Multi-Messenger and Multi-Wavelength emission from Galaxy Clusters hosting AGNs



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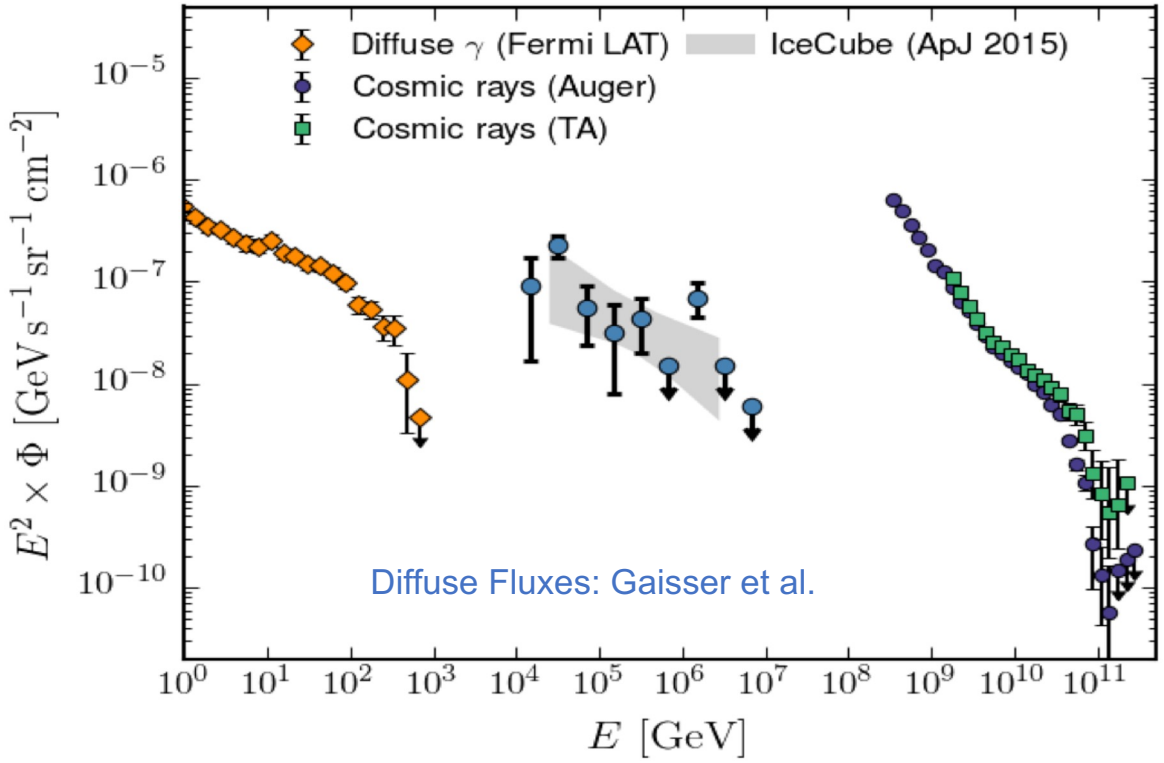
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Rafael Alves Batista (IAP Paris, France)

Elisabete Maria de Gouveia Dal Pino (IAG – USP, Brazil)

Motivation

High-energy diffuse fluxes are comparable

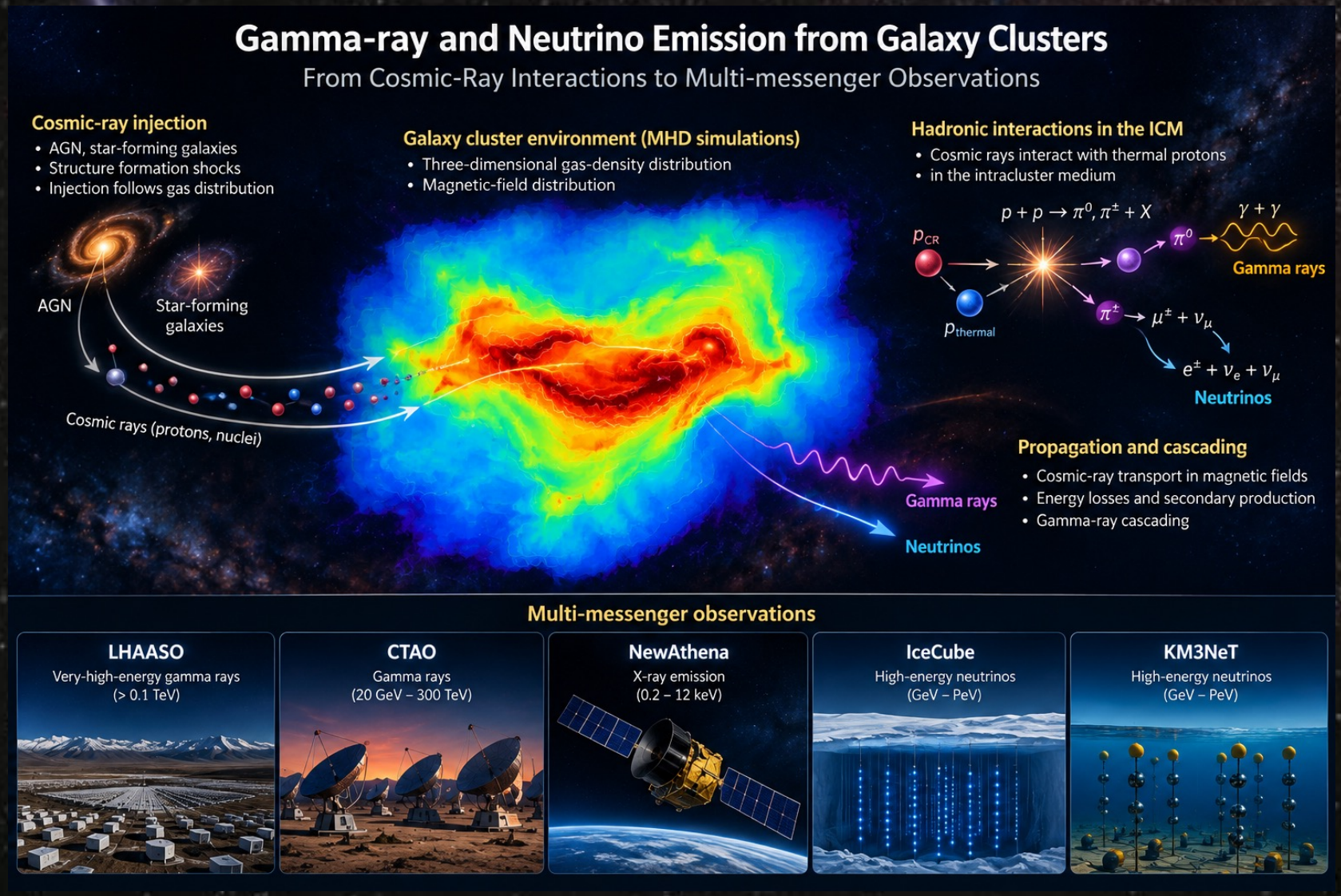


MAYBE

Galaxy Clusters hosting AGN are suitable candidates for diffuse multi-messenger:
size ~ 1 Mpc, B ~ 10^{-6} G,
n ~ 10^{-2} cm^{-3} & T ~ 10^{8} K

- ***CRs, neutrinos and gamma rays have common origin?***
- ***Single class of astrophysical sources can produce them?***

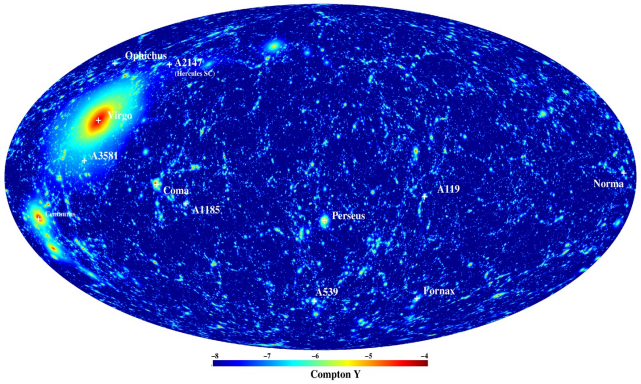
WORKFLOW


Gamma-ray and Neutrino Emission from Galaxy Clusters
From Cosmic-Ray Interactions to Multi-messenger Observations
Cosmic-ray injection
• AGN, star-forming galaxies
• Structure formation shocks
• Injection follows gas distribution
AGN
Star-forming galaxies
Cosmic rays (protons, nuclei)
Galaxy cluster environment (MHD simulations)
• Three-dimensional gas-density distribution
• Magnetic-field distribution
Hadronic interactions in the ICM
• Cosmic rays interact with thermal protons
• in the intracluster medium
$p + p \rightarrow \pi^0, \pi^\pm + X$
p_{CR}
$p_{thermal}$
π^0
$\gamma + \gamma$
Gamma rays
$\pi^\pm$
$\mu^\pm + \nu_\mu$
$e^\pm + \nu_e + \nu_\mu$
Neutrinos
Gamma rays
Neutrinos
Propagation and cascading
• Cosmic-ray transport in magnetic fields
• Energy losses and secondary production
• Gamma-ray cascading
Multi-messenger observations
LHAASO
Very-high-energy gamma rays
(> 0.1 TeV)
CTAO
Gamma rays
(20 GeV – 300 TeV)
NewAthena
X-ray emission
(0.2 – 12 keV)
IceCube
High-energy neutrinos
(GeV – PeV)
KM3NeT
High-energy neutrinos
(GeV – PeV)

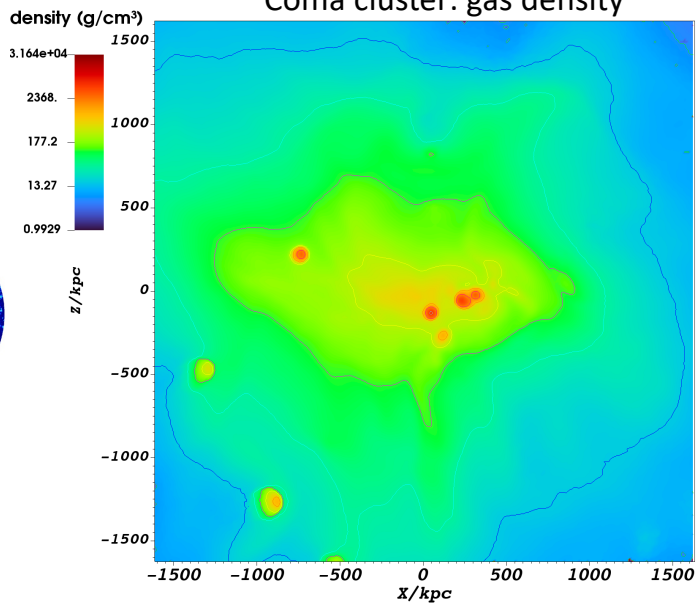
MHD Simulations of Galaxy Clusters hosting AGN

MHD simulation provides the background environment of galaxy clusters across redshift

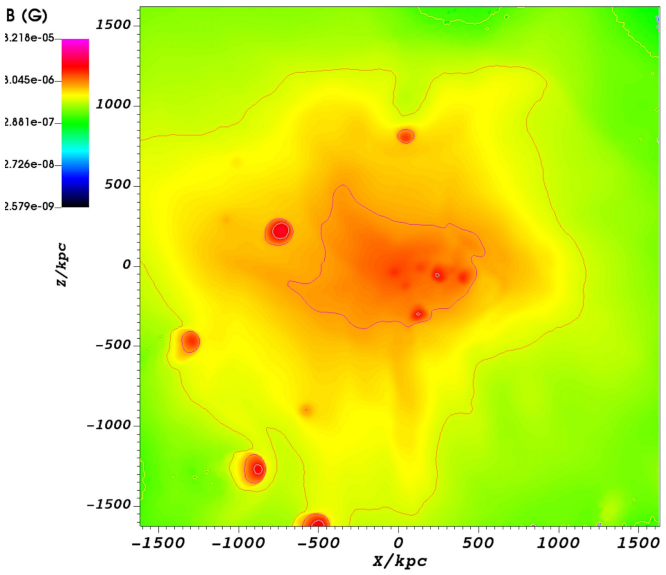
MHD SLOW simulation: cross identified local galaxy clusters within 500 Mpc
Dolag et al. 2023



Coma cluster: gas density



Coma cluster: BField



MHD + Monte Carlo simulations

SLOW Sim.: Magnetic-field, Gas density, Bremsstrahlung radiation
Background photo fields: CMB, EBL, and Radio background

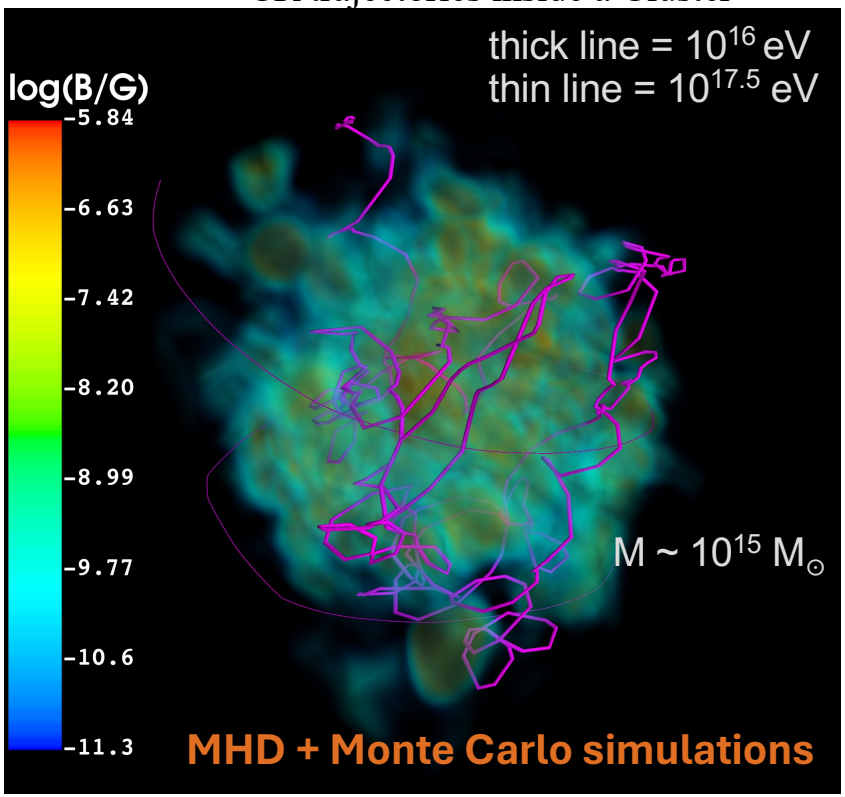
Monte-Carlo code: CRPropa3
Cosmic Ray Propagation
(Hadronic and leptonic)

Interactions: photohadronic, photonuclear, hadronuclear, and electromagnetic cascade

Low energy ($<10^{17}$ eV) CRs: Diffusive
High Energy ($> 10^{17}$ eV) CRs:
Semi-diffusive or Ballistic

Computationally very expensive: Tackled with AI/ML

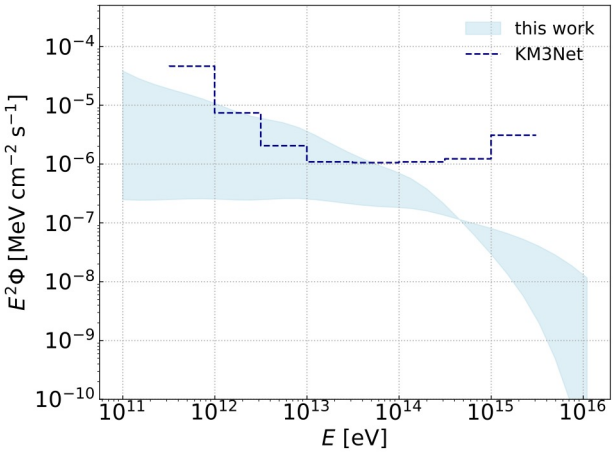
CR trajectories inside a Cluster

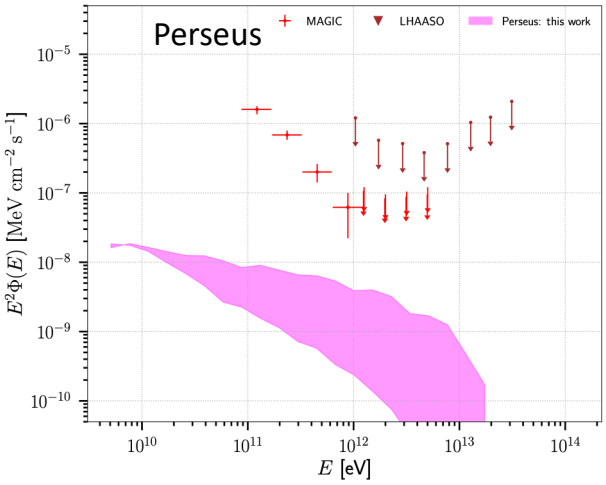


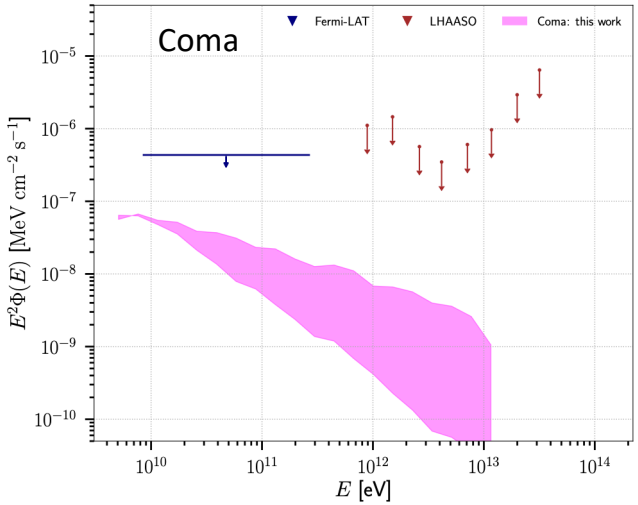
Hussain et al. Nat. Commun.

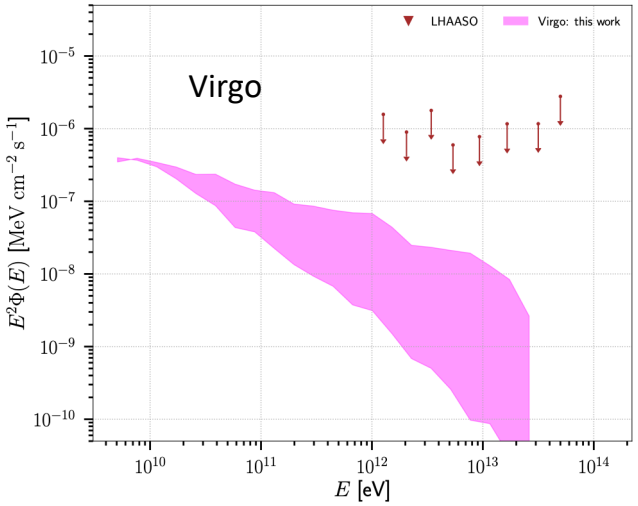
Gamm rays and neutrino from individual clusters

Parameters:
Index = 2.0 - 2.5
$E_{max} = 10^{16} – 10^{17}$ eV
$X_{CR} = E_{CR} / E_{thermal} = 0.01$







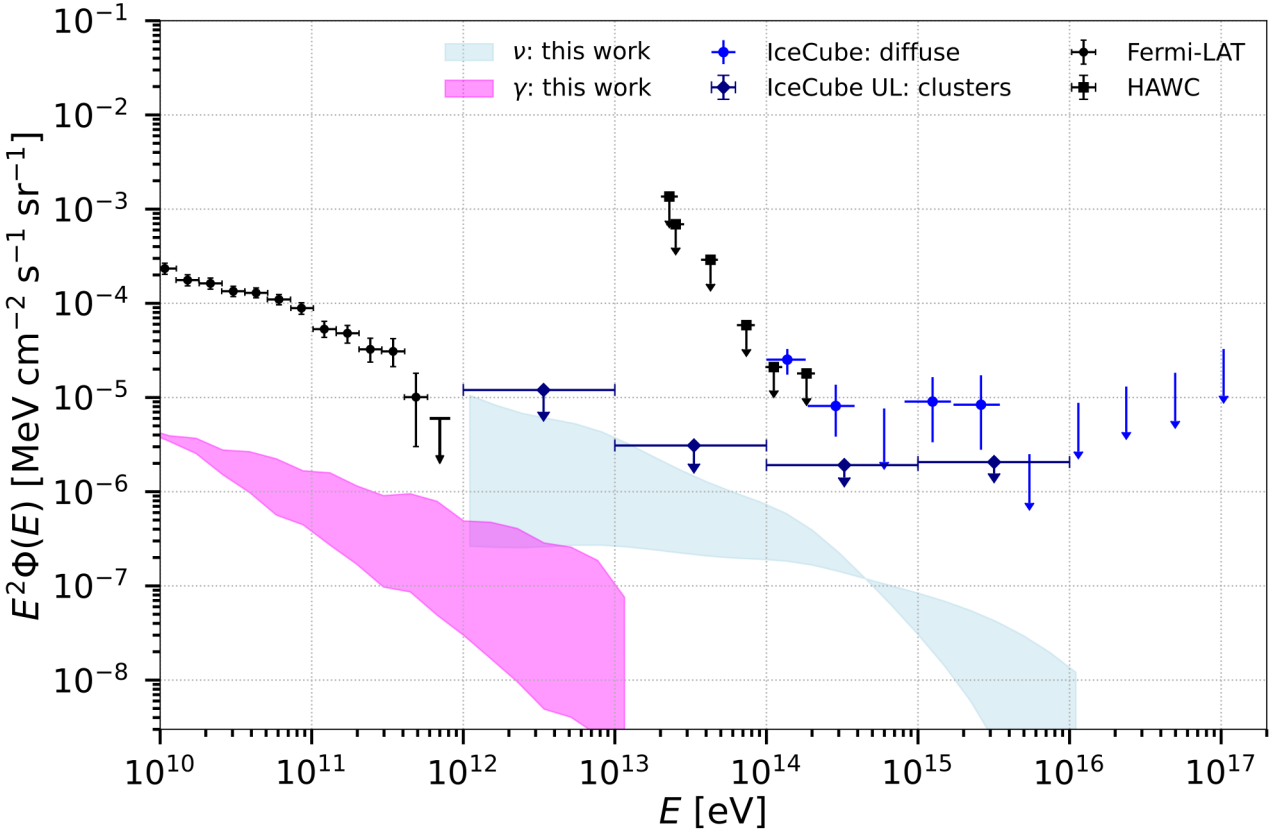


Integrated Gamma-ray and Neutrino Emission from Galaxy Clusters

Galaxy Clusters (GC):
within 500 Mpc & M > 10^{14} M_{sun}

GC contribution to diffuse
Gamma-ray background is limited

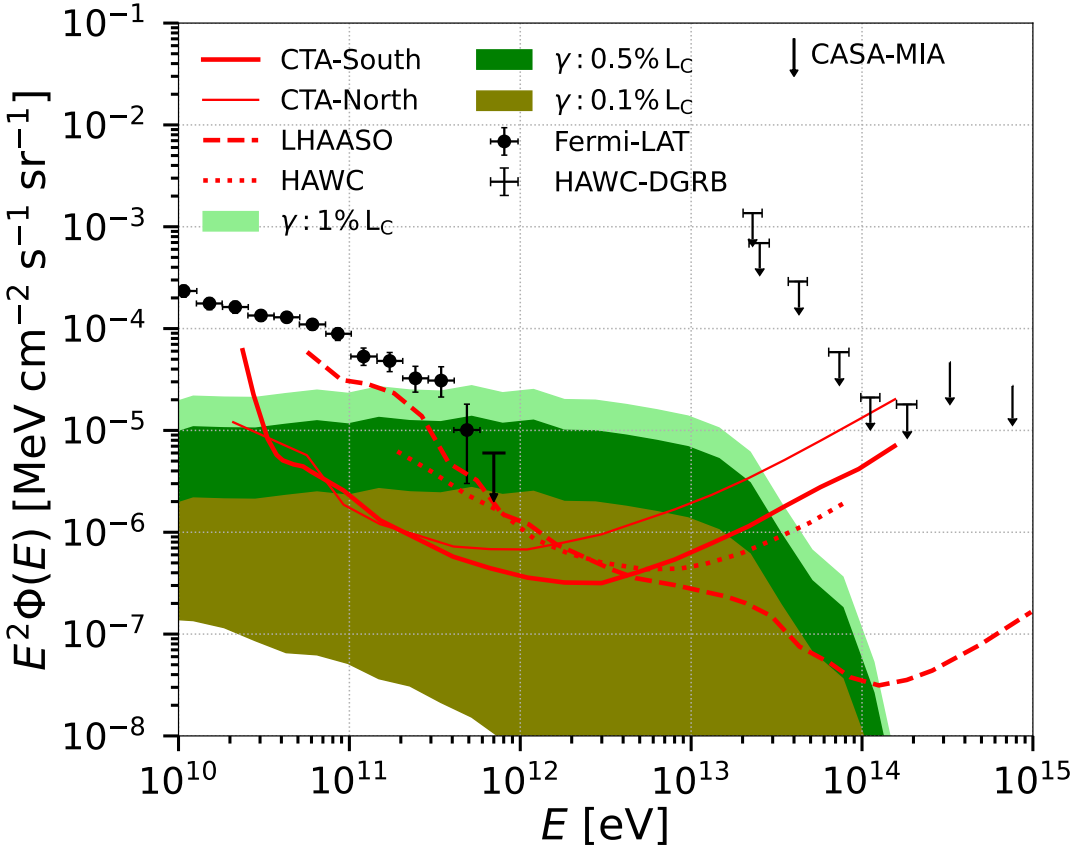
GC contribution to diffuse
Neutrino background is comparable
with the IceCube upper limits



S. Hussain et al. 2026

Gamma-ray observations

Comparing with sensitivities
Of gamma-ray observatories



Multi-Messenger Testing: Facilities like POEMMA can determine if cluster-center AGNs generate detectable high-energy gamma-ray and neutrino signatures.

Next step | A machine-learning emulator for galaxy clusters

Physical Input
- Cluster mass and distance
- Gas-density profile
- Magnetic-field profile
- CR spectral index, Emax and normalization

Simulation Library
- MHD cluster environments
- CRPropa transport and interactions
- Gamma-ray and neutrino spectra
- Parameter variations where available

Predictions
- Gamma-ray spectra
- Neutrino spectra
- Fast parameter exploration
- Uncertainty estimates

Done

Goal: **predict emission from new clusters without rerunning the full Monte Carlo pipeline.**

ML Emulator
Gaussian Processes
Gradient-boosted trees
Neural networks

Probing Cluster Magnetic Fields with Multimessenger Emission

Gamma rays — Fermi-LAT, CTAO, LHAASO
Spectral shape, spatial morphology and limits; attenuation and electromagnetic cascades

Neutrinos — IceCube, KM3NeT
Hadronic emission and upper limits; complementary to gamma-ray constraints

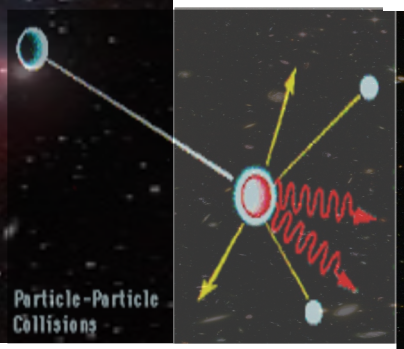
Inference strategy / first test: Nearby clusters Perseus and Coma

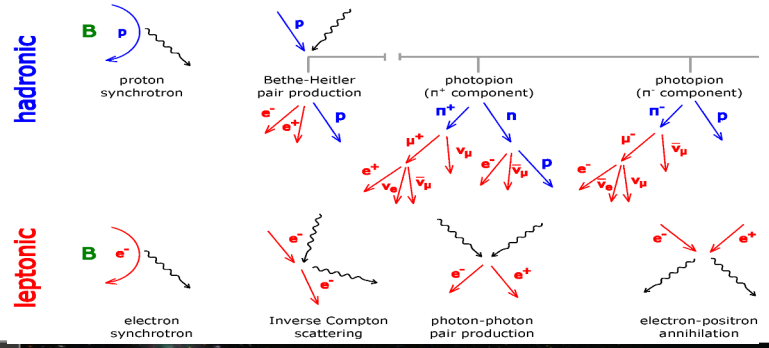
- Vary B_o, radial profile and turbulence coherence scale
- first fix CR injection
- then vary it to quantify degeneracies.
- Use an ML emulator + Bayesian inference to accelerate parameter exploration.

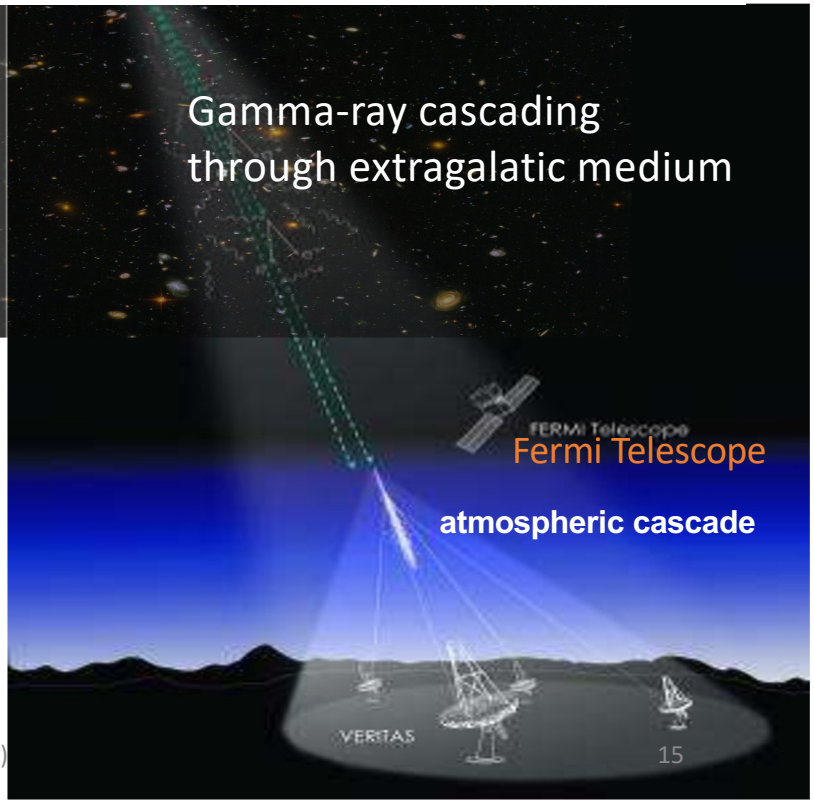
- **Magnetic-field constraints are model-dependent; X-ray and radio information can help break degeneracies.**
- **Identifying which combinations of gamma-ray, neutrino, X-ray, and radio observations can actually break these degeneracies.**

Thanks



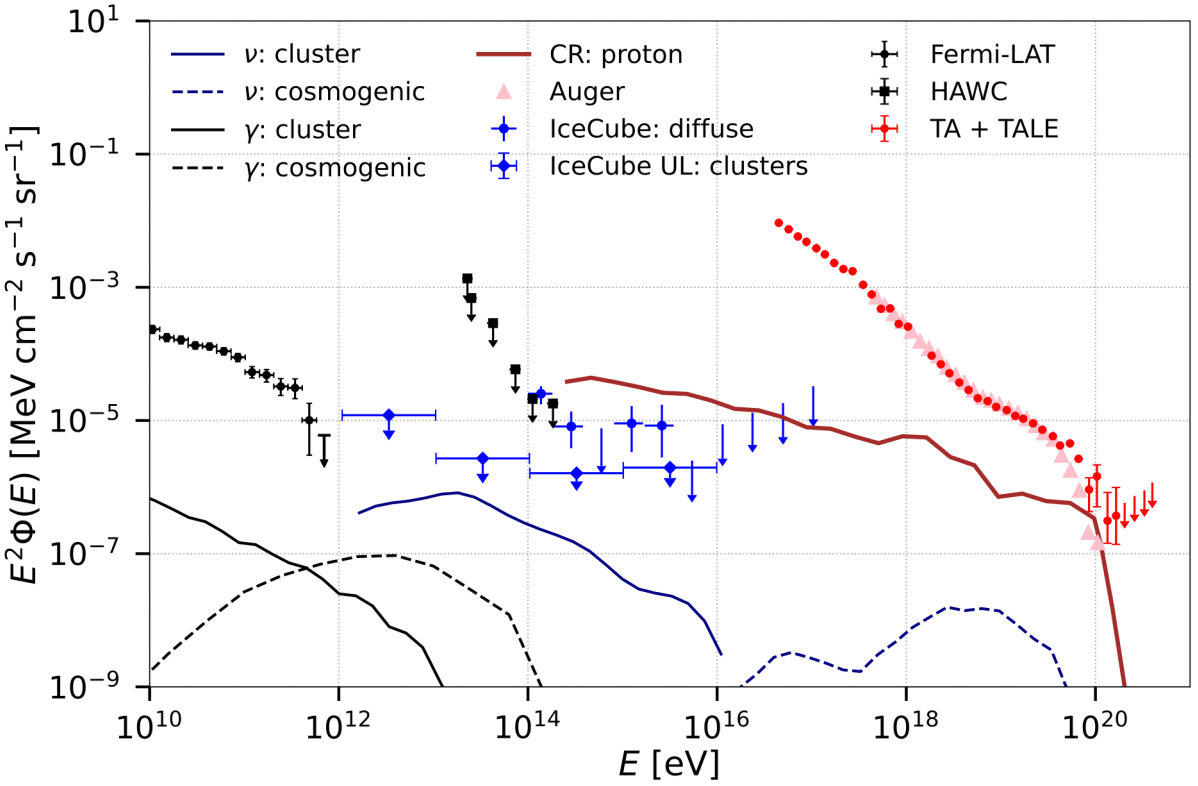






Methodology

Results



Hussain et al., ICRC, 2023