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Simulations of the Synchrotron Cosmic Web

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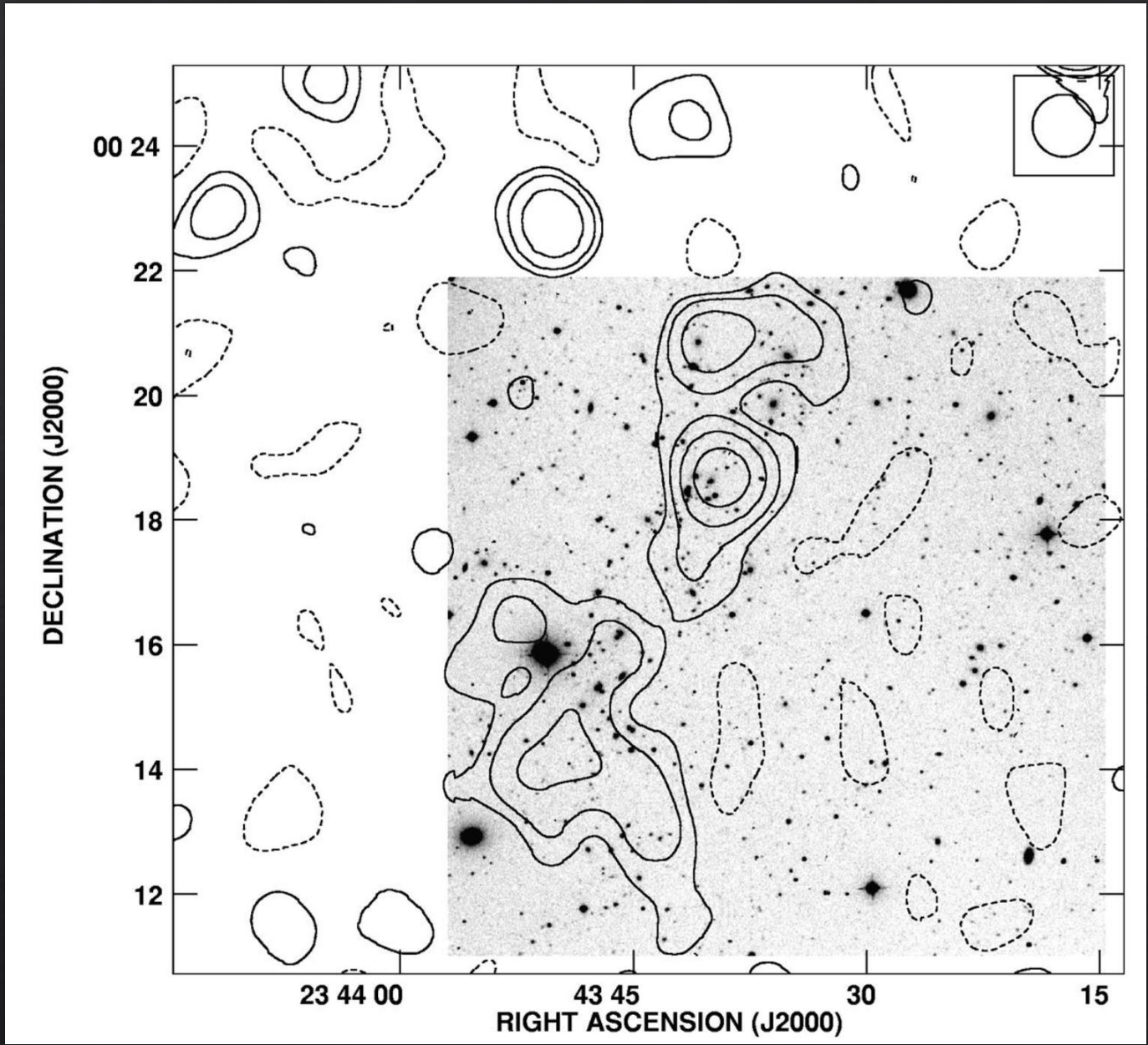
Cosmic Magnetism in Voids and Filaments 2023

z=0.276

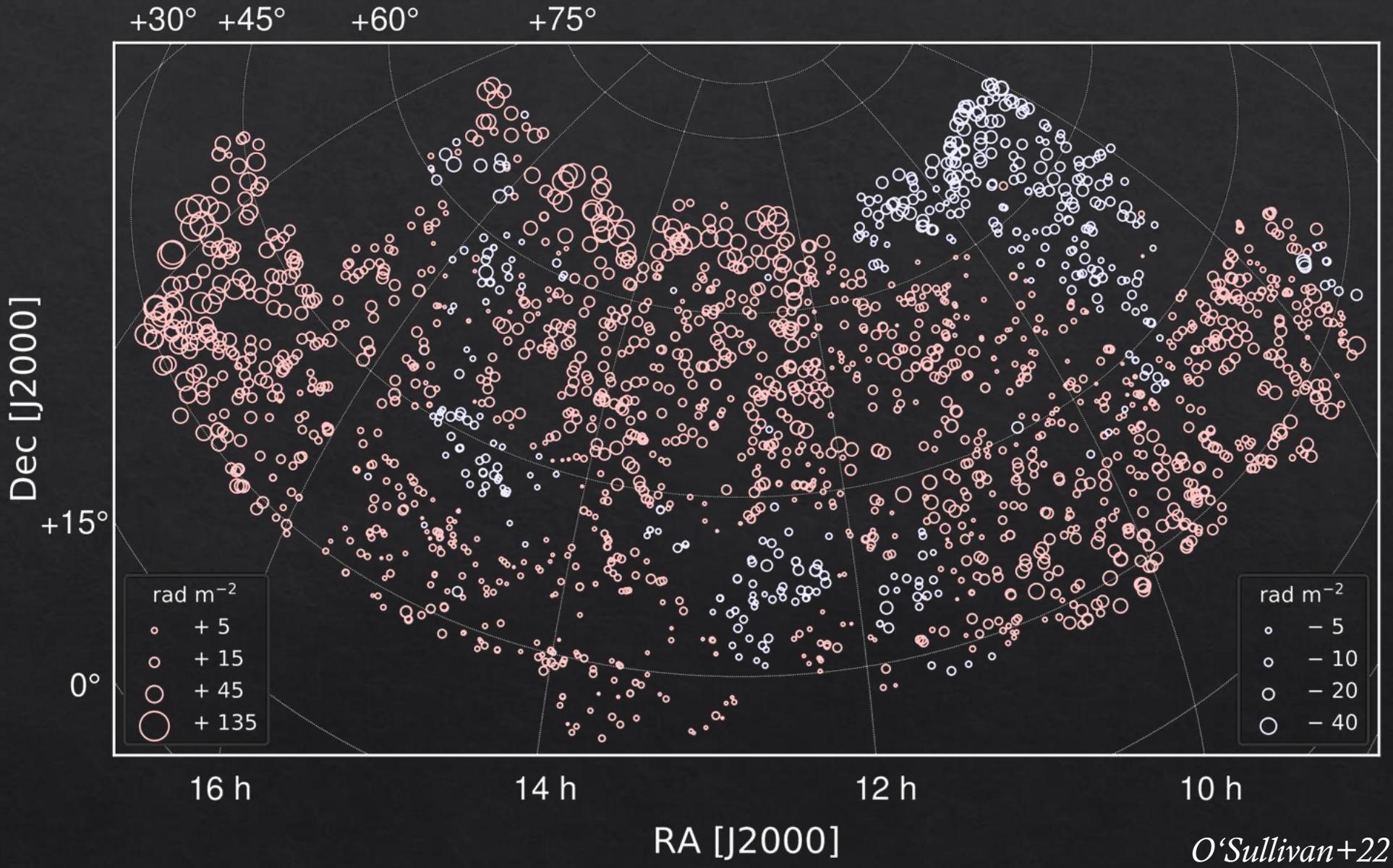
Synchrotron Emission from the Cosmic Web

- Hierarchical structure formation leads to gas accretion
- Gas dissipates energy in shocks:
  - Merger shocks (cluster periphery)
  - Accretion shocks (onto clusters/filaments)
- Electron acceleration via „diffusive shock acceleration“ (DSA)
- Synchrotron Emission due to magnetic field



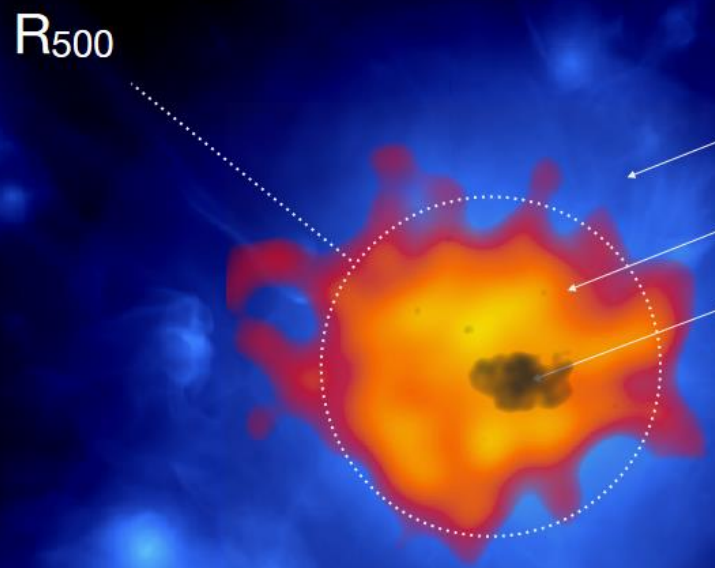
Bagchi+02

What about the magnetic field? -> 10 nG

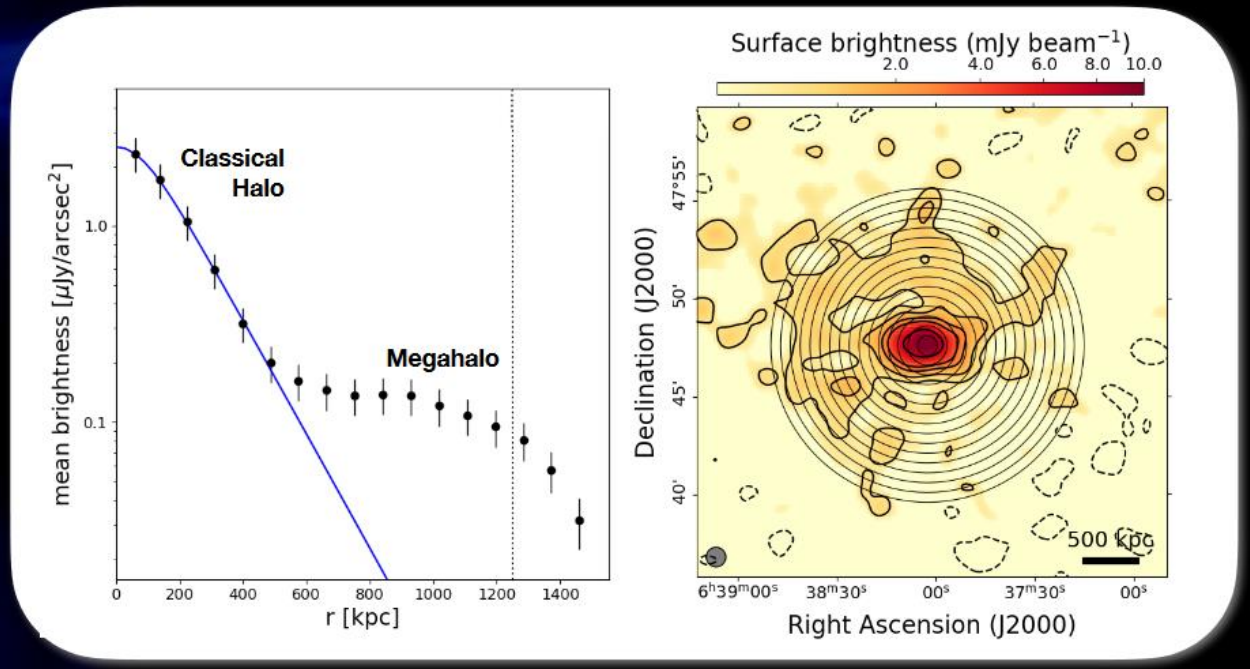


O'Sullivan+22

What about the rel. Electrons? -> Mega Halos



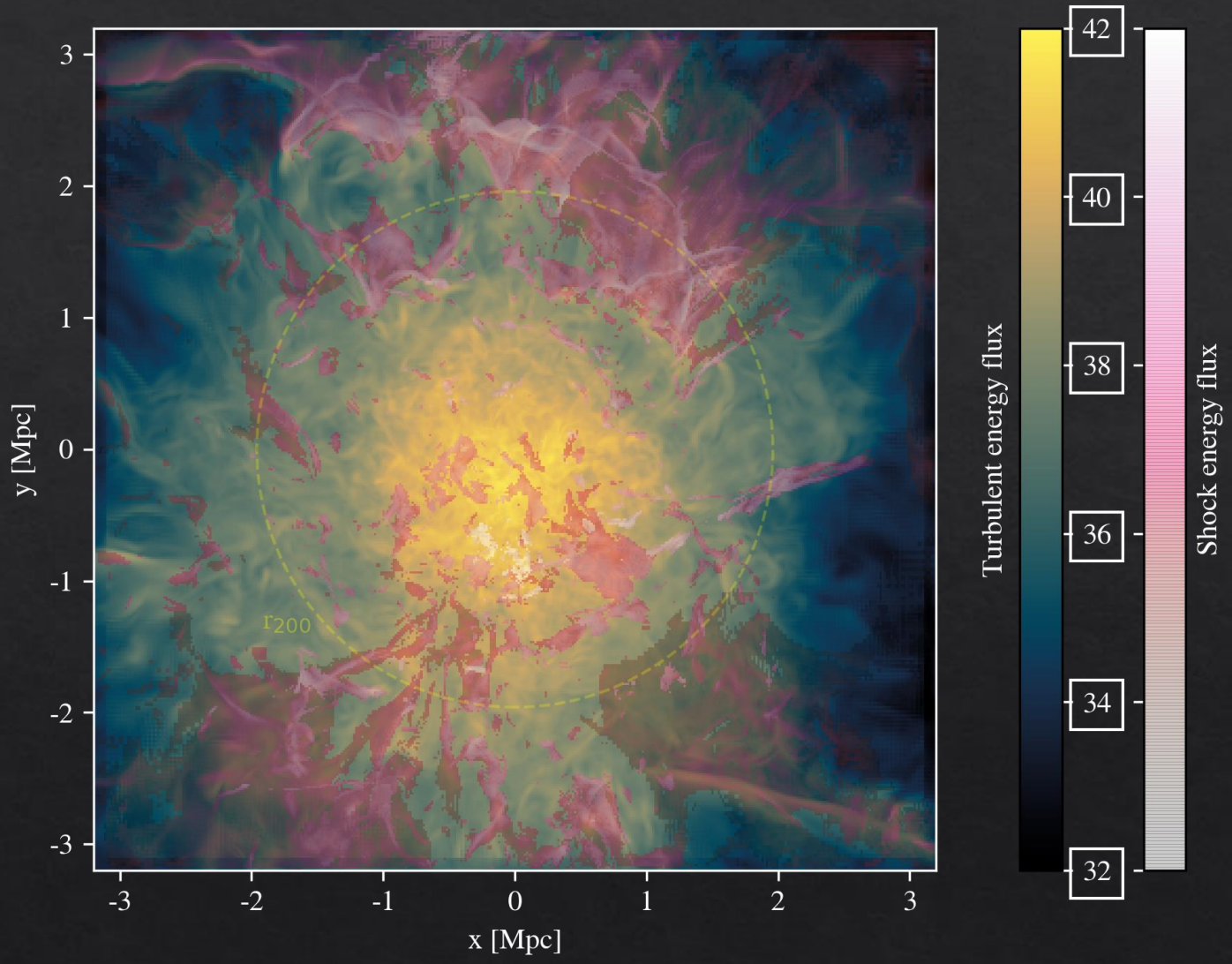
- Gas density (computer simulation)
- Megahalo - radius = 1400 kpc
- Classical halo - radius = 352 kpc



Cuciti+22

Relativistic Electrons

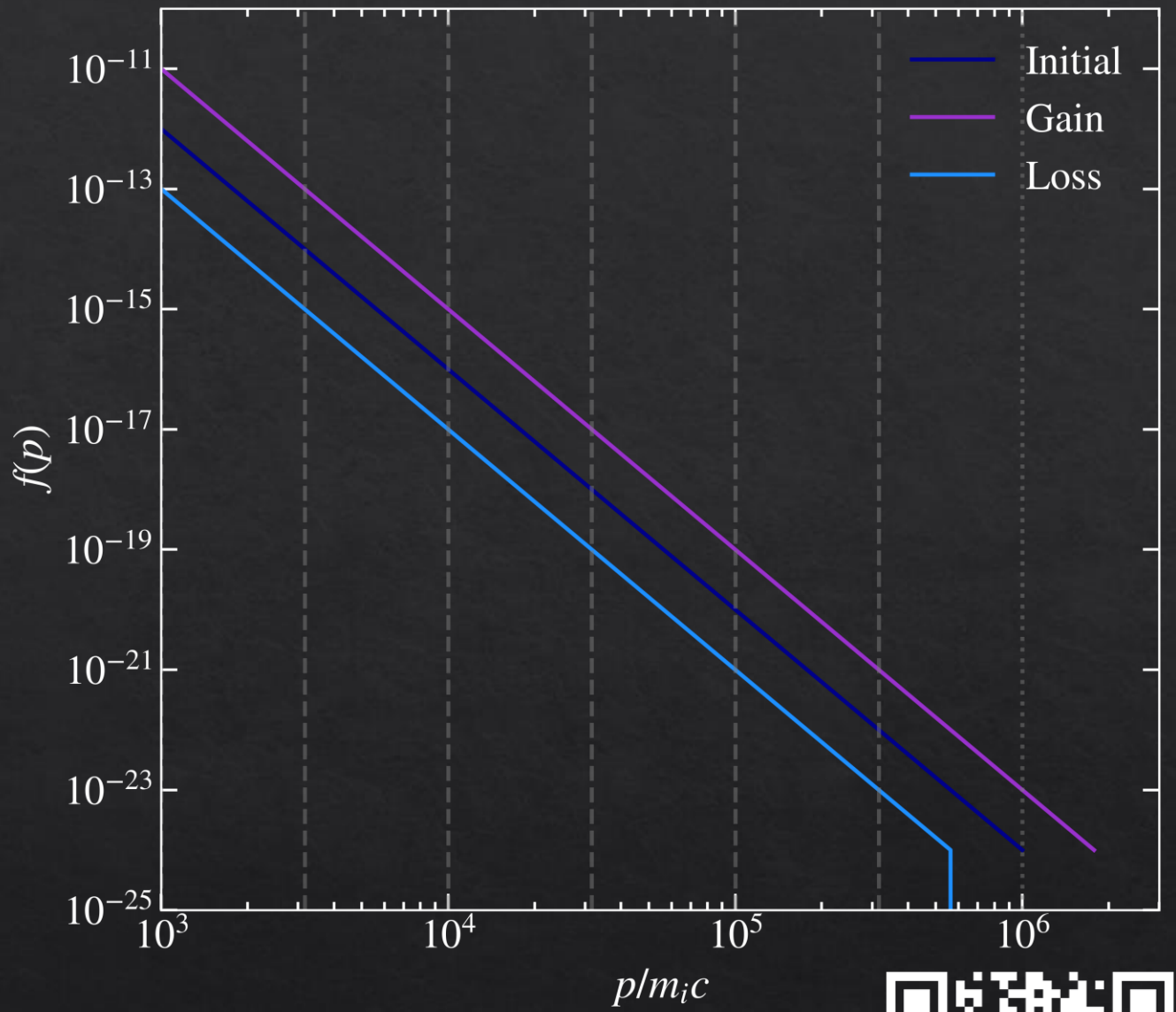
- Mega Halos hint towards significant relativistic CR electrons in the cluster periphery
- Cooling times of electrons: t ~ 100-500 Myrs
- Something needs to re-energize electrons!
- Insights from simulations



Botteon+22

A Spectral CR Model

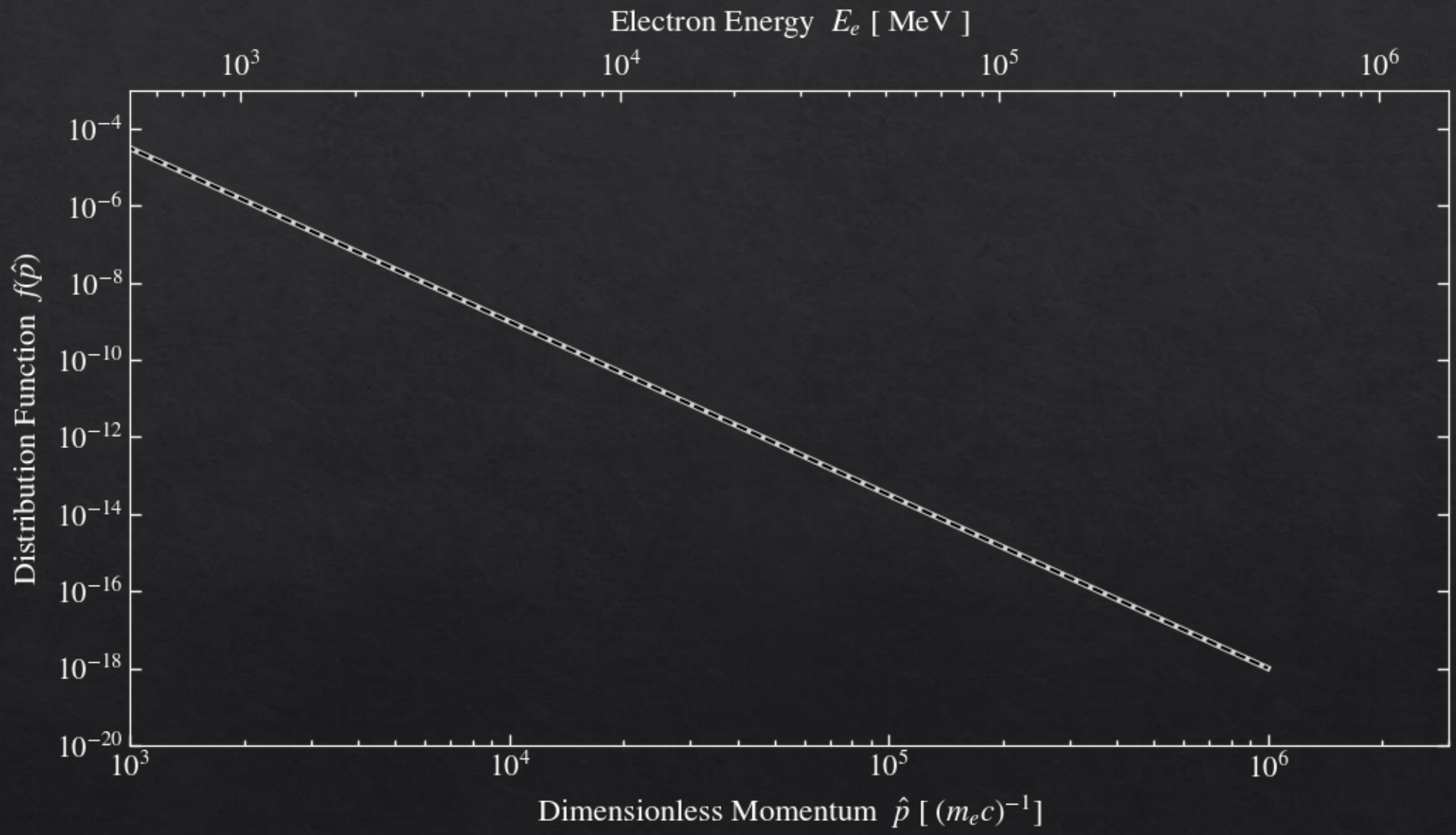
- Populations of CR protons and electrons attached to each SPH particle
- Discretized as Piece-wise powerlaw
- Evolve Distribution Function **f(p)** at every timestep of the simulation
- Feedback via pressure component
- Observables from distr. function



Dashed lines: Bin boundaries
Dotted line: Spectral Cutoff

CRESCENDO *(LMB+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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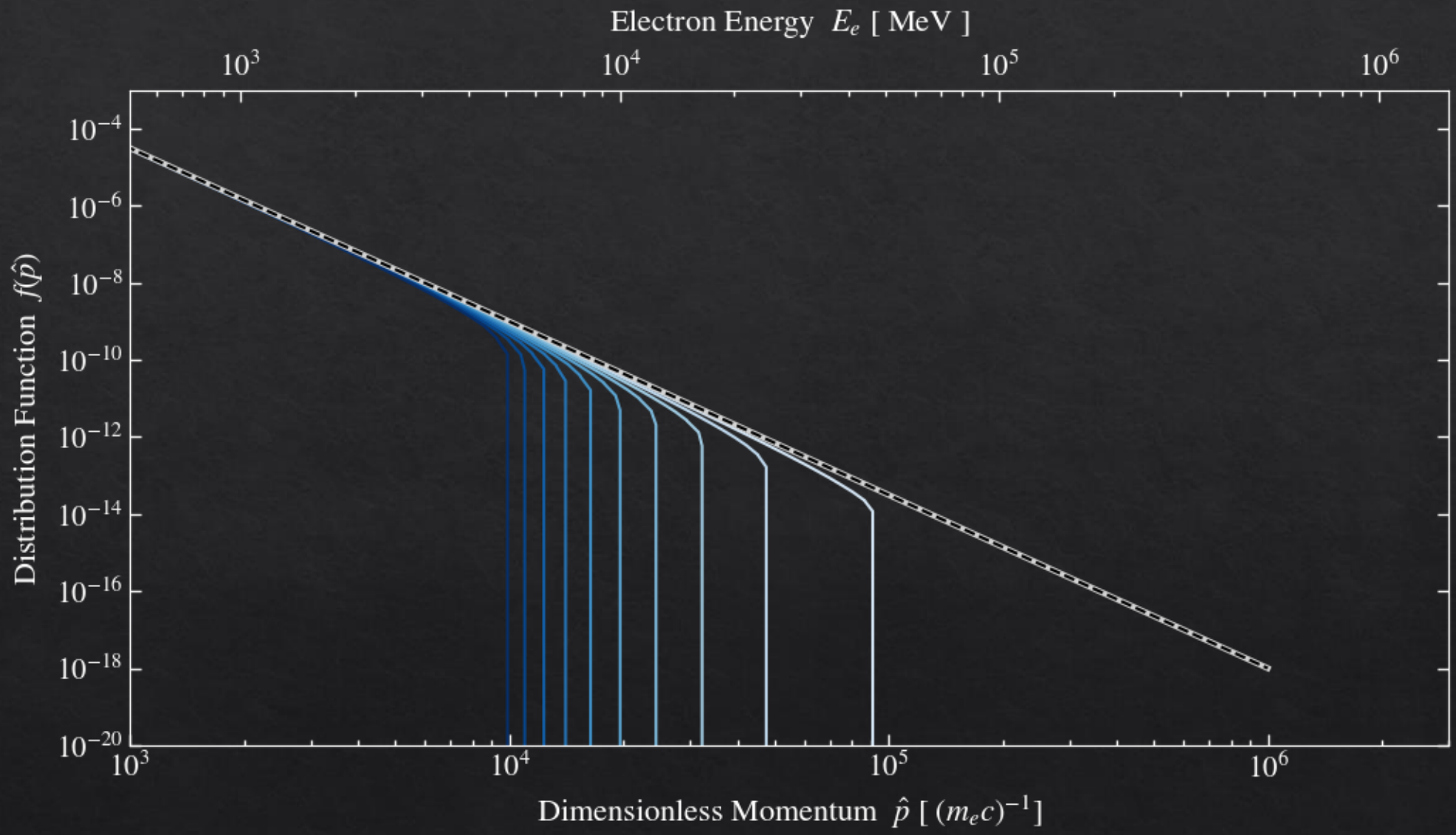

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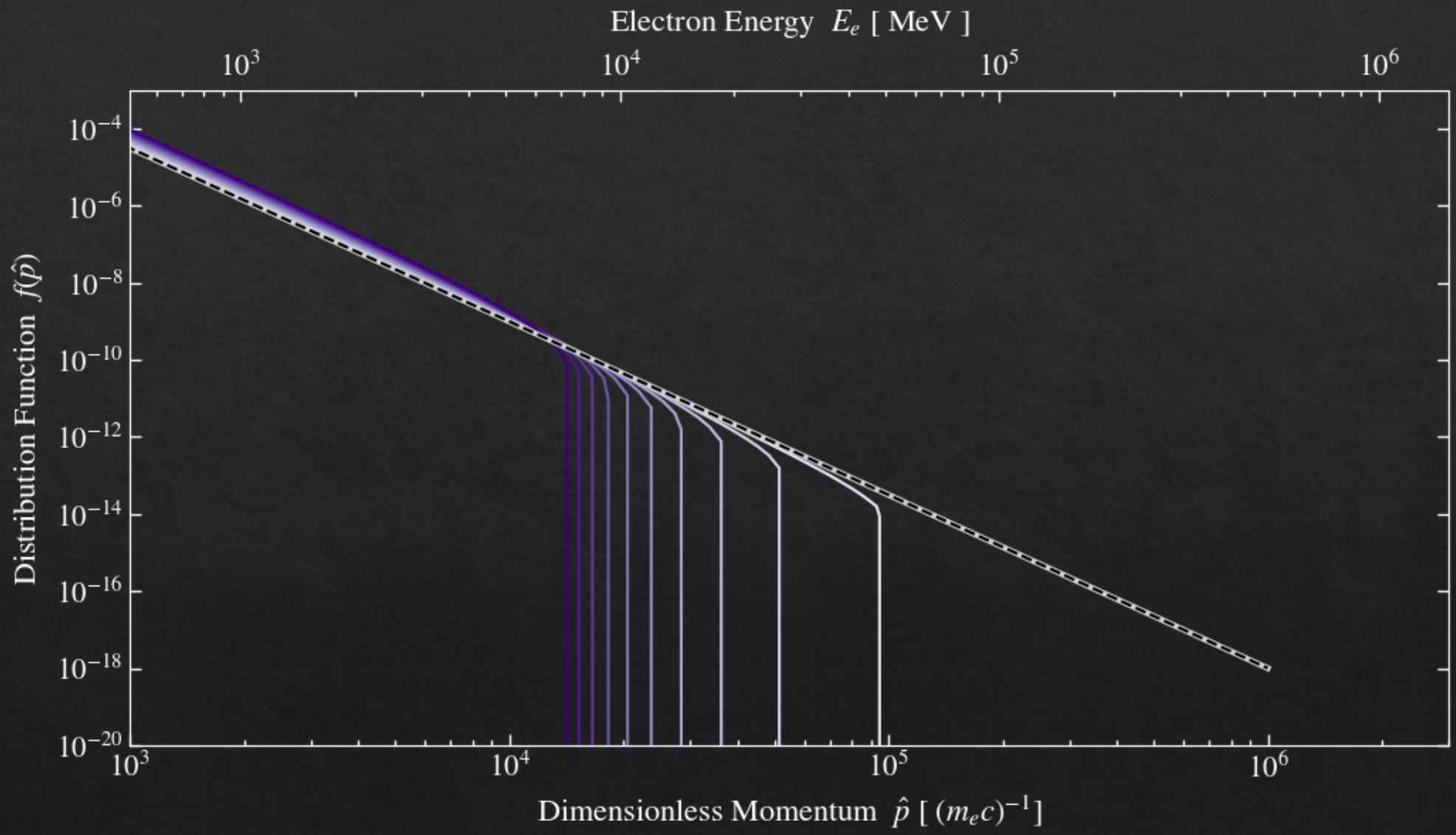

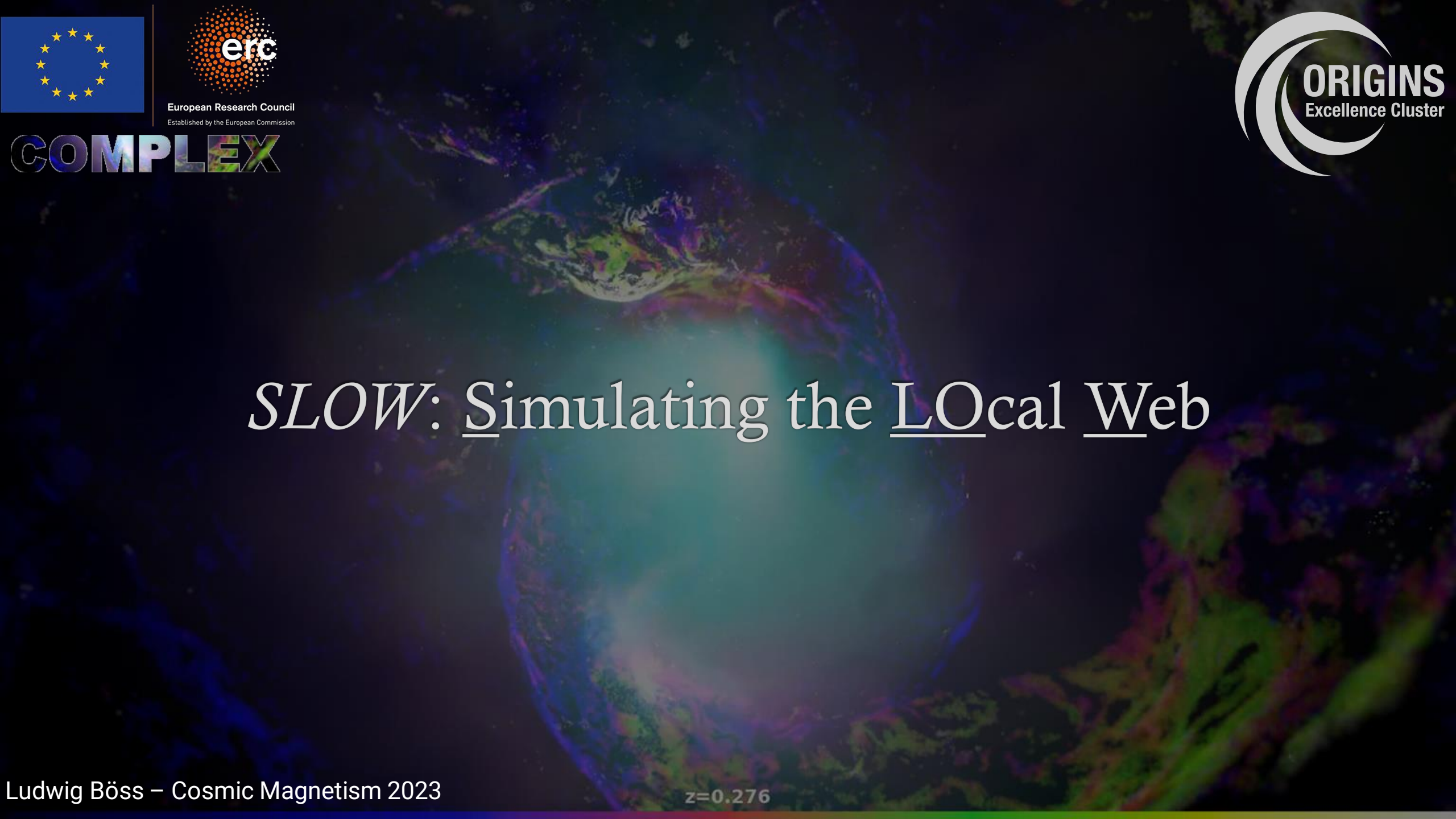
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SLOW: Simulating the LOcal Web
z=0.276

SLOW - Fact Sheet

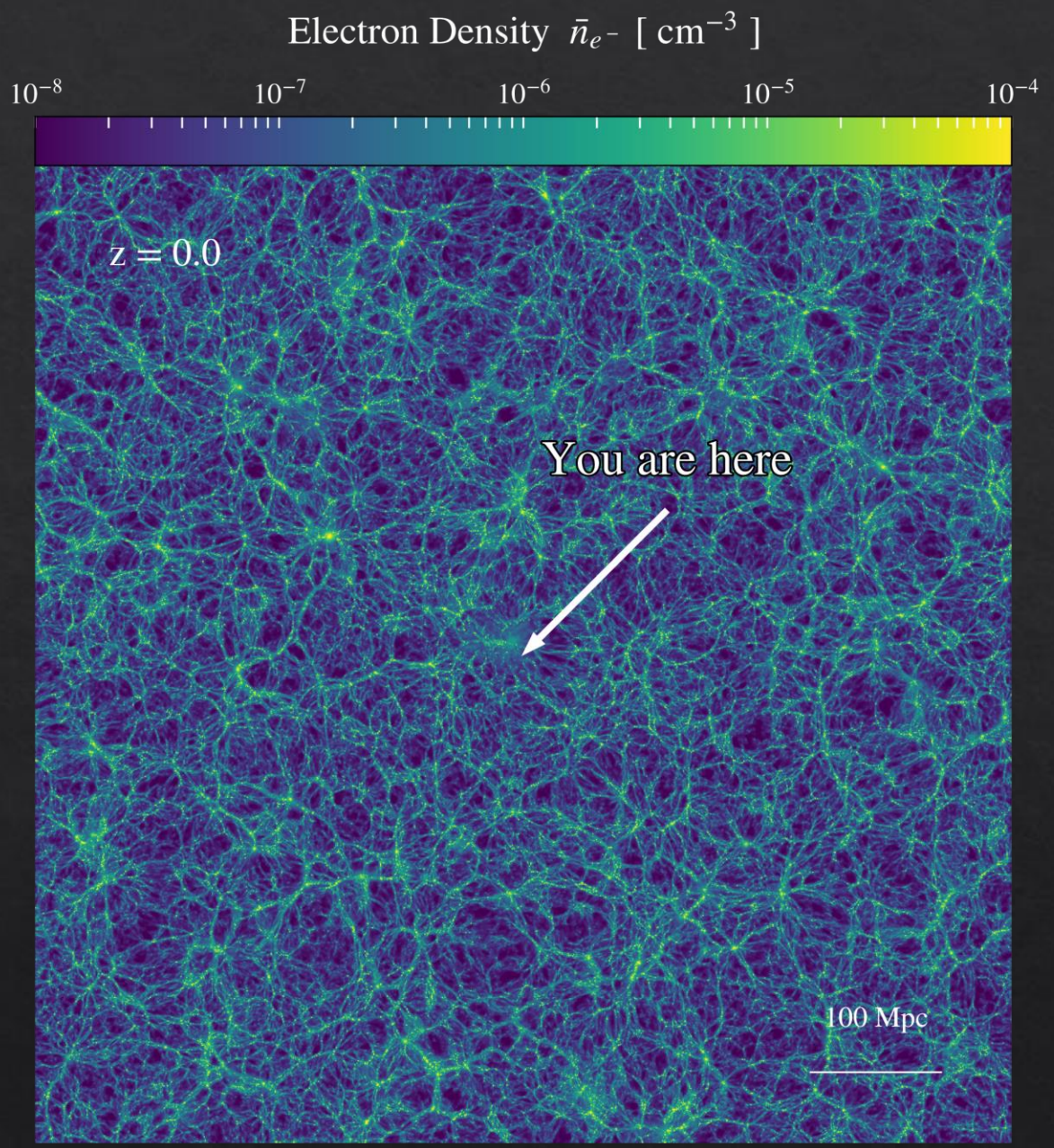
- 500 Mpc/h boxes
- Constrained ICs (Sorce+14)
- Resembles the local observed universe
- Non-radiative MHD simulation + Spectral Cosmic Rays (protons (12bins) & electrons (24bins) over 6 dex)
- Particle resolution:

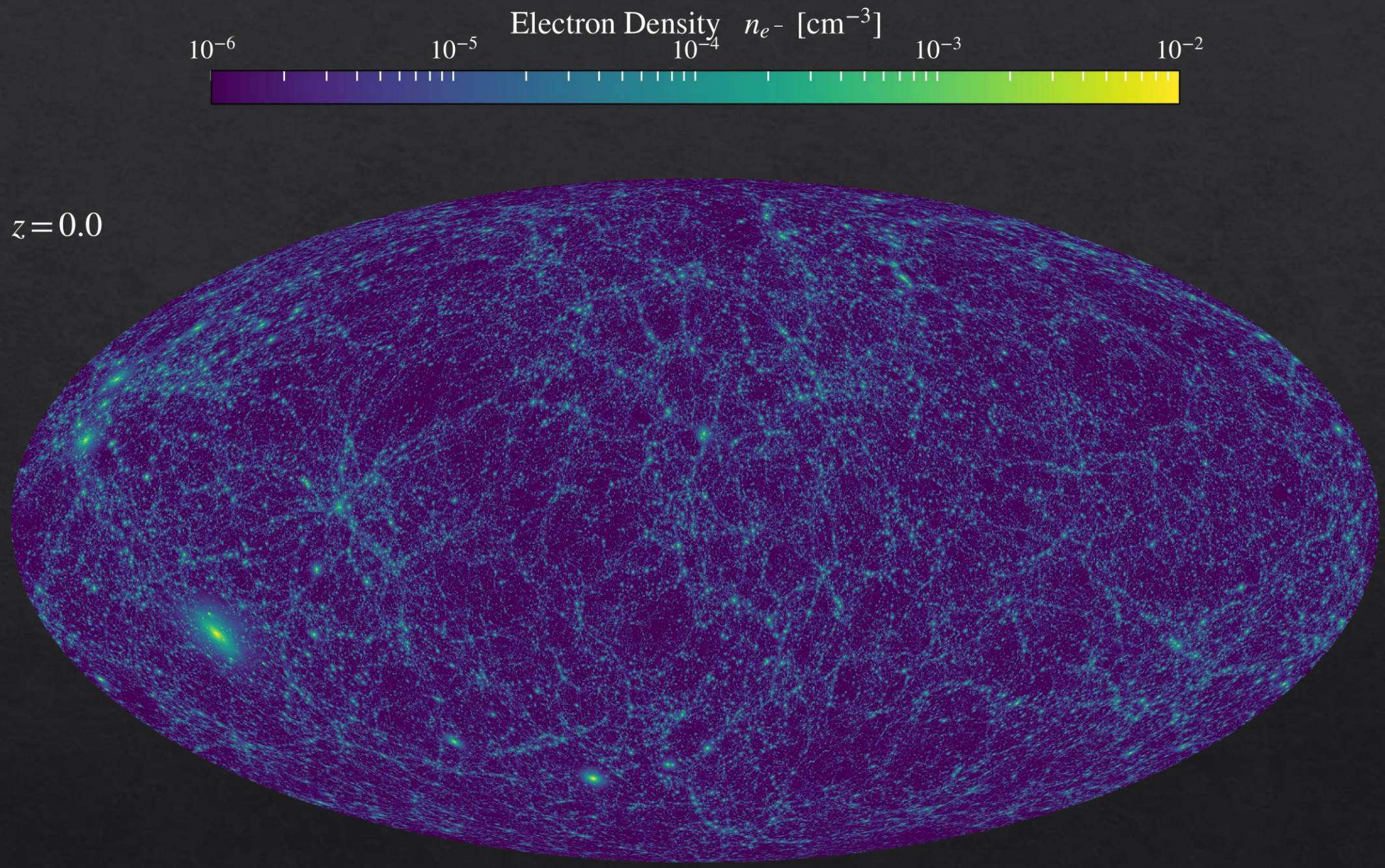
$$N = 2 \times 3072^3 \approx 2 \times 3 \cdot 10^{10}$$

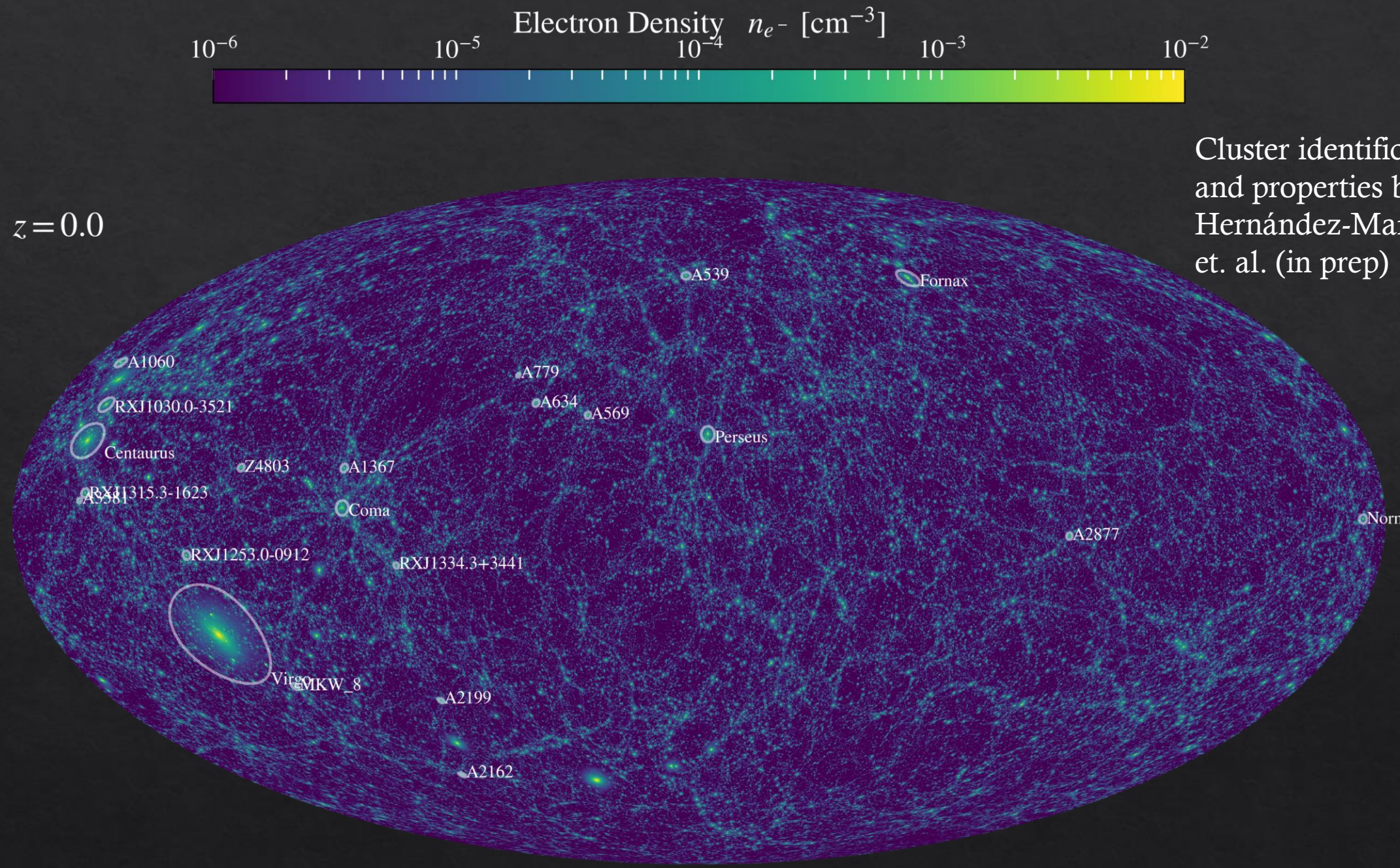
- Mass resolution:

$$m_{\mathrm{DM}} \approx 4.5 \times 10^8 M_\odot$$
$$m_{\mathrm{gas}} \approx 8.5 \times 10^7 M_\odot$$

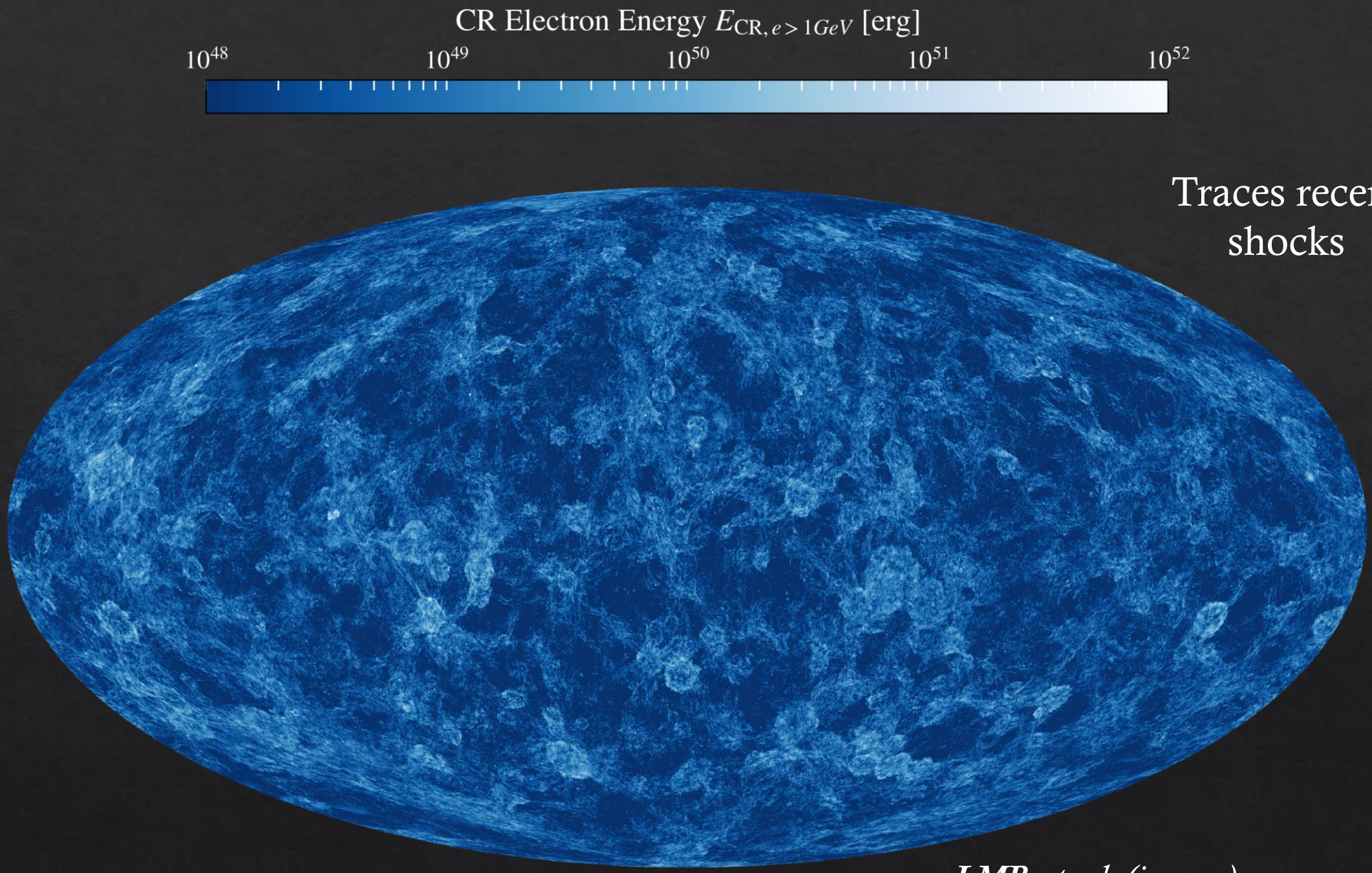
~ 2x Magneticum hr




Electron Density n_{e^-} [cm^{-3}]
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
$z = 0.0$

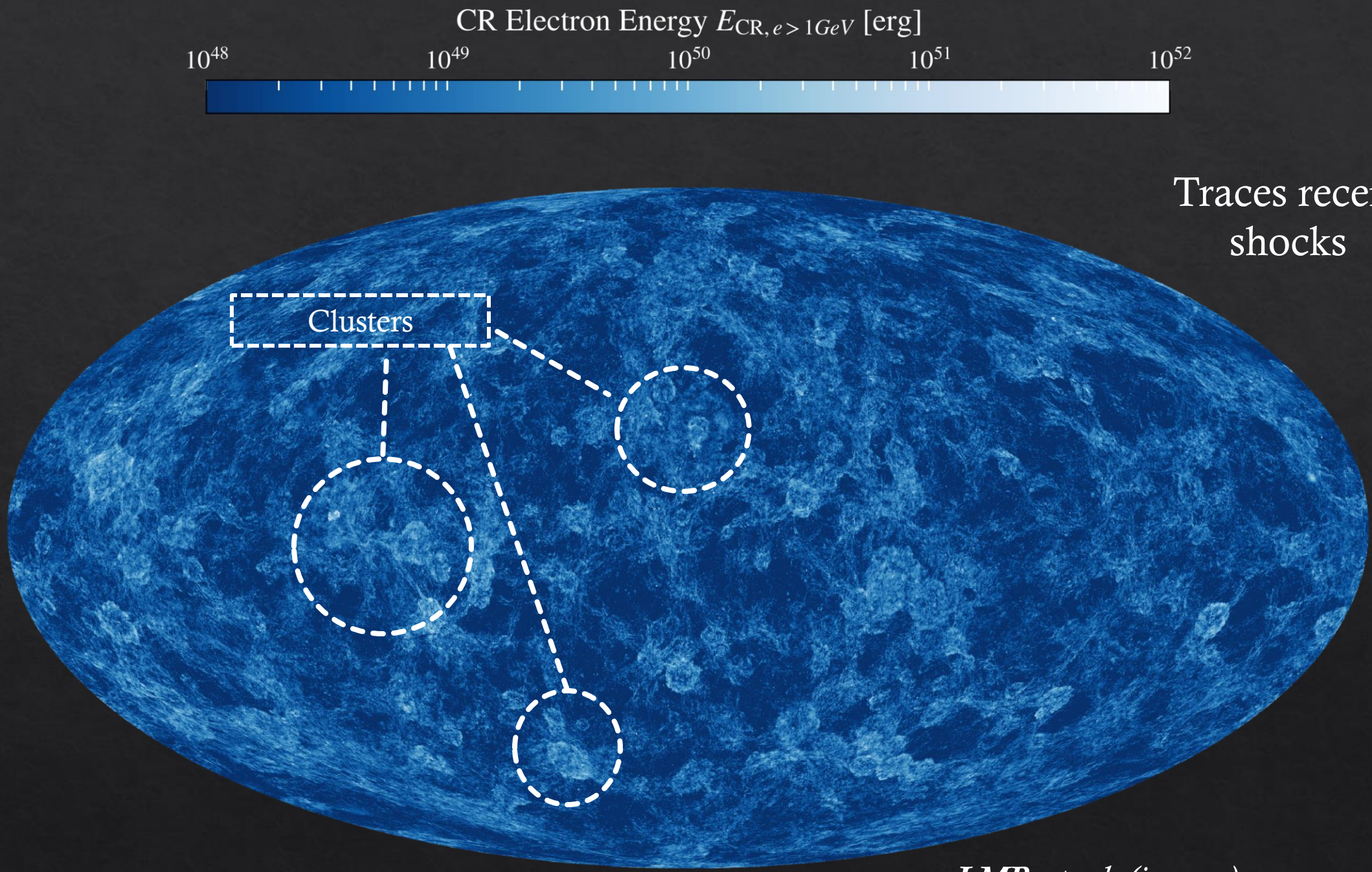


Cluster identification and properties by Hernández-Martinez et. al. (in prep)



Traces recent shocks

LMB, et. al. (in prep)



Traces recent shocks

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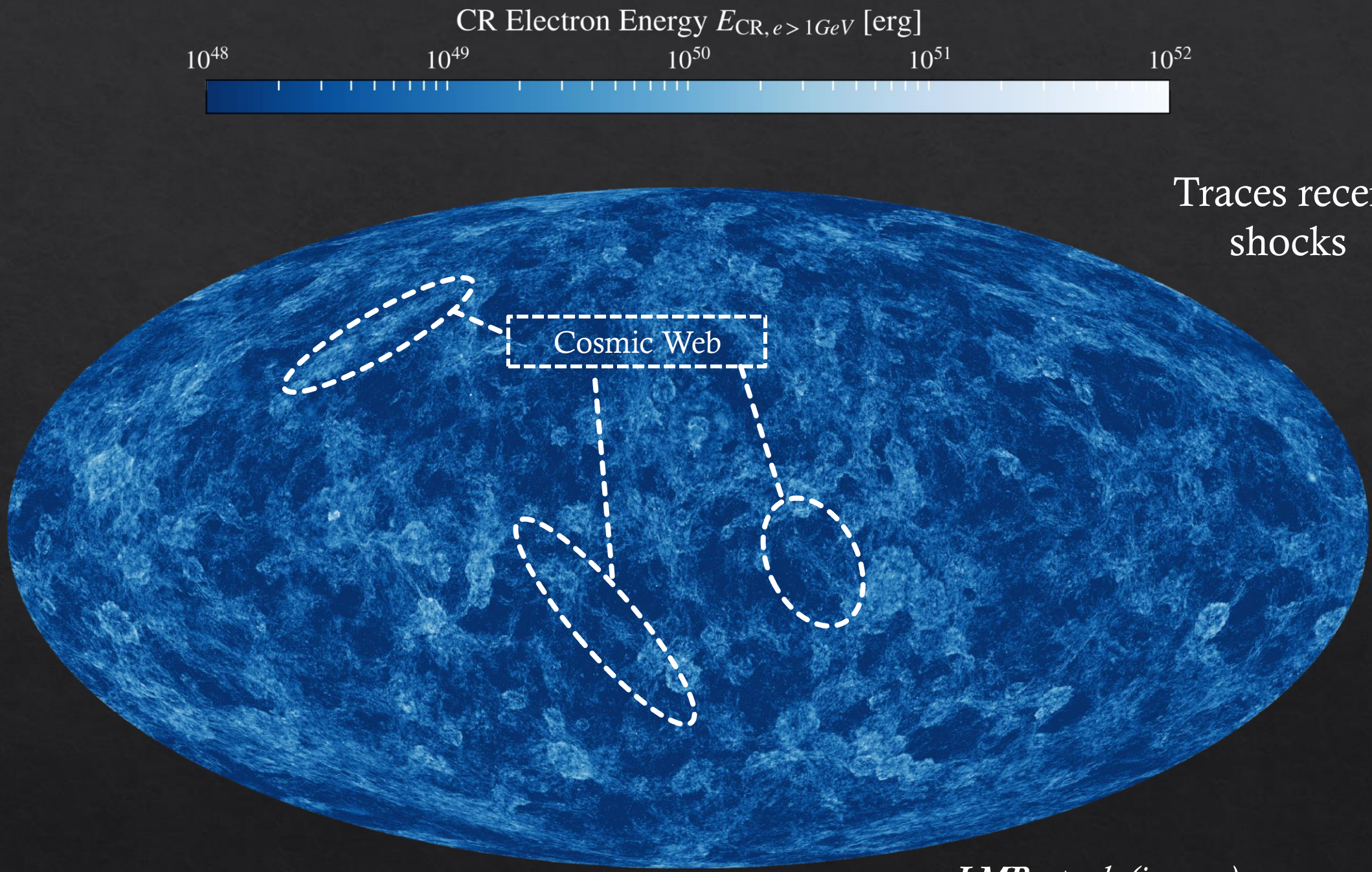
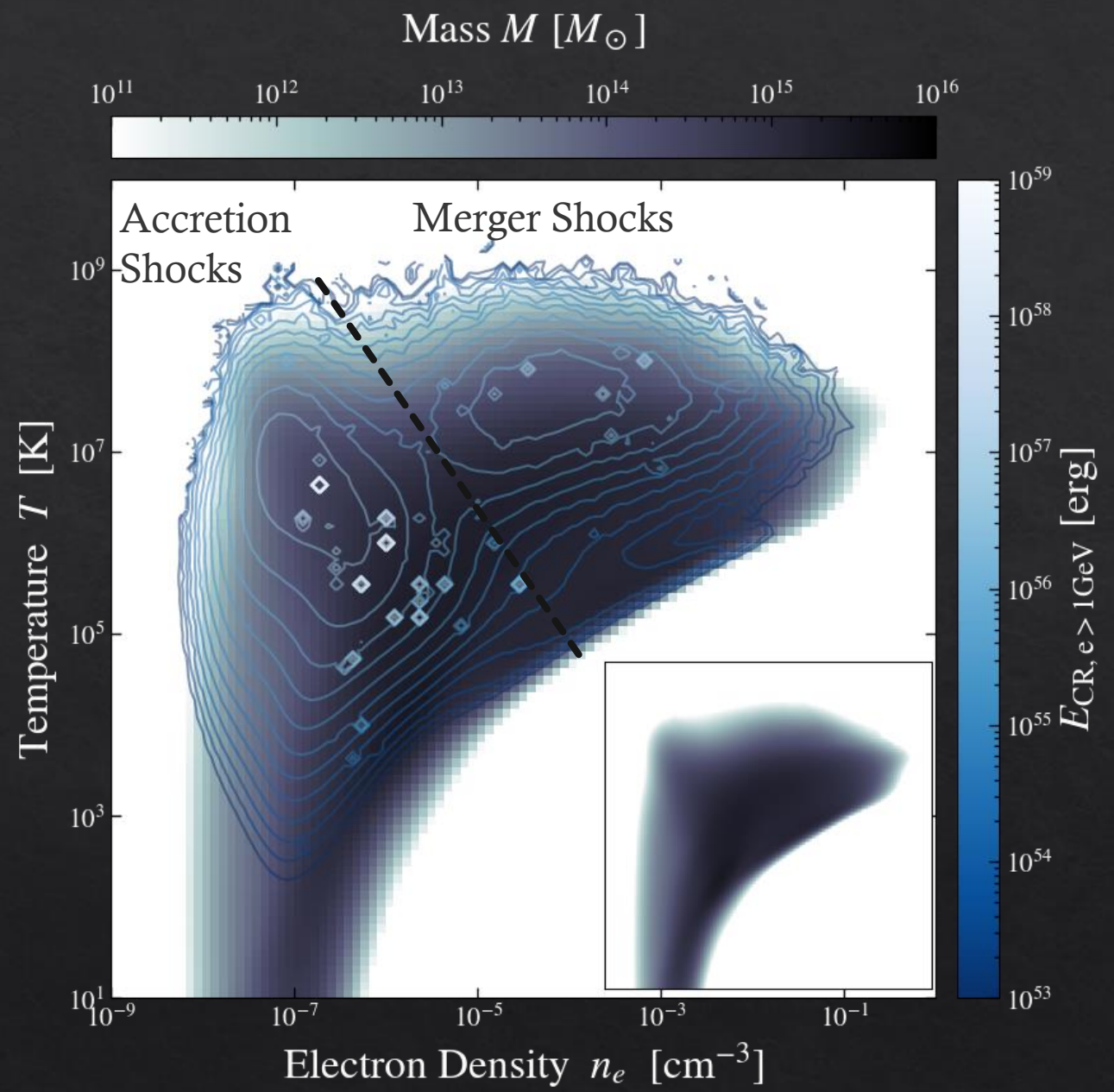


Traces recent shocks

LMB, et. al. (in prep)

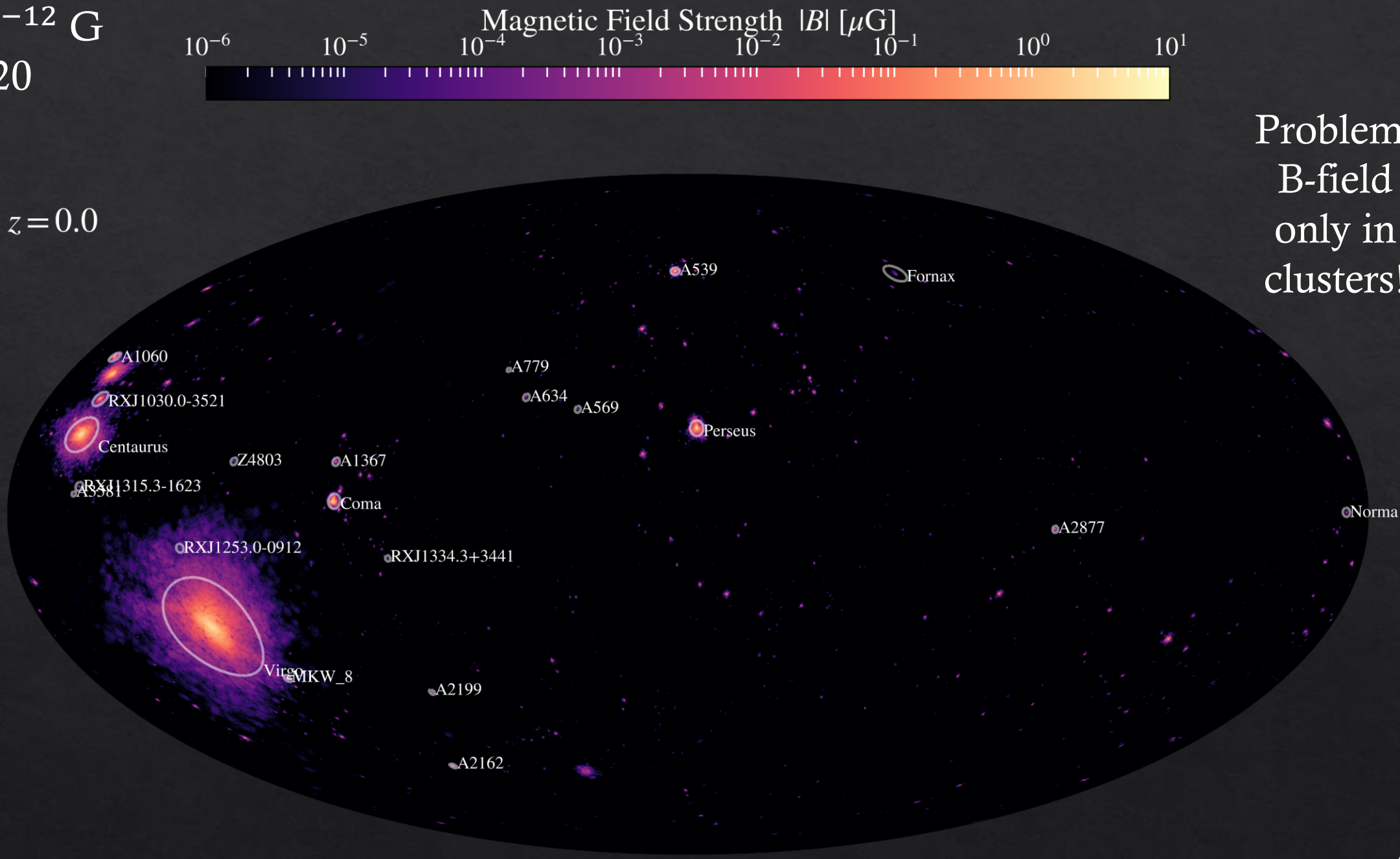
CR Electron injection

- Phase-space analysis
- 2 distinct populations:
  - Merger shocks
  - Accretion shocks
- Efficient acceleration in both regimes
- What about the magnetic field?



LMB, et. al. (in prep)

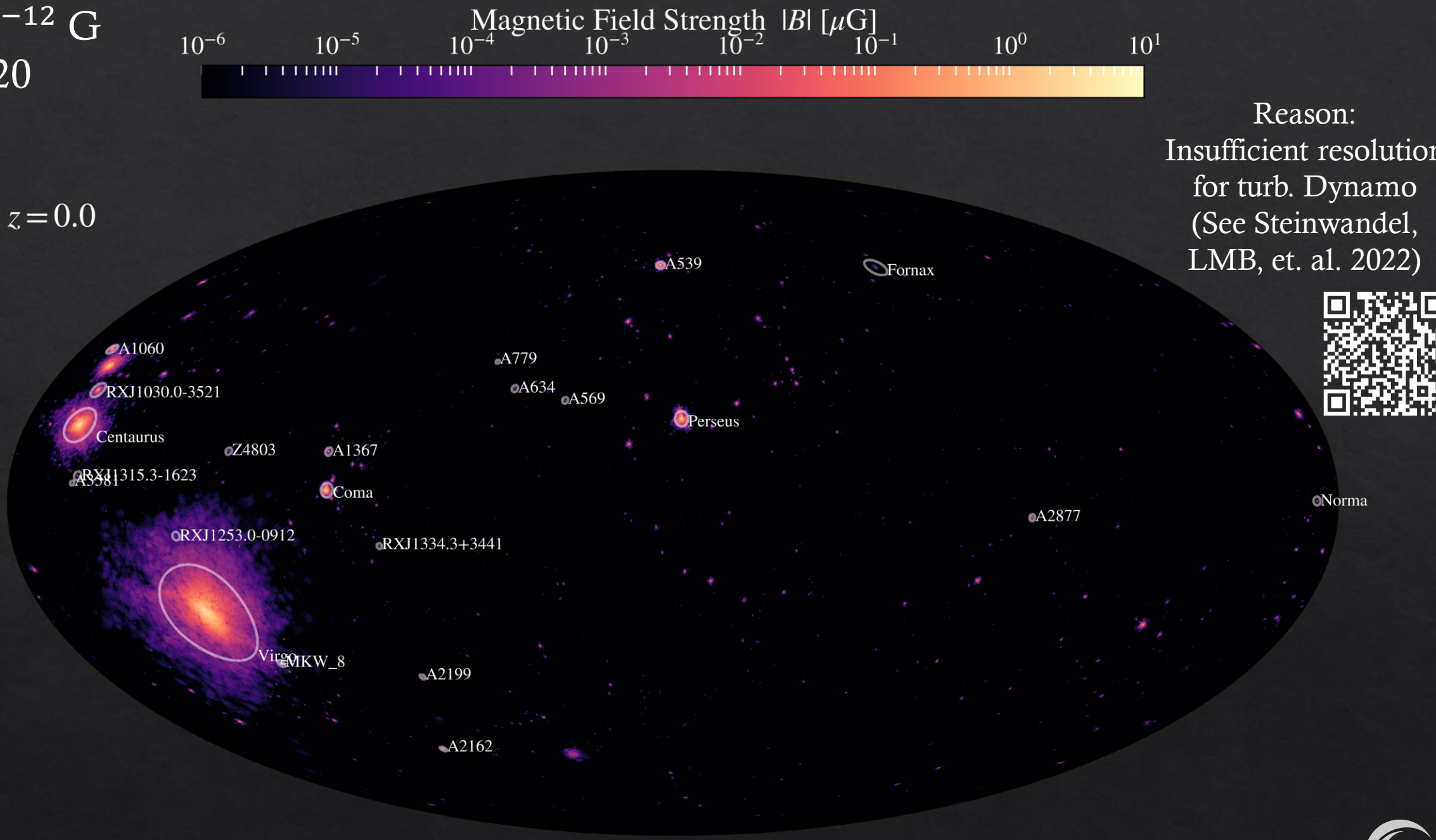
$B_0 = 10^{-12}$ G
at $z = 120$



Problem:
B-field
only in
clusters!

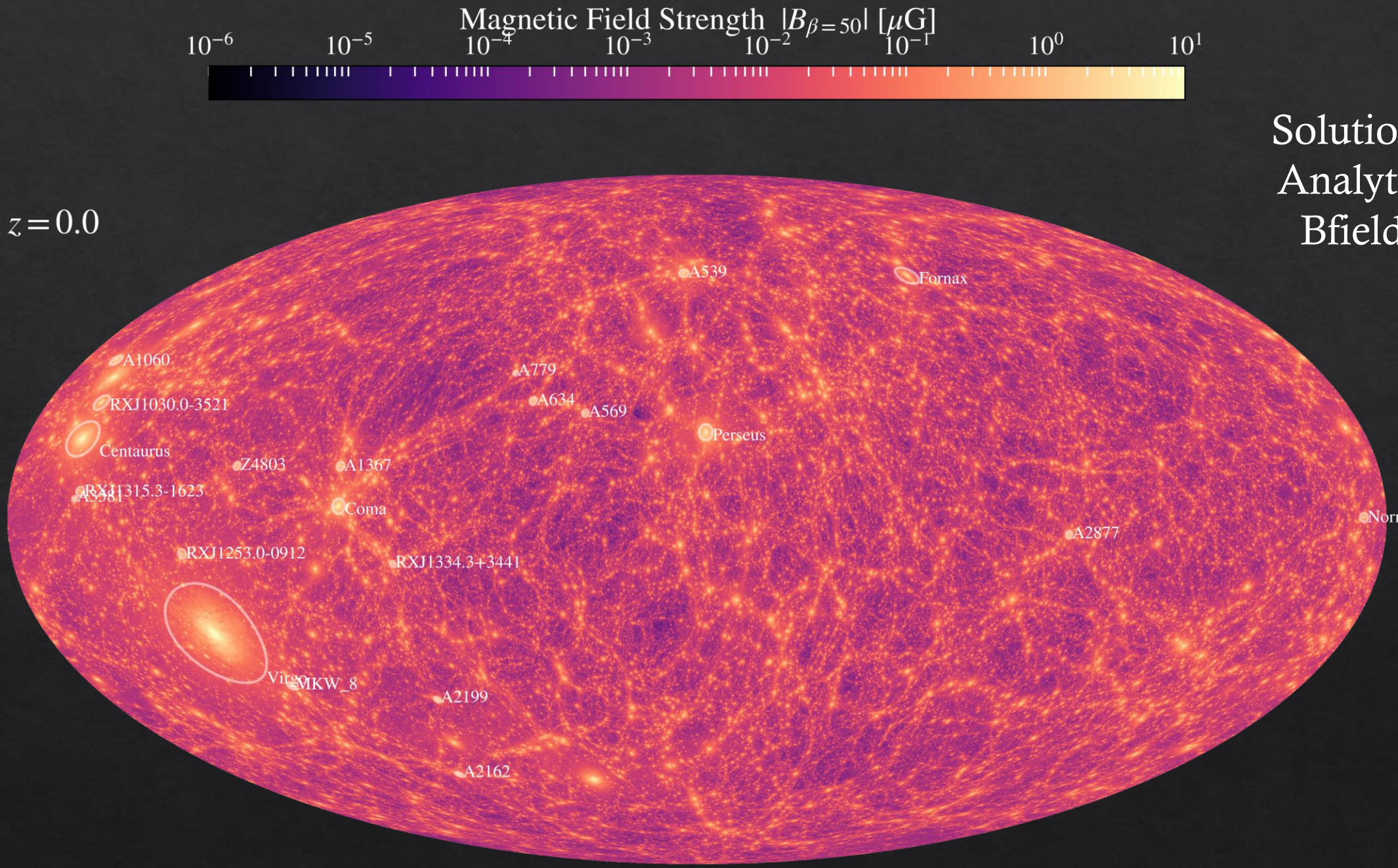
LMB, et. al. (in prep)

$B_0 = 10^{-12}$ G
at $z = 120$



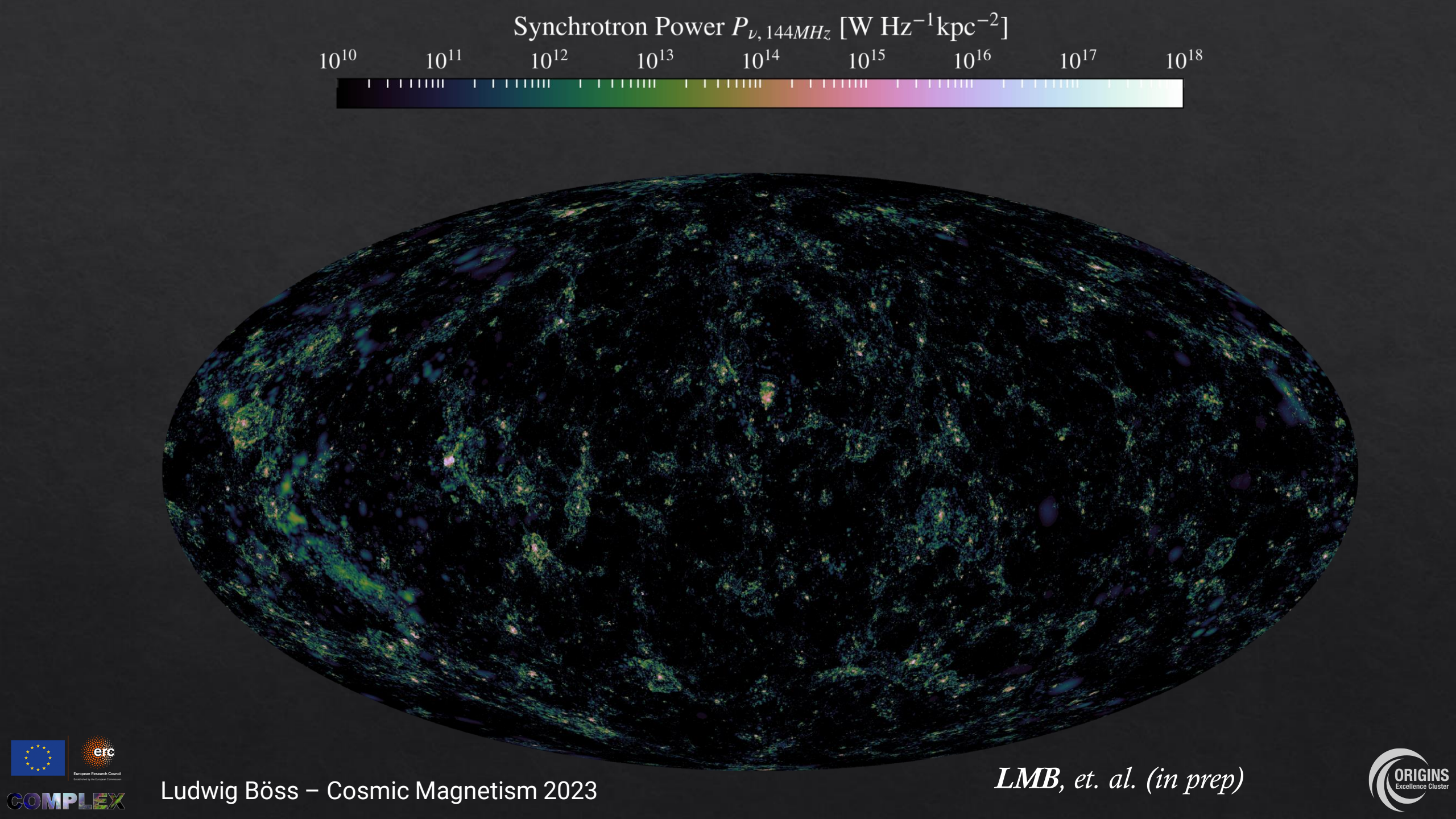
Reason:
Insufficient resolution
for turb. Dynamo
(See Steinwandel,
LMB, et. al. 2022)

LMB, et. al. (in prep)



Solution: Analytic Bfield

LMB, et. al. (in prep)



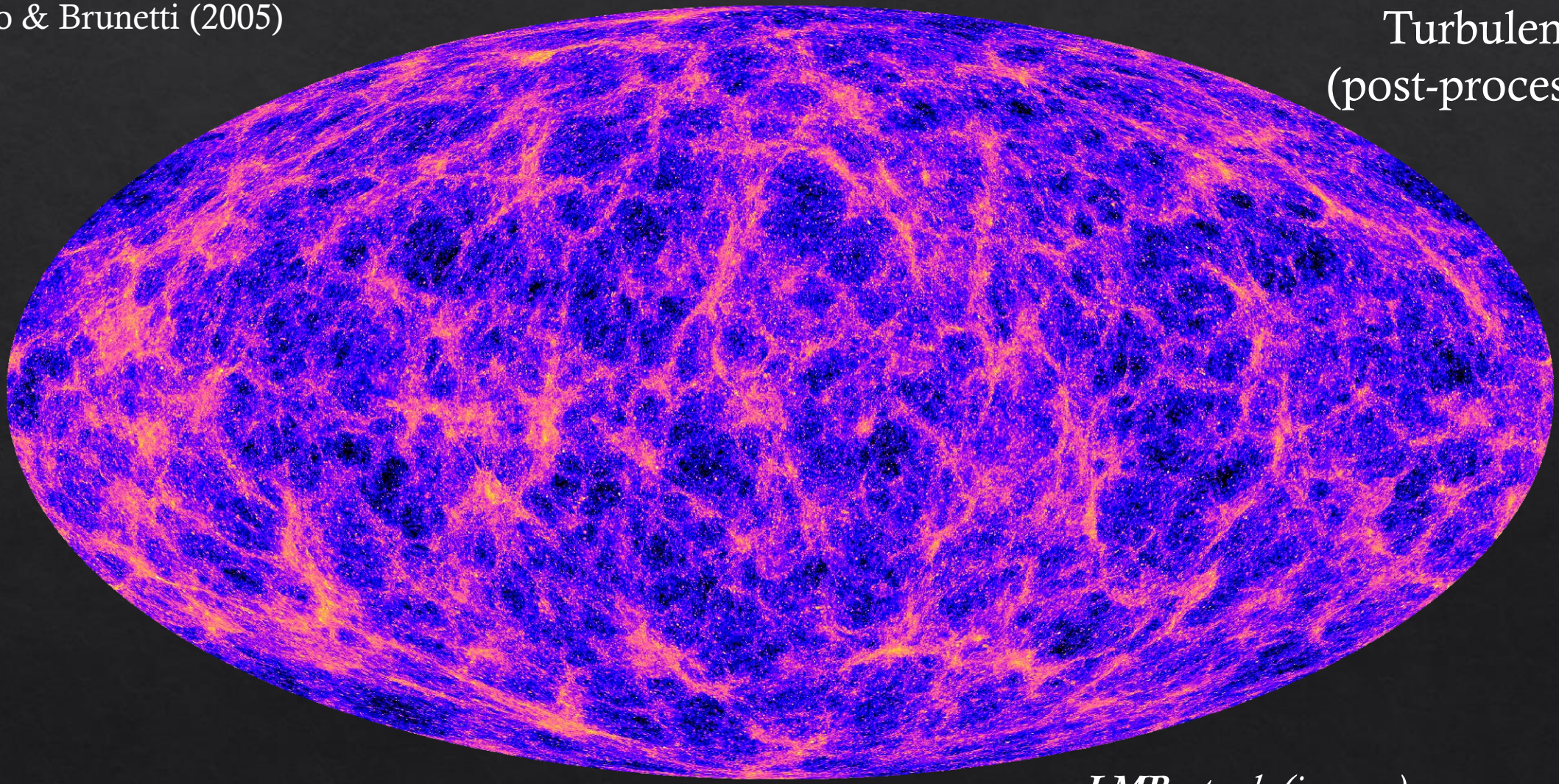
LMB, et. al. (in prep)

Re-Acceleration Coefficient D_0 [s^{-1}]

10^{-19} 10^{-18} 10^{-17}

Based on:
Cassano & Brunetti (2005)

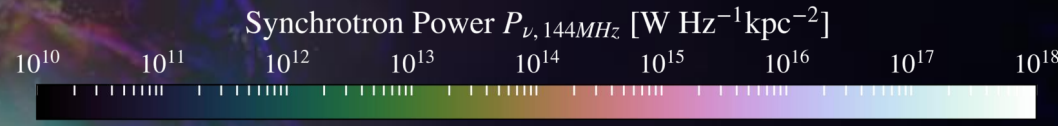
Next Step:
Turbulence
(post-processing)



LMB, et. al. (in prep)

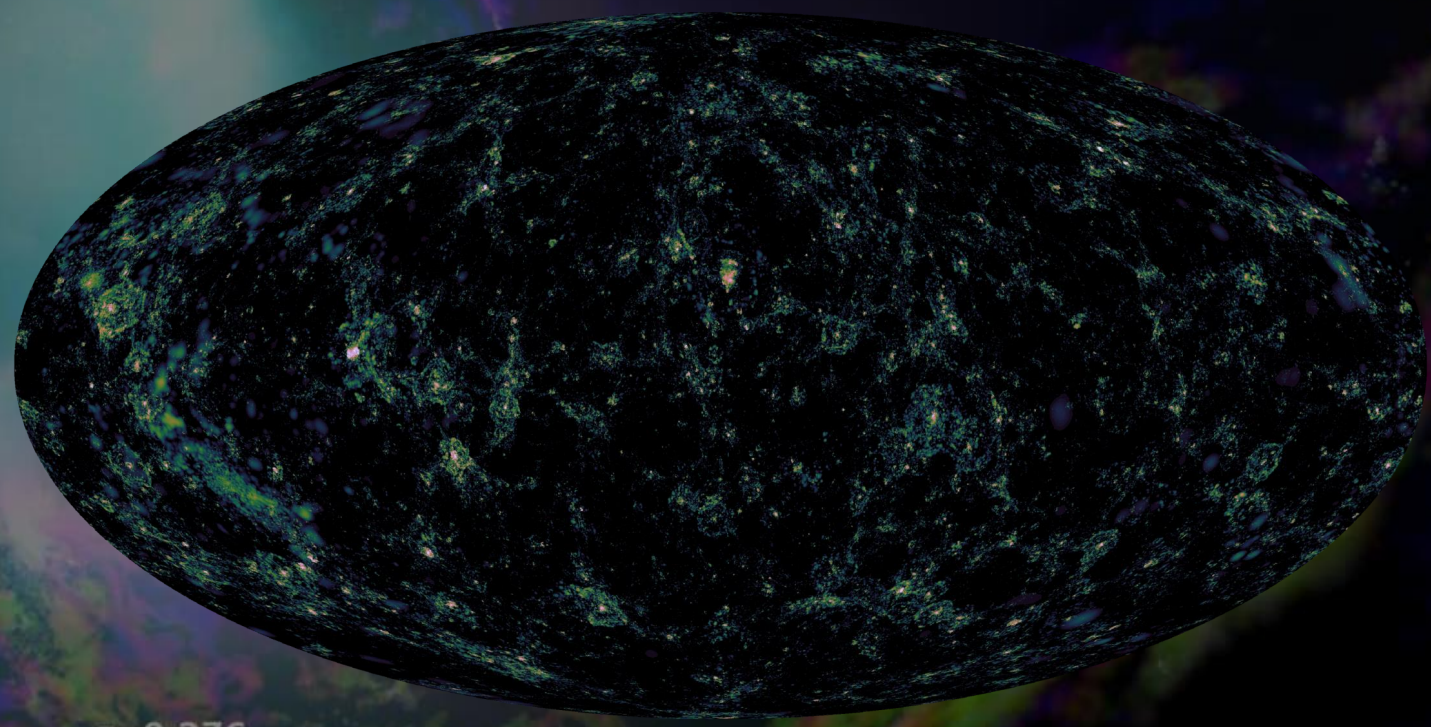
Conclusion

- First current gen simulation with a spectral CR model
- Consistent injection around filaments and in clusters
- Prediction for radio emission



Outlook

- Radio Emission of Coma, Perseus and Virgo (*Dolag, LMB, in prep.)*
- Predictions for allsky Gamma-Ray Emission (*LMB et. al., in prep*)

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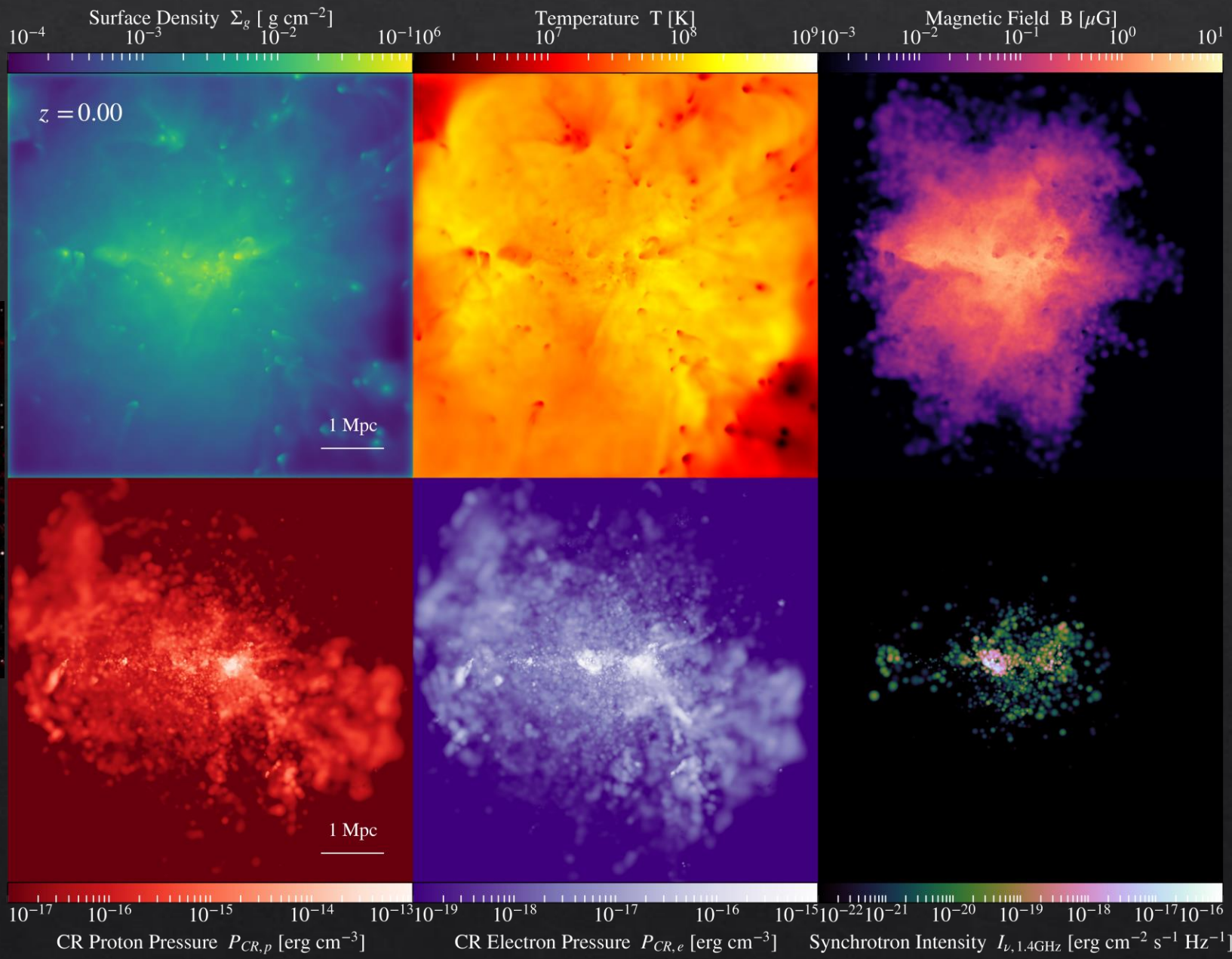
Coma Cluster

Bonafede+22

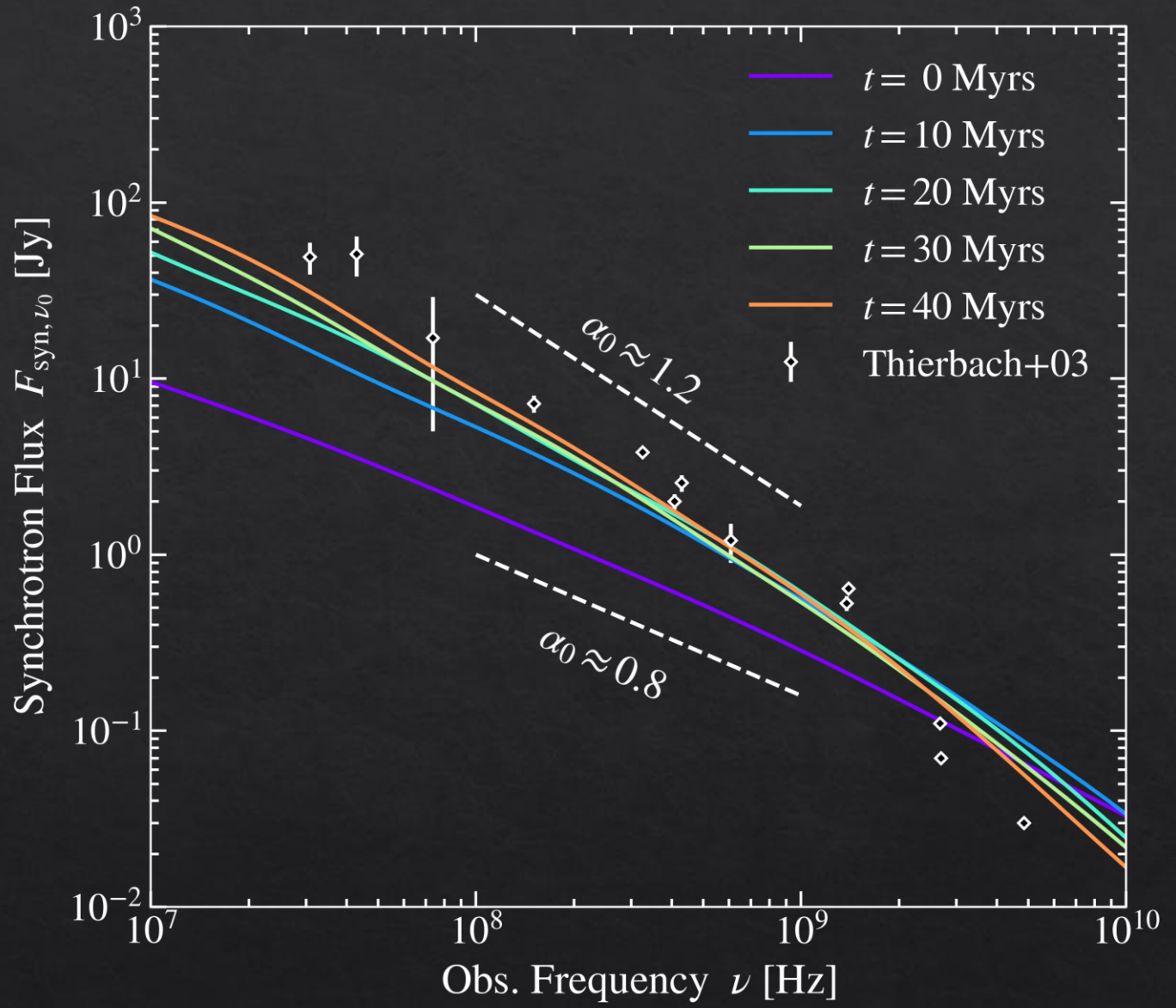


*Dolag, **LMB**, et. al. (in prep)*

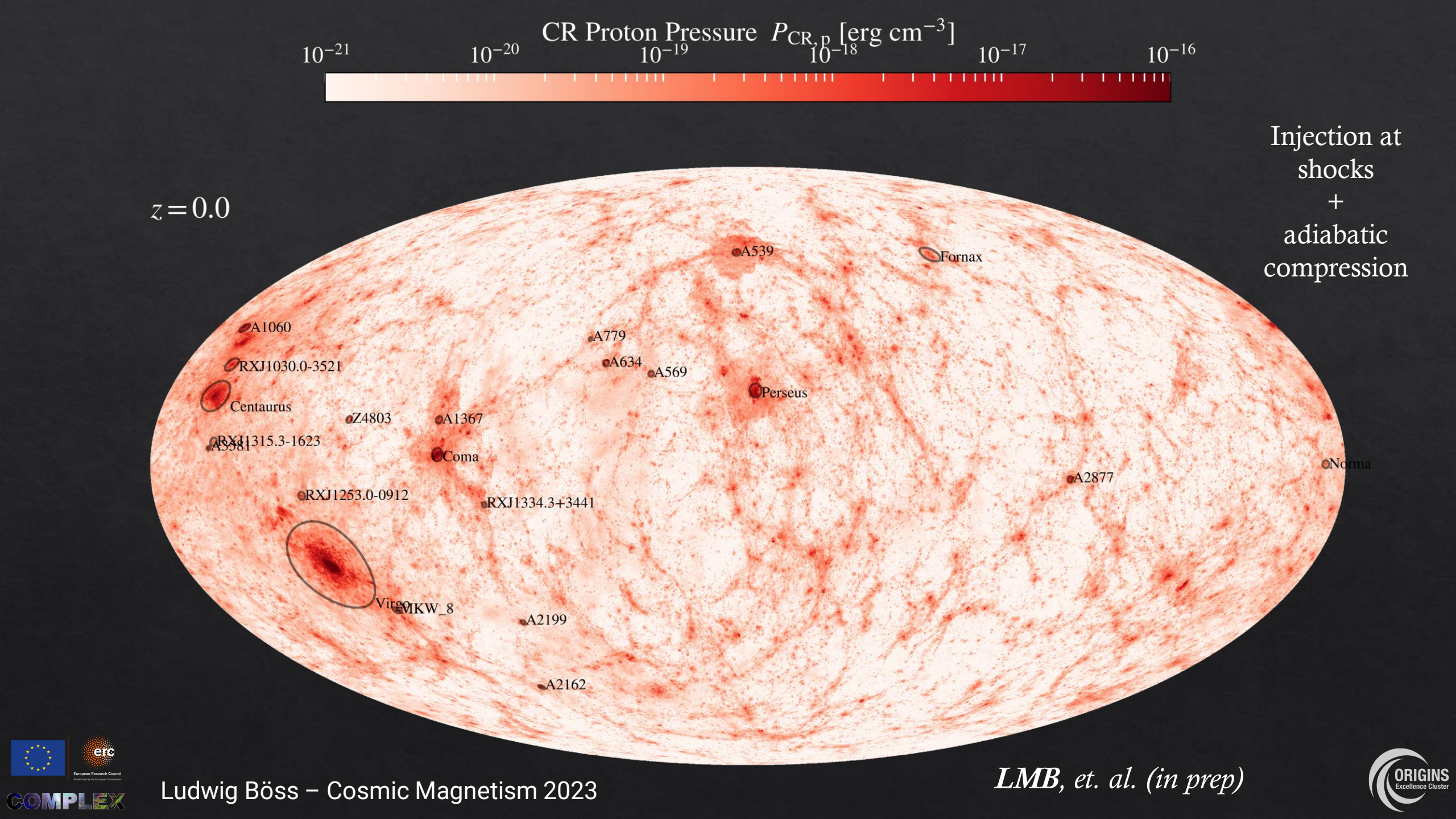
Coma Cluster

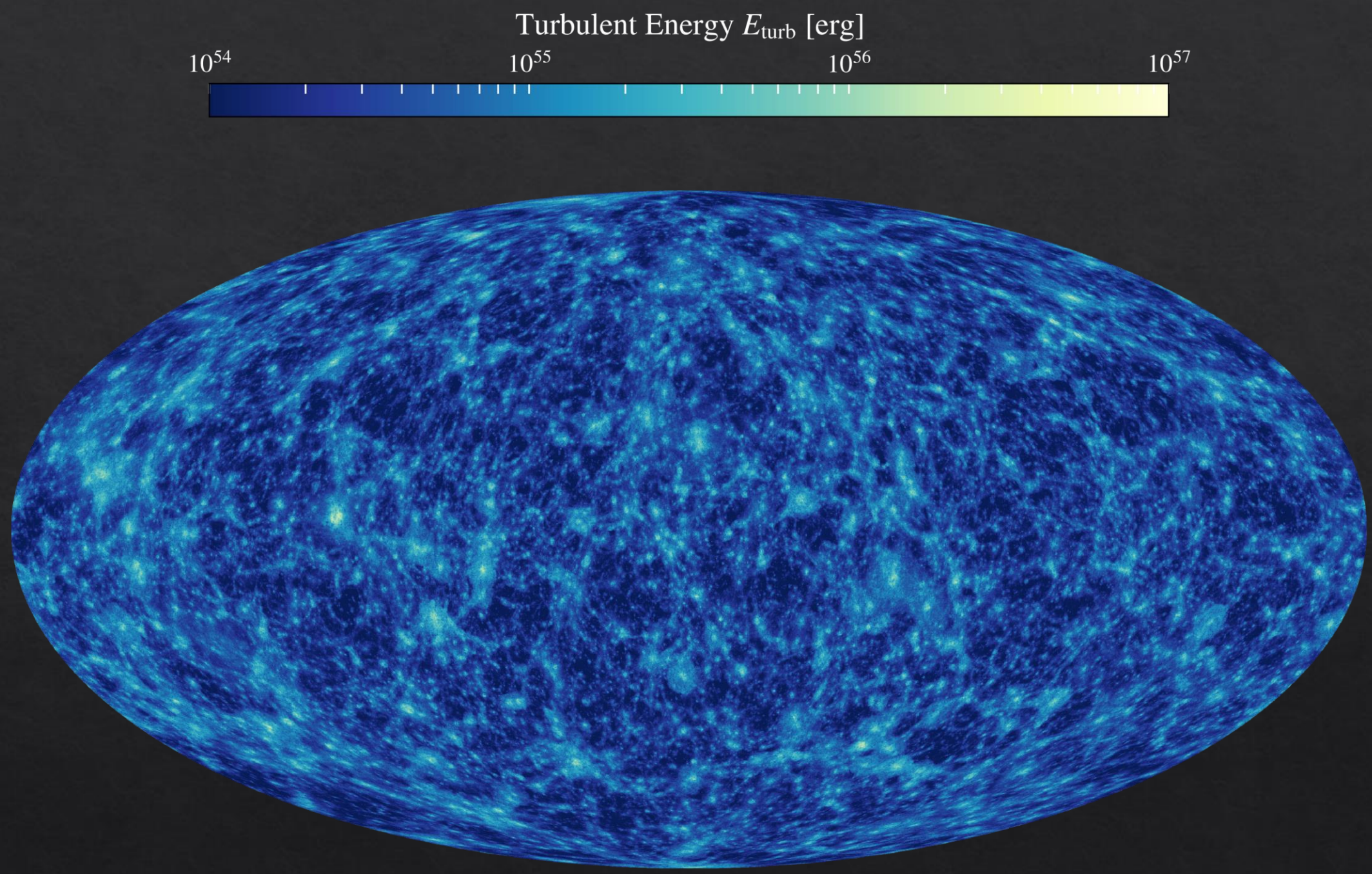
- Initially: Shock injected spectrum
- Post-process with re-acceleration + cooling for 40 Myrs
- Spectral steepening due to turbulence
- Excellent agreement with observations

$$L_\nu \propto B^{\alpha_0+1}$$



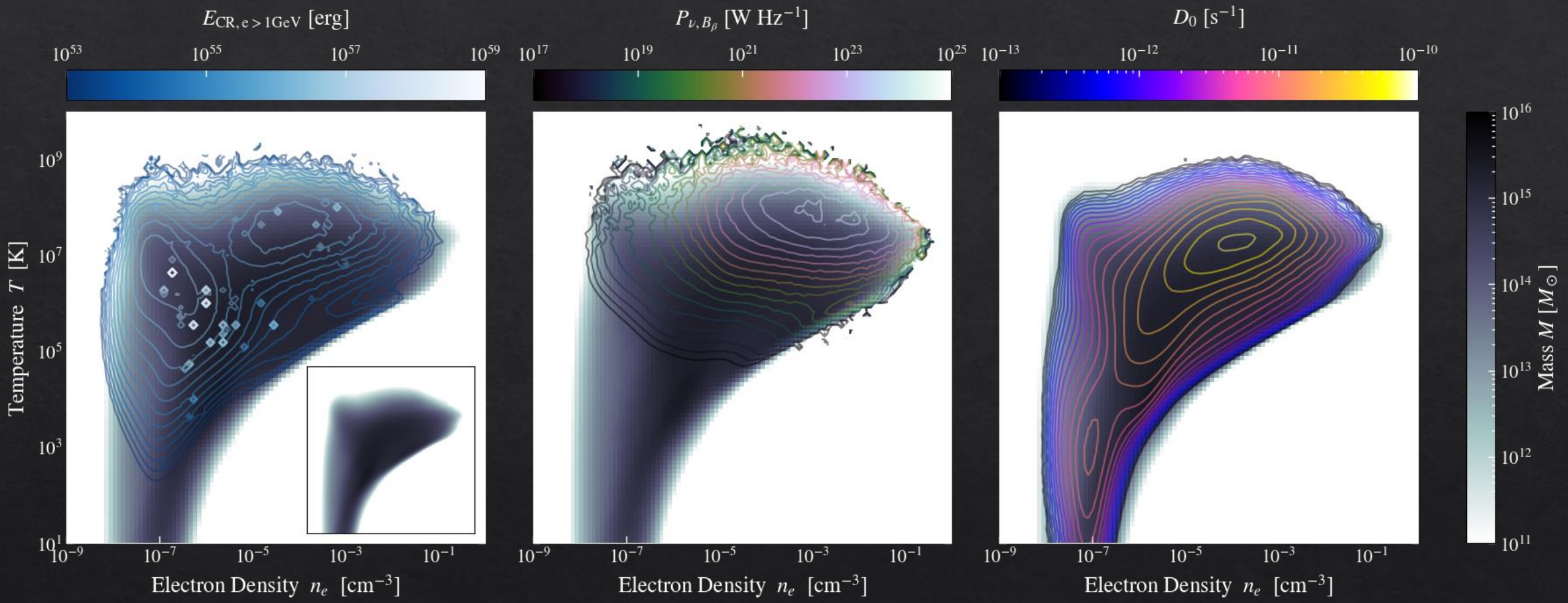
*Dolag, **LMB**, et. al. (in prep)*


CR Proton Pressure $P_{CR,p}$ [erg cm^{-3}]
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
$z = 0.0$
Injection at shocks + adiabatic compression
A539
Fornax
A1060
A779
A634
A569
RXJ1030.0-3521
Perseus
Centaurus
Z4803
A1367
RXJ1315.3-1623
A3581
Coma
Norma
A2877
RXJ1253.0-0912
RXJ1334.3+3441
Virgo
MKW_8
A2199
A2162
LMB, et. al. (in prep)


Turbulent Energy E_{turb} [erg]
10^{54}
10^{55}
10^{56}
10^{57}

Two injection regions, but currently only one emission region!

Can turbulent re-acceleration change this picture?



CR Injection

- On-the-fly shock finder
- Fraction of shock energy converted to CRs
- Fraction dependent on:
  - Mach number
  - Magnetic field angle
- Spectral slope dependent on shock compression
- Efficiency models:

https://github.com/LudwigBoess/DSAModels.jl