

Contribution of Galaxy Clusters to Diffuse Gamma-rays and Neutrinos

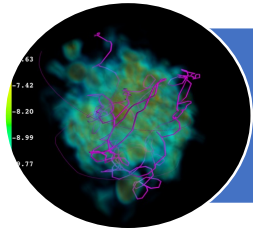
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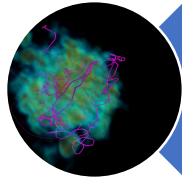
Elisabete M. de Gouveia Dal Pino, Rafael Alves Batista, Klaus Dolag



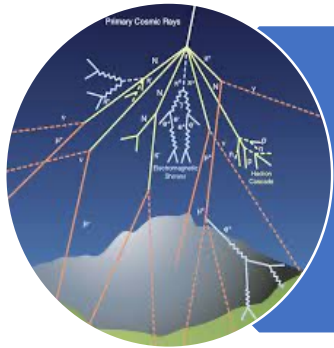
Outline



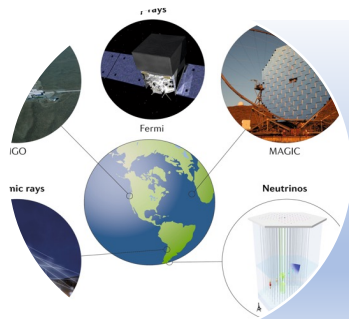
Cosmic-rays and clusters of galaxies



Propagation and interactions of cosmic rays:
MHD and Monte-Carlo simulations

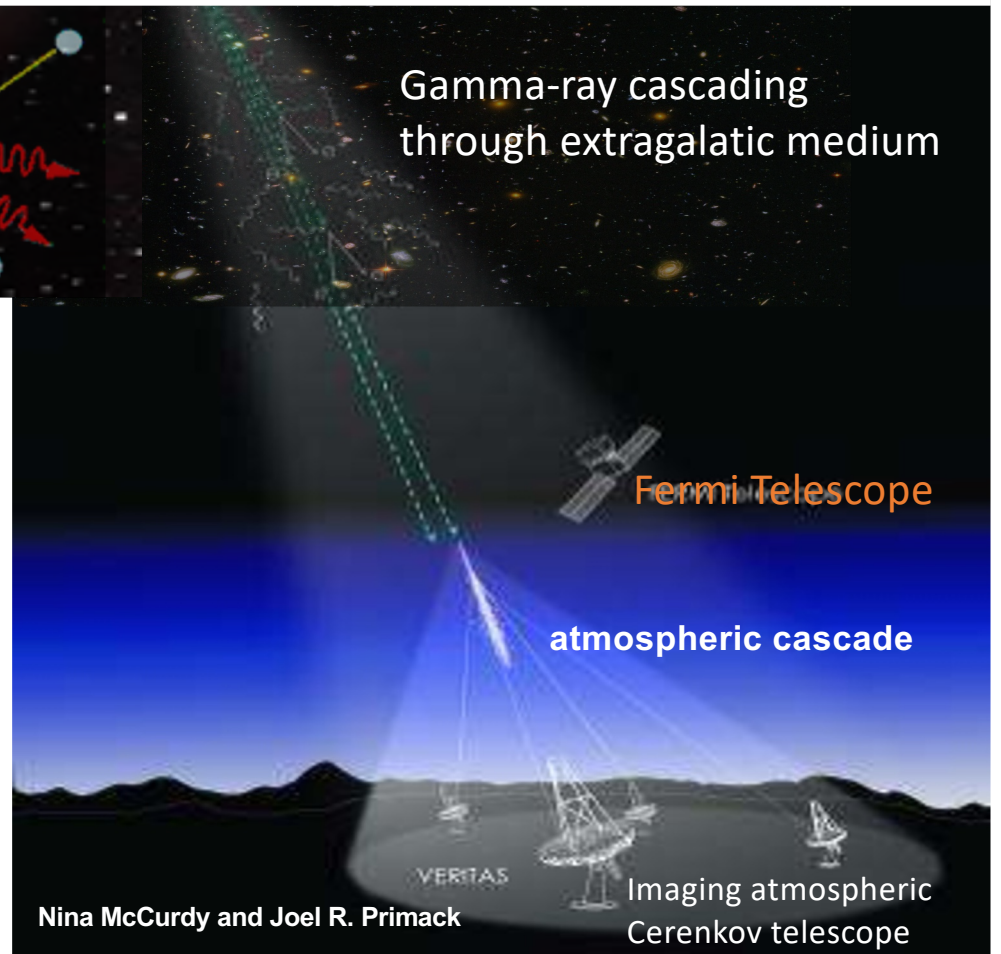
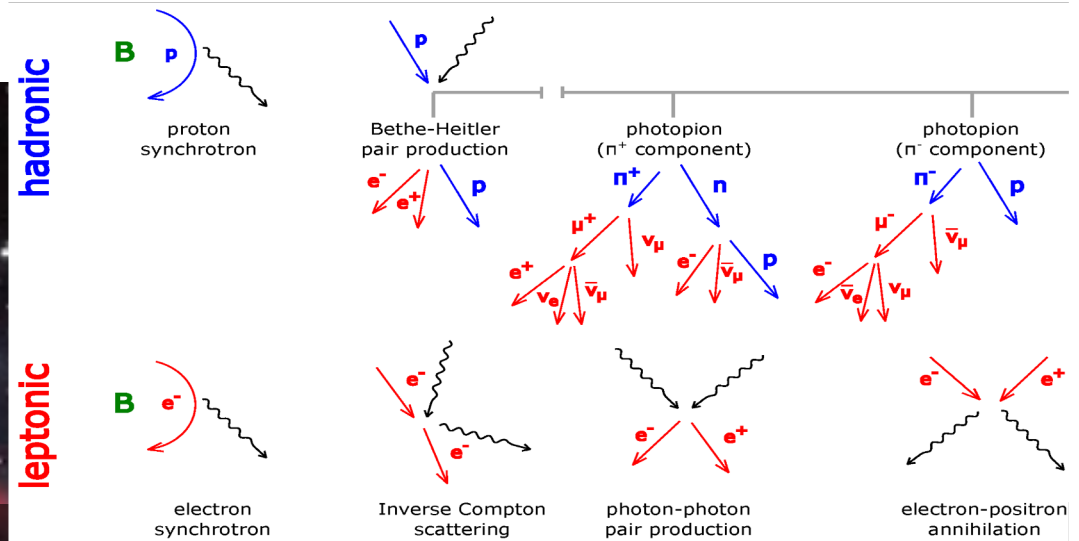
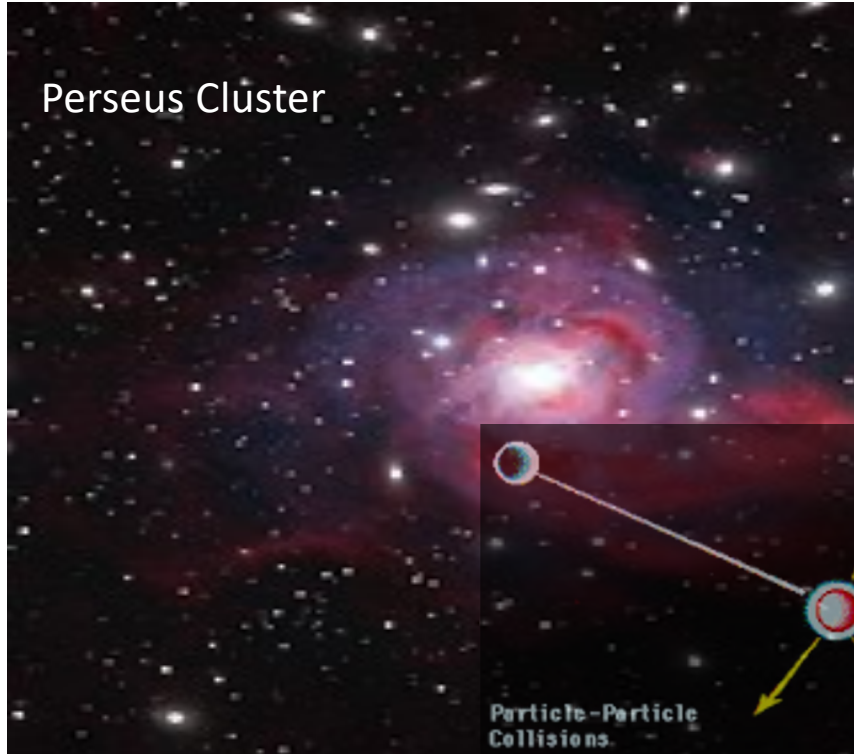


Linking complementary high-energy astrophysical messengers:
Cosmic rays, Neutrino, and Gamma rays



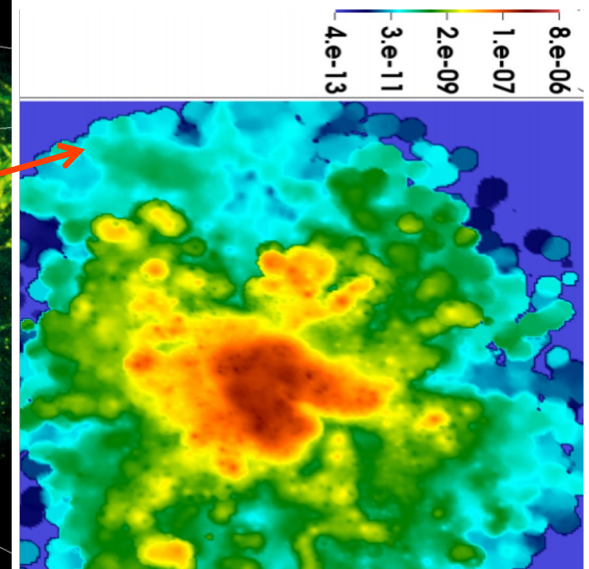
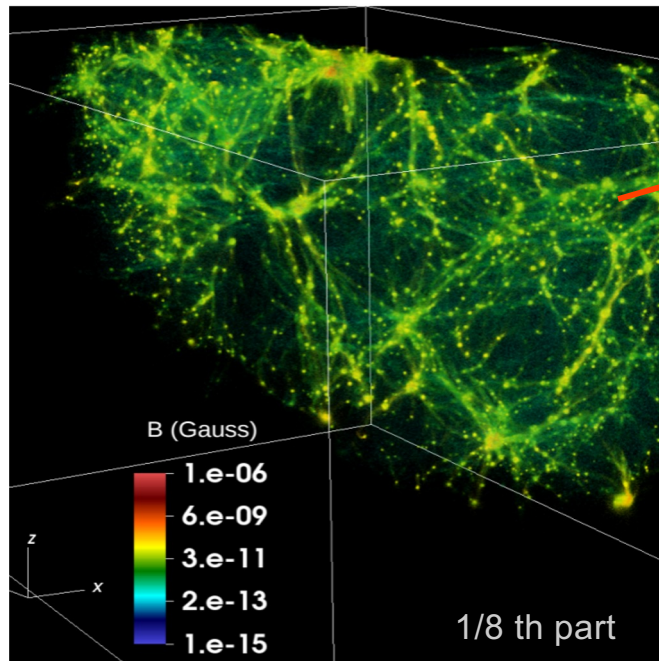
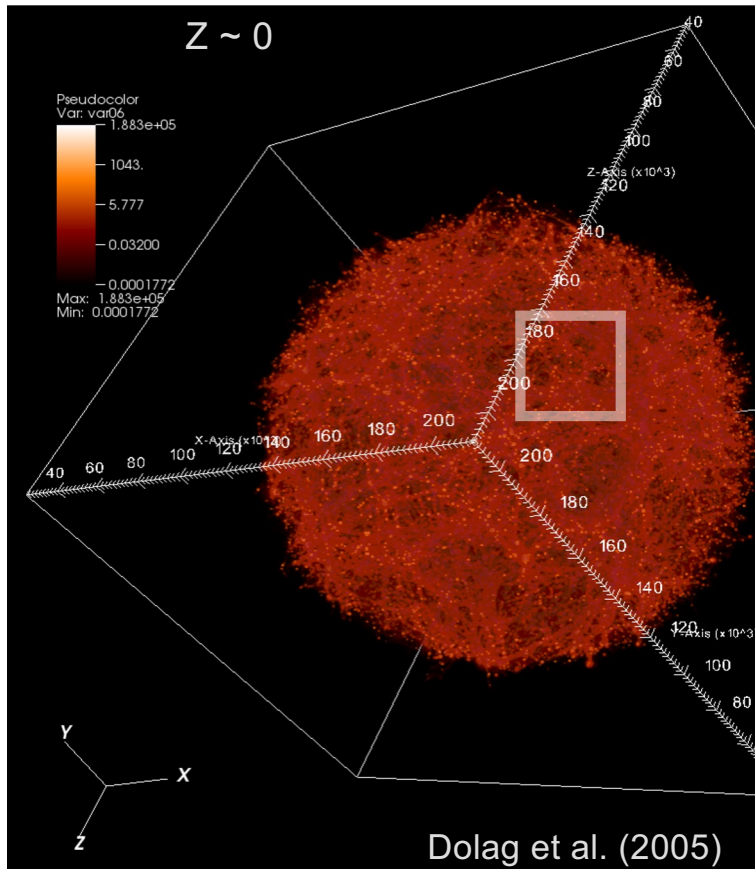
Multi-messenger Common Sources?

Schematic Diagram



High-energy multi messengers
Emission and Observations

Cosmological 3D-MHD simulation



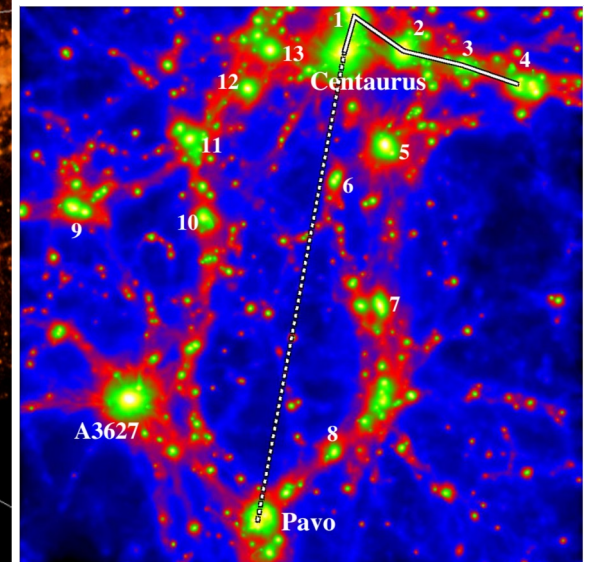
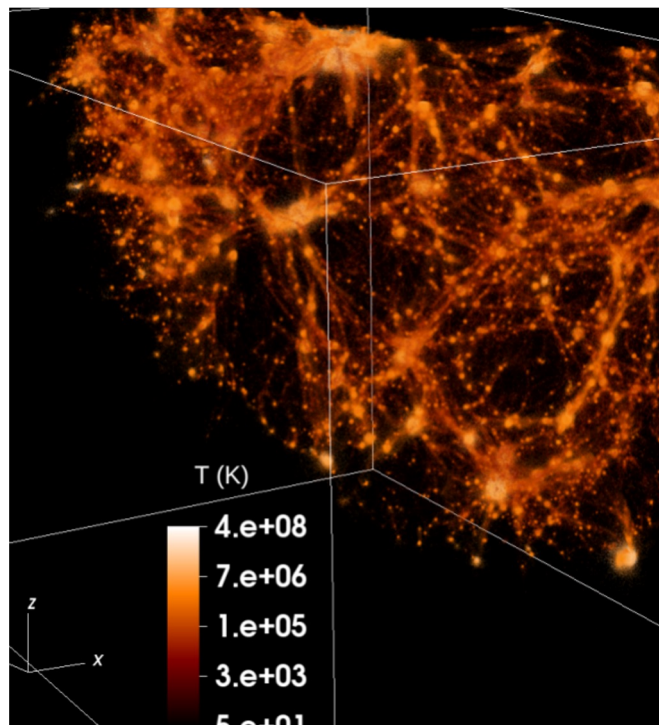
$$M \sim 10^{14.5} M_{\text{sun}}$$

SPH GADGET simulations
(Springel 2005)

Large-scale structure, filaments, and clusters, $z < 5.0$

seed magnetic field $\sim 10^{-12}$ [G]

Maximum spatial resolution ~ 10 kpc



CR Propagation Simulation

Mass range: $10^{12} < M/M_{\odot} < 10^{15.5}$

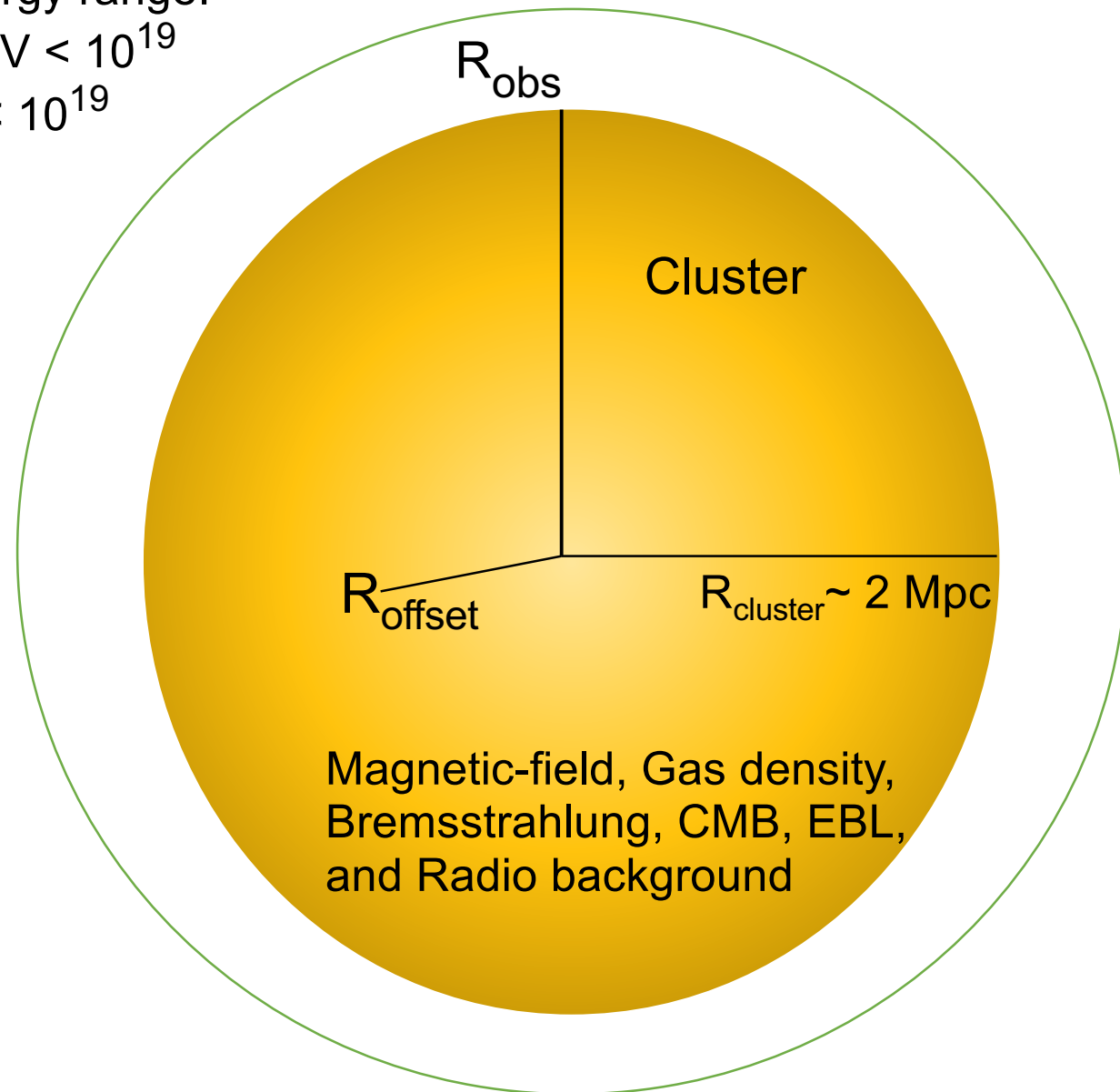
Injected CR (proton) energy range:

Gamma-rays: $10^{11} < E/\text{eV} < 10^{19}$

Neutrinos: $10^{14} < E/\text{eV} < 10^{19}$

Redshift = $z < 5.0$

$R_{\text{offset}} = 300 \text{ kpc}, 1 \text{ Mpc}$



CR trajectories inside a Cluster

For $E = 10^{17}$ eV, $B = 10^{-6}$ G,

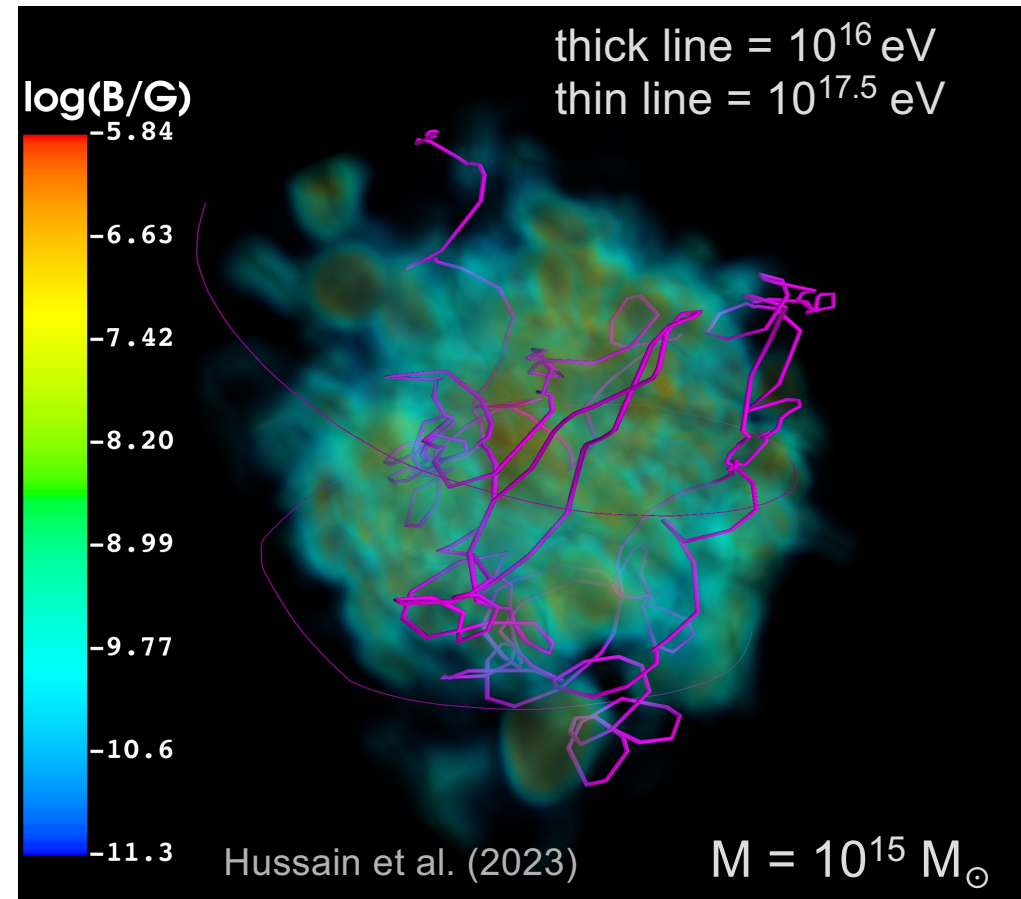
Larmor Radius $\sim 1.08(E/10^{15} \text{ eV}) / Z (B/\mu\text{G}) \text{ pc} \sim 100 \text{ pc}$

Low energy ($< 10^{17}$ eV) CRs: Diffusive

High Energy ($> 10^{17}$ eV) CRs:

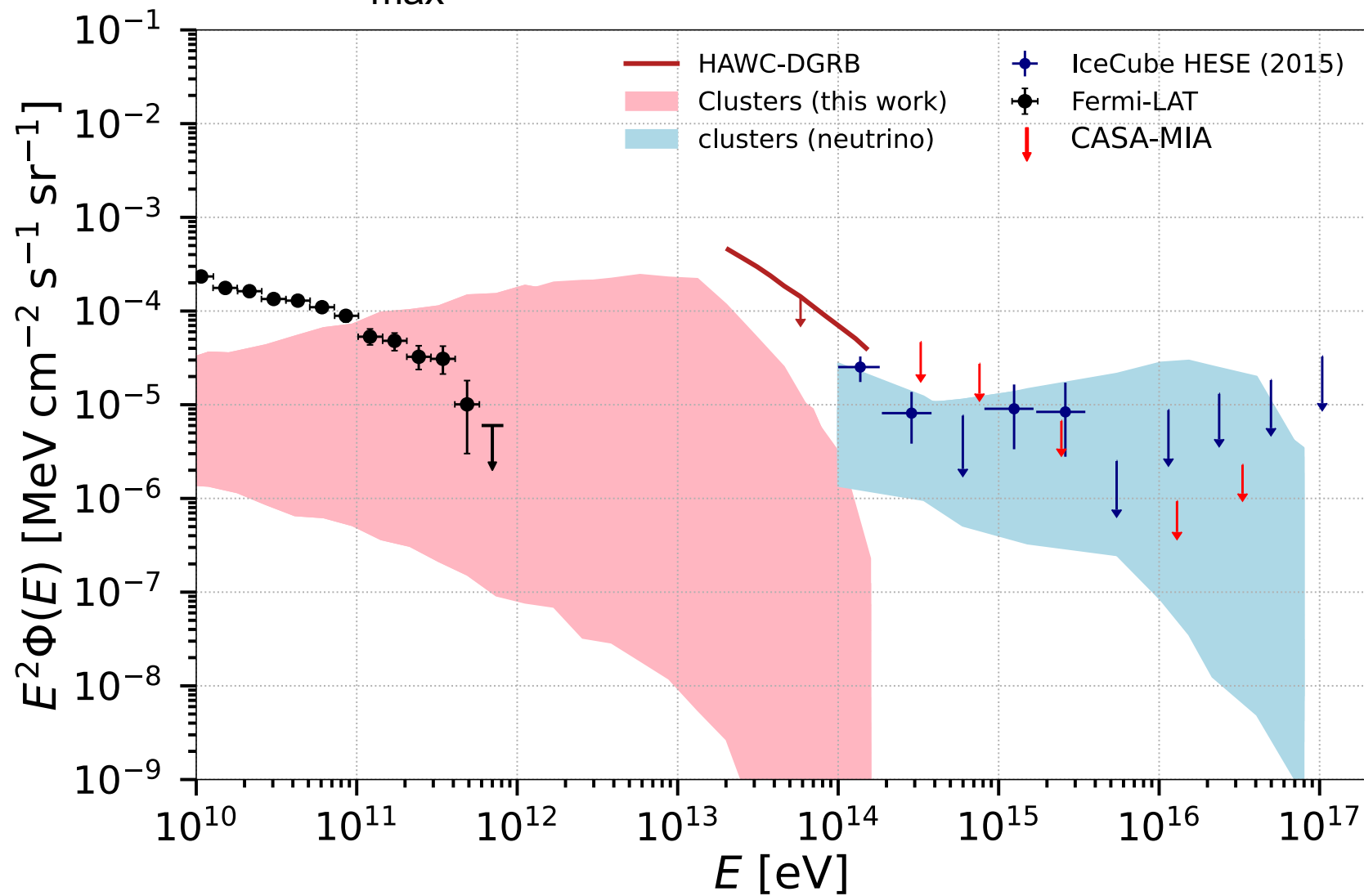
Semi-diffusive or Ballistic

Combined cosmological MHD simulations
with Monte Carlo simulations



Gamma-rays and neutrinos from clusters of galaxies

$$E_{\text{max}} = 10^{16} - 10^{17} \text{ eV}, \alpha = 1.5 - 2.5$$

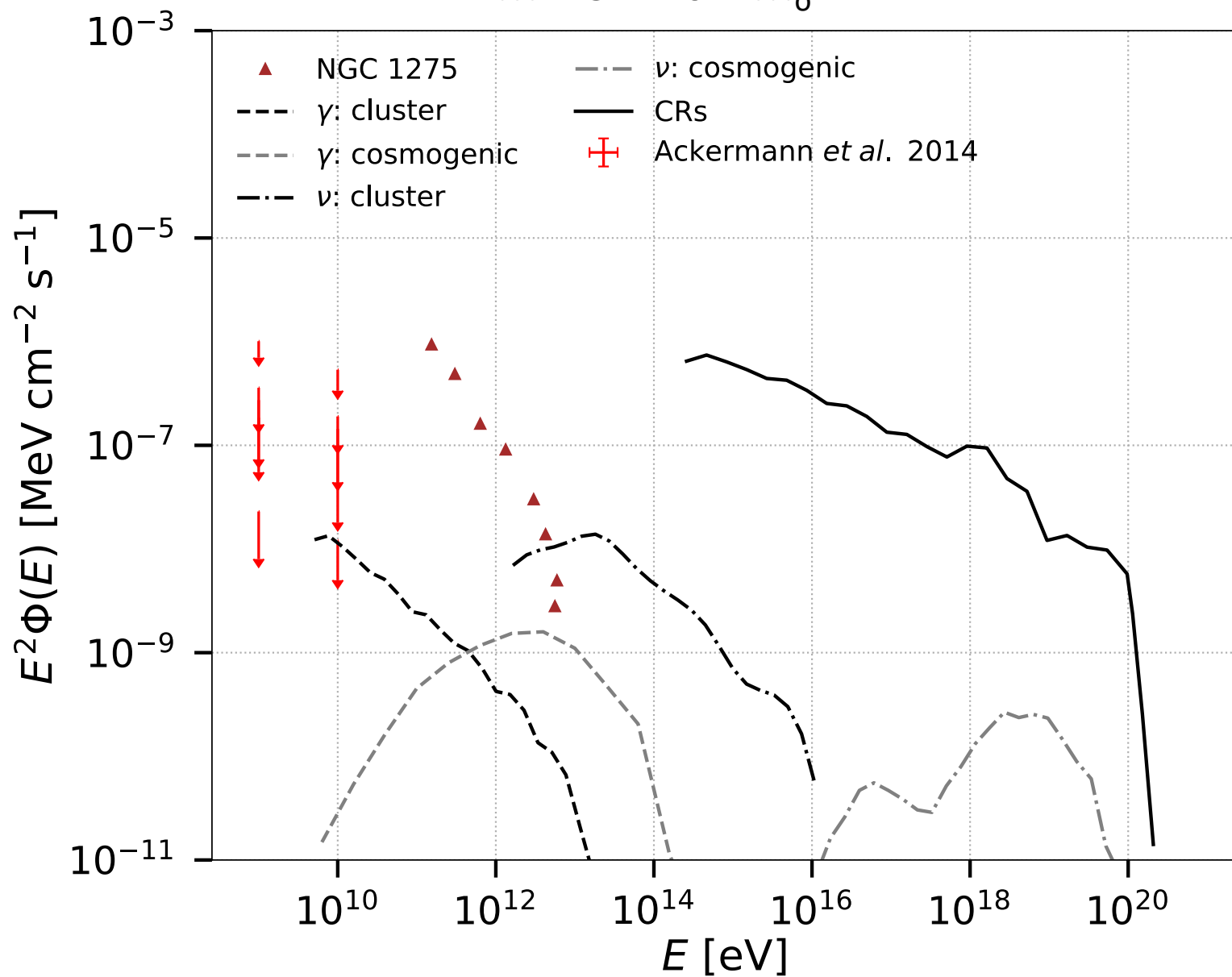


Multi-messenger from Perseus-like Cluster

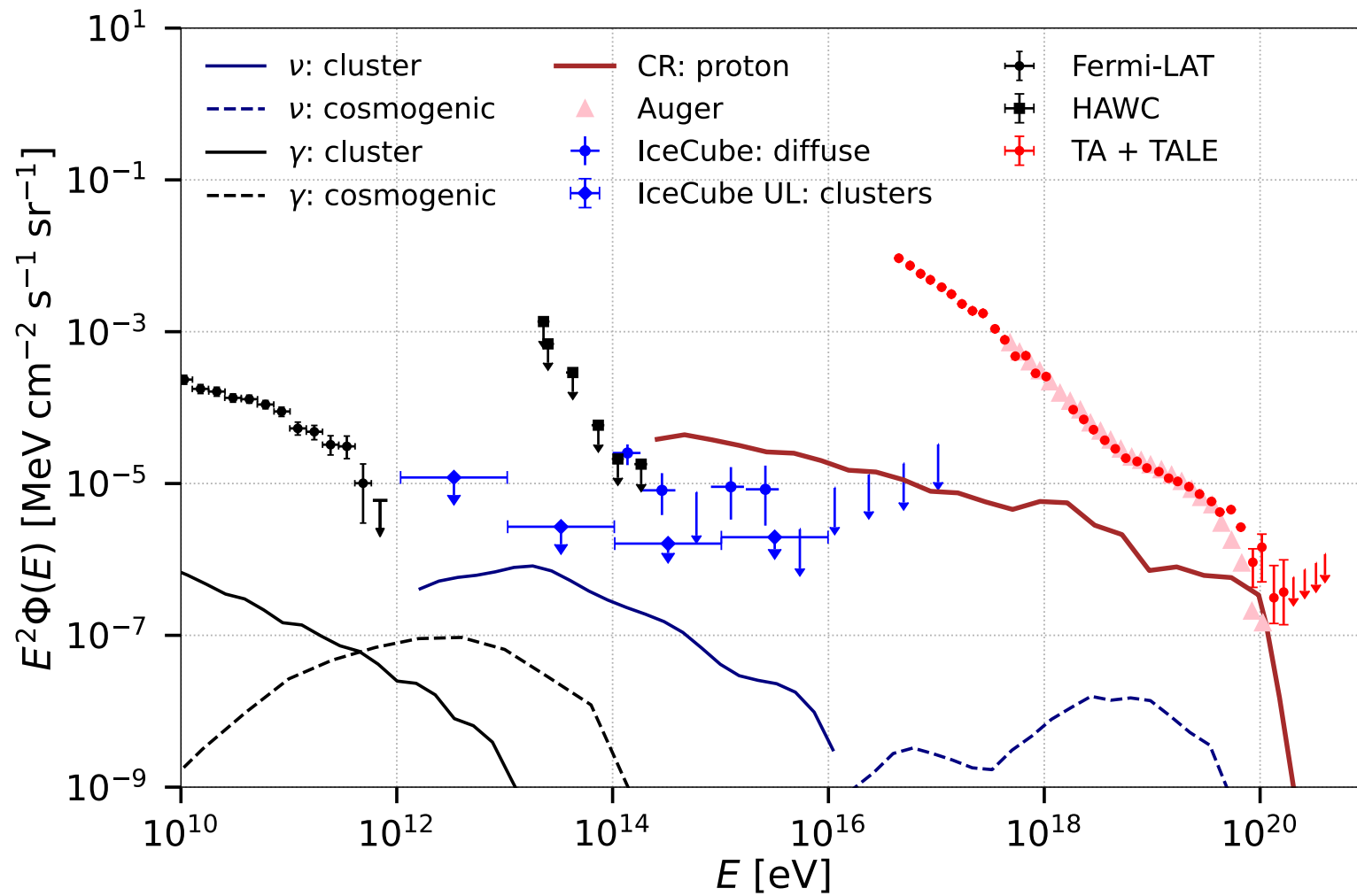
$M \sim 5 * 10^{14} M_{\odot}$

NGC 1275:
SALON 1996 – 2012

Fermi-LAT:
Cluster gamma-ray
upper limit



Multi-messenger from Perseus-like Sources



Summary and Conclusions

- Contribution of clusters of galaxies to the observed diffuse neutrinos and gamma-rays
- Most important channels to produce high-energy photons and neutrino are: inelastic proton-proton collisions and CRs interactions with the CMB

Neutrino flux from clusters is comparable with observations of the IceCube, especially between the energies 100 TeV and 10 PeV *Hussain, S., et al., MNRAS (2021)*

Gamma-ray flux from clusters can contribute to a fairly large fraction to the diffuse gamma-rays background above 100 GeV observed by the Fermi-LAT
Hussain, S., et al., Nature Communications (2023)

These results might be confirmed by LHAASO, upcoming CTA and IceCube-Gen2, GRAND...



Thanks