The Dynamical Role of Cosmic Rays in Galaxies

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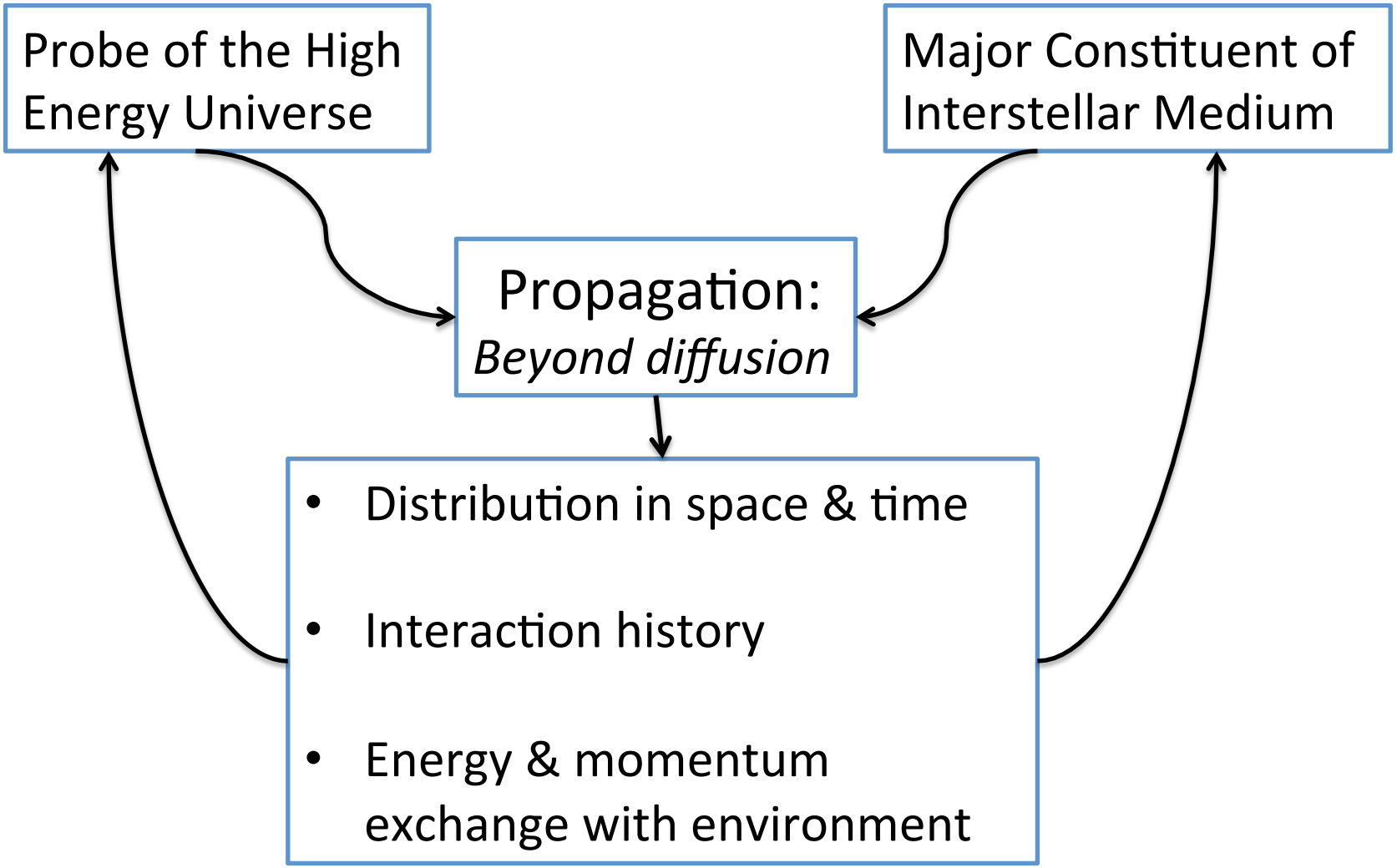
Green means presentation here.

The Dual Roles of Cosmic Rays



Plan of This Talk

- Brief review of collisionless processes
  - Self confinement & extrinsic confinement
  - Fluid treatment for global problems
- Application to galactic winds & star formation feedback
- Mesoscale processes
  - Stability of galactic disks
  - Cool clouds: the bottleneck effect
  - High flux conditions near sources

Interactions

Collisional

- Remote sensing
- Energetics
- Composition
- Chemistry

Ask a particle physicist

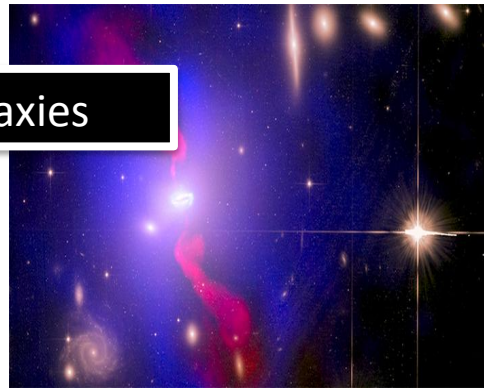
Collisionless

- Nature of scattering: how elastic or inelastic?
- Energy & momentum flow
- Macroscopic effect on medium

Ask a plasma physicist

Applications

Galaxy formation & evolution



Active galaxies

Galactic winds

Galaxy clusters

Perpendicular Dynamics: Easy

Cosmic ray force balance:

(ignore gravity & inertia)

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

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

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

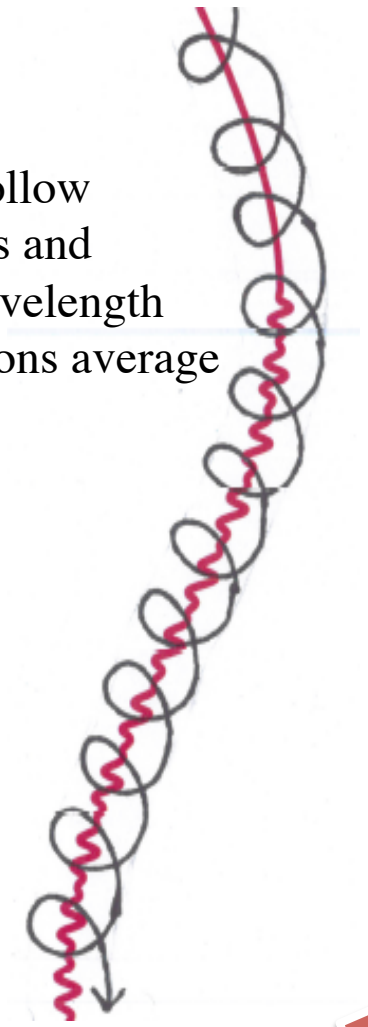
$$= \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} - \nabla_\perp P_c.$$

Pressure gradient introduced through Lorentz force

Parallel Dynamics: Subtle

Gyroresonant Scattering

Orbits follow fieldlines and short wavelength fluctuations average out.



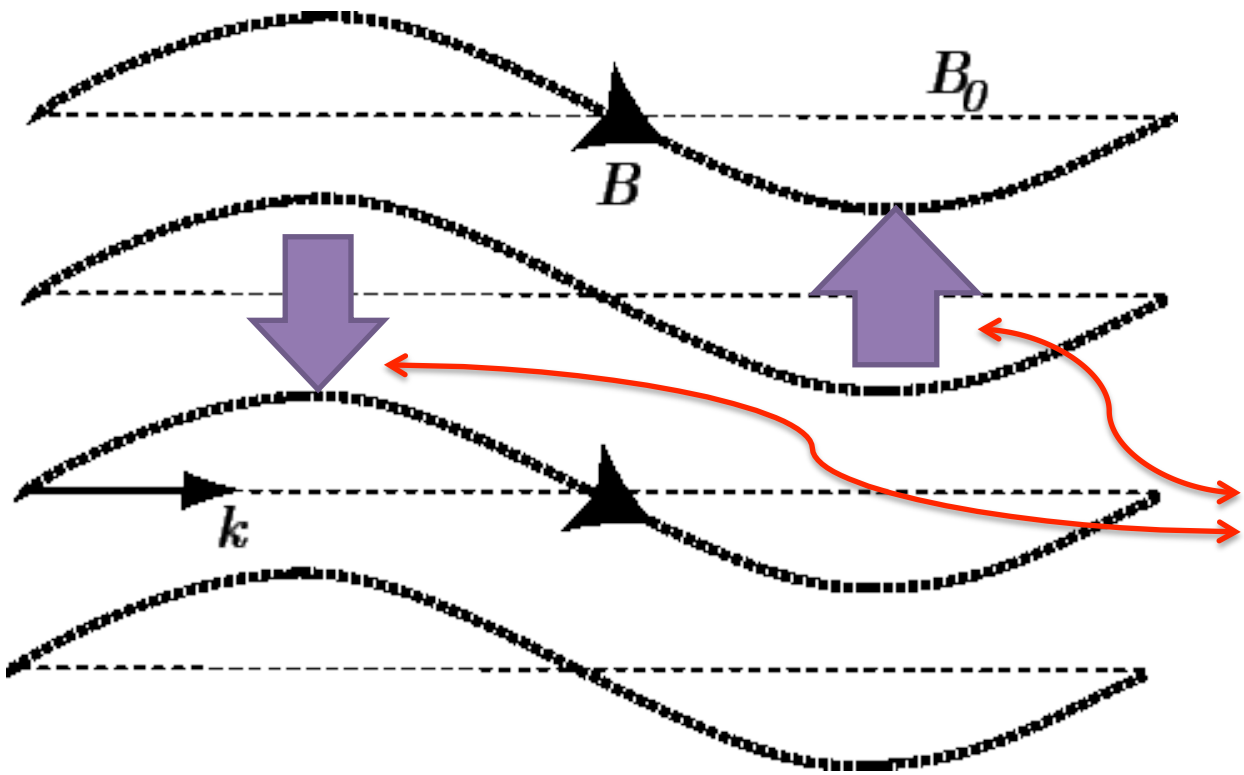
$$\omega - kv\mu = \pm\omega_c;$$

Resonant scattering

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

Unlike this image, the scattering agents are Alfven waves

What is an Alfven Wave?



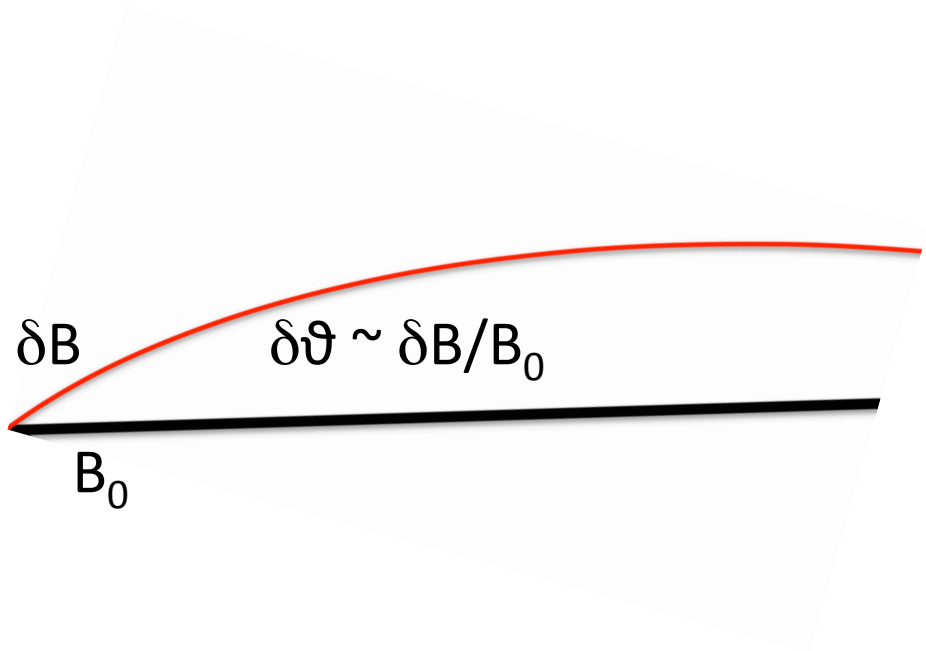
Low frequency electromagnetic wave driven by magnetic tension.

Alfven speed $v_A = B/(4\pi\rho)^{1/2} \sim 2.2\ (B_\mu/n^{1/2})$ km/s

Linear polarization shown here; superposition of circular polarization

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:
$v_A/c \ll 1$.

Here the Subject Bifurcates

Self-Confinement Picture:

- Waves generated by the cosmic rays themselves through velocity space streaming anisotropy, excited only in direction of streaming.

Extrinsic Turbulence Picture

- Waves are part of a turbulent cascade, generally propagate in both directions.

The Streaming Instability

$$\Gamma_{cr}(k) \sim \omega_{ci} \frac{n_{cr}(> p_1)}{n_i} \left(\frac{v_D}{v_A} > 1 \right)$$

- $n_{cr}(> p_1)$ is the number density of cosmic rays which can resonate with the wave $(p > p_1(k))$
- For a $p^{-\alpha}$ spectrum $(E^{2-\alpha})$ spectrum, $n_{cr}(> p_1) \propto p_1^{3-\alpha}$.
- Since there is always some thermal damping of the waves, self confinement can't work above some energy, depending on conditions.

This energy is probably 100 – 300 GeV for average Milky Way cosmic ray fluxes. Scales with overall flux.

Kulsrud, Wentzel, late 1960's.

Self Confinement Picture

Under the self confinement picture, cosmic rays stream down their pressure gradient & amplify co-propagating waves such that:

- 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.

Cosmic rays transfer energy & momentum to the waves, which transfer it to the thermal gas.

Extrinsic Turbulence Picture

Under the extrinsic turbulence picture, cosmic rays give energy to co-propagating waves & absorb it from counter-propagating waves such that

- Cosmic rays exert a force on the thermal gas $-\nabla P_c$,
- No net heating of the gas
- 2nd order Fermi acceleration at rate $(v_A/c)^2$ x (scattering rate).

Both Pictures Include Diffusion

Self-confinement:

- Calculated from instability theory
- Larger in environments where waves are strongly damped

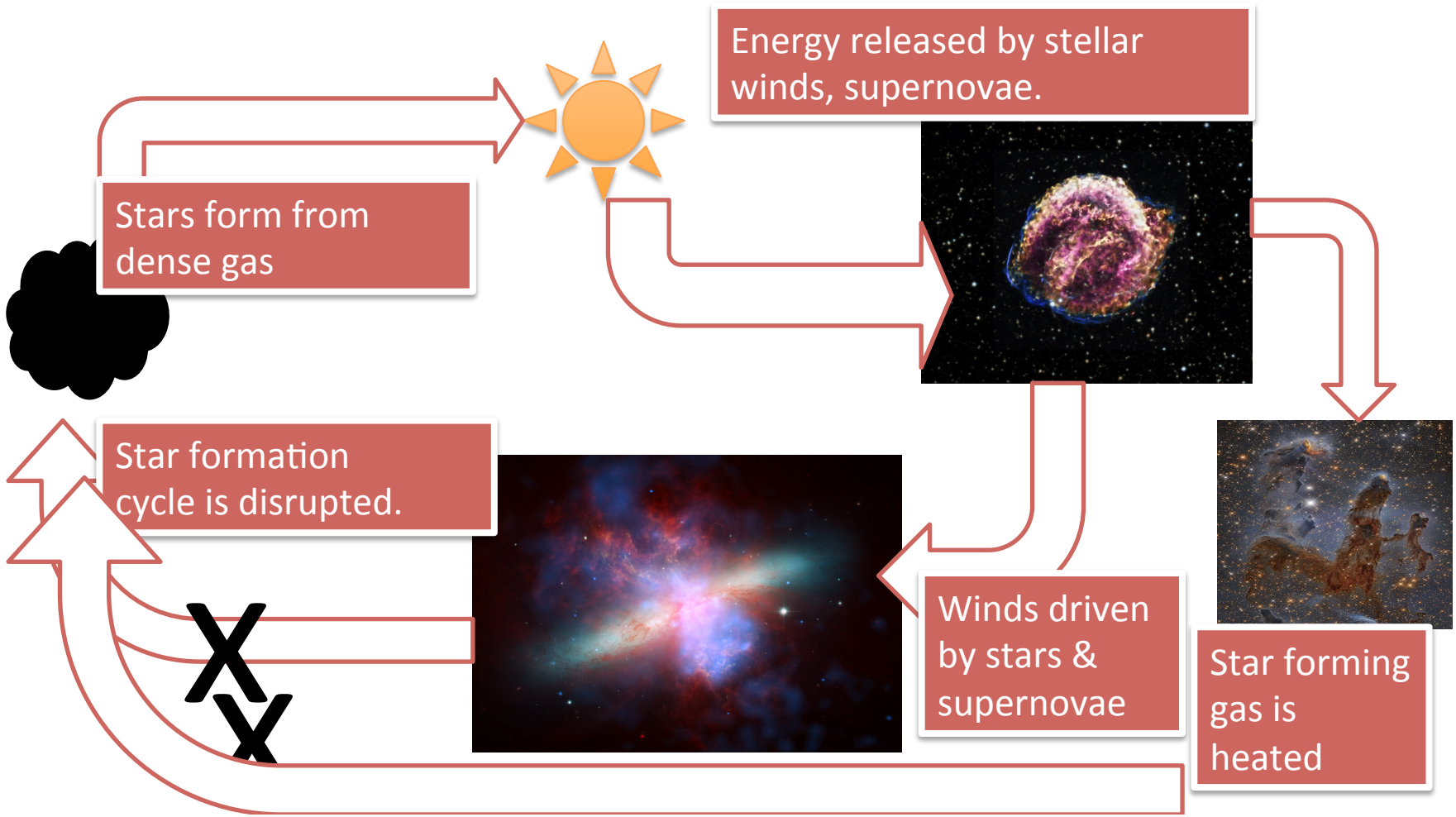
Extrinsic turbulence:

- Specified by wave spectrum.

Application to Galactic Winds

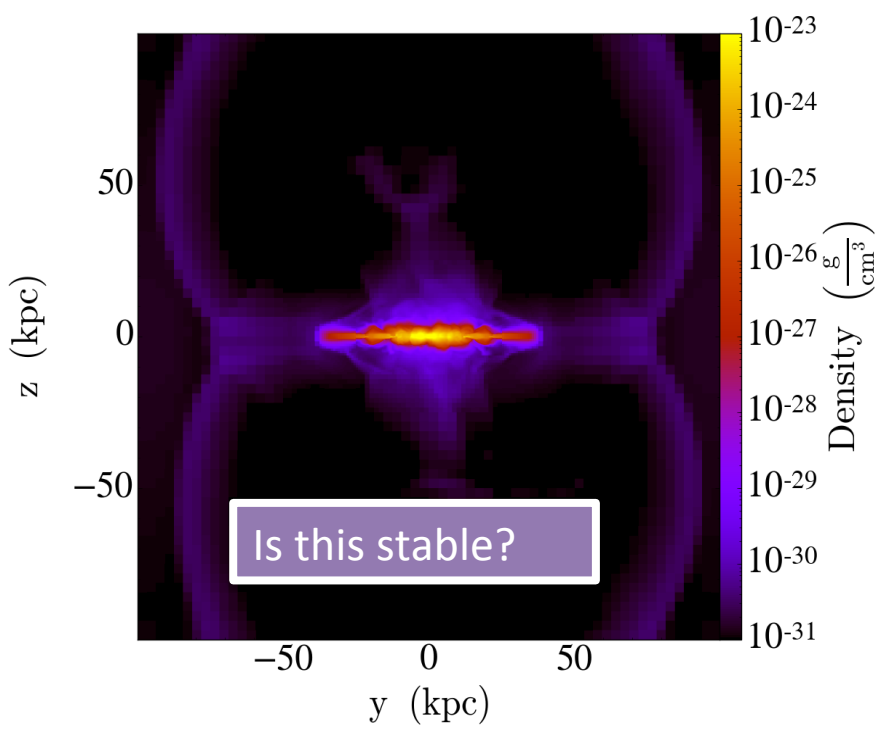
Star Formation Feedback: The idea that star formation is inherently self-limiting.

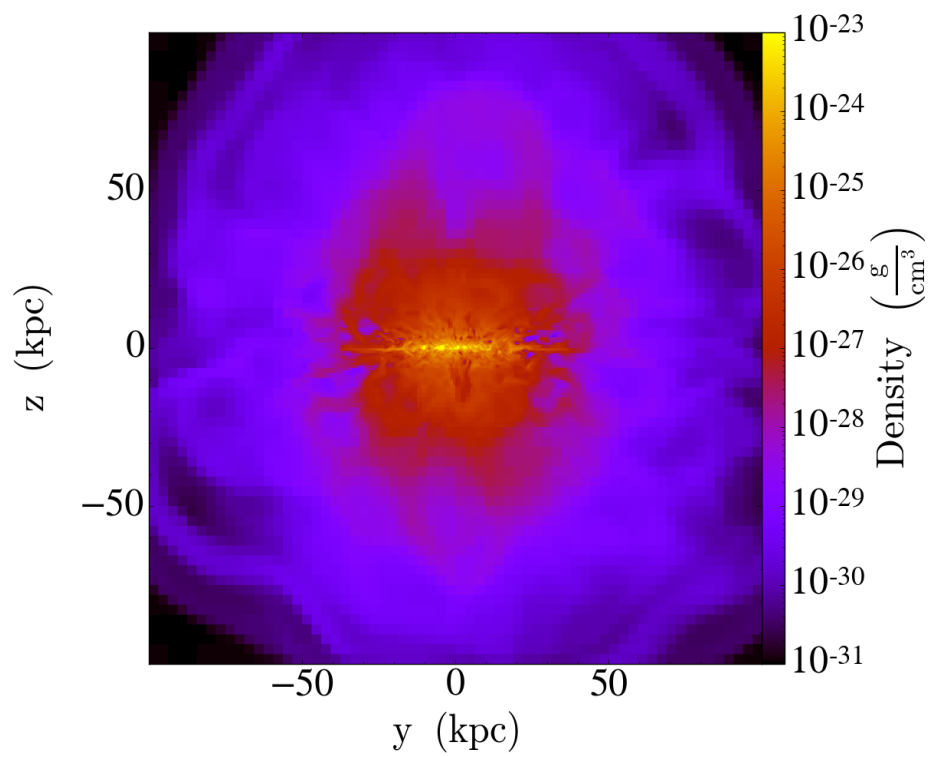
Observationally motivated & *key* to galaxy formation.



Galactic Winds in 3D

Numerical simulation of gas density in a star forming galactic disk, seen edge on. Cosmic rays are injected where stars form (Ruszkowski, Yang, & EZ 2017)

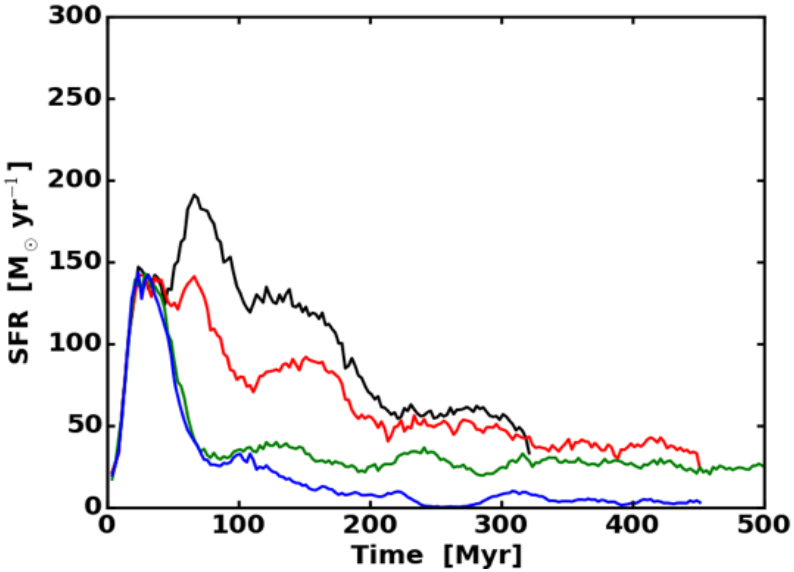


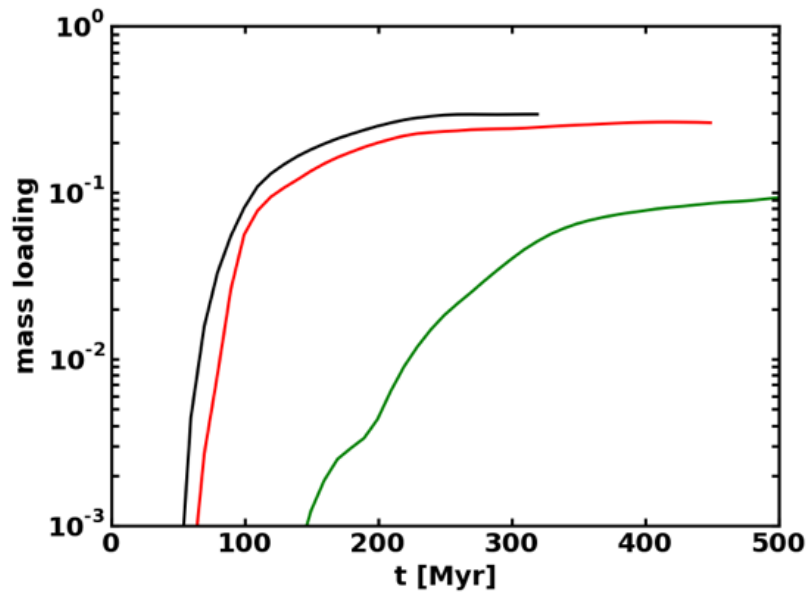


Left panel: Cosmic rays are frozen to the gas. Right panel: Cosmic rays stream at v_A relative to the gas. Milky Way – like galactic disk

Cosmic Ray Transport Matters

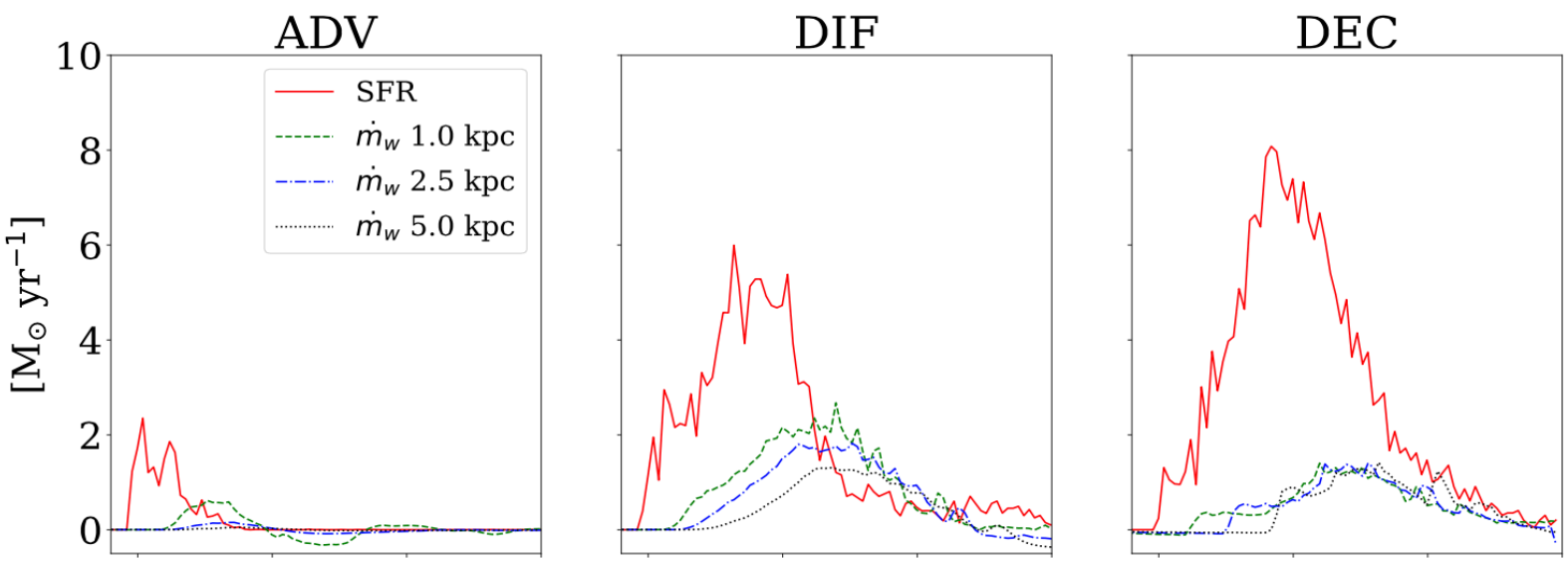
Blue curve is balanced, extrinsic turbulence (f = 0).





Colors denote f = v_D/v_A. Blue: f = 0. Green: f = 1. Red: f = 4. Black: f = 8. No wind is launched for f = 0 (Ruszkowski, Yang, & EZ 2017).

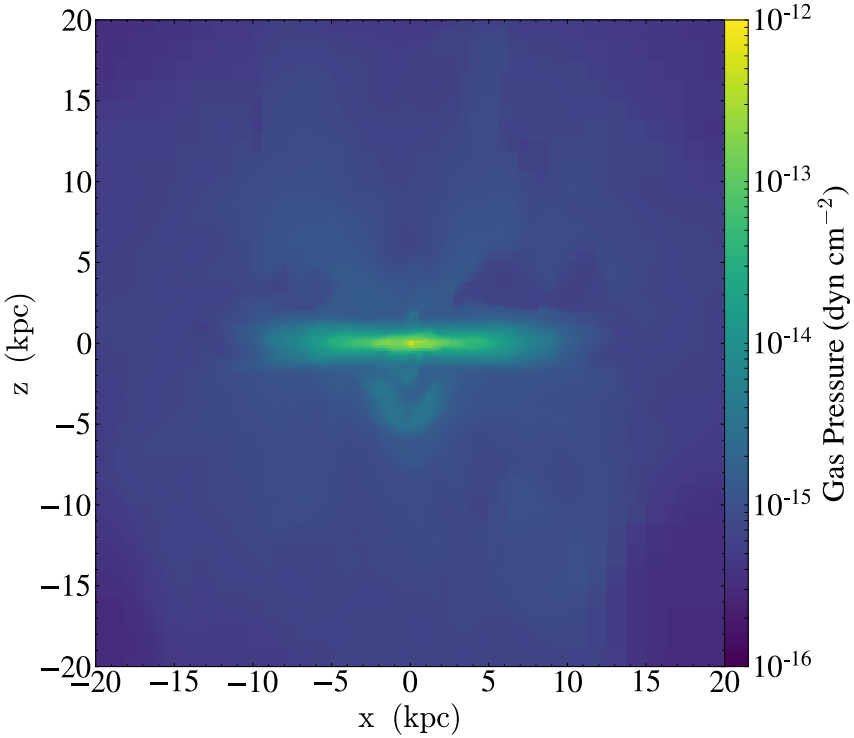
Accounting for Weak Ionization

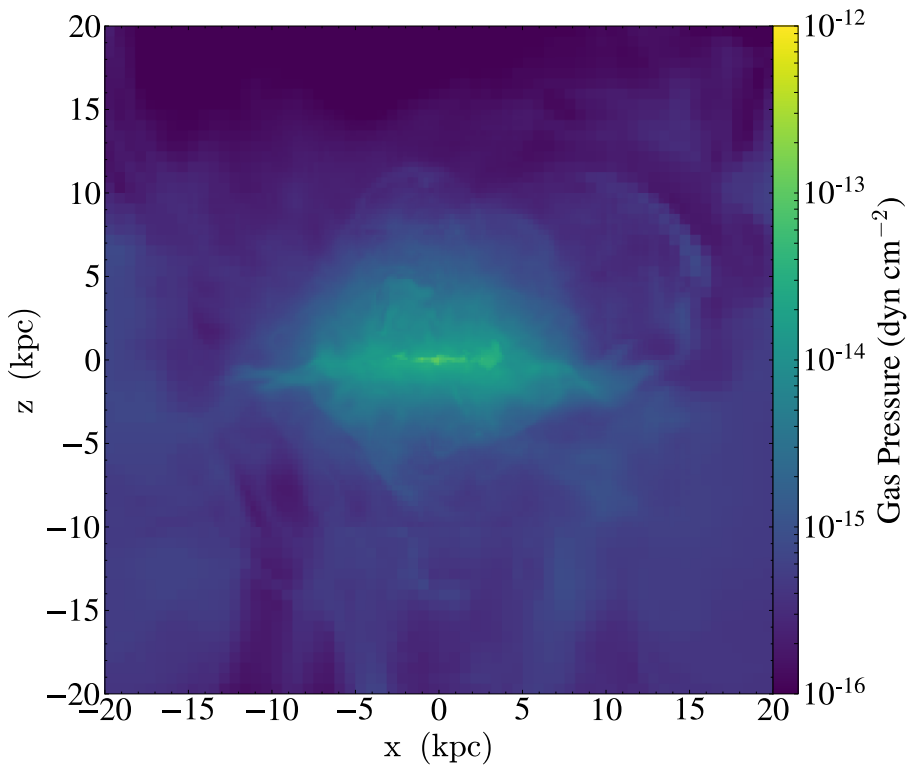


Comparison of star formation & mass loss rates for 3 treatments of transport. ADV is advection with no diffusion or streaming, DIF includes field aligned diffusion, DEC includes 30 x greater diffusion in cold gas. From Farber, Ruszkowski, Yang, & EZ 2017.

Large Magellanic Cloud

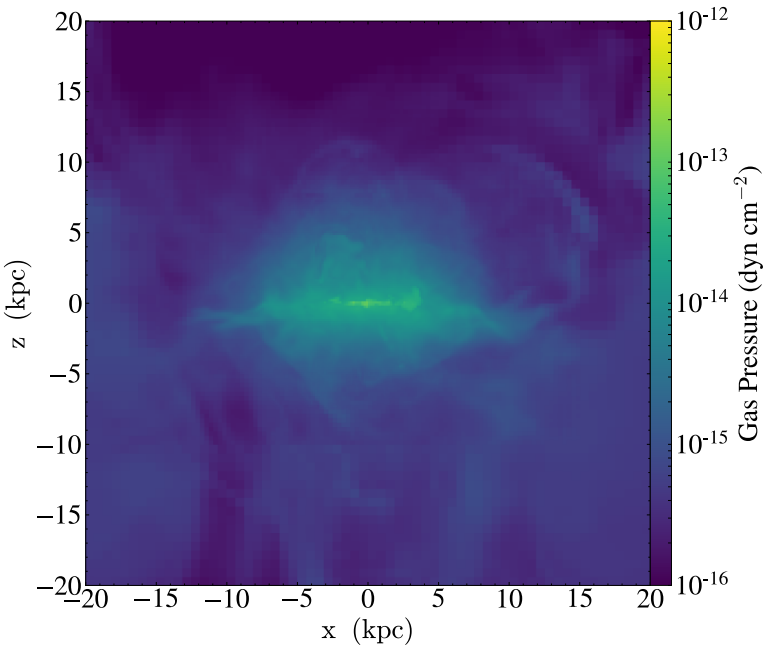
(Chad Bustard, in preparation. See his poster)

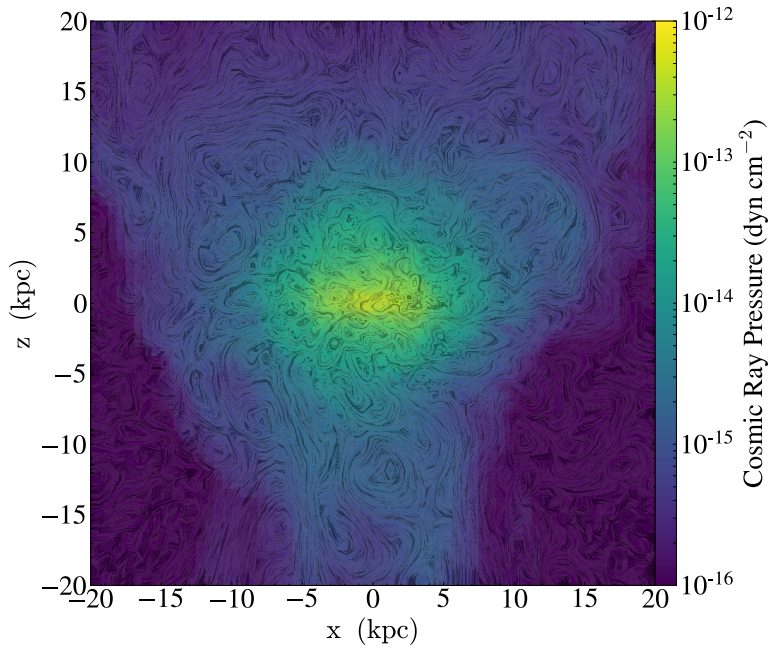




Gas pressure in edge on view of a Magellanic –type galaxy. Supernova heated gas Is driven out of the galactic plane. Left: no cosmic rays. Right: 10% of supernova energy goes into cosmic rays, which propagate under self confinement model.

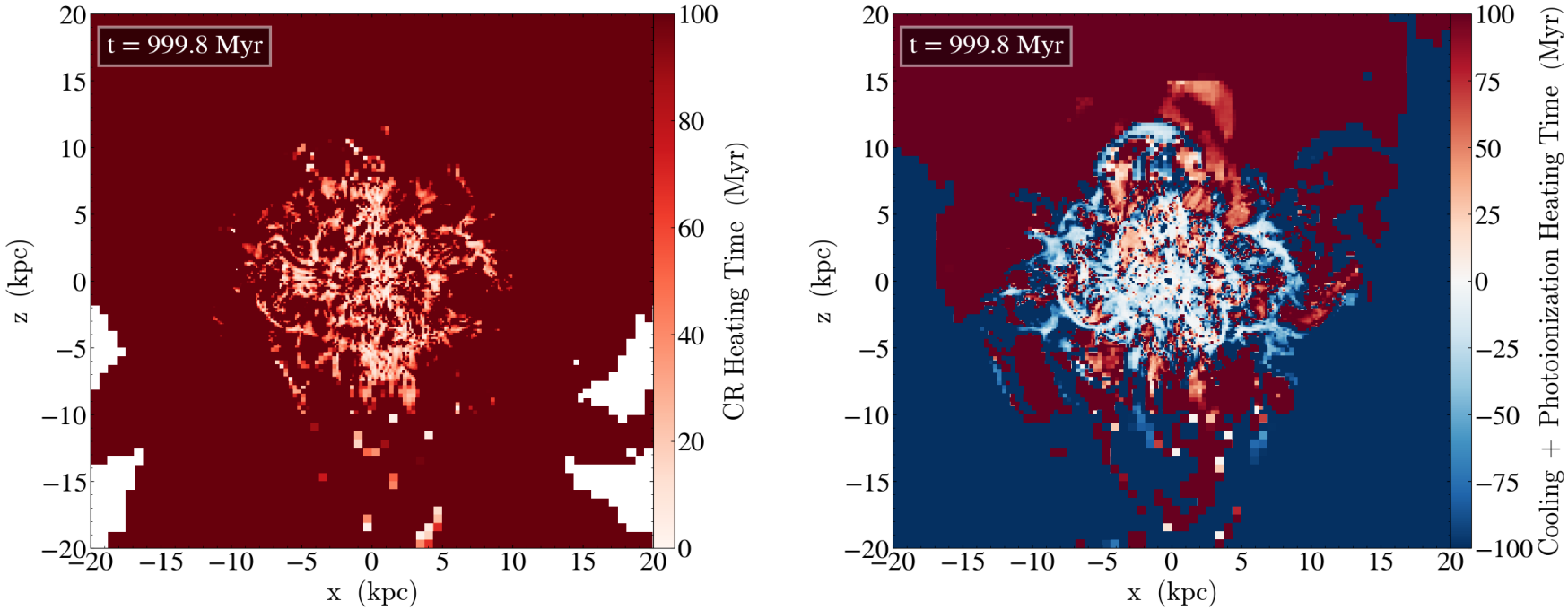
Cosmic Ray *vs* Gas Pressure





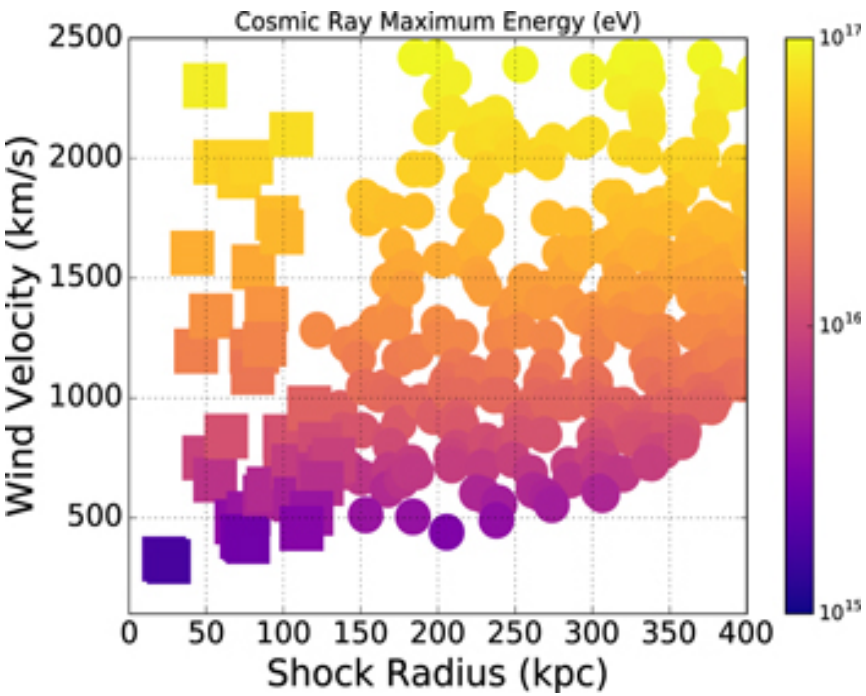
Left: Same gas pressure image from previous slide. Right: Cosmic ray pressure at the same time (Bustard et al, in preparation & poster).

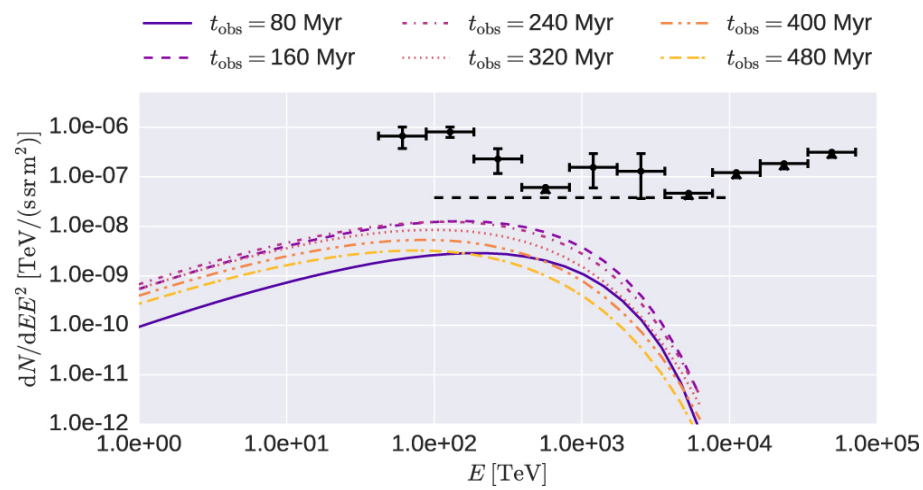
Role of Cosmic Ray Heating: Observable Signatures?



Left: Cosmic ray heating time (thermal energy density/heating rate). Right: Same for radiative cooling & heating. Cosmic ray heating is an important part of the energy budget at large heights. (Bustard et al. in preparation & poster).

Another Cosmic Ray Diagnostic?





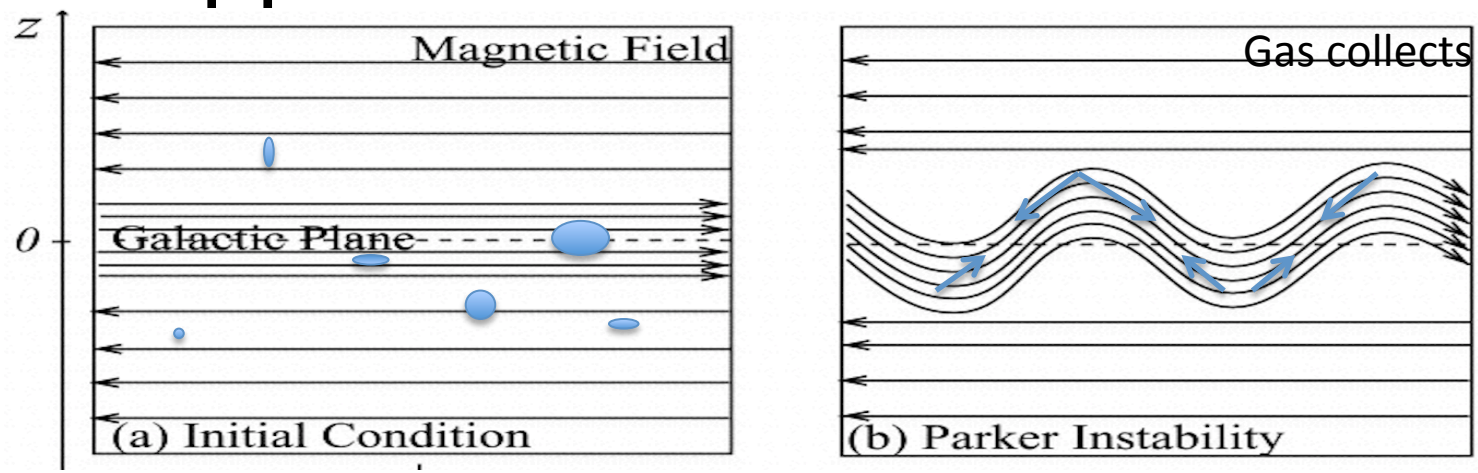
Left: Maximum cosmic ray energy resulting from 100Myr of maximally efficient DSA at a simple model of the Galactic Wind Termination Shock (Bustard et al. 2017). Right: Neutrino fluxes resulting from propagating GWTS cosmic rays in the wind zone, compared with IceCube 2017 results (Merten et al. 2018).

Mesoscale Phenomena

These scales feed back on the microscales and affect the global scales (but may be difficult to resolve).

- Stability of stratified galactic disks
- “Bottlenecks” & cosmic ray acceleration of cool clouds
- High flux interactions near sources

Is Magnetically & Cosmic Ray Supported Galactic Gas Stable?



``Parker Instability"; Newcomb 1961 energy principle analysis w/o cosmic rays; add cosmic rays (Zweibel & Kulsrud 1975). Energy released by falling is offset by energy required to compress.

Parker's work predated fluid theory & he left this out.

$$-\frac{d\rho}{dz} > \frac{\rho^2 g_z}{\gamma_g P_g + \gamma_{cr} P_{cr}},$$

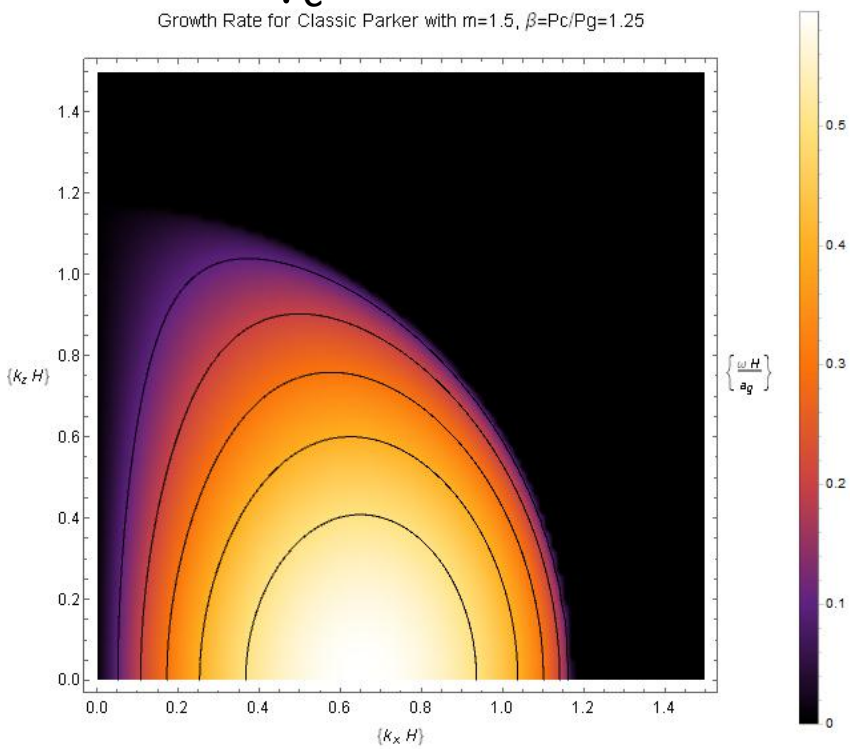
for stability (without Alfvenic streaming).

Importance of Parker Instability

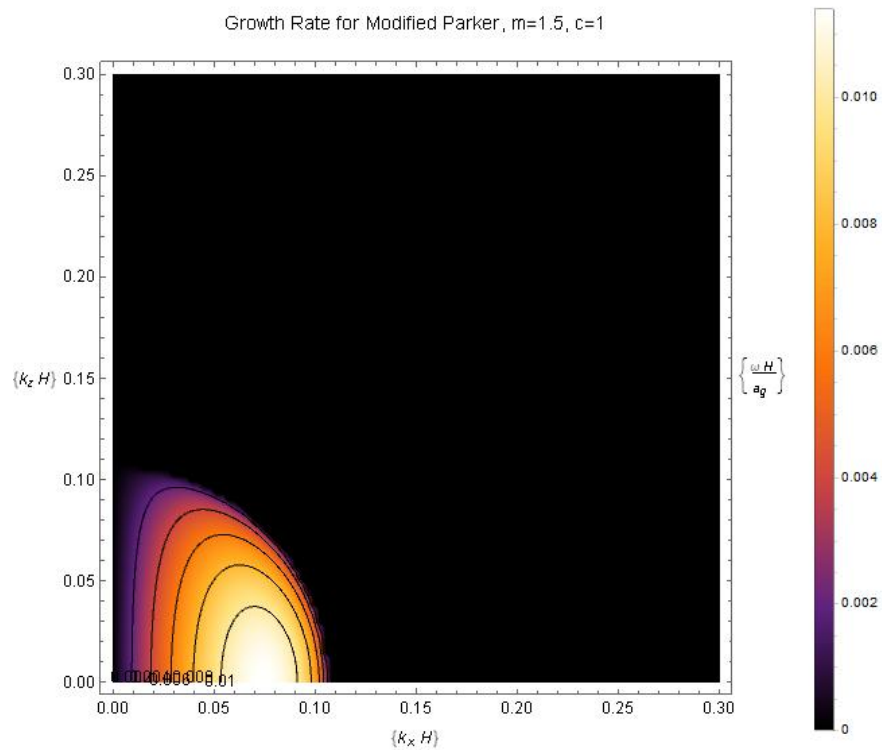
- Limit fraction of pressure support from magnetic fields & cosmic rays?
- Key part of galactic dynamo?
- Create pockets of dense gas that can initiate formation of molecular clouds & eventually stars?
- Path for cosmic rays to sculpt their own environments.

Effect of Cosmic Ray Compressibility

$\gamma_c = 0$



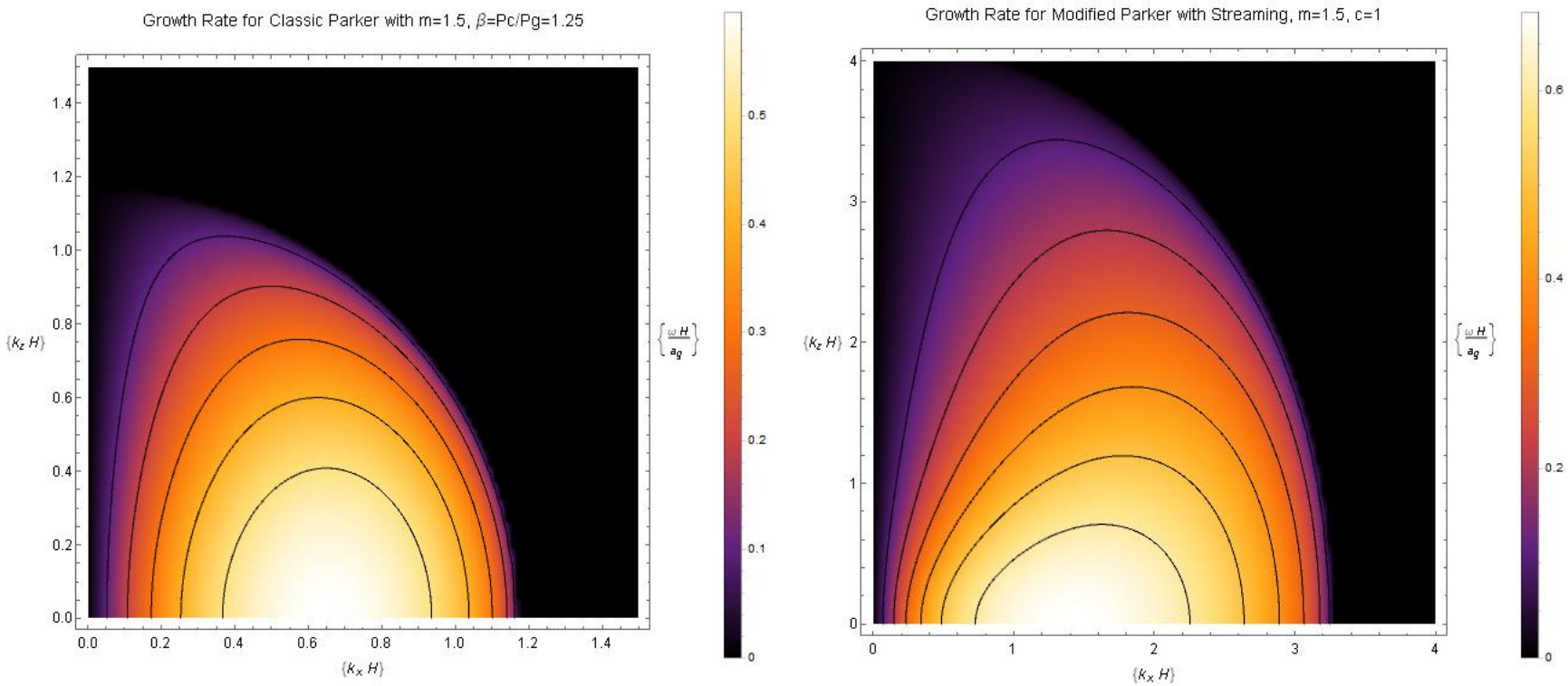
$\gamma_c = 4/3$



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 Heintz & EZ 2018 (& poster).

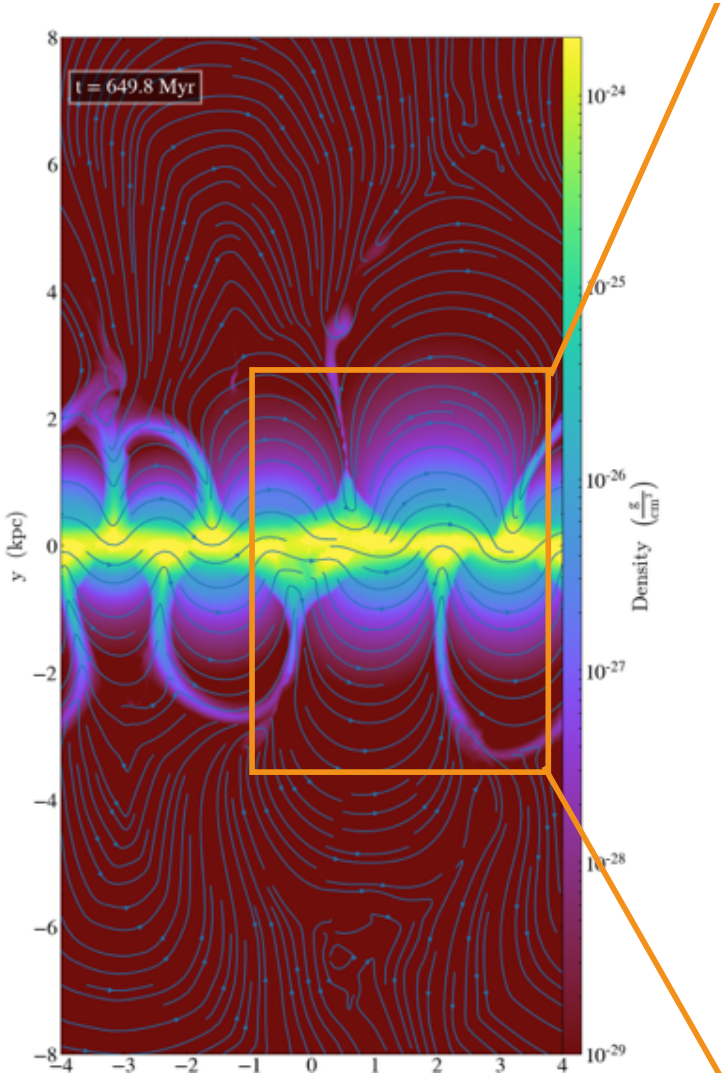
Effect of Cosmic Ray Streaming

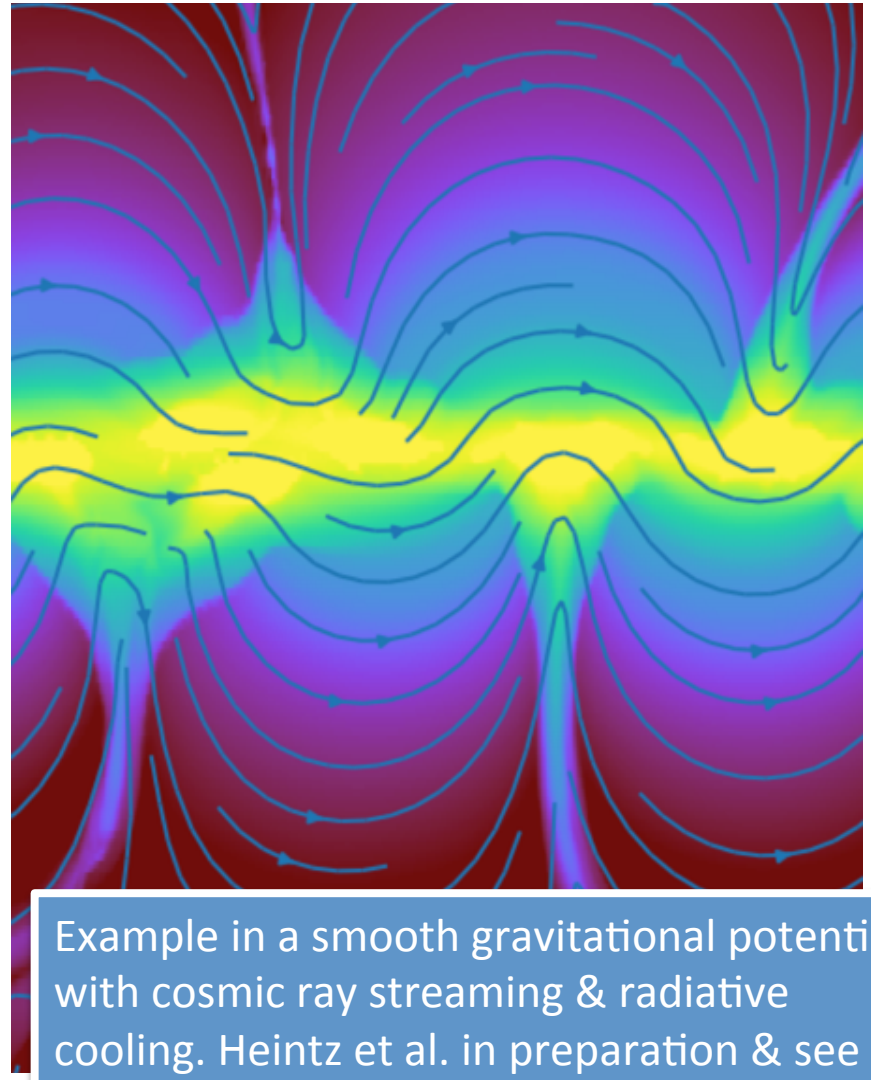
$\gamma_c = 0$ Alfvenic streaming & $\gamma_c = 4/3$



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

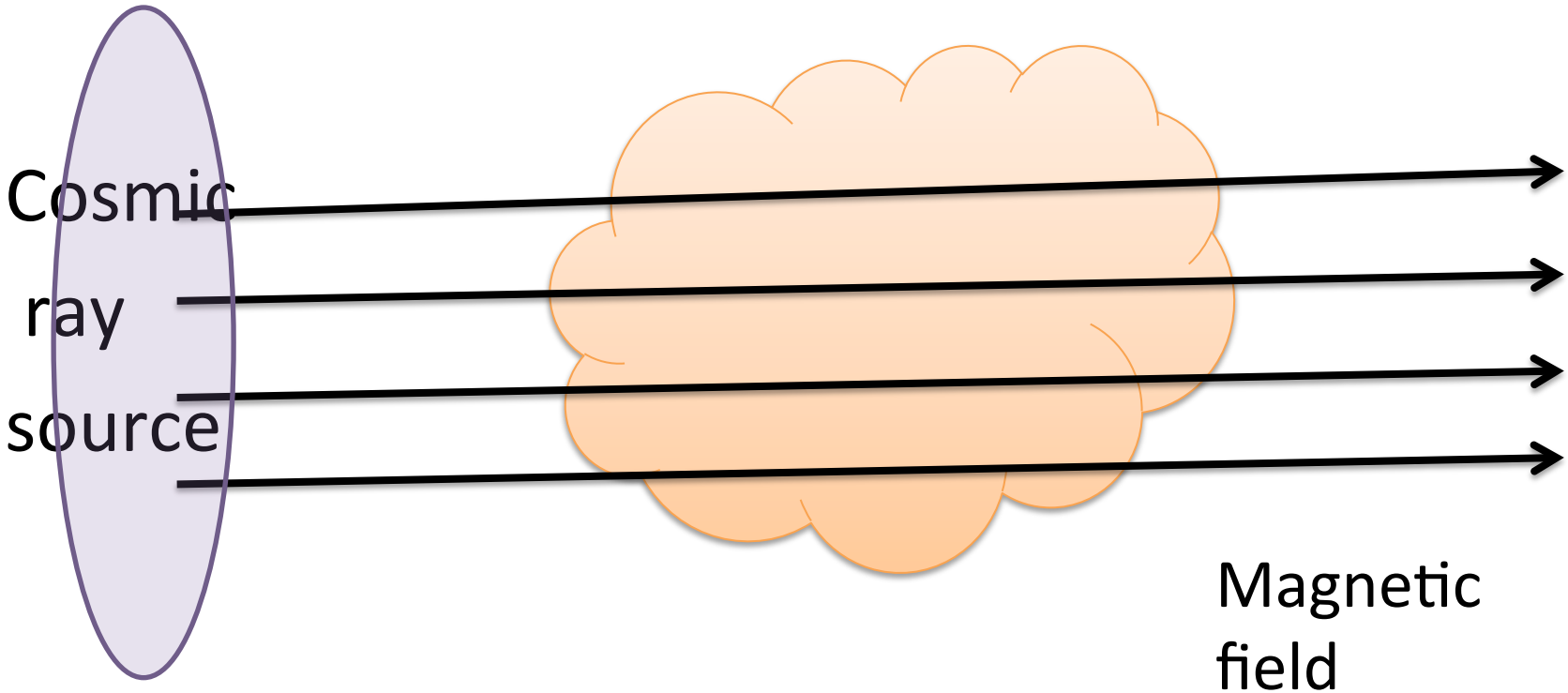
Evolution of an Unstable System





Example in a smooth gravitational potential, with cosmic ray streaming & radiative cooling. Heintz et al. in preparation & see poster.

Acceleration of Cool Clouds in Galactic Halos *(Wiener, Oh, EZ 2017)*

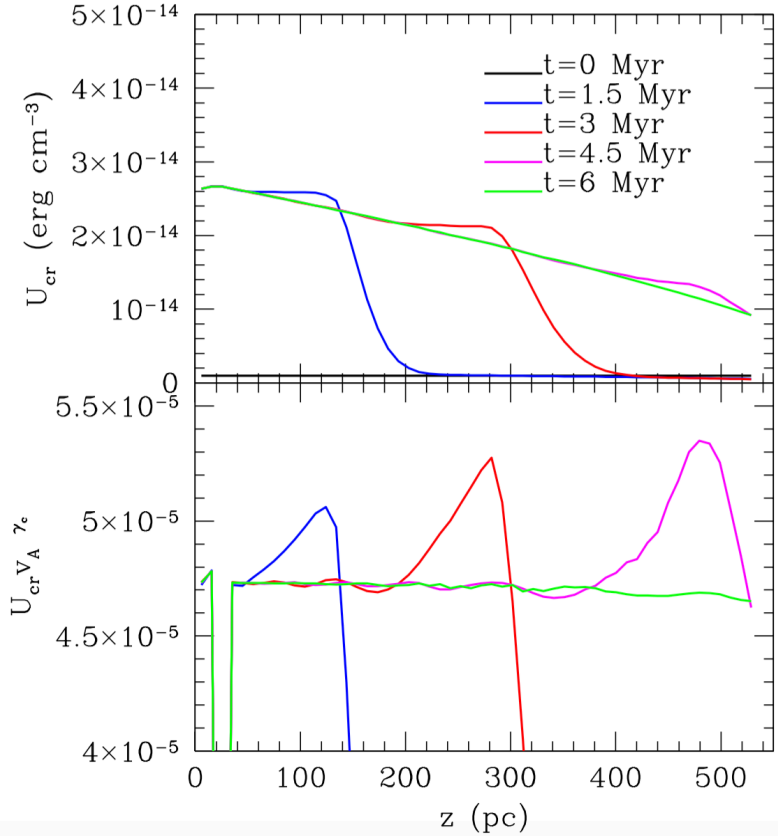


Hot gas

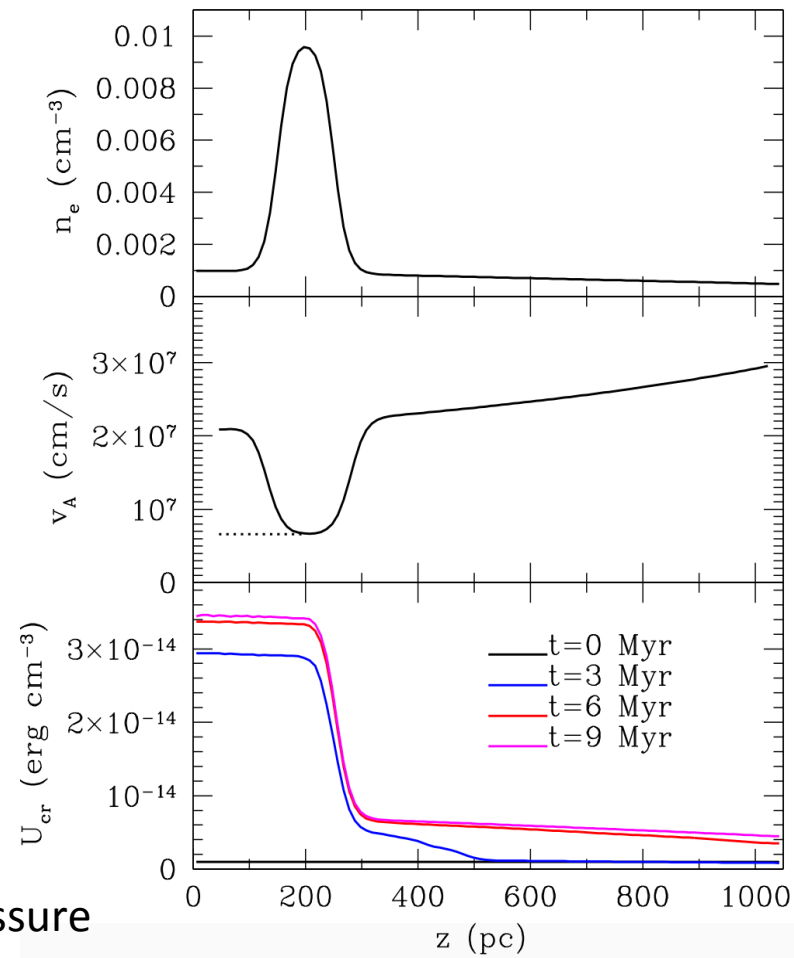
Explain multiphase gas in galactic winds?

Bottleneck Effect

No Cloud



Cloud

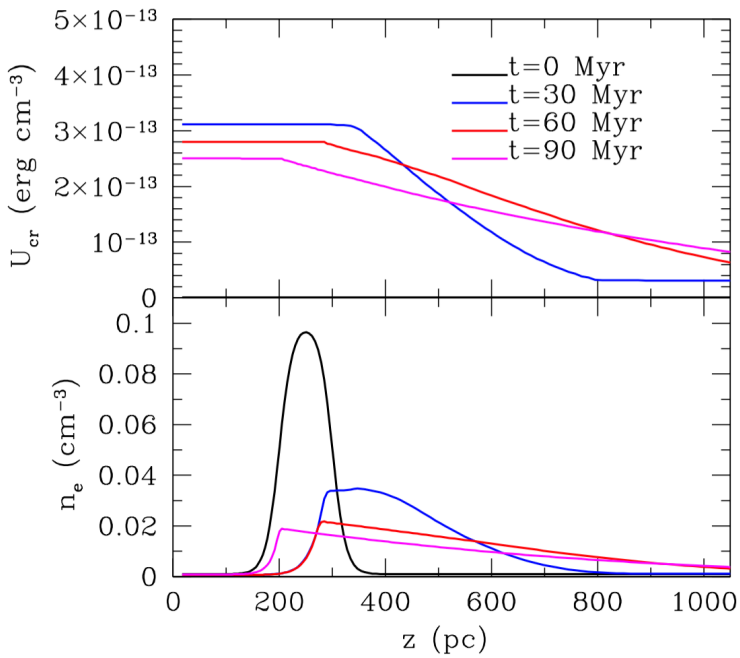


Left: Cosmic rays streaming down their pressure gradient at v_A evolve to constant $U_c v_A^{\gamma_c/2}$. If v_A has a minimum, U_c behind it must go flat (Right).

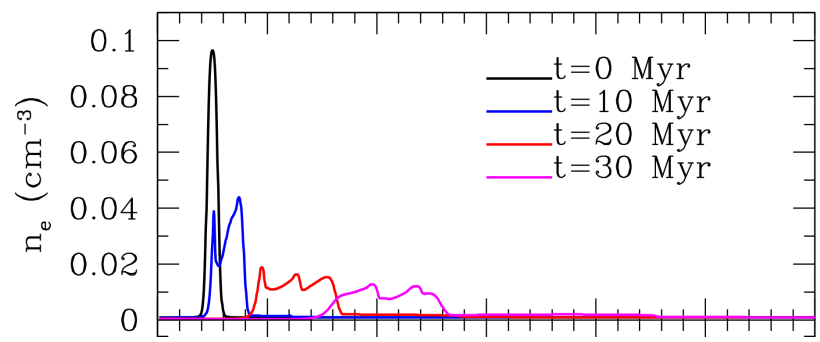
Wiener, Oh, EZ (2017)

Cloud Accelerated by Cosmic Ray Pressure

Wiener, Oh, EZ 2016

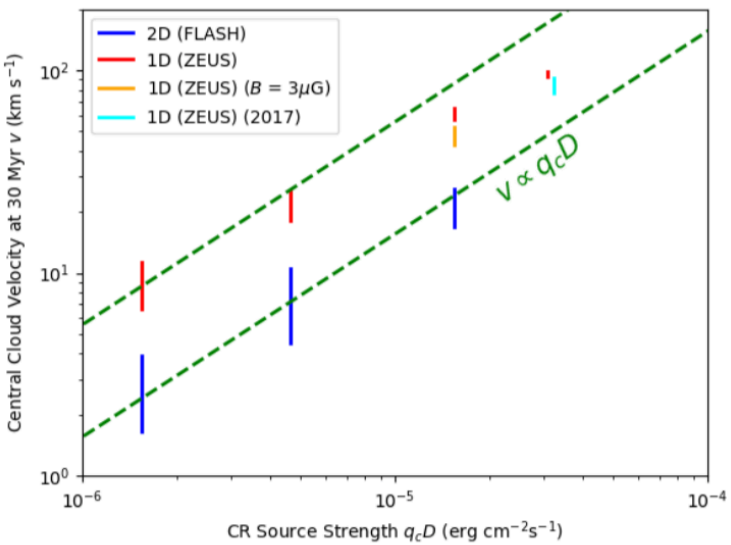


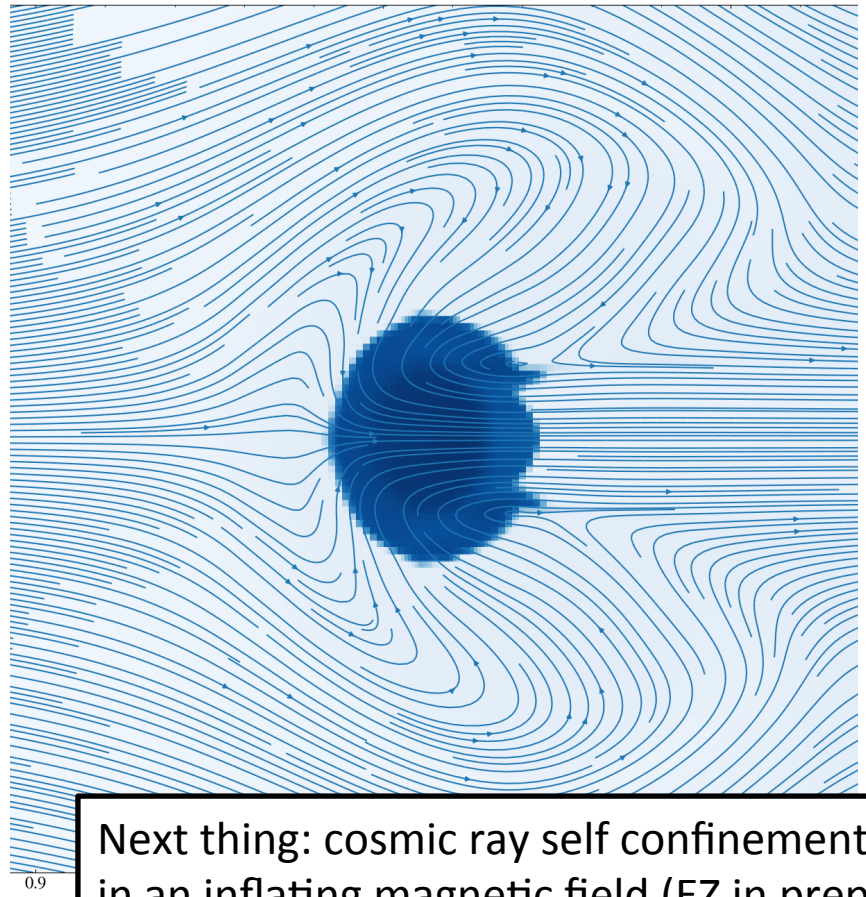
Top: Cosmic ray pressure. Bottleneck is to the left & moves back as gas is accelerated toward the right (bottom). Cloud evaporates due to heating.



Efficient radiative cooling accelerates cloud without destroying it.

2D Effects





Left: cloud velocity vs cosmic ray source strength in 1D & 2D. Right: distortion of magnetic field behind cloud due to pressure buildup. Wiener & EZ 2019.

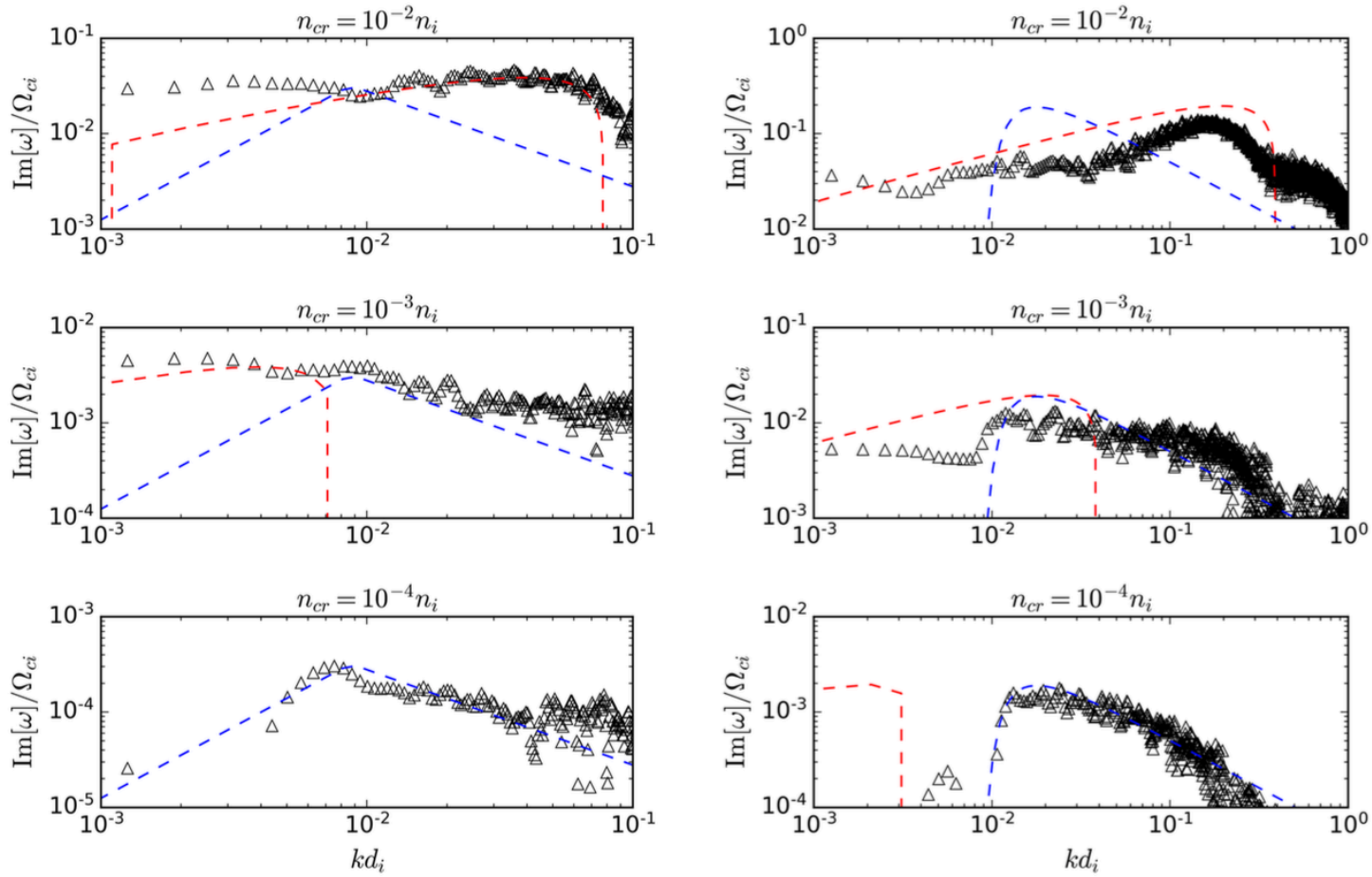
Next thing: cosmic ray self confinement in an inflating magnetic field (EZ in prep).

Coupling Near Cosmic Ray Sources

(see Caprioli group esp. Haggerty talks & posters).

- At sites of DSA (or weak magnetic fields), the gyroresonant instability is replaced by a nonresonant instability driven by the electron current ("Bell Modes").
- These are not Alfven waves. Our expressions for momentum and energy transfer break down.
- **Very important to replace them to accurately model star formation feedback.**

Relativistic Hybrid Simulation of Instability



First step. Instability growth rates vs wavenumber measured from simulations compared with analytical theory of resonant (blue) & resonant (red) instabilities. We can do it. (Haggerty et al. in prep & poster).

Summary & Conclusions

- The high energy probe & dynamical feedback aspects of cosmic ray astrophysics are linked by propagation theory.
- Empirically based diffusion theory is an important constraint but can't resolve fundamental questions about cosmic ray-thermal gas interactions.
- Cosmic ray transport on microscales matters for macroscopic, global phenomena like galactic winds.