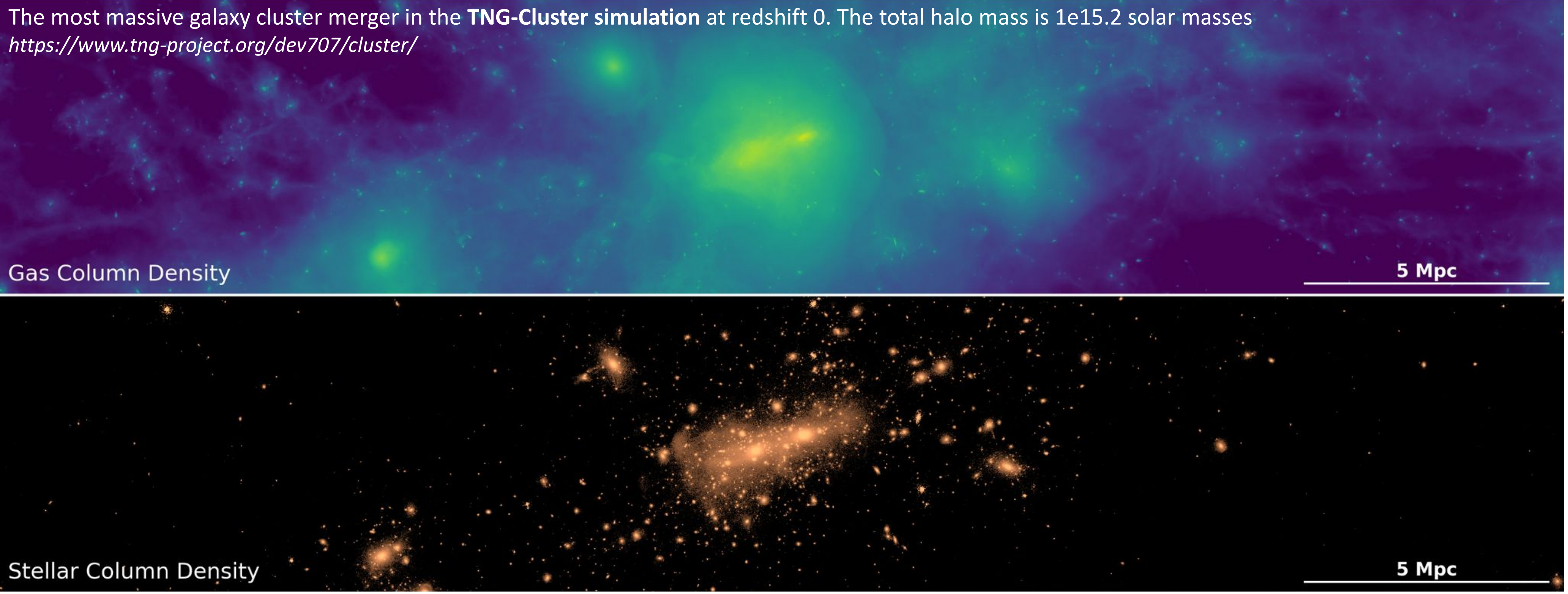
The most massive galaxy cluster merger in the **TNG-Cluster simulation** at redshift 0. The total halo mass is 1e15.2 solar masses
https://www.tng-project.org/dev707/cluster/



Elusive diffuse γ-ray emission in galaxy clusters: the role of CR transport

Paper submitted to Nature Astronomy: Efficient micromirror confinement of sub-TeV cosmic rays in galaxy clusters
https://arxiv.org/abs/2311.01497

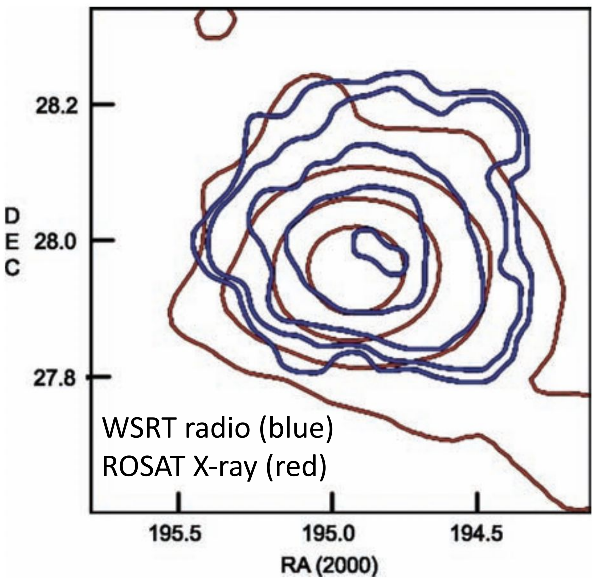
Patrick Reichherzer[1], 2023/11

with:
A. Bott[1], R. Ewart[1], G. Gregori[1], P. Kempski[2], M. Kunz[2], and A. Schekochihin[1]

[1] *University of Oxford* [2] *Princeton University*

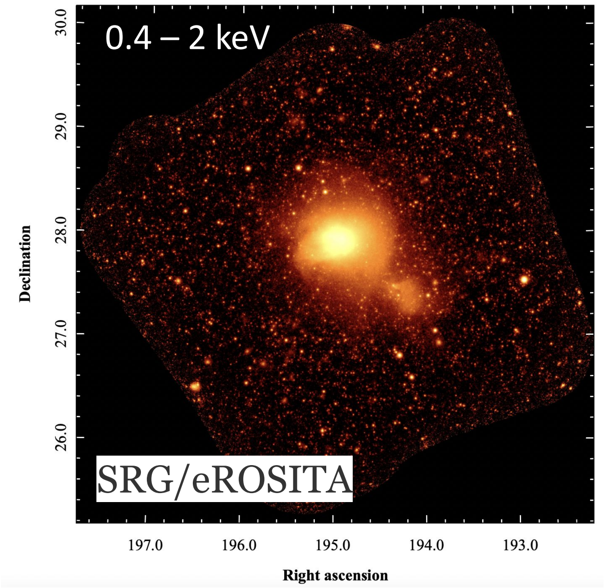
Non-ambiguous detection of diffuse γ-ray emission still elusive

Radio & X-rays



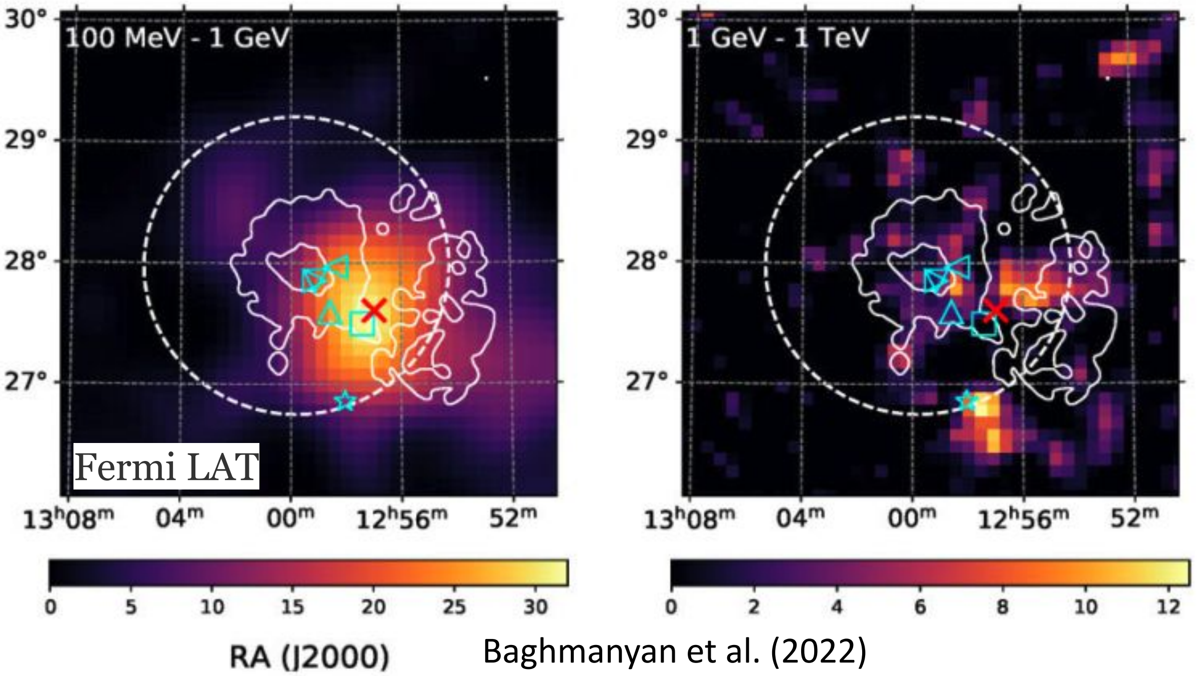
Brown & Rudnick (2014)

X-rays



Churazov et al. (2021)

γ-rays



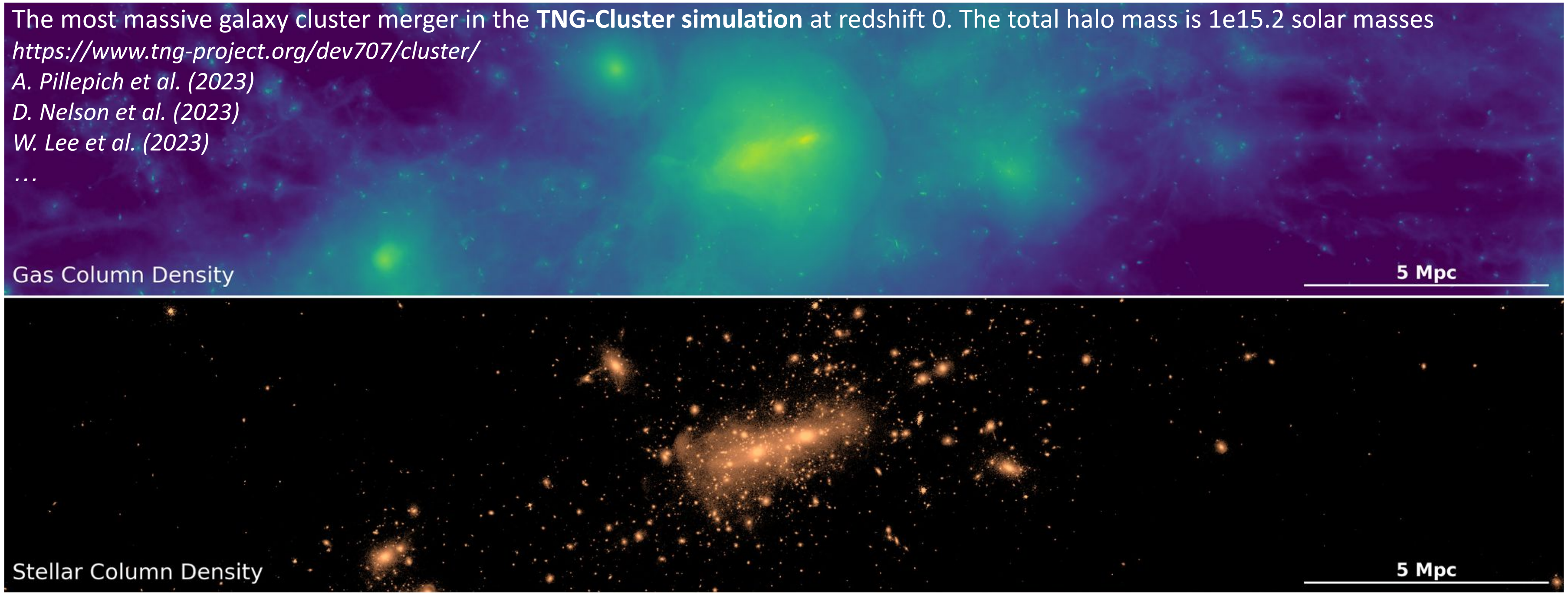
Baghmanyan et al. (2022)

diffuse emission

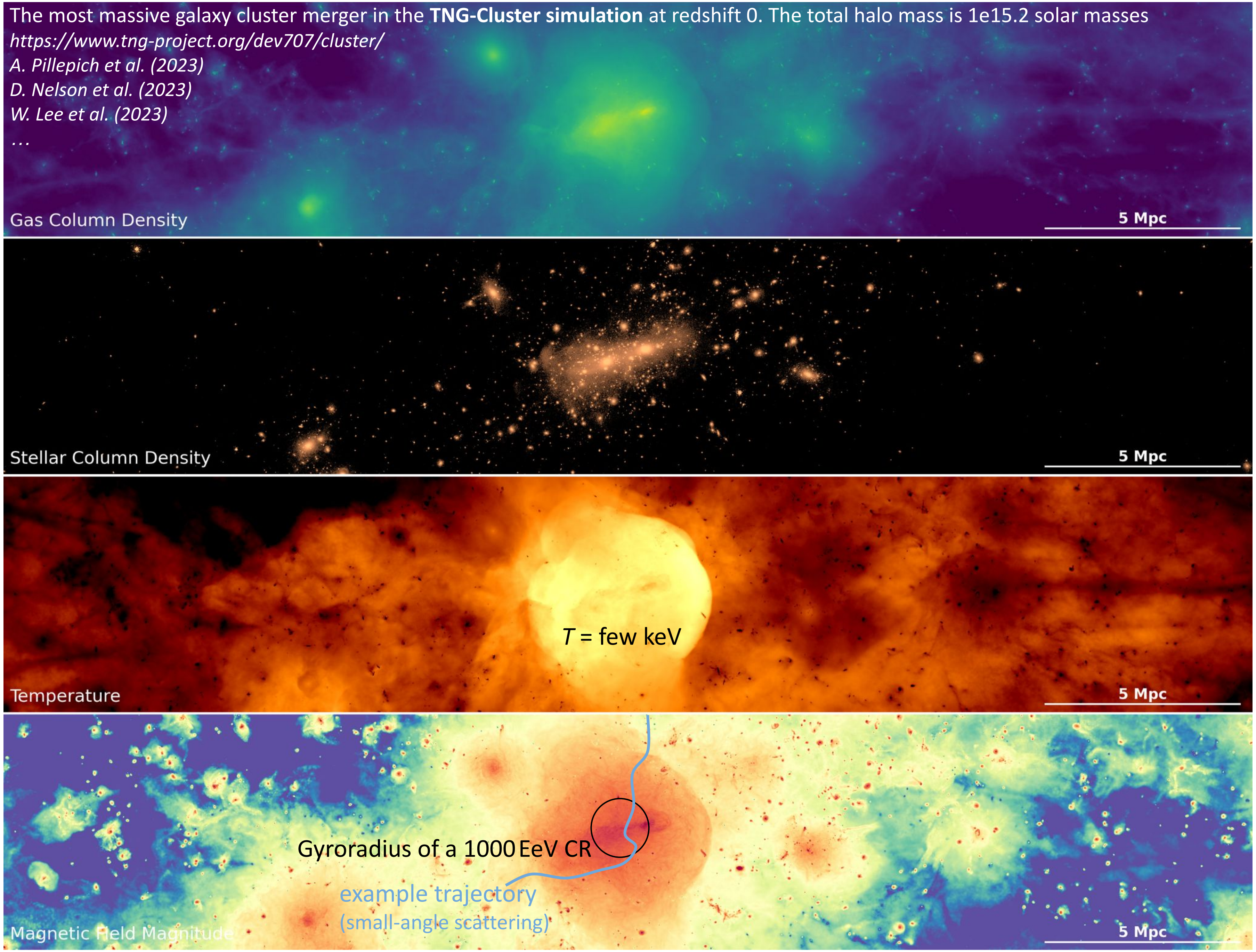
non-ambiguous detection of diffuse γ-ray emission elusive

- Differences in morphology due to
  - emitting particle types (thermal plasma vs. CRs)
  - source distributions of emitting particles
  - **transport of emitting particles (streaming, diffusing, (quasi-)ballistic)**

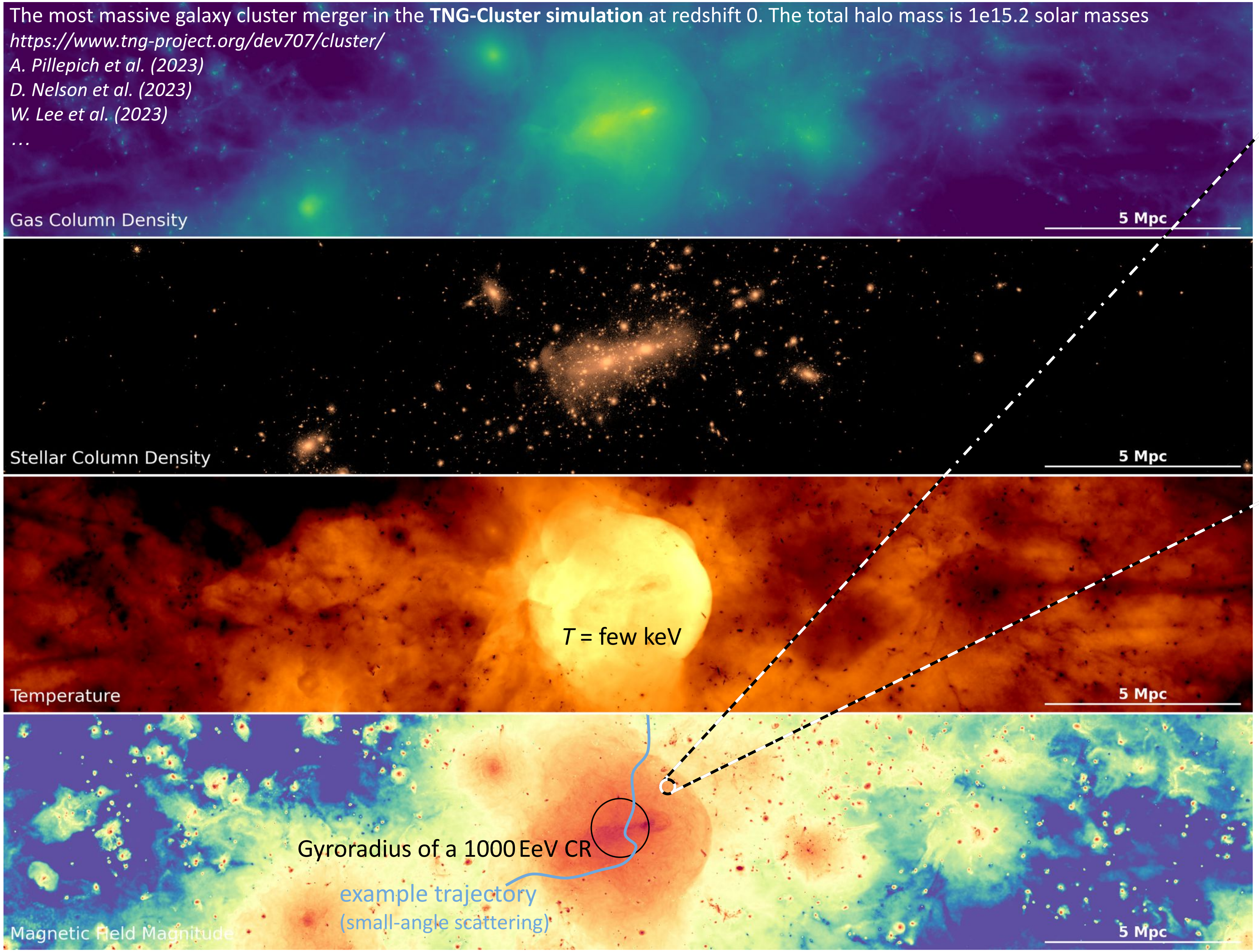
Scale hierarchy in galaxy clusters relevant for CR transport

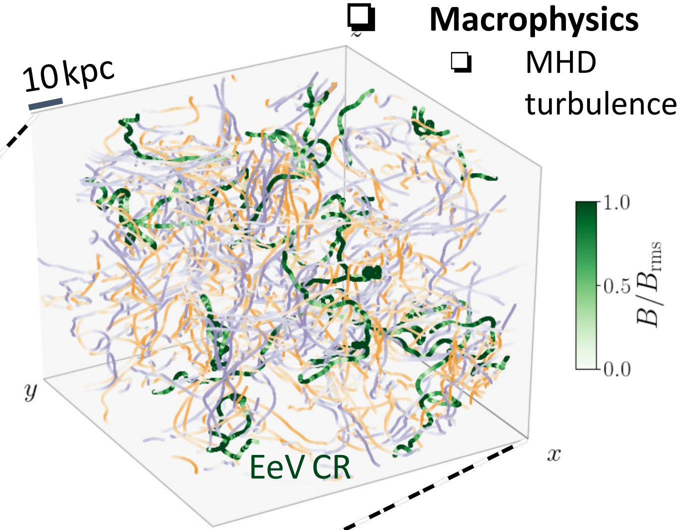


Scale hierarchy in galaxy clusters relevant for CR transport



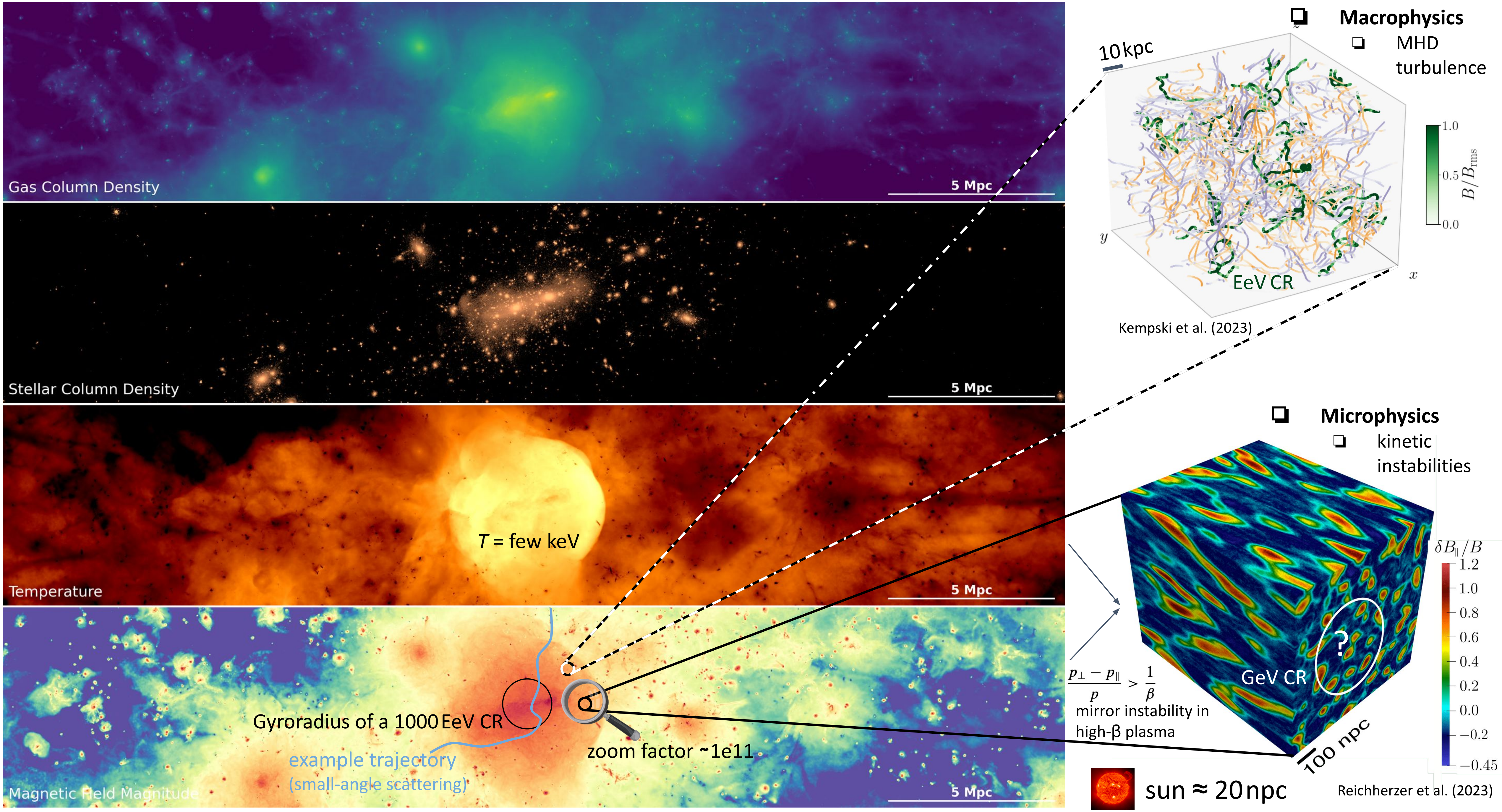
Scale hierarchy in galaxy clusters relevant for CR transport





Kempski et al. (2023)

Scale hierarchy in galaxy clusters relevant for CR transport



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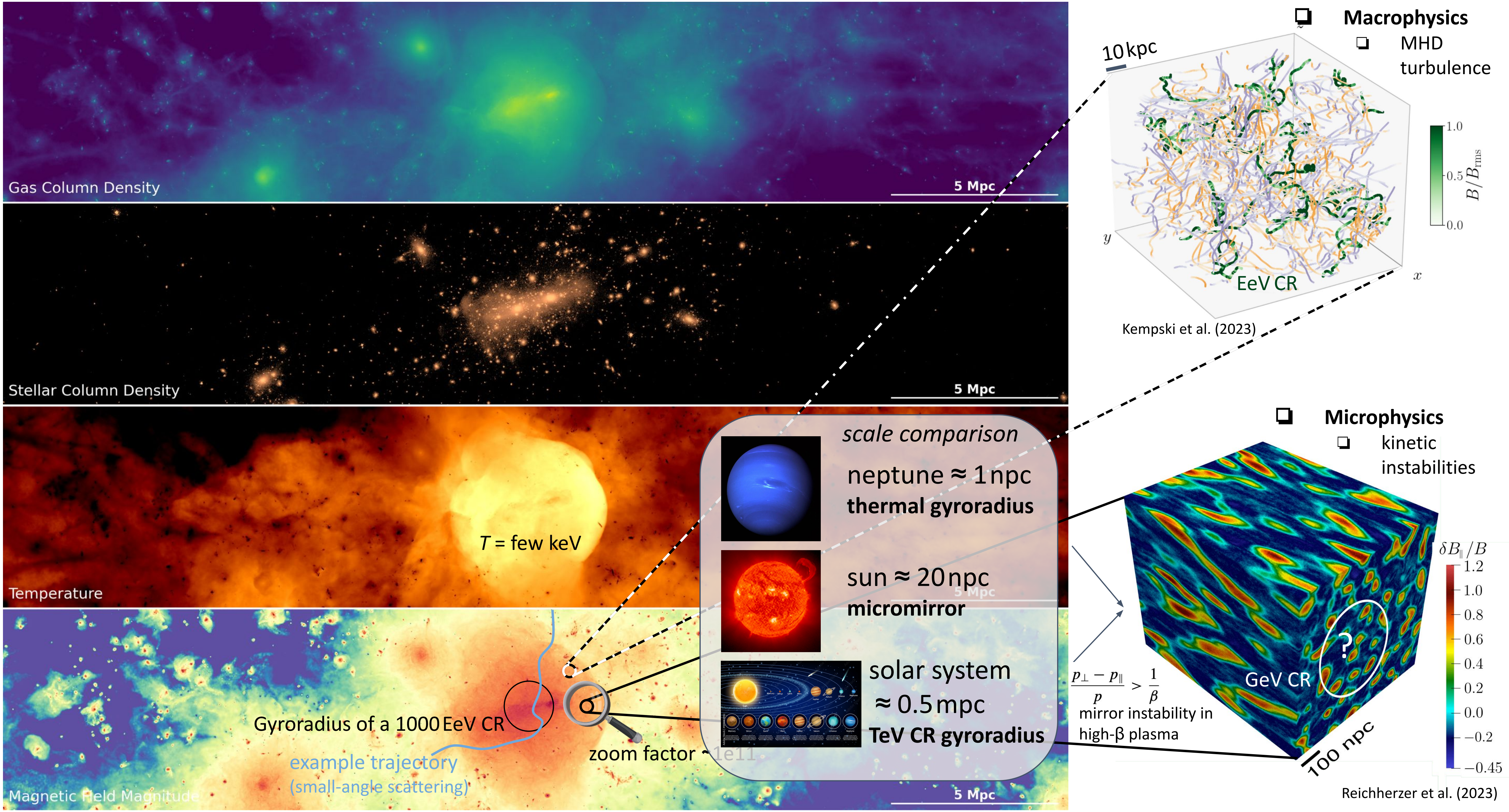
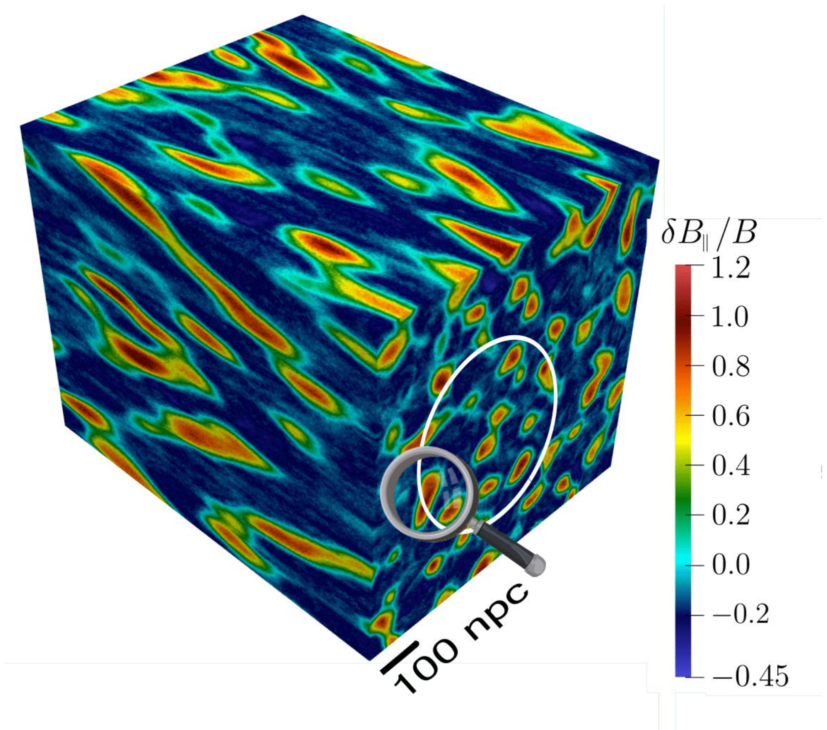
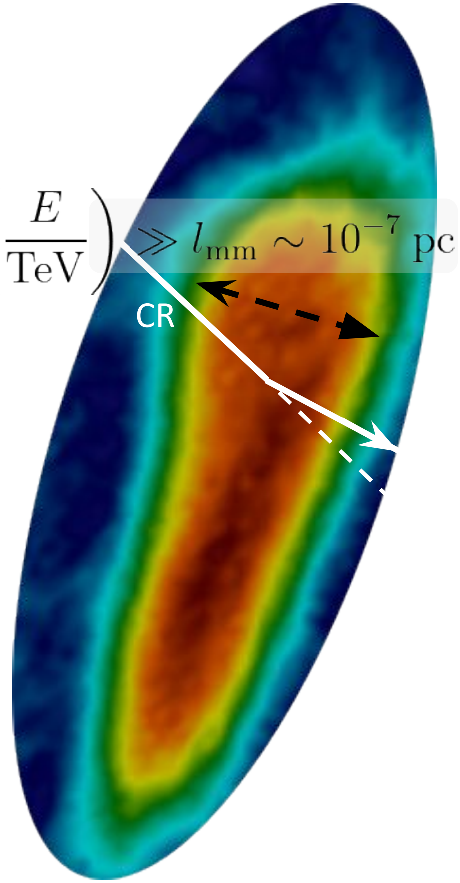


Effect of micromirrors on large-scale CR transport



$$r_\mathrm{g} \sim 10^{-4}\,\mathrm{pc}\left(\frac{E}{\mathrm{TeV}}\right) \gg l_\mathrm{mm} \sim 10^{-7}\,\mathrm{pc}$$



Deflection in micromirror:

$$\delta \boldsymbol{v} \sim \frac{q}{\gamma m c v}\int_0^{l_\mathrm{mm}} \mathrm{d}l\, \boldsymbol{v} \times \delta \boldsymbol{B}_\mathrm{mm}$$

$$\delta\Theta \sim \frac{|\delta \boldsymbol{v}|}{c} \sim \frac{l_\mathrm{mm}}{r_\mathrm{g}}\frac{\delta B_\mathrm{mm}}{B}$$

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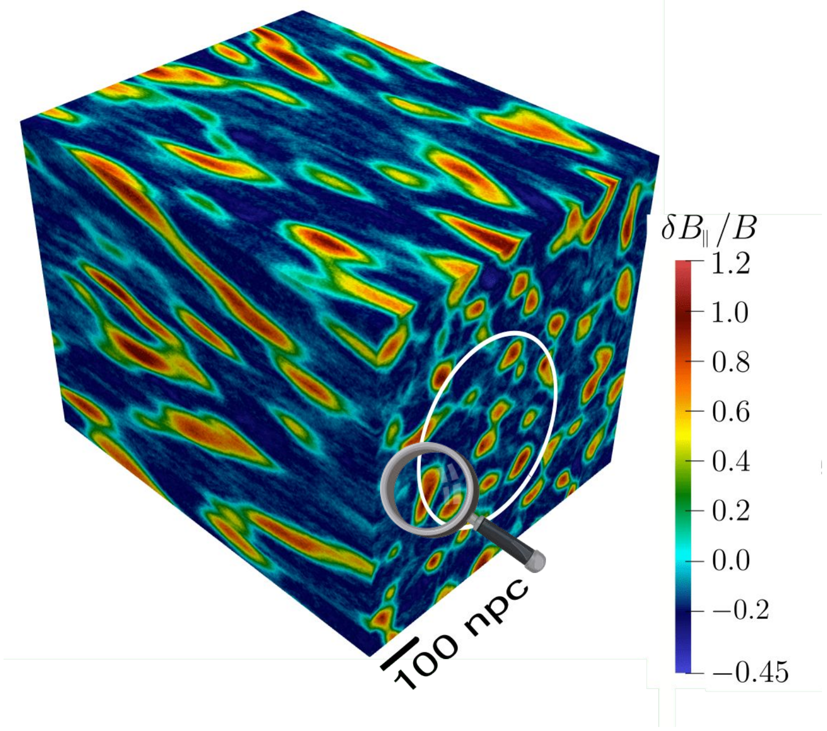

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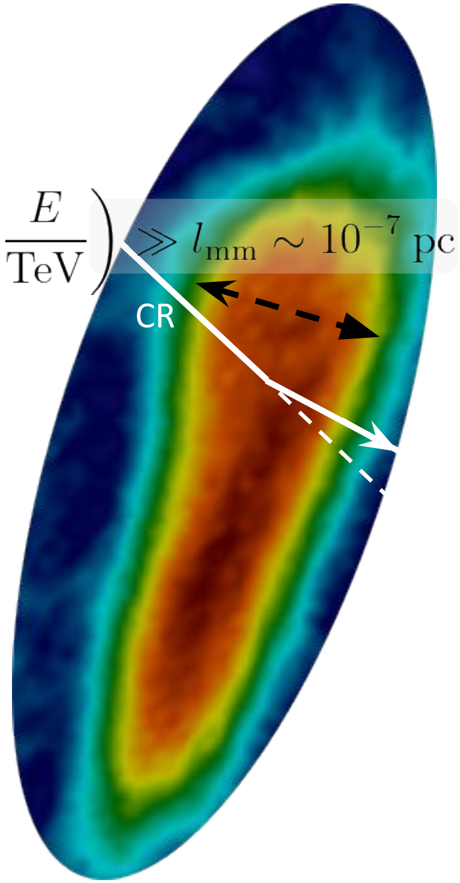

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$$\delta\Theta \sim \frac{|\delta \boldsymbol{v}|}{c} \sim \frac{l_{\mathrm{mm}}}{r_{\mathrm{g}}} \frac{\delta B_{\mathrm{mm}}}{B}$$

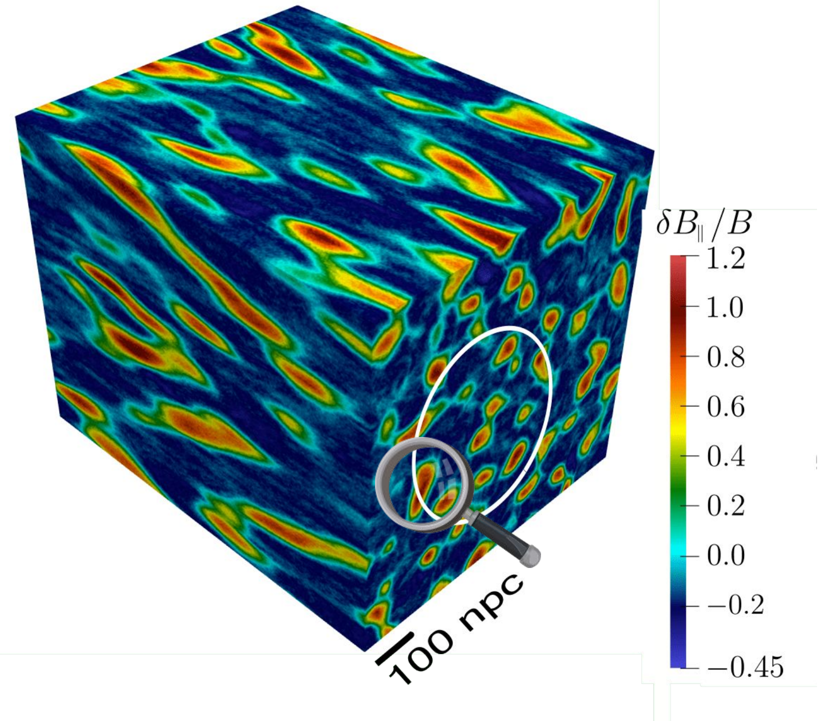
Assuming that these deflections add up as random walk, the scattering rate is

$$\nu_{\mathrm{mm}} \sim \frac{\delta\Theta^2}{\delta t} \sim \frac{c\, l_{\mathrm{mm}}}{r_{\mathrm{g}}^2} \left(\frac{\delta B_{\mathrm{mm}}}{B}\right)^2 ,$$

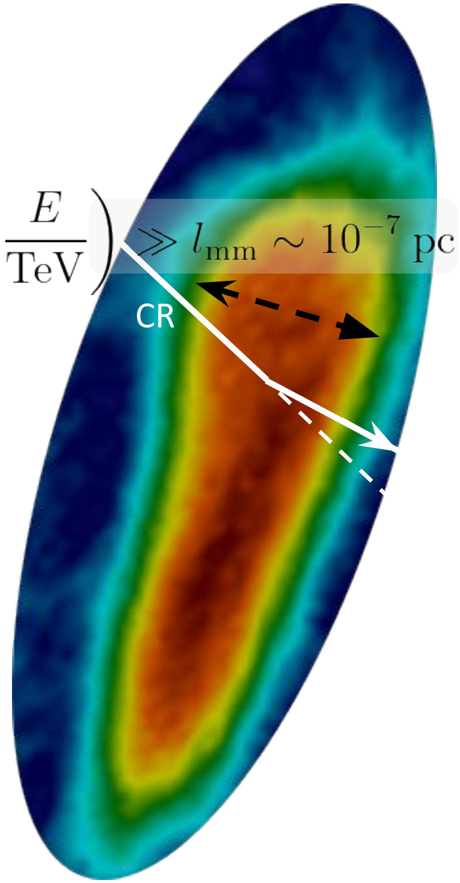
which implies a spatial diffusion coefficient of

$$\kappa_{\mathrm{mm}} \sim \frac{c^2}{\nu_{\mathrm{mm}}} \sim \frac{c\, r_{\mathrm{g}}^2}{l_{\mathrm{mm}}} \left(\frac{\delta B_{\mathrm{mm}}}{B}\right)^{-2} \propto E^2 l_{\mathrm{mm}}^{-1} .$$

Effect of micromirrors on large-scale CR transport



$$r_{\rm g} \sim 10^{-4}\,{\rm pc}\left(\frac{E}{\rm TeV}\right) \gg l_{\rm mm} \sim 10^{-7}\,{\rm pc}$$



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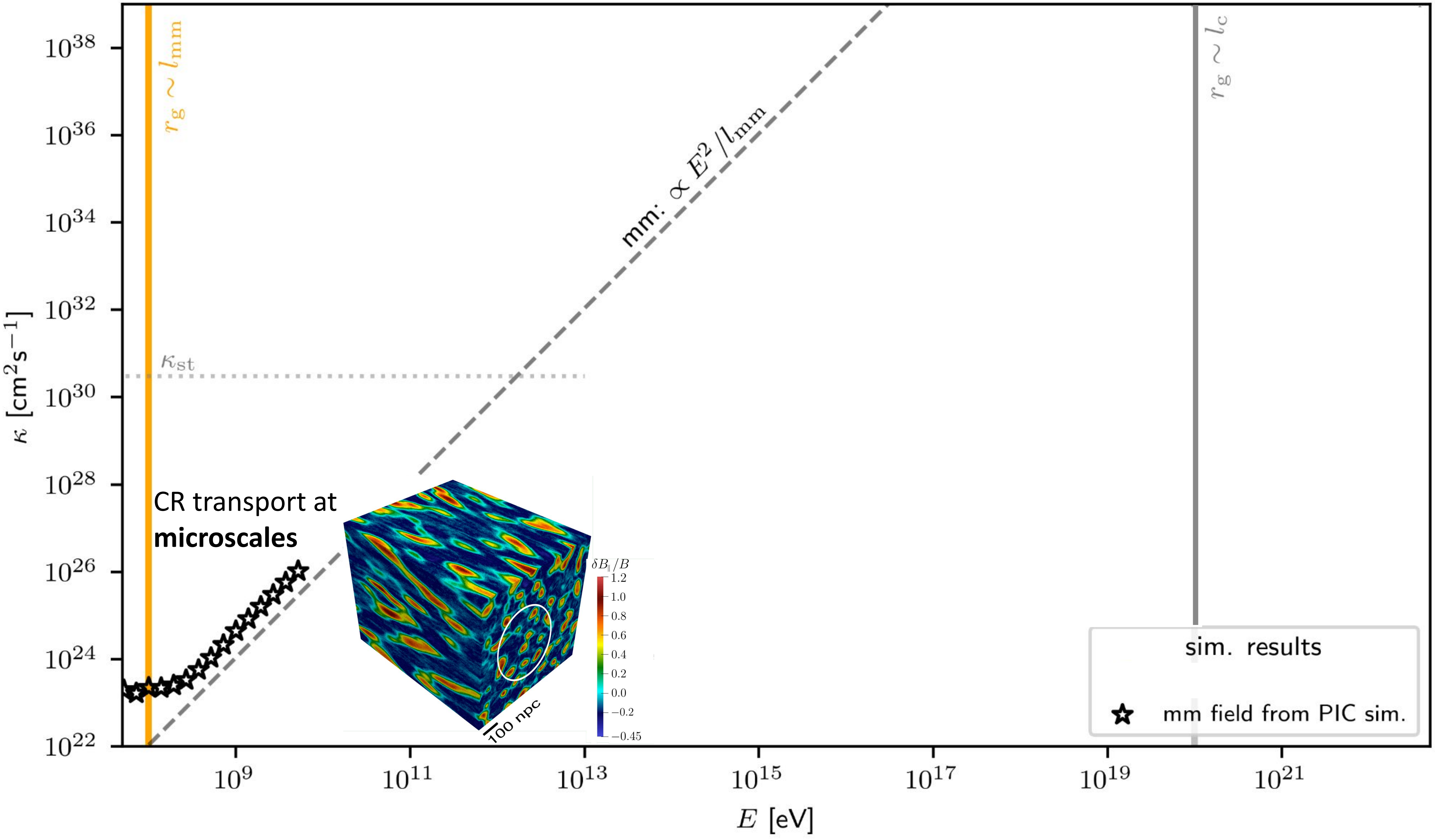
which implies a spatial diffusion coefficient of

$$\kappa_{\rm mm} \sim 10^{30}\, Z^{-2}\left(\frac{T}{5\,{\rm keV}}\right)^{-1/2}\left(\frac{B}{3\,\mu{\rm G}}\right)^{-1}\left(\frac{\delta B_{\rm mm}/B}{1/3}\right)^{-2}\left(\frac{E}{\rm TeV}\right)^2 {\rm cm^2\,s^{-1}}$$

CR transport regimes in ICM



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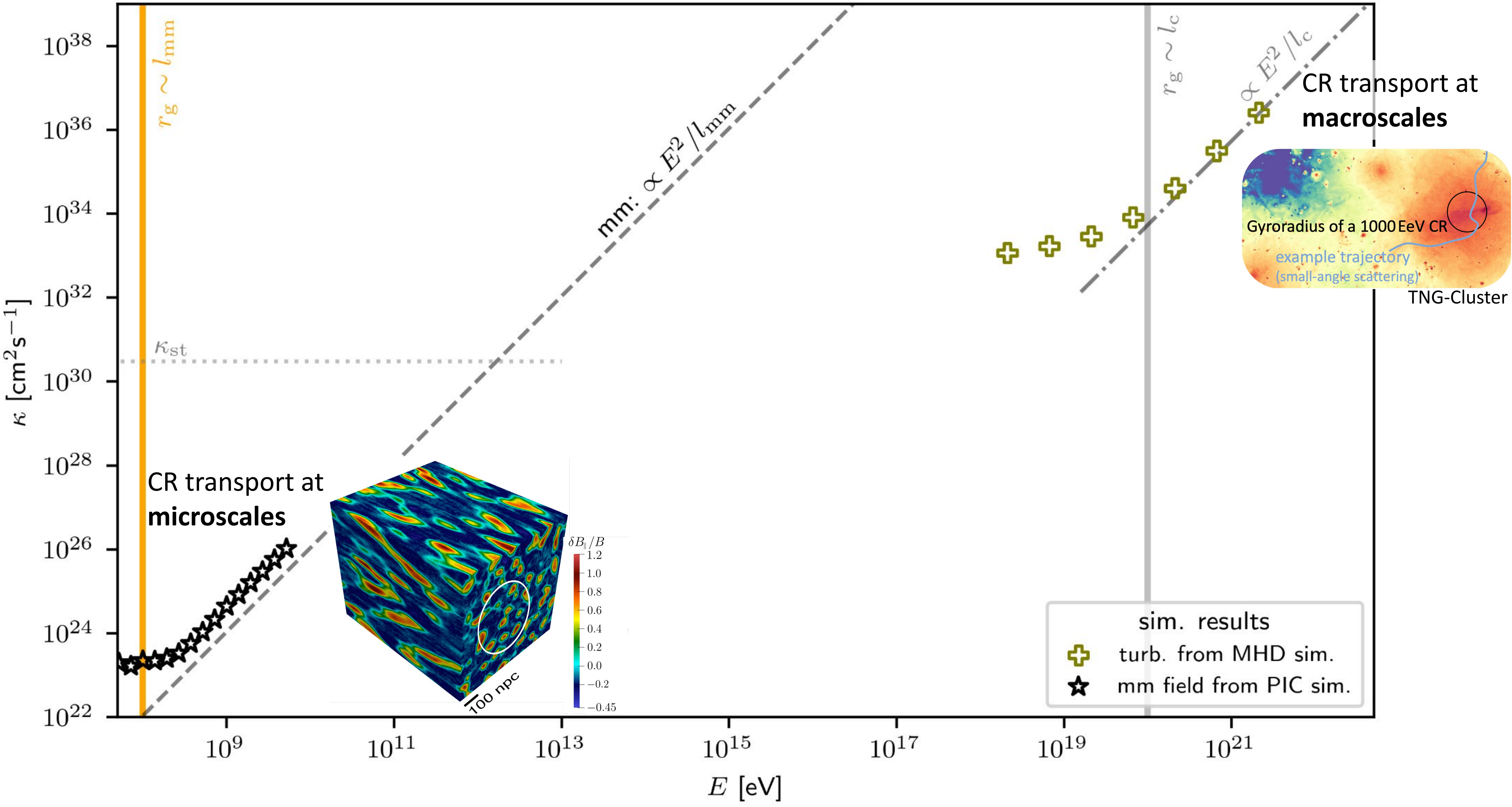

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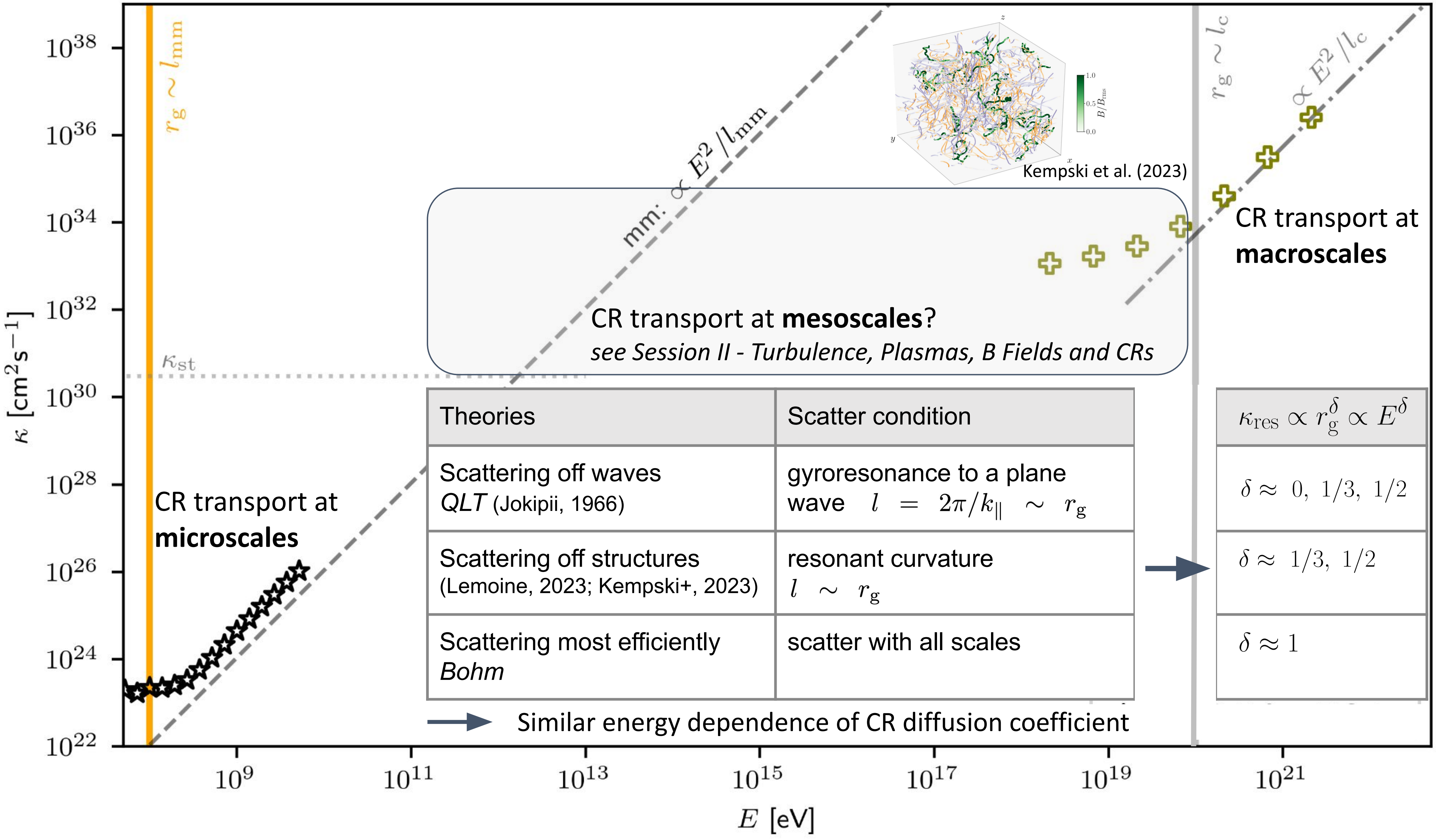


CR transport at **microscales**

CR transport at **mesoscales**?

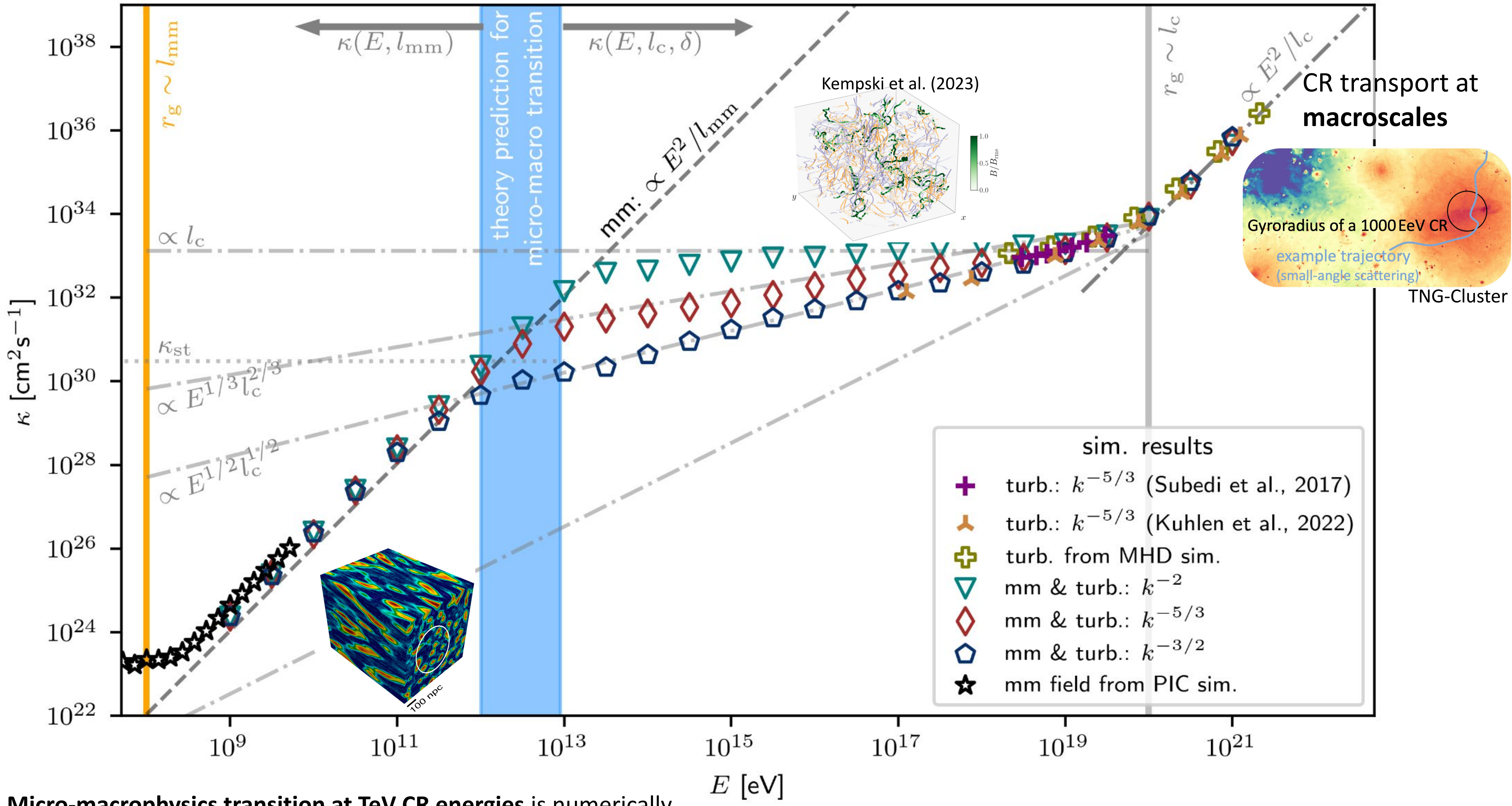
see Session II - Turbulence, Plasmas, B Fields and CRs

CR transport at **macroscales**

Theories	Scatter condition	$\kappa_{res} \propto r_g^{\delta} \propto E^{\delta}$
Scattering off waves *QLT* (Jokipii, 1966)	gyroresonance to a plane wave $l = 2\pi/k_{\parallel} \sim r_g$	$\delta \approx 0,\ 1/3,\ 1/2$
Scattering off structures (Lemoine, 2023; Kempski+, 2023)	resonant curvature $l \sim r_g$	$\delta \approx 1/3,\ 1/2$
Scattering most efficiently *Bohm*	scatter with all scales	$\delta \approx 1$

Similar energy dependence of CR diffusion coefficient

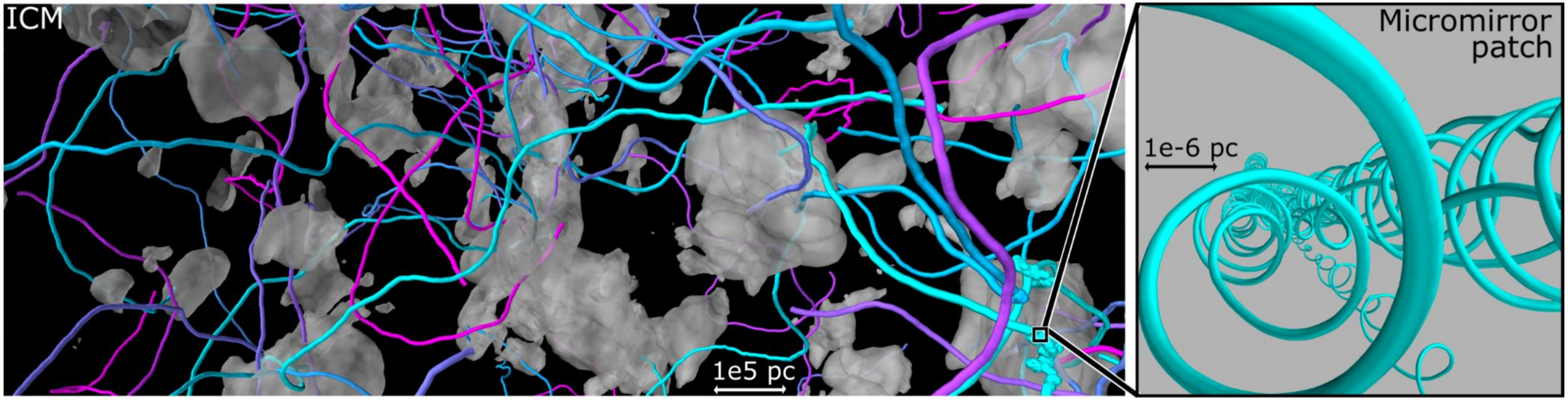
CR transport regimes in ICM



→ **Micro-macrophysics transition at TeV CR energies** is numerically confirmed using synthetic turbulence. We use PIC and MHD to validate the consistency of our numerical approach at micro and macroscales.

Case of spatially intermittent micromirrors

In reality: micromirrors form only where turbulence causes local magnetic field amplification strong enough to generate a pressure anisotropy beyond the mirror-instability threshold ⟶ we turn micromirror scattering on only if the CR is seeing a magnetic field above a certain threshold



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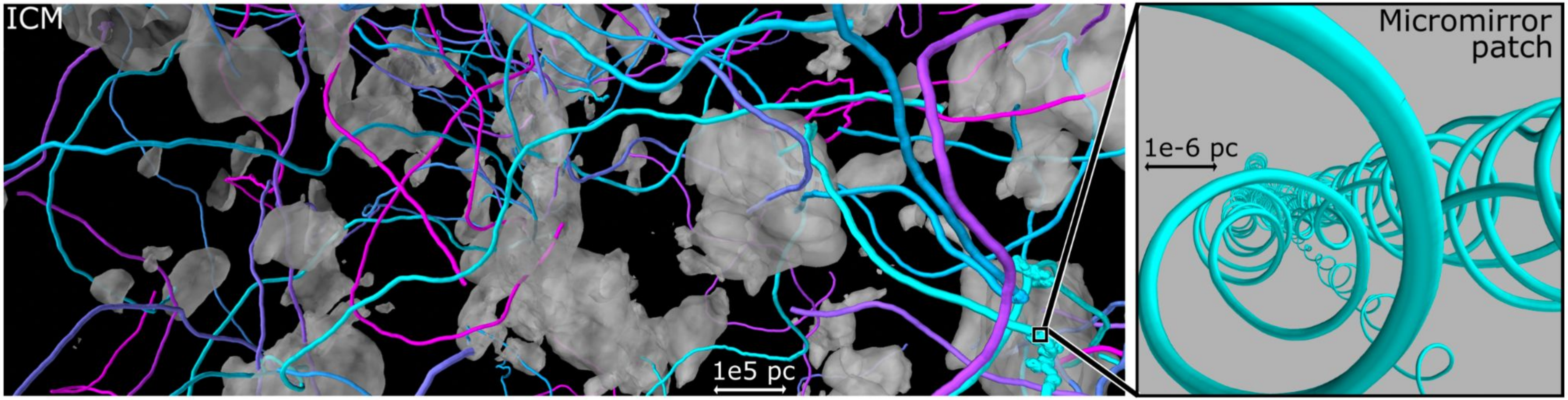


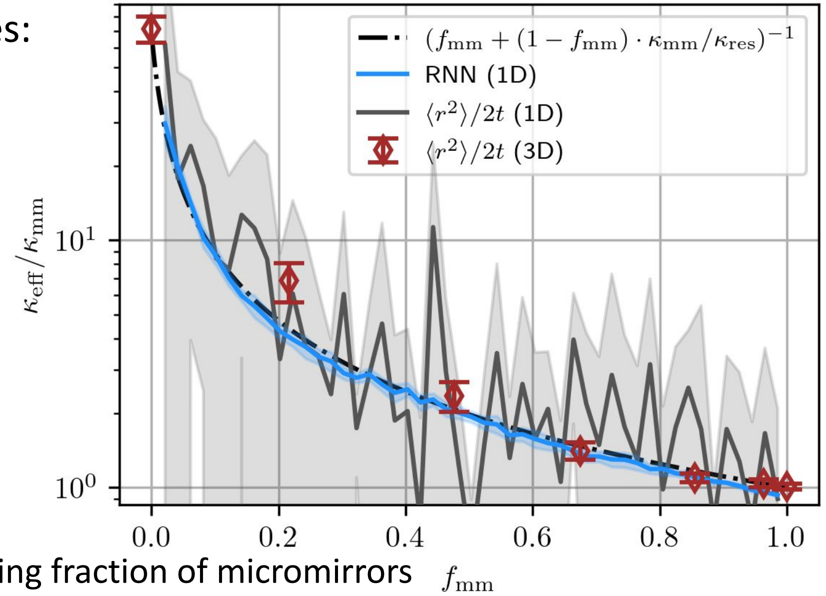
The effective scattering rate in a two-phase medium is the average of the two rates:

$$\nu_{\rm eff} \sim f_{\rm mm}\,\nu_{\rm mm} + (1 - f_{\rm mm})\,\nu_{\rm res}$$

Then the effective diffusion coefficient is:

$$\kappa_{\rm eff} \sim \frac{\kappa_{\rm mm}}{f_{\rm mm} + (1 - f_{\rm mm})\kappa_{\rm mm}/\kappa_{\rm res}}$$

⟶ Only minor modification of our cruder $(f_{\rm mm} = 1)$ estimate



Summary of results & implications

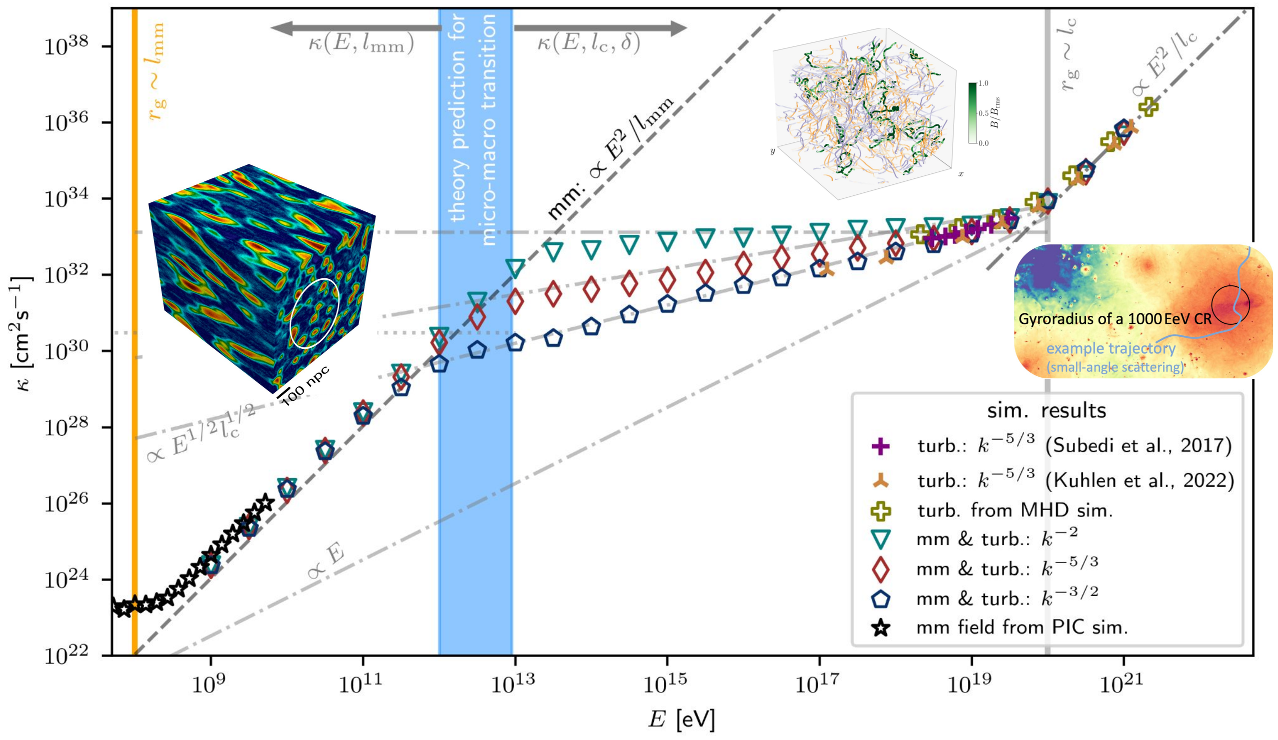
Results:

- ❑ Effect on macroscopic sub-TeV CR diffusion from magnetic micromirrors

$$\kappa_{\mathrm{mm}} \sim 10^{30}\mathrm{cm}^2\mathrm{s}^{-1}\left(\frac{l_{\mathrm{mm}}}{100\,\mathrm{npc}}\right)^{-1}\left(\frac{B}{3\,\mu\mathrm{G}}\right)^{-2}\left(\frac{\delta B_{\mathrm{mm}}/B}{1/3}\right)^{-2}\left(\frac{E}{\mathrm{TeV}}\right)^{2}$$

- ❑ Minor modification of only considering patches of micromirrors

$$\kappa_{\mathrm{eff}} \sim \frac{\kappa_{\mathrm{mm}}}{f_{\mathrm{mm}} + (1-f_{\mathrm{mm}})\kappa_{\mathrm{mm}}/\kappa_{\mathrm{res}}}$$



Implications of increased collisionality (suppressed diffusion coefficients) in high-β plasmas:

- ❑ **Traps sub-TeV CRs near emission sources within galaxy clusters, addressing non-detection of diffuse γ-ray emission**

$$\frac{\gamma_{\mathrm{SI}}}{\nu_{\mathrm{mm}}} \sim 4\times10^{-5}\left(\frac{B}{3\,\mu\mathrm{G}}\right)^{-1}\left(\frac{E}{\mathrm{TeV}}\right)^{0.4}\left(\frac{l_{\mathrm{mm}}}{100\,\mathrm{npc}}\right)^{-1}\left(\frac{\delta B_{\mathrm{mm}}/B}{1/3}\right)^{-2}$$

- ❑ Potential suppression of the CR streaming instability
- ❑ CRs being “frozen” within the plasma as gas density and magnetic field evolve
  - ❑ a presumption already used in models of dynamic evolution of galaxy clusters

paper link

patrick.reichherzer@physics.ox.ac.uk

UNIVERSITY OF OXFORD

Implications on CR self-confinement

1. The growth rate of the resonant streaming instability is:

$$\gamma_{\rm SI} \sim \Omega_{\rm CR} \frac{n_{\rm CR}(>E)}{n_i} \left(\frac{v_{\rm st}}{v_{\rm A}} - 1 \right) \sim 3 \times 10^{-14}\,{\rm s}^{-1} \left(\frac{B}{3\,\mu{\rm G}} \right) \left(\frac{E}{\rm TeV} \right)^{-1.6}$$

$\left(v_{\rm st}/v_{\rm A} \sim 2 \text{ and } n_{\rm CR}(>E)/n_i \sim 10^{-7} (E/{\rm GeV})^{1-\alpha}, \text{ with } \alpha \approx 2.6 \right)$

$$\frac{\gamma_{\rm SI}}{\nu_{\rm mm}} \sim 4 \times 10^{-5} \left(\frac{B}{3\,\mu{\rm G}} \right)^{-1} \left(\frac{E}{\rm TeV} \right)^{0.4} \left(\frac{l_{\rm mm}}{100\,{\rm npc}} \right)^{-1} \left(\frac{\delta B_{\rm mm}/B}{1/3} \right)^{-2}$$

→ With such a large effective collisionality in the system, it is very unlikely that what is, in essence, a collisionless, resonant instability can survive.

2. Let us pretend that the instability is not suppressed:

$$\kappa_{\rm st} \sim l_{\rm c} v_{\rm st} \gtrsim l_{\rm c} v_{\rm A} \sim 10^{30} \left(\frac{l_{\rm c}}{100\,{\rm kpc}} \right) \left(\frac{v_{\rm A}}{100\,{\rm km/s}} \right) {\rm cm}^2\ {\rm s}^{-1}$$

$$\frac{\kappa_{\rm mm}}{\kappa_{\rm st}} \sim 1 \left(\frac{E}{\rm TeV} \right)^{2} \left(\frac{l_{\rm mm}}{100\,{\rm npc}} \right)^{-1} \left(\frac{l_{\rm c}}{100\,{\rm kpc}} \right)^{-1} \left(\frac{B}{3\,\mu{\rm G}} \right)^{-2} \left(\frac{\delta B_{\rm mm}/B}{1/3} \right)^{-2} \left(\frac{v_{\rm A}}{100\,{\rm km/s}} \right)^{-1}$$

→ Scattering of sub-TeV CRs at micromirrors increases the effective CR collisionality in high-β environments. This would potentially undermine the CR streaming instability