Open question for plasma physics in galaxies: ISM, CGM and galactic winds

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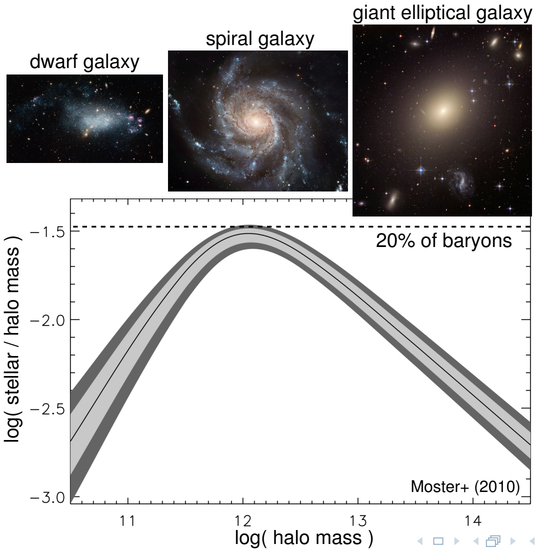
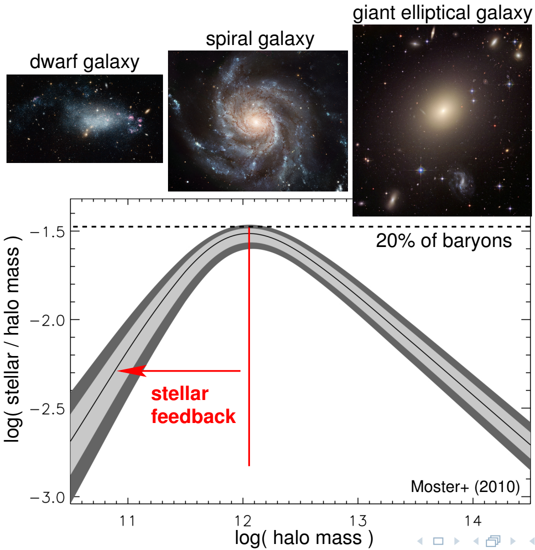
Plasma Observatory: Astrophysics Science Working Group, May 2025

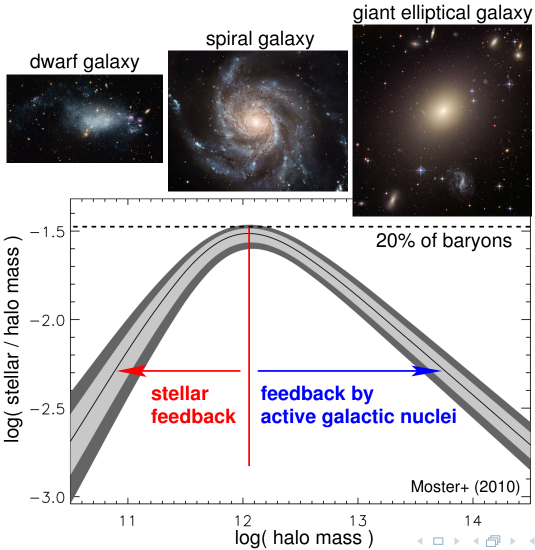
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



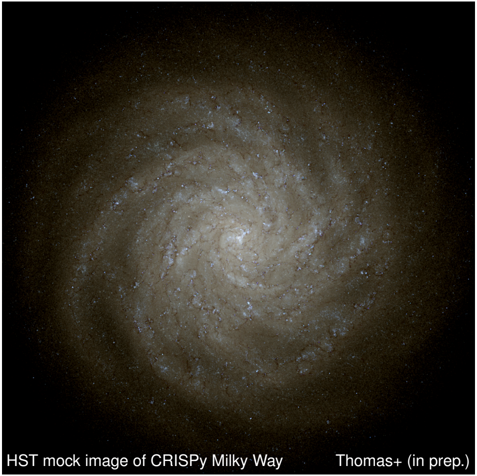
Stellar feedback

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- thermal pressure provided by supernovae or active galactic nuclei?
- radiation pressure and photoionization by massive stars and quasars?
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?

Cosmic ray transport in galaxies

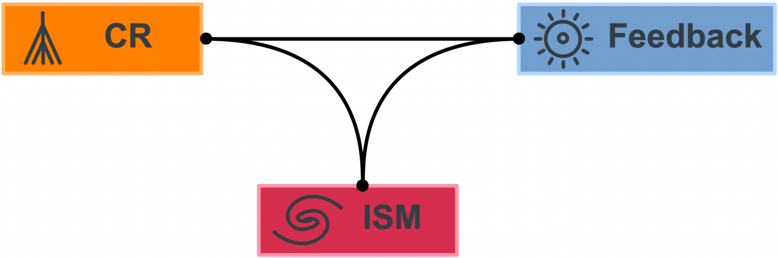


- CR transport in galaxies demands modeling non-linear Landau damping (in warm/hot phase) and ion-neutral damping (in disk)
- this requires resolving the multi-phase structure of the ISM
- development of CRISP framework (**C**osmic **R**ays and **I**nter**S**tellar **P**hysics, Thomas+ 2025)

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics

Feedback

CR

ISM

Chemistry

- Full H – H_2 – He chemistry
  sets ionization degree
- First ionization stages of C – O – Si
  low temperature cooling
- Photoelectric heating by dust

Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics

CR

ISM

Feedback

- Improved SNe treatment (manifestly isotropic)
  and stellar winds
- FUV NUV OPT radiation fields (reverse ray tracing)
  absorbed by dust – impacting **Chemistry**
- Metal enrichment

Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics

Feedback

ISM

CR

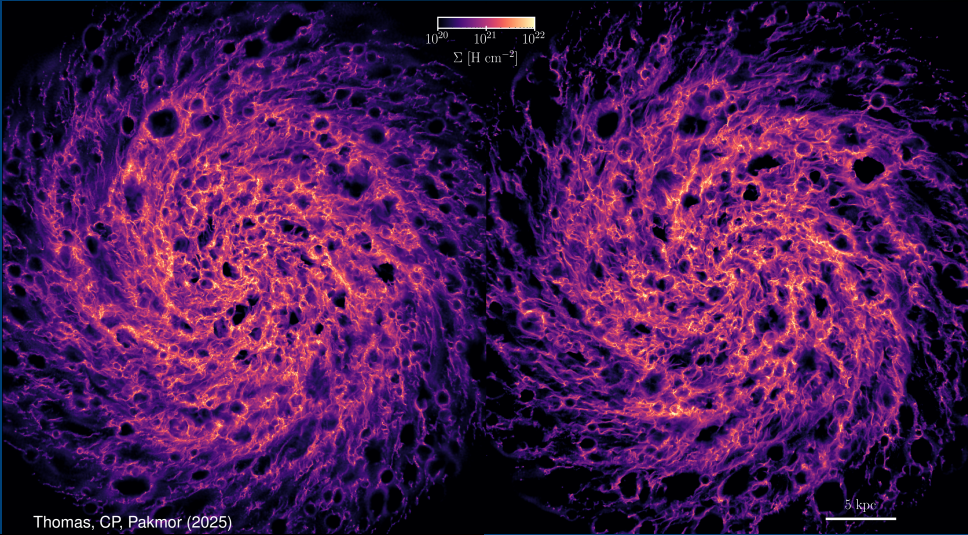
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting **Chemistry**
- CR microphysics

Follow $\varepsilon_{\mathrm{cr}}$ and v_{cr}

Self-consistently evolve κ_{cr}

Thomas, CP, Pakmor (2025)

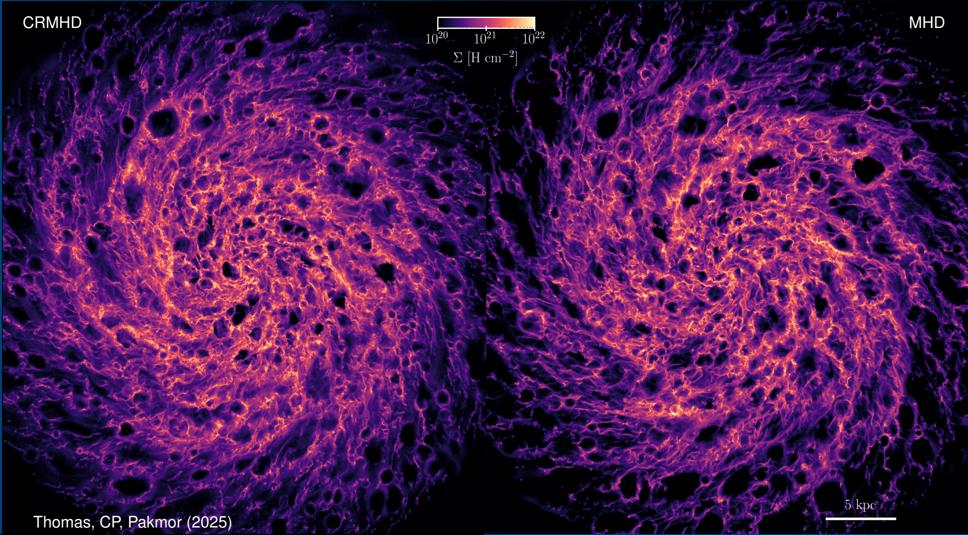
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

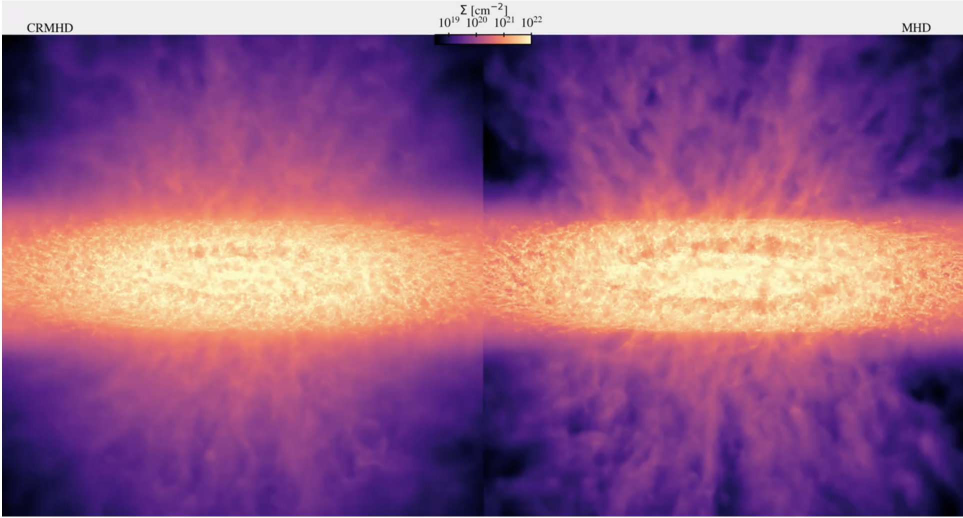
Multi-phase ISM modeling

Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves



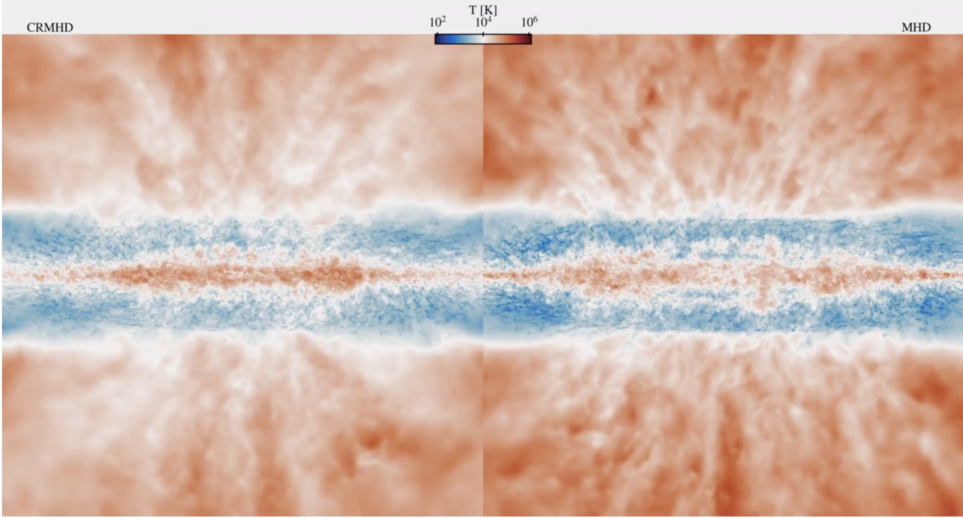
Simulated Milky Way: surface density

Cosmic rays drive galactic winds, ram pressure propells mainly galactic fountains



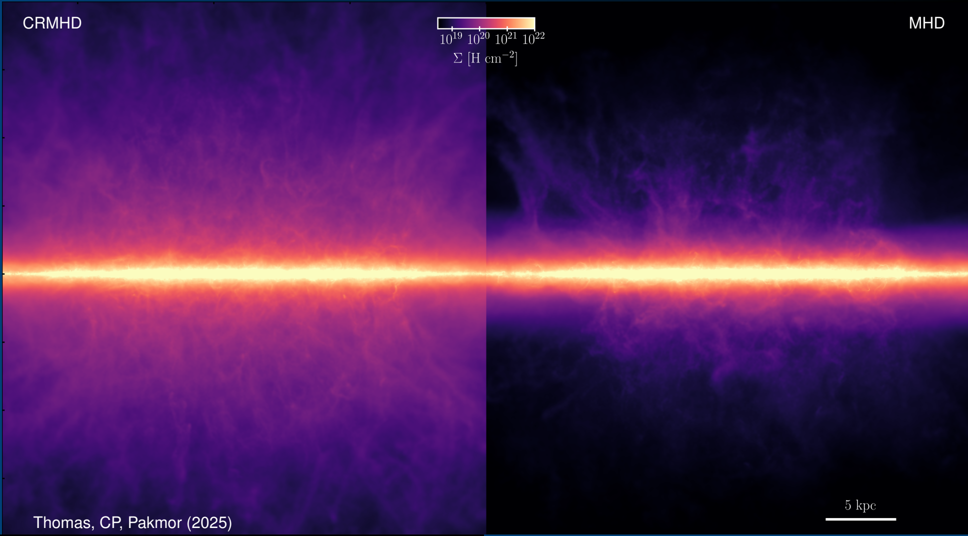
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

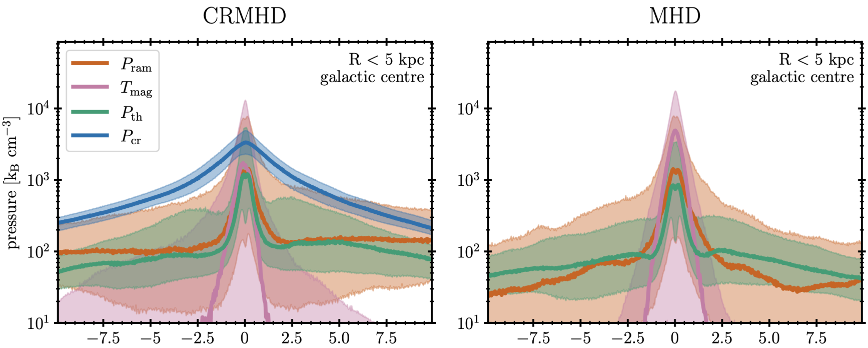


Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Cosmic ray driven wind: mechanism

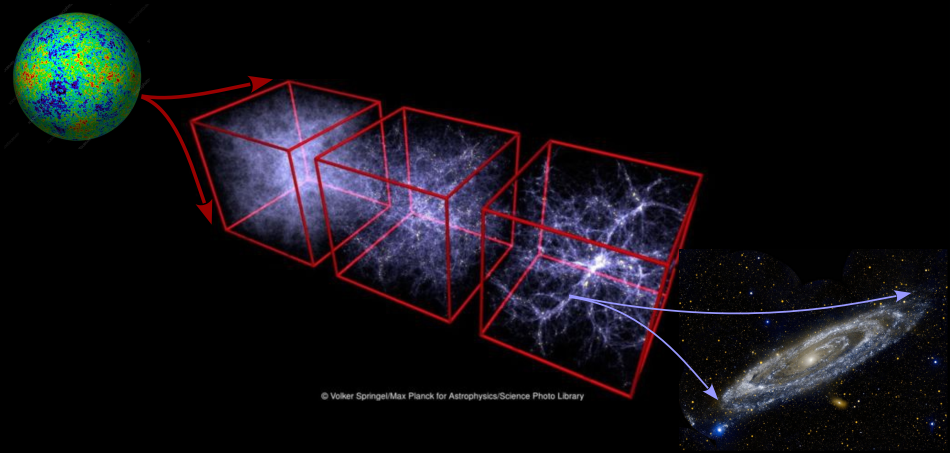


Thomas, CP, Pakmor (2025)

- CR pressure gradient dominates over thermal and ram pressure gradient and drives outflow:

$$|\nabla P_{\rm cr} + \nabla P_{\rm th}| > \rho|\nabla\Phi|$$

Cosmological galaxy formation



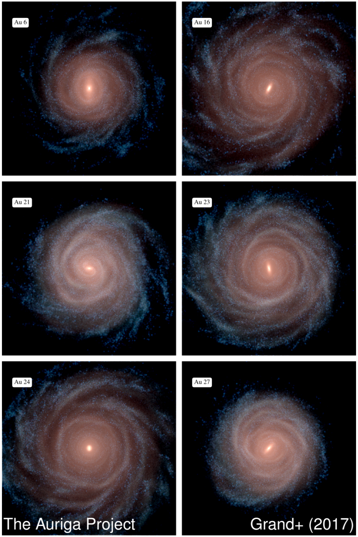
Cosmic rays in cosmological galaxy simulations

The galaxy formation model

- primordial and metal line cooling
- sub-resolution model for star formation (Springel+ 03)
- mass and metal return from stars to ISM
- cold dense gas stabilized by pressurized ISM
- thermal and kinetic energy from supernovae modeled by isotropic wind – launched outside of SF region
- black hole seeding and accretion model (Springel+ 05)
- thermal feedback from AGN in radio and quasar mode
- uniform magnetic field of 10^{-10} G seeded at $z = 128$

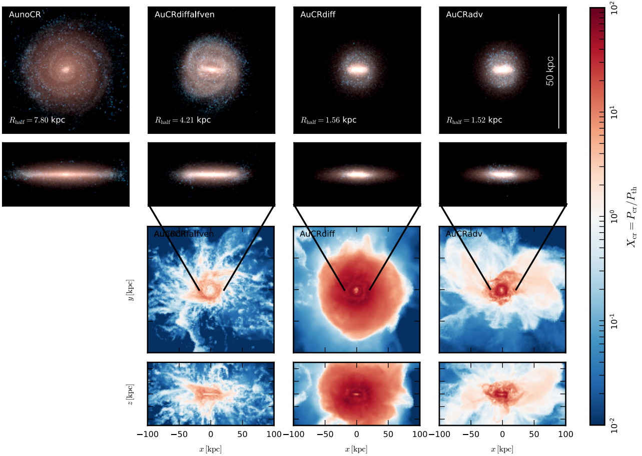
Simulation suite (Buck, CP+ 2020)

- 2 galaxies, baryons with $5 \times 10^4\,\mathrm{M}_\odot \sim 5 \times 10^6$ resolution elements in halo, 2×10^6 star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling



Cosmic rays in cosmological galaxy simulations

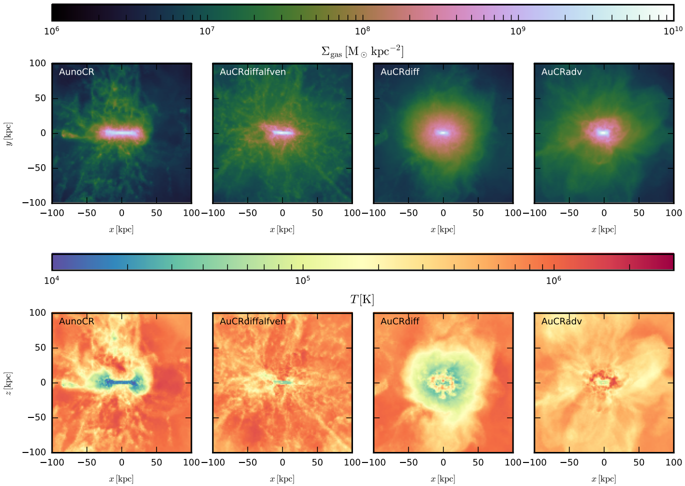
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor, Grand, Springel (2020)

Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium



Buck, CP, Pakmor, Grand, Springel (2020)

Plasma formulae

- Plasma beta $\beta = \frac{P_{\mathrm{th}}}{P_B}$
- Sonic Mach number $\mathcal{M}_{\mathrm{s}} = \frac{v}{c_{\mathrm{s}}}$
- Alfvénic Mach number $\mathcal{M}_{\mathrm{A}} = \frac{v}{v_{\mathrm{A}}} = \mathcal{M}_{\mathrm{s}}\sqrt{\frac{\gamma}{2}\beta}$
- Spitzer mean free path:

$$\lambda_{\mathrm{mfp}} \sim \frac{1}{\pi n_{\mathrm{i}} \ln\Lambda}\left(\frac{k_{\mathrm{B}}T_{\mathrm{e}}}{Ze^2}\right)^2, \text{ where } n_{\mathrm{i}} = x_{\mathrm{ion}}n$$

$$\ln\Lambda \sim \ln\frac{\lambda_{\mathrm{D}}}{r_{\mathrm{e}}} \sim \ln\sqrt{\frac{(k_{\mathrm{B}}T)^3}{n_{\mathrm{e}}4\pi Z^3e^6}}$$

- Alfvén speed $v_{\mathrm{A}} = \frac{B}{\sqrt{\mu_0 n_{\mathrm{i}} m_{\mathrm{i}}}}$
- Plasma frequency $\omega_{\mathrm{e}} = \sqrt{\frac{e^2 n_{\mathrm{e}}}{\epsilon_0 m_{\mathrm{e}}}} = \sqrt{\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}}\omega_{\mathrm{i}}$
- Cyclotron frequency $\Omega_{\mathrm{i0}} = \frac{eB}{m_{\mathrm{i}}}$
- Ion skin depth $d_{\mathrm{i}} = \frac{v_{\mathrm{A}}}{\Omega_{\mathrm{i0}}} = \frac{c}{\omega_{\mathrm{i}}}$

Plasma parameters in the ISM

	ISM		
parameters	cold ($x_{\rm ion} \sim 10^{-3}$)	warm	hot
T [K]	10	10^4	$10^6 - 10^7$
n [cm^{-3}]	10^3	1	$10^{-2} - 10^{-3}$
$\lambda_{\rm mfp}$ [cm]	10^6	5×10^{11}	3×10^{17}
B [μG]	30	3	0.3
$v_{\rm A}$ [km s^{-1}]	60	6	6
β	0.03	3	300
$\mathcal{M}_{\rm s}$	$0.1 - 1$	$0.3 - 10$	0.1
$\mathcal{M}_{\rm A}$	0.01	$0.5 - 20$	0.5
$\omega_{\rm e}$ [s^{-1}]	5×10^4	5×10^4	5×10^3
$\Omega_{\rm i0}$ [s^{-1}]	0.3	3×10^{-2}	3×10^{-3}
$d_{\rm i}$ [cm]	2×10^7	2×10^7	2×10^8

Plasma parameters in the CGM and ICM

parameters	CGM	ICM
T [K]	10^6	$10^7 - 10^8$
n [cm^{-3}]	10^{-3}	$10^{-3} - 10^{-4}$
λ_{mfp} [cm]	3×10^{17}	5×10^{21}
B [μG]	0.5	1
v_{A} [km s^{-1}]	30	100
β	10	100
$\mathcal{M}_{\mathrm{s}}$	0.1	$0.1 - 2$
$\mathcal{M}_{\mathrm{A}}$	0.3	$1 - 20$
ω_{e} [s^{-1}]	1×10^3	1×10^3
Ω_{i0} [s^{-1}]	5×10^{-3}	1×10^{-2}
d_{i} [cm]	7×10^8	7×10^8

Review on cosmic ray feedback

Astron Astrophys Rev (2023) 31:4
https://doi.org/10.1007/s00159-023-00149-2

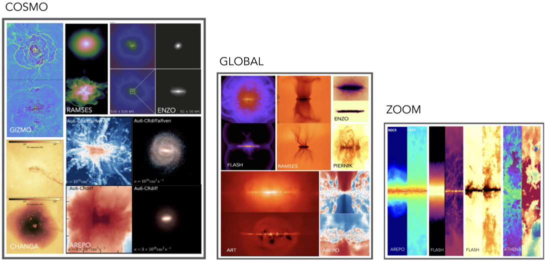
REVIEW ARTICLE

Check for updates

Cosmic ray feedback in galaxies and galaxy clusters

A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

Mateusz Ruszkowski[1,3] · Christoph Pfrommer[2]



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

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