# Turbulence and Cosmic Rays in direct simulations of cluster mergers


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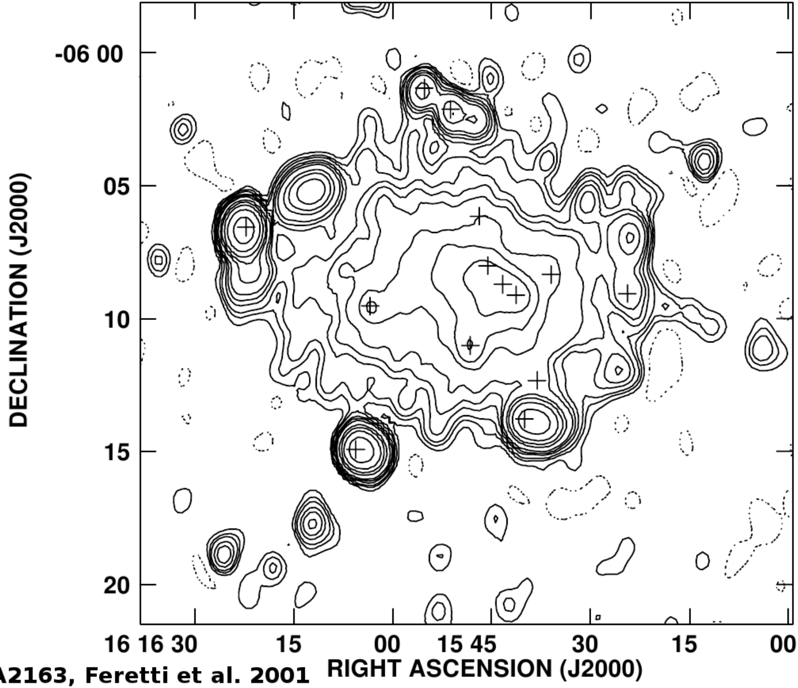



A2163, Feretti et al. 2001

# Introduction

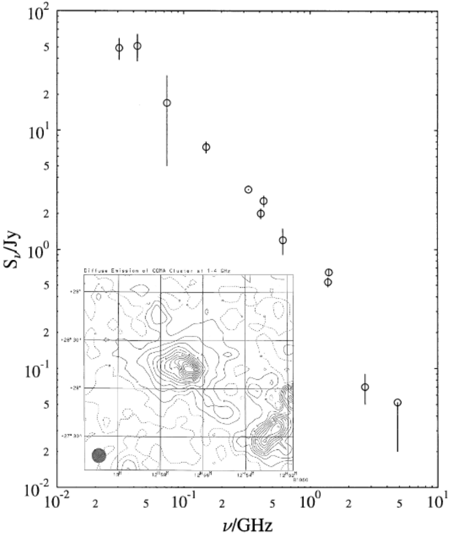
## Radio Haloes

**Radio Haloes :**

- steep spectrum radio sources
- synchrotron radiation from relativistic electrons ($\gamma \approx 10^4$) in *magnetic field* ($|B| \approx 1\,\mu G$)
- $\approx$ 50 radio haloes known today
- association with cluster merger
- 30 % in a complete sample

**Why should we care ?**

- probes microphysics of ICM: cosmic rays, magnetic fields, *turbulence*, thermal gas
- Main science goal of LOFAR



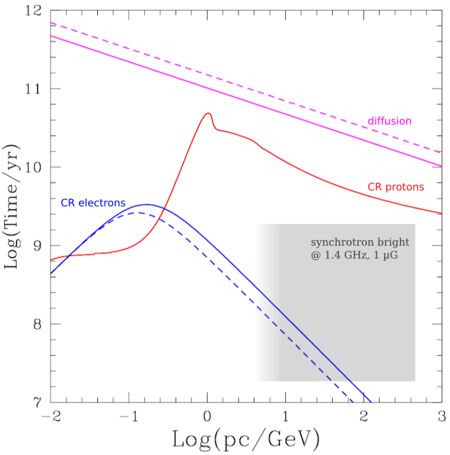

A1656 (Coma) : Deiss et al. 1997

# Introduction

## The Diffusion Problem

Synchrotron Radiation from **CR electrons**

- losses:
  - synchrotron
  - inverse Compton
  - Coulomb scattering
- lifetime : $E/\dot{E} \approx 10^8$ yr
- local injection
- Random walk with Alvén speed ( scattering , streaming inst.) effective speed $\approx 100$ km/s
- $\Rightarrow$ diffusion length **10 kpc** (Jaffe 1977)




modified from Blasi et al. '07

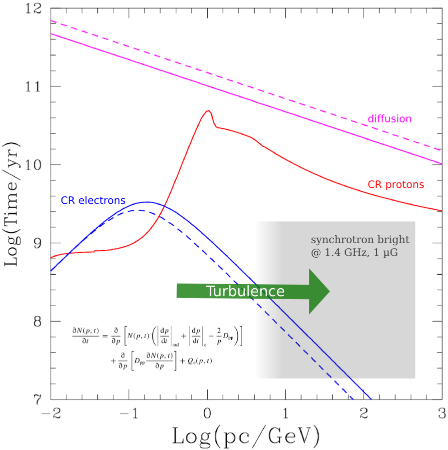
# Introduction

## Reacceleration Models

Solve by **stochastic reacceleration** of CR electrons (e.g. Petrosian '01):

- minimum of cooling processes at $\gamma \approx 200$
- cluster merger injects turbulence in the ICM
- CR electrons couples to MHD turbulence (TTD)
- induces non-linear momentum diffusion to higher energies

$\Rightarrow$ complex physics.
Put into astrophysical simulations




modified from Blasi et al. '07

# Simulations & Reacceleration Models

- Implementation as a subgrid model to SPH simulations:
  1. Model SPH turbulent energy at the scale of the smoothing length.
  2. Specify sub-grid model of reacceleration.
  3. Numerically solve Fokker-Planck equation.
- First direct simulation of a cluster merger with Reacceleration using MHD-GADGET).

$\Rightarrow$ CR dynamics in postprocessing on 8 Million particles

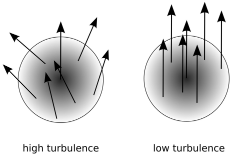
# Simulations & Reacceleration Models

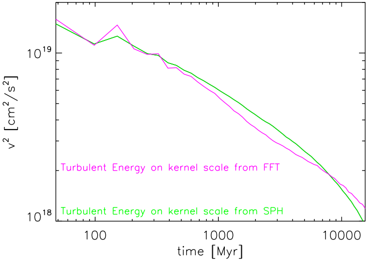
## SPH Turbulence

Estimate turbulence as **RMS velocity dispersion** inside SPH kernel.

**Idealised simulation:**

- Ideal decaying subsonic turbulence
- Periodic box
- Homogeneous density field
- Map velocity to a grid
- Inspect power spectra from grids FFT
- Correct for CIC kernel & shot-noise

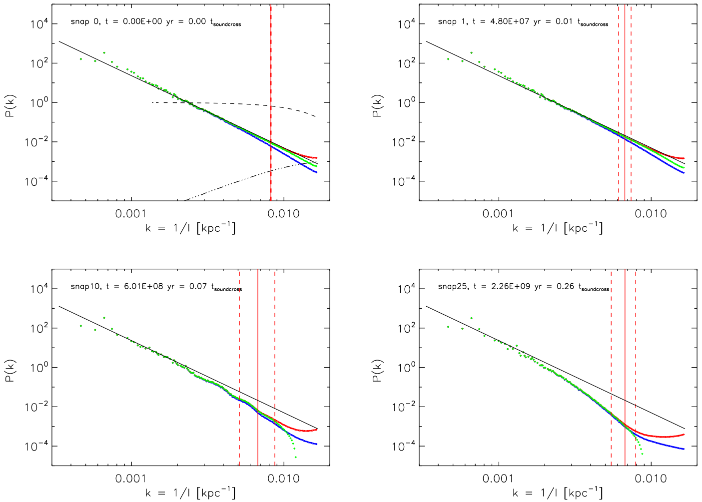



Donnert et al. in prep.

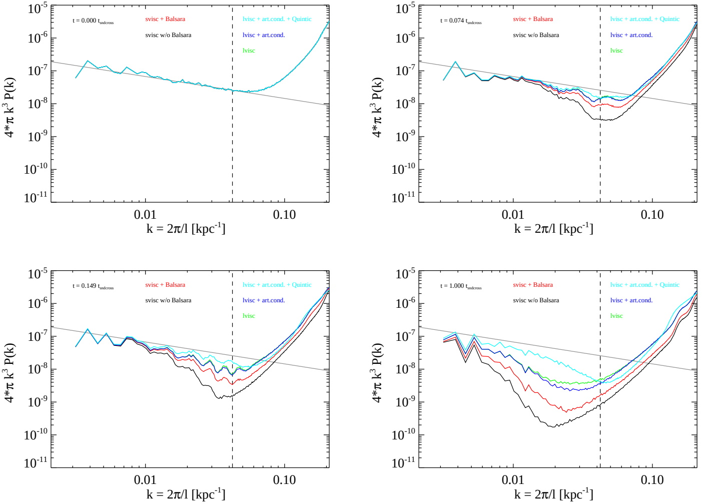
# Simulations & Reacceleration Models

## Power Spectra



# Interlude: Turbulence in SPH

## compare Bauer & Springel 2011, Price 2011



**Fokker-Planck** equation of isotropic CR electron spectrum N(p);
Stochastic diffusion in momentum space

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial p}\left(N \cdot \left[\left|\frac{dp}{dt}\right|_{loss} - \frac{2}{p} D_{\mathrm{pp}}\right]\right) + \frac{\partial}{\partial p}\left(D_{\mathrm{pp}} \frac{\partial N}{\partial p}\right) + Q(p,t) - \frac{N(p,t)}{T_{esc}}$$

**Competing** Mechanisms in momentum space:

- losses: Synchrotron, IC, Coulomb $\left|\frac{dp}{dt}\right|_{loss}$
- systematic gain: $\frac{2}{p} D_{\mathrm{pp}}$
- stochastic gain (broadening): $\frac{\partial}{\partial p}\left(D_{\mathrm{pp}} \frac{\partial N}{\partial p}\right)$
- injection (power law), leakage (neglect): $+Q(p,t) - \frac{N(p,t)}{T_{esc}}$

**Wave-particle coupling**, Fermi 2 acceleration:
*Model $D_{pp}$ from turbulent energy*

# Simulations & Reacceleration Models

## Resonant Coupling of Turbulence and CRs: TTD

**Modelling of $\mathbf{D_{pp}}$ uncertain**, ICM plasma physics not testable in laboratory. $\Rightarrow$ *least efficient model*

- Resonant wave-particle interaction:

$$\omega - k_{\parallel} v_{\parallel} - n\Omega = 0$$

- Fast magnetosonic (compression) waves: $\mathbf{k} \perp \mathbf{B}$, $n = 0$
- Assume turbulence is Kolmogorov: $W(\mathbf{k}) \propto k^{-5/3}$
- Formulate balance equation, CRe damp a fraction $\eta$:

$$\int E \left(\frac{\partial f(p)}{\partial t}\right) d^3p = \eta \int d\mathbf{k}\Gamma(k) W(\mathbf{k})$$

- (Brunetti & Lazarian 2007):

$$D_{pp} \propto \eta \frac{E_{turb}^2}{scale \times c_{sound}^2}$$

*Solve Fokker-Planck numerically ...*

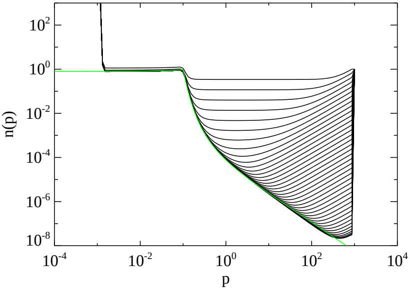
# Simulations & Reacceleration Models

## A numerical Fokker-Planck Solver

**Solve** Fokker Planck equation for every particle :

- MPI Parallel
- Gadget Format 2 Input
- Written in C
- Numerical Method : Chang & Cooper 1970
- Open and Closed boundary conditions realisable

**Test Case** : Hard-Sphere Equation (Park & Petrosian 1996)




Donnert et al. in prep.

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial p}\left(p^2 \frac{\partial n}{\partial p} - pn + n\right) - n + \delta(p - 0.1)\Theta(t)$$

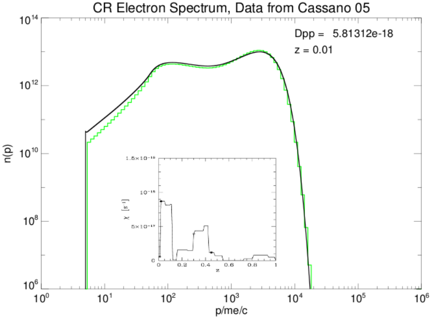
# Simulations & Reacceleration Models

## A numerical Fokker-Planck Solver

**Advantage** of Chang & Cooper Method :

- Very Stable
- Logarithmic p Grid
- Large timesteps
- Small Number of gridcells

Typical Spectral Evolution of CRe with **10000** (black) and **100** (green) gridpoints.
Input Data from Cassano et al. 2005.

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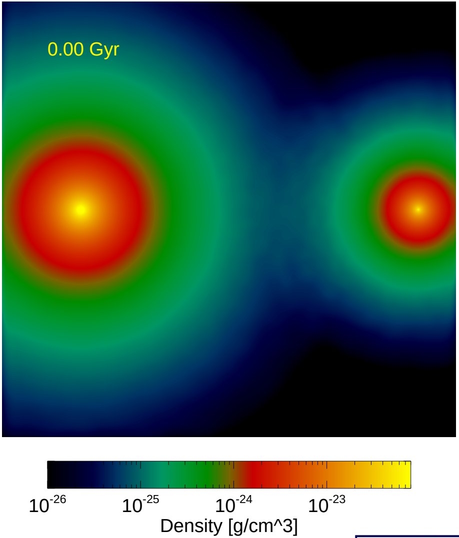
# Simulations & Reacceleration Models

## Cluster collision, Setup

Setup **Toymodel Cluster collision**:

- Masses $8 \times 10^{14} M_\odot$ and $2 \times 10^{14} M_\odot$
- $256^3$ particles
- Zero energy orbit
- DM profile: Hernquist with scale 500 kpc
- Random magnetic field from vector potential with $5 \mu G$ in the core.
- Radial decline of $B$ like COMA (Bonafede et al. 2010)



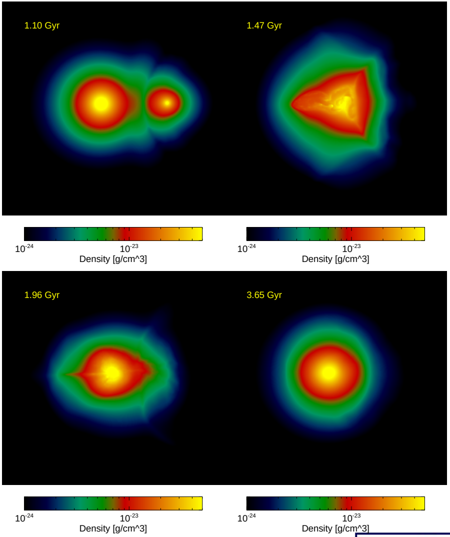
# Simulations & Reacceleration Models

## Cluster collision, Movies

**Evolution**

- Core of small cluster is disrupted
- Shock waves in directions of collision
- Amplification and decay of magnetic field
- Several DM core passages
- Turbulence "brightens" spectra

**Movie**

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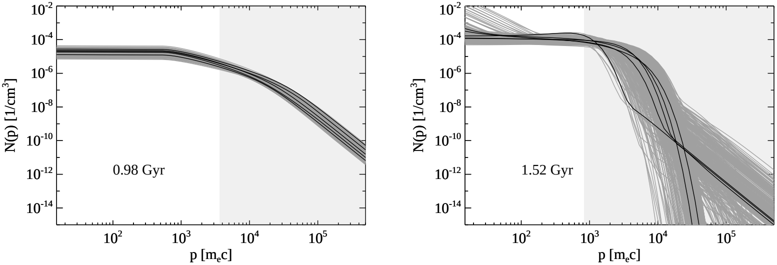
# Simulations & Reacceleration Models

## CR electron spectra



# Simulations & Reacceleration Models

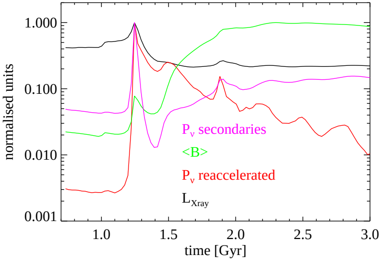
## Cluster collision - Lightcurve & Spectrum

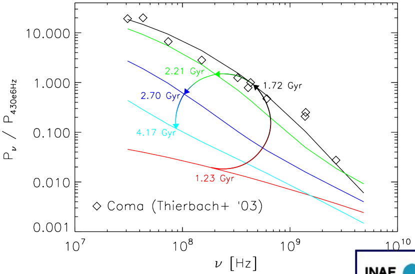
**Run Fokker Planck code**

- Constant injection of secondary CR electrons
- Momentum Grid of 100 points

**Evolution**

- Infall shock leads to first peak
- Small DM core stirrs big cluster
- Turbulence "brightens" spectra
- Radio Halo is switched off after 1 Gyr
- Pure hadronic model $j_\nu \propto \rho^2 B^\alpha$



# Summary

- Radio haloes are large scale, diffuse, non-thermal emission from galaxy clusters
- Merging galaxy clusters host MHD-turbulence
- Reacceleration models light up clusters through turbulence
- First ever simulation of reacceleration in clusters.

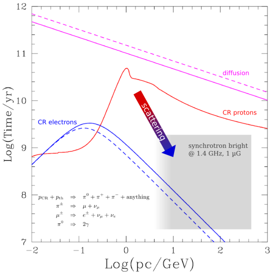
*Reacceleration can not be neglected in radio halo models*

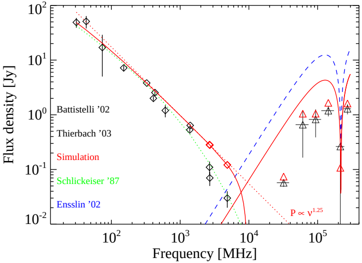
**Thank You !**

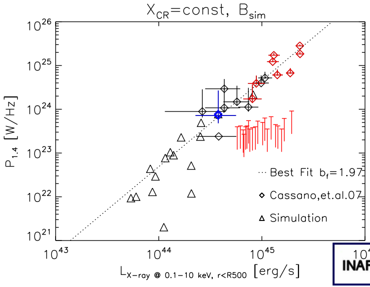
# Introduction

## Simple hadronic approaches

(Donnert et al. 2010a,b)




- CR proton population leads to *global* injection of CR electrons
- ?? Break in synchrotron spectrum ??
- ?? Bimodality ??

$\Rightarrow$ more complete models needed