Galaxy Clusters as Laboratories for Astroparticle Physics

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in collaboration with

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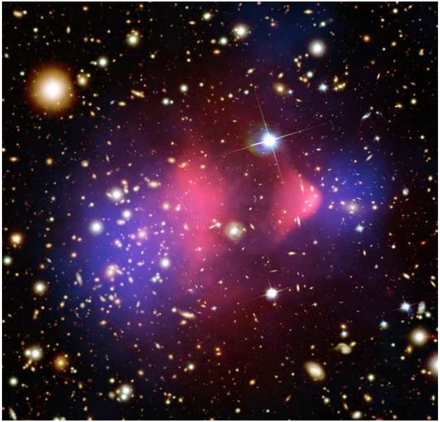
Outline

1. Cosmological simulations
    - Introduction
    - Physics in simulations
    - Cosmic rays in galaxy clusters
2. Non-thermal signatures
    - Overview
    - Radio emission
    - Gamma-ray emission
3. Dark matter signatures
    - Indirect detection
    - Boost factors
    - Constraining models

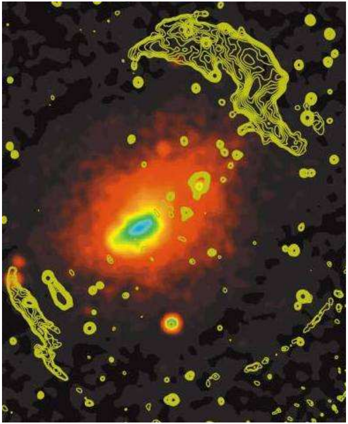
Outline

Cluster mergers: *the* most energetic cosmic events



1E 0657-56 (“Bullet cluster”)

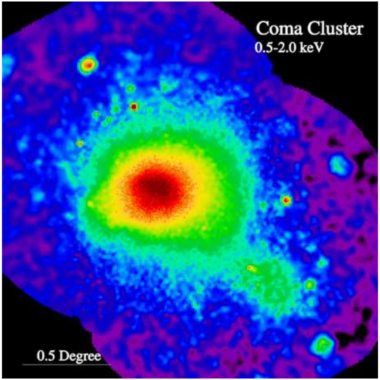
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

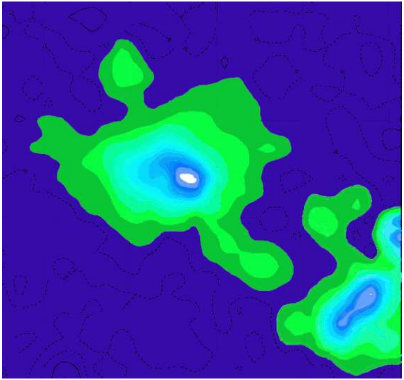
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

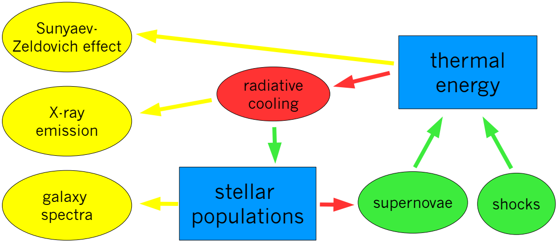
High-Energy Astrophysics in Galaxy Clusters

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
  → history of individual clusters: cluster archeology
  → 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

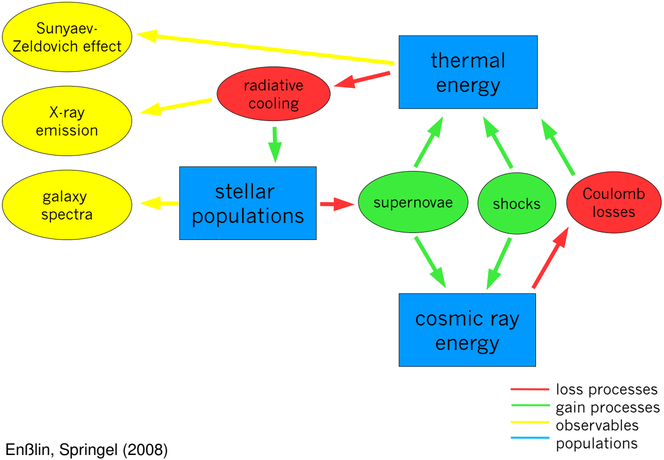
🟥 loss processes
🟩 gain processes
🟨 observables
🟦 populations

C.P., Enßlin, Springel (2008)

Cosmological simulations with cosmic ray physics

Cluster observables:

Physical processes in clusters:



Sunyaev-Zeldovich effect

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Coulomb losses

cosmic ray energy

🟥 loss processes
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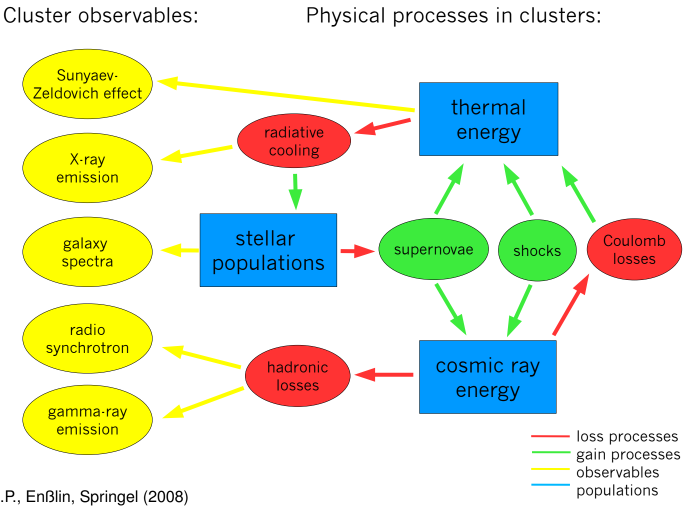
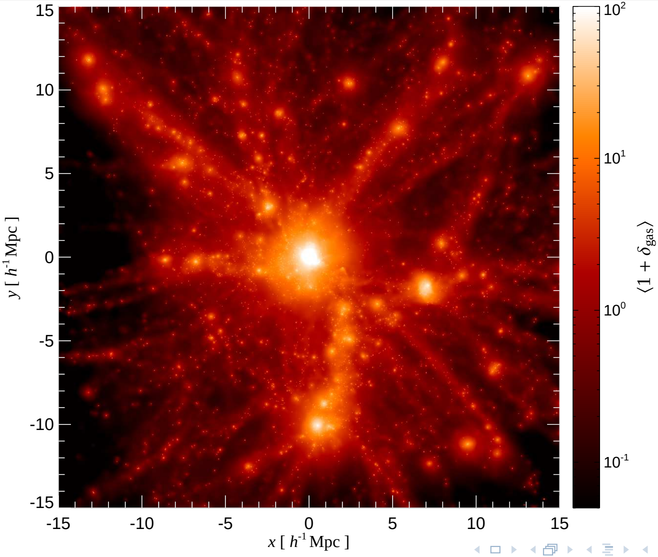
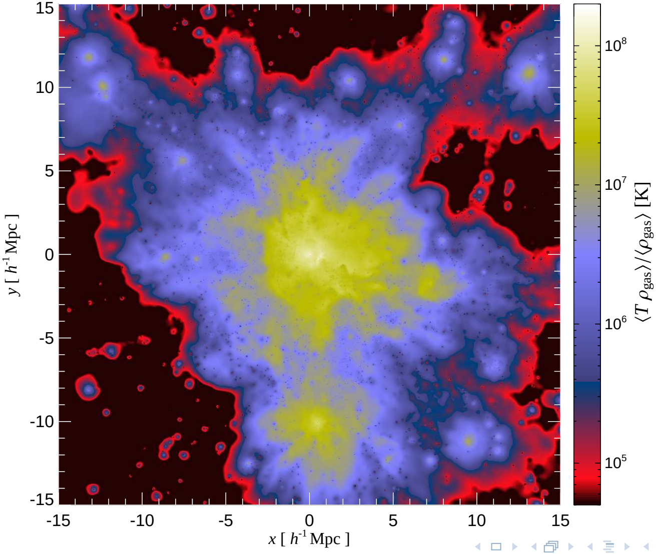


C.P., Enßlin, Springel (2008)

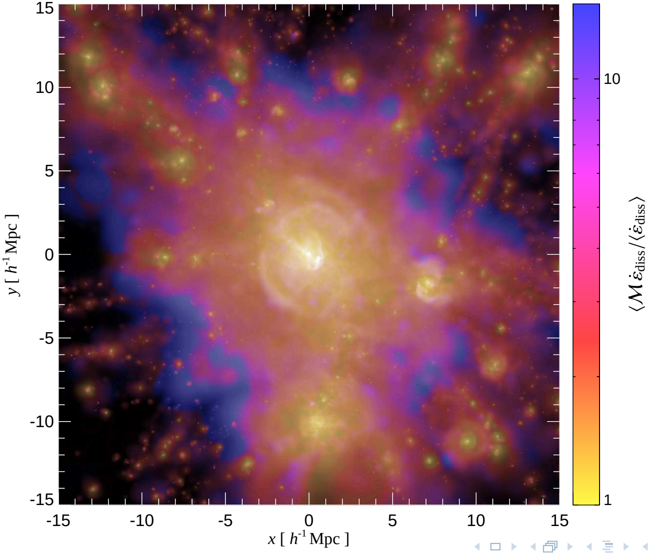
Cosmological cluster simulation: gas density



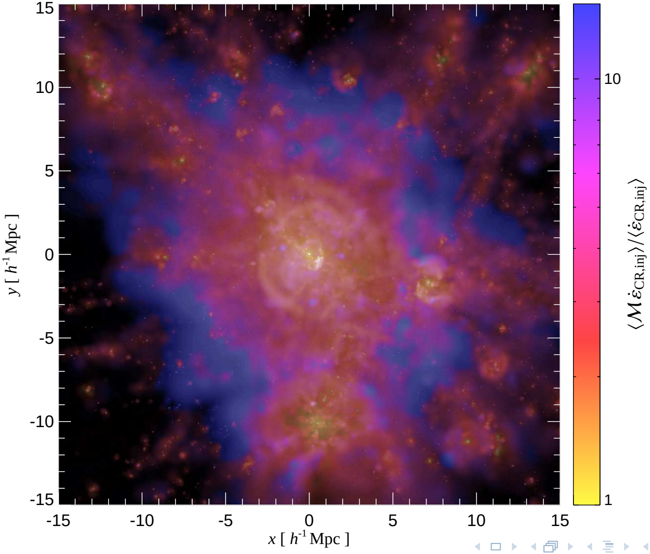
Mass weighted temperature



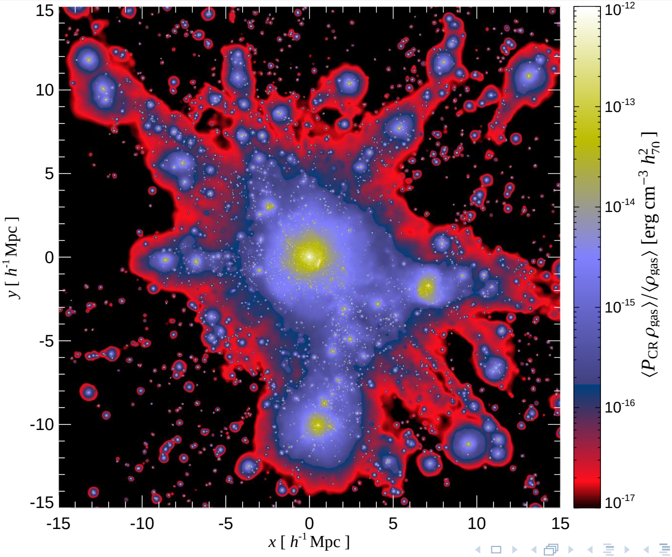
Shock strengths weighted by dissipated energy



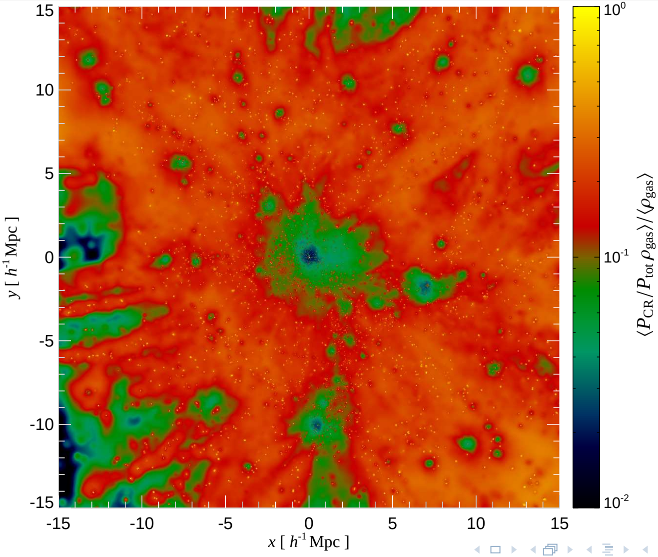
Shock strengths weighted by injected CR energy



Evolved CR pressure



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



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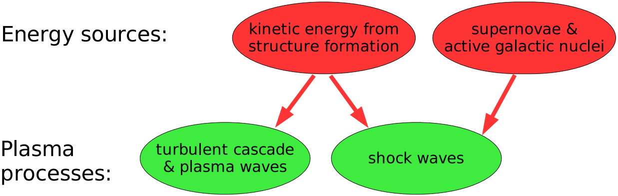
HITS

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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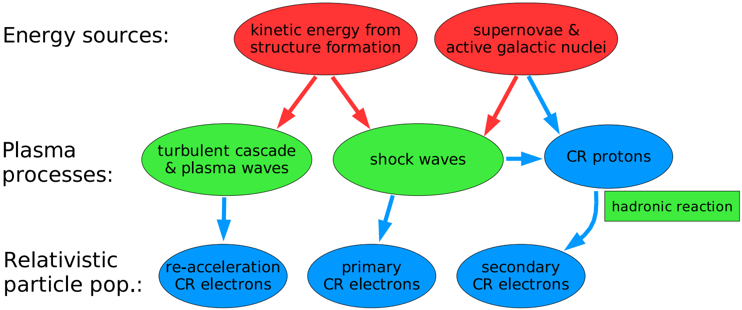

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shock waves

CR protons

hadronic reaction

Relativistic particle pop.:

re-acceleration CR electrons

primary CR electrons

secondary CR electrons

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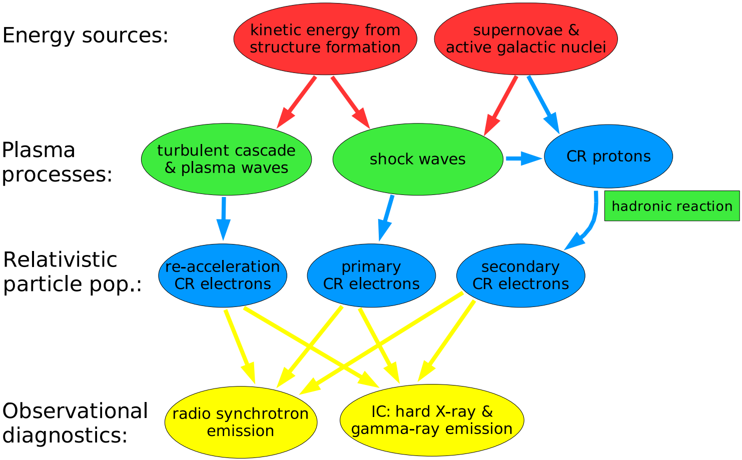

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Observational diagnostics:

radio synchrotron emission

IC: hard X-ray & gamma-ray emission

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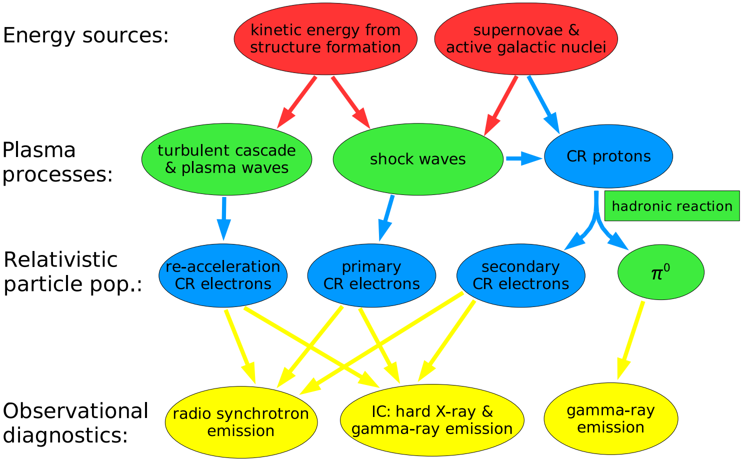

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π^0

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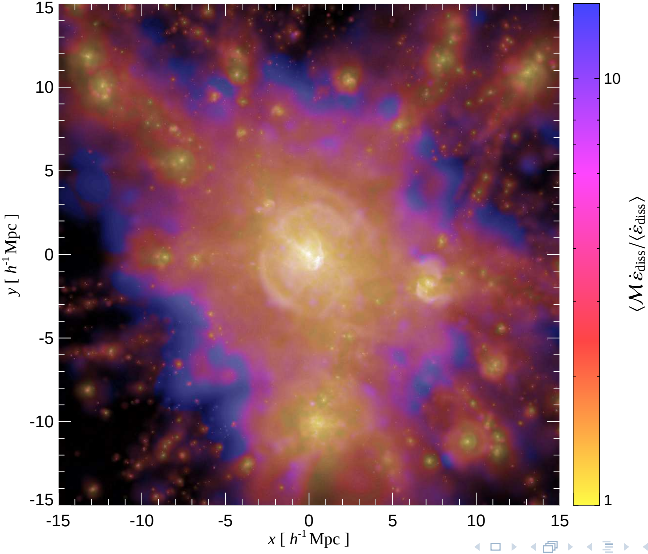
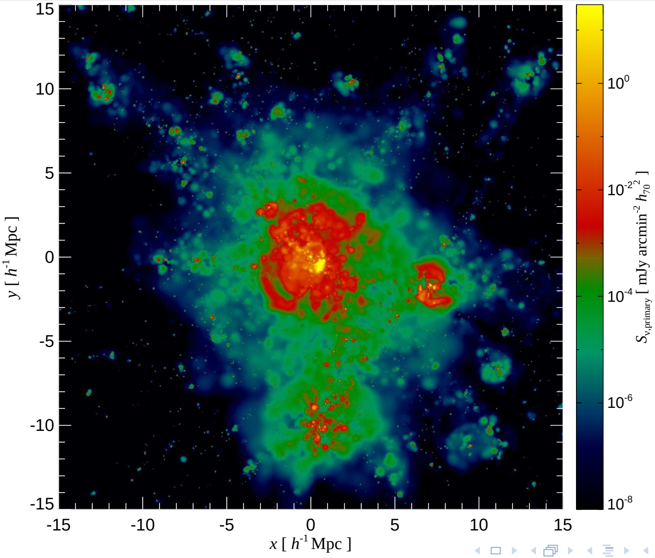
gamma-ray emission

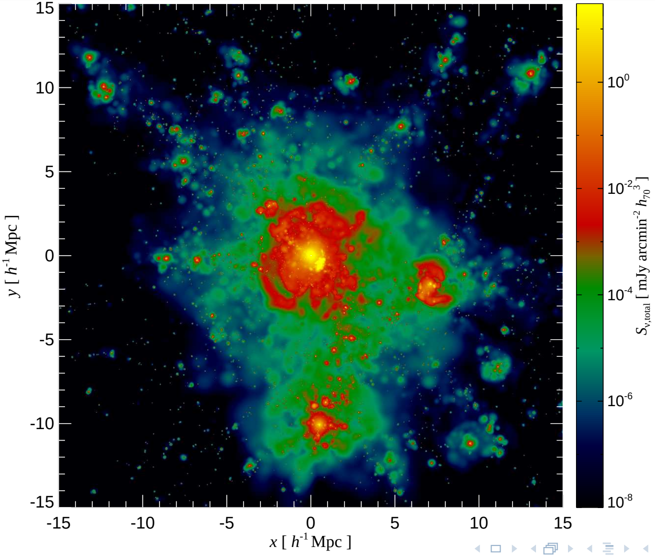
Structure formation shocks



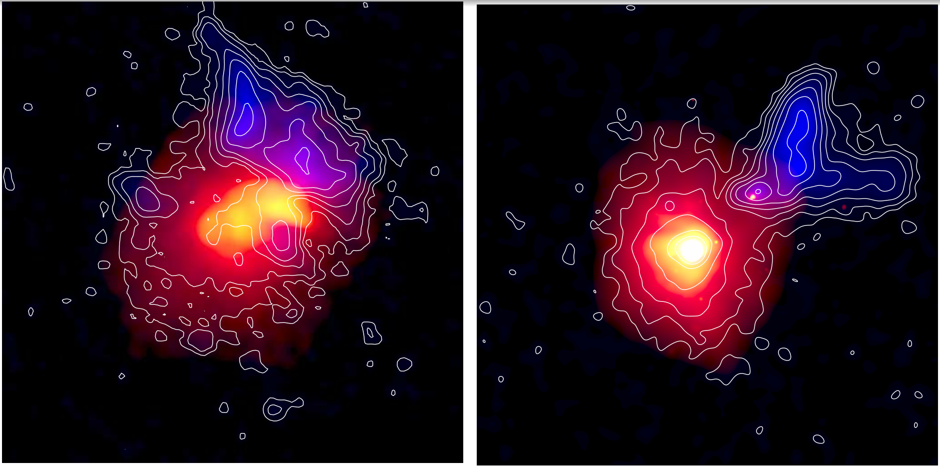
Radio gischt: shock-accelerated CRe



Radio gischt + central hadronic halo = giant radio halo

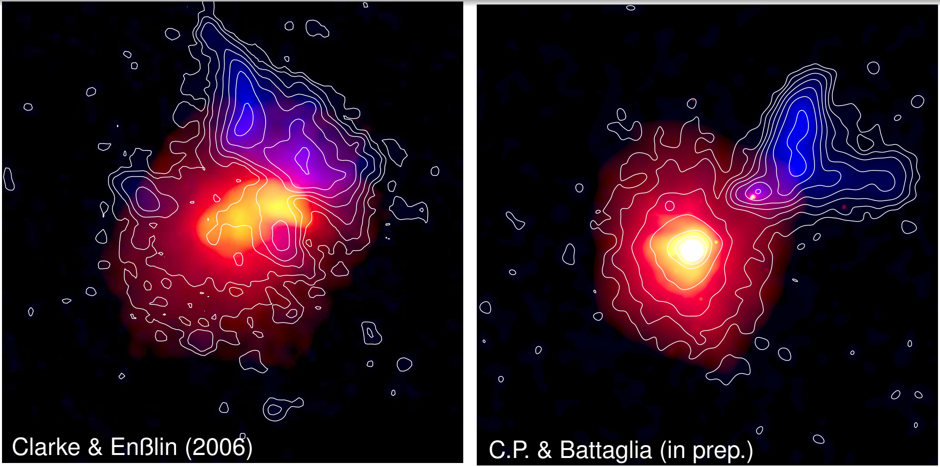


Which one is the simulation/observation of A2256?



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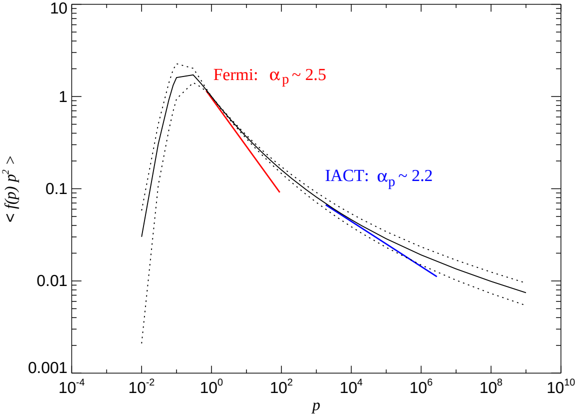
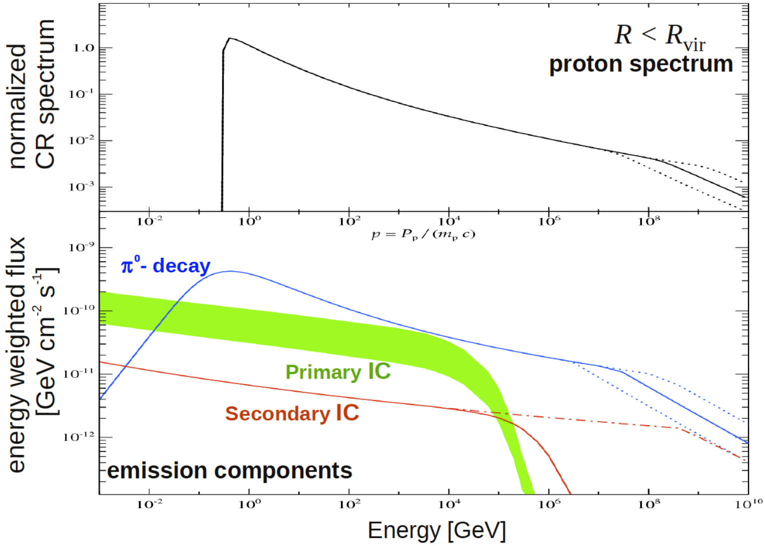
Universal CR spectrum in clusters (Pinzke & C.P. 2010)



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 gamma-ray spectra (Pinzke & C.P. 2010)



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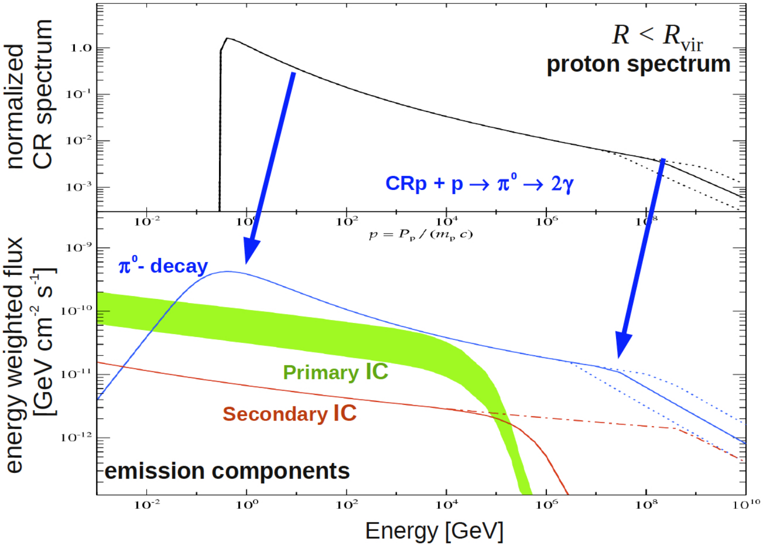

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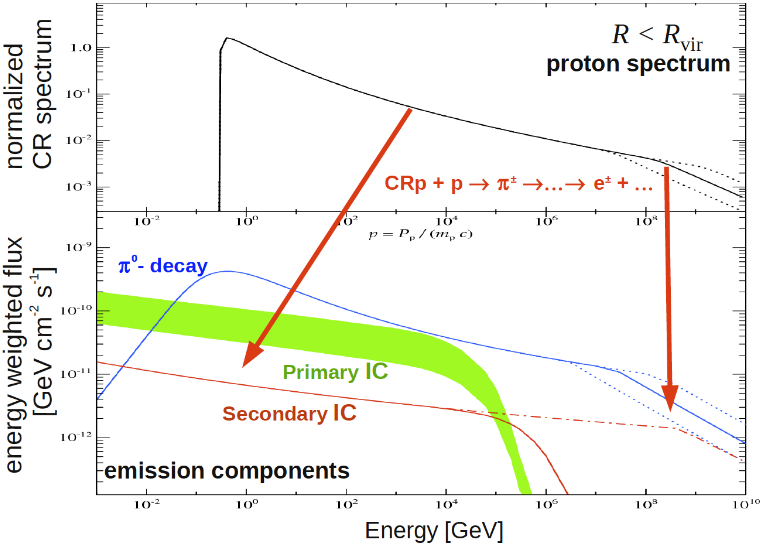
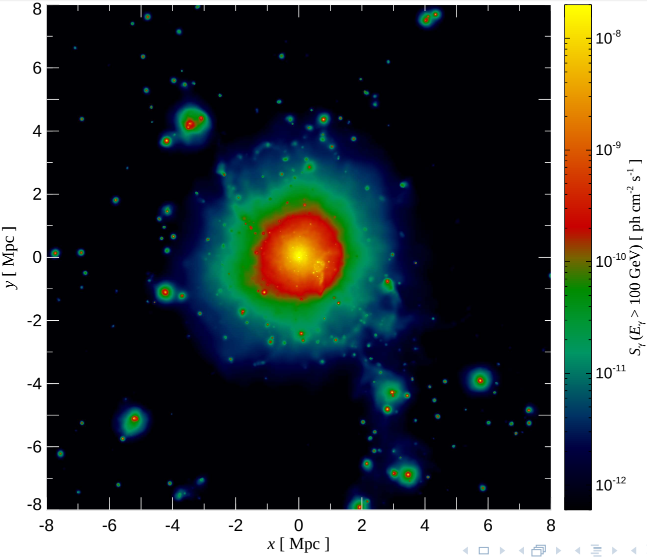
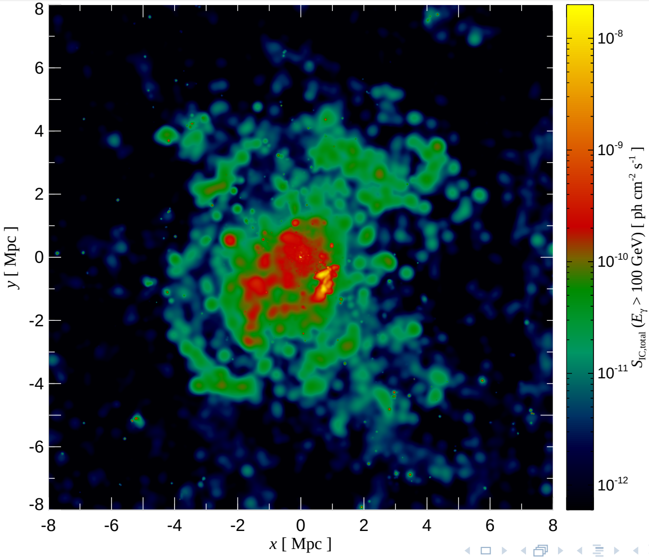


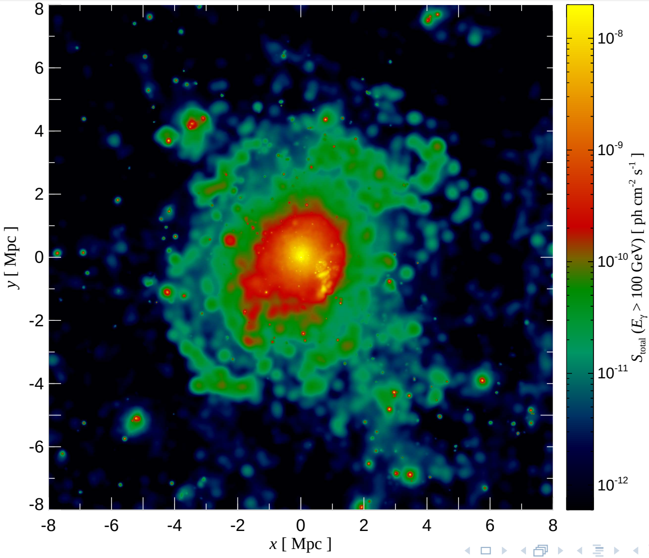
Hadronic gamma-ray emission, $E_\gamma > 100$ GeV



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

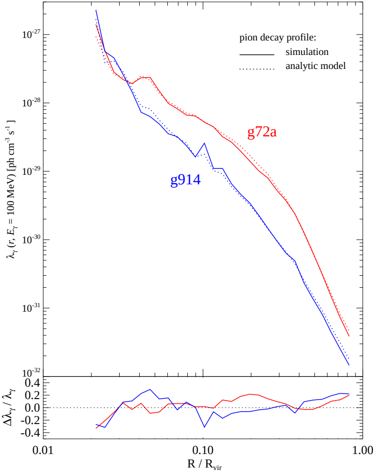


Total gamma-ray emission, $E_\gamma > 100$ GeV

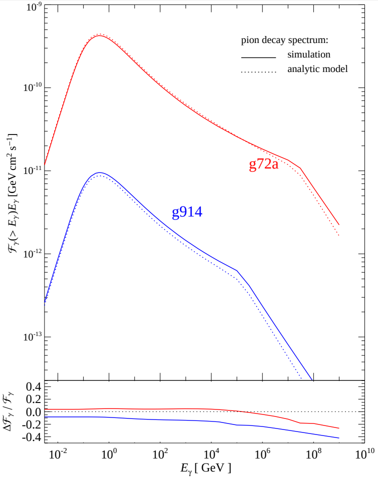


An analytic model for the cluster gamma-ray emission

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

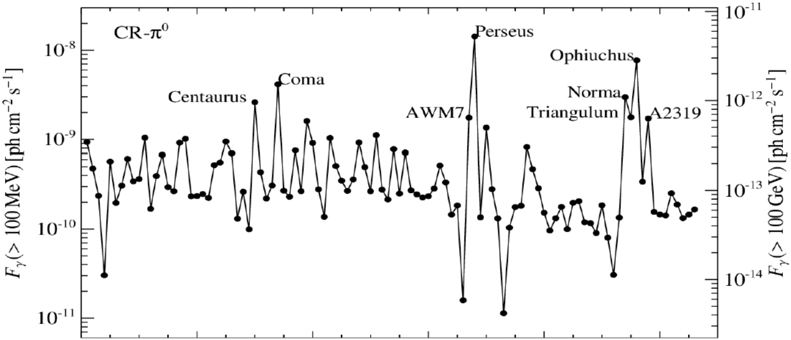


Spatial gamma-ray emission profile



Pion decay spectrum

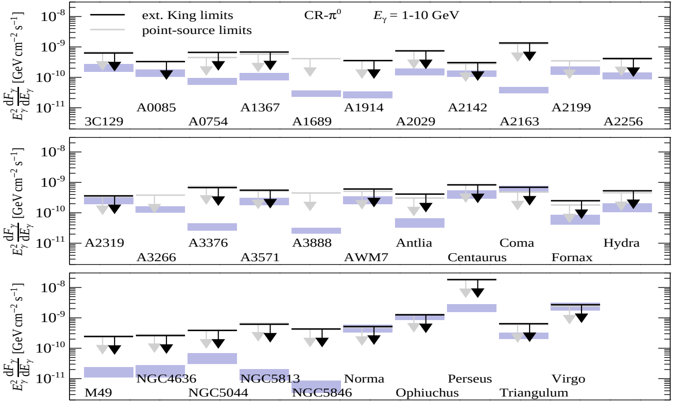
Gamma-ray flux predictions (Pinzke, C.P., Bergström 2011)



Using CR model to predict gamma-ray emission from a sample of the brightest 107 X-ray clusters (extended HIFLUGCS)

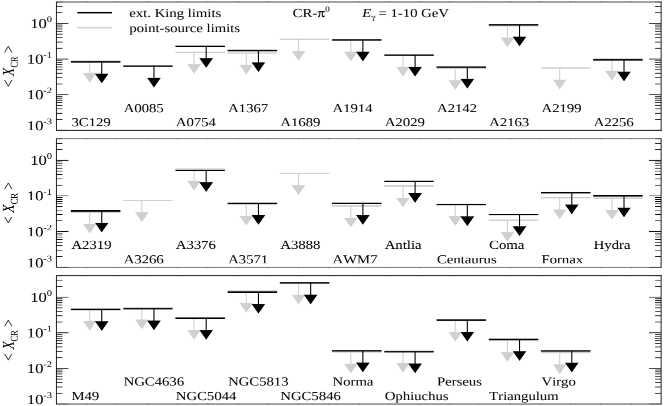
High central target densities for pion production in ***Perseus.***
→ Brightest cluster in gamma-rays!

Flux predictions vs. observations (Pinzke, C.P., Bergström 2011)



Upper limits set by Fermi-LAT after ∼18 months of operation vs. predicted gamma-ray fluxes; in the coming years we can probe the gamma-ray emission models with Fermi-LAT.

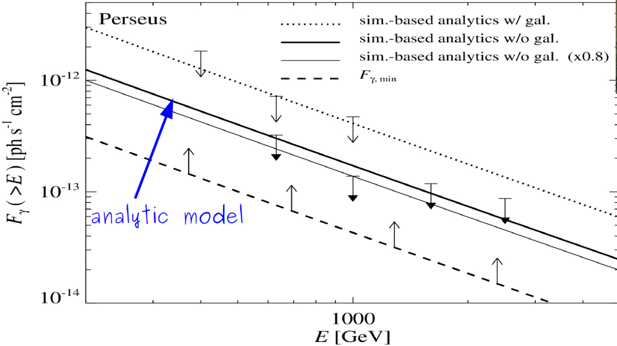
Relative CR pressure constraints (Pinzke, C.P., Bergström 2011)



The best limits on relative CR pressure $X_{CR} = P_{CR}/P_{th}$ are derived for Norma, Coma, Ophiuchus, A2319 (and Virgo) of the order of a few percent, with typical limits around 10%.

Perseus cluster observations by MAGIC

Magic - Imaging Air Cerenkov Telescope
Observation time: 85 h (effective hours); ***deepest observation of a cluster ever***
Flux upper limits: 1.4×10^{-13} [ph cm^{-2} s^{-1}] for $\Gamma=-2.2$ ($E > 1$ TeV)
Aleksic et al. 2012; Aleksic et al. 2010



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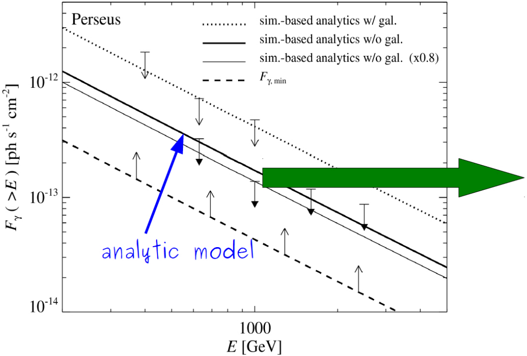

Constraining the average cosmic ray-to-thermal pressure to < 1.7% for the entire cluster

Conclusions on high-energy astrophysics 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

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

Conclusions on high-energy astrophysics in clusters

New generation of observatories

How can we read out this information about non-thermal populations?
→ new era of multi-frequency experiments:

- LOFAR, GMRT, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- NuSTAR: hard X-ray satellite ($E \simeq (1 - 100)$ keV)
- Fermi γ-ray space telescope ($E \simeq (0.1 - 300)$ GeV)
- MAGIC, H.E.S.S., Veritas, CTA: imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

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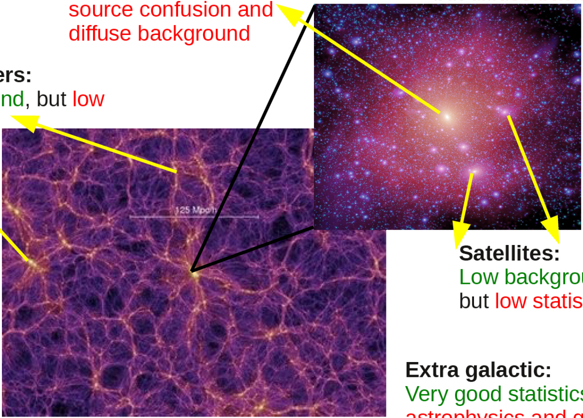
Indirect DM searches: modeling

- supersymmetric particles are Majorana particles
→ annihilate and produce gamma rays

$$N_\gamma = \left[\int_{\mathrm{LOS}} \rho_\chi^2 \, \mathrm{d}l_\chi\right] \frac{\langle \sigma v \rangle}{2 M_\chi^2} \left[\int_{E_{\mathrm{th}}}^{M_\chi} \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{SUSY}} A_{\mathrm{eff}}(E)\, \mathrm{d}E\right] \frac{\Delta\Omega}{4\pi} \tau_{\mathrm{exp}}$$

- astrophysics: contains the uncertainty about the DM profile with its central behavior and the substructure distribution
- particle physics: assuming DM is supersymmetric, there is the uncertainty about the cross section, neutralino mass, and decay channels
- detector properties: energy dependent effective area, detector response, scanning strategy, . . .

Indirect DM searches: sources



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

Milky Way halo:
Very good statistics,
but diffuse background

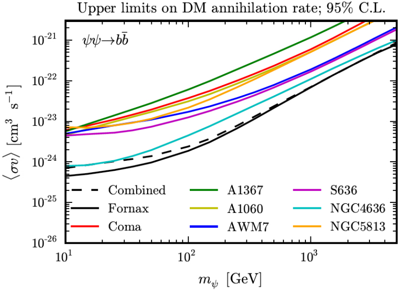
Galaxy clusters:
Low background, but low
statistics

Satellites:
Low background,
but low statistics

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

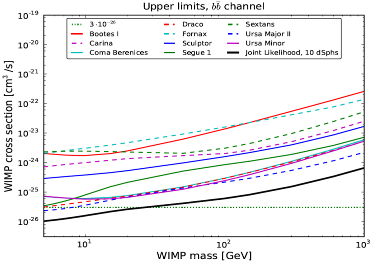
DM searches in clusters vs. dwarfs

Galaxy clusters:



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

Dwarf galaxies:

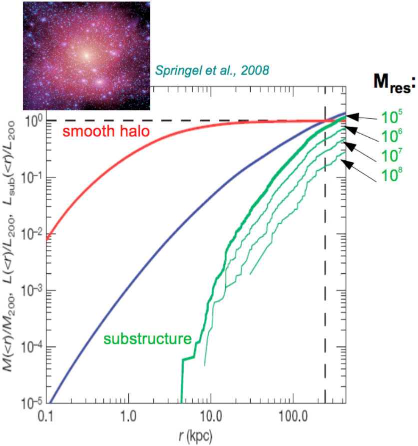


Ackermann et al. (Fermi-LAT) 2011

- combined limits for dwarf galaxies $\sim$ 20 times more constraining
- high-resolution CDM simulations predict substructures that boost the γ-ray flux → clusters should outshine dwarfs by $\gtrsim 10$

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

Enhancement from DM substructures


Springel et al., 2008

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

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

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

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

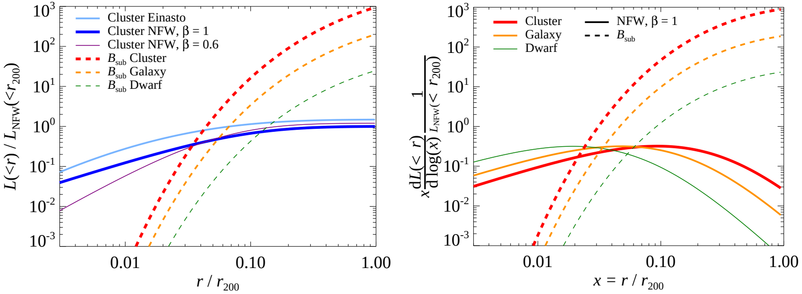
Hofmann, Schwarz and Stöcker, 2008
Green, Hofmann and Schwarz, 2005

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

Luminosity boosted by ~1000 in clusters

Pinzke et al. 2011, Gao et al 2011

Spatial DM distribution

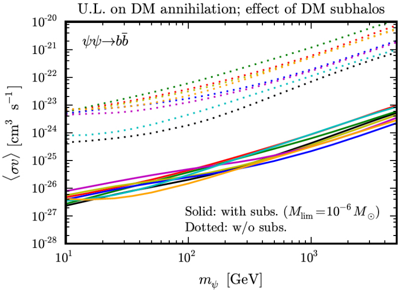


Pinzke, C.P., Bergström 2011

- 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

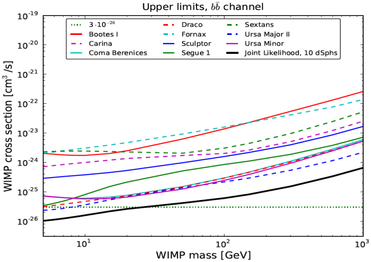
DM searches in clusters vs. dwarfs

Clusters with substructures:



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

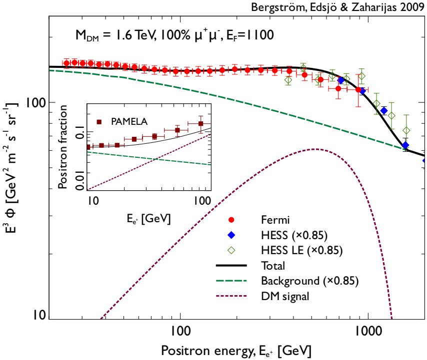
Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

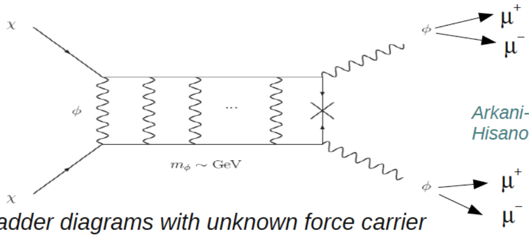
- galaxy clusters $\sim$ 10 times more constraining than dwarf satellites when accounting for substructures!

Sommerfeld enhancement



- DM annihilating into leptons can explain the excess of e^+/e^- seen by PAMELA/Fermi-LAT
- need enhancement of cross-section over standard value $\rightarrow$ Sommerfeld enhancement: $\langle \sigma \upsilon \rangle \sim c/\upsilon$ (Arkani-Hamed et al. 2009)

Sommerfeld enhancement



ladder diagrams with unknown force carrier

Arkani-Hamed et al. 2009
Hisano, Matsumoto, and Nojiri 2004

$$\langle\sigma v\rangle \approx \langle\sigma v\rangle_0 \times (c/v)$$

$$v = 960\ \mathrm{km/s} \times (M_{200}/10^{15}\ M_\odot)^{1/3}$$

$$\Downarrow$$

$$\boxed{L_{xx} \sim \langle\sigma v\rangle \int dV\ \rho^2}$$

Boost from sommerfeld enhancement (SFE) in the Milky Way DM halo is limited to $\lesssim$ 400. Saturated boost can be larger.

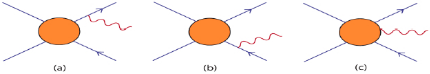
Finkbeiner et al. 2010

DM-induced gamma rays: *leptophilic models*

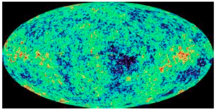
Annihilation rate in these models enhanced by **Sommerfeld effect** as well as **DM substructures**.

Gamma-ray emission components:

- Final state radiation



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



DM-induced gamma rays: *SUSY benchmark models*

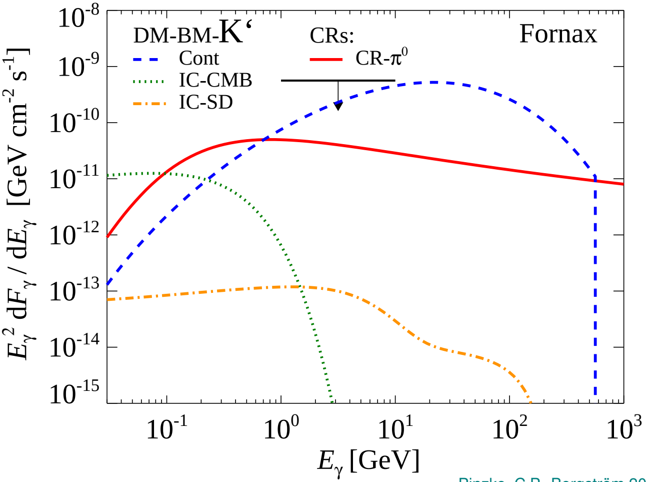
Representation of high mass (~1 TeV) DM models with high gamma-ray emission.

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

Gamma-ray emission components:

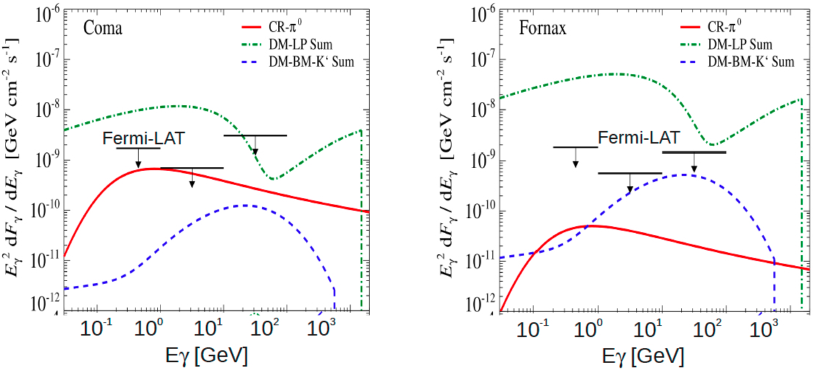
- Annihilating neutralinos emitting continuum emission
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)

Gamma-ray spectrum: benchmark DM model vs. CRs



Pinzke, C.P., Bergström 2011

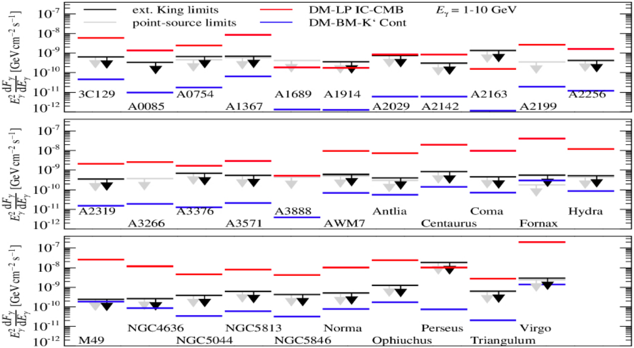
Comparing clusters and emission processes



Pinzke, C.P., Bergström 2011

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

DM flux predictions vs. observations



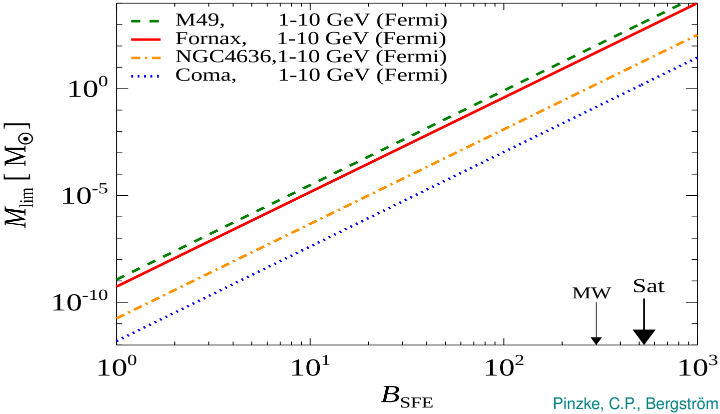
Pinzke et al. 2011

Emission from leptophilic models in most clusters detectable with Fermi-LAT after 18 months of operation.

Supersymmetric DM models will start being probed in coming years.

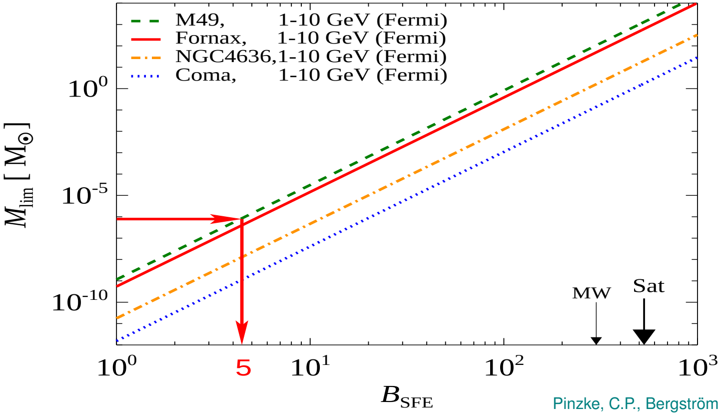
Brightest clusters: Fornax, Ophiuchus, M49, Centaurus (and Virgo).

Constraining boost factors *(leptophilic models)*



Pinzke, C.P., Bergström 2011

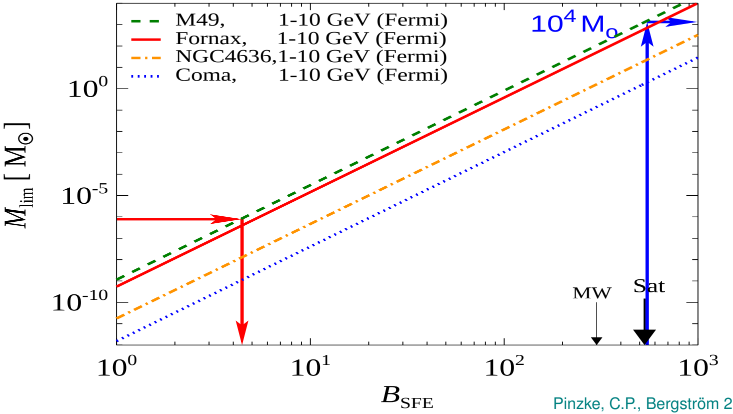
Constraining boost factors *(leptophilic models)*



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 $M_{\text{min}} \simeq 10^{-6}\,\text{M}_\odot$)
- flat brightness profiles and spatially extended $\rightarrow$ challenging for IACTs, better probed by Fermi-LAT

Leptophilic DM models:

- Fermi-LAT data constrains the Sommerfeld enhancement to < 5
- if DM interpretation of lepton excess seen by PAMELA/Fermi is correct, then smallest subhalos have $M > 10^4\,\text{M}_\odot$

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

Non-thermal signatures:

- Pinzke & Pfrommer, *Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution*, 2010, *MNRAS*, 409, 449.
- Pfrommer, *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*, 2008, *MNRAS*, 385, 1242.
- 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.
- 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.

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.