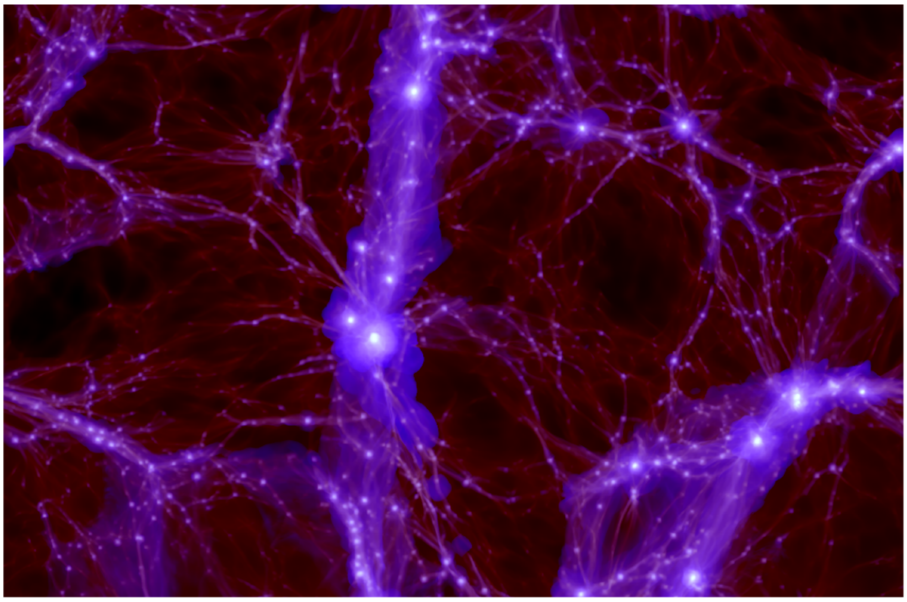
Limiting the Shock Acceleration Efficiency of CR with Simulations and Observations of Galaxy Clusters

KAW9 - Ulsan 10-12 July 2017



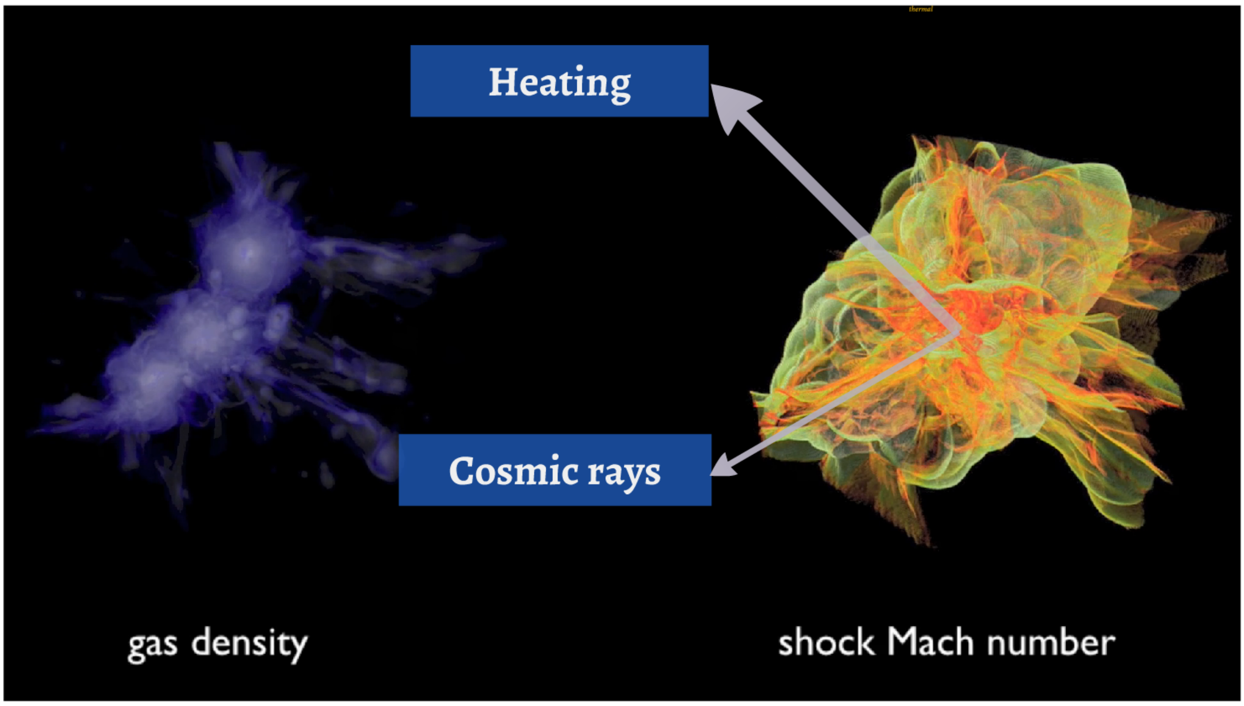
Franco Vazza (IRA-Bologna & Univ. Hamburg)

+M.Brüggen, D. Wittor, C. Gheller, D.Eckert, G. Brunetti, B. Huber, A. Bonafede, A. Stubbe

AstroFIt 2 Astronomy Fellowships in Italy

The shocking and turbulent life of a galaxy cluster(1)

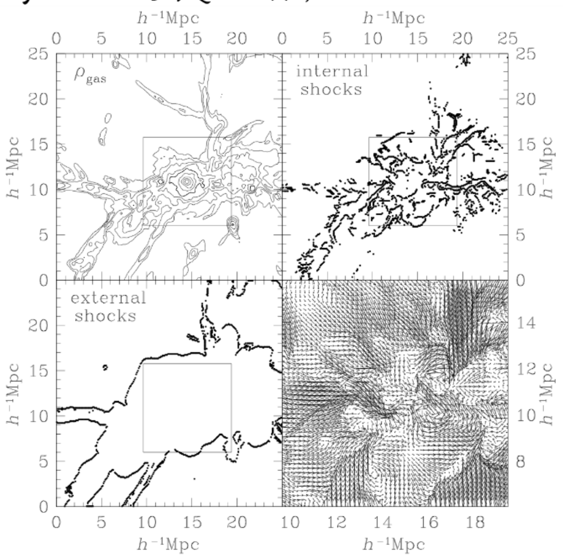
3D rendering by T. Jones & D.Porter



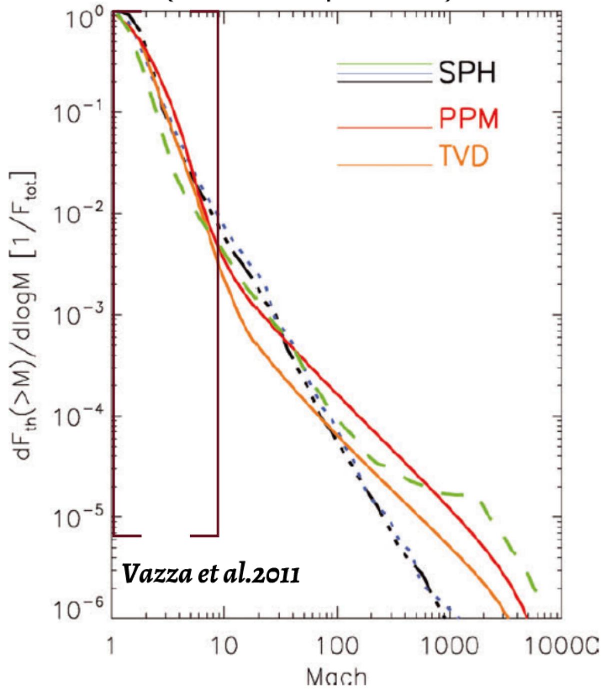
ITASCA SIMULATED CLUSTER SAMPLE 2016, FV, Jones et al.

Shocks and structure formation: early numerical simulations

Ryu et al.2003 ; Quilis+97 ; Miniati+2000



Dissipated energy flux (code comparison)

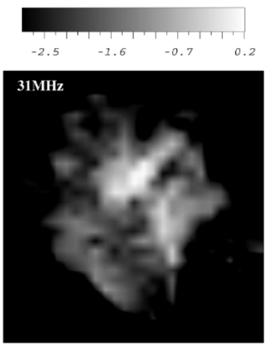


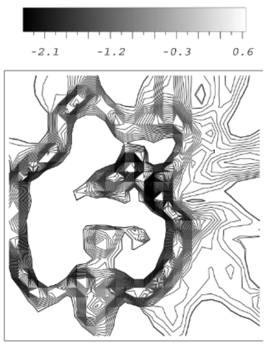
Later confirmed by:
grid methods: Skillman+08,Vazza+09,Planelles+12...
sph methods: Pfrommer+06,Hoeft+08...
moving mesh: Schaal & Springel 2015

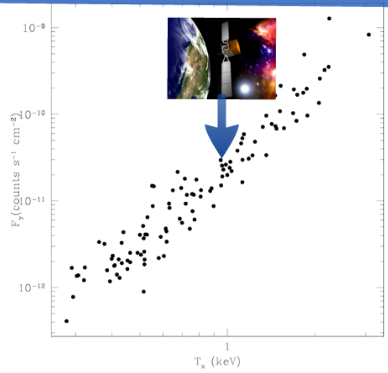
Cosmic rays in cosmological simulations

Eulerian: Miniati+01

Cosmological simulations of (passive) CRe/p injected by shocks

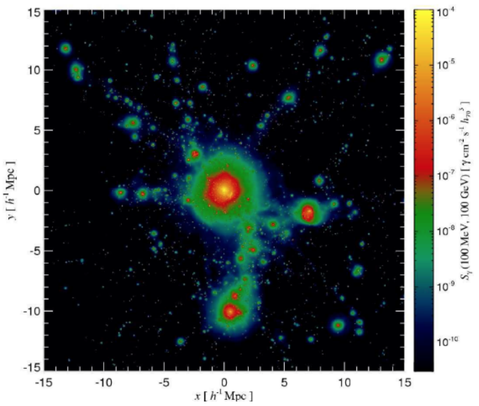




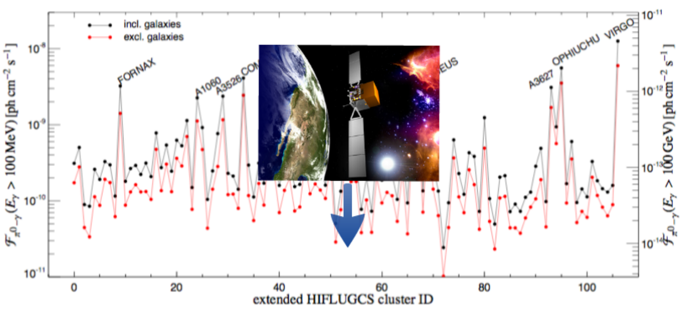


Lagrangian: Pfrommer+07,08; Jubelgas+08

Pion decay γ-ray emission (E_γ > 100 MeV):



2-fluid model in Gadget, pressure feedback from CRp; spectral description (power-laws)



Basic idea of my 2012..2016 works:

- Time-integrated effect of particle acceleration?
- Include "basic" CR-physics after injection: compression, heating, *re-acceleration*
- Additional CR players: supernovae, AGN...
- Use Gamma obs. to limit shock efficiency

A 2-fluid model for Cosmic Rays in Enzo

FV et al.2012, 2013, 2014, 2016 ...based on Kang & Jones 02, Miniati 07, Pfrommer+07, Guo & Oh 08)

CR advection $$\frac{\partial E_{cr}}{\partial t} + \nabla \cdot (E_{cr}\mathbf{v}) + P_{cr} \cdot \nabla \cdot \mathbf{v} = 0. \qquad \gamma_{cr} = 4/3.$$

CR energy & pressure $$P_{cr} = (\gamma_{cr} - 1)\rho e_{cr} = (\gamma_{cr} - 1)E_{cr}$$

CR injection by shocks $$\phi_{cr} = \eta(M) \cdot \frac{\rho_u v_s^3}{2} = \eta(M) \cdot \frac{\rho_u c_s^3 M^3}{2} \qquad e_{cr} = \frac{\phi_{cr}}{\rho} \cdot \frac{dt_1}{dx_1}$$

Effective pressure & local sound speed $$\gamma_{eff} = \frac{(\gamma P_g + \gamma_{cr} P_{cr})}{P_g + P_{cr}} \qquad c_s' = \sqrt{\frac{\gamma P_g + \gamma_{cr} P_{cr}}{\rho}}$$

Cosmological expansion $$\frac{\partial e_{cr}}{\partial t} = -3\frac{(\gamma_{cr} - 1)\dot{a}}{a} e_{cr}.$$

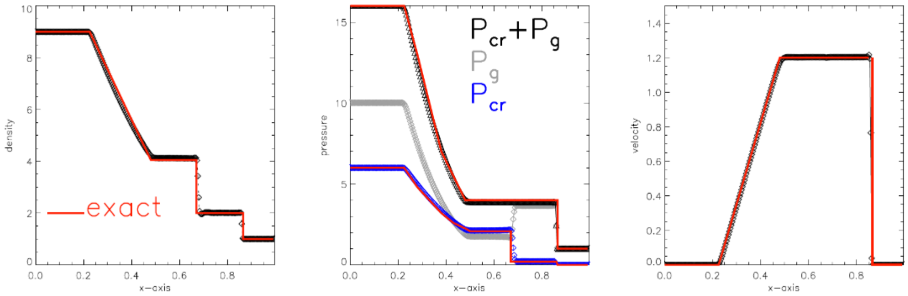
Gas-CR heating/losses $$\Gamma_{coll} = -\zeta_c \frac{n_e}{\text{cm}^{-3}} \frac{E_{cr}}{\text{erg cm}^{-3}} \text{erg s}^{-1} \text{cm}^{-3},$$

+ other source terms for CRs: SN & AGN

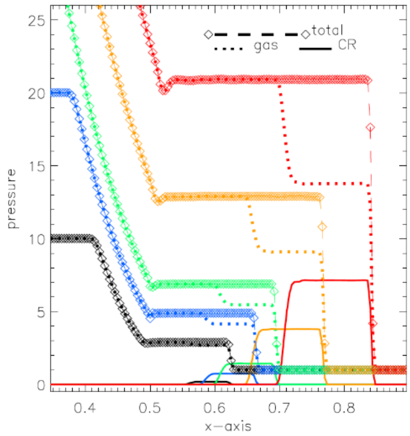
A 2-fluid model for Cosmic Rays in Enzo

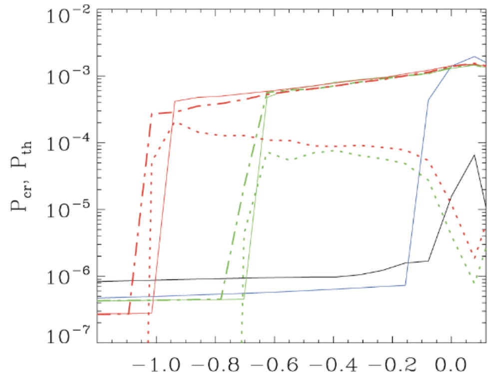
Tests:

1-D shock tube



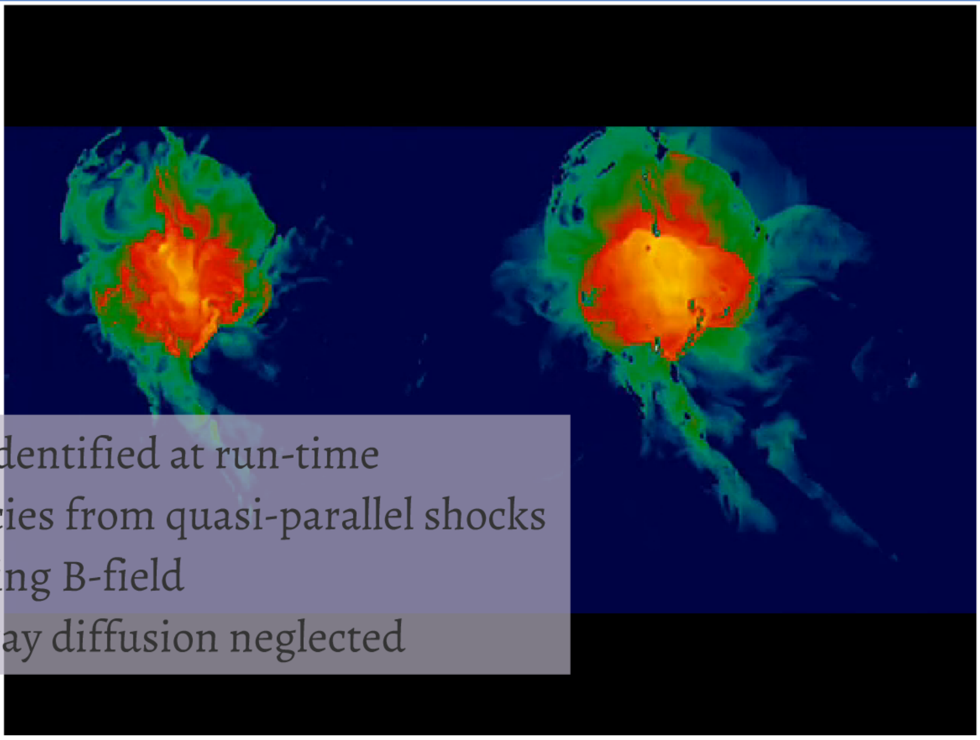
Injection depending on Mach





Zeldovich pancake

A 2-fluid model for Cosmic Rays in Enzo

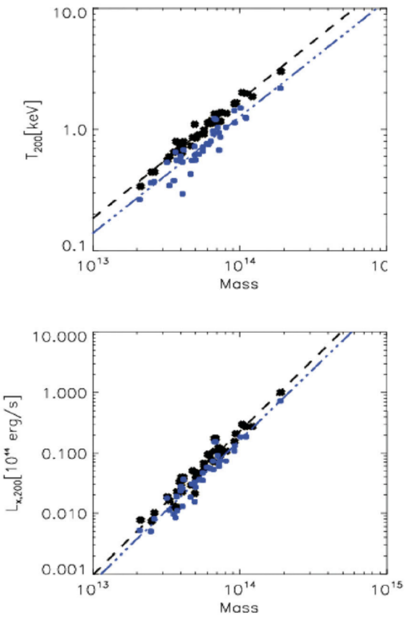


- shocks identified at run-time
- efficiencies from quasi-parallel shocks
- no limiting B-field
- cosmic ray diffusion neglected

Vazza et al. 2012 MNRAS

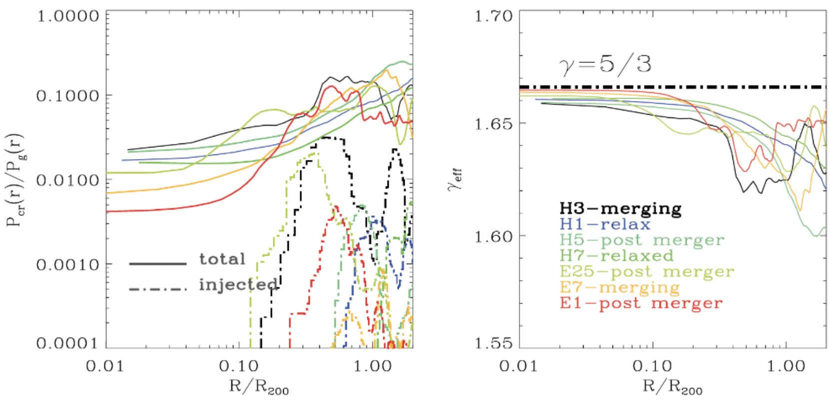
A 2-fluid model for Cosmic Rays in Enzo

Effects on scaling relations



(! trends opposite than in SPH)

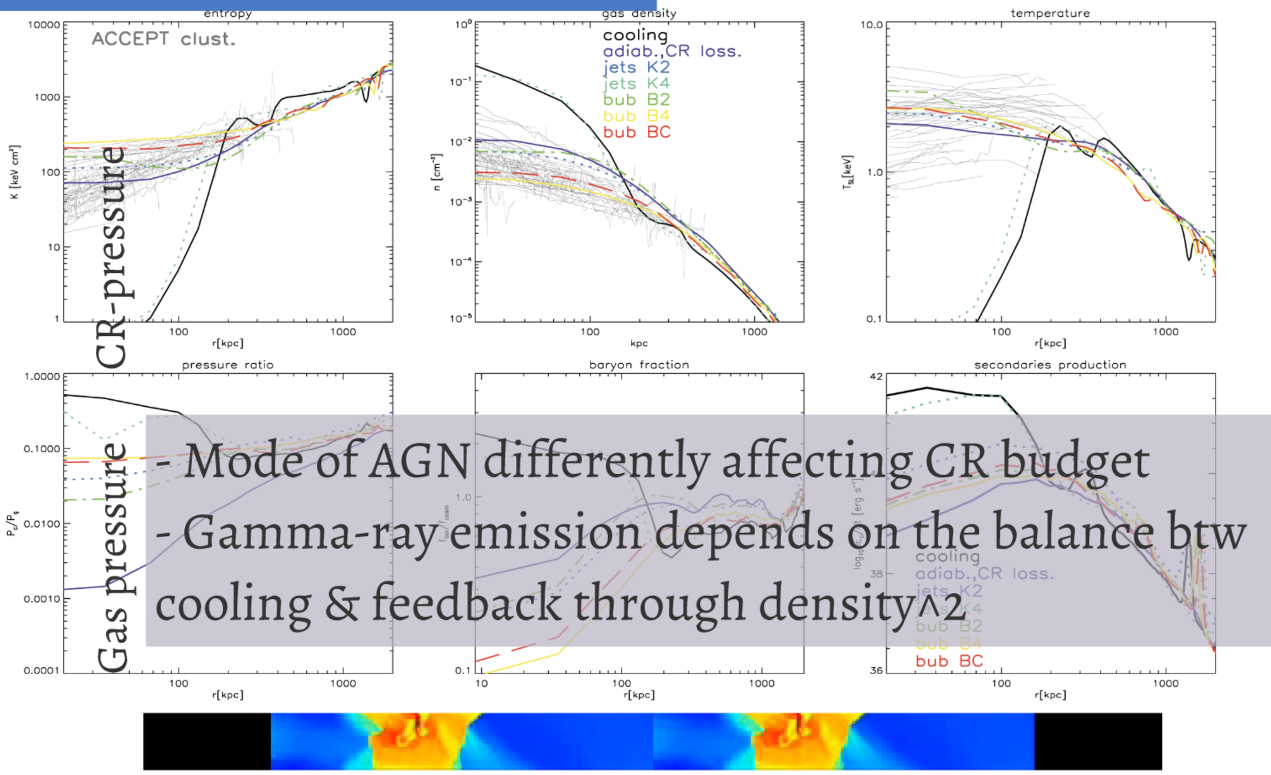
CR-profile and effective gamma



~2012 Results based on larger efficiencies (Kang & Jones 2007)

Vazza et al. 2012 MNRAS

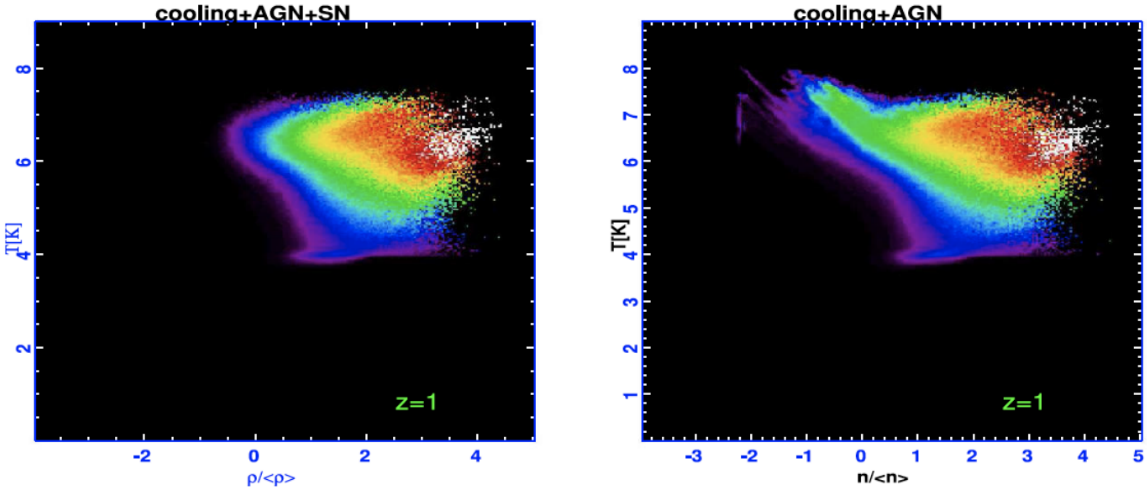
Effects of feedback



- Mode of AGN differently affecting CR budget
- Gamma-ray emission depends on the balance btw cooling & feedback through density^2

Vazza et al. 2013 MNRAS

Effects of Supernovae (z=2)

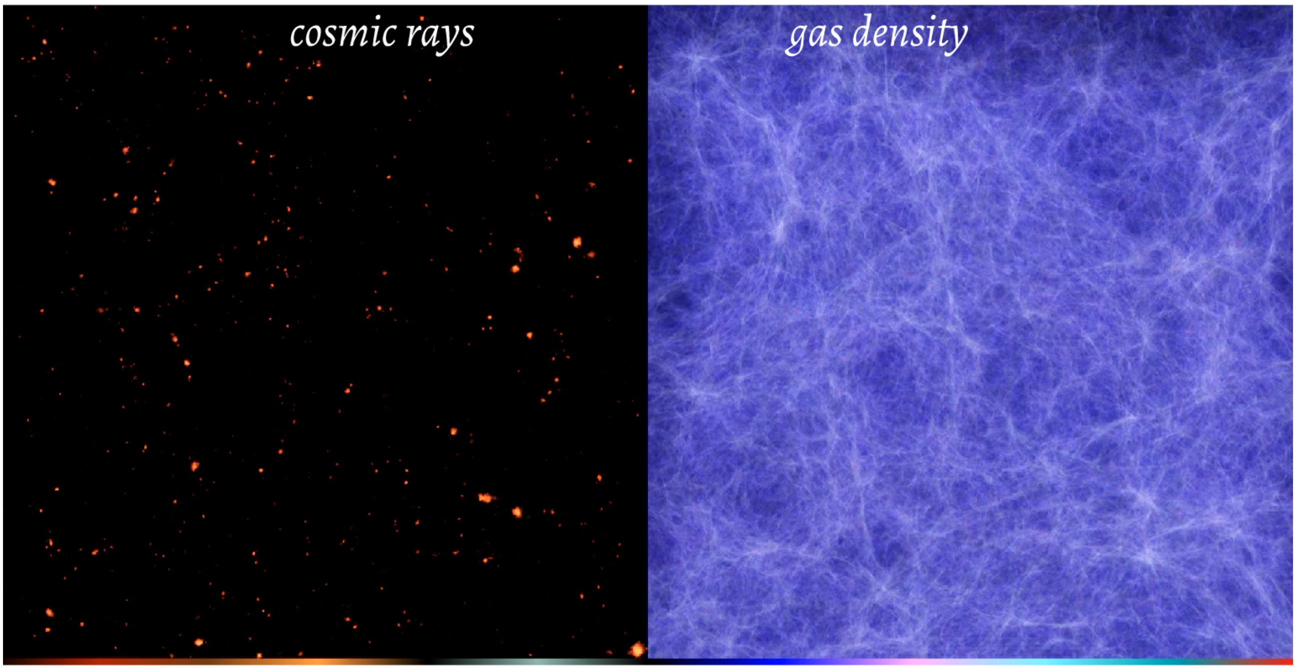


- Outflows of gas+CR enriching the IGM by z~2
- No big effects in the ICM by z~0

Vazza et al. 2014 MNRAS

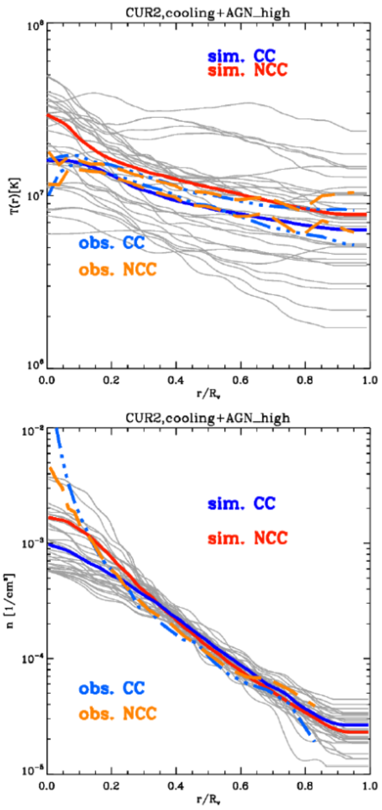
Where are the CR-protons?

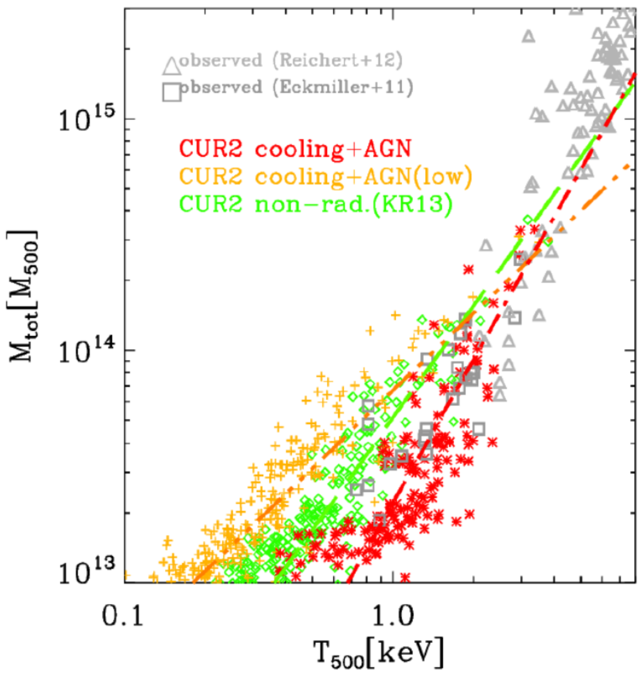
Largest simulations of cosmic rays in cosmology



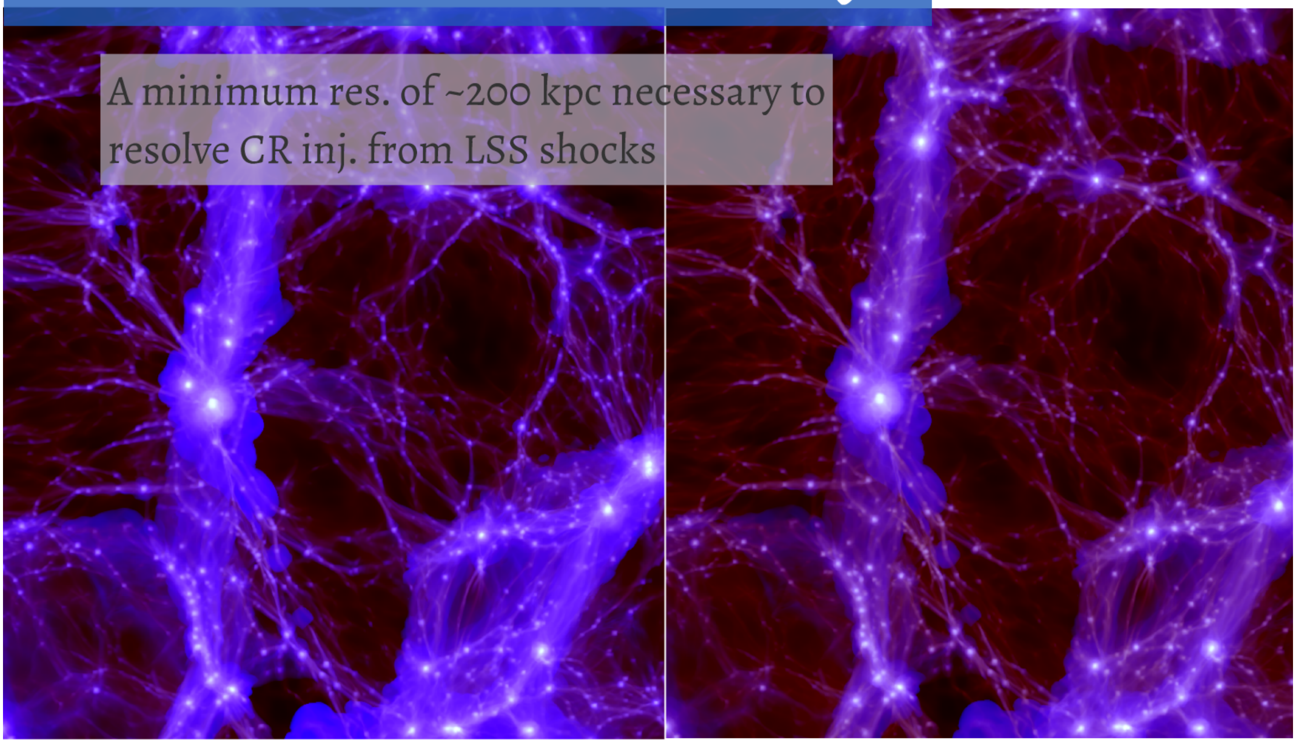
~2 million CPU hours on CURIE@Genci, Prace project 2014

Thermal scaling relations





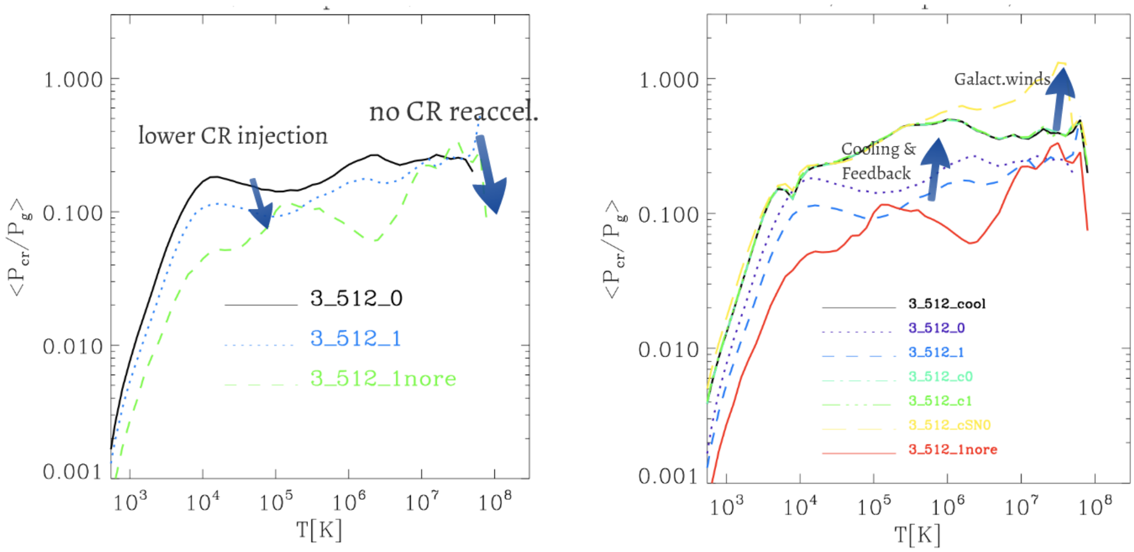
Distribution of cosmic rays



THERMAL ENERGY

COSMIC RAY ENERGY

Systematic survey of effects



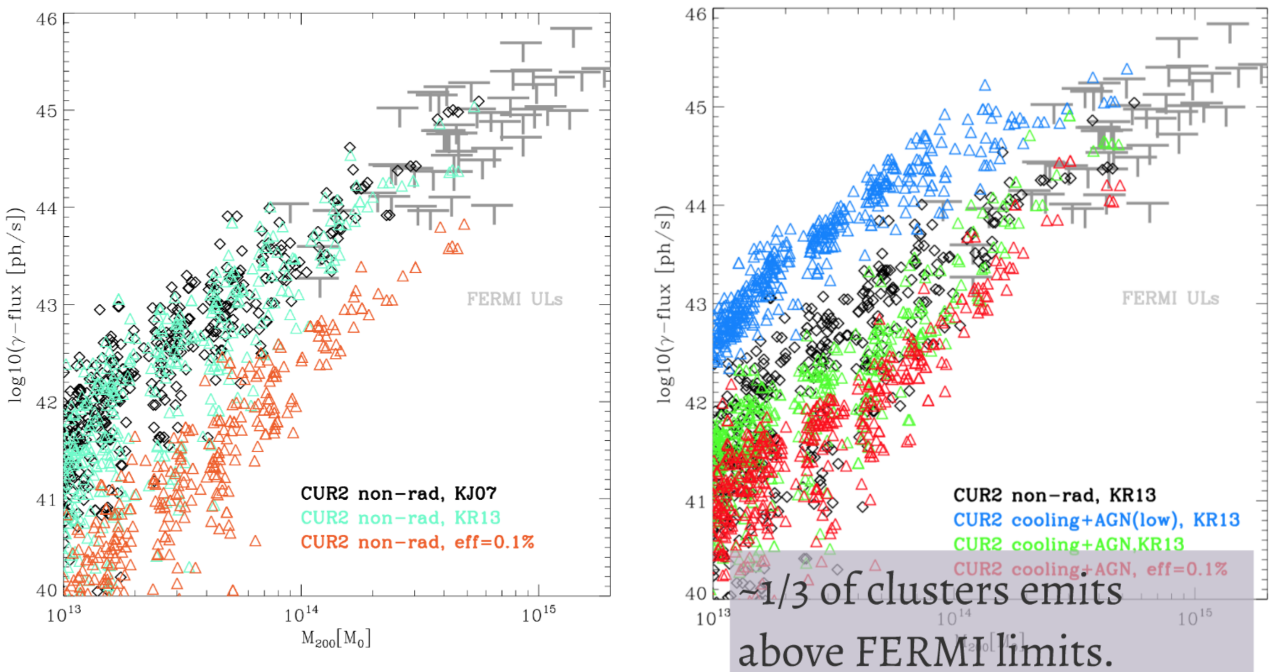
Shock efficiency for M<5 crucial for clusters

Re-acceleration relevant for most environments

Baryon physics can affect CR-budget in all environments

Where are the CR protons?

Simulated Gamma-Mass relations

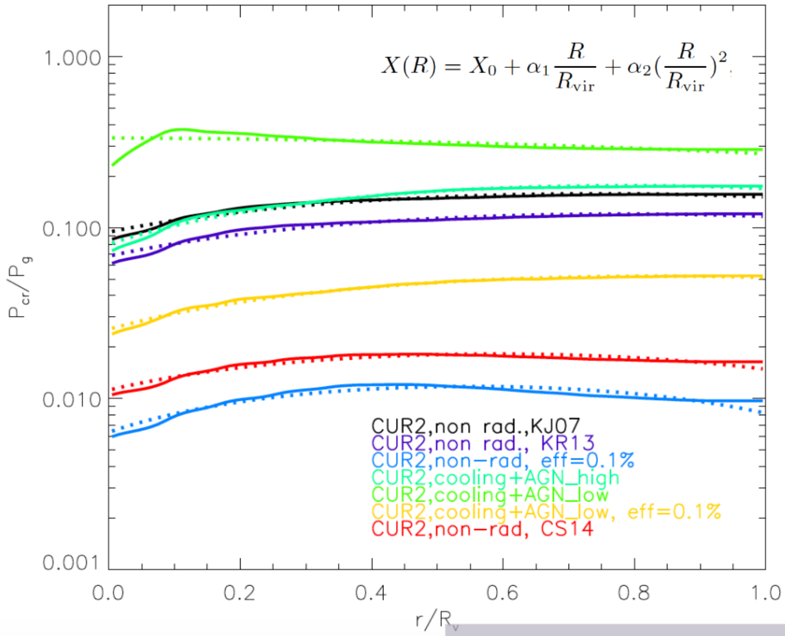


~1/3 of clusters emits above FERMI limits.

Vazza, Bruggen, Wittor, Gheller, Eckert & Stubbe 2016 MNRAS

Where are the CR-protons?

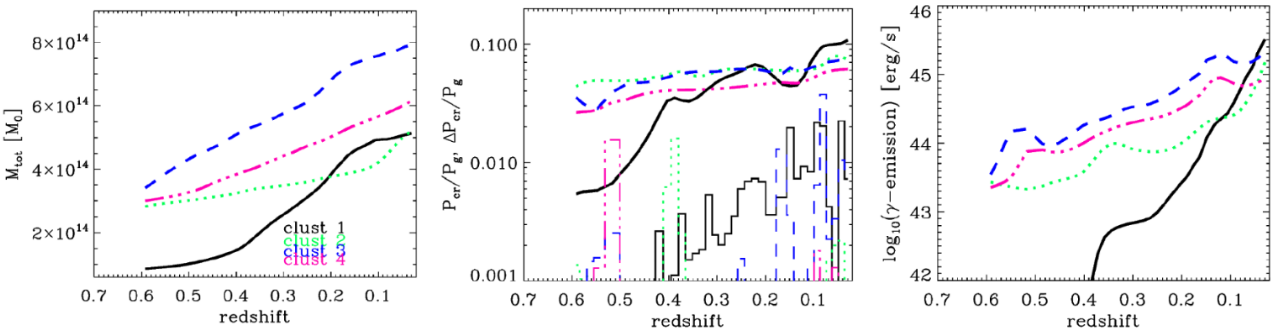
Radial distribution of CR/gas pressure ratio

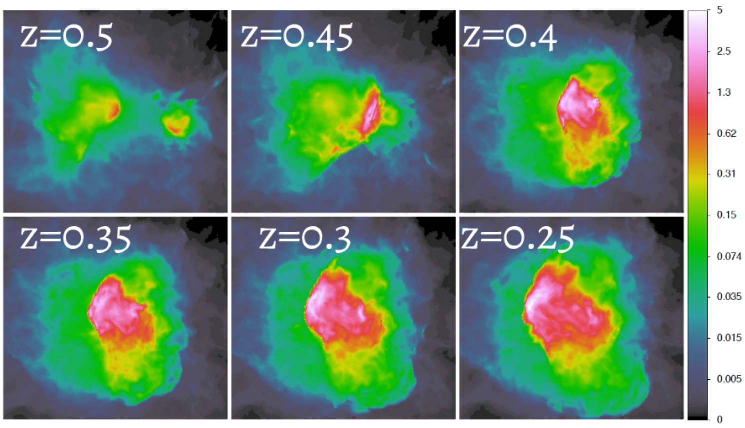


- *flat* radial profiles
- allowed ~% level of ICM energy, as in Fermi+14.
- mostly constrains accelerat. efficiency in cluster shocks (M<5)

Efficiency <0.1% not to violate FERMI limits

Evolutionary tracks of 4 clusters

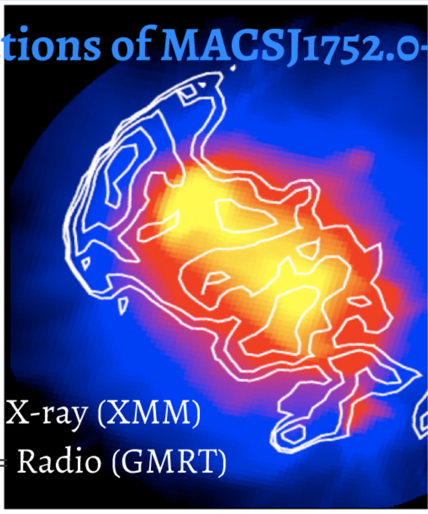




>10 scatter in hadronic emission related to mergers

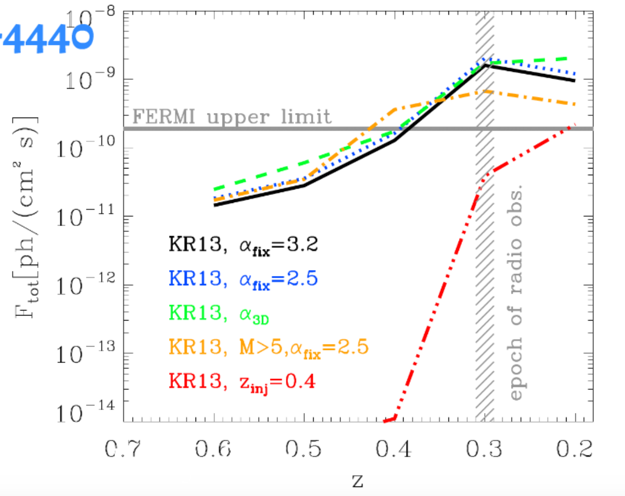
A radio-gamma test?

Resimulations of MACSJ1752.0+4440



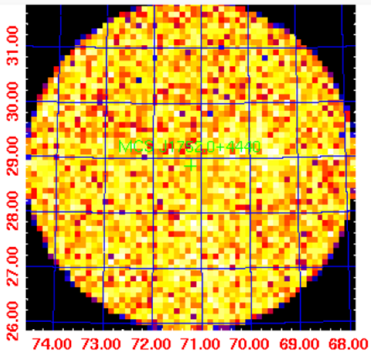
colors= X-ray (XMM)

contours= Radio (GMRT)

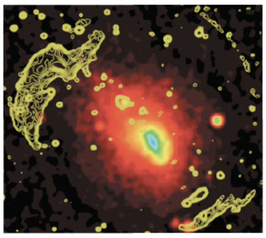


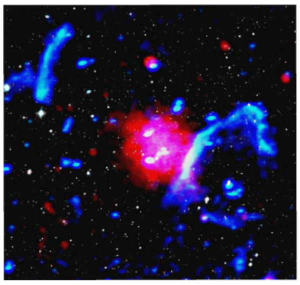
The major merger tests the acceleration by M~4.5 shocks

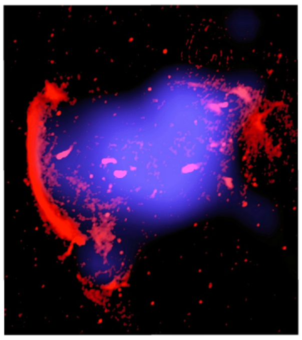
Emission at the Fermi level just using CRs from last merger

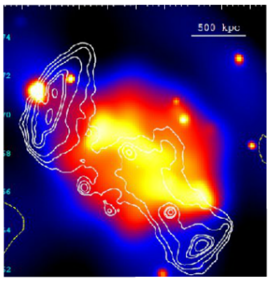


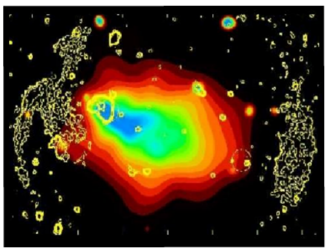
Double radio relics as a testbed for particle acceleration?



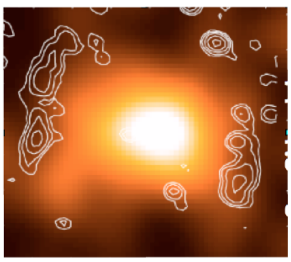


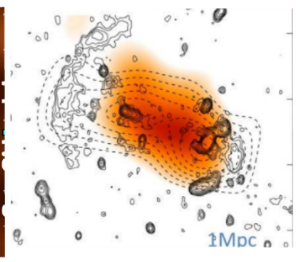


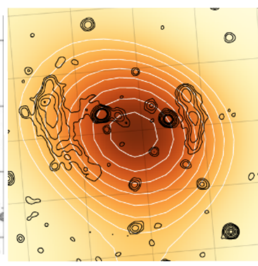




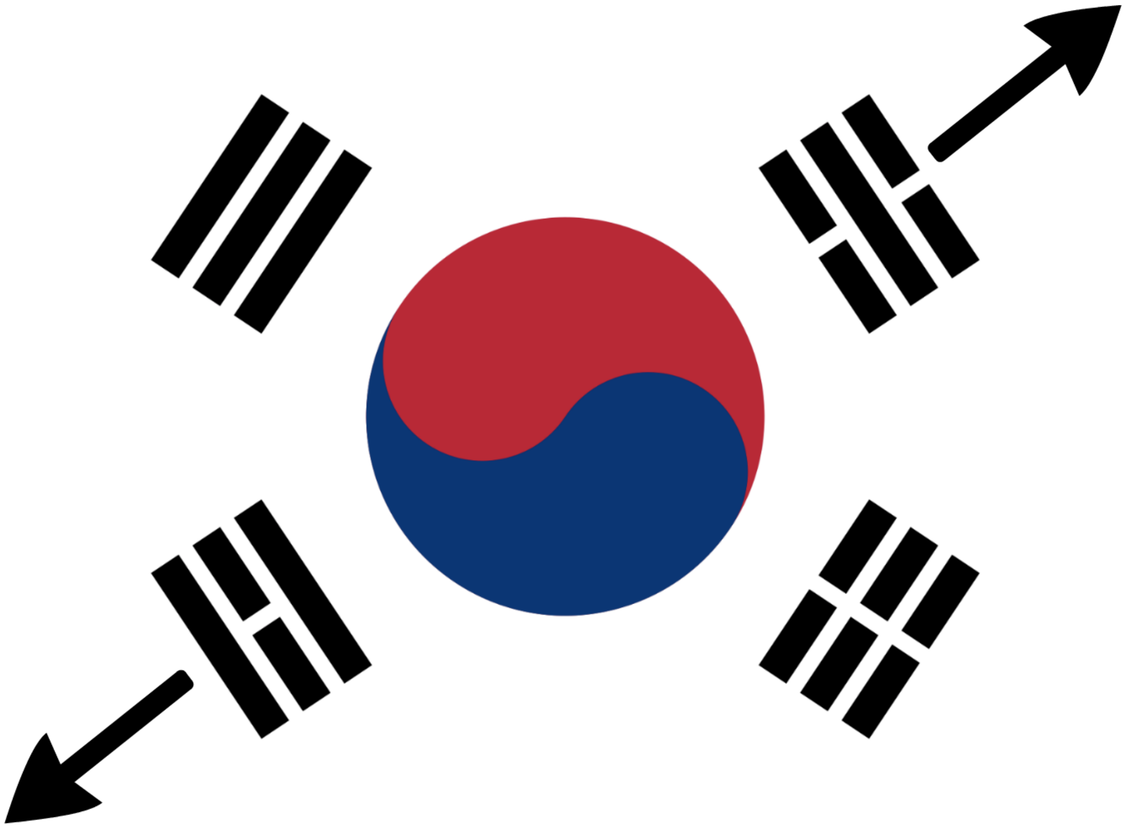
Credits (clockwise ord): Rottgering, Bonafede, Van Weeren,Bonafede, Bacghi, Bonafede Van Weeren, deGasperin







Double radio relics as a testbed for particle acceleration?



Do radio relics challenge diffusive shock acceleration?

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Electron and proton acceleration efficiency by merger shocks in galaxy clusters

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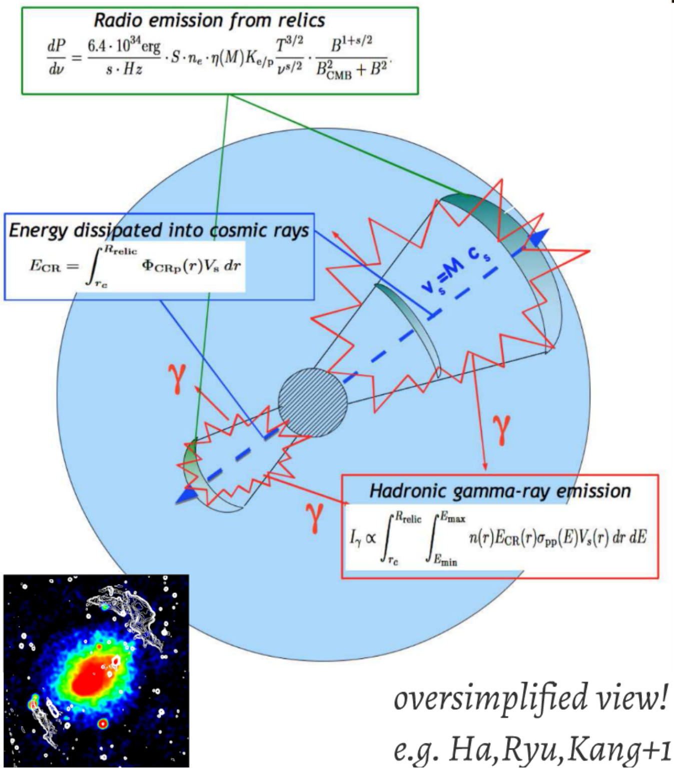
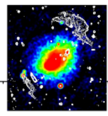


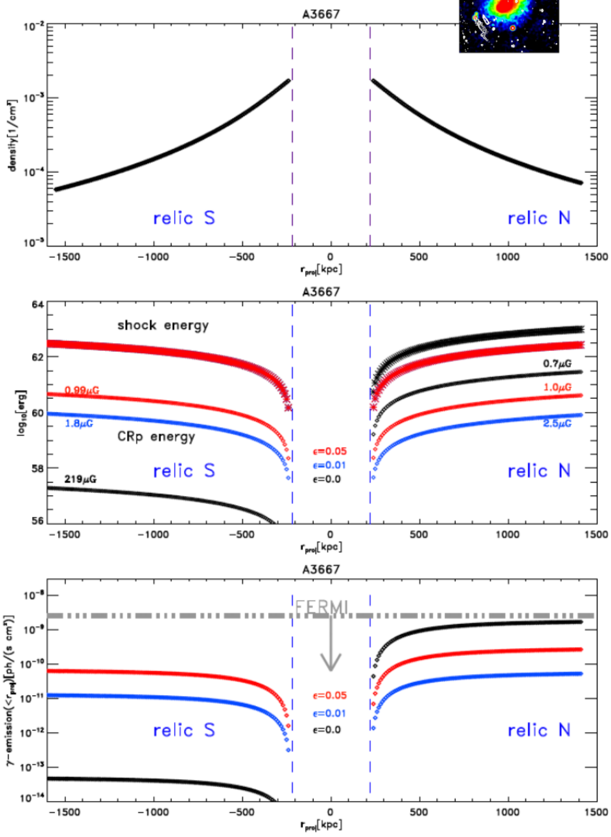
oversimplified view!
e.g. Ha,Ryu,Kang+17

Semi-analytical method:

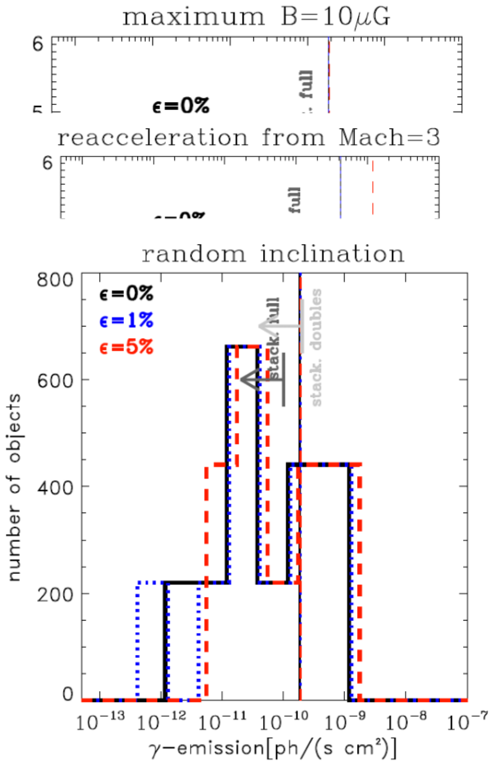
- observed relics & cluster parameters
- trajectory of pair of shocks
- injection of CRs from eta(M)
- compute gamma-ray emission

Single case : A3667



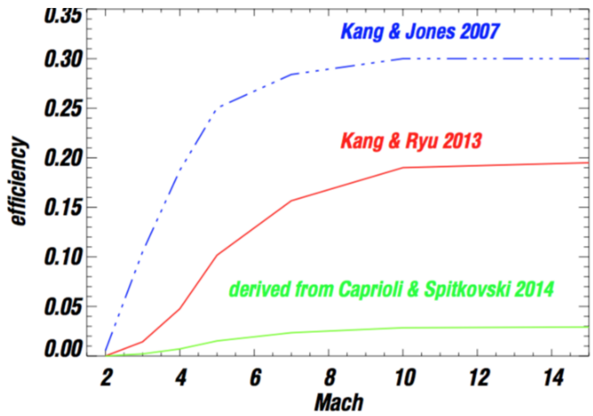


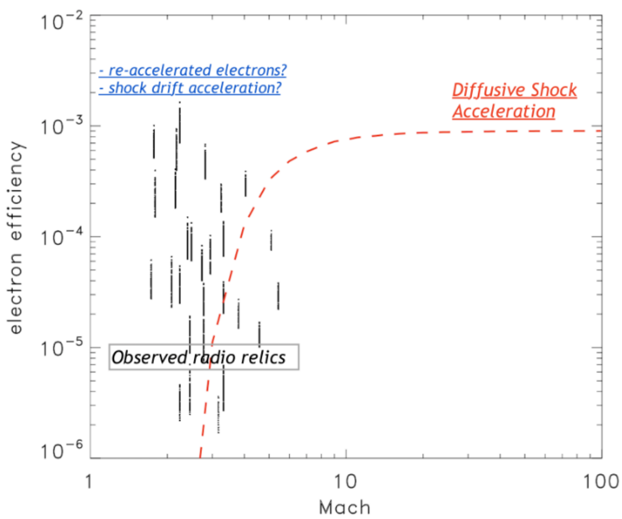
Stacking

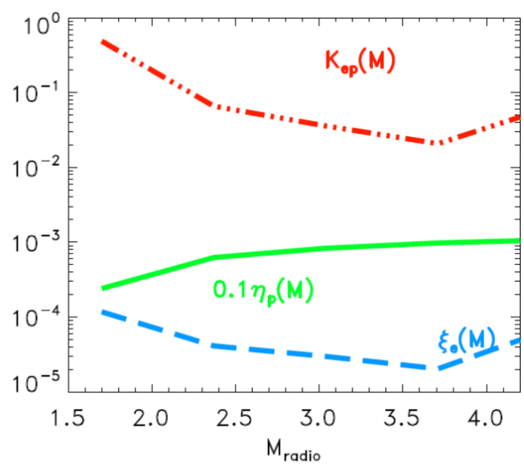


~1/3 of objects > U.L.

- Results in line with trends fron
- Stresses the role of M<5 merge
- Problem applies to clusters wit





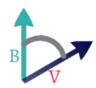


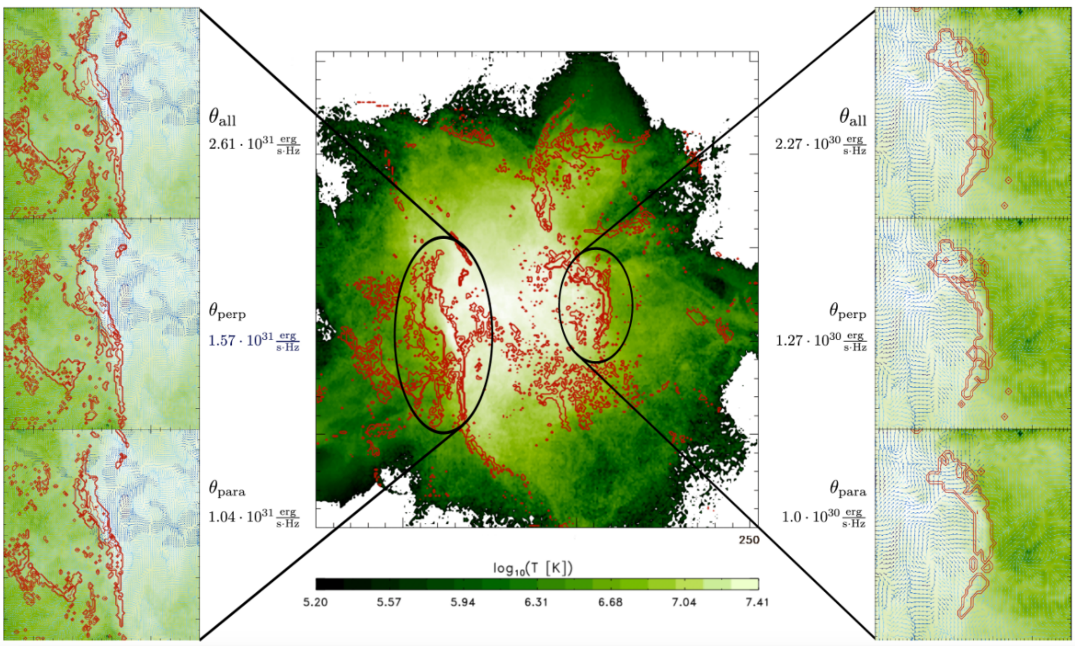
What are the possible solutions?

- Re-acceleration of old electrons? *(Pinzke+13,Kang+13)* — possible, but we still need to get rid of CR-protons.
- Cosmic ray streaming? *(Ensslin+10, Zandanel+11, Wiener+15)* — clusters with halos? radial magnetic fields?
- Non maxwellian distribution? *(Kang+15)* — possible.
- Other mechanisms beyond DSA? *(Guo+15,Caprioli+15)* — possible?

Investigating the role of shock obliquity and SDA

Properties of radio relic emission may depend on shock *obliquity*

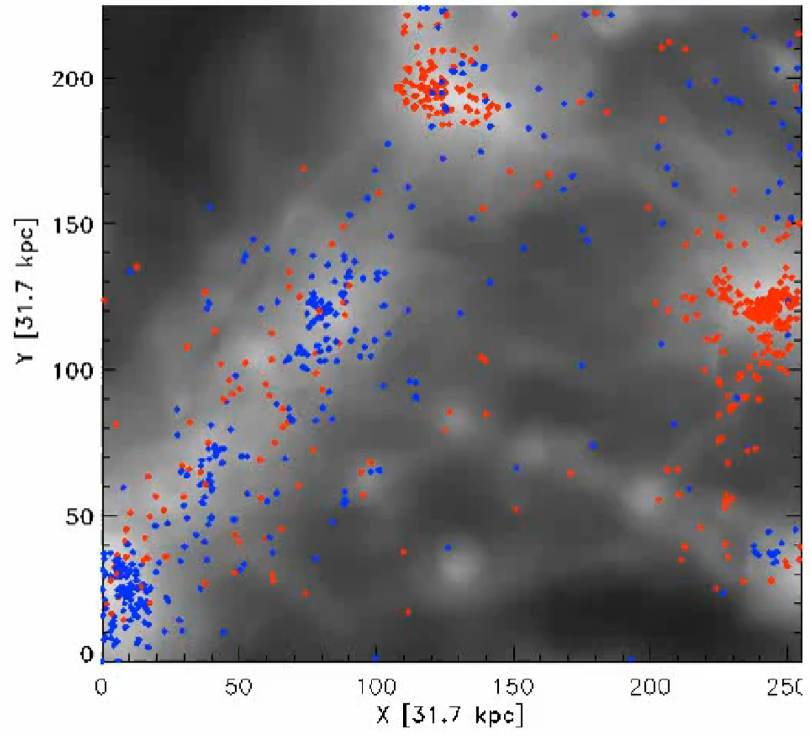




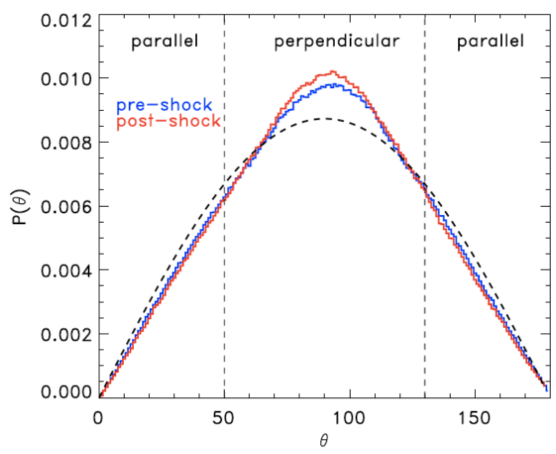
Wittor et al. 2016,2017

Investigating the role of shock obliquity and SDA

Using tracer particles to track the enrichment of cosmic rays

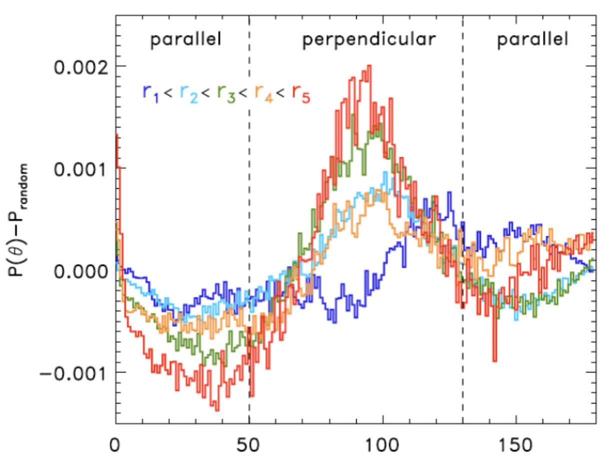


Obliquity & cosmic ray acceleration in the ICM



Angles ~random in most of volume

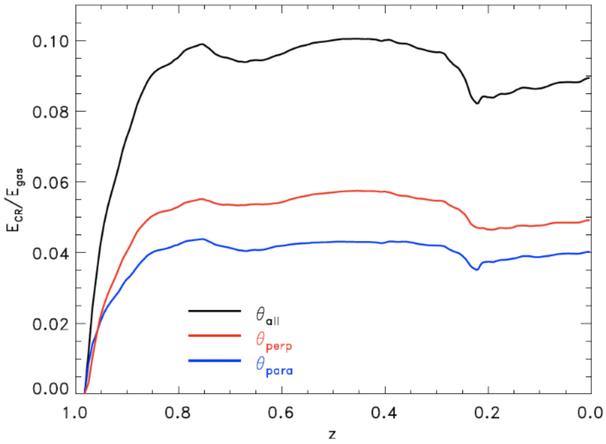
Small excess of ~parallel shocks in outskirts

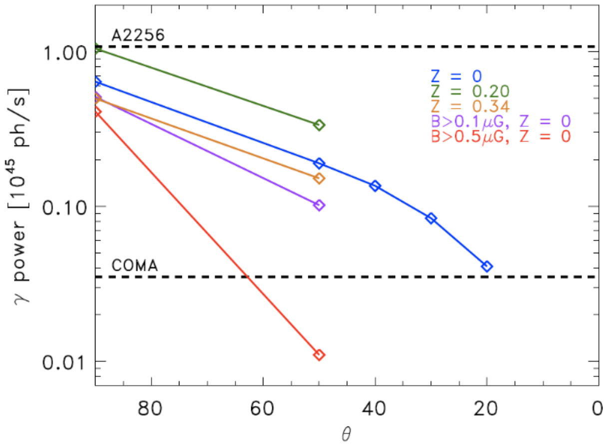


Obliquity & cosmic ray acceleration in the ICM

- ENZO-MHD, 5 levels of AMR
- Lagrangian tracers to simulate CRs

(Wittor, FV, Brüggen, MNRAS 2017)



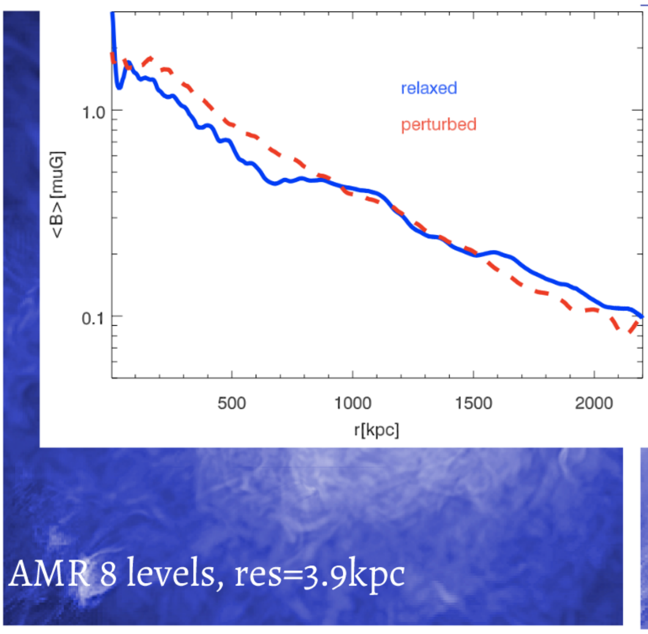


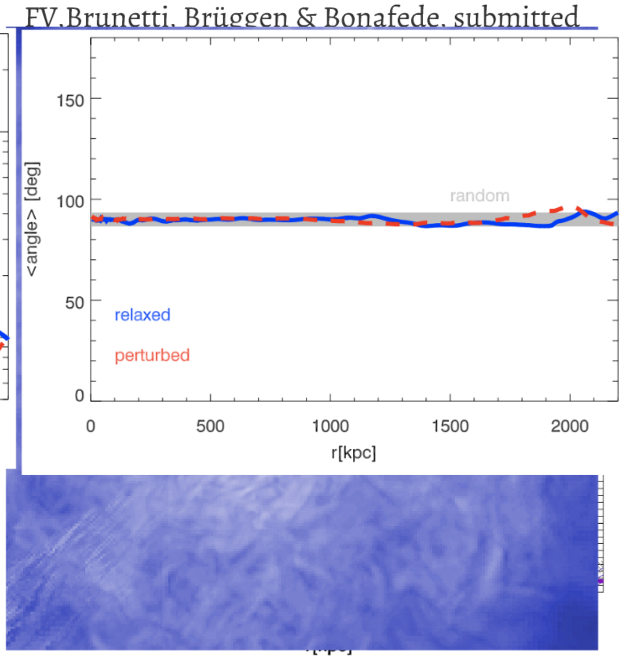
Only limiting acceleration to <20 deg shuts of hadronic emission

Only limiting acceleration to >0.5 muG shuts of hadronic emission

Bonus: cluster B-fields and CR escape?

FV,Brunetti, Brüggen & Bonafede, submitted





Is the B-field more aligned in a relaxed cluster?

No.

Summary/Open questions

Obs+Theory: from volume wide U.L. to limiting shock acceleration

Accel. of CR-protons:
less than <1% for ICM shocks

Accel. of CR-electrons:
apparently CRe/CRp~1-10%

"New" players: shock obliquity? non-Maxwellian stat.? re-acceleration? criticality?

Theoretical numerical/challenges vs ... which new observations?