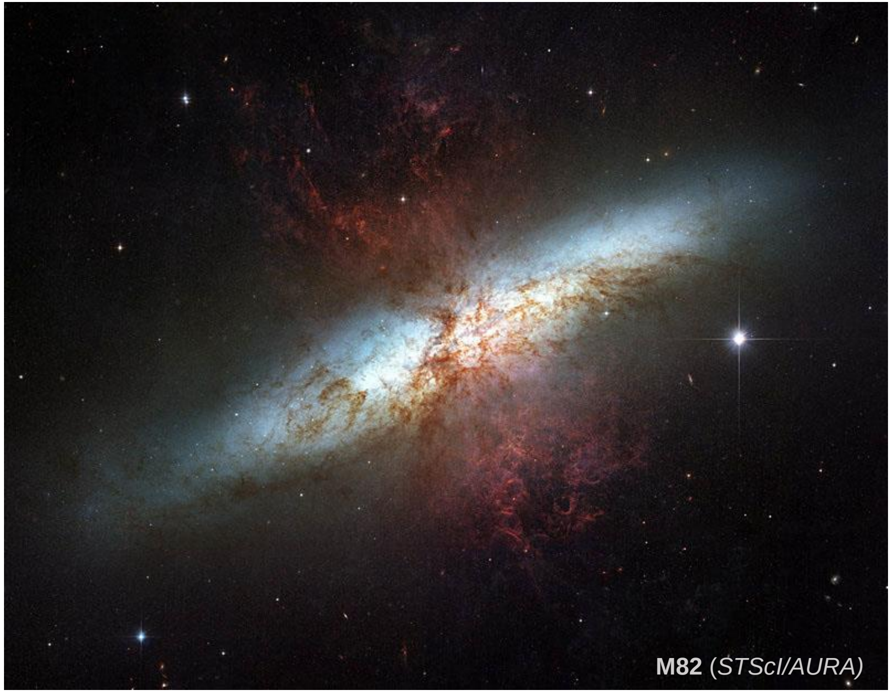
The role of cosmic rays in galaxy evolution

Volker Springel



M82 *(STScI/AURA)*

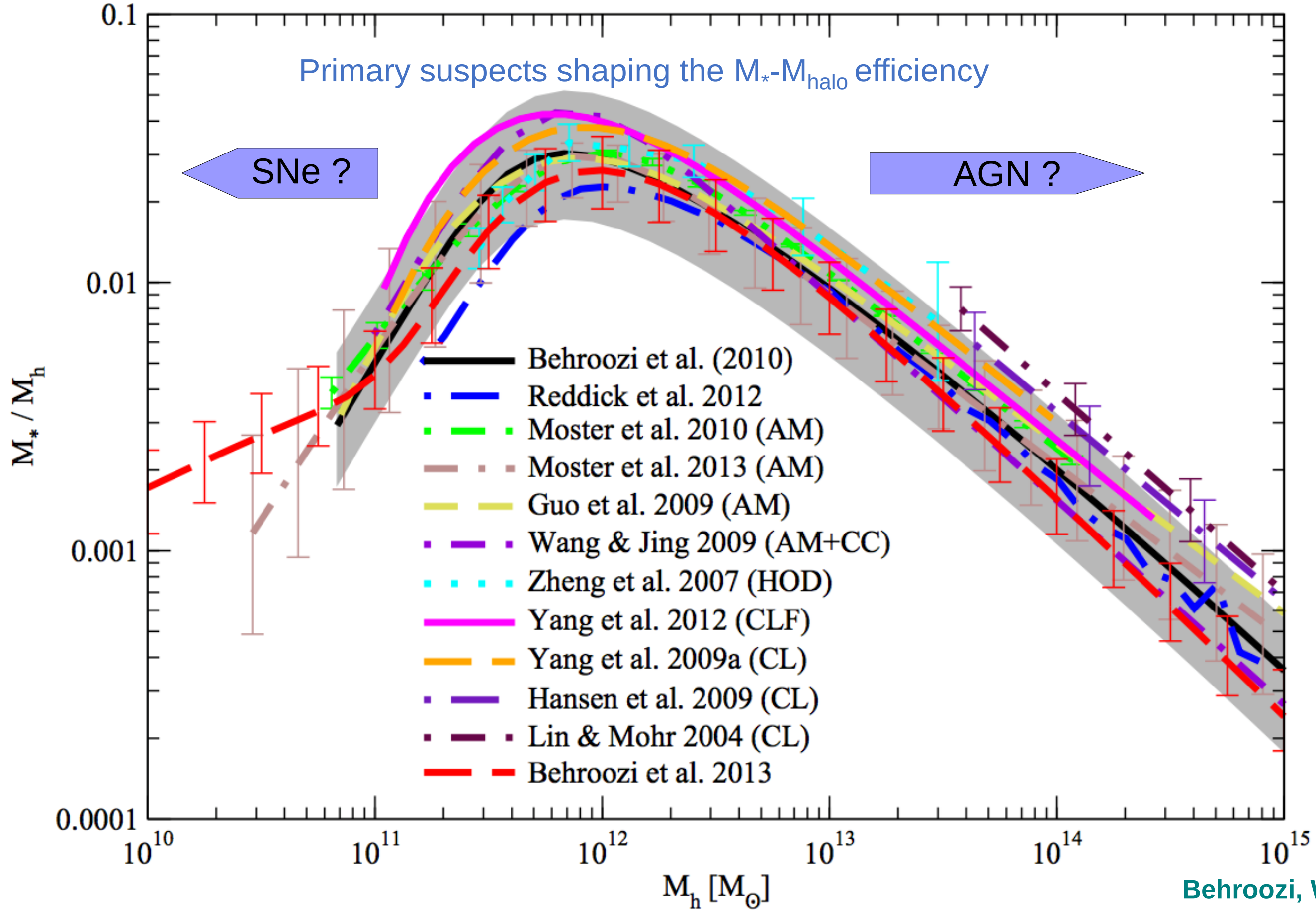
- The need for (cosmic ray) feedback in galaxy formation
- Cosmic rays as drivers of galactic outflows
- Cosmic rays in galaxy clusters
- Structure formation shocks and cosmic rays

Max-Planck-Institute
for Astrophysics

HazelHen, 7.4 Pflops
HLRS Stuttgart

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

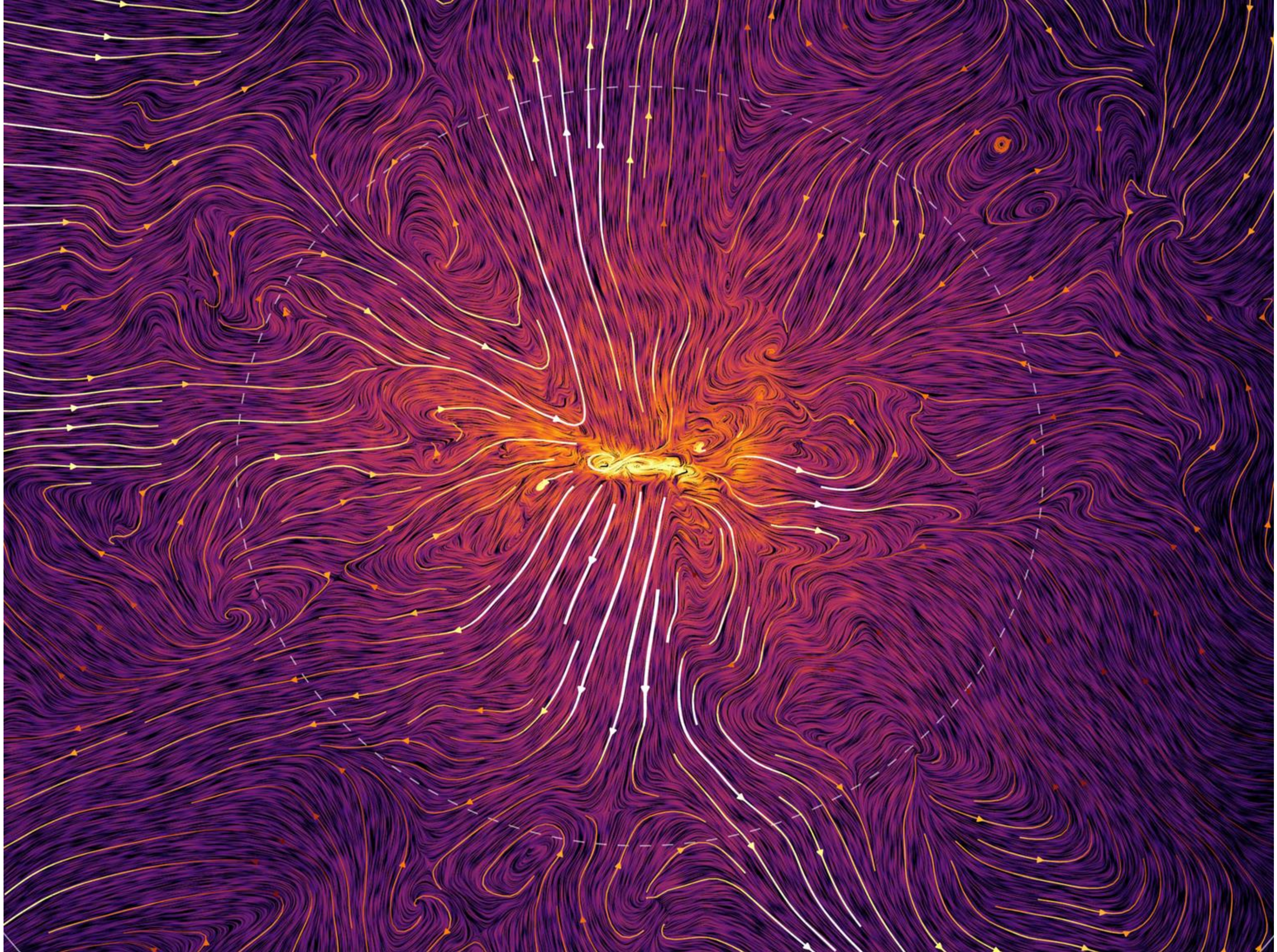
MODULATION OF GLOBAL STAR FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS



Behroozi, Wechsler & Conroy (2013)

How can galaxies shed a substantial fraction of their baryonic content?

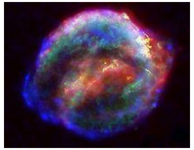
MFLOWS IN THE CIRCUM-GALACTIC MEDIUM IN A GALAXY FROM THE TNG-50 SIMULATION



Nelson et al. (2019)

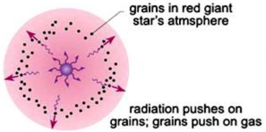
But what physics is responsible for feedback in the first place?

- Supernova explosions (energy & momentum input)
- Stellar winds
- AGN activity
- Radiation pressure on dust
- Photoionizing UV background and Reionization
- Modification of cooling through local UV/X-ray flux
- Photoelectric heating
- Cosmic ray pressure
- Magnetic pressure and MHD turbulence
- TeV-blazar heating of low density gas
- Exotic physics (decaying dark matter particles, etc.)

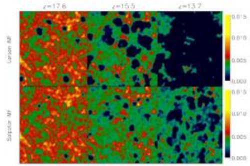


Kepler's Supernova

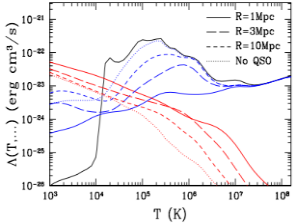
Bubble Nebula

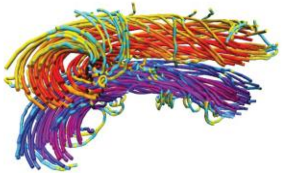


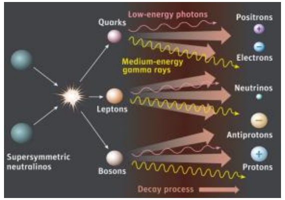
Ciardi al. (2003)



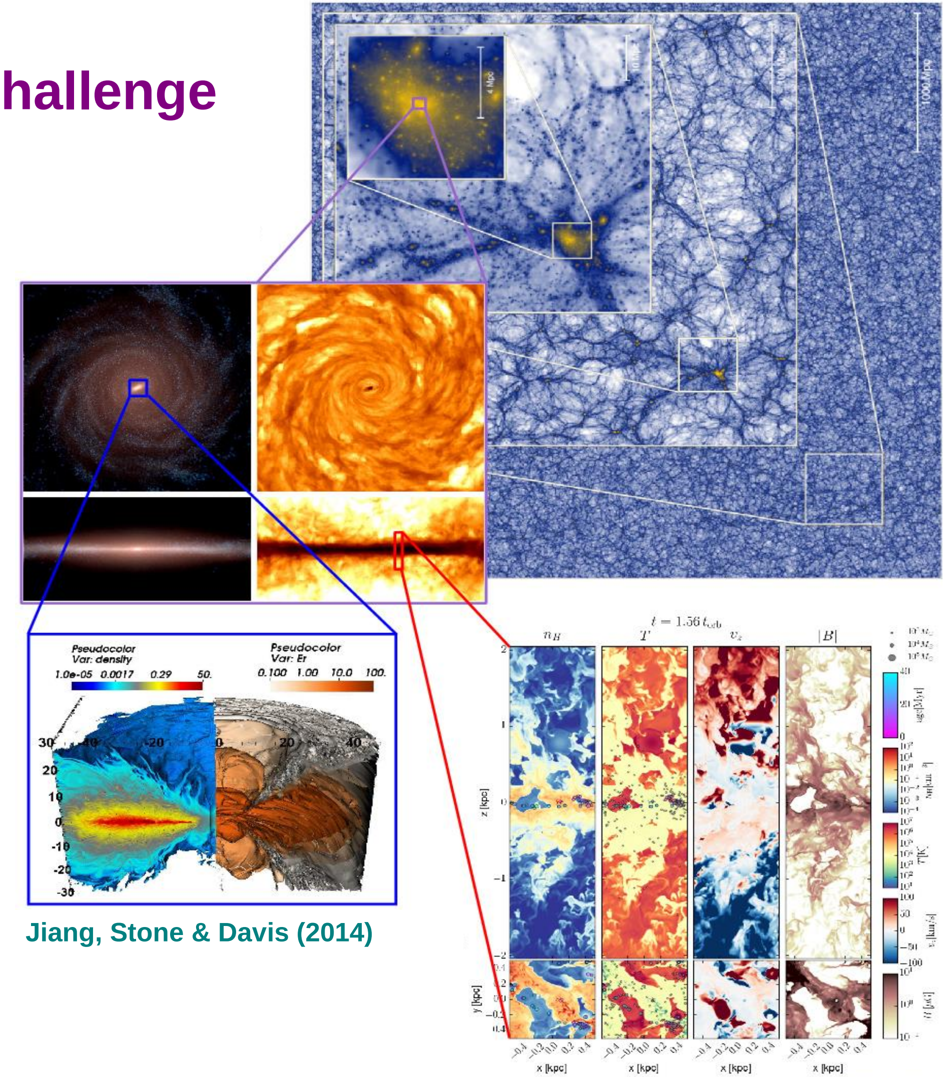
Gneding & Hollon (2012)







The dynamic range challenge



Angulo et al. (2012)

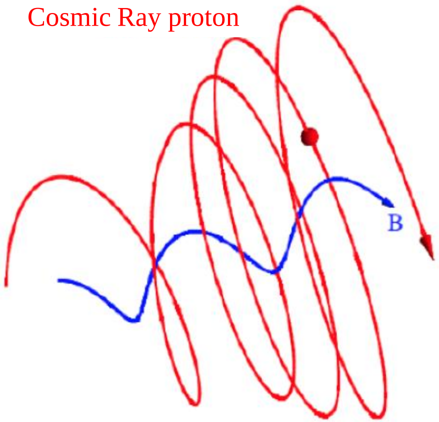
Grand et al. (2016)

Jiang, Stone & Davis (2014)

Kim & Ostriker (2016)

The Cosmic Ray dynamics is coupled to magnetic fields permeating the gas

INTERACTIONS OF COSMIC RAYS AND MAGNETIC FIELDS



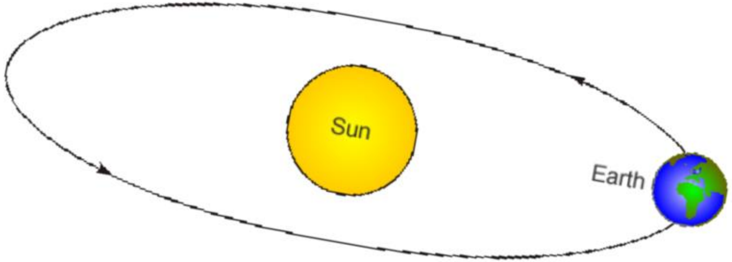
Cosmic rays scatter on magnetic fields – this lets them exert a pressure on the thermal gas, and diffuse relative to their rest frame.

Streaming instability:

- CRs can in principle move rapidly along field lines (with c), which acts to reduce any gradient in their number density.
- But if $c_s > v_A$, CRs excite Alfven waves (streaming instability)
- scattering off this wave field in turn limits the CR bulk speed to a much smaller, effective streaming speed v_{str}
- streaming speed: $$\mathbf{v}_{\rm str} = -v_{\rm str}\frac{\nabla P_{\rm cr}}{|\nabla P_{\rm cr}|}$$ $$v_{\rm str} = \lambda \max(c_S, v_A)$$ $$\lambda \sim 1$$

Adding cosmic rays to galaxy formation simulations makes the dynamic range problem much harder

GYRO-RADIUS COMPARED TO THE SIZE OF A GALAXY



Milky Way-like galaxy:

$$r_{\mathrm{gal}} \sim 10^4\ \mathrm{pc}$$

gyro-orbit of GeV cosmic ray:

$$r_{\mathrm{cr}} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6}\ \mathrm{pc} \sim \frac{1}{4}\ \mathrm{AU}$$

→ **Need to develop an effective two-fluid theory that can be treated with hydrodynamical methods**

CR dynamics and transport complicates fluid dynamics considerably

COSMIC RAY DYNAMICS WITHOUT SOURCE AND SINK TERMS

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \mathbf{F} = \boldsymbol{S}$$

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \varepsilon \\ \varepsilon_{\rm cr} \\ \boldsymbol{B} \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v}^{\rm T} + P\mathbf{1} - \boldsymbol{B}\boldsymbol{B}^{\rm T} \\ (\varepsilon + P)\boldsymbol{v} - \boldsymbol{B}\,(\boldsymbol{v}\cdot\boldsymbol{B}) \\ \varepsilon_{\rm cr}\boldsymbol{v} + (\varepsilon_{\rm cr} + P_{\rm cr})\boldsymbol{v}_{\rm st} - \kappa_\varepsilon \boldsymbol{b}\,(\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\rm cr}) \\ \boldsymbol{B}\boldsymbol{v}^{\rm T} - \boldsymbol{v}\boldsymbol{B}^{\rm T} \end{pmatrix}, \quad \boldsymbol{S} = \begin{pmatrix} 0 \\ \boldsymbol{0} \\ P_{\rm cr}\,\boldsymbol{\nabla}\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr} + \Lambda_{\rm th} + \Gamma_{\rm th} \\ -P_{\rm cr}\,\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr} + \Lambda_{\rm cr} + \Gamma_{\rm cr} \\ \boldsymbol{0} \end{pmatrix}$$

$$P = P_{\rm th} + P_{\rm cr} + \frac{\boldsymbol{B}^2}{2} \qquad \varepsilon = \varepsilon_{\rm th} + \frac{\rho \boldsymbol{v}^2}{2} + \frac{\boldsymbol{B}^2}{2} \qquad \boldsymbol{v}_{\rm st} = -\frac{\boldsymbol{B}}{\sqrt{\rho}}\,\mathrm{sgn}(\boldsymbol{B}\cdot\boldsymbol{\nabla}P_{\rm cr})$$

Energy equation:

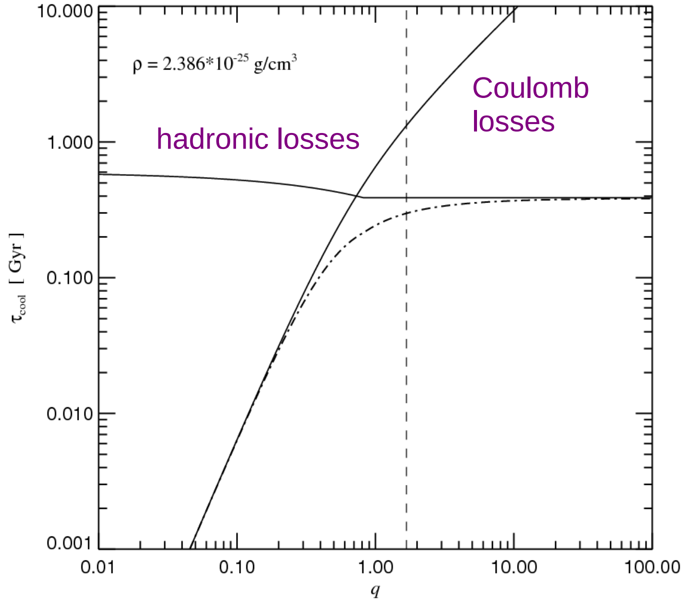
cosmic ray streaming, nasty(!) numerically

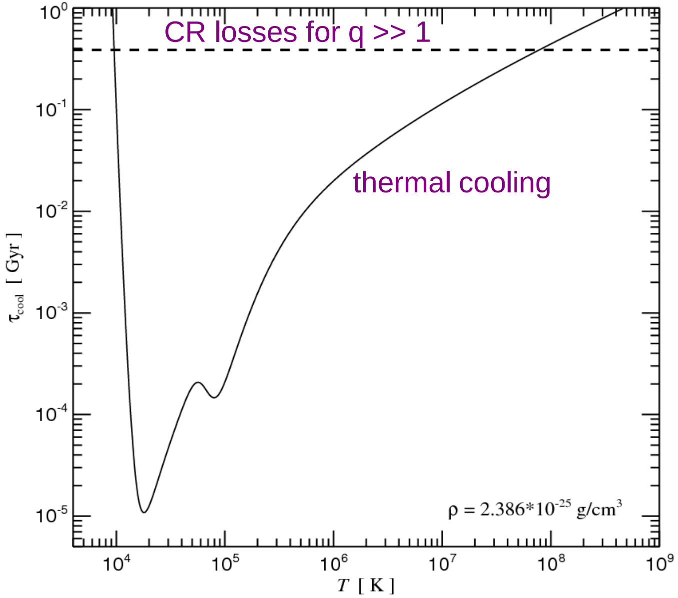
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot\left[\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st}) - \kappa_\varepsilon \boldsymbol{b}\,(\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\rm cr})\right] = -P_{\rm cr}\,\boldsymbol{\nabla}\cdot(\boldsymbol{v} + \boldsymbol{v}_{\rm st}) + \Lambda_{\rm cr} + \Gamma_{\rm cr}$$

anisotropic diffusion

CRs have a larger dissipation timescale than thermal cooling, and the softer equation of states keeps the pressure high in outflows

COMPARISON OF DISSIPATION TIMESCALES





Also important: Softer equation of state, $P \sim \rho^{4/3}$ (buoyancy effects!)

Jubelgas et al. (2006)

And, CR dissipation dumped into thermal reservoir increases the pressure.

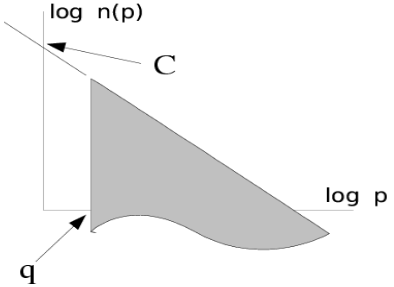
$$\Delta E/V = P/(\gamma - 1) = P_{cr}/(\gamma_{cr} - 1)$$

The Galactic cosmic ray energy spectrum provides a significant contribution to the total ISM pressure

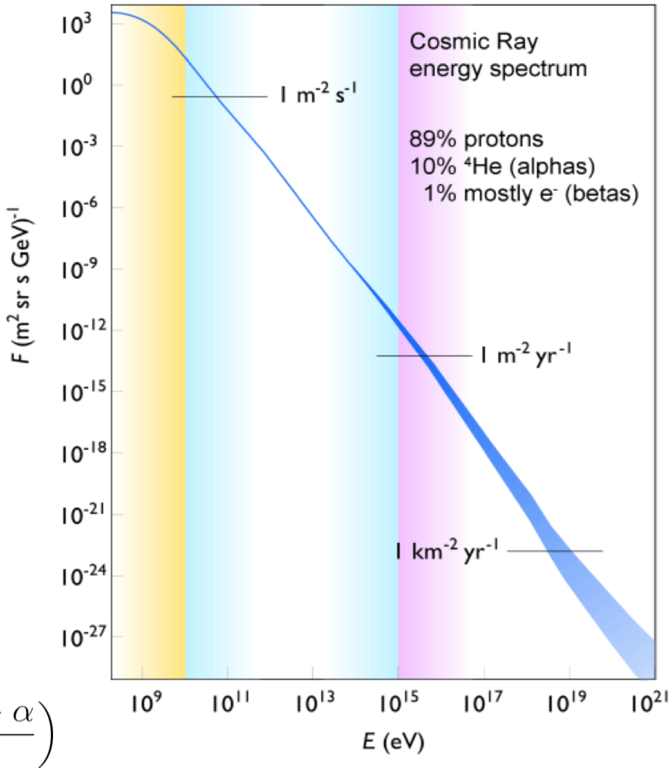
GLOBAL PROPERTIES OF GALACTIC COSMIC RAYS

Approximation as an isotropic power-law in momentum

$$f(p) = \frac{\mathrm{d}N}{\mathrm{d}p\,\mathrm{d}V} = C\,p^{-\alpha}\theta(p-q)$$



$$P_{\mathrm{CR}} = \frac{C\,m_{\mathrm{p}}c_{\mathrm{light}}^2}{6}\,\mathcal{B}_{\frac{1}{1+q^2}}\left(\frac{\alpha-2}{2},\frac{3-\alpha}{2}\right)$$



data compiled by Swordy

energy density in cosmic rays:
comparable to thermal and magnetic energy densities in ISM (equipartition)

main production mechanisms:

- supernova shocks (10-30% of the energy appears as CRs)
- large-scale structure formation shocks

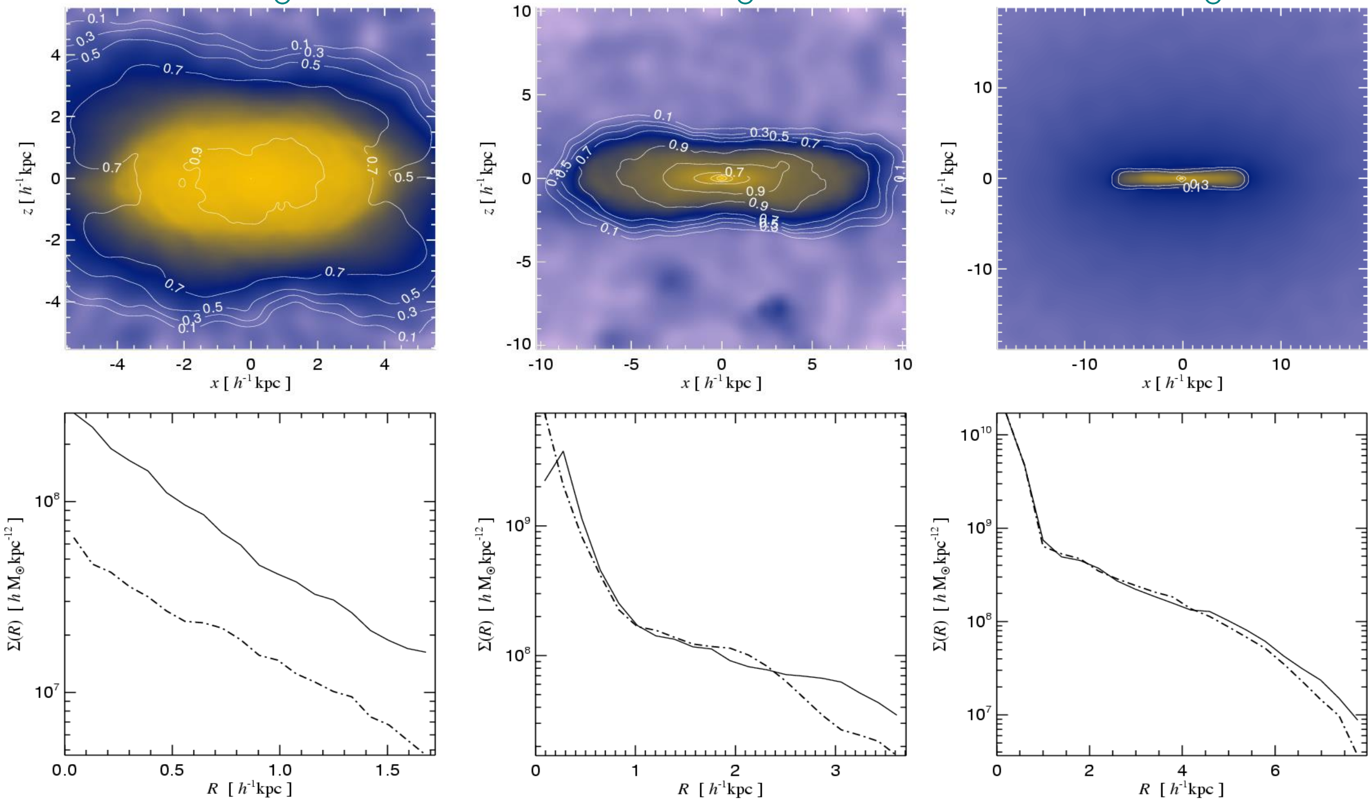
main dissipation mechanisms:

- Coulomb losses
- hadronic interactions, mostly pion production
- Bremsstrahlung (negligible for protons)

Cosmic rays injected by supernovae affect star-forming dwarf galaxies

EDGE-ON GAS AND PRESSURE MAPS AND STELLAR PROFILES

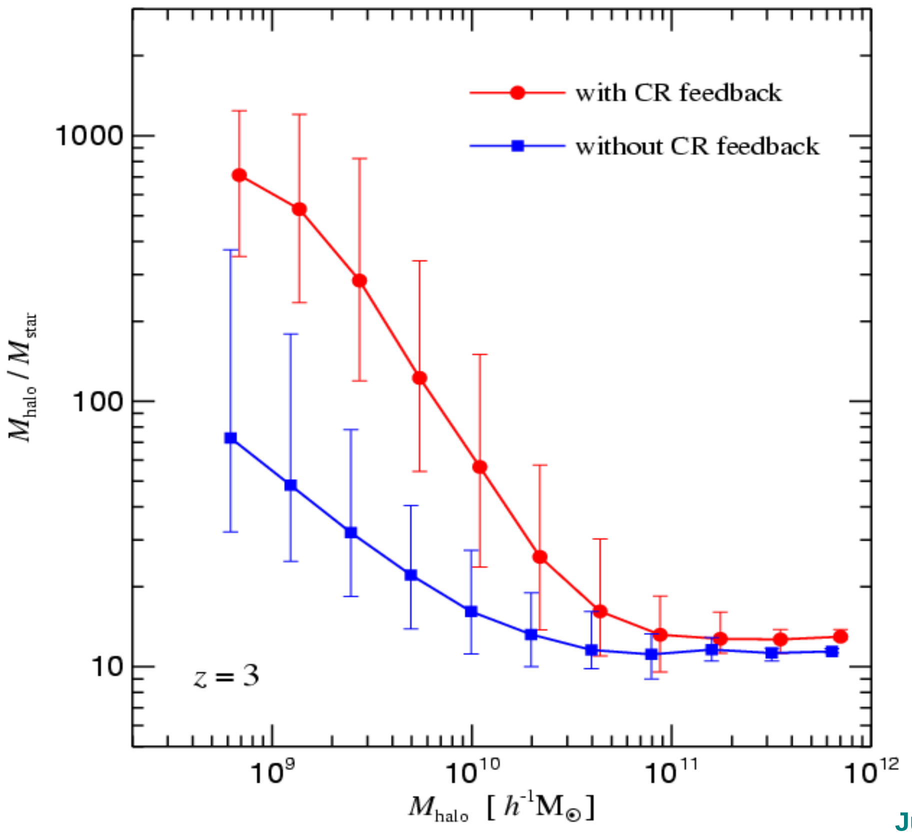
$M = 10^{10}\ M_\odot/h$ | $M = 10^{11}\ M_\odot/h$ | $M = 10^{12}\ M_\odot/h$

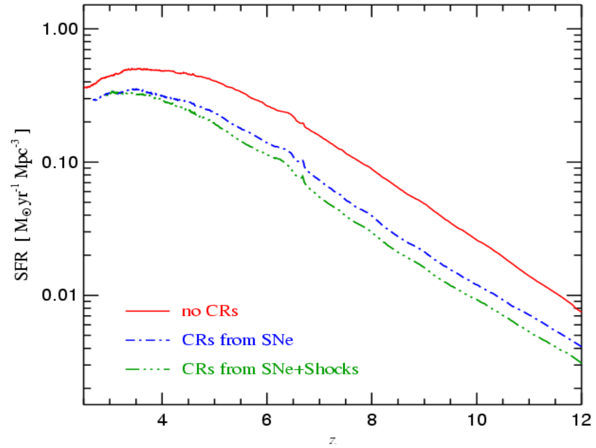


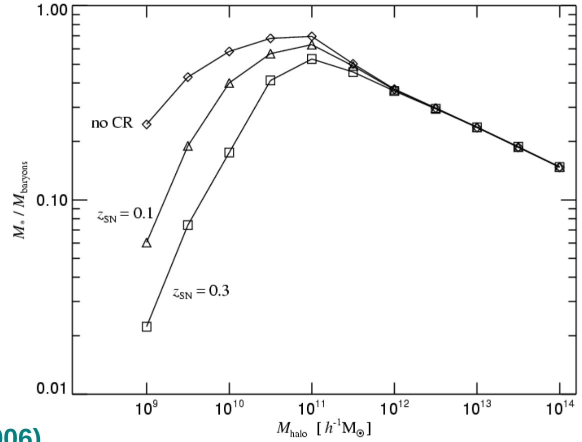
Jubelgas, Springel, Pfrommer, Enßlin (2006)

Early simulations of cosmic rays injected by supernovae already found a significant impact on the star-formation history

MASS-TO-LIGHT RATIO OF HIGH-REDSHIFT GALAXIES



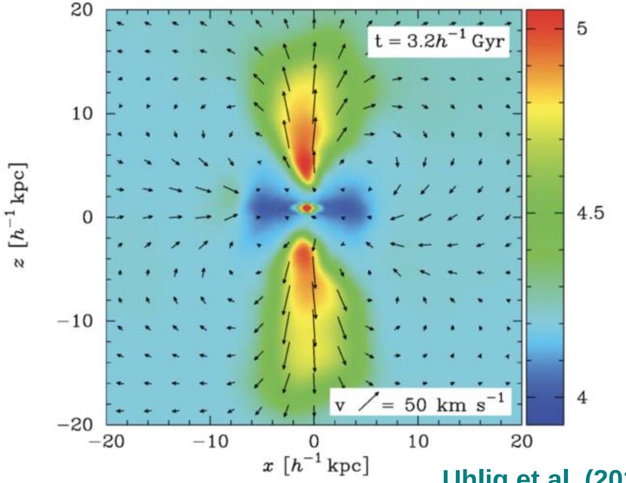




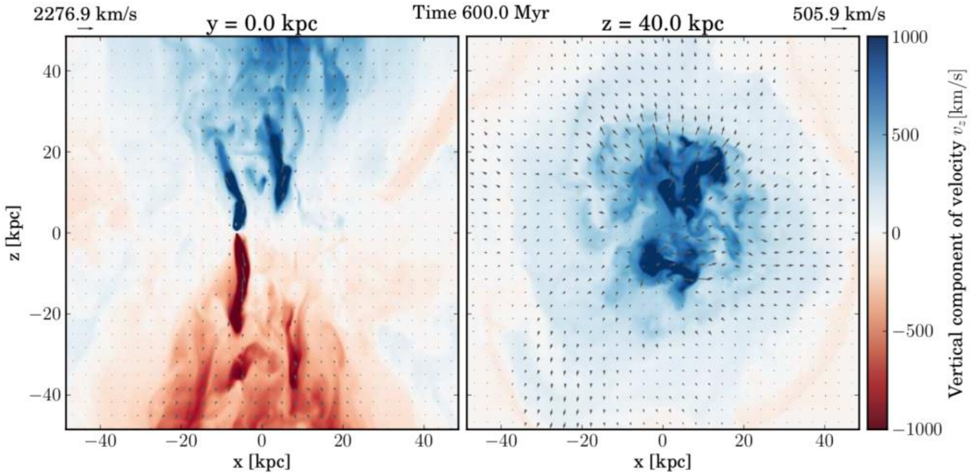
Jubelgas et al. (2006)

Cosmic rays can drive galactic winds when coupled with transport processes

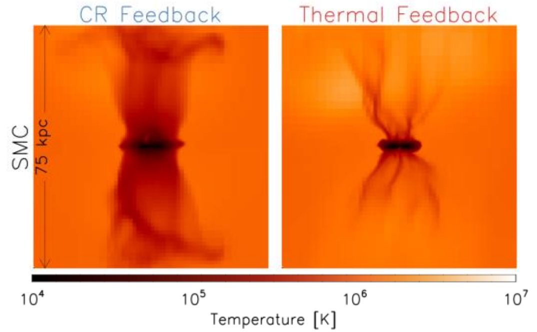
DISK SIMULATIONS BY DIFFERENT GROUPS



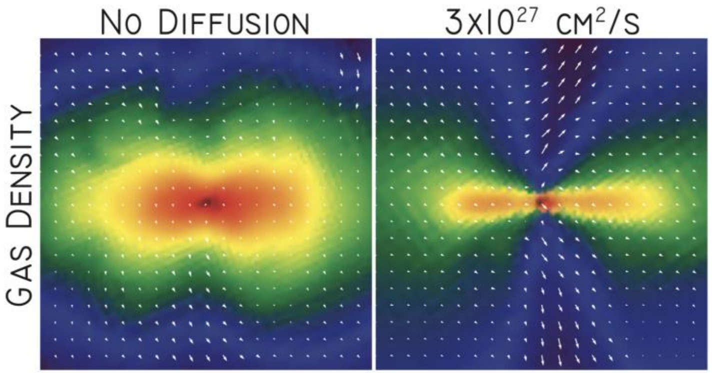
Uhlig et al. (2012)



Hanasz et al. (2013)



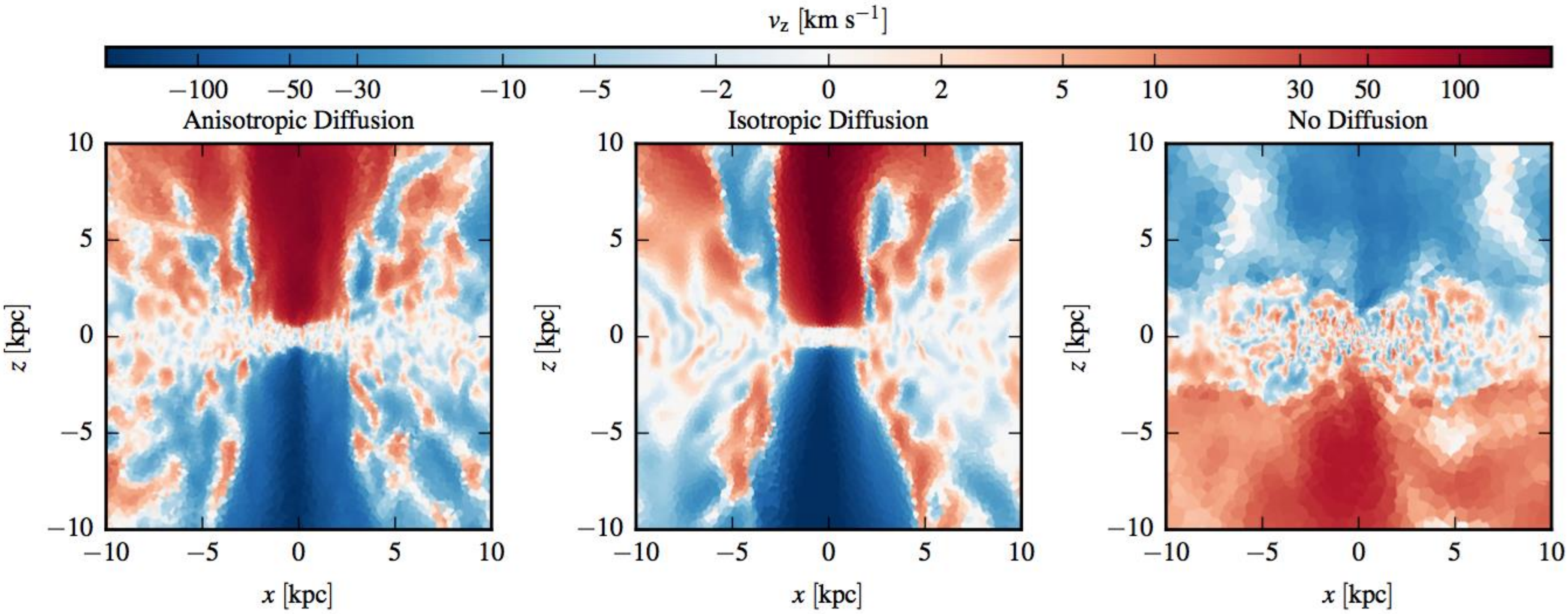
Booth et al. (2013)



Salem et al. (2014)

Transport processes of CRs are critical for driving galactic winds

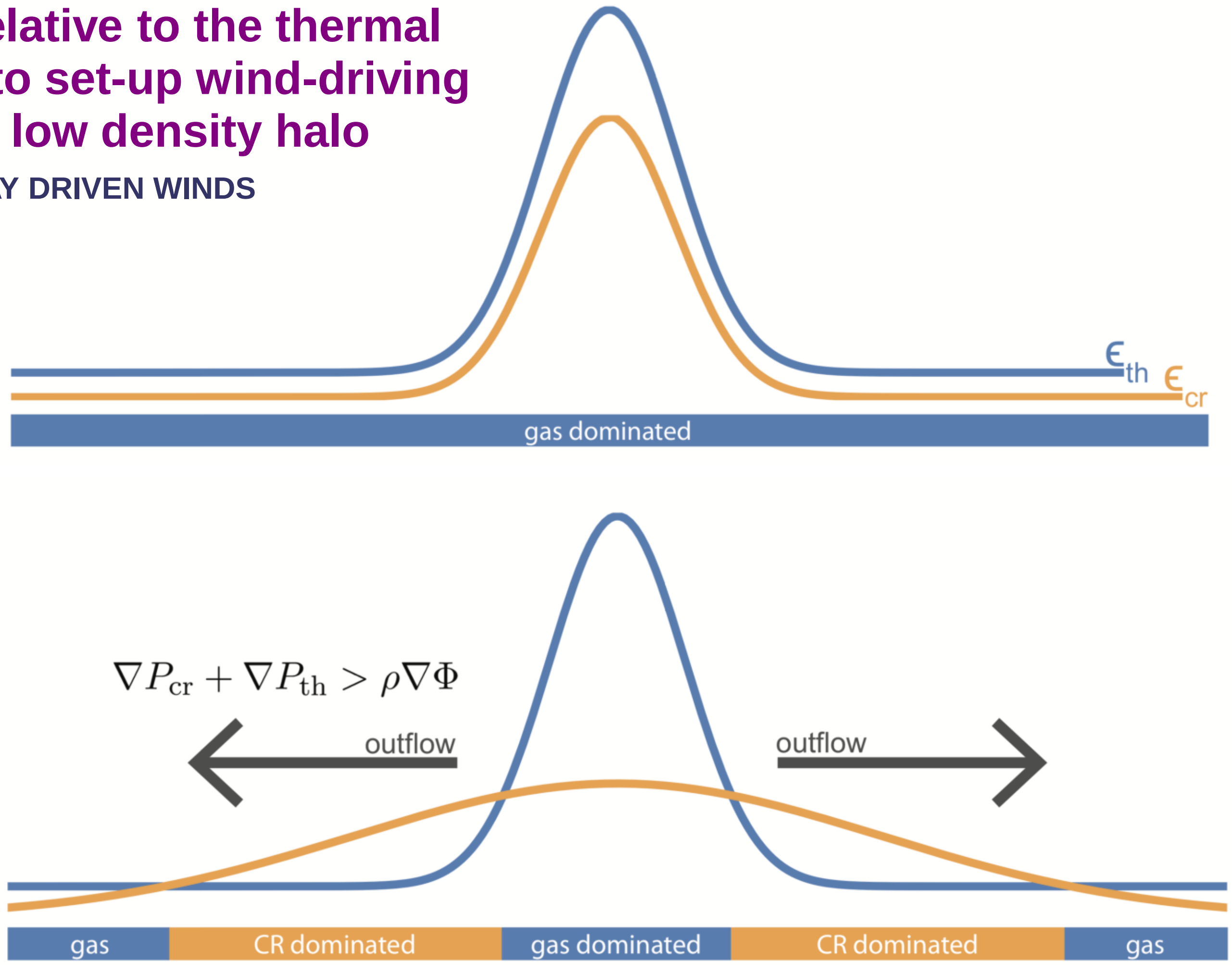
COMPARISON OF DISK GALAXY EVOLUTION WITH DIFFERENT COSMIC RAY PHYSICS



Pakmor et al. (2016)

Transport of CRs relative to the thermal energy is required to set-up wind-driving CR gradients in the low density halo

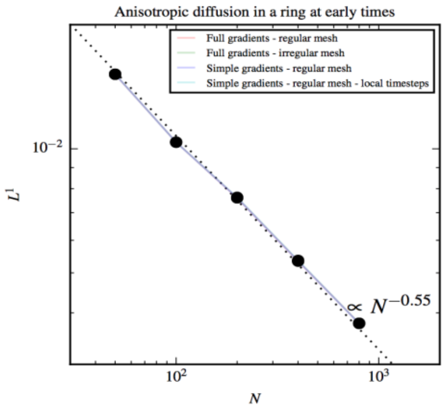
MECHANISM OF COSMIC-RAY DRIVEN WINDS



Salem & Bryan (2014)

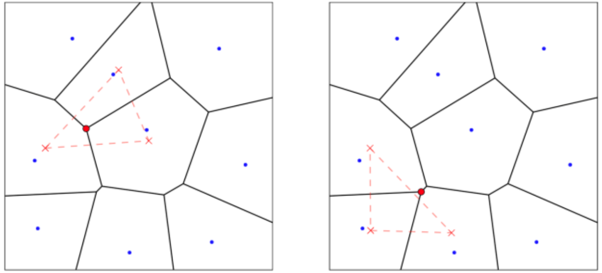
Semi-implicit anisotropic transport of CRs with individual timesteps on an unstructured mesh

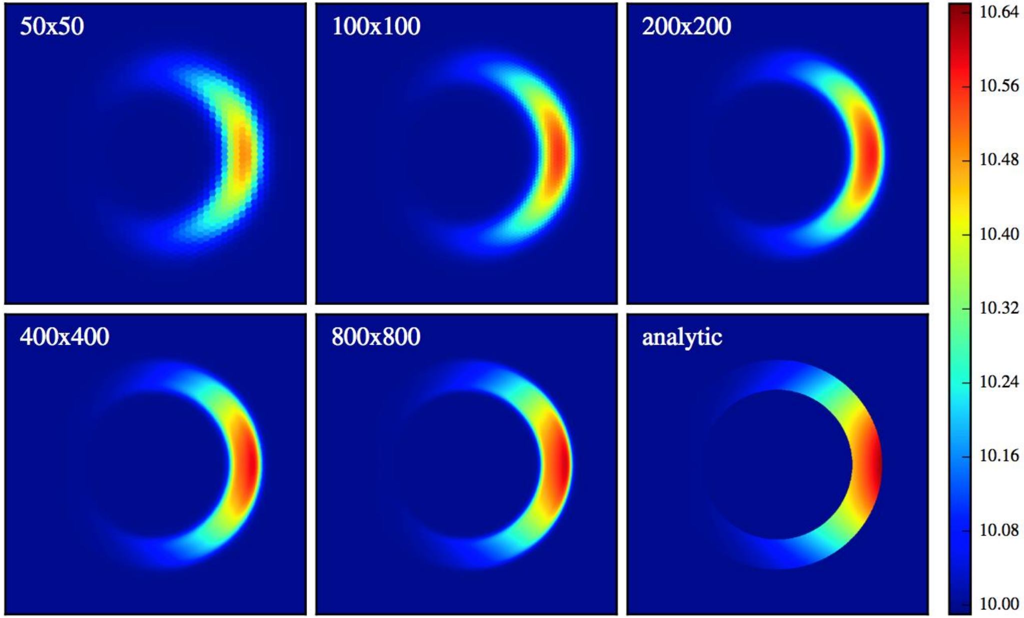
CONVERGENCE STUDY OF THE “RING TEST”



Pakmor et al. (2016)

corner-based gradient estimates



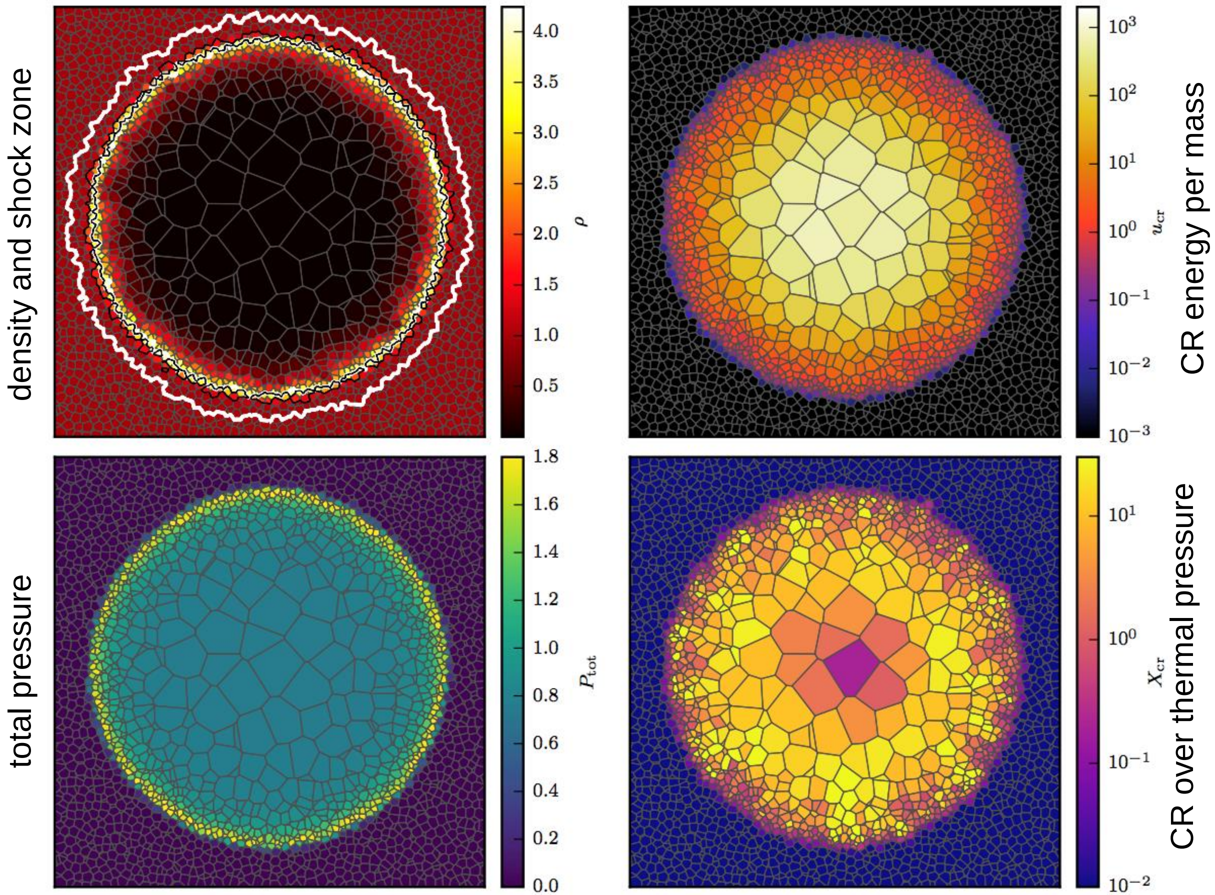


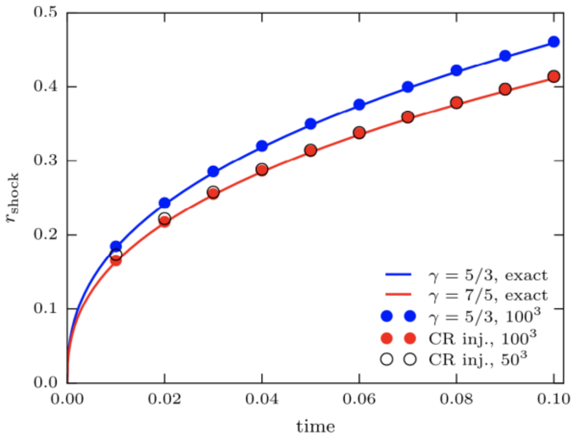
- conservative
- does not violate entropy constraint
- allows for semi-implicit integration with individual timesteps
- multi-grid accelerated iterative solver (HYPRE/GMRES) with algebraic preconditioner

Cosmic ray poduction at a spherical blast wave

SLICES THROUGH THE CENTER

$\zeta = 0.5$



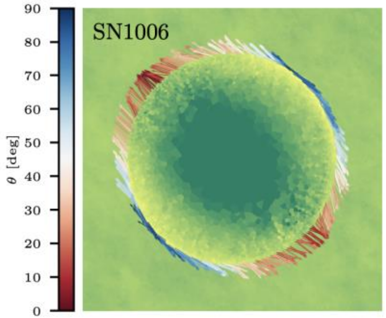


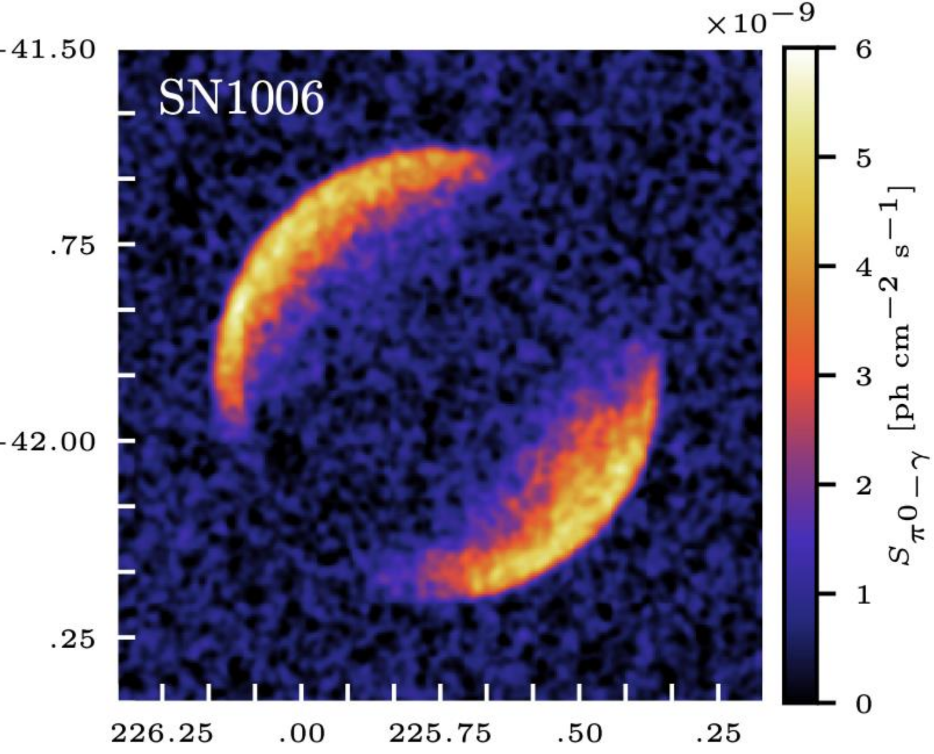
Pfrommer et al. (2016)

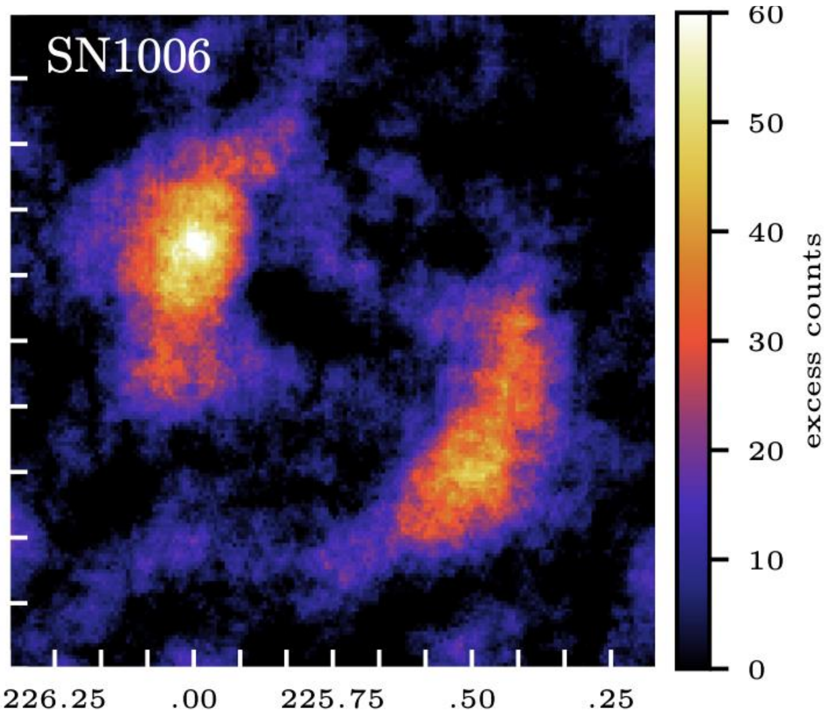
Magnetic obliquity modulated CR production can reproduce the gamma-ray morphology of supernova remnants

MAPS OF GAMMA-RAY BRIGHTNESS IN SIMULATIONS AND HESS OBSERVATIONS

Pais, Pfrommer & Ehlert (2018)







Stratified-box simulations of SN feedback demonstrate the importance of CRs for driving outlows

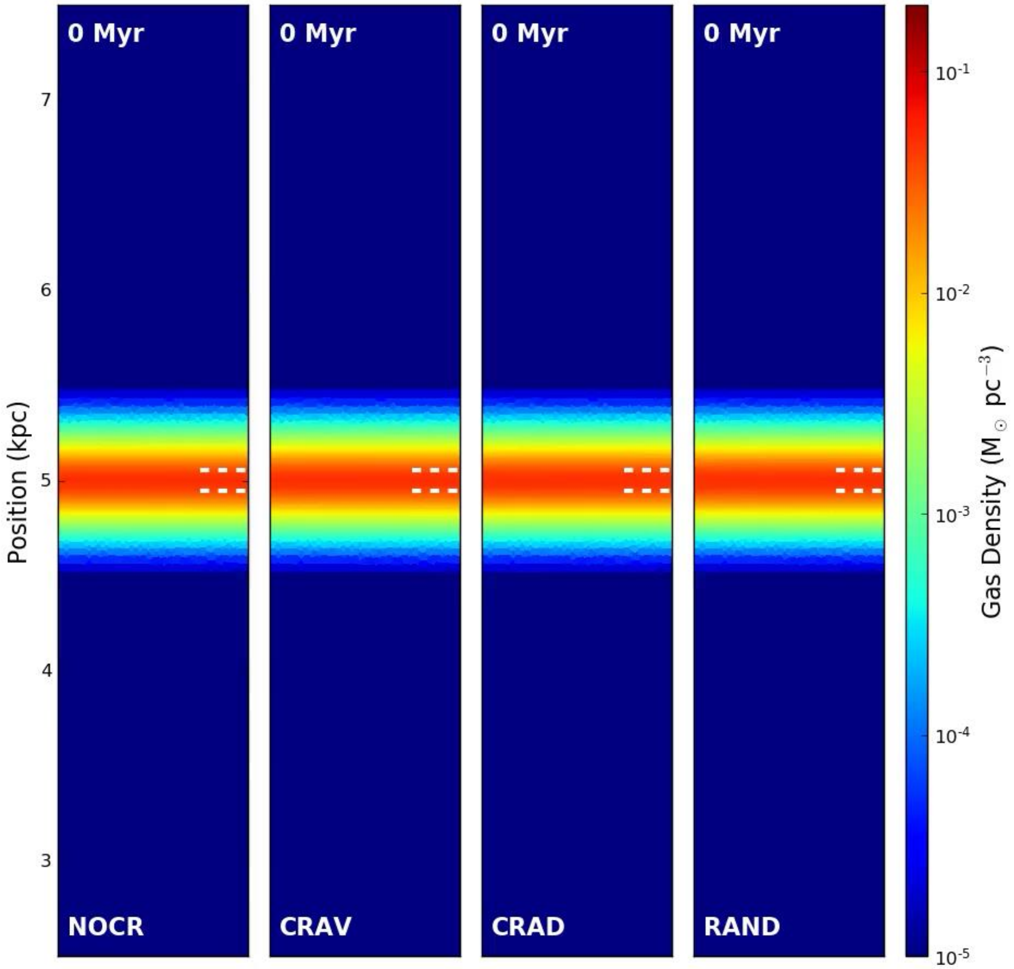
DIFFERENT MODES OF SUPERNOVA FEEDBACK

with gas self-gravity and
stationary stellar potential

self-shielding with TreeCol

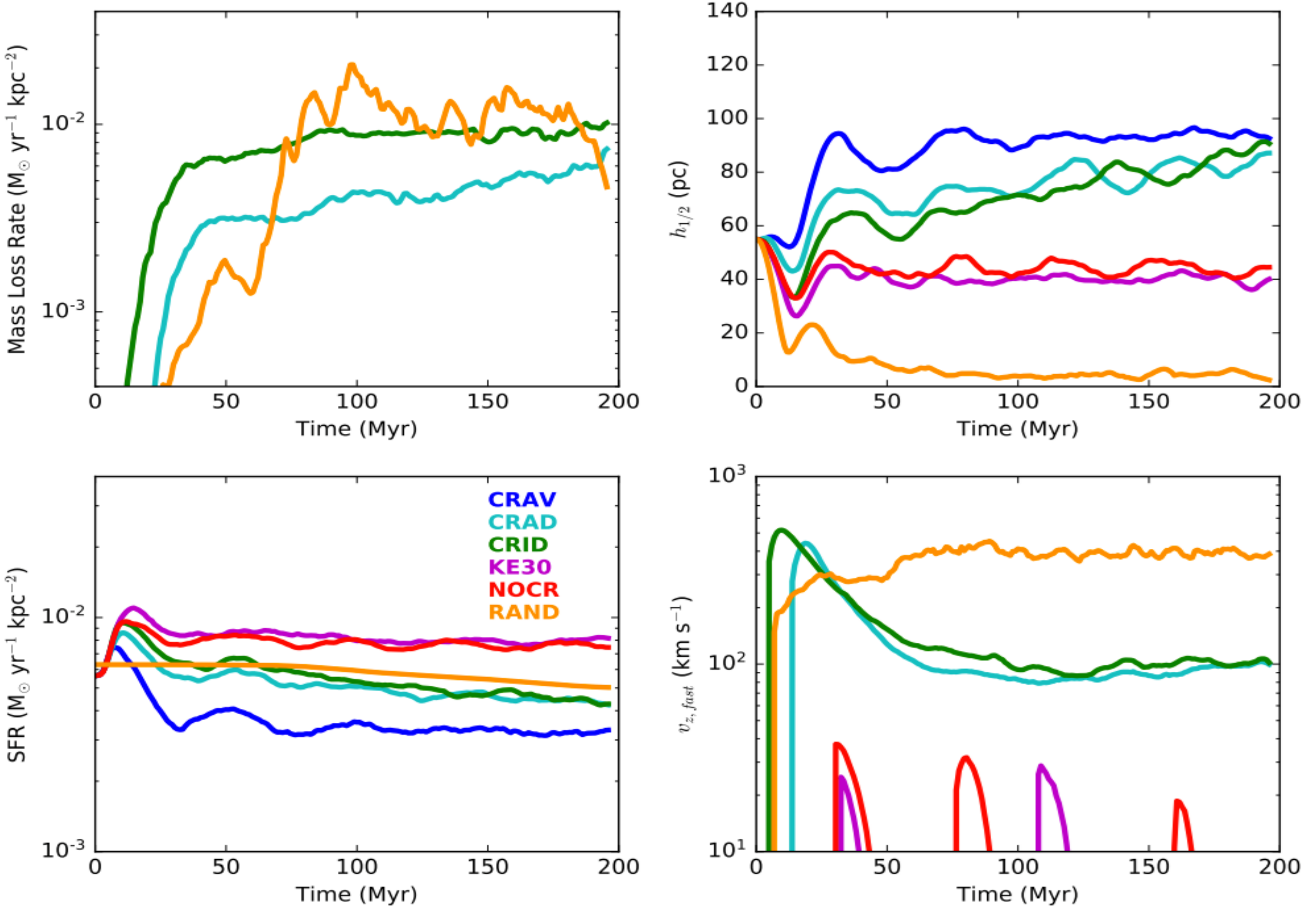
$\Sigma_0 = 10\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}$
$f_g = 0.1$
$m_t = 10\ \mathrm{M}_\odot$
$\varepsilon = 0.165\ \mathrm{pc}$

Simpson et al. (2016)



Cosmic ray transport processes reduce the star formation and sustain mass loaded winds

COMPARSON OF THE TIME EVOLUTION FOR DIFFERENT FEEDBACK MODELS

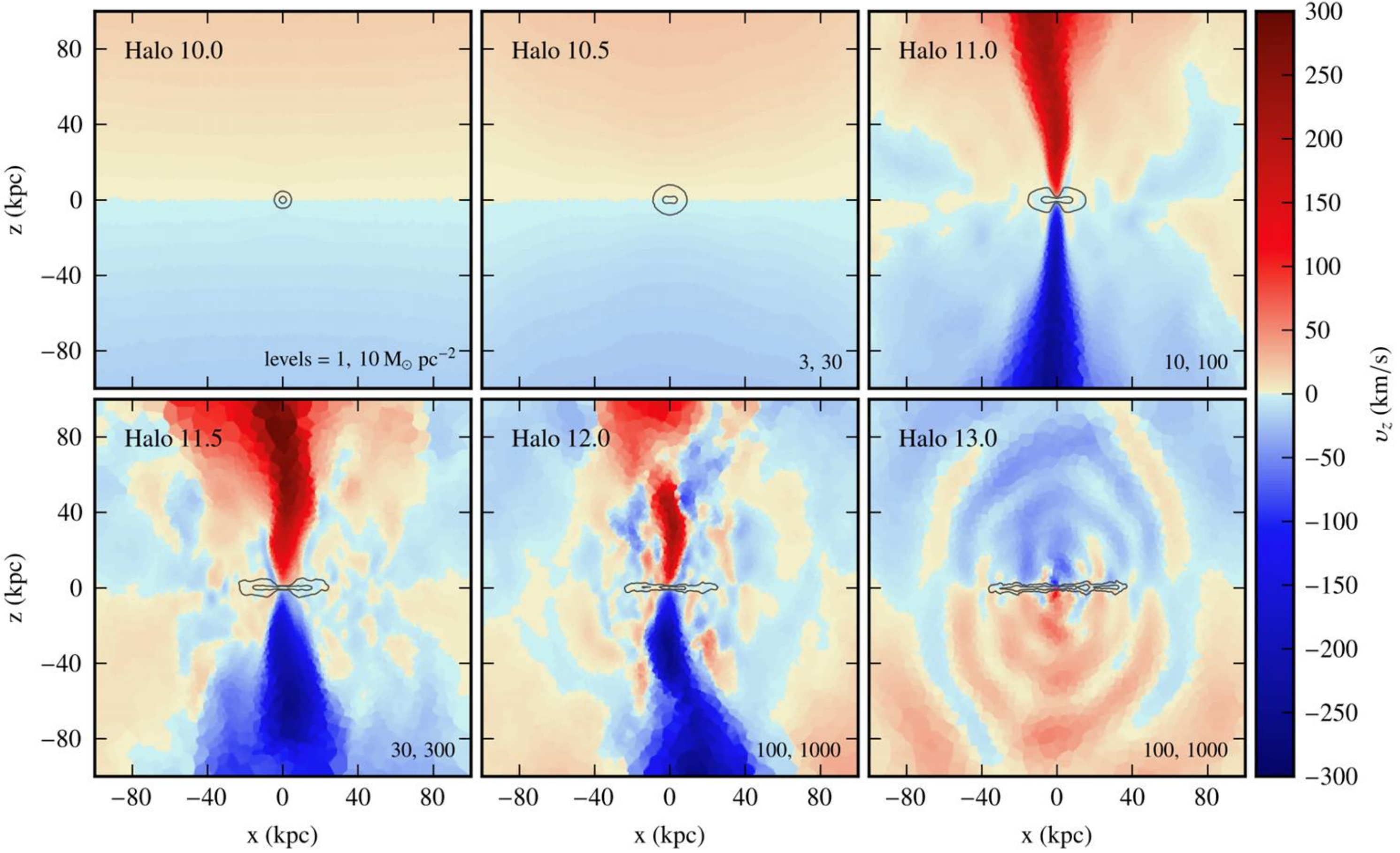


Simpson et al. (2016)

The efficiency of cosmic ray driven winds is a strong function of halo mass

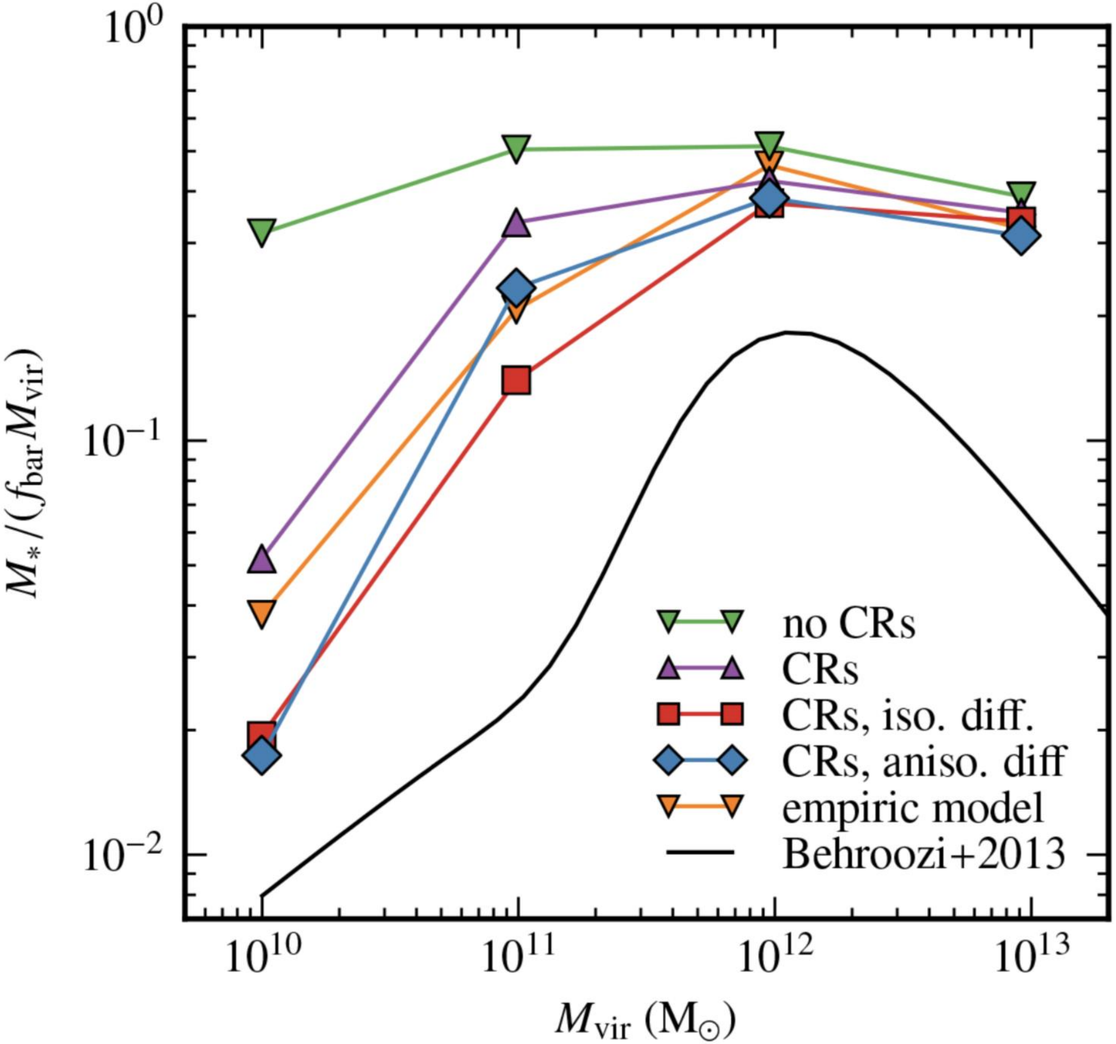
OUTFLOW VELOCITIES IN ISOLATED GALAXIES OF DIFFERENT SIZE

Jacob et al. (2017)



Cosmic rays suppress star formation more strongly in small halos

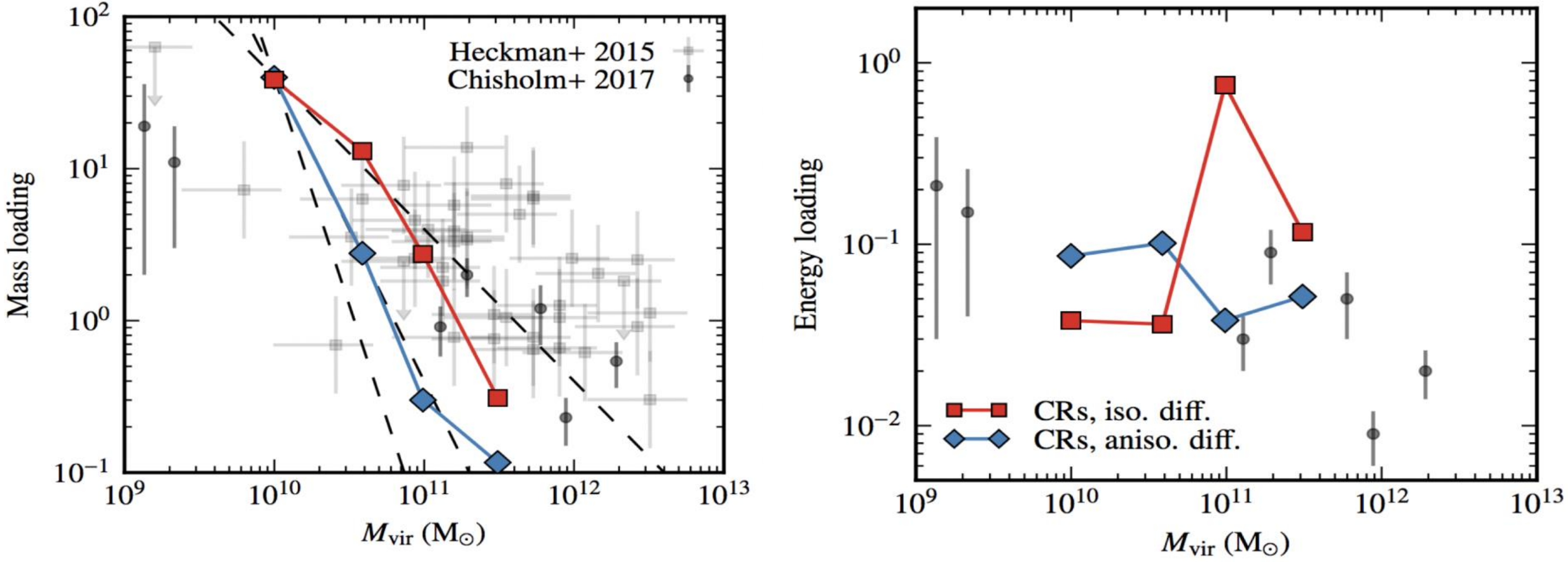
STAR FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS



Jacob et al. (2017)

The mass loading of CR-driven winds depends strongly on halo mass, whereas the energy loading is flat

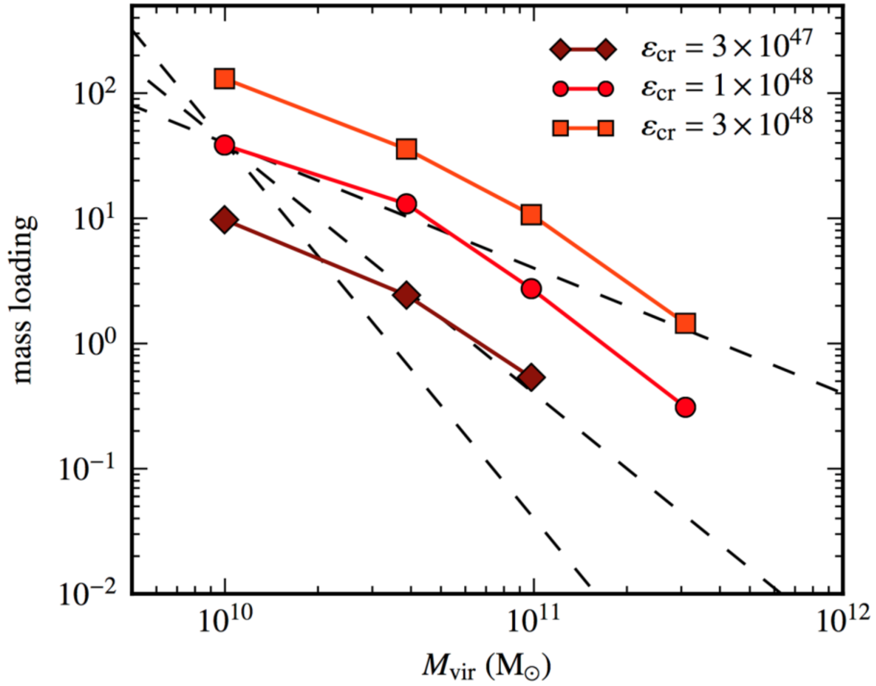
PROPERTIES OF CR DRIVEN WINDS AS A FUNCTION OF HALO MASS

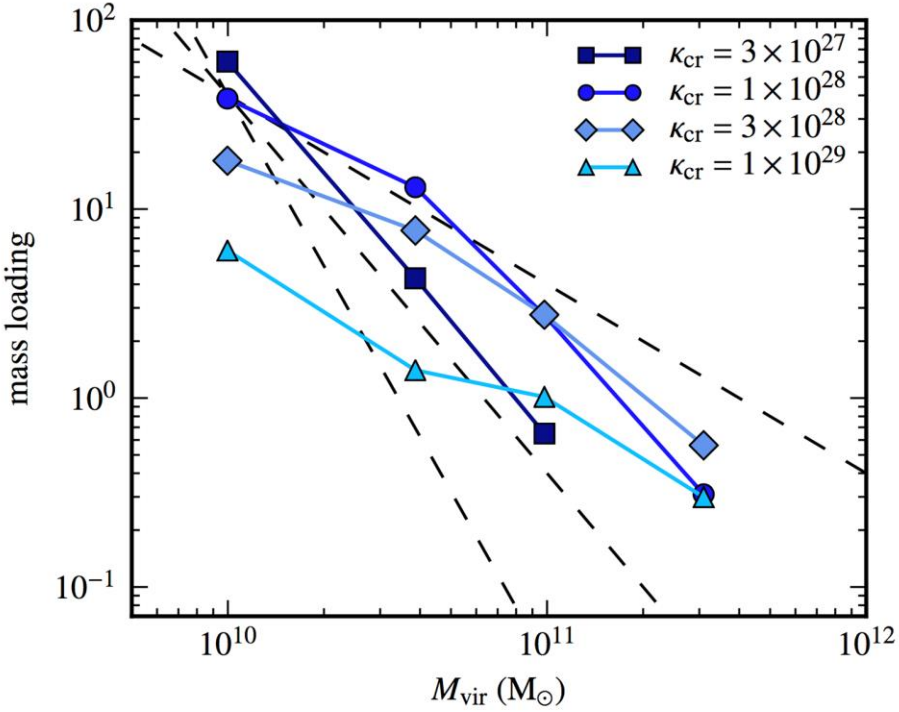


Jacob et al. (2017)

The unknown CR diffusion constant and injection efficiency represent important uncertainties

MASS LOADING OF CR-DRIVEN WINDS FOR DIFFERENT MODEL PARAMETERS

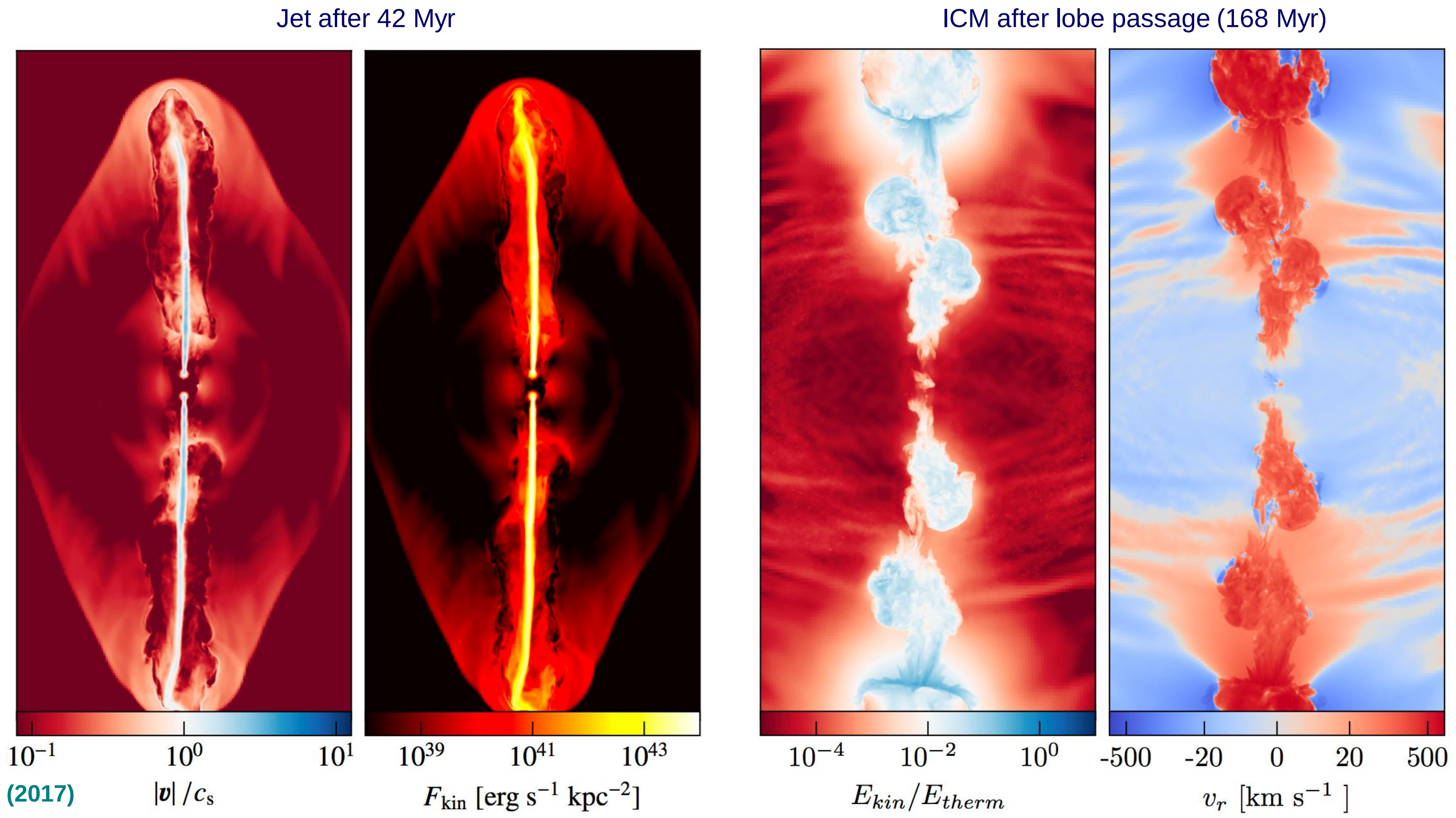




Jacob et al. (2017)

Jet injection by BHs in high-resolution "zoom" galaxy cluster simulations

HEATING CLUSTERS THROUGH JET-ICM INTERACTIONS



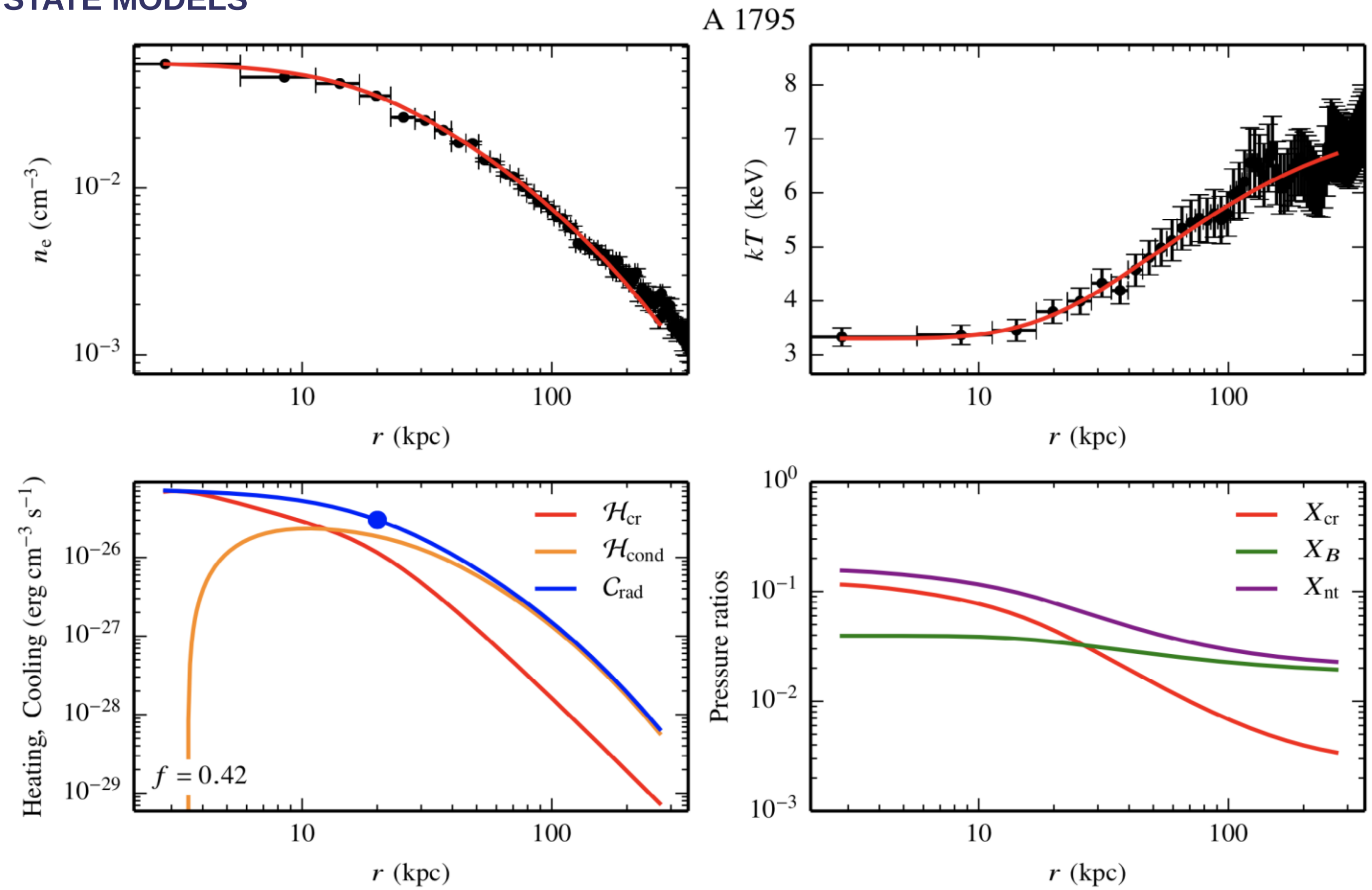
Weinberger et al. (2017)

Cosmic ray heating combined with thermal conduction can offset cooling flows in clusters without radio mini halos

Jacob & Pfrommer (2017)

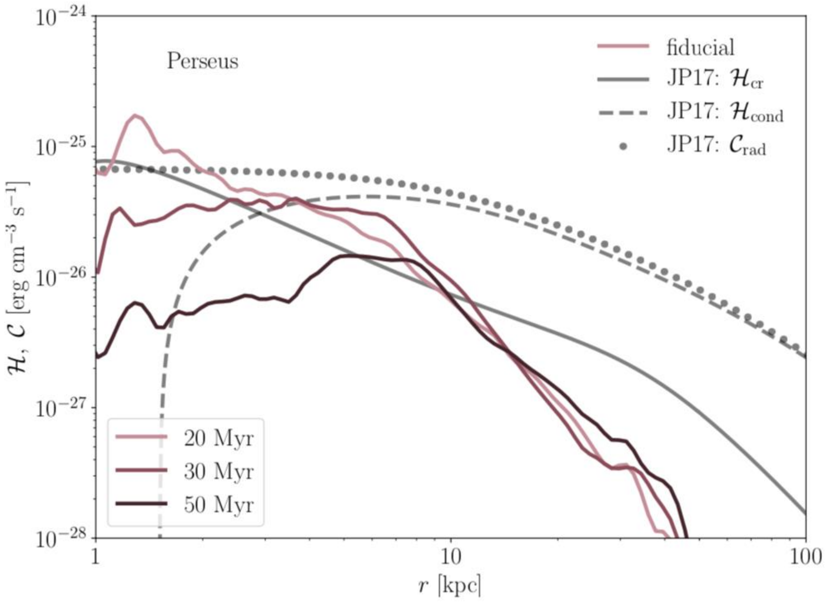
ONE-DIMENSIONAL STEADY STATE MODELS

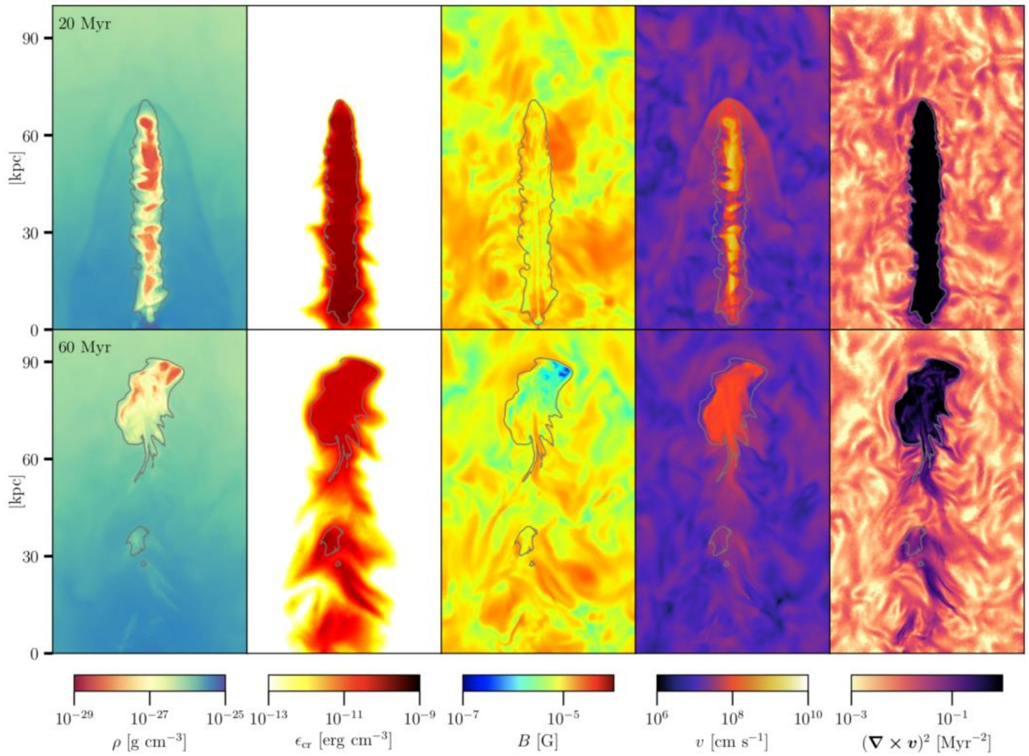
- CR heating dominates in the centre
- Conductive heating takes over at large radii (for 0.42 Spitzer)
- Modest mass-deposition rates of order 1 $M_\odot$/yr



First jet simulations with explicit cosmic ray injection show a similar heating effect as the one-dimensional models

COSMIC RAY FILLED JETS AND SPHERICALLY AVERAGED HEATING PROFILES





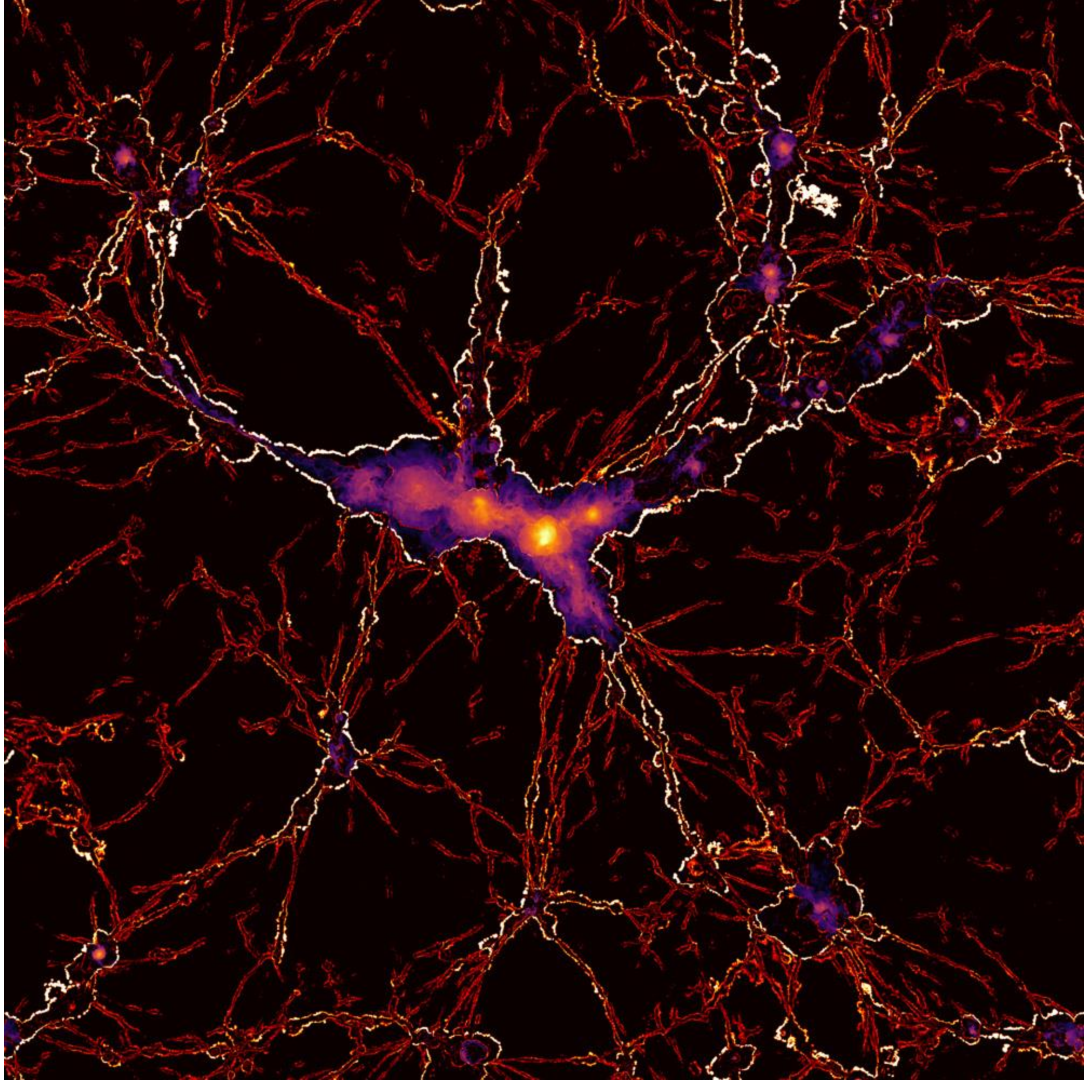
Ehlert et al. (2018)

Clusters of galaxies are surrounded by high Mach-number accretion shocks

LARGE-SCALE STRUCTURE SHOCKS IN ILLUSTRIS-TNG

Could this by an important source of cosmic rays influencing galaxy evolution?

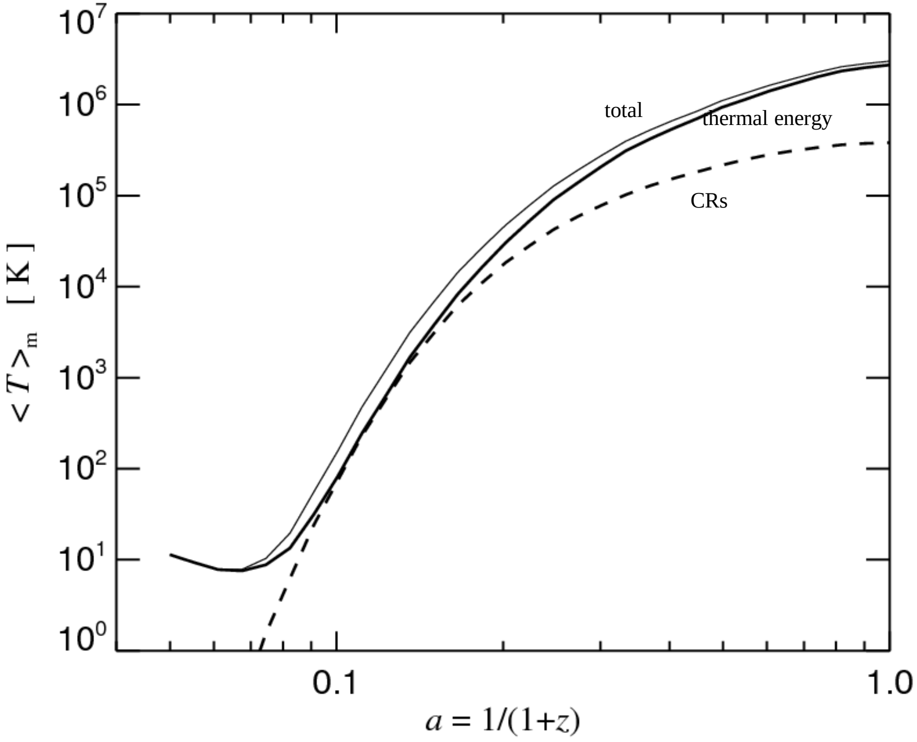
IllustrisTNG Collaboration (2018)



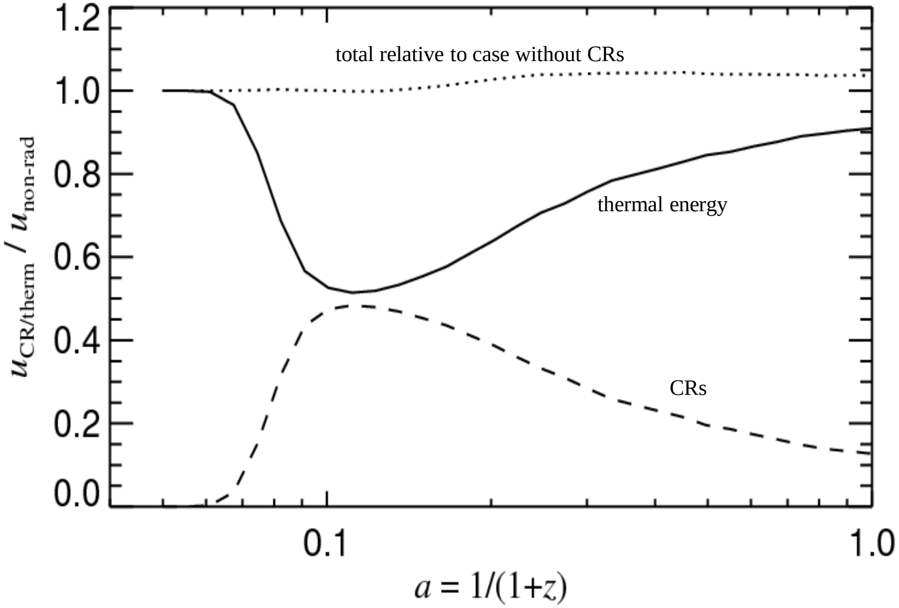
Large-scale structure shocks introduce a significant cosmic ray component into the IGM, especially at high redshift

(pioneered by Miniati et al. 2001)

TIME EVOLUTION OF THE MEAN ENERGIES IN CRs AND THERMAL GAS

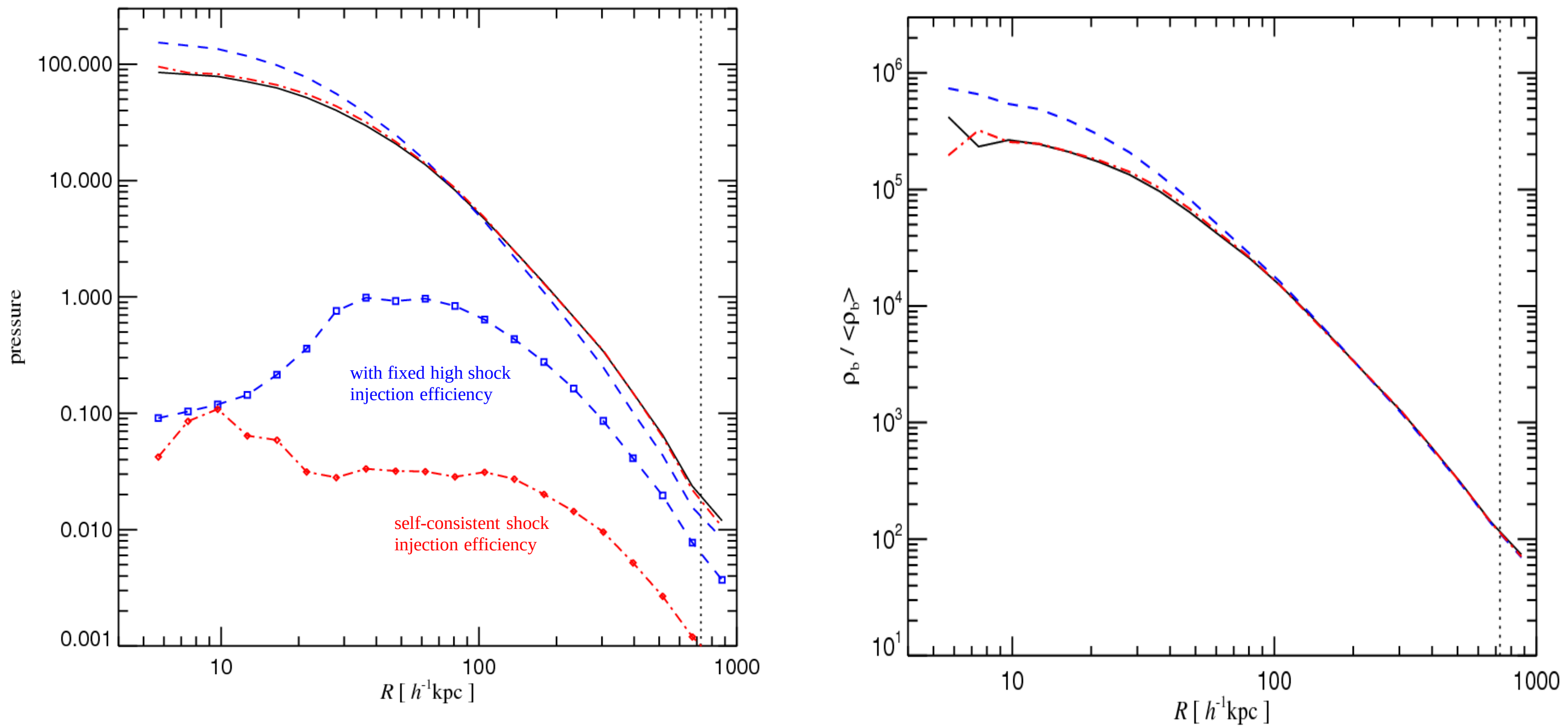


Jubelgas et al. (2006)



While these shock-induced CRs somewhat increase the compressibility of the gas, the CRs do not become important in the inner regions due to their softer equation of state

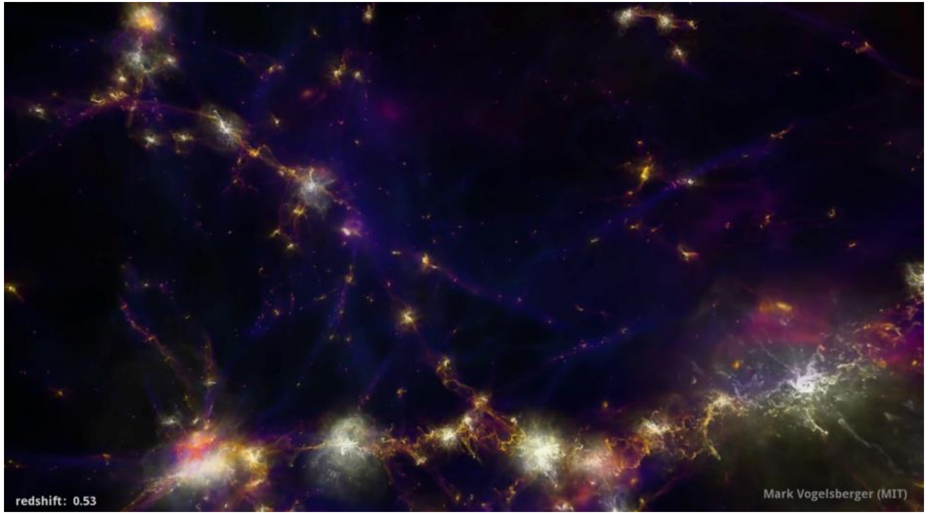
COMPARISON OF RADIAL PRESSURE AND DENSITY PROFILES

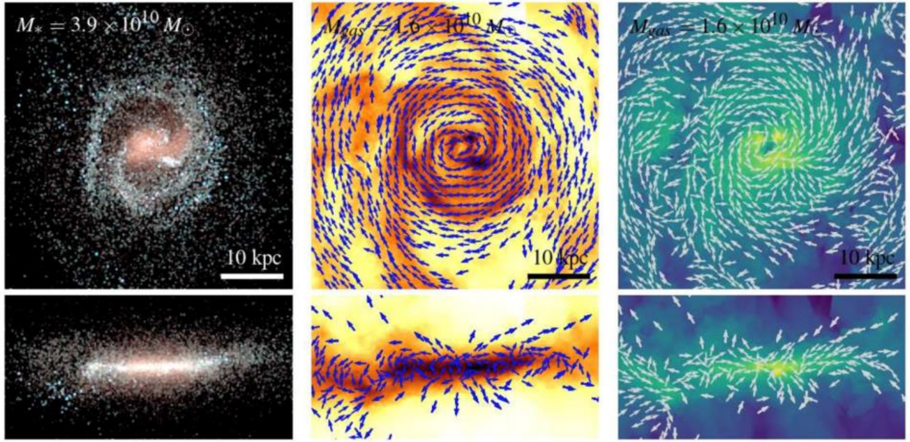


Jubelgas et al. (2006)

Modern MHD simulations of galaxy formation can predict the amplification of primordial fields in halos and galaxies

MAGNETIC FIELD STRENGTH IN ILLUSTRIS-TNG

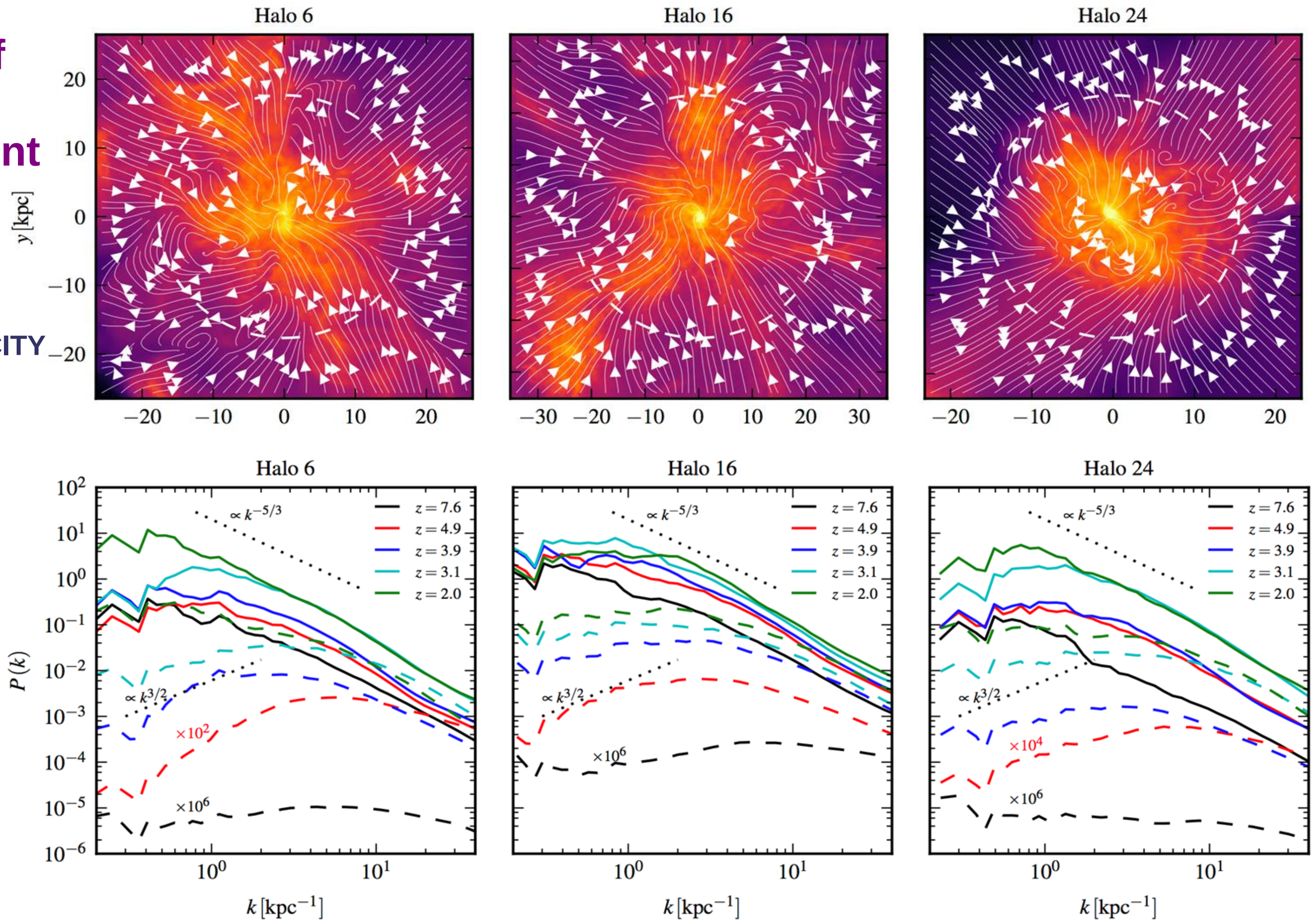




Marinacci et al. (2018)

Amplification of B-field occurs through turbulent small-scale dynamo

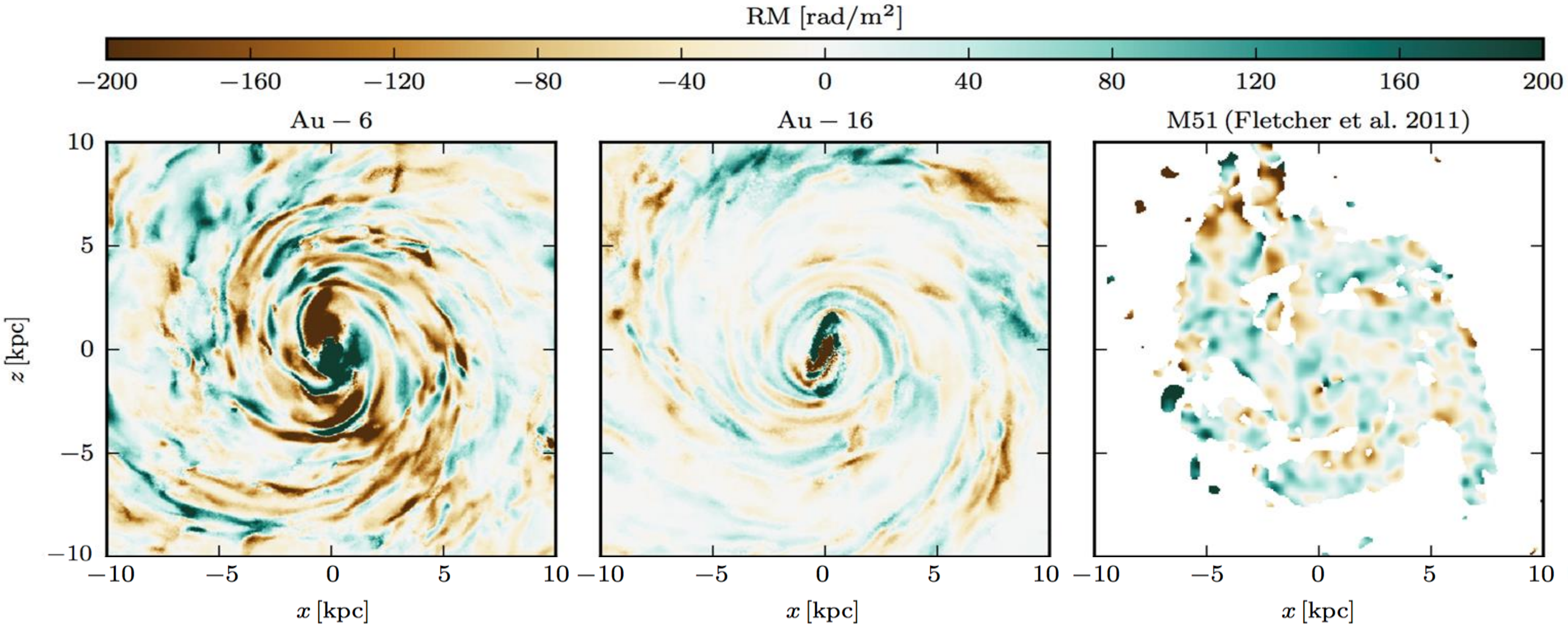
VELOCITY FIELD AND EVOLUTION OF VELOCITY AND B-FIELD POWER SPECTRA



Pakmor et al. (2017)

Faraday rotation maps provide one of the best ways to observationally probe the magnetic field in galaxies

COSMOLOGICAL PREDICTIONS FROM AURIGA COMPARED TO OBSERVATIONS OF M51

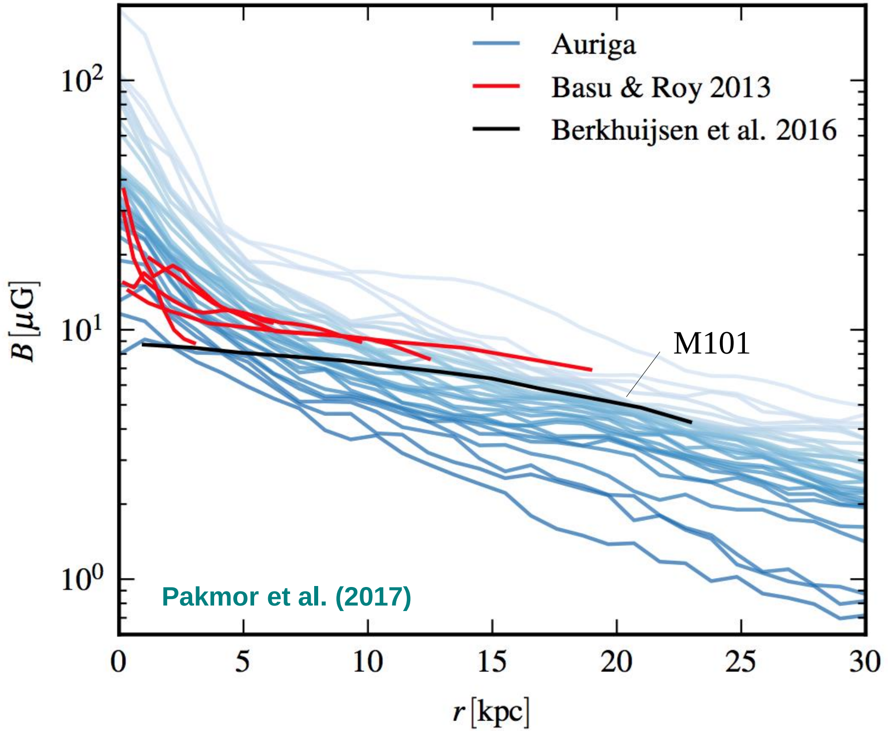


$$RM = \frac{e^3}{2\pi m_e^2 c^3} \int n_e(l)\, \vec{B}(l) \cdot d\vec{l},$$

Pakmor et al. (2018)

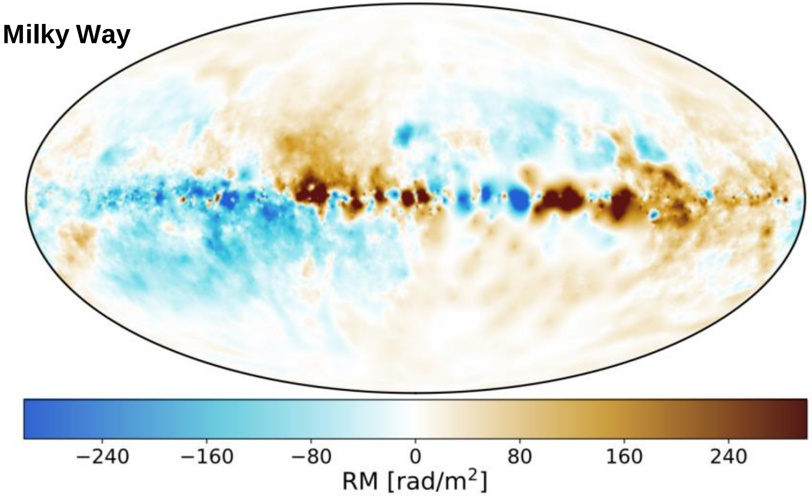
The predicted radial magnetic field strength and Faraday rotation signal matches the Galaxy very well

B-FIELD STRENGTH AND FARADAY ROTATION MAPS



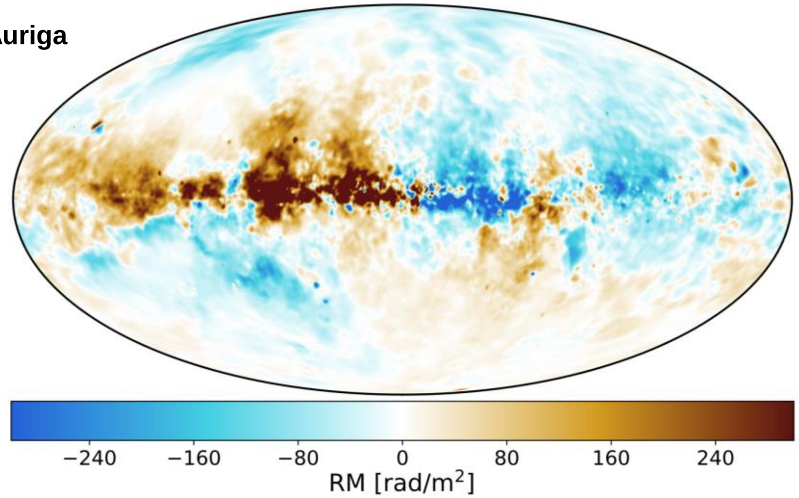
Pakmor et al. (2017)

Milky Way



Reissl et al. (2018)

Auriga

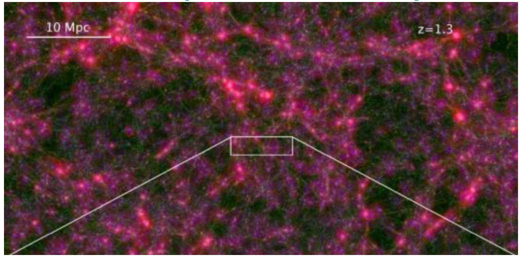


Hydrodynamical cosmological simulations of galaxy formation have made tremendous progress in recent years

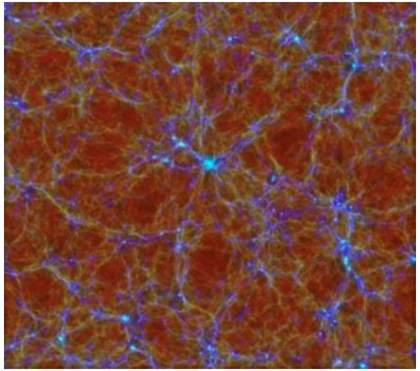
AN INCOMPLETE OVERVIEW OF SOME OF THE LARGER PROJECTS

Illustris (Vogelsberger et al. 2014)

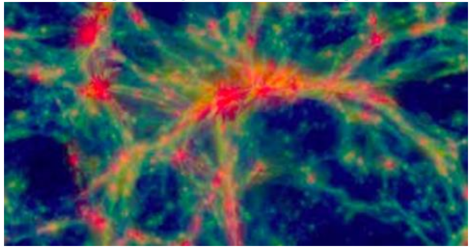
Horizon-AGN (Dubois et al. 2014)



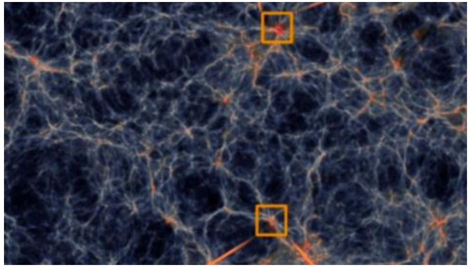
Magneticum (Dolag et al. 2014)



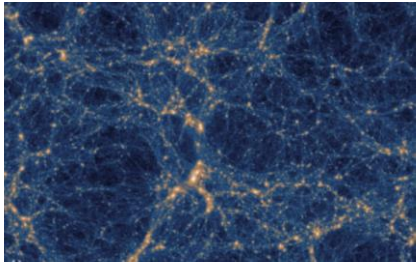
EAGLE (Schaye et al. 2015)



MassiveBlack II (Khandai et al. 2015)



TNG (Illustris Collaboration 2017)



→ **The next generation will likely include cosmic rays!**

Take home points

- ΛCDM relies on very **strong galactic outflows** to successfully form galaxies.
- **CR transport processes** seem to be able to readily drive winds in low mass galaxies.
- The **scaling of mass-loading and energy-loading** is promising, but the effect seems not strong enough to alone explain the faint-end of the galaxy luminosity function.
- **Cluster cooling flows** and the star formation in BCG galaxies may in part be regulated by **jet-driven CR-heating of the ICM.**
- **Cosmic rays from accretion shocks** probably play little if any role in galaxy evolution.

TNG50 Simulation