# Acceleration of TeV particles in structure formation shocks

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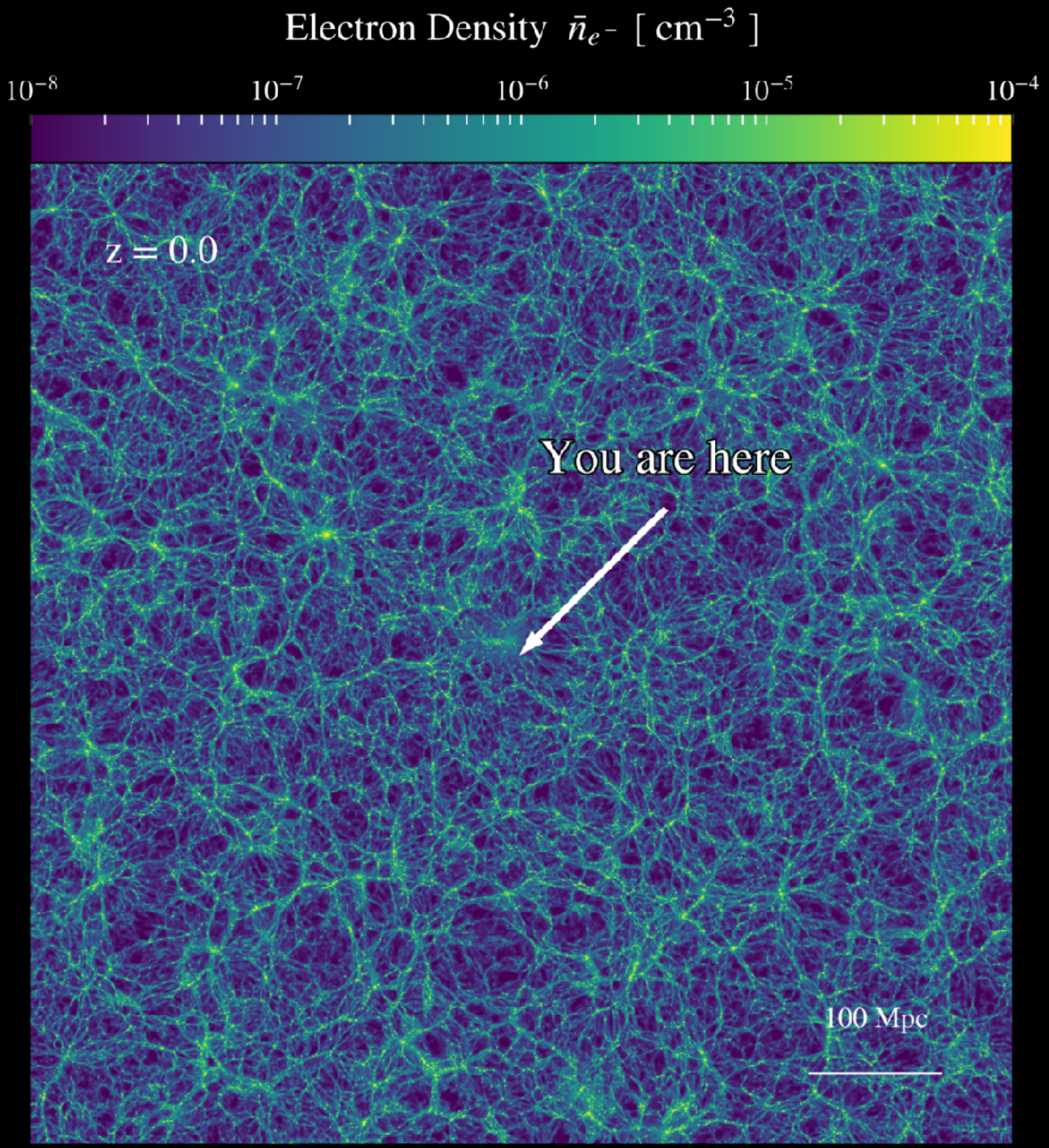
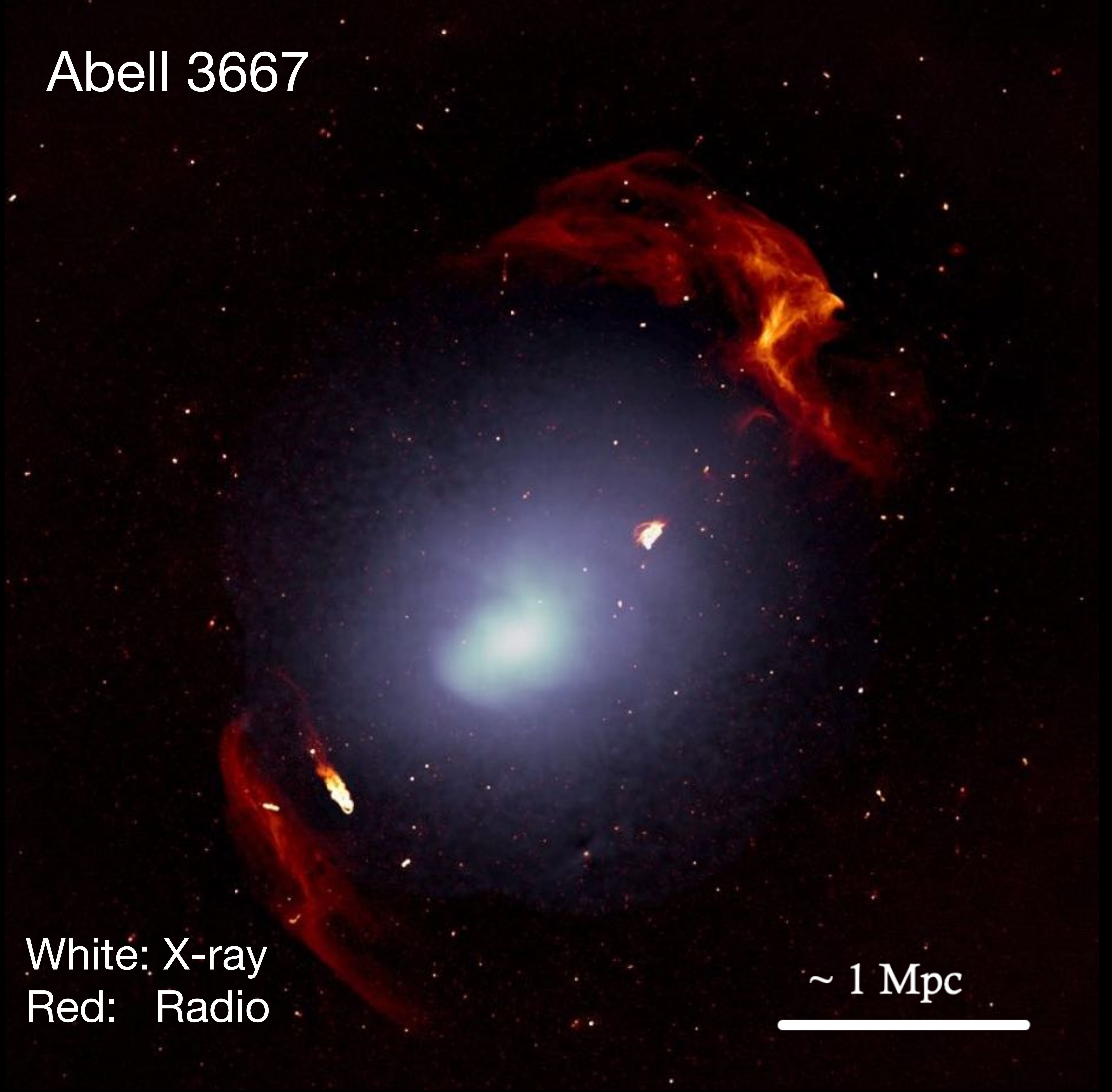
# Cosmic large-scale structure

- Cosmic Web
  - Voids
  - Filaments
  - Nodes / Galaxy Clusters
- Formation via gravitational collapse
- Gravitational energy transformed to kinetic / thermal energy (mainly via shocks/turbulence)



# Cosmic rays in galaxy clusters

- Relativistic electrons & protons
- Accelerated by shocks / AGN
- Tracers of magnetic field
- Observable as radio relics and radio halos
- Additional non-thermal pressure component from CR protons (below ~1%)




De Gasperin et al. (2022)

# A spectral cosmic ray model for cosmological simulations

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# Challenges for cosmological simulations

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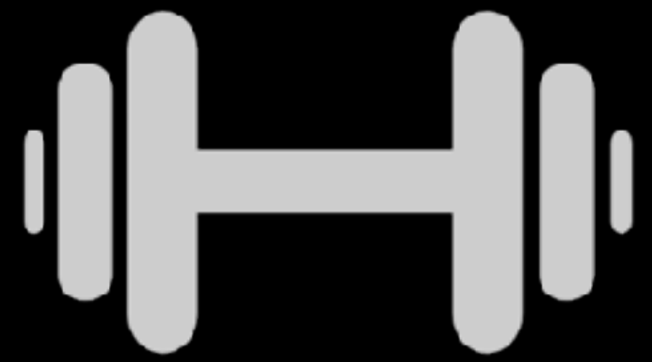
$$m_{e^-} \approx 10^{-27}\text{g} \rightarrow m_{\text{GasP}} \approx 10^{38}\text{g}$$

$$\Rightarrow \text{Factor } \; 10^{65}$$

# Challenges for cosmological simulations

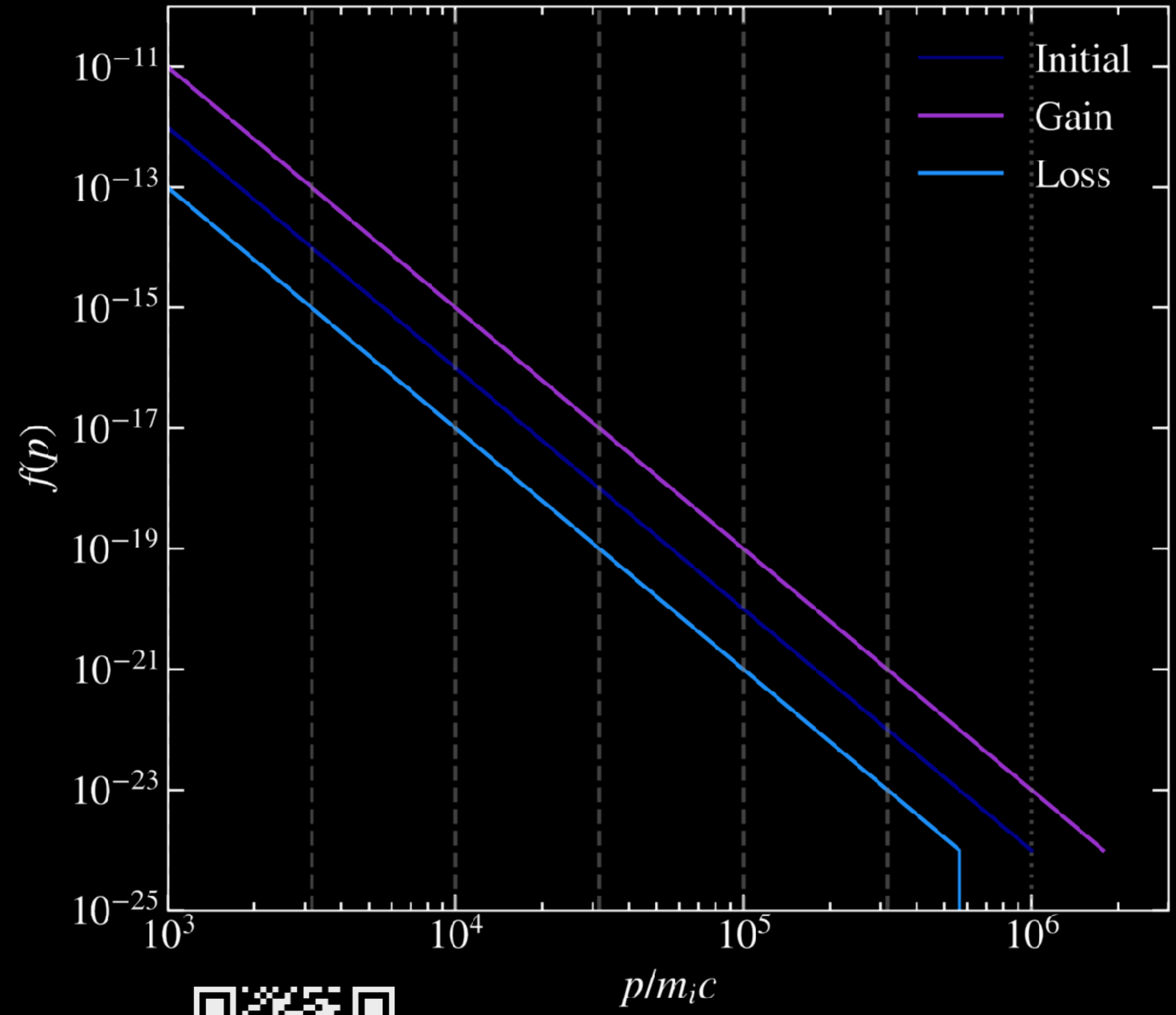


$$m_{e^-} \approx 10^{-27}\mathrm{g} \to m_{\mathrm{GasP}} \approx 10^{38}\mathrm{g}$$
$$\Rightarrow \text{Factor } 10^{65}$$

$$r_{e^-} \approx 10^{-17}\mathrm{cm} \to r_L \approx 10^{13}\mathrm{cm} \to r_{\mathrm{GasP}} \approx 10^{21}\mathrm{cm}$$
$$\Rightarrow \text{Factor } 10^{38}$$

# CRESCENDO

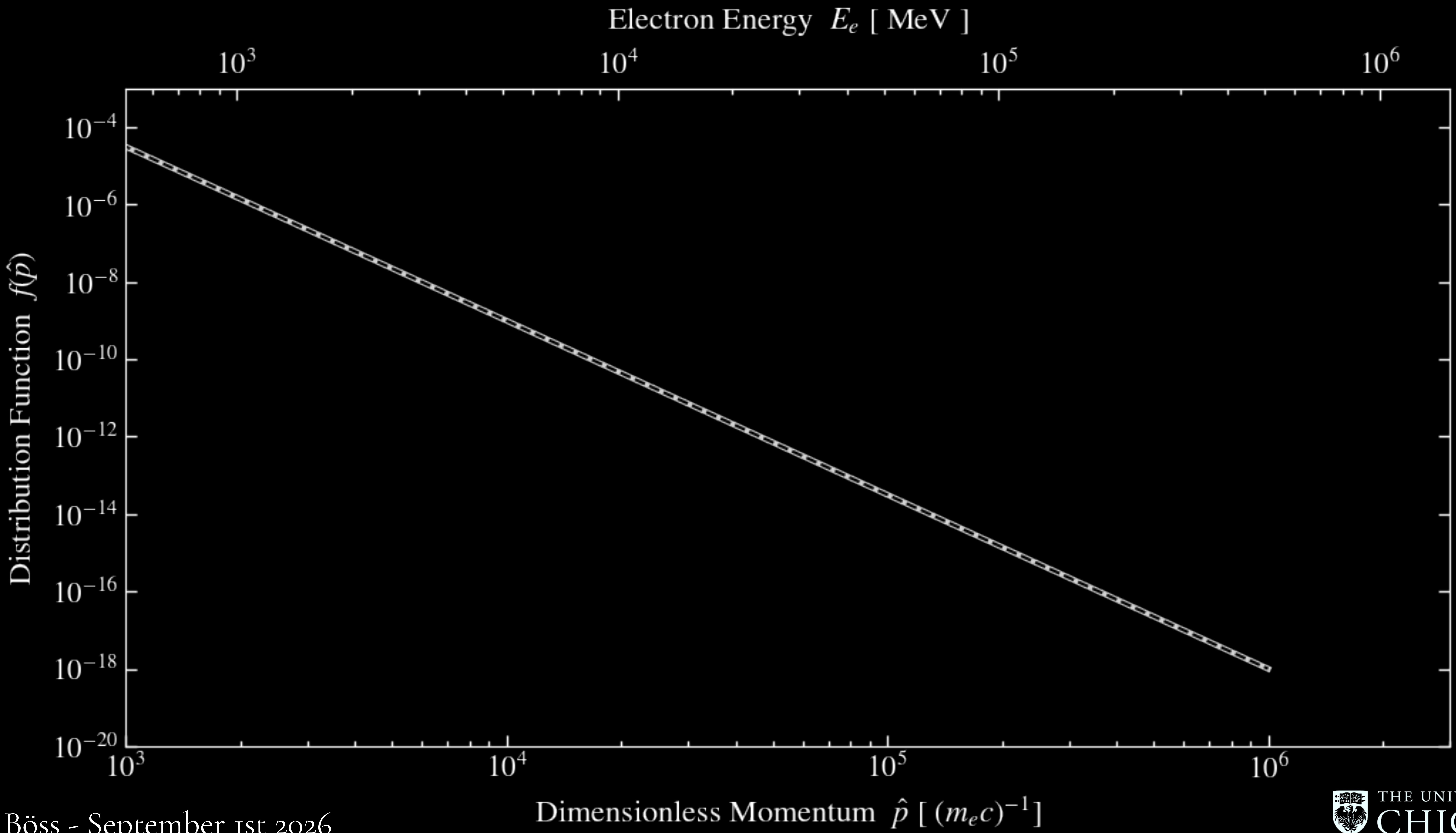
- We treat populations of CR electrons and protons (Miniati 2001)
- Attached to each resolution element
- Discretized as piece-wise power law
- Evolve distribution function f(p) at every timestep
- Feedback via pressure component
- Observables from distr. function




Dashed lines: bin boundaries
Dotted line: spectral cutoff

Böss+2023

$$\frac{Df(p,t)}{Dt} = \nabla\left(\kappa(p)\nabla f(p,t)\right) + \left(\frac{1}{3}\nabla\cdot\mathbf{u}\right)p\frac{\partial f(p,t)}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[\sum_l b_l f(p,t) + D_{\mathrm{pp}}\frac{\partial f(p,t)}{\partial p}\right]\right) + j(\mathbf{x},p)$$



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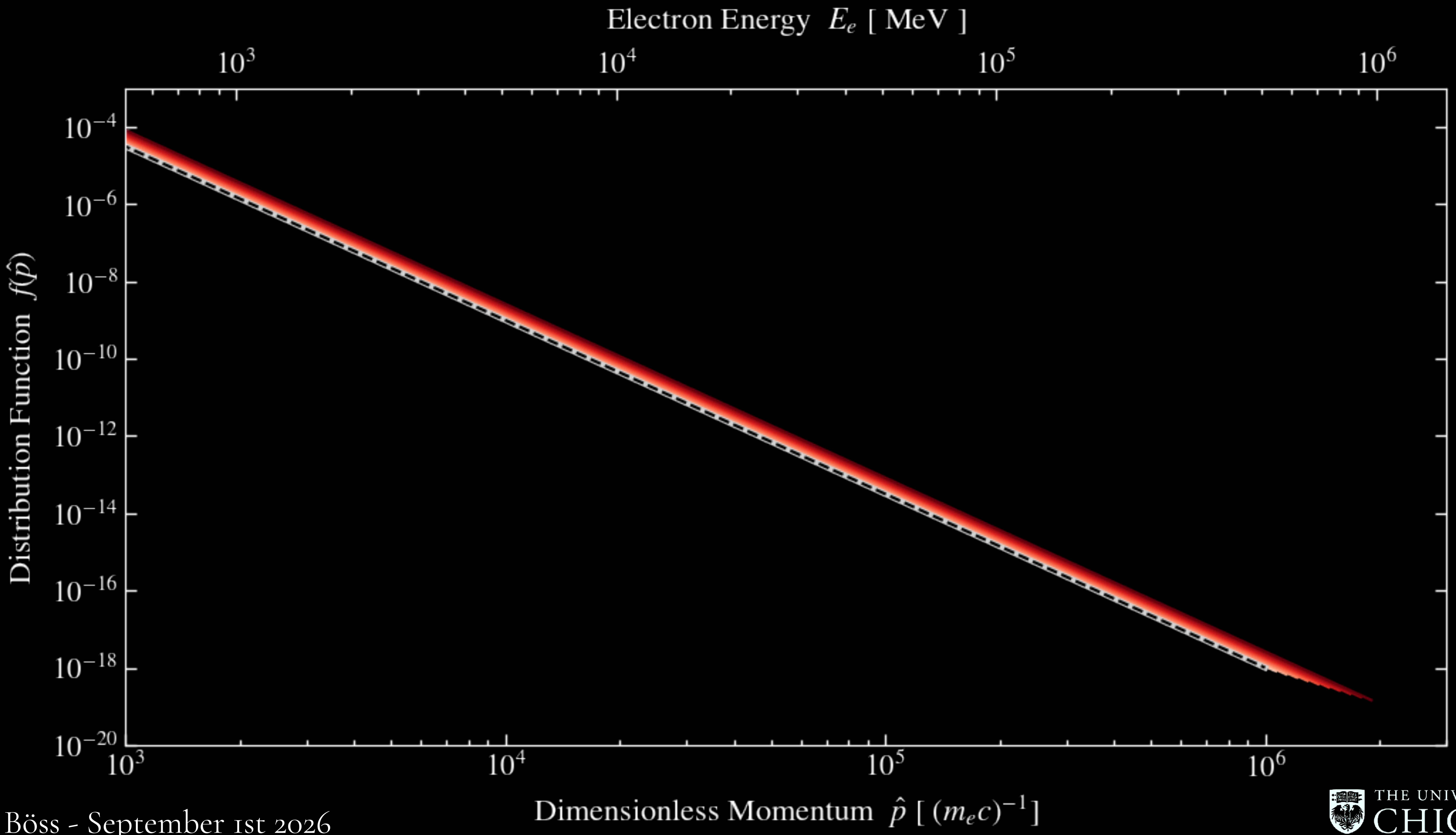

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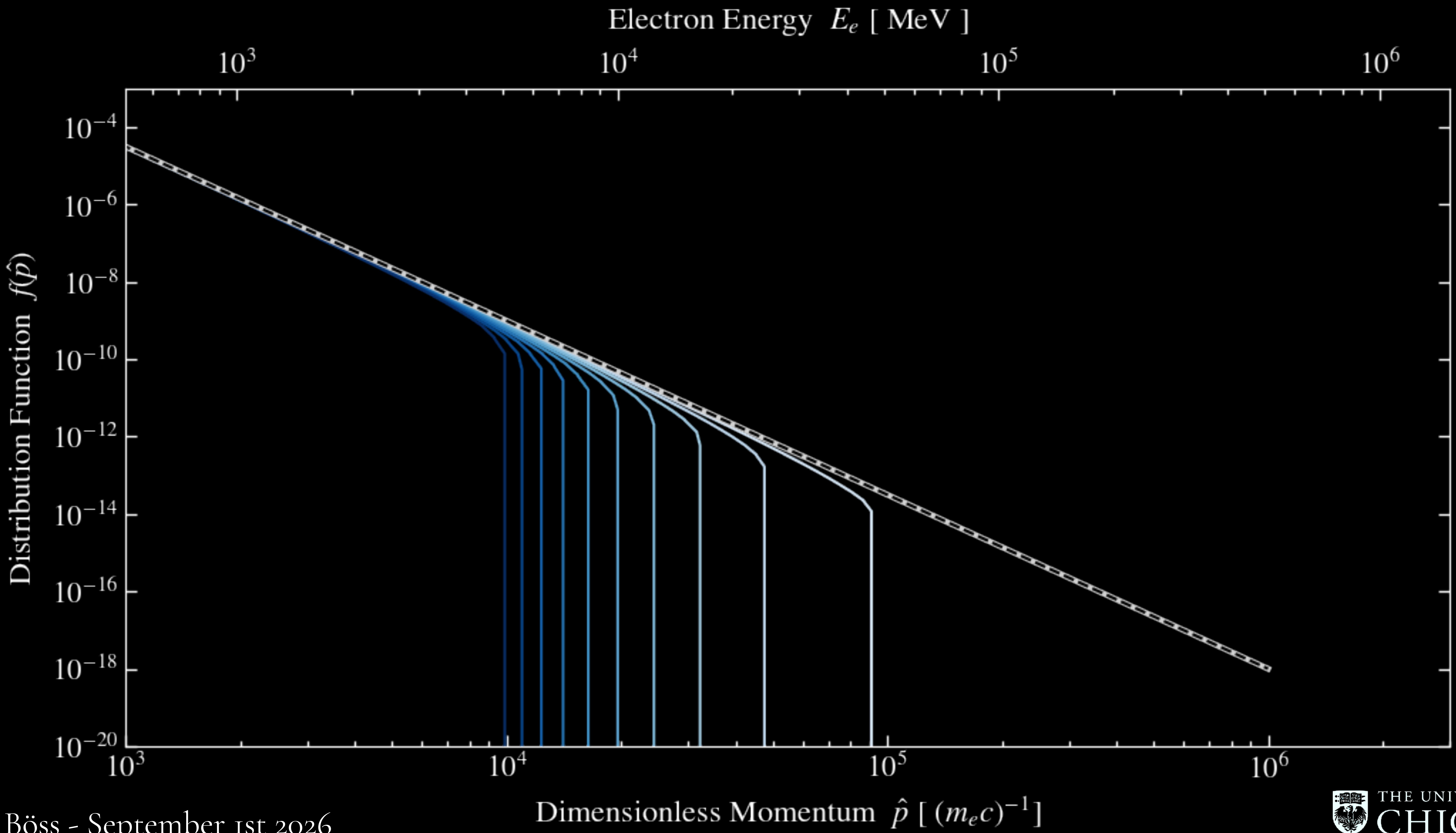

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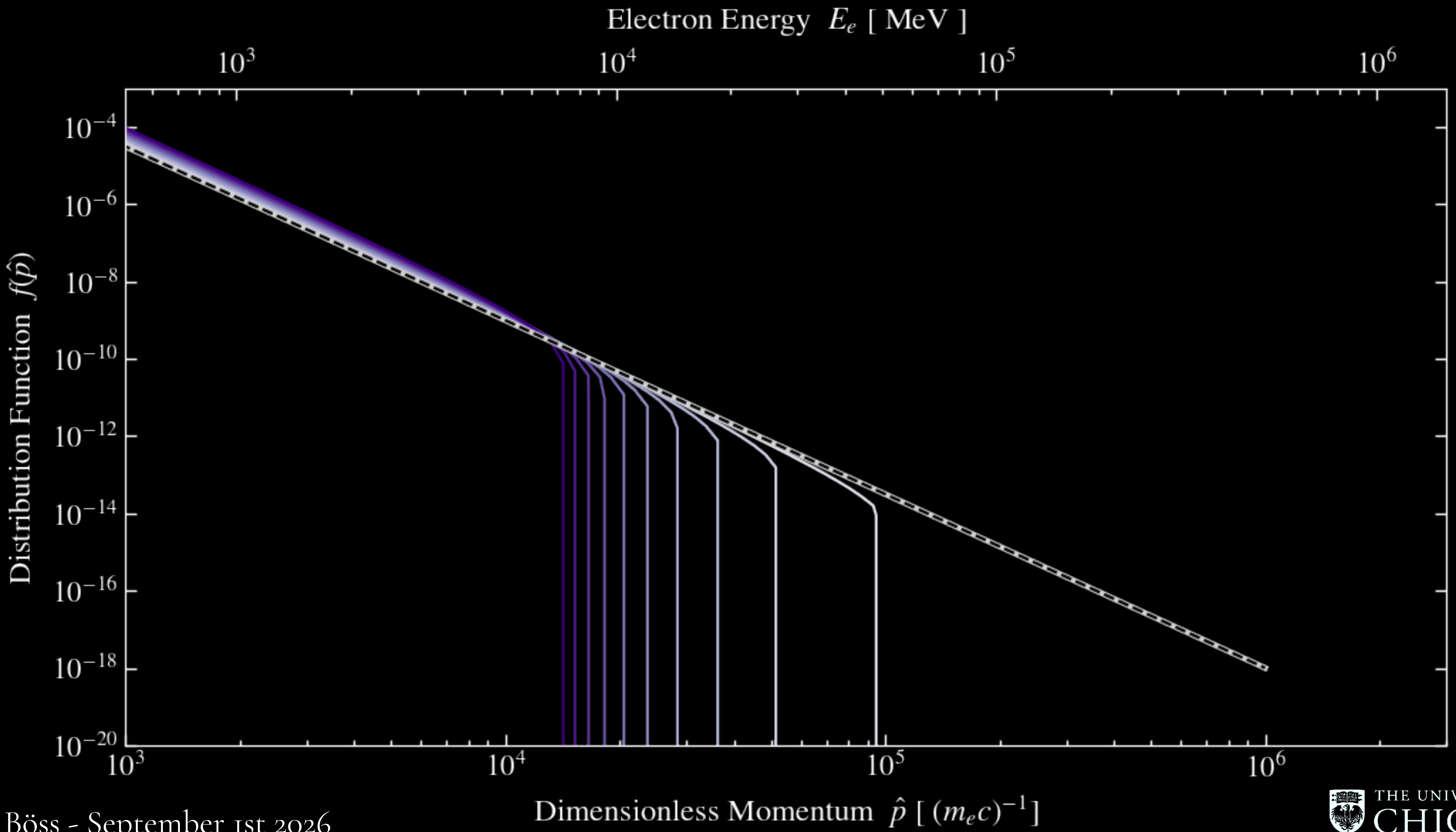

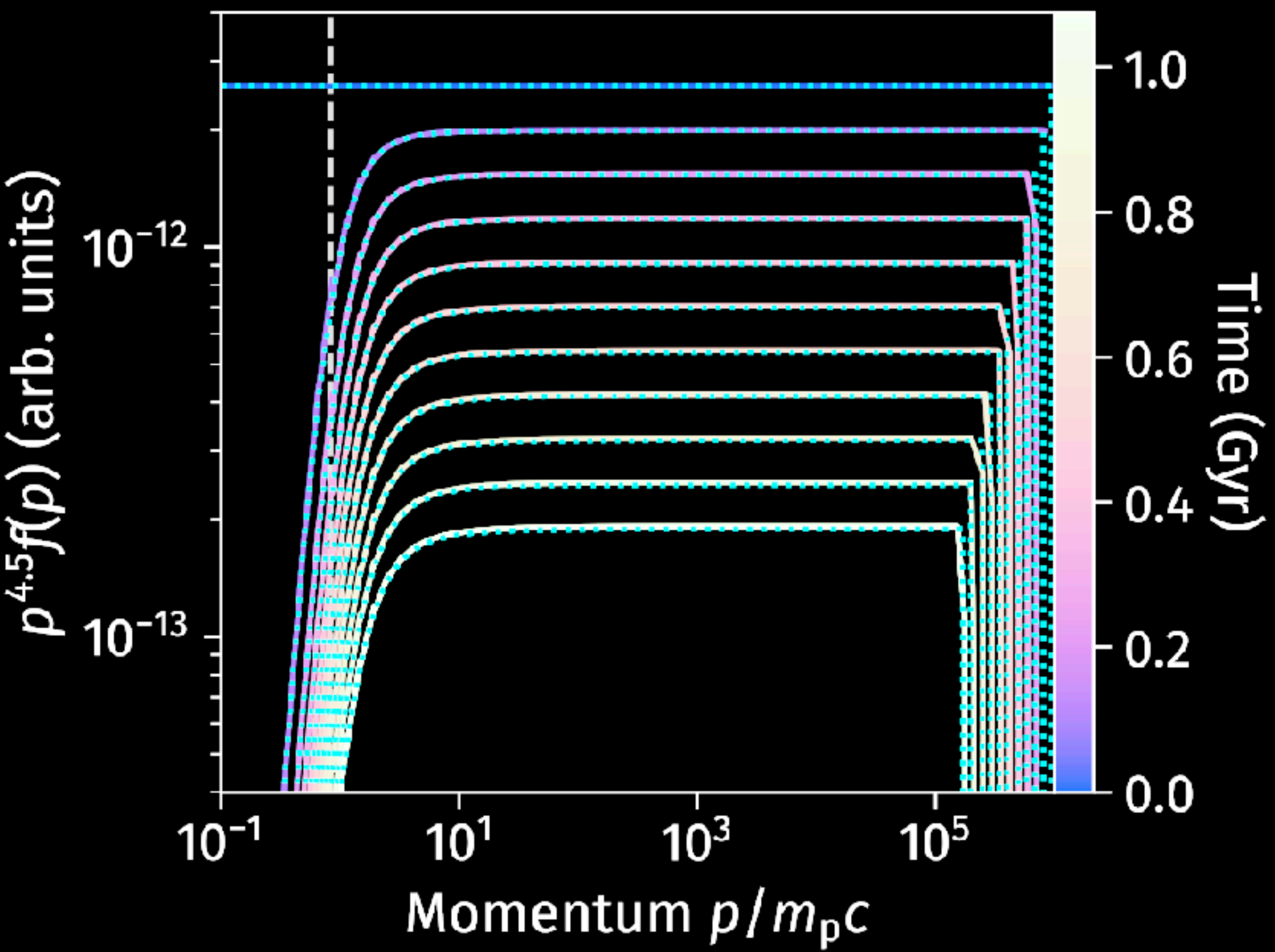


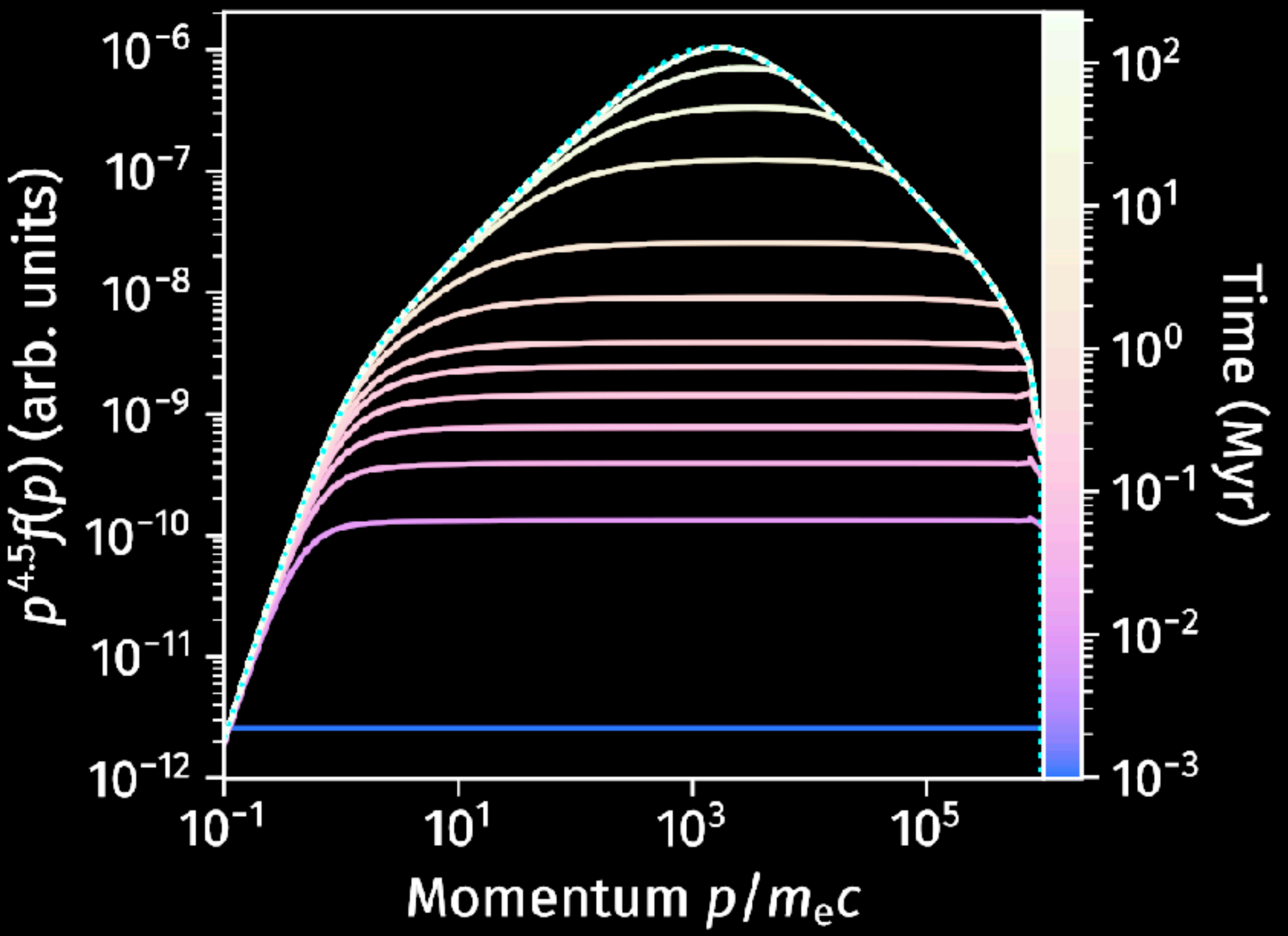


Protons:
- Coulomb losses
- Hadronic losses

Electrons:
- Coulomb losses
- Bremsstrahlung losses
- Synchrotron/IC losses

Karner, LMB, Dolag, Khabibullin (arXiv:2607.14363)

# Self-consistent synchrotron emission




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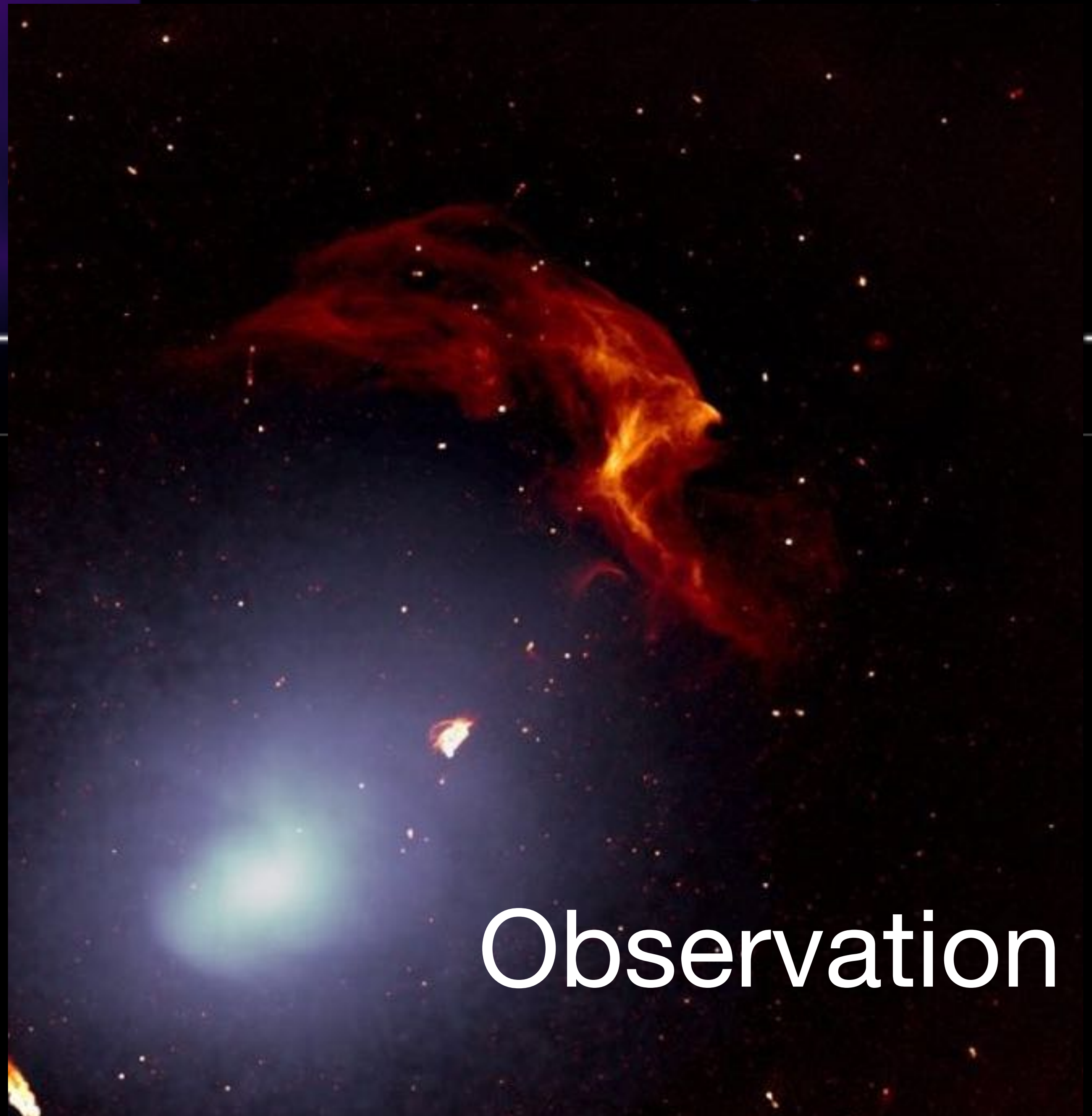




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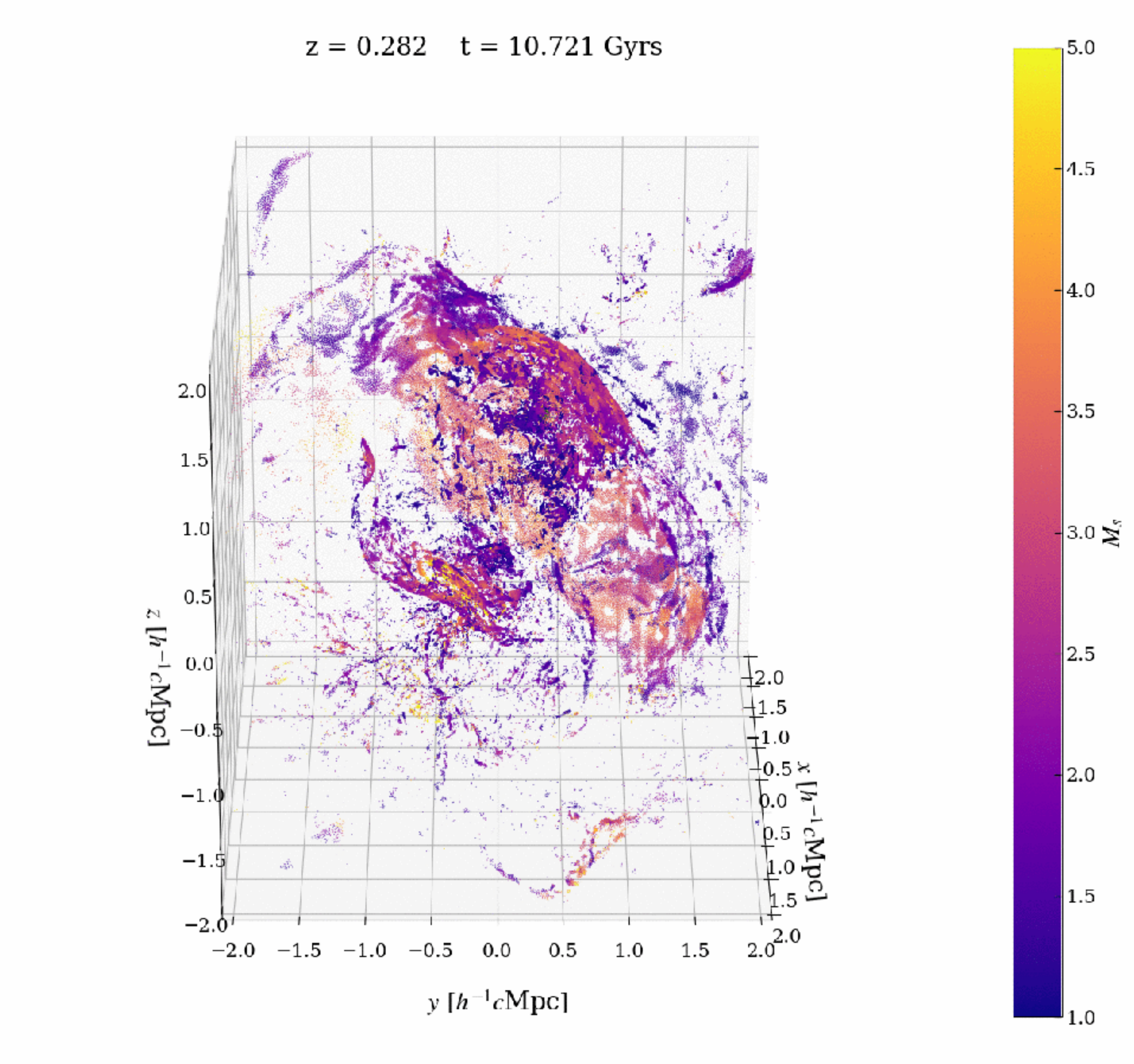
# Merger shocks

- Simulations allow insights into:
  - Complex geometries
  - Overlapping shocks
  - Intricate surface structures
  - Time evolution
  - Mach number variations across the shock surface



# Bridging scales:
# DSA with magnetic micro mirrors

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# Magnetic micromirrors:
# Magnetic field structures in the ICM that efficiently confine CRs

Reichherzer et al. (2025)


What happens if a shock runs through such a medium?

Diesing, LMB, Caprioli (2026, ApJ, arXiv:2510.23700)

# Magnetic micromirrors

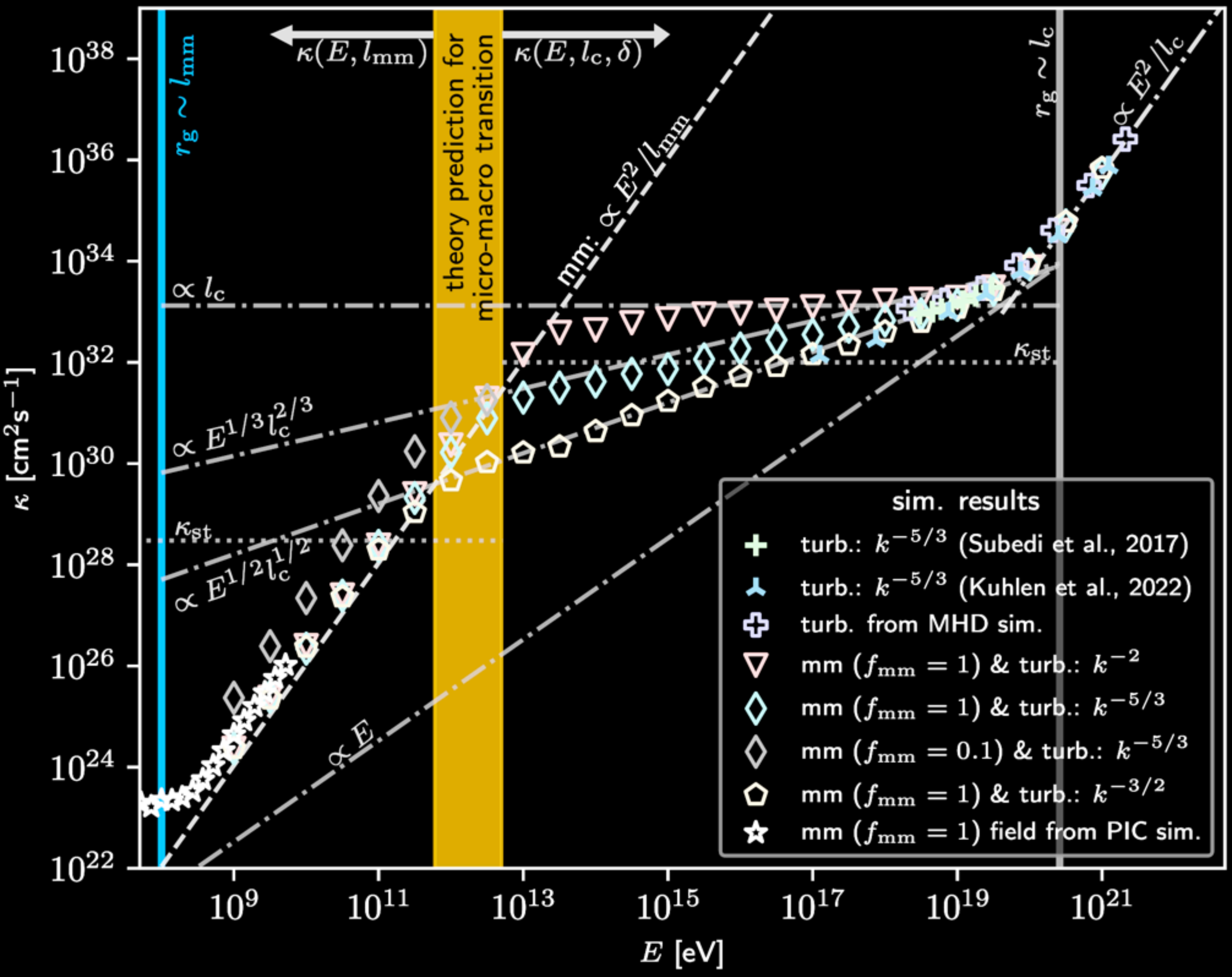
- Compute the time CRs can be confined within macromirrors

$$\tau_{\rm acc} \simeq 19\ \text{yr} \times R/(R-1) \times Z^{-2} T_{\rm 5keV} B_{3\mu\rm G}^{-1} \delta B_{\rm mm,1/3}^{-2} E_{\rm GeV}^{2} v_{\rm sh,8}^{-2}$$

- Solve for the maximum energy of the particles

$$E_{\rm max,\ mm} \simeq 73\ \text{GeV} \times (R/(R-1))^{-1/2} \times Z\, \tau_{\rm sh,6}^{1/2}\, T_{\rm 5keV}^{1/4}\, B_{3\mu\rm G}^{1/2}\, \delta B_{\rm mm,1/3}\, v_{\rm sh,8}\, f_{\rm mm,-1}^{1/2}$$

- This provides the upper end of the injected spectrum



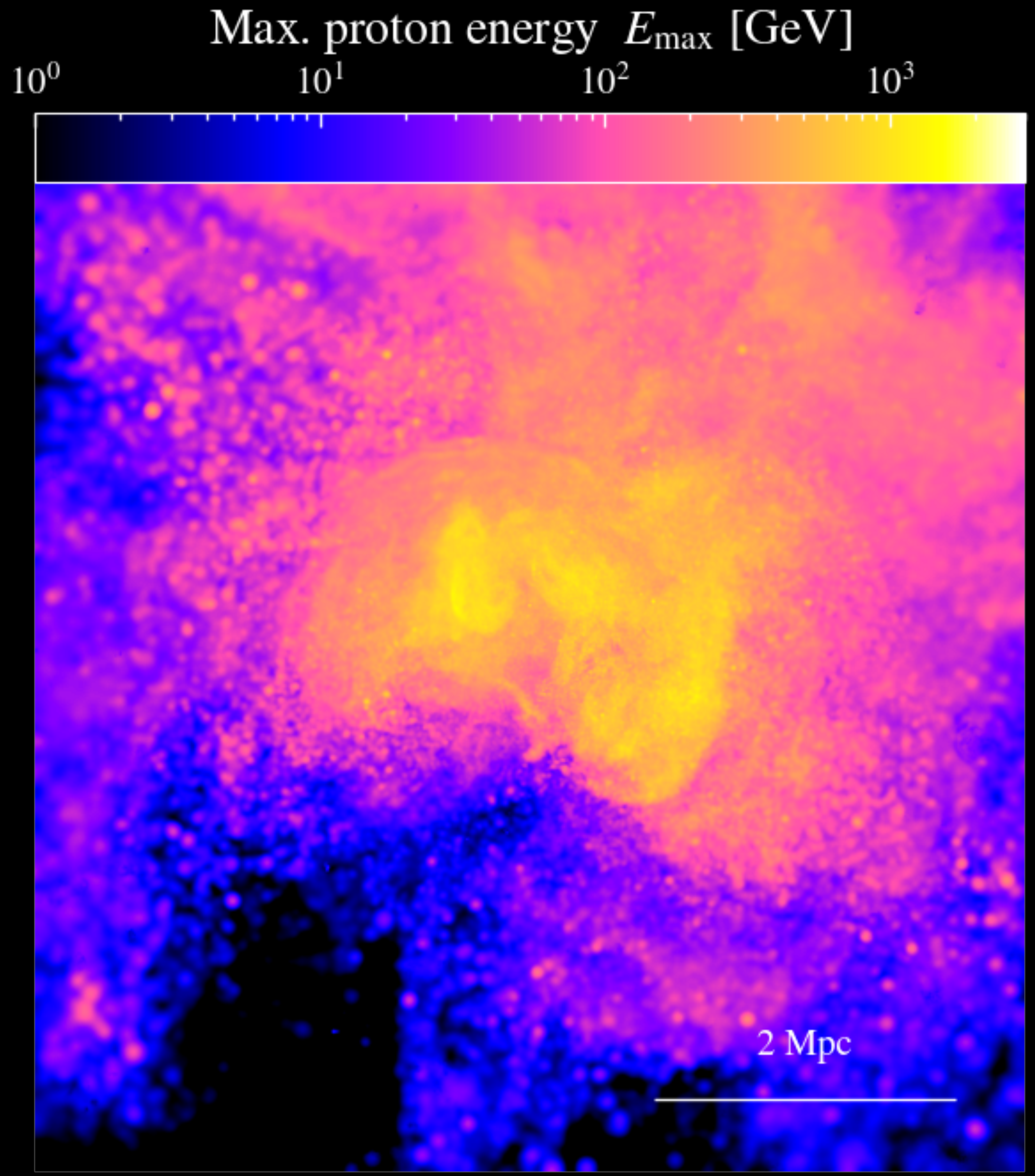
Reichherzer et al. (2026)

# Magnetic micromirrors:
# Sub-grid model implemented in cosmological zoom-in simulation


Diesing, LMB, Caprioli (2026)

# Magnetic micromirrors

- Maximum energy for protons accelerated in shocks with micromirror confinement
- Computed on-the-fly
- Emax in shocks ~1 TeV
- Volume-filling ~100 GeV
- Consistent with $\gamma$-ray limits because of CR proton distribution dominating in low-density gas




Diesing, LMB, Caprioli (2026)

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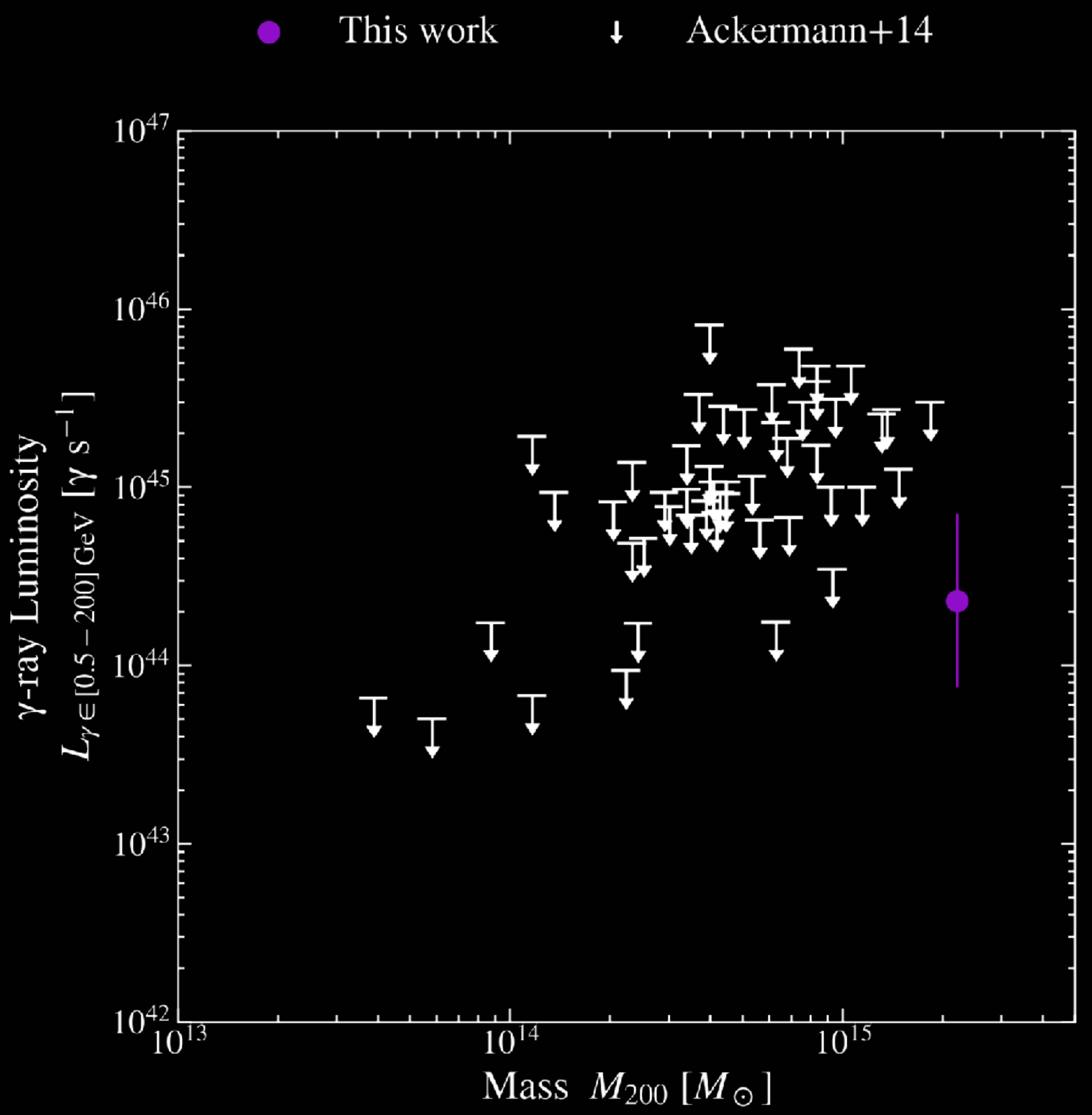
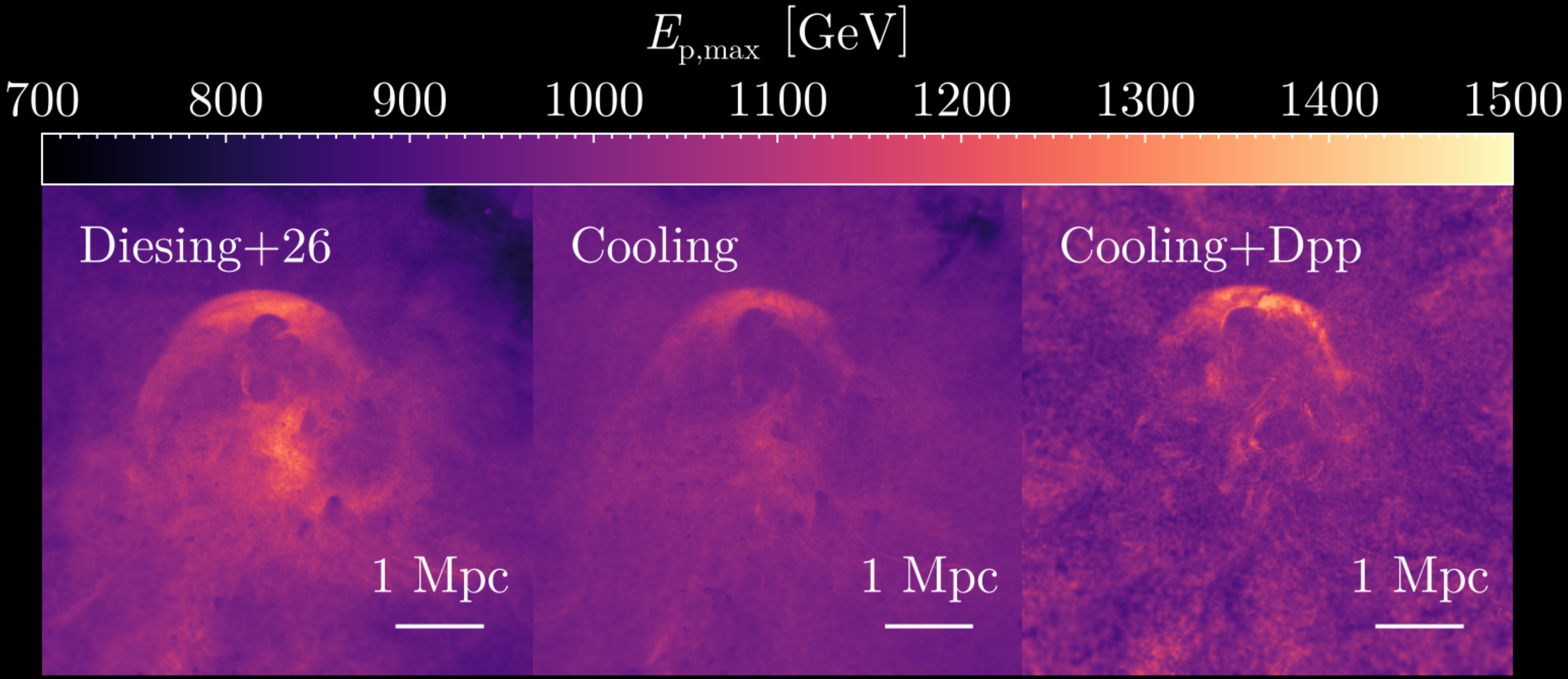



Diesing, LMB, Caprioli (2026)

# Impact of cooling and re-acceleration



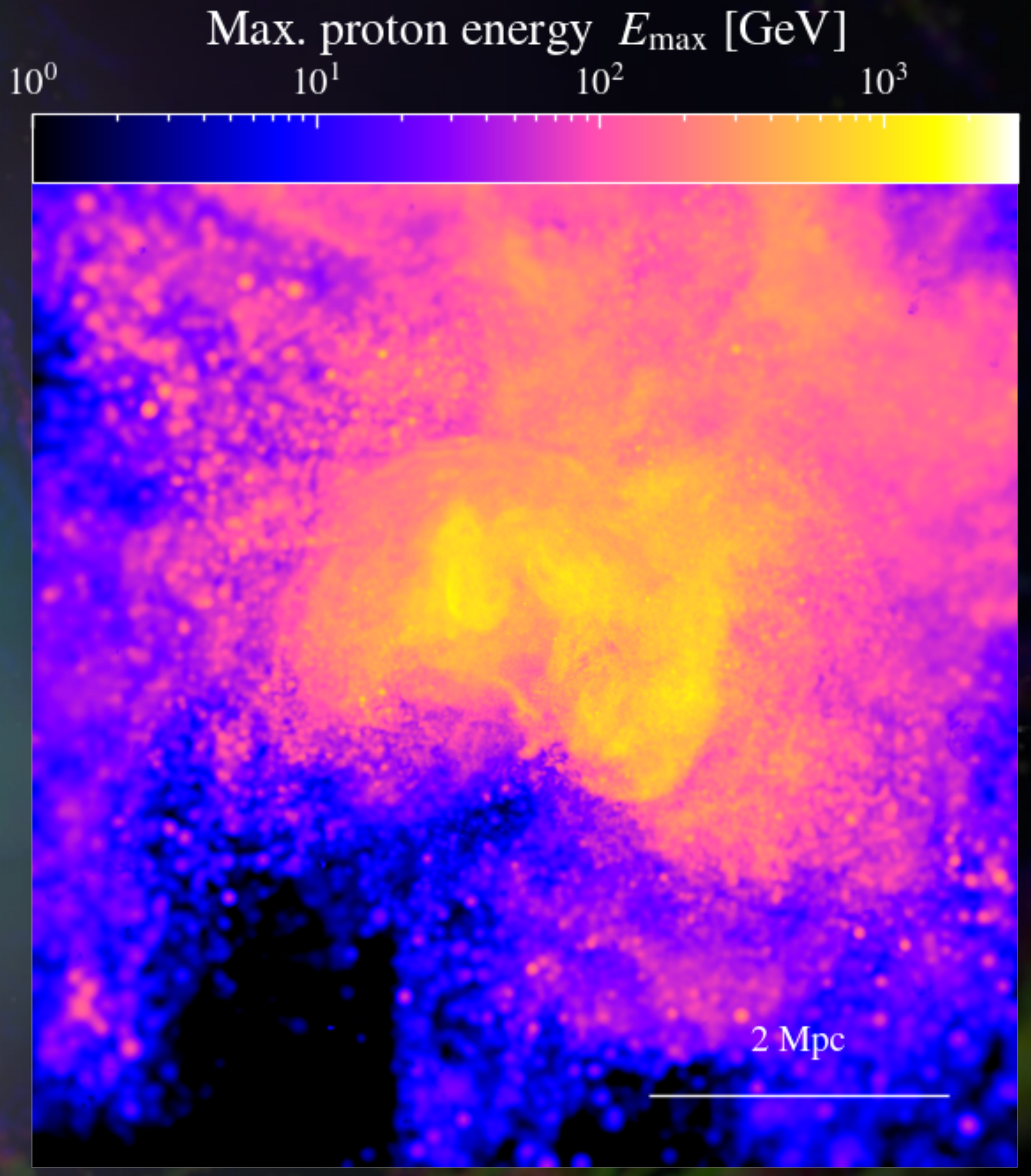

Preliminary

# Conclusion

- Self-consistent simulation of shocks and CR spectra on cosmological scales
- Allows to bridge the scale between micro- and macro physics
- Volume-filling protons with ~100 GeV, peaking ~1 TeV

# Outlook

- In-house construction of sub-grid models for DSA
- Inclusion of more feedback physics (AGN jets, SNe [Karner,LMB+26])




Diesing, LMB, Caprioli (2026)