How cosmic rays shape galaxies

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in collaboration with

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Outline

1. Introduction and Motivation
   - Galaxy formation
   - Shock acceleration
   - Cosmic ray physics
2. Simulating galaxies
   - Physical Processes
   - Interstellar medium
   - Global galaxies
3. AGN feedback
   - Radio and γ-ray emission
   - Cosmic-ray heating
   - Simulations

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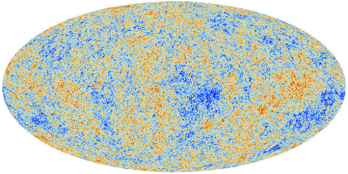
Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

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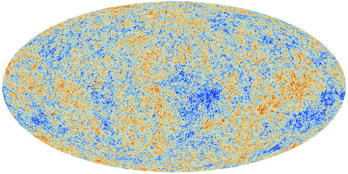

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dropping pebbles into the pond generates expanding waves that interfere with each other

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- galaxies and clusters form at sites of constructive interference of those primordial waves

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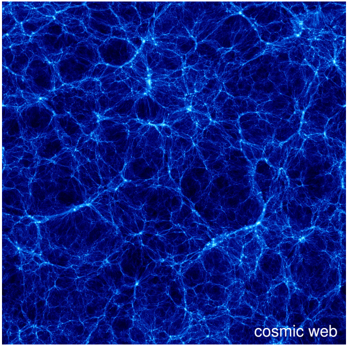

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- cosmic matter assembles in the "cosmic web" through gravitational instability
- galaxies form as "beats on a string" along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

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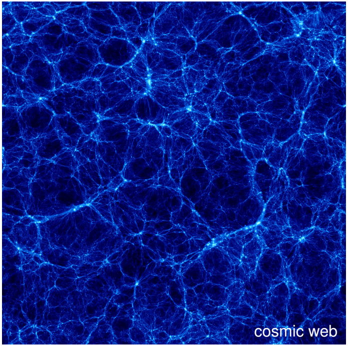

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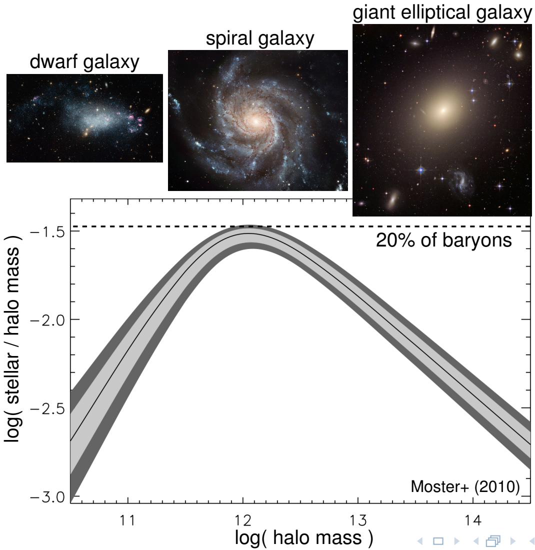
Puzzles in galaxy formation


Puzzles in galaxy formation



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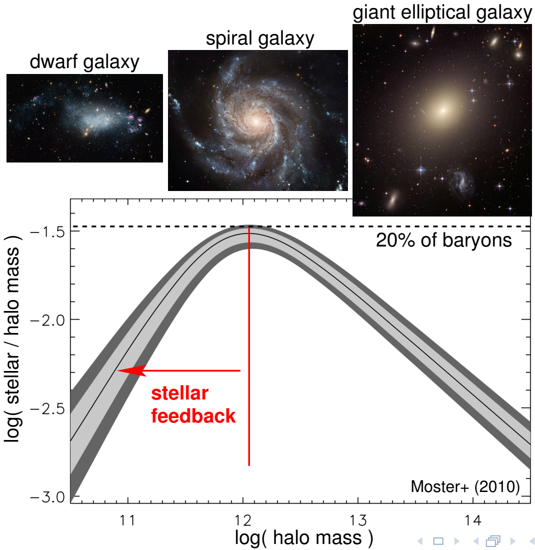

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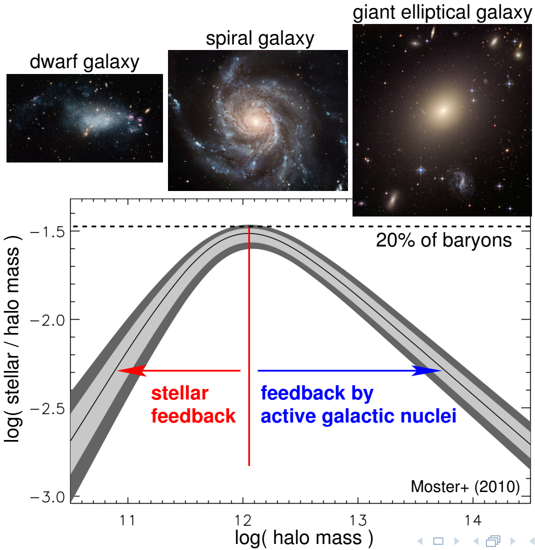

Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process

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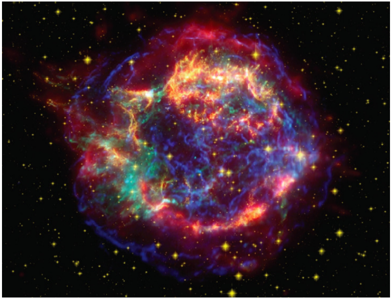
3. the solution of all problems in galaxy formation

Feedback by 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

Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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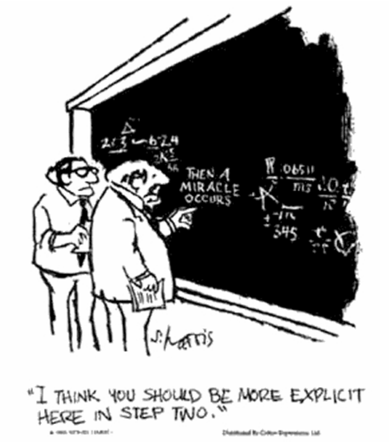

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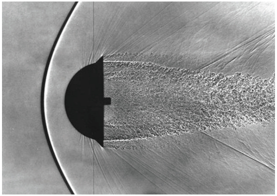
Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.

thickness $\sim$ mean free path $\lambda_{\rm mfp}$

in air, $\lambda_{\rm mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.



slide concept Spitkovsky

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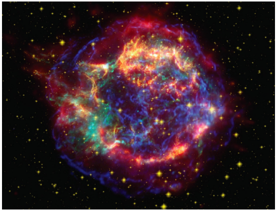

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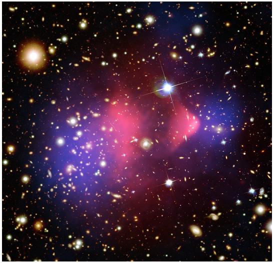


clusters/galaxies, Coulomb collisions set $\lambda_{\rm mfp}$:
$\lambda_{\rm mfp} \sim L_{\rm cluster}/10$, $\lambda_{\rm mfp} \sim L_{\rm SNR}$

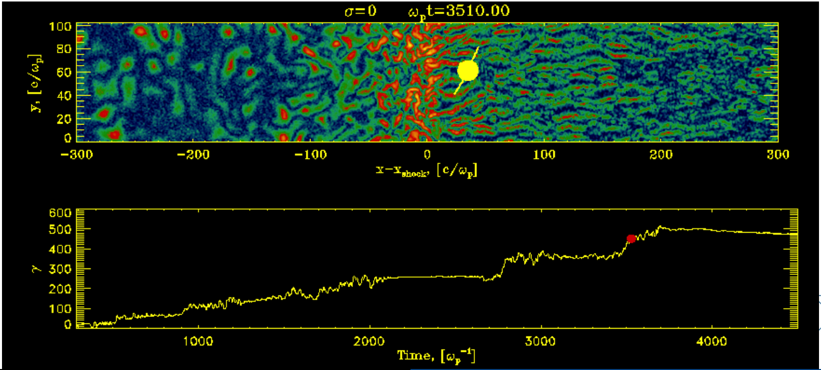
Mean free path $\gg$ observed shock width!

$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields
$\rightarrow$ collisionless shocks

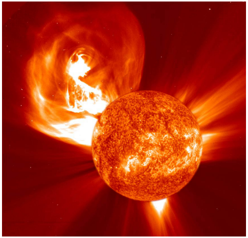
slide concept Spitkovsky

Particle acceleration at relativistic shock, $B_0 = 0$

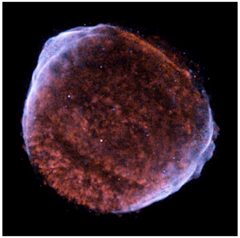
- self-generated magnetic turbulence scatters particles across the shock
- each crossing results in energy gain – Fermi process
- movie below shows magnetic filaments in the shock frame (top), particle energy is measured the downstream frame (bottom): particle gains energy upon scattering in the upstream (Spitkovsky 2008)



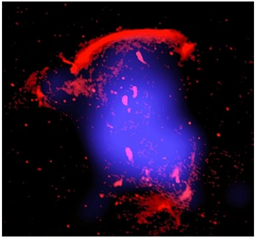
Astrophysical shocks



solar system shocks $\sim R_\odot$
coronal mass ejection (SOHO)



interstellar shocks $\sim$ 20 pc
supernova 1006 (CXC/Hughes)

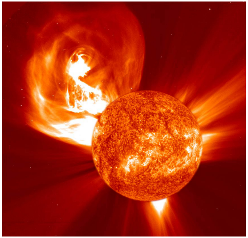


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

Astrophysical shocks

astrophysical collisionless shocks can:

- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions



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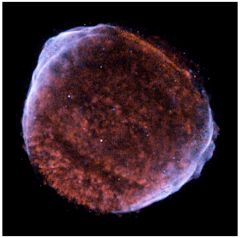

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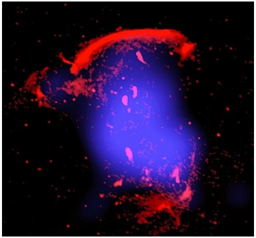

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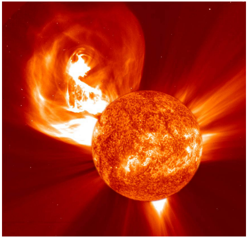
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



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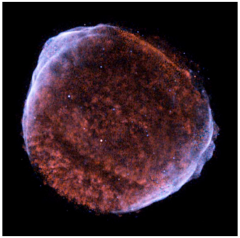

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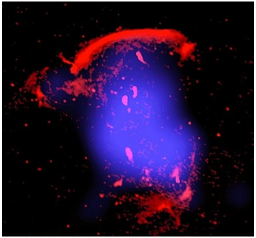

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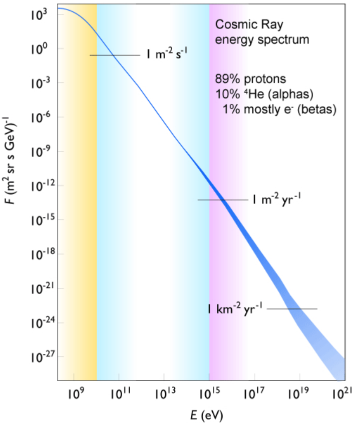
Galactic cosmic ray spectrum



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

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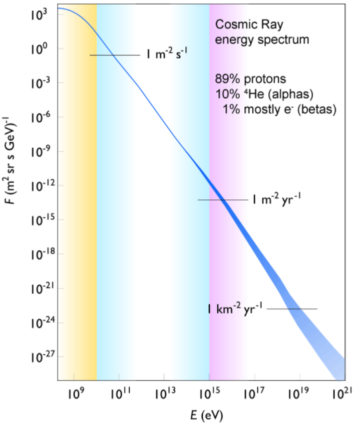

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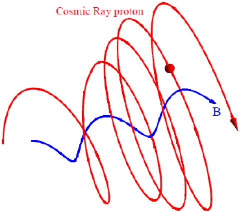
- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

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



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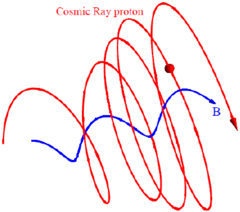

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- 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 $\boldsymbol{B}$):

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

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

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

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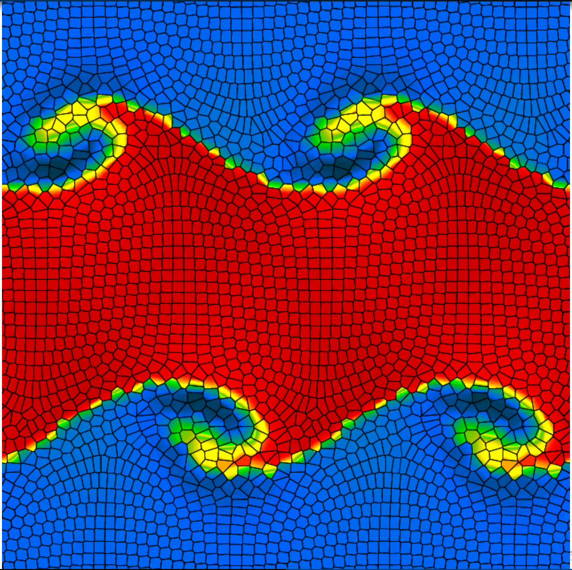
$$\Longleftrightarrow \quad \frac{\partial\varepsilon_{\mathrm{cr}}}{\partial t} + \nabla\cdot\left[\varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}})\right] = -P_{\mathrm{cr}}\nabla\cdot(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}})$$

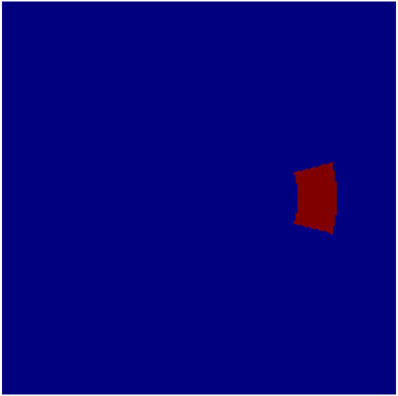
Outline

Cosmological moving-mesh code AREPO (Springel 2010)



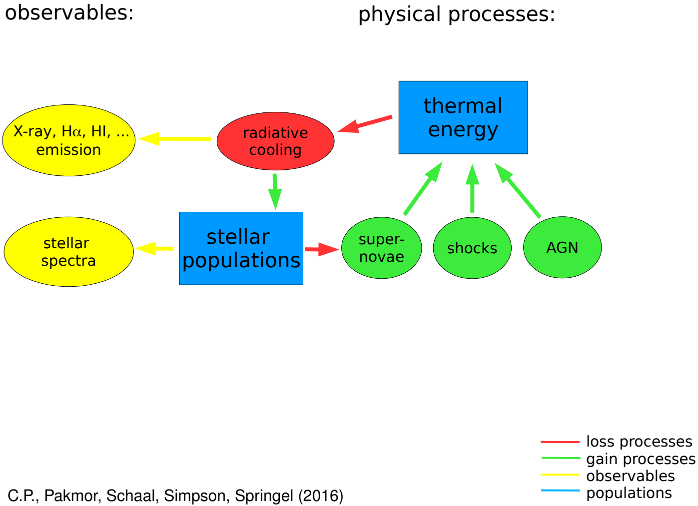
Anisotropic CR diffusion

- 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 – flowchart

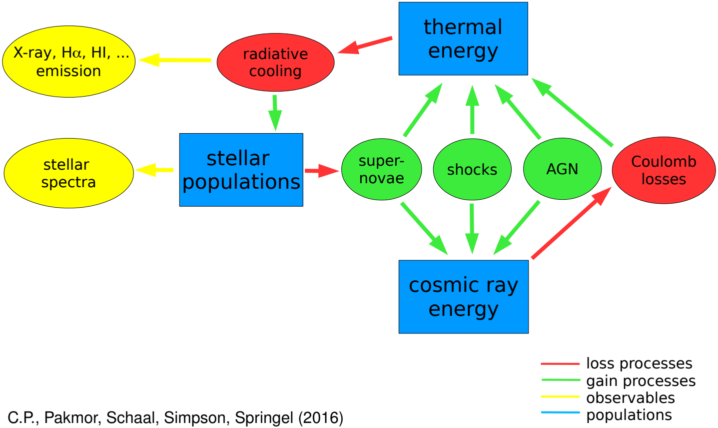


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

observables:

physical processes:



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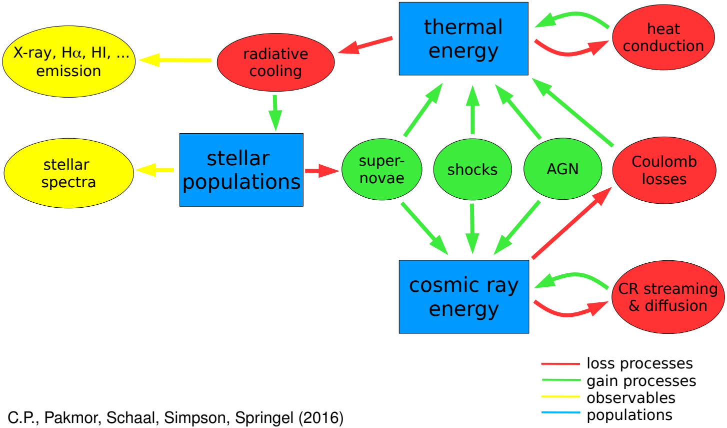

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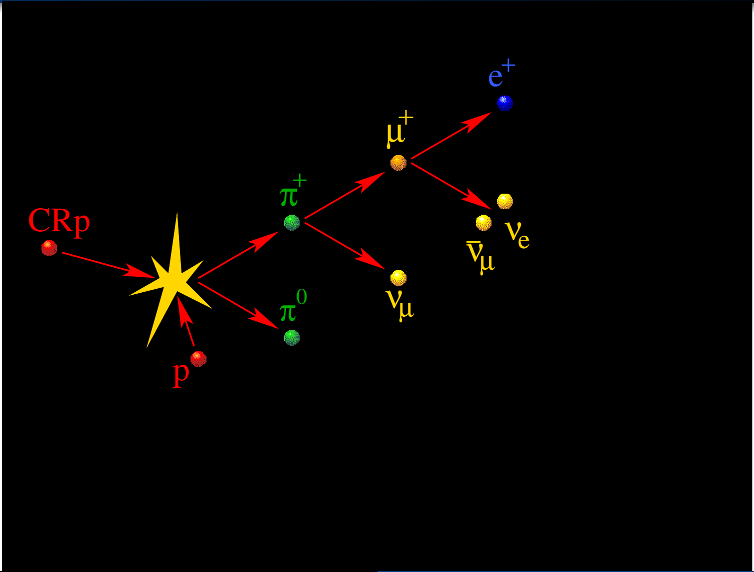
Hadronic cosmic ray proton interaction



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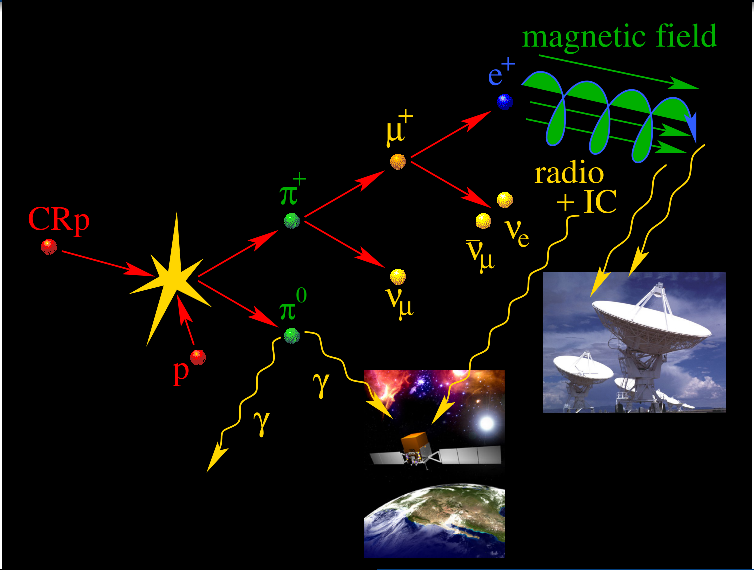

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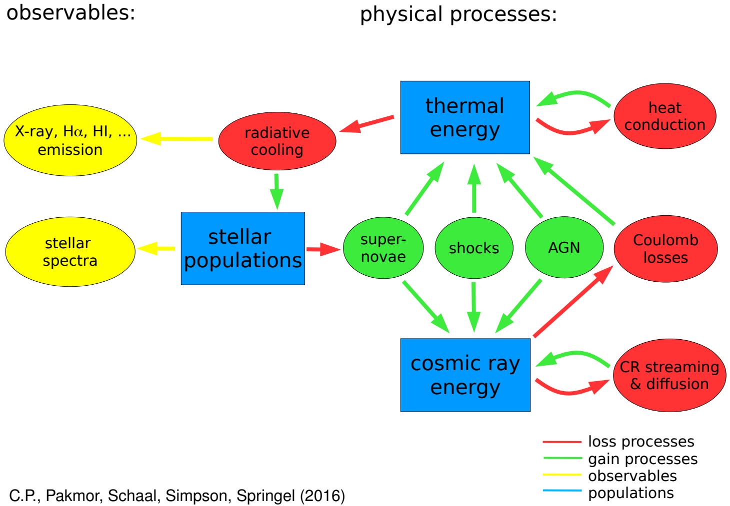

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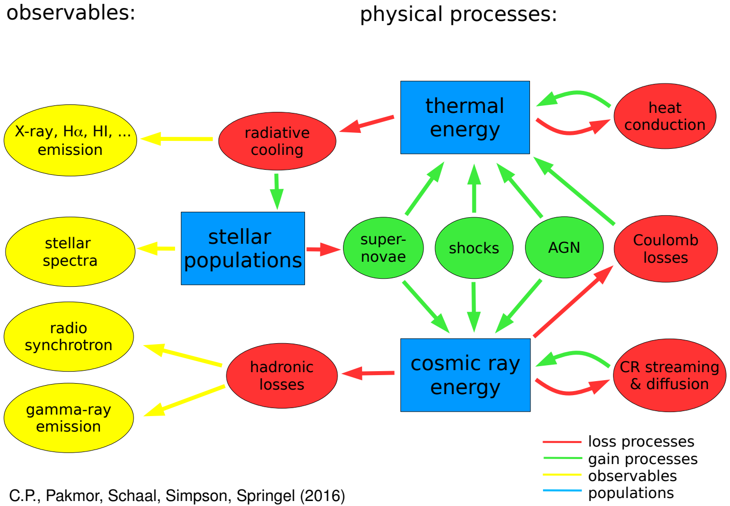

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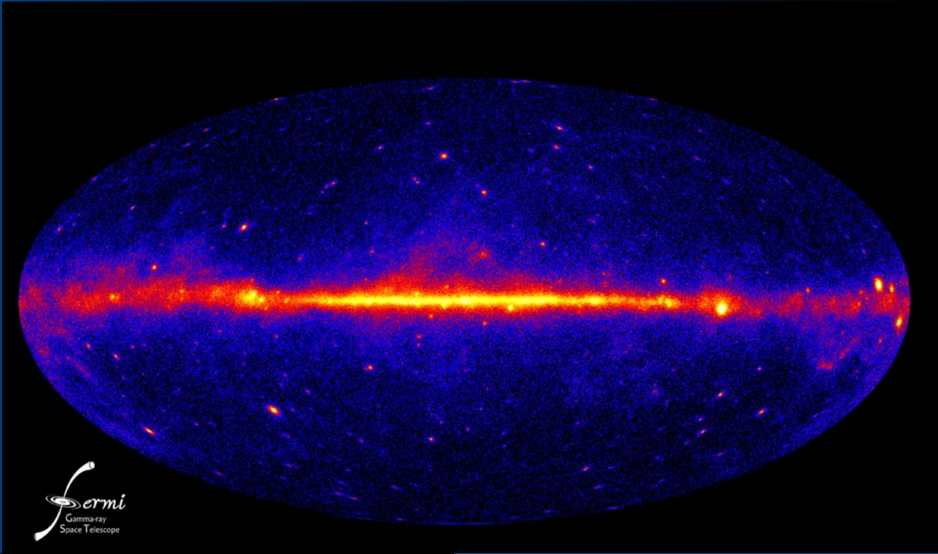
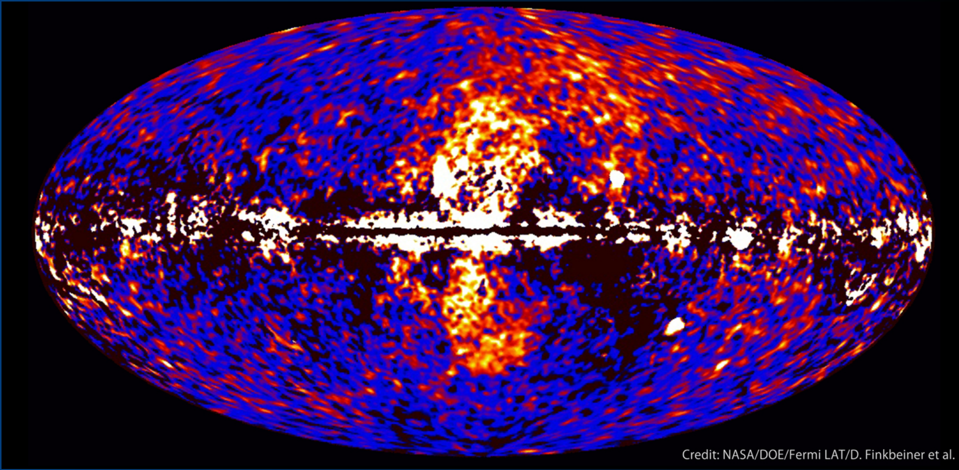
Gamma-ray emission of the Milky Way



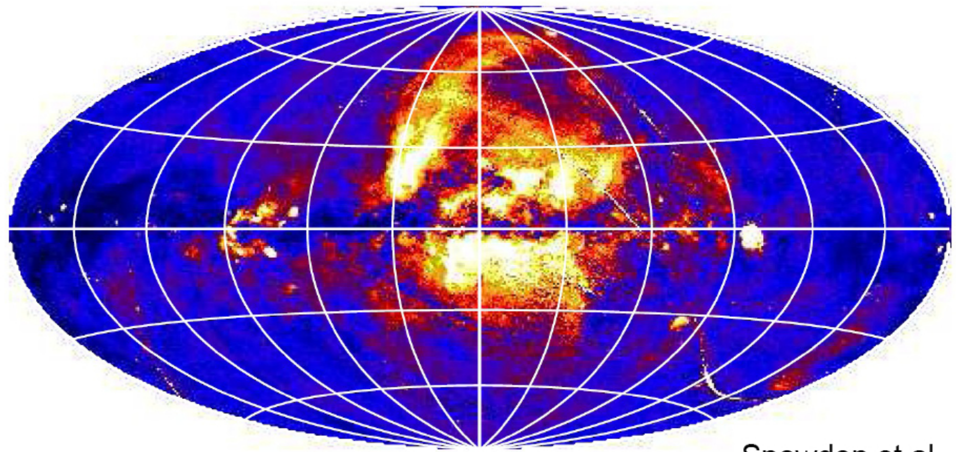
Galactic wind in the Milky Way?

Fermi gamma-ray bubbles



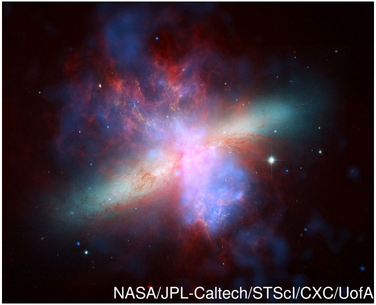
Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



Snowden et al.,

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?

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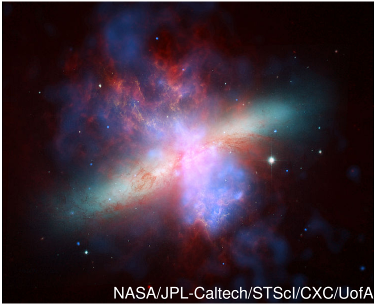

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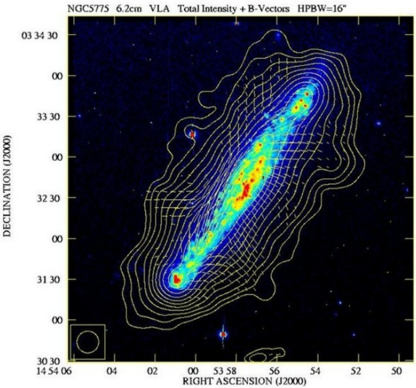
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

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

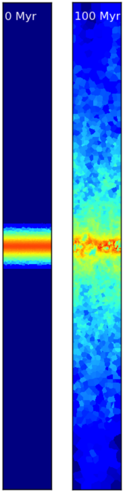


Tüllmann+ (2000)

- 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

A model for the multi-phase interstellar medium

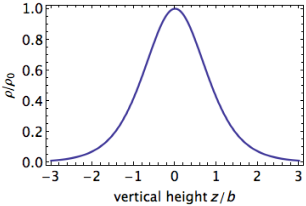
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

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

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

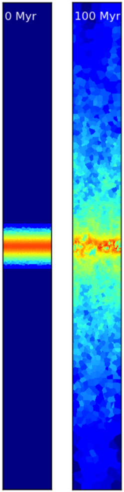


- self-gravity
- atomic & molecular cooling network, self-shielding (Glover & Clark 2012, Smith+ 2014)
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (C.P.+ 2016, Pakmor+ 2016)

HITS

A model for the multi-phase interstellar medium

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



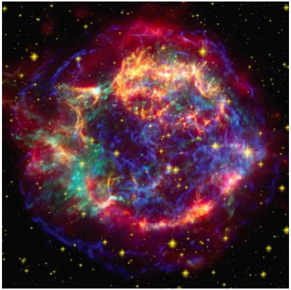
Simpson+ (2016)

- star formation rate:

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

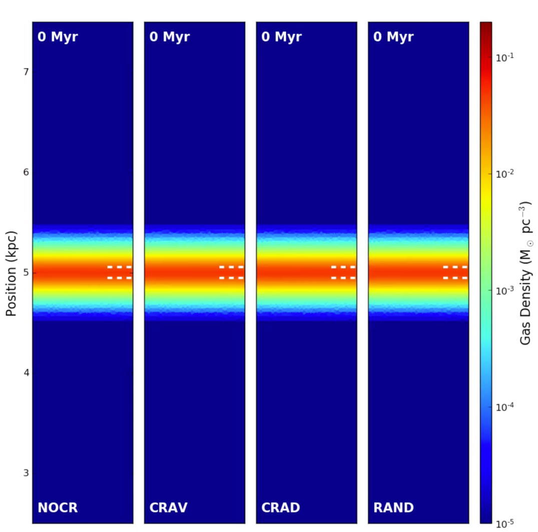
- supernova rate:

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



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

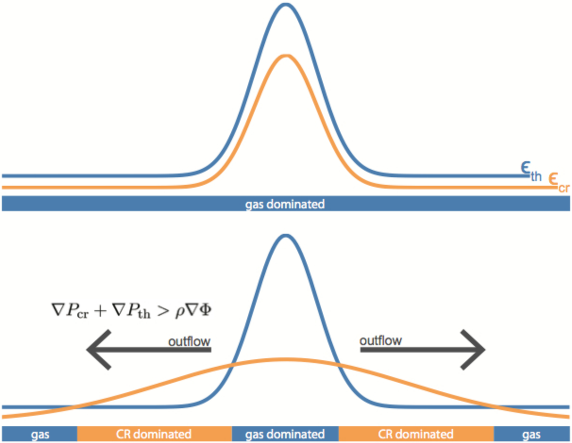
Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

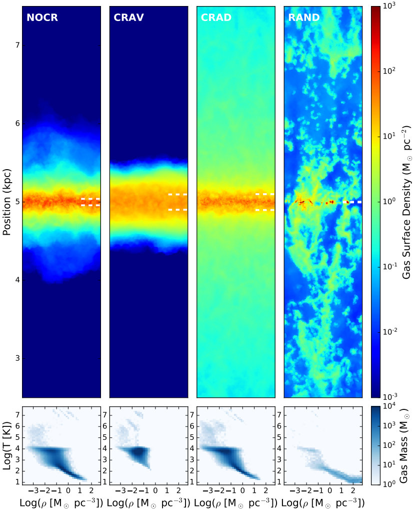
Cosmic ray driven wind: mechanism



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

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

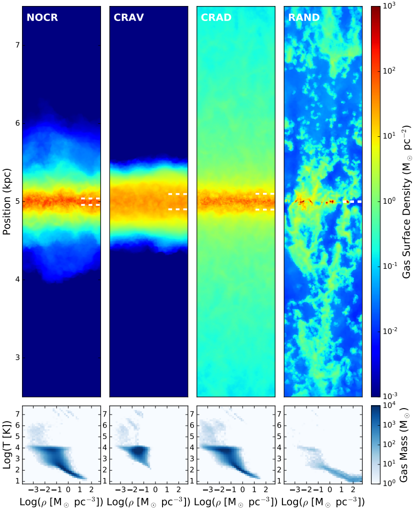
Interstellar medium – turbulence and outflows



Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)

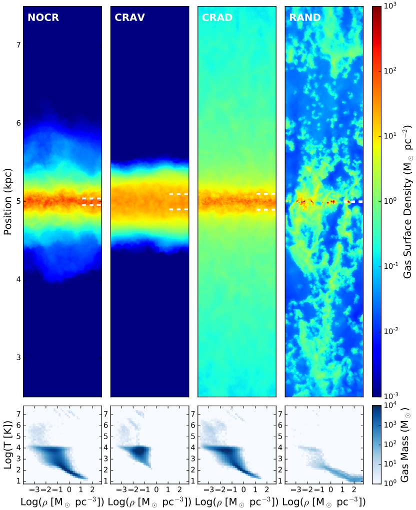
Interstellar medium – turbulence and outflows



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)
  $\rightarrow$ velocity and clumpiness differ

Interstellar medium – turbulence and outflows

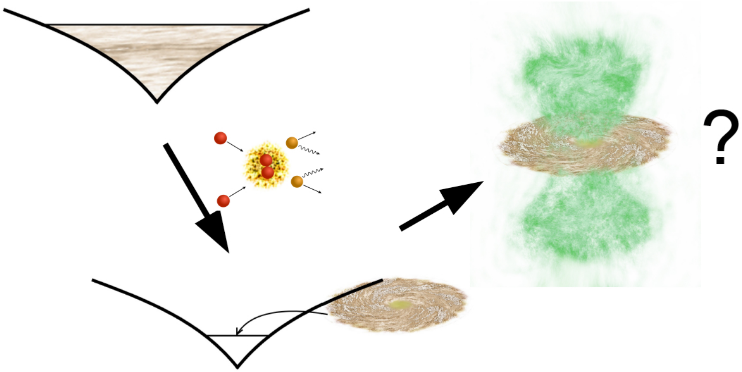


Simpson+ (2016)

- 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) $\rightarrow$ velocity and clumpiness differ
- CR + turbulent pressure self-regulate ISM $\rightarrow$ scale height $h_{1/2} \approx 100$ pc; ISM in RAND collapses to dense phase

$\Rightarrow$ **CR physics is essential for correctly modeling the ISM!**

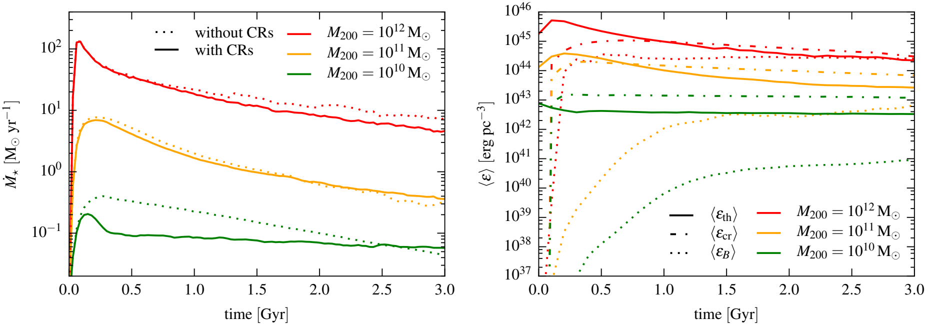
Galaxy simulation setup: 1. cosmic ray advection



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

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

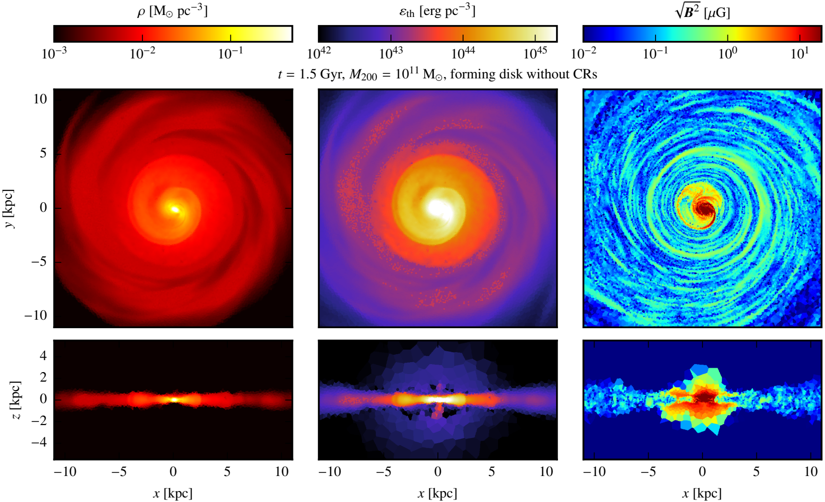
Time evolution of SFR and energy densities



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

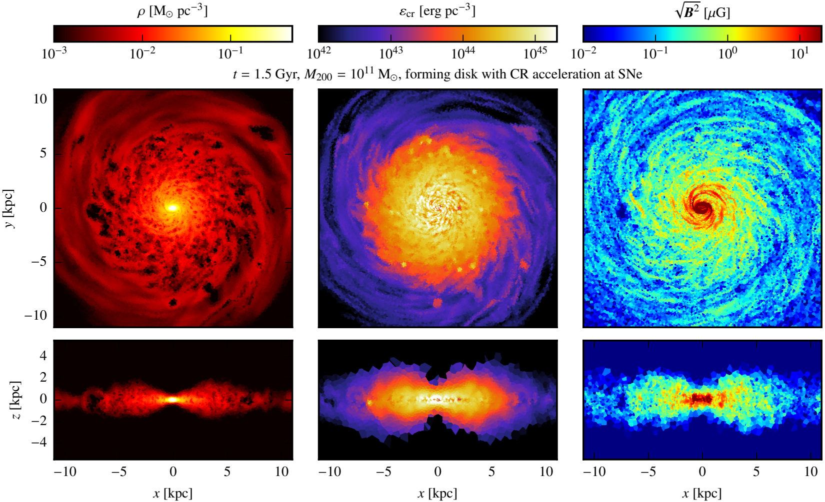
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



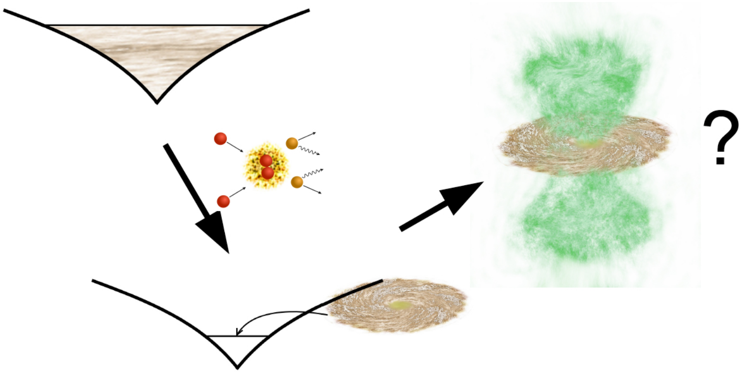
C.P., Pakmor, Schaal, Simpson, Springel (2016)

MHD galaxy simulation with CRs



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

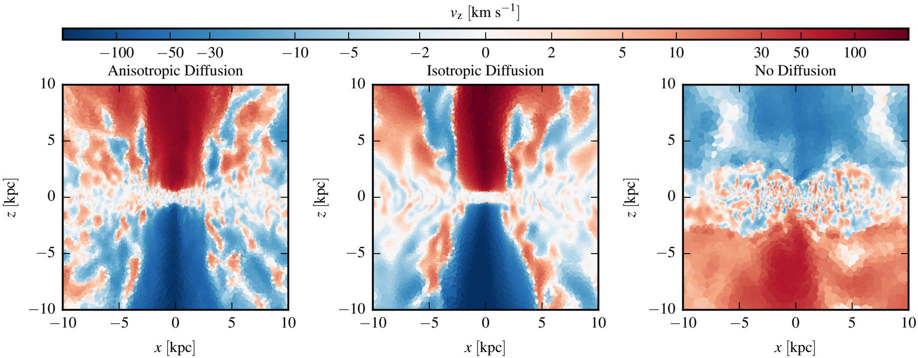
Galaxy simulation setup: 2. cosmic ray diffusion



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} $M_\odot$

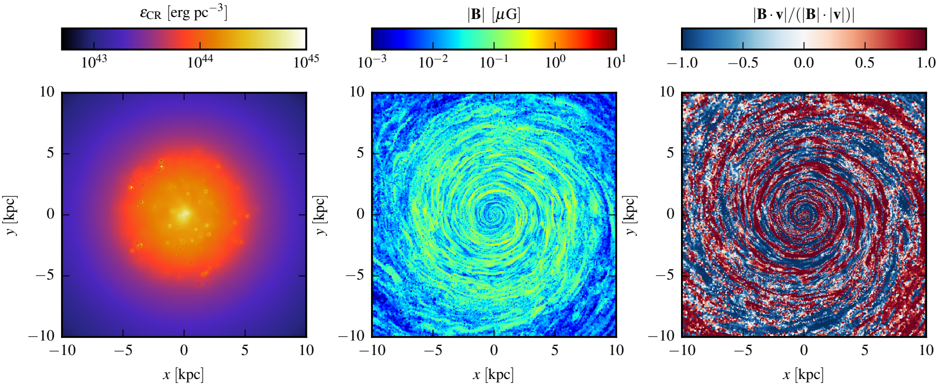
MHD galaxy simulation with CR diffusion



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

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

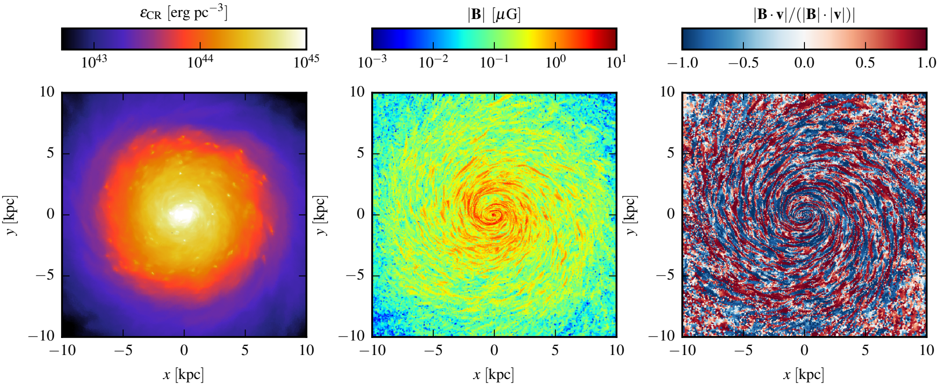
MHD galaxy simulation with CR isotropic diffusion



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

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

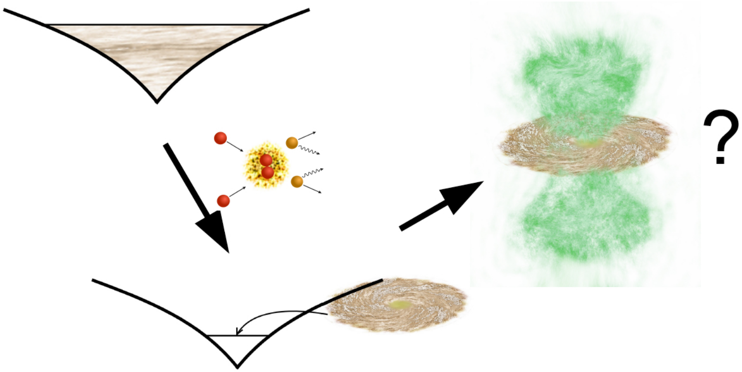
MHD galaxy simulation with CR anisotropic diffusion



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

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

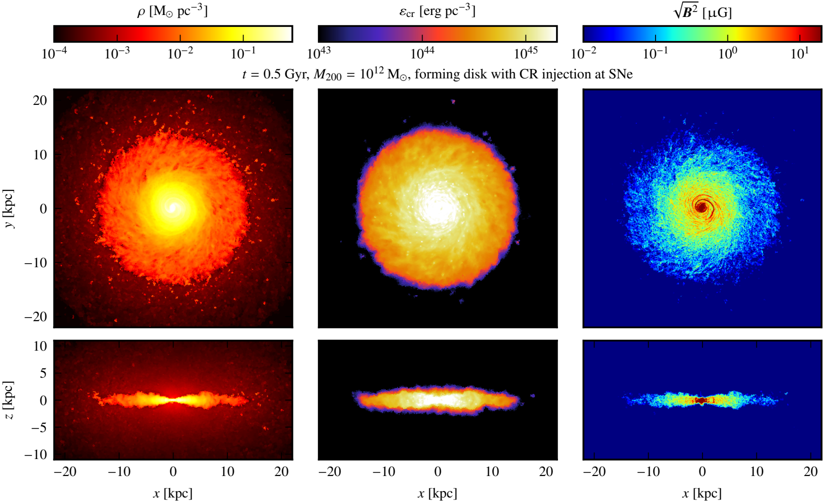
Galaxy simulation setup: 3. non-thermal emission



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

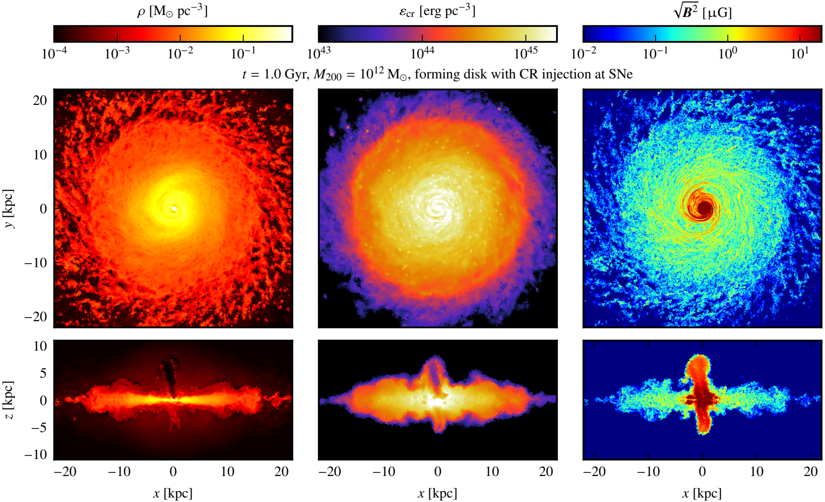
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



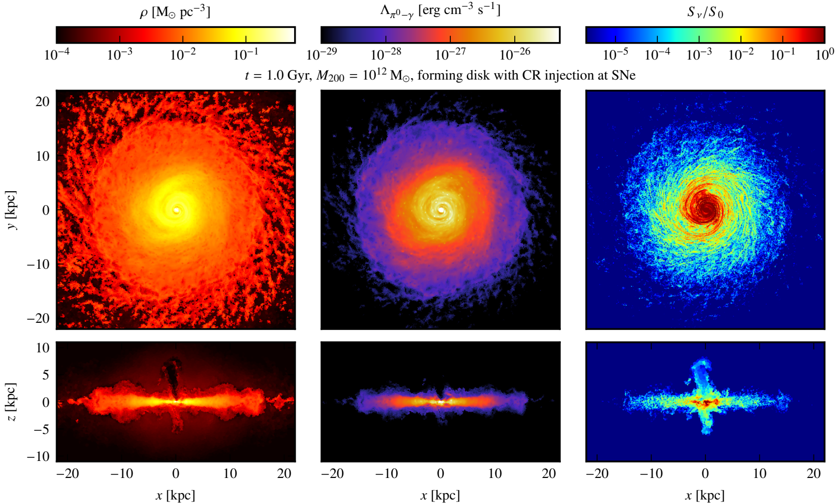
C.P., Pakmor+ (in prep.)

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



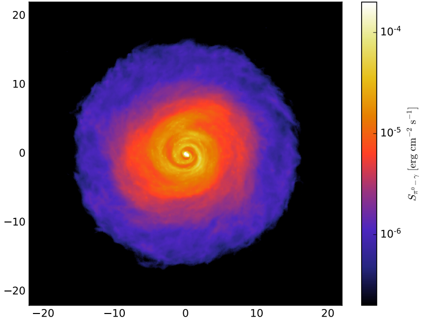
C.P., Pakmor+ (in prep.)

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



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

Projected γ-ray emission of Milky Way-like galaxy

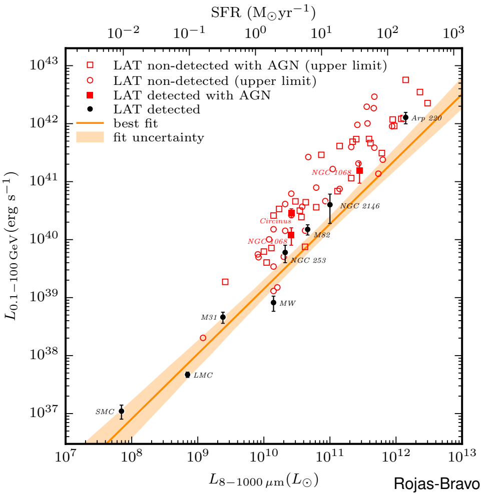


C.P., Pakmor+ (in prep.)

- 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 $\rightarrow L_{\text{FIR}} - L_\gamma$

Far infra-red – gamma-ray correlation

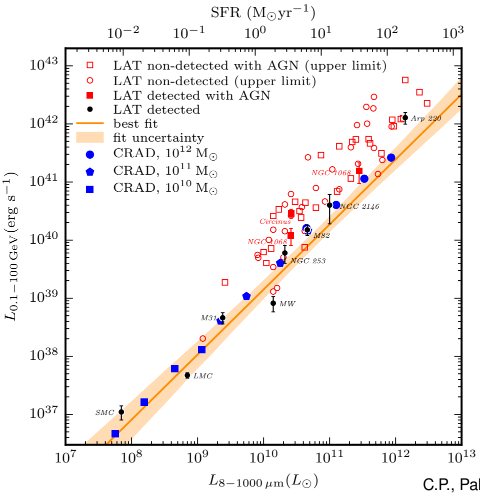
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



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Far infra-red – gamma-ray correlation

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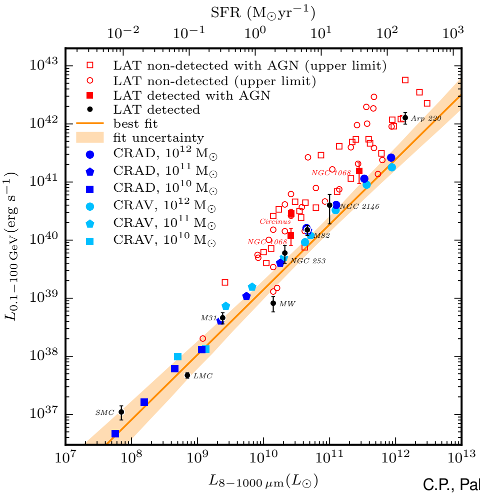

C.P., Pakmor+ (in prep.)

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

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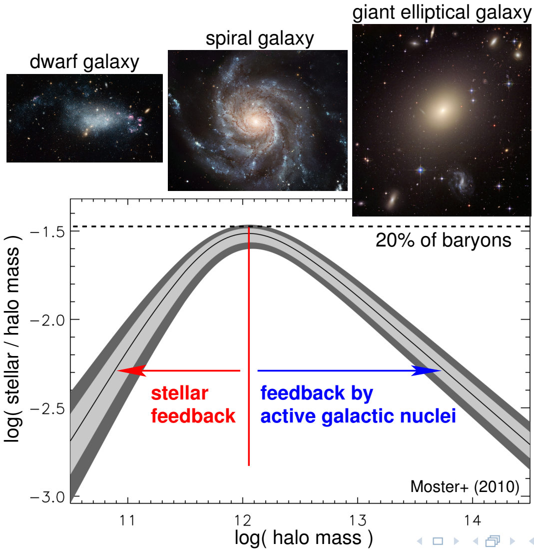
outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

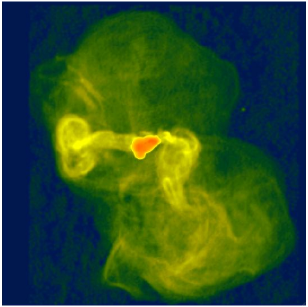
need: comparison to resolved radio/γ-ray observations $\rightarrow$ **SKA/CTA**

Outline

Puzzles in galaxy formation



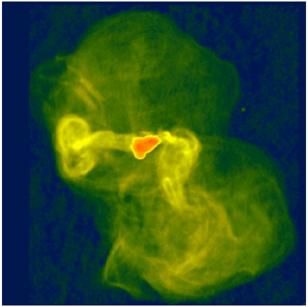
Messier 87 at radio wavelengths



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

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!

Messier 87 at radio wavelengths



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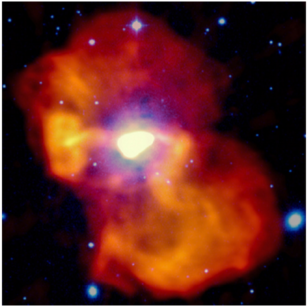


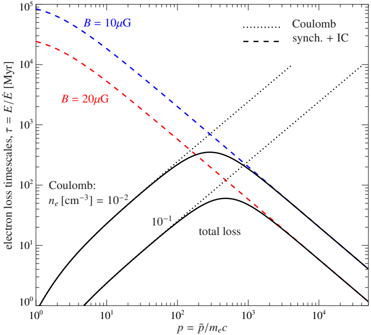
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: halo confined to same region at all frequencies and no low-ν spectral steepening $\rightarrow$ puzzle of “missing fossil electrons”

Solution to the "missing fossil electrons" problem

solution:

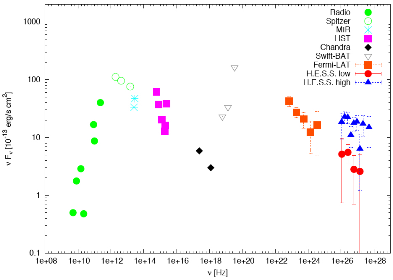
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



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

$$\mathcal{H}_{\rm cr} = |\boldsymbol{v}_{\rm A} \cdot \nabla P_{\rm cr}|$$

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

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

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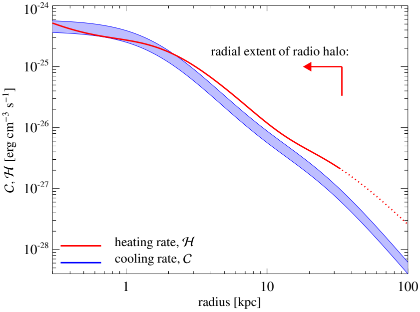
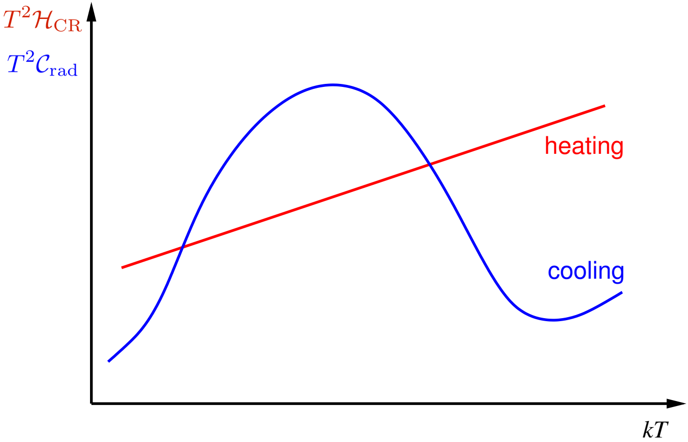


C.P. (2013)

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

Local stability analysis (1)



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

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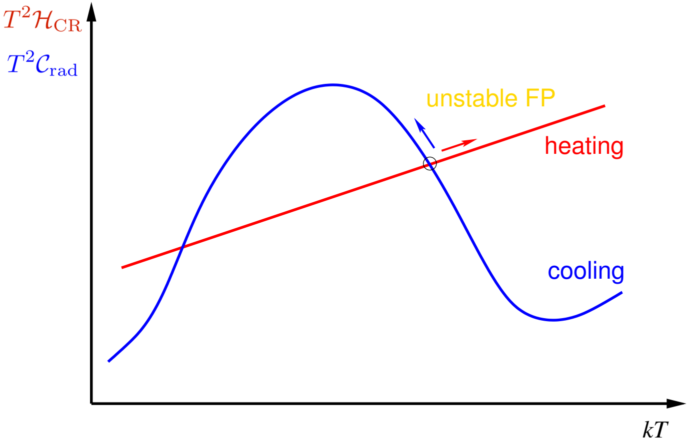

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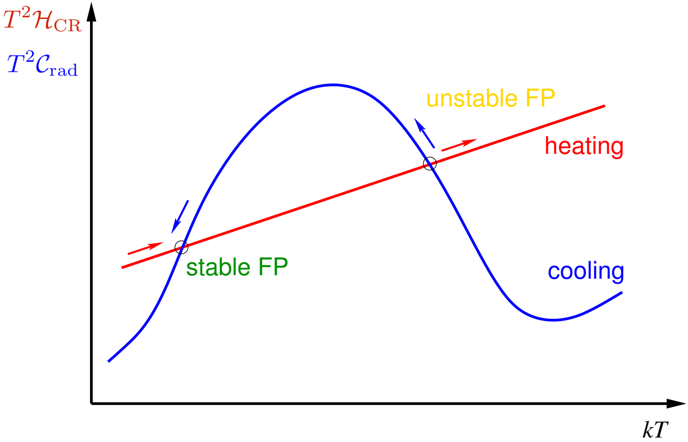

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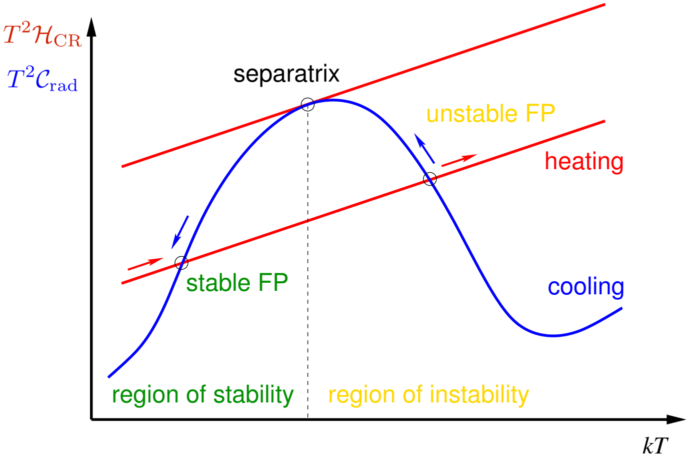

- isobaric perturbations to global thermal equilibrium
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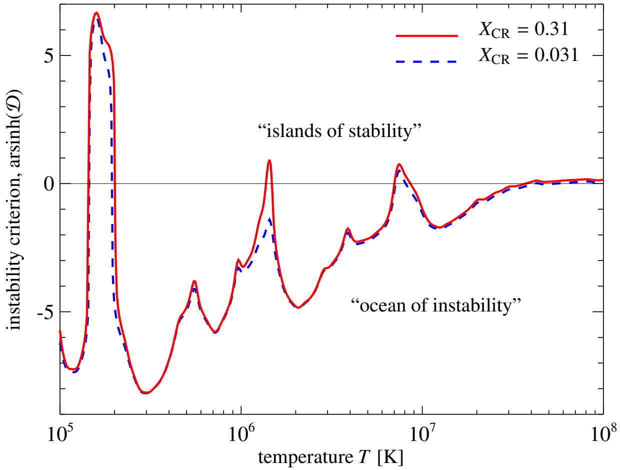
Local stability analysis (2)

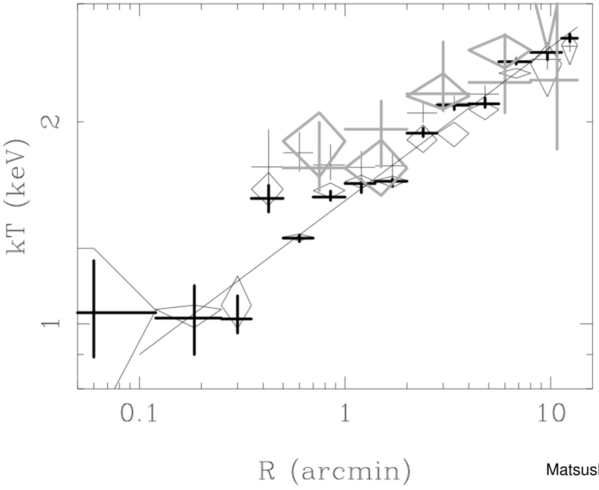
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

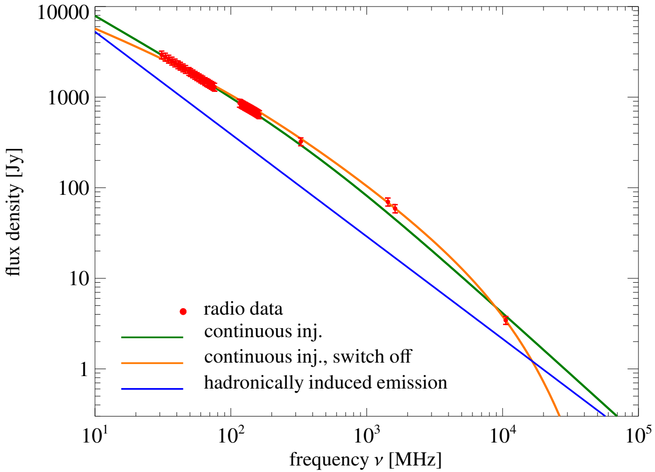
Virgo cluster cooling flow: temperature profile

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



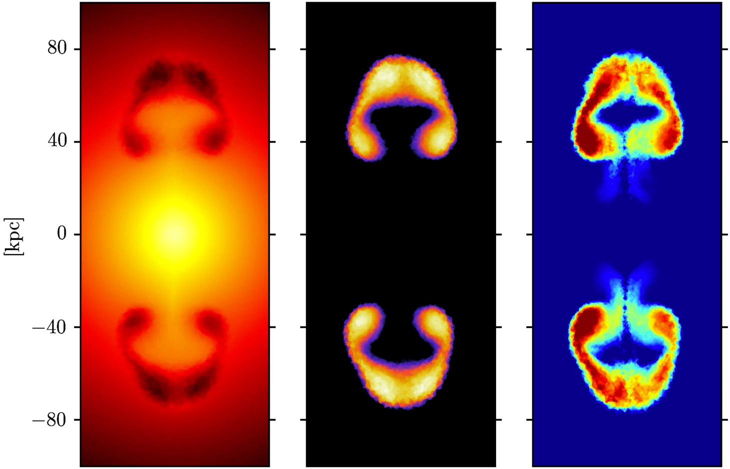
Matsushita+ (2002)

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 $X_{\text{cr}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the radio halo ($r < 35$ kpc)
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outlook: couple CRs to AGN jet model, simulate anisotropically steaming CRs, cosmological cluster simulations

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

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, 827, L29.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL, 824, L30.
- Pakmor, Pfrommer, Simpson, Kannan, Springel, *Semi-implicit anisotropic cosmic ray transport on an unstructured moving mesh,* 2016, MNRAS, 462, 2603.

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.