FIRE
Feedback In Realistic Environments

Constraining Magnetic Fields and Cosmic-Ray Transport in Galaxies with Synthetic Synchrotron Observations

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with Phil Hopkins, Gina Panopoulou, Iryna Butsky, Raphael Skalidis, Cameron Hummels + others!

Caltech

Building Galaxies from Scratch, University of Vienna

Magnetic fields (**B**) are an important component of galaxies

Interstellar and circumgalactic medium (ISM and CGM) hydrostatics (Boulares & Cox 1990; van de Voort+2021)

dynamics of molecular clouds and thermal instabilities in the CGM (Crutcher 2012; Ji+2018)

determine the transport of cosmic rays (CRs) through ISM and into CGM, which can be *very significant*,
(but remains highly uncertain... Ruszkowski & Pfrommer 2023 for a recent review)


M51, HST image + **B** lines from synchrotron polarization
Borlaff+2021

Measuring extragalactic **B** and CRs is difficult + indirect: synchrotron emission is one common way to investigate

Emission from CRs gyrating around magnetic field lines

$$I_{Synch} \sim \int B_{\perp}^{2} * e_{CR} \, dl$$

Need to make simplifying assumptions to break this degeneracy!

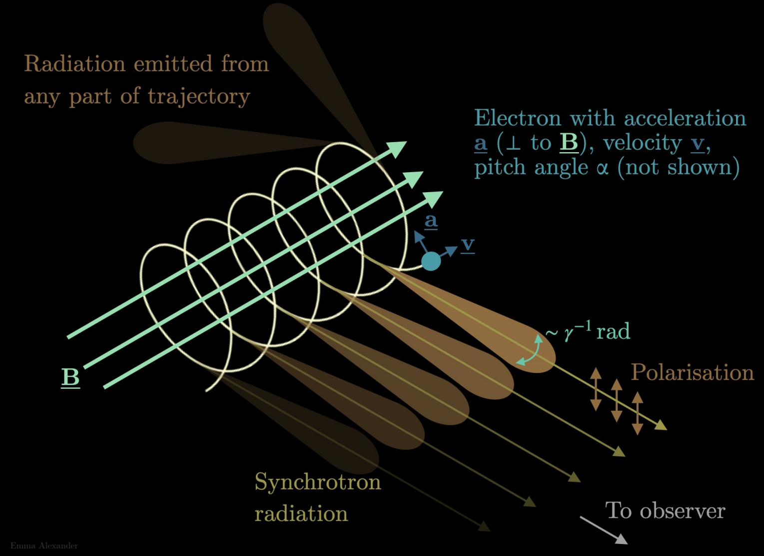
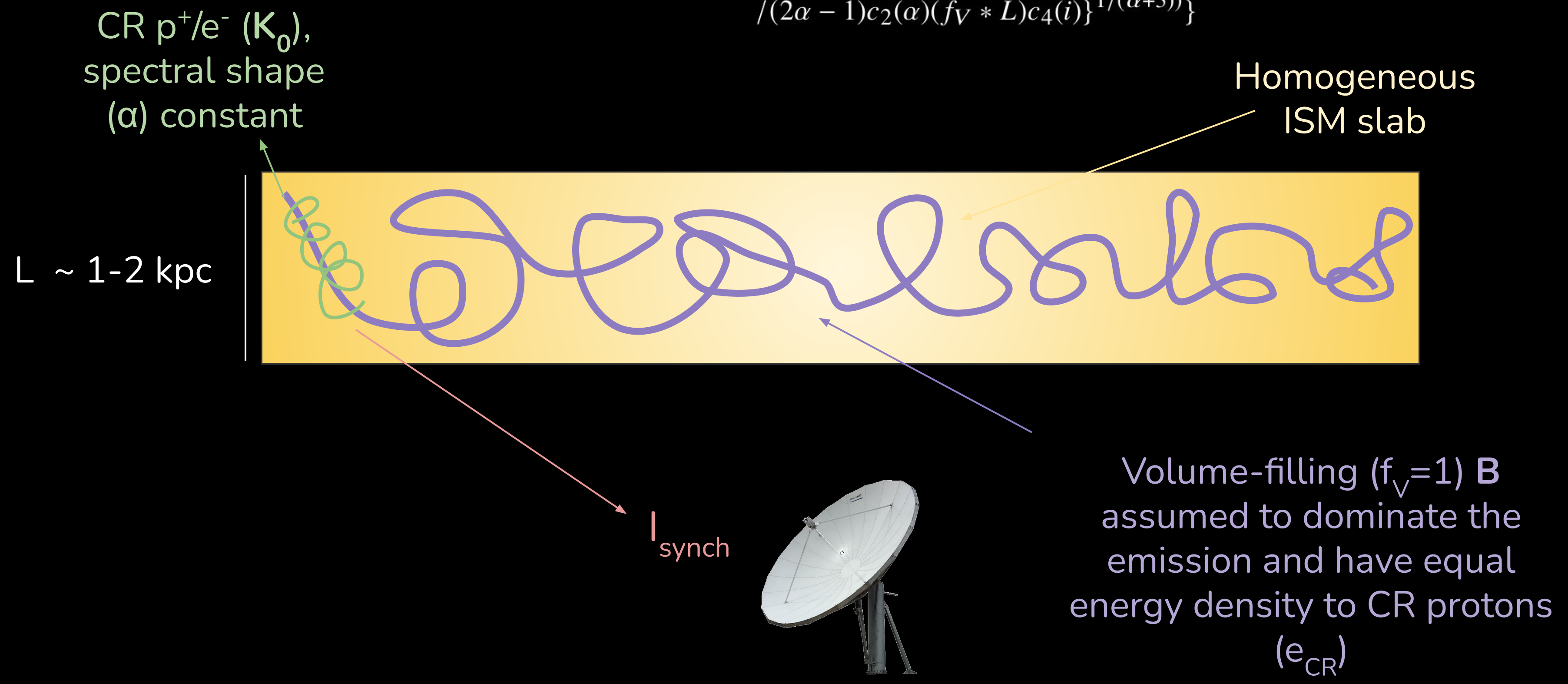


Image courtesy of [Emma Alexander]

The Synchrotron Equipartition Model

Beck & Krause 2005 (BK05)

$$\mathbf{B}_{\rm eq} = \{4\pi(2\alpha+1)(\mathbf{K}_0+1) I_\nu E_p^{1-2\alpha}(\nu/2c_1)^\alpha \,/\,(2\alpha-1)c_2(\alpha)(f_V * L)c_4(i)\}^{1/(\alpha+3))}\}$$

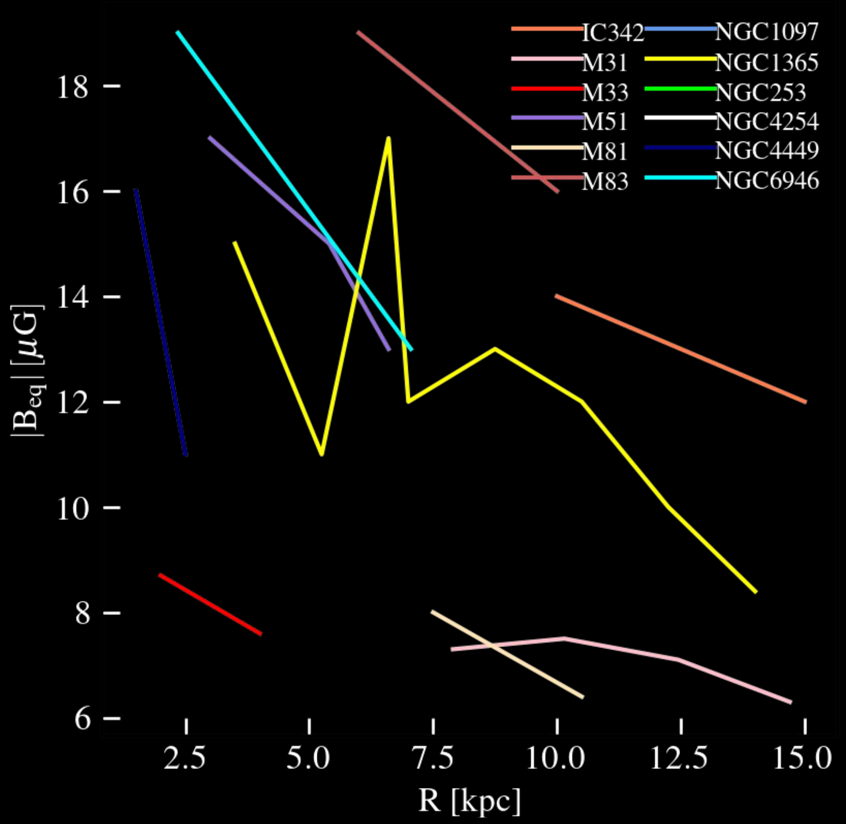


Our **B** estimates often boil down to a few points per galaxy *at best*

Many come from equipartition assumptions (BK05)

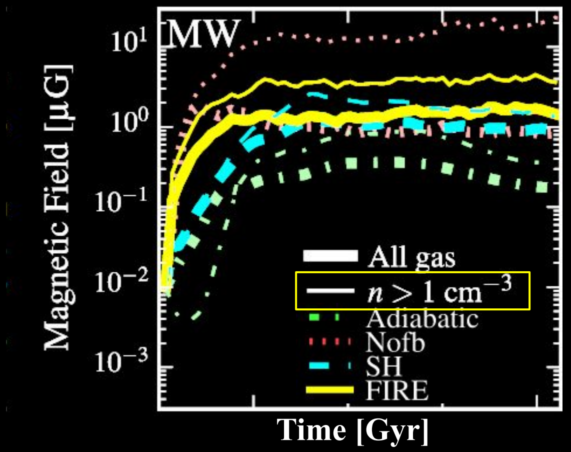
But do these hold? And *what* ***B*** is this actually measuring?

Needs forward modeling!



Beck+2019

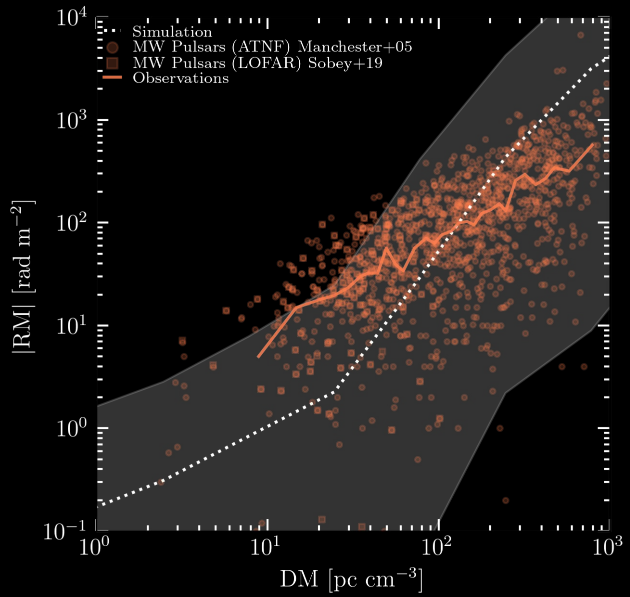
We can finally forward-model **B** and CRs from cosmological initial conditions in high detail!



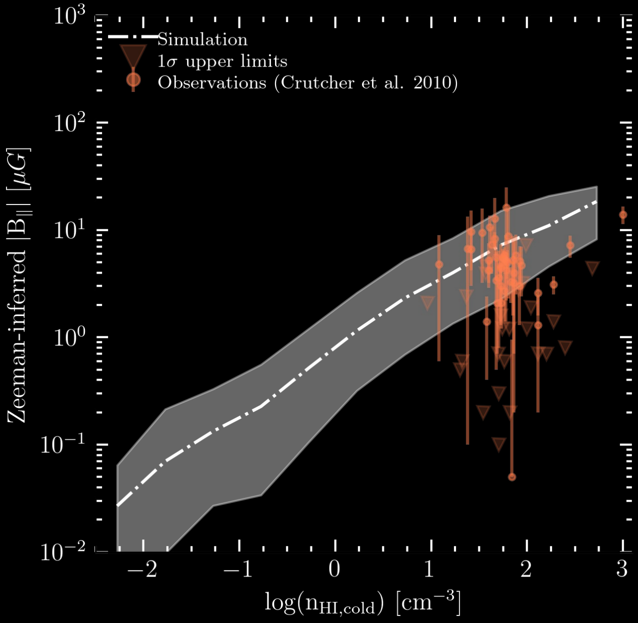
Simulation feedback models vary considerably - accurate B-field saturation strength, morphologies in dense SF gas requires crucial physics (Su+2018)

- High-res zoom-in, cosmological sims run with *GIZMO* (Hopkins+2018, 2022)
- Explicit treatment of stellar feedback, cooling
- Resolve multi-phase ISM
- Ideal MHD, anisotropic conduction+viscosity
- CRs from SNe injection

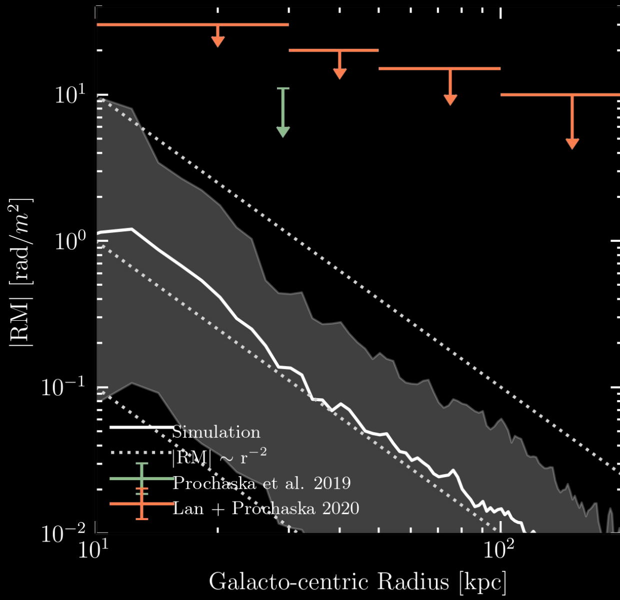
FIRE-2 Simulations produce realistic |B| and geometries in simulated L^* galaxies (**Ponnada+2022, MNRAS**)



Warm, Ionized ISM
(Dispersion and Rotation Measures)

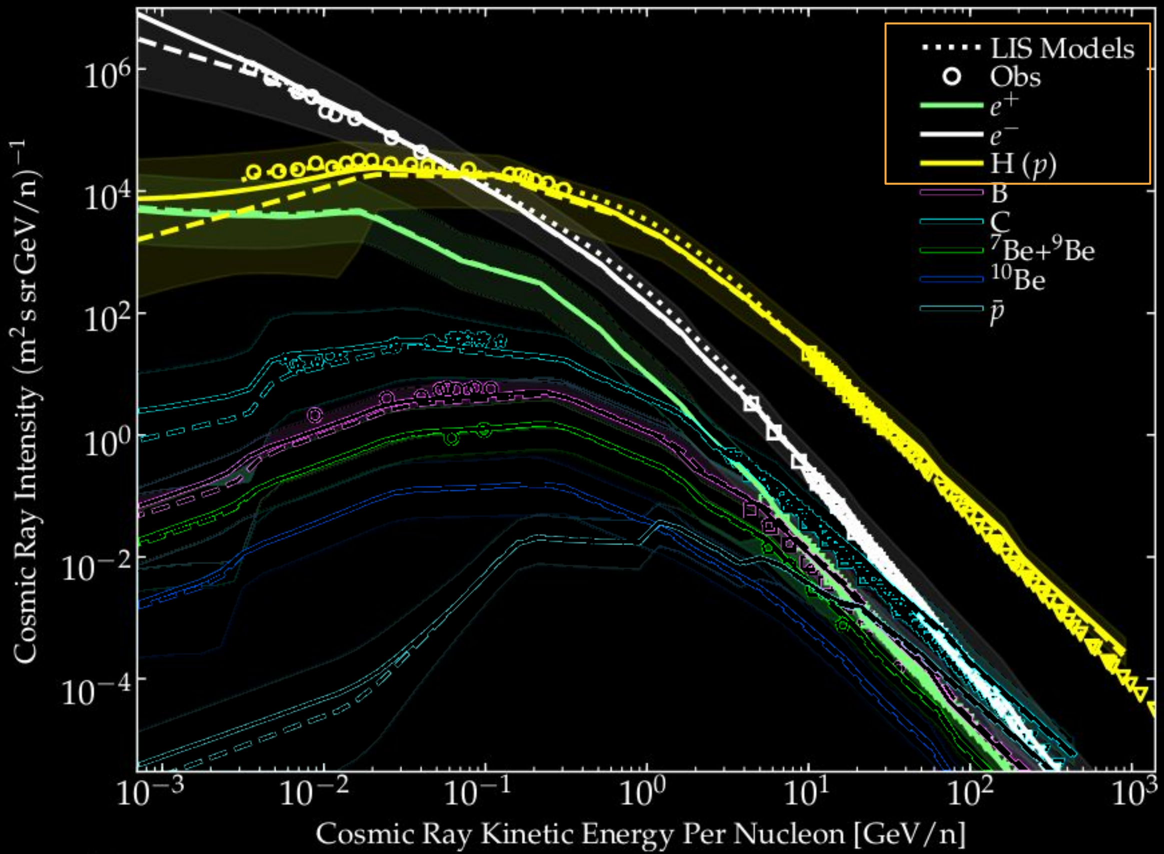


Cold, Neutral ISM
(Zeeman Splitting)



Hot, Ionized CGM
(Rotation Measures)

Now with fully resolved CR p^+, e^-, e^+, and secondary spectra! (Hopkins+2022)



CRs injected from SNe and fast OB winds with $j(R) \sim R^{-\psi}$, $\psi \sim 4.2$

10% of initial (pre-shock) SNe KE into hadrons, 0.2% into leptons

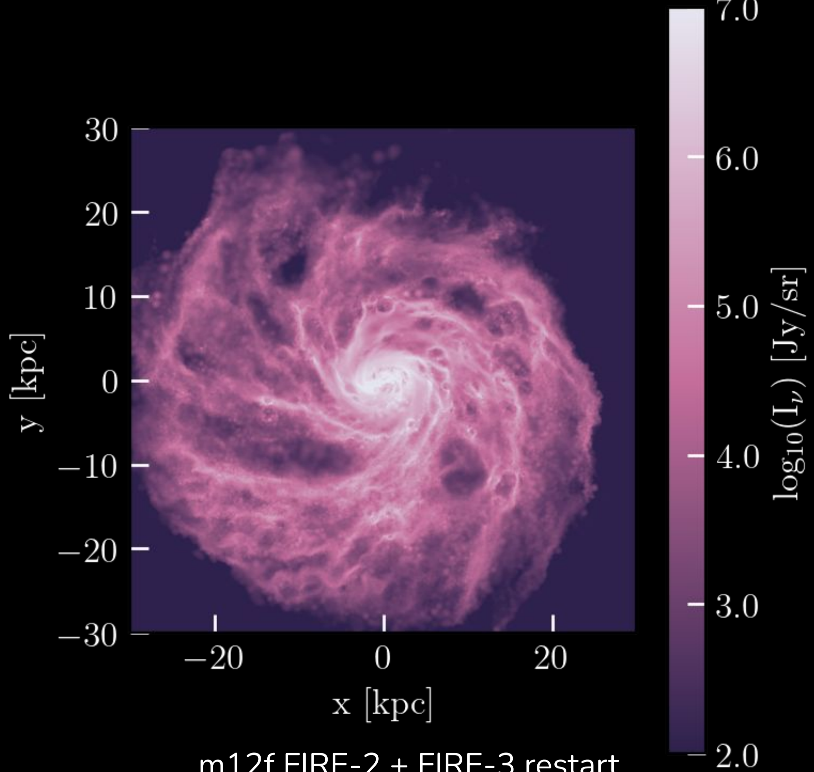
$\kappa_{eff} = \kappa_0 (E/E_{1\,GeV})^{\delta}$, $\delta = 0.5$

Forward modeling synchrotron emission from simulations with self-consistently evolved |B|, CR

Take internally evolved CRe spectrum j_e

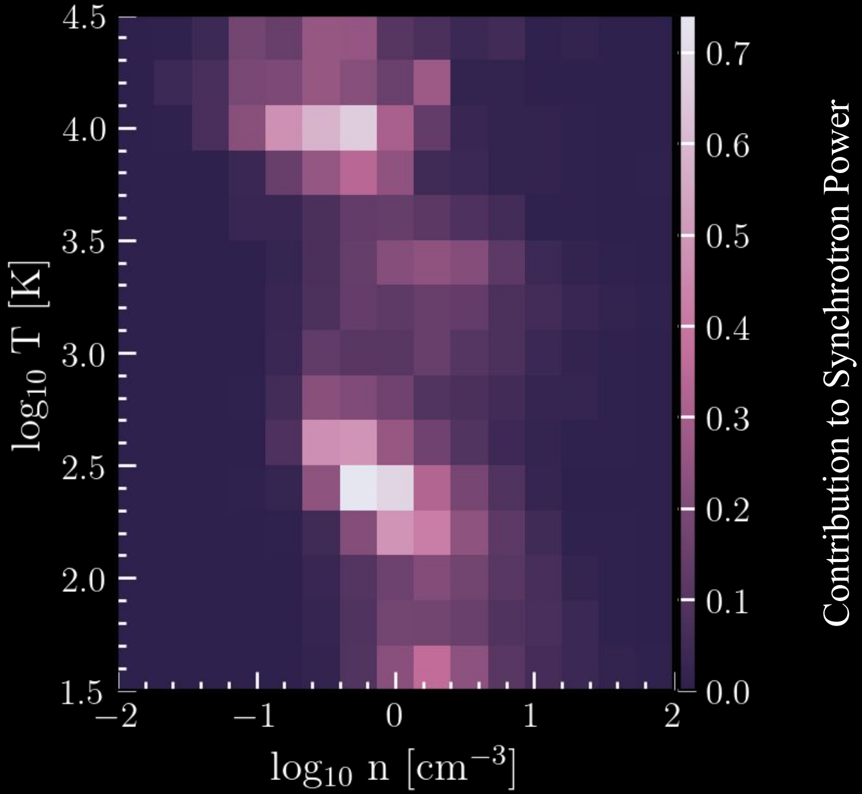
Compute $\boldsymbol{\varepsilon}_\nu(B_\perp, e_{CR})$ for each CRe bin within gas cell, integrating over spectrum

Integrate $\boldsymbol{\varepsilon}_\nu(B_\perp, e_{CR})$ along line of sight - I_ν, Q_ν, U_ν



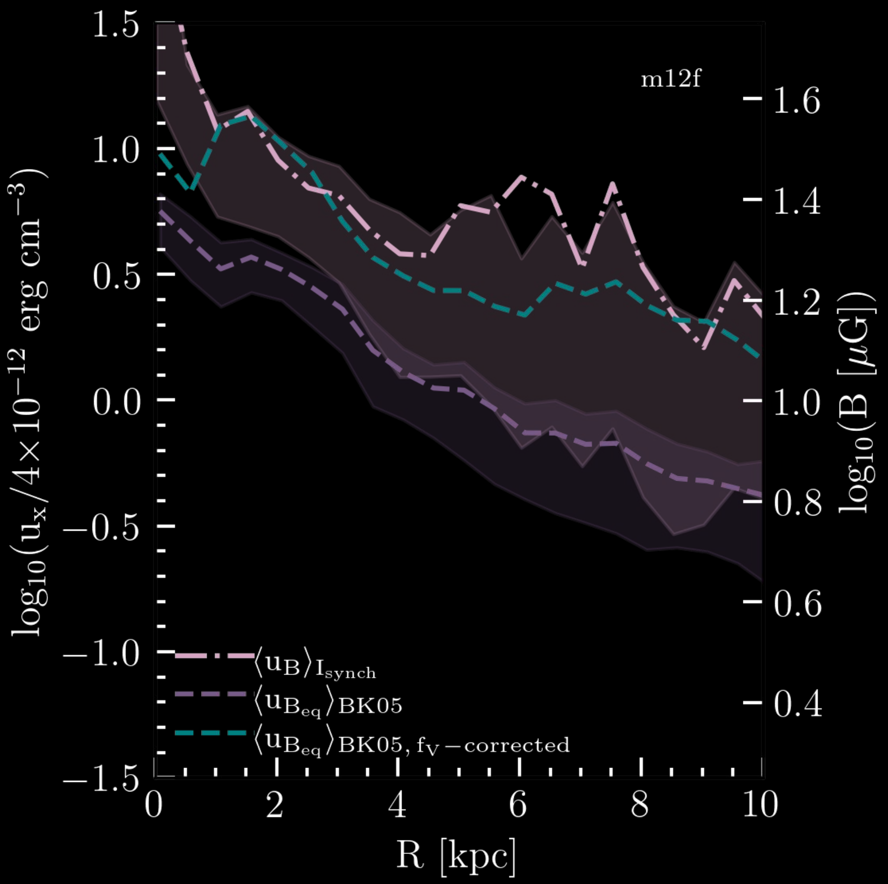
m12f FIRE-2 + FIRE-3 restart

Most of emission comes from the **WNM/CNM**, ***not*** the most volume-filling phases of the ISM (WIM/HIM)



Ponnada+2024a, MNRAS

The traditional equipartition model can underpredict **B** in the emitting gas by factors of ~2-3, primarily due overestimating L (or f_V)



Ponnada+2024, MNRAS

An interpretive toy model suggests deviation is largely due to small scale height and clumping of emission regions

$u_B(z)$ and $u_{CR}(z)$ allowed to vary (non-equipartition)

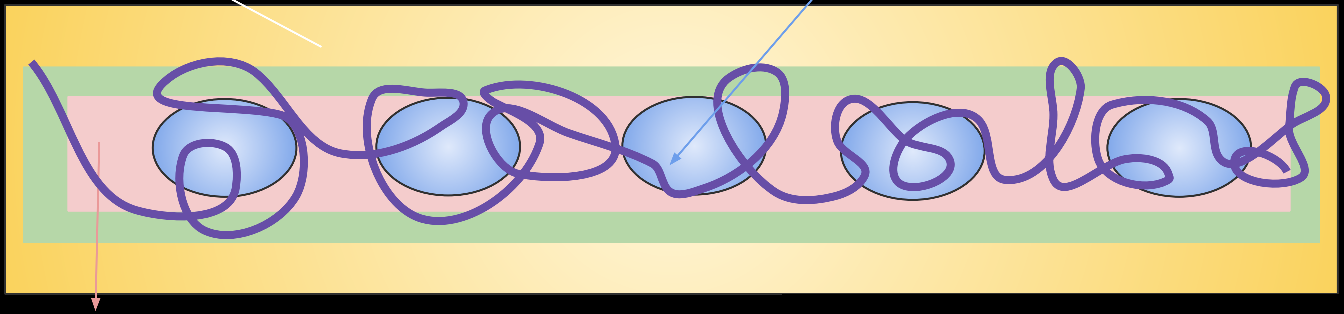
$$\langle u_{\rm B} \rangle = \langle u_{\rm B_0} \rangle e^{-(|z|/H_B)}$$

$$\langle e_{\rm CR} \rangle = \psi * \langle u_{\rm B_0} \rangle \left(\frac{\langle u_{\rm B} \rangle}{\langle u_{\rm B_0} \rangle} \right)^{\beta}$$

Multi-phase ISM with clumping factor

$$P_V(\ln \delta_{u_B}) = \frac{V_{tot}}{\sqrt{2\pi S_\delta}} \exp\left\{ -\frac{(\ln \delta_{u_B} + S_\delta/2)^2}{2 S_\delta} \right\}$$

$H_B < L$



Dense, neutral, midplane gas dominates the emission

$$\langle u_{\rm B_0} \rangle = \left(\frac{\gamma \langle I_\nu \rangle}{2\psi C * H_B \exp\left\{ \frac{S_\delta (\gamma - 1)\gamma}{2} \right\}} \right)^{2/(\alpha+3)}$$

At the cost of introducing physical parameters due to relaxing assumptions, can get a better hold of *what* ***B*** or $\mathbf{e}_{\mathbf{CR}}$ *we estimate (weighted by* I_{synch}*, V, etc.)!*

Ponnada+2024a, MNRAS

Cosmic rays may be important, depending on their transport. What about plasma-physically motivated models of transport?

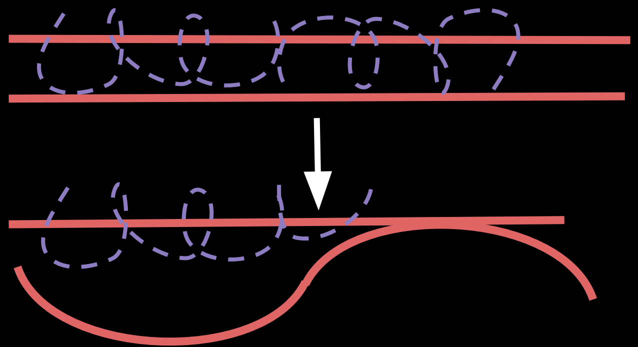
(Hopkins+2021)

“Extrinsic Turbulence” (ET)

Scatter off magnetic field fluctuations in background medium

$$\kappa_{\parallel,ET} \sim 10^{32}\mathrm{cm}^2\mathrm{s}^{-1}\mathcal{M}_{\mathrm{A}}^{-2}\ell_{\mathrm{turb,kpc}}\mathrm{f}_{\mathrm{turb}}$$

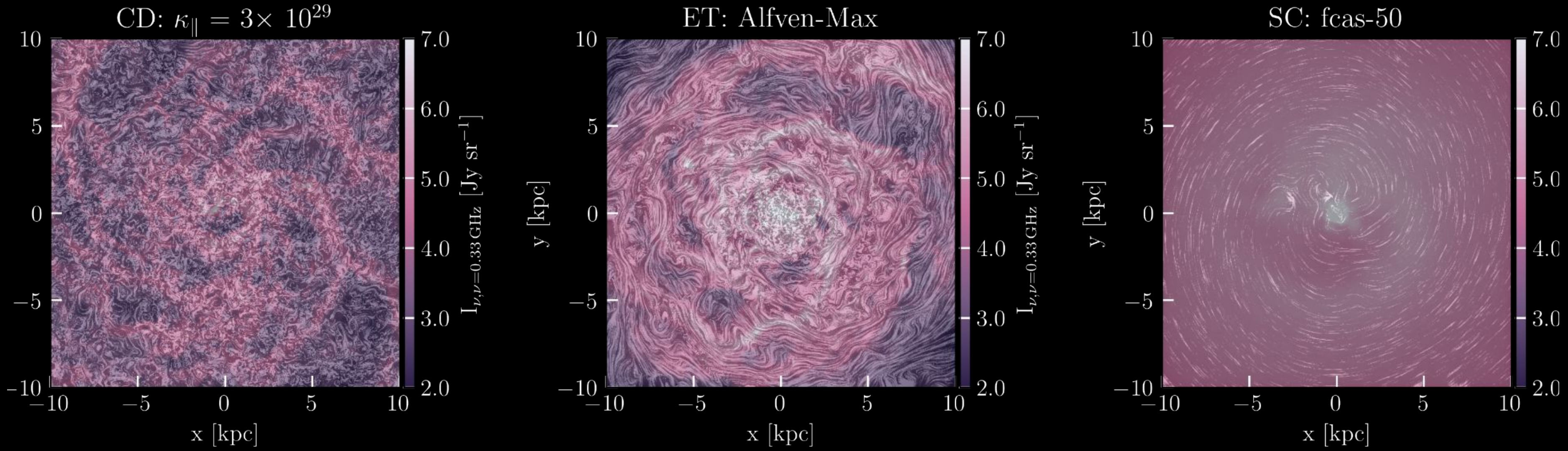
“Self-Confinement” (SC)



Scatter off self-excited gyro-resonant Alfven Waves

$$\kappa_{\parallel,SC} \sim 6 \times 10^{26}\mathrm{cm}^2\mathrm{s}^{-1}\frac{\gamma_{\mathrm{L}}\Gamma_{-11}\ell_{\mathrm{cr,kpc}}\mathrm{f}_{\mathrm{ion}}^{1/2}\mathrm{n}_1^{1/2}\mathrm{f}_{\mathrm{QLT}}}{\mathrm{e}_{\mathrm{cr,eV}}}$$

Different micro-physically motivated[1] CR transport models tell a tale of hysteresis in synchrotron emission![*]



m12i with different CR physics, all else equal

Ponnada+2024b, in review, MNRAS

[1] with some plausible ad-hoc re-normalizations

[*]single-bin FIRE-2 L_* runs (*not spectrally resolved*)

In short,

Synchrotron emission can be dominated by relatively dense phases of the ISM

Equipartition model with fiducial assumptions can underpredict **B** in this emitting gas by factors of ~2-3, primarily due overestimating f_V

There is not a *single* **B** in the ISM! - it is clumpy, stratified and multi-phase

Different CR transport prescriptions predict different gas properties + synchrotron!

Paper I

Check out the papers here!

Paper II

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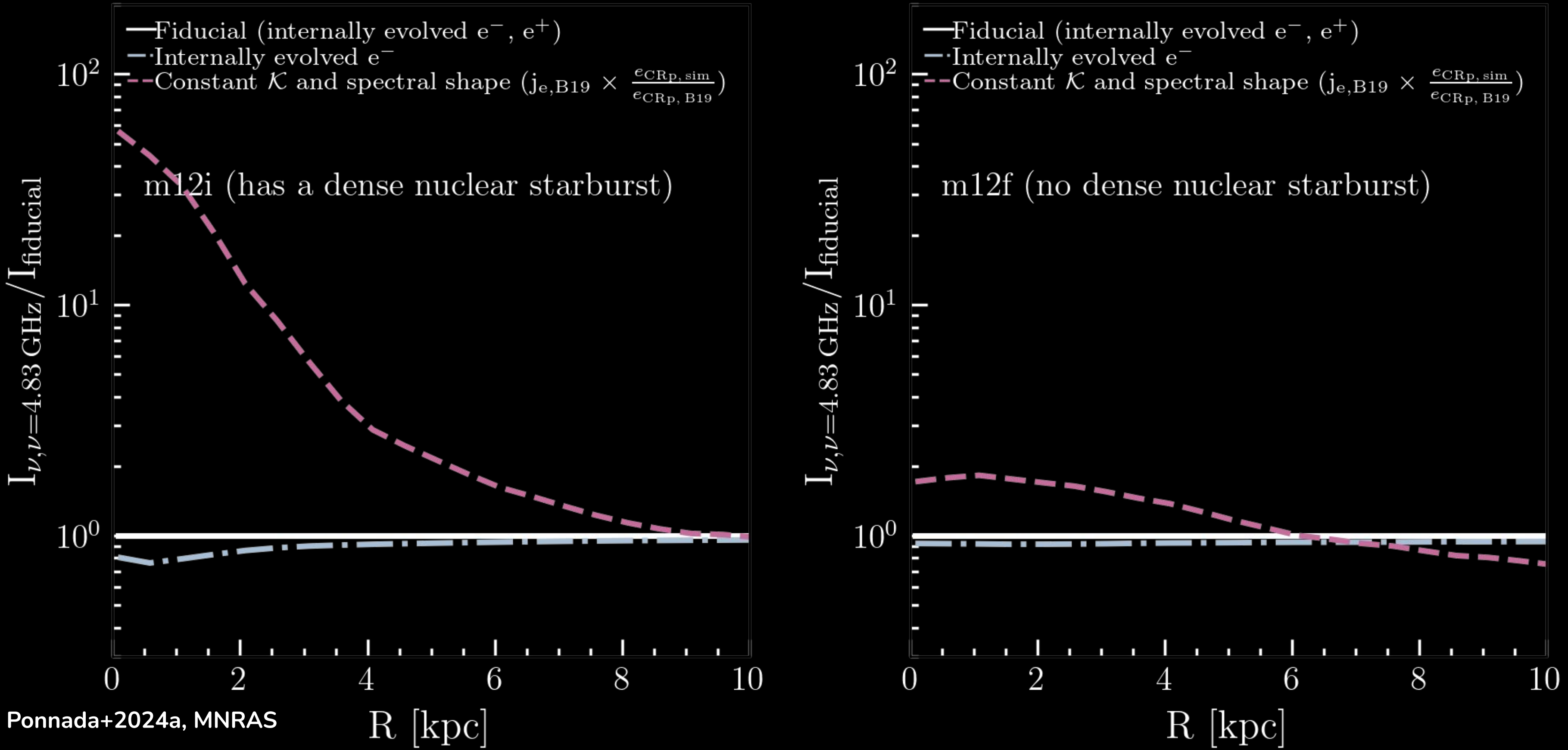
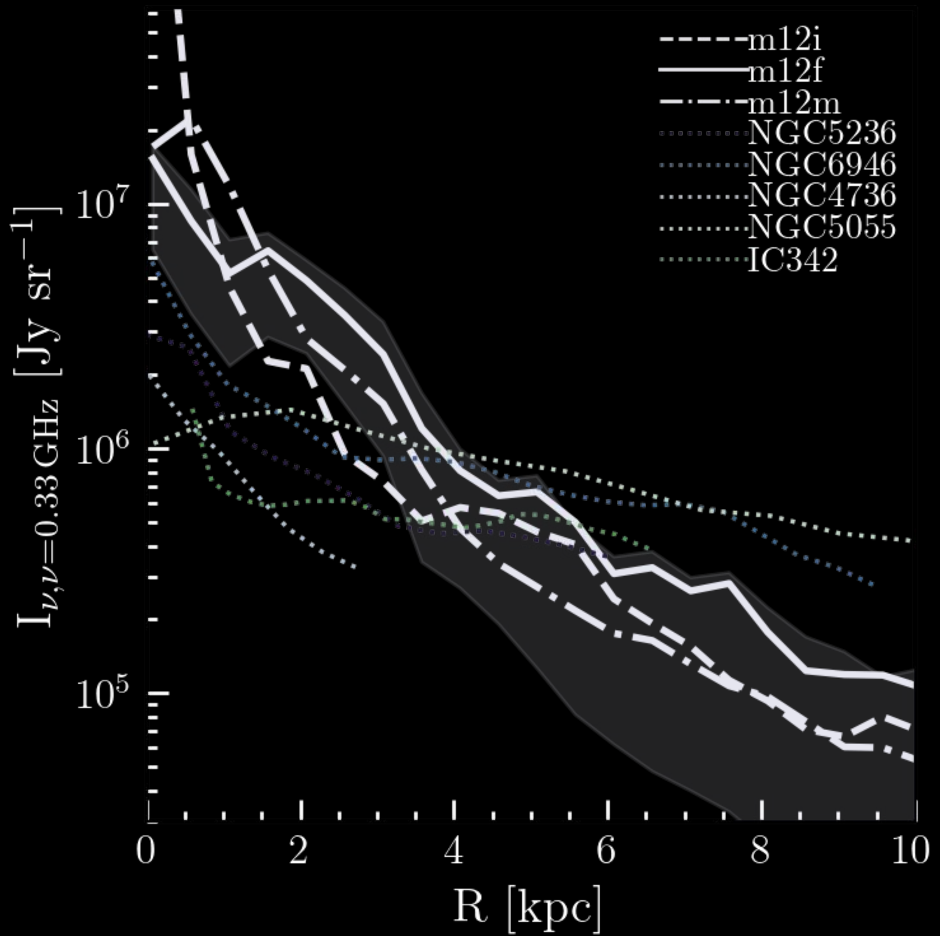
Thank you for your attention! Questions?

Spectral variation not so important for typical spiral galaxy conditions, but can be significant where losses are large!

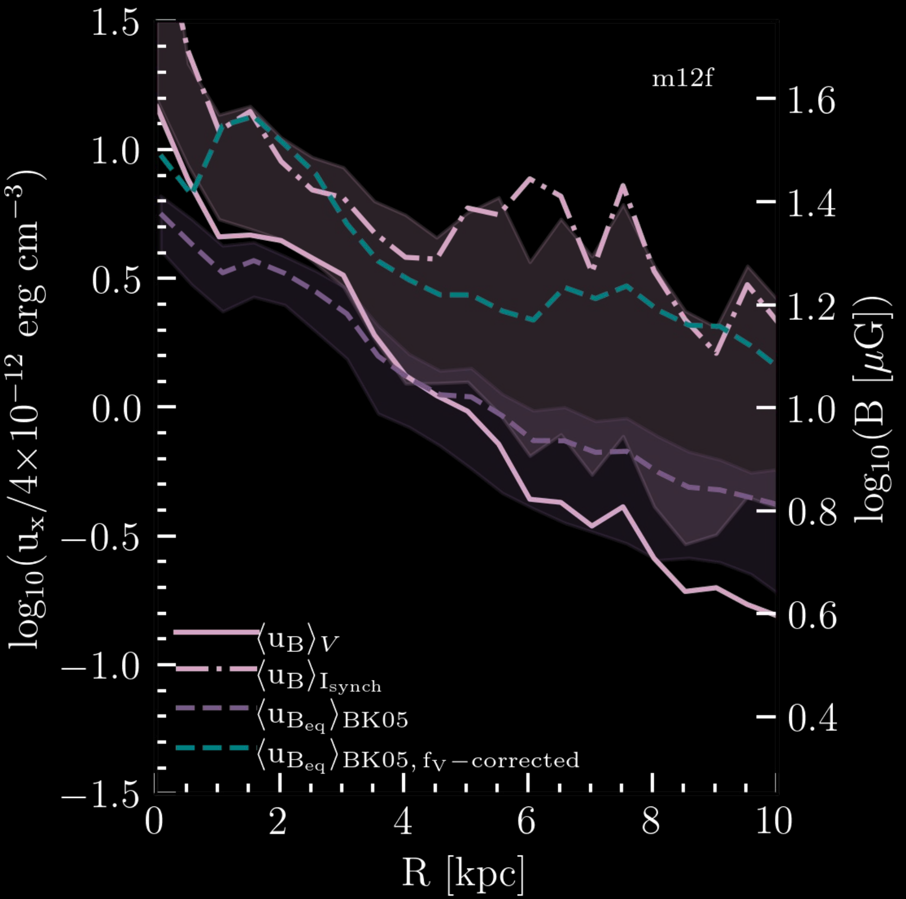


Ponnada+2024a, MNRAS

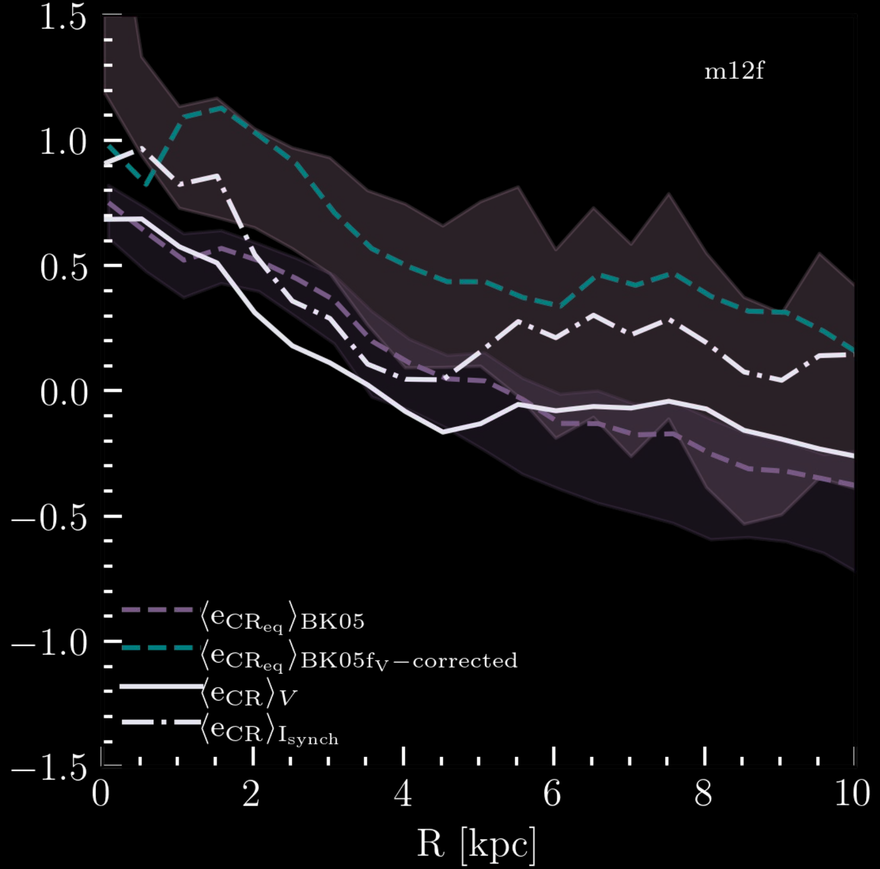
FIRE-3 L_* galaxies in OoM agreement with observed nearby face-on spiral galaxies



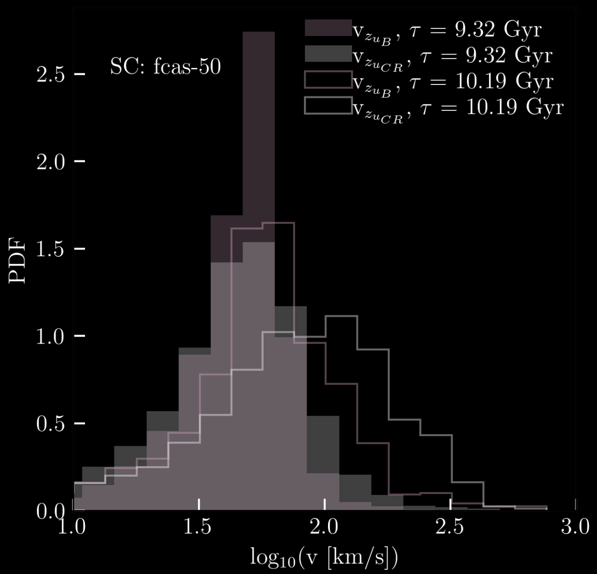
BK05 *can* get volume-weighted B, but is due to a conspiracy of factors, can also under-/over-predict in inner/outer disk by factor ~ 1.5x



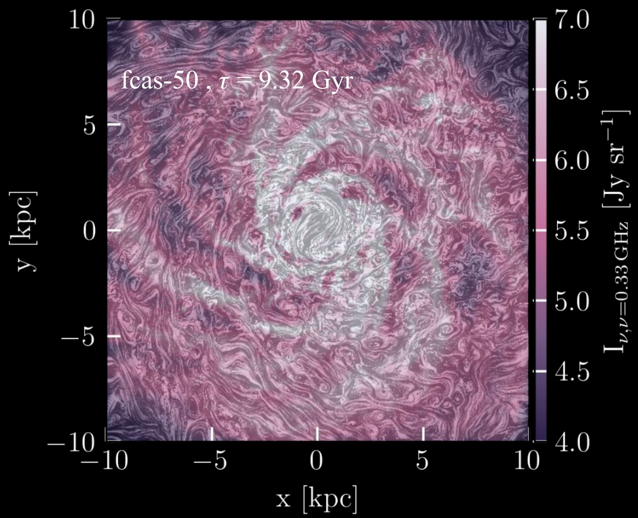
Traditional equipartition model also under-predicts e_{CR} in emitting gas, though not to same degree as u_B

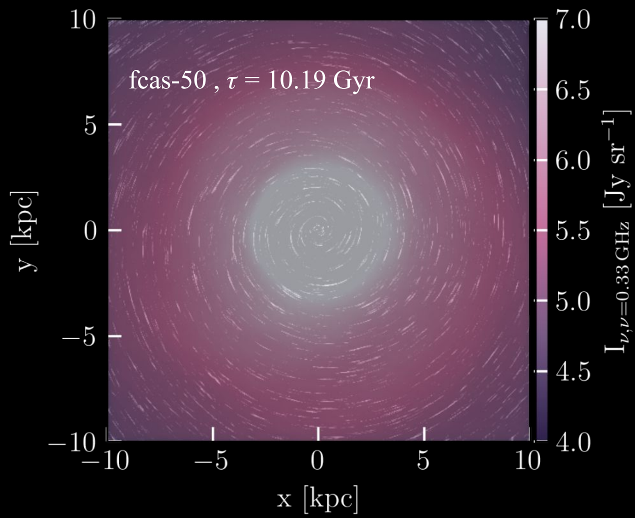


SC models can undergo extreme ejective feedback via CR-driven winds due to 'SC runaway'



SC runaway leads to 'ejective' feedback event, driving winds out of the galaxy





Leads to changes in morphology, B + phase structure, coincident with change in synchrotron properties

Ponnada+2024a, in review, MNRAS