High-energy astrophysics in the multi-messenger era

Cosmic Magnetic Fields and Cosmic Ray Propagation Connections in Galaxy Clusters

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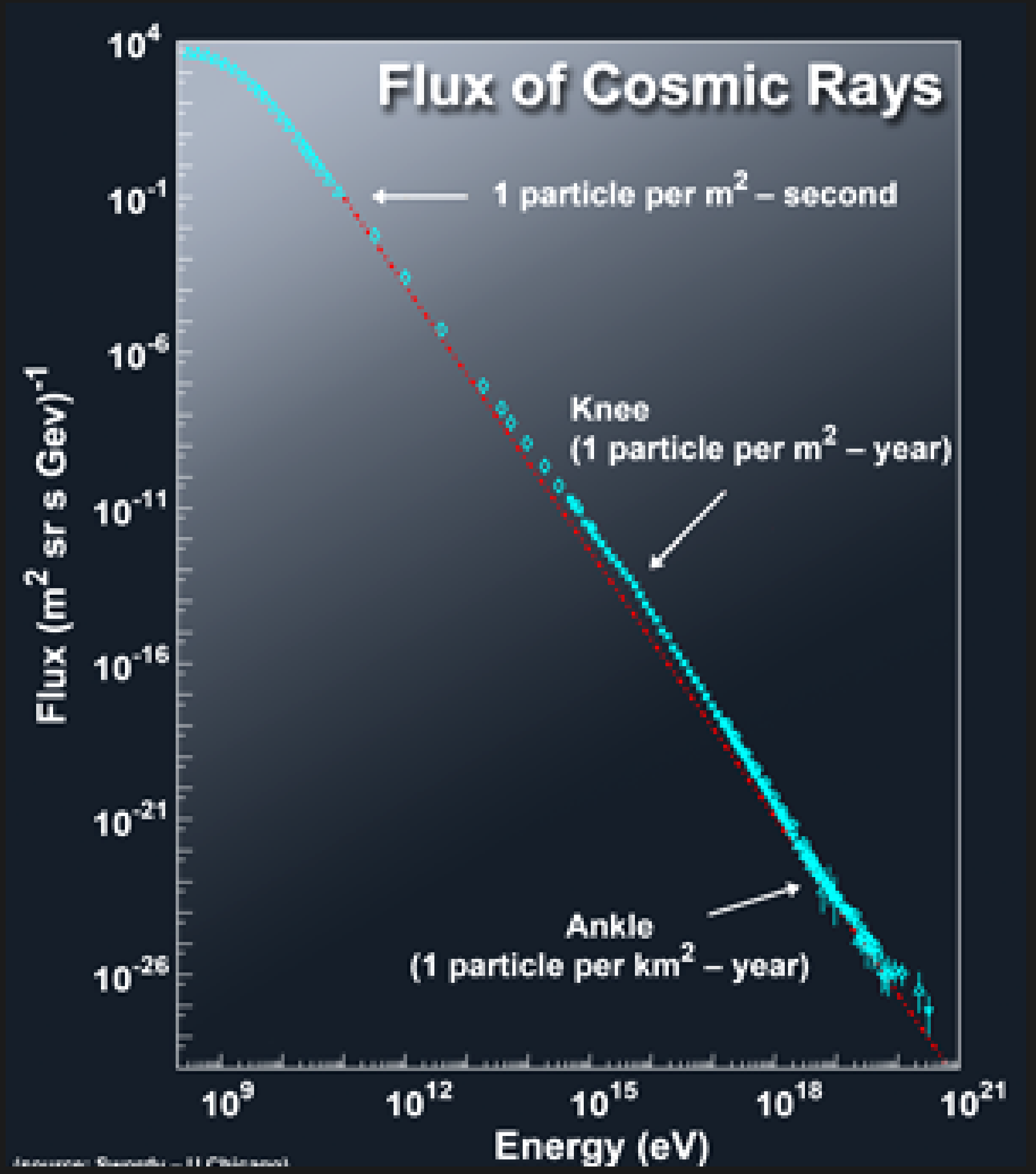
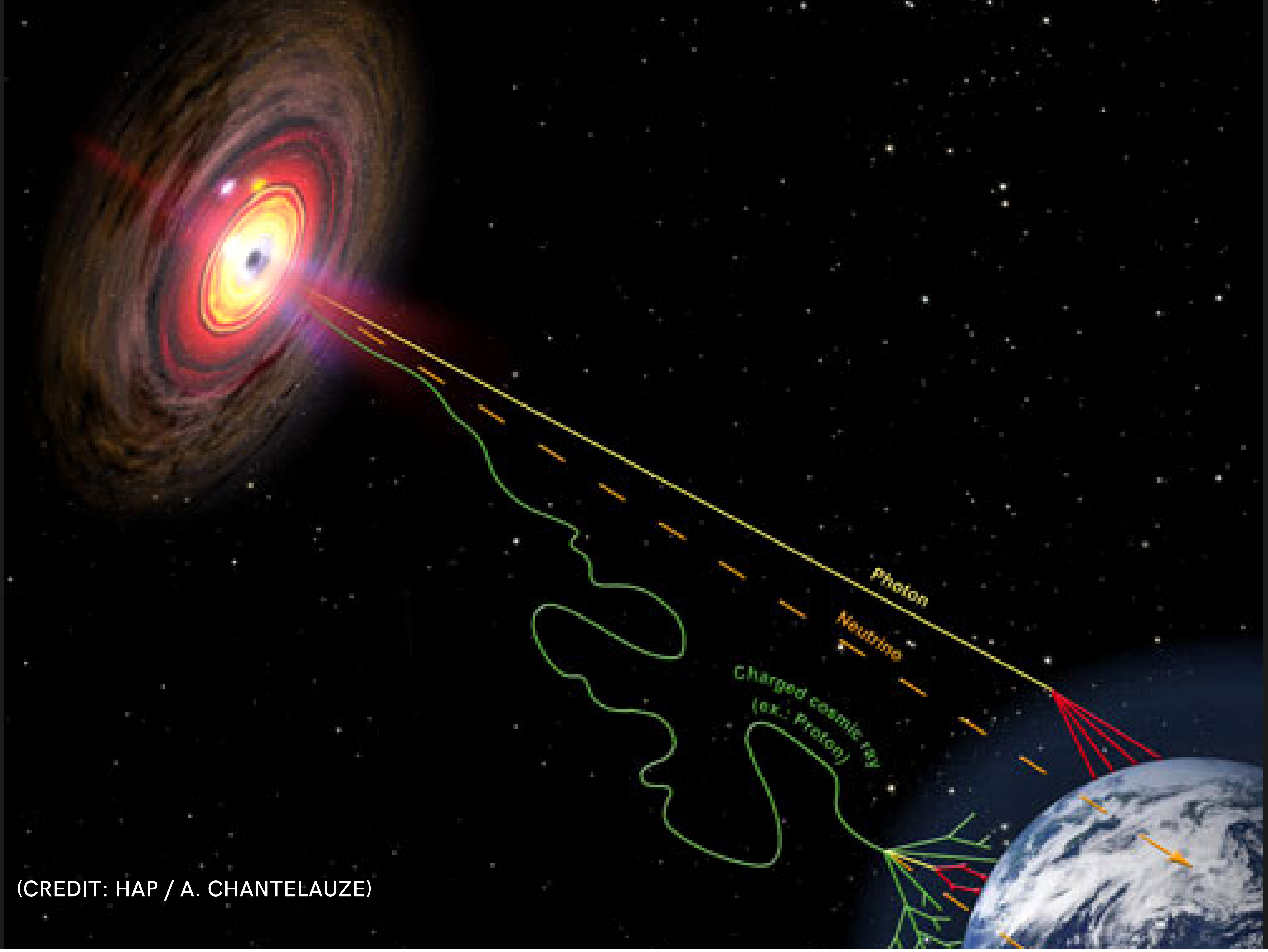


(CREDIT: HAP / A. CHANTELAUZE)



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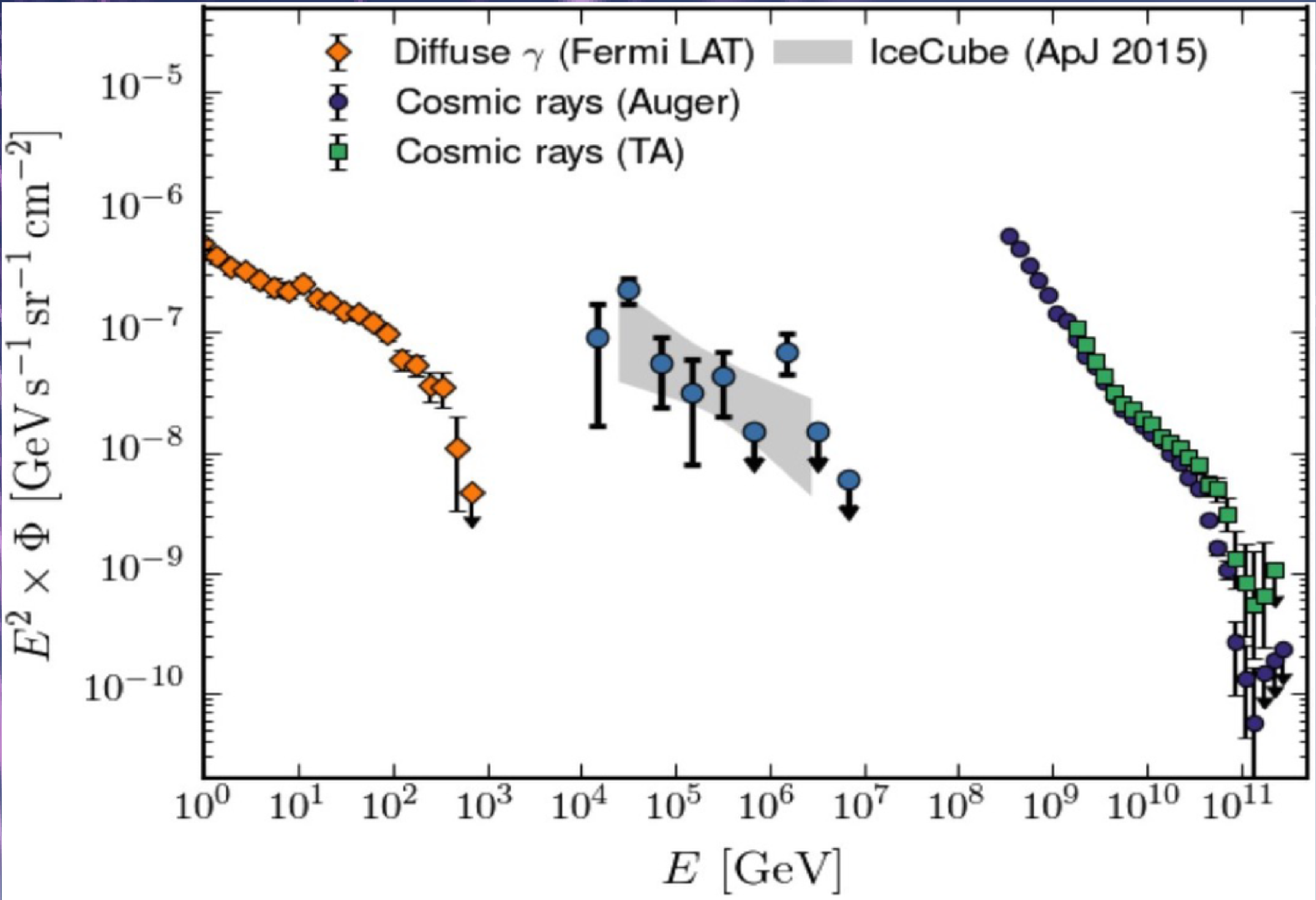
Cosmic Rays

CRs with energies $E > 10^{18}$ eV have most likely an extragalactic origin



GAISSER 2017;
FANG & MURASE 2018

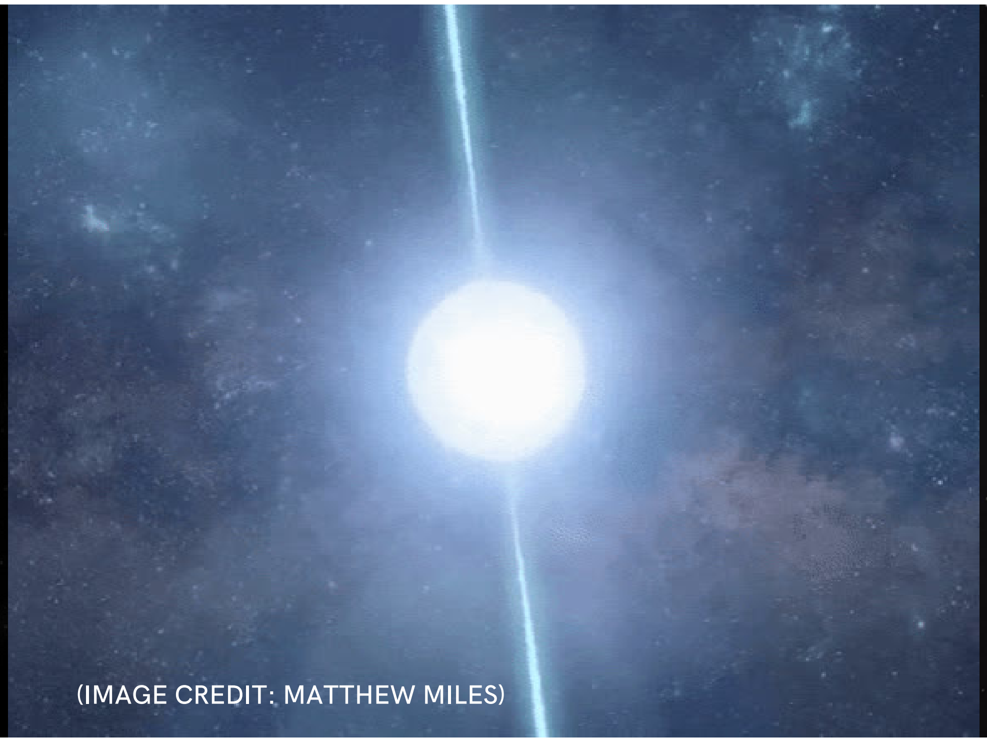
The origin of UHECRs (E > 10^{18} eV), diffuse neutrino, and gamma-ray background are among the major mysteries in astrophysics.

(CREDIT: NASA)

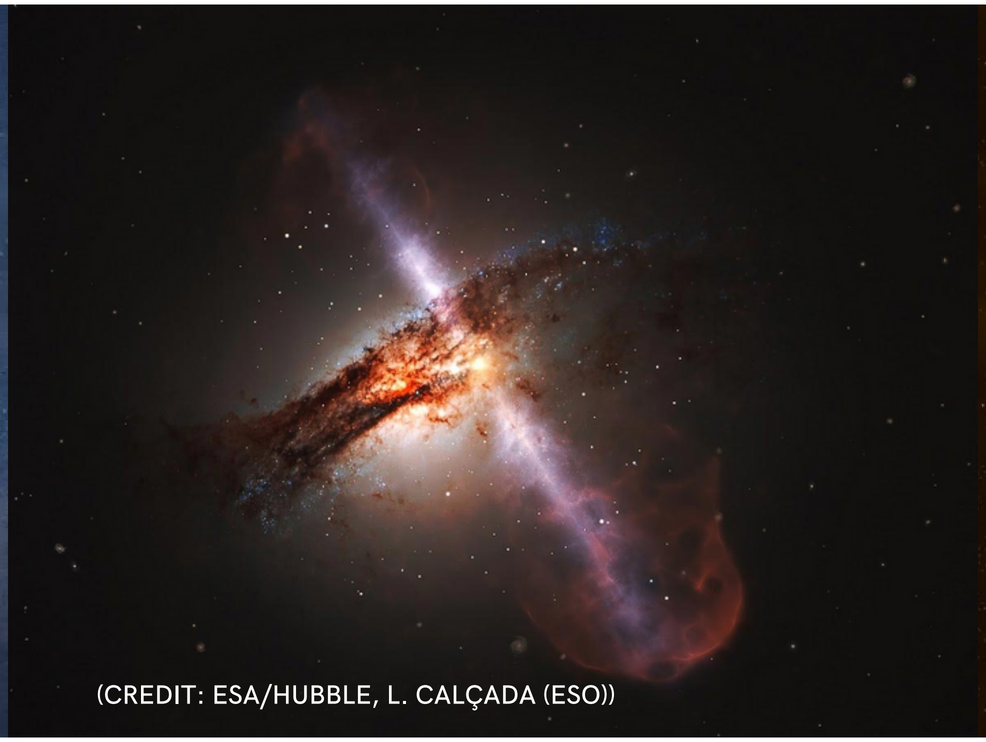
Potential source populations

STAR-FORMING GALAXIES

(SFGs)

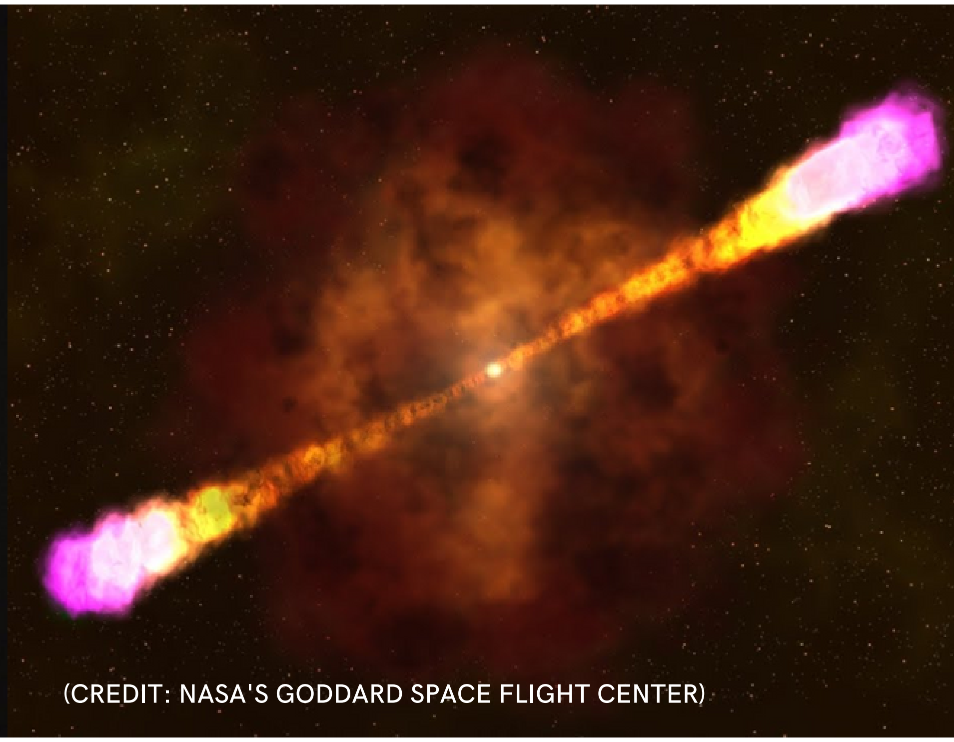


PULSARS



ACTIVE GALACTIC NUCLEI

(AGNs)



GAMMA-RAY BURSTS

(GRBs)

and/or

Galaxy clusters

(which contain all these classes of source)

Due to their size, clusters of galaxies can potentially produce CRs up to very-high energies via large-scale shocks and turbulent acceleration.

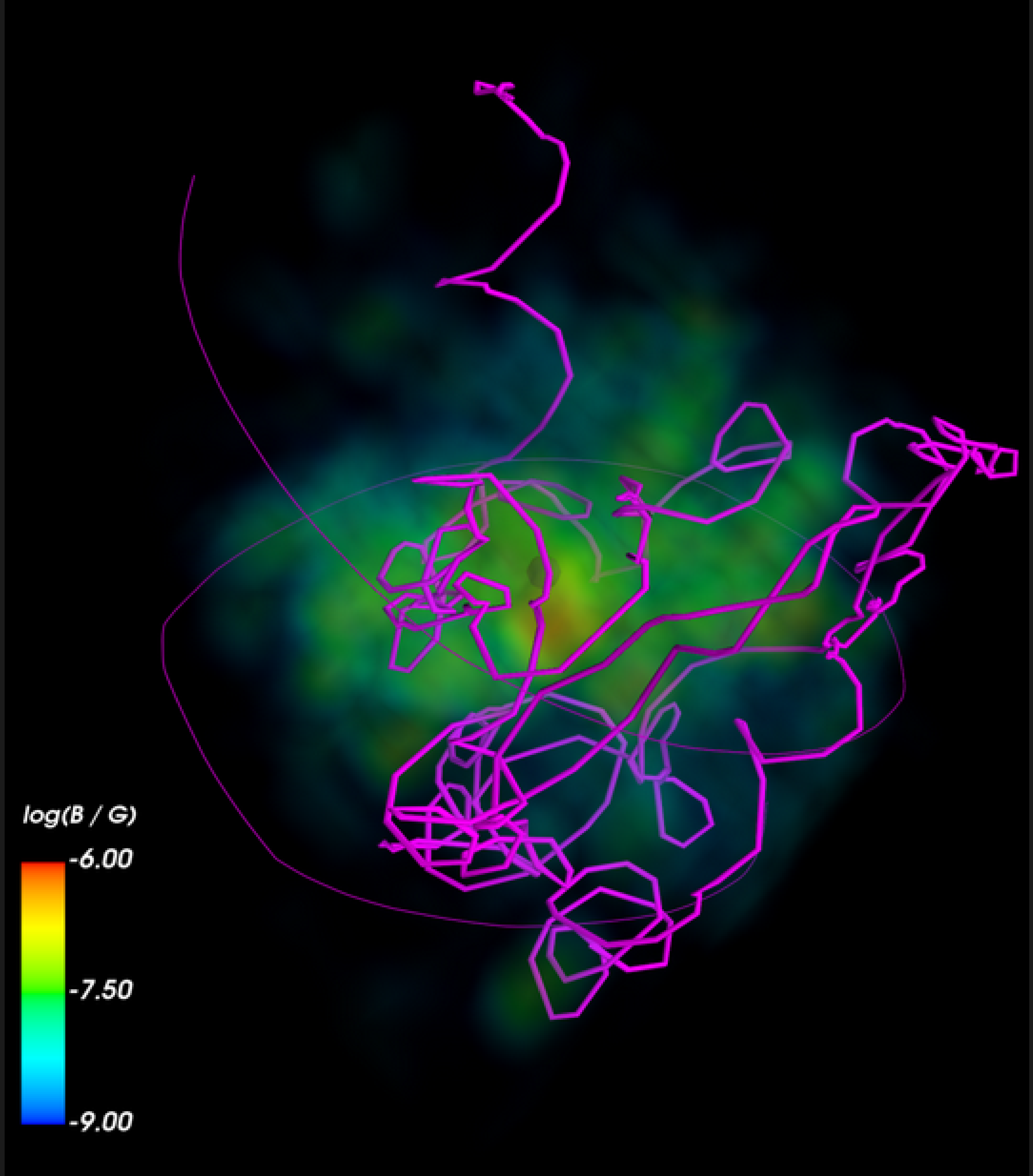
(CREDIT: HUBBLE)

(CREDIT: NASA, ESA, S. RODNEY (JOHN HOPKINS UNIVERSITY, USA))

Previous work

They explored the contribution of clusters of galaxies to the observed flux of CRs producing diffuse neutrino and gamma-ray.

Hussain, Alves-Batista, de Gouveia
Dal Pino, Dolag (2021, 2022)



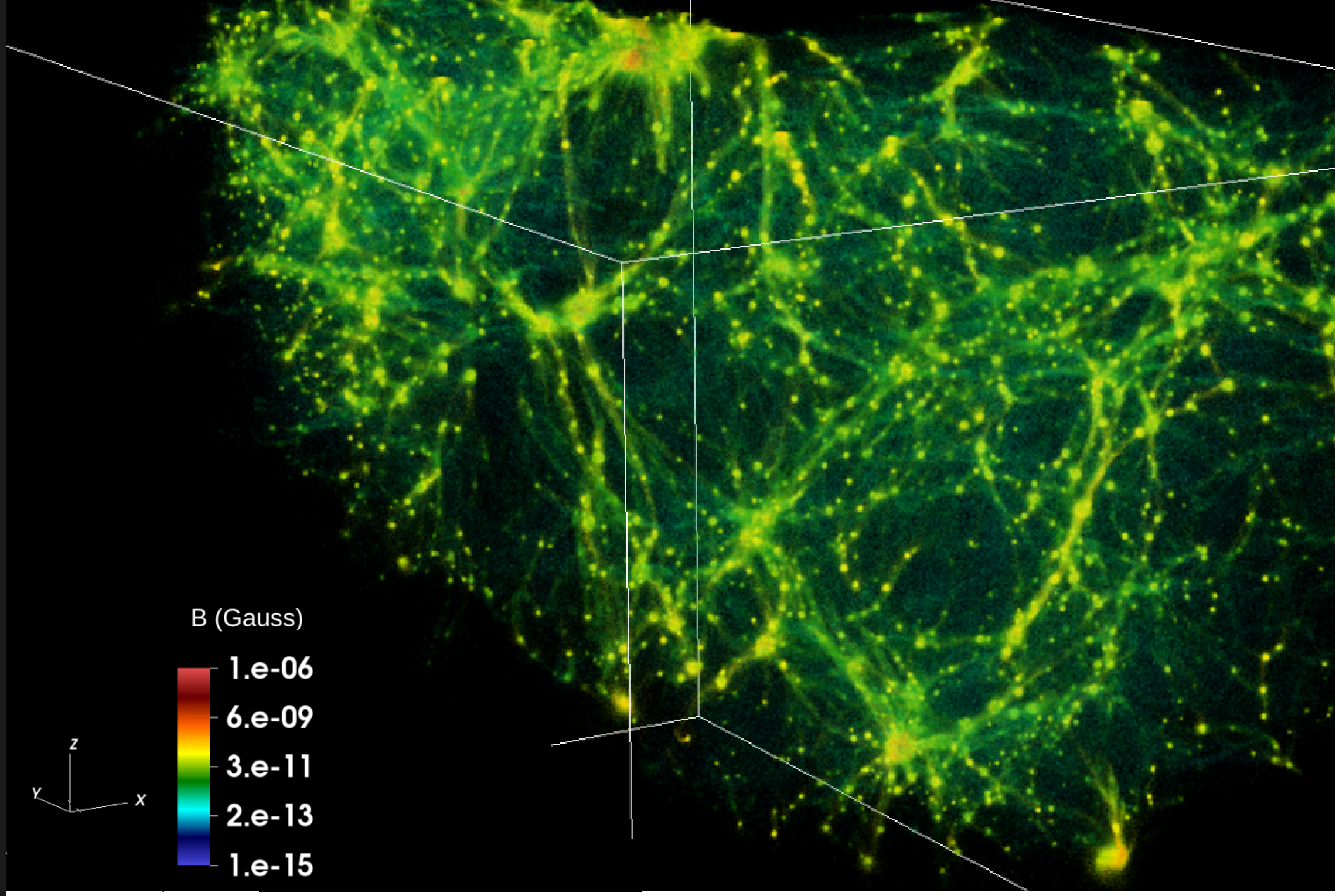
MAIN RESULTS

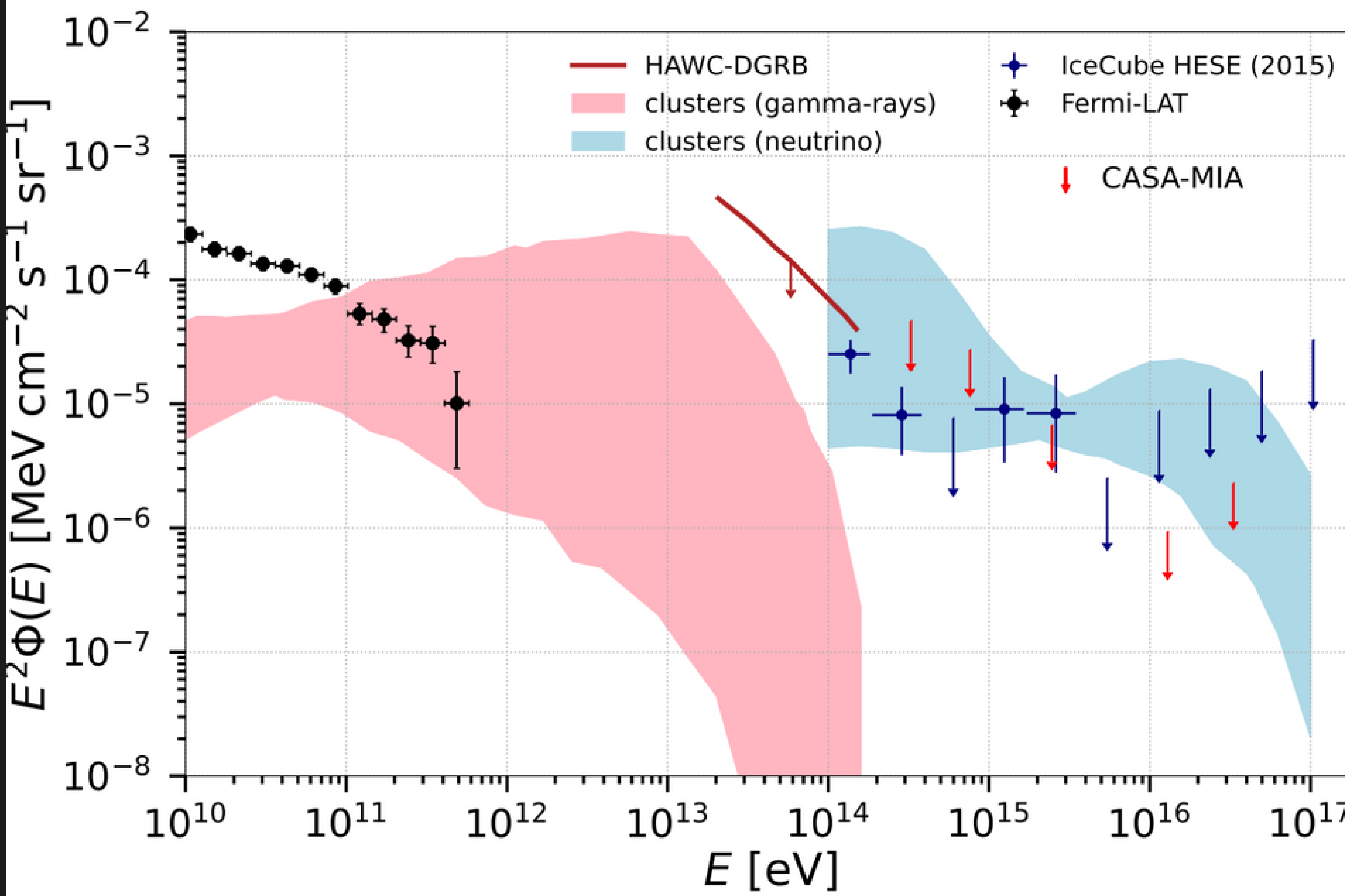
Clusters can contribute to a fairly large fraction of the highest energy photon flux observed by Fermi-LAT.

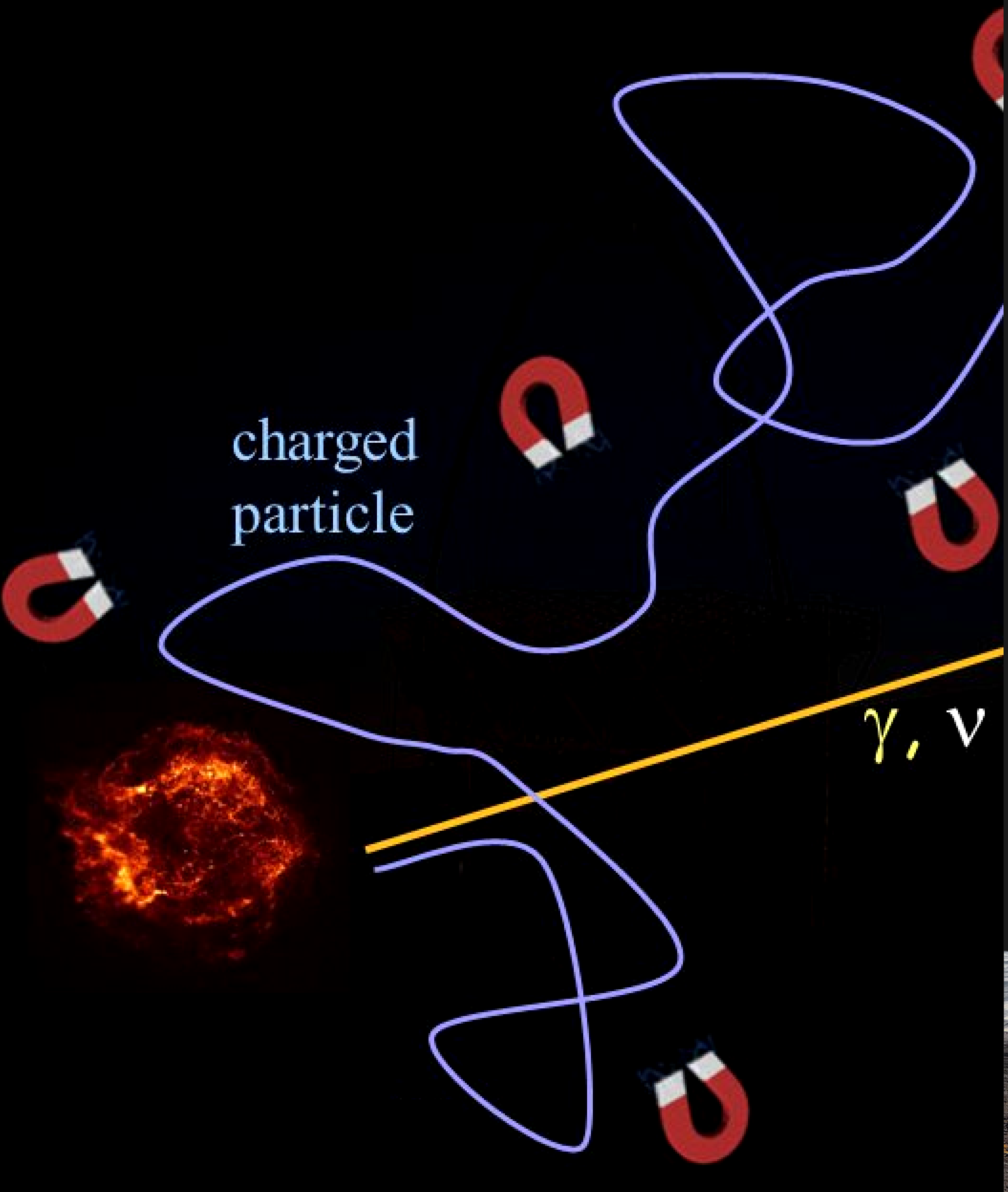
The neutrinos flux they obtained provides a substantial fraction of the observed emission by the IceCube at the highest energies.

The high-energy fluxes of gamma-rays and neutrinos from clusters are comparable with the DGRB and the diffuse neutrino background.

Hussain, Alves-Batista, de Gouveia Dal Pino, Dolag (2021, 2022)



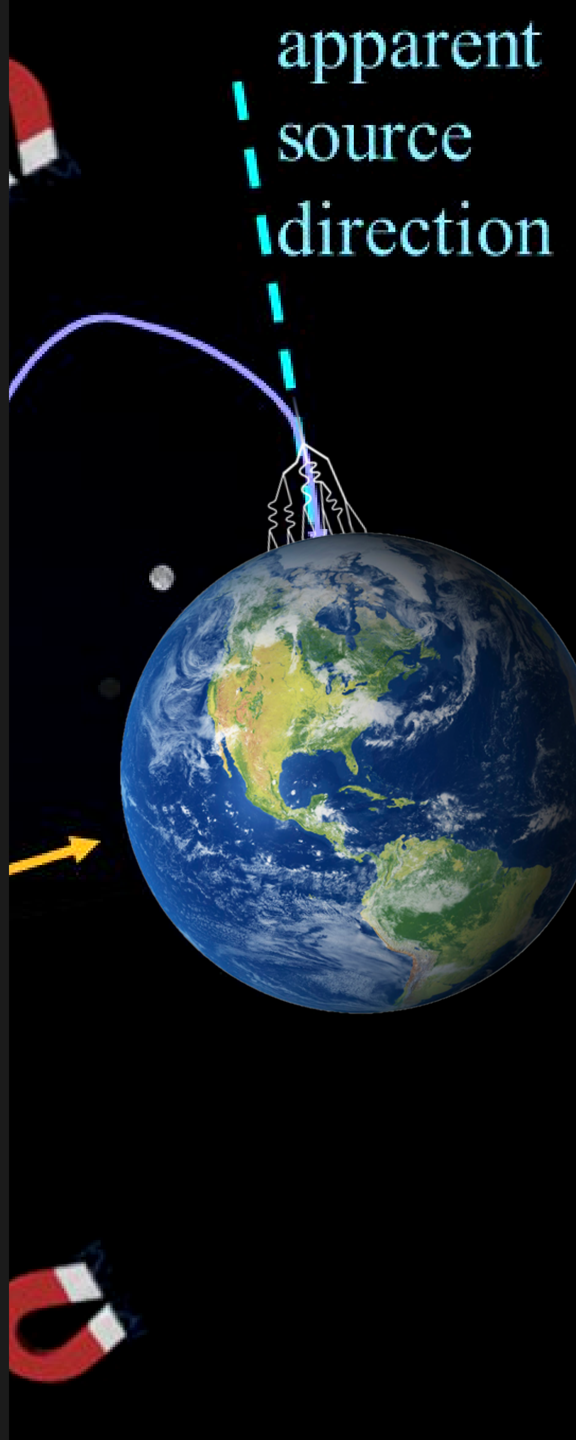


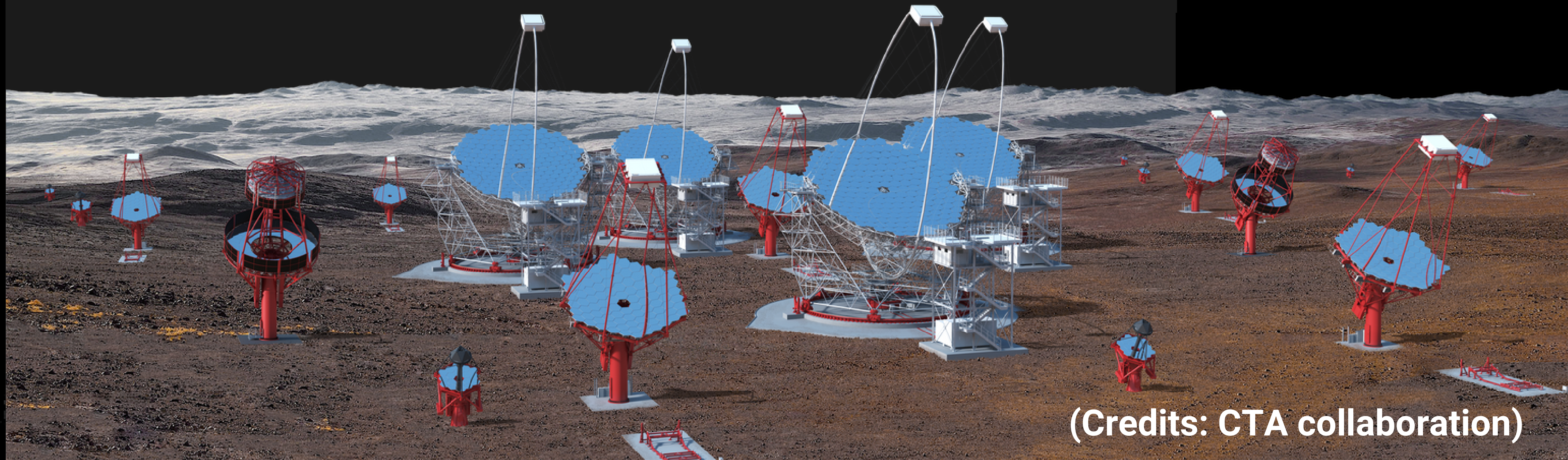


(Credits: Pratik Majumdar)

and now ...

Our aim here is to explore MF origin via turbulent dynamo and its connections with CRs propagation and radiative losses in clusters.





(Credits: CTA collaboration)

ICM...

Nº 1 **HOT IONIZED PLASMA: T ~ 1 - 10keV**

Nº 2 **DIFUSE: n ~10^{-4} - 10^{-2} cm^{-3}**

Nº 3 **TURBULENT DUE TO SEVERAL SOURCES**

- Galaxy collisions, mergers, shock waves, galactic winds and jets
  - (e.g, Lazarian 2006a; Durret & Lima Neto 2008; Govoni & Feretti 2004; Enßlin et al. 2005).

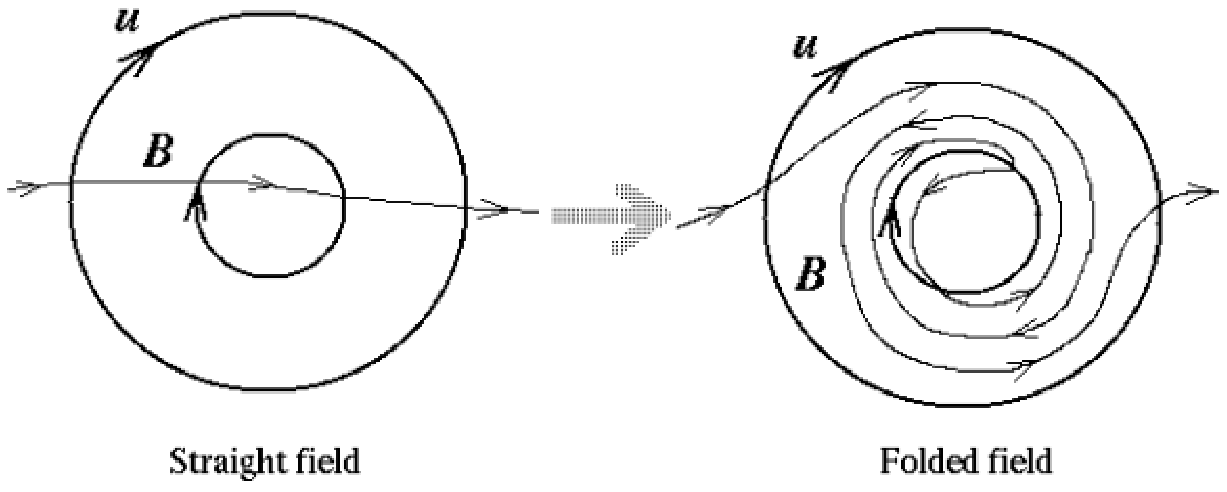
Nº 4 **MAGNETIZED: B ∼1–10 μG (Faraday rotation and Synchrotron emission)**

(Carilli & Taylor 2002; Bonafede et al. 2010; Govoni & Feretti 2004)

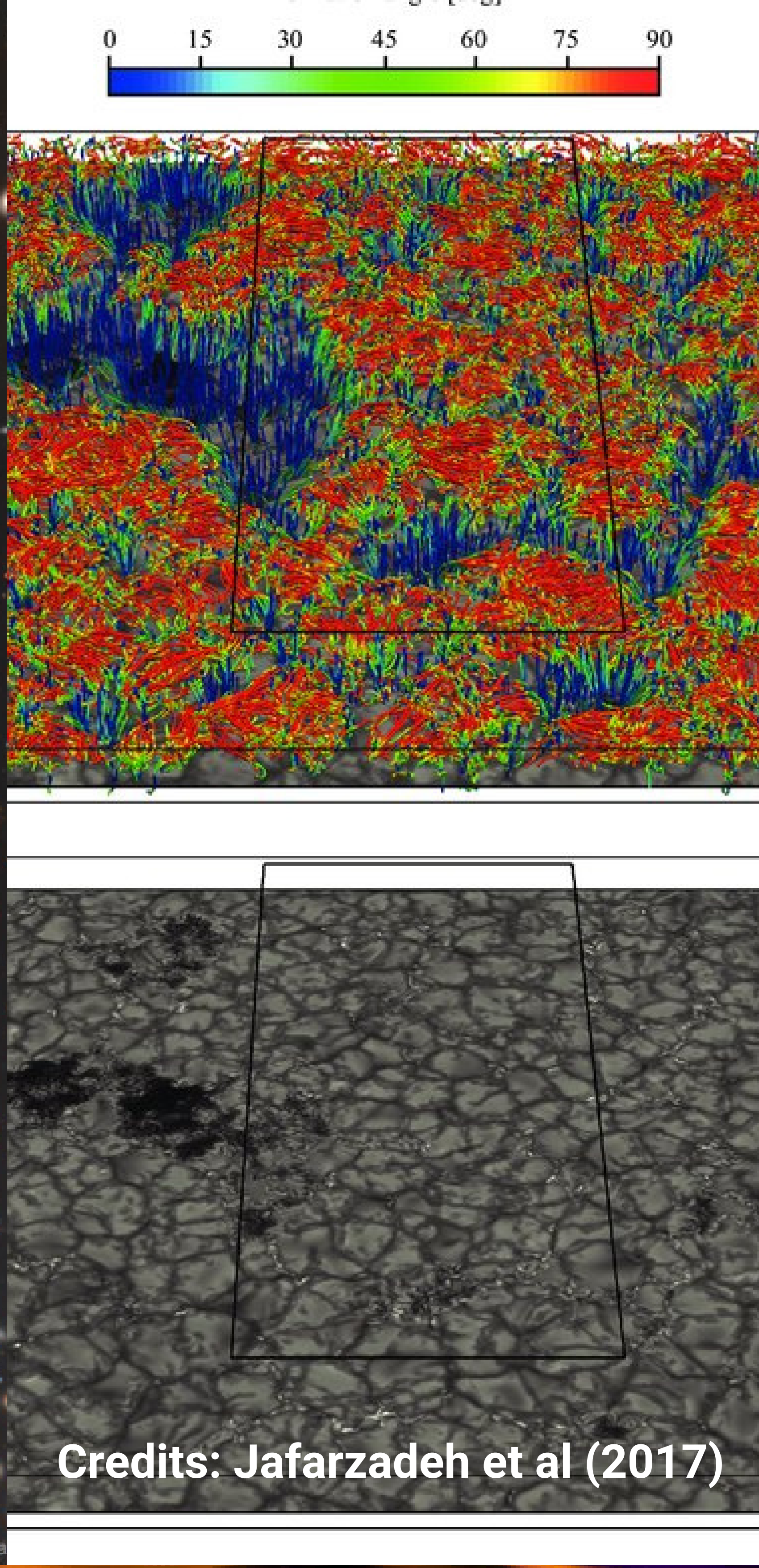
Nº 5 **FIELDS ARE RESULTING FROM THE FLUCTUATION DYNAMO (I.E. TURBULENT)**

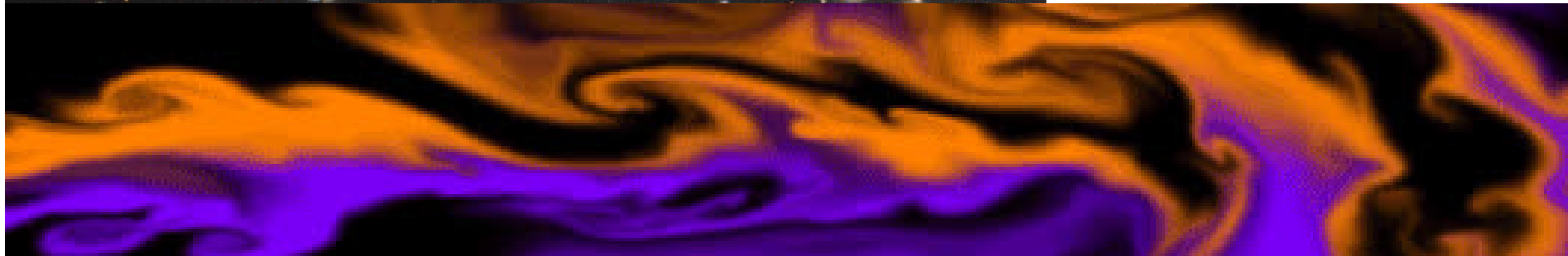
Small Scale Dynamos (SSD)

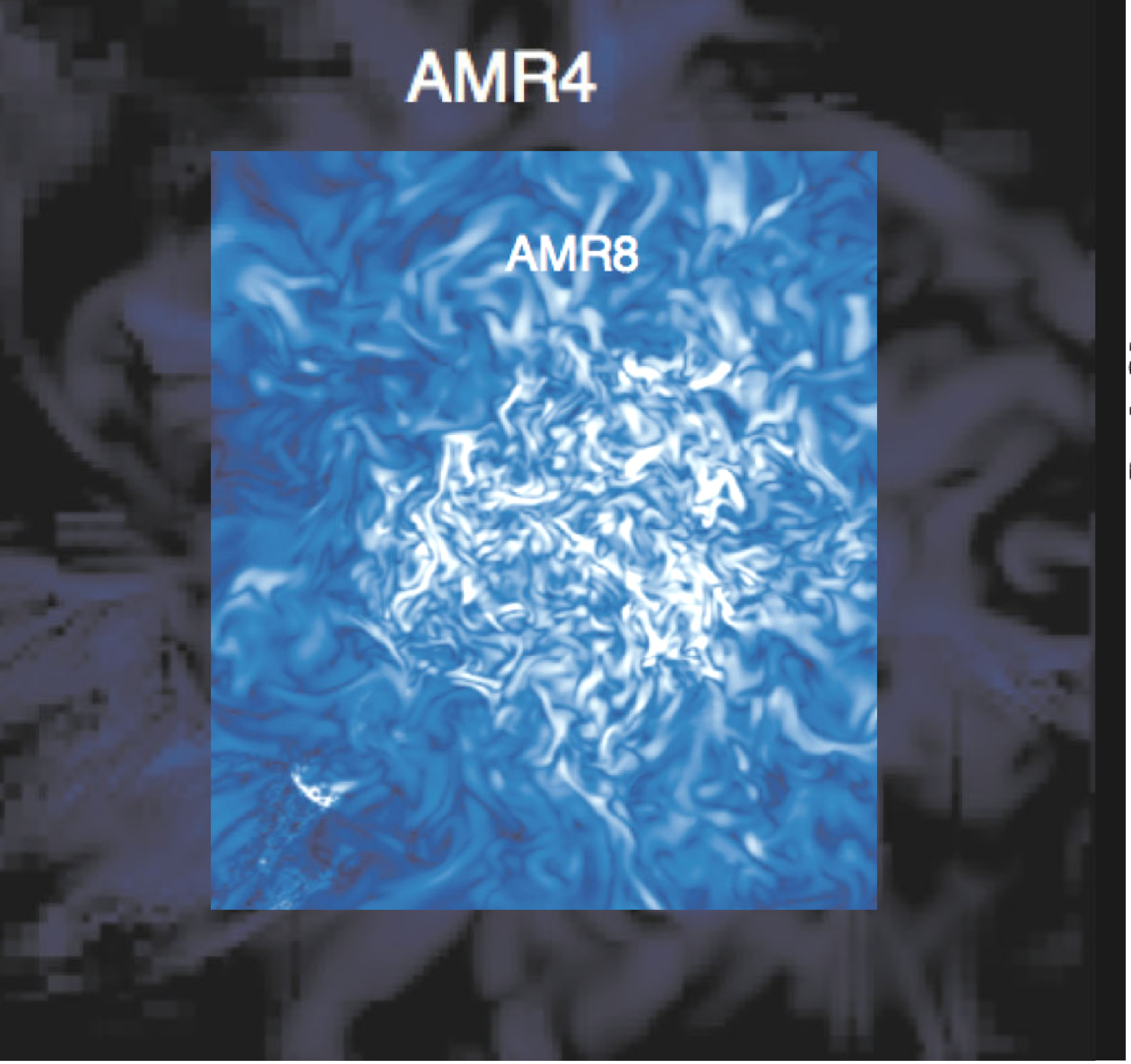
They are associated with the turbulent motions of the constituent plasma and exist at scales below those at which the turbulence is forced

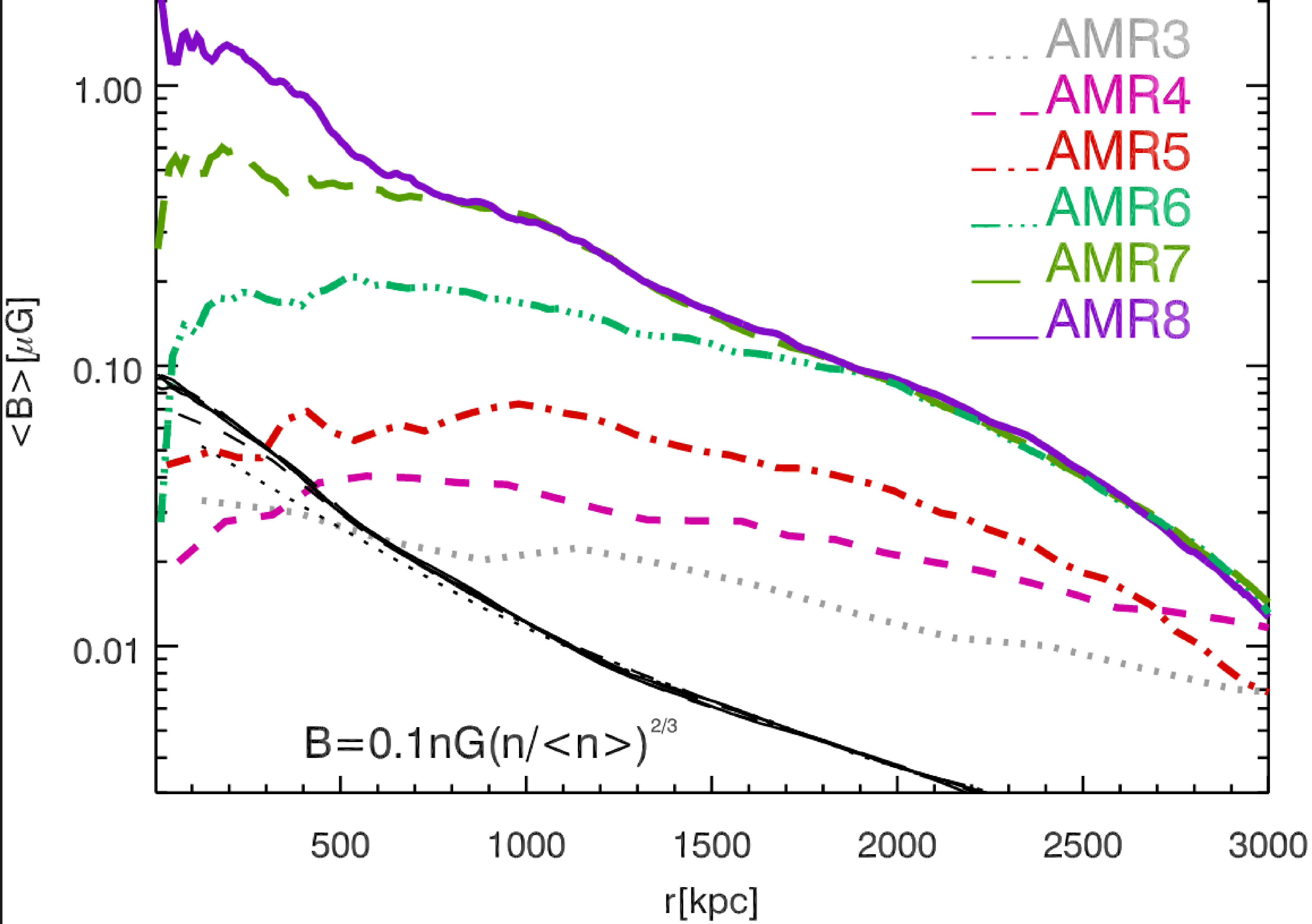


Schekochihin et al (2004)









Vazza et al (2018)

Their simulations covered the innermost region of a cluster and showed evidence of a small-scale dynamo and local amplification of magnetic fields to values similar to those found in observations (~2 **μ**G in the innermost Mpc^3 region).

Simulation 3D MHD - colissionless

(USING PLUTO CODE - MIGNONE ET AL, 2012)

Run	Res.	ε	μ_B^{-1}	μ^{-1}	η^{-1}	$\langle u_{rms}^2\rangle_t^{1/2}$	$\langle B_0^2\rangle^{1/2}$	Re	Limiters
MHD	256^3	1	∞	1500	1500	1.43	10^{-3}	340	-
HWL	256^3	1	$0.96nkT_i\tau_i$	p/ν_i	1500	1	10^{-3}	239	Hard-Wall

THIS WORK:

Hard-wall limiters

$$-\frac{B^2}{4\pi} \leqslant \Delta p \leqslant \frac{B^2}{8\pi}$$

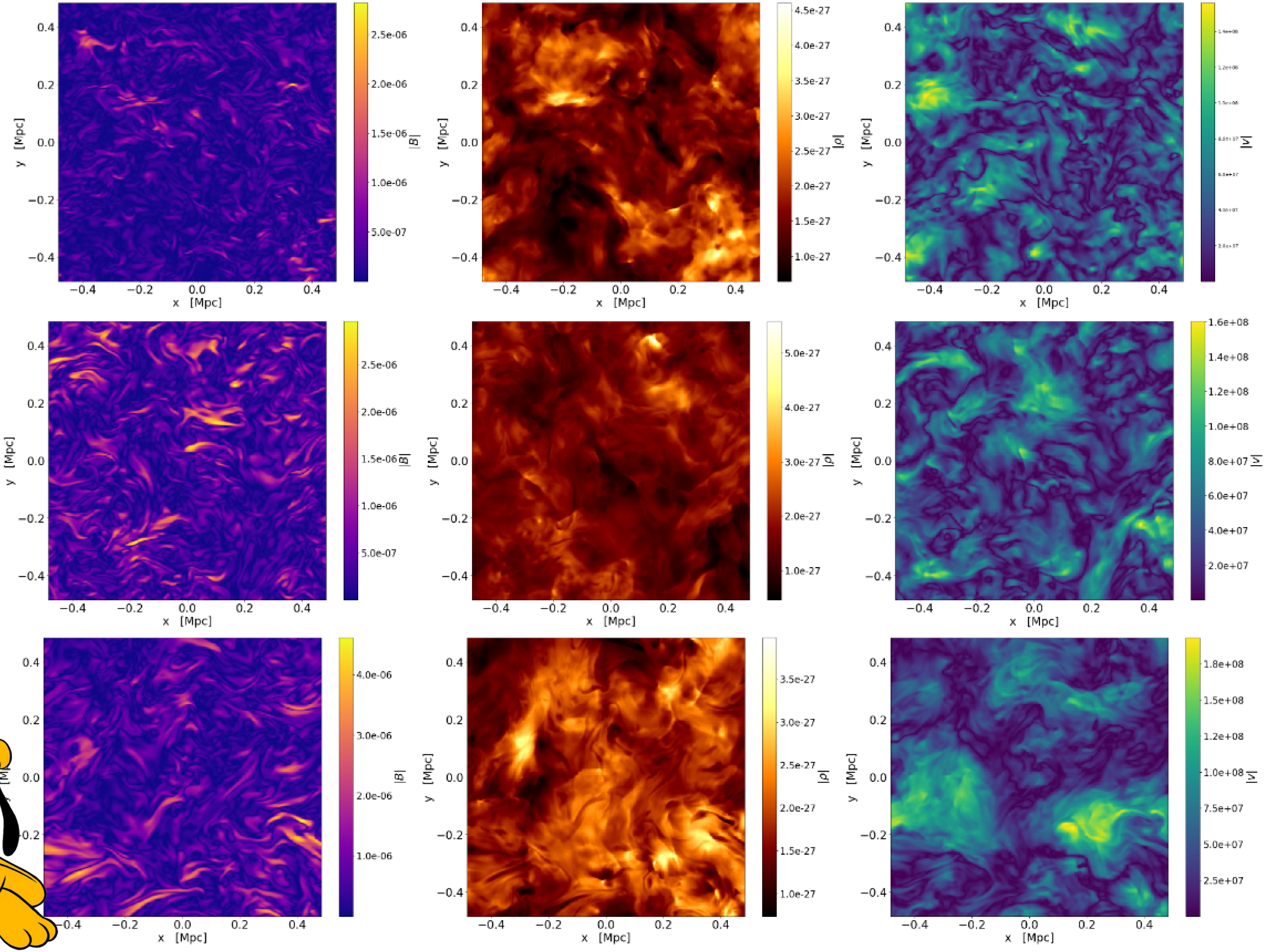
- on the mirror ($\Delta p > 0$) side

$$\Delta p = min\left(\frac{B^2}{8\pi}, 3\mu_B \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u}\right)$$

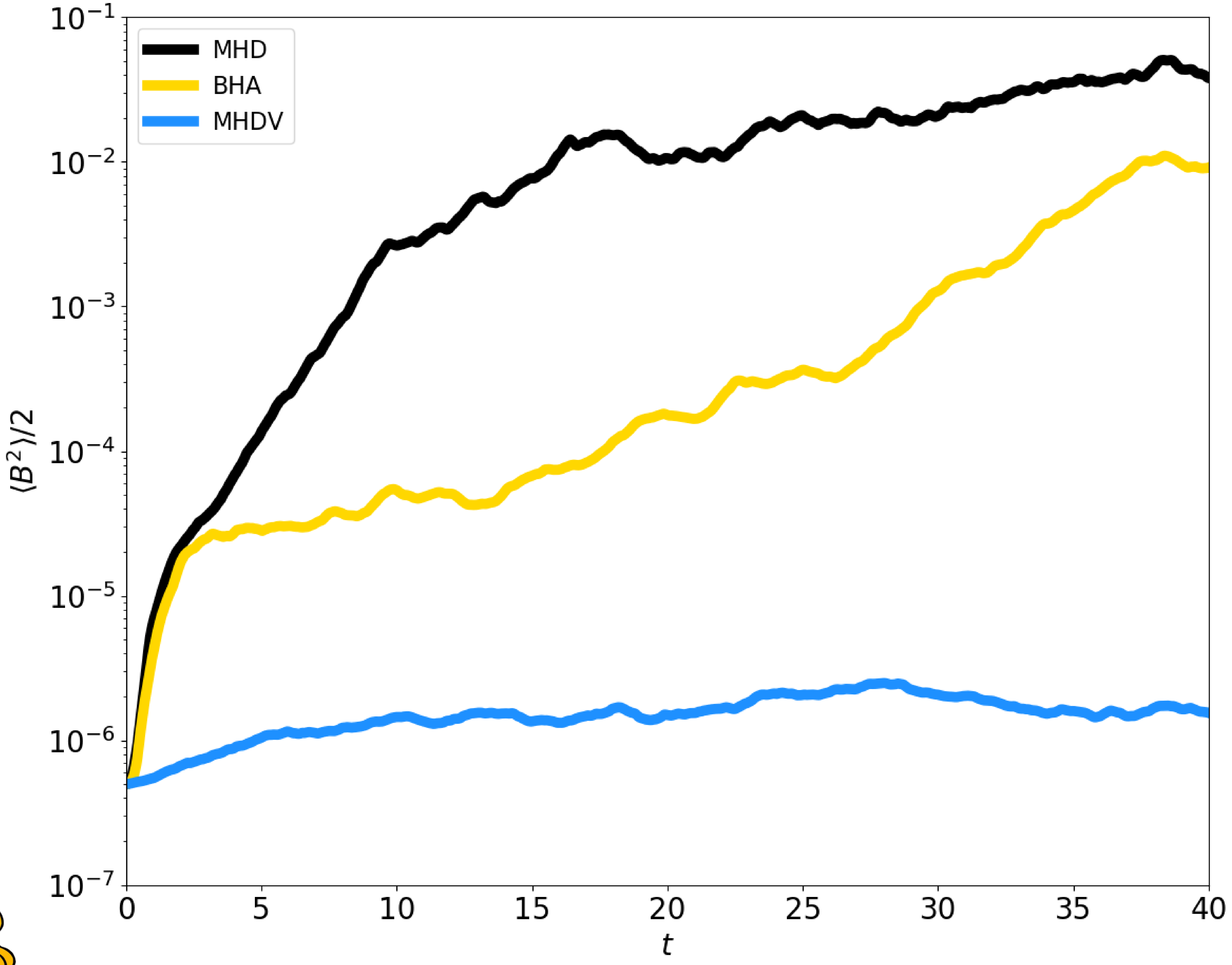
- on the firehose ($\Delta p < 0$) side

$$\Delta p = max\left(-\frac{B^2}{4\pi}, 3\mu_B \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u}\right)$$

PRELIMINAR RESULTS:



PLUTO CODE



MHD
BHA
MHDV
$\langle B^2 \rangle/2$
t
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
5
10
15
20
25
30
35
40

Ackermann et al (2014) - Clusters: A400, A1367, and A311220.

NEXT STEPS:

Simulation 3D MHD High resolution

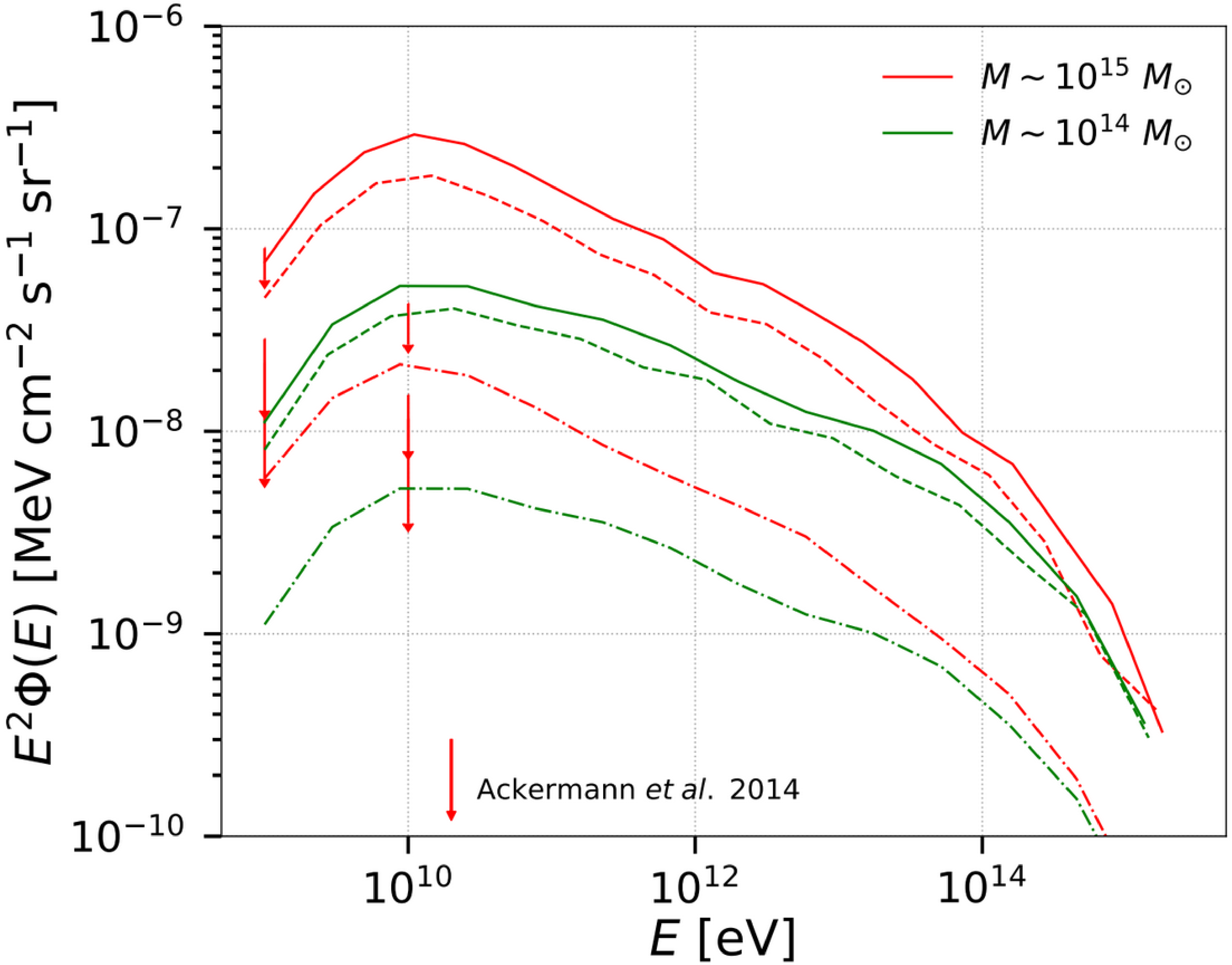
(E.G VAZZA ET AL, 2018)

+

CR-PROPA

(ALVES-BATISTA ET AL, 2016)

To derive the flux of gamma-rays and neutrinos from individual clusters with higher resolution



(HUSSAIN, ALVES BATISTA, DE GOUVEIA DAL PINO, DOLAG 2022, SUBMITTED).

Thank You