The quest for high-energy γ-ray emission from galaxy clusters

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in collaboration with

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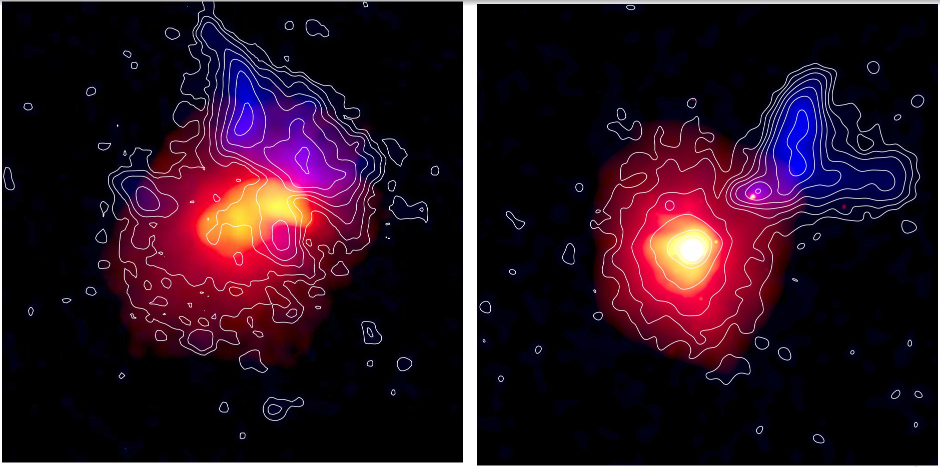
Which one is the simulation/observation of A2256?



red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

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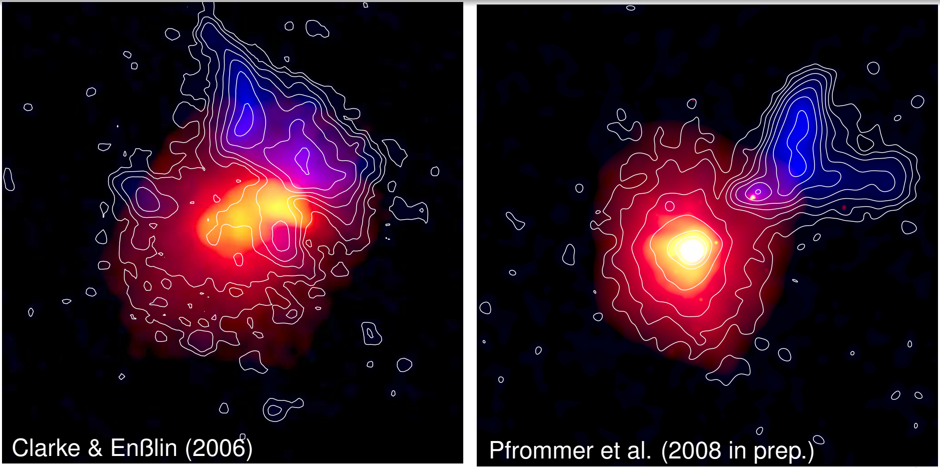
Observation – simulation of A2256



red/yellow: thermal X-ray emission,
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Take home messages of this talk

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters
   $\rightarrow$ illuminating the process of structure formation
2. Predicted sample and properties of γ-ray clusters for GLAST and IACTs
3. Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE γ-ray emission:
   - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - nature of dark matter
   - gold sample of cluster for precision cosmology

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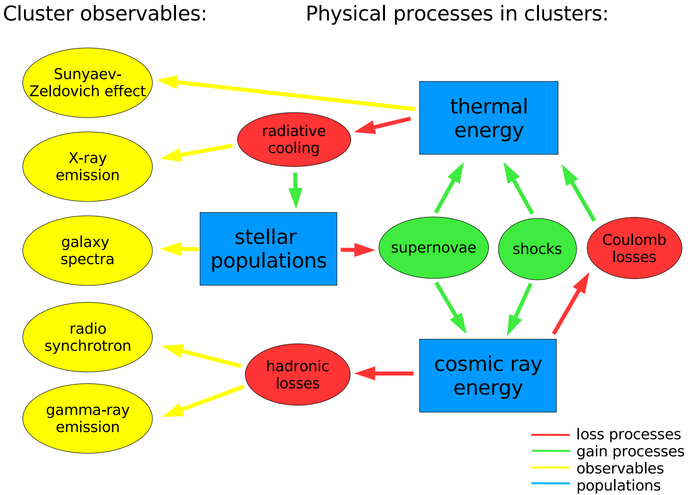
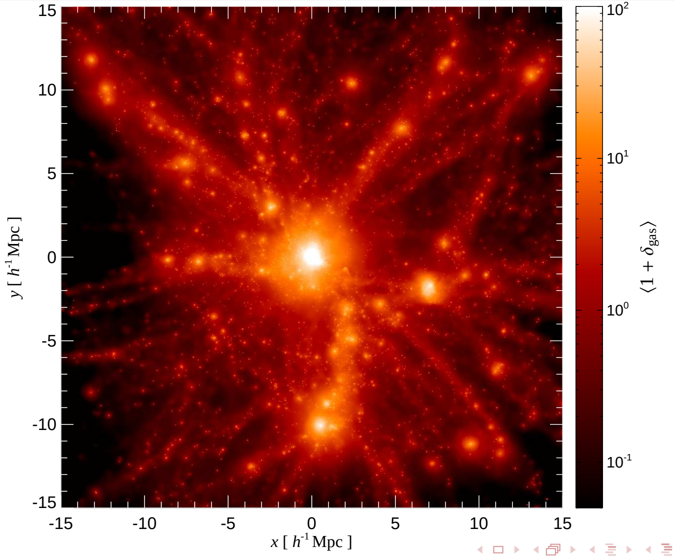
Radiative simulations with CR physics



Radiative cool core cluster simulation: gas density



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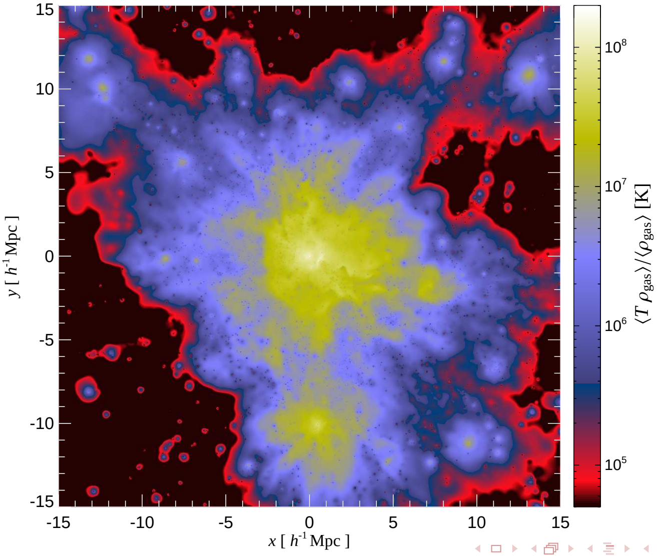
Mass weighted temperature



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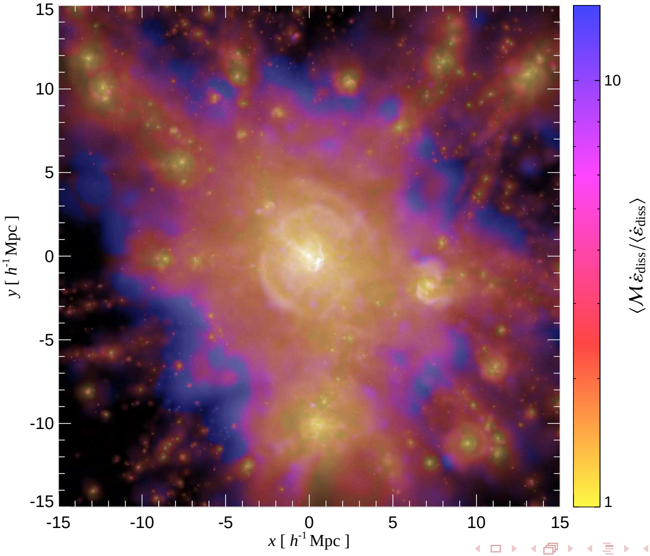
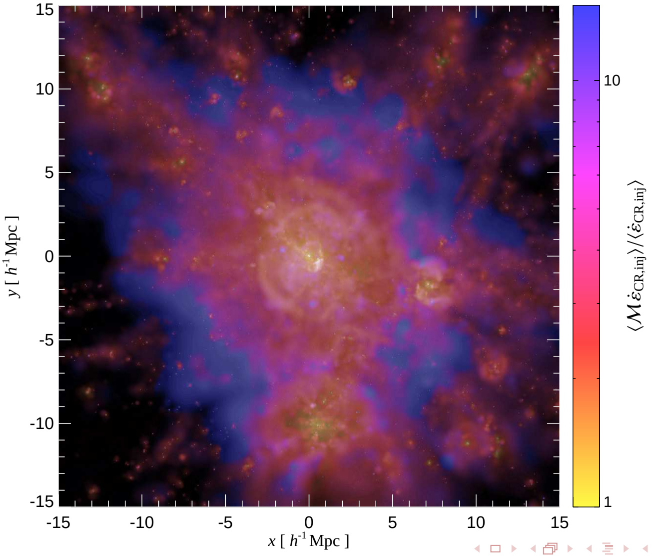
Mach number distribution weighted by $\varepsilon_{\rm diss}$



Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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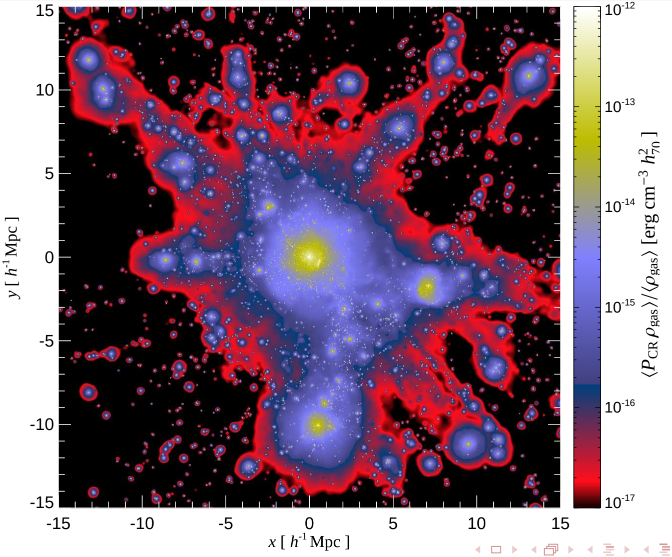
CR pressure P_{CR}



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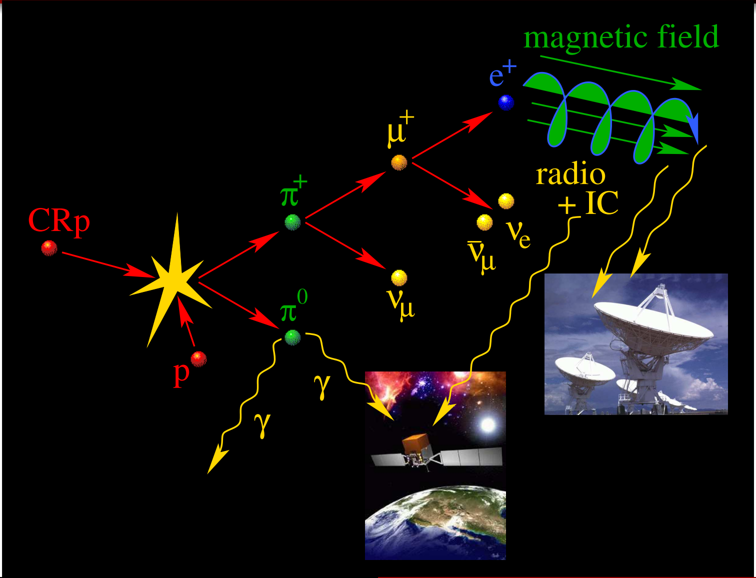
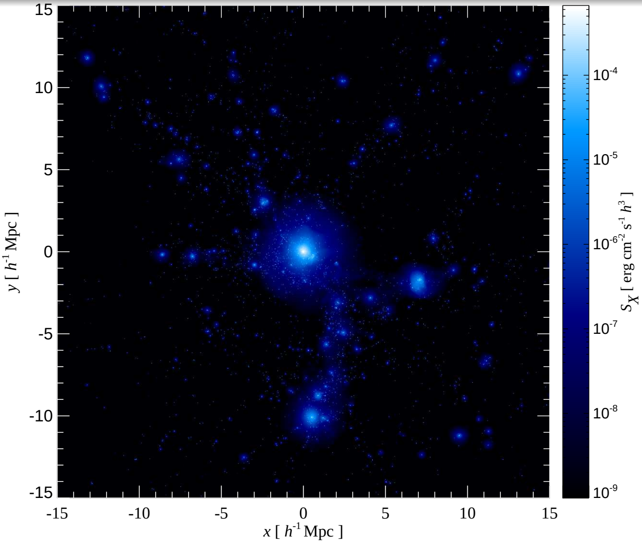
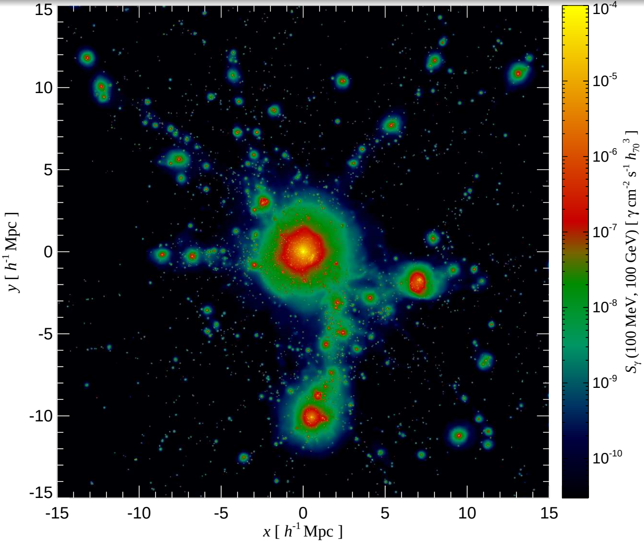
Hadronic cosmic ray proton interaction



Thermal X-ray emission



Hadronic γ-ray emission, $E_\gamma > 100$ MeV



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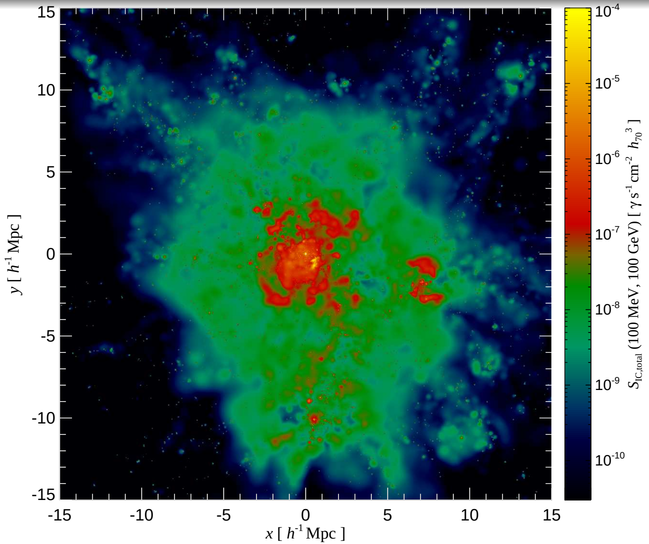
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ MeV



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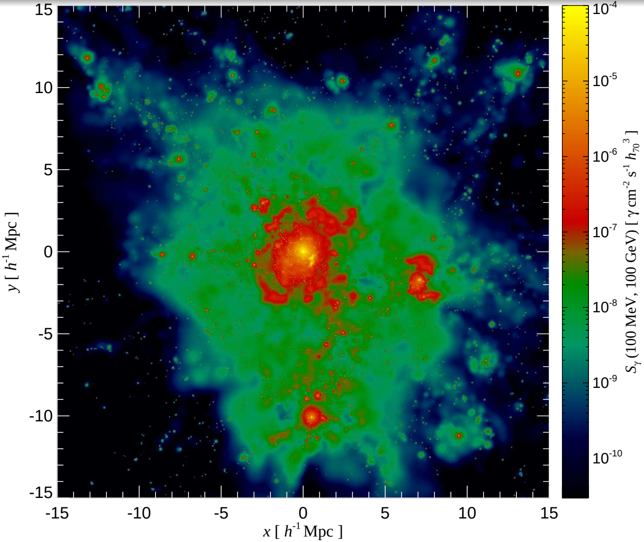
Total γ-ray emission, $E_\gamma > 100$ MeV



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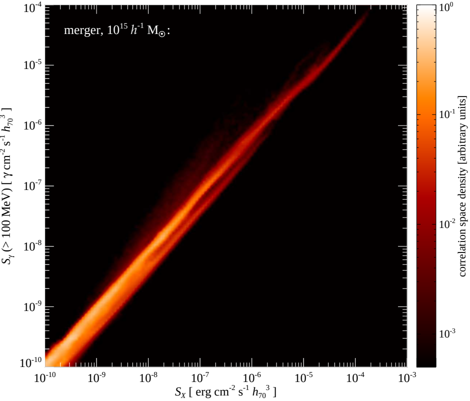
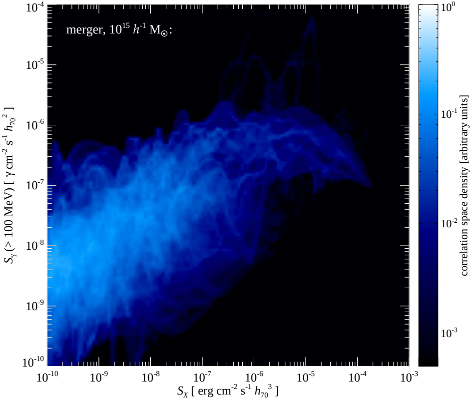
Correlation between thermal X-ray and γ-ray emission



Correlation with pion decay/sec. IC emission,

merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot / h$



Correlation with primary IC emission,

merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot / h$

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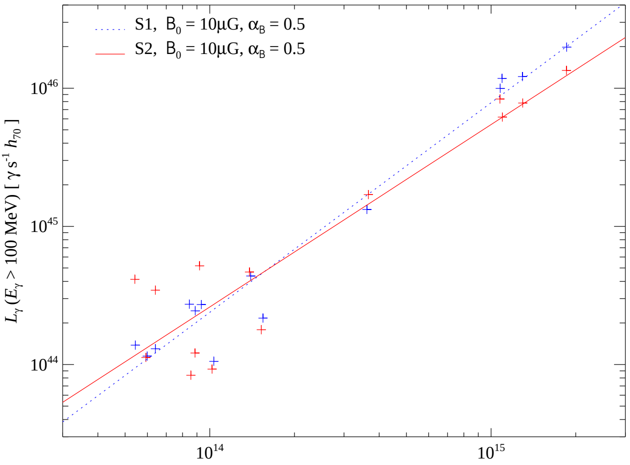
Gamma-ray scaling relations



Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) → predictions for GLAST

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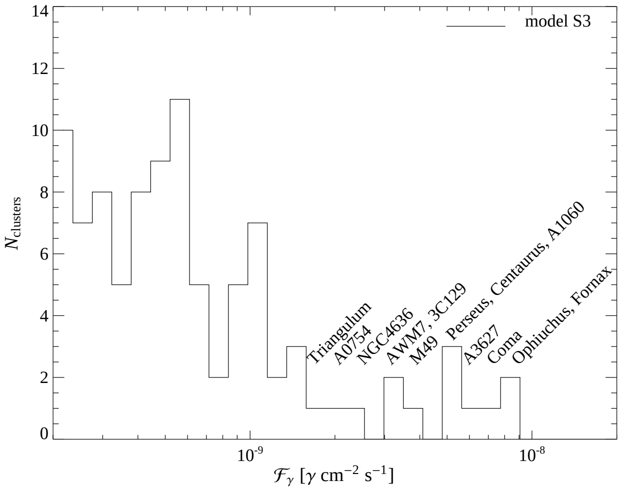
Predicted cluster sample for GLAST



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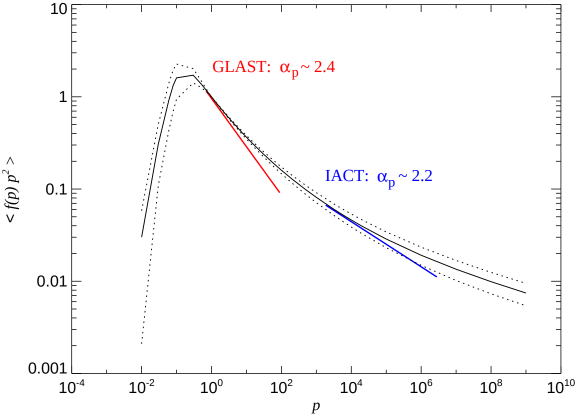
Universal CR spectrum in clusters



Preliminary: normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & Pfrommer, in prep.)

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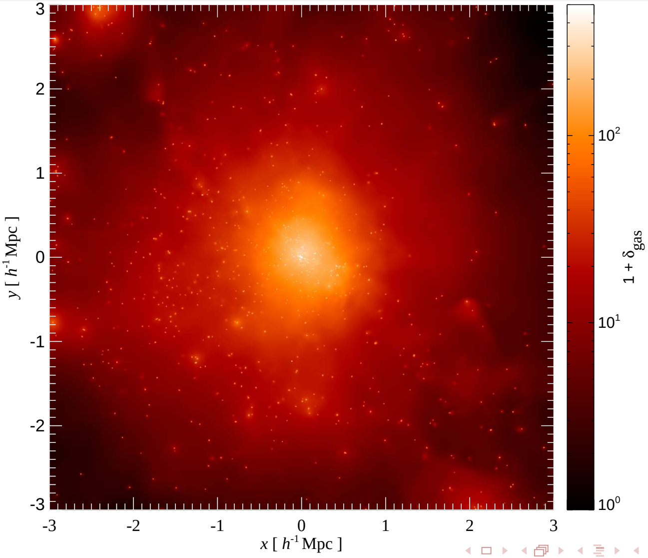
Radiative cool core cluster simulation: gas density



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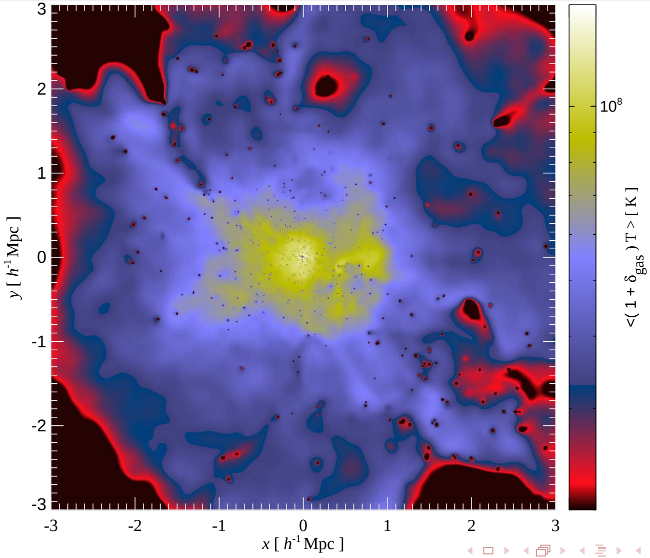
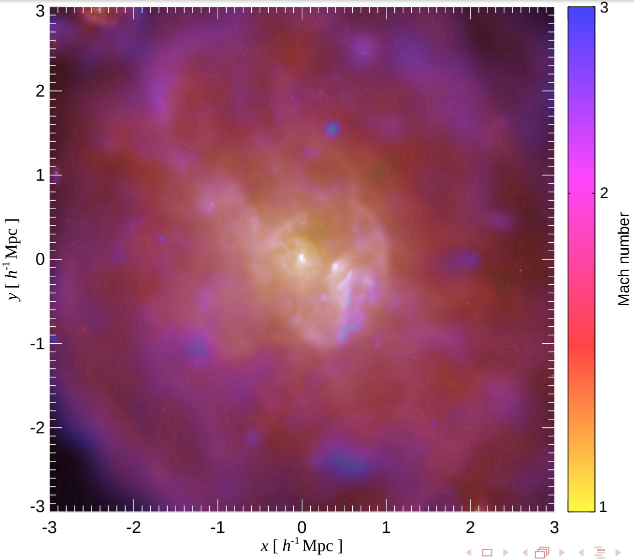
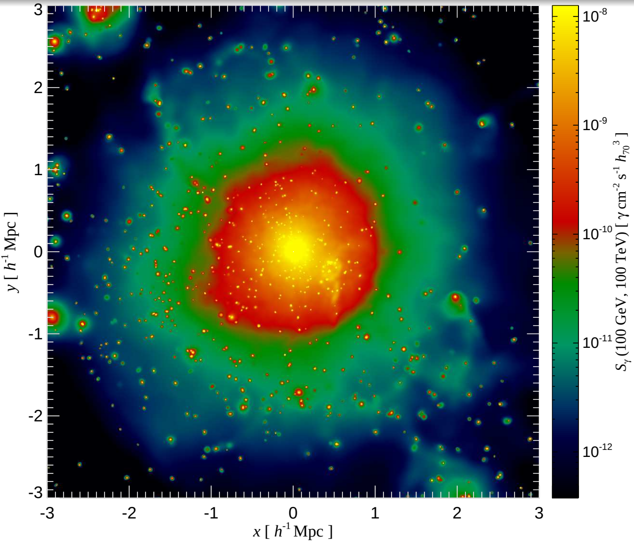
Mass weighted temperature



Mach number distribution weighted by $\varepsilon_{\rm diss}$



Hadronic γ-ray emission, $E_\gamma > 100$ GeV



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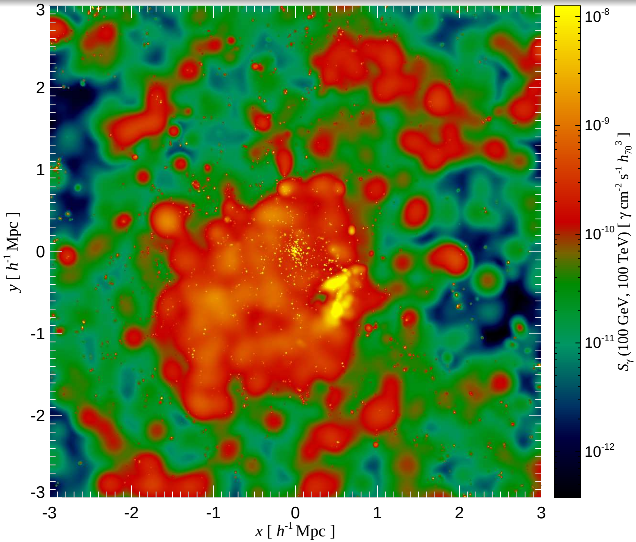
Inverse Compton emission, $E_{\rm IC} > 100$ GeV



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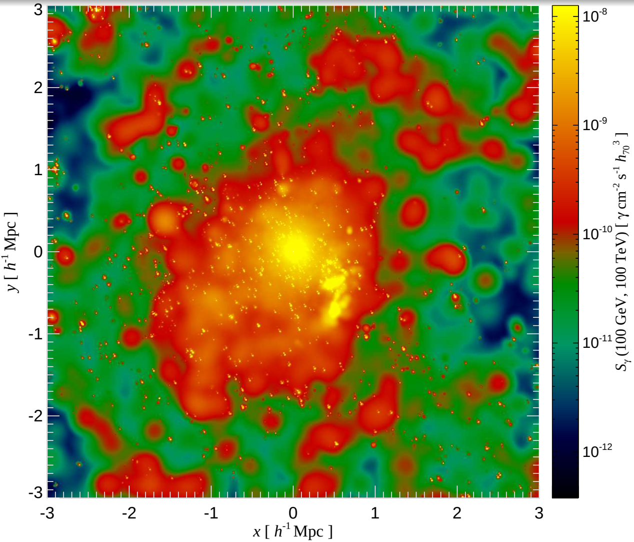
Total γ-ray emission, $E_\gamma > 100$ GeV



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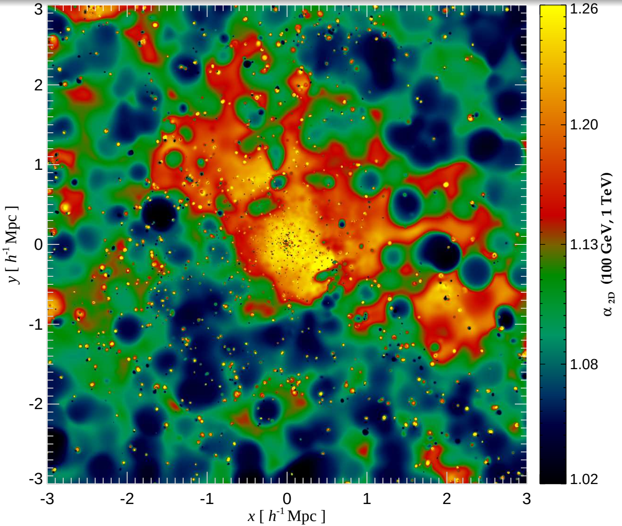
Photon index $\Gamma_{100\ \mathrm{GeV}}^{1\ \mathrm{TeV}}$



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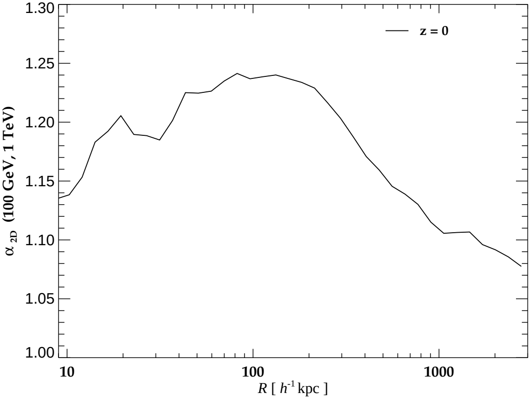
Profile of photon index $\Gamma^{1\ \mathrm{TeV}}_{100\ \mathrm{GeV}}$

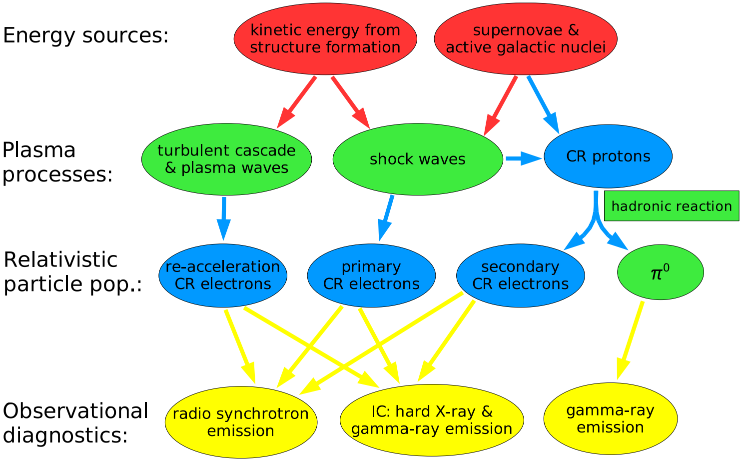


Smooth variation of Γ: inner parts dominated by pion decay, transition to primary IC from formation shocks at cluster periphery and WHIM

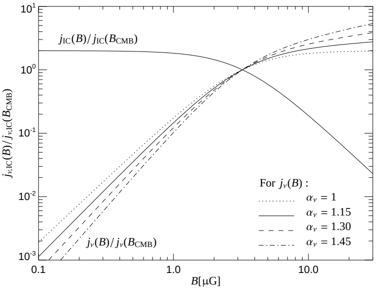
→ bright prospects for DM annihilation! (Pinzke & Pfrommer, in prep.)

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



Minimum γ-ray flux in the hadronic model (1)



Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{CMB}$!

Synchrotron luminosity:

$$L_\nu = A_\nu \int dV\, n_{CR} n_{gas} \frac{\varepsilon_B^{(\alpha_\nu+1)/2}}{\varepsilon_{CMB} + \varepsilon_B}$$

$$\rightarrow A_\nu \int dV\, n_{CR} n_{gas} \quad (\varepsilon_B \gg \varepsilon_{CMB})$$

γ-ray luminosity:

$$L_\gamma = A_\gamma \int dV\, n_{CR} n_{gas}$$

$\rightarrow$ minimum γ-ray flux:

$$\mathcal{F}_{\gamma,\min} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$

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Minimum γ-ray flux in the hadronic model (2)

Minimum γ-ray flux ($E_\gamma > 100$ MeV) for the Coma cluster:

CR spectral index	2.0	2.3	2.6	2.9
$\mathcal{F}_\gamma$ [$10^{-10}\gamma\, cm^{-2} s^{-1}$]	0.8	1.6	3.4	7.1

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\text{gas}}/20$ and B-fields derived from Faraday rotation studies, $B_0 = 3\,\mu$G: $\mathcal{F}_{\gamma,\text{COMA}} \gtrsim 2 \times 10^{-9}\gamma\, cm^{-2} s^{-1} = \mathcal{F}_{\text{GLAST, 2yr}}$
- Non-detection by GLAST seriously challenges the hadronic model.

Summary

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters
   $\rightarrow$ illuminating the process of structure formation
2. Brightest γ-ray clusters for GLAST and IACTs: Ophiuchus, Fornax, Coma, Norma, Perseus, Centaurus
3. Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE γ-ray emission:
   - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - nature of dark matter
   - gold sample of cluster for precision cosmology

Literature for the talk

- Pfrommer, 2008, MNRAS, 385, 1242,
  Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211,
  Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission
- Pinzke, Pfrommer, in prep.
- Pfrommer, Battaglia, Pinzke, in prep.

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