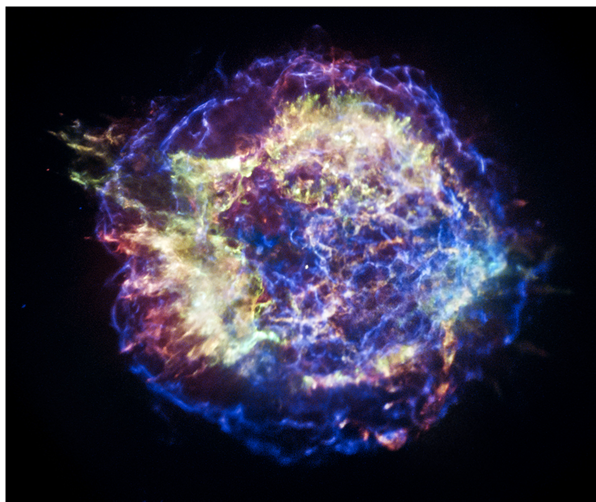
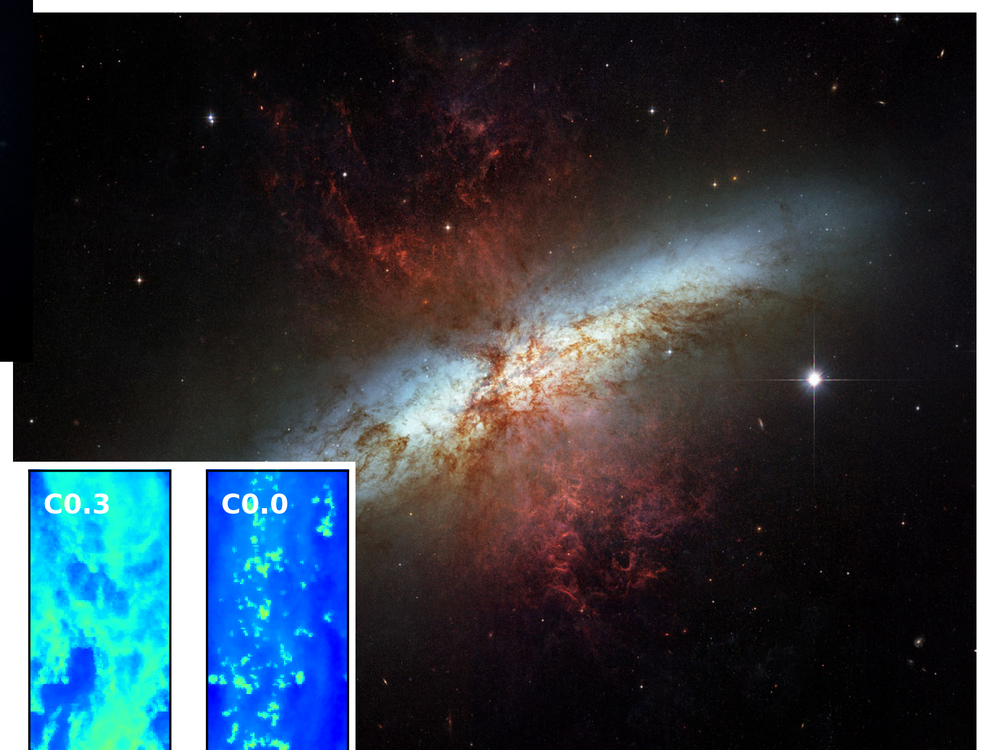
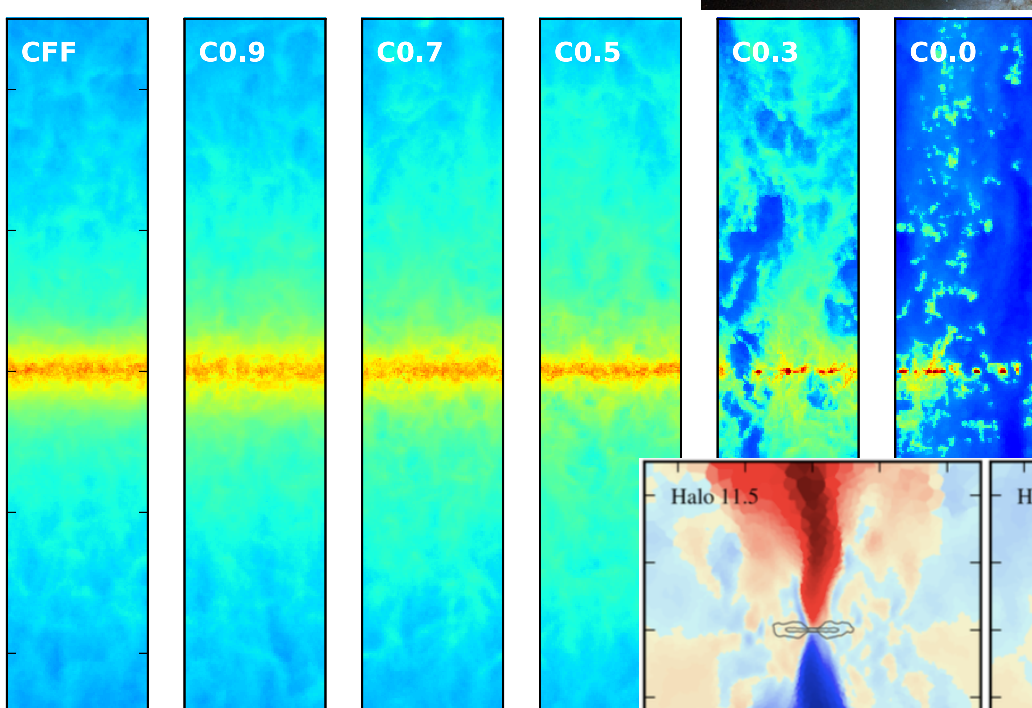
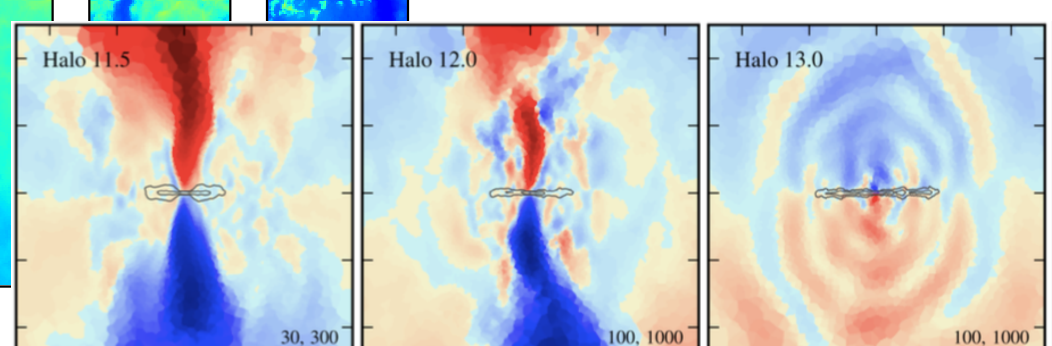
Launching Galactic Outflows from the ISM with Cosmic Rays









Christine Simpson
EFI McCormick Fellow
University of Chicago

KITP Astrophysical Plasmas Workshop
Aug. 27, 2019

Outline

1. Galactic winds - an important aspect of galaxy formation

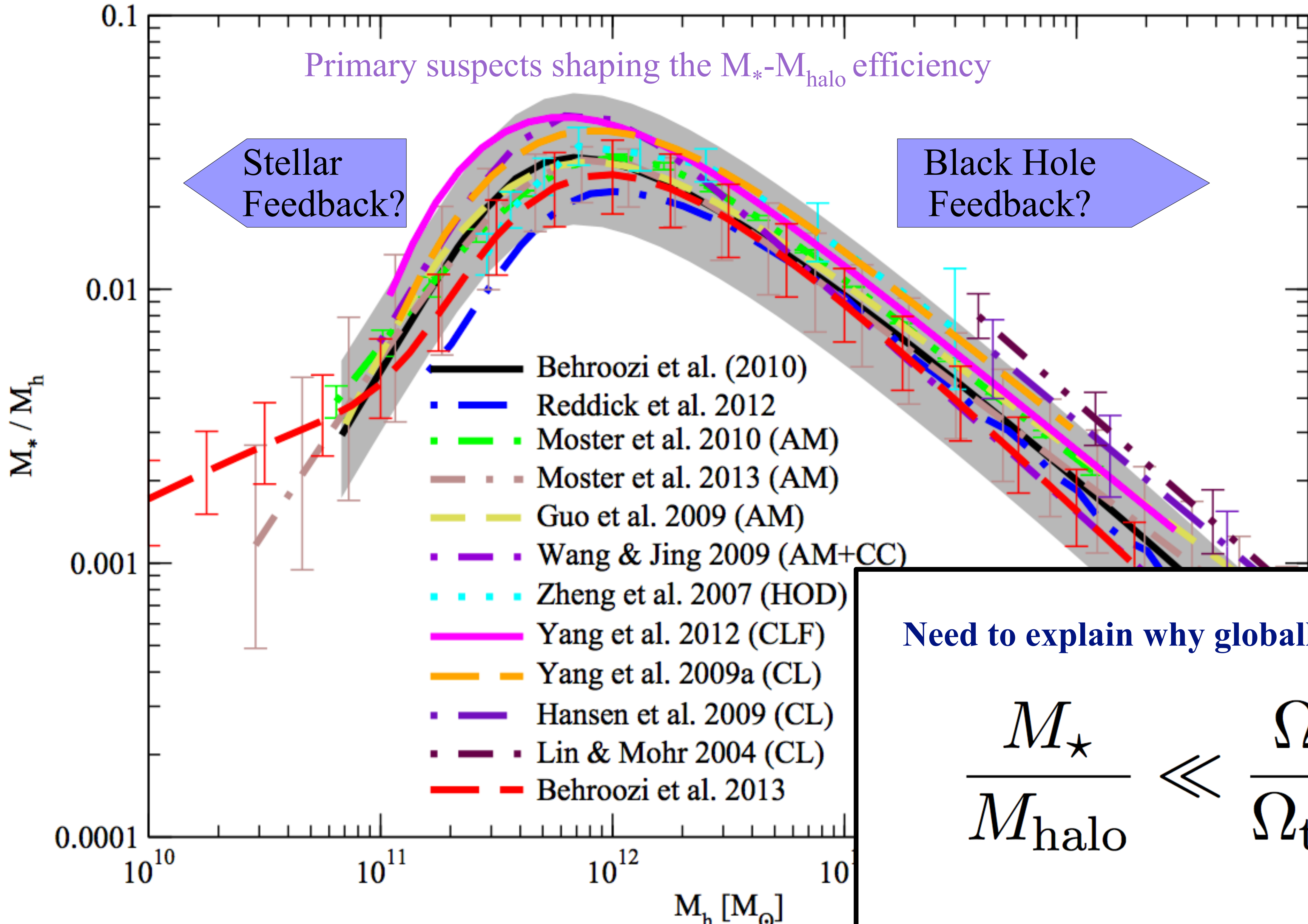
2. Cosmic Rays - an energy reservoir in the Galaxy with interesting transport properties

3. Simulations of Cosmic Rays in the ISM & galaxies

4. Some thoughts and future directions

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

MODULATION OF GLOBAL STAR FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS

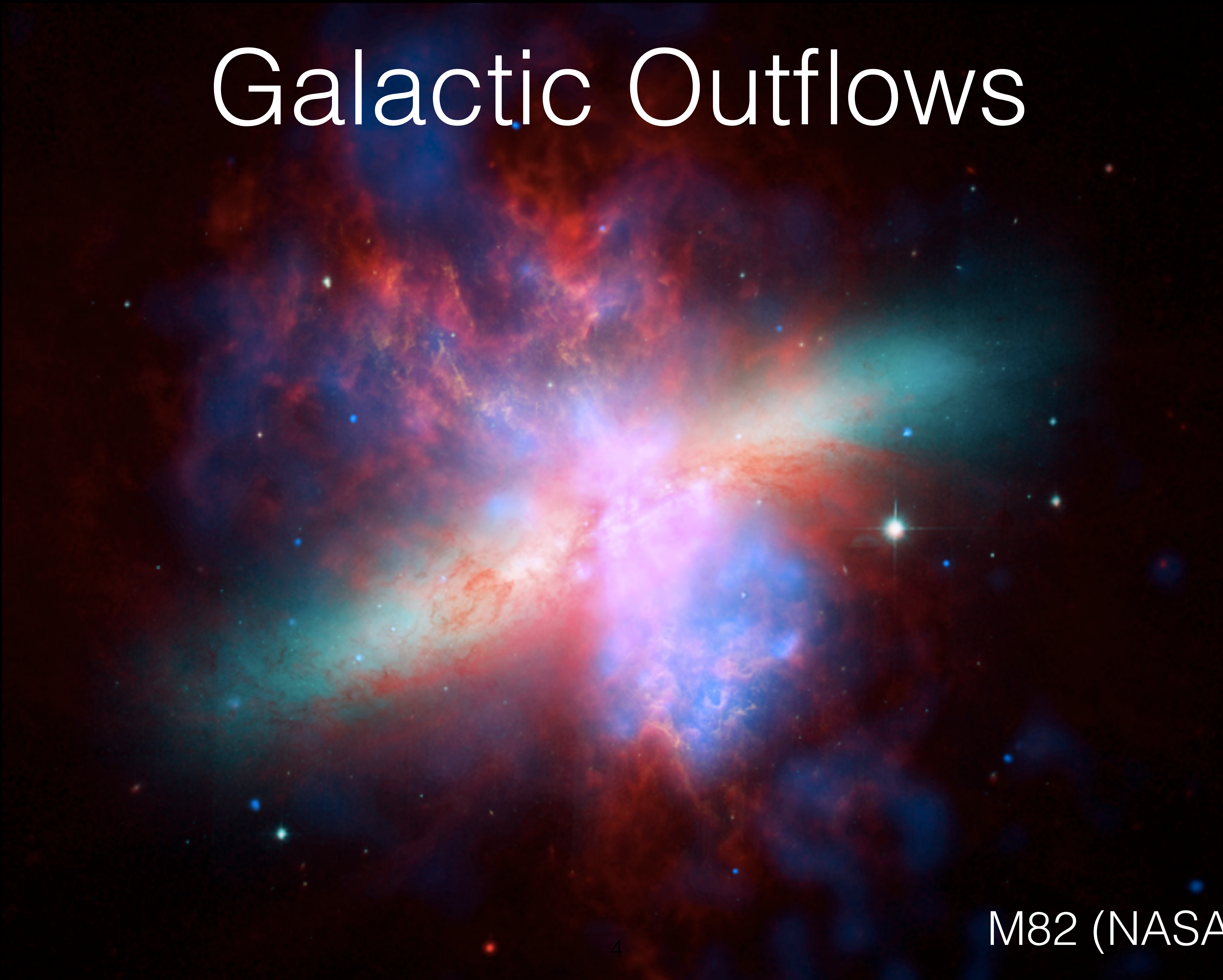


Need to explain why globally:

$$\frac{M_\star}{M_{\rm halo}} \ll \frac{\Omega_b}{\Omega_{\rm tot}}$$

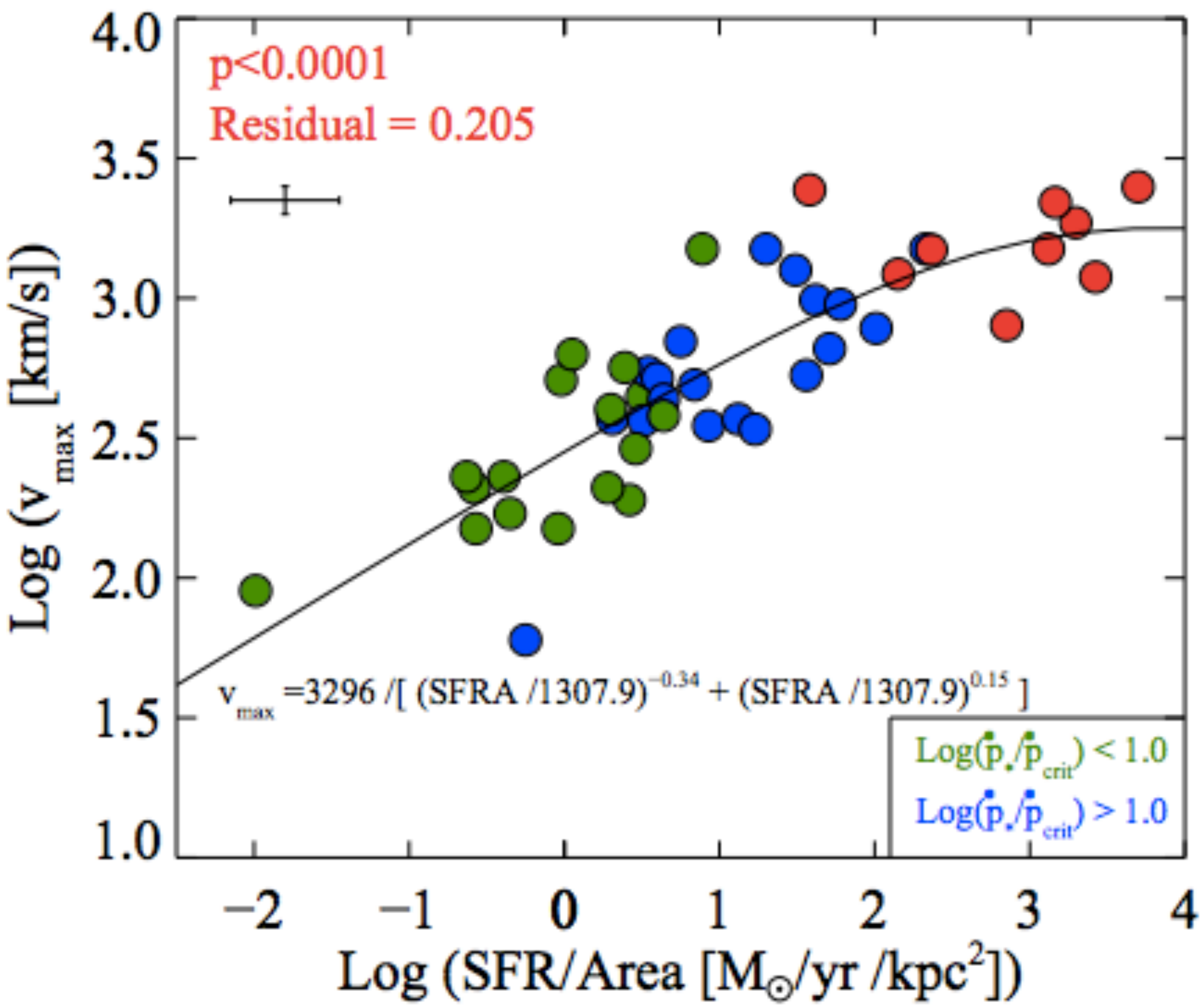
Behroozi, Wechsler & Conroy (2013)

Galactic Outflows



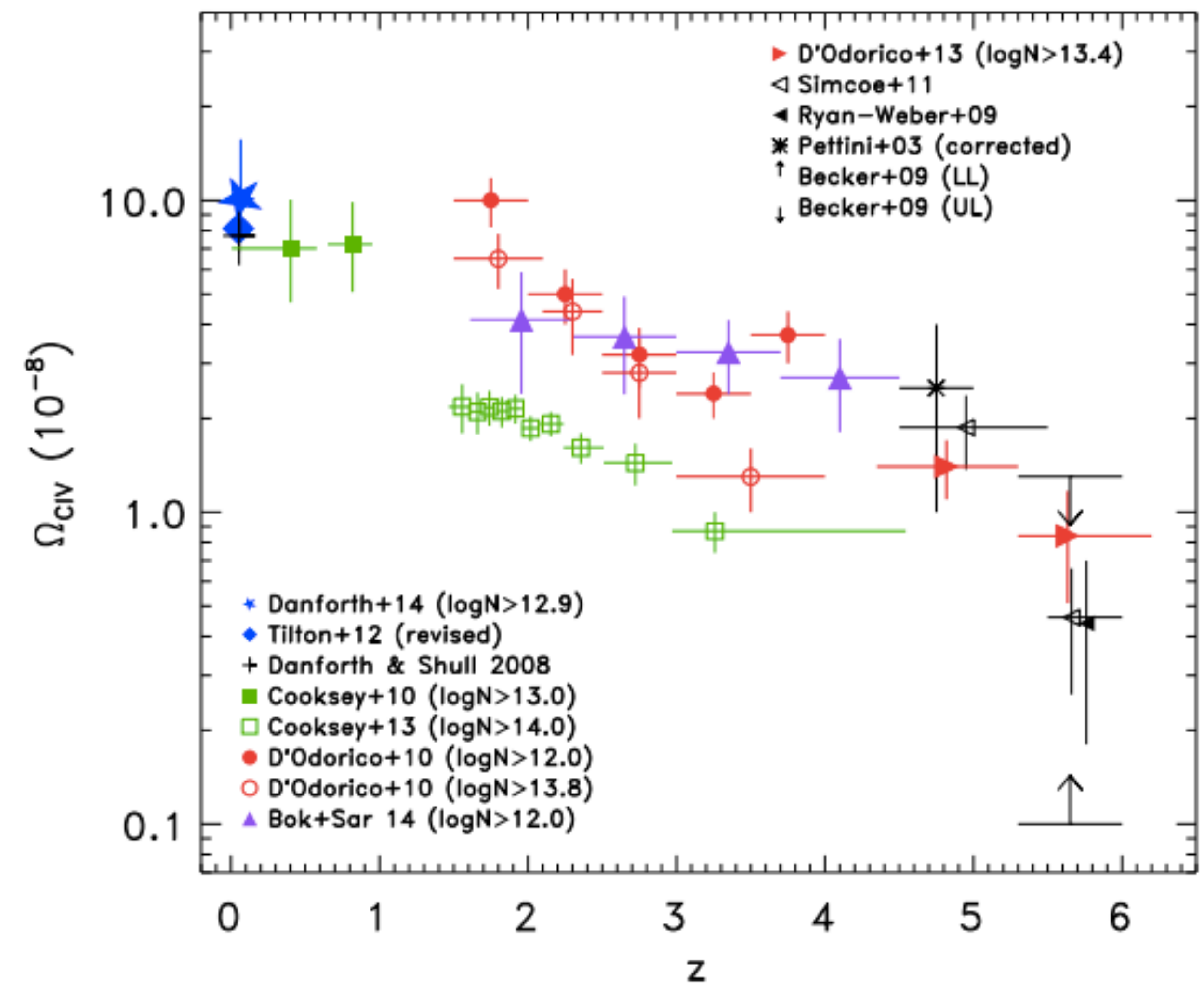
M82 (NASA)

Evidence for Outflows



Heckman & Borthakur 2016

Dynamics of warm gas in local starbursts

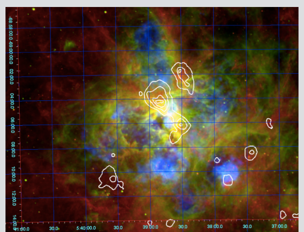
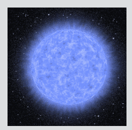
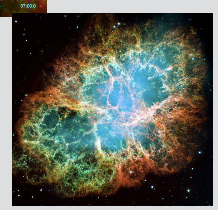


Shull et al. 2014

Metal pollution of the IGM over cosmic time

How does stellar feedback couple between scales?

Stars
0.1 AU
SN +
HII regions
10 - 100s pc

Galactic
scale
winds

10s kpc

IGM
Groups
Clusters

Mpcs

Processes:

Thermal Heating

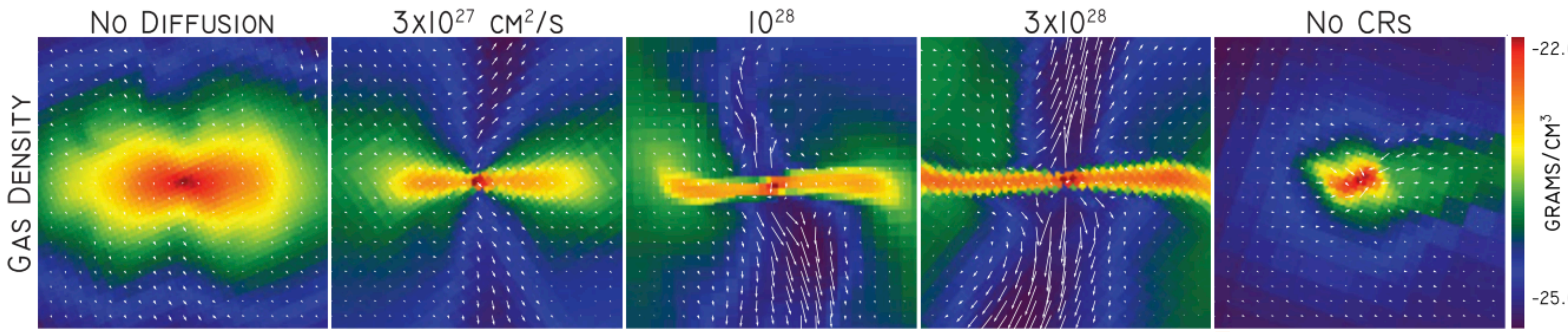
Momentum from clustered SN

Radiation (ionization & pressure)

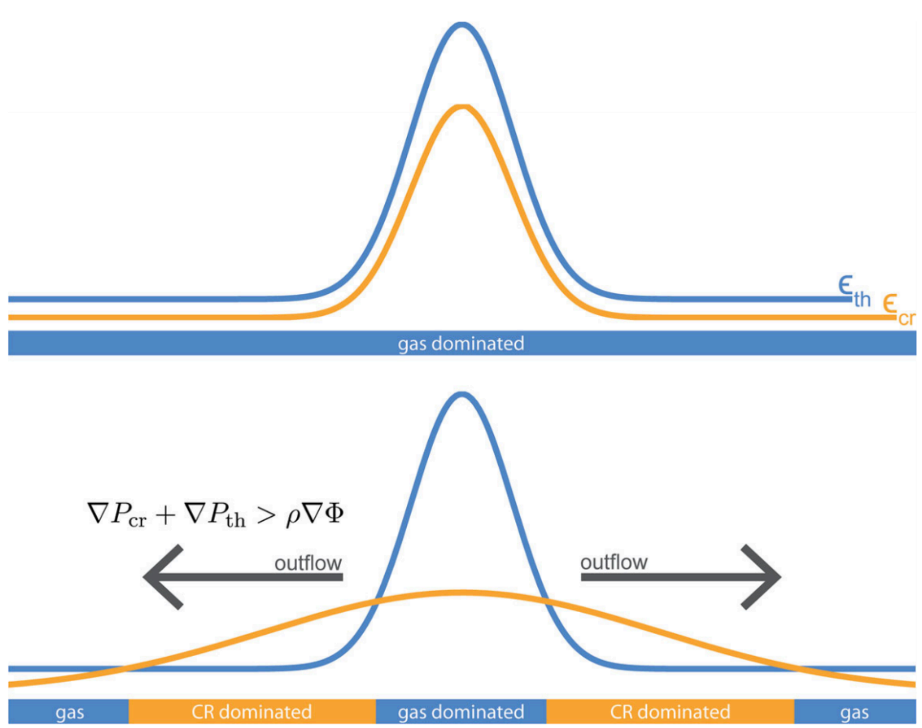
Cosmic Rays

Simulations of CRs on galactic scales

- Salem & Bryan 2014 - first 3D simulation of CR transport in full galaxy simulation with hydrodynamics



$$\partial_t \epsilon_{CR} + \nabla \cdot (\epsilon_{CR} \boldsymbol{u}) = -P_{CR}(\nabla \cdot \boldsymbol{u}) + \nabla \cdot (\kappa_{CR} \nabla \epsilon_{CR}) + \Gamma_{CR}$$



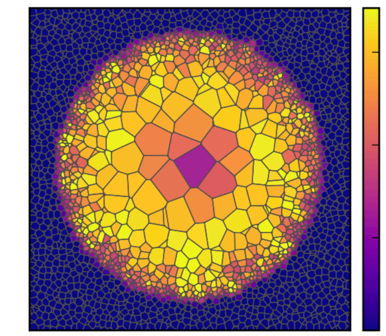
- Model CRs as a second fluid
- 5+ coding groups now working on this problem in galaxy formation
- All model diffusion, some also model streaming

Cosmic Rays in AREPO

Pfrommer, Pakmor, Schaal, Simpson & Springel 2017
Pakmor, Pfrommer, Simpson, Kannan & Springel 2016

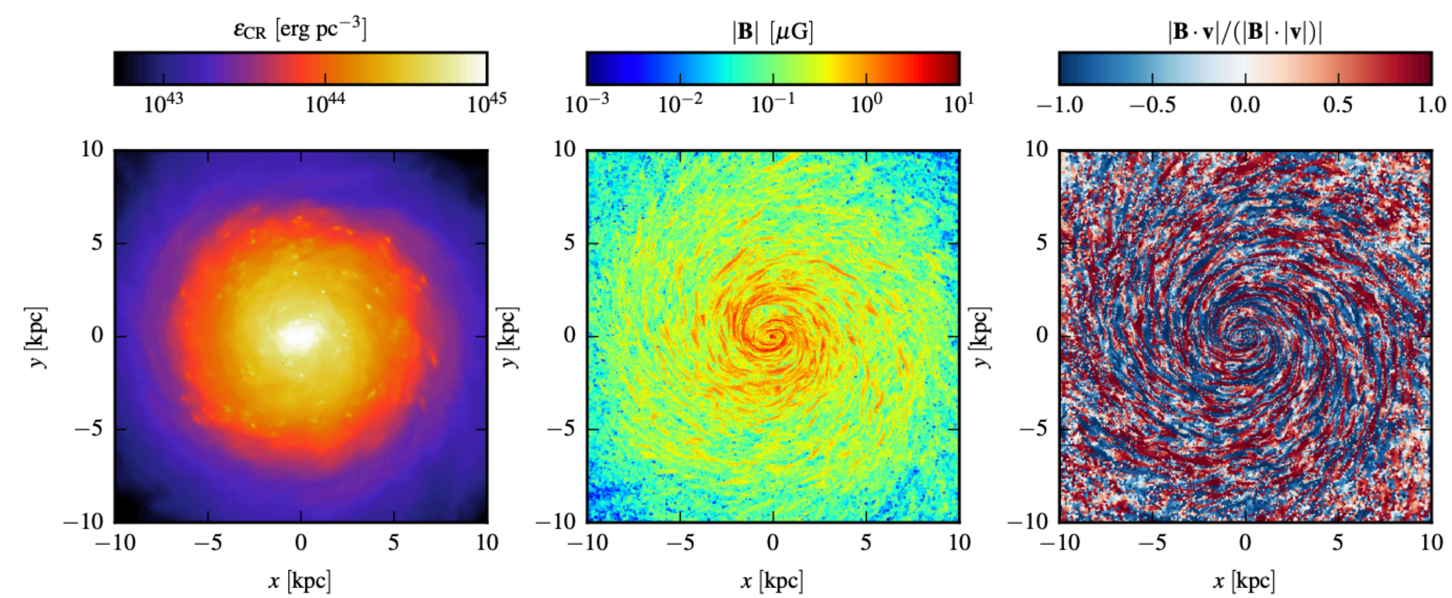
$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot \left[\varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}}) - \kappa_{\varepsilon} \boldsymbol{b} \left(\boldsymbol{b} \cdot \boldsymbol{\nabla} \varepsilon_{\mathrm{cr}}\right)\right] = -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot (\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}}) + \Lambda_{\mathrm{cr}} + \Gamma_{\mathrm{cr}}$$

anisotropic diffusion

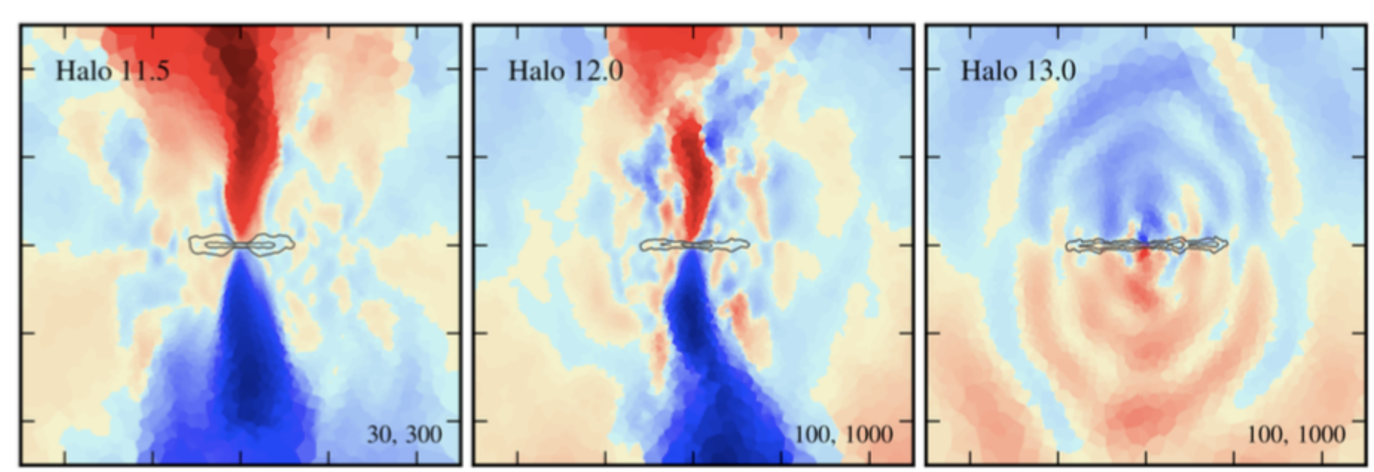


Pfrommer et al. 2017

- CRs are modeled as a 2nd fluid
- They impact the dynamics of the thermal gas through their pressure
- We assume the CRs are imperfectly coupled to the thermal gas - this gives an ‘advection’ term and a ‘diffusion’ term, controlled by the diffusivity kappa
- Diffusion is anisotropic -> goes along magnetic field lines
- Include Coulomb and Hadronic losses -> a fraction of CR energy thermalizes in dense gas



Pakmor et al. 2016

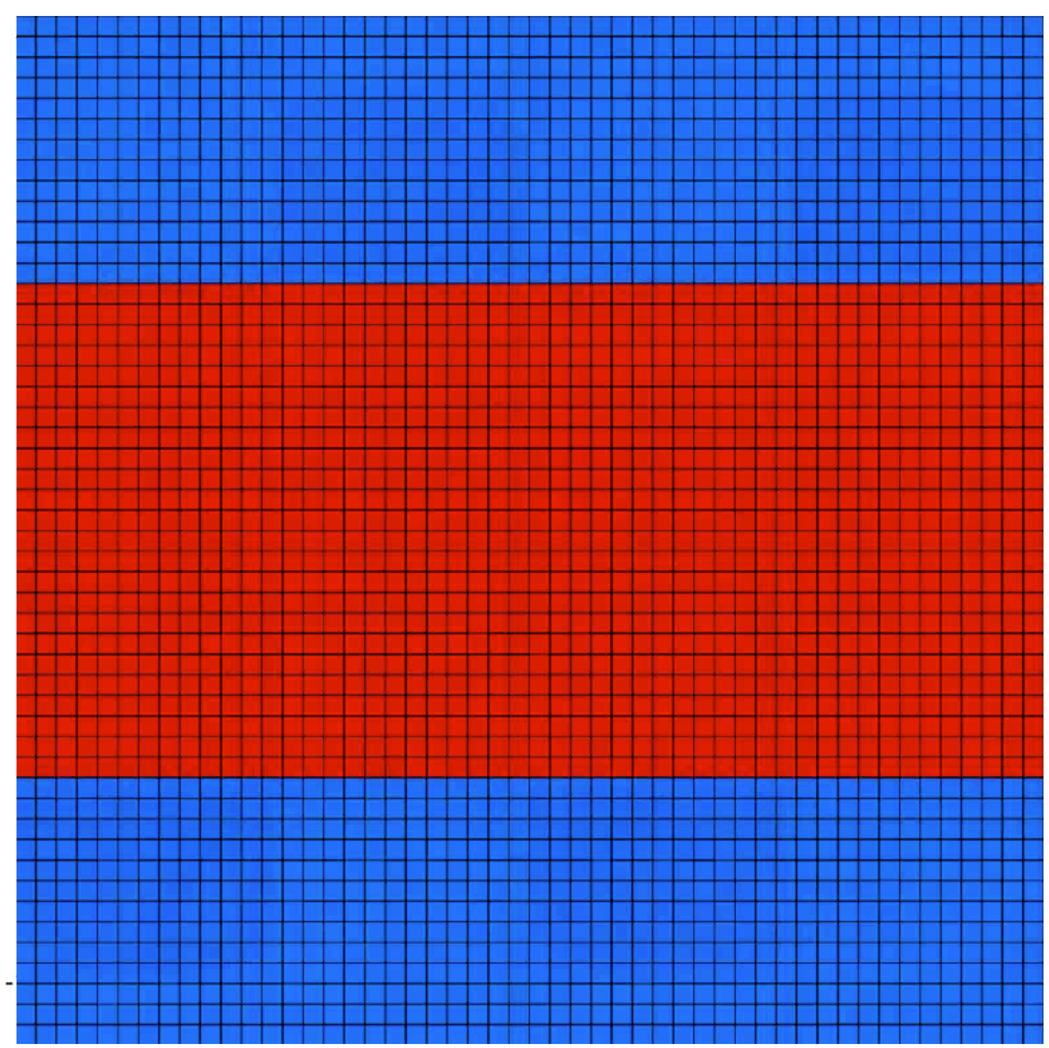


Jacob et al. 2018

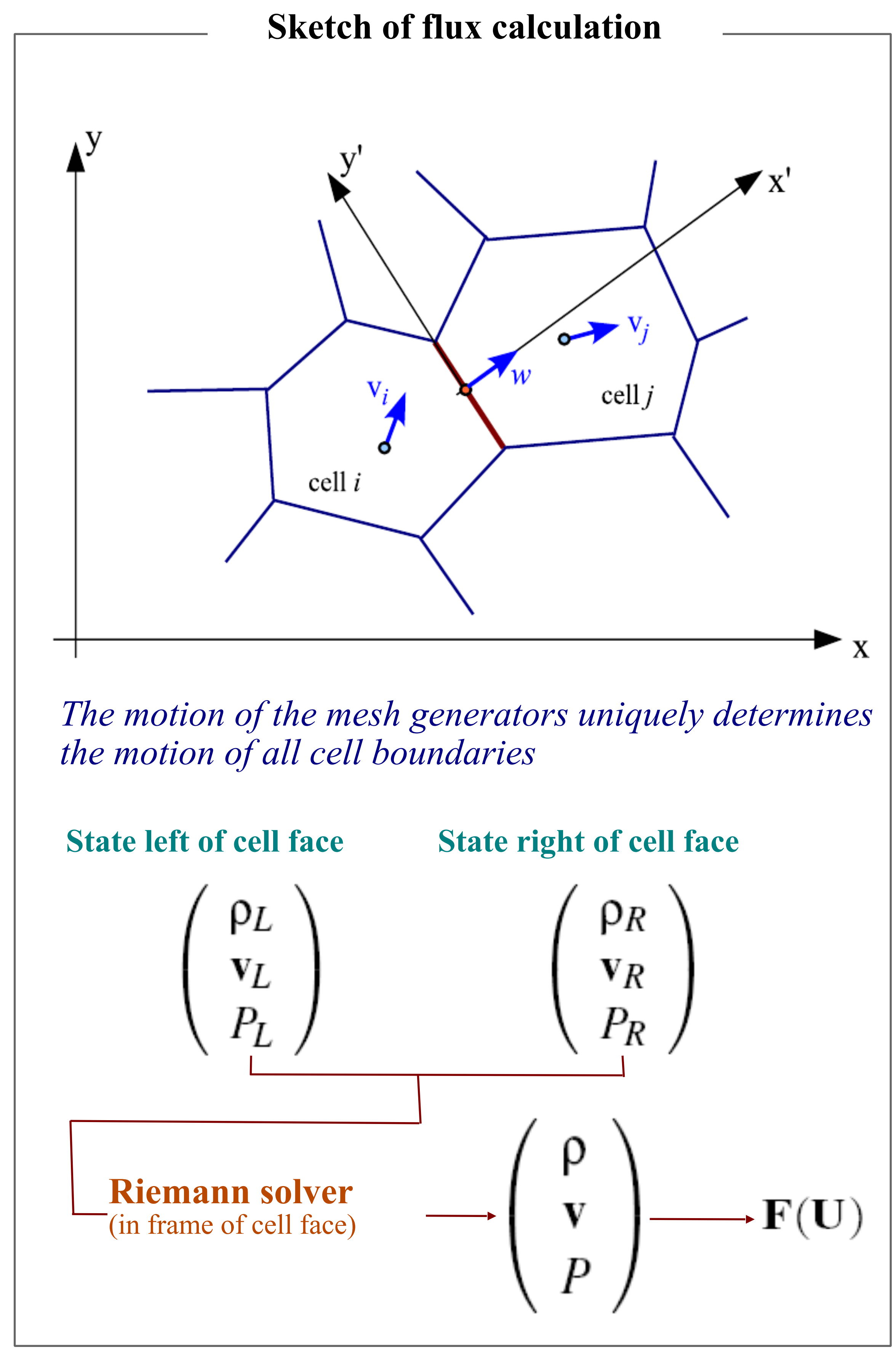
The **moving-mesh hydrodynamics** with **AREPO**

PRINCIPAL ADVANTAGES

- Low numerical viscosity, very low advection errors
- Full adaptivity and manifest Galilean invariance
- Makes larger timesteps possible in supersonic flows
- Crucial accuracy improvement over SPH technique



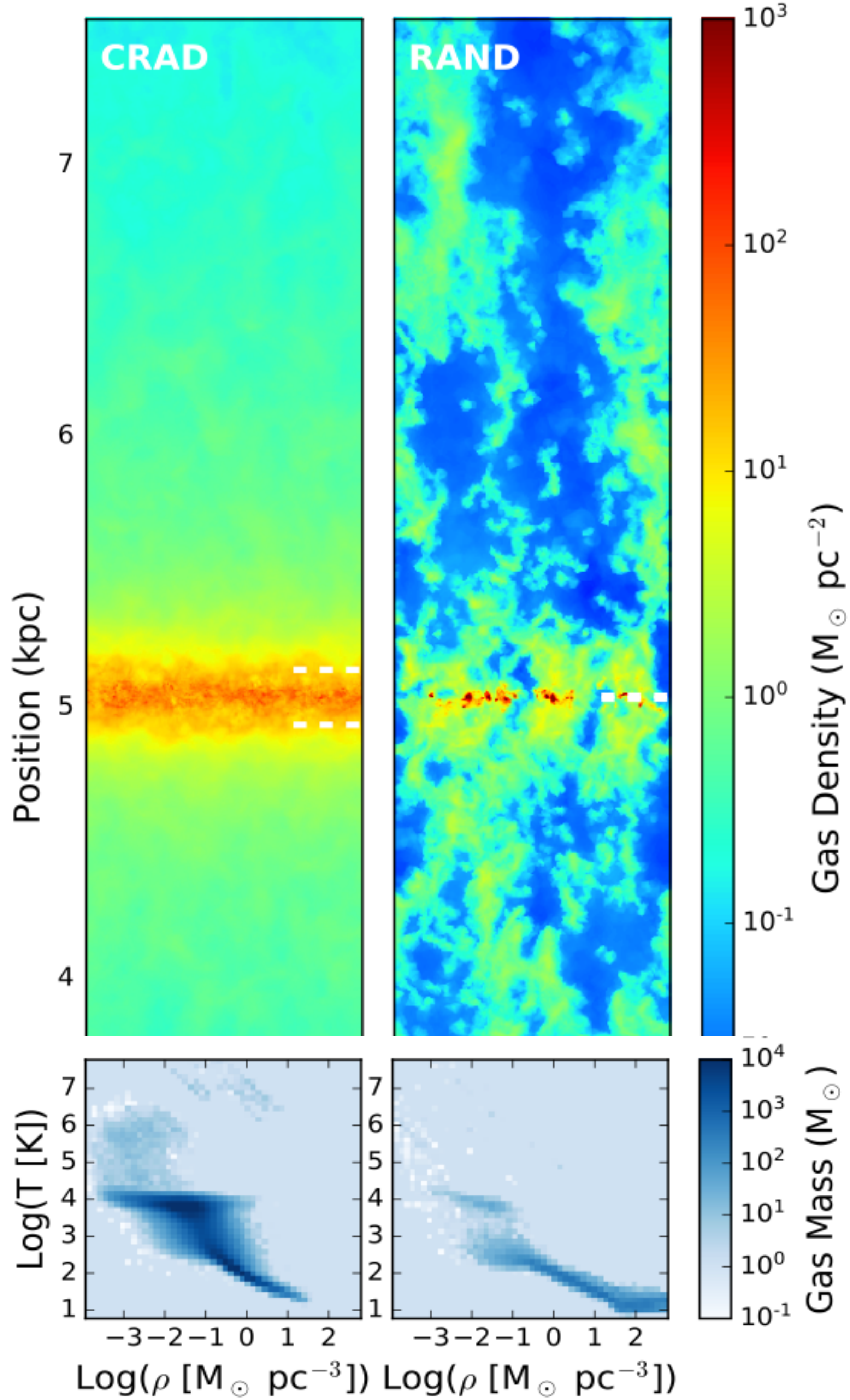
Springel (2010)

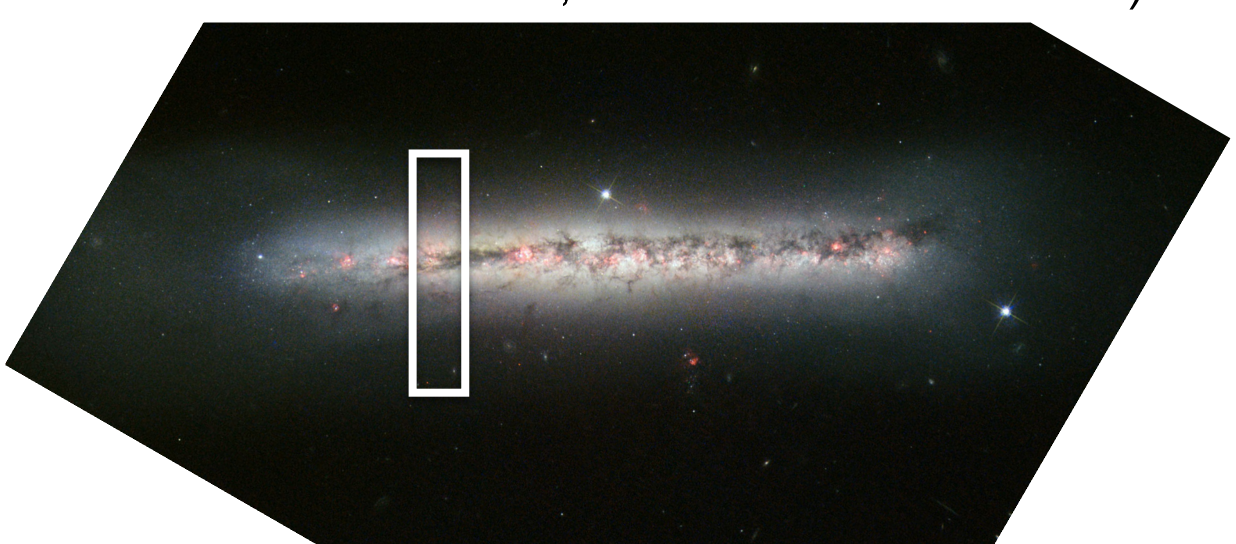


Stratified-box simulations of SN feedback in the ISM

Simpson et al. (2016)

- MHD Simulations (1kpc x 1kpc x 10kpc)
- Model stratified box in initial isothermal equilibrium (10^4 K), MW-like conditions
  - MHD, self-gravity, uniform ISRF
- Employ atomic & molecular cooling network (Glover et al.) & TreeCol self-shielding (Clark et al.)
- $m_{cell} = 10\ M_\odot$, $dx_{min} = 1$ pc
- Individual SNe are placed in ISM (10^{51} erg)
- CR models put 10% of SN energy in CRs; include Coulomb & Hadronic losses
- Test CR diffusion & advection models (Pfrommer et al. 2017, Pakmor et al. 2016)





Cosmic Ray Diffusion can drive outflows

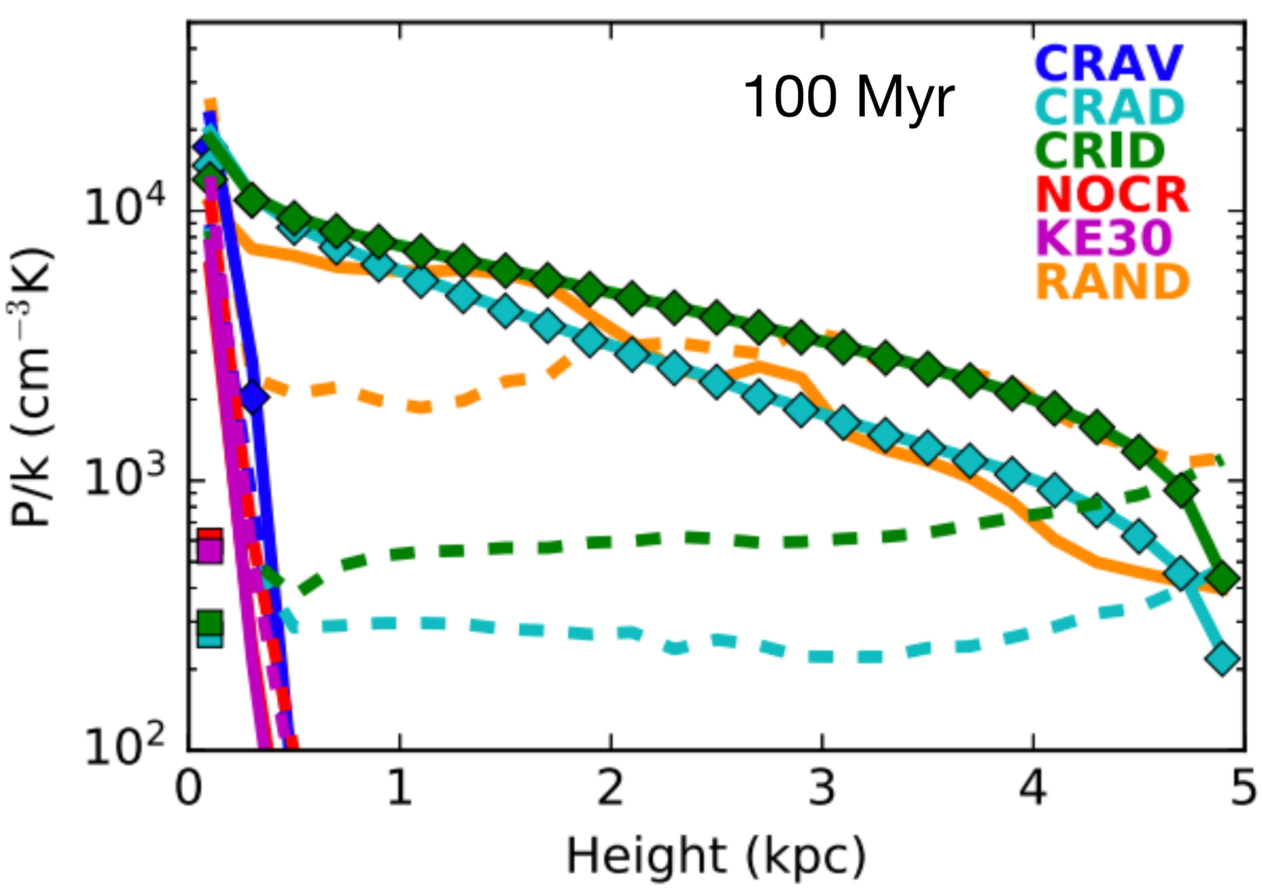
(Simpson et al. 2016)

Probability of SNe:

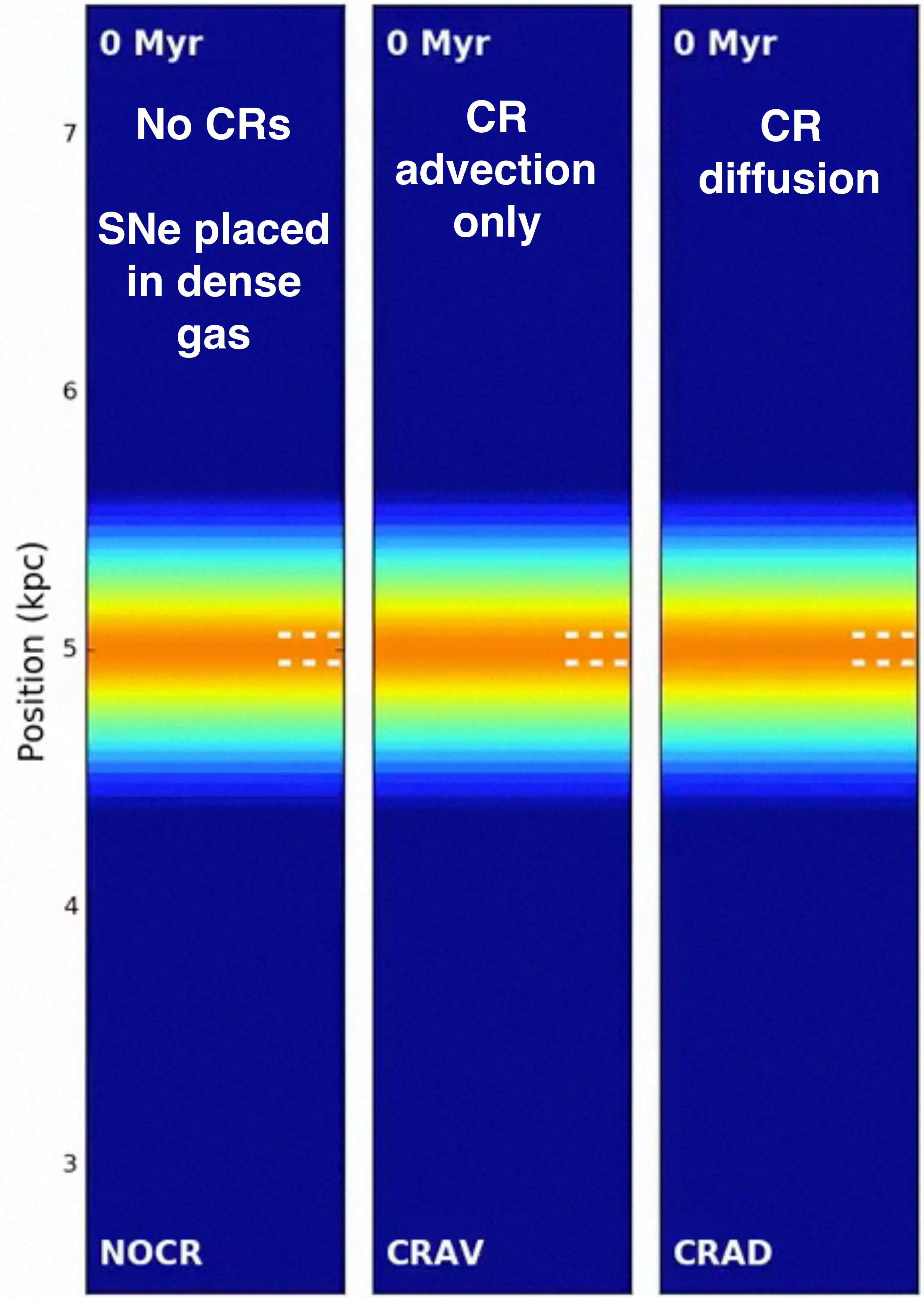
$$p_i = sfr_i \times \frac{1.8 \text{ SNe}}{100 \text{ M}_\odot} \times \frac{\Delta t}{m_i}$$

$$sfr_i = \epsilon \frac{m_i}{t_{ff,i}}$$

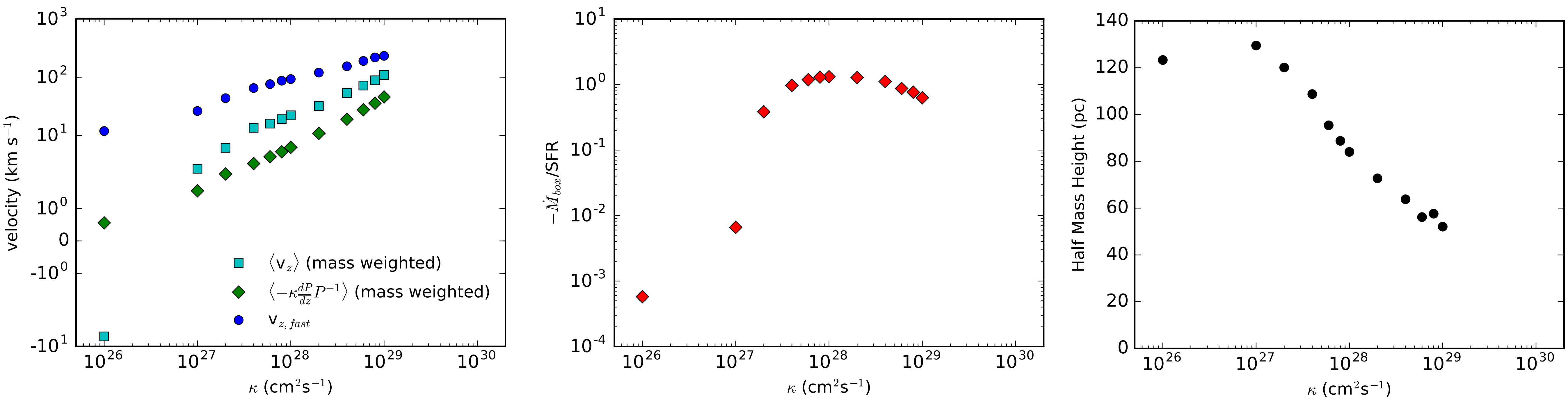
Pressure vs. Height



Projections of Gas Density



Diffusivity - Wind Relation



Simpson et al. in prep

Quantities averaged over final 10 Myr

Energy equation:

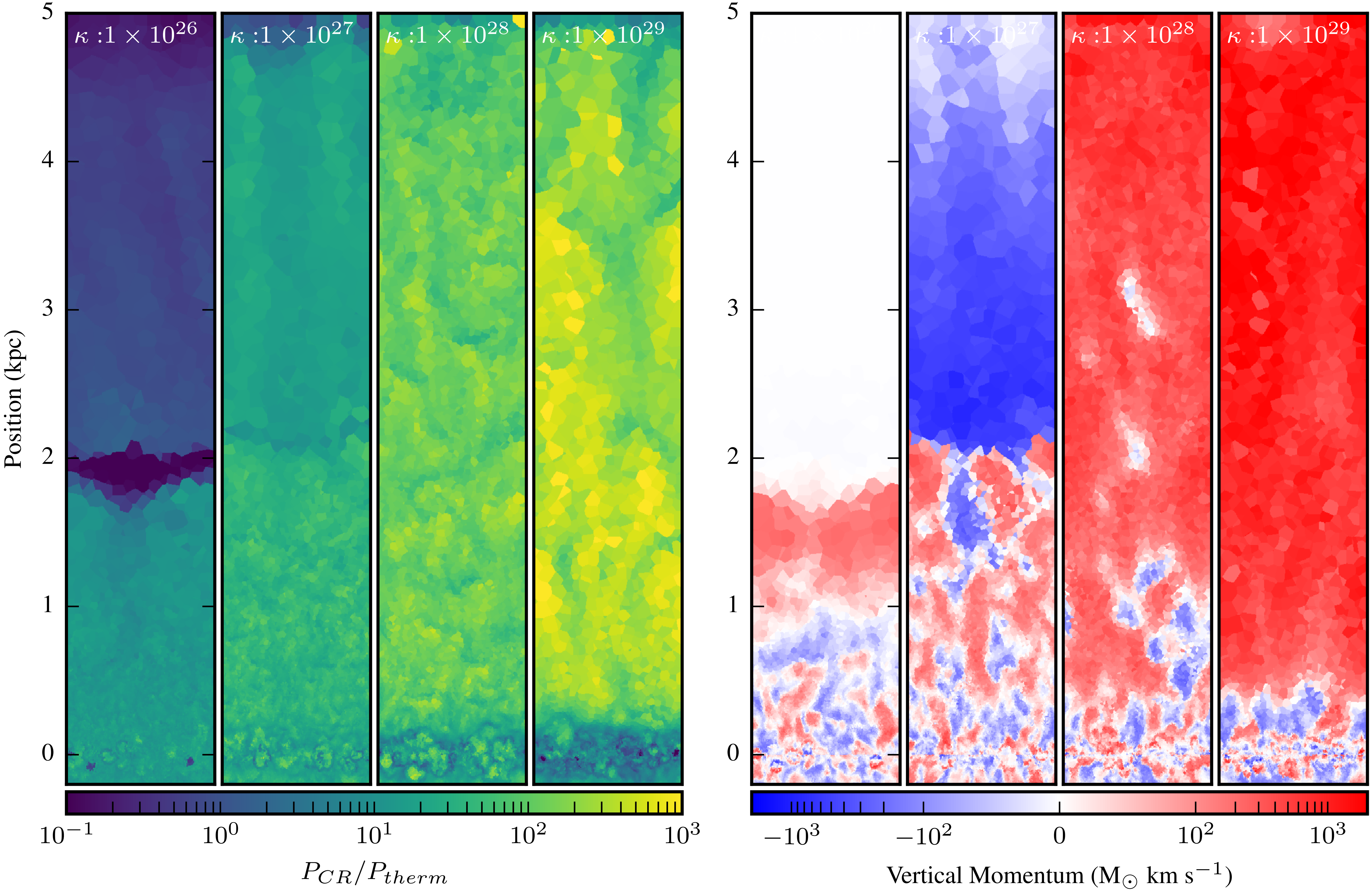
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \nabla \cdot [\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st}) - \kappa_\varepsilon \boldsymbol{b}\,(\boldsymbol{b} \cdot \nabla \varepsilon_{\rm cr})] = -P_{\rm cr}\, \nabla \cdot (\boldsymbol{v} + \boldsymbol{v}_{\rm st}) + \Lambda_{\rm cr} + \Gamma_{\rm cr}$$

anisotropic diffusion: fiducial kappa: 10^{28} cm^2 s^{-1}

- Varying diffusivity kappa adjusts outflow speed but not mass loading
- Slowing the diffusion (low kappa) puffs up the disk
- In reality, kappa likely varies within the galaxy - future work

Diffusivity - Wind Relation

after 100 Myr

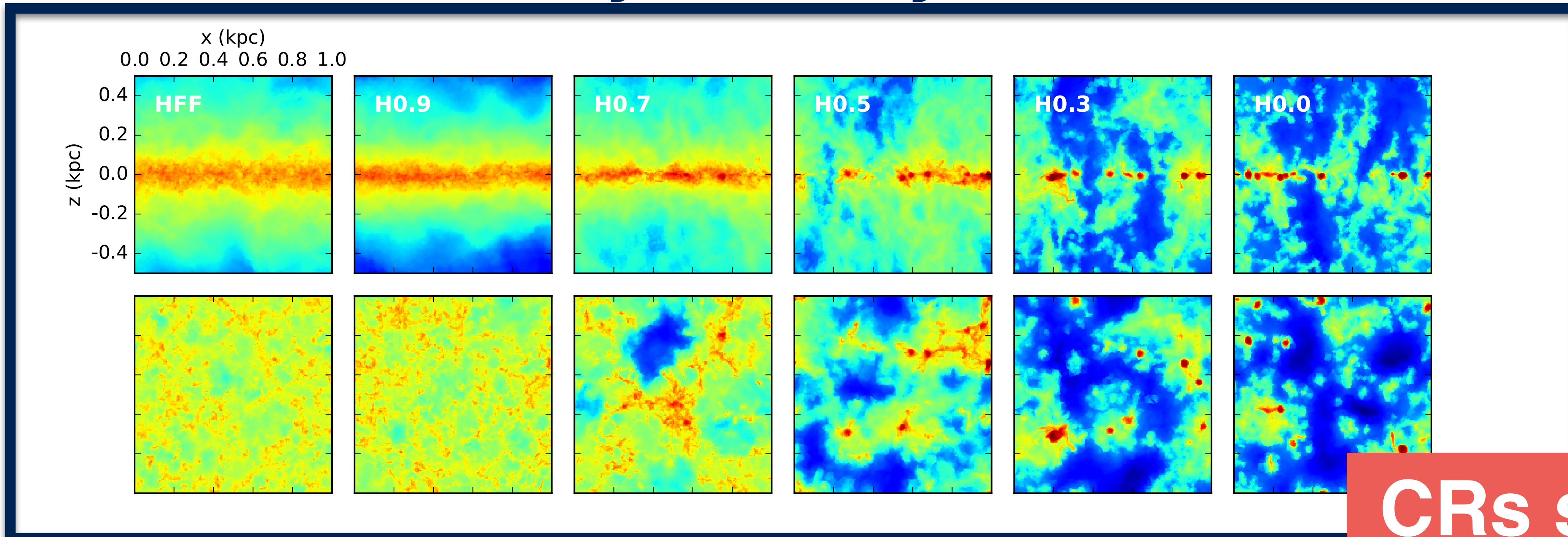


Placement of SN events

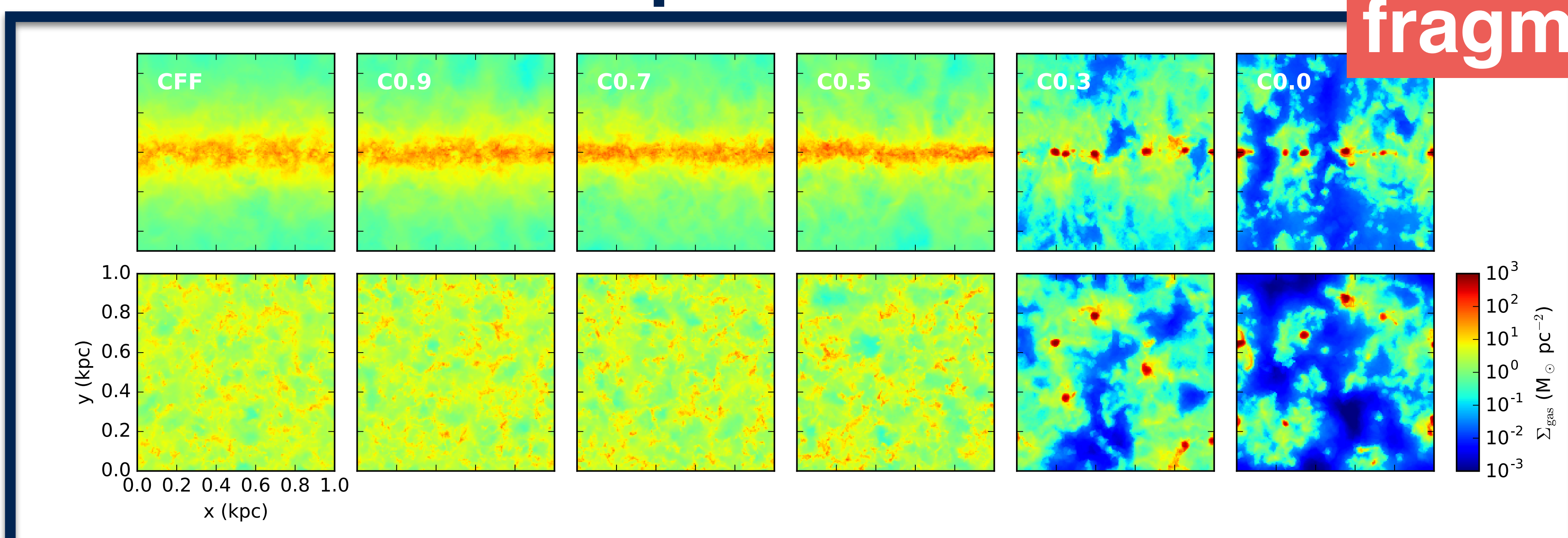
$$\mathrm{sfr}_i^{\mathrm{mix}} = \mathrm{sfr}_i^{\mathrm{ff}} \times \frac{SFR_{\mathrm{KS}}}{\sum \mathrm{sfr}_i^{\mathrm{ff}}} \times (1 - f_{\mathrm{rand}})$$

Random Fraction →

Hydro only



Anisotropic CR Diffusion

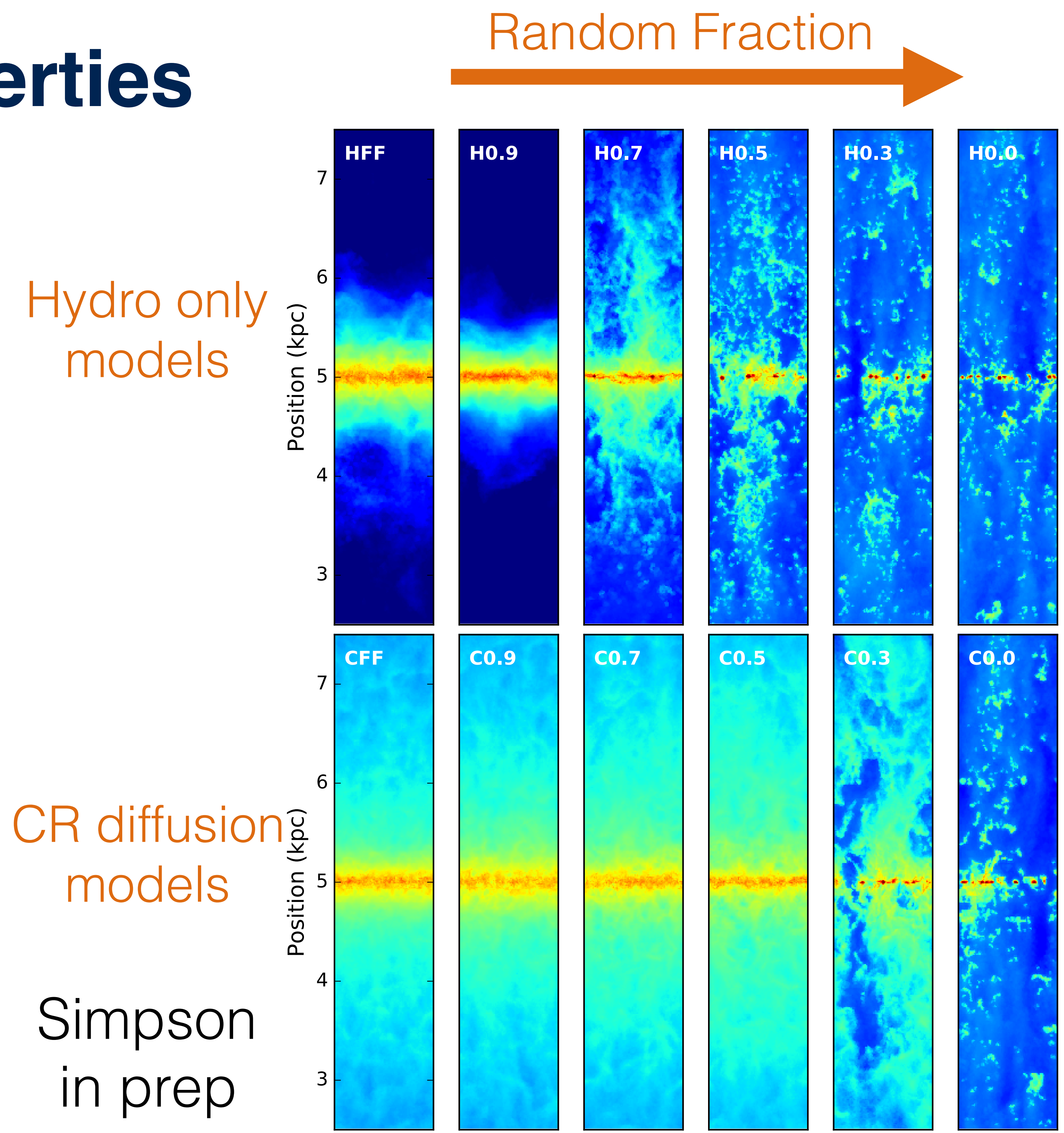


CRs stabilize ISM against fragmentation

Simpson in prep

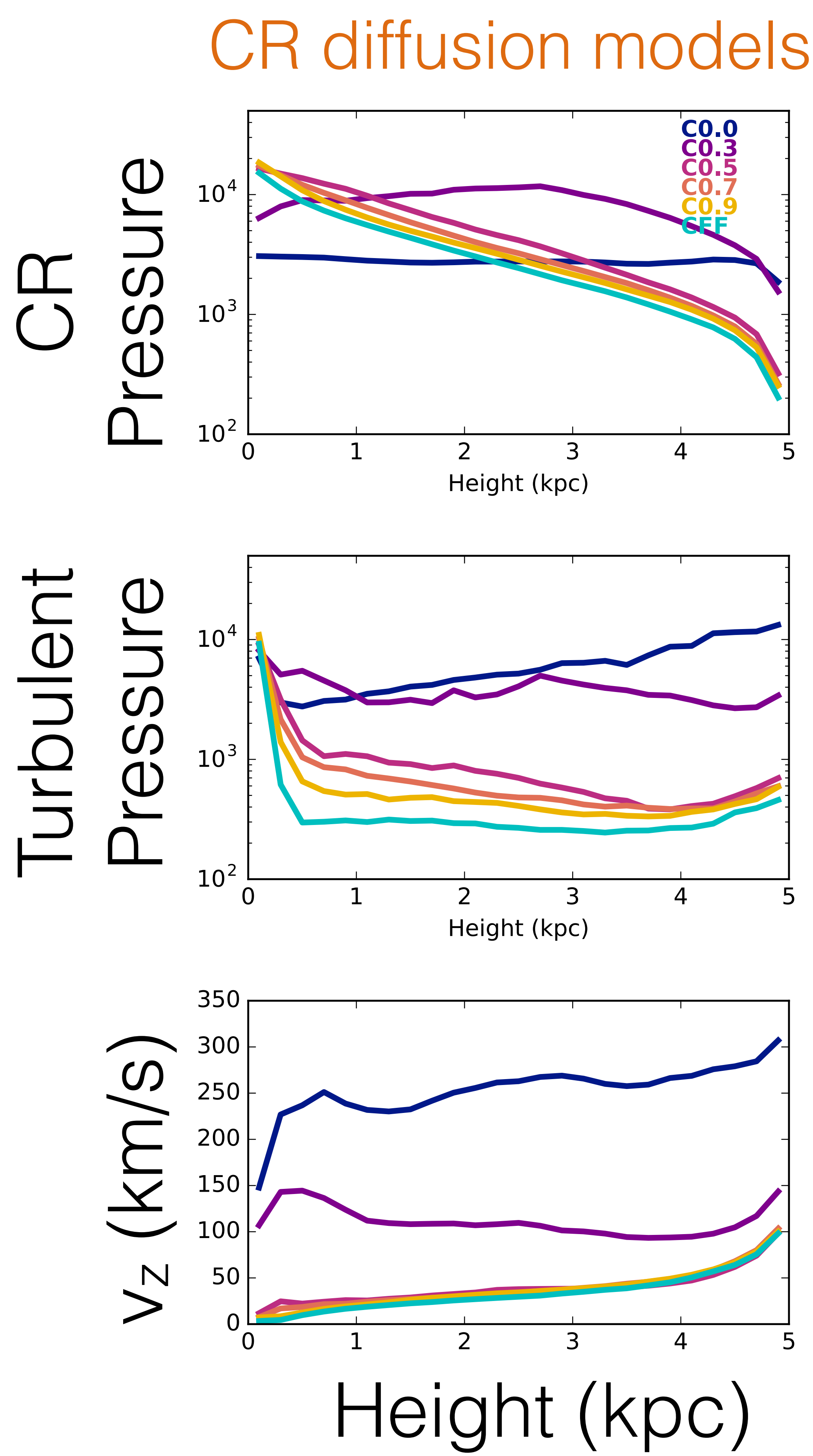
Wind Properties

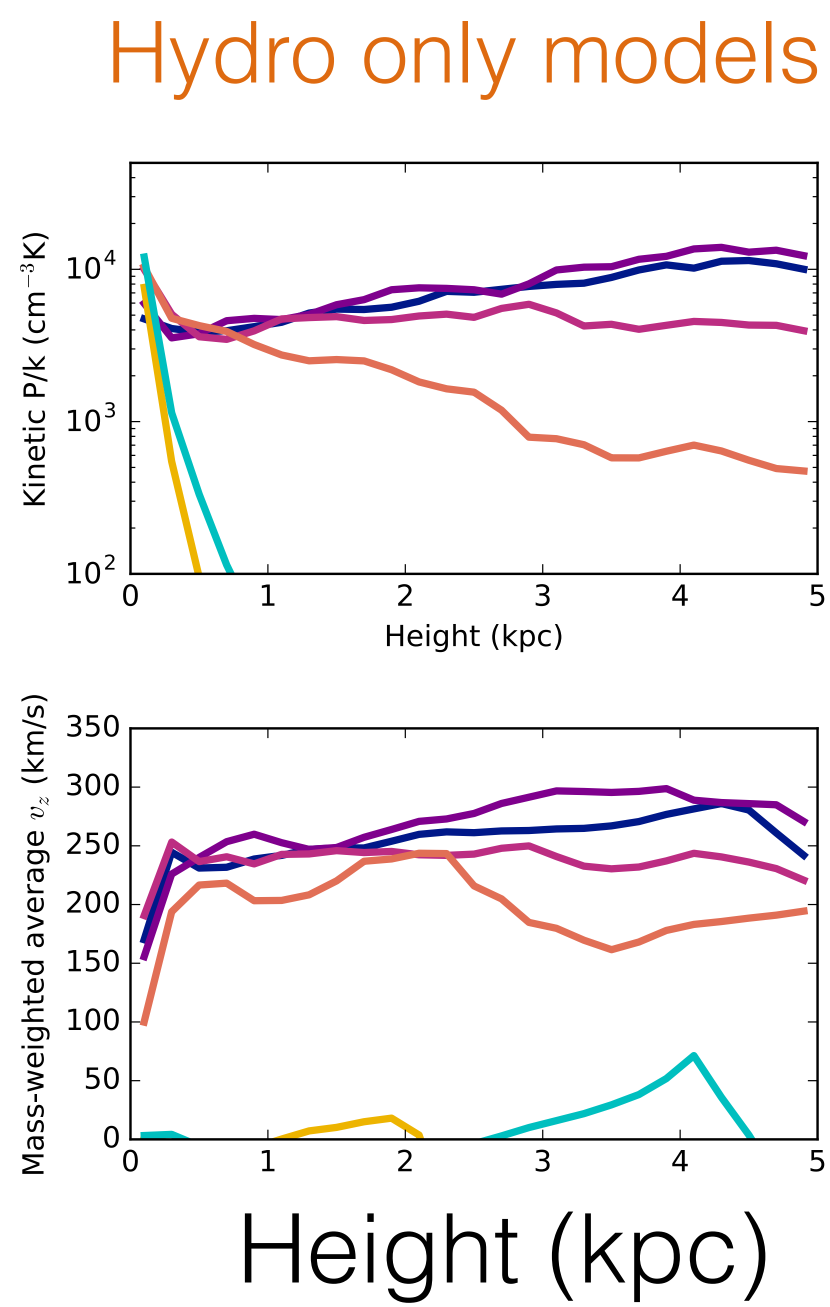
CRs drive smooth & slow outflows



Simpson in prep

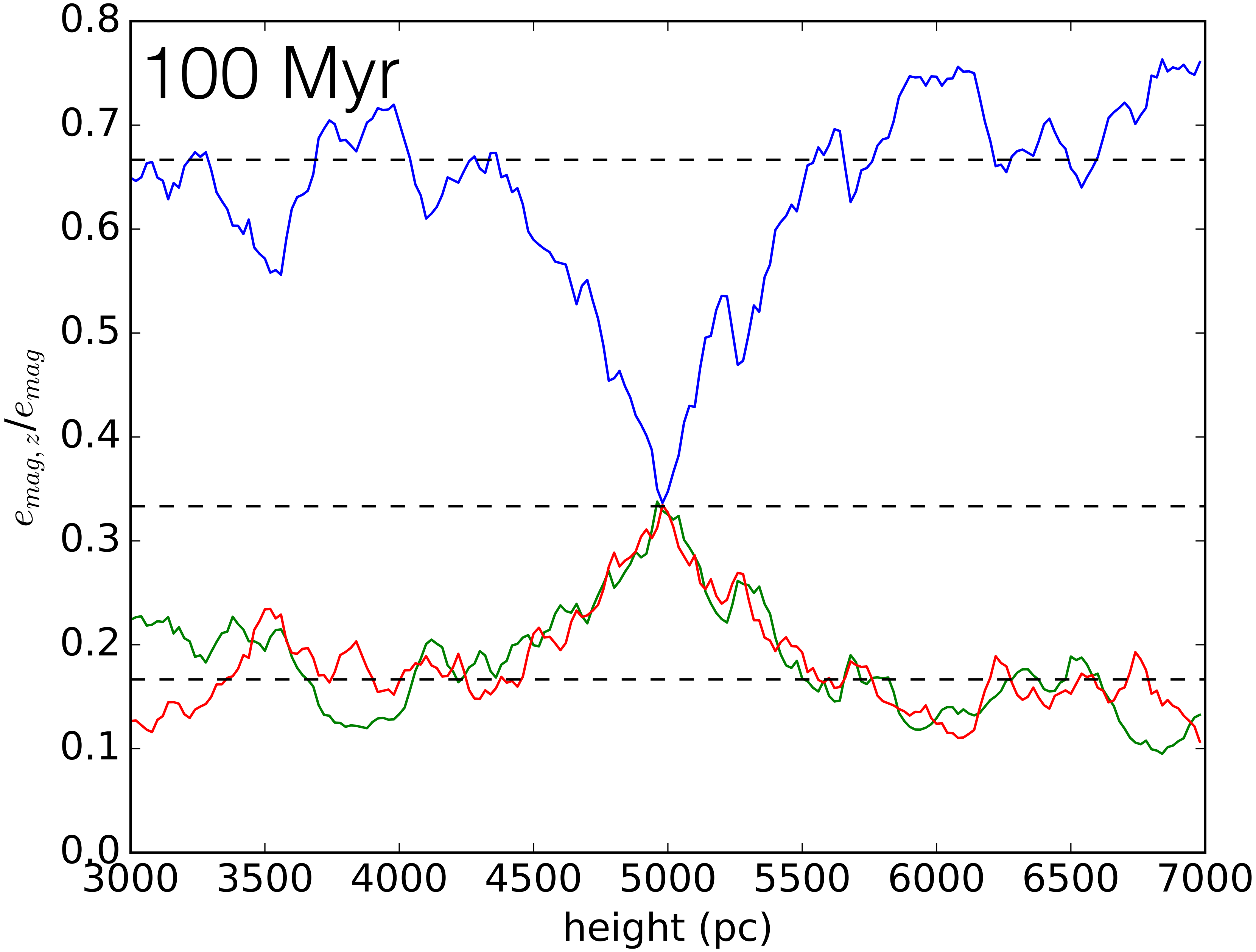
If CR pressure dominates, CRs set the wind speed





Simpson in prep

Magnetic Fields

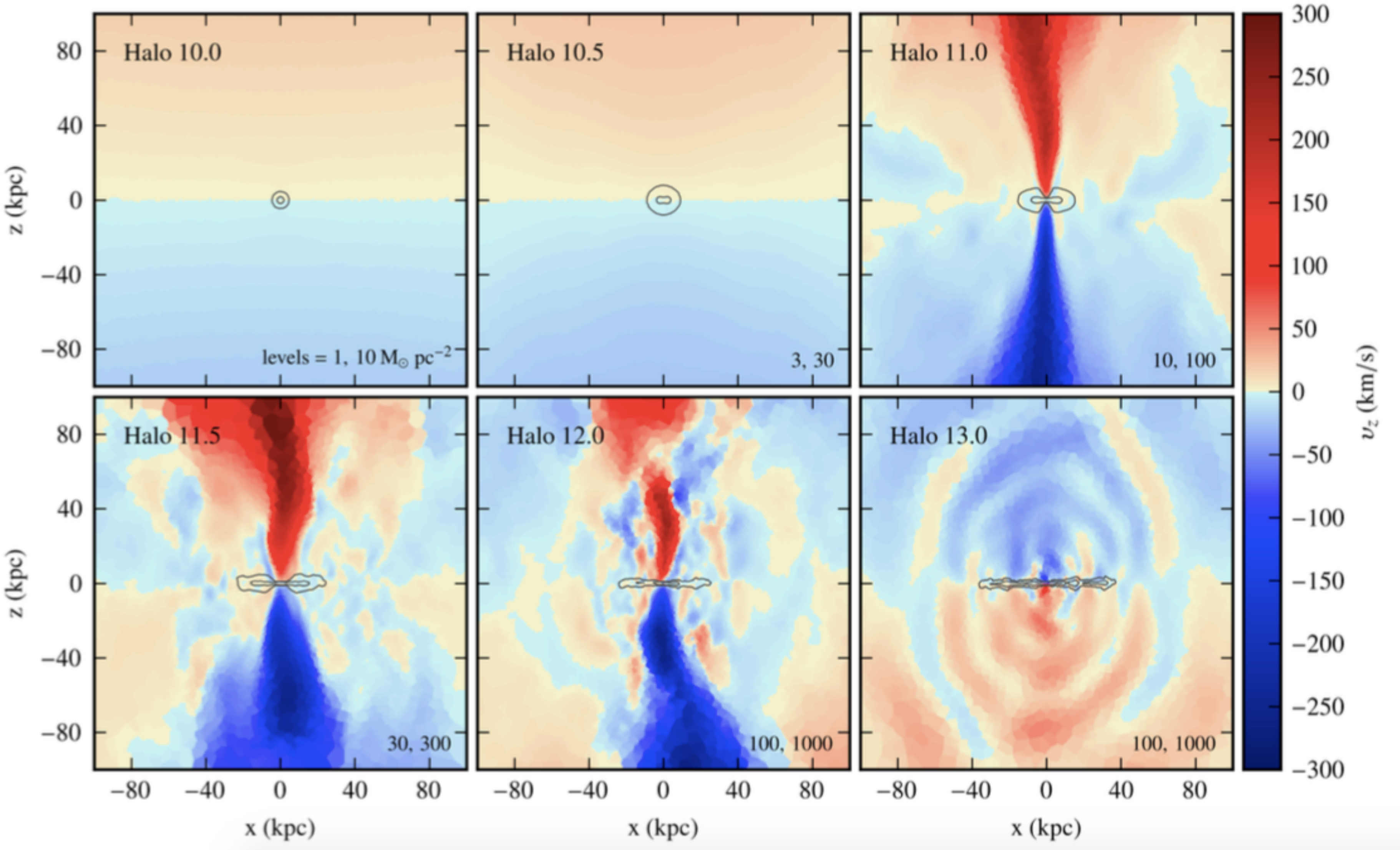


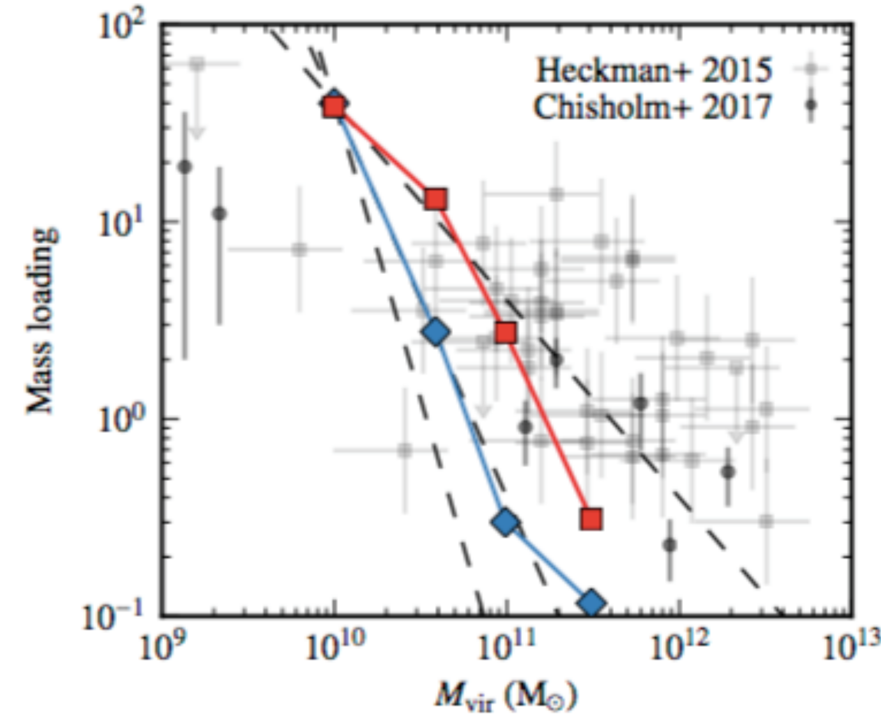
- Start with a field oriented in the horizontal direction
- After 100 Myr, see a randomly oriented field in the midplane
- Some vertical ordering above a certain height
- This seems to vary with placement model - more analysis needed!

Blue: z
Red, green: x,y

Full disk models: outflow dependence on halo mass

Jacob, RP, Simpson, VS & CP (2018)

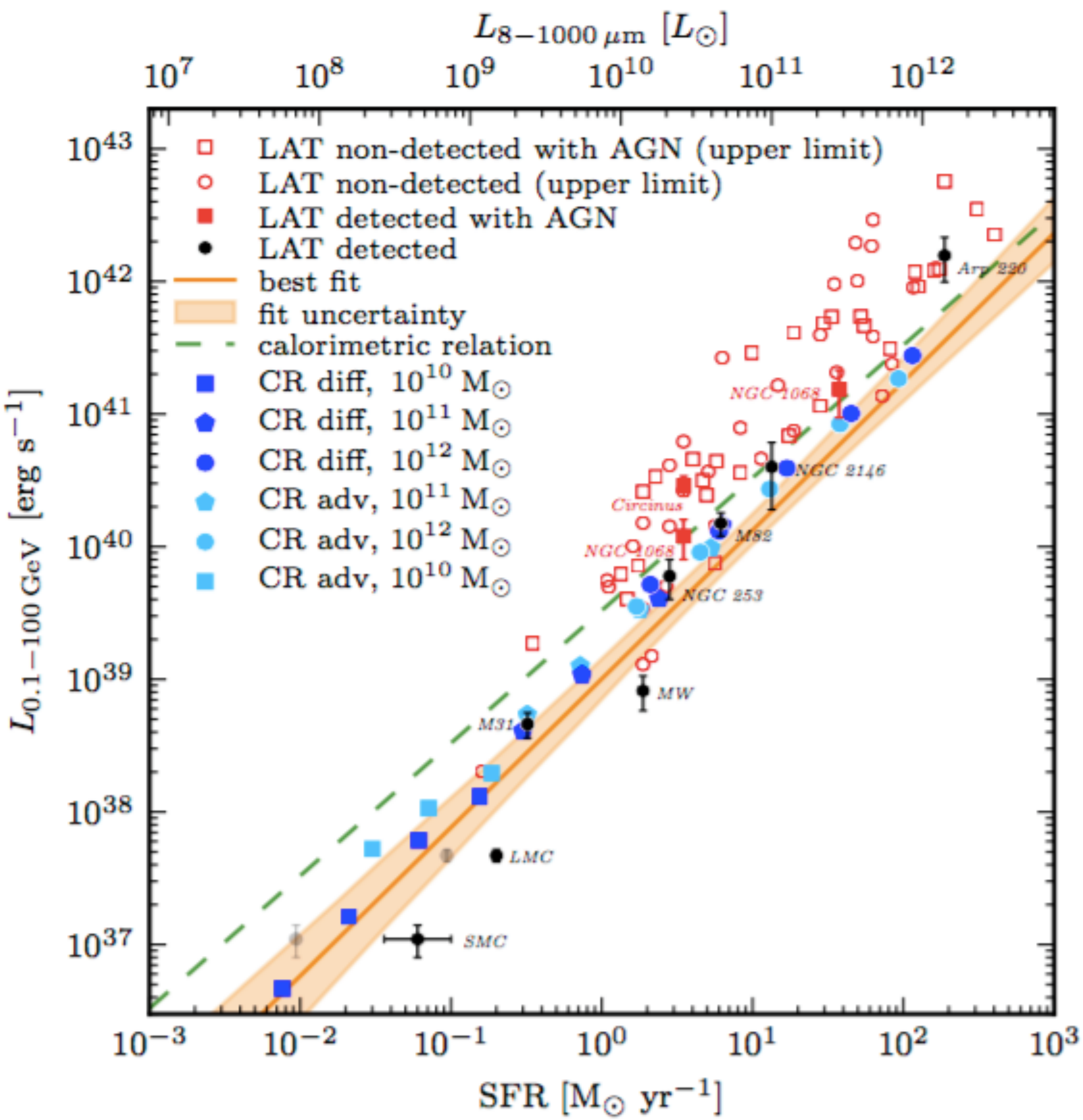


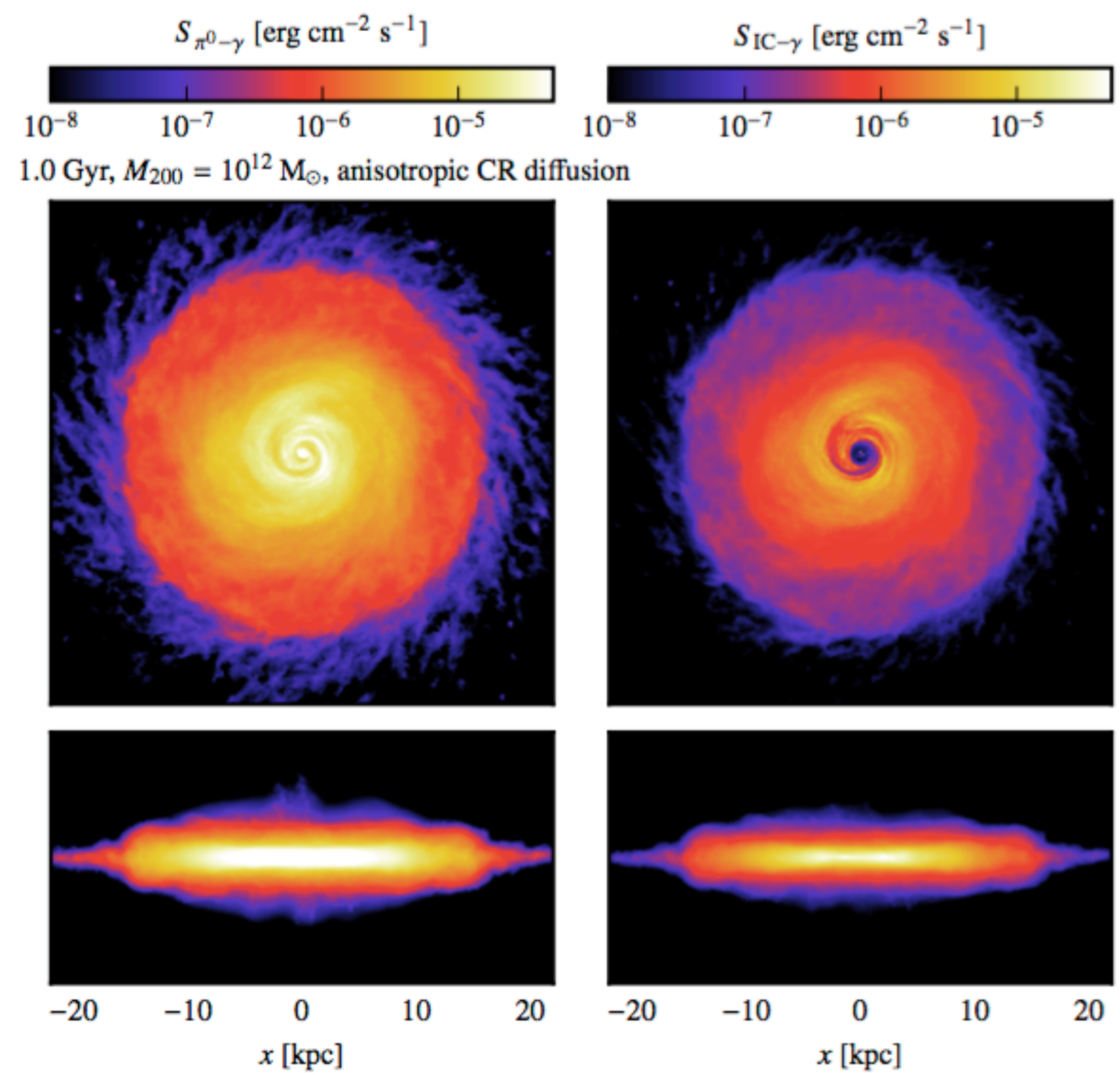


- Subgrid treatment for star formation & ISM
- Replaced previous wind model with CR diffusion
- All halos with log(M/Msun) between 10 and 12 produce outflows

Gamma Ray Flux Predictions

Pfrommer, RP, Simpson & VS (2017)





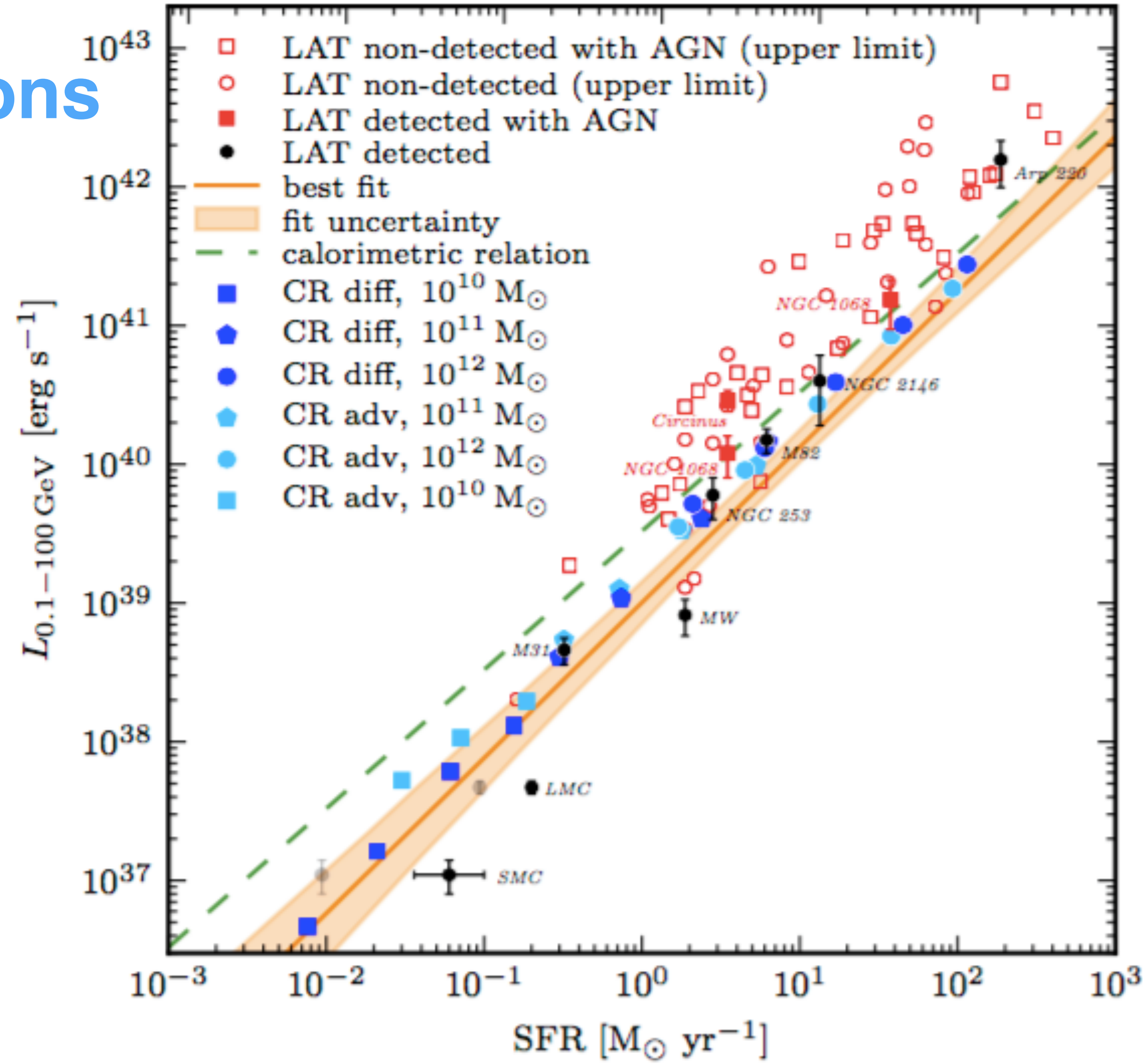
Pion decay

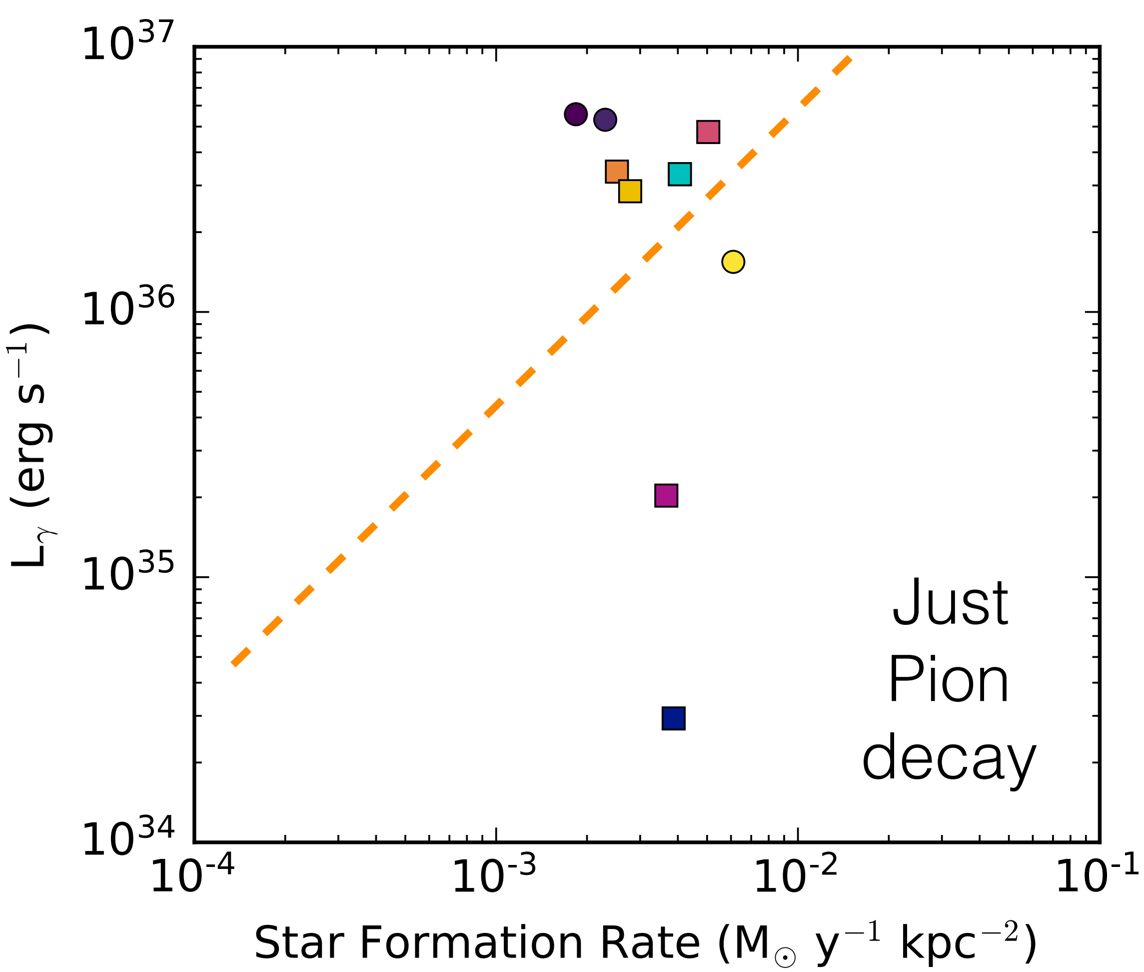
Inverse Compton

Gamma Ray Flux Predictions

Preliminary results:

- Models with more mass in dense phase drop below the relation due perhaps to Coulomb & Hadronic loss model
- Also a trend with kappa - low kappa places you above the relation



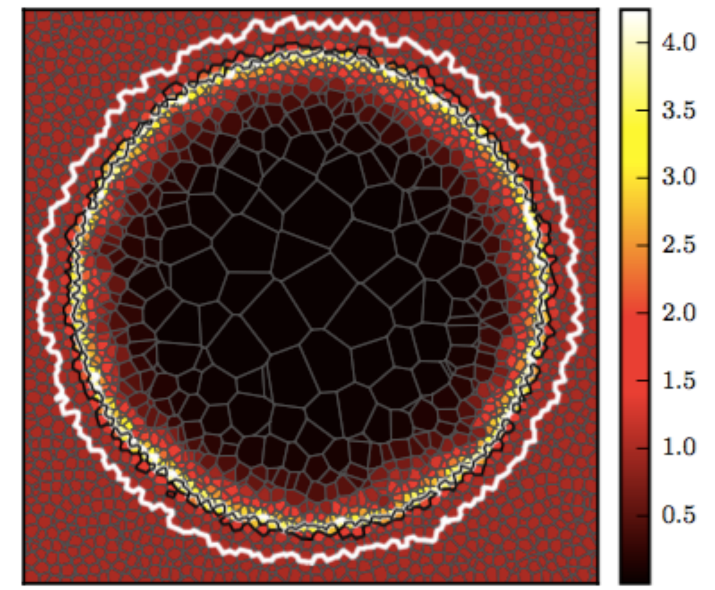


Squares - Constant kappa, varying SN placement

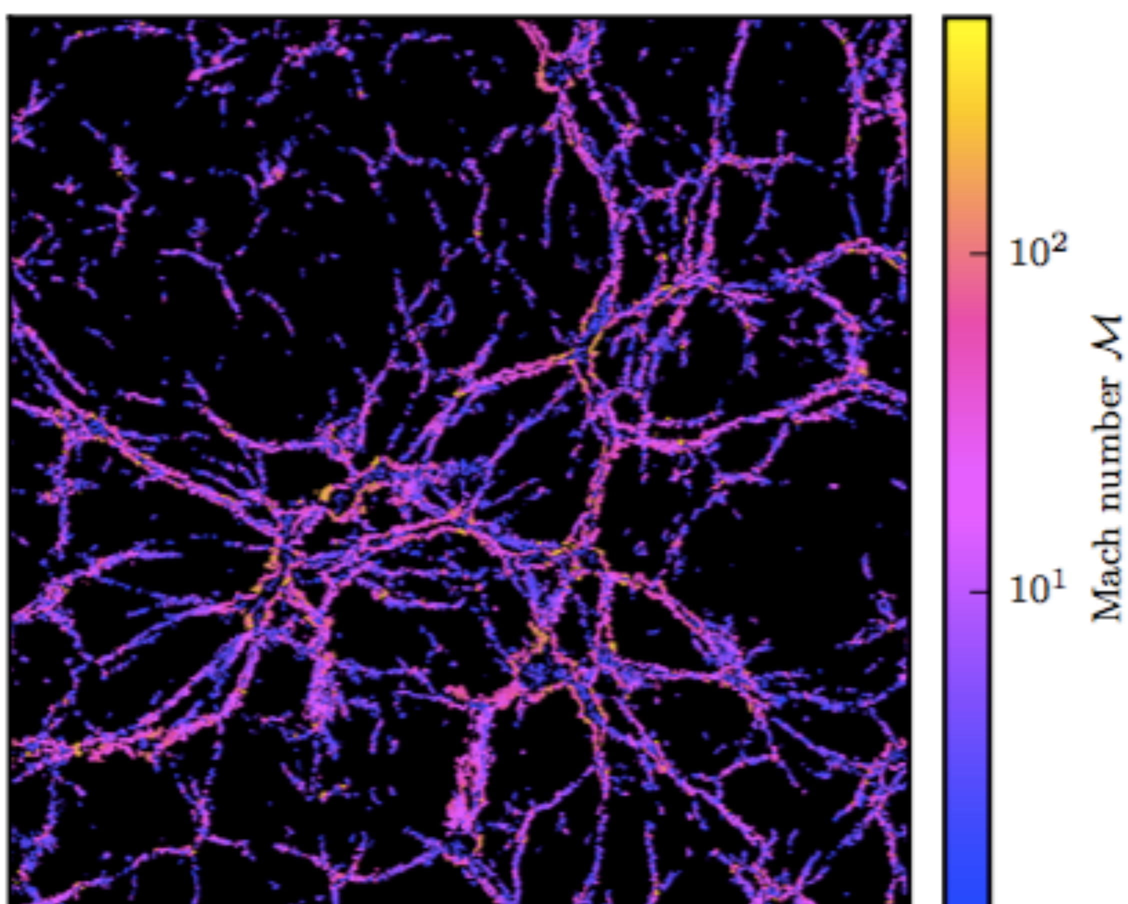
Circles - Constant SN placement, varying kappa

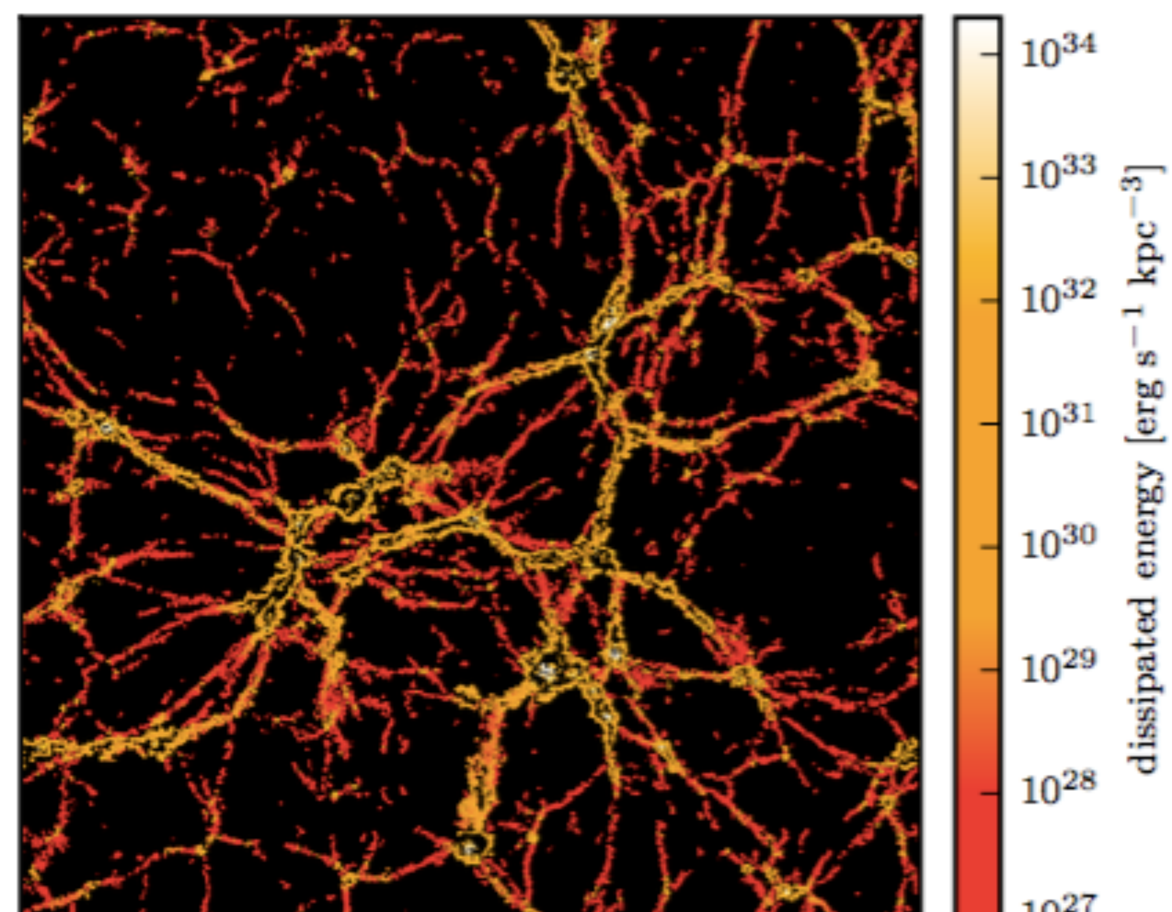
Shock Injection

- Previous models have injected CRs by hand with thermal SN energy
- Alternatively, we can inject CRs at sites of shocks



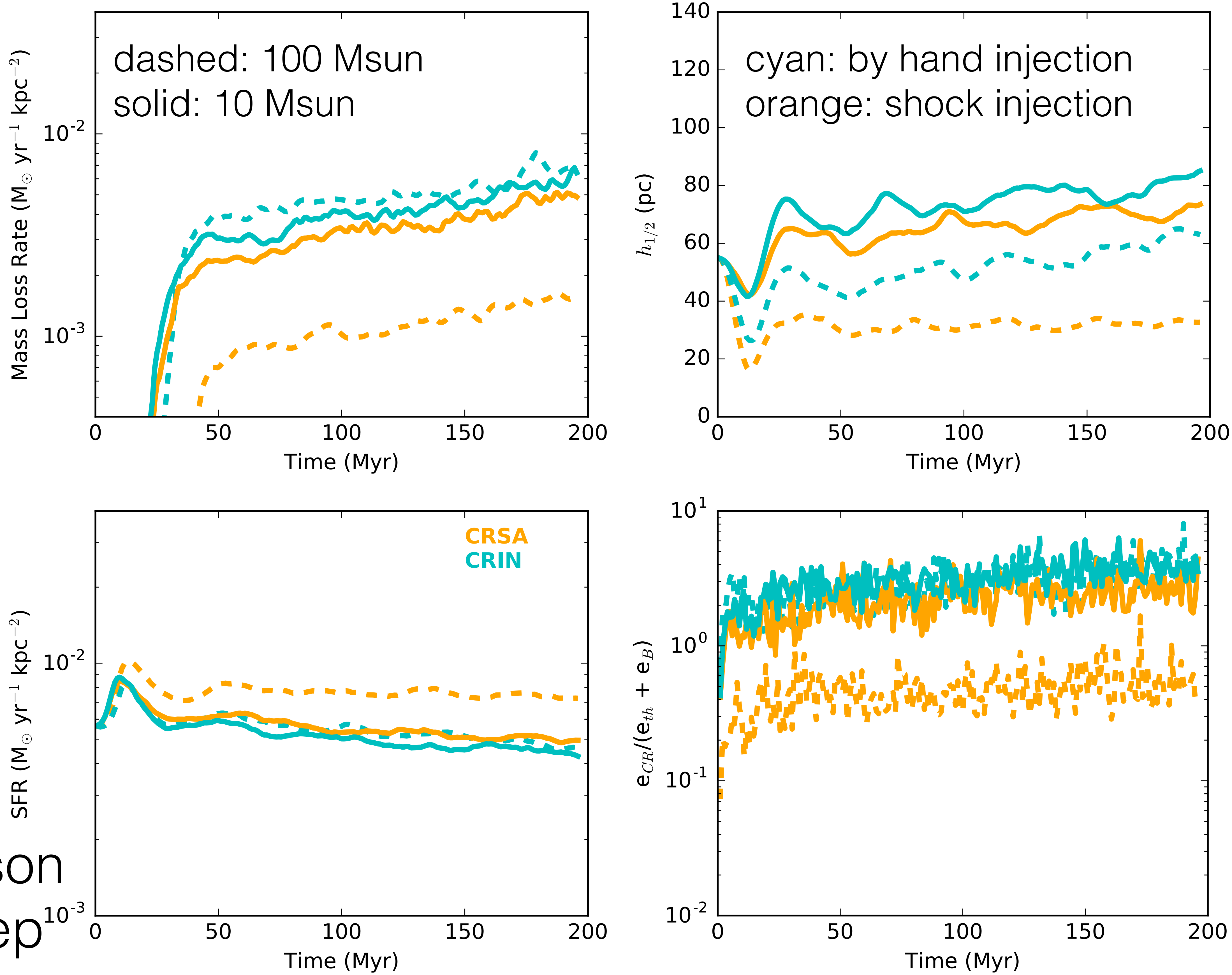
$$\Delta E_{\mathrm{cr}} = \zeta(\mathcal{M}_1, \theta)\, E_{\mathrm{diss}}$$





Pfrommer, Pakmor, Schaal, Simpson & Springel 2016

Shock injection comparison…



Simpson in prep

Conclusions

- Galactic Winds are an important phenomena and a necessary ingredient in galaxy formation
- CR pressure gradients can drive outflows and CR pressure impacts the fragmentation of the ISM - this should be physics we include in a complete galaxy model
- Simulations of CR transport show CR diffusion (and possibly streaming) is the effect that produce flows on galactic scales
- More work is needed in different environments and combined with other physical effects to make progress