The fundamental uncertainties of cosmic rays on galactic scales

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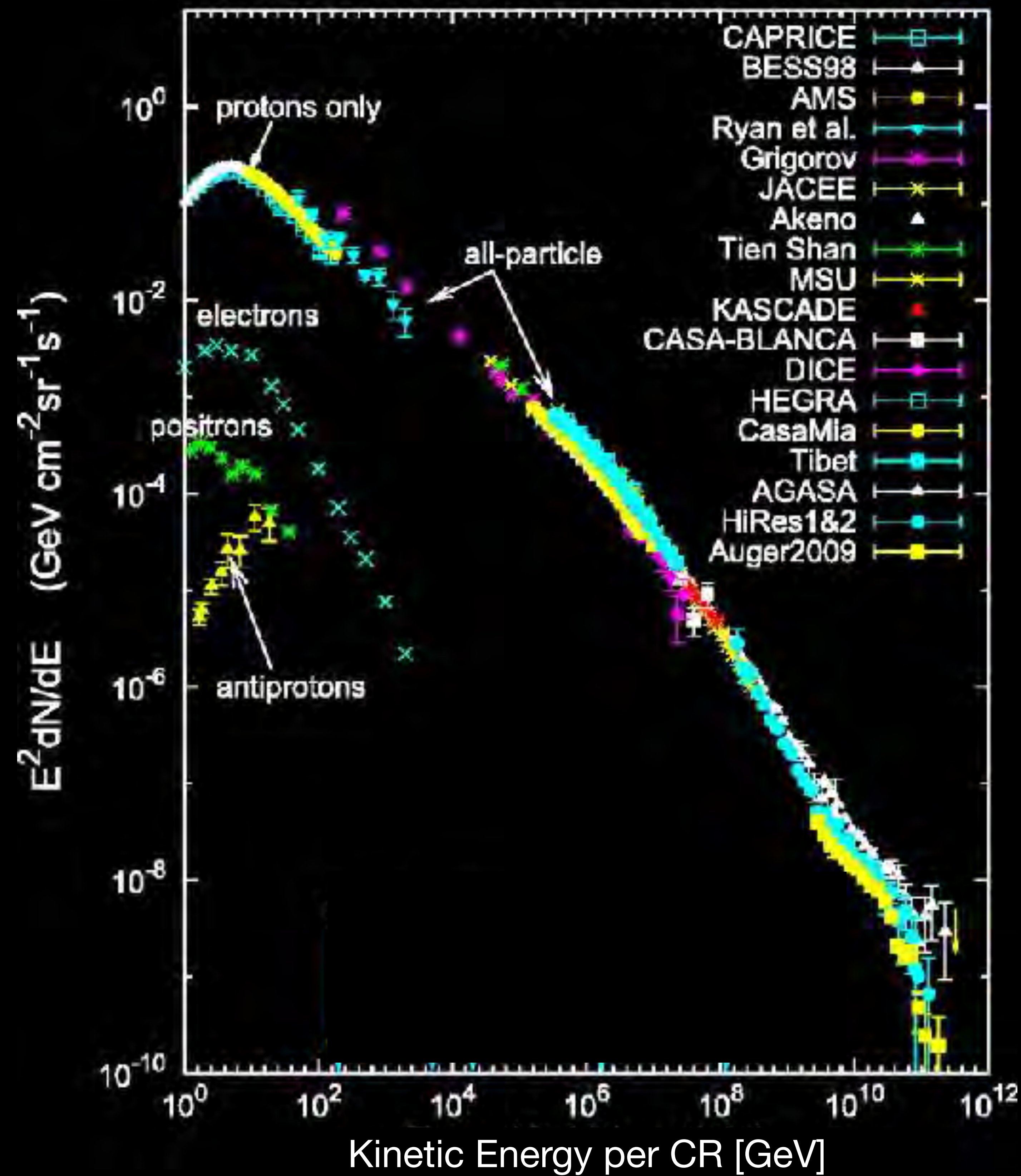
FIRE & STARFORGE teams

Cosmic Rays: Some Background

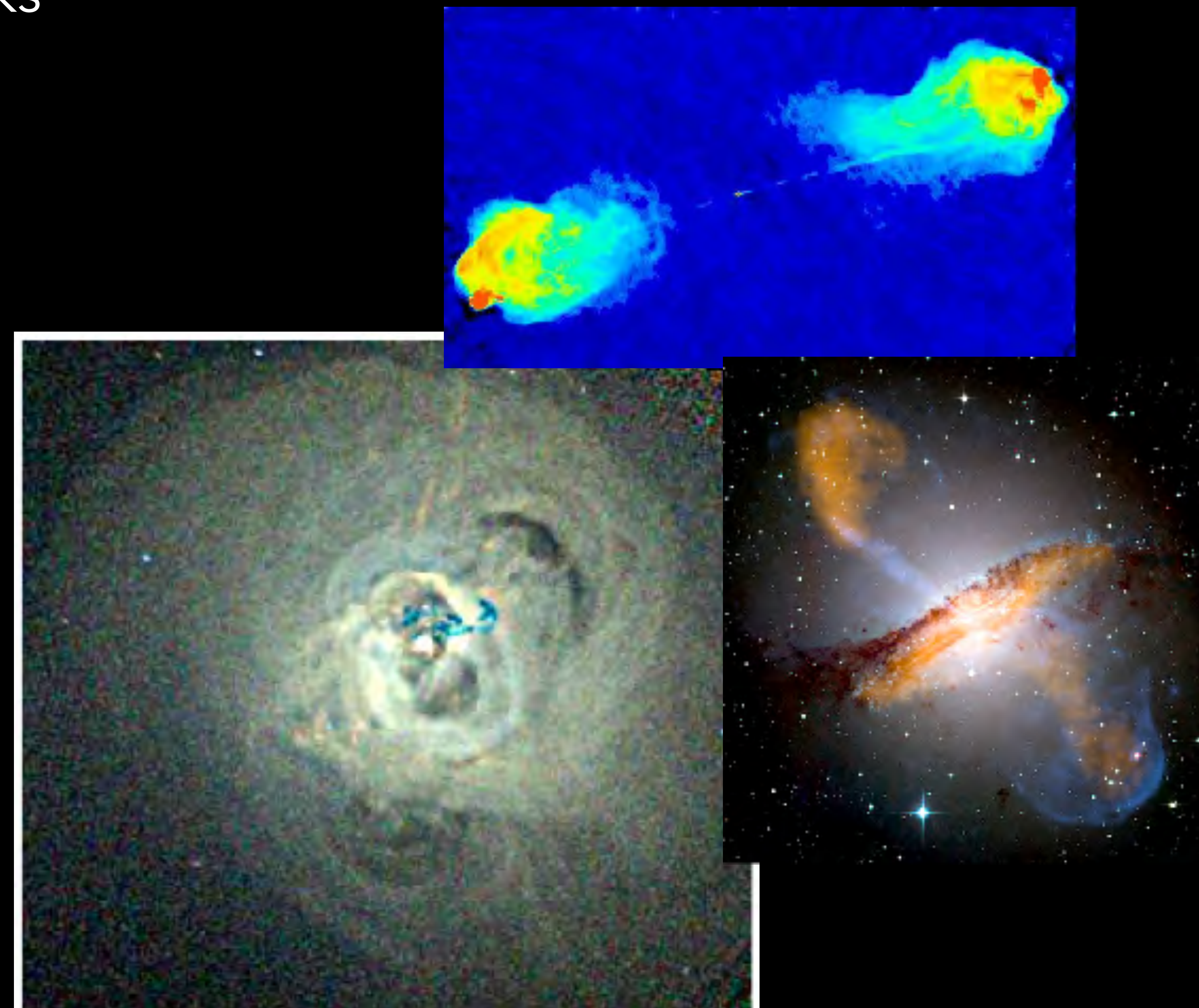
- Relativistic particles: energy/pressure in ~GeV (mildly-relativistic) protons
- Local ISM: CR Pressure ~ equipartition, but “smoother” (scale height ~ kpc)
- “Cooling” (loss) time ~ 30 Myr ($\mathrm{cm}^{-3}/n_{\rm gas}$)
- ~10% of SNe energy, ~% of AGN



Cosmic Rays: Primary Sources

AGN "radio" or "jet" mode

Accelerated in SNe/strong shocks



Power: ~10% ejecta energy

Power: ~% of $\dot{M}_{\rm BH}\, c^2$?

(jet >~ cooling luminosities; Allen, Best, & others)

Cosmic Rays:

Conventional wisdom:

- CRs could be important in the warm/ionized ISM, or in a ± 1 kpc "halo"

- CR transport derives from some mix of "extrinsic turbulence" and "self-confinement"

Cosmic Ray Propagation: there is a "correct" formulation (and it's not Fokker-Planck)

Streaming/ Diffusive transport · Radiative Losses · "Adiabatic" · Streaming Losses · Diffusive Reacceleration · Injection & Catastrophic Losses

$$D_t \bar{f}_0 + \nabla \cdot (v \bar{f}_1 \hat{\mathbf{b}}) = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\mathscr{R}\bar{f}_0 + p\bar{f}_0(\mathbb{D} : \nabla \mathbf{u}) + \bar{\nu}\, p\left\{\frac{\bar{v}_A}{v}\bar{f}_1 + \frac{\chi v_A^2}{v^2}\frac{\partial \bar{f}_0}{\partial \ln p}\right\}\right)\right] + j$$

$$D_t \bar{f}_1 + \hat{\mathbf{b}} \cdot \nabla \cdot (v\, \mathbb{D}\, \bar{f}_0) = -\bar{\nu}\left[\bar{f}_1 + \frac{\chi \bar{v}_A}{v}\frac{\partial \bar{f}_0}{\partial \ln p}\right]$$

Diffusive transport + magnetic focusing

Streaming transport

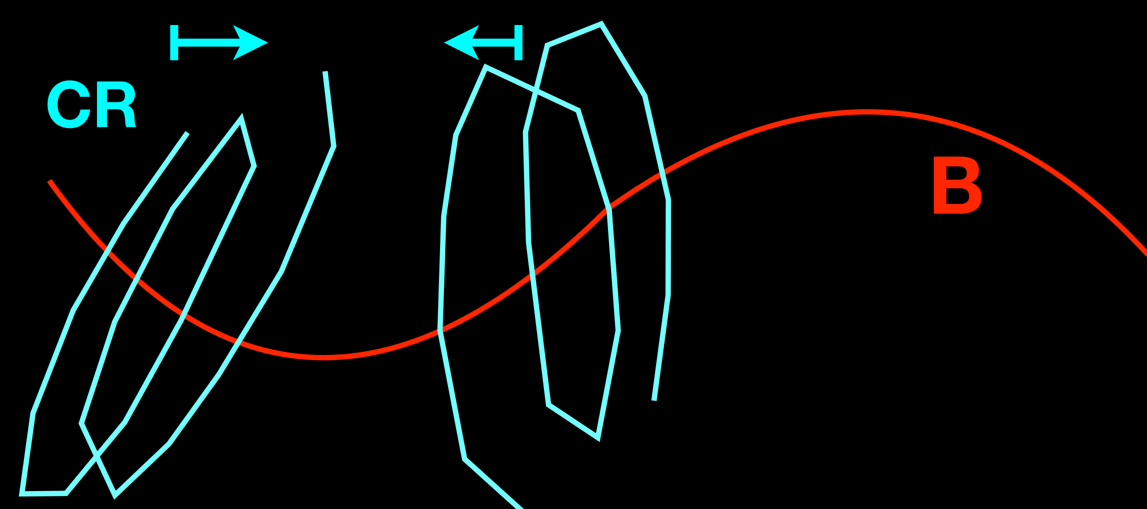
(Diffusivity: $\kappa \sim \frac{c^2}{\nu}$)

(Streaming: $v_{\rm bulk} \sim \frac{\kappa}{\ell}$)

CR Scattering Rate

PFH, Squire, & Butsky
arXiv:2103.10443

See also: Zweibel+ '17, Thomas & Pfrommer '22



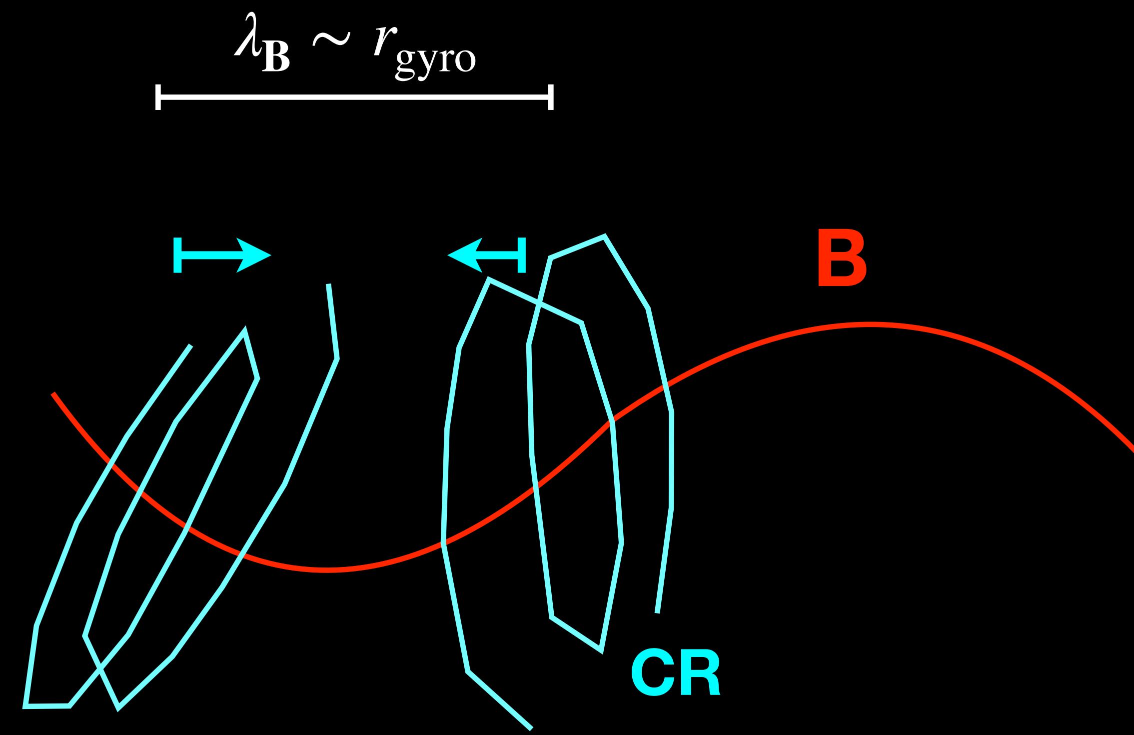
$$\lambda_{\mathbf{B}} \sim r_{\rm gyro} \sim 0.1\,{\rm au}\left(\frac{E_{\rm CR}}{\rm GeV}\right)\left(\frac{\mu{\rm G}}{|\mathbf{B}|}\right)$$

Cosmic Rays: Propagation

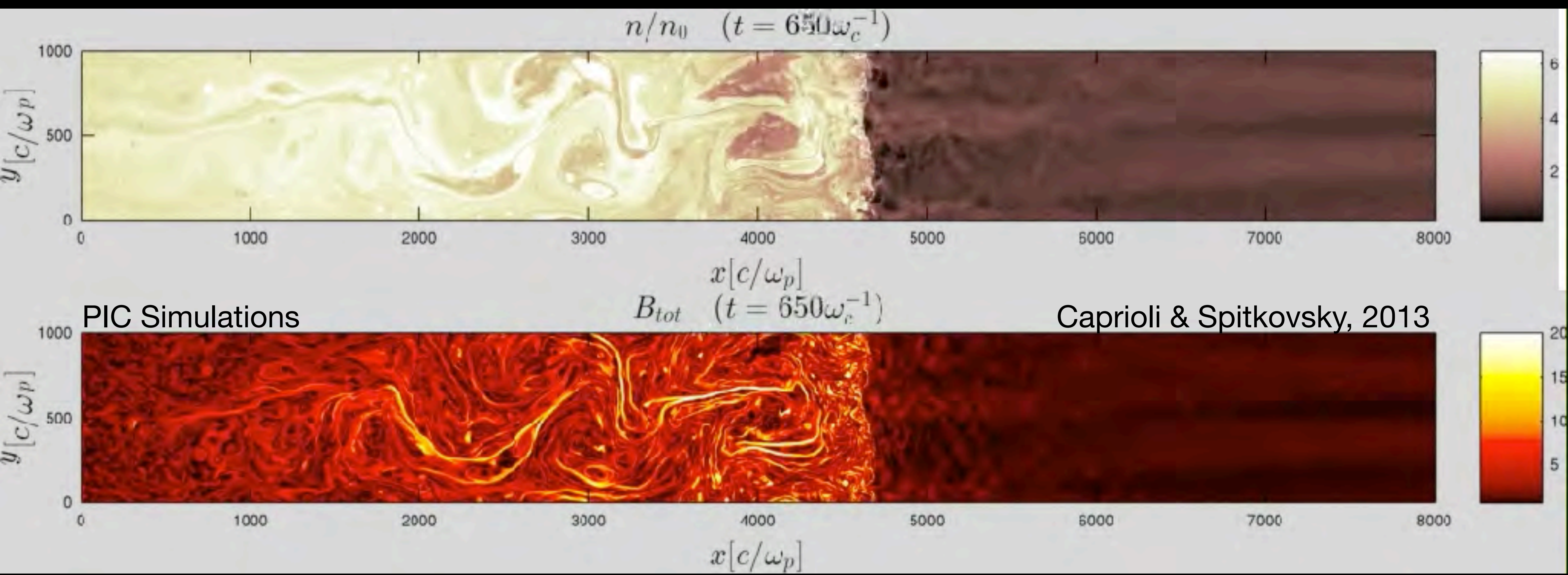
"Scatter" off B-field fluctuations:

scattering rate $\nu \sim \Omega_{\rm gyro} \dfrac{|\delta \mathbf{B}(\lambda \sim r_{\rm gyro})|^2}{|\mathbf{B}|^2}$

$\rightarrow$ Diffusivity or streaming: $\kappa \sim \dfrac{c^2}{\nu}$, $v_{\rm bulk} \sim \dfrac{\kappa}{\ell} \ll c$



$r_{\rm gyro} \sim 0.1\ {\rm au} \left(\dfrac{E_{\rm CR}}{\rm GeV}\right)\left(\dfrac{\mu{\rm G}}{|\mathbf{B}|}\right)$

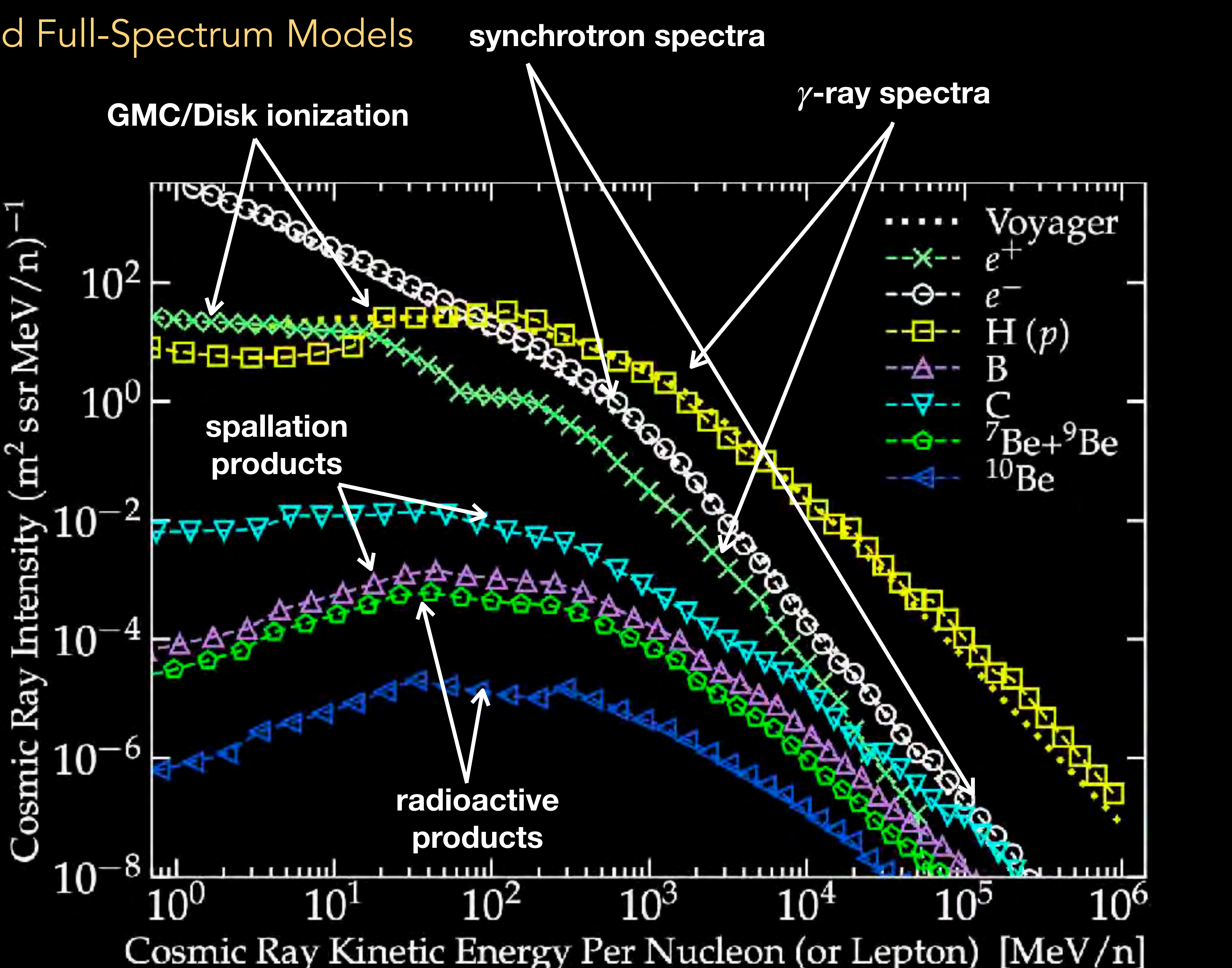


PIC Simulations

Caprioli & Spitkovsky, 2013

So How Do We Deal With This?

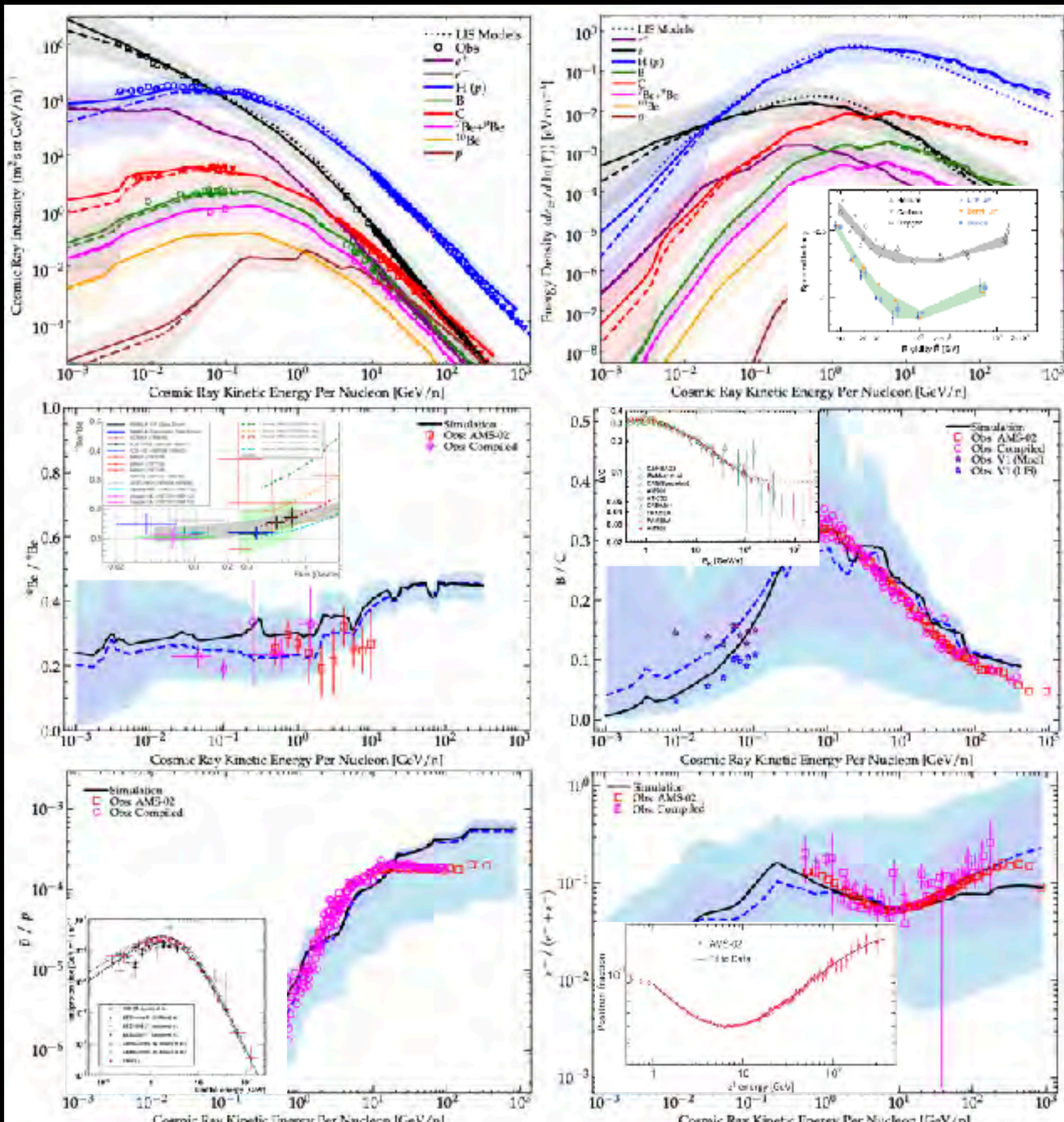
Need Full-Spectrum Models



Fit *everything* with a "typical" ISM scattering rate

PFH, Butsky, Panopoulou, Ji et al.
arXiv: 2109.09762





CR Spectra & Species/Isotopic Ratios:

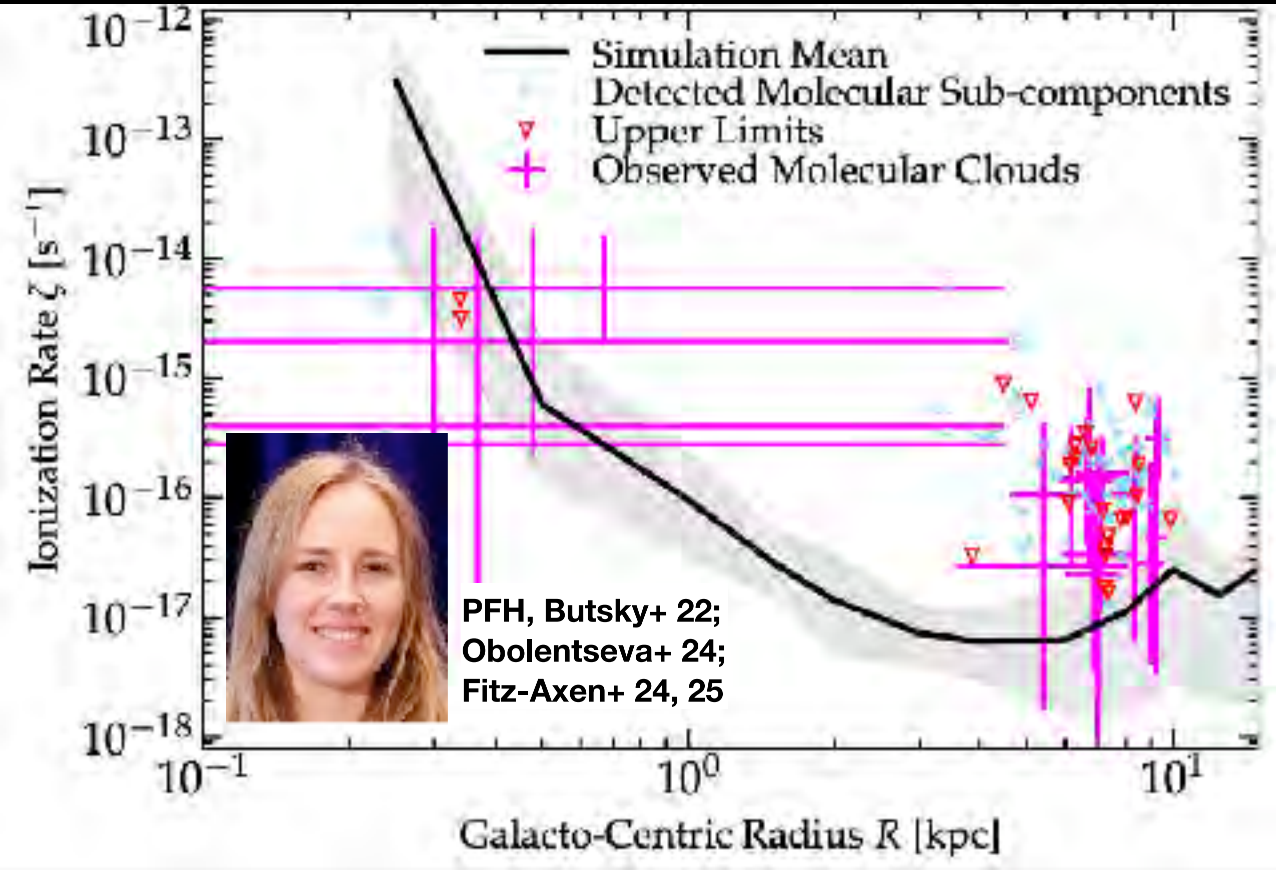
$e^-, e^+,$
$p/H, \bar{p},$
$He, Li,$
$^{7}Be, ^{9}Be, ^{10}Be,$
$B,$
$C, N, O,$
$Fe,$
…

<1 MeV through >TeV *modeled explicitly*

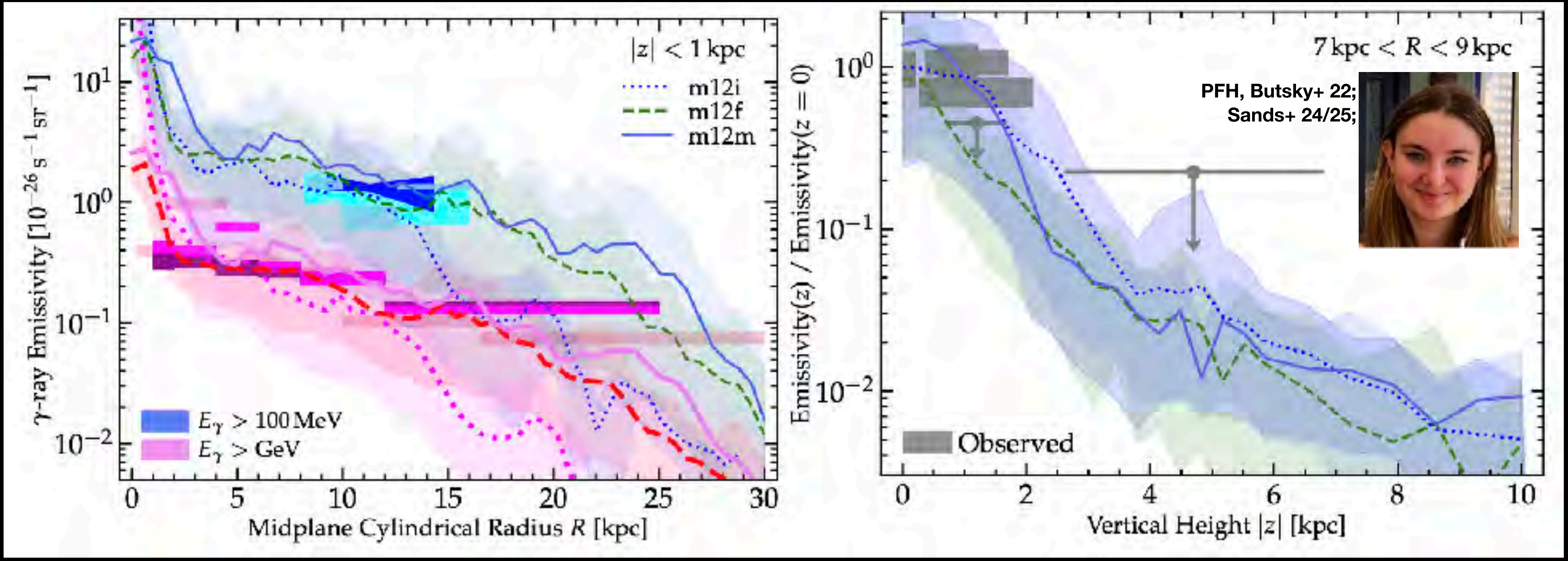
First Spectral CR-MHD Galaxy simulations!

Cosmic Rays: Calibration Works!

MW CR ionization:
vs. Galactic radius,
GMC column density



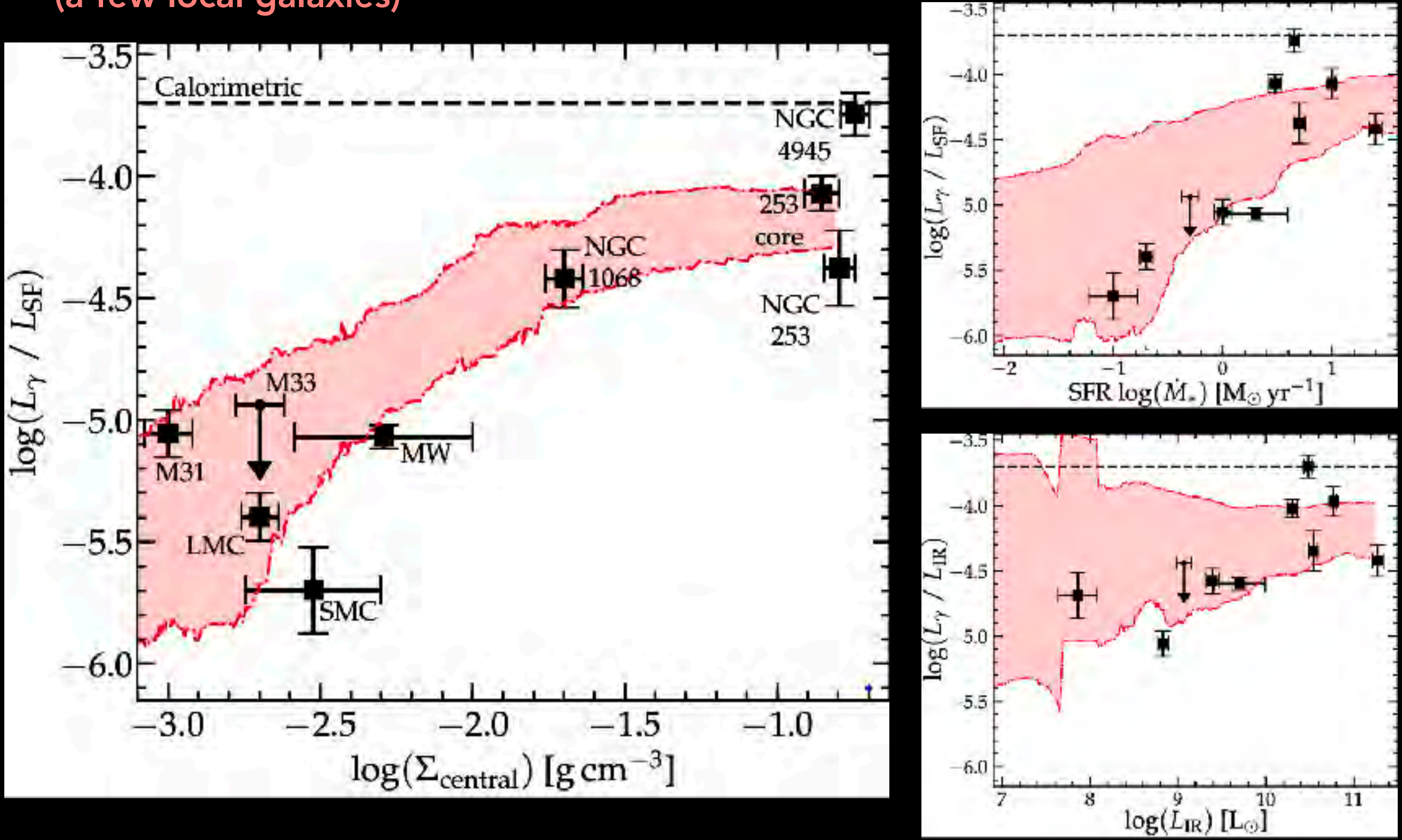
MW γ-ray spectra & maps



Cosmic Rays: Calibration Works!

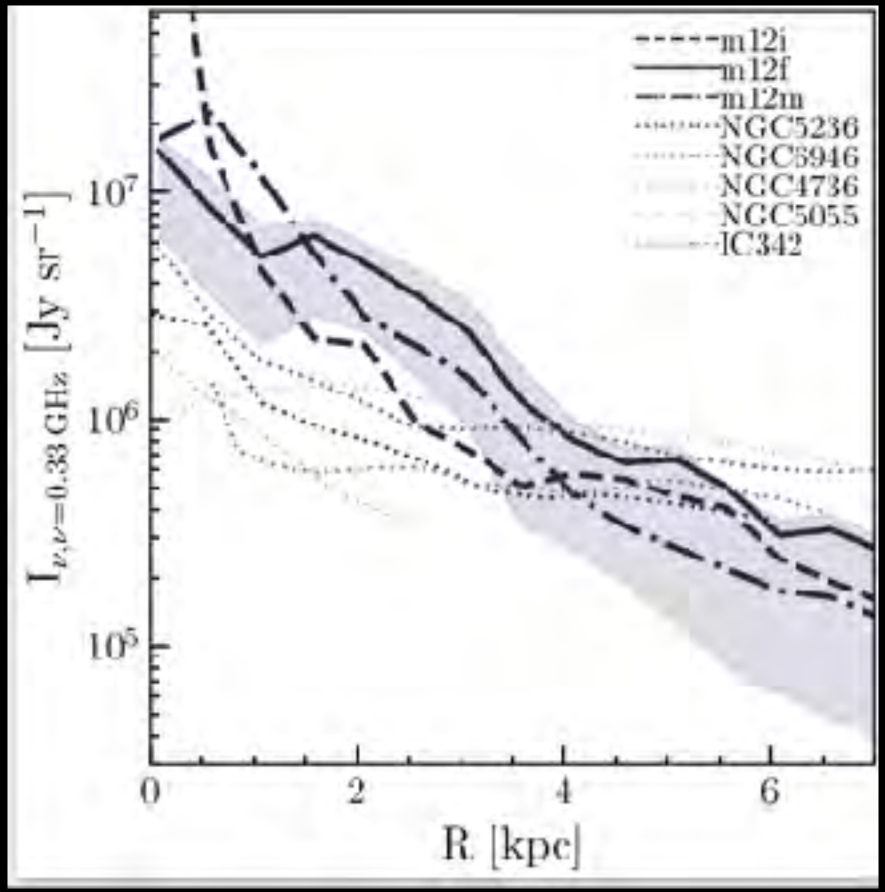
Chan et al. '19
PFH, Squire+ 20, 22b

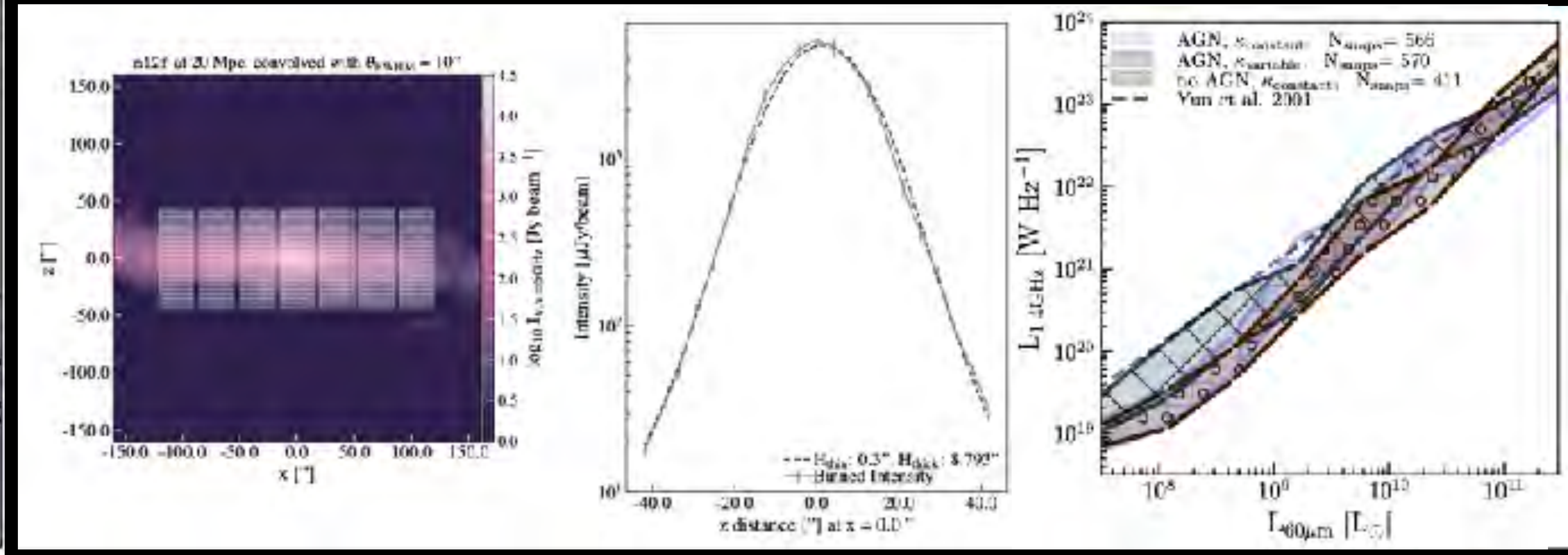
Galaxy-integrated γ-rays
(a few local galaxies)



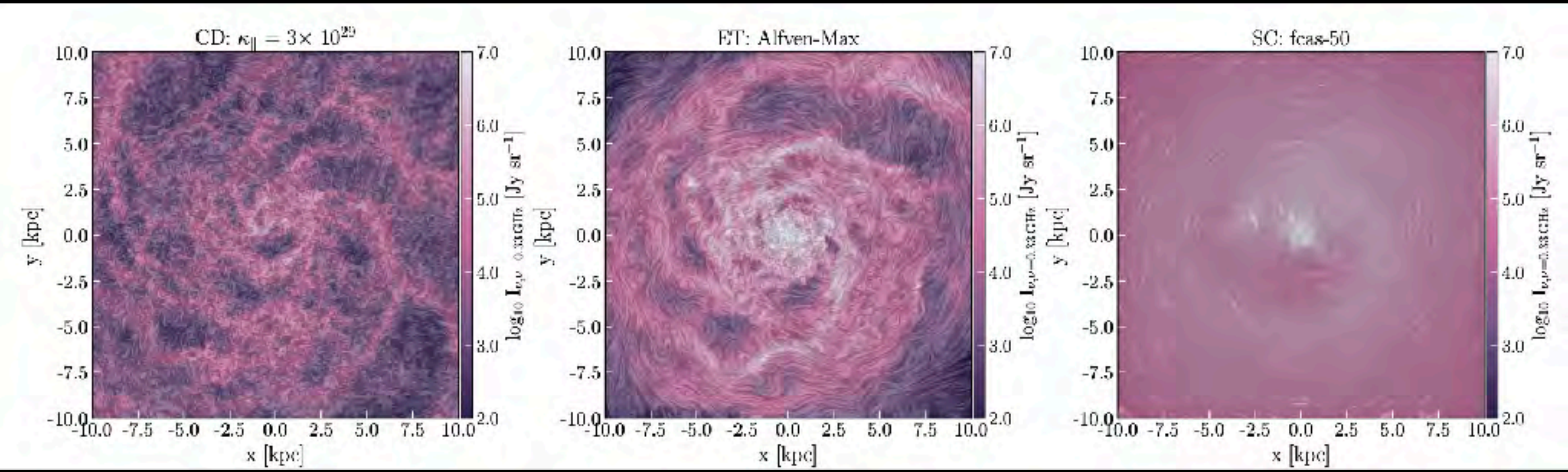
Cosmic Rays: Calibration Works!

Ponnada+ 24b, 24c, 24d





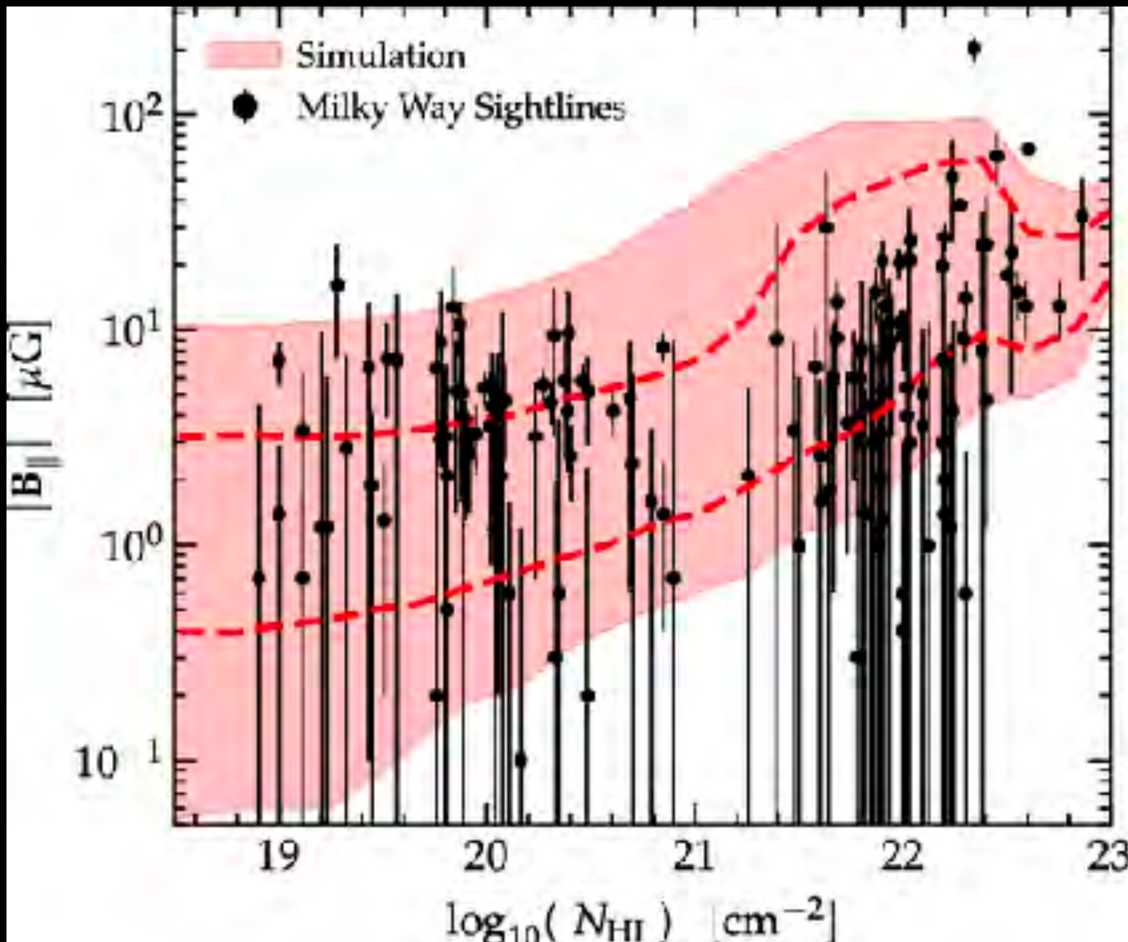
Synthetic Synchrotron Spectra & Images



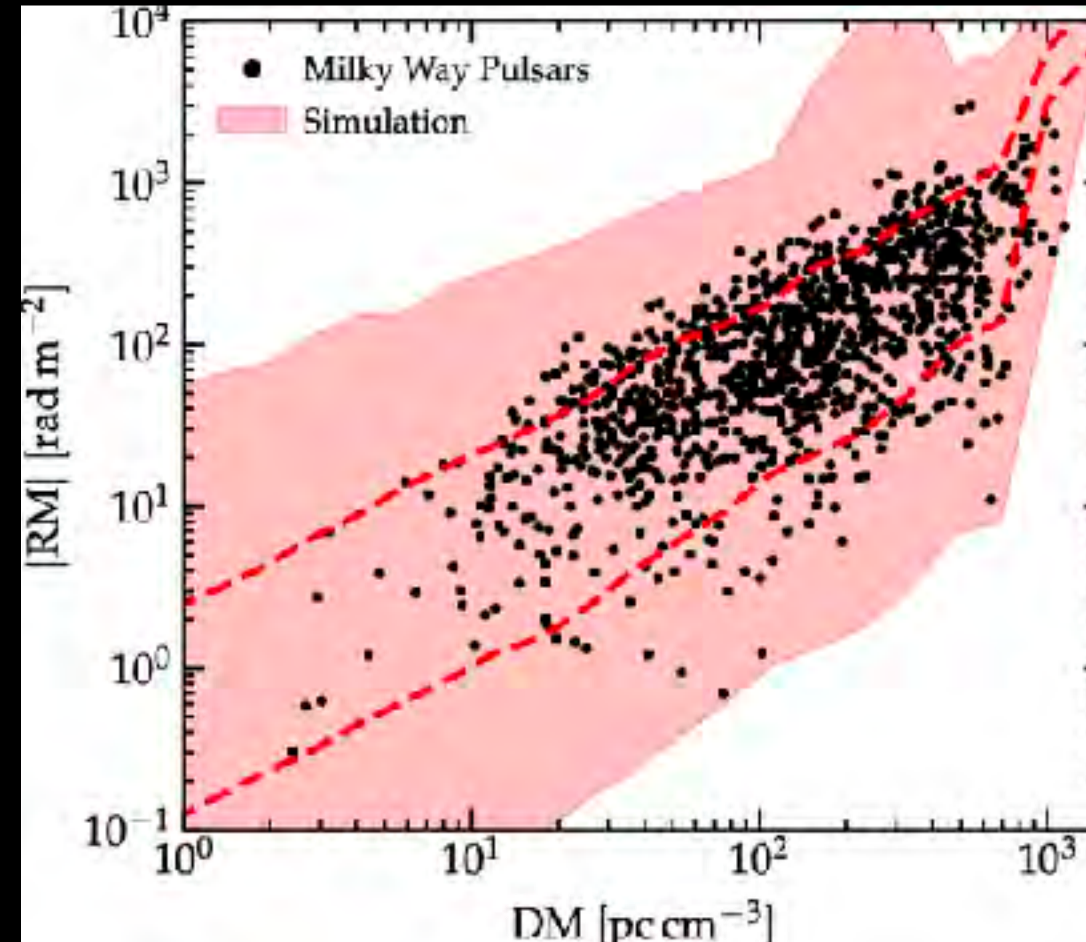
Check: Magnetic Fields

Ponnada+ 22b
Goyal & Ponnada '25

Mock Zeeman Observations

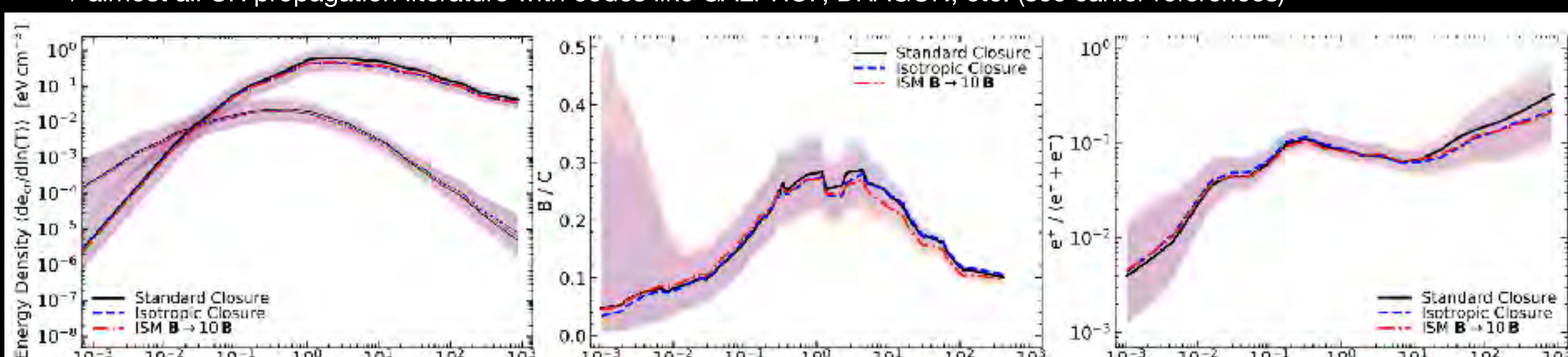


Mock Pulsar RM/DM Observations



also vs obs: Su et al. '17, Su et al. '18, Guszejnov et al. '20, Guszejnov et al. '21, Ponnada et al. '22

B-field amplitude largely irrelevant: Guo et al. '16, Su et al. '19 & '20, Genoli et al. '19, Chan et al. '19, Hopkins et al. '20 & '21,
+ almost all CR propagation literature with codes like GALPROP, DRAGON, etc. (see earlier references)



Empirically: Remarkable Consensus

$$\bar{\nu}_{\rm eff} \sim \nu_9\, 10^{-9}\, {\rm s}^{-1}\, \beta\, (R/{\rm GV})^{-\delta}$$

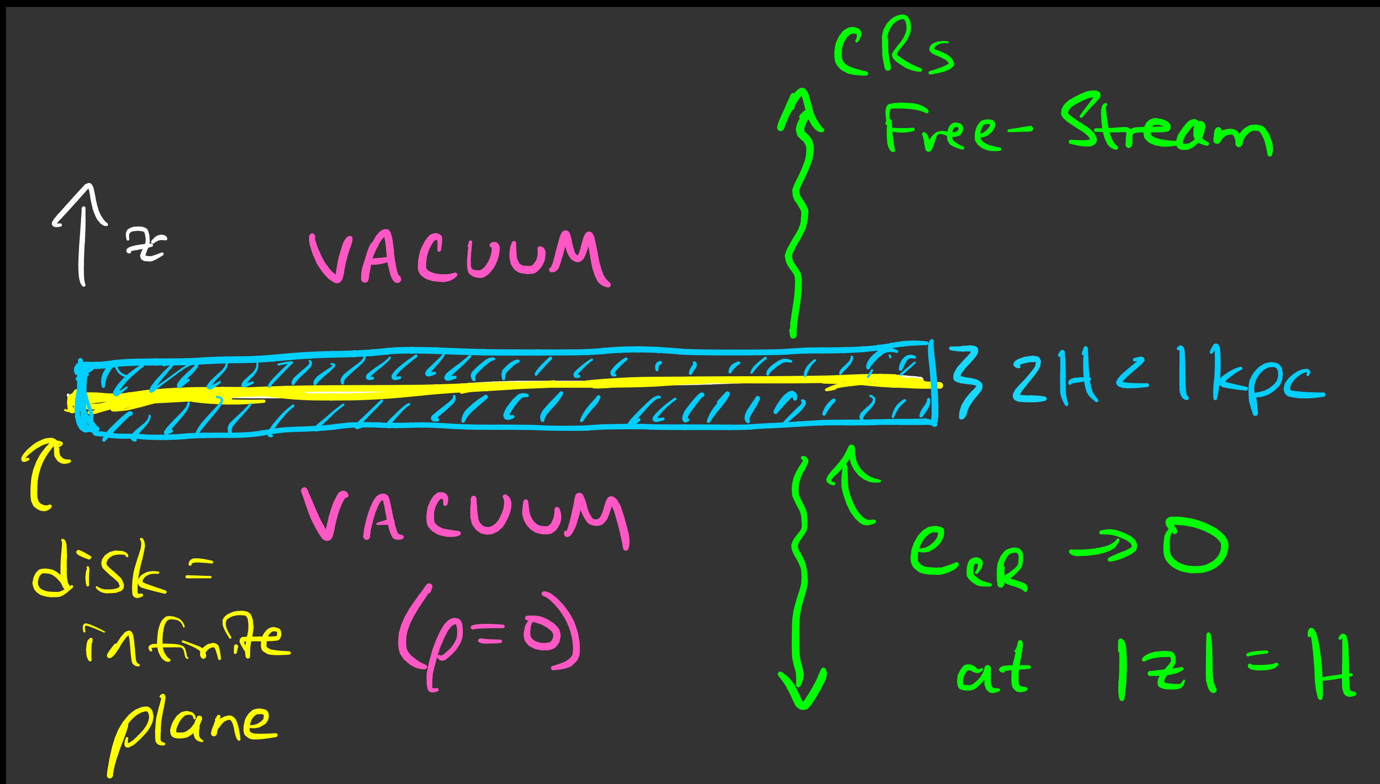
CR-MHD Simulations	GIZMO	$\nu_9 \sim 1, \quad \delta \sim 0.5 - 0.7$
CR Propagation in "Static" MW Model (Fokker-Planck):	GALPROP	$\nu_9 \sim 0.95, \ \delta \sim 0.5 - 0.6$
	DRAGON2	$\nu_9 \sim 0.8, \ \ \delta \sim 0.4 - 0.6$
Semi-Analytic Models:	Flat-Halo Diffusion	$\nu_9 \sim 1, \quad \delta \sim 0.4 - 0.7$
	USINE	$\nu_9 \sim 0.9 - 2, \ \delta \sim 0.5 - 0.6$
Gamma-Ray Data (MW & Local Group)	Fermi-LAT	$\nu_9 \sim 0.5 - 1, \ \delta \sim 0.3 - 1$

Blasi & Amato '12
Vladimirov et al. '12
Gaggero et al. '15
Guo et al. '16
Jóhannesson et al. '16
Cummings et al. '16
Korsmeier & Cuoco '16
Evoli et al. '17
Di Mauro et al. '17
Genolini et al. '17
Evoli et al. '18
Maurin '18
Amato & Blasi '18
Chan et al. '19
Derome et al. '19
Genolini et al. '19
PFH, Squire, Chan et al. '20
Korsmeier & Cuoco '21
PFH, Butsky, Panopoulou et al. '21
de la Torre Luque et al. '21
Korsmeier & Cuco '22
Di Mauro, Korsmeier, Cuoco '23
Butksy, Nakum et al. '23

(Isotropic-equivalent $D_{\rm iso,\,0} \sim (0.7 - 2)\, 10^{29}\, {\rm cm}^2\, {\rm s}^{-1}$ at peak of CR spectrum ~0.5-5 GV)

Note: Historical "Degeneracy"

OLD

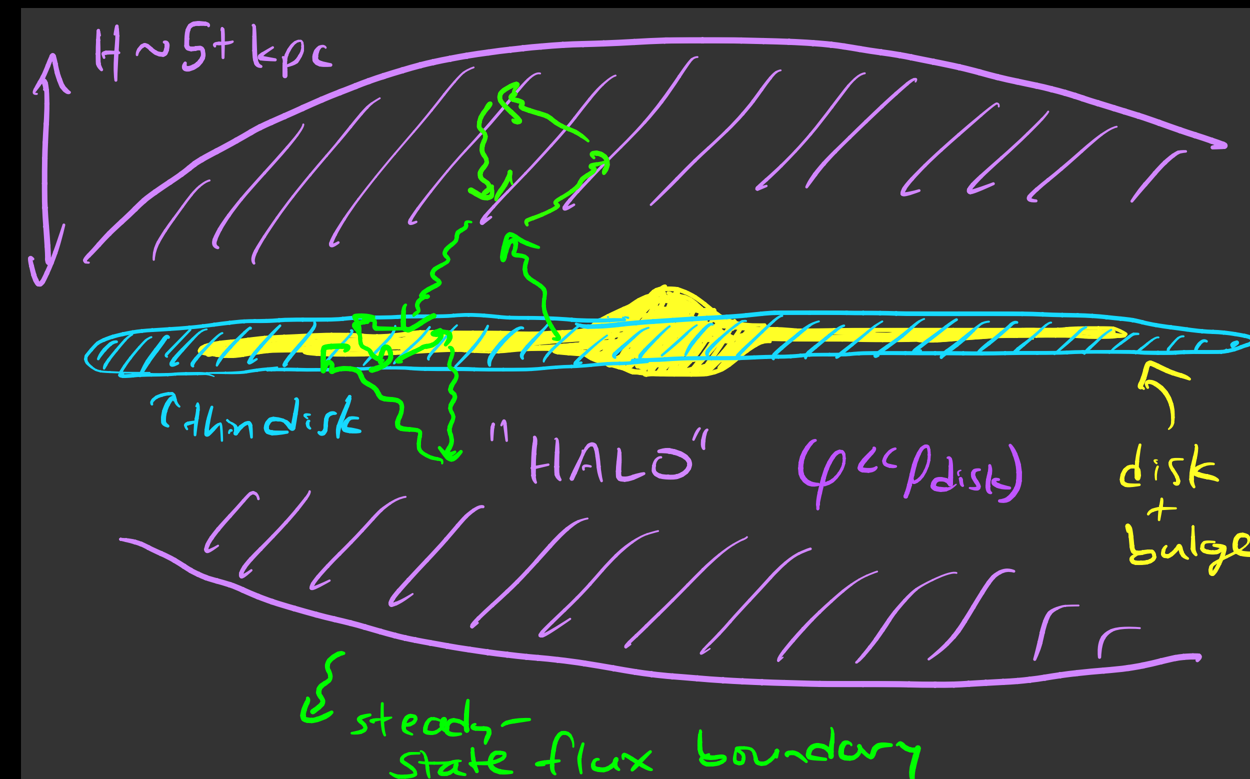


$$\Delta t_{\rm residence} \sim \frac{(200\,{\rm pc})^2}{D_{\rm diffusion}} \sim \frac{H_{\rm disk}^2}{c^2}\,\nu$$

(needs to be small)

Secondaries ~ column =
grammage = $\rho_{\rm disk}\, c\, \Delta t_{\rm residence}$

MODERN



$$\Delta t_{\rm residence} \sim \frac{({\rm few\ kpc})^2}{D_{\rm diffusion}} \sim \frac{L_{\rm halo/gal}^2}{c^2}\,\nu$$

(bigger!)

grammage = $\rho_{\rm thin}\, c\, \Delta t_{\rm residence,\,thin}$
($\Delta t_{\rm residence,\,thin} \ll \Delta t_{\rm residence}$)

So let's use that model and run with it

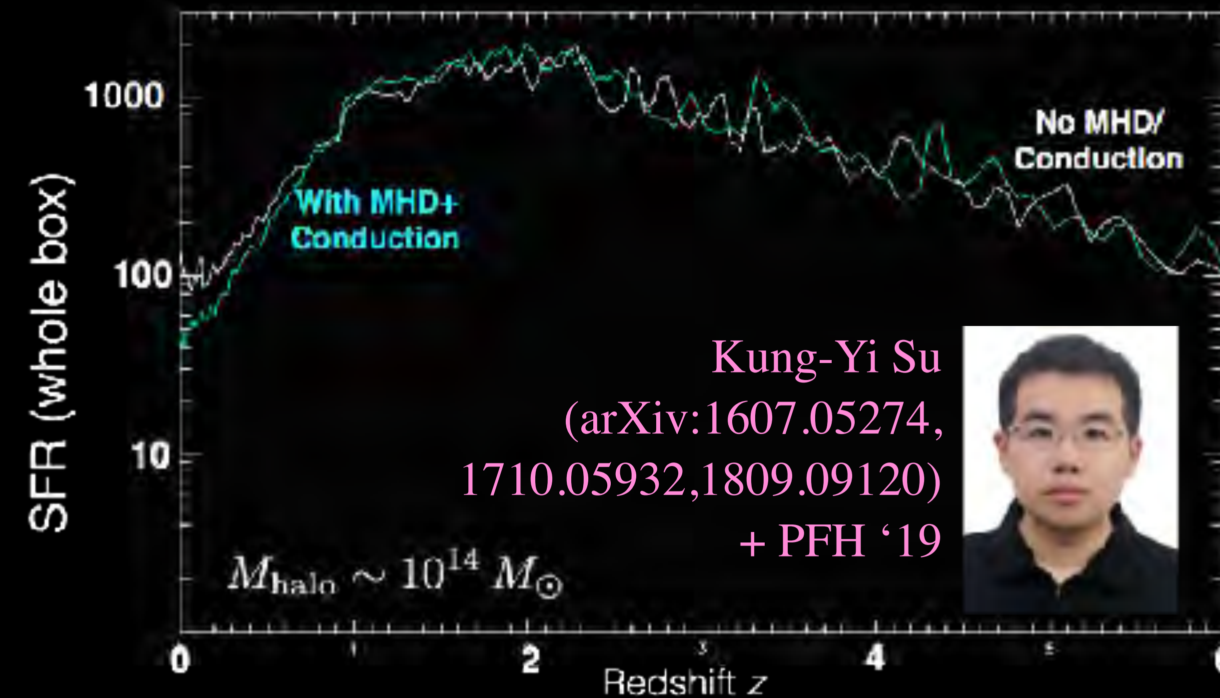
Magnetic Fields, Conduction, Viscosity: Don't Do Much

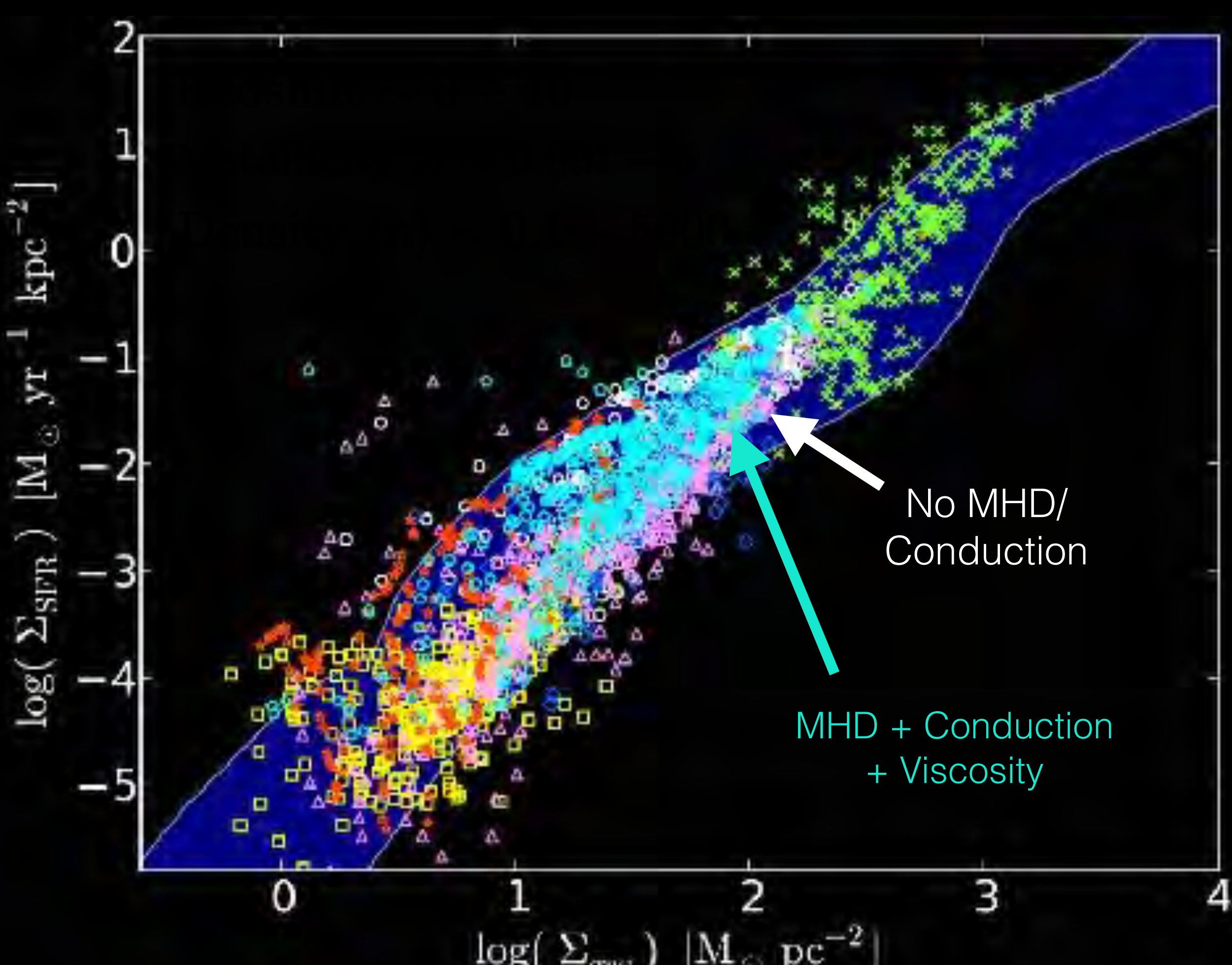
(If you care about bulk galaxy/CGM/IGM properties)

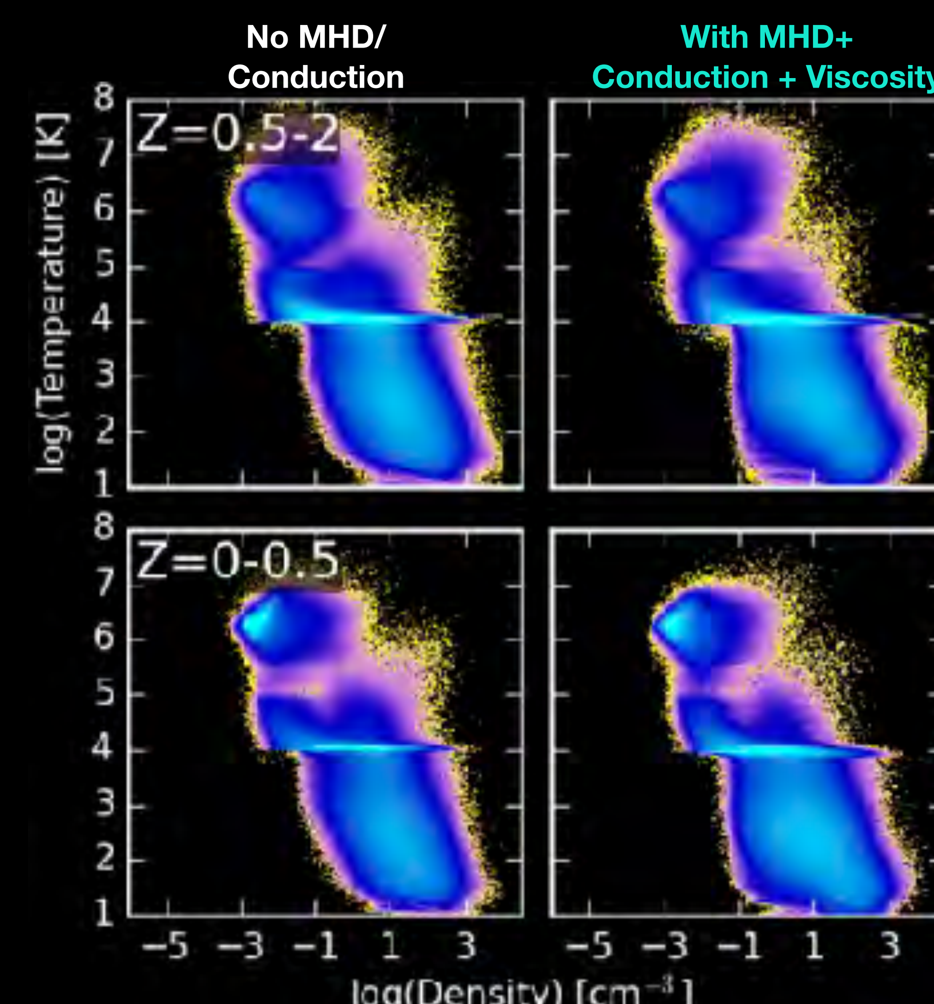
Gas is tightly coupled to fields, but…
B not *dynamically* dominant (>> pc scales)

- ***Traces* large-scale structure, doesn't *drive* it**
- **Supersonic turbulent dynamo dominates**
- **Bulk properties are <u>*feedback-regulated*</u>**

(Kotarba+10, Dubois+10, Federrath+11,17, Tricco+Price16, PFH+ 15, 19, 20, Girichidis+ 18, Su+ 16,17,19,22, Rieder+Teyssier+16,17, Pakmor+ 17, Chan+ 18, Steinwandel+ 21, 23, Martin-Alvarez+ 21, 23)



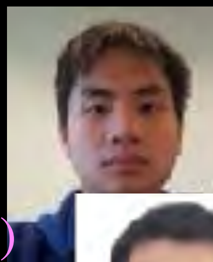




Cosmic Rays: *Could* Be Important

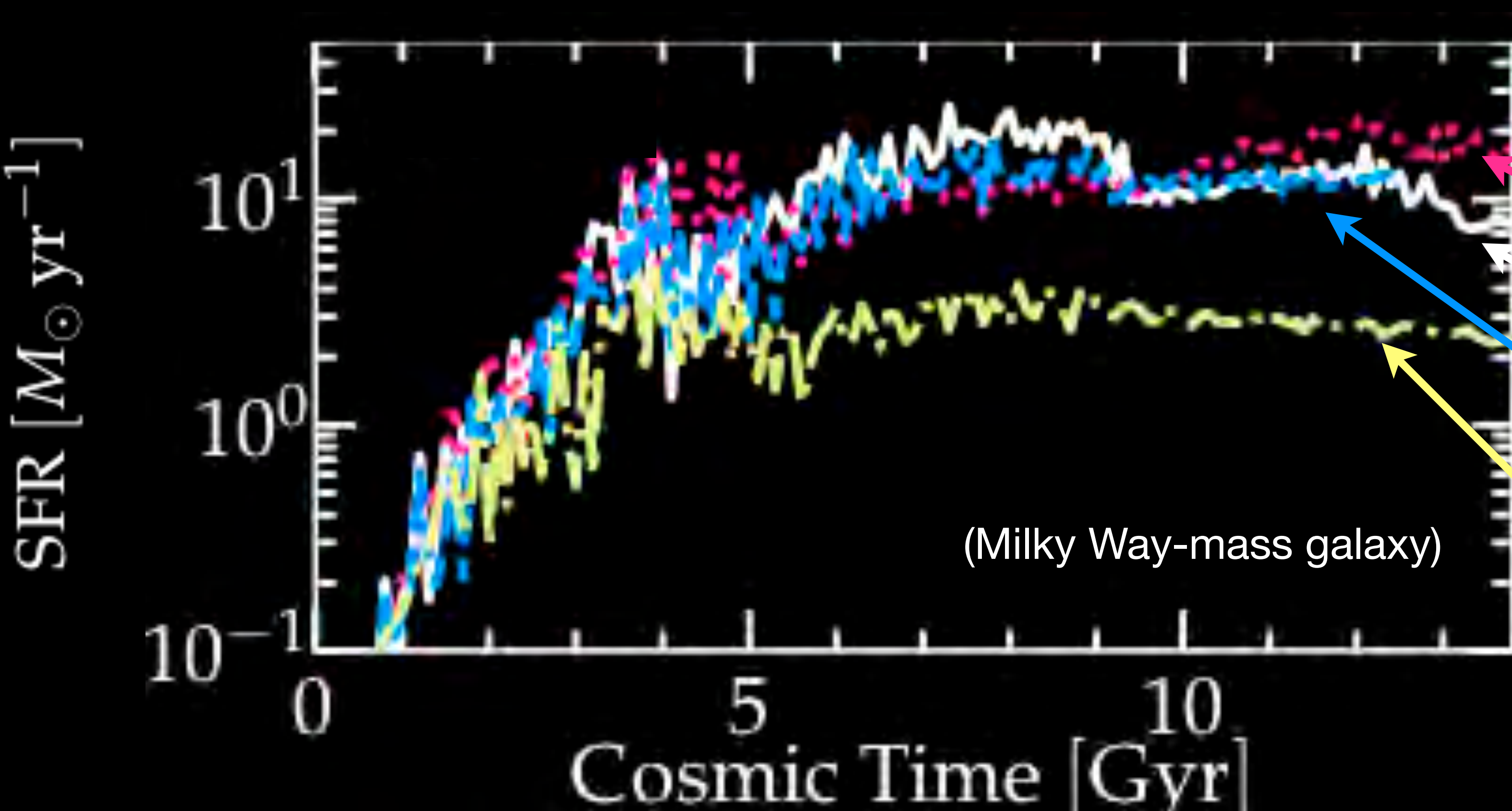
BUT does depend *sensitively* on propagation physics

TK Chan+ (SNe)
(1812.10496)



Kung-Yi Su+ (AGN)
(1812.03997,
2102.02206,
2310.17692)

Sarah Wellons
(cosmological:
2203.06201)



No CRs

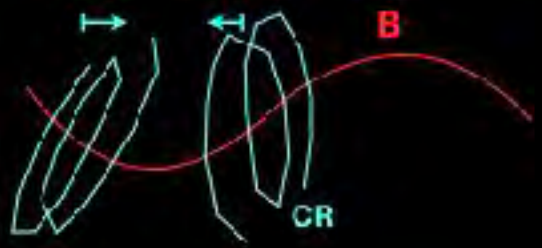
"Too Fast": ($\kappa_\parallel \gg 3 \times 10^{30}\ \mathrm{cm^2\ s^{-1}}$)

"Too Slow": ($\kappa_\parallel \lesssim 3 \times 10^{28}\ \mathrm{cm^2\ s^{-1}}$)

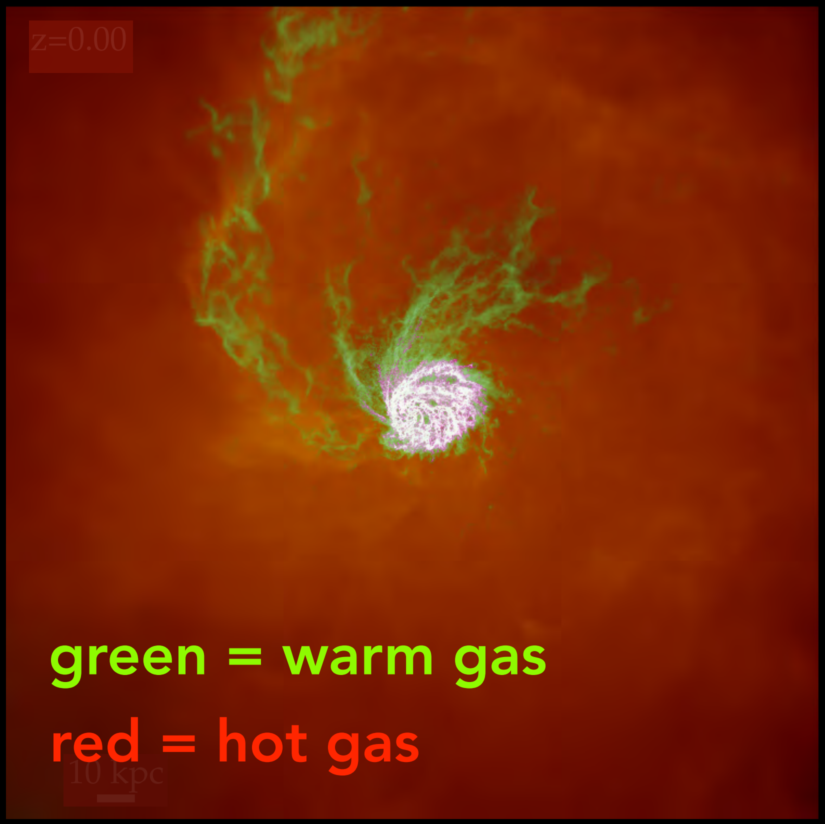
"Sweet Spot": ($\kappa_\parallel \sim 3 \times 10^{29}\ \mathrm{cm^2\ s^{-1}}$)

- Even then: CR effects <u>weak</u> in dwarfs & high-redshift galaxies

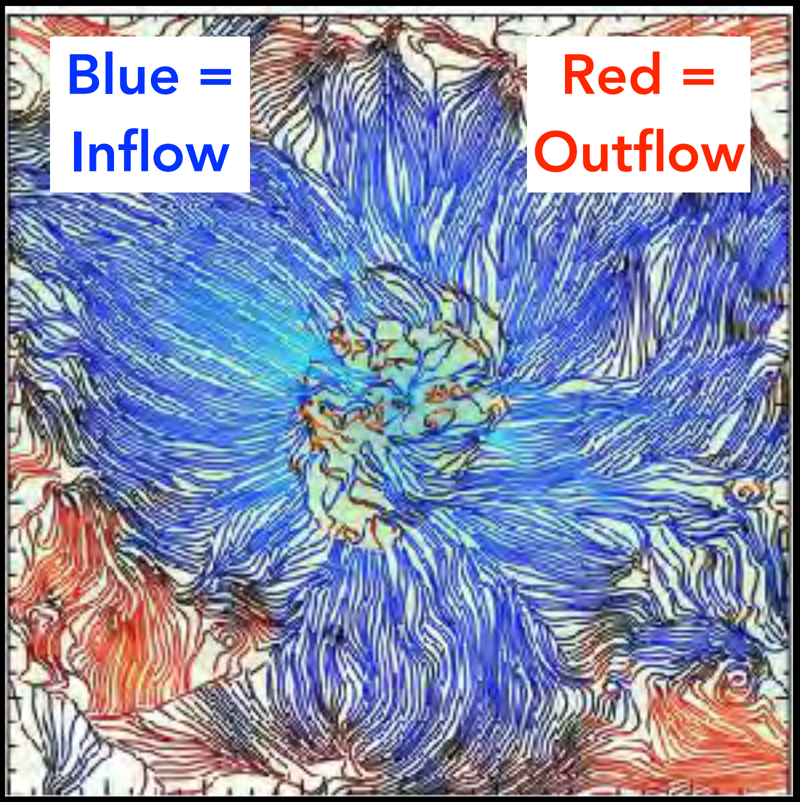
Example: Cosmic Rays



Temperature Map



Velocity Streamlines



CRs do nothing (escape CGM)

Iryna Butsky

L* galaxies: Chan+ 19
Quenching: Su+ 19, 20, 21
ISM: PFH+ 20, 21, Chan+ 22
CGM: Ji+ 21,22, Butsky+ 18,22
Eqs/Methods: PFH+ 22,23, Ji+ 22

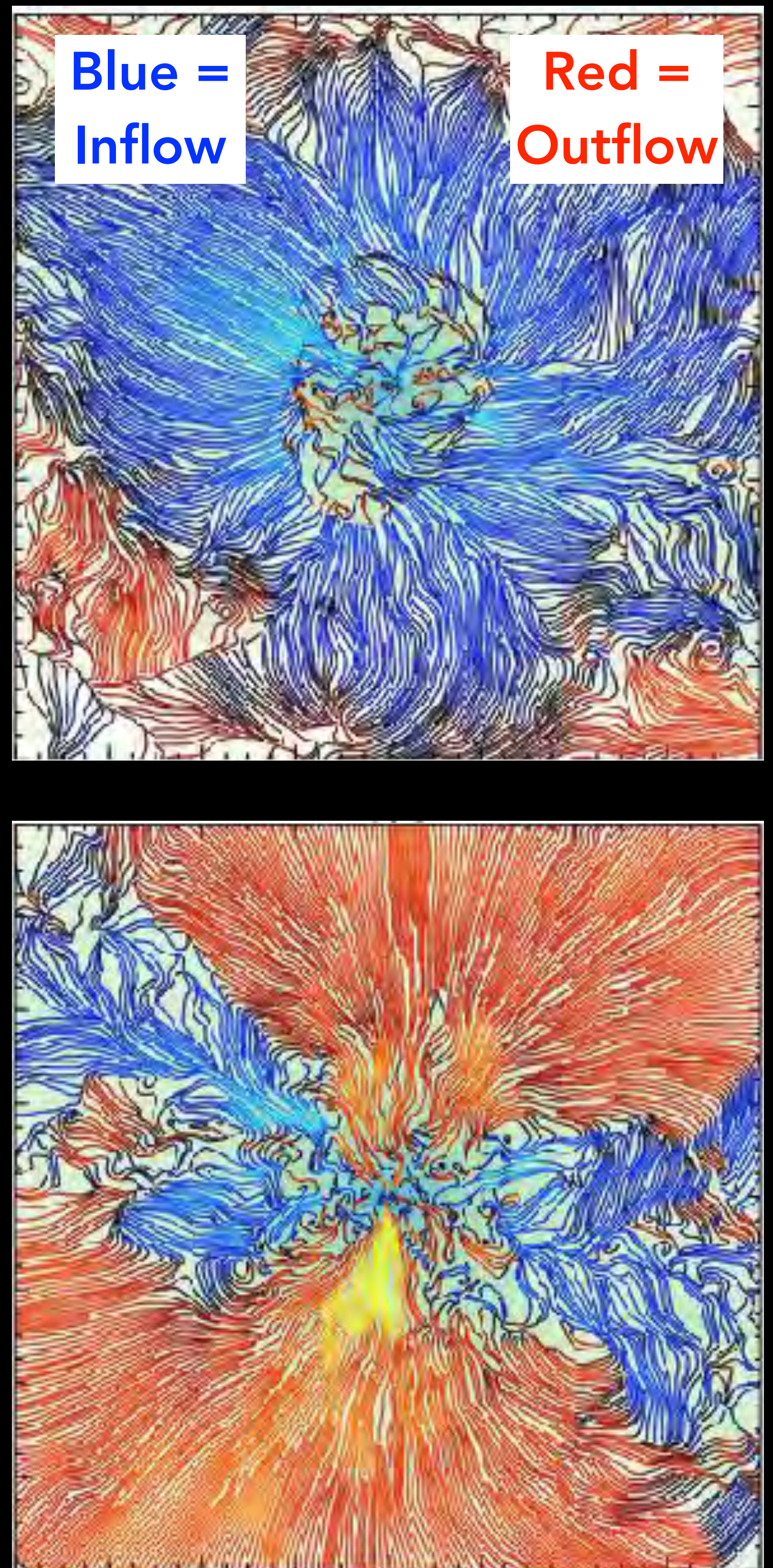
CGM in a "CR Pressure Dominated Halo" is Very Different

Suoqing Ji
1909.00003

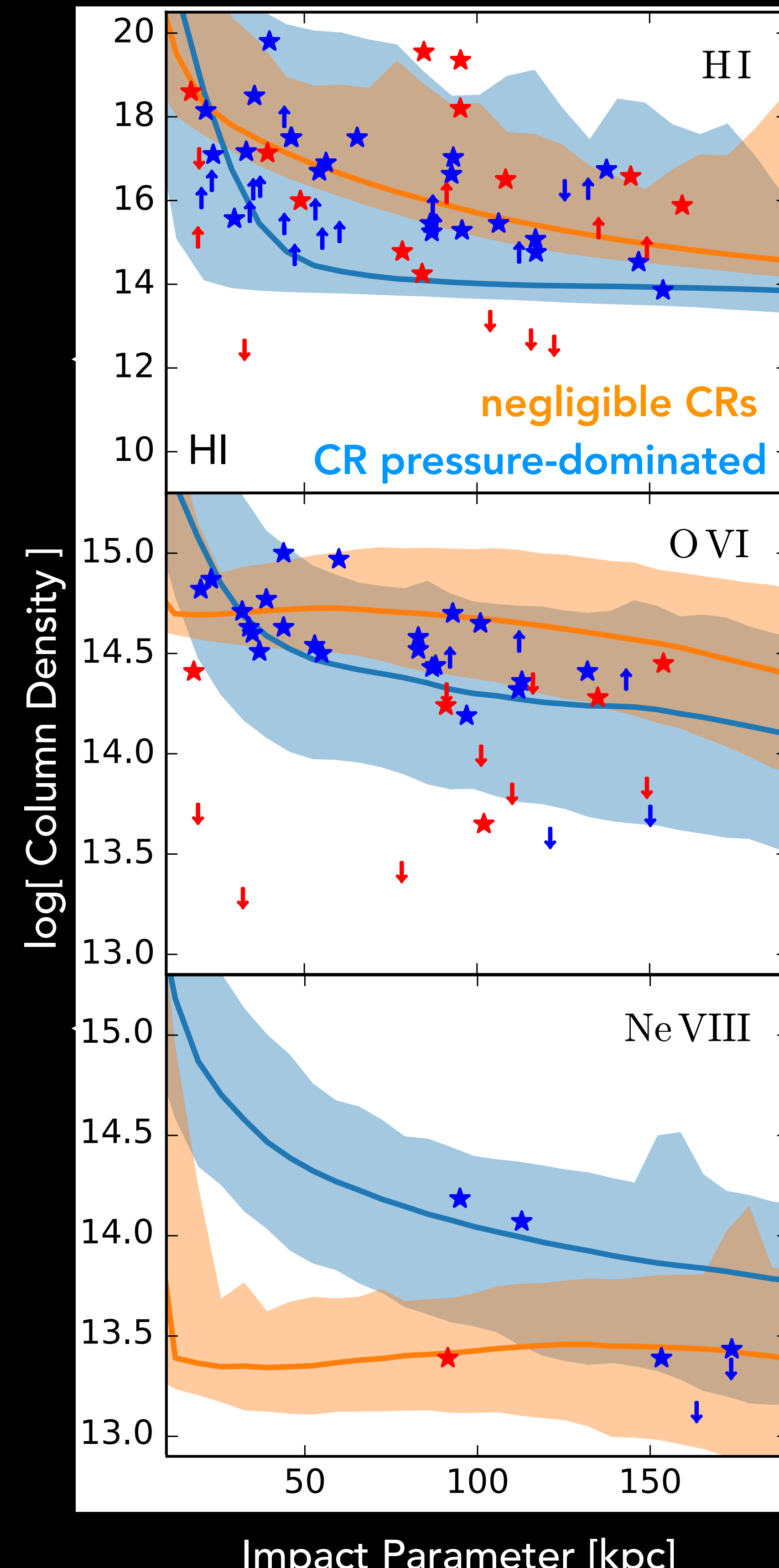
Temperature Map

-100 kpc +100 kpc

Velocity Streamlines

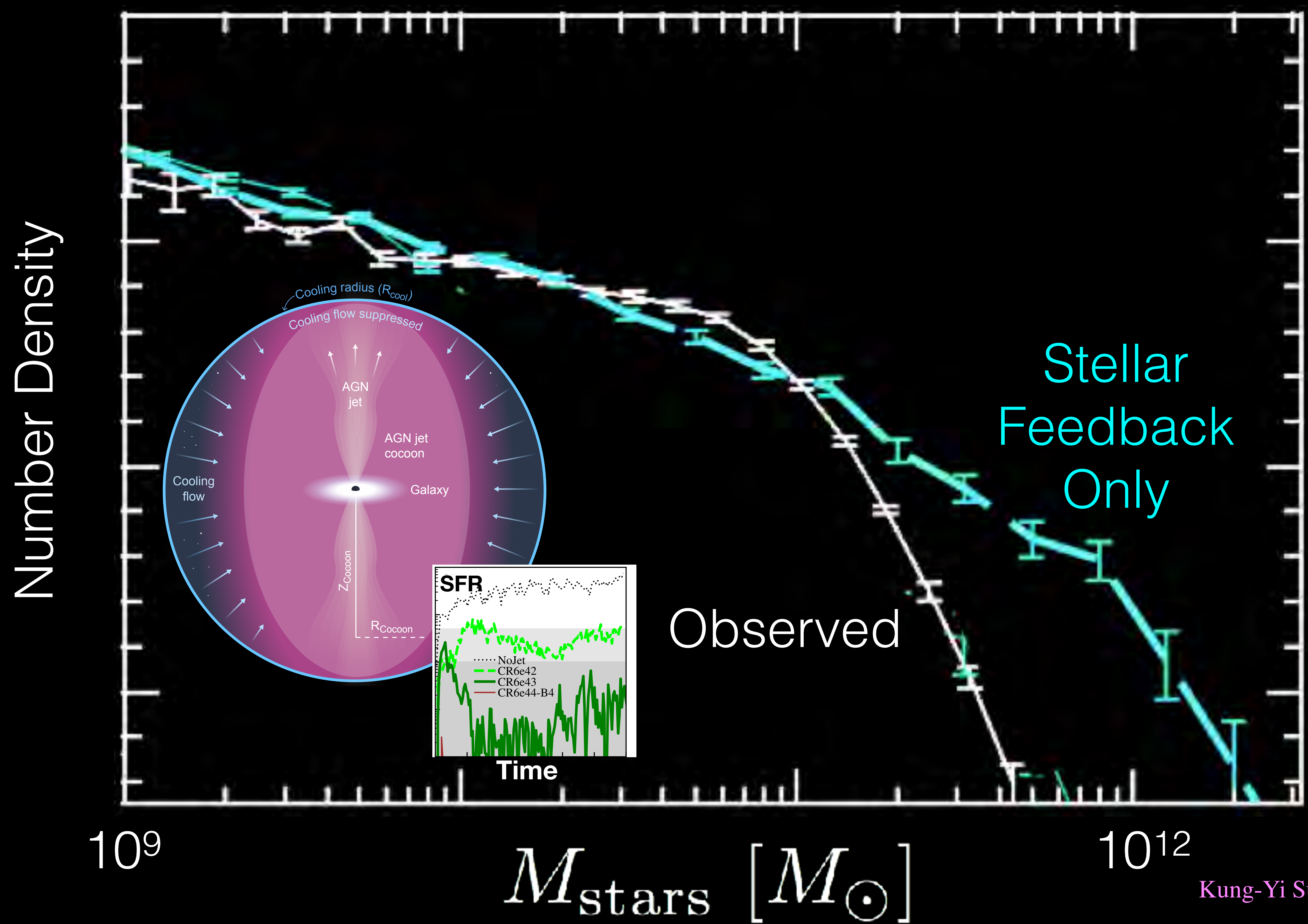


1 Mpc +1 Mpc



Require Additional Physics for "Quenching": CRs can do it!

CR Jets can Resolve Cooling Flows for Far Less Energy



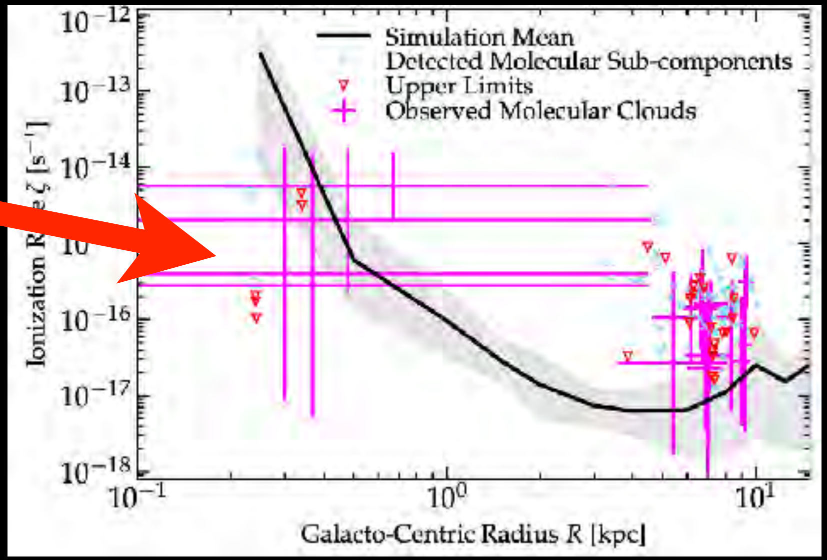
Kung-Yi Su (2102.02206
2310.17692)
(+ Su et al. '19, '20)

Great!

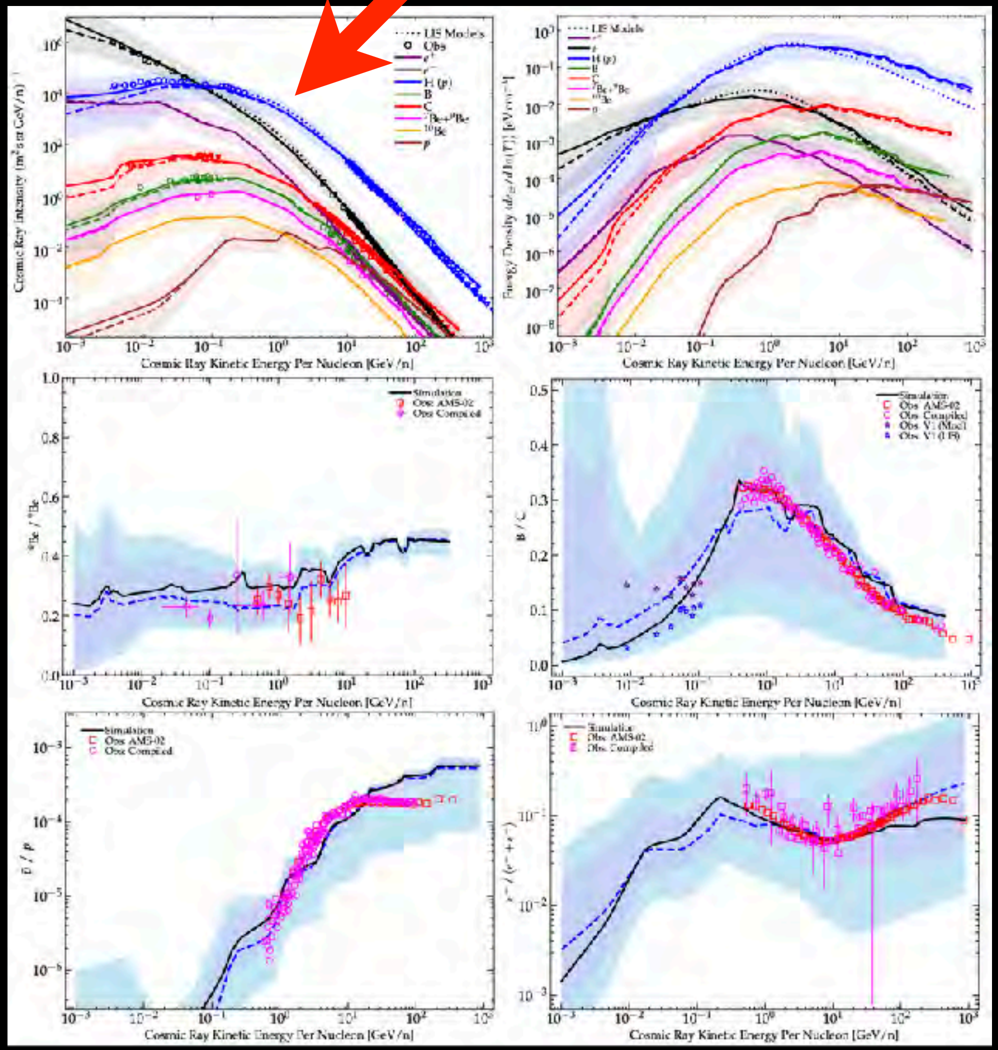
What’s the Problem?

Data only constrain ISM & "thick disk"

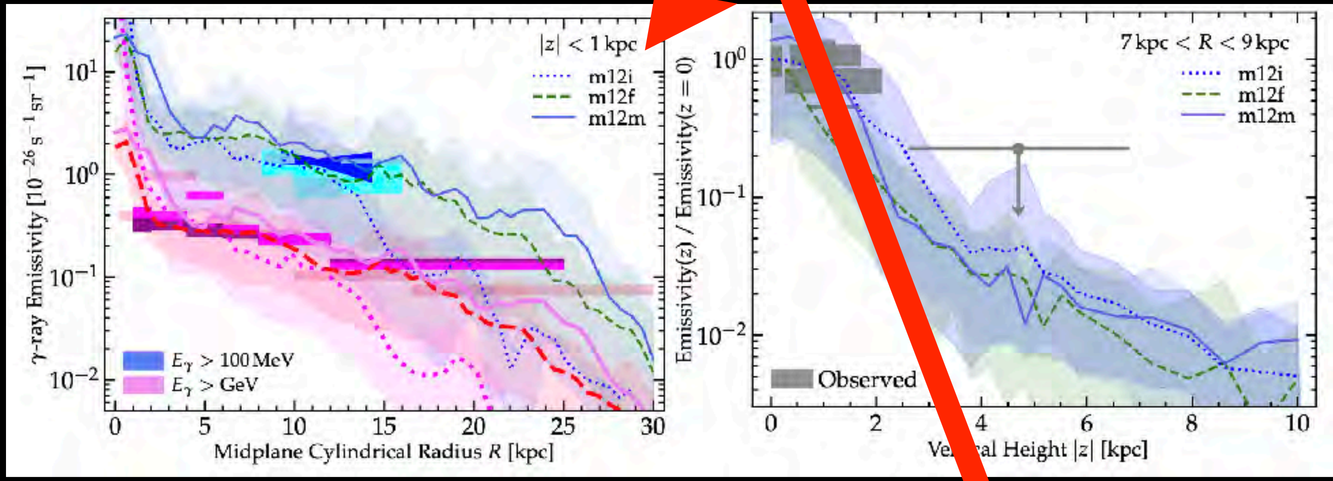
ISM GMCs

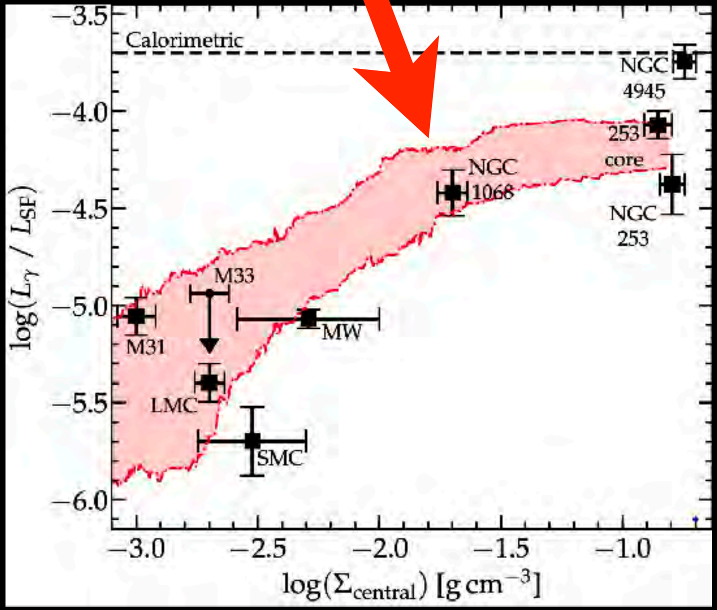


1 Position (Solar System)



ISM at |z|<1 kpc





e^-, e^+,

p/H, $\bar{p}$,

He, Li,

^{7}Be, ^{9}Be, ^{10}Be,

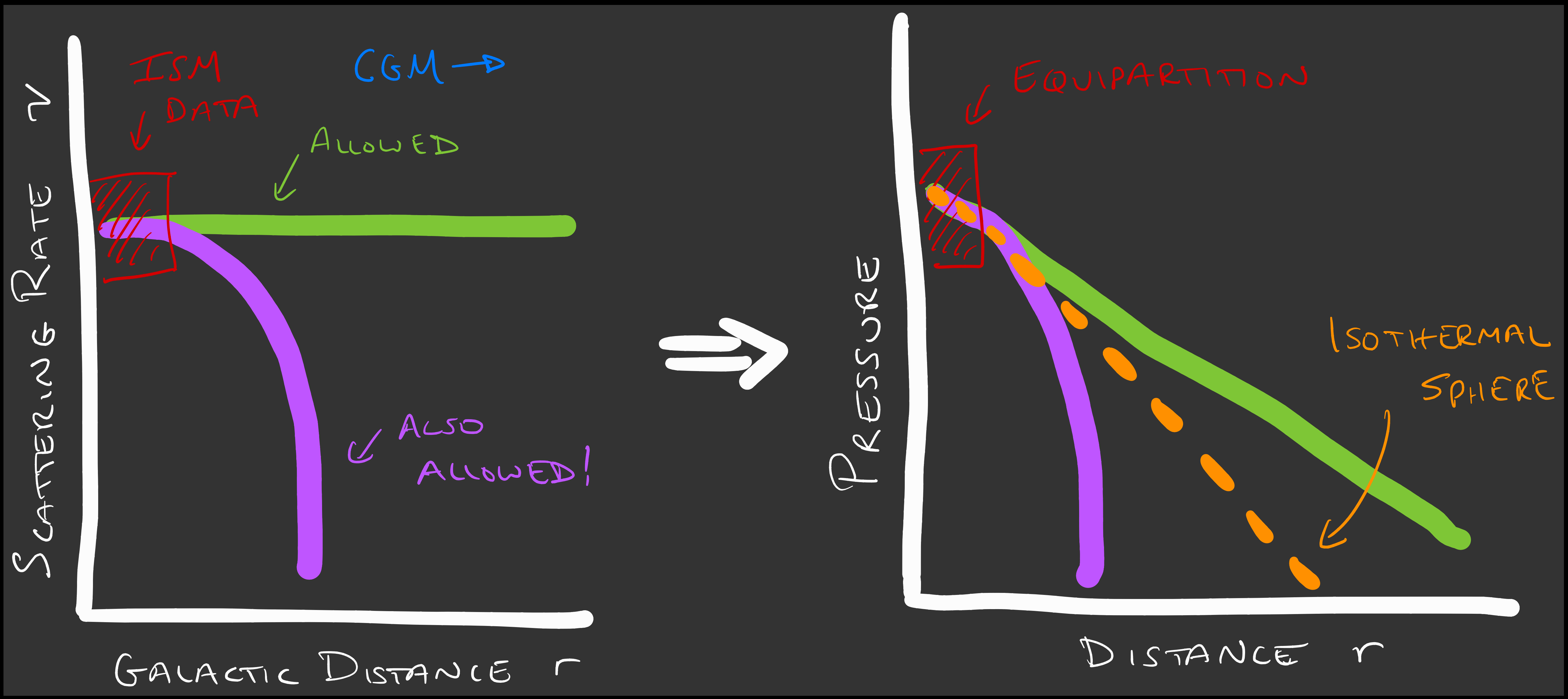
B,

C, N, O,

Fe,

...

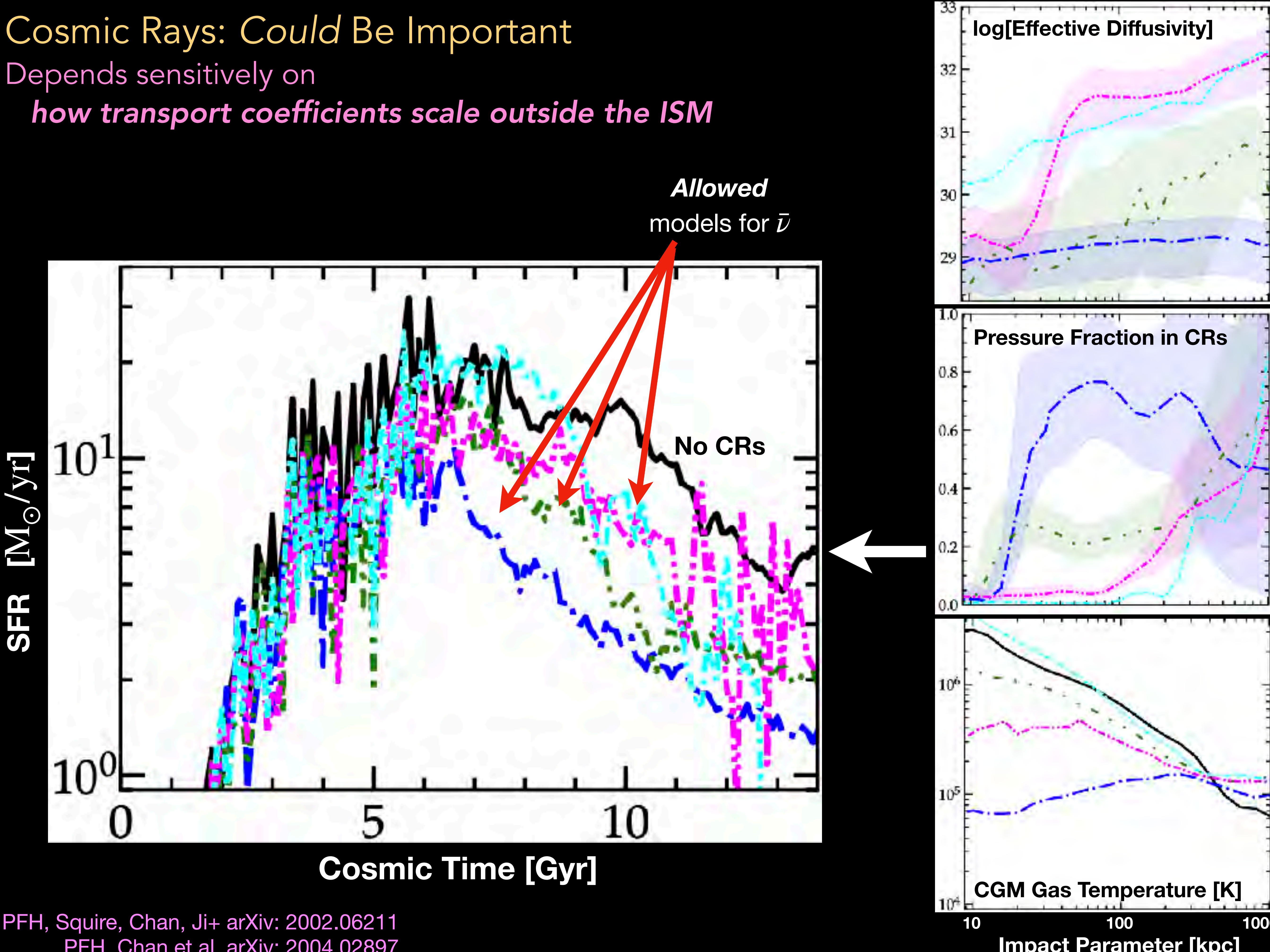
CR Pressure Profile



$$P_{cr} \propto e_{cr} \propto \frac{\dot{E}_{cr}}{\kappa_{cr}\, r} \propto \frac{\nu_{cr}(r)}{r}$$

Cosmic Rays: *Could* Be Important

Depends sensitively on
how transport coefficients scale outside the ISM



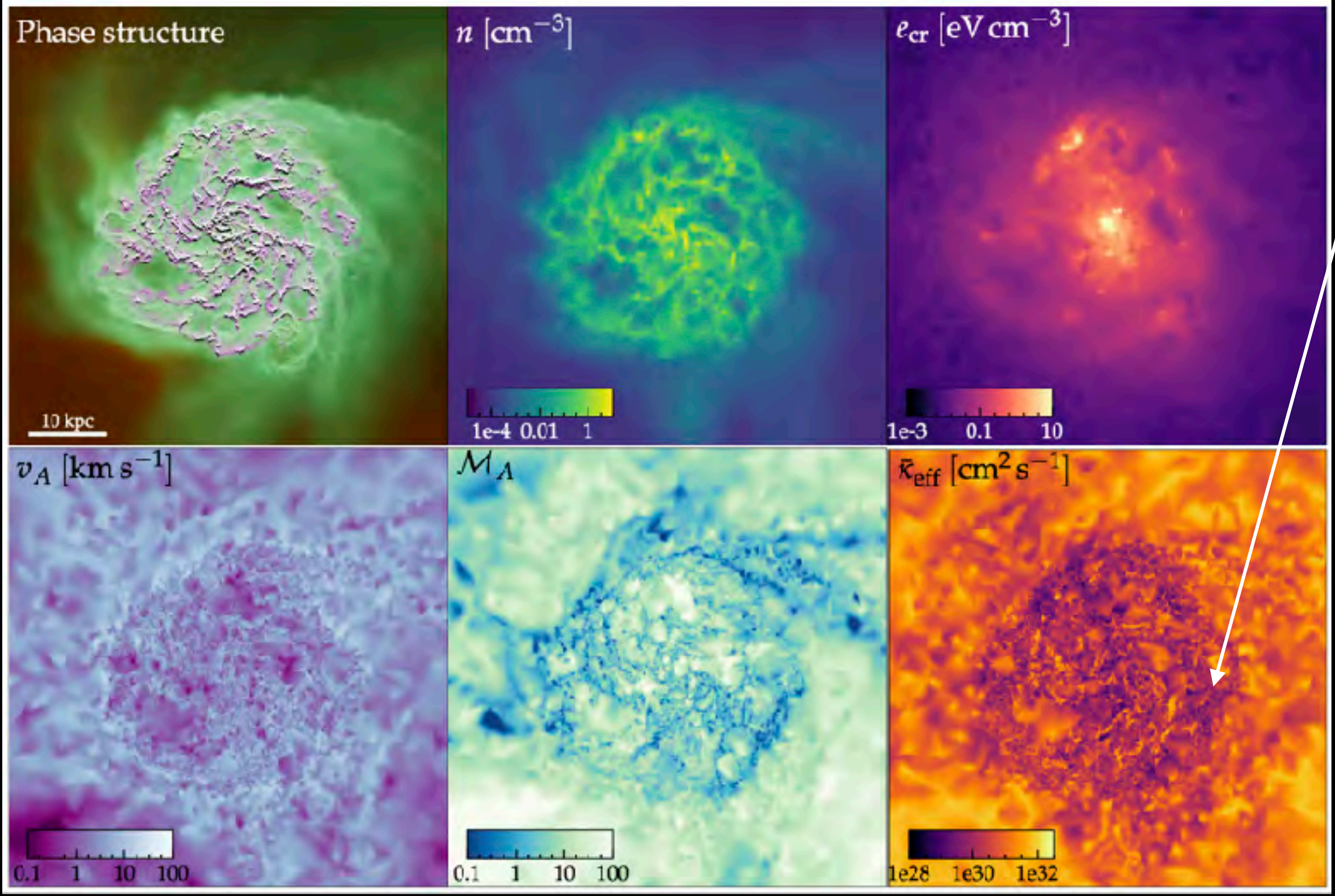
PFH, Squire, Chan, Ji+ arXiv: 2002.06211
PFH, Chan et al. arXiv: 2004.02897

Guide with Theory?

Cosmic Ray Propagation Is Deeply Uncertain

Different CR Transport models can vary up to ~10 dex (!!!)

- ISM & CGM are multi-phase & complicated:



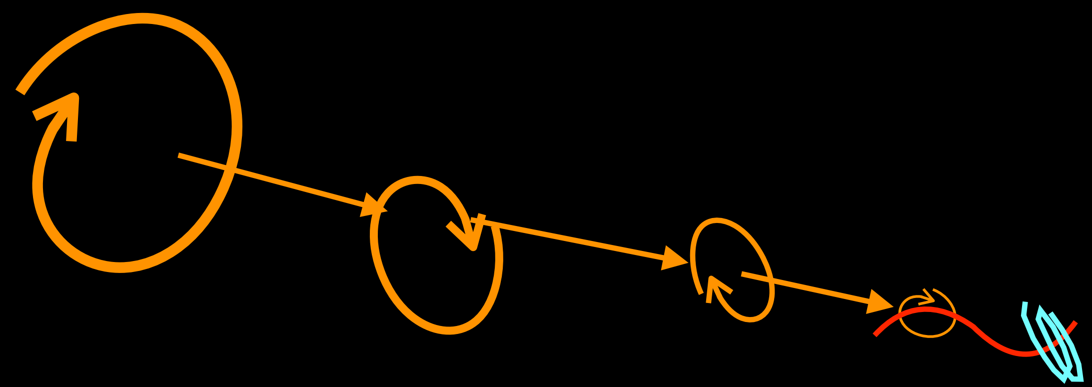
(e.g. Yan+Lazarian 04, Chandran 00, Kempski+Quataert 20, Squire+PFH 20, Armillotta+ 21,22 etc.)

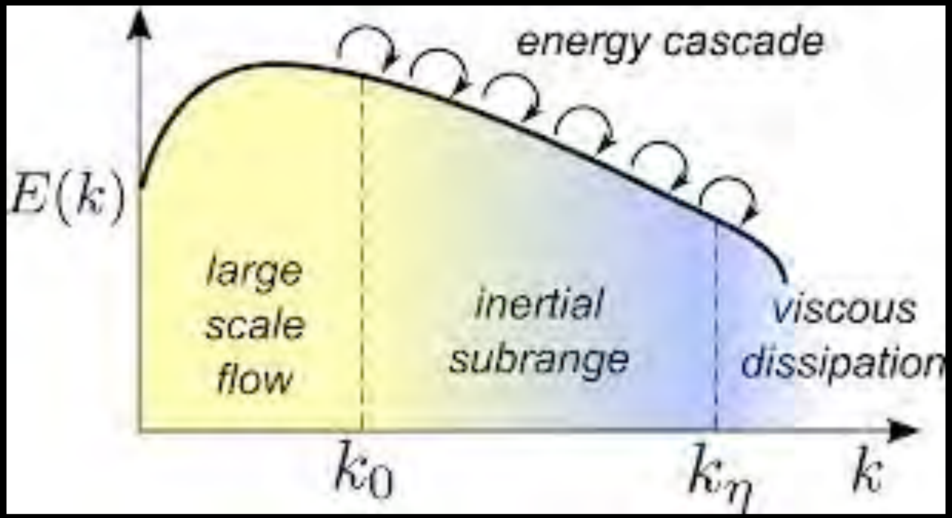
- Do CRs couple to neutrals?
- Turbulence slows down or speeds up CRs?
- Are low-energy CRs trapped, or dominated by different sources?
- Do (GeV) CRs escape/decouple in the halo/CGM?

PFH+ arXiv: 2002.06211, 2004.02897

Theory Fails *Catastrophically*

PFH, Squire, Butsky, & Ji
2112.02153





1. **<u>Turbulent cascade</u>? ("extrinsic turbulence")**

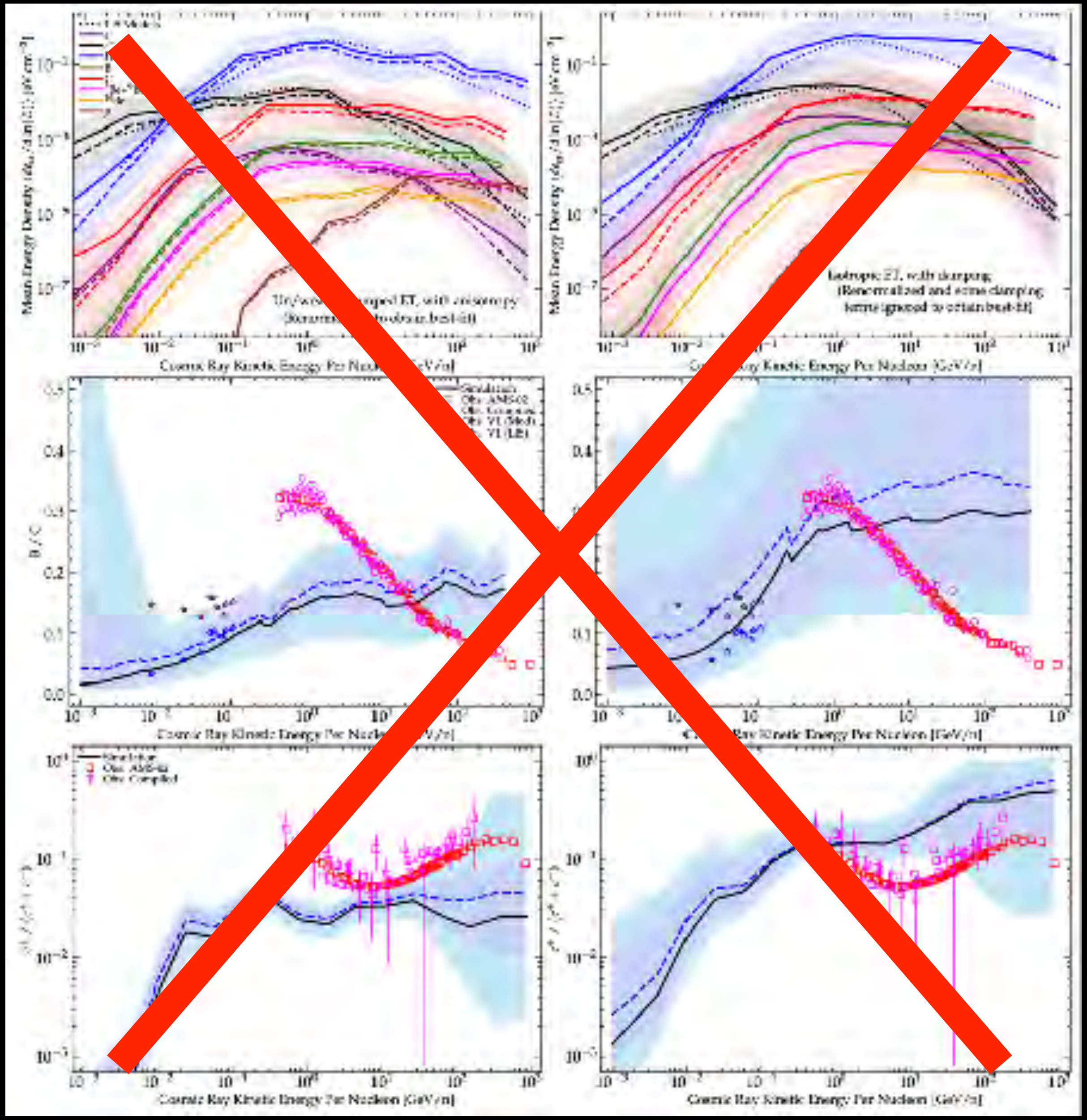
 a) Normalization wrong: $\sim 10^3 - 10^6$

 b) Wrong spectral shapes: → "flat"

 c) Mathematically *impossible* for higher-energy CRs to have lower scattering rates/residence times!

  - Alfvenic/Slow cascade: geometry

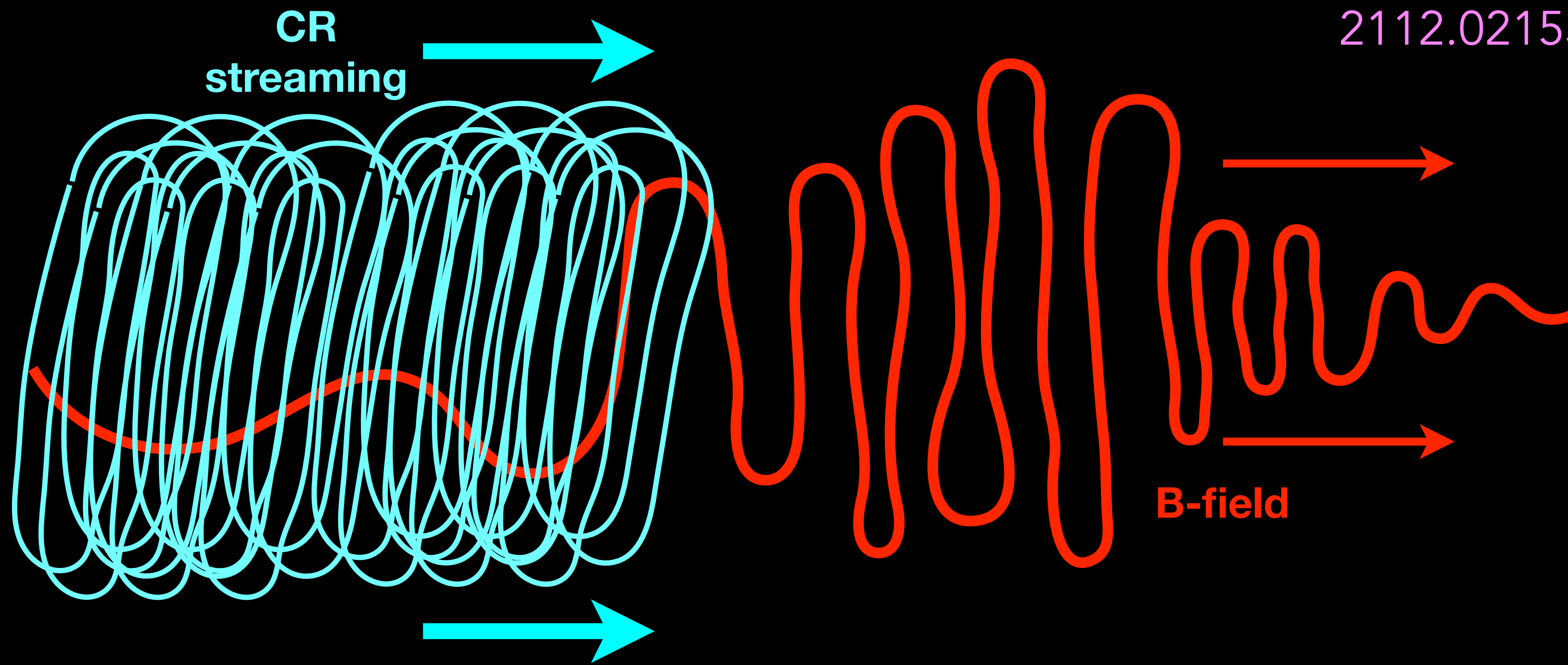
  - Fast cascade: dissipation ($\ll 100\,\mathrm{au}$, i.e. < TeV CRs)



See also: Chandran '00, Yan & Lazarian '02, '04, '08; PFH '21, '22; Fornieri '21; Kempski & Quataert '21

Theory Fails *Catastrophically*

PFH, Squire, Butsky, & Ji
2112.02153

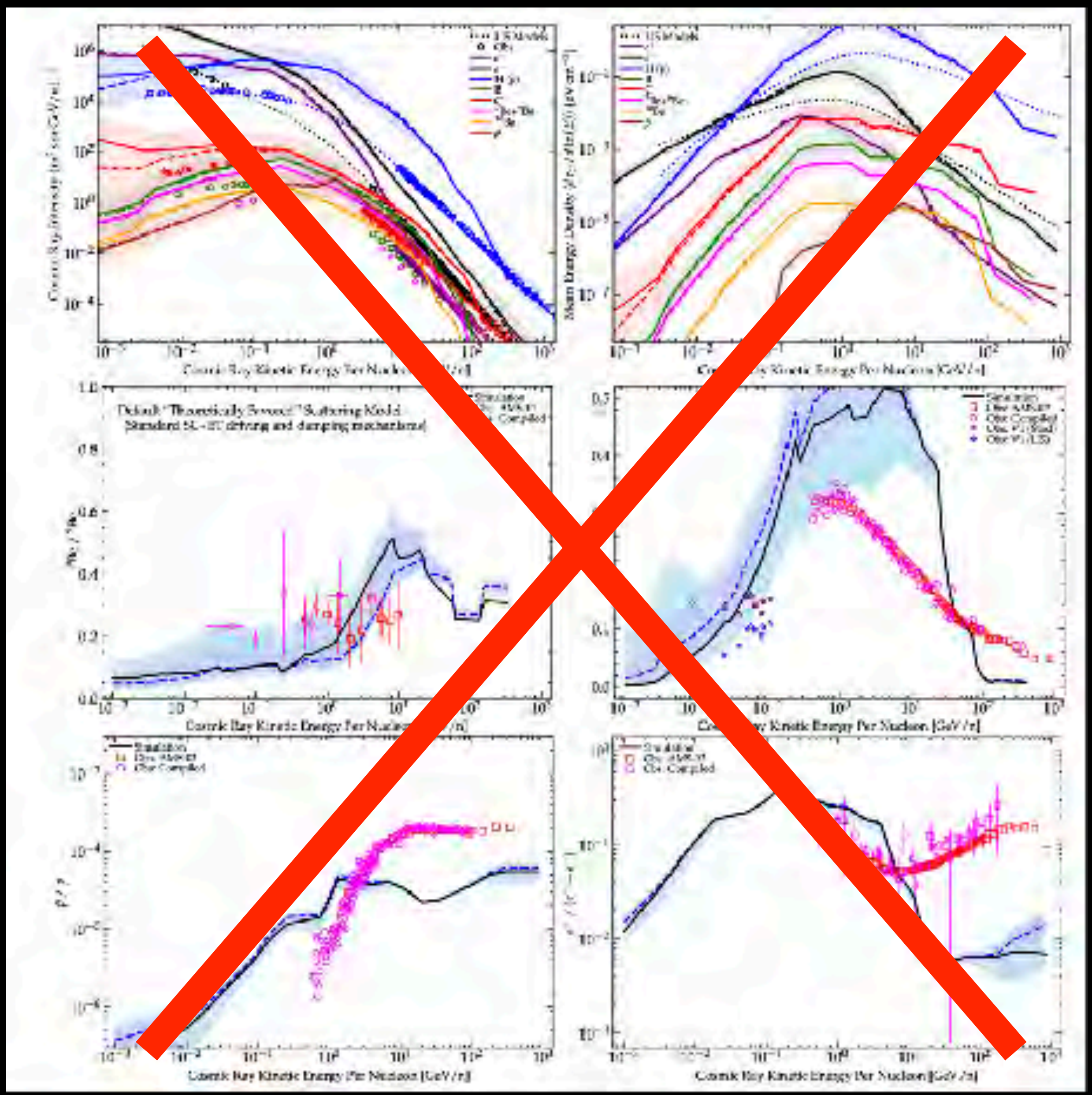


2. <u>Excited by CRs</u>? (“self-confinement”)

a) Normalization wrong: ~ 100

b) Wrong spectral shapes: → “peaked”

c) No steady-state solutions
with lower residence time for higher-E CRs!

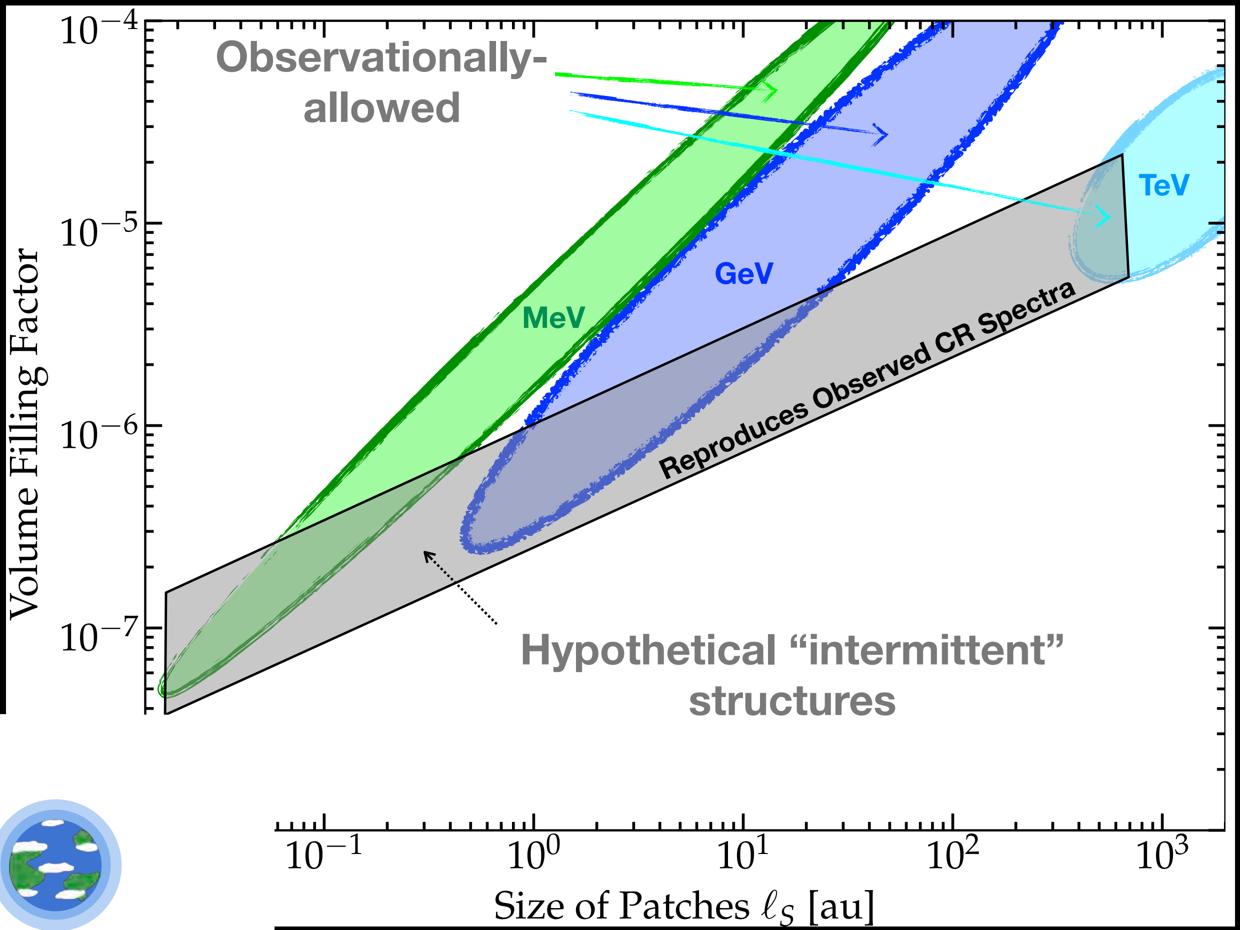


See also: Skilling ’71, Cesarsky ’71, Kempski & Quataert ’21, PFH ’21

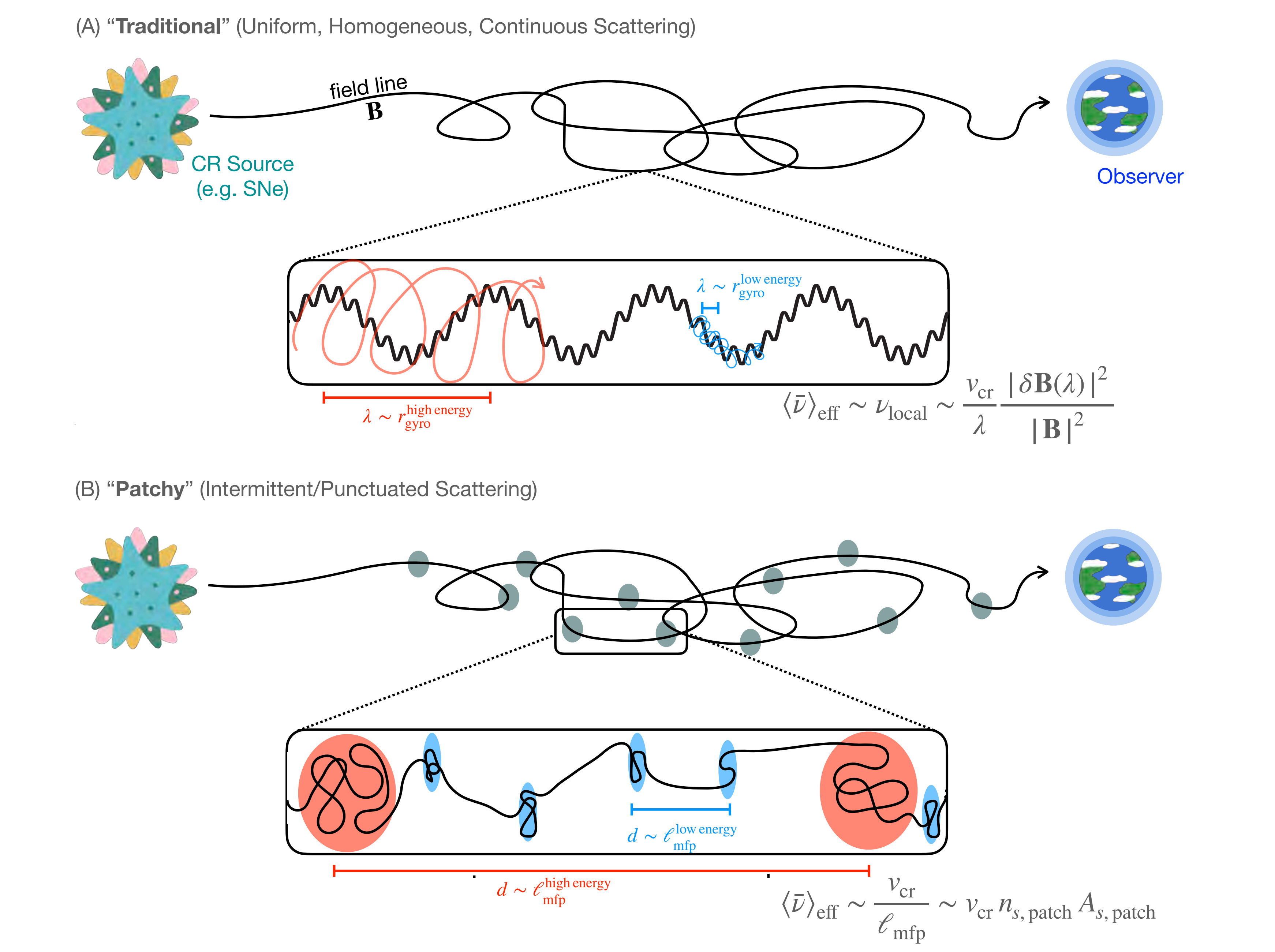
Where to From Here?

1. **Qualitatively different** assumptions

e.g. What if CR scattering comes primarily from
a small number of “strong” scattering structures?



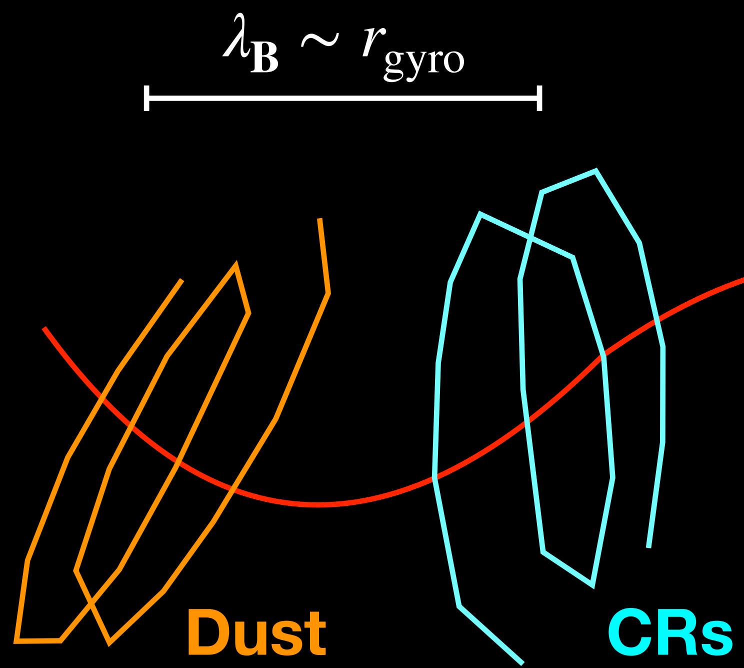
Remarkably similar to
extreme radio plasma events
in the ISM!!!

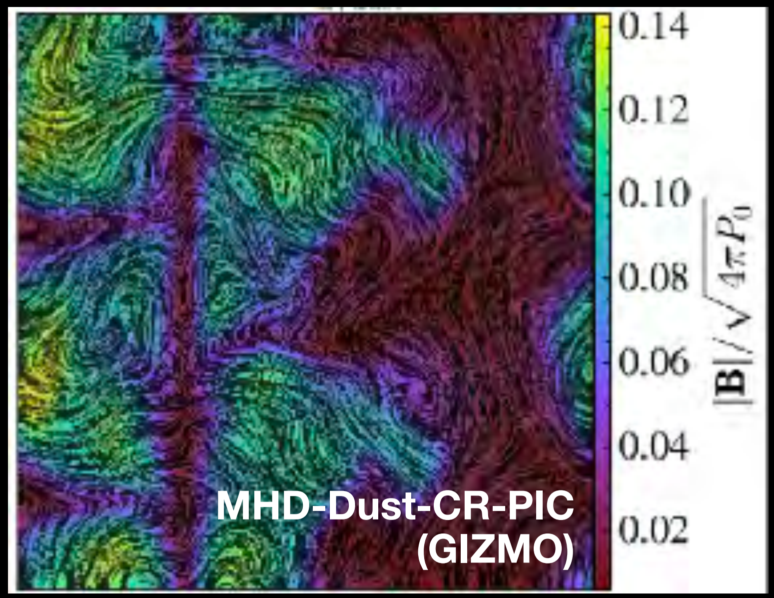



Butsky+ arXiv:2308.06316
Kempski+ arXiv:2304.12335
Li & Kempski+ (prep)
Fielding+ 23, 24

Where to From Here?

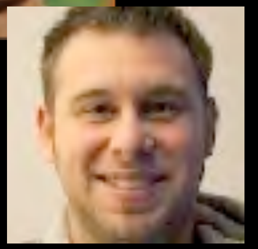
2. **Qualitatively different** drivers





$$r_{\rm gyro,\,dust} \sim 0.1\,{\rm au}\left(\frac{\epsilon_{\rm grain}}{0.03\,\mu{\rm m}}\right)^2 \left(\frac{\delta v}{c_s}\right)\left(\frac{10^4\,{\rm K}}{T}\right)^{1/2}\left(\frac{\mu{\rm G}}{B}\right) \sim r_{\rm gyro,\,cr} \sim 0.1\,{\rm au}\left(\frac{E_{\rm cr}}{\rm GeV}\right)\left(\frac{\mu{\rm G}}{B}\right)$$

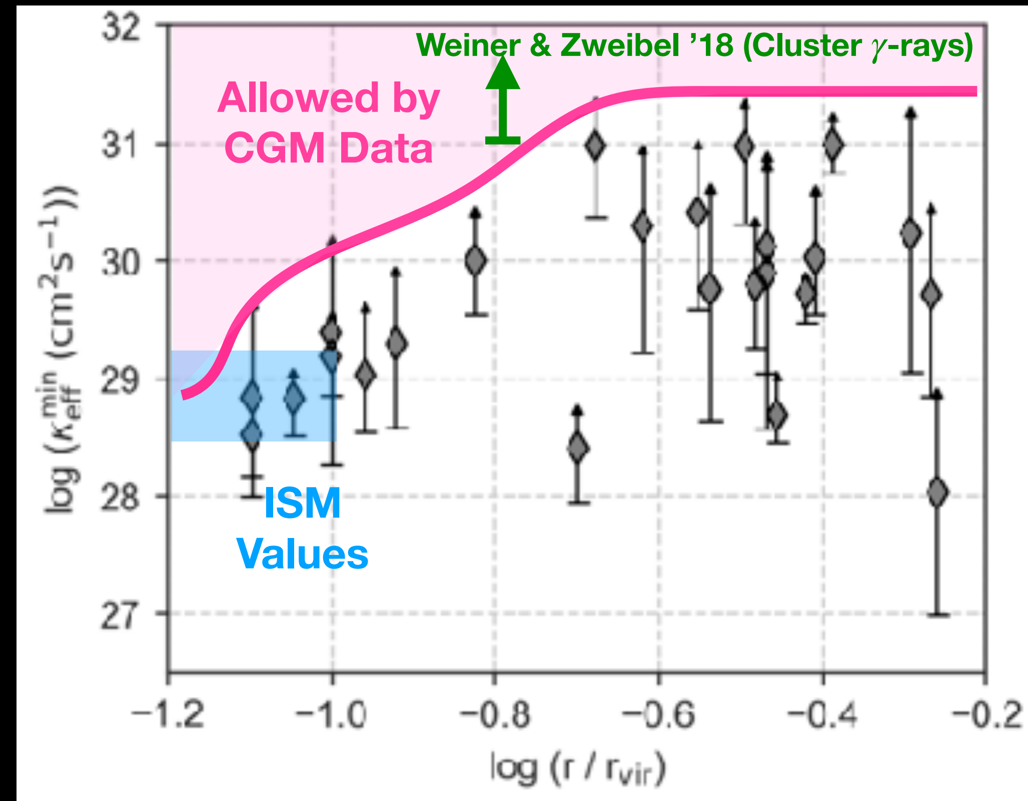
- **Weak RDIs:** CR self-confinement -> B-field oscillations -> dust oscillations -> collisional damping -> ***weaker*** scattering
- **Strong RDIs:** Dust RDIs -> B-field oscillations -> ***stronger*** CR scattering



Squire, PFH+ 2011.02497
Ji et al., 2112.00752
Uli Steinwandel et al. (prep)

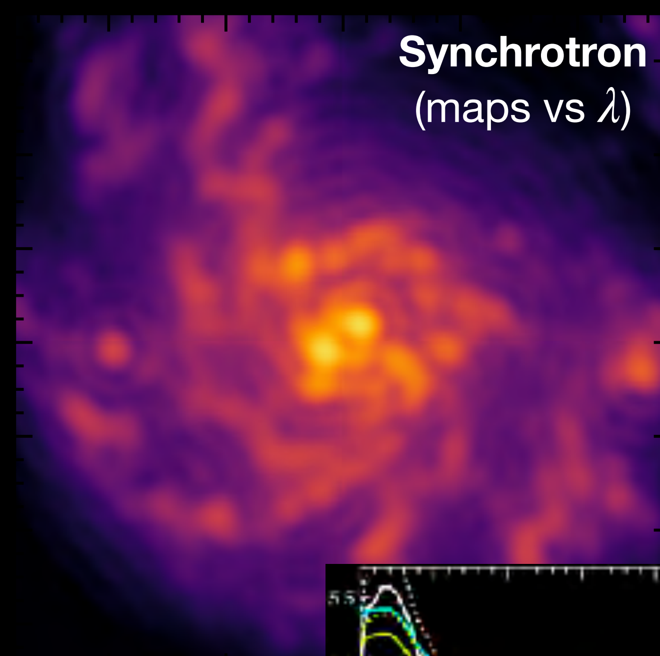
3. Novel Constraints

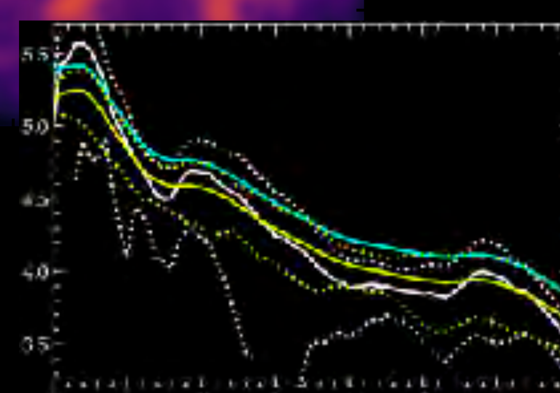
Butsky, Nakum, Ponnada, Hummels, Ji, & PFH (arXiv:2210.14232)



- Scattering rate $\bar{\nu}_s$ ***must decrease*** in the CGM!

Ponnada, Panopoulou, et al. arXiv:2309.04526

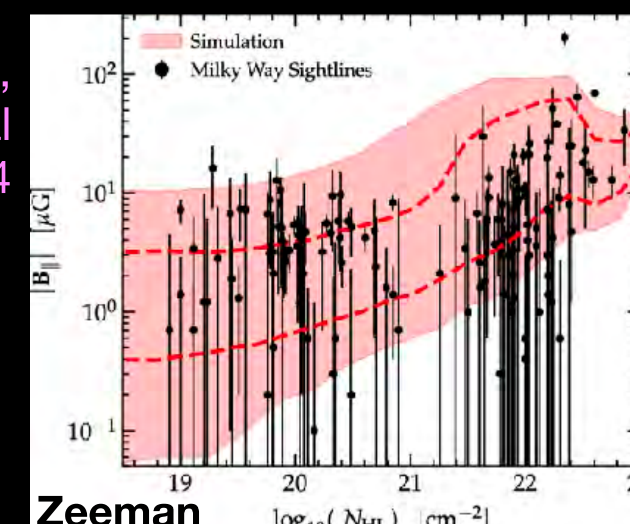


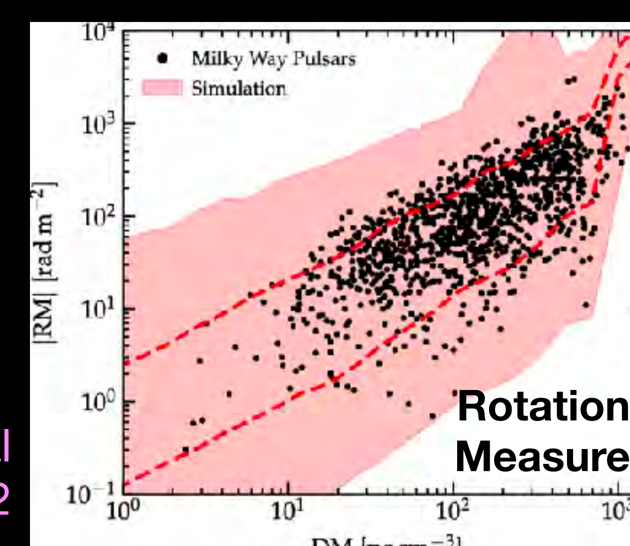


- Synchroton profiles & ISM substructure vs obs:

  SC-like models ($\nu \propto e_{\rm cr}^{-1}$) ***strongly disfavored***

Ponnada, Panopoulou, Butsky et al arXiv:2206.04764





Ponnada, Butsky et al arXiv:2309.16752

Example Viable, Allowed Model

$$\bar{\nu}_{\rm eff} \sim 10^{-9}{\rm s}^{-1}\beta\left(\frac{R}{\rm GV}\right)^{-1/2} \times \mathscr{M}_s^{2/3}\left(\frac{\mathbf{B}}{\mu G}\right)^{-1/3}\left(\frac{n}{{\rm cm}^{-3}}\right)^{1/2}\left(\frac{T}{10^4\,K}\right)^{-1/2}\left(\frac{\ell_{\rm turb}}{100\,{\rm pc}}\right)^{-2/3}$$

"Normal" ISM scaling

not at all
like ET or SC!

Some $\mathscr{F}_{\rm plasma}(\mathbf{B}, \mathscr{M}_A, T, \ldots)$
~ 1 in warm ISM/inner CGM
$\ll 1$ in outer CGM

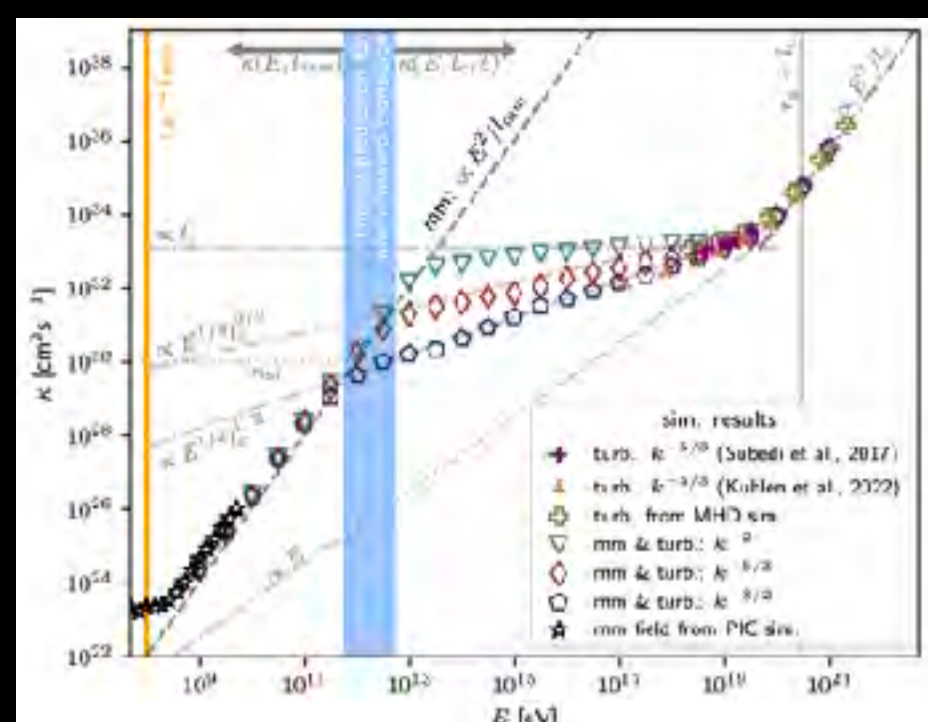
(Here kind of like Yan & Lazarian '04, but *R* dependence not at all like that model! And many $\mathscr{F}_{\rm plasma}$ allowed!)

BUT

Even more caution:
arXiv:2311.01497

if $\beta \gg 1$,
$T \gg 10^6\,K$,
$\lambda_{\rm ion,\,MFP} \gg R_{\rm halo}$

(e.g. ICM)



Extremely
strong
confinement!

Conclusions

CRs ***could*** play a major role on galactic & CGM scales

- Re-accelerate “slow” outflows, support cold gas: (Butksy+, Ji+, Salem+, PFH+, Wiener+, Su+, Rosdahl+, Chan+, Dubois+, DeFelippis+, Steinwandel+, Dolag+, Rodriguez Montero+, Ramesh+, Tsung+, Peschken+, and more!)
- Quench massive galaxies (K-Y Su+ [many papers], Goyal+, Ponnada+, Wellons+, Ruszkowski+)

There is a ***correct*** set of (full-spectrum) CR transport eqns:

- Resolution > gyro: PFH+22, 23 & Thomas+Pfrommer 22: *not the same as Jiang & Oh eqns*!
- Resolution < gyro: Bai+ 15 (Ji & PFH 22 for reduced-c)

BUT

- depends *crucially* on scattering rate *where we have almost no data*
- old “self-confinement” & “extrinsic turbulence” models *cannot be the whole story*
  - patchy/intermittent scattering? related to radio scattering?

    (Butsky+23b, Kempski+23, Fielding+ 23, Li & Kempski+ 24, Ponnada+ 25)
- novel constraints needed!
  - scattering must *decrease* in CGM/ICM (Butsky+23a)
  - “SC-like” models ($\nu \propto e_{\rm cr}$) strongly *disfavored* (PFH+23, Ponnada+23a,b)