Multi-phase gas in and around galaxies: the impact of cosmic rays, magnetic fields and cooling processes

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in collaboration with

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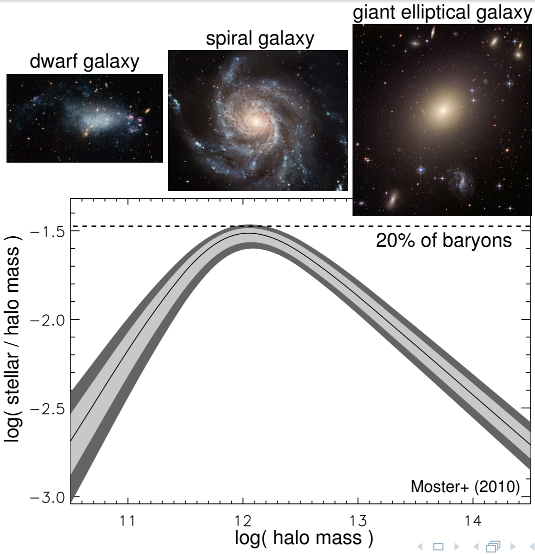
Outline

1. Galaxy formation
   - Puzzles in galaxy formation
   - Multiphase gas in galaxies
   - Cosmological simulations
2. Cosmic ray transport
   - Introduction and motivation
   - Cosmic ray hydrodynamics
   - Radio synchrotron harps
3. Cold cloud in a hot wind
   - Impact of magnetic fields cloud interaction
   - Cloud growth and destruction
   - Conclusions

AIP

Puzzles in galaxy formation

Puzzles in galaxy formation



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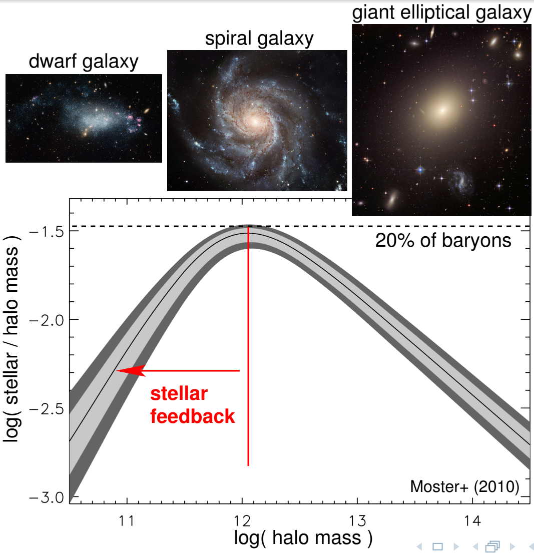

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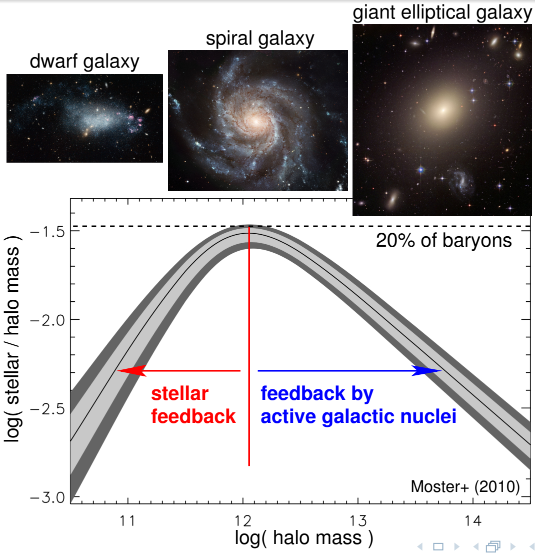

Feedback

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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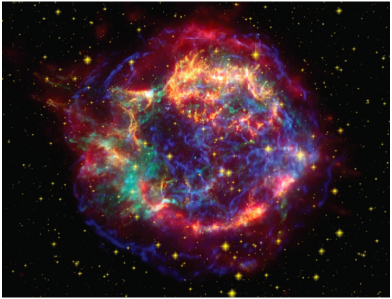
3. the solution of all problems in galaxy formation

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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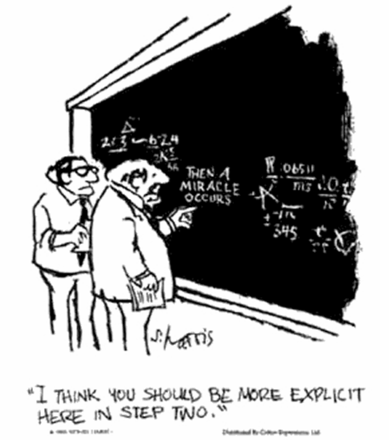

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Multiphase gas in winds

Kinematic signatures of M82 wind consistent with a hot outflow bounded by a cone of atomic and molecular gas:

- hot 10^6-10^7 K ionized gas is traced by X-rays (Strickland+ 2004, 2007)
- warm 10^4 K atomic gas is traced by HI and Hα (Yun+ 1994, Lee+ 2009)
- cold 10-20 K molecular gas is traced by CO (Leroy+ 2015)

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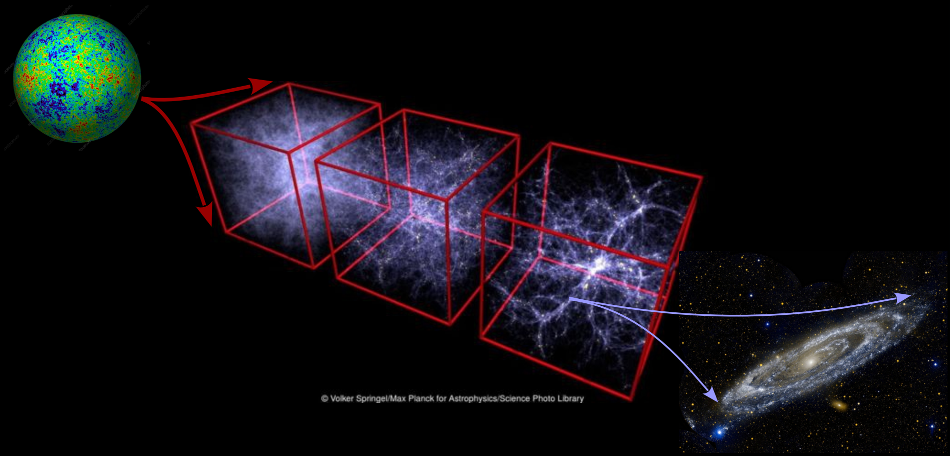
How can we accelerate a warm cloud by a hot wind?

- wind ram pressure aided by magnetic tension acting on the cloud
- cosmic ray (CR) pressure gradient applying work on the cloud
- thermal instability of hot wind that cools & transfers momentum

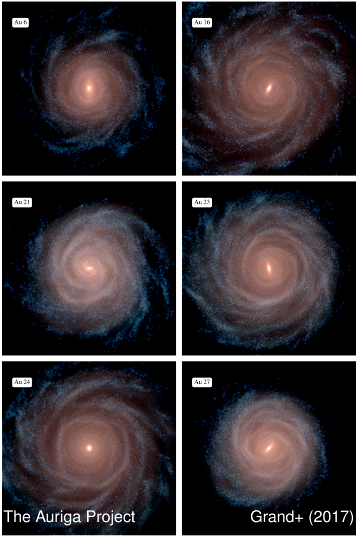
Cosmological galaxy formation



Cosmic rays in cosmological galaxy simulations

Auriga galaxy formation model

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



The Auriga Project
Grand+ (2017)

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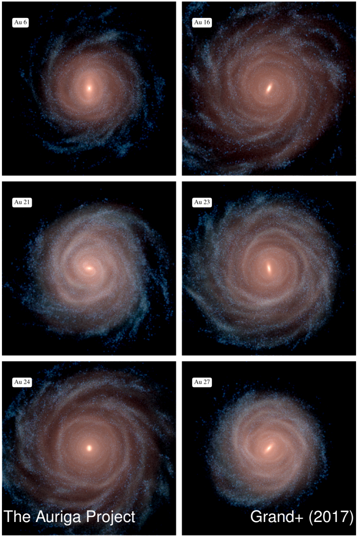
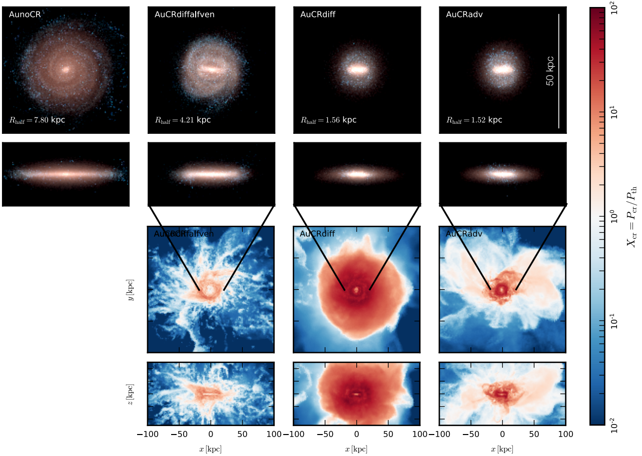
Simulation suite (Buck+ 2020)

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



Cosmic rays in cosmological galaxy simulations

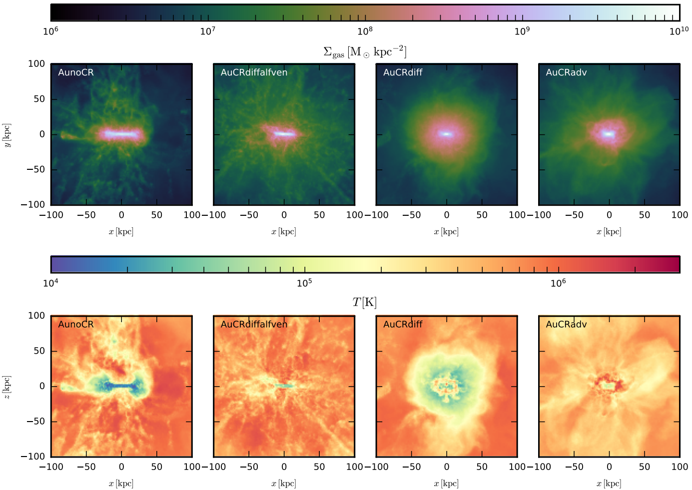
Auriga MHD models: CR transport changes disk sizes but not the stellar mass



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

Cosmic rays in cosmological galaxy simulations

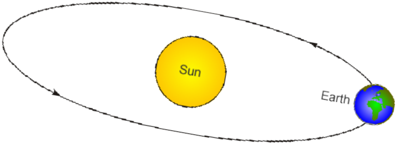
Auriga MHD models: CR transport modifies the circum-galactic medium



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

Outline

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

$$r_{\rm gal} \sim 10^4 \text{ pc}$$

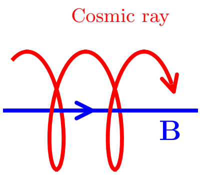
gyro-orbit of GeV cosmic ray:

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

$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

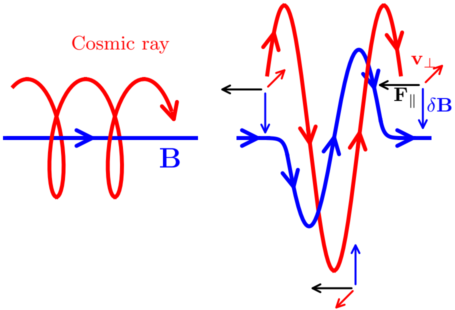
Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2019)

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields



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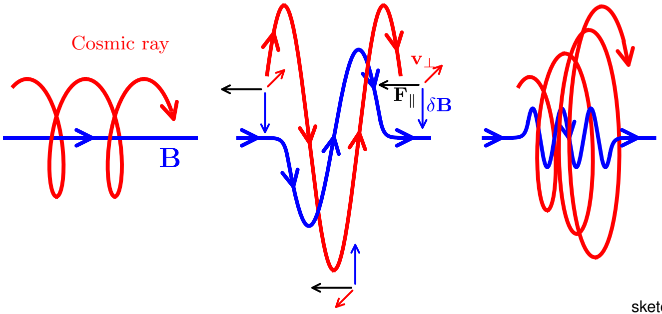
- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

Interactions of CRs and magnetic fields



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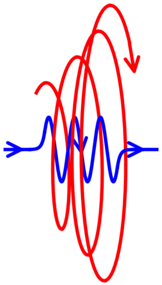
- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and 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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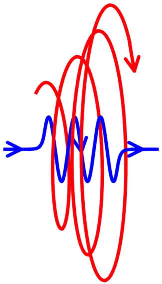

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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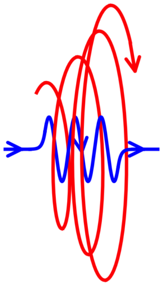
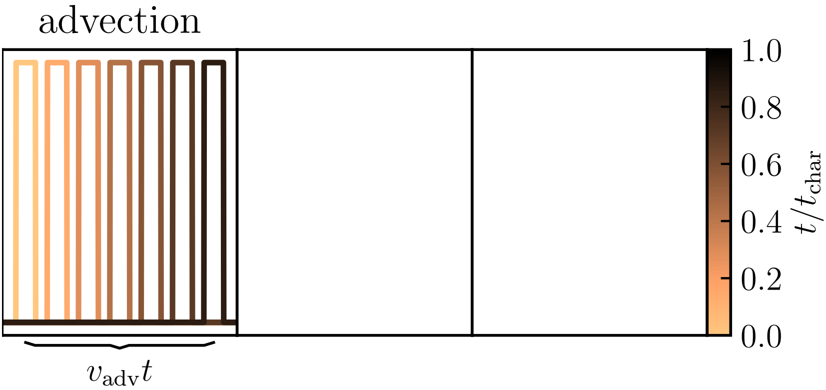


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

Modes of CR propagation



Thomas, CP, Enßlin (2020)

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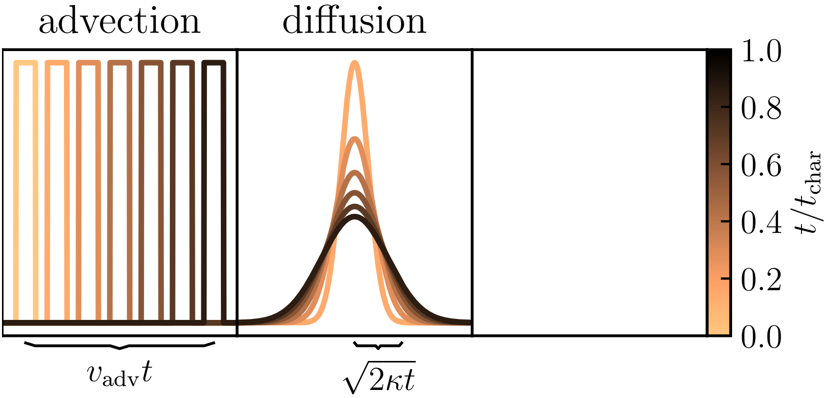

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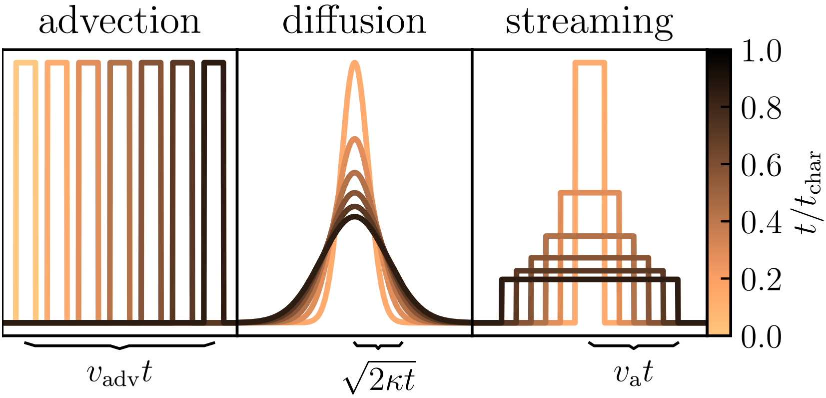

Thomas, CP, Enßlin (2020)

Analogies of CR and radiation hydrodynamics

CRs and radiation are relativistic fluids

regime	CR transport	radiation HD analogy
• tangled $\boldsymbol{B}$, strong scattering	CR diffusion	diffusive transport in clumpy medium
• resolved $\boldsymbol{B}$, strong scattering	CR streaming with $\boldsymbol{v}_\mathrm{a}$	Thomson scattering ($\tau \gg 1$) $\rightarrow$ advection with $\boldsymbol{v}$
• weak scattering	CR streaming and diffusion	flux-limited diffusion/ M1 closure ($\tau \gtrsim 1$)
• no scattering	CR propagation with c	vacuum propagation

Jiang & Oh (2018), Thomas & CP (2019)

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Jiang & Oh (2018), Thomas & CP (2019)

but: *CR hydrodynamics is charged RHD*
$\rightarrow$ ***take gyrotropic average and account for anisotropic transport***

CR vs. radiation hydrodynamics

- capitalize on analogies of CR and radiation hydrodynamics (Jiang & Oh 2018)
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$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f}_{\mathrm{cr}} = -\boldsymbol{w}_{\pm} \cdot \frac{\boldsymbol{bb}}{3\kappa_{\pm}} \cdot [\boldsymbol{f}_{\mathrm{cr}} - \boldsymbol{w}_{\pm}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})] - \boldsymbol{v} \cdot \boldsymbol{g}_{\mathrm{Lorentz}} + S_{\varepsilon}$$

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Alfvén wave velocity in lab frame: $\boldsymbol{w}_{\pm} = \boldsymbol{v} \pm \boldsymbol{v}_{\mathrm{a}}$,
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- lab-frame equ's for radiation energy and momentum density, ε and $\boldsymbol{f}/c^2$
  (Mihalas & Mihalas, 1984, Lowrie+ 1999):

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{f} = -\sigma_{\mathrm{s}}\boldsymbol{v}\cdot\left[\boldsymbol{f} - \boldsymbol{v}\cdot(\varepsilon\mathbf{1} + \mathbf{P})\right] + S_{\mathrm{a}}$$

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- ***problem:*** *CR lab-frame equation requires resolving rapid gyrokinetics!*

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- ***solution:*** *transform in comoving frame and project out gyrokinetics!*

Alfvén-wave regulated CR transport

- comoving equ's for CR energy and momentum density (along $\boldsymbol{B}$), $\varepsilon_{\mathrm{cr}}$ and f_{cr}/c^2, and Alfvén-wave energy densities $\varepsilon_{\mathrm{a},\pm}$ (Thomas & CP 2019)

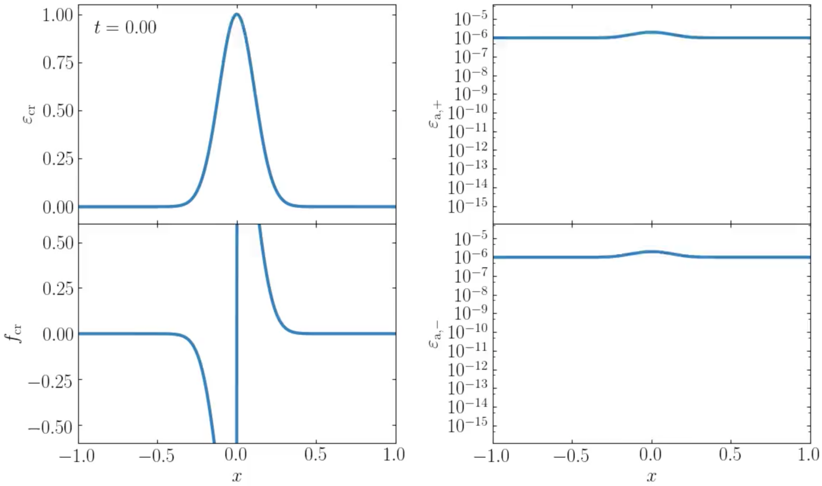
$$
\begin{aligned}
\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} &+ \boldsymbol{\nabla}\cdot[\boldsymbol{v}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})+\boldsymbol{b}f_{\mathrm{cr}}] = \boldsymbol{v}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} \\
&- \frac{v_{\mathrm{a}}}{3\kappa_+}\left[f_{\mathrm{cr}} - v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right] + \frac{v_{\mathrm{a}}}{3\kappa_-}\left[f_{\mathrm{cr}} + v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right],
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial f_{\mathrm{cr}}/c^2}{\partial t} &+ \boldsymbol{\nabla}\cdot\left(\boldsymbol{v}f_{\mathrm{cr}}/c^2\right) + \boldsymbol{b}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} = -(\boldsymbol{b}\cdot\boldsymbol{\nabla}\boldsymbol{v})\cdot(\boldsymbol{b}f_{\mathrm{cr}}/c^2) \\
&- \frac{1}{3\kappa_+}\left[f_{\mathrm{cr}} - v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right] - \frac{1}{3\kappa_-}\left[f_{\mathrm{cr}} + v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right],
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial \varepsilon_{\mathrm{a},\pm}}{\partial t} &+ \boldsymbol{\nabla}\cdot[\boldsymbol{v}(\varepsilon_{\mathrm{a},\pm}+P_{\mathrm{a},\pm}) \pm v_{\mathrm{a}}\boldsymbol{b}\varepsilon_{\mathrm{a},\pm}] = \boldsymbol{v}\cdot\boldsymbol{\nabla}P_{\mathrm{a},\pm} \\
&\pm \frac{v_{\mathrm{a}}}{3\kappa_\pm}\left[f_{\mathrm{cr}} \mp v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right] - S_{\mathrm{a},\pm}.
\end{aligned}
$$

Non-equilibrium CR streaming and diffusion

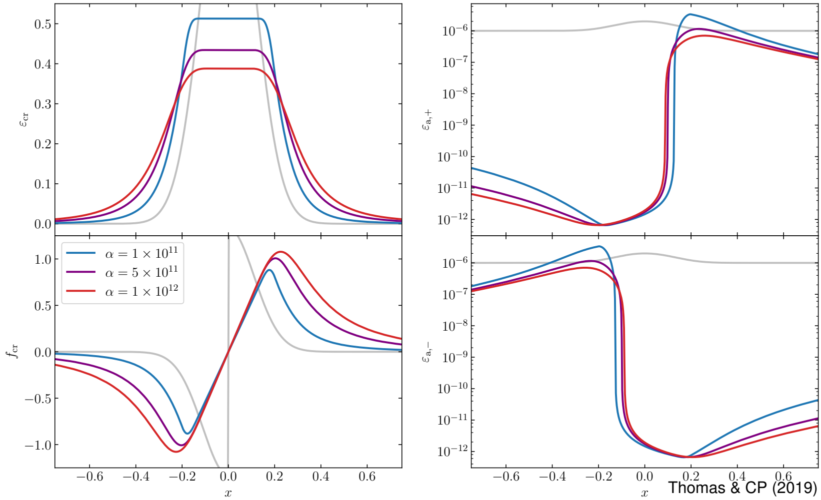
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

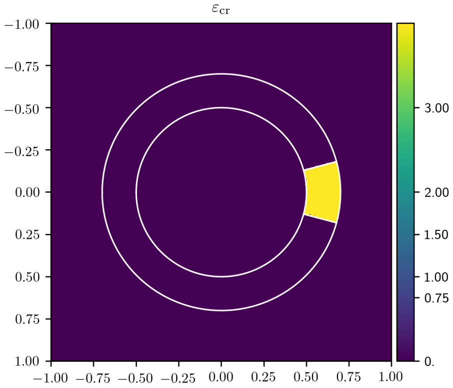


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

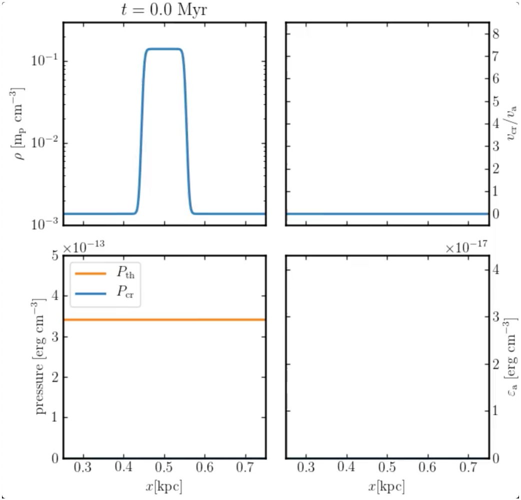
CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, ...
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, CP, Pakmor (2021)

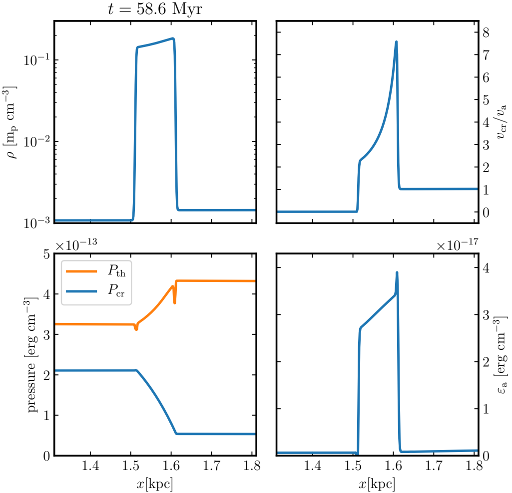
CR flux accelerates a warm, dense cloud



$$v_A = \frac{B_0}{\sqrt{4\pi\rho}}$$

Thomas, CP, Pakmor (2021), see also Wiener+ (2017, 2019)

CR flux accelerates a warm, dense cloud

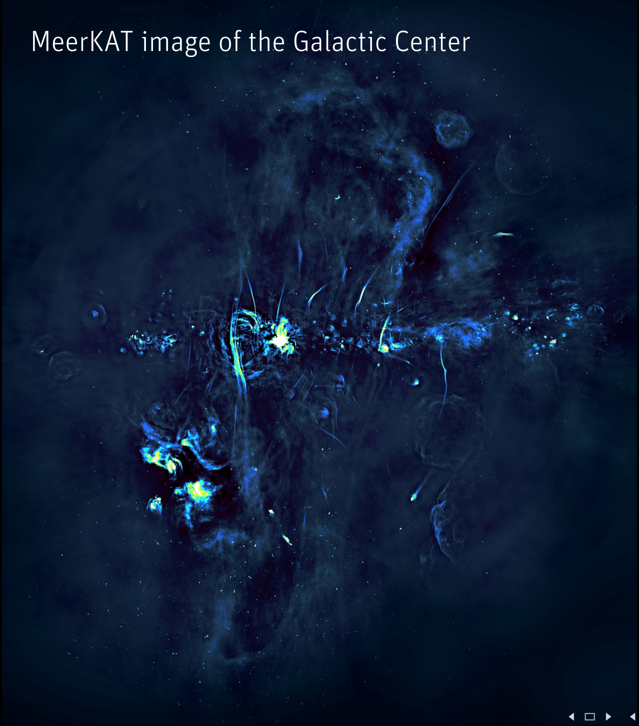


$$v_A = \frac{B_0}{\sqrt{4\pi\rho}}$$

Thomas, CP, Pakmor (2021), see also Wiener+ (2017, 2019)

MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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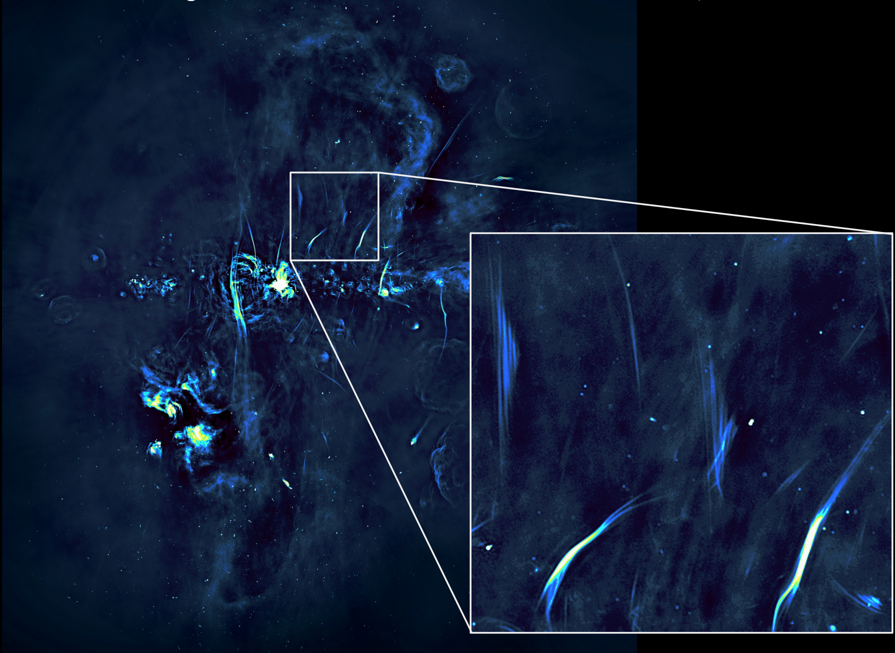
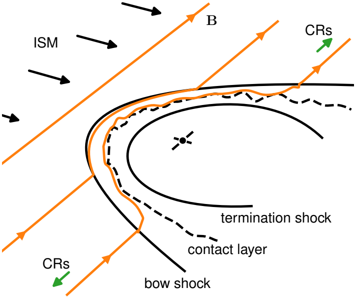


Radio synchrotron harps: the model

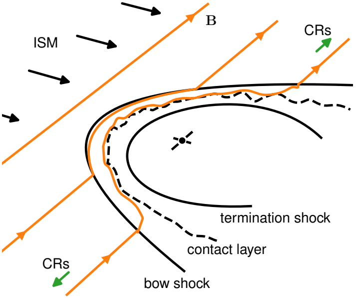
shock acceleration scenario



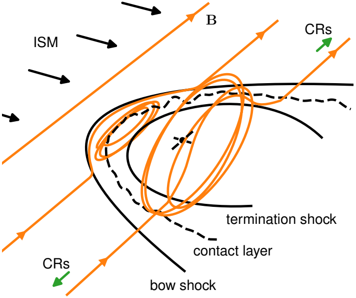
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

shock acceleration scenario



magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

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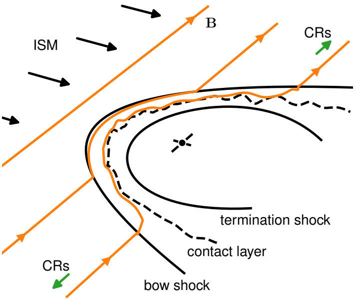
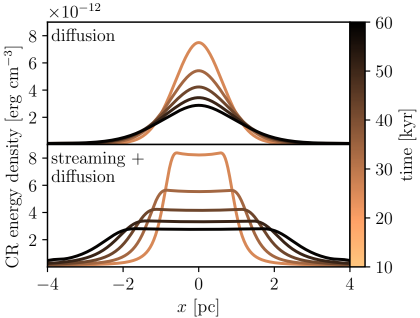
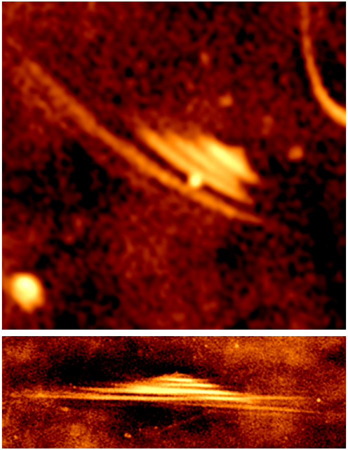


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion

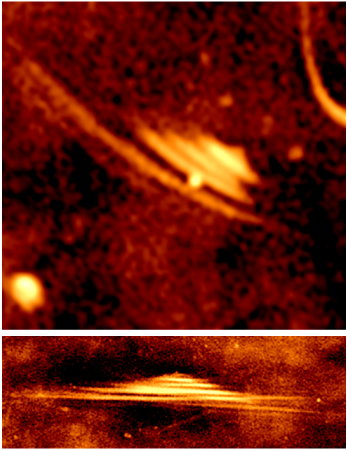


Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation



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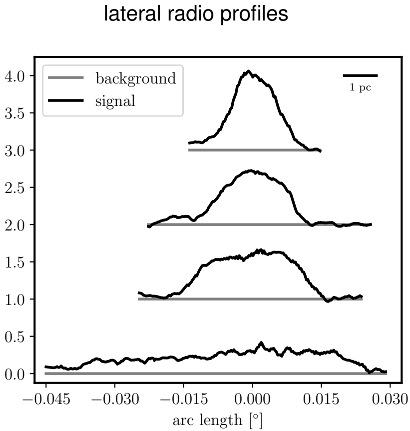
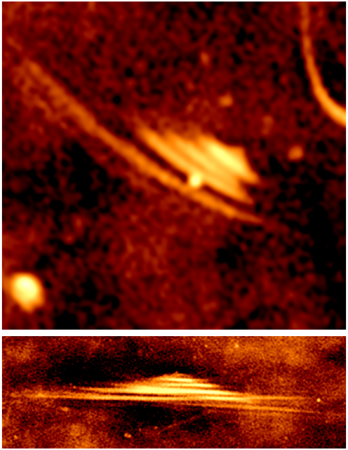
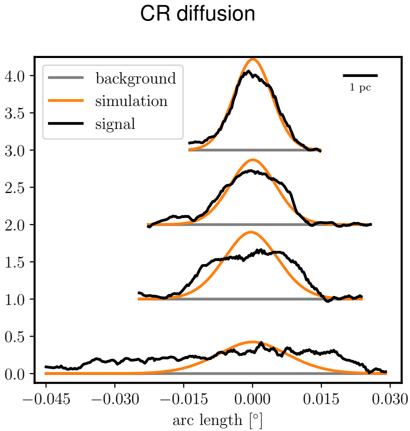


Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation

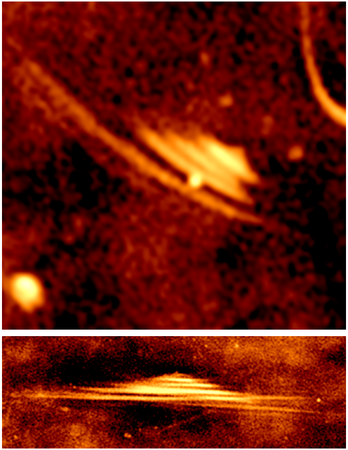


Haywood+ (Nature, 2019)



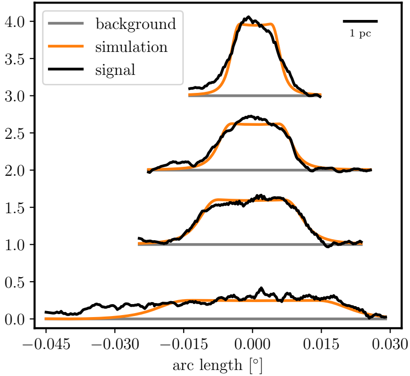
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

CR streaming and diffusion



Thomas, CP, Enßlin (2020)

Outline

Interaction of a cold cloud with a hot wind

Interaction of a cold cloud with a hot wind: the regimes of cloud growth and destruction and the impact of magnetic fields

Martin Sparre[1,2★], Christoph Pfrommer[2,1] and Kristian Ehlert[2]

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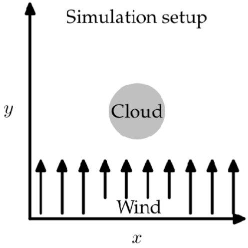
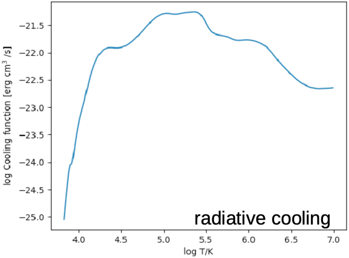
[2] *Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany*



$T_{\mathrm{cloud}} = 10^4$ K
$n_{\mathrm{cloud}} = 0.1$ cm^{-3}
$R = 25$ pc

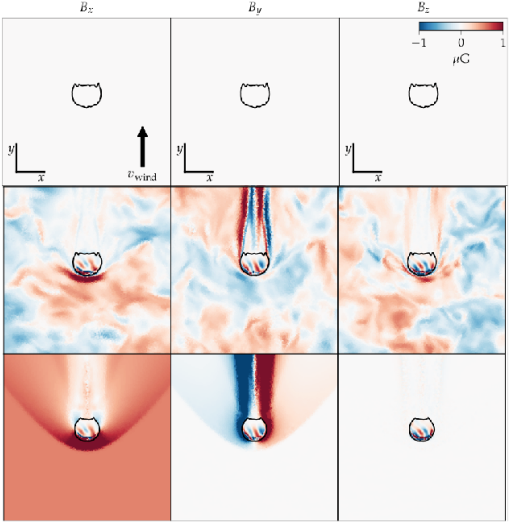
$T_{\mathrm{wind}} = 5.0 \times 10^6$ K
$n_{\mathrm{wind}} = 2 \times 10^{-4}$ cm^{-3}
$M = 1.5$

$\beta = 10$ or ∞ ($\beta \equiv P_{\mathrm{th}}/P_B$)



AIP

Magnetic field configurations



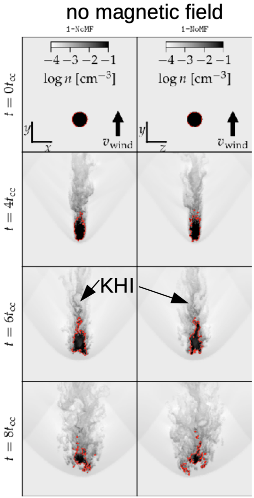
no magnetic field

turbulent ***B***

uniform ***B***

Sparre, CP, Ehlert (2020)

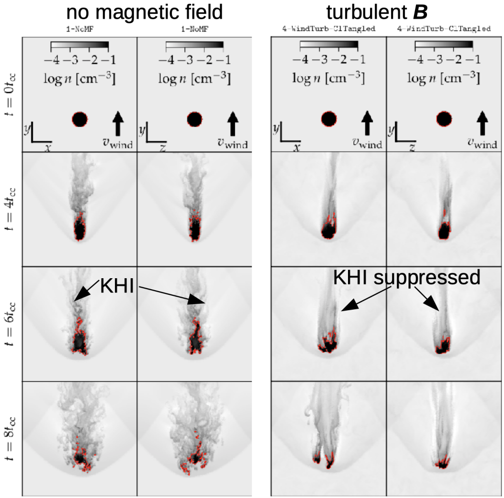
Magnetic field alters dynamics of cloud shattering



Sparre, CP, Ehlert (2020)

KHI = Kelvin Helmholtz instability

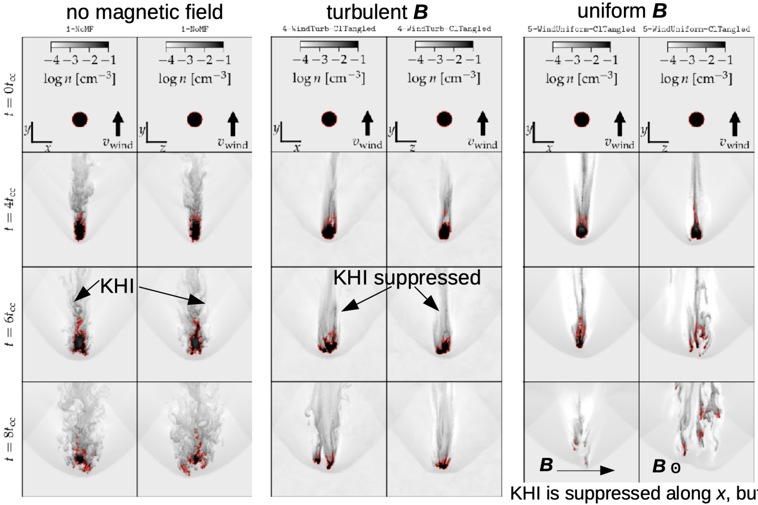
Magnetic field alters dynamics of cloud shattering



Sparre, CP, Ehlert (2020)

A magnetic field suppresses the Kelvin-Helmholtz instability (KHI) in the wake of the cloud

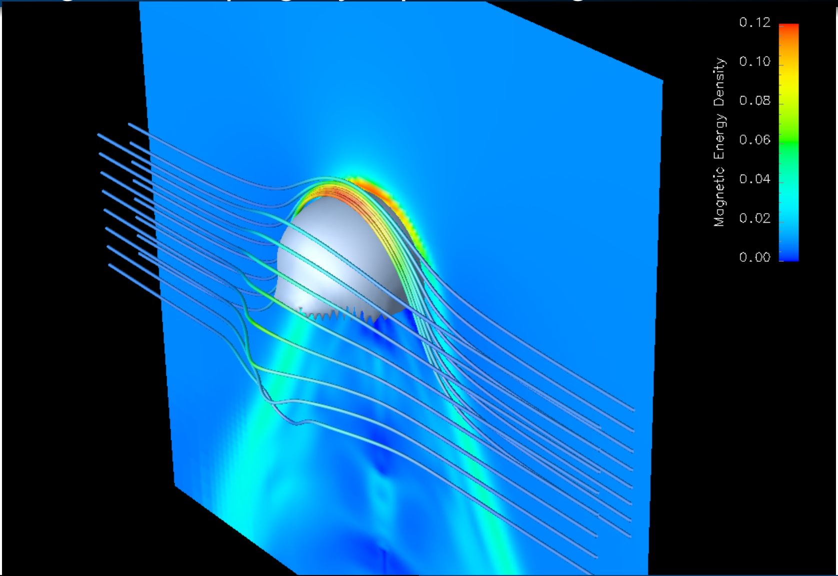
Magnetic field alters dynamics of cloud shattering



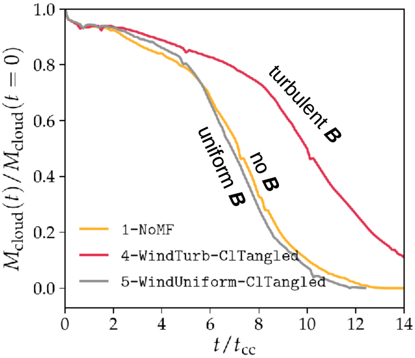
KHI is suppressed along x, but not z

Sparre, CP, Ehlert (2020)

A magnetic draping layer protects against instabilities

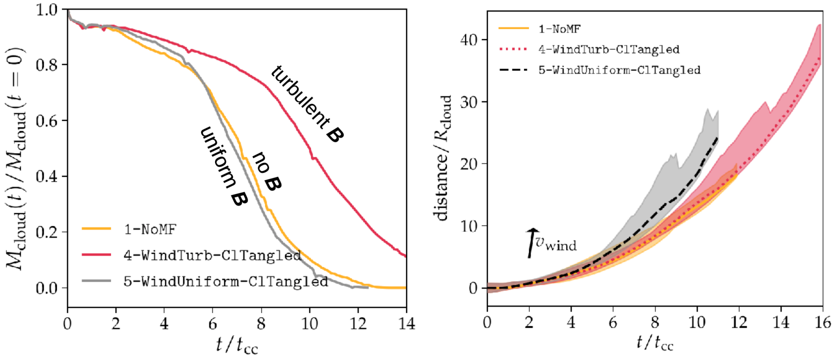


A turbulent *B* field extends cloud's lifetime



$$t_{\rm cc} \equiv \frac{R_{\rm cloud}}{v_{\rm wind}} \sqrt{\frac{\rho_{\rm cloud}}{\rho_{\rm wind}}}.$$

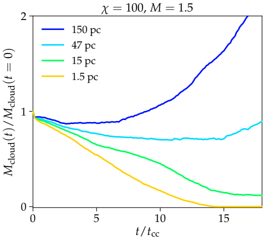
A uniform *B* field initially accelerates cloud more



- KHI instability shatters a **small cloud** into small pieces that mix with and dissolve into the hot wind
- magnetic field protects against instabilities and increases survival time by 30%, but does not halter the cloud's destruction

(Sparre, CP, Ehlert 2020)

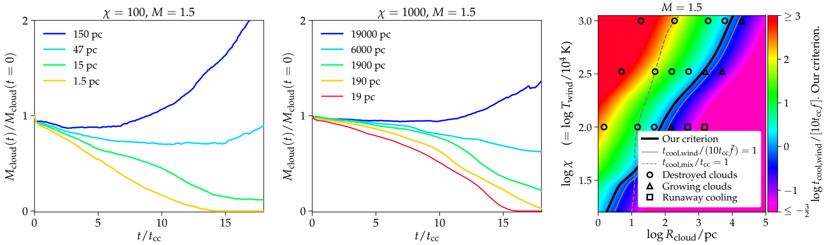
The growth regime



- ram-pressure stripped gas from a **large cloud** mixes with the hot wind to intermediate temperatures
- thermal instability causes further cooling and **net accretion of hot gas to the cold tail**
- **momentum transfer from hot wind to cooled accreted material** implies fast outflow of cold/warm phase: transformational understanding of galactic winds!

(Armillotta+ 2017, Gronke & Oh 2018, 2019, Li+ 2019, Sparre+ 2020, Kanjilal+ 2020)

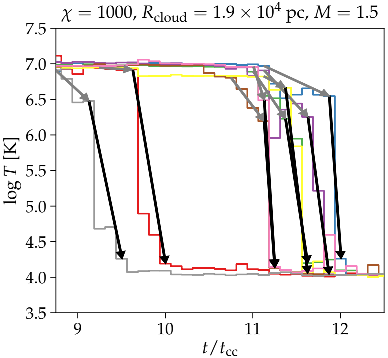
The growth regime



- **hot-wind cooling time sets transition radius** and not the mixed-phase cooling time ⇒ cloud growth criterion (Sparre+ 2020):

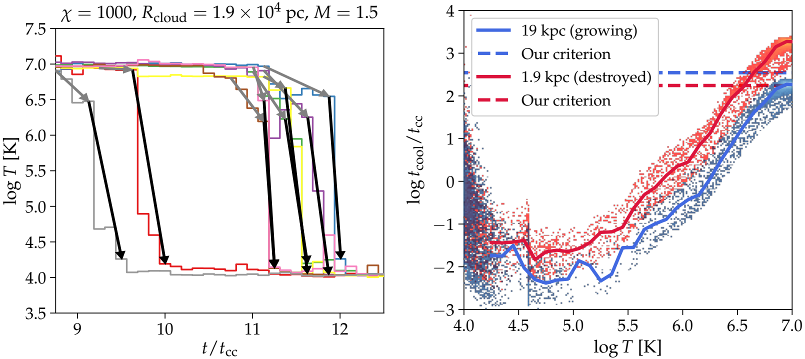
$$\frac{t_{\rm cool,wind}}{t_{\rm cc}} < 10 f(M, R_{\rm cloud}, n_{\rm wind}, v_{\rm wind})$$

Tracer analysis reveals physics of transition radius



- rate-limiting step in cooling process is the initial decline from 10^7 K to $10^{6.5}$ K (Sparre, CP, Ehlert 2020)

Tracer analysis reveals physics of transition radius



- rate-limiting step in cooling process is the initial decline from 10^7 K to $10^{6.5}$ K (Sparre, CP, Ehlert 2020)
- initial decline of $T_{\rm wind}$ is caused by **mixing or compressible fluctuations** $\Rightarrow$ scatter in $t_{\rm cool}$ at fixed temperature

AIP

Conclusions

CR transport in multiphase plasmas:

- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- synchrotron harps: CR streaming dominates over diffusion
- CR bottleneck effect causes acceleration of warm cloud

Conclusions

CR transport in multiphase plasmas:

- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- synchrotron harps: CR streaming dominates over diffusion
- CR bottleneck effect causes acceleration of warm cloud

Interaction of a cold cloud with a hot wind:

- magnetic field protects against instabilities and increases the survival time
- destruction regime: transport of dense gas to several kpcs hard to explain because cloud shatters and dissolves in the wind
- growth regime: momentum transfer from hot wind to the cooling and accreting material implies fast outflow of cold/warm phase

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

Cosmic ray transport:

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- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Enßlin, *Probing cosmic ray transport with radio synchrotron harps in the Galactic center,* 2020, ApJL, 890, L18.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment cosmic-ray hydrodynamics on a moving mesh,* 2021, MNRAS, in press, arXiv:2010.11960.

Cold cloud in a hot wind:

- Dursi & Pfrommer, *Draping of Cluster Magnetic Fields over Bullets and Bubbles – Morphology and Dynamic Effects,* 2008, ApJ, 677, 993.
- Sparre, Pfrommer, Vogelsberger, *The physics of multiphase gas flows: fragmentation of a radiatively cooling gas cloud in a hot wind,* 2019, MNRAS, 482, 5401.
- Sparre, Pfrommer, Ehlert, *Interaction of a cold cloud with a hot wind: the regimes of cloud growth and destruction and the impact of magnetic fields*, 2020, MNRAS, 499, 4261.