Cosmic Rays in Galaxies: From Microscales to Macroscales

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The Contributions of Professor Parker

Professor Parker moved plasma effects in astrophysics from the fringe to the mainstream *("What about magnetic field used to be a JOKE!")*.

He did this through a unique scientific style that combined clearly articulated physical reasoning, analytical math, & the ability to distill issues to their essence.

He had unbounded curiosity and left his mark on every problem he touched. No one has more equations and processes named after them. ***This talk focusses on cosmic rays.***

Plan of This Talk

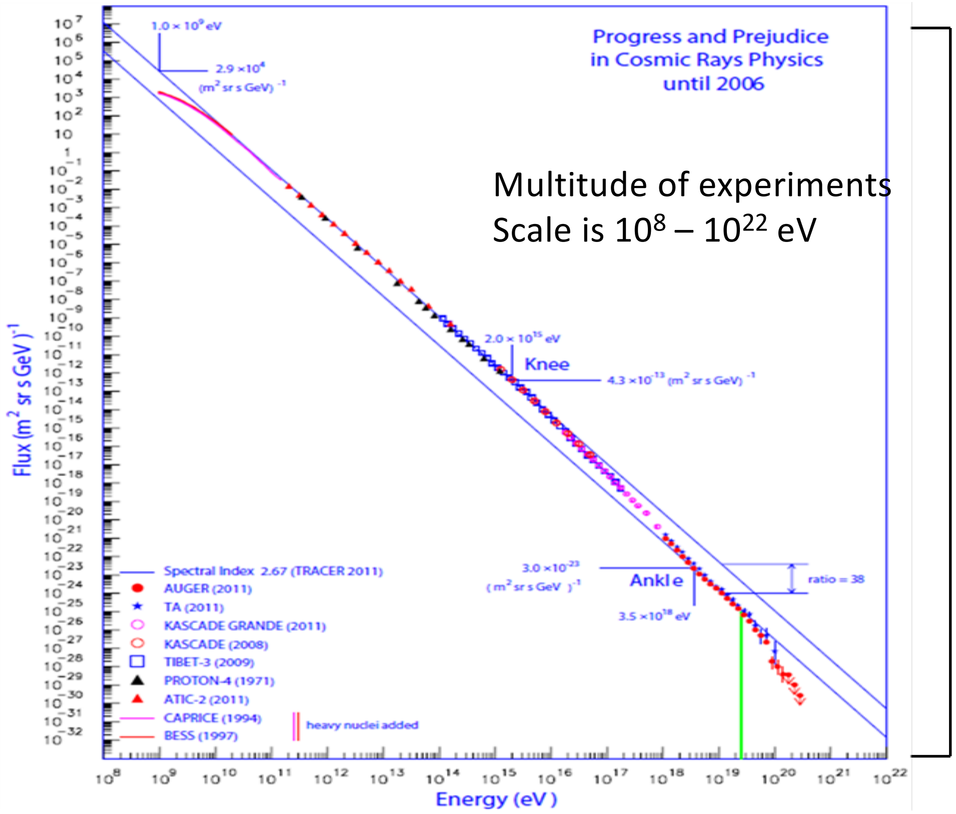
- A few salient properties of cosmic rays.
- Cosmic ray propagation in the interstellar medium.
- Parker’s Instability
- Some unsolved problems

Cosmic Rays at a Glance

- Cosmic rays are the relativistic charged particle component of interstellar, circumgalactic, and galaxy cluster plasmas.
  - Broken power law distribution in energy from < 1 GeV to 10’s of EeV
  - Essentially collisionless *(but radiative processes & collisions -> observational tools).*
- Exchange energy & momentum with ambient gas through scattering from kinetic scale fluctuations: *The Microscales*
- A fluid theory describes how they can:
  - drive global instabilities in galaxies & galaxy clusters,
  - heat interstellar & intracluster gas
  - quench star formation
  - launch outflows on galactic scales.

  The Macroscales
- But there are many incomplete aspects of this picture.

Cosmic Ray Energy Spectrum



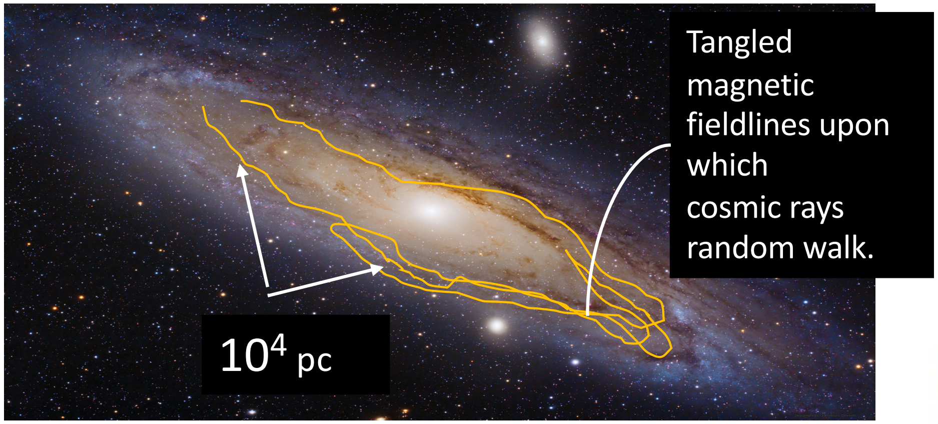
Multitude of experiments
Scale is $10^8 – 10^{22}$ eV

- Mostly protons (n_i/n_e ~ 50 – 100)
- U_{cr} ~ 1 eV cm$^{-3,}$ similar to magnetic, thermal, & radiation energy densities in galaxies
- n_{cr} ~ 3 10^{-10} cm^{-3}
- <E> ~ 3 GeV
- Above ~ 10^9 GeV, not magnetically confined by Galactic magnetic field.

Summary of Cosmic Ray Properties

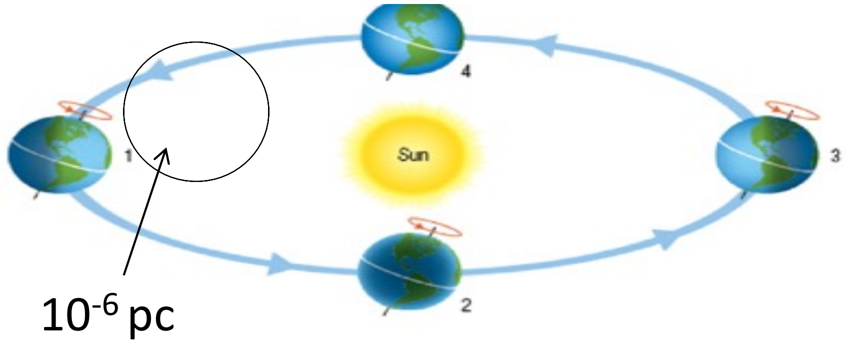
- Cosmic rays are accelerated from the interstellar medium in events, probably supernova remnant shocks, that produce an ~ E^{-2} spectrum
- Spectrum is steepened by energy dependent losses & escape.
- GeV cosmic rays are confined to the Milky Way for ~ 2 10^7 yr & scattered with a mean free path λ ~ 1 pc. ~10% of non ν supernova power required to maintain energy density in a steady state.
- Detected in star forming galaxies over a wide range of sizes, ages & activity levels.

Cosmic Ray Propagation is a Multiscale Problem



Milky Way-like galaxy

Average cosmic ray gyro-orbit

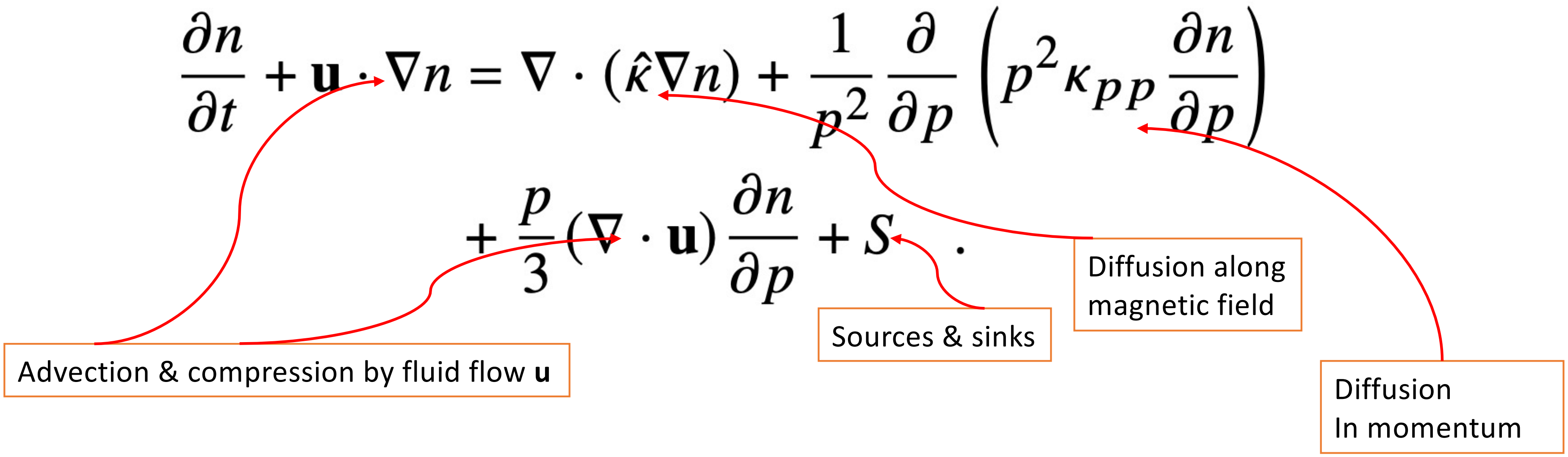


Even if we had an exact representation of the galactic magnetic field, we could never integrate enough cosmic ray orbits or account for all processes. *Must resort to a statistical description. Parker provided an early one.*

Fluid theory for global modeling must describe a collisionless, non- Maxwellian component. *Near isotropy makes this possible.*

Parker’s Transport Equation For Cosmic Rays

with an Isotropic Phase Space Distribution n(x,p,t)



$$\frac{\partial n}{\partial t} + \mathbf{u}\cdot\nabla n = \nabla\cdot(\hat{\kappa}\nabla n) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\kappa_{pp}\frac{\partial n}{\partial p}\right)$$
$$+\frac{p}{3}(\nabla\cdot\mathbf{u})\frac{\partial n}{\partial p} + S \quad .$$

Advection & compression by fluid flow **u**

Sources & sinks

Diffusion along magnetic field

Diffusion In momentum

Statistical description appears as physical & momentum space diffusion. Field line geometry appears through anisotropy of spatial diffusion.

Magnetically mediated interaction between cosmic rays and thermal gas.

Perpendicular Dynamics is Straightforward

Cosmic ray force balance:

$$\nabla_\perp P_c = \frac{\boldsymbol{J}_c \times \boldsymbol{B}}{c}$$

Lorentz force on thermal gas: $\boldsymbol{J}_g \times \boldsymbol{B}/c$

$$= \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} - \frac{\boldsymbol{J}_c \times \boldsymbol{B}}{c}$$

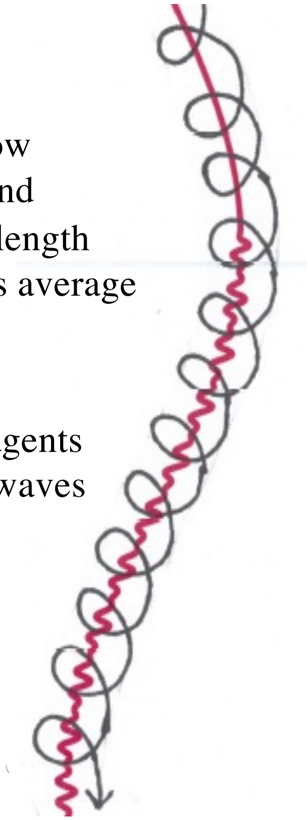
$$= \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} - \nabla_\perp P_c.$$

Cosmic ray pressure gradient introduced through Lorentz force

Parallel Dynamics: Gyroresonant Scattering

Orbits follow fieldlines and short wavelength fluctuations average out.

Scattering agents are Alfven waves

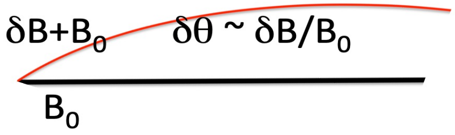


$$\omega - kv\mu = \pm\omega_c;$$

$$\mu \equiv \frac{v_\parallel}{v}$$

Estimate Diffusion Coefficient

Scattering frequency



$$\nu \sim \frac{\langle(\delta\theta)^2\rangle}{\delta t}$$

$$\sim \omega_c \left(\frac{\delta B}{B_0}\right)^2$$

Scattering is nearly elastic: $v_A/c << 1$.

Theories Diverge over Source of Waves

Waves generated by the cosmic rays themselves through streaming instability: **Self-Confinement**

Classical Cosmic Ray Hydrodynamics

Waves are present as part of a turbulent cascade: **Confinement by Extrinsic Turbulence**

Generalized Cosmic Ray Hydrodynamics

See EZ2017 for bridging these theories.

Gyroresonant Amplification of Alfven Waves

$$\Gamma_{cr} = \frac{\pi^2 q^2}{2}\frac{v_A^2}{c^2}\sum_{\pm}\int \delta(\omega - kv\mu \pm \omega_c)\, v(1-\mu^2)\left[\frac{\partial f}{\partial p} + \left(\frac{kv}{\omega}-\mu\right)\frac{1}{p}\frac{\partial f}{\partial \mu}\right] p^2\, dp\, d\mu,$$

resonance

damping

excitation by anisotropy

For drift anisotropy, a simple approximation to the growth rate:

$$\Gamma_{cr} \sim C\omega_{ci}\frac{n_{cr}}{n_i}\left(\frac{v_D}{v_A}-1\right)$$

Γ_{cr} = 0 means cosmic ray isotropy in the wave frame.

Here & elsewhere we’re interested in the bulk cosmic rays with γ ~ 1

Fokker – Planck (F-P) Equation

Back reaction of waves (subscript 1) on zero order cosmic ray distribution function f_0

$$\frac{df_0}{dt} = -\left\langle \frac{q}{m}\left(\boldsymbol{E}_1 + \frac{v \times \boldsymbol{B}_1}{c}\right) \cdot \boldsymbol{\nabla}_p f_1 \right\rangle$$
$$= \boldsymbol{\nabla}_p \cdot \boldsymbol{D} \cdot \boldsymbol{\nabla}_p f_0.$$

Pitch angle scattering ($D_{\mu\mu}$) dominates:

Scattering frequency $\nu \sim \omega_c(\delta B/B)^2$

$D_{p\mu} = D_{\mu p}$ are order (v_A/c)

D_{pp} is order $(v_A/c)^2$, requires waves traveling in both directions

Assumes small angle scattering by nearly periodic, randomly phased waves.

Energy Equation

Multiply F-P eqn. by particle energy ε & integrate over momentum space:

$$\underbrace{\frac{\partial U_c}{\partial t}}_{\text{Energy density}} + \underbrace{\boldsymbol{\nabla} \cdot \tilde{\boldsymbol{W}}_c}_{\text{Energy flux}} = \underbrace{- \int d\omega dk 2\Gamma_c(\omega, k) I(\omega, k)}_{\text{Energy transfer to waves}}$$

Frequent Scattering Approximation

Relate anisotropy to spatial gradient:

$$D_{\mu\mu}\frac{\partial f_0}{\partial \mu} + D_{\mu p}\frac{\partial f_0}{\partial p} = -\frac{v(1-\mu^2)}{2}\frac{\partial f_0}{\partial z}$$

Left hand side related to Γ_c integrand! Energy equation simplifies to:

$$\frac{\partial U_c}{\partial t} + \boldsymbol{\nabla}\cdot\tilde{\boldsymbol{W}}_c = \boldsymbol{v}_A\cdot\boldsymbol{\nabla}P_c.$$

Heating looks like friction, & instability growth rate can be written in terms of pressure gradient.

Balance Wave Damping & Excitation to Ascertain Degree of Confinement

- Ion – neutral friction
  - *Important in H I, H_2 gas*
- Nonlinear energy transfer to thermal ions
  - *Important in hot gas*
- Distorted by wandering of background field
  - *Important when small scale turbulence is present, enhanced at high β* by $\beta^{1/2}$.

In steady state, damping balances growth, determining the streaming rate, wave amplitude, wave dissipation rate, & constraining the diffusion rate.

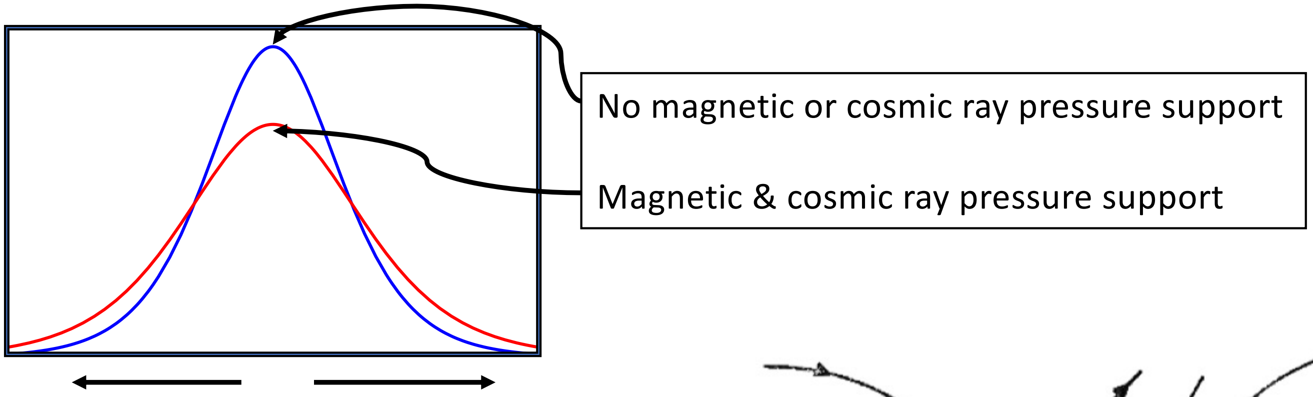
In the Milky Way, self-confinement works below 100-200 GeV (where most of the pressure is) but this is sensitive to damping rates.

Summary of the Fluid Treatment

- Classical Cosmic Ray Hydrodynamics (CCRH)
  - Cosmic rays exert a force on the thermal gas $-\nabla P_c$,
  - Cosmic rays heat the gas at the rate $|\mathbf{v}_A \cdot \nabla P_c|$
  - $P_c/\rho_g^{\gamma_c/2}$ is constant along magnetic flux tubes.
- For Generalized Cosmic Ray Hydrodynamics (GCRH), where confinement is from extrinsic turbulence, leave out streaming & heating.
- Numerical implementation methods by Sharma, Jiang & Oh, Thomas & Pfrommer.

Applied to a range of gas dynamics problems in galaxies and beyond.

Parker’s Instability: A Large Scale Instability of Stratified Disks Supported by Magnetic Fields & Cosmic Rays



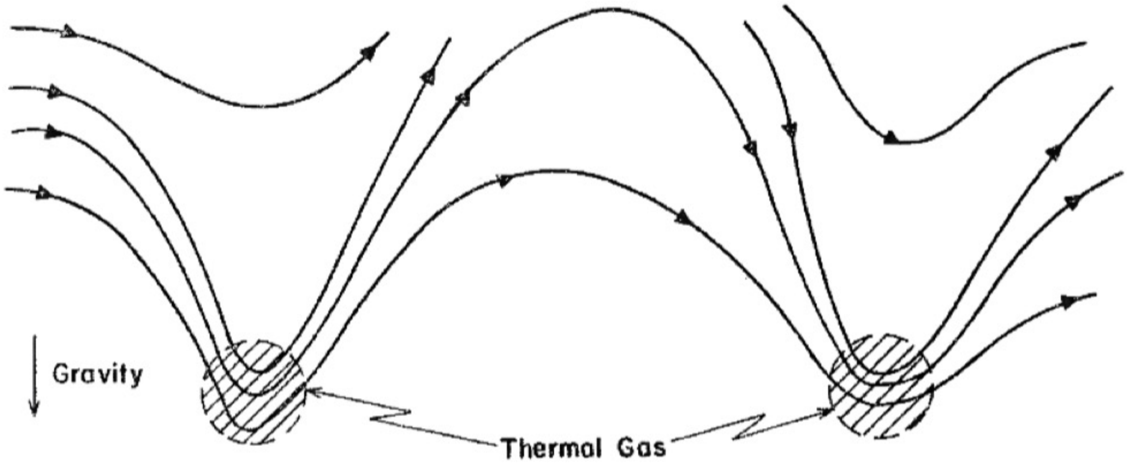
No magnetic or cosmic ray pressure support

Magnetic & cosmic ray pressure support

Distance from Galactic Plane

Free energy source: gravitational potential energy

Must exceed the work needed to compress gas in the valleys.



Parker 1966

Parker (1966) Quantified These Considerations

$$P_g \equiv \rho u^2$$

$$\alpha \equiv \frac{B^2}{8\pi P_g}$$

$$\beta \equiv \frac{P_c}{P_g}$$

α & β are constants

$$H = \frac{u^2}{g}(1 + \alpha + \beta)$$

Gas supported above its natural scale height by magnetic fields and cosmic rays

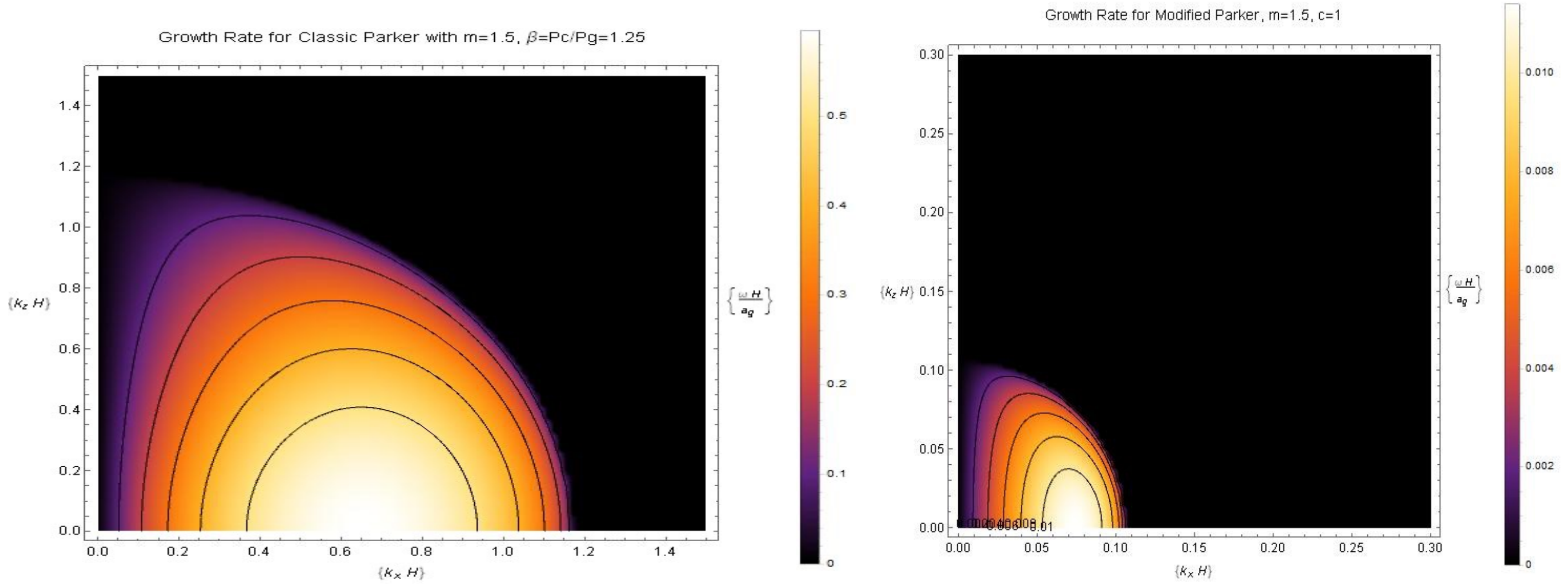
$$\gamma_g > \frac{(1 + \alpha + \beta)^2}{1 + \frac{3\alpha}{2} + \beta}$$

Required for stability. Parker argued $\gamma_g = 1$**, γ_c=0.**

Enduring Message of Classic Parker

- Parker’s Instability sets an upper limit to the fraction of hydrostatic support that can be provided to a gas layer by magnetic fields and cosmic rays
  - Rayleigh-Taylor analogy: light fluid/heavy fluid
  - Compressibility of ISM is critical to determining that level
    - *Thermal pressure is partly turbulent pressure (Zweibel & Kulsrud 1975)*
    - *Extremes of temperature greater than appreciated in the 1960s*
    - *Cosmic ray physics*
- Applications to accretion disks & galactic dynamo as well as the vertical structure of the disk.

Effect of Cosmic Ray Compressibility



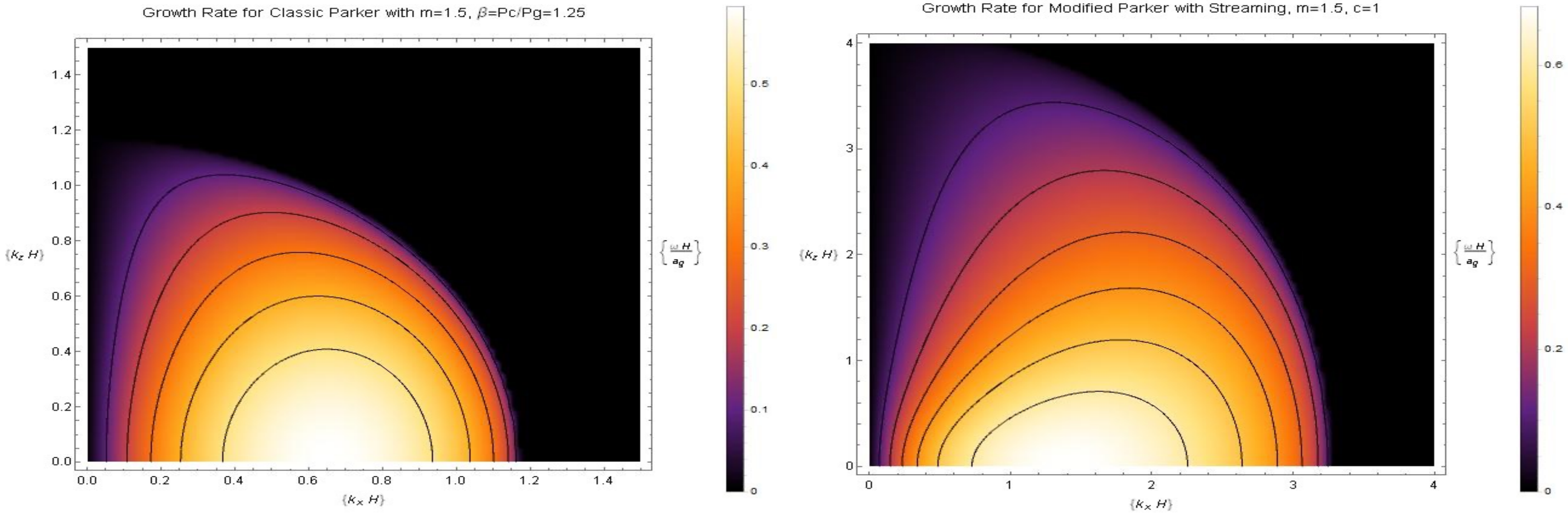
$\gamma_c = 0$ $\gamma_c = 4/3$

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 EH & EZ 2018.

Effect of Cosmic Ray Streaming

$\gamma_c = 0$

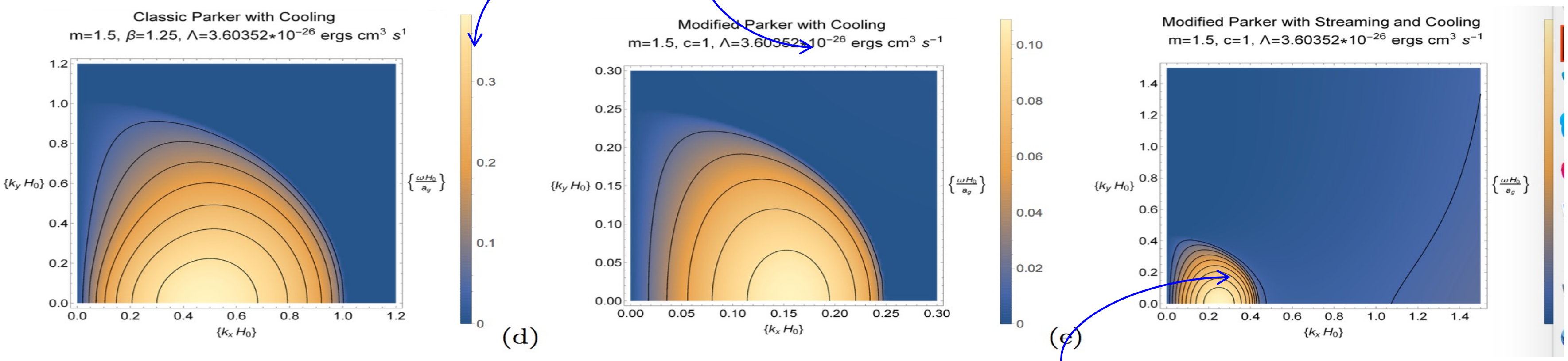
Alfvenic streaming & $\gamma_c = 4/3$



Growth rate contours in the horizontal (k_x) , vertical (k_z) plane for γ_c =0 (“Classic Parker”) and γ_c = 4/3. From EH & EZ 2018. Cosmic ray heating increases the growth rate & destabilizes shorter wavelengths.

Effects of Radiative Cooling

More unstable: softens thermal gas eqn. of state


Classic Parker with Cooling
m=1.5, β=1.25, Λ=3.60352$\star 10^{-26}$ ergs cm^3 s^1

Modified Parker with Cooling
m=1.5, c=1, Λ=3.60352$\star 10^{-26}$ ergs cm^3 s^{-1}

Modified Parker with Streaming and Cooling
m=1.5, c=1, Λ=3.60352$\star 10^{-26}$ ergs cm^3 s^{-1}

(d)

(e)

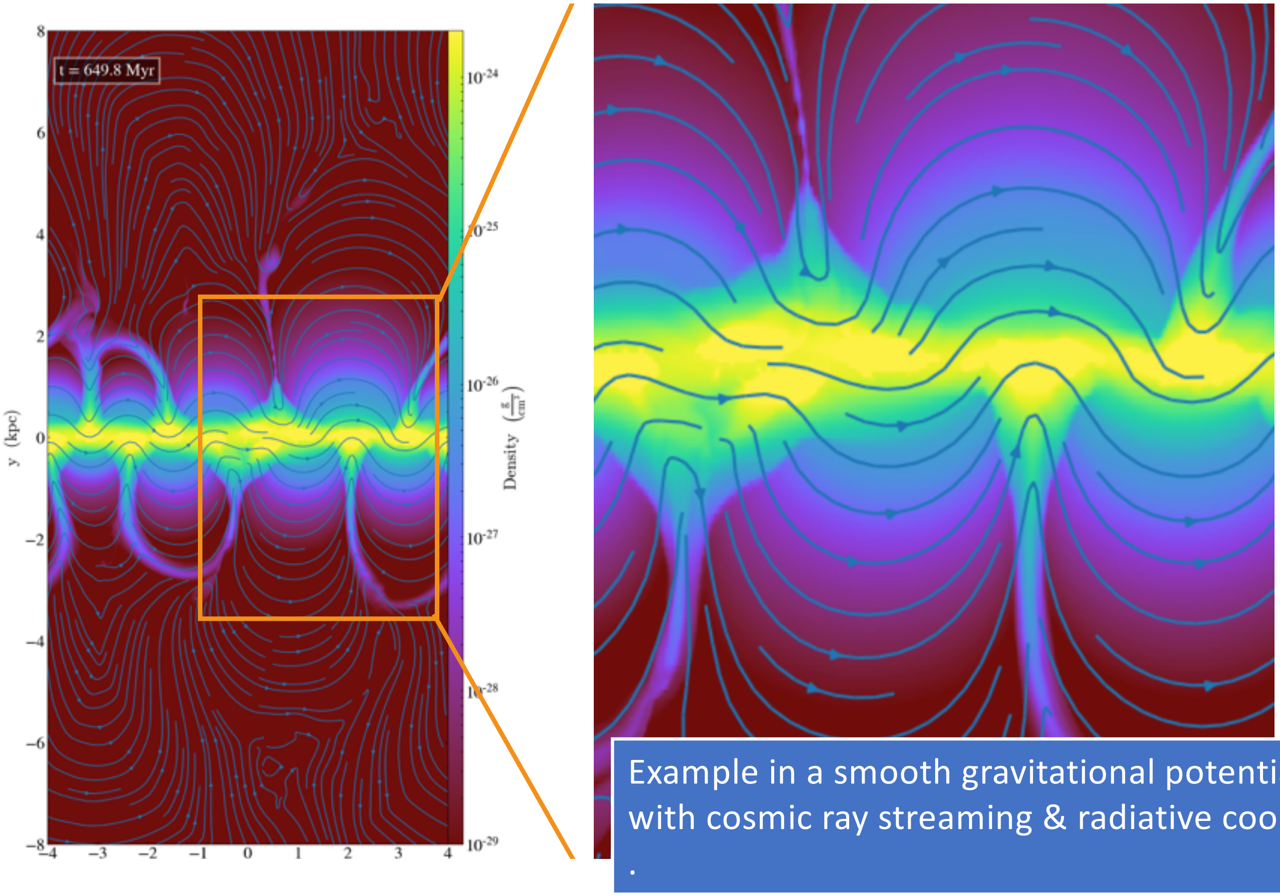
More stable: reduced effect of cosmic ray heating

HBZ 2019

Modeling with FLASH – HBZ 2019

- Isothermal layer in a tanh(z/H) gravitational field (*smooth*).
- Radiative cooling can be implemented.
- Cosmic ray streaming & diffusion along. magnetic field lines can be implemented.
- Rotation, self gravity, & stellar energy input not yet included.

Density Evolution of an Unstable System



Example in a smooth gravitational potential, with cosmic ray streaming & radiative cooling.
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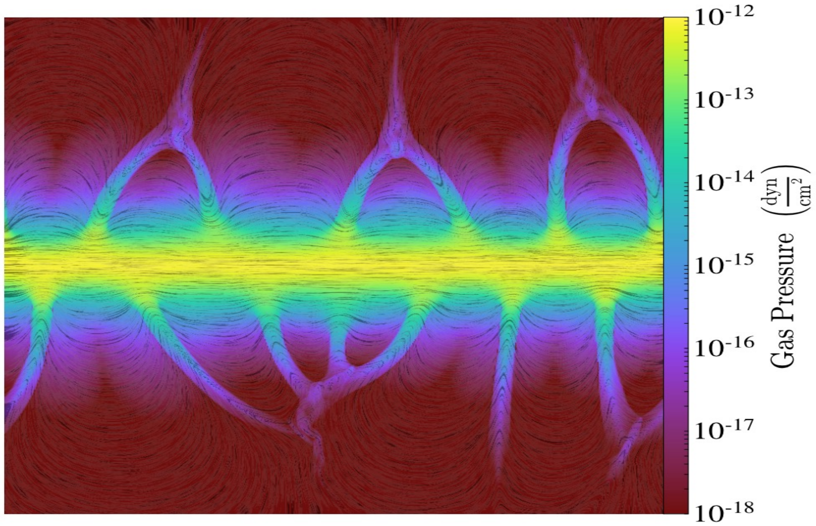
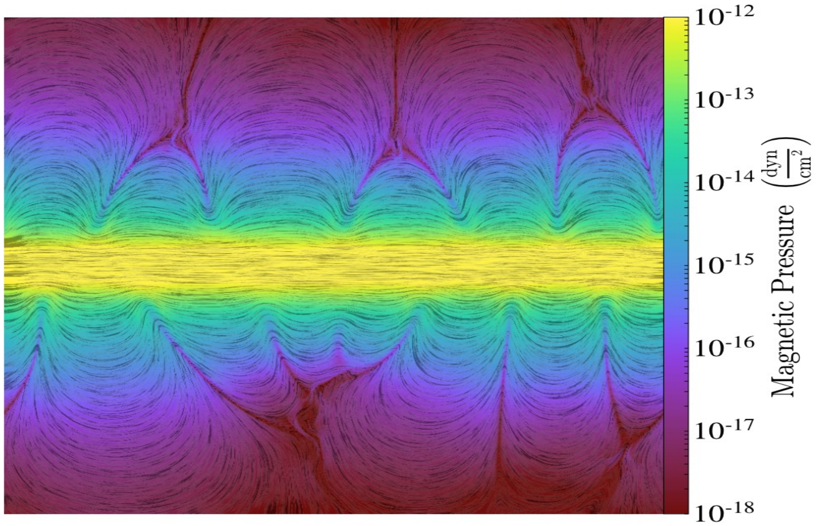
Pressure – Magnetic Field Lines Overplotted





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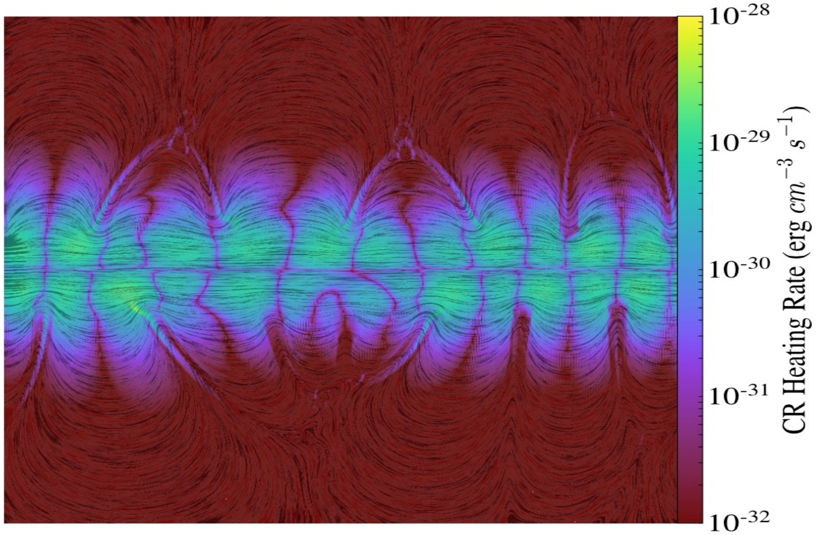
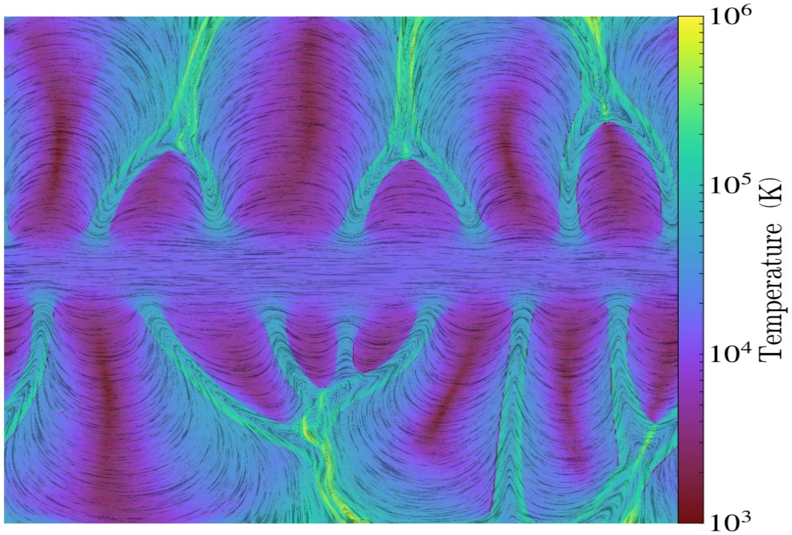
Heating & Temperature

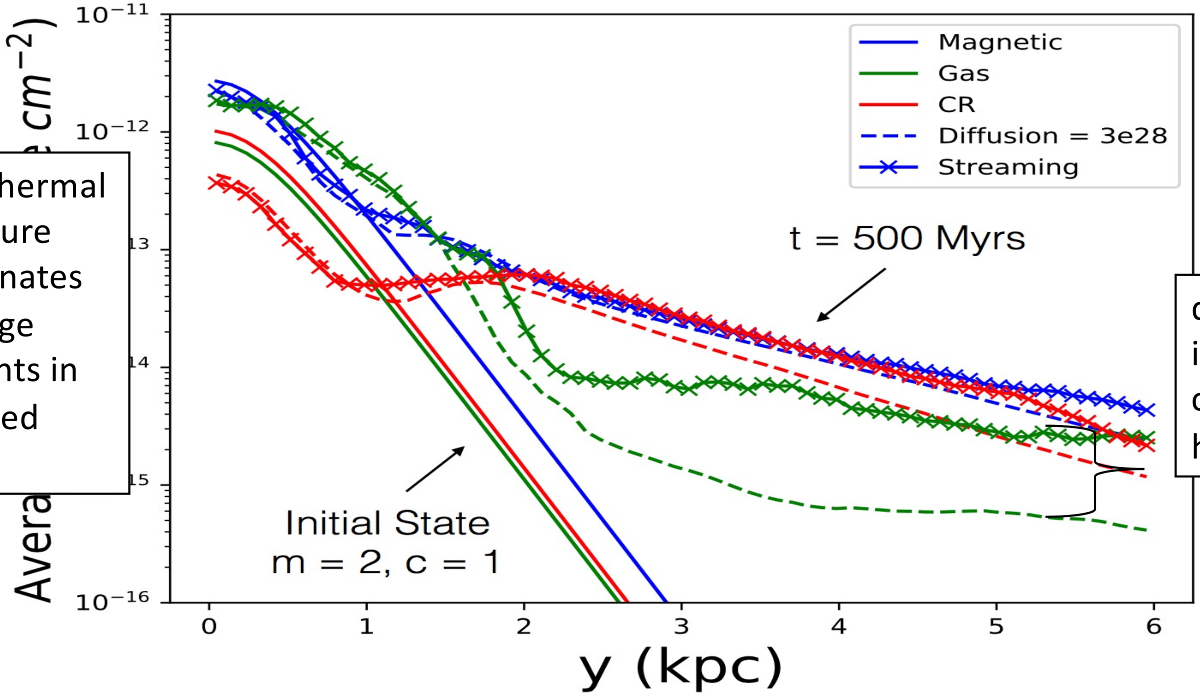




EH,CB, EZ

Radiative cooling is not included here.

Pressure Profiles

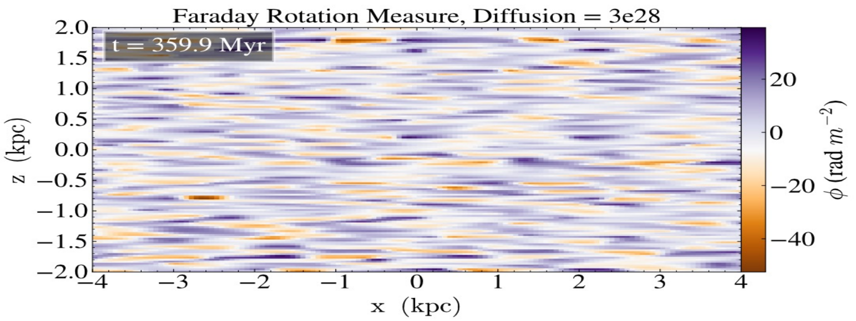


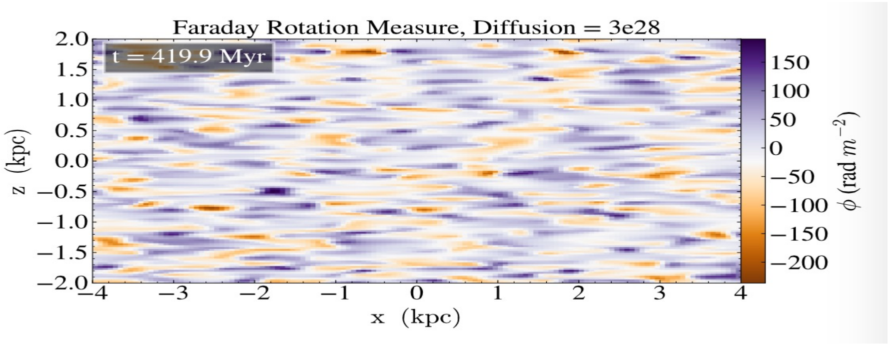
Nonthermal Pressure dominates at large heights in evolved state

difference is due to cosmic ray heating

Parker in 3D

Top down view of rotation measures that would be seen in face on disk with fully developed Parker





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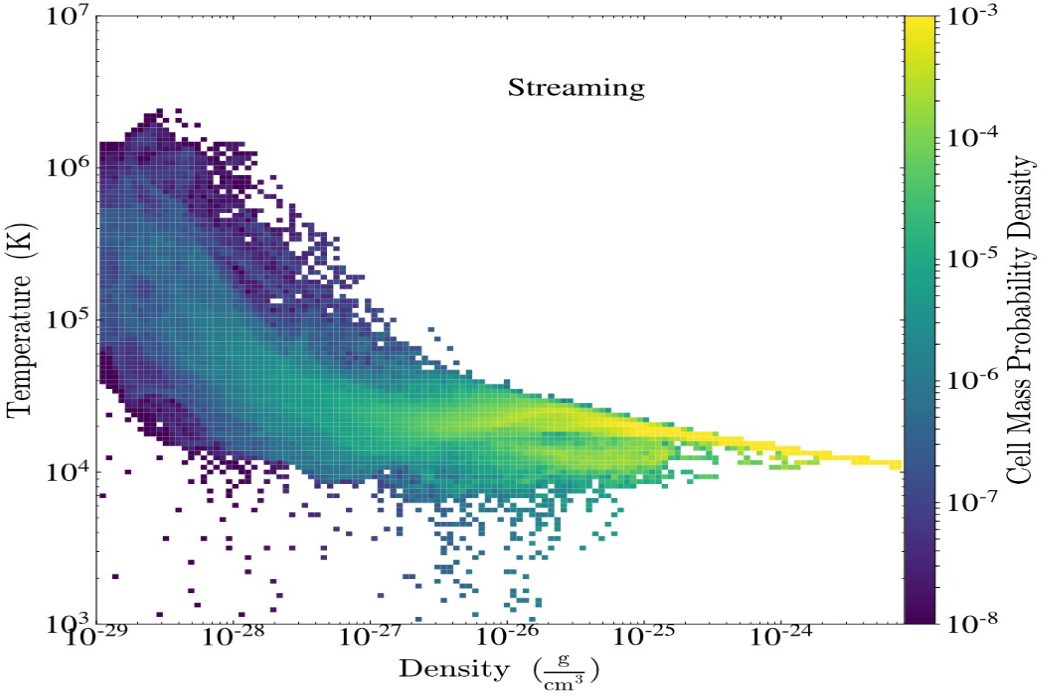
Short in-plane wavelength perpendicular to B means structure would be difficult to see edge on *(Talk by Rainer Beck!).*

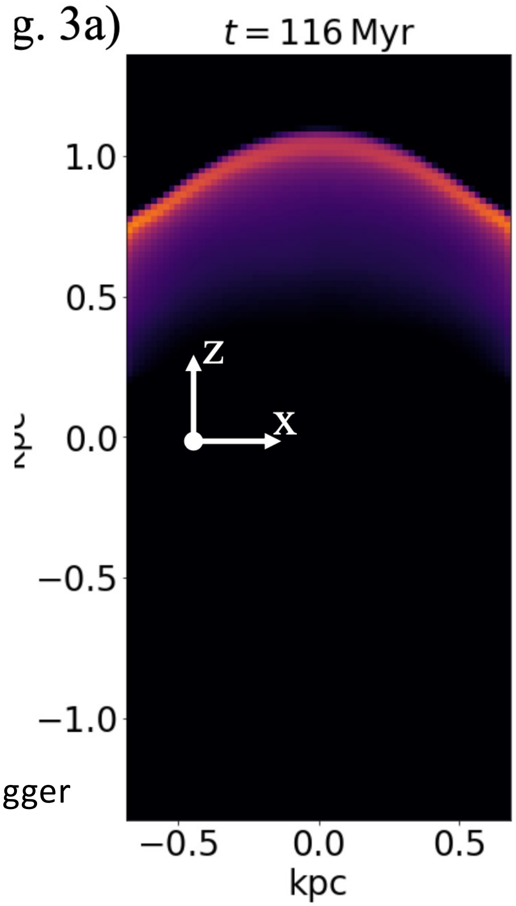
Thermal Phase Plot

Radiative cooling
is included
but unstable
T gas is present.

HBZ



Recent Work on Buoyancy



Roark Habegger

- Localized cosmic ray injection by single or clustered supernovae.
- Cosmic ray pressure pushes & heats thermal gas, driving a flow & evacuating the tube
- Buoyant flux tube rises
  - Is this faster than the Parker Instability itself?
  - Does it matter if the background medium is Parker unstable?

Summary

- Parker's instability exists when modern cosmic ray transport is included.
  - Stability of puffed up disks in simulations with no streaming or diffusion but $\gamma_c = 4/3$ is probably real.
  - Both streaming and diffusion enhance the instability, but the heating due to streaming is notable.
  - Instability produces dense pockets of cold gas and a halo dominated by nonthermal pressure on timescales of 0.5 Gyr.

Some Important Unsolved Problems

- Growth and damping of anisotropy instabilities in an inhomogeneous, e.g. turbulent background. *Important for estimating whether cosmic rays are well confined & how much they heat the thermal gas.*
- Full theory of diffusive propagation. *Important for developing a theory for the energy dependence of the diffusion coefficient & how cosmic rays cross fieldlines.*
- Propagation in a clumpy medium. Bottlenecks and time dependent propagation. Full implementation of confinement by pressure anisotropy in fluid models. *Important for understanding whether cosmic ray coupling pervades space & time or is intermittent.*