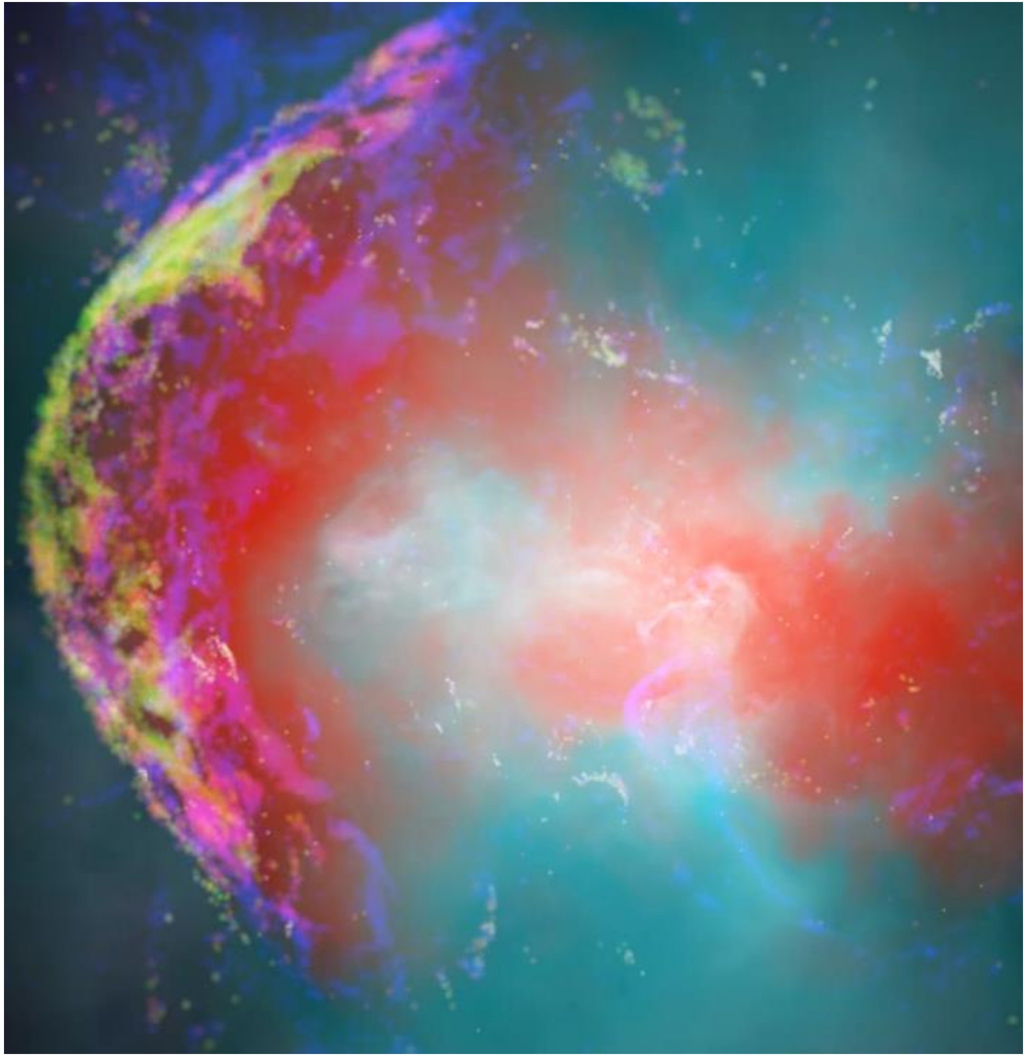


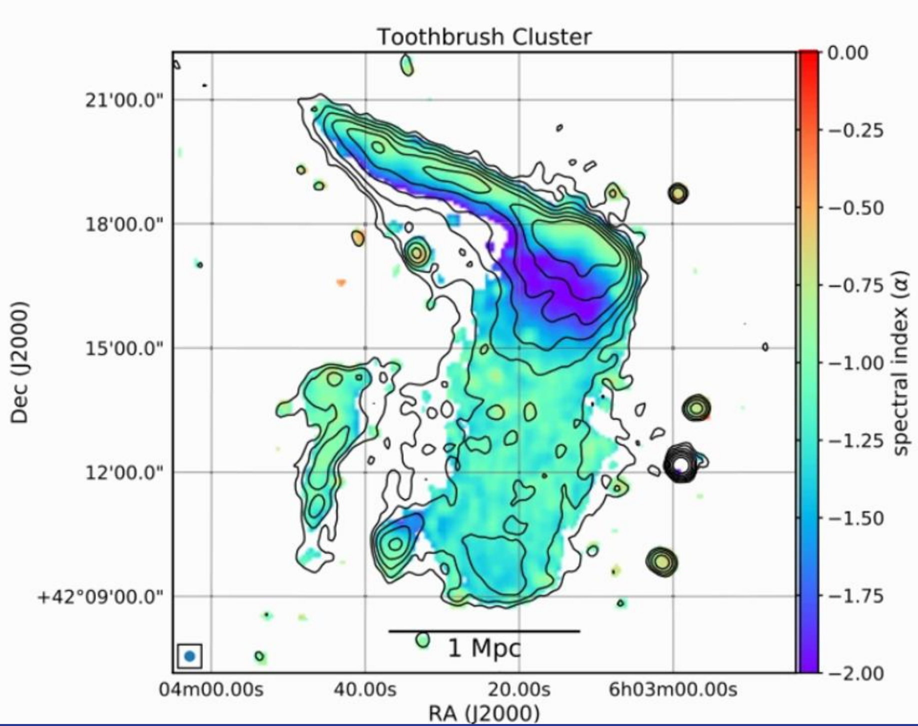
A Spectral Cosmic Ray Model for Cosmological Simulations

Ludwig Böss • Klaus Dolag • Harald Lesch

ICRC – 16.7.2021

Motivation

- CRs -> relativistic, charged particles
- Tracers of magnetic field
- Additional non-thermal pressure component from CR protons (very small in clusters)
- Observable Radio Relics and Radio Halos



van Weeren+19

Color: Spectral index
Contours: Radio intensity

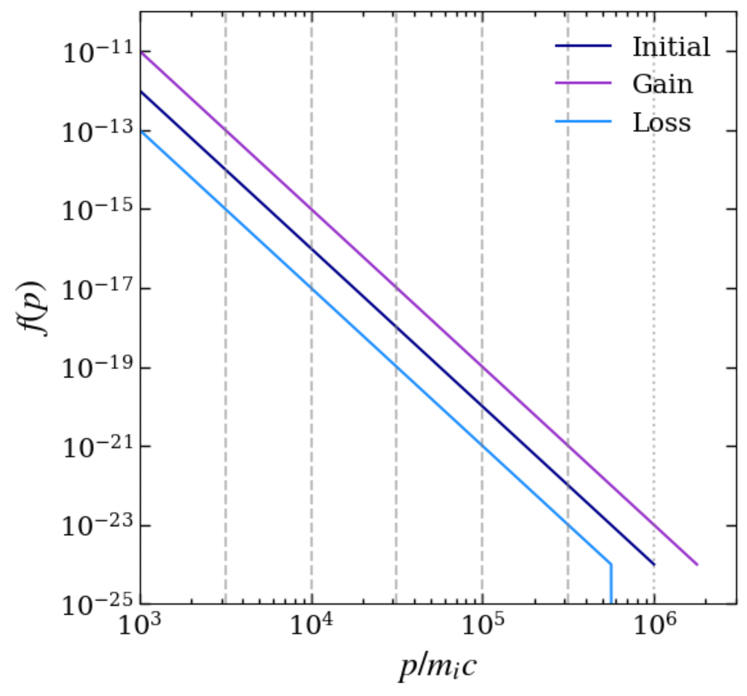
The Model

4 Basic assumptions

1. Every SPH particle contains a population of CRs -> additional fluid component.
2. CRs are distributed in momentum space following a piece-wise power law function.
3. Boundary conditions:
   - Bottom: Open
   - Top: Closed
4. CRs follow gamma-law equation of state.

$$P_{CR} = (\gamma_{CR} - 1)\rho E_{CR}$$

$$f(p) = f_i \left(\frac{p}{p_i} \right)^{-q_i}$$



The Model

Diffusion-convection Equation

$$f(x,p,t)$$

1) Advection
2) (Spatial) Diffusion
3) Expansion/Collapse
4) Radiative losses
5) Diffusion in momentum-space
6) Source term
7) Catastrophic losses

$$\underbrace{\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x}}_{(1)} - \underbrace{\frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right)}_{(2)} =$$

$$\underbrace{\frac{1}{3}\frac{\partial u}{\partial x}p\frac{\partial f}{\partial p}}_{(3)} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[\underbrace{b_l}_{(4)} + \underbrace{D_p\frac{\partial f}{\partial p}}_{(5)}\right]\right) + \underbrace{j(x,p)}_{(6)}$$

$$- \underbrace{\frac{f}{t_c}}_{(7)}$$

The Model

Diffusion-convection Equation

$$f(x,p,t)$$

1) Advection
2) (Spatial) Diffusion
3) Expansion/Collapse
4) Radiative losses
5) Diffusion in momentum-space
6) Source term
7) Catastrophic losses

$$\underbrace{\frac{Df}{Dt}}_{(1)}$$

$$\underbrace{\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x}}_{(1)} - \underbrace{\frac{\partial}{\partial x}\left(\kappa \frac{\partial f}{\partial x}\right)}_{(2)} =$$

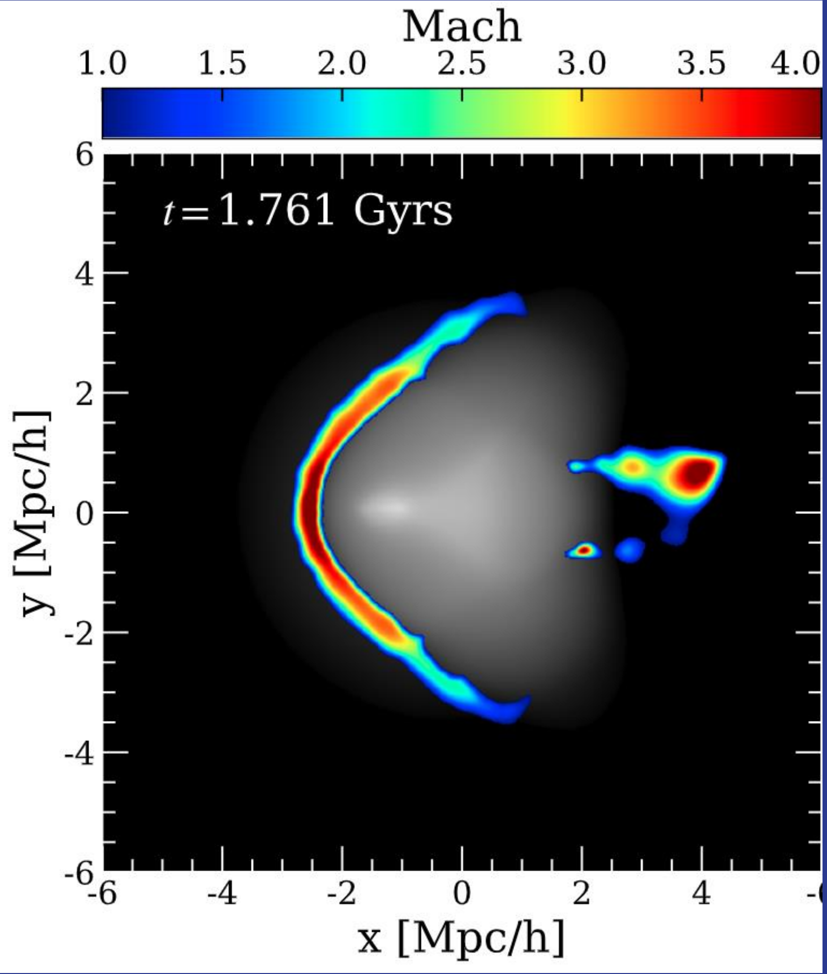
$$\underbrace{\frac{1}{3}\frac{\partial u}{\partial x} p \frac{\partial f}{\partial p}}_{(3)} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[\underbrace{b_l}_{(4)} + \underbrace{D_p \frac{\partial f}{\partial p}}_{(5)}\right]\right) + \underbrace{j(x,p)}_{(6)}$$

$$- \underbrace{\frac{f}{t_c}}_{(7)}$$

The Model

Sources - Shocks

- On-the-fly shockfinder (Beck+16)
- At the shock: Shock Energy is converted to CR Energy
- Energy conversion efficiency dependent on shock mach number and B-field geometry
- Spectral slope dependent on shock compression + B-field

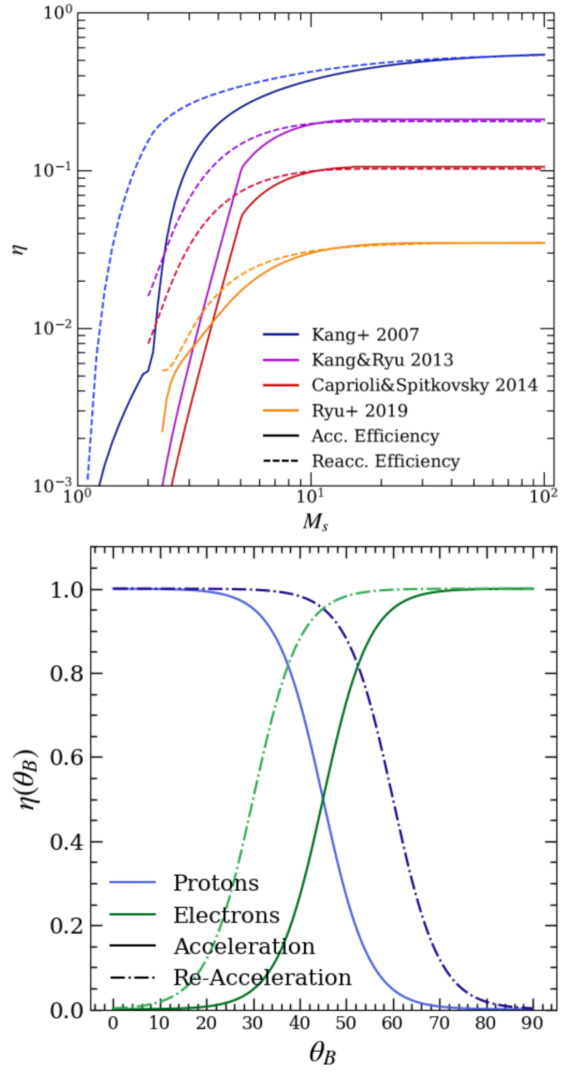


The Model

Sources - Shocks

- 4 Mach number dependent efficiency models
- 1 Geometry dependent efficiency model

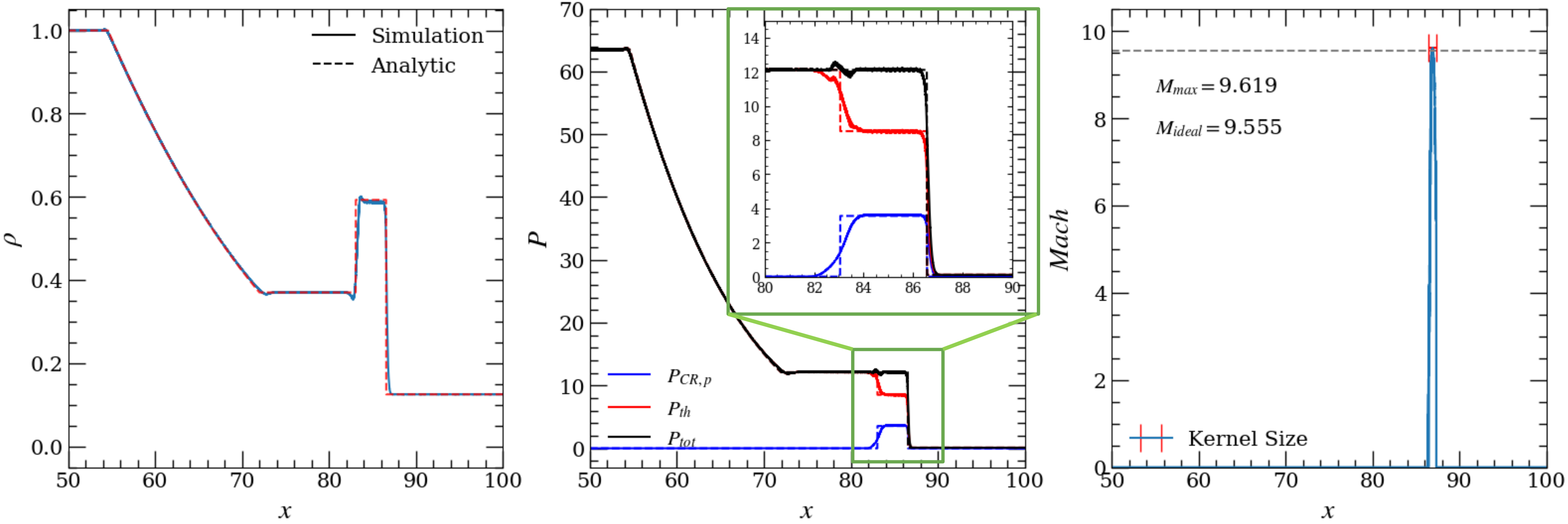
$$\eta(M, \theta_B) = \eta(M) \cdot \eta(\theta_B)$$



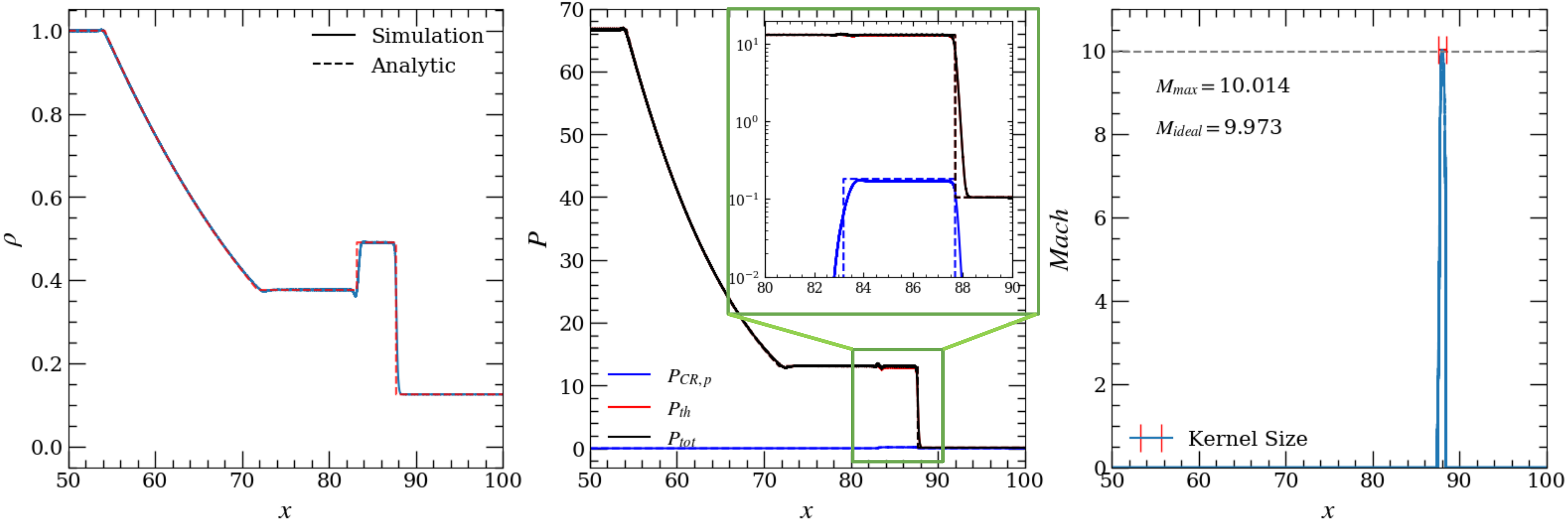
Caprioli & Spitkovsky 2014

Pais+18

Pfrommer+17 Test



Ryu+19 efficiancy



The Model

Radiative Losses

Currently implemented:

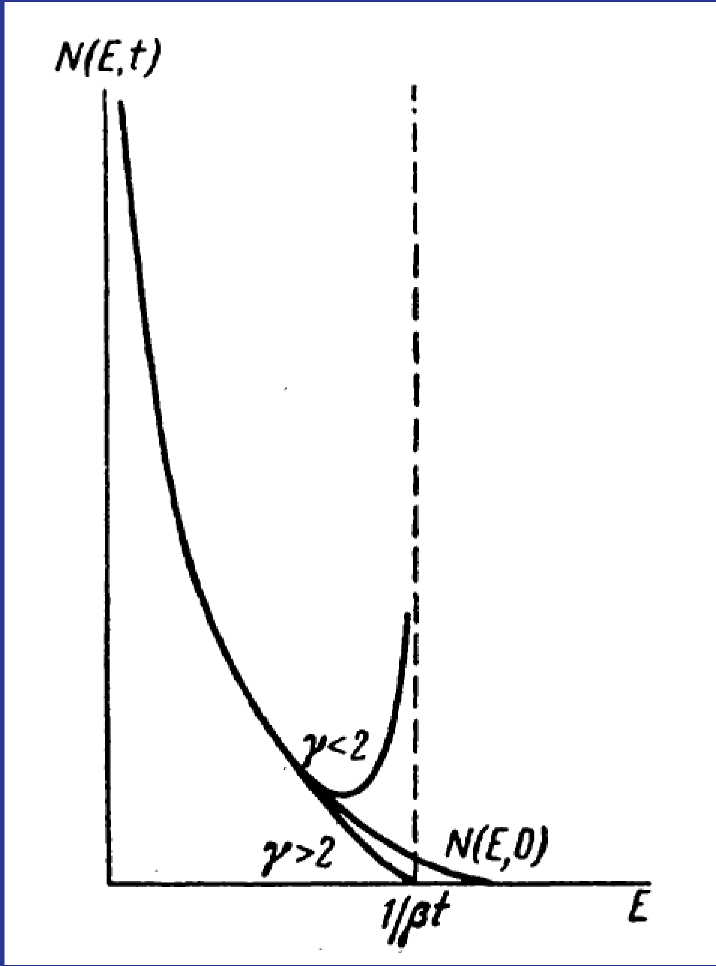
- Losses due to synchrotron radiation.

$$b_{l,syn} \propto U_B p^2 \qquad U_B = \frac{B^2}{8\pi}$$

- Losses due to inverse compton scattering with CMB-photons.

$$b_{l,ic} \propto U_{CMB} p^2$$

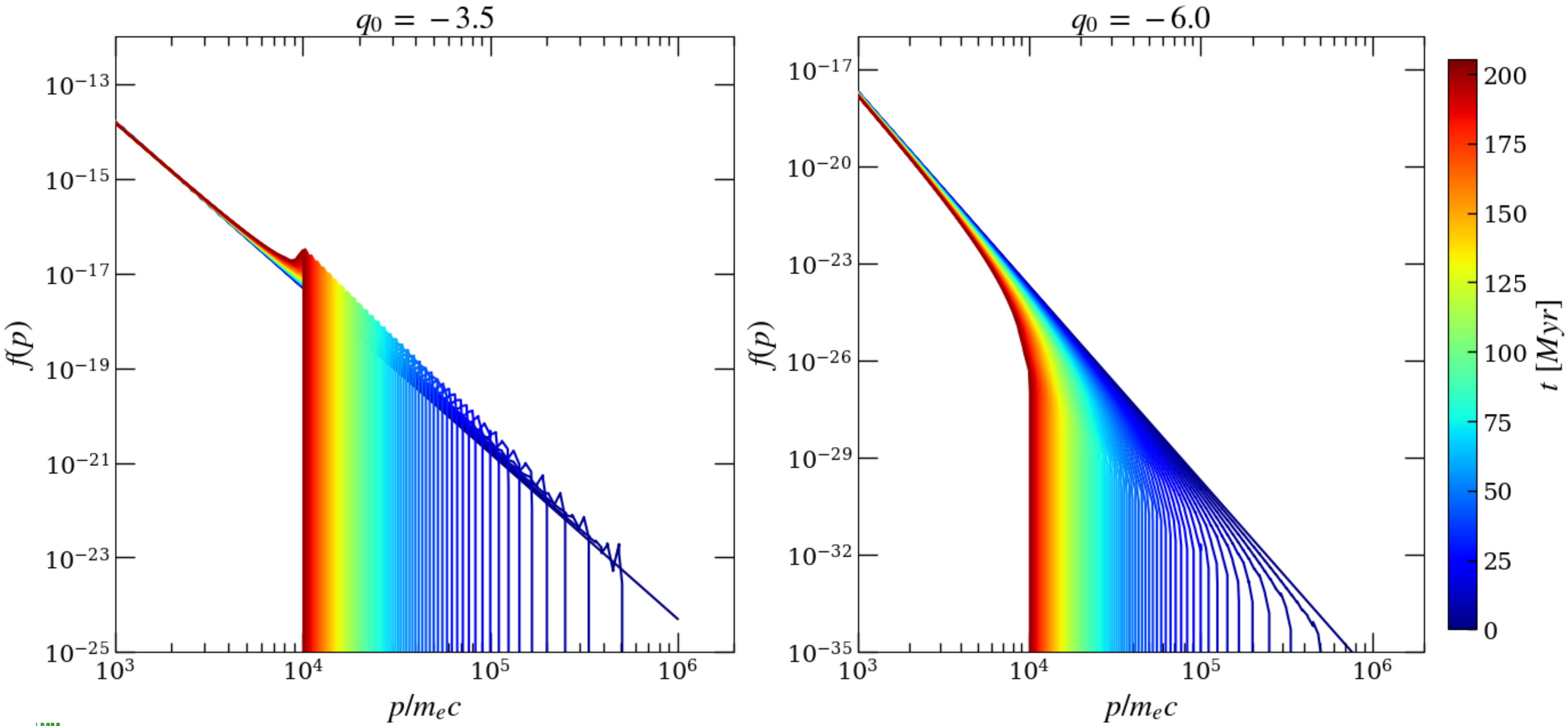
$$U_{CMB} \sim (1+z)^4$$



Kardashev (1962)

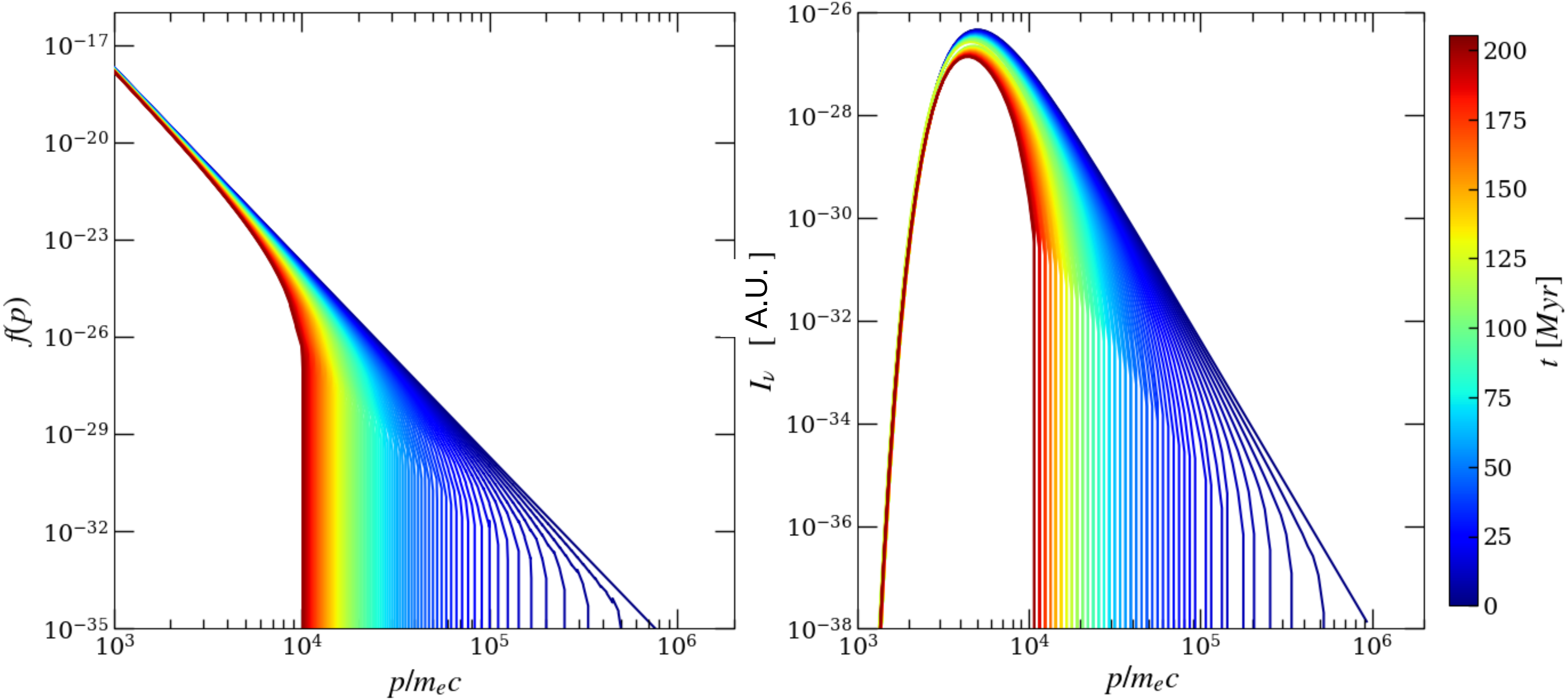
Inverse Compton scattering

N_bins = 192



Synchrotron Emission at 1.44 GHz

N_bins = 192

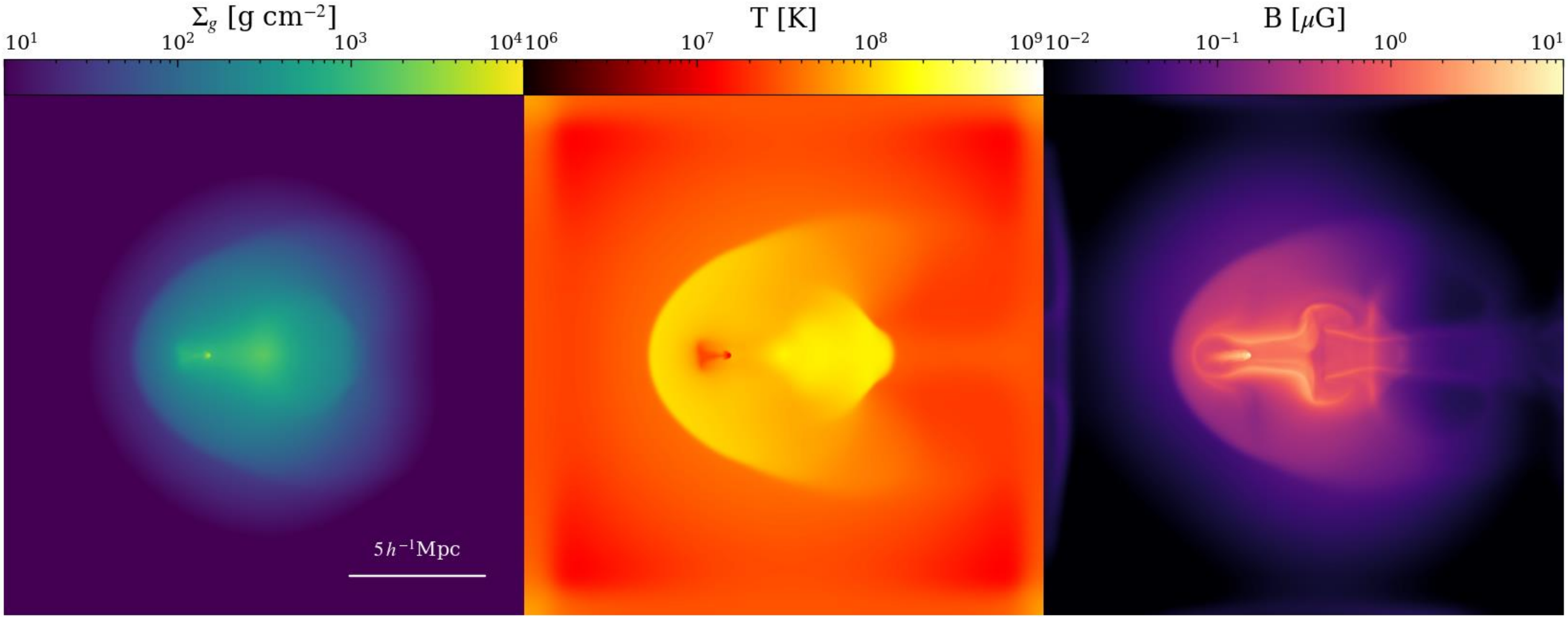


Bringing it all together

Cluster Merger

Cluster Merger

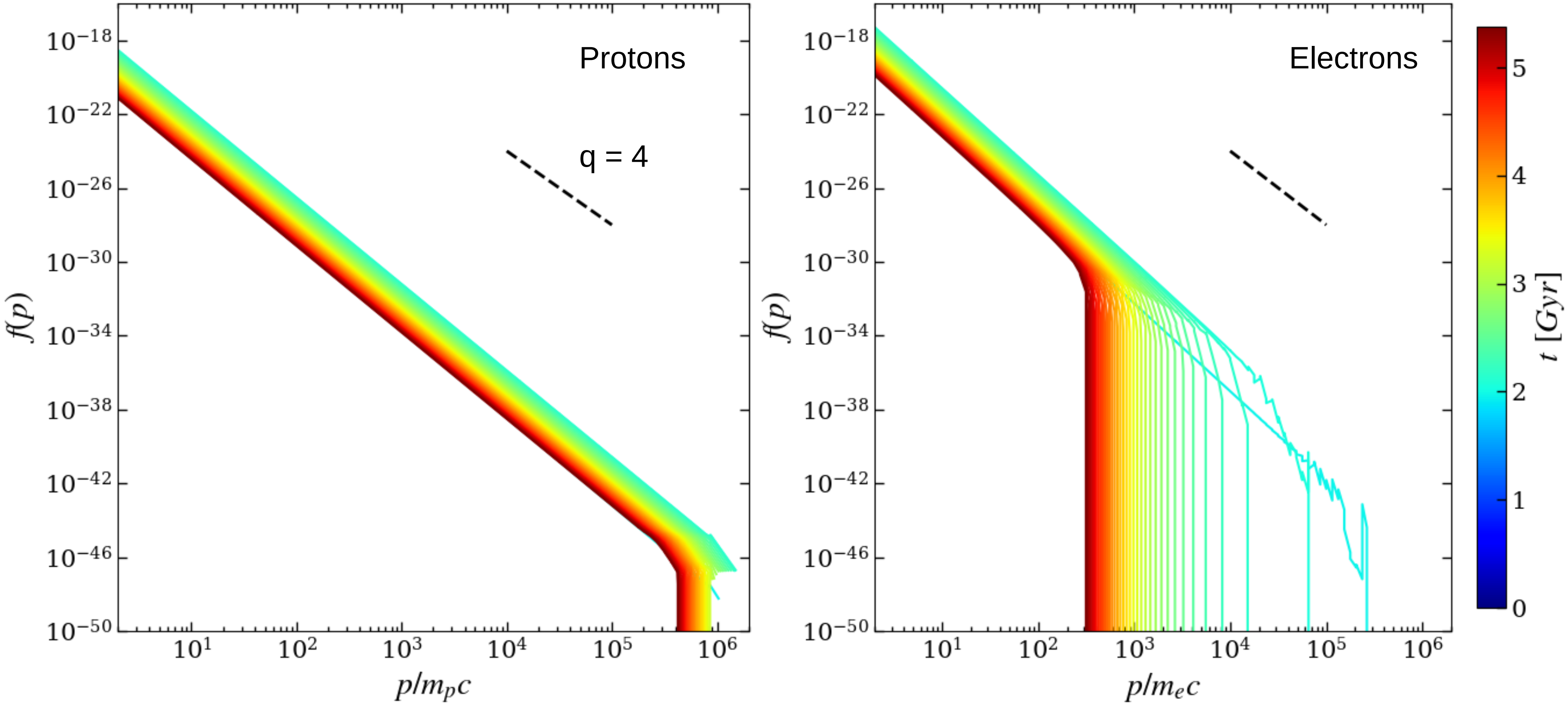
N_bins = 96



Initial Conditions from ToyCluster (Donnert 2014)

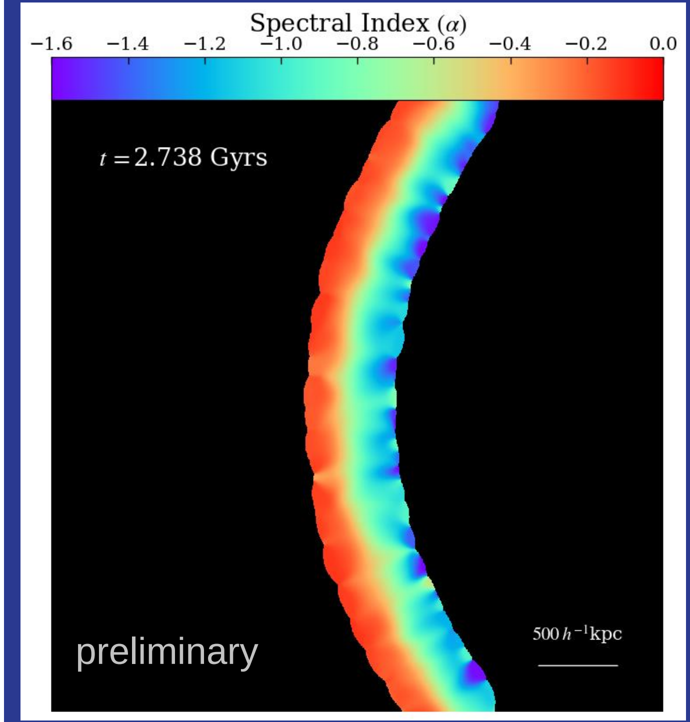
Cluster Merger

N_bins = 96

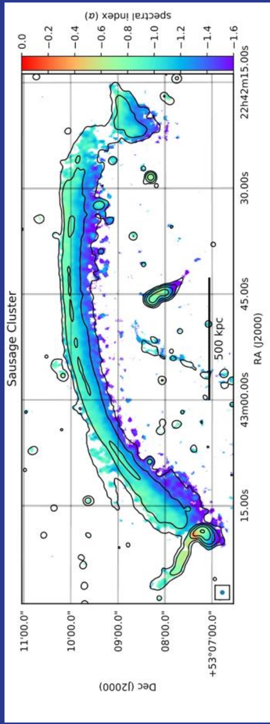


Radio Relics

- We observe spectral steepening over the relic
- Larger acceleration zone (resolution!)
- Flatter sprectra due to stronger shock



This Work



van Weeren+19

Conclusion

- Hydrosolver stays stable with the 2-fluid model.
- Capturing the acceleration efficiency is quite accurate.
- The cooling model shows nice convergence to analytic solution.
- Future work: Zoom simulations with working model to see effect on cosmological scales.

Thank you for your attention!