How cosmic rays shape galaxies

Christoph Pfrommer[1]

in collaboration with

R. Pakmor, K. Schaal, C. Simpson, R. Weinberger, V. Springel,
R. Kannan, F. Marinacci, S. Glover, P. Clark, R. Smith

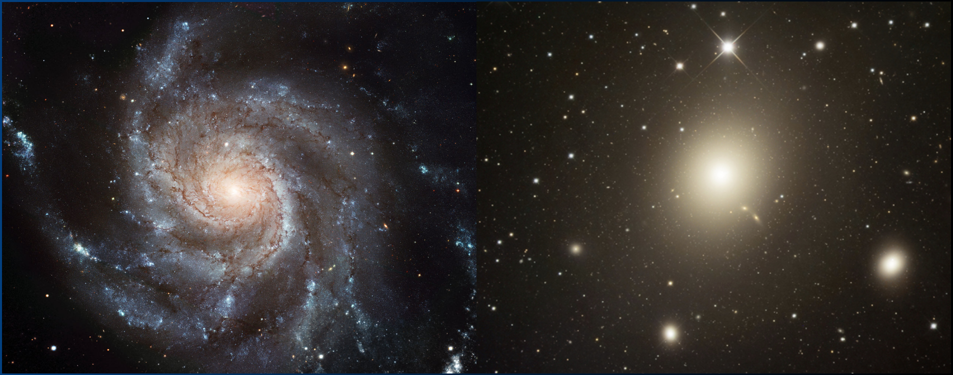
[1]Heidelberg Institute for Theoretical Studies

Heidelberg Joint Astronomical Colloquium - July 2016

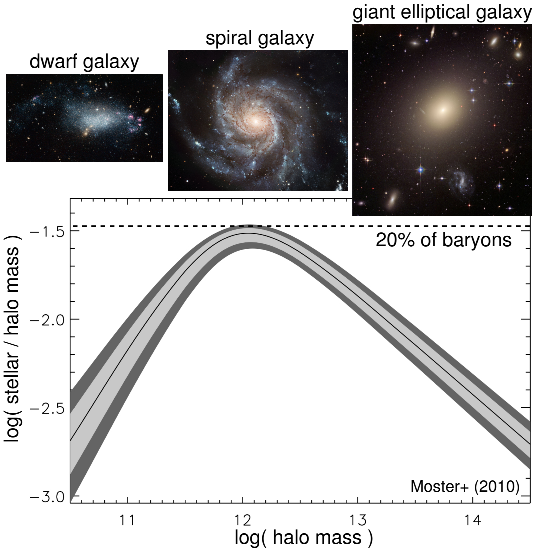
Outline

1. Introduction and Motivation
   - Puzzles in galaxy formation
   - Galactic winds
   - Cosmic rays
2. Galaxy formation
   - Physical Processes
   - Interstellar medium
   - Galaxy simulations
3. AGN feedback
   - Radio and γ-ray emission
   - Cosmic-ray heating
   - Simulations

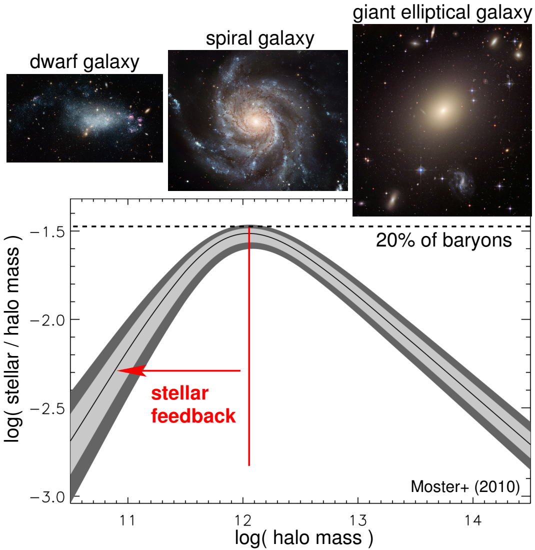
Puzzles in galaxy formation



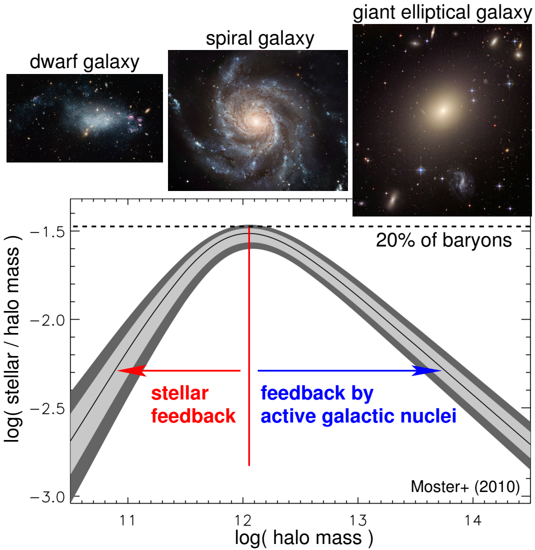
Puzzles in galaxy formation



Puzzles in galaxy formation

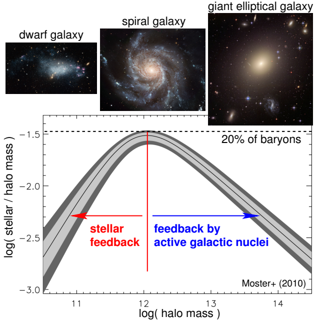


Puzzles in galaxy formation



HITS

Puzzles in galaxy formation



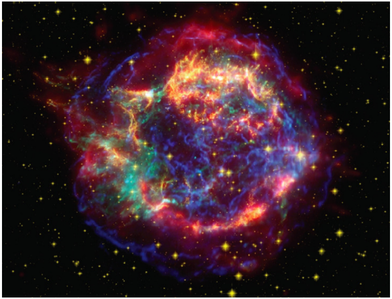
Bright-end of luminosity function:

- astrophysical solutions:
  AGN/quasar feedback, . . .

Faint-end of luminosity function:

- dark matter (DM) solutions:
  warm DM, interacting DM, DM from late decays, large annihilation rates, . . .
- astrophysical solutions:
  - preventing gas from falling into DM potential wells:
    increasing entropy by reionization, blazar heating . . .
  - preventing gas from forming stars in galaxies:
    suppress cooling (photoionization, low metallicities), . . .
  - pushing gas out of galaxies:
    supernova/quasar feedback → **galactic winds**

Galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

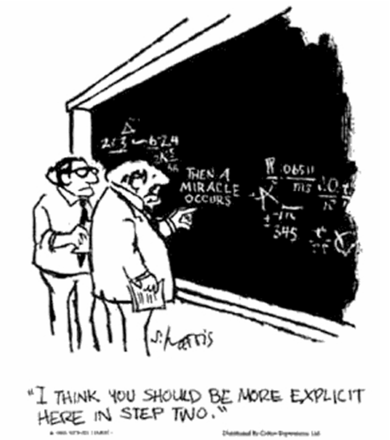
Galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

Galactic winds

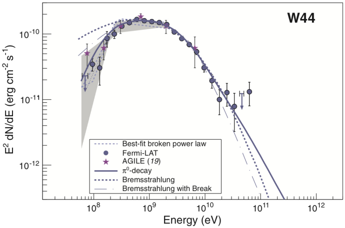


- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

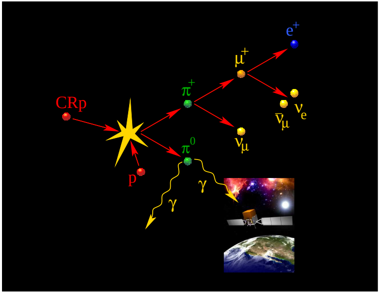
The role of supernova remnants

- supernova remnant shocks amplify magnetic fields and accelerate CR electrons up to $\sim$ 100 TeV (narrow X-ray synchrotron filaments observed by *Chandra*)
- pion bump provides evidence for CR proton acceleration (*Fermi*/AGILE γ-ray spectra)

Fermi observations of W44:



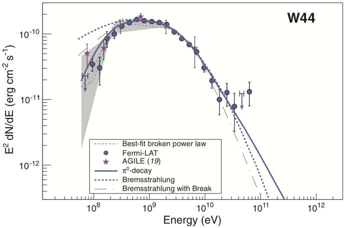
Ackermann+ (2013)



The role of supernova remnants

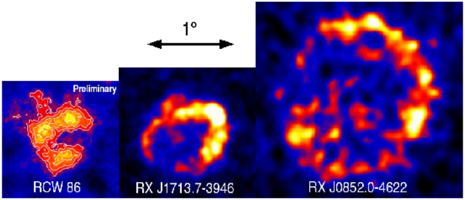
- supernova remnant shocks amplify magnetic fields and accelerate CR electrons up to $\sim$ 100 TeV (narrow X-ray synchrotron filaments observed by *Chandra*)
- pion bump provides evidence for CR proton acceleration (*Fermi*/AGILE γ-ray spectra)
- shell-type SNRs show evidence for efficient shock acceleration beyond $\sim$ 100 TeV (HESS TeV γ-ray observations)

Fermi observations of W44:



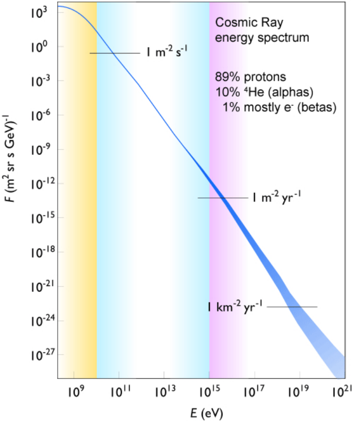
Ackermann+ (2013)

HESS observations of shell-type SNRs:



Hinton (2009)

Galactic cosmic ray spectrum

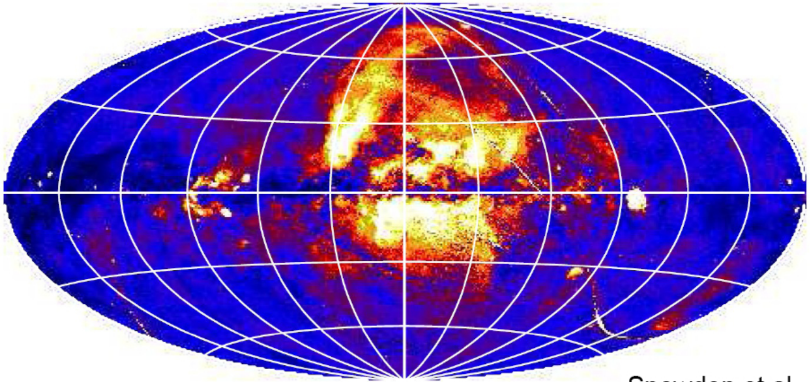


data compiled by Swordy

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Galactic wind in the Milky Way?

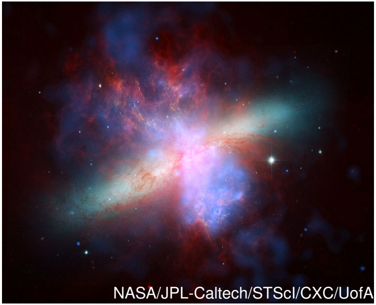
Diffuse X-ray emission in our galaxy



Snowden et al., 2007

. . . as suggested by Everett+ (2008) and Everett, Schiller, Zweibel (2010)

How are galactic winds driven?



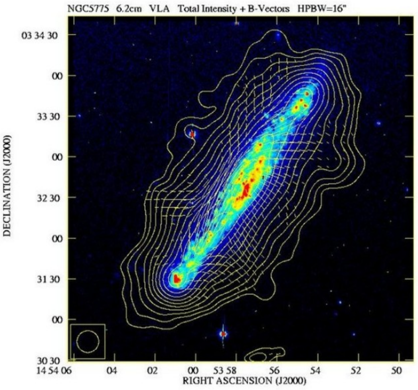
super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

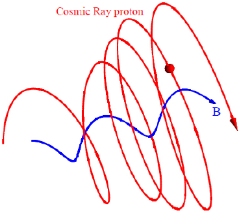


Tüllmann+ (2000)

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^\gamma$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind $\rightarrow$ "CR battery"
- poloidal ("open") field lines at wind launching site $\rightarrow$ CR-driven Parker instability

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

- total CR velocity $\boldsymbol{v}_{\mathrm{cr}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\mathrm{gas}}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\mathrm{st}} = -\frac{\boldsymbol{B}}{\sqrt{4\pi\rho}} \frac{\boldsymbol{b}\cdot\nabla P_{\mathrm{cr}}}{|\boldsymbol{b}\cdot\nabla P_{\mathrm{cr}}|}, \qquad \boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\nabla\varepsilon_{\mathrm{cr}}}{\varepsilon_{\mathrm{cr}}},$$

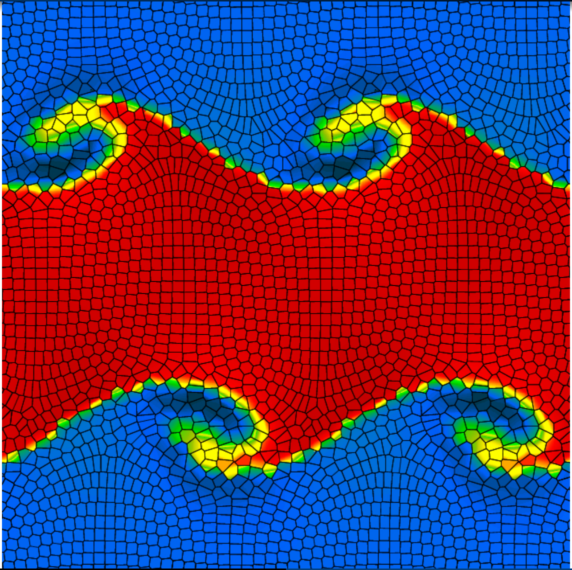
- energy equations with $\varepsilon = \varepsilon_{\mathrm{th}} + \rho v^2/2$:

$$\frac{\partial\varepsilon}{\partial t} + \nabla\cdot\left[(\varepsilon + P_{\mathrm{th}} + P_{\mathrm{cr}})\boldsymbol{v}\right] = P_{\mathrm{cr}}\nabla\cdot\boldsymbol{v} - \boldsymbol{v}_{\mathrm{st}}\cdot\nabla P_{\mathrm{cr}}$$

$$\frac{\partial\varepsilon_{\mathrm{cr}}}{\partial t} + \nabla\cdot\left[P_{\mathrm{cr}}\boldsymbol{v}_{\mathrm{st}} + \varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}})\right] = -P_{\mathrm{cr}}\nabla\cdot\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}}\cdot\nabla P_{\mathrm{cr}}$$

$$\Longleftrightarrow \quad \frac{\partial\varepsilon_{\mathrm{cr}}}{\partial t} + \nabla\cdot\left[\varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}})\right] = -P_{\mathrm{cr}}\nabla\cdot(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}})$$

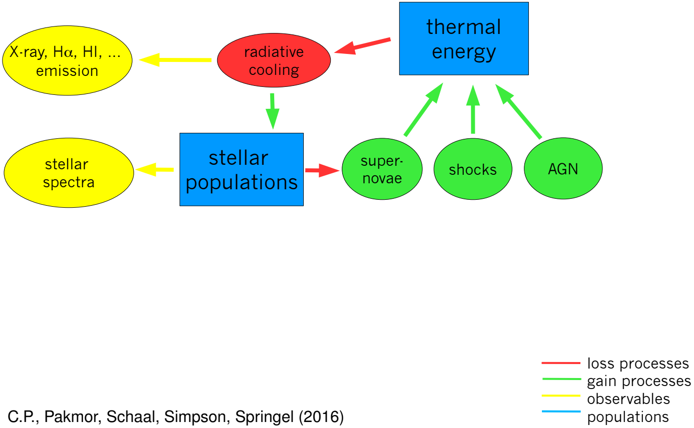
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:

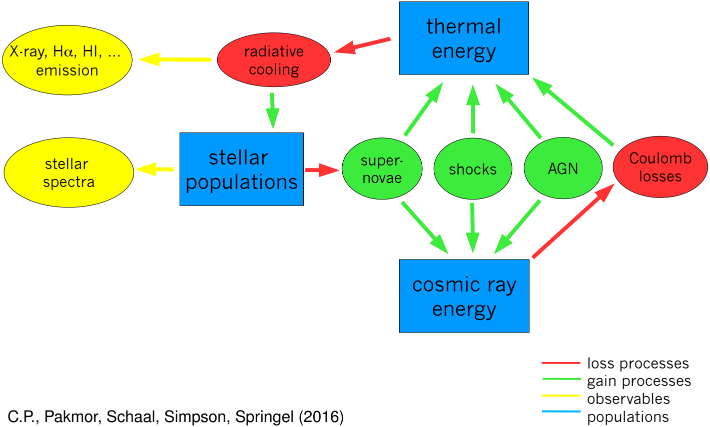


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

ISM observables:

Physical processes in the ISM:

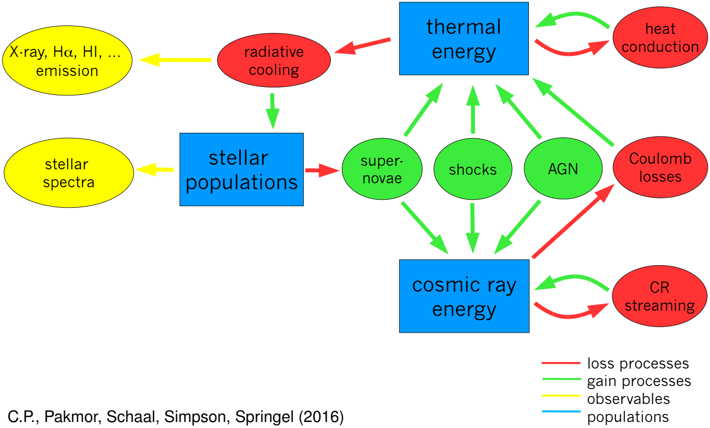


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

ISM observables:

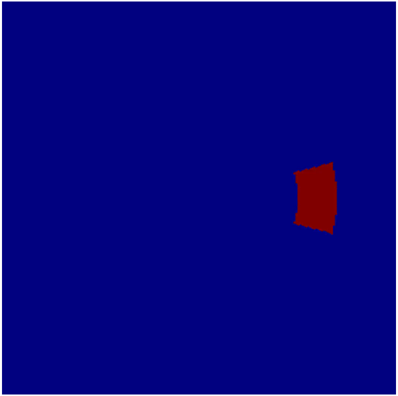
Physical processes in the ISM:



C.P., Pakmor, Schaal, Simpson, Springel (2016)

Anisotropic CR diffusion

- diffusion of CR energy density along magnetic field lines
- implemented on unstructured mesh in AREPO
- implicit solver with local time stepping
- obeys 1. and 2. law of thermodynamics (energy conserving and $\Delta S \geq 0$)

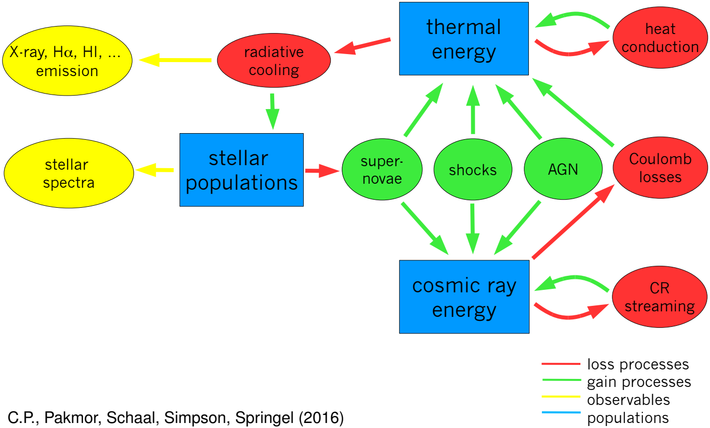


Pakmor, C.P., Simpson, Kannan, Springel (2016)

Simulations with cosmic ray physics

ISM observables:

Physical processes in the ISM:

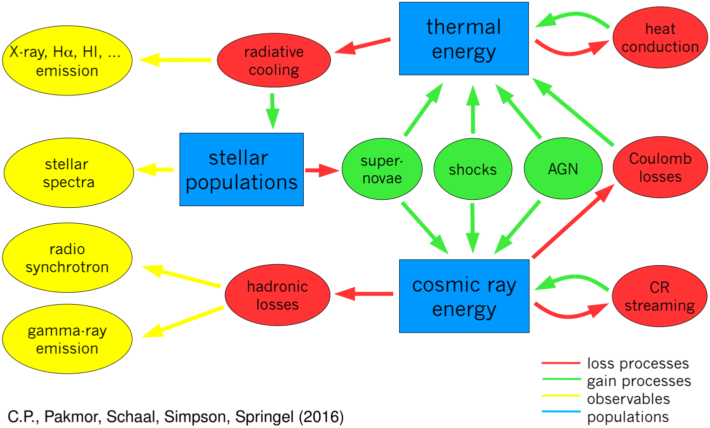


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

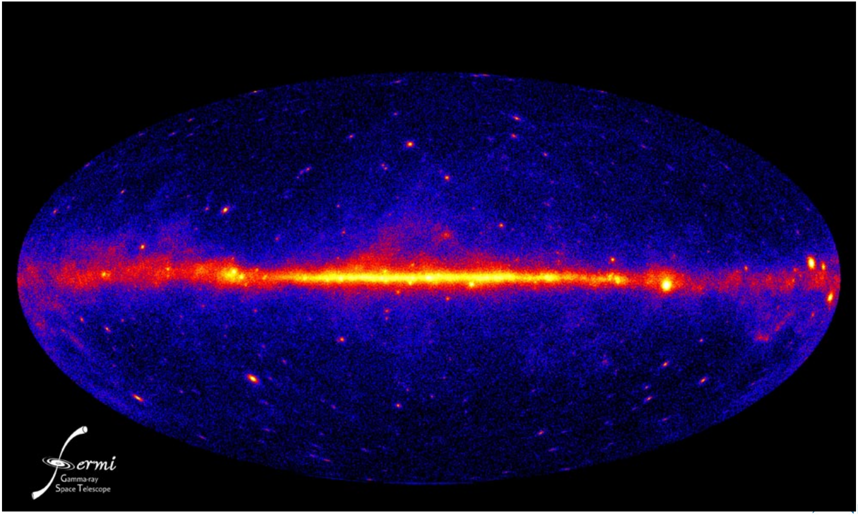
ISM observables:

Physical processes in the ISM:

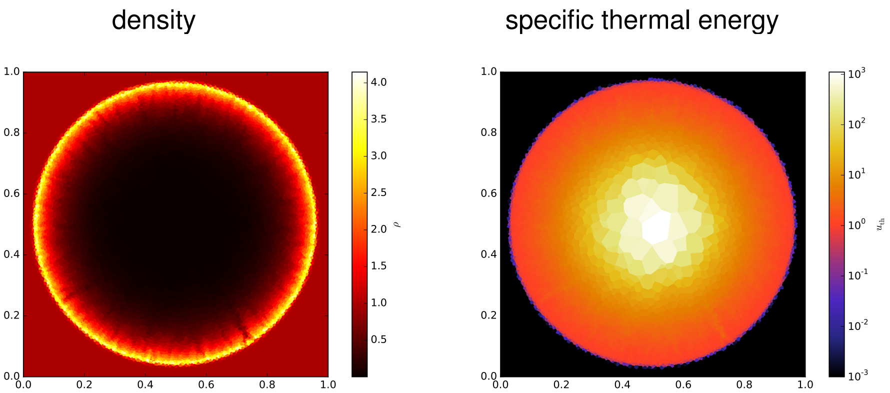


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Gamma-ray emission of the Milky Way



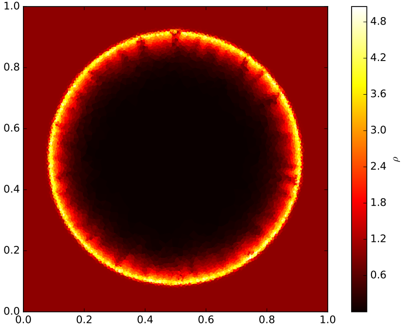
Sedov explosion



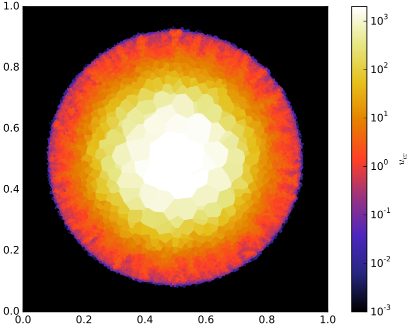
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Sedov explosion with CR acceleration

density



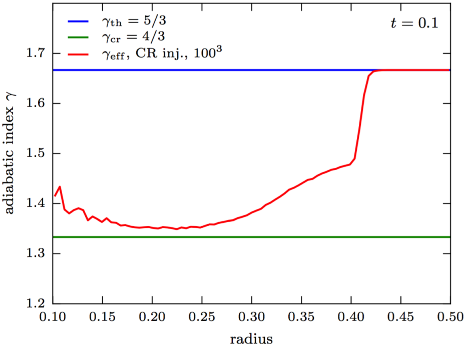
specific cosmic ray energy



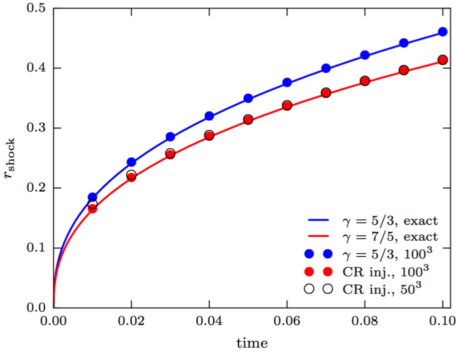
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Sedov explosion with CR acceleration

adiabatic index



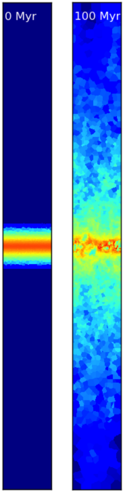
shock evolution



C.P., Pakmor, Schaal, Simpson, Springel (2016)

A model for the multi-phase interstellar medium

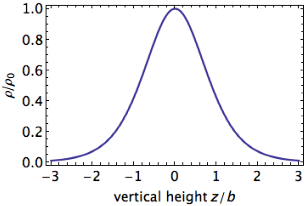
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

- isothermal disk with $T_0 = 10^4$ K
- hydrostatic equilibrium:

$$f_g \nabla^2 \Phi = 4\pi G \rho$$

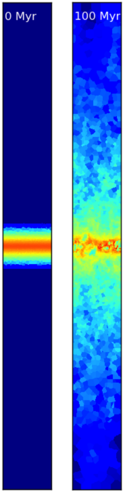


- self-gravity
- atomic & molecular cooling network, self-shielding (Glover & Clark 2012, Smith+ 2014)
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (C.P.+ 2016, Pakmor+ 2016)

HITS

Supernova feedback

Explore supernovae-driven outflows at high resolution – stratified box simulations



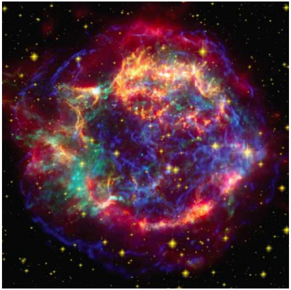
Simpson+ (2016)

- star formation rate:

$$\dot{M}_{*,i} = \epsilon \frac{M_i}{t_{\mathrm{dyn},i}}$$

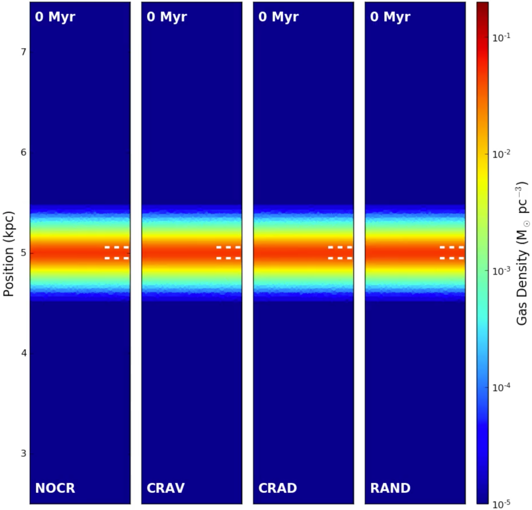
- supernova rate:

$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{*,i} \frac{1.8 \text{ events}}{100 \mathrm{M}_\odot}$$



- supernova energy $E_{\mathrm{SN}} = 10^{51}$ erg distributed over 32 nearest neighbors
- input in form of thermal, kinetic, or cosmic ray energy

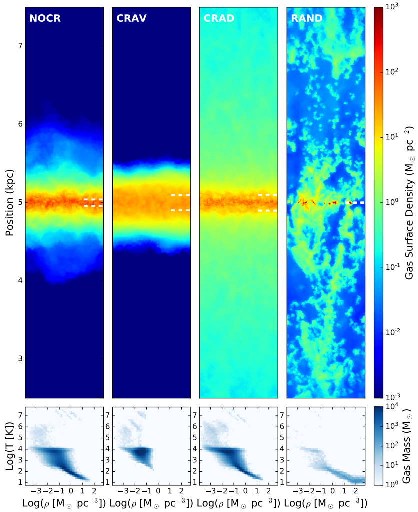
Interstellar medium – turbulence and outflows



Simpson+ (2016)

- NOCR: purely thermal SNe
- CRAV: CR advection, $\{f_{\rm cr}, f_{\rm th}\} = \{0.1, 0.9\}$
- CRAD: anisotropic CR diffusion
- RAND: random injection

Interstellar medium – turbulence and outflows

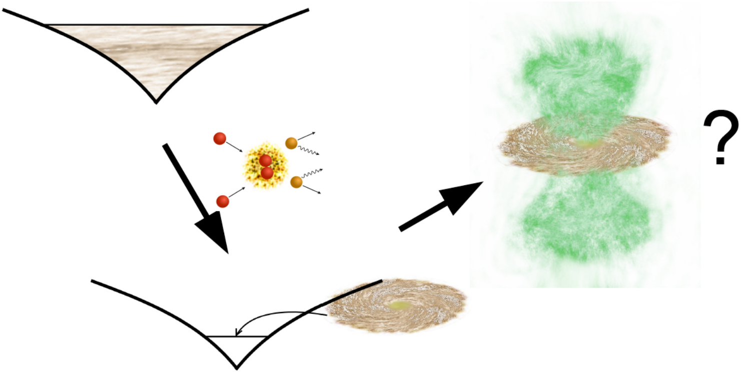


Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND) → velocity and clumpiness differ
- CR + turbulent pressure self-regulate ISM → scale height $h_{1/2} \approx 100$ pc; ISM in RAND collapses to dense phase

⇒ **CR physics is essential for correctly modeling the ISM!**

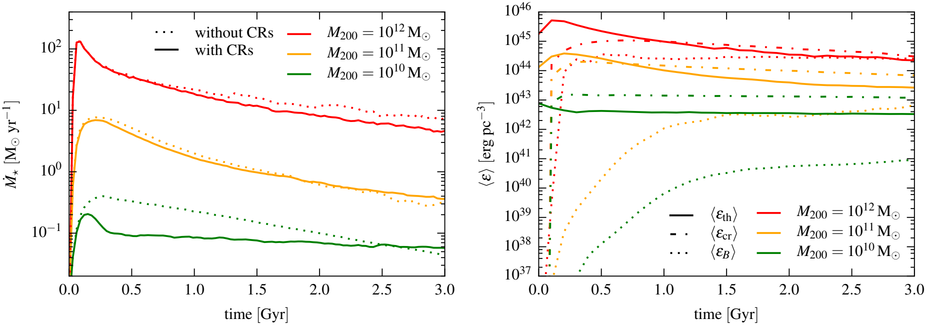
Galaxy simulation setup: 1. cosmic ray advection



C.P., Pakmor, Schaal, Simpson, Springel (2016)
Simulating cosmic ray physics on a moving mesh

MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

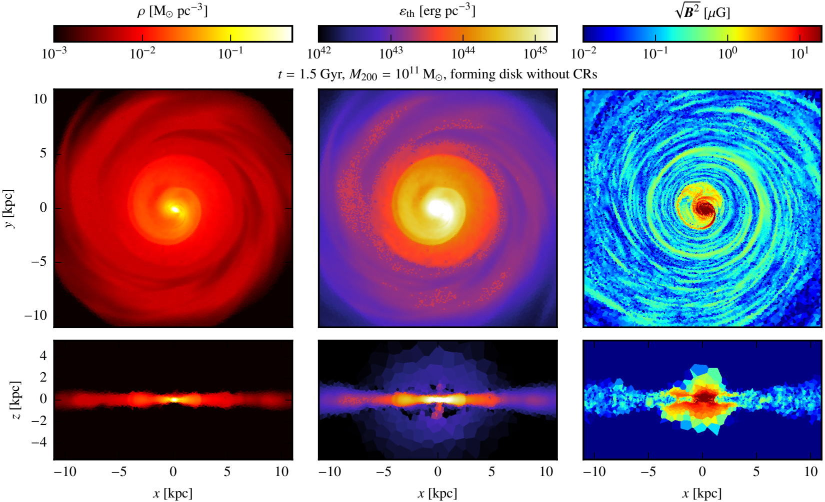
Time evolution of SFR and energy densities



C.P., Pakmor, Schaal, Simpson, Springel (2016)

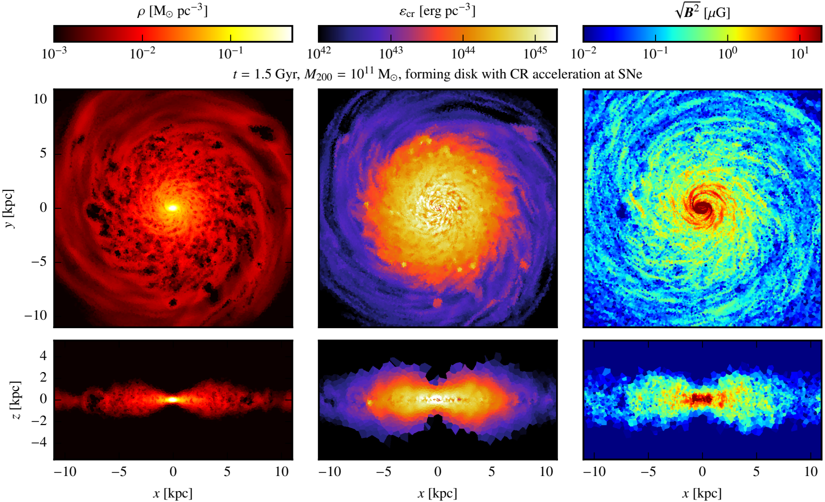
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



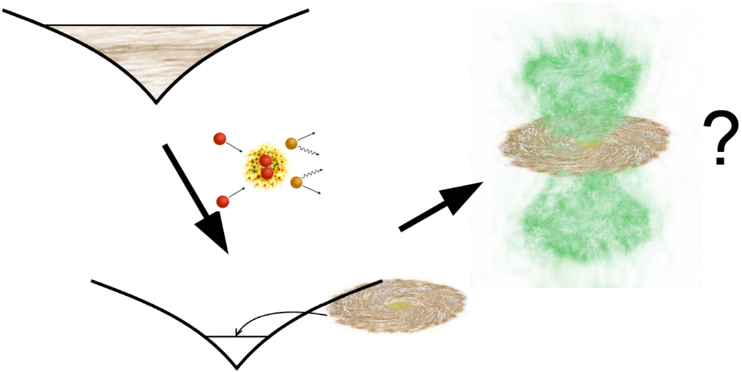
C.P., Pakmor, Schaal, Simpson, Springel (2016)

MHD galaxy simulation with CRs



C.P., Pakmor, Schaal, Simpson, Springel (2016)

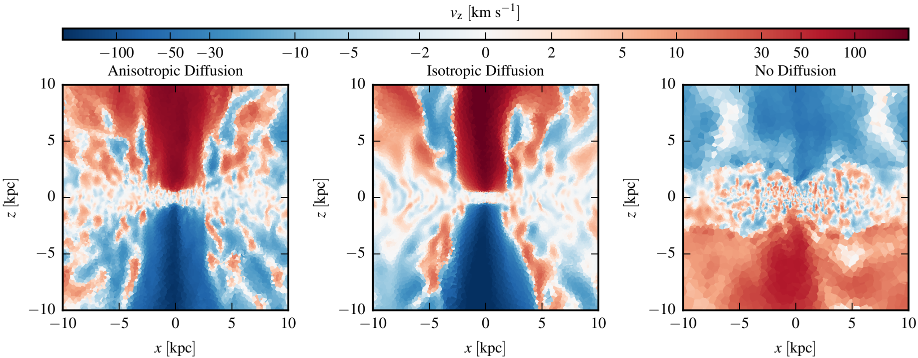
Galaxy simulation setup: 2. cosmic ray diffusion



Pakmor, C.P., Simpson, Springel (2016)
Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies

MHD + CR advection + diffusion: 10^{11} $M_\odot$

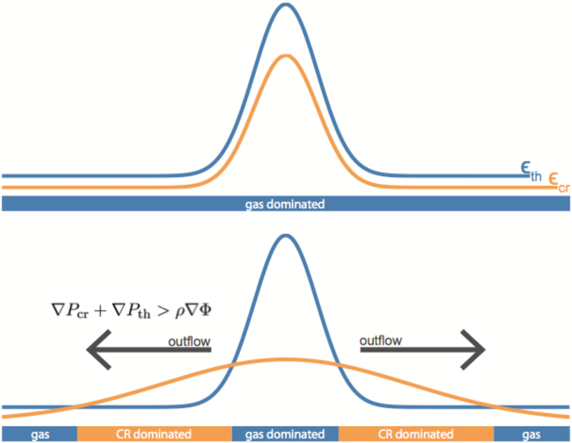
MHD galaxy simulation with CR diffusion



Pakmor, C.P., Simpson, Springel (2016)

- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

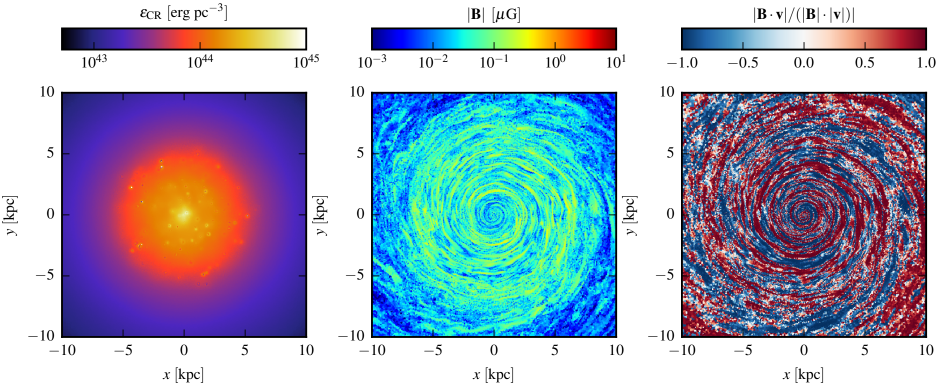
Cosmic ray driven wind: mechanism



CR streaming: Uhlig, C.P.+ (2012)

CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

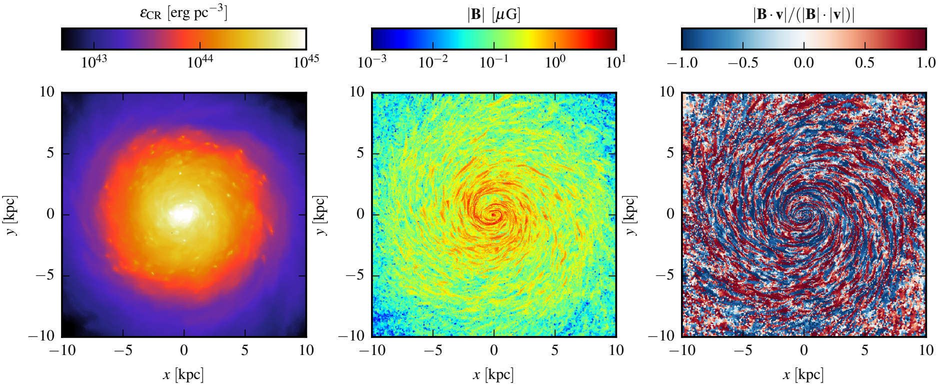
MHD galaxy simulation with CR isotropic diffusion



Pakmor, C.P., Simpson, Springel (2016)

- CR diffusion strongly suppresses SFR
- strong outflow quenches magnetic dynamo to yield $B \sim 0.1\ \mu\text{G}$

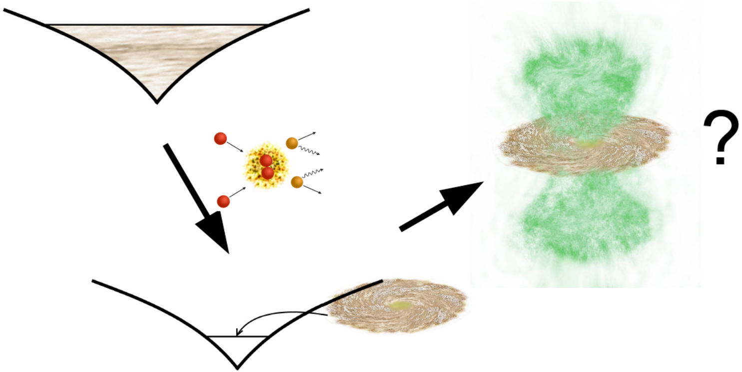
MHD galaxy simulation with CR anisotropic diffusion



Pakmor, C.P., Simpson, Springel (2016)

- anisotropic CR diffusion also suppresses SFR
- reactivation of magnetic dynamo: growth to observed strengths

Galaxy simulation setup: 3. non-thermal emission

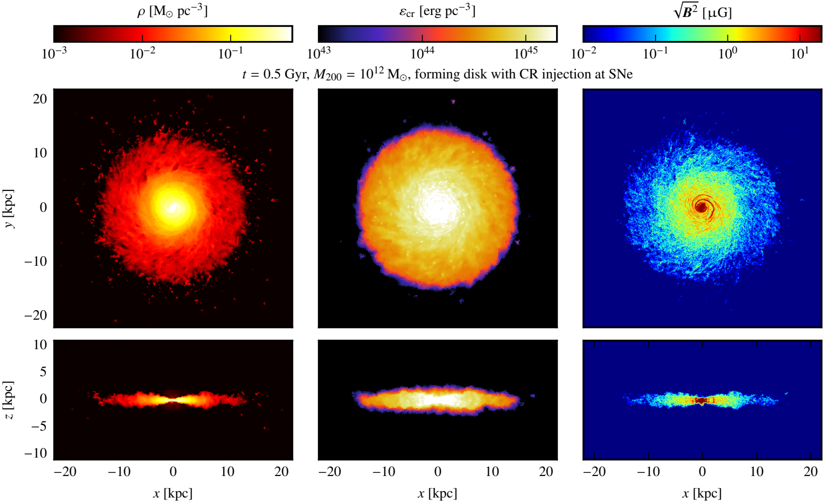


C.P., Pakmor+ (in prep)
Non-thermal radio and gamma-ray emission in isolated disk galaxies

MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

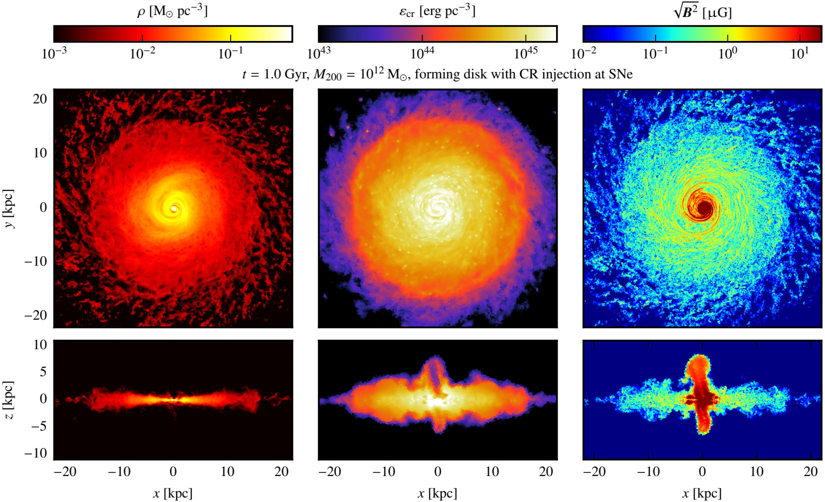
HITS

Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



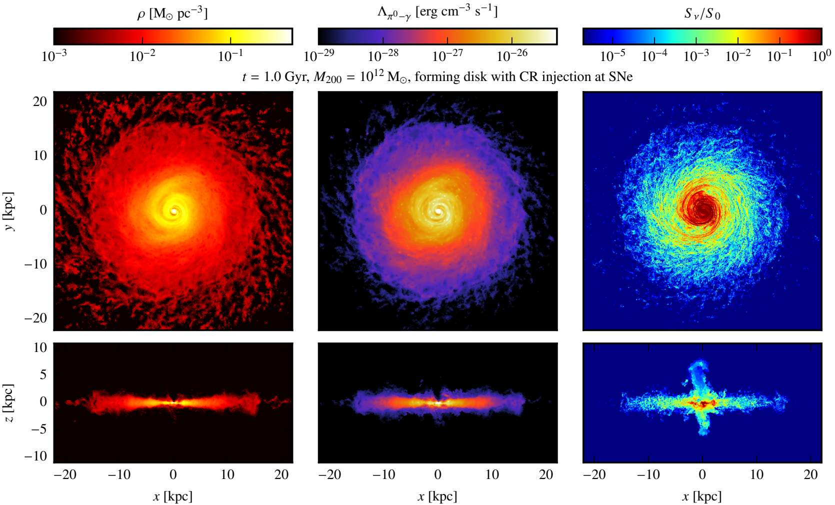
C.P., Pakmor+ (in prep.)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



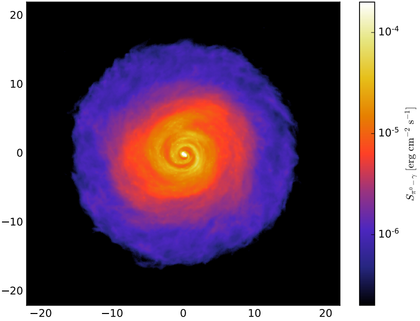
C.P., Pakmor+ (in prep.)

γ-ray and radio emission of Milky Way-like galaxy



C.P., Pakmor+ (in prep.)

Projected γ-ray emission of Milky Way-like galaxy

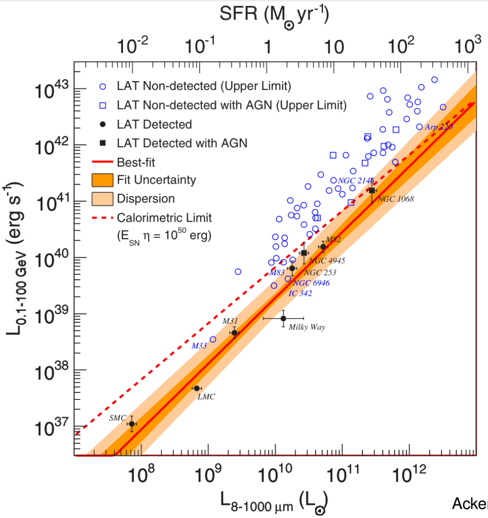


C.P., Pakmor+ (in prep.)

- pion decay γ-ray emission shows no *Fermi*-like bubbles due to low density in wind region $\rightarrow$ leptonic emission? (Selig+ 2015)
- compute gamma-ray luminosity $\rightarrow L_{\mathrm{FIR}} - L_{\gamma}$

Far infra-red – gamma-ray correlation

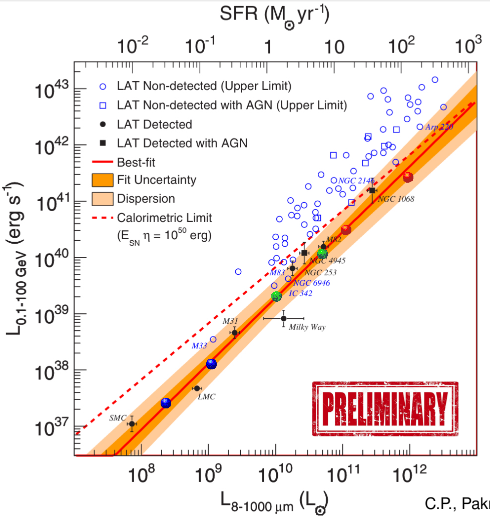
Universal conversion: star formation → cosmic rays → gamma rays



Ackermann+ (2012)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



C.P., Pakmor+ (in prep.)

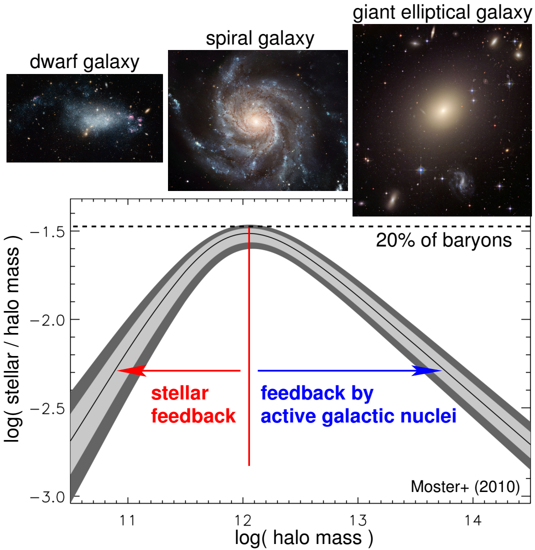
Conclusions on cosmic-ray feedback in galaxies

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- no hadronic *Fermi*-like bubbles $\rightarrow$ leptonic emission?
- $L_{\mathrm{FIR}} - L_\gamma$ correlation allows to test calorimetric assumption

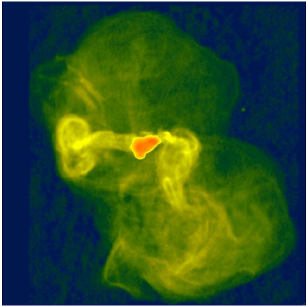
outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

need: comparison to resolved radio/γ-ray observations $\rightarrow$ **SKA/CTA**

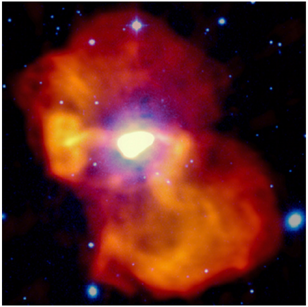
Puzzles in galaxy formation



Messier 87 at radio wavelengths



ν = 1.4 GHz (Owen+ 2000)



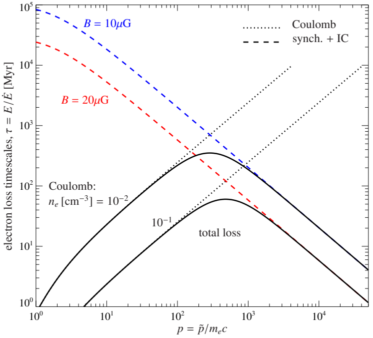
ν = 140 MHz (LOFAR/de Gasperin+ 2012)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons → time-integrated 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)
- 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:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



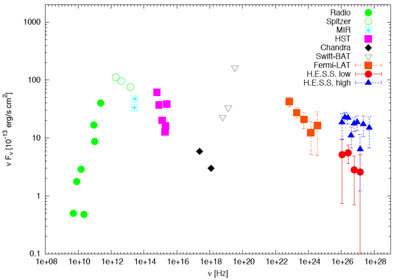
C.P. (2013)

The gamma-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!**

AGN feedback = cosmic ray heating (?)

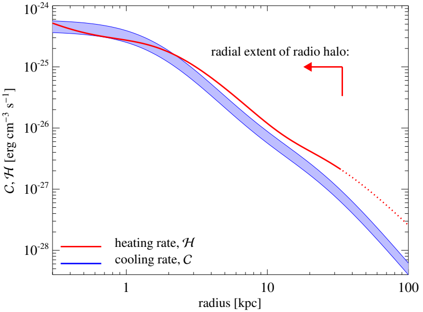
hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_{\rm st} \cdot \nabla P_{\rm cr}$$

(Loewenstein+ 1991, Guo & Oh 2008, Enßlin+ 2011, Wiener+ 2013, C.P. 2013)

- calibrate $P_{\rm cr}$ to γ-ray emission and $|\boldsymbol{v}_{\rm st}| = |\boldsymbol{v}_{\rm A}|$ to radio/X-ray emission $\rightarrow$ spatial heating profile

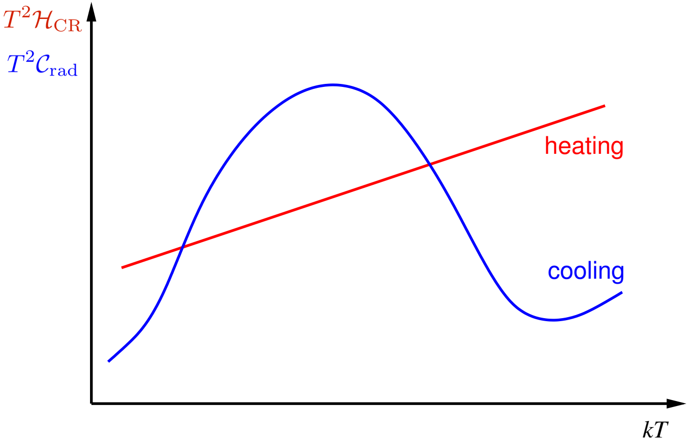


C.P. (2013)

$\rightarrow$ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous “cooling flow problem” in galaxy clusters!

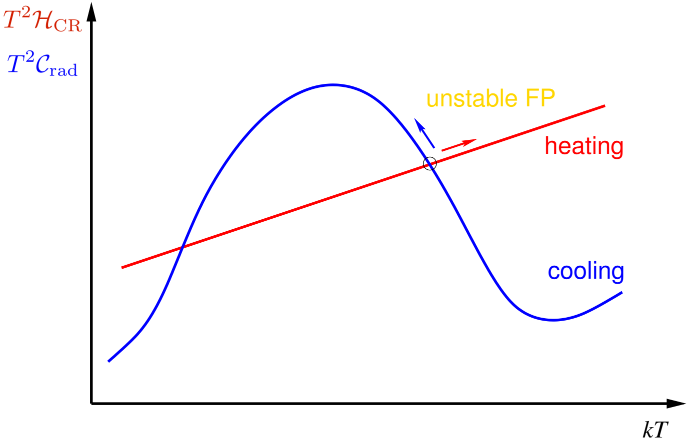
HITS

Local stability analysis (1)



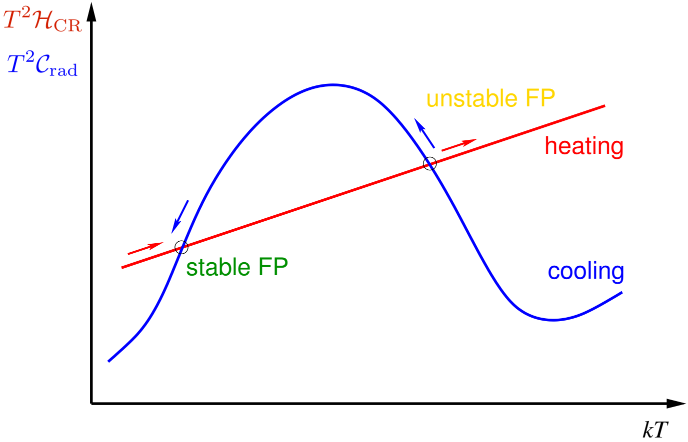
- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (1)



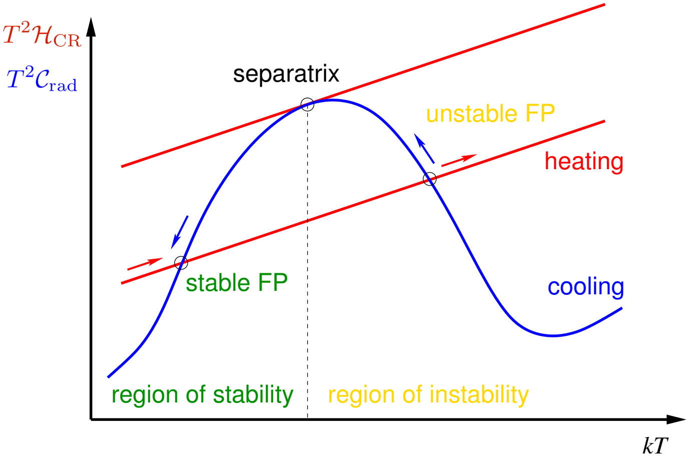
- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (1)



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

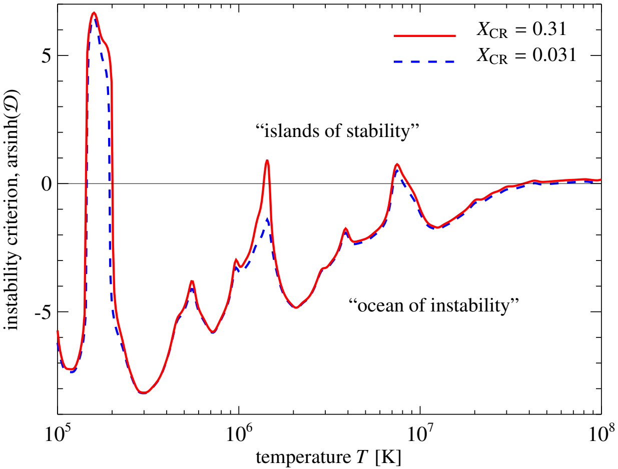
Local stability analysis (1)



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

Local stability analysis (2)

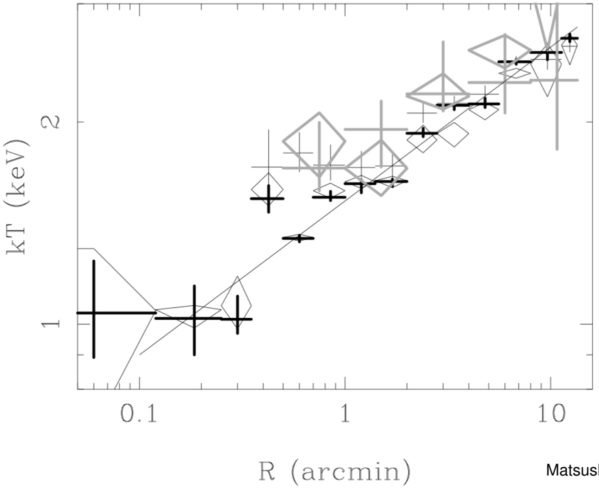
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

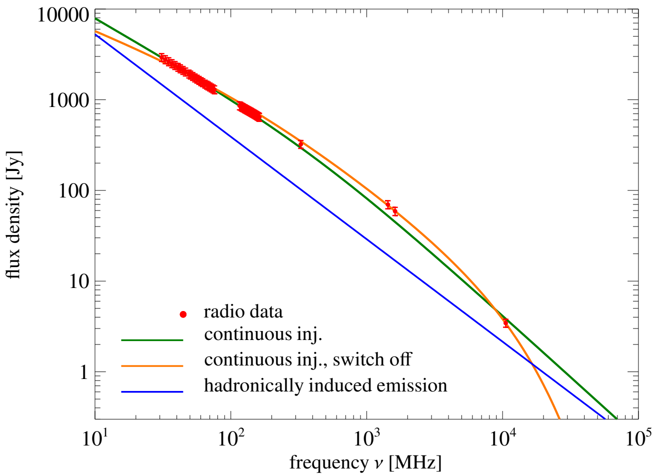
Virgo cluster cooling flow: temperature profile

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



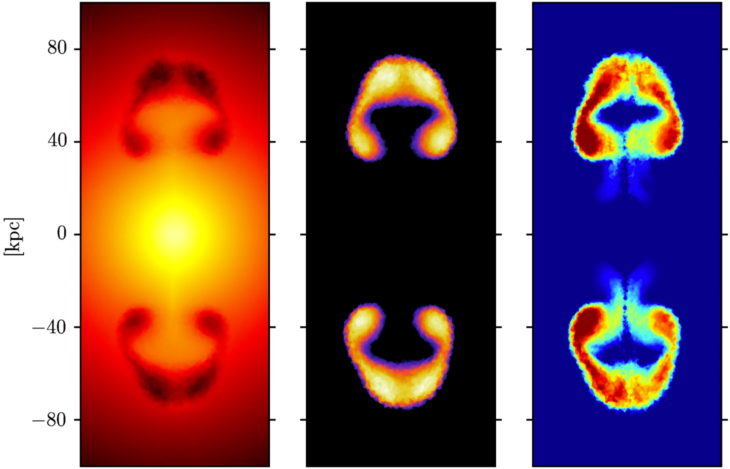
Matsushita+ (2002)

Prediction: flattening of high-ν radio spectrum



C.P. (2013)

Jet simulation: gas density, CR energy, *B* field



Weinberger+ in prep.

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 within the radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: couple CRs to AGN jet model, simulate anisotropically steaming CRs, cosmological cluster simulations

need: deeper radio/γ-ray observations $\rightarrow$ **SKA/CTA**

HITS

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN–646955).

Literature for the talk

A multi-phase model of the interstellar medium:

- Simpson, Pakmor, Marinacci, Pfrommer, Springel, Glover, Clark, Smith, *The role of cosmic ray pressure in accelerating galactic outflows,* 2016, ApJL.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2016, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Pakmor, Pfrommer, Simpson, Kannan, Springel, *Semi-implicit anisotropic cosmic ray transport on an unstructured moving mesh,* 2016, MNRAS.

AGN feedback by cosmic rays:

- 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, 779, 10.