Cosmic Rays in Galaxy

Provisional

Formation: A ^ Summary

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Including work by Chad Bustard, Roark Habegger, Evan Heintz, Josh Wiener, & Sherry Wong (UW)
Also Ryan Farber, Peng Oh, Mateusz Ruszkowski, Karen Yang

Why Interesting & Why Provisional?

<u>Interesting</u>

- Significant part of interstellar energy budget
- Star formation & black hole feedback
- Impact on circumgalactic & intergalactic medium
- Role in galactic dynamo

- <u>Provisional</u>
  - Evolving picture of galaxy evolution from JWST
  - Interaction with host medium depends on cosmic ray transport theory.
    - Transport theory depends on physics of waves & turbulence

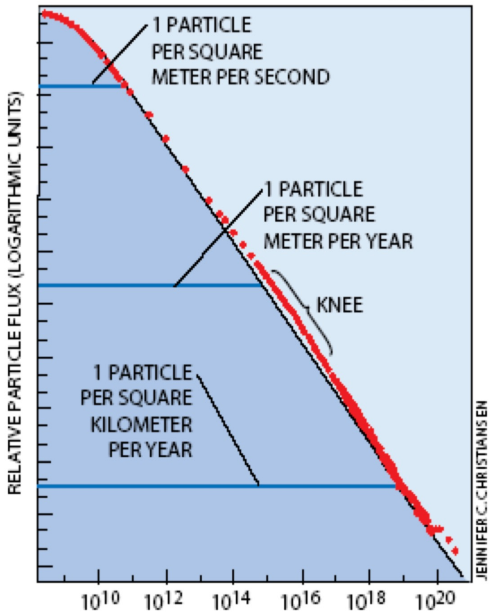
Effects of kinetic scale plasma waves & instabilities are seen at Mpc scales.

Plan of This Talk

- Cosmic rays at a glance
- A brief review of transport theory with the goals of
  - characterizing how cosmic rays exchange momentum & energy with the thermal gas.
  - deriving a fluid theory to describe cosmic ray interactions at large scales.
- Some examples of cosmic ray effects under these transport models
  - Restructuring the interstellar medium
  - Galactic winds & star formation feedback
  - The Eddington Limit for cosmic rays
- Summary & conclusions

Cosmic Rays at a Glance

Scientific American, (c) 1998



The spectrum, simplified.
From HAWC

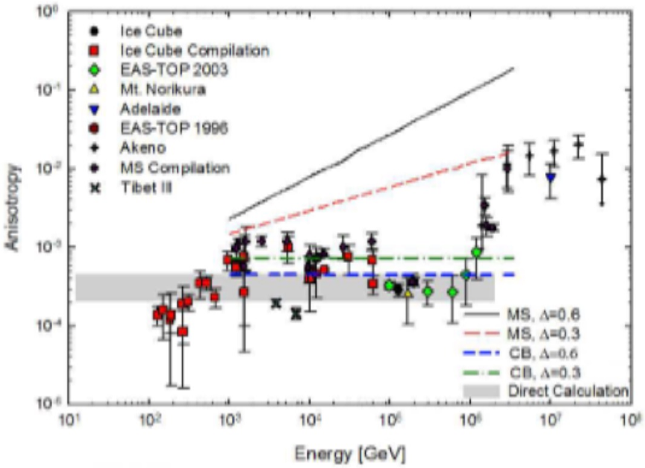
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Declining power law in energy.

Most of the energy density & pressure come from protons of a few GeV.

Highly isotropic in arrival direction.

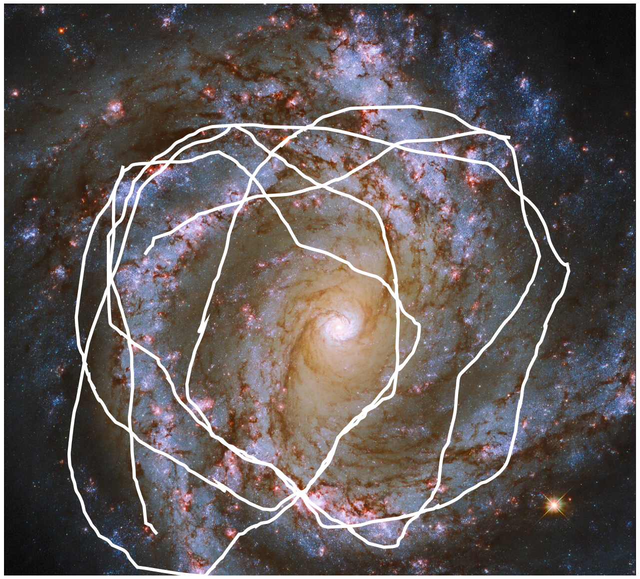
GeV cosmic rays are confined in the Milky Way for ~ 10^7 yr.



Anisotropy from Burch & Cowsik 2010

Transport Theory & Fluid Treatment

potw2114a.jpg (JPEG Image, 1280 × 1249 pixels) — Scaled (62%)   https://cdn.spacetelescope.org/archi



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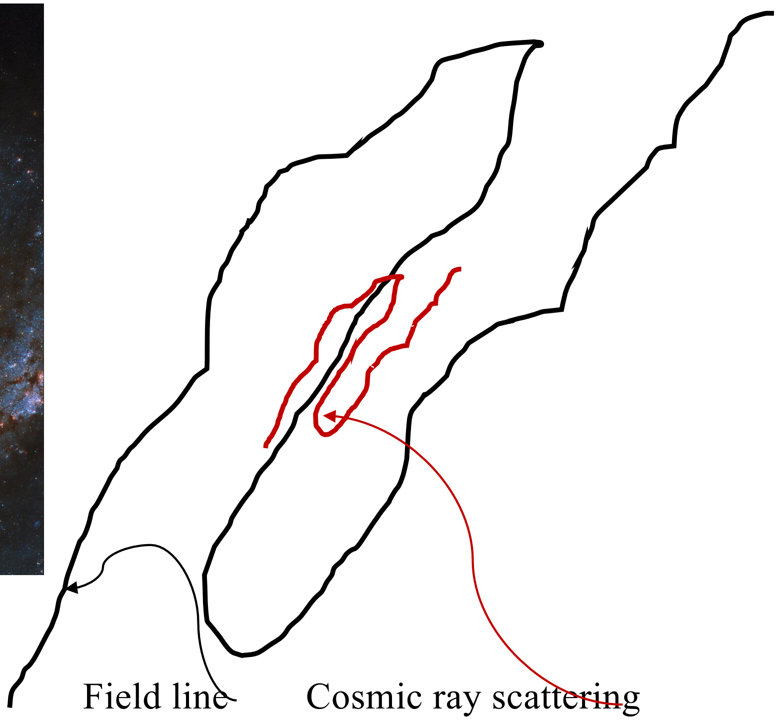
Magnetized spiral galaxy
(ESO image)

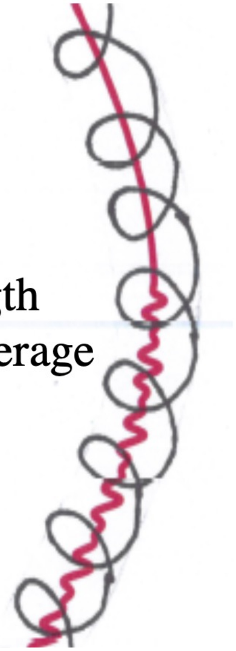


Field line

Cosmic ray scattering
up & down field line

Solar system scale

Orbits follow
fieldlines and
short wavelength
fluctuations average
out.



Agents of scattering

Review of Propagation Models

- ***Streaming:*** Cosmic rays couple to thermal gas by scattering from MHD waves they excite by streaming down their pressure gradient.

Stream relative to the gas at

$$\mathbf{v_{Ai}} \equiv \frac{\mathbf{B}}{(4\pi\rho_i)^{1/2}}$$

Heat the gas at the rate

$$H = \mathbf{v_{Ai}} \cdot \nabla P_c$$

"Continuity" condition

$$P_c \propto \rho_i^{2/3}$$

along each magnetic flux tube.

- ***Diffusion:*** Cosmic rays scatter from extrinsic turbulence

Diffuse through the gas with diffusivity κ.

- ***Advection:*** Limit of small diffusivity.

Behave like a relativistic gas

$$P_c \propto \rho_i^{4/3}$$

In all these models, cosmic rays exert a force on the gas through their pressure gradient, but heating only occurs in self confinement case, & outcomes are very different.

More About the Waves

- Propagate in *plasma* component; damped by ion-neutral collisions
- Damped by background turbulence/field line wandering, which shears them apart
- Damped nonlinearly by thermal ions

In self confinement theory, balance cosmic ray excitation against streaming to determine anisotropy & diffusivity

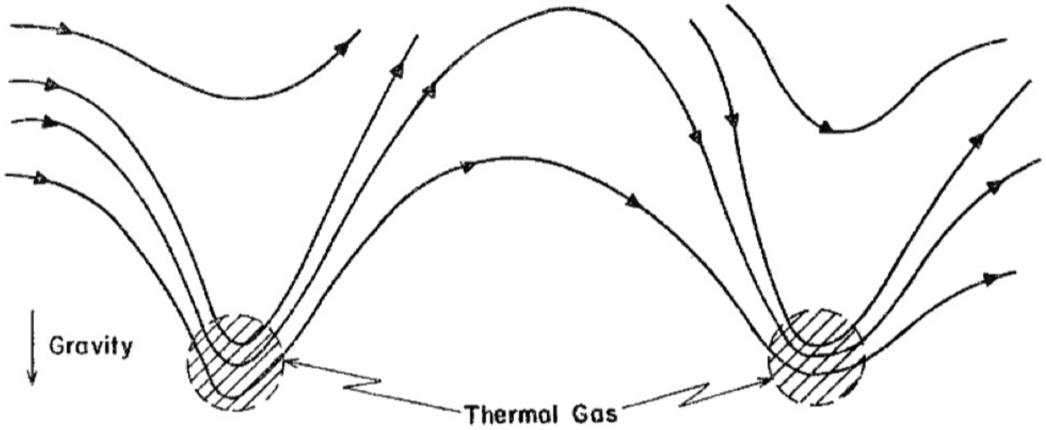
In extrinsic turbulence theory, damping affects properties of cascade.

Have we identified all relevant damping mechanisms?

Propagation Models in Action

Role of Magnetic Fields & Cosmic Rays in Structuring Galactic Disks

Parker's Instability: Parker 1966*



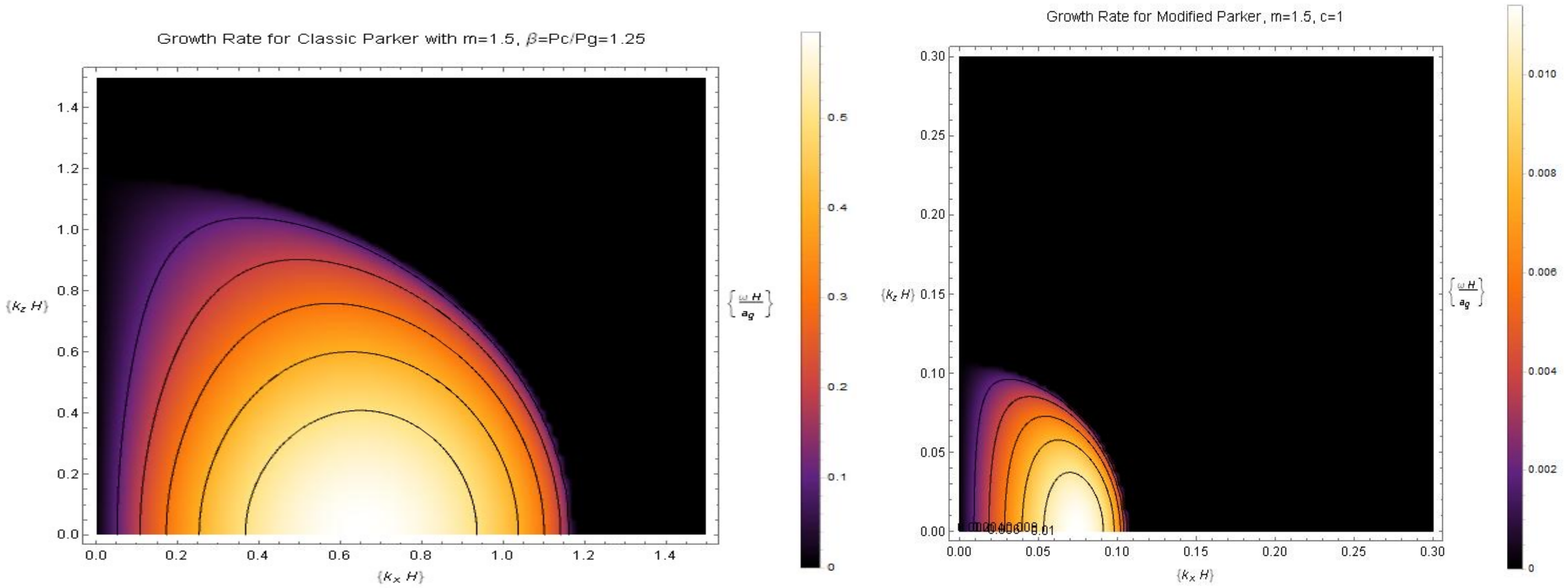
<u>Free energy source :</u> gravitational potential energy of gas supported above its natural scale height by magnetic fields & cosmic rays.

<u>Energy cost</u>: work needed to compress the gas & bend magnetic field lines.

<u>Effects</u>: restructuring ISM, galactic dynamo, magnetic buoyancy in accretion disks.

* Streaming instability & its consequences introduced in 1969

Cosmic Rays *Stabilize* Parker with Advective Transport; Streaming & Diffusion are *Destabilizing*.

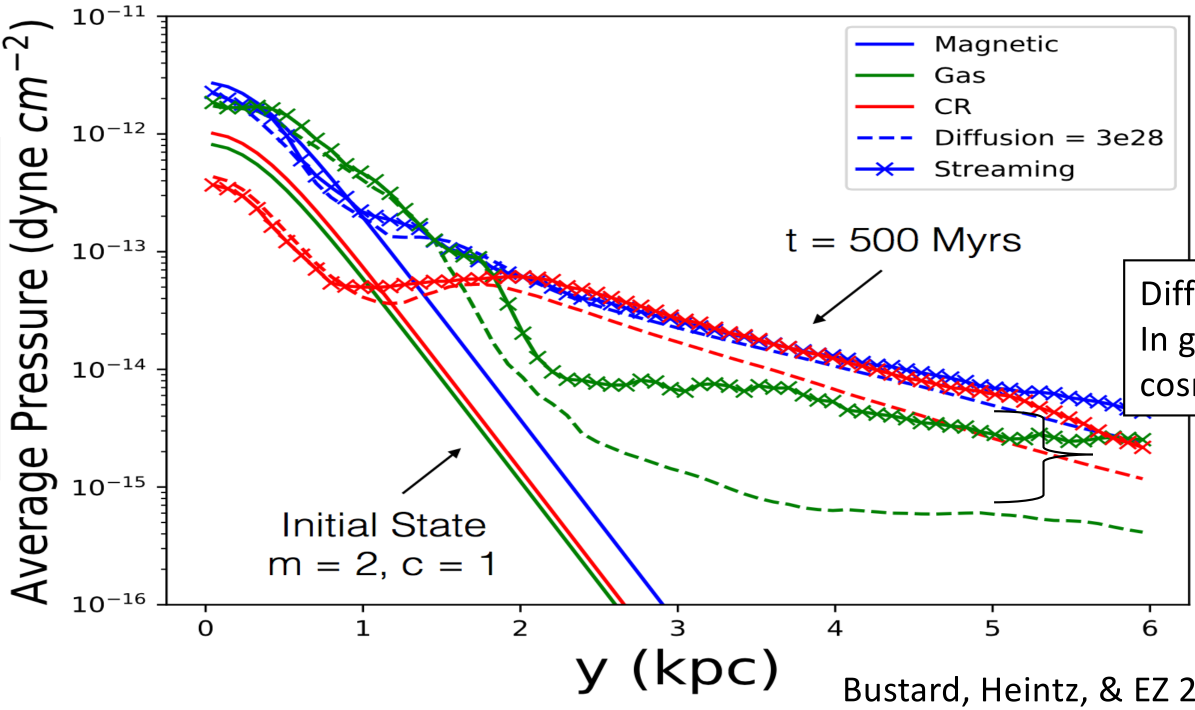

$\gamma_c = 0$

$\gamma_c = 4/3$

Growth rate contours in the horizontal (k_x) , vertical (k_z) plane for γ_c =0 ("Classic Parker") and γ_c = 4/3. Note different scales.
From Heintz & EZ 2018.

Given Enough Time & Favorable Cosmic Ray Transport, Parker Instability Works as Claimed

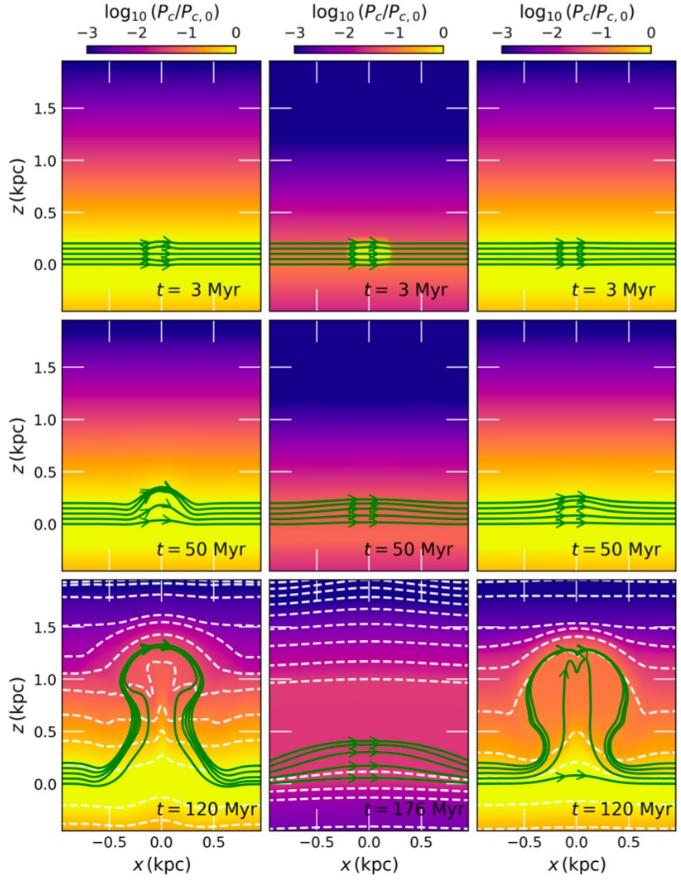
Nonthermal Pressure dominates at large heights in evolved state



Difference In gas pressure is due to cosmic ray heating.

Bustard, Heintz, & EZ 2020

Buoyancy Effects & Accelerated Timescales with Localized Injection (Habegger, EZ, Wong 2023)

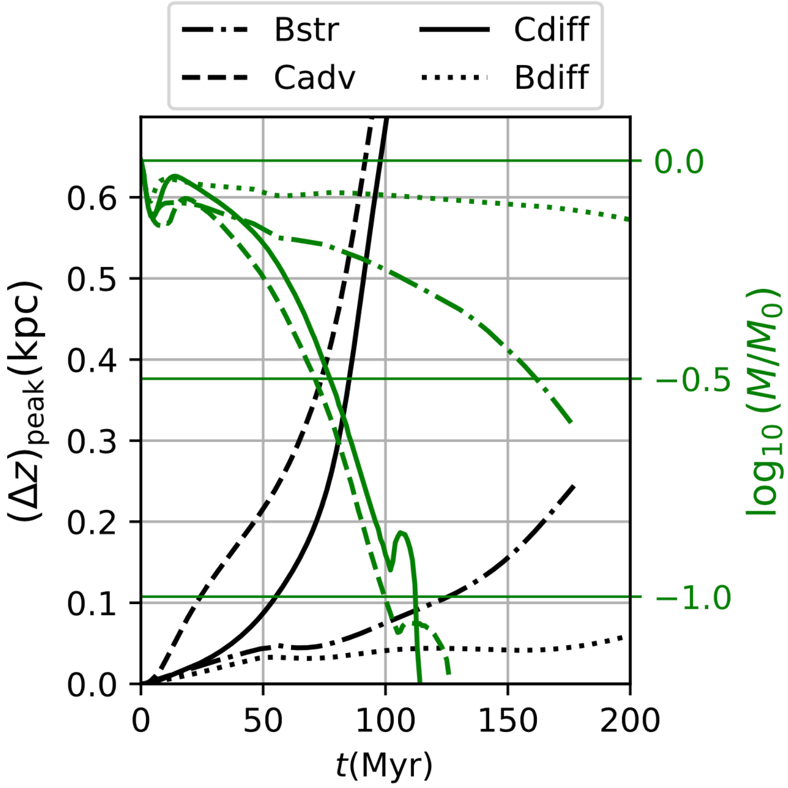


Results of instantaneous cosmic ray injection onto a magnetic flux tube (shown in green) slightly above the midplane of a 2kpc wide, 3D box of ISM (MW parameters). Cosmic ray pressure pushes gas out of the tube, which becomes buoyant, rises, and drains material even faster.

The 3 columns contrast different models of transport.

- Left: Advection
- Center: Streaming
- Right: Diffusion.

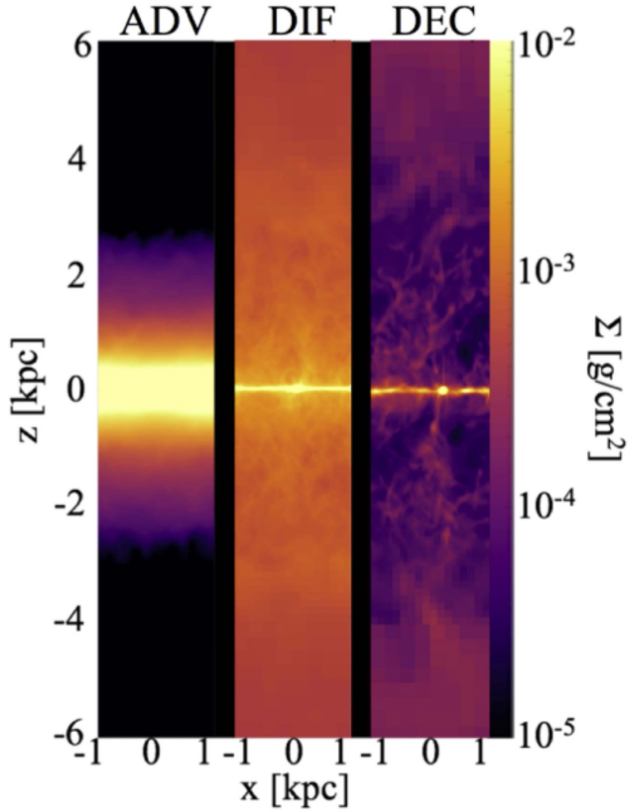
Quantification of Flux Tube Rise & Mass Evacuation



- We have recovered cosmic ray buoyancy.
  - Puzzling stabilization by stiff cosmic ray eqn. of state is resolved.
  - Must resolve 3rd dimension; lifting is harder in 2D.
- Restructuring is significantly faster with a finite amplitude kick.
  - Does the Parker Instability make a difference at all? **Yes!** Flux tube only continues rising if background is unstable.

Accounting for Ion-Neutral Damping

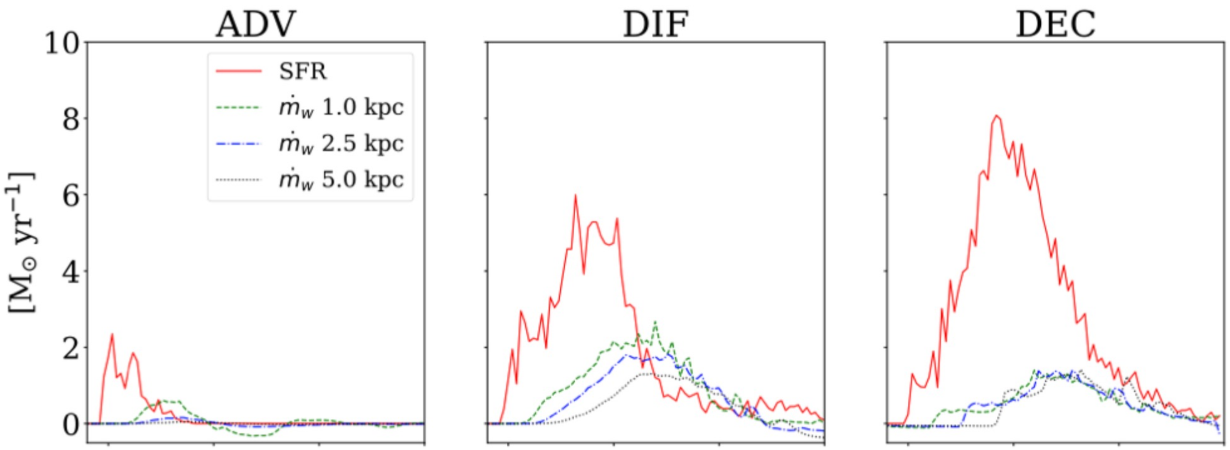
(Farber et al. 2018)



Model of a star forming galactic disk

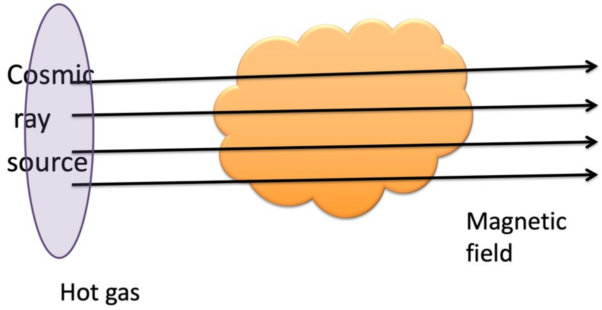
- Advection (ADV): cosmic rays are frozen to the gas
- Diffusion (DIF): uniform diffusivity
- Decoupling (DEC): 30X higher diffusivity in cold regions (proxy for weakly ionized).

Mass Loss & Star Formation Rates



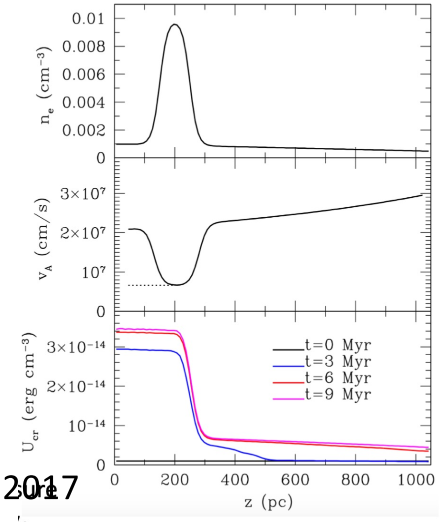
- With decoupling, the cold, dense is left behind & the hot, diffuse gas is blown out.
- With advection, star formation is suppressed, but the ISM is too heavy to lift *at the resolution of our study*.
- The two diffusive models have about the same mass loss rates.

The Bottleneck Story: (Bustard, Oh, Ruszkowski, Wiener)

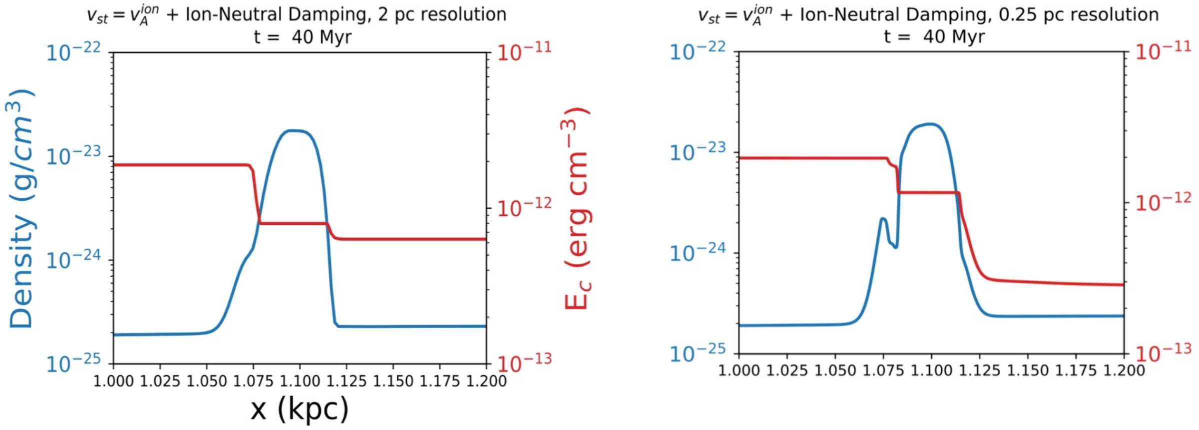


Partial Ionization & Resolution Effects

Here is what happens in a weakly ionized cloud – v_A *in the plasma* increases. A bottleneck forms on the far side and, depending on ionization vs density, also on the near side.

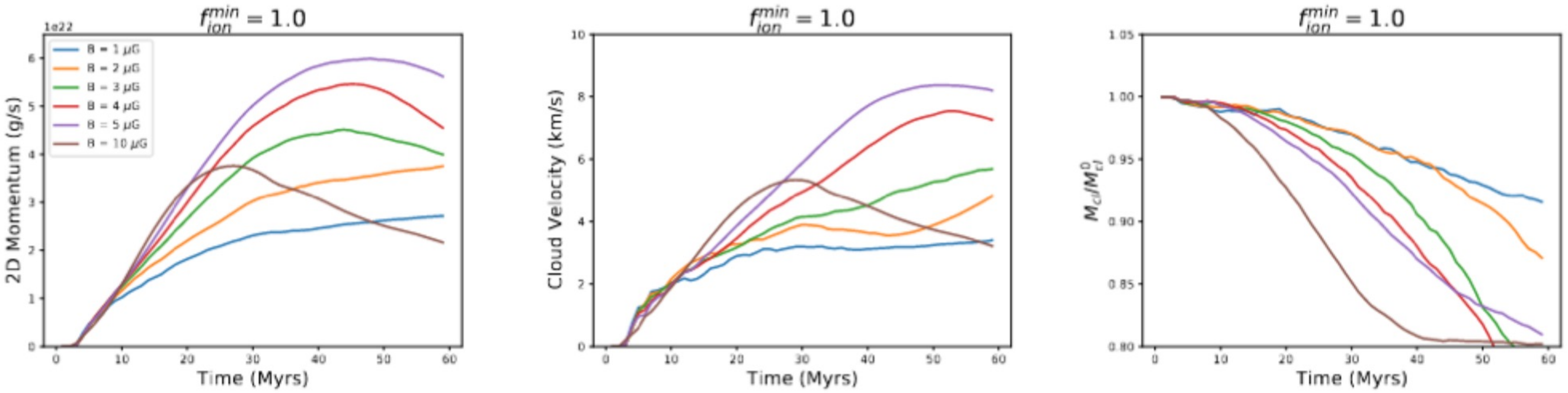


WOZ 2017



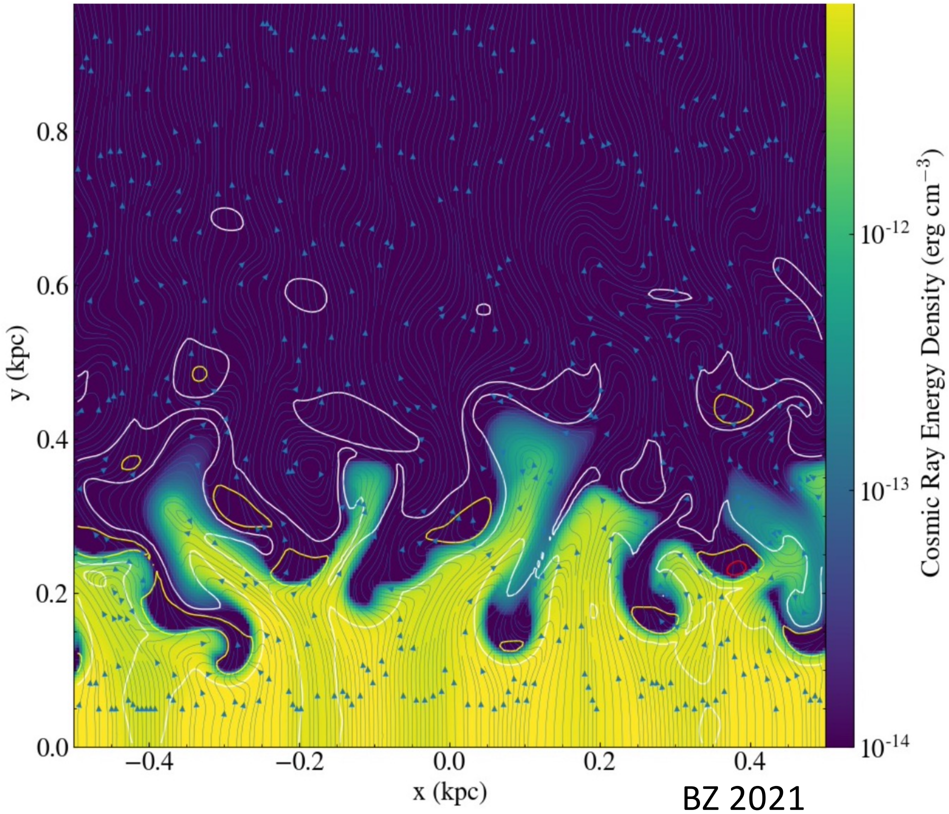
BZ 2021

Cosmic Ray Pressure Buildup Accelerates Clouds & Heating Erodes Them *(Bustard & EZ 2021)*

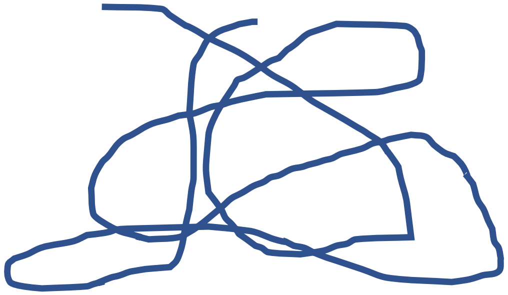


Momentum, velocity, & mass of fully ionized clouds vs time as functions of magnetic field strength. A weak field Is warped around the cloud, reducing momentum input. A strong field leads to a reduced thermal pressure pulse.

Bottlenecks in a Clumpy Medium



BZ 2021

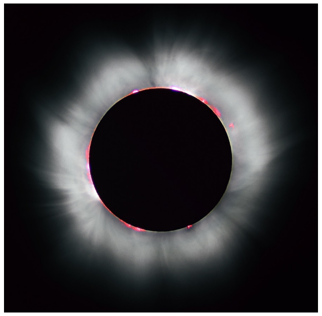


Given the tangled topology of astrophysical magnetic fields & clumpiness of interstellar gas, the streaming picture must be highly intermittent & time dependent.

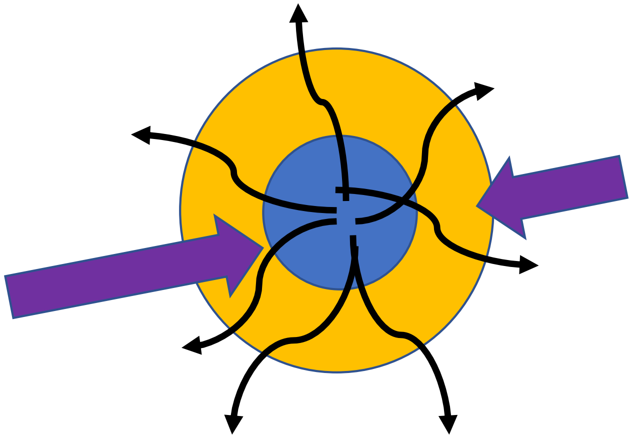
Density & ionization fronts must be well resolved to get the pressurization & momentum input right.

An Eddington Limit for Cosmic Rays?

Socrates et al. 2008, Crocker et al. 2020, Heintz & EZ 2022



Parker’s argument for a solar wind: the asymptotic pressure of an isothermal corona >> interstellar pressure → corona must be expanding.

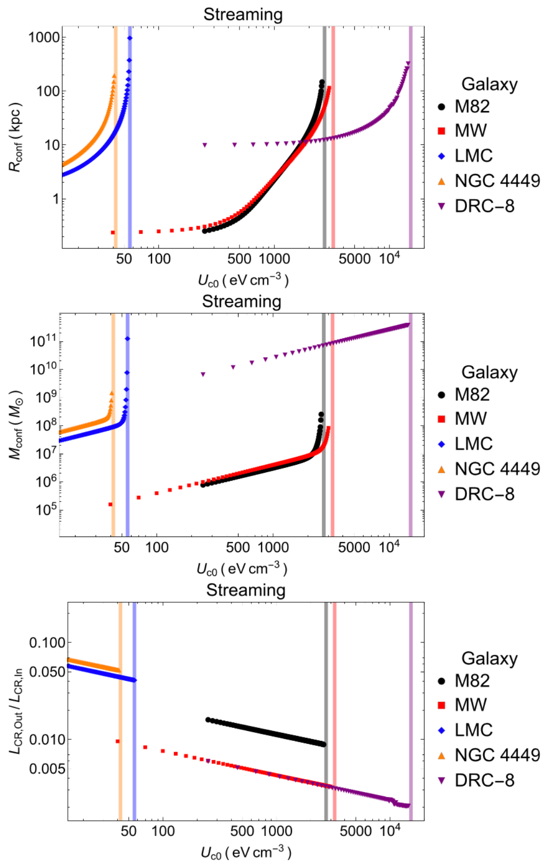


Central molecular zone with high SFR that sets base P_c

Cosmic ray supported envelope: Can it always be confined by the CGM?

Addressed this for CR streaming, advection, diffusion, & calorimetric (sources balance losses) in 5 prototypical galaxy models

Results: Models



How the radius of confinement, mass confined & ratio of final to initial cosmic ray luminosity vary with base cosmic ray energy density, assuming transport by streaming.

Results: Summary

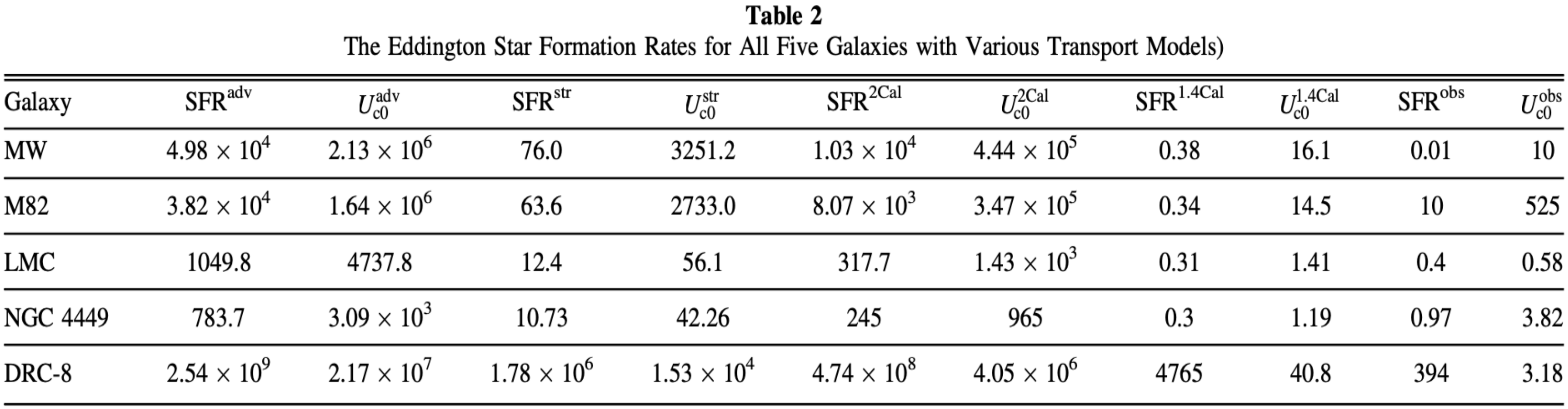


Table 2

The Eddington Star Formation Rates for All Five Galaxies with Various Transport Models)

Galaxy	$\mathrm{SFR}^{\mathrm{adv}}$	$U_{\mathrm{c0}}^{\mathrm{adv}}$	$\mathrm{SFR}^{\mathrm{str}}$	$U_{\mathrm{c0}}^{\mathrm{str}}$	$\mathrm{SFR}^{\mathrm{2Cal}}$	$U_{\mathrm{c0}}^{\mathrm{2Cal}}$	$\mathrm{SFR}^{\mathrm{1.4Cal}}$	$U_{\mathrm{c0}}^{\mathrm{1.4Cal}}$	$\mathrm{SFR}^{\mathrm{obs}}$	$U_{\mathrm{c0}}^{\mathrm{obs}}$
MW	4.98×10^4	2.13×10^6	76.0	3251.2	1.03×10^4	4.44×10^5	0.38	16.1	0.01	10
M82	3.82×10^4	1.64×10^6	63.6	2733.0	8.07×10^3	3.47×10^5	0.34	14.5	10	525
LMC	1049.8	4737.8	12.4	56.1	317.7	1.43×10^3	0.31	1.41	0.4	0.58
NGC 4449	783.7	3.09×10^3	10.73	42.26	245	965	0.3	1.19	0.97	3.82
DRC-8	2.54×10^9	2.17×10^7	1.78×10^6	1.53×10^4	4.74×10^8	4.05×10^6	4765	40.8	394	3.18

These are what the SFR and resulting base cosmic ray densities would have to be to reach the Eddington Limit, together with the observed U_c

The Eddington Limit is a well founded concept, but only dwarf starburst galaxies come close to approaching it, and only for transport by streaming.

Summary & Conclusions

- Cosmic rays carry a major fraction of the interstellar energy density.
- Confined magnetically & coupled collisionlessly to thermal background by a magnetic field.
  - Scattered by kinetic scale waves that are excited by the cosmic rays themselves or extrinsically generated in a turbulent cascade.
- Cosmic ray effects are sensitive to how they interact with microscale magnetic fluctuations, **so we have to get that right**.
  - Buoyancy, bottlenecks, pressurization, heated interfaces, momentum deposition, star formation rates.

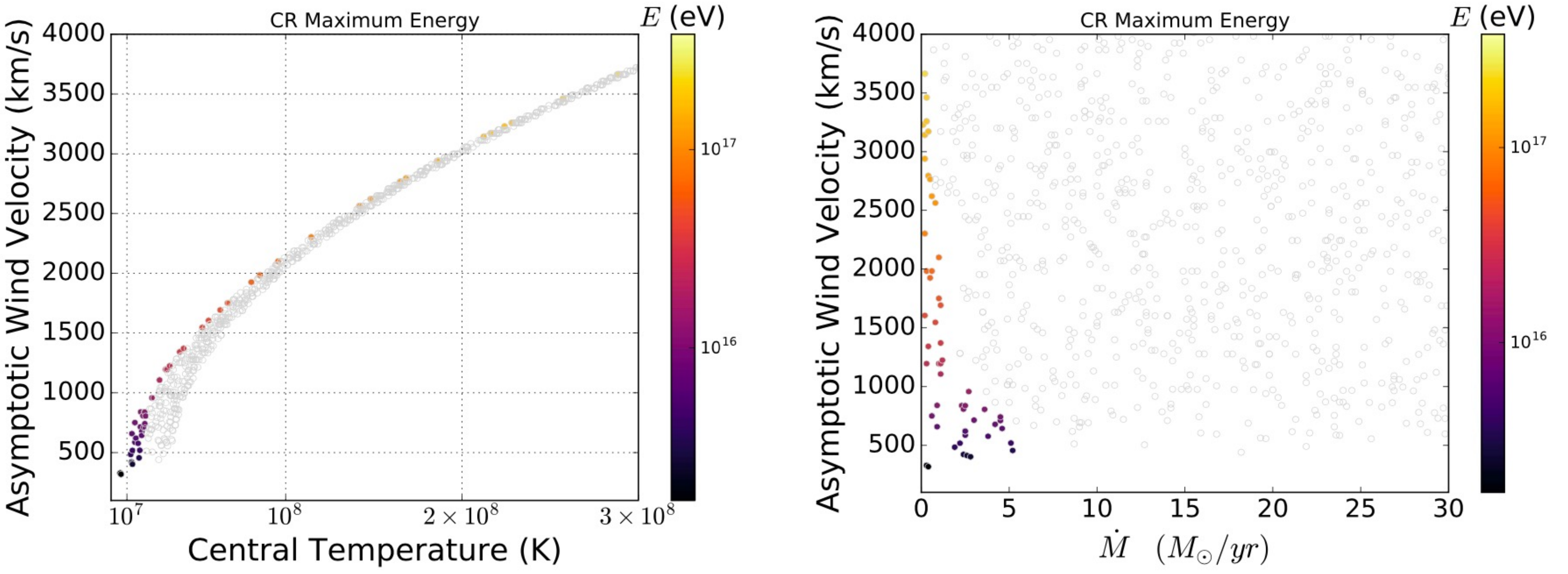
What are the next steps?

Future and Ongoing Challenges

- Beyond the fluid model: refine observational predictions by resolving energy spectrum.
  - Cosmic ray driven chemistry
- Improved understanding of the scattering fluctuations, especially nonlinear effects & interaction with background turbulence.
  - Important for choosing the right propagation model
  - Special effects near sources & at very low magnetic field strengths
- Multiscale challenges: adequate spatial resolution & subgrid prescriptions for interfaces and other small scales.

There has never been a better time!
Thank you!

About 10% of Galactic Wind Luminosity Could Be Converted to Cosmic Rays, Most of Which would be Swept into the CGM



Results for thermally driven galactic wind models. Colored points show cosmic ray energies & wind properties for which return to the galaxy is feasible. Grey points represent particles which are lost (Bustard, EZ, Cotter 2017)