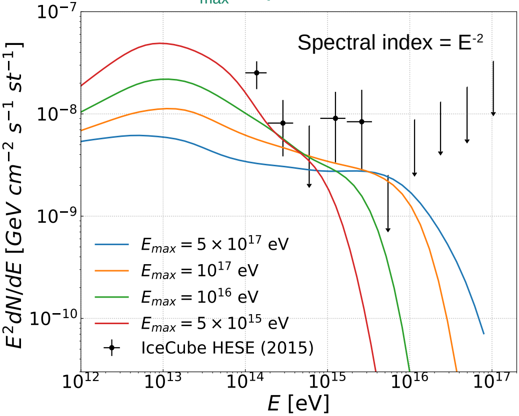
- Clusters at $z \leq 0.3$ amounts for Major contribution (Hussain et al., MNRAS 2021)
- Clusters at $0.3 \leq z \leq 1$ amounts for the largest contribution Fang & Olinto (2016)

Total Flux of Neutrinos: dependence on spectral index and E_{max}

Spectral Index dependence



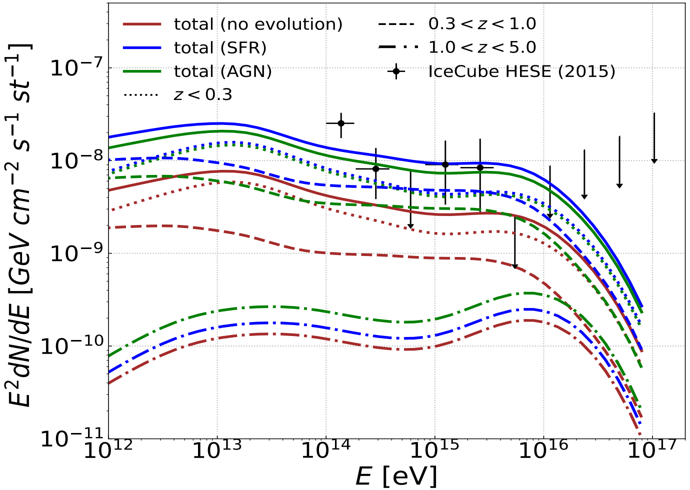
E_{max} dependence



Hussain et al., MNRAS 2021

Total Flux of Neutrinos: effects of CRs source evolution

Spectral index = E^{-2} and $E_{max} = 5 * 10^{17}$ eV



Redshift evolution of CR sources like AGN and SFR can enhance the flux of neutrinos

Hussain et al., MNRAS 2021

Conclusions

- CRs of $E < 10^{17}$ eV are trapped in clusters due to magnetic field ($\sim 10^{-6}$ G) and interactions with the ICM gas.
- Neutrino flux (> PeV) comes from the more massive clusters as they have more CR interactions
- Most of the neutrino flux comes from nearby clusters at $z < 0.3$ (which has more massive clusters).
- Redshift evolution of CR sources like AGN and SFR, enhance the flux of neutrinos.
- The integrated neutrino flux from ICM can account for sizeable percentage of the IceCube observations, mainly in energy range 100 TeV - 10 PeV.
- For details see, Hussain et al., MNRAS 2021, arXiv: 2101.07702.