The impact of cosmic rays on galaxy formation: passive spectators or active drivers?

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in collaboration with

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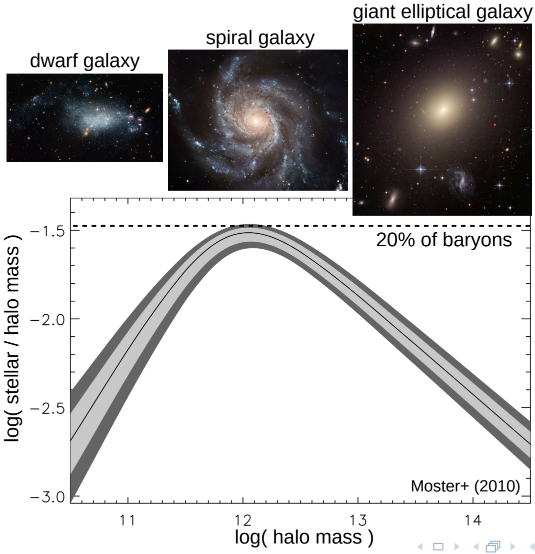
Outline

1. Introduction
   - Puzzles
   - Galactic winds
   - Cosmic ray physics

2. Simulations
   - Physics
   - Forming galaxies
   - Streaming or diffusion?

Puzzles in galaxy formation



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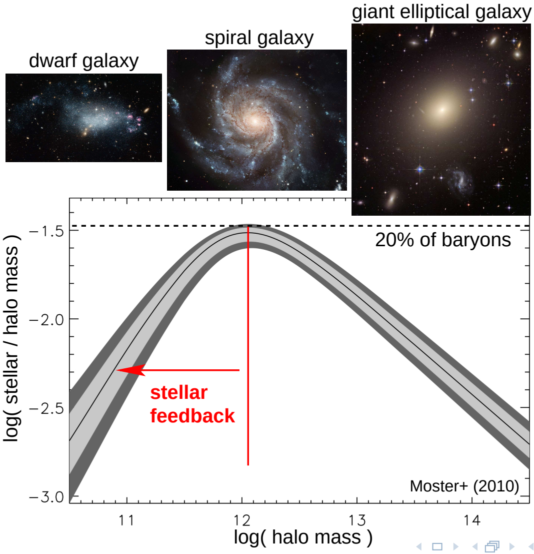

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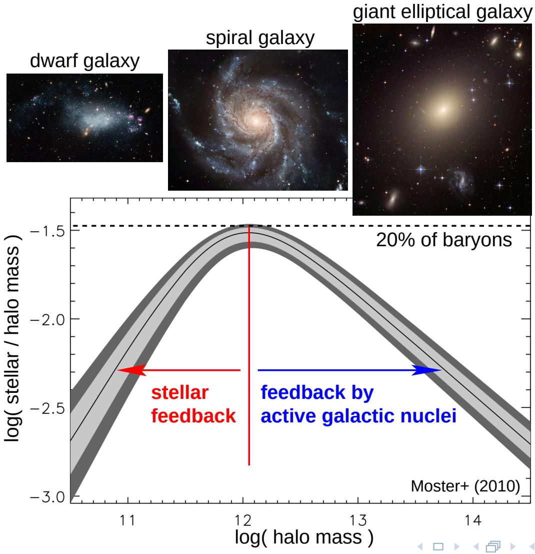

How are galactic winds driven?

super wind in M82

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

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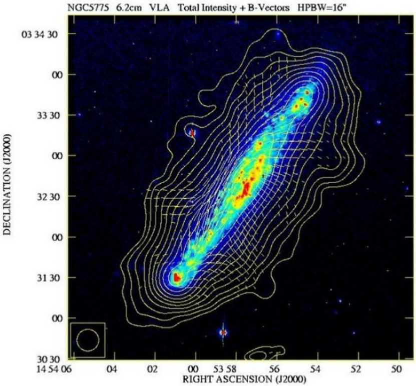
observed energy equipartition between cosmic rays, thermal gas and magnetic fields

→ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

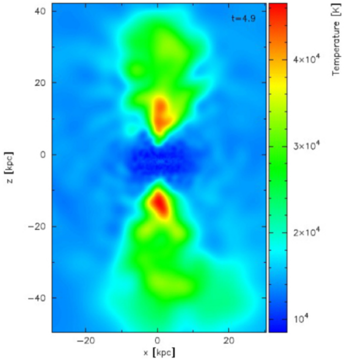
Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface



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 → "CR battery"
- poloidal ("open") field lines at wind launching site → CR-driven Parker instability

Cosmic-ray driven winds – literature

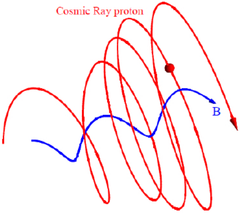


Uhlig, C.P.+ (2012)

- previous theoretical works:
  Ipavich (1975), Breitschwerdt+ (1991), Zirakashvili+ (1996), Ptuskin+ (1997), Breitschwerdt+ (2002), Socrates+ (2008), Everett+ (2008, 2010), Samui+ (2010), Dorfi & Breitschwerdt (2012)
- previous 3D simulations:
  CR streaming: Uhlig, C.P.+ (2012)
  CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → 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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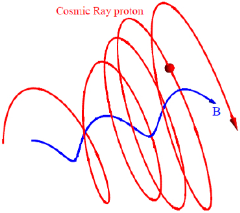

→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

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 $\boldsymbol{B}$):

$$\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{A}} \frac{\boldsymbol{\nabla} P_{\mathrm{cr}}}{|\boldsymbol{\nabla} P_{\mathrm{cr}}|} \text{ with } v_{\mathrm{A}} = \sqrt{\frac{\boldsymbol{B}^2}{4\pi\rho}}, \qquad \boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}} \frac{\boldsymbol{\nabla} P_{\mathrm{cr}}}{P_{\mathrm{cr}}},$$

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

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

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

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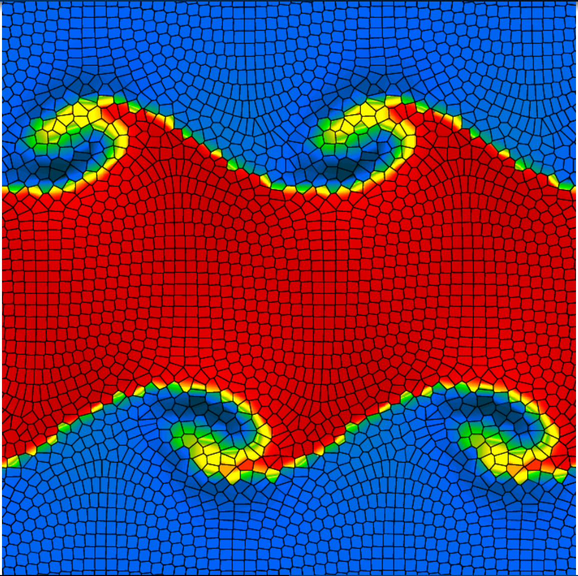
\Longleftrightarrow \quad \frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot \left[\varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}})\right] &= -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot (\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}})
\end{aligned}$$

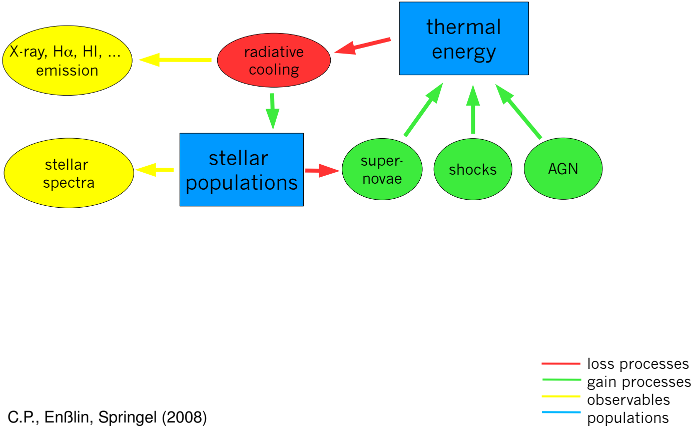
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:



C.P., Enßlin, Springel (2008)

Simulations with cosmic ray physics

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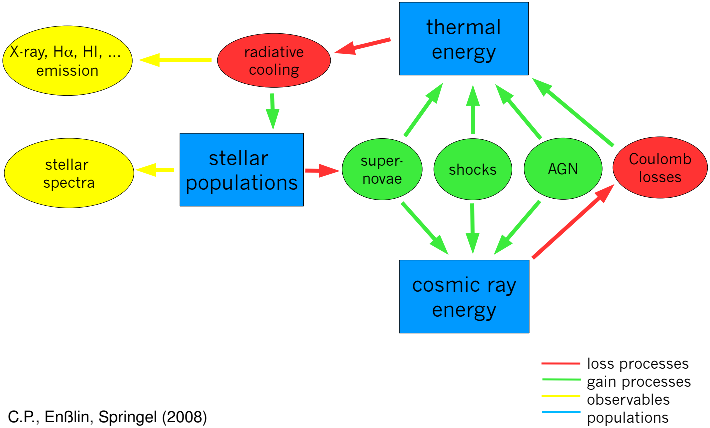

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Simulations with extended cosmic ray physics

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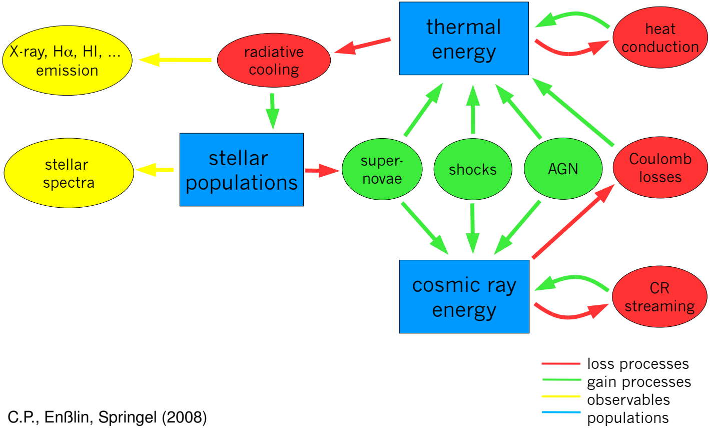

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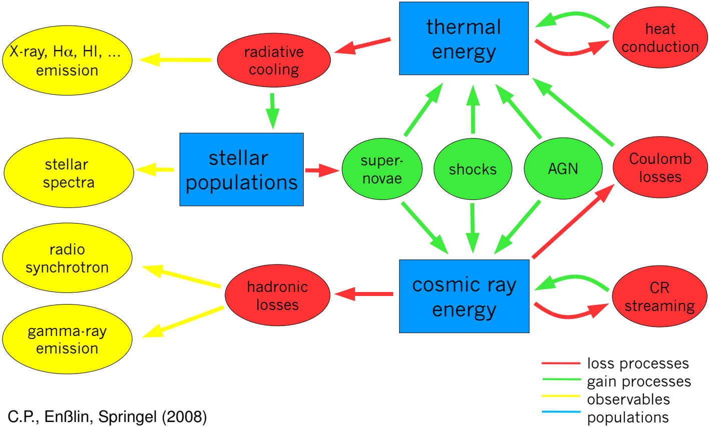

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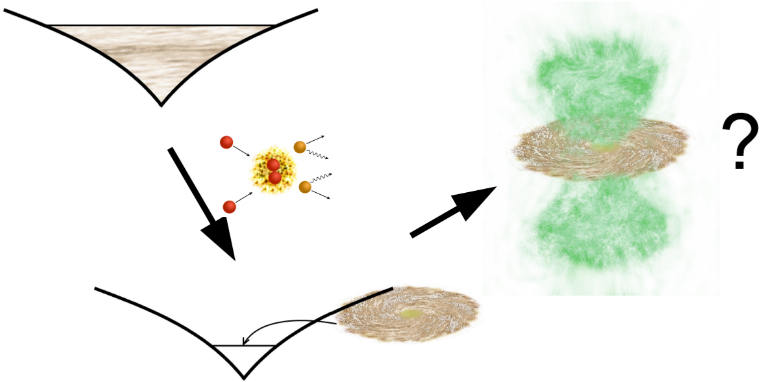
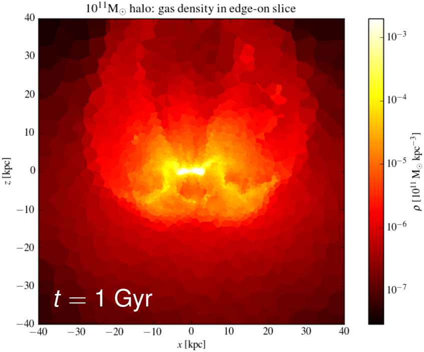
Simulation setup

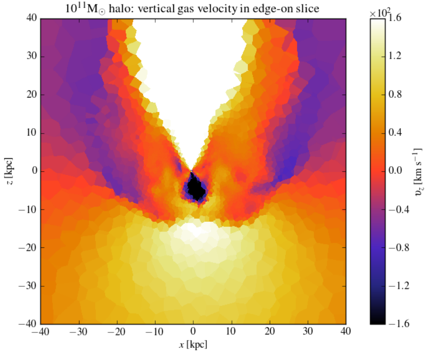


Pfrommer, Pakmor, Springel, in prep.

note: MHD + CR physics with isotropic CR diffusion

CR driven winds: density and vertical velocity





- CR pressure launches super wind that escapes from the halo
- forming disk collimates the wind into a biconical morphology with a time-varying opening angle

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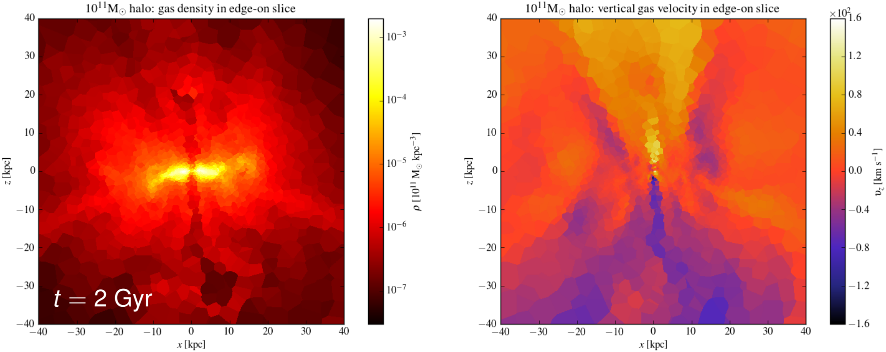

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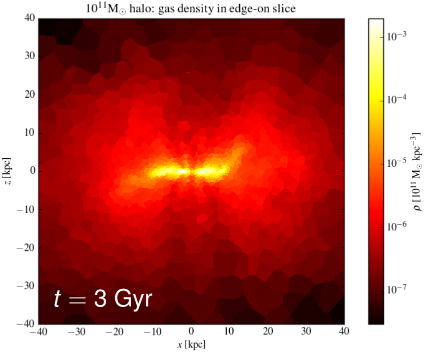

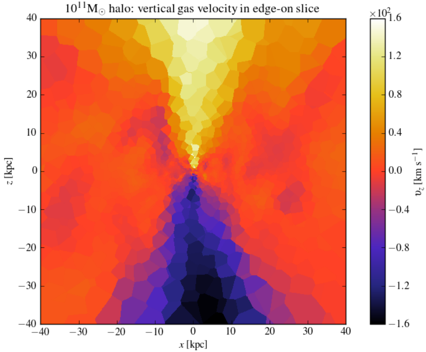

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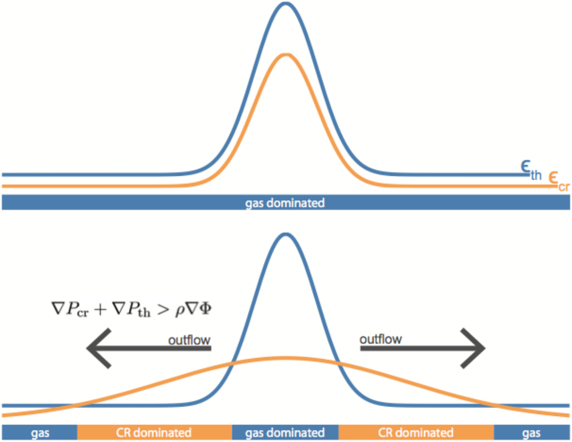
Cosmic ray driven wind: mechanism



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

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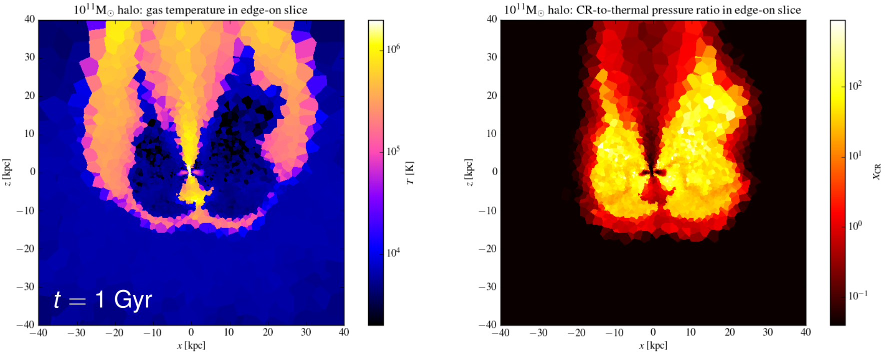
CR driven winds: temperature and $X_{cr} = P_{cr}/P_{th}$



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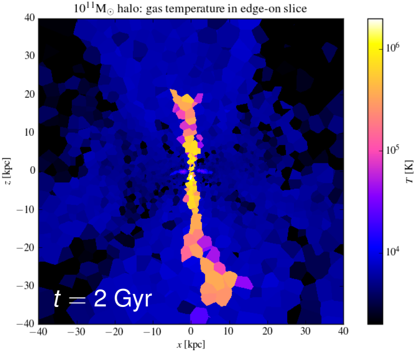

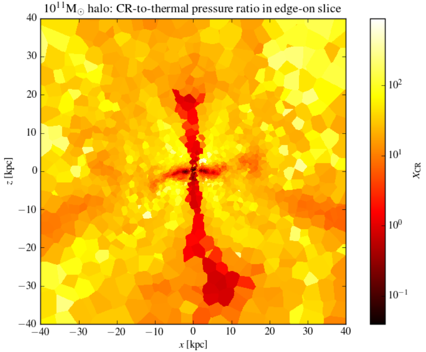

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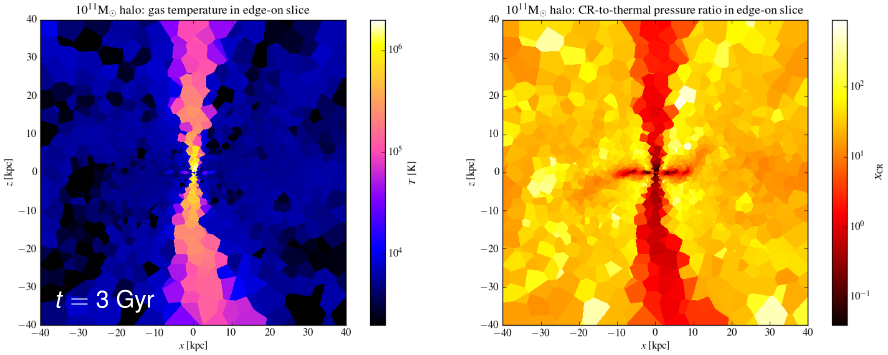

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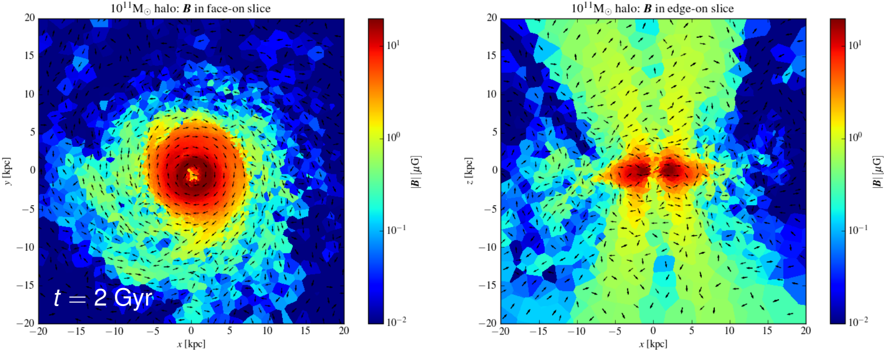
CR driven winds: *B* field, face and edge-on view



- disk: magnetic shear amplification aligns ***B*** with velocity field
- halo: X-shaped ***B*** morphology due to time varying collimation
- narrower wind → faster outflow → lower density channel

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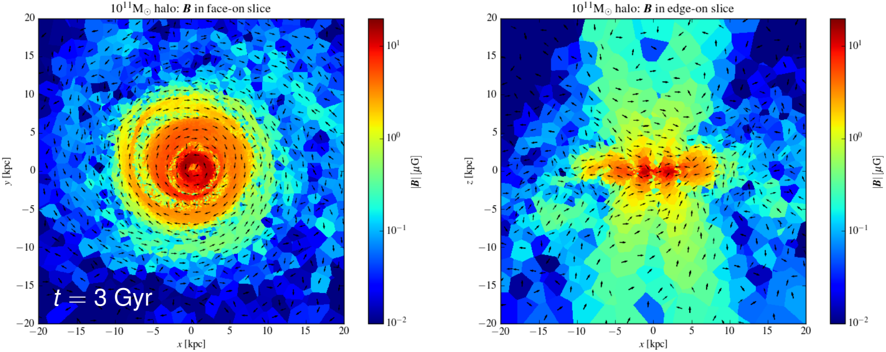

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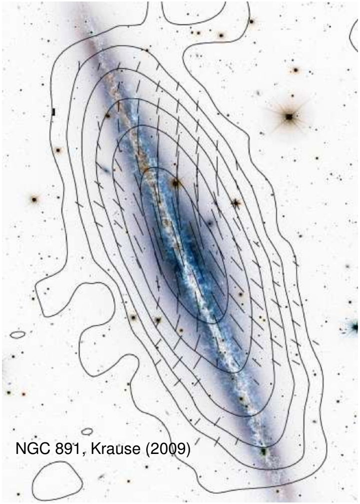
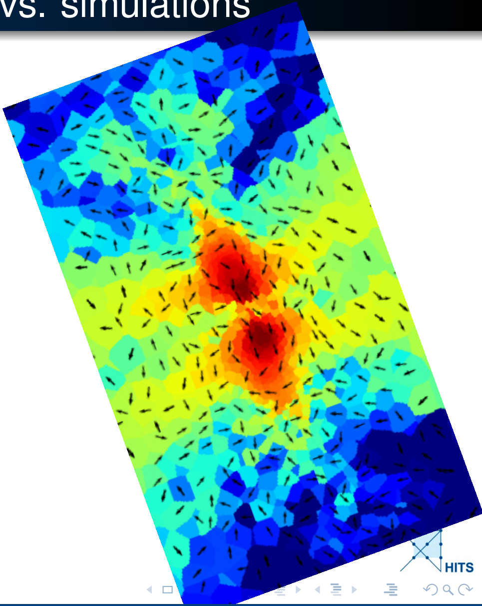
Halo *B* field: observations vs. simulations



NGC 891, Krause (2009)



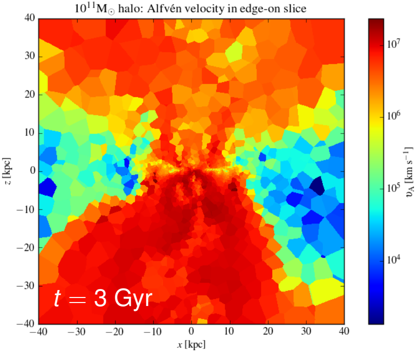
CR streaming vs. diffusion: estimates

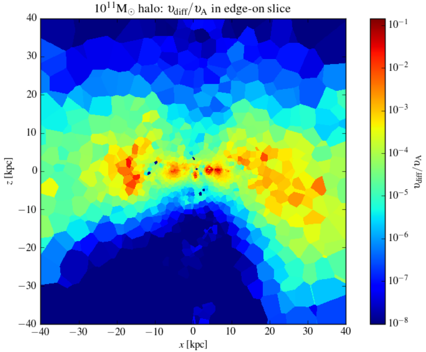
- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:

$$v_{\mathrm{diff}} \equiv \kappa \frac{|\nabla P_{\mathrm{cr}}|}{\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}} \stackrel{!}{<} v_{\mathrm{A}}$$

$\Rightarrow$ limit on diffusion coefficient κ (varies spatially and temporarily)

CR driven winds: v_A and v_{diff}/v_A





- 3 Gyr: stationary outflow with thick CR disk $\rightarrow v_{diff}/v_A < 1$
  (using a Galactic diffusion coefficient $\kappa \simeq 10^{28}\,\mathrm{cm^2\,s^{-1}}$)

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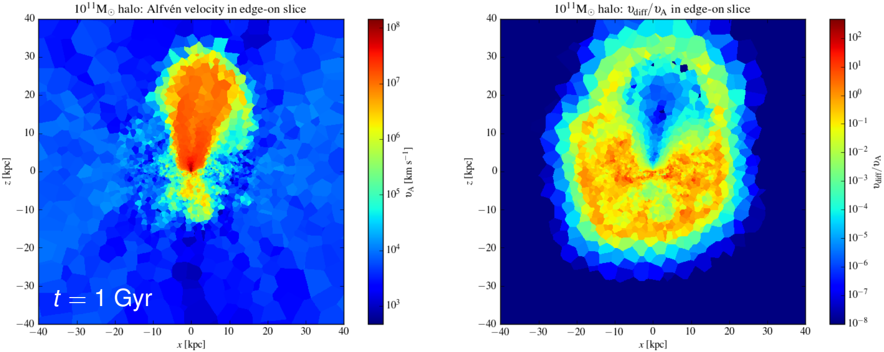

- 3 Gyr: stationary outflow with thick CR disk $\rightarrow v_{diff}/v_A < 1$
  (using a Galactic diffusion coefficient $\kappa \simeq 10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$)
- <2 Gyr: small CR injection regions $\rightarrow v_{diff}/v_A \gg 1$!

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- what happens during CR injection at a supernova remnant?

$$v_{\rm diff} \sim \frac{\kappa}{4 L_{\rm cr}} \sim 10^3 \text{ km s}^{-1} \; \kappa_{28} L_{\rm cr,10\ pc}^{-1} \sim 100 v_{\rm A}$$

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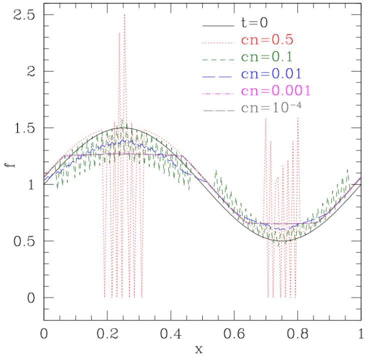
$\Rightarrow$ flux-limited CR diffusion: prohibitively expensive because of von-Neumann-type time step constraint ($\Delta t \propto \Delta x^2/\kappa$), even for implicit solvers

$\Rightarrow$ simulate CR streaming!

Modeling CR streaming

A challenging hyperbolic/parabolic problem



Sharma+ (2010)

- streaming equation (no heating):

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \nabla \cdot [(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}) \boldsymbol{v}_{\mathrm{st}}] = 0$$

$$\boldsymbol{v}_{\mathrm{st}} = -\mathrm{sgn}(\mathbf{B} \cdot \nabla P_{\mathrm{cr}}) \boldsymbol{v}_{\mathrm{A}}$$

- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy can overshoot and develop unphysical oscillations

- idea: regularize equations, similar to adding artificial viscosity $\rightarrow$ diffusive at extrema, advective at gradients

AREPO MHD simulations of CR driven galactic winds

the good: CR diffusion successfully launches super winds that

- expel a large fraction of gas from the halo
- heat the halo gas and circumgalactic medium → X-rays?
- enrich halo/circumgalactic medium with X-shaped ***B*** fields
- suppress subsequent star formation

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the bad: constant (Galactic) diffusivity too simplified:

- adequate for stationary outflow with thick CR disk
- fails for non-equilibrium conditions during disk formation

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