A Lagrangian View on the γ-ray and diffuse Radio Emission in Galaxy Clusters

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Outline

Goal

Combine Eulerian magneto-hydrodynamical simulations with Lagrangian tracer particles to study the observational signatures of cosmic rays in galaxy clusters.

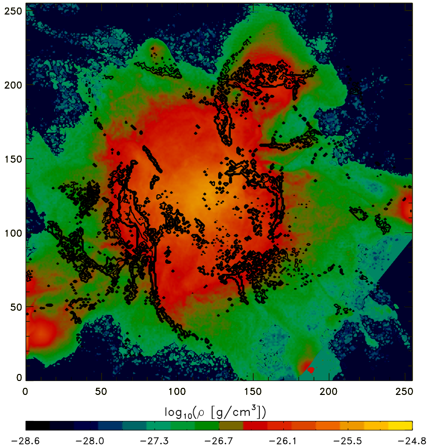
1. Simulations
2. Where are the γ-rays?
3. M_X vs $M_{\rm radio}$

Simulations

ENZO

- simulate galaxy cluster with ENZO
- $z \in [30, 0]$
- $M(z \approx 0) \approx 9.7 \cdot 10^{14} M_\odot$
- major merger at $z \approx 0.27$

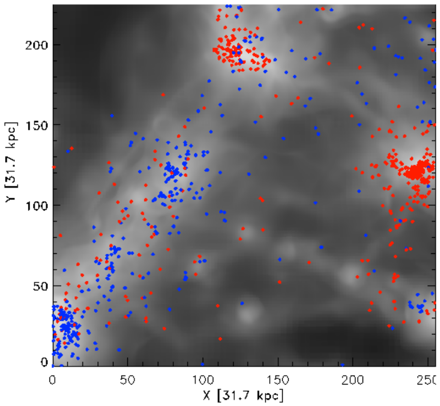
$\Rightarrow$ two radio relics (using Hoeft & Brüggen 2007):
  - $2.61 \cdot 10^{31}$ erg s^{-1} Hz^{-1}
  - $2.27 \cdot 10^{30}$ erg s^{-1} Hz^{-1}



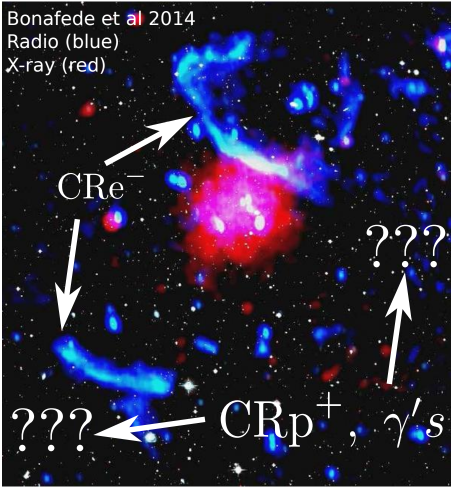
CRaTer: Cosmic-Ray-Tracers

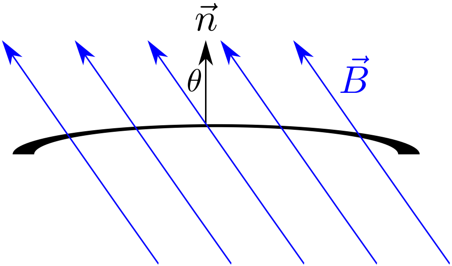
- Lagrangian Tracers on top of the ENZO-code
- particles advected passively with the fluid from $z = 1$ to $z = 0$
- mass resolution: $m \approx 10^8 M_\odot$

  $\Rightarrow \sim 1.33 \cdot 10^7$ tracers at $z = 0$
- follow the cosmic-rays
  - detect shocks
  - compute Mach number
  - compute obliquity
  - compute cosmic-ray energy (using Kang & Ryu 2013 efficiencies)



Where are the γ-rays?





PIC-Simulations

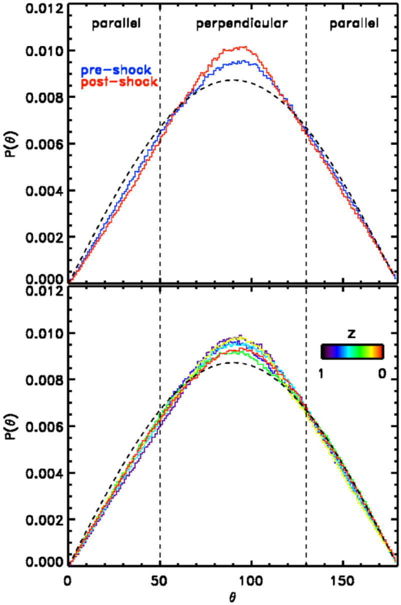
- protons accelerated by DSA need $\theta < 50°$ (quasi-parallel)[a]
- electrons accelerated by SDA need $\theta > 50°$ (quasi-perpendicular)[b]

[a] Caprioli & Spitkovsky 2014
[b] Guo & Sironi & Narayan 2014

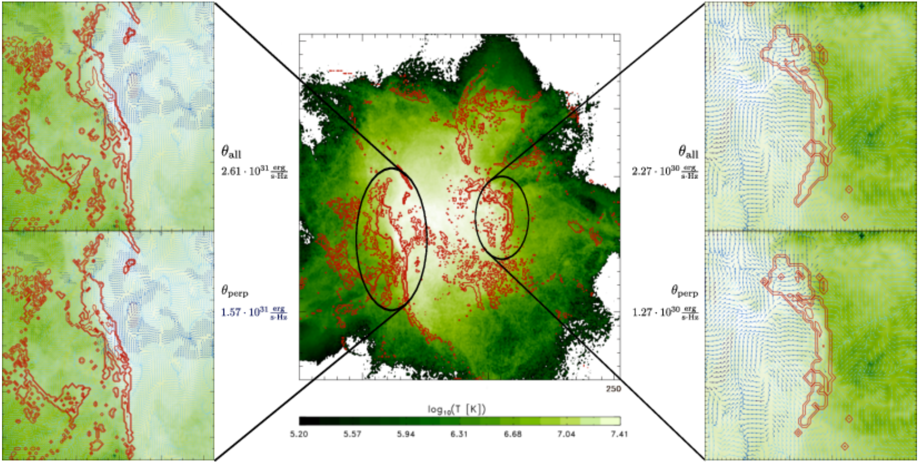
- follows the distribution of random angles in the three-dimensional space $\sim \sin(\theta)$
- shock compresses $P(\theta_{\mathrm{pre}})$
- turbulence decompresses $P(\theta_{\mathrm{pre}})$

$\Rightarrow$ by theory expect more perpendicular than parallel shocks

$\Rightarrow$ How does this affect the radio and γ-ray emission?

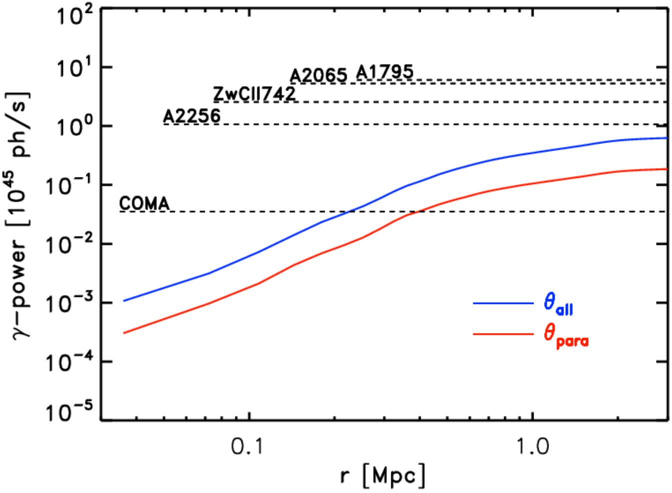


Effect on the Radio Emission



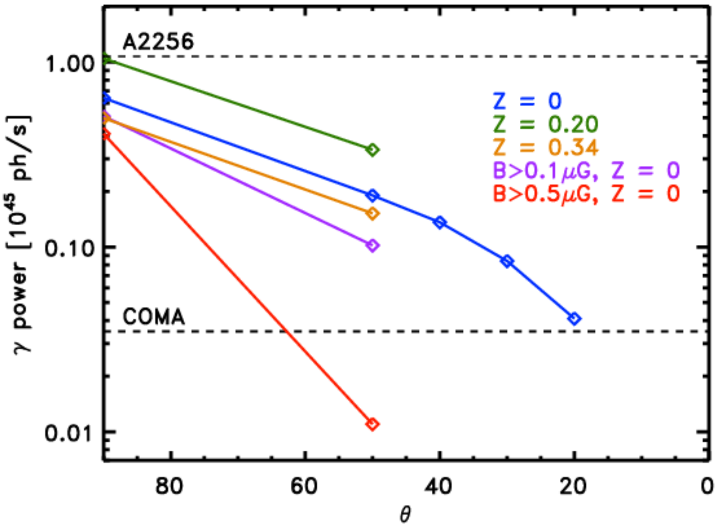
reduced by ~ 1.66 and $\sim 1.79 \Rightarrow$ no dramatic change

Effect on the γ-rays Emission



reduced by ~ 3.4, but still above Fermi-Limits from Ackermann et al. 2014 and 2016

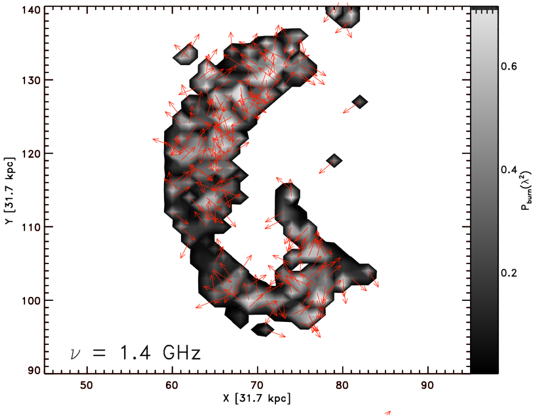
Additional Mechanisms?



for more information see Wittor et al. 2016, 2017

M_X vs M_{radio}

In the Progress: Polarization



in collaboration with Matthias Hoeft:

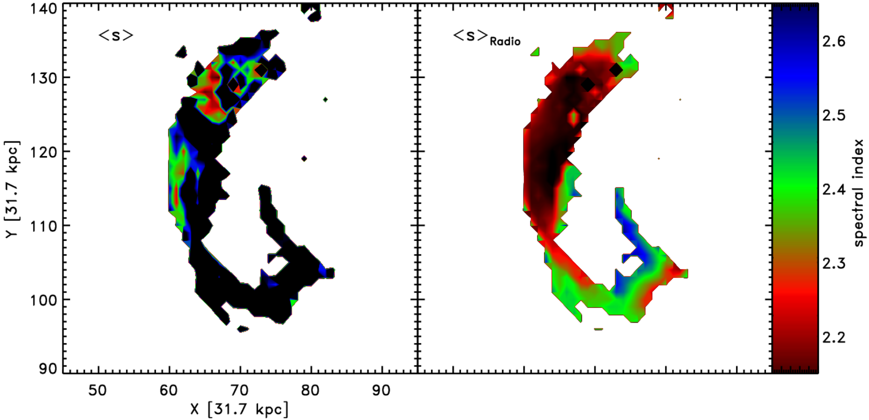
- use CRaTer to study the polarization properties of radio relics
- $\langle P(\lambda^2) \rangle \sim 30\ \%$

$\Rightarrow$ stay tuned for more in the future!

- Burn 1966: observed polarization of the integrated emission
- single injection of cosmic rays and no aging (yet)

$\Rightarrow$ obtained additional information on: spectral indices, Mach number etc

Spectral Index: $s = (r+2)/(r-1)$



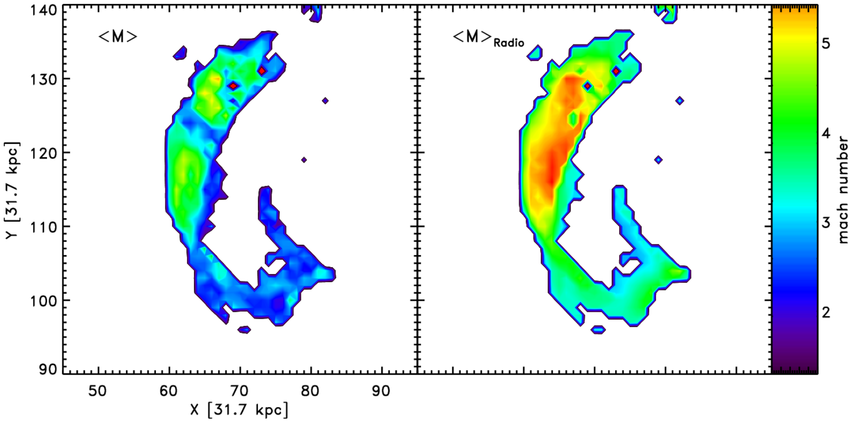
mean non-weighted s

$\langle s \rangle \sim 2.3$

mean radio-weighted s

$\langle s \rangle_{\mathrm{radio}} \sim 3.0$

Mach Number: $M = \sqrt{\frac{4}{5}\frac{T_{\rm new}}{T_{\rm old}}\frac{\rho_{\rm new}}{\rho_{\rm old}} + 1}$



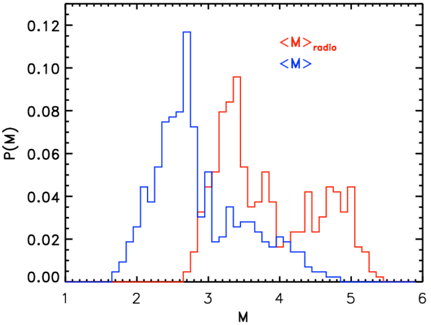
mean non-weighted M

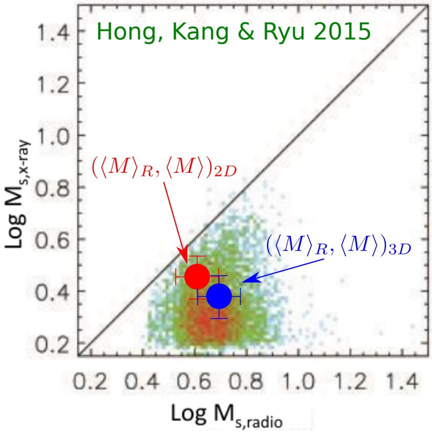
$\langle M \rangle \sim 2.9$

mean radio-weighted M

$\langle M \rangle_{\rm radio} \sim 3.9$

Distribution of Mach Numbers





⇒ radio seems to be sensitive only to the high Mach numbers (“overestimates” the true Mach number), while X-ray might trace the true mean Mach number

Summary

Where are the γ-rays?:

... θ follows the distribution of random vectors in a 3D space

... even more quasi-perpendicular shocks due to compression by shock waves

... θ does not effect the observed radio emission

... θ might be an explanation for the missing $\gamma-$ray emission

... but additional requirement needed, e.g. B_{min}

... for more information see Wittor et al. 2016, 2017

M_X vs M_{radio}:

... no uniform Mach number across the relic

... $\langle M \rangle_{\mathrm{radio}}$ higher than the average Mach number, both in 2D and 3D

... X-ray seems to trace mean Mach number

... radio observation might be biased to larger Mach numbers

... could be a reason for the discrepancy in some cases

Thank you for you attention!

Any questions?