Non-thermal Emission from Galaxy Clusters: Cosmic Rays and Dark Matter

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in collaboration with

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Outline

1. Cosmological simulations
   - Introduction
   - Physics in simulations
   - Cosmic rays in galaxy clusters
2. Non-thermal signatures
   - Radio emission
   - Gamma rays
   - AGN feedback
3. Dark matter searches
   - Models
   - Sources
   - Constraints

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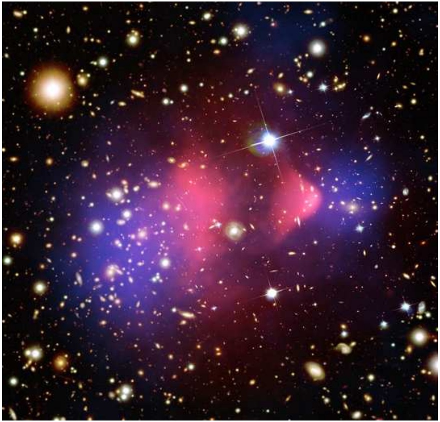
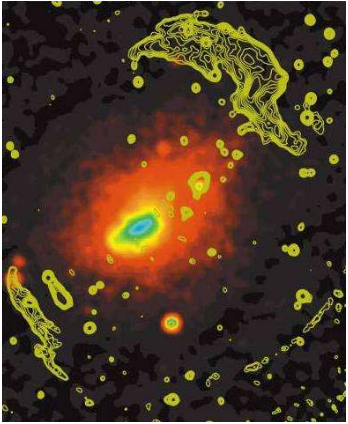
Cluster mergers: *the* most energetic cosmic events



1E 0657-56 (“Bullet cluster”)

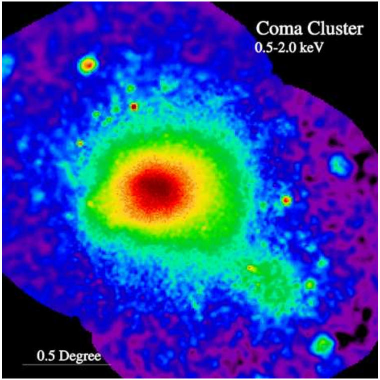
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

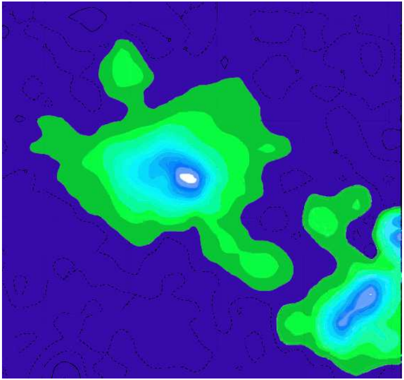
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

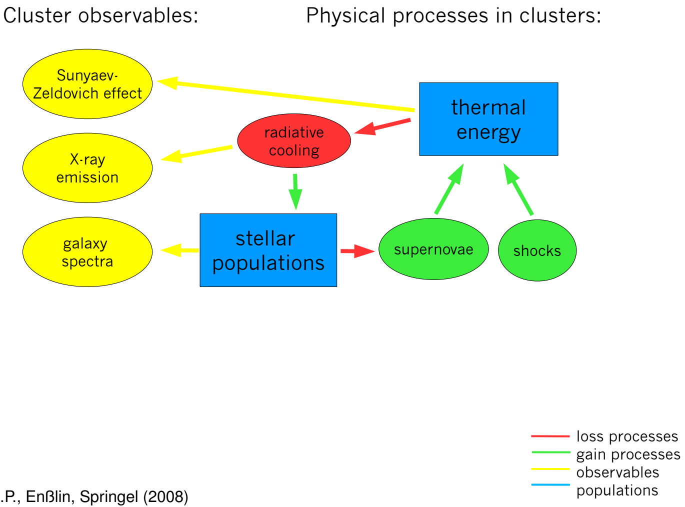
(Deiss/Effelsberg)

High-Energy Astrophysics in Galaxy Clusters

Understanding non-thermal emission (from radio to γ rays)

- plasma astrophysics:
  → shock and particle acceleration
  → large-scale magnetic fields
  → turbulence
- structure formation and galaxy cluster cosmology:
  → illuminating the process of structure formation
  → cosmic ray feedback: shaping the thermal cluster history
  → calibrating thermal cluster observables: cluster cosmology
- indirect detection of dark matter:
  → cosmic ray vs. DM annihilation γ rays

Cosmological simulations – flowchart



Cluster observables:

Physical processes in clusters:

Sunyaev-Zeldovich effect

X-ray emission

galaxy spectra

radiative cooling

thermal energy

stellar populations

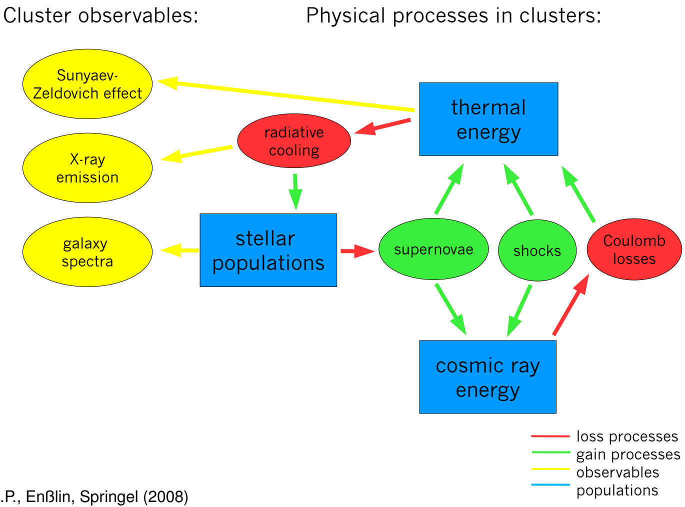
supernovae

shocks

- loss processes
- gain processes
- observables
- populations

C.P., Enßlin, Springel (2008)

Cosmological simulations with cosmic ray physics



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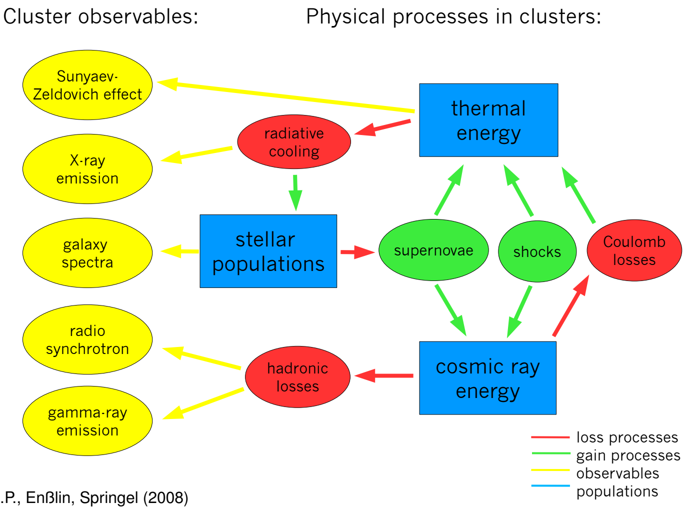
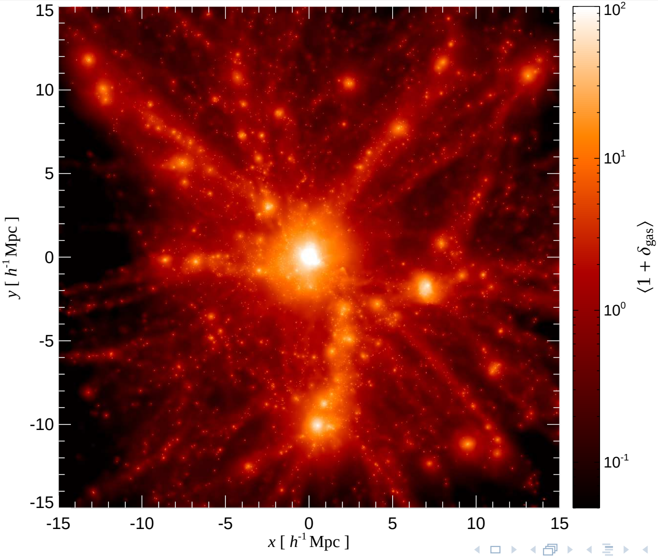


Cluster observables:

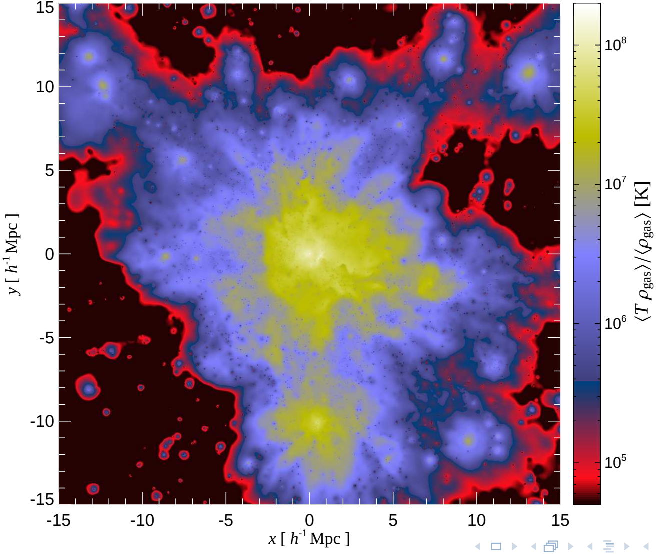
Physical processes in clusters:

C.P., Enßlin, Springel (2008)

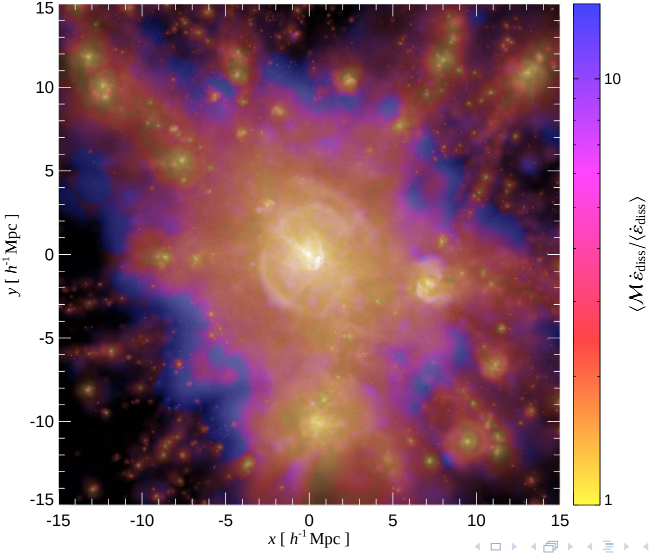
Cosmological cluster simulation: gas density



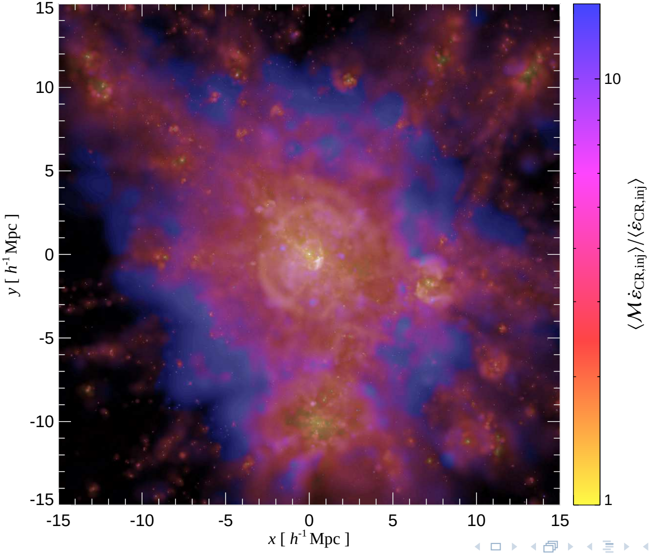
Mass weighted temperature



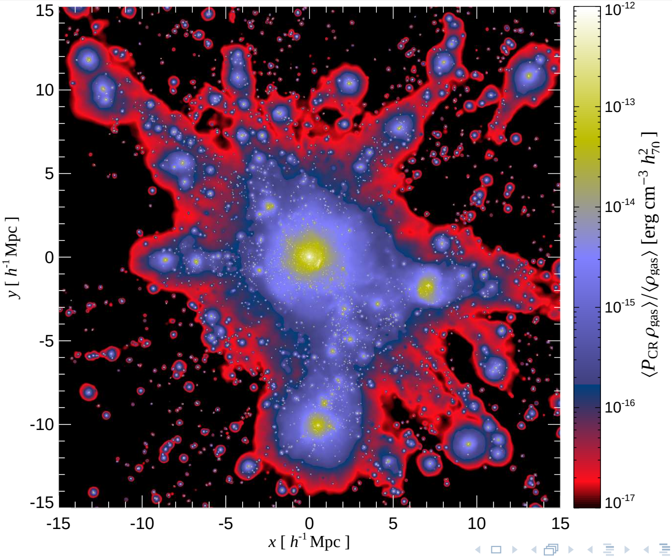
Shock strengths weighted by dissipated energy



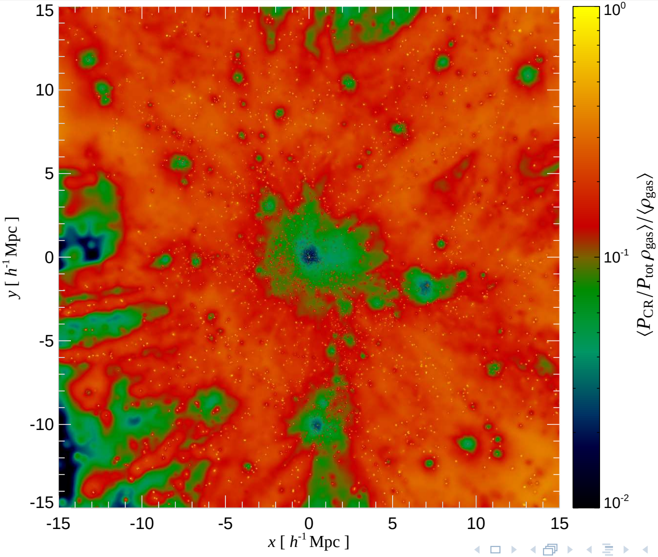
Shock strengths weighted by injected CR energy



Evolved CR pressure



Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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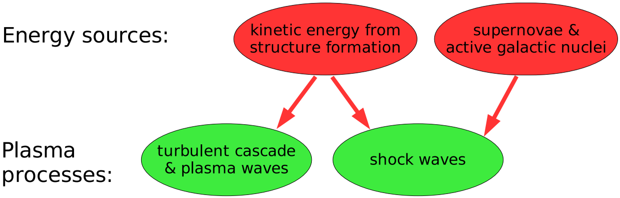
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



Energy sources:

kinetic energy from structure formation

supernovae & active galactic nuclei

Plasma processes:

turbulent cascade & plasma waves

shock waves

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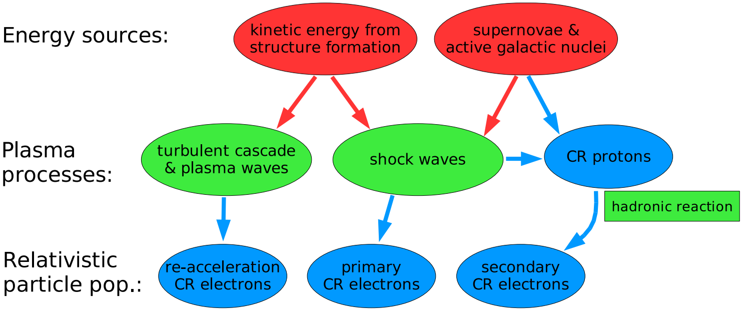

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CR protons

hadronic reaction

Relativistic particle pop.:

re-acceleration CR electrons

primary CR electrons

secondary CR electrons

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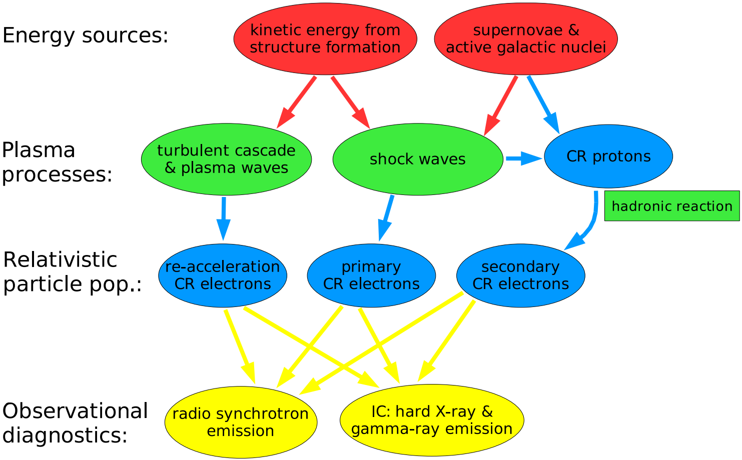

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Observational diagnostics:

radio synchrotron emission

IC: hard X-ray & gamma-ray emission

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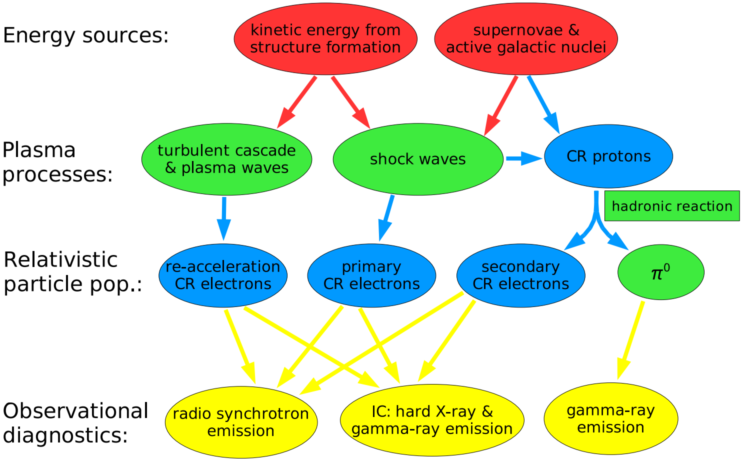

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π^0

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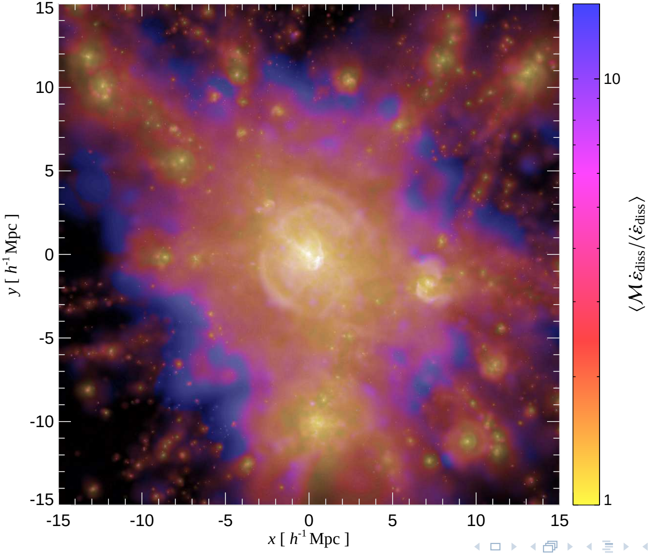
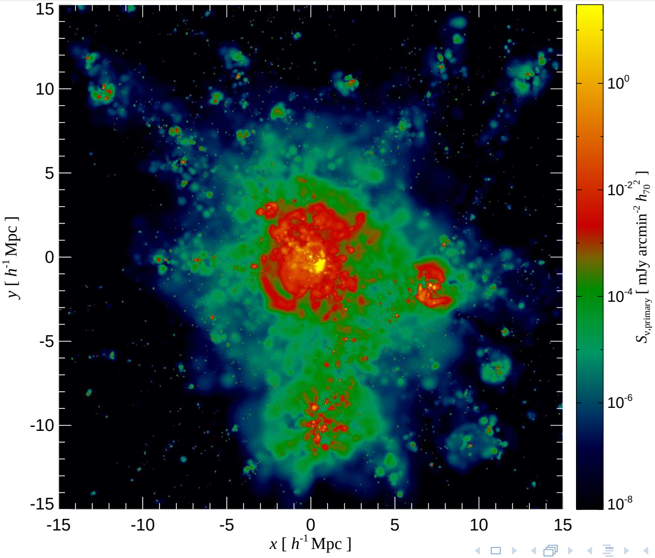
gamma-ray emission

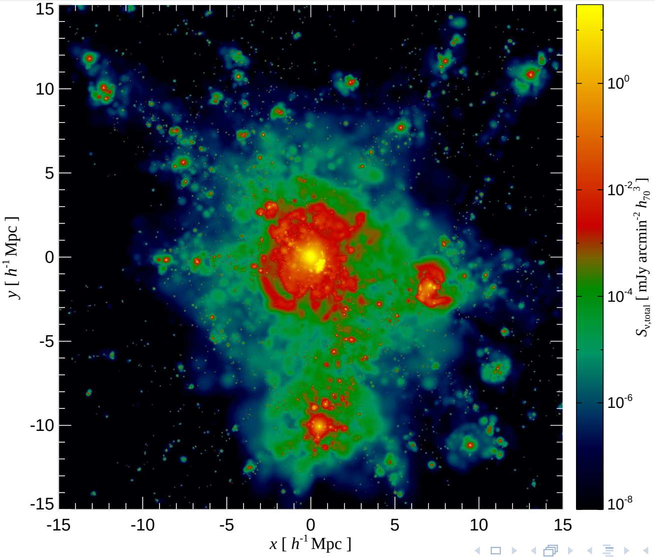
Structure formation shocks



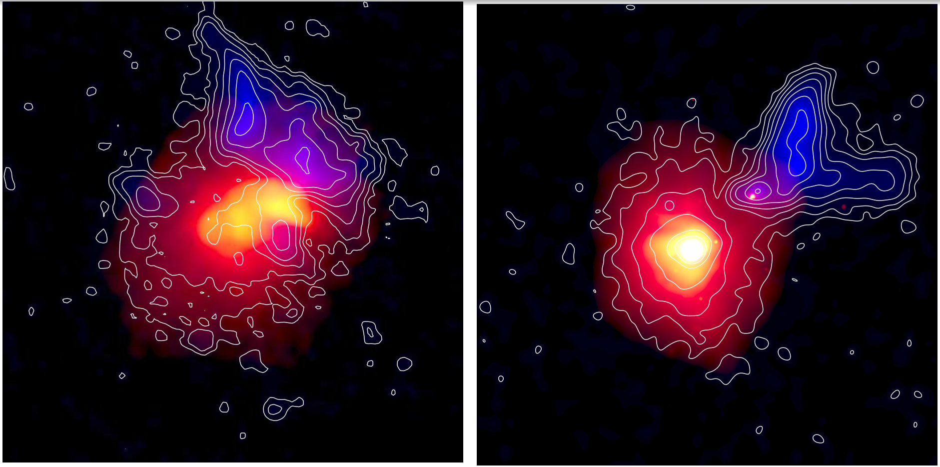
Radio gischt: shock-accelerated CRe



Radio gischt + central hadronic halo = giant radio halo

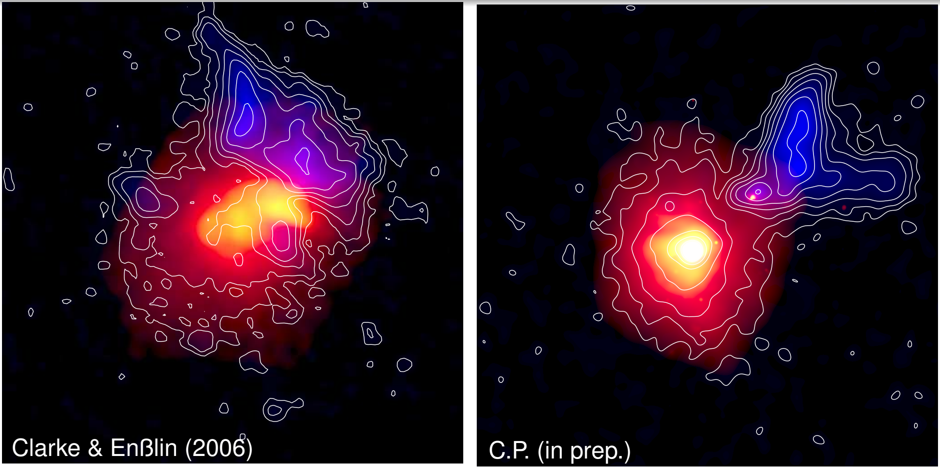


Which one is the simulation/observation of A2256?



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

Observation – simulation of A2256



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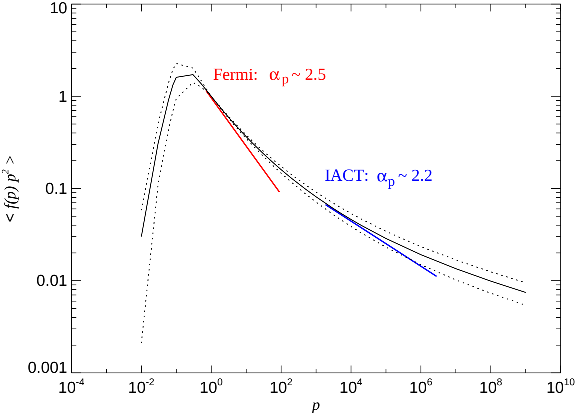
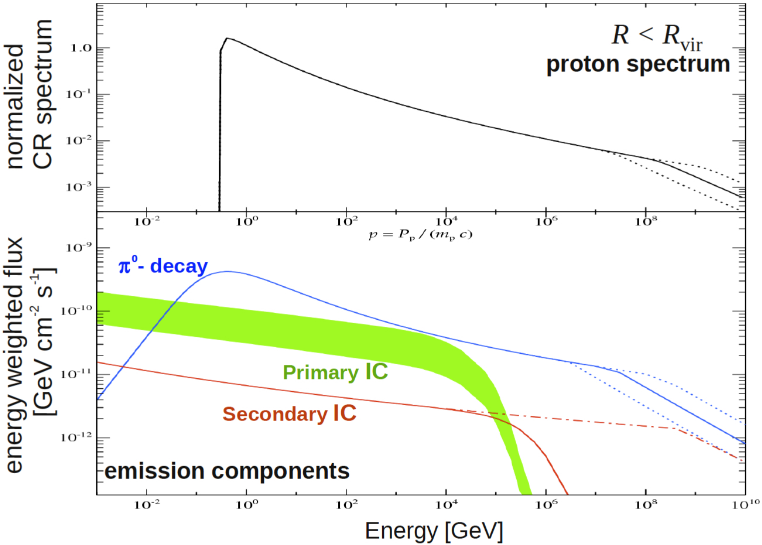
Universal CR spectrum in clusters (Pinzke & C.P. 2010)



Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history.

CR proton and γ-ray spectra (Pinzke & C.P. 2010)



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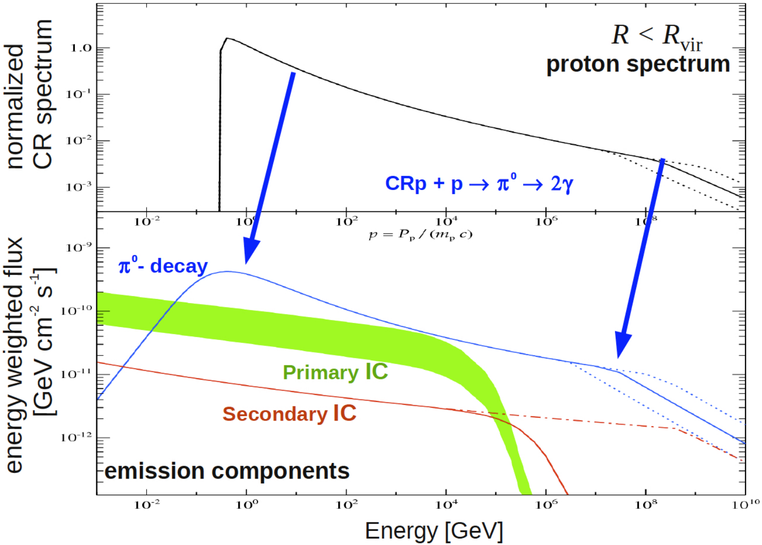

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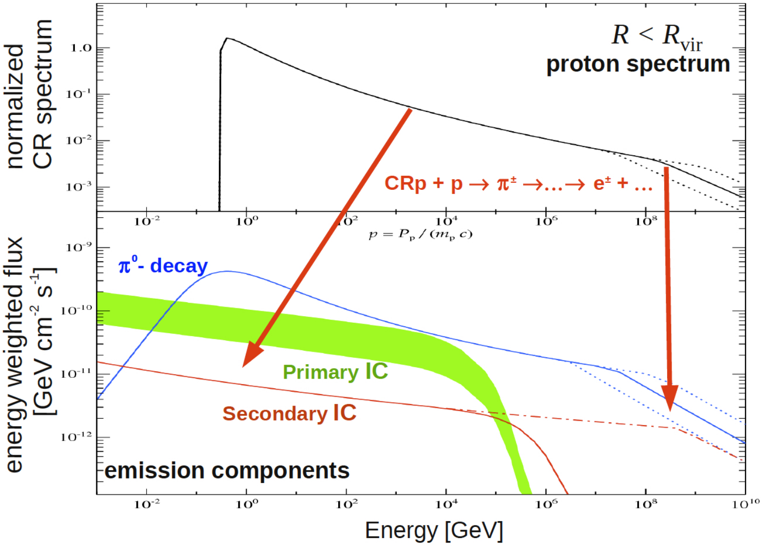
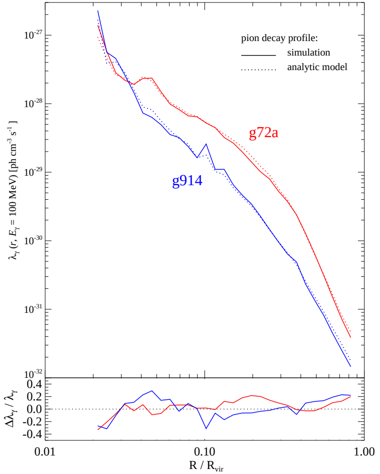
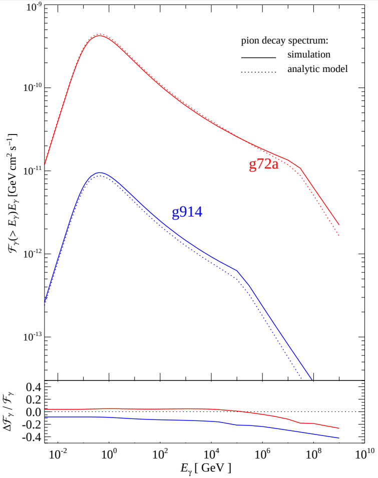


An analytic model for the cluster γ-ray emission

Comparison: simulation vs. analytic model, $M_{\mathrm{vir}} \simeq (10^{14}, 10^{15})\,\mathrm{M}_\odot$



Spatial γ-ray emission profile



Pion decay spectrum

Constraining CR physics with γ-ray observations

- non-detections constrain $P_{\mathrm{CR}}/P_{\mathrm{th}} < 1.7\%$ in Coma and Perseus and to $\lesssim 1\%$ in a stacked sample of 50 *Fermi* clusters
- constrains maximum shock acceleration efficiency to $< 50\%$
- hydrostatic cluster masses not significantly biased by CRs: important for cluster cosmology!

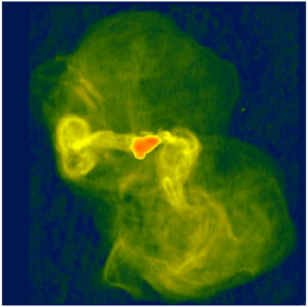
Conclusions on non-thermal signatures in clusters

Exploring the memory of structure formation

- primary, shock-accelerated CR electrons resemble current accretion and merging shock waves
- CR protons/hadronically produced CR electrons trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities
- *Fermi*, MAGIC, VERITAS non-detections of γ rays from clusters start to limit CR acceleration efficiencies to $< 50\%$
  (or tell us about CR transport processes)

→ Multi-messenger approach from the radio to γ-ray regime!

Virgo cluster cooling flow: M87 at radio wavelengths



$\nu = 1.4$ GHz (Owen+ 2000)

- expectation: low frequencies sensitive to fossil electrons ($E \sim 100$ MeV) → time-integrated activity of AGN feedback!

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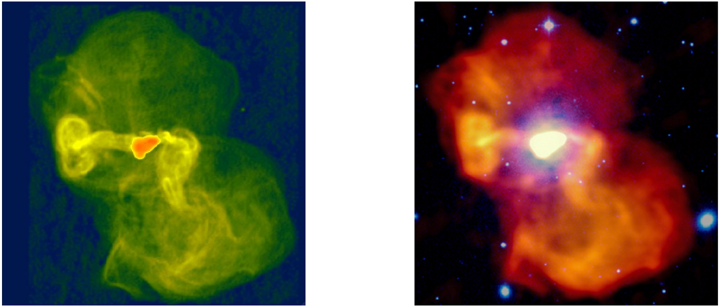


$\nu = 1.4$ GHz (Owen+ 2000)

$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- expectation: low frequencies sensitive to fossil electrons ($E \sim 100$ MeV) → time-integrated activity of AGN feedback!
- LOFAR: halo confined to same region at all frequencies and no low-ν spectral steepening → puzzle of “missing fossil electrons”

Solutions to the “missing fossil electrons” problem

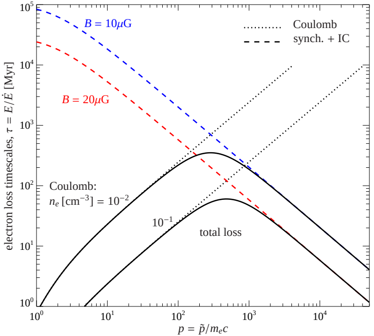
solutions:

- special time: M87 turned on $\sim$ 40 Myr ago after long silence
  $\Leftrightarrow$ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)

Solutions to the “missing fossil electrons” problem

solutions:

- special time: M87 turned on $\sim$ 40 Myr ago after long silence
  $\Leftrightarrow$ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions



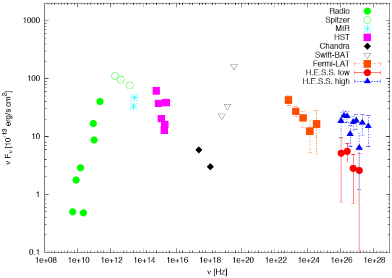
C.P. (2013)

The γ-ray picture of M87

- high state is time variable
  $\rightarrow$ jet emission
- low state:
  (1) steady flux

  (2) γ-ray spectral index (2.2)
  $=$ CRp index
  $=$ CRe injection index as probed by LOFAR

  (3) spatial extension is under investigation (?)

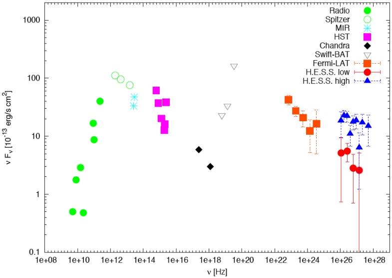


Rieger & Aharonian (2012)

$\rightarrow$ **confirming this triad would be smoking gun for first γ-ray signal from a galaxy cluster!**

Estimating the CR pressure in M87

- X-ray data → n and T profiles
- assume $X_{\rm CR} = P_{\rm CR}/P_{\rm th}$ (self-consistency requirement)
- $F_\gamma \propto \int \mathrm{d}V\, P_{\rm CR}\, n$ enables to estimate $X_{\rm CR} = 0.31$ (allowing for Coulomb cooling with $\tau_{\rm Coul} = 40\,\mathrm{Myr}$)



Rieger & Aharonian (2012)

→ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)

Cosmic-ray heating vs. radiative cooling (1)

CR Alfvén-wave heating:

$$\mathcal{H}_{\mathrm{CR}} = -\boldsymbol{\upsilon}_A \cdot \nabla P_{\mathrm{CR}} = -\upsilon_A \left(X_{\mathrm{CR}} \nabla_r \langle P_{\mathrm{th}} \rangle_\Omega + \frac{\delta P_{\mathrm{CR}}}{\delta l} \right)$$

- Alfvén velocity $\upsilon_A = B/\sqrt{4\pi\rho}$ with $B \sim B_{\mathrm{eq}}$ from LOFAR and ρ from X-ray data
- X_{CR} calibrated to γ rays
- P_{th} from X-ray data
- pressure fluctuations $\delta P_{\mathrm{CR}}/\delta l$ (e.g., due to weak shocks of $\mathcal{M} \simeq 1.1$)

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- X_CR calibrated to γ rays
- P_th from X-ray data
- pressure fluctuations $\delta P_\mathrm{CR}/\delta l$ (e.g., due to weak shocks of $\mathcal{M} \simeq 1.1$)

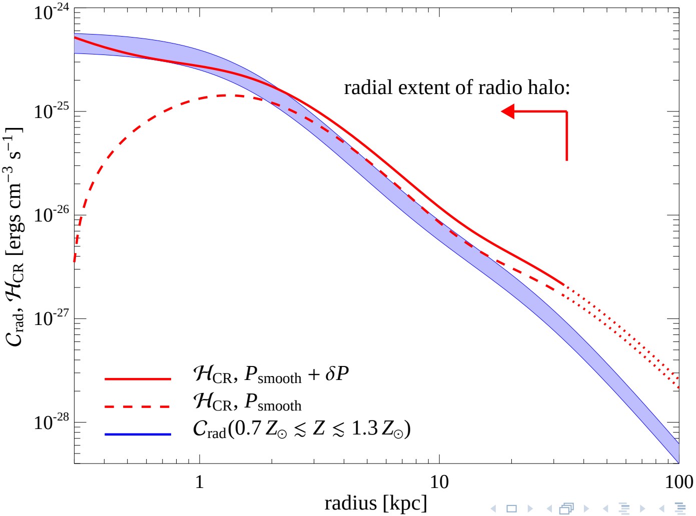
radiative cooling:

$$\mathcal{C}_\mathrm{rad} = n_e n_t \Lambda_\mathrm{cool}(T, Z)$$

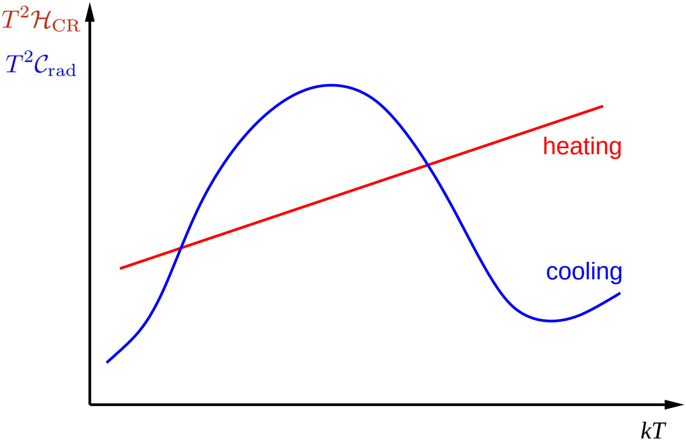
- cooling function Λ_cool with $Z \simeq Z_\odot$ determined from X-ray data

Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



Local stability analysis (1)



- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

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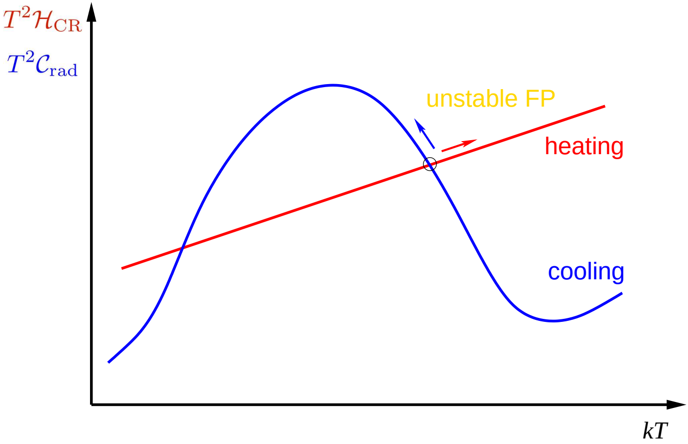

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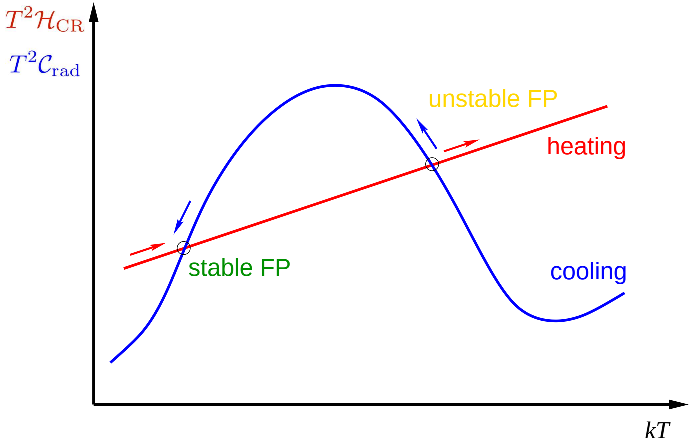

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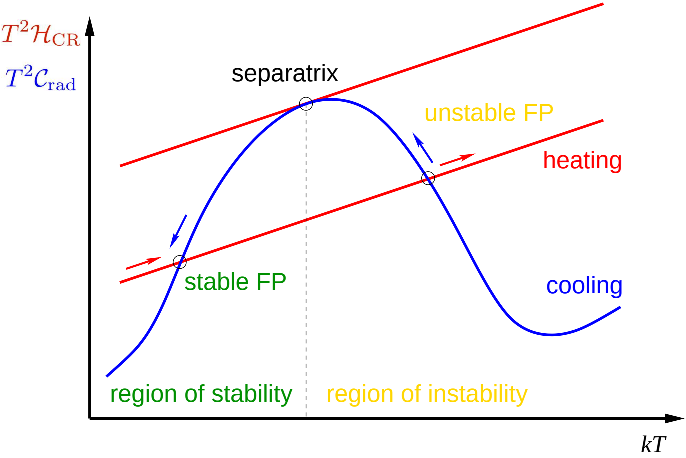

- isobaric perturbations to global thermal equilibrium
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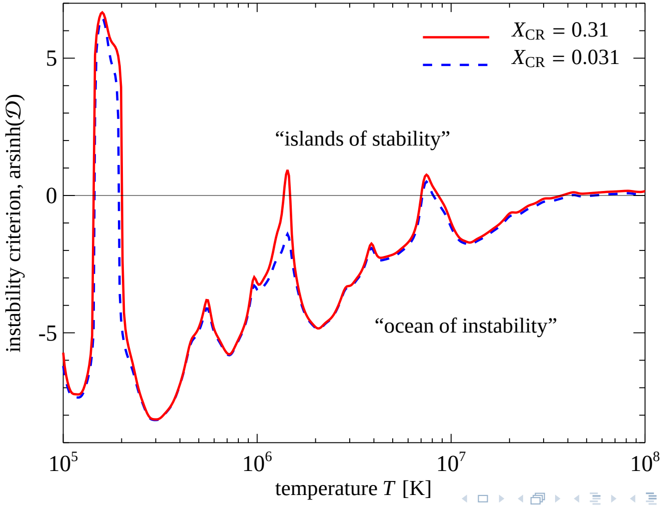
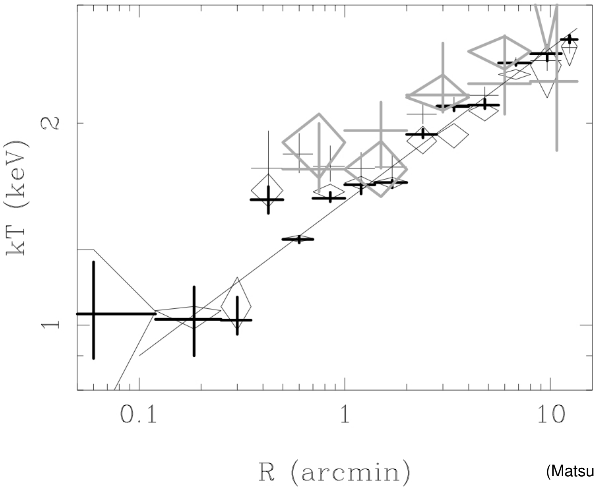
Local stability analysis (2)

Theory predicts observed temperature floor at $kT \simeq 1$ keV



Virgo cluster cooling flow: temperature profile

X-ray observations confirm temperature floor at $kT \simeq 1$ keV



(Matsushita+ 2002)

Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of “missing fossil electrons” solved by mixing with dense cluster gas and Coulomb cooling
- predicted γ rays identified with low state of M87 $\rightarrow$ estimate CR-to-thermal pressure of $X_{\mathrm{CR}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, . . .

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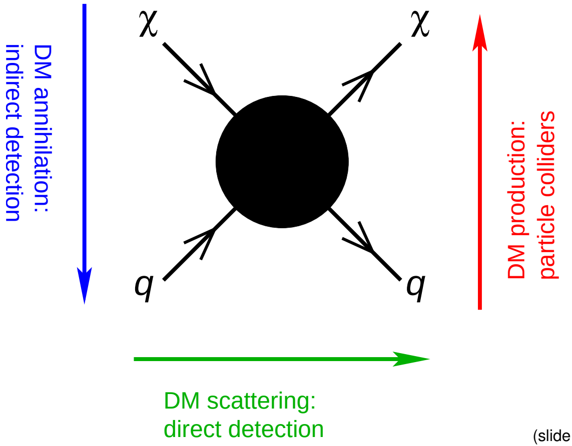
Searching for dark matter (DM)

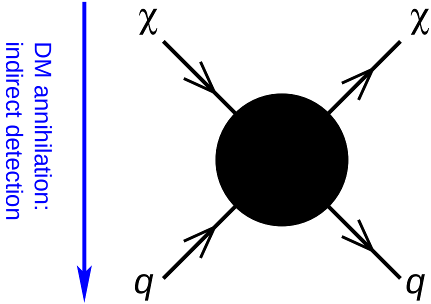
correct relic density → DM annihilation in the Early Universe



(slide concept Feng)

1. “Standard” supersymmetric DM

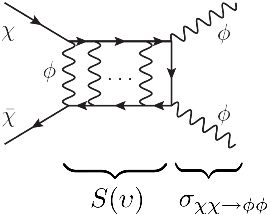
consider benchmark models of **supersymmetric DM**



DM annihilation:
indirect detection

2. DM with Yukawa-type interactions

- heavy DM interacts through light force carrier ϕ
- repeated exchange of ϕ → Sommerfeld effect
- multiply cross-section by enhancement factor S



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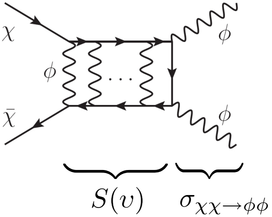
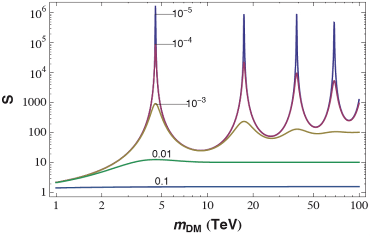
- heavy DM interacts through light force carrier ϕ
- repeated exchange of ϕ $\rightarrow$ Sommerfeld effect
- multiply cross-section by enhancement factor S
- near bound state resonances expected:
  - off resonance: $S \propto v^{-1}$
  - on resonance: $S \propto v^{-2}$

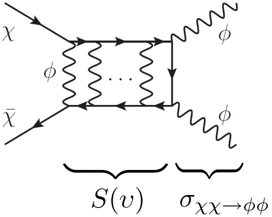


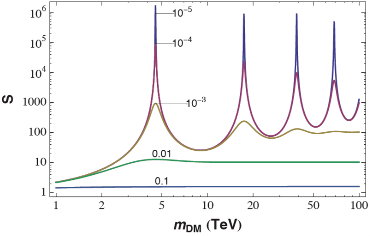


Lattanzi, Silk (2009)

2. DM with Yukawa-type interactions

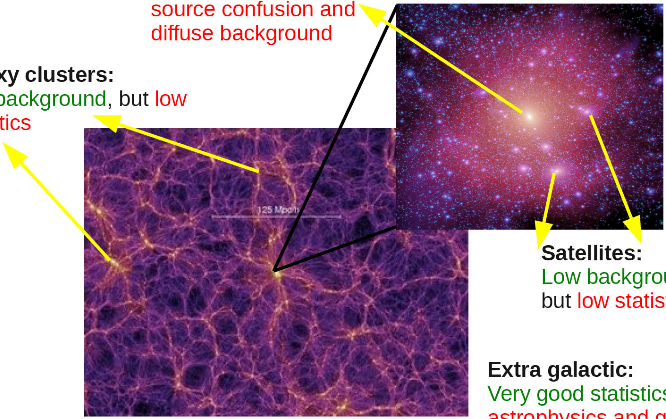
- heavy DM interacts through light force carrier ϕ
- repeated exchange of ϕ $\rightarrow$ Sommerfeld effect
- multiply cross-section by enhancement factor S
- near bound state resonances expected:
  - off resonance: $S \propto v^{-1}$
  - on resonance: $S \propto v^{-2}$
- for $m_\phi \lesssim 100$ MeV, ϕ can only decay into leptons (e, μ) $\rightarrow$ leptophilic DM





Lattanzi, Silk (2009)

Indirect DM searches: sources



Galactic center:
Good statistics, but
source confusion and
diffuse background

Milky Way halo:
Very good statistics,
but diffuse background

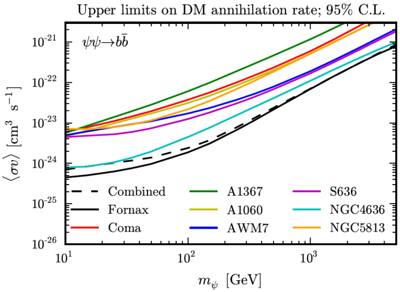
Galaxy clusters:
Low background, but low
statistics

Satellites:
Low background,
but low statistics

Extra galactic:
Very good statistics, but
astrophysics and galactic
diffuse foregrounds

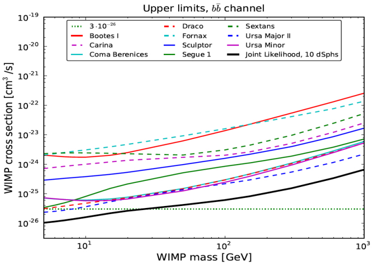
DM searches in clusters vs. dwarfs

Galaxy clusters:



Huang et al. 2011 (see also Ando & Nagai 2012)

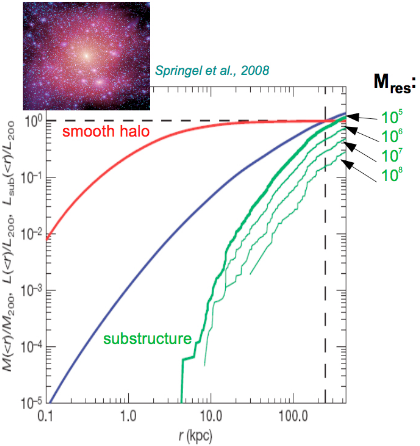
Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

- combined limits for dwarf galaxies ∼ 20 times more constraining
- is this really true? → consider substructure!

Enhancement from DM substructures



Springel et al., 2008

Constant offset in the luminosity from substructures between different mass resolutions in the simulation ($M_{\rm res}$).

$$\mathrm{Norm} \propto M_{\rm res}^{-0.226}$$

Extrapolate to the minimal mass of dark matter halos ($M_{\rm min}$) that can form.

The cold dark matter scenario suggests $M_{\rm min} \sim 10^{-6}\, M_\odot$.

Hofmann, Schwarz and Stöcker, 2008
Green, Hofmann and Schwarz, 2005

$$L_{\rm sub}(<r) \propto (M_{200} / M_{\rm res})^{0.226}$$

→ **Luminosity boosted by ~1000 in clusters**

Pinzke et al. 2011, Gao et al 2011

Galaxy clusters vs. dwarf galaxies

- DM annihilation flux of smooth (unresolved) halo:

$$F \propto \int \mathrm{d}V \frac{\rho^2}{D^2} \sim f(c)\,\frac{M}{D^2}$$

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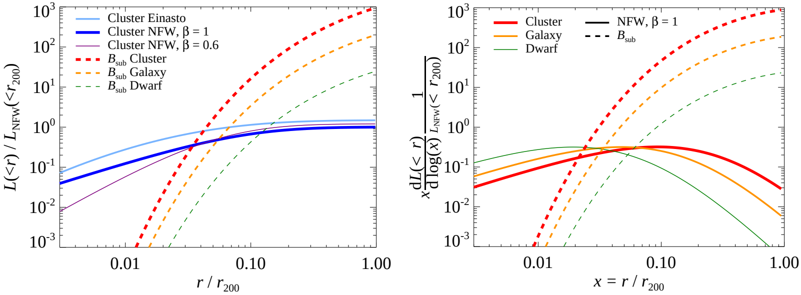
- DM substructure is less concentrated compared to the smooth halo (dynamical friction, tidal heating and disruption): the DM luminosity is dominated by substructure at the virial radius, *if* present!
  → these regions are tidally stripped in dwarf galaxies
  → in cluster, subhalos enhance DM luminosity by up to 1000

(e.g., Pinzke, C.P., Bergström 2011; Gao et al. 2011)

Spatial DM distribution

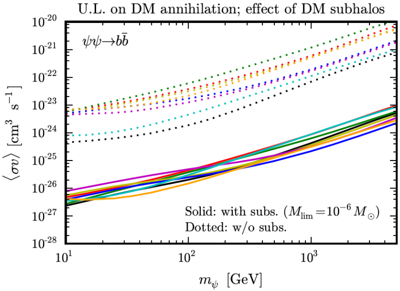


Pinzke, C.P., Bergström 2011

- form of smooth density profile only important for central region, majority of smooth flux accumulates around $r \simeq r_s/3$
- emission from substructures dominated by outer regions → spatially extended
- large boost in clusters (~ 1000); smaller boost in dwarf satellites (~ 20) → much smaller if outskirts are tidally stripped

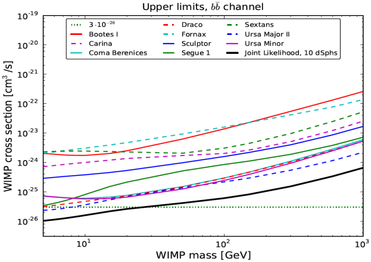
DM searches in clusters vs. dwarfs

Clusters with substructures:



Huang et al. 2012 (see also Ando & Nagai 2012)

Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

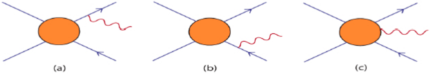
- galaxy clusters $\sim$ 10 times more constraining than dwarf satellites when accounting for substructures!

DM-induced γ rays: *leptophilic models*

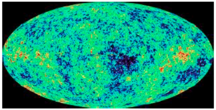
Annihilation rate in these models enhanced by **Sommerfeld effect** as well as **DM substructures**.

Gamma-ray emission components:

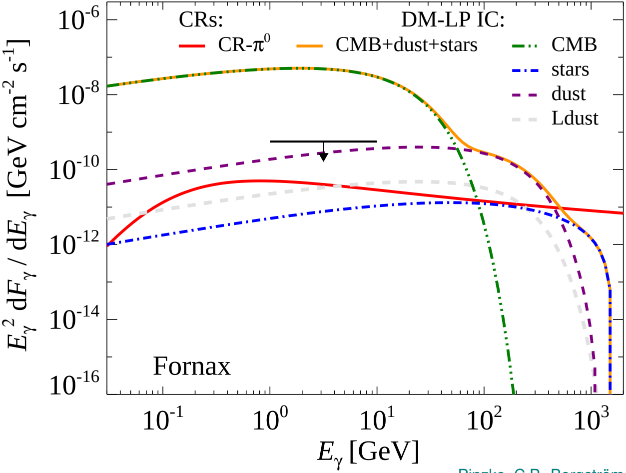
- Final state radiation



- IC on background radiation fields (CMB, starlight and dust)



Gamma-ray spectrum: leptophilic DM vs. CRs



Pinzke, C.P., Bergström 2011

DM-induced γ rays: *SUSY benchmark models*

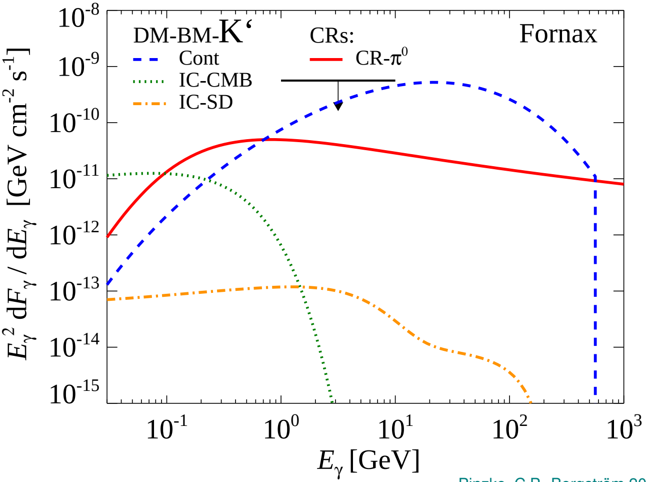
Representation of high mass (~1 TeV) DM models with high gamma-ray emission.

Luminosity **boosted by substructures** in the smooth DM halo.

Gamma-ray emission components:

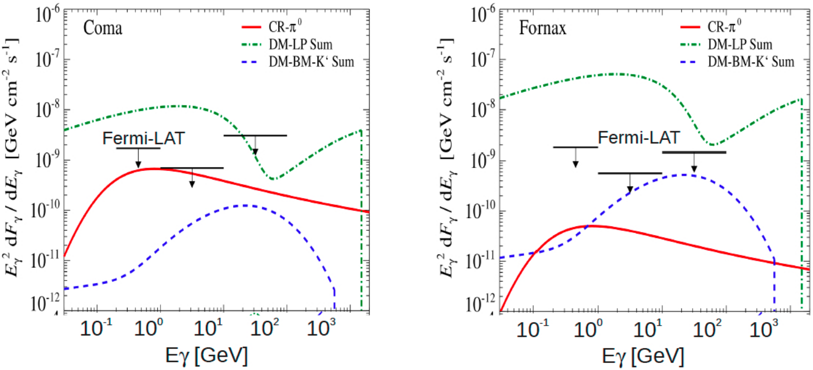
- Annihilating neutralinos emitting continuum emission
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)

Gamma-ray spectrum: benchmark DM vs. CRs



Pinzke, C.P., Bergström 2011

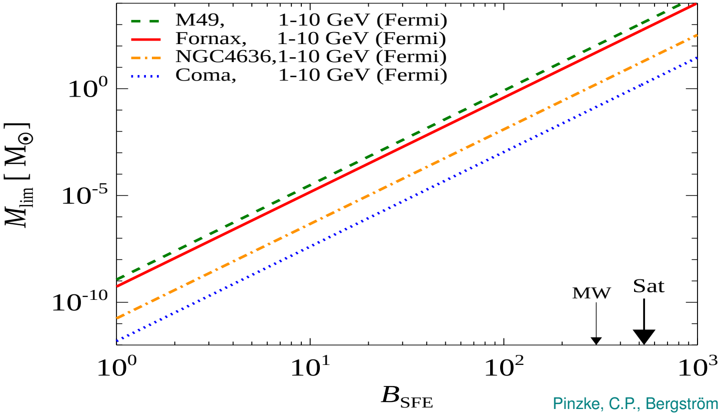
Comparing clusters and emission processes



Pinzke, C.P., Bergström 2011

- **Fornax:** comparably high DM-induced γ-ray flux and low CR-induced emission → tight limits on DM properties
- **Coma:** CR-induced emission soon in reach for Fermi

Constraining boost factors *(leptophilic models)*



Pinzke, C.P., Bergström 2011

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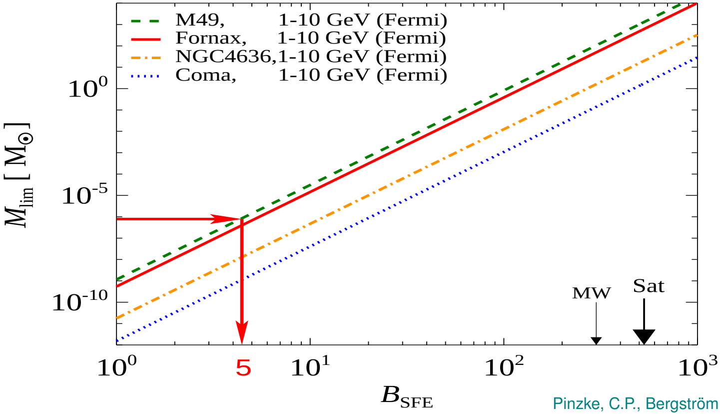
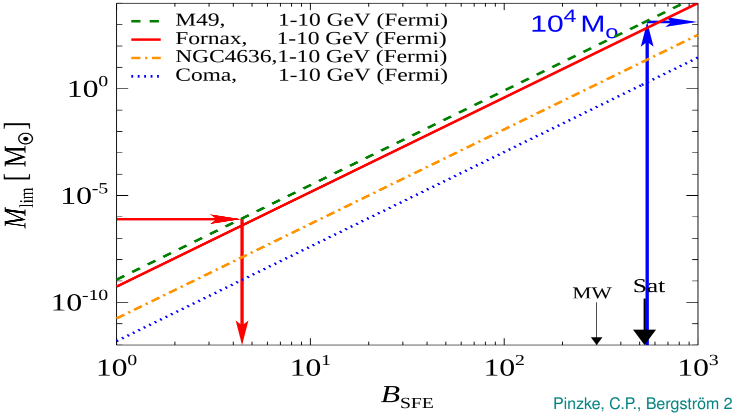


Pinzke, C.P., Bergström 2011

- Fornax and M49 constrain the saturated boost from Sommerfeld enhancement (SFE) to < 5

Constraining boost factors *(leptophilic models)*



Pinzke, C.P., Bergström 2011

- Alternatively, if SFE is realized in Nature, this would limit the substructure mass to $M_{\rm lim} > 10^4 M_\odot$ – a challenge for structure formation and most particle physics models (van den Aarssen et al. 2012)

Conclusions on dark matter searches in clusters

Galaxy clusters are competitive sources for constraining dark matter:

- cluster luminosity boosted by $\sim$ 1000 (for $M_{\mathrm{min}} \simeq 10^{-6}\,\mathrm{M}_\odot$)
- flat brightness profiles and spatially extended → challenging for IACTs, better probed by Fermi-LAT

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Leptophilic DM models:

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- if DM interpretation of lepton excess seen by PAMELA/Fermi is correct, then smallest subhalos have $M > 10^4\,\mathrm{M}_\odot$

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SUSY benchmark models:

- accounting for substructure boost allows to constrain interesting DM parameter space ($\langle\sigma v\rangle \lesssim 3\times10^{-26}\,\text{cm}^3\,\text{s}^{-1}$, $m_\chi \gtrsim 100$ GeV)

Literature for the talk

Cosmic rays in clusters:

- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*, 2007, *MNRAS*, 378, 385.
- Pfrommer, Enßlin, Springel, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*, 2008, *MNRAS*, 385, 1211.
- Pinzke & Pfrommer, *Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution*, 2010, *MNRAS*, 409, 449.
- Pfrommer, *Toward a comprehensive model for feedback by active galactic nuclei: new insights from M87 observations by LOFAR, Fermi and H.E.S.S.*, 2013, *ApJ*, in print, arXiv:1303.5443.

Dark matter signatures:

- Pinzke, Pfrommer, Bergström, *Prospects of detecting gamma-ray emission from galaxy clusters: cosmic rays and dark matter annihilations*, 2011, *Phys. Rev. D* 84, 123509.
- Pinzke, Pfrommer, Bergström, *Gamma-rays from dark matter annihilations strongly constrain the substructure in halos*, 2009, *Phys. Rev. Lett.*, 103, 181302.