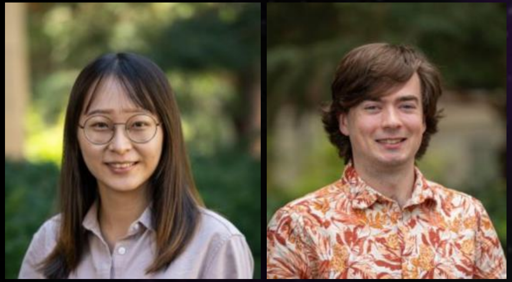
Cosmic Ray Feedback

UNIVERSITY OF MICHIGAN

Mateusz Ruszkowski



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Max Planck Institut für Astrophysik

Philipp Kempski
Princeton University

Julien Fuchs
École polytechnique

Outline

CR physics & astrophysical feedback: acceleration & transport

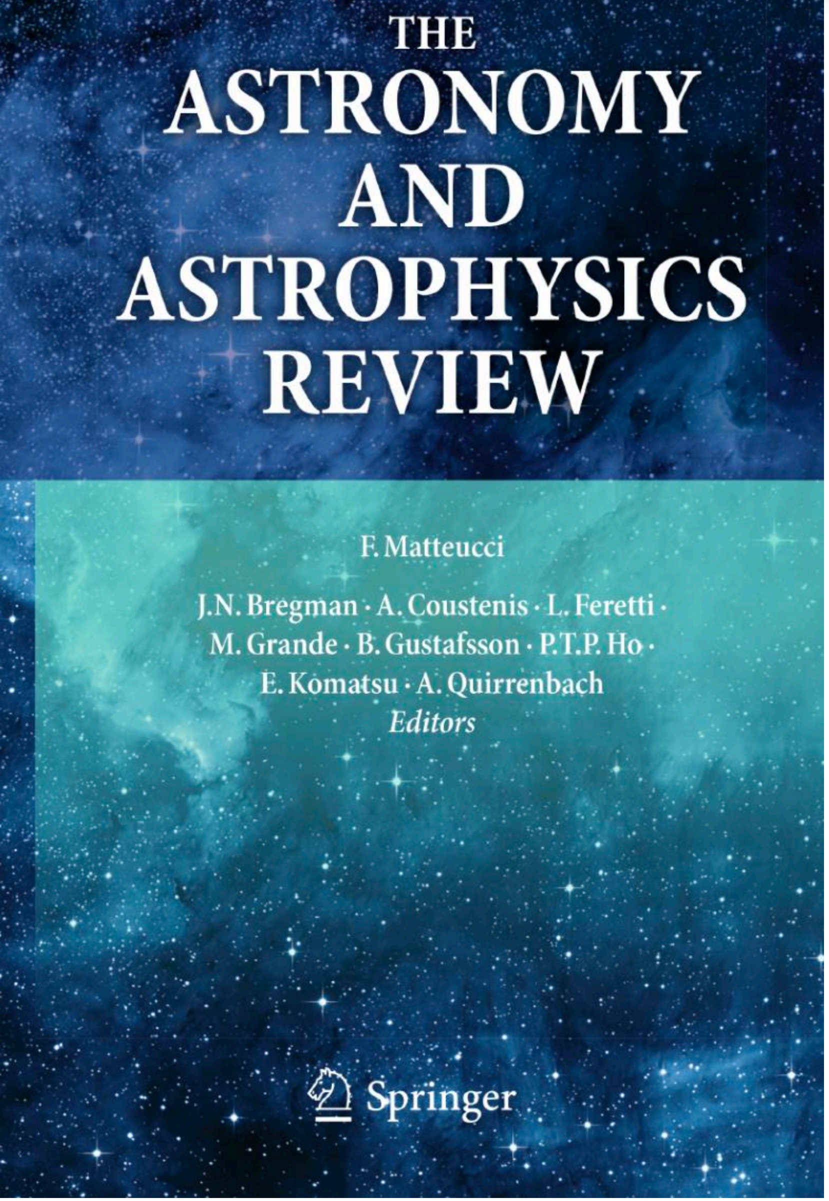
How do CRs shape SFR, star clusters, galactic outflows?

Impact of CRs on the CGM

Commercial break

Fundamental challenges facing CR transport models

Can we test CR models?



SPRINGER NATURE

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Astron Astrophys Rev (2023) 31:4
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REVIEW ARTICLE

Check for updates

Cosmic ray feedback in galaxies and galaxy clusters

A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

Mateusz Ruszkowski[1,3] · Christoph Pfrommer[2]

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Abstract
Understanding the physical mechanisms that control galaxy formation is a fundamental challenge in contemporary astrophysics. Recent advances in the field of astrophysical feedback strongly suggest that cosmic rays (CRs) may be crucially important for our understanding of cosmological galaxy formation and evolution. The appealing features of CRs are their relatively long cooling times and relatively strong dynamical coupling to the gas. In galaxies, CRs can be close to equipartition with the thermal, magnetic, and turbulent energy density in the interstellar medium, and can be dynamically very important in driving large-scale galactic winds. Similarly, CRs may provide a significant contribution to the pressure in the circumgalactic medium. In galaxy clusters, CRs may play a key role in addressing the classic cooling flow problem by facilitating efficient heating of the intracluster medium and preventing excessive star formation. Overall, the underlying physics of CR interactions with plasmas exhibit broad parallels across the entire range of scales characteristic of the interstellar, circumgalactic, and intracluster media. Here we present a review of the state-of-the-art of this field and provide a pedagogical introduction to cosmic ray plasma physics, including the physics of wave–particle interactions, acceleration processes, CR spatial and spectral transport, and important cooling processes. The field is ripe for discovery and will

M. Ruszkowski, C. Pfrommer have shared first authorship with the authors contributing equally to this work

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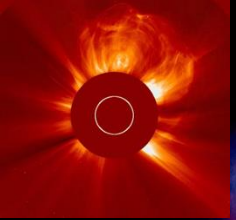
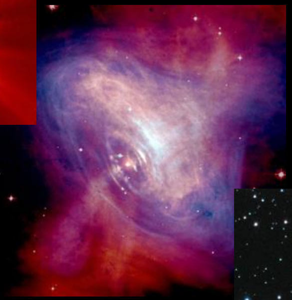
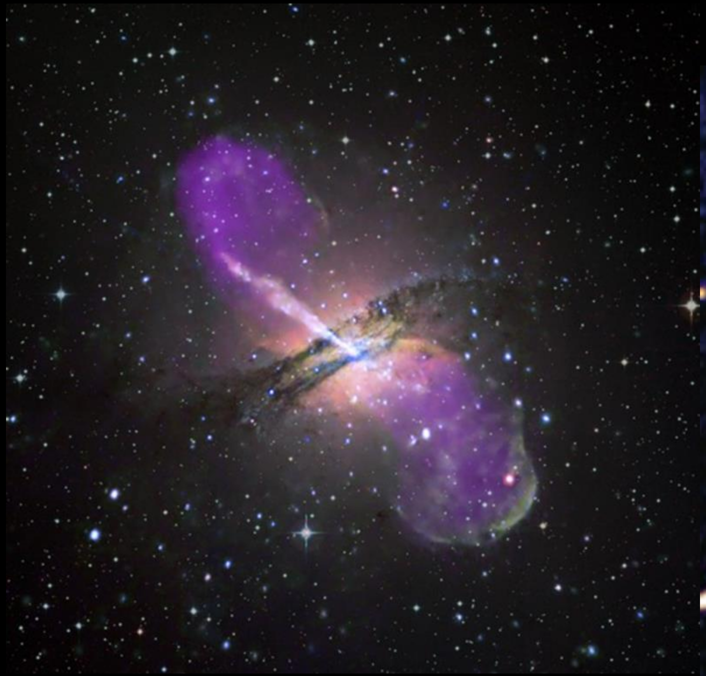
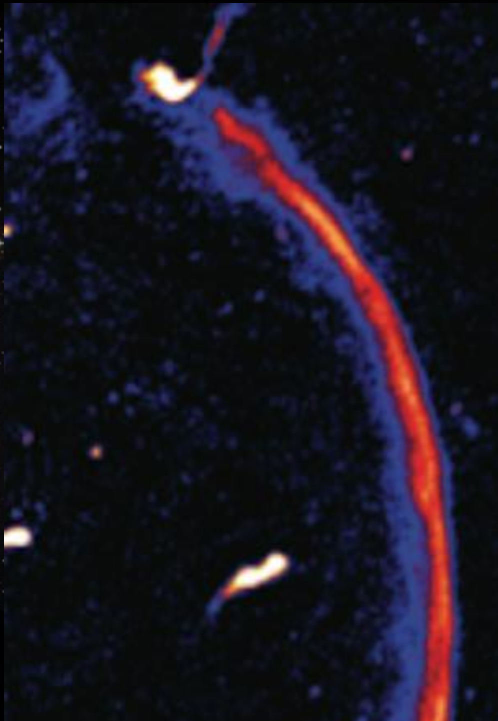
Ruszkowski & Pfrommer 2023

(**237** pages …)

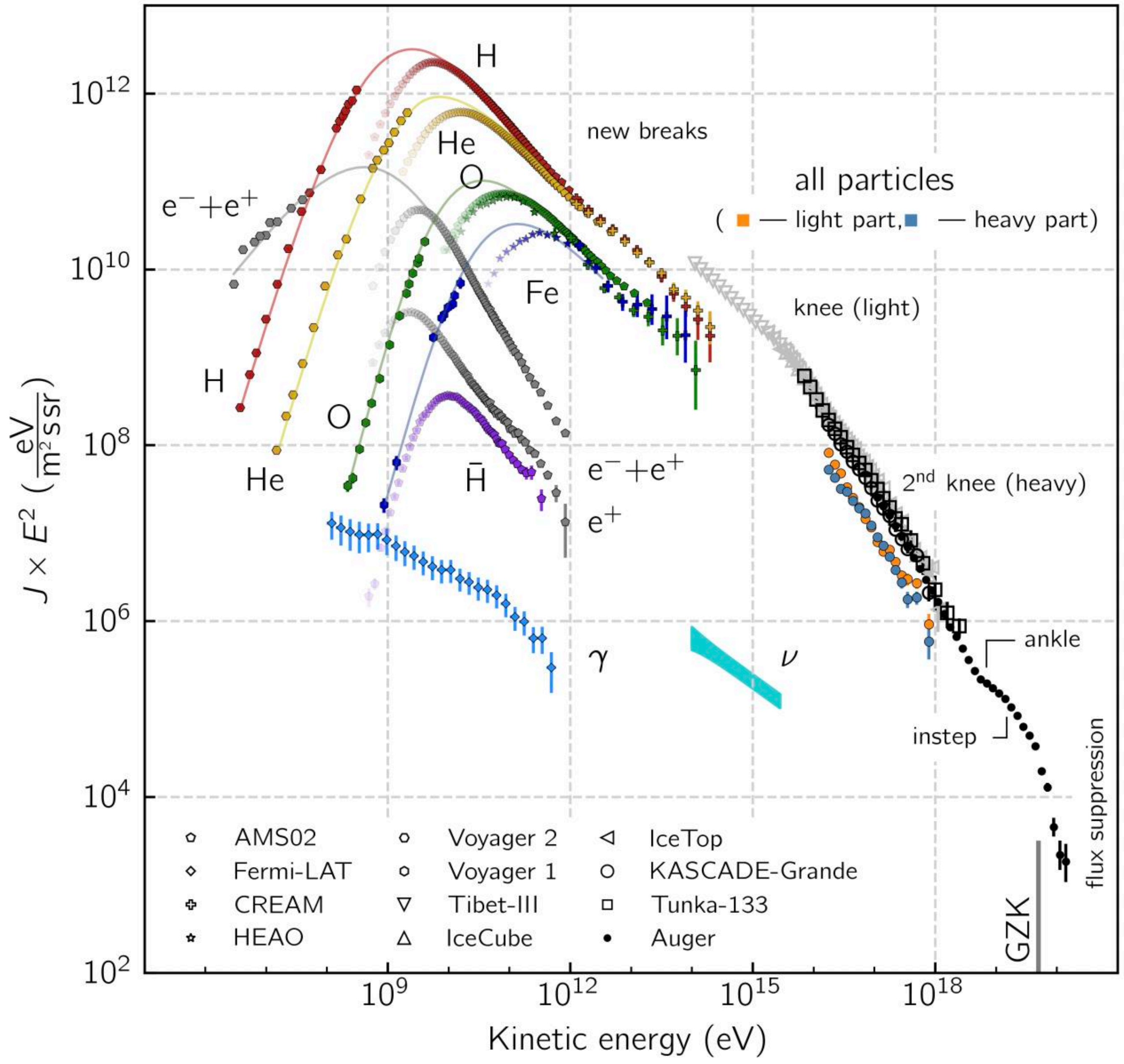
Answers to everything you always wanted to know about cosmic rays but were afraid to ask…

CRs are everywhere!

dynamical range of physical scales > a million



Ruszkowski & Pfrommer (2023); original figure from Lenok (2022); extended to include e^+ -e^- data from *Voyager* 2 (Stone et al. 2019)

Fundamental reasons why CRs are important for feedback:

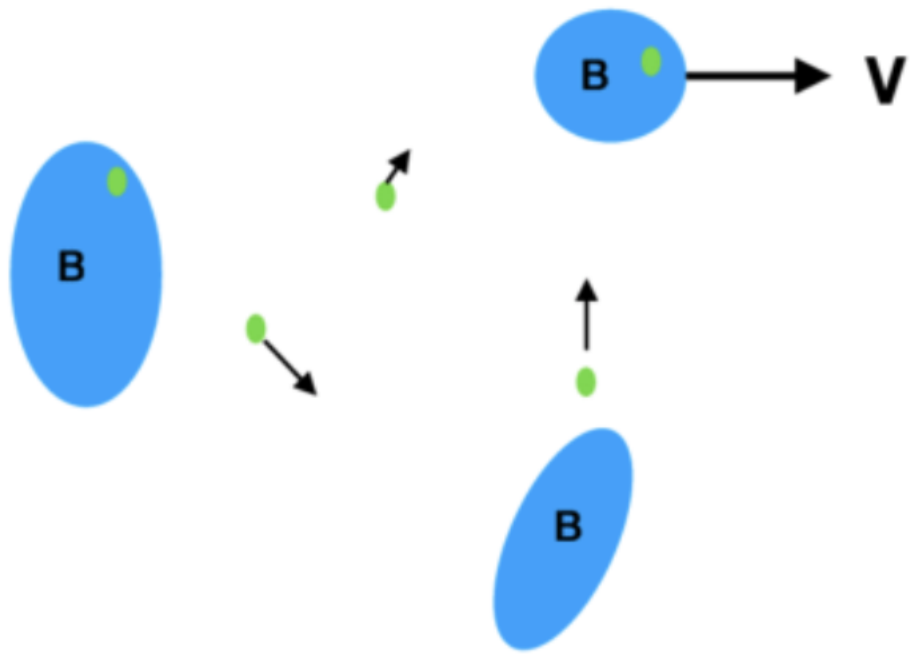
$$e_{\rm cr} \sim e_{\rm th} \sim e_{\rm turb} \sim e_{\rm B} \sim 1\ {\rm eVcm}^{-3}$$

slow cooling

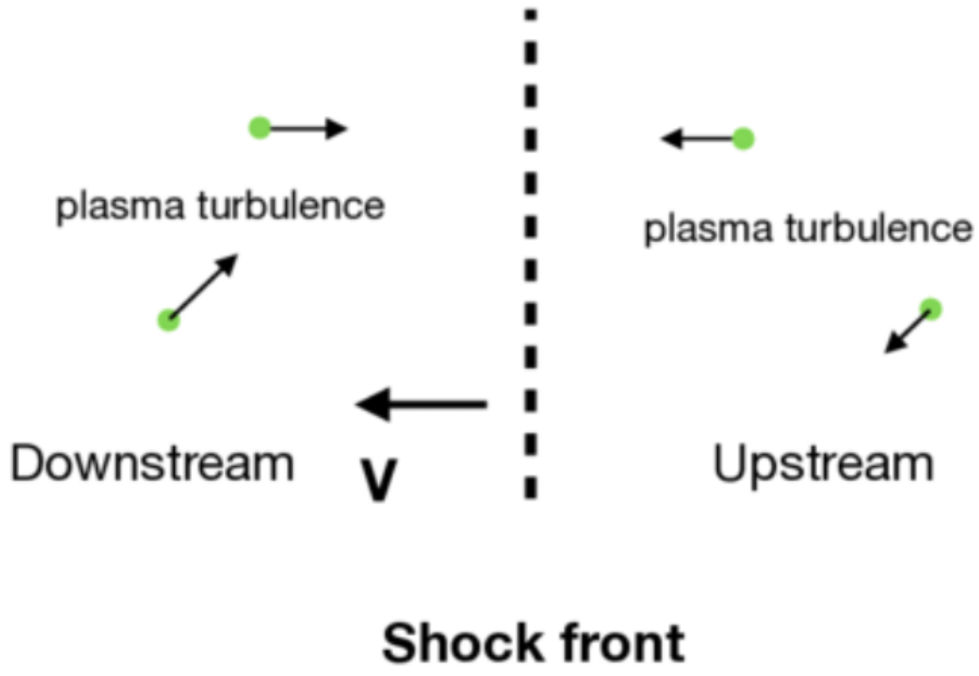
heating/ionization

good coupling to thermal plasma

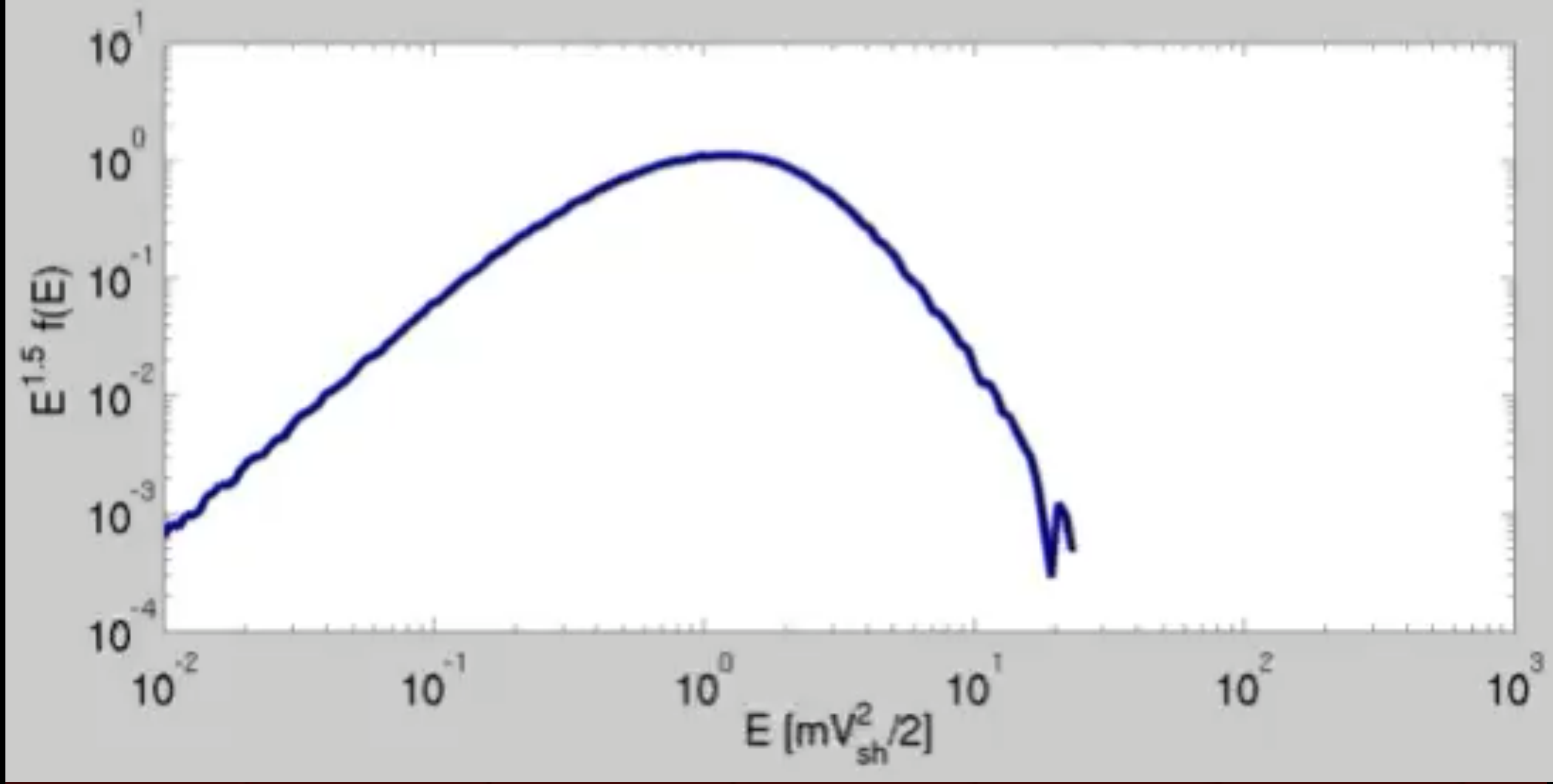
What mechanisms produce CRs?



2nd-order Fermi acceleration



1st-order Fermi acceleration

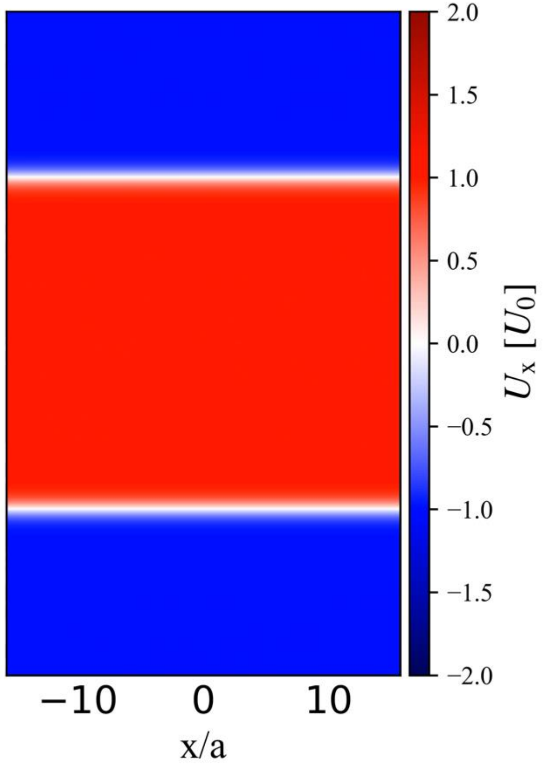


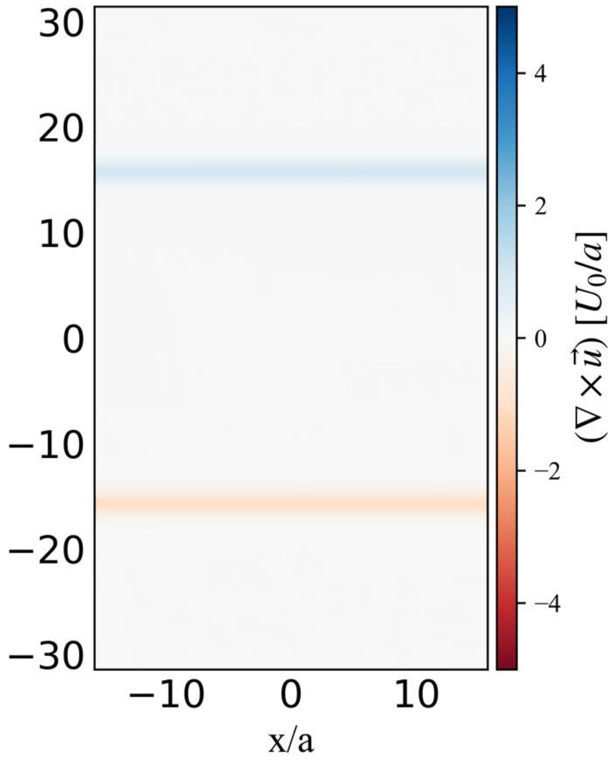
Hybrid-PIC DSA simulations
of CR acceleration in SNRs

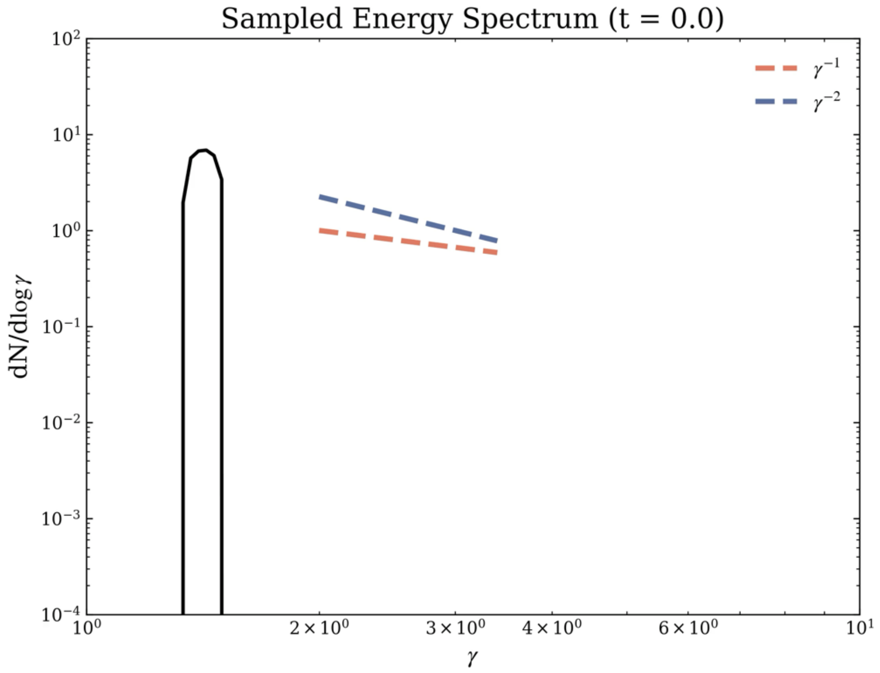
Caprioli & Spitkovsky (2014)

CR acceleration efficiency ~ 10%

CR turbulent shear layer acceleration







Liu, Ruszkowski, Zweibel, Sun et al. (in prep)

MHD-PIC Athena++ simulations

Milky Way-like galaxy

$$r_{\mathrm{galaxy}} \sim 10^4\ \mathrm{pc}$$

gyroradius of a GeV CR

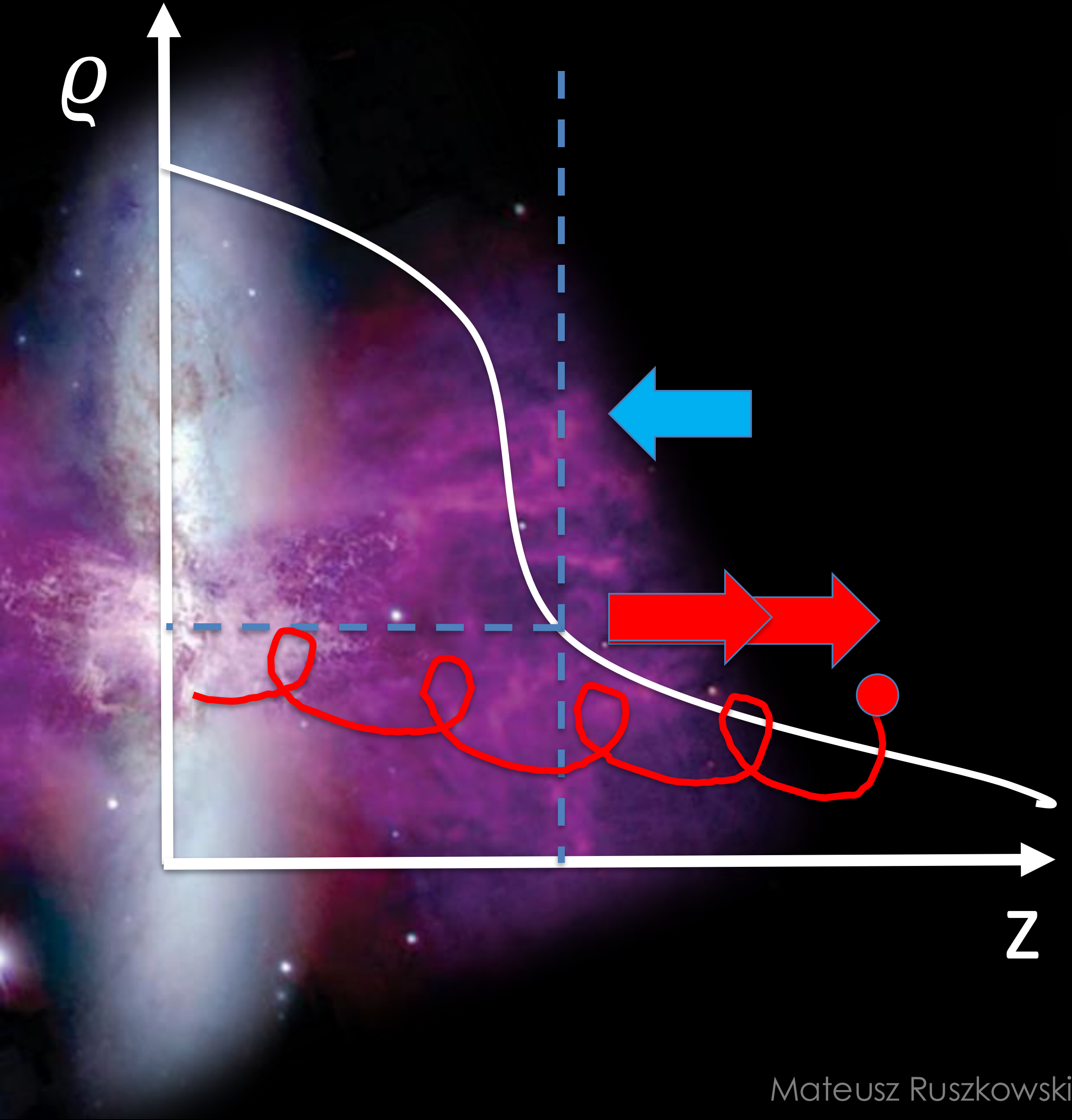
$$r_{\mathrm{cr}} = \frac{p_\perp}{eB} \sim 10^{-6}\ \mathrm{pc} \sim \mathcal{O}(\mathrm{AU})$$

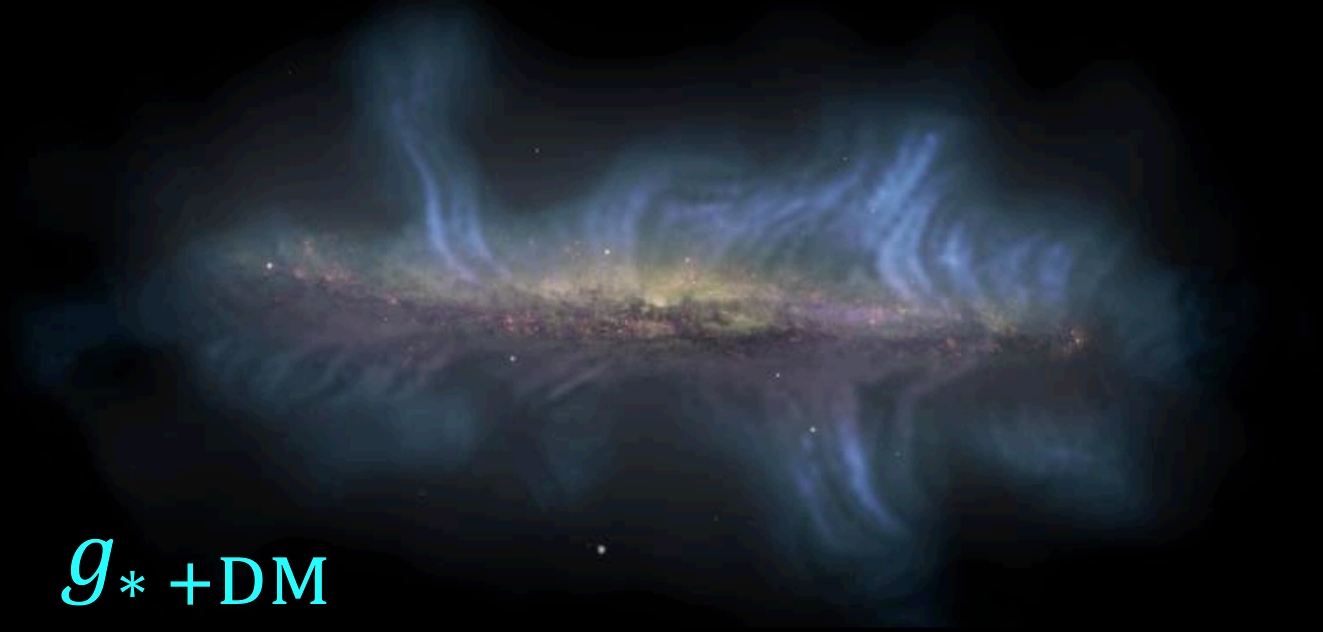
In order to handle this large dynamical range, we need a fluid theory for a collisionless nonthermal component.

Zweibel (2017), Jiang & Oh (2018), Thomas & Pfrommer (2019)

wind launching by CRs

English, Stein, Miskolczi (CHANG-ES collaboration)





g_{*} +DM

$$a_{CR} = -\frac{1}{\varrho}\nabla P_{CR} > g_{*}$$

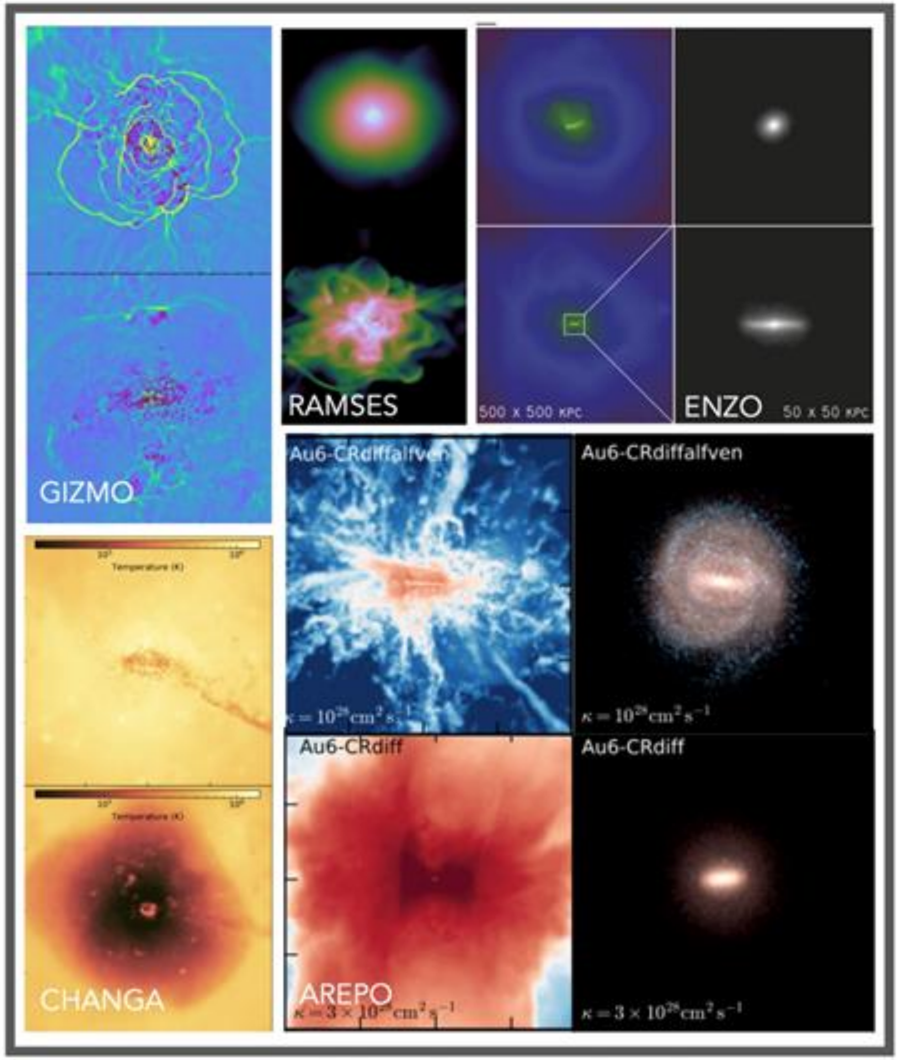
Eddington limit for CRs

$$\frac{L_{\rm Edd,cr}}{4\pi r^2}\hat{\boldsymbol{r}} = -\frac{\kappa}{\gamma_{\rm cr}-1}\nabla P_{\rm cr} = -\frac{\kappa}{\gamma_{\rm cr}-1}\rho\boldsymbol{g}$$

$$L_{\rm Edd,cr} = \frac{4\pi G M\kappa\rho}{\gamma_{\rm cr}-1}$$

$$L_{\rm Edd,cr}/L_{\rm Edd,\gamma} \sim \lambda_{\rm mfp,cr}/\lambda_{\rm mfp,\gamma} \ll 1$$

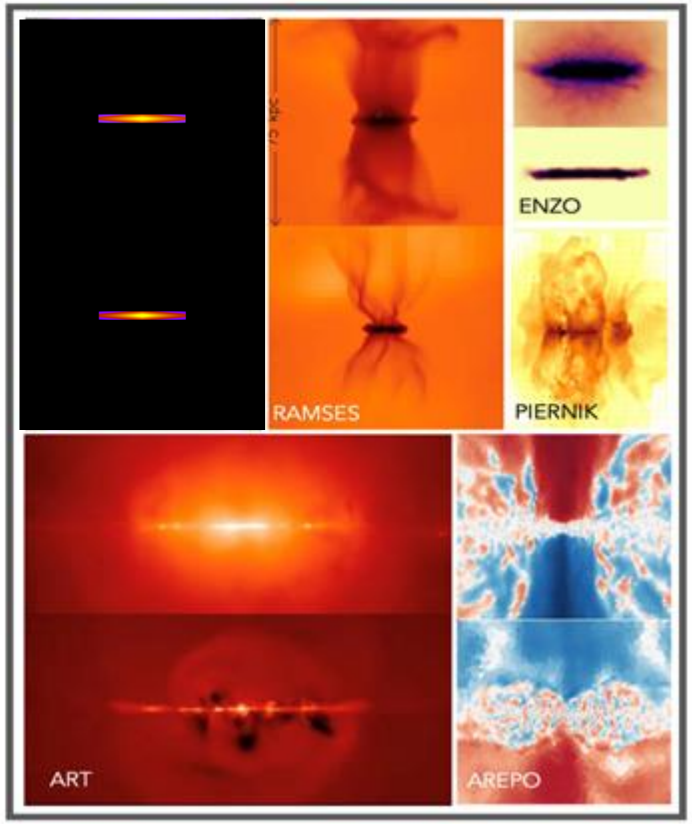
COSMO



Ji et al. (2021); Liang et al. (2016); Salem et al. (2016);
Butsky et al. (2020); Buck et al. (2020)

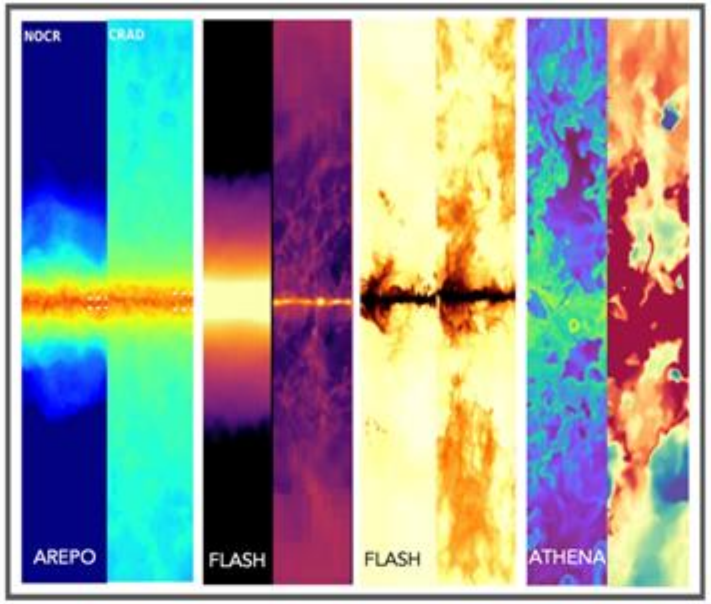
Ruszkowski et al. (2017b); Booth et al. (2013);
Butsky and Quinn (2018); Hanasz et al. (2013);
Semenov et al. (2021); Pakmor et al. (2016b)

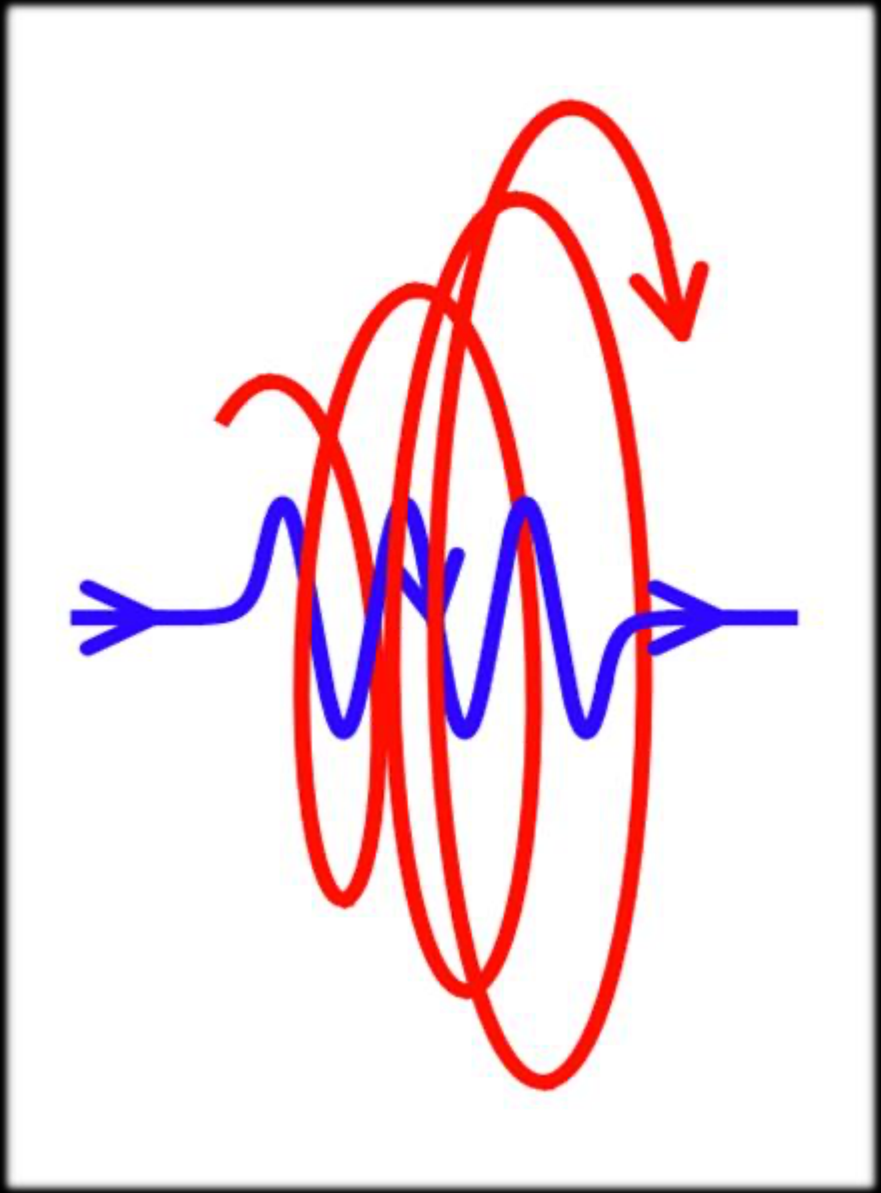
GLOBAL



Simpson et al. (2016); Farber et al. (2018);
Girichidis et al. (2018); Armillotta et al. (2021)

ZOOM



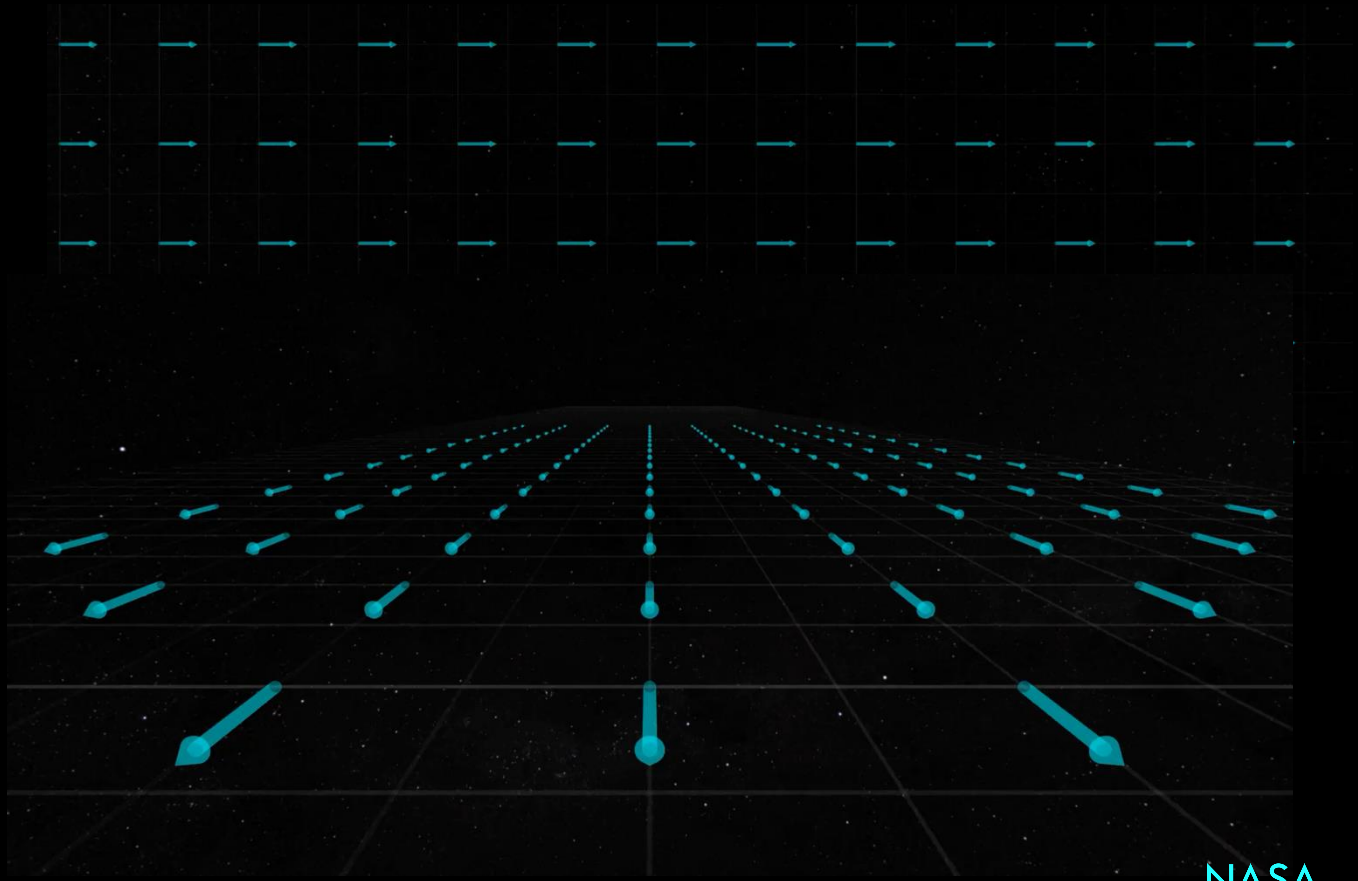


Courtesy of Pfrommer & Jacob

wavelength ~ Larmor radius: resonance

$$F_L = q\boldsymbol{v} \times \boldsymbol{B}$$

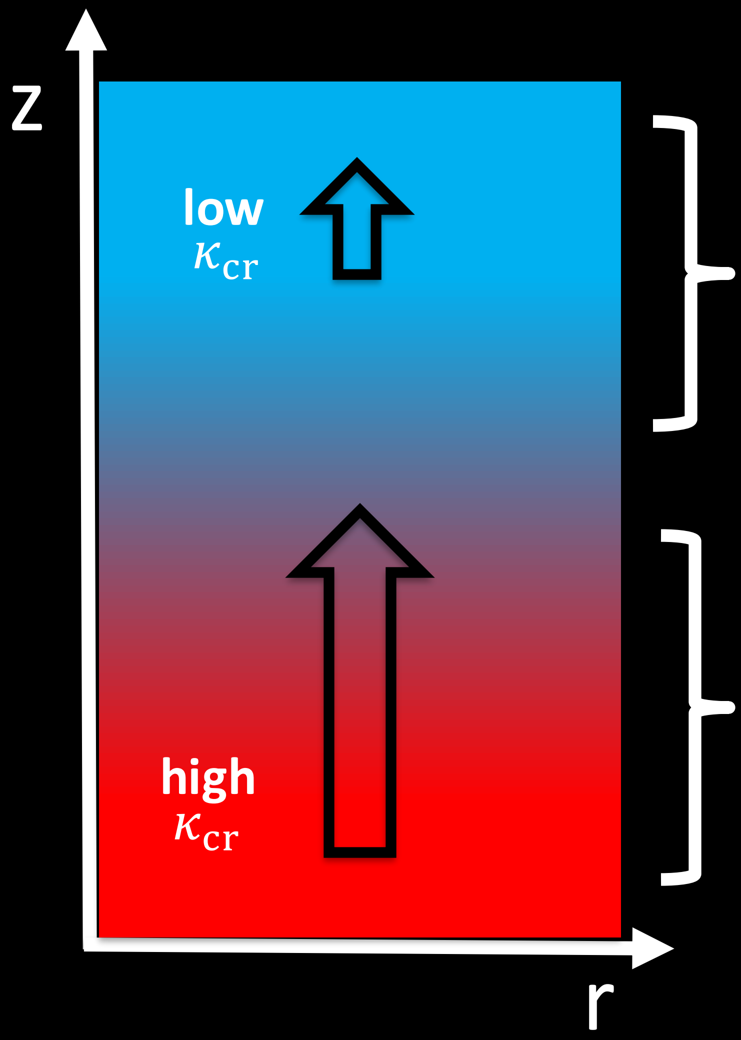
Lorentz force: no change in particle energy in the wave frame



NASA

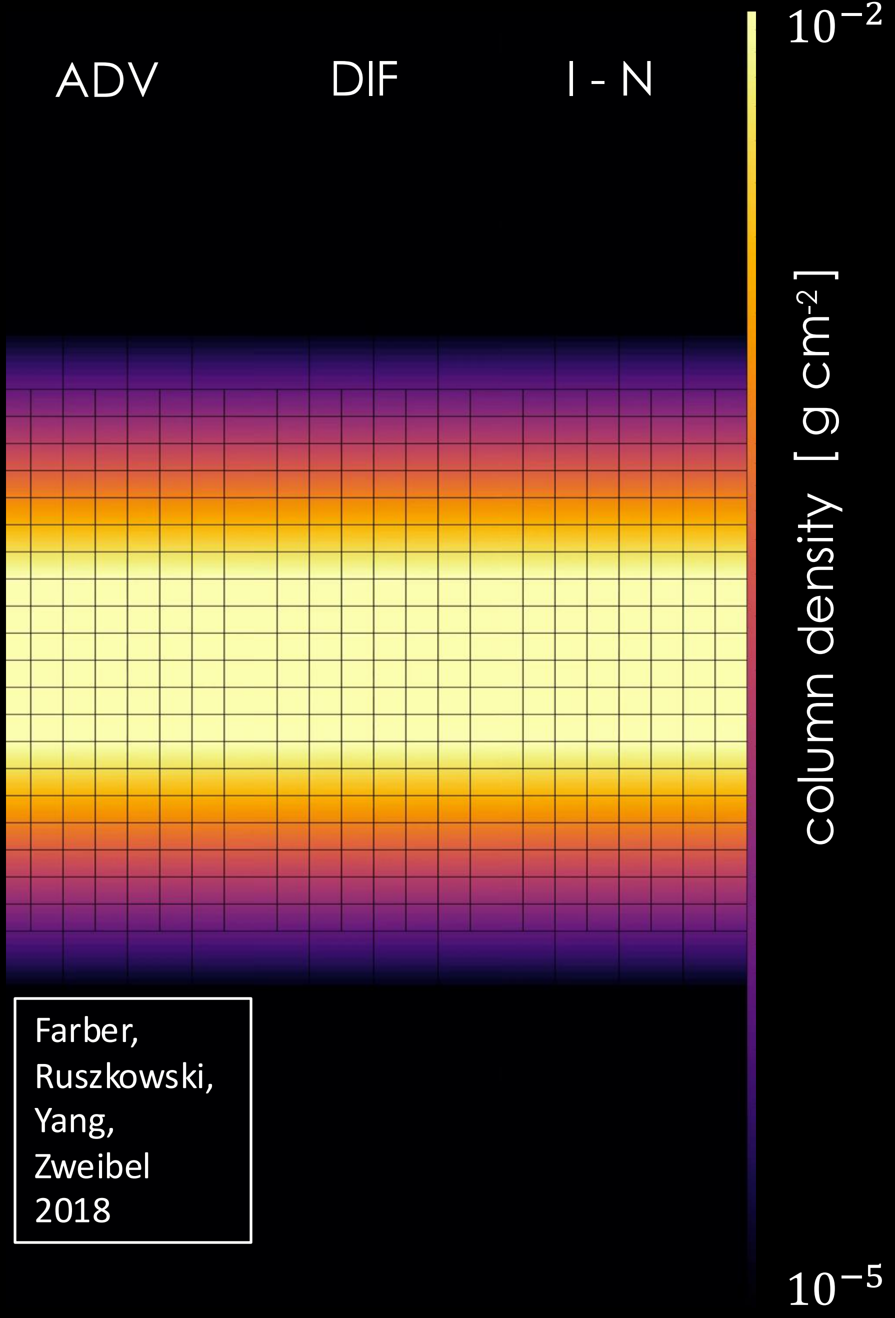
Fast CR transport in low T ISM

[Spatial dependence of CR transport]



high T

low T (wave damping by ion-neutral friction)



Farber, Ruszkowski, Yang, Zweibel 2018

ISM

Chemistry

- Full H – H_2 – He chemistry
  sets ionization degree
- First ionization stages of C – O – Si
  low temperature cooling
- Photoelectric heating by dust

Feedback

- Improved SNe treatment (manifestly isotropic)
  and stellar winds
- FUV NUV OPT radiation fields (reverse ray tracing)
  absorbed by dust – impacting **Chemistry**
- Metal enrichment

CR

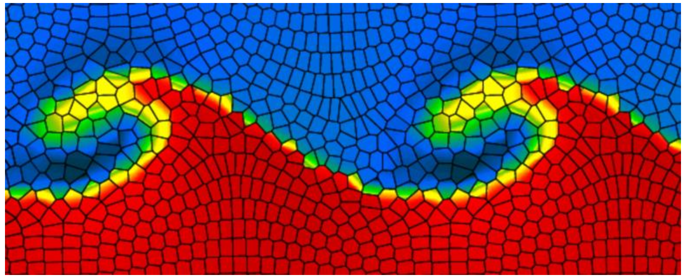
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting **Chemistry**
- CR microphysics

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics

Thomas, Pfrommer, Pakmor (2024)

Arepo code

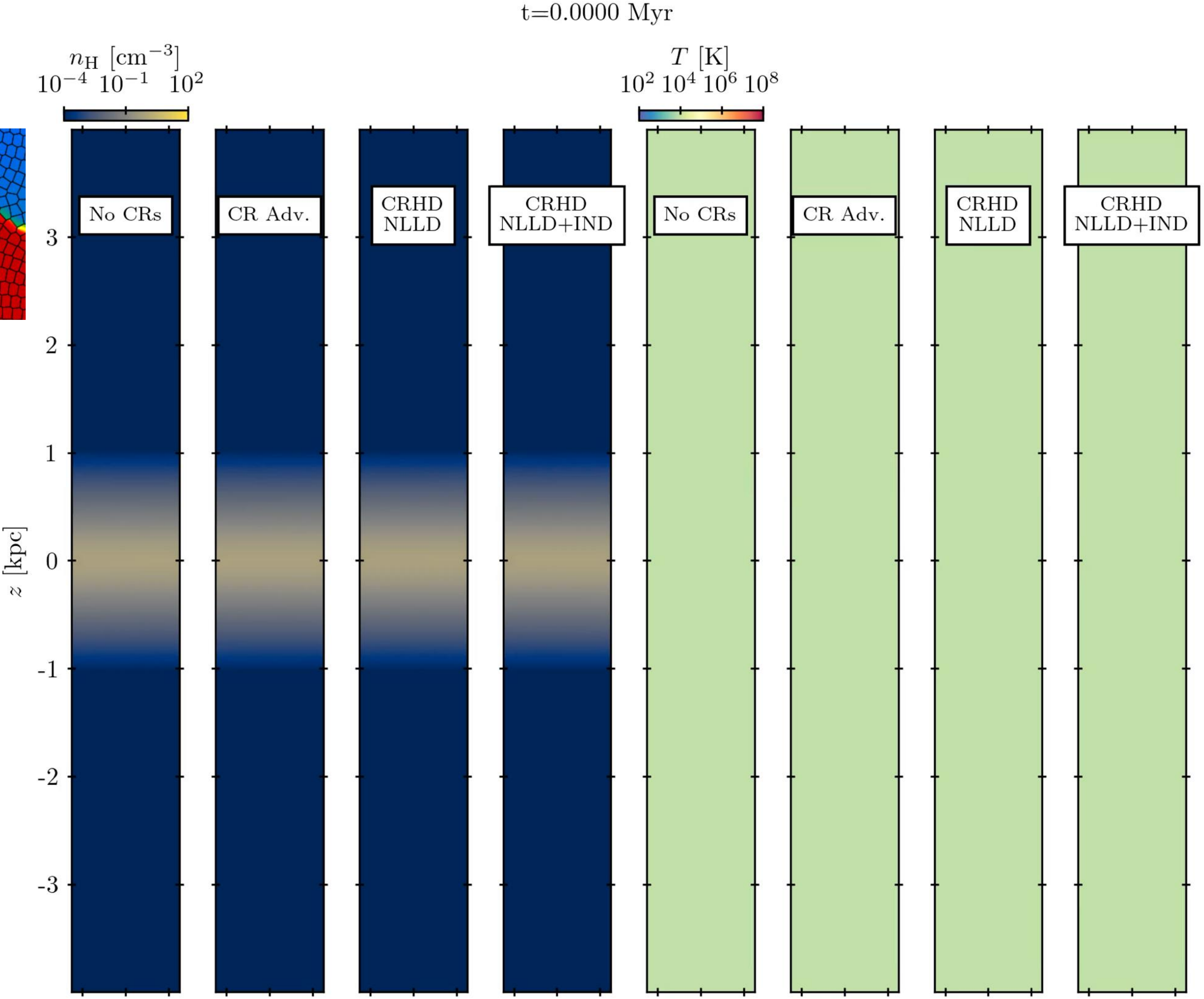


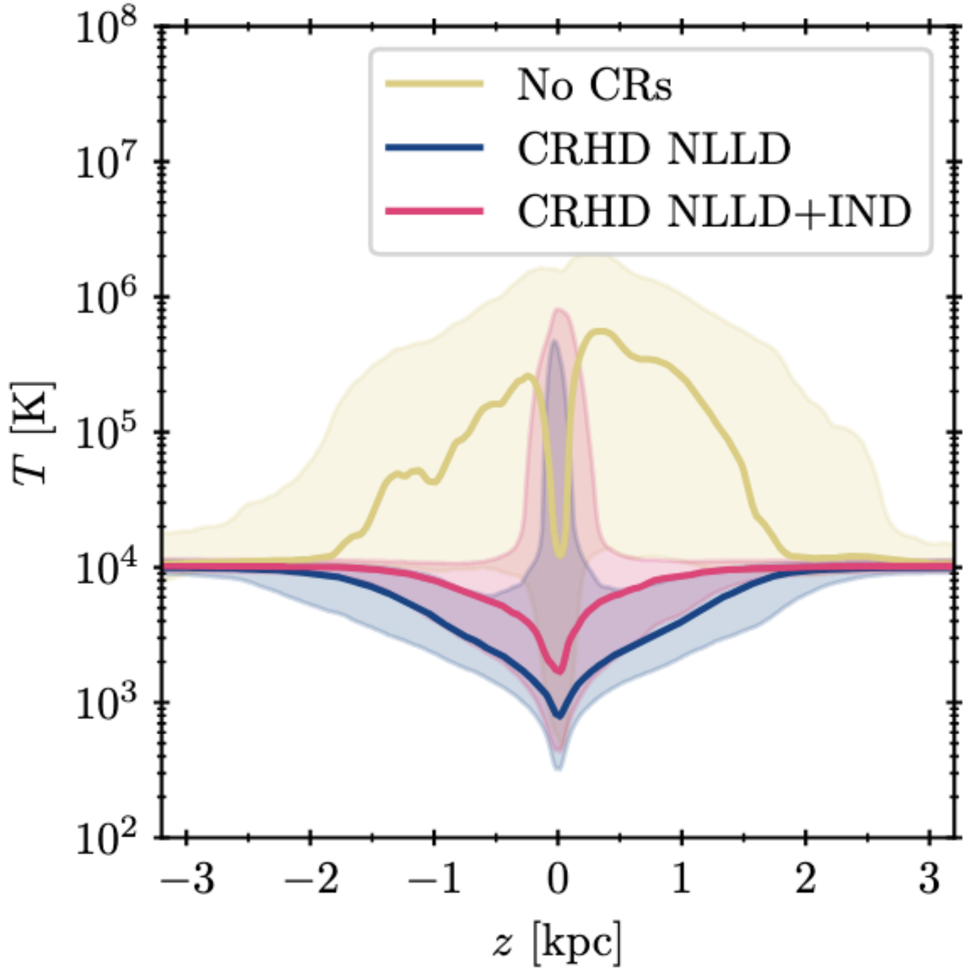
Sike, Thomas, Ruszkowski, Pfrommer, Weber (2025a)

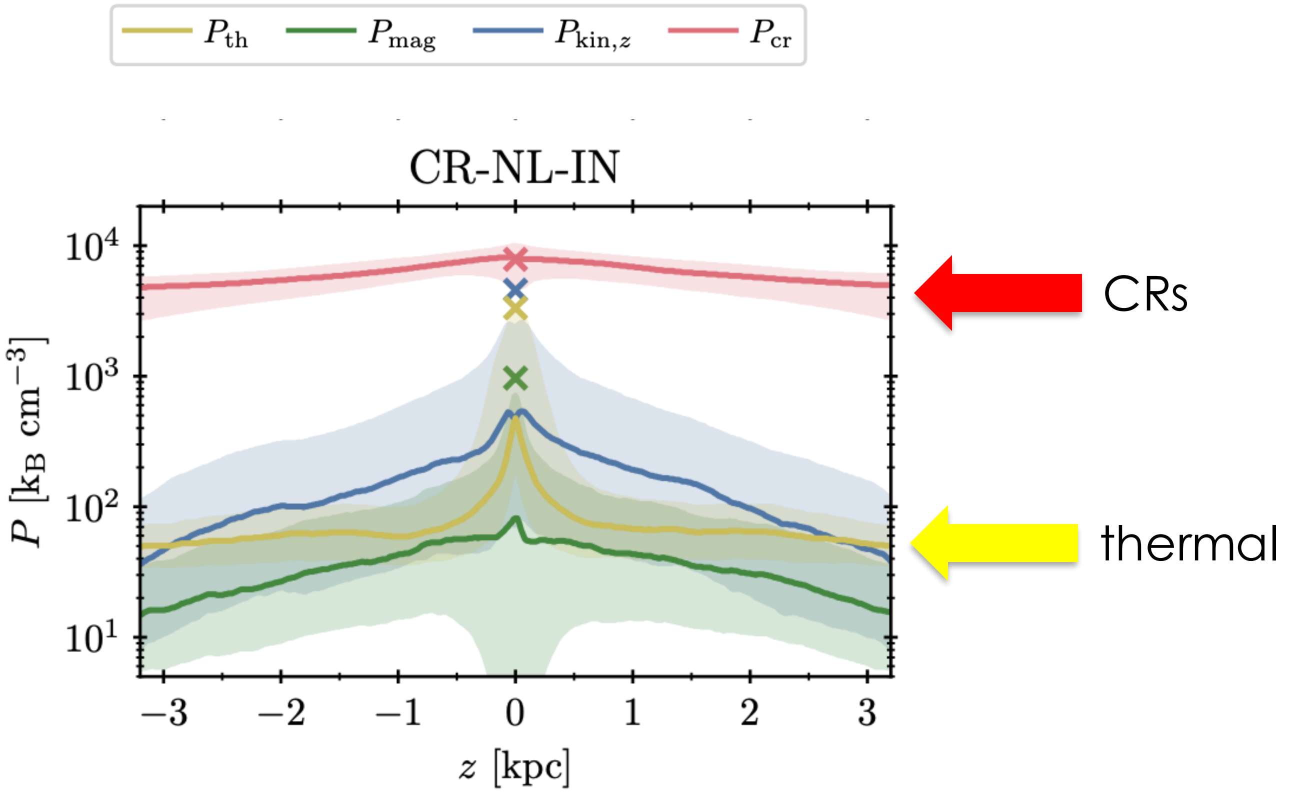
multiple SNe

superbubbles

~1pc resolution



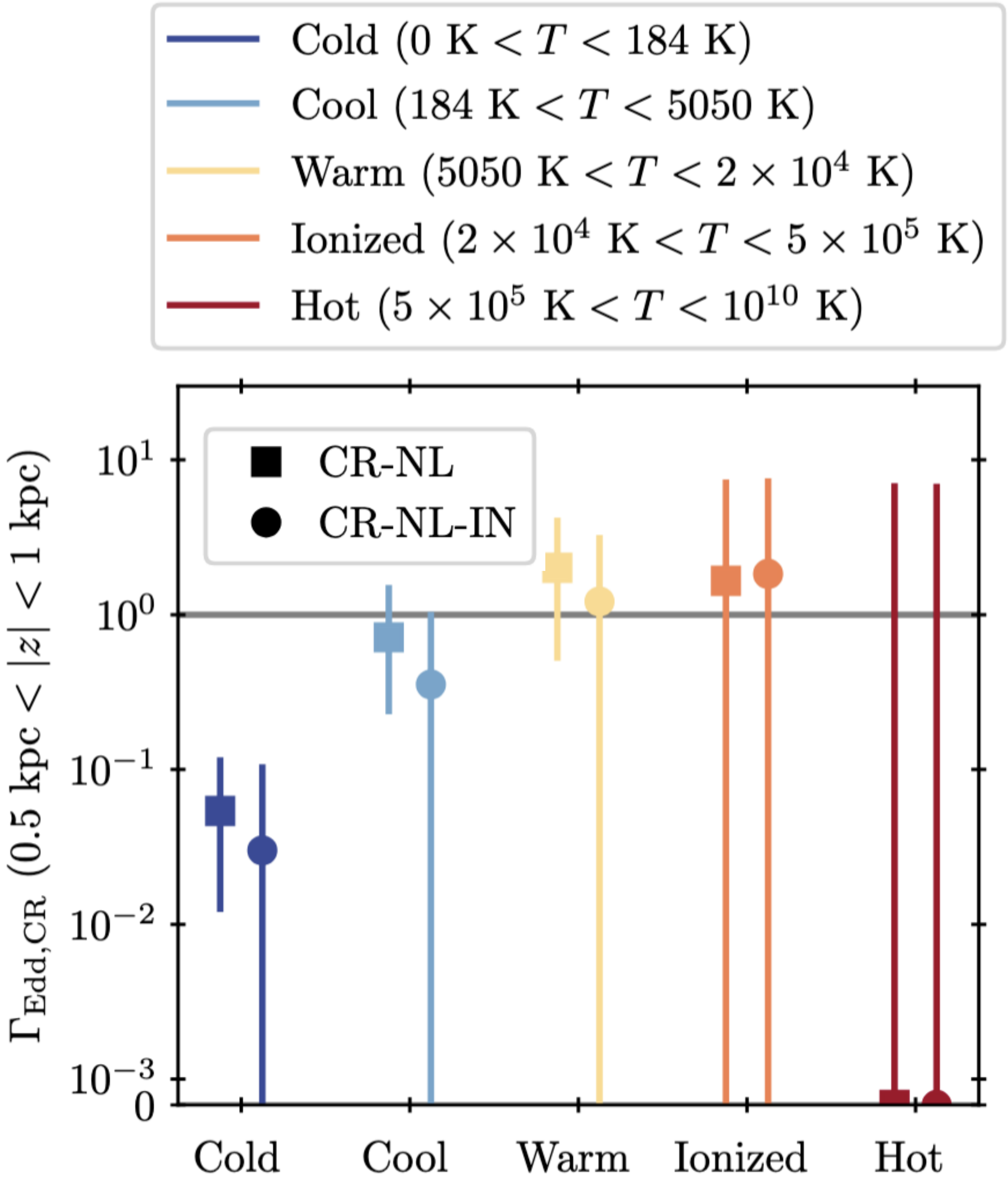




CR winds are colder / multiphase / supersonic

CR winds are **CR-pressure-dominated**

Sike, Thomas, Ruszkowski, Pfrommer, Weber (2025a)



CR Eddington factors:

$$\Gamma_{\mathrm{Edd,CR}} \equiv -\frac{a_{\mathrm{CR},z}}{a_{\mathrm{grav}}}, \quad a_{\mathrm{CR},z} = \frac{\nabla P_{\mathrm{CR}} \cdot \boldsymbol{e}_z}{\rho}$$

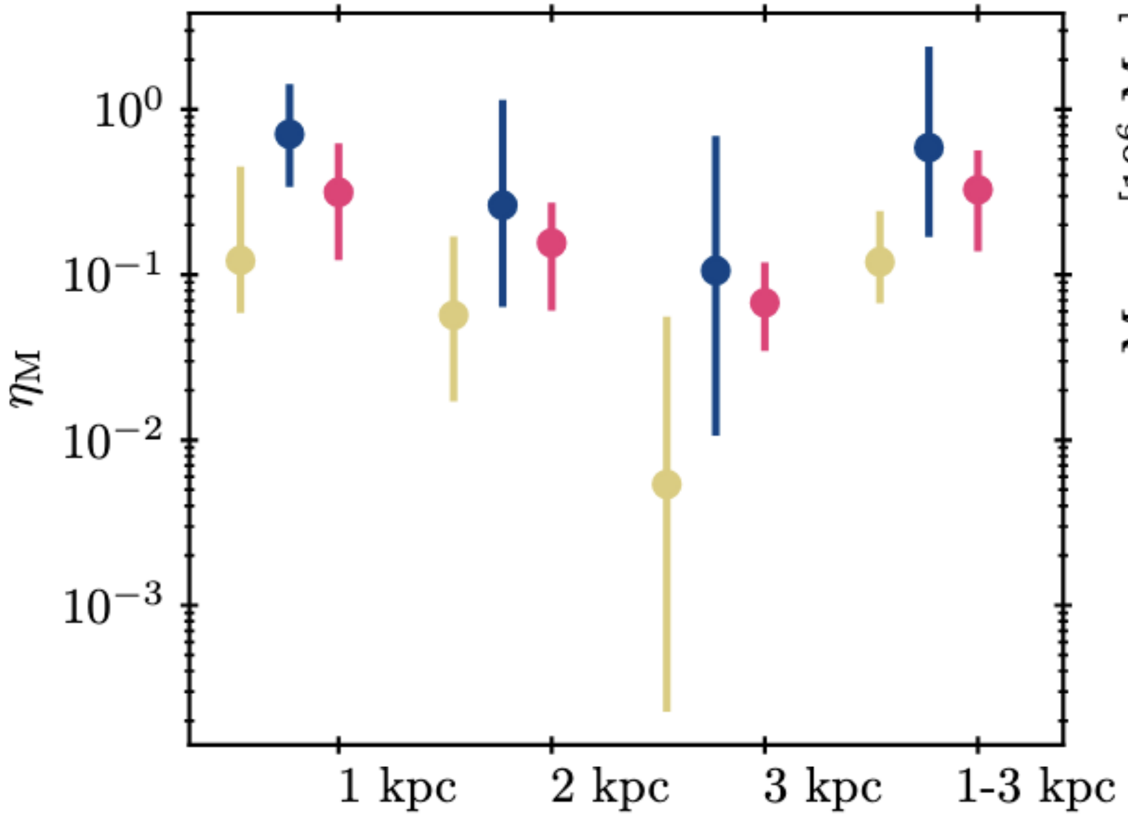
CRs drive winds despite decoupling from the cold ISM due to IN damping

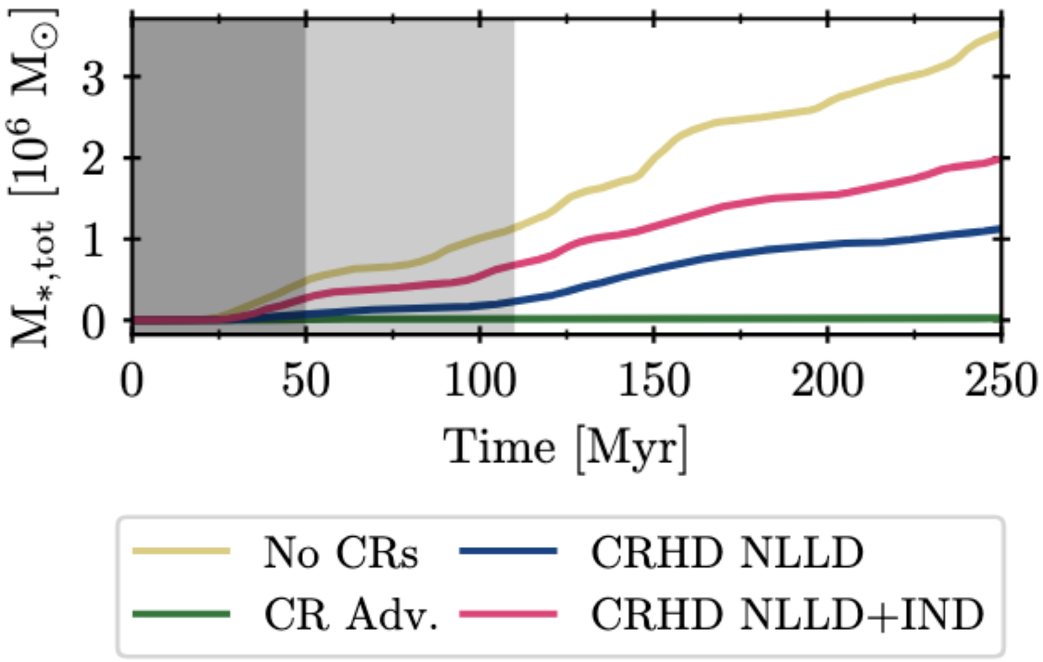
CRs accelerate warm & ionized phase

CRs do not accelerate hot phase

Sike, Thomas, Ruszkowski, Pfrommer, Weber (2025a)

CRs have a strong impact on SFR

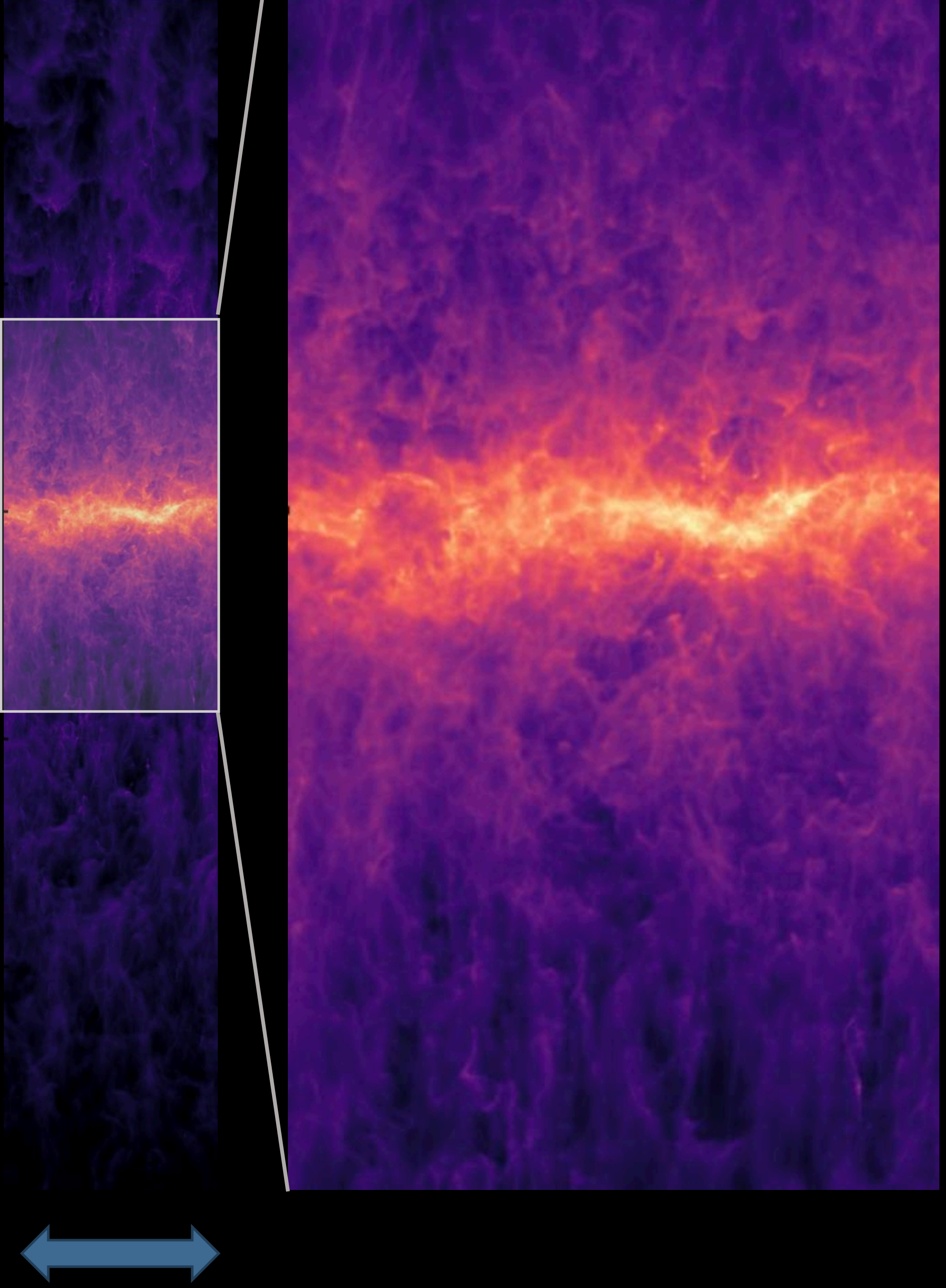


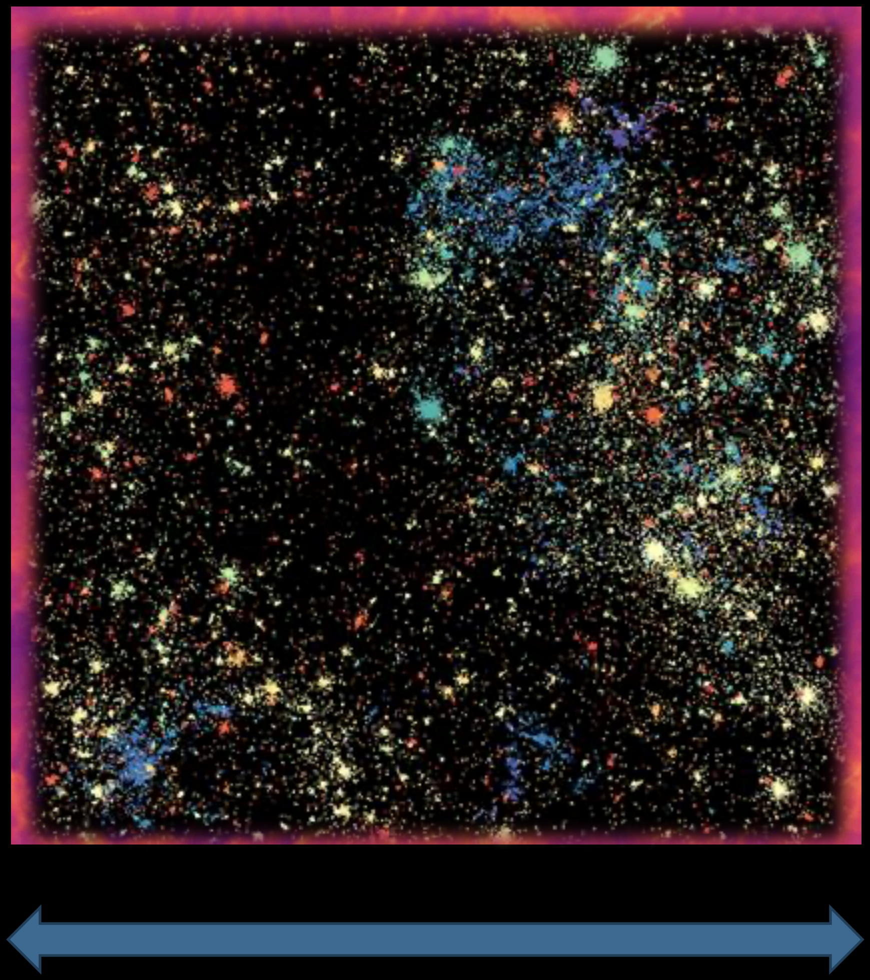


CR reduce star formation

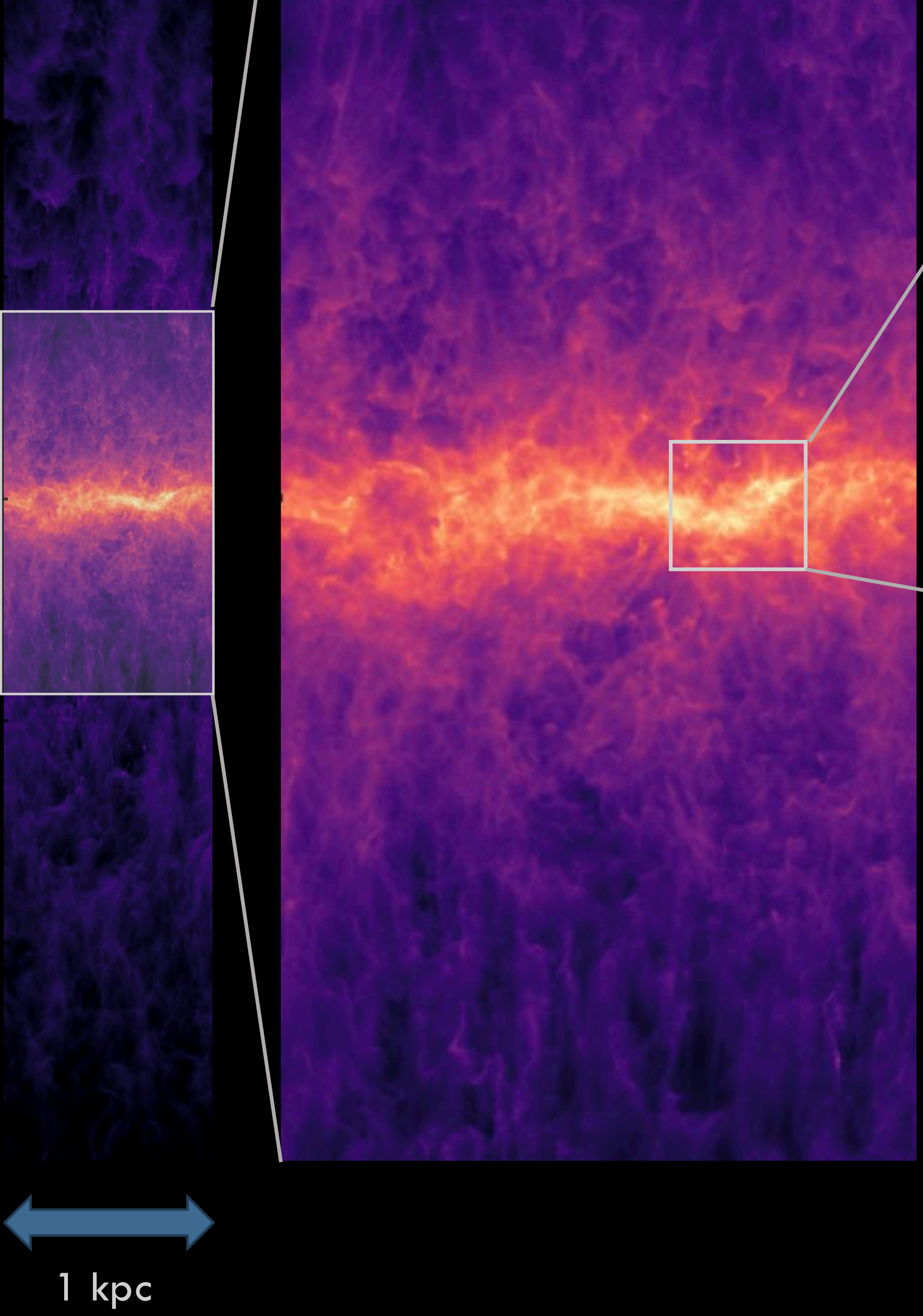
CR-driven mass loading ~4x larger than in the MHD case

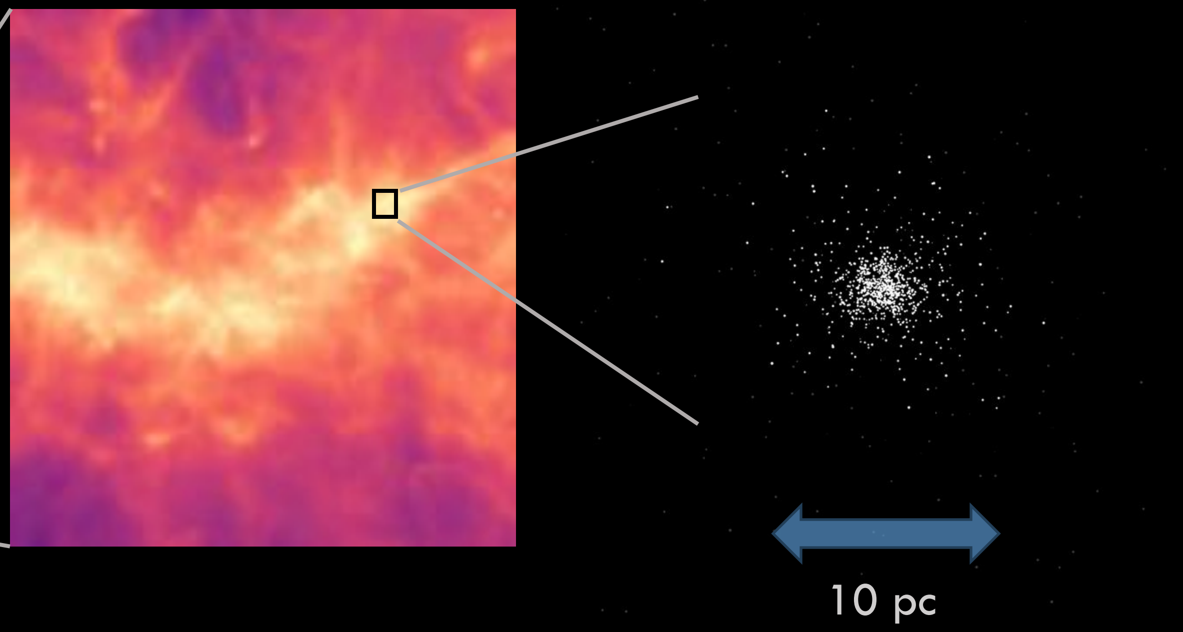
Sike, Thomas, Ruszkowski, Pfrommer, Weber (2025a)





Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)



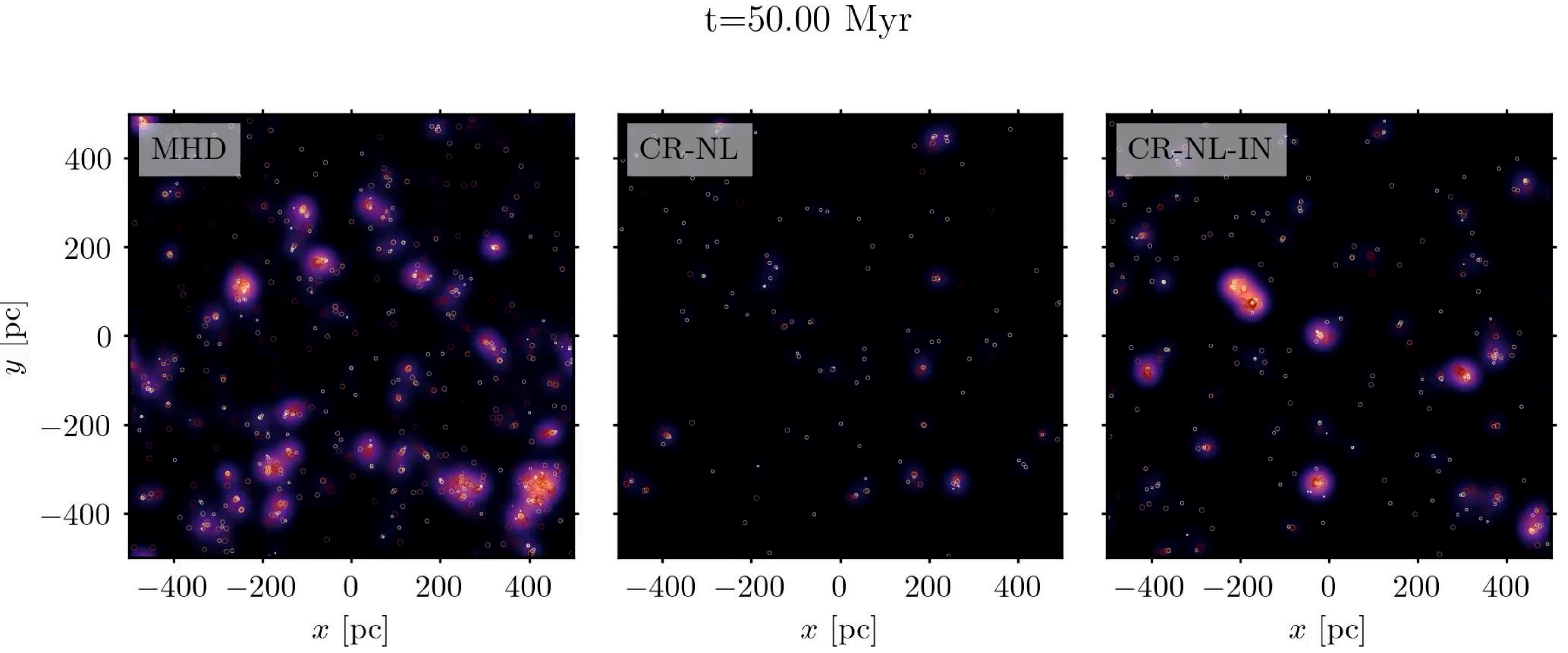


young stellar clusters !!!

properties dependent
on cosmic ray physics

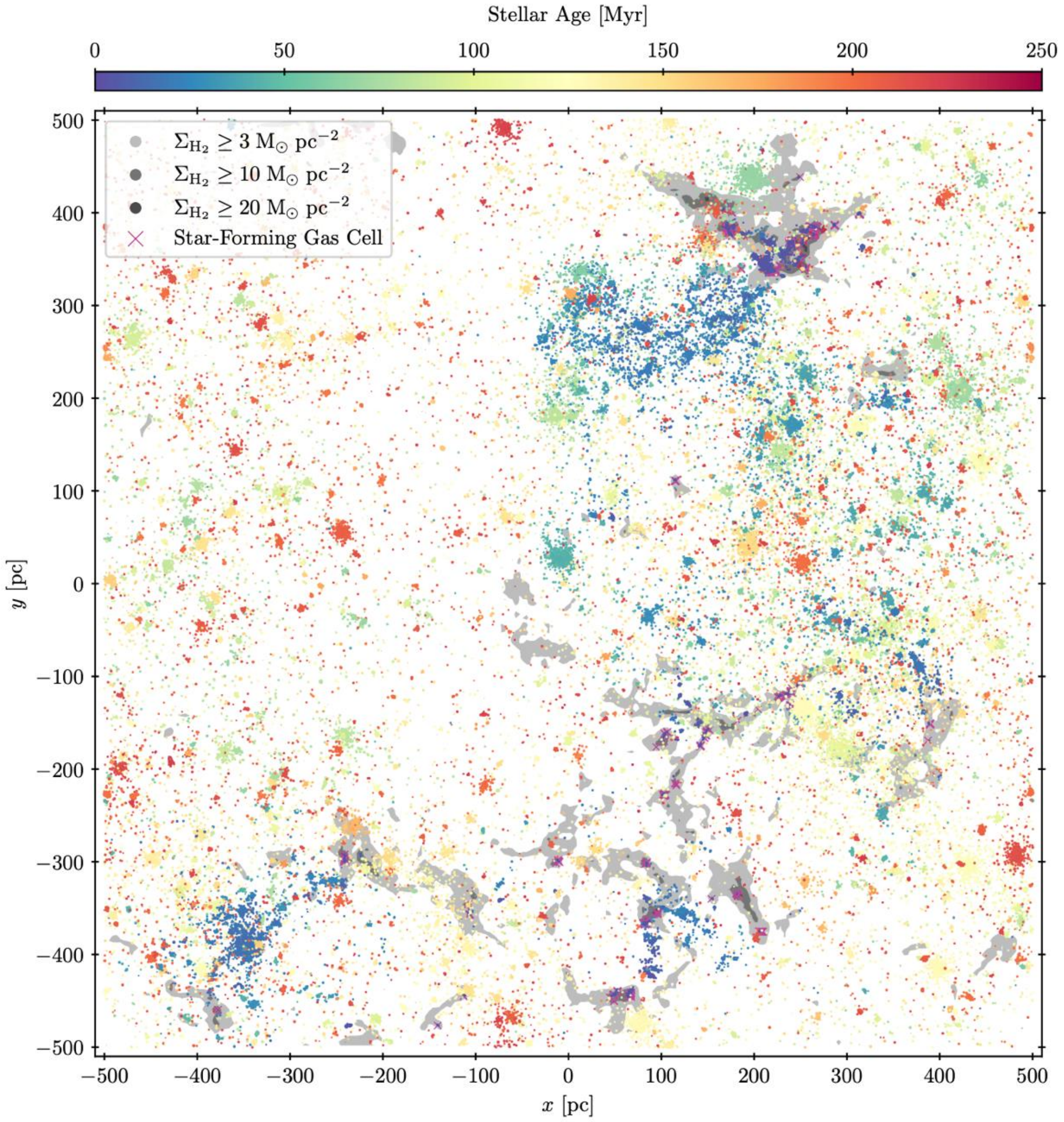
Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)

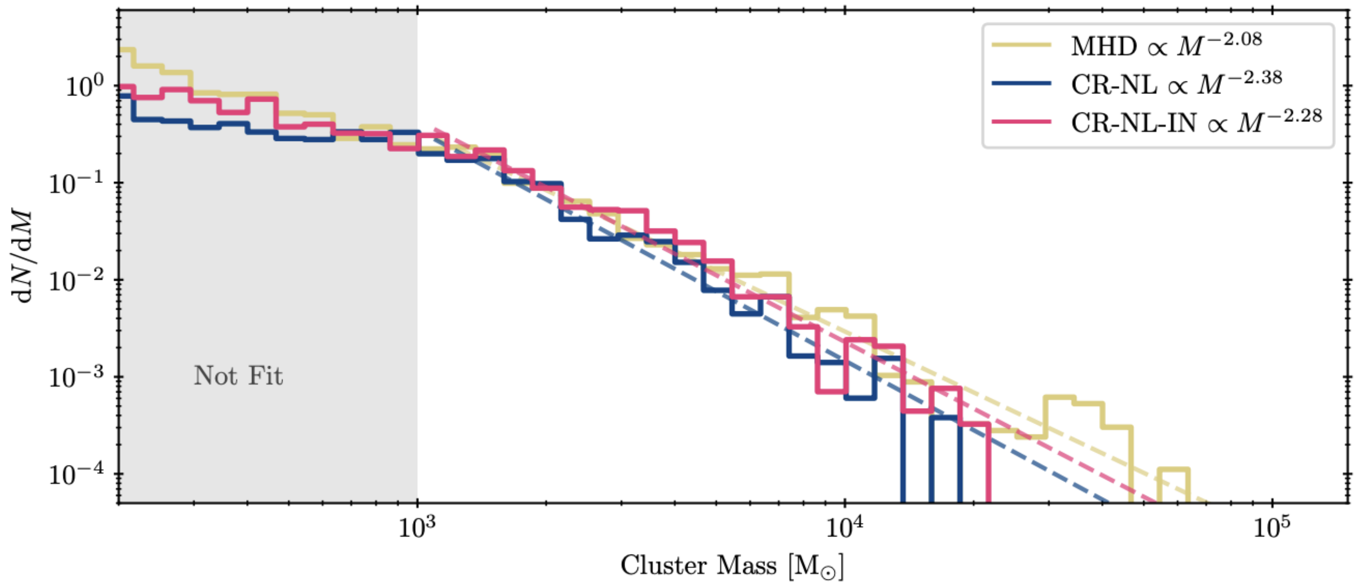
Clustered SN feedback & CR transport



Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)

Jackson Pollock plot





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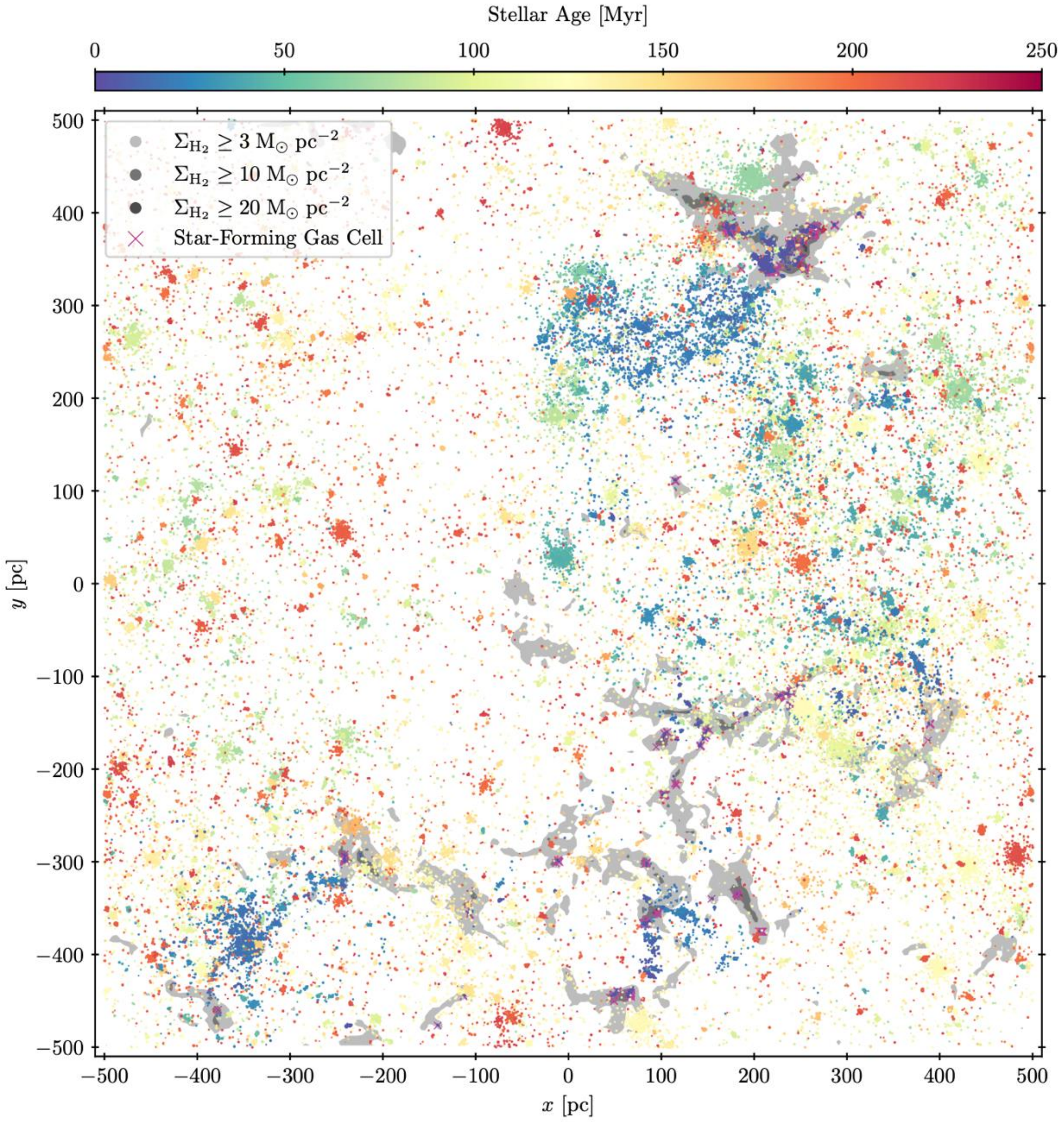
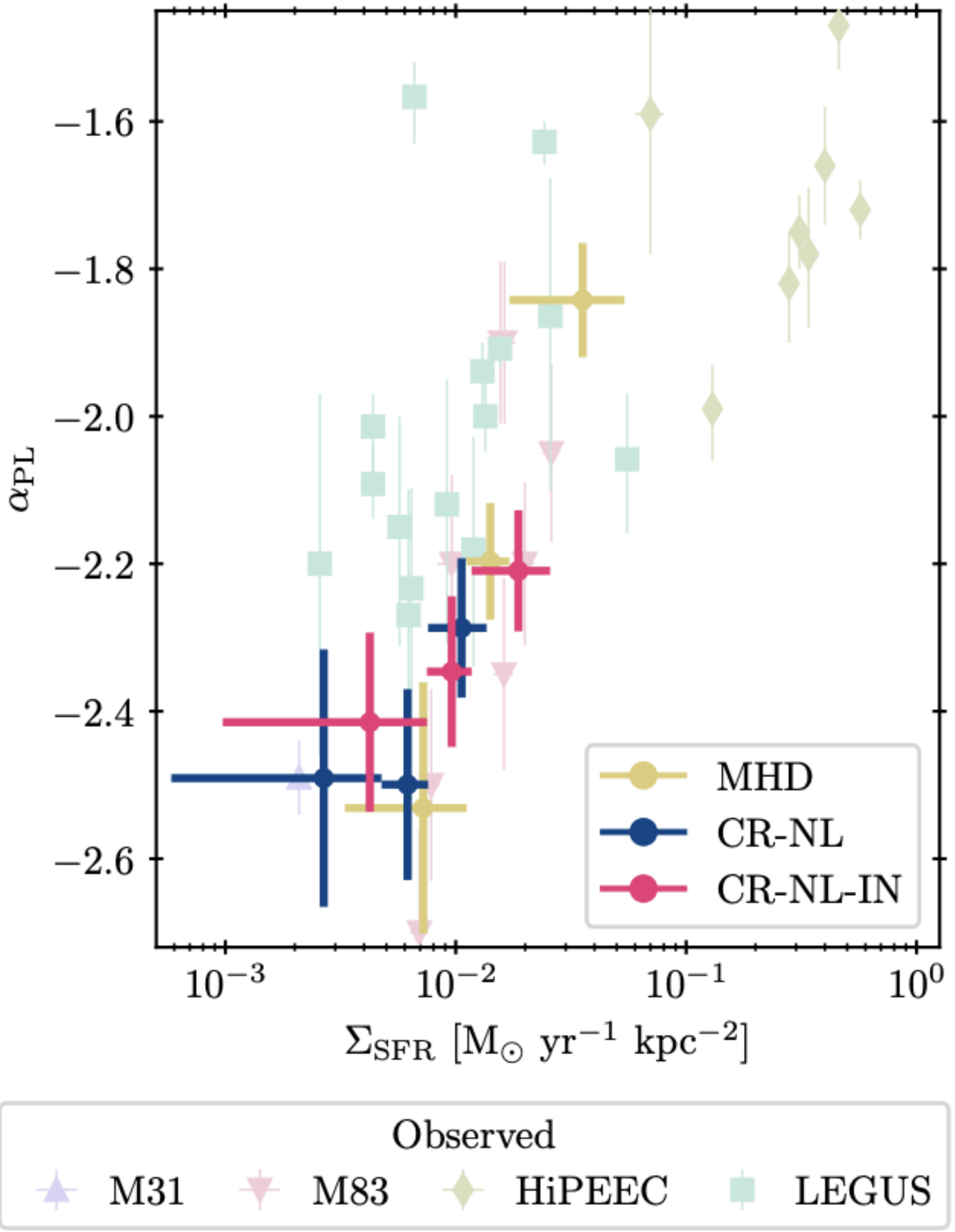
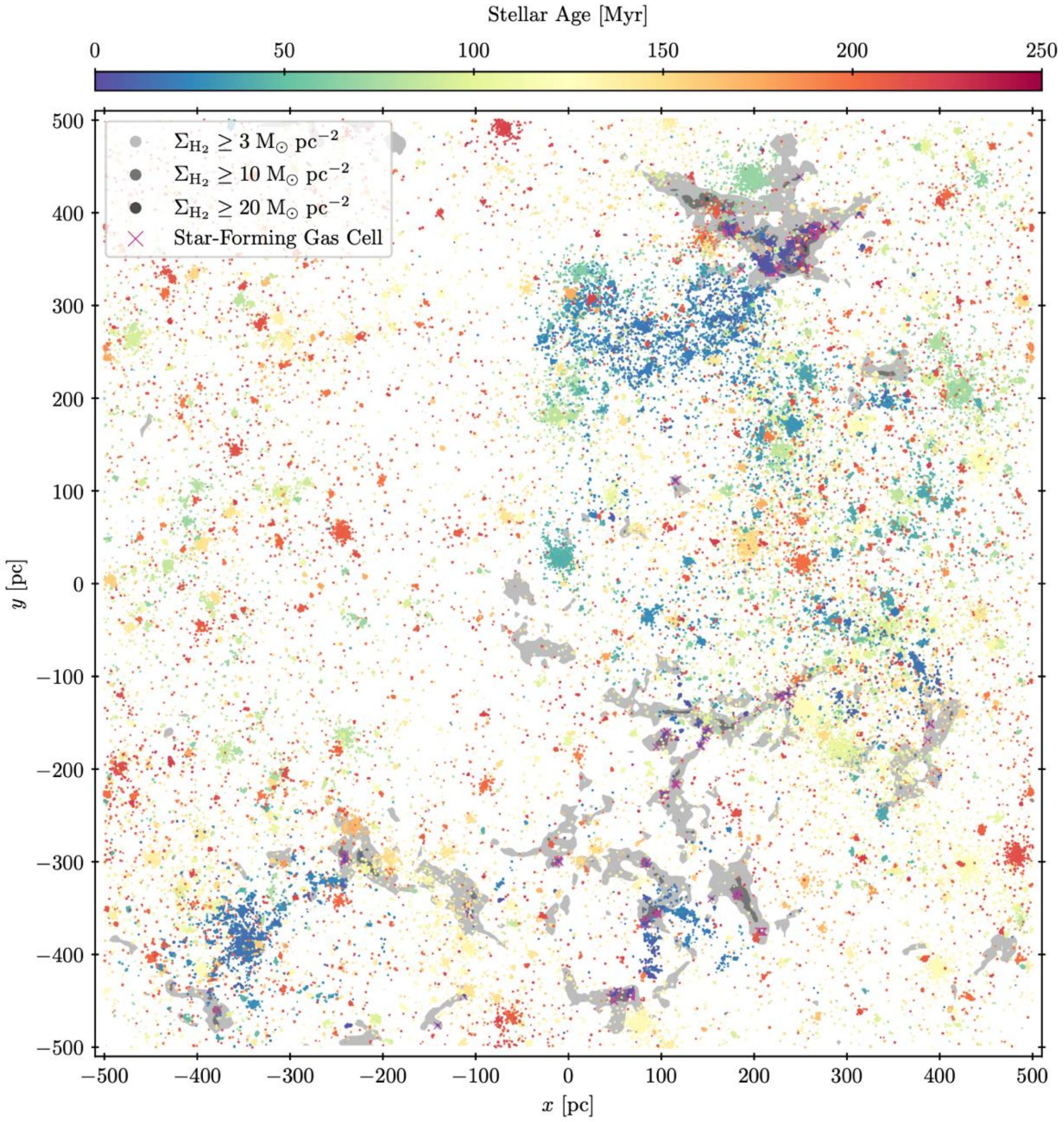
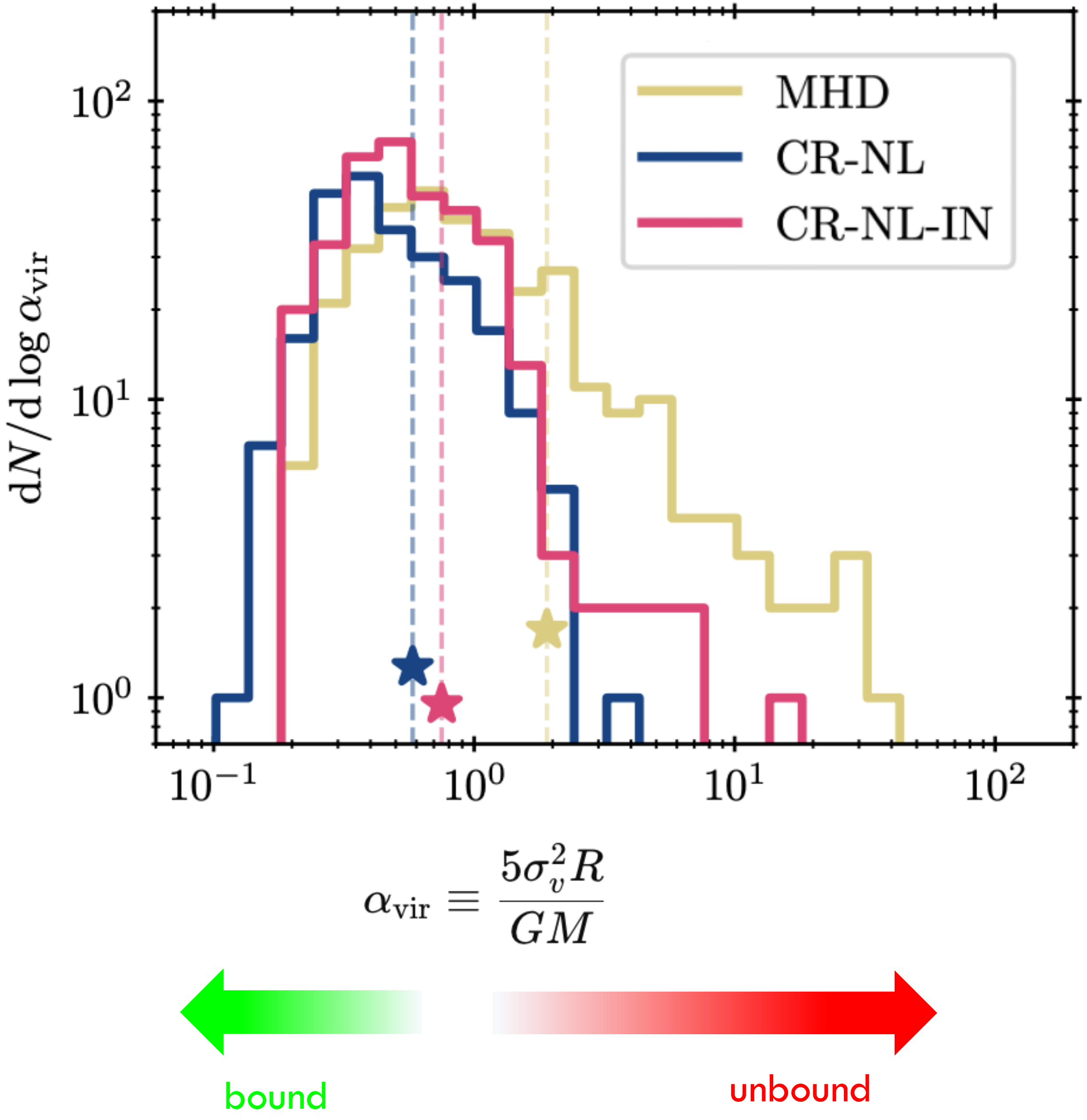




Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)





Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)

Most nearby young star clusters formed in three massive complexes

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Check for updates

Cameren Swiggum[1✉], João Alves[1], Robert Benjamin[2], Sebastian Ratzenböck[1,3], Núria Miret-Roig[1], Josefa Großschedl[1,4], Stefan Meingast[1], Alyssa Goodman[5], Ralf Konietzka[5], Catherine Zucker[5], Emily L. Hunt[6] & Sabine Reffert[6]

Efforts to unveil the structure of the local interstellar medium and its recent star-formation history have spanned the past 70 years (refs. 1–6). Recent studies using precise data from space astrometry missions have revealed nearby newly formed star clusters with connected origins[7–12]. Nonetheless, mapping young clusters across

Formation and evolution of new primordial open cluster groups: Feedback-driven star formation

Guimei Liu (刘桂梅)[1,2], Yu Zhang (张余)[1,2], Jing Zhong (钟靖)[3], Li Chen (陈力)[3,2], Xiangcun Meng (孟祥存)[4,5], and Kai Wu (吴开)[6]

A Number of nearby Moving Groups May Be Fragments of Dissolving Open Clusters

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From moving groups to star formation in the Solar Neighborhood

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The Origin of the Cluster of Local Interstellar Clouds

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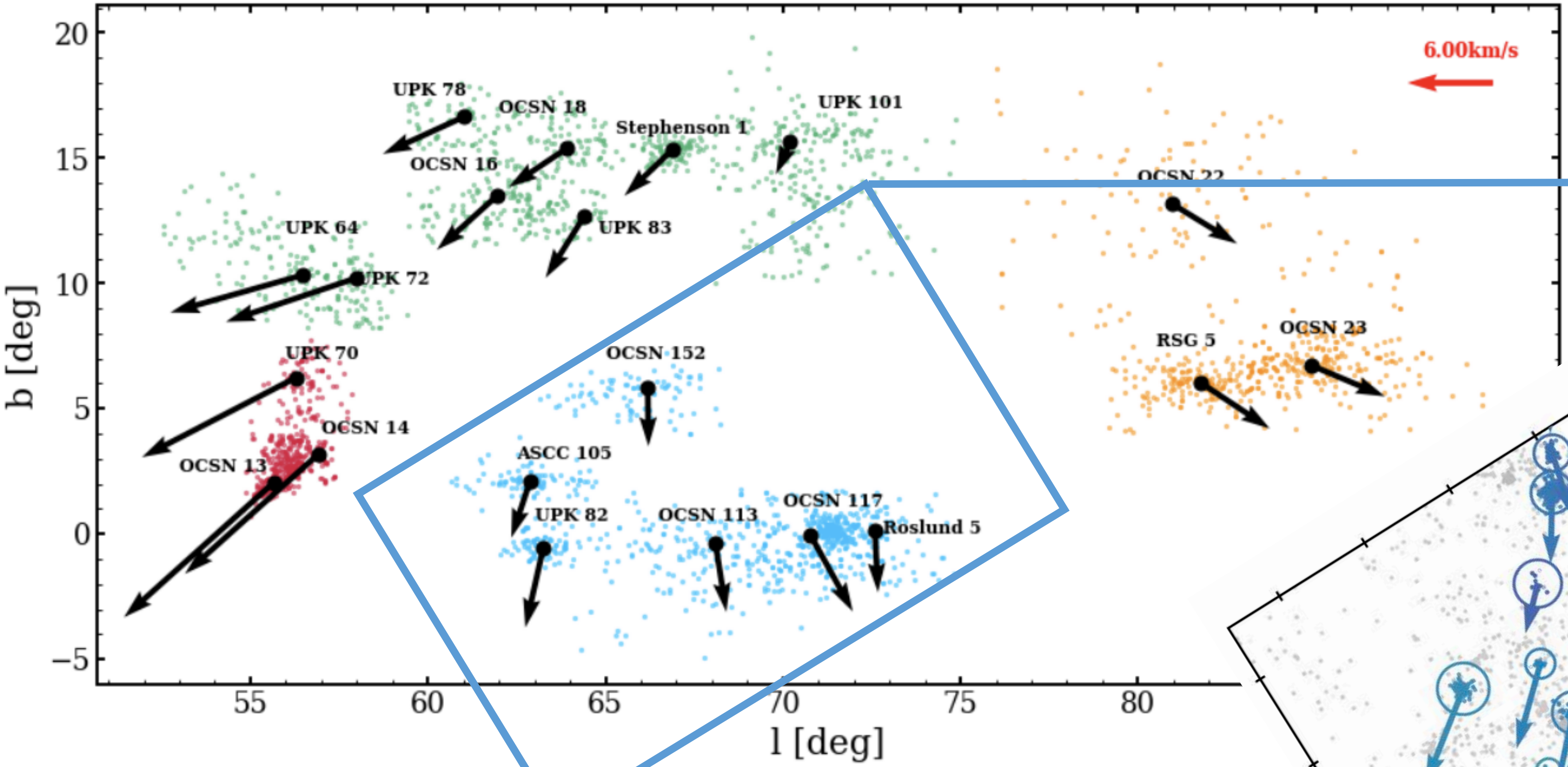
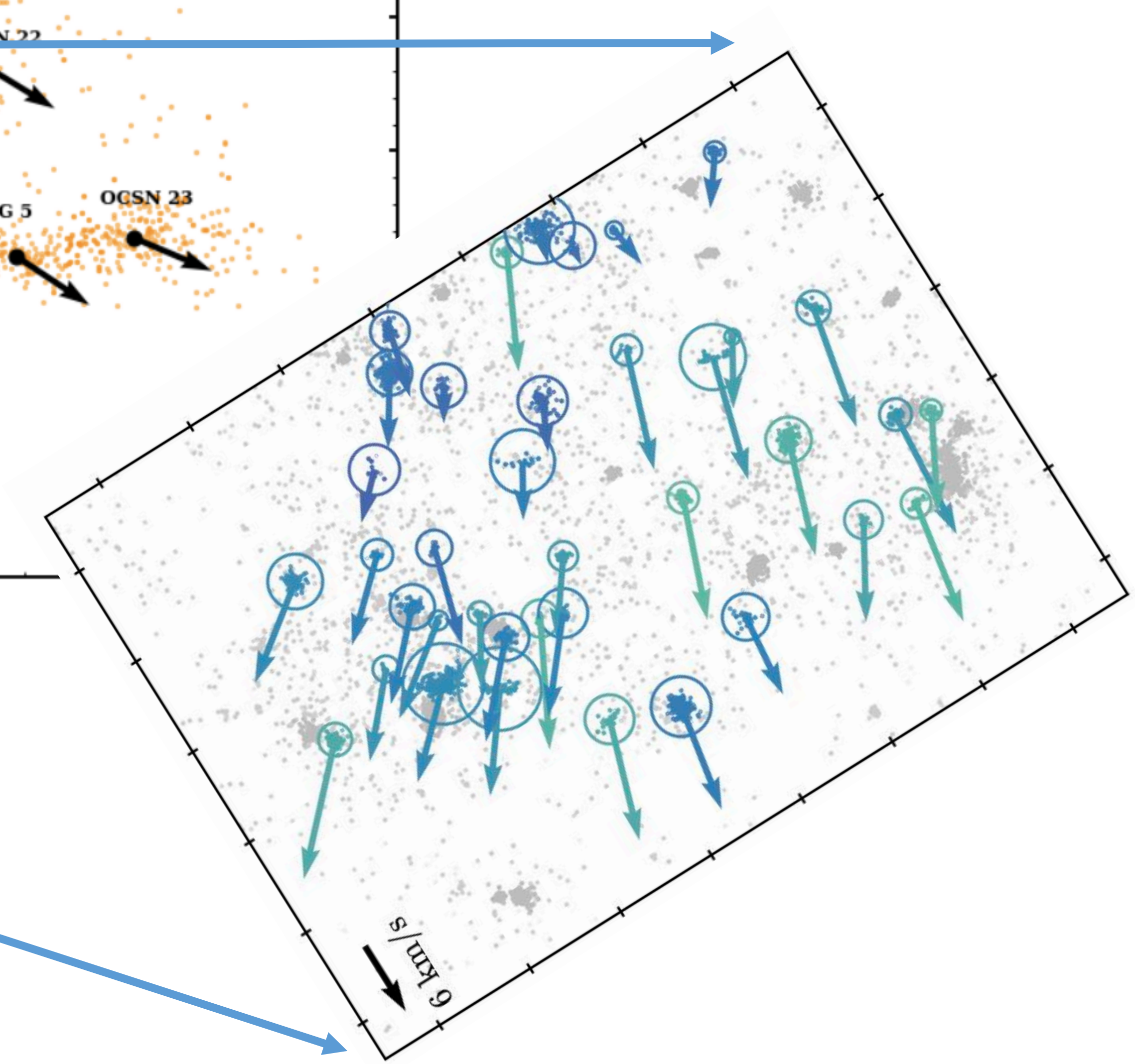
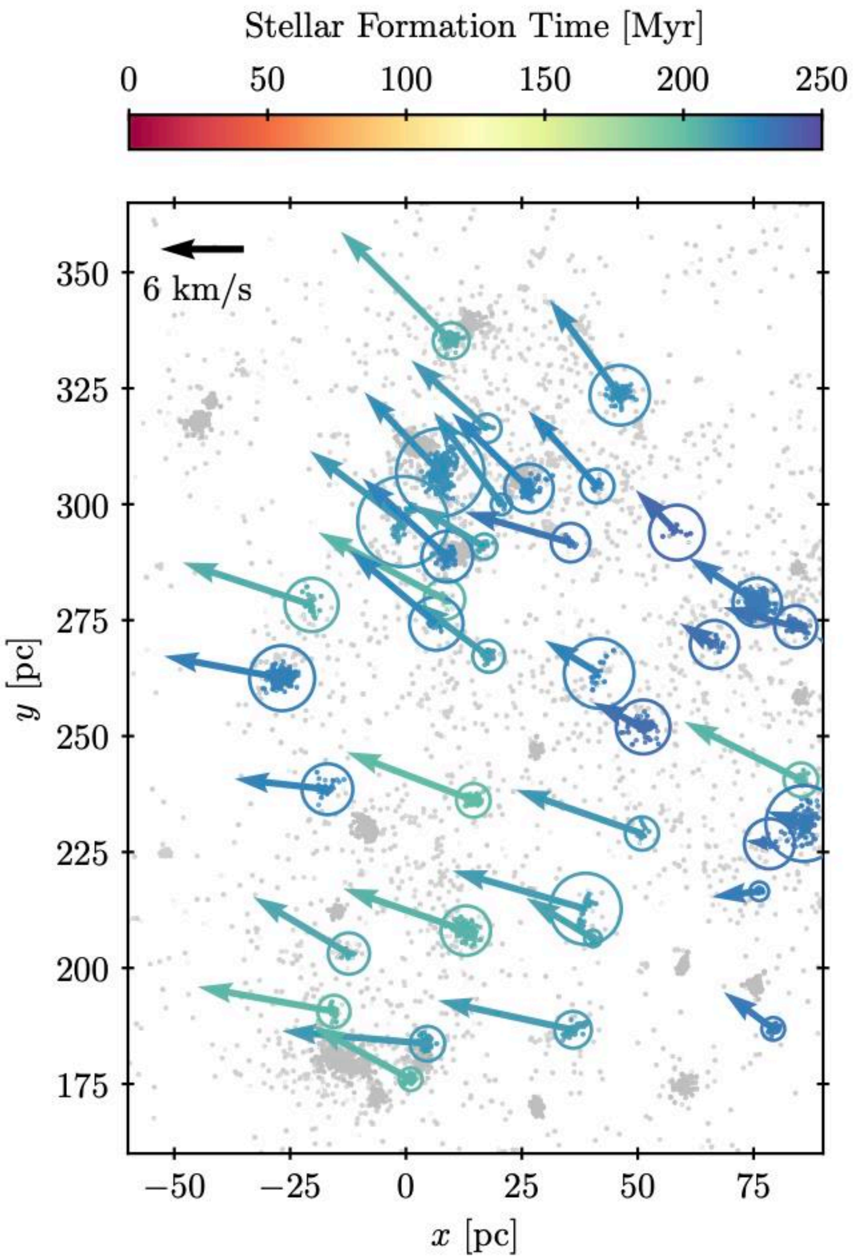
[3] Astronomy Department and Van Vleck Observatory, Wesleyan University, Middletown, CT 06459, USA
[4] Department of Physics, Sarah Lawrence College, Bronxville, NY 10708, USA
[5] JILA, University of Colorado and NIST, Boulder, CO 80309-0440, USA

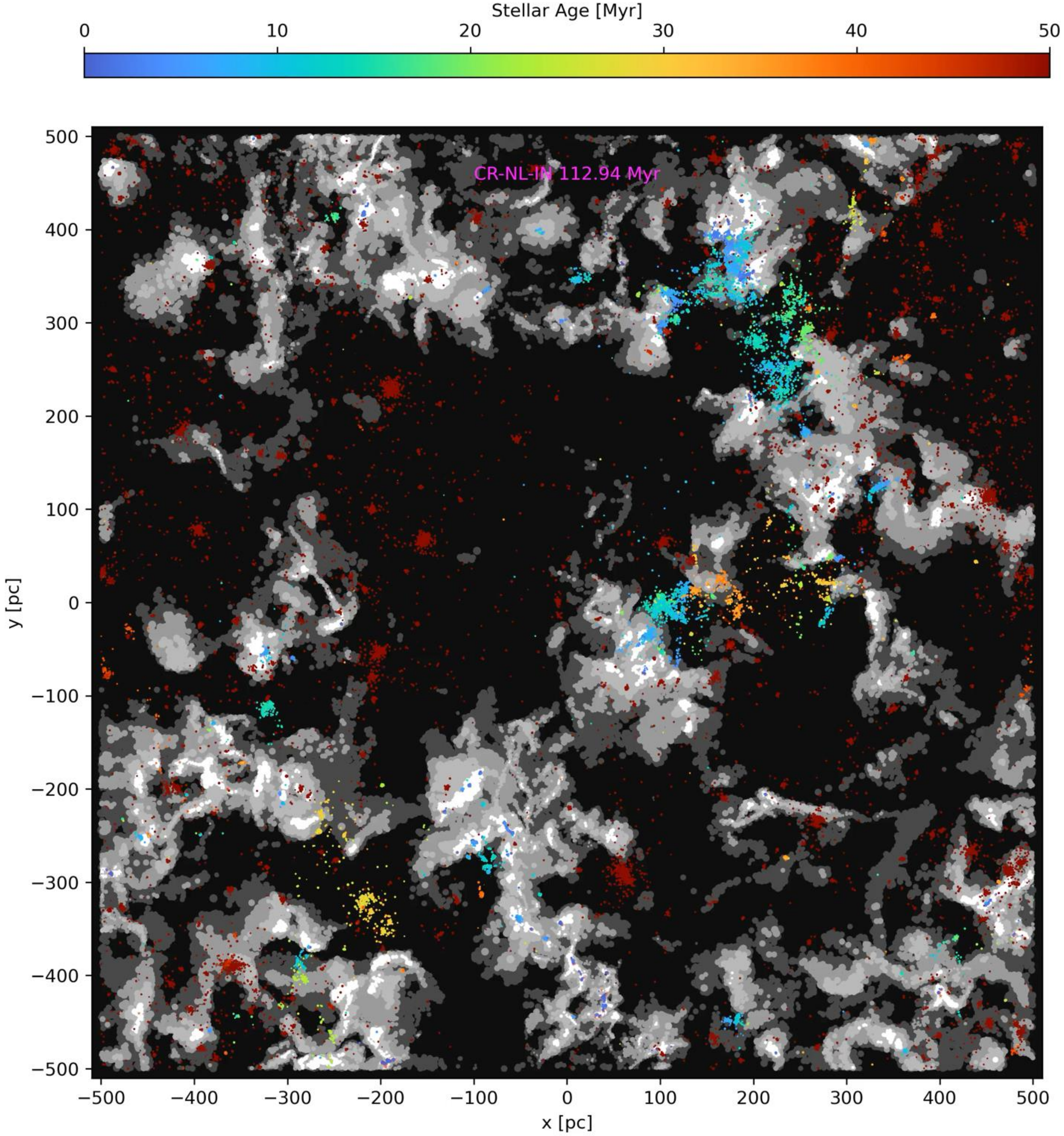


Liu et al. (2025)

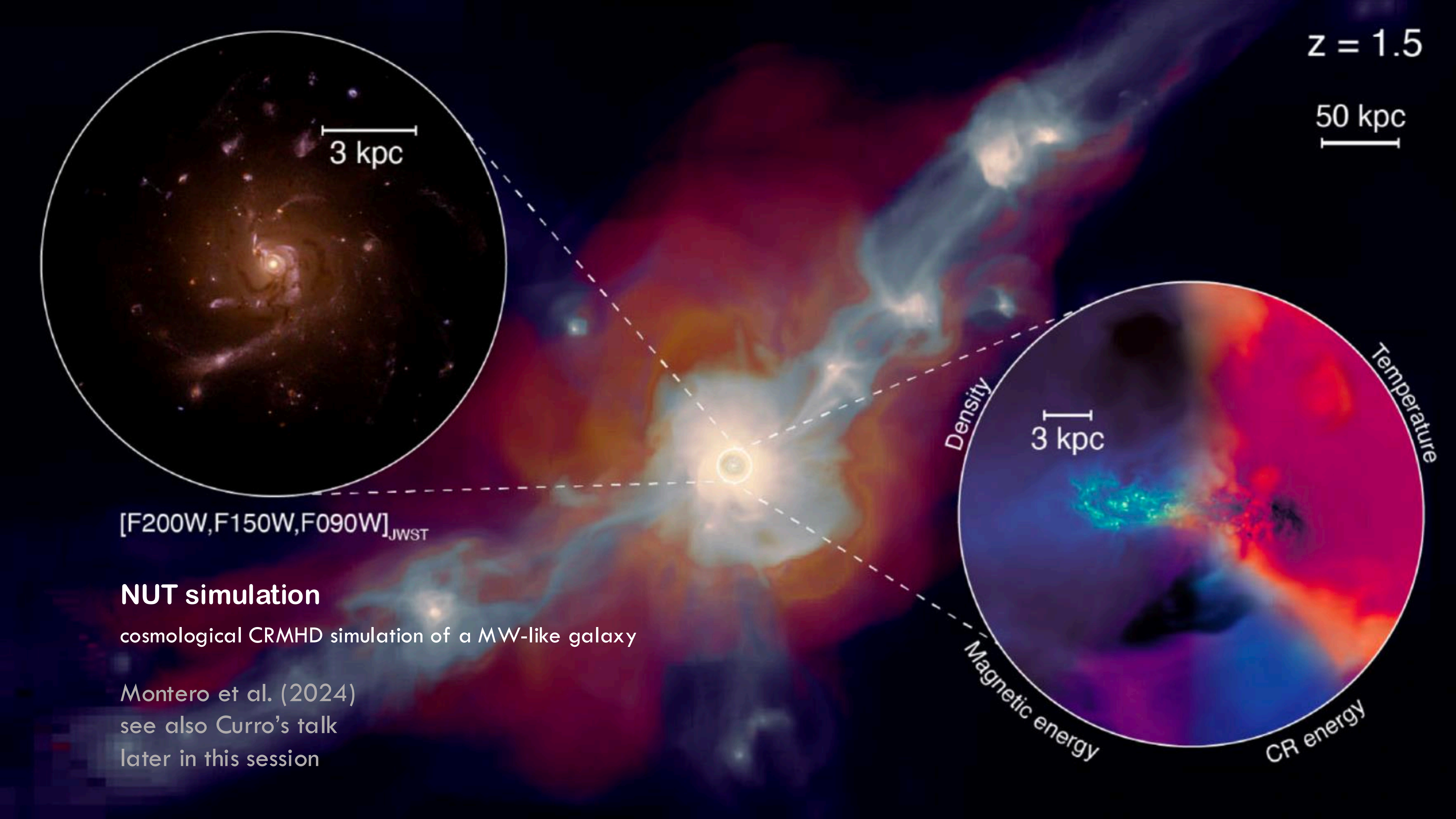


Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)





Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2025b, in prep.)

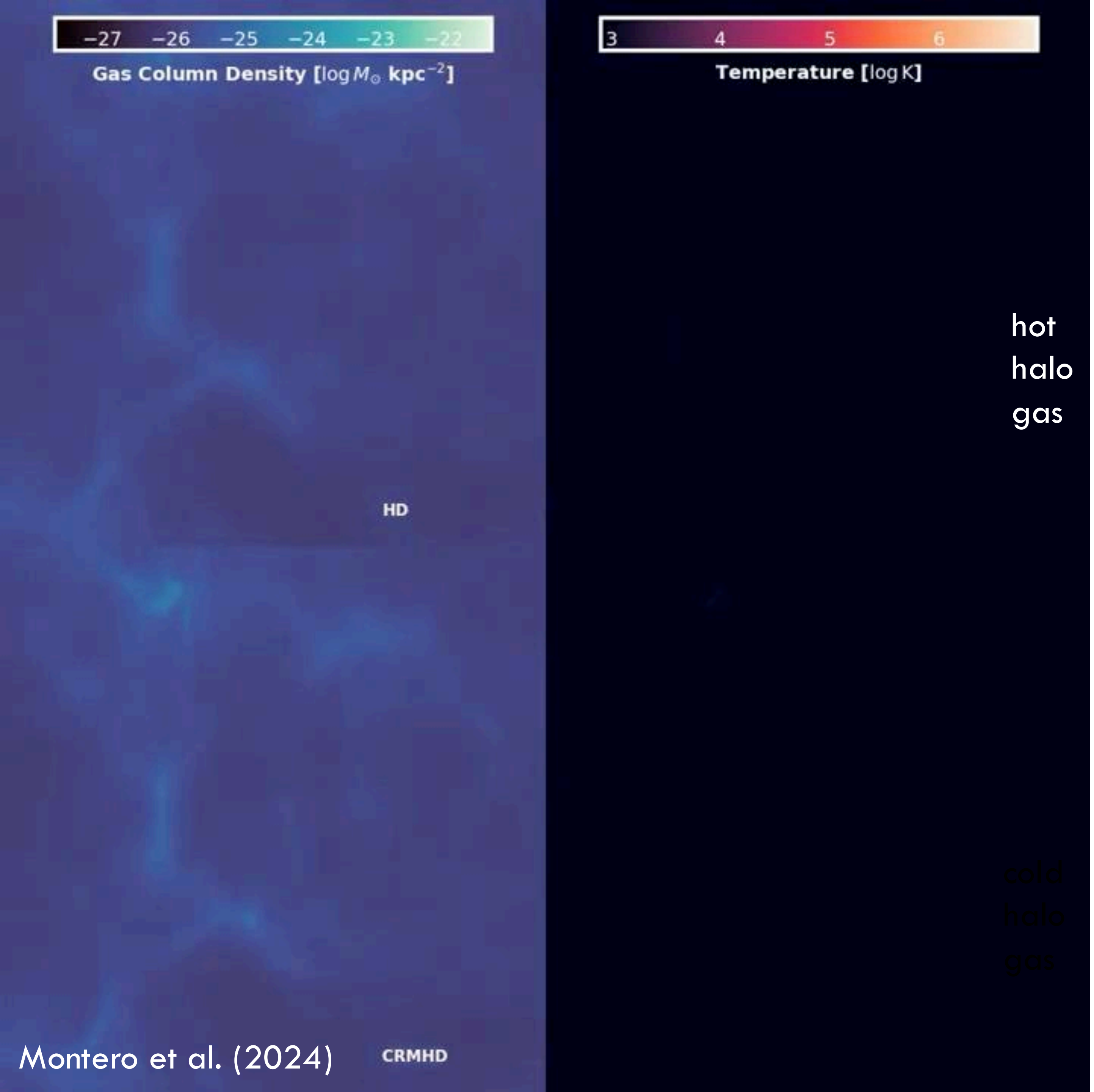


NUT simulation

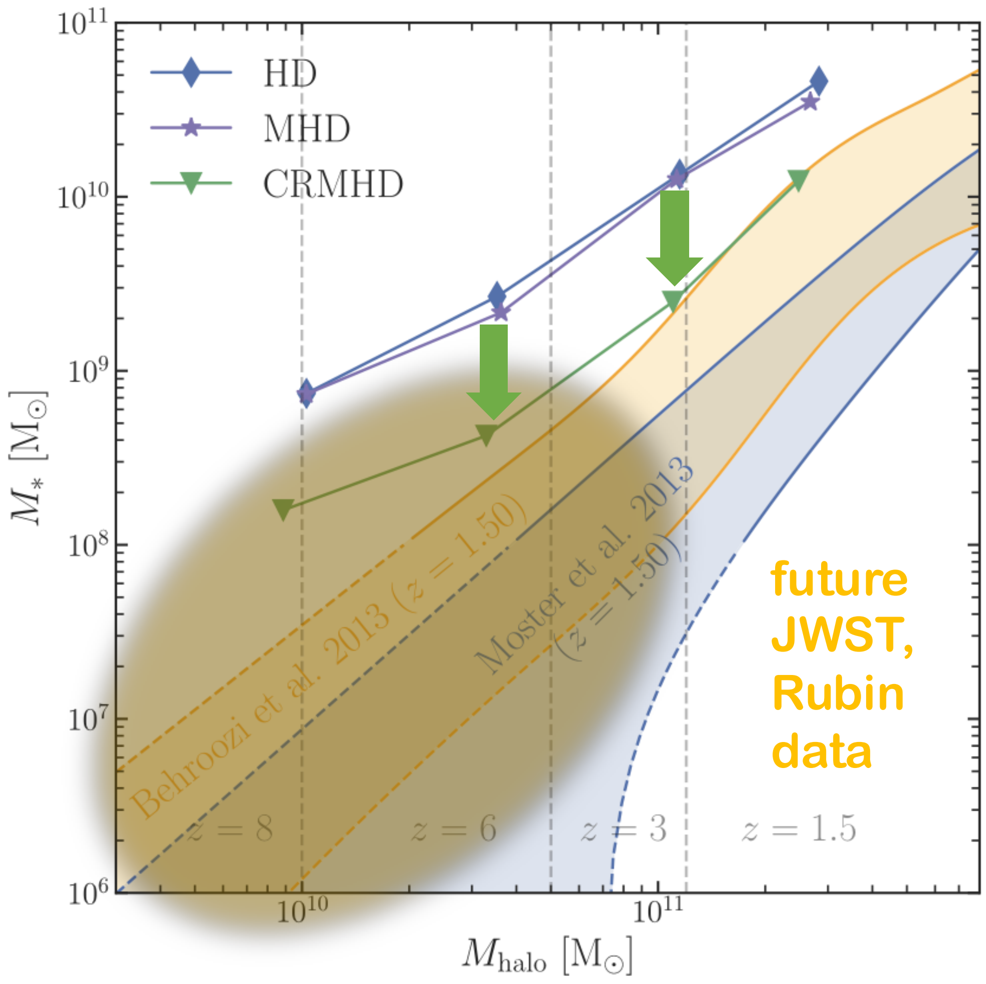
cosmological CRMHD simulation of a MW-like galaxy

Montero et al. (2024)
see also Curro's talk
later in this session

CRs & reduced stellar mass



Montero et al. (2024)

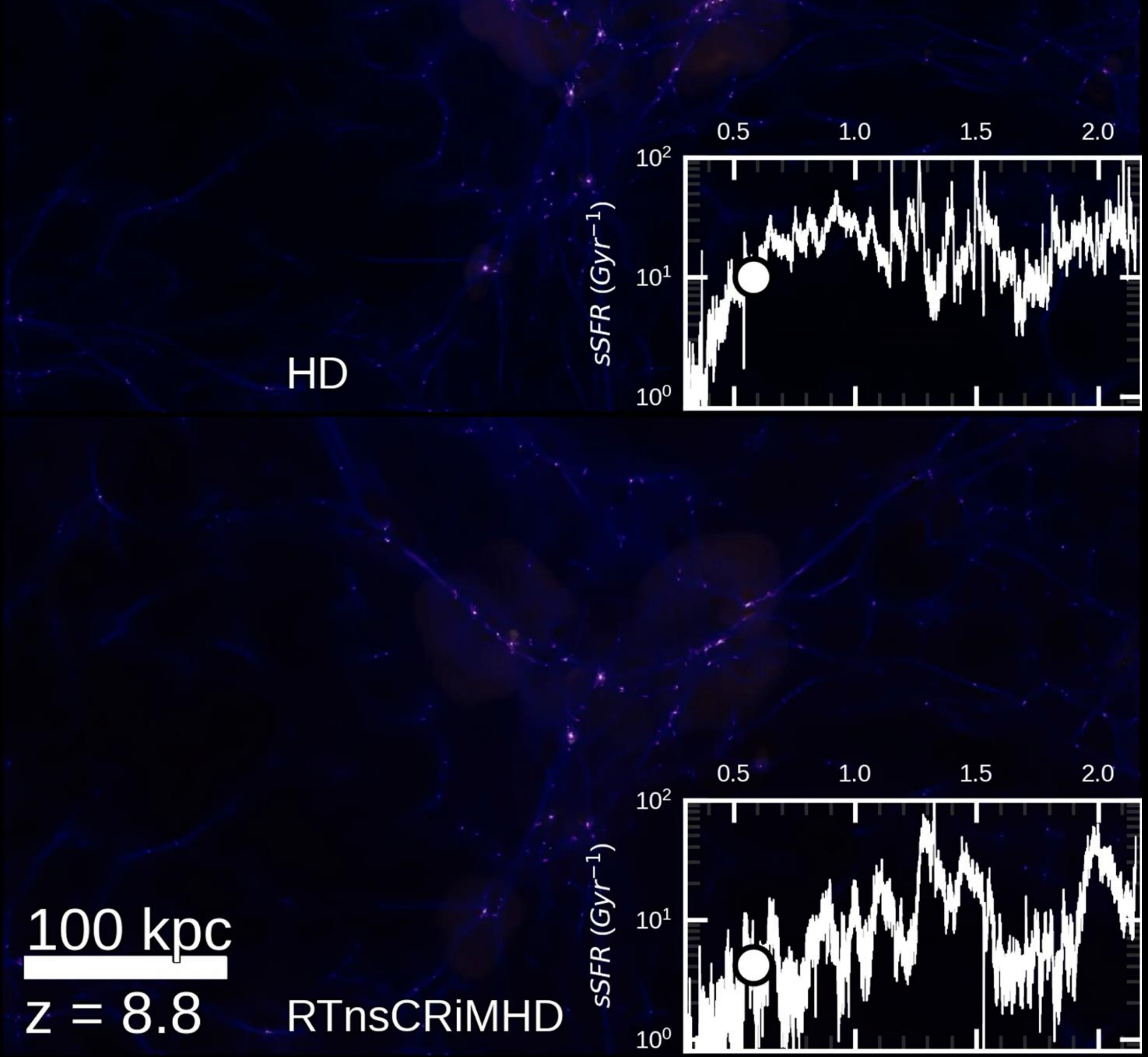


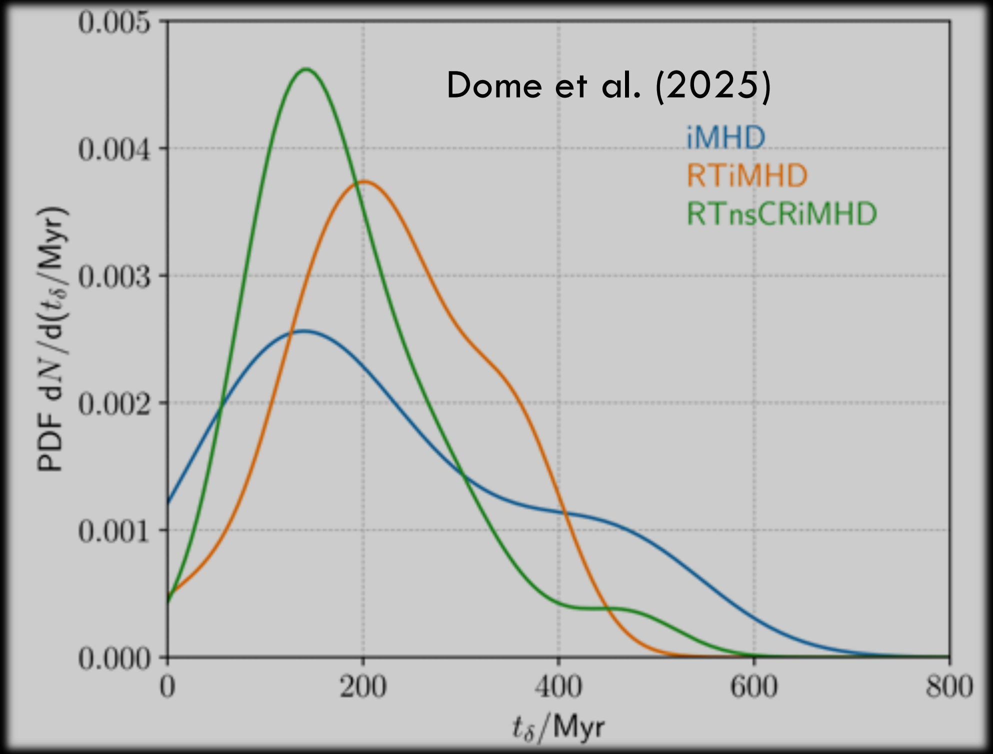
M/HD transform most baryons into stars

CRMHD predicts 10x lower stellar mass

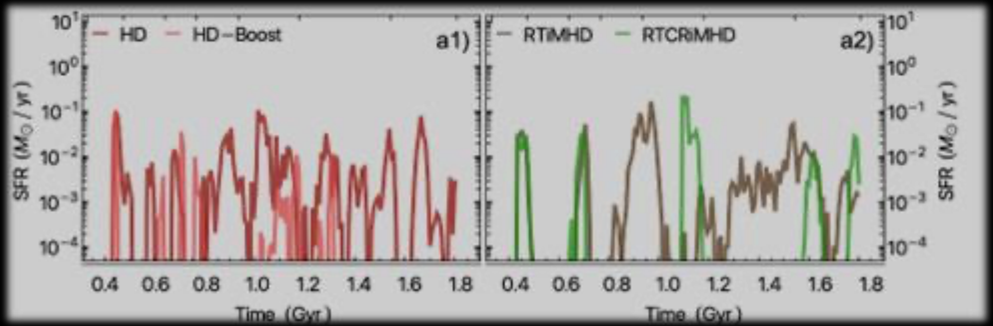
CRs & bursty star formation

AZAHAR project Martin-Alvarez et al. (2025)



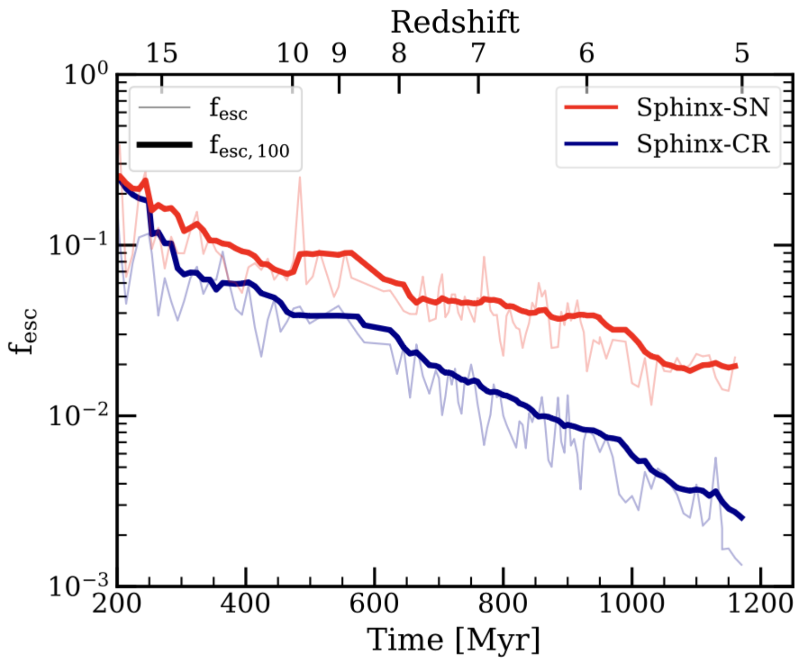


increased burstiness in multiphysics models
with SN feedback, radiative transfer, and CRs

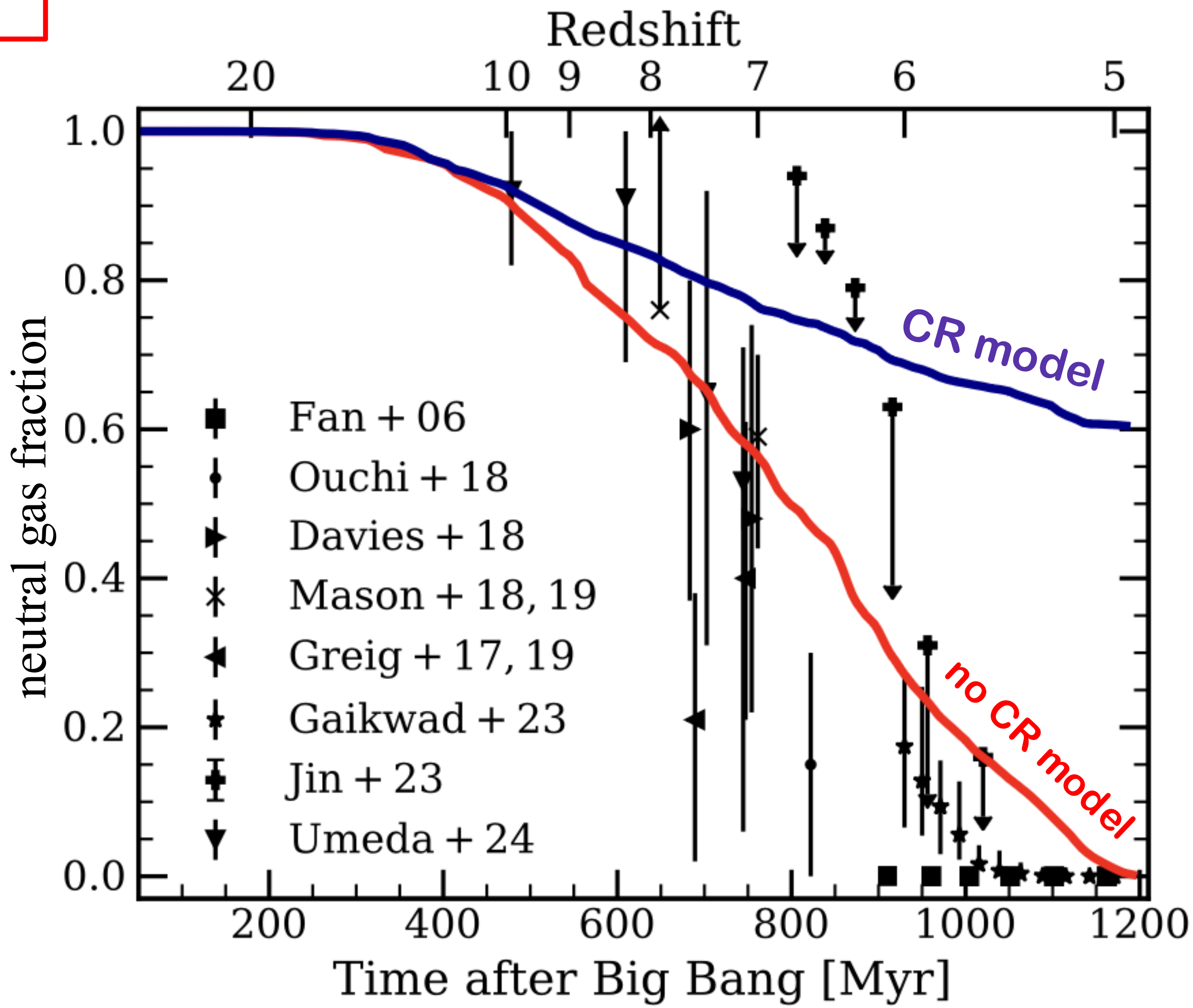


see also bursty star formation w/ CRs in dwarfs
Pandora project Martin-Alvarez et al. (2025)

CRs & reionization of the Universe



Farcy et al. (2025)



w/o CRs:
SN create cavities in the ISM
facilitate photon escape

w/ CRs:
CR feedback fills the cavities with gas
suppression of photon escape (near SF sites)

we need better CR transport models


WE INTERRUPT THIS PROGRAM FOR A
COMMERCIAL BREAK

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

program dates: Jan 4 to Mar 11, 2027
application deadline: **Nov 28, 2025**

Cosmic Rays in Astrophysical Systems: From the Sun to Galaxies and Beyond

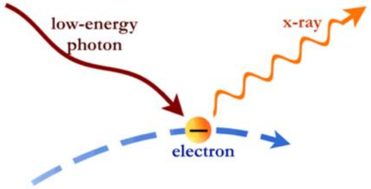
Coordinators: Greg Bryan, Christoph Pfrommer, Mateusz Ruszkowski, and Ellen Zweibel

Scientific Advisors: Eve Ostriker, Eliot Quataert, and Volker Springel

How can we use observations to
test models of CR transport and CR feedback ?

CRs in the CGM

$$\epsilon_X \sim \frac{4}{3} h\nu_{\rm IC}\, n_{\rm cr,\,e^\pm}\, n_{\rm photons}\, \sigma_T\, c$$

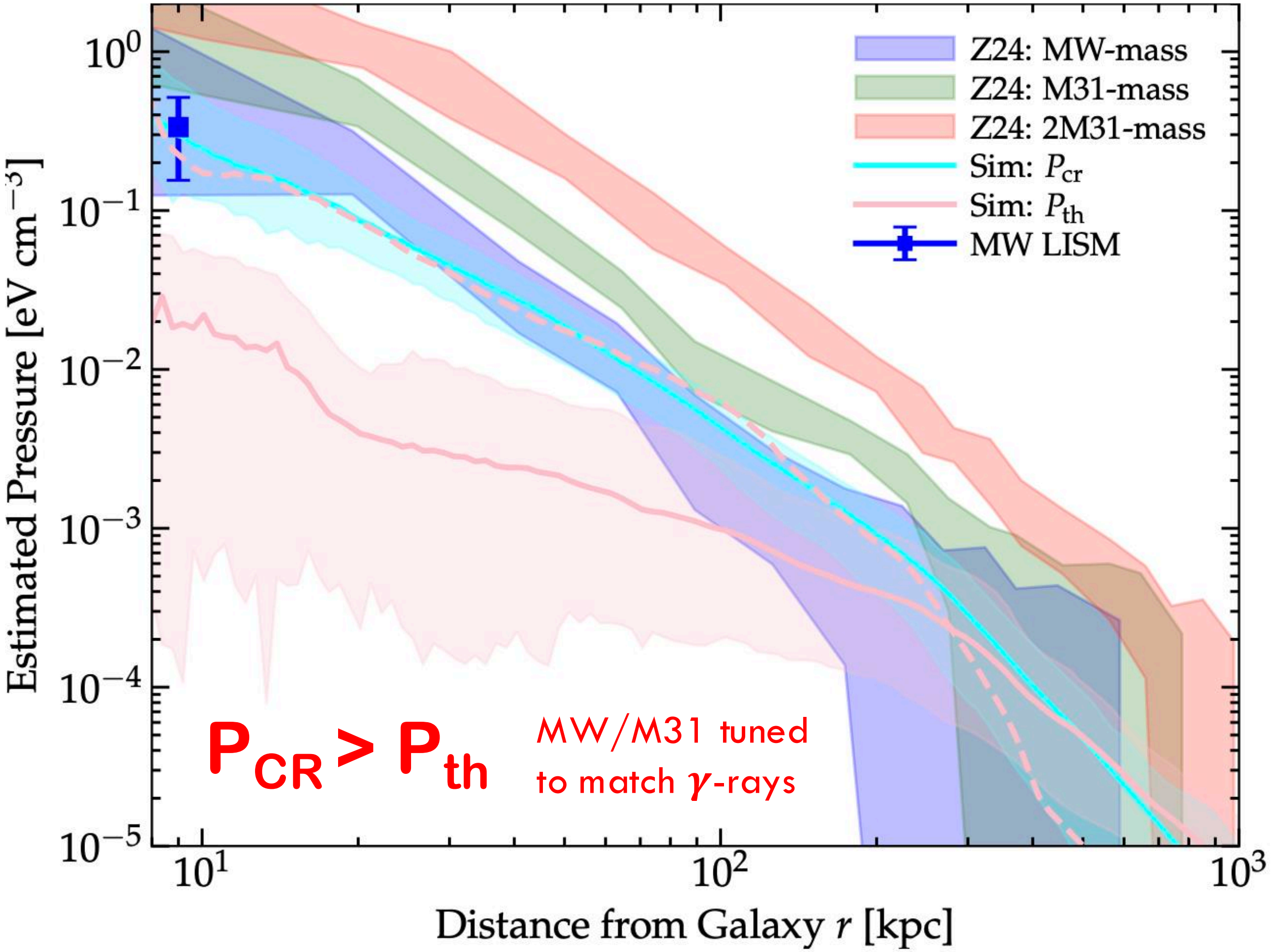


$$n_{\rm cr,\,e^\pm} \sim \frac{f_{\rm loss}\, \dot{E}_{\rm cr,\,\ell}}{4\pi\, v_{\rm st,\,eff}\, r^2}$$

Ji et al. (2020)

$$\frac{S_{X,\,\rm keV}}{\rm erg\,s^{-1}\,kpc^{-2}} \sim 10^{35.3} \left(\frac{\dot{E}_{\rm cr,\,\ell}}{10^{40}\,\rm erg\,s^{-1}}\right)\left(\frac{100\,\rm km\,s^{-1}}{v_{\rm st,\,eff}(R)}\right) \times \left(\frac{100\,\rm kpc}{R}\right) f_{\rm loss}\, E_{\rm cr,GeV}\,(1+z)^4$$

correct (shallow)
slope of X-ray profile



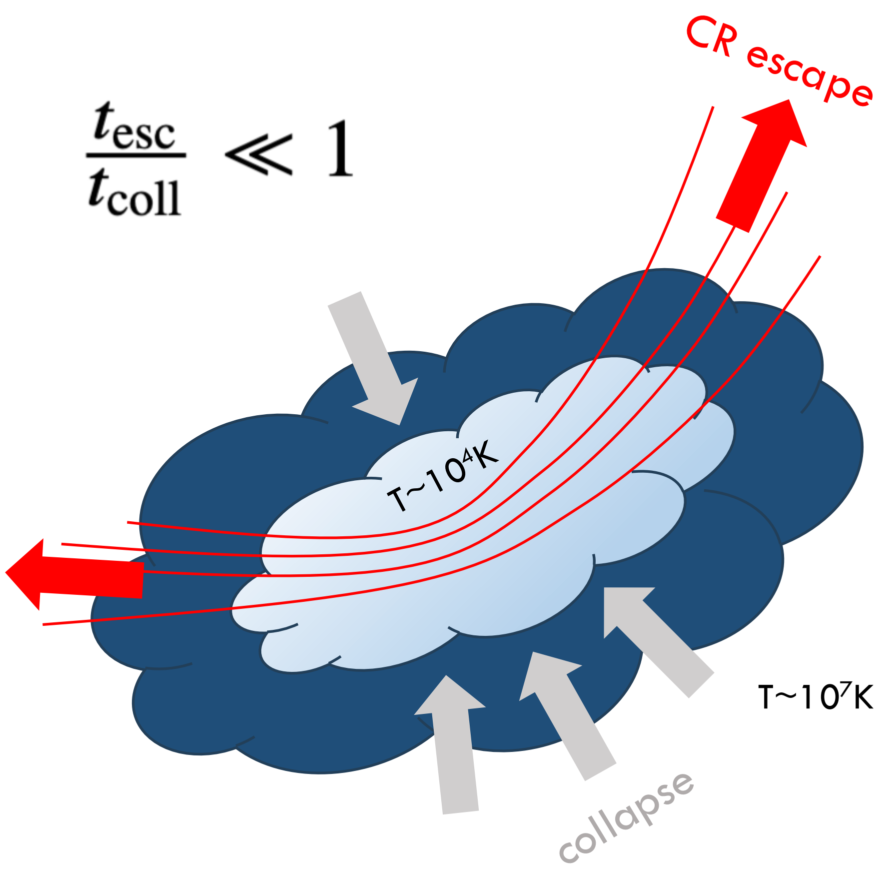
if X-rays due to IC → DIRECT measurement of CR pressure !!

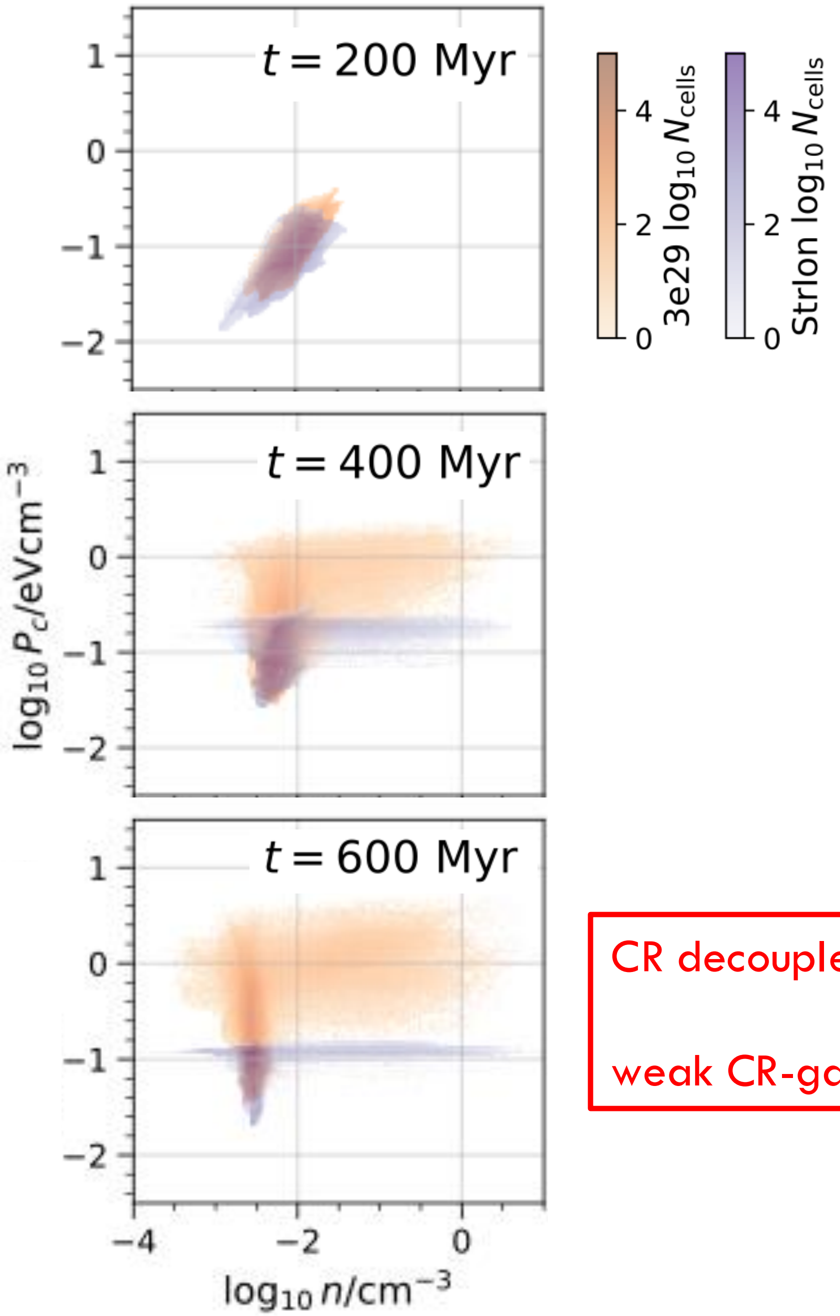
Idea can be applied to post-processing of any existing CR MHD sims

Hopkins et al. (2025), Lu et al. (2025)

see also Quataert & Hopkins (2025):
large impact of accumulated BH CRs
on gas in group-mass halos at $\sim r_{\rm vir}$

CR transport physics has a dramatic impact on γ-rays from CGM

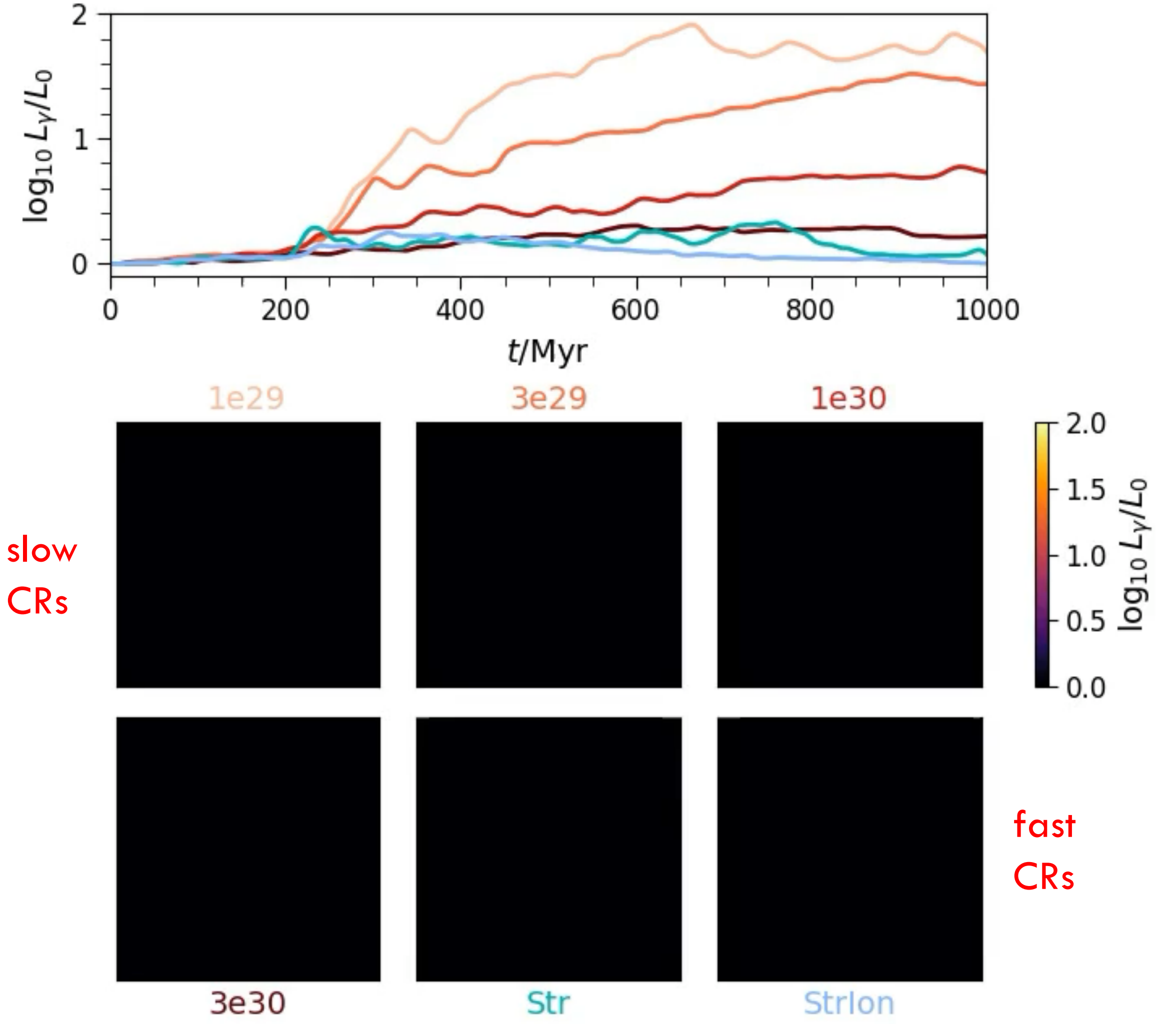


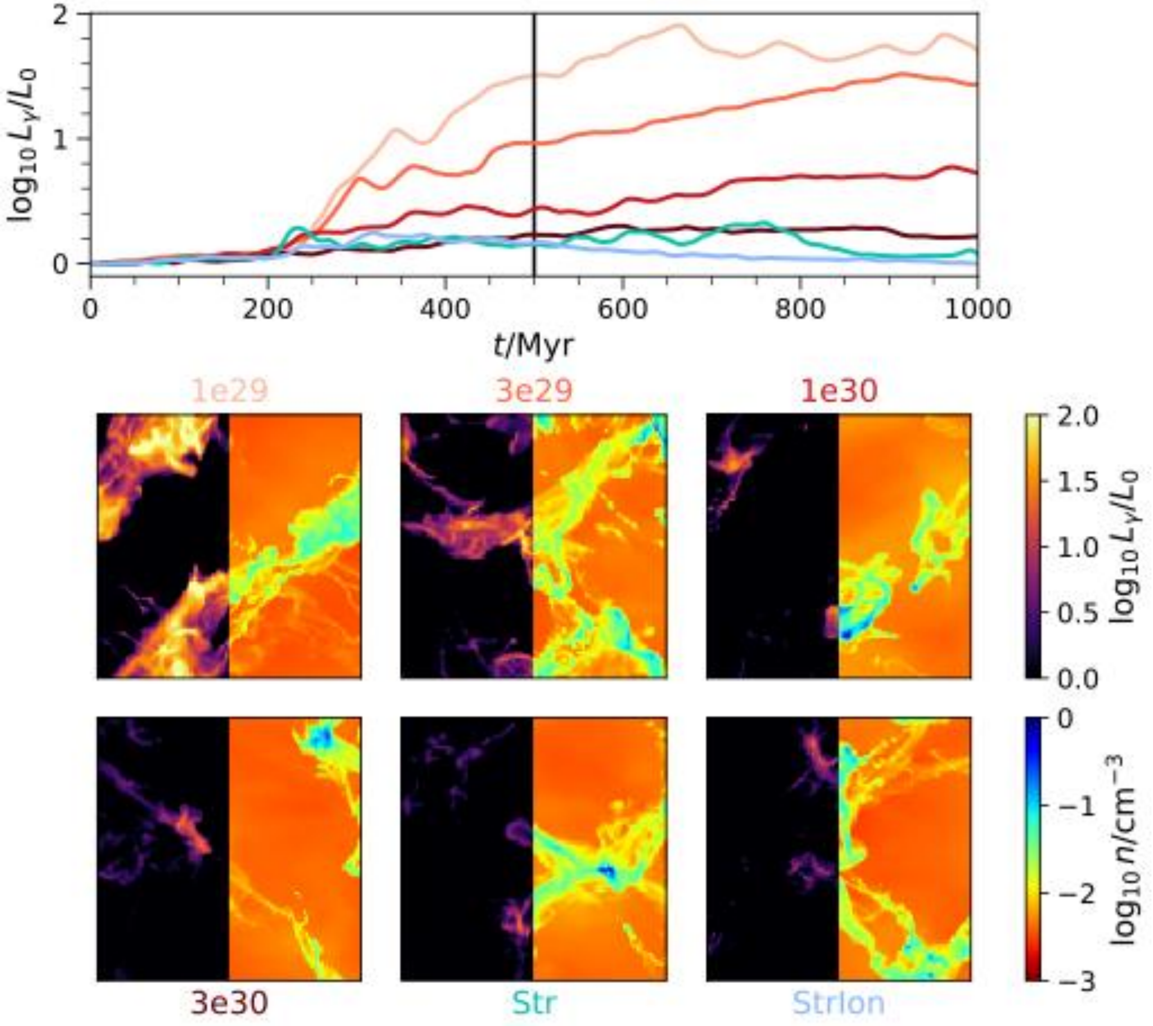


CR decouple from the gas

weak CR-gas correlation

Habegger, Ruszkowski, Zweibel (in prep.)



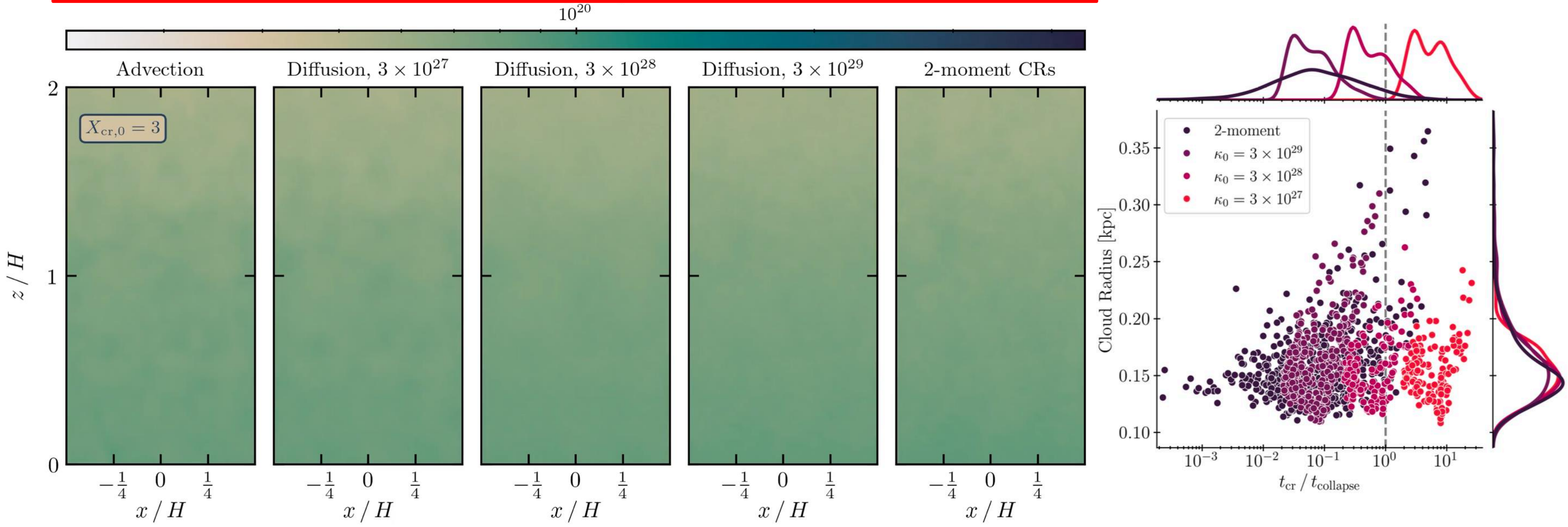


Habegger, Ruszkowski, Zweibel (in prep.)

plenty of cold gas, fast CR transport

little γ-rays

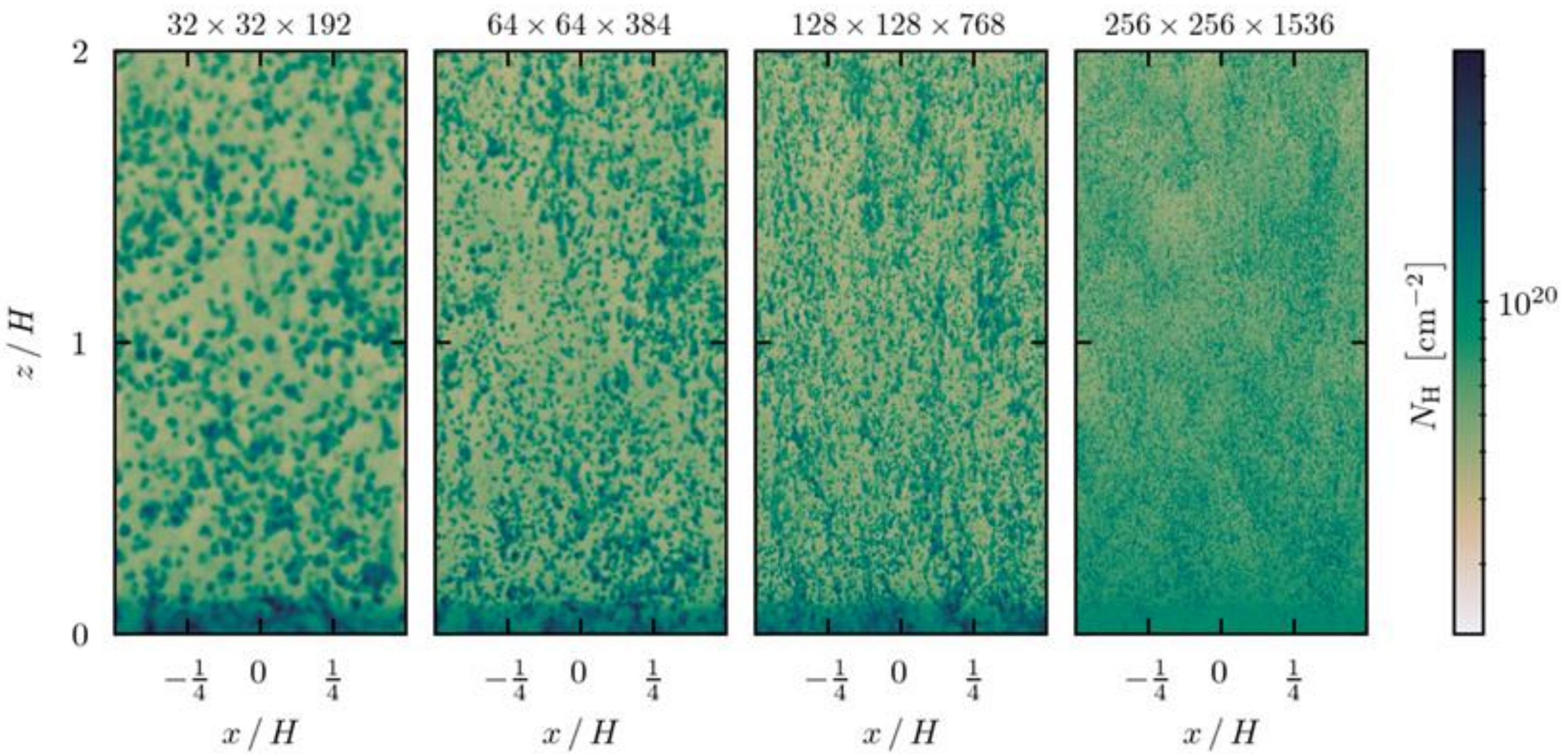
CR transport physics has dramatic impact on CGM cloud formation

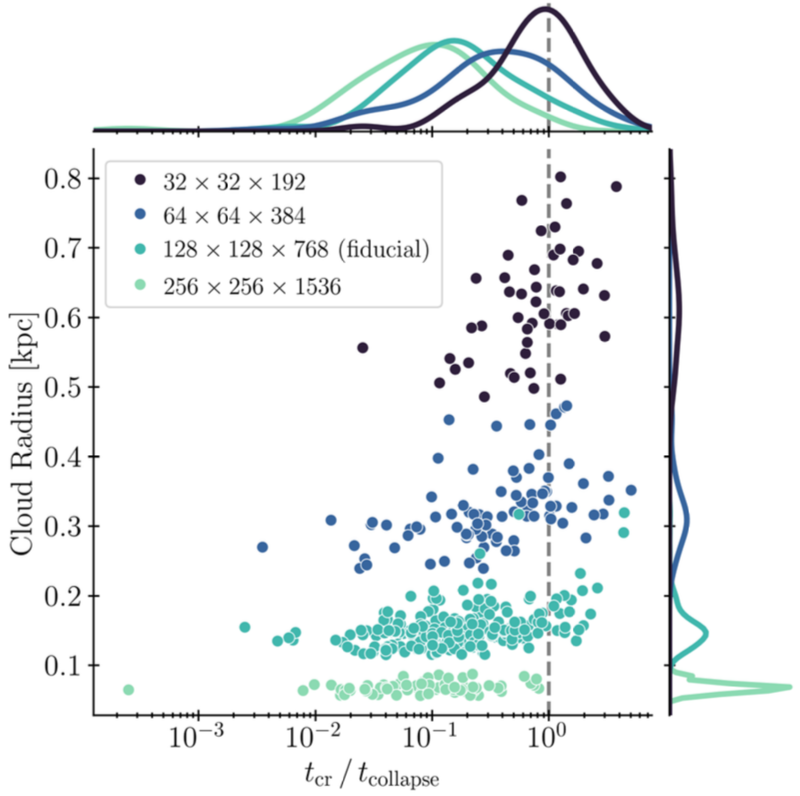


Weber et al. (2025)

important cautionary note:

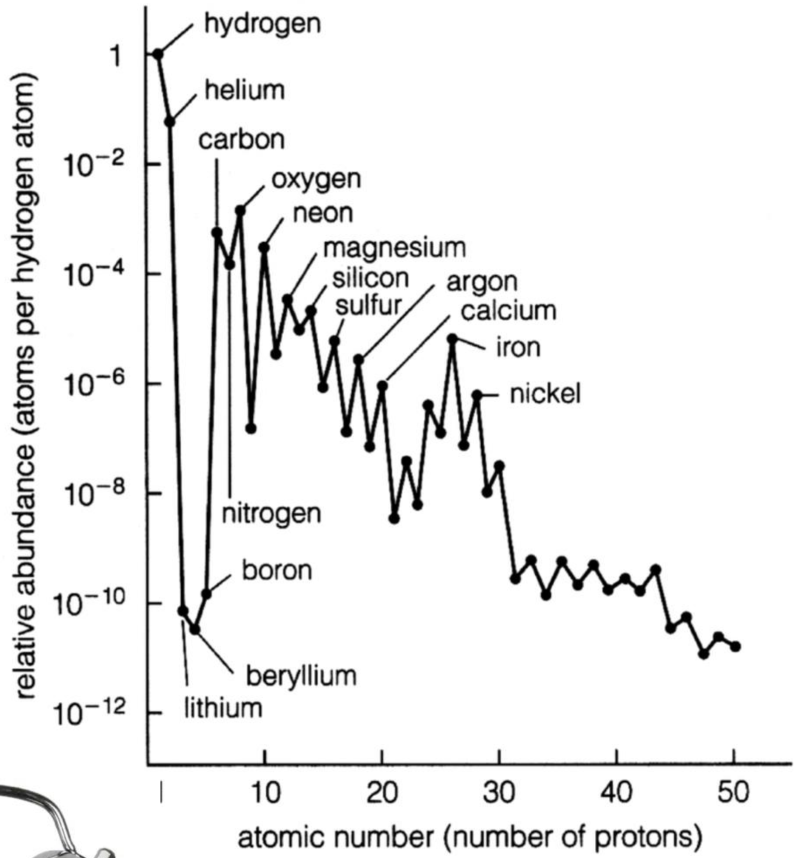
resolution matters!

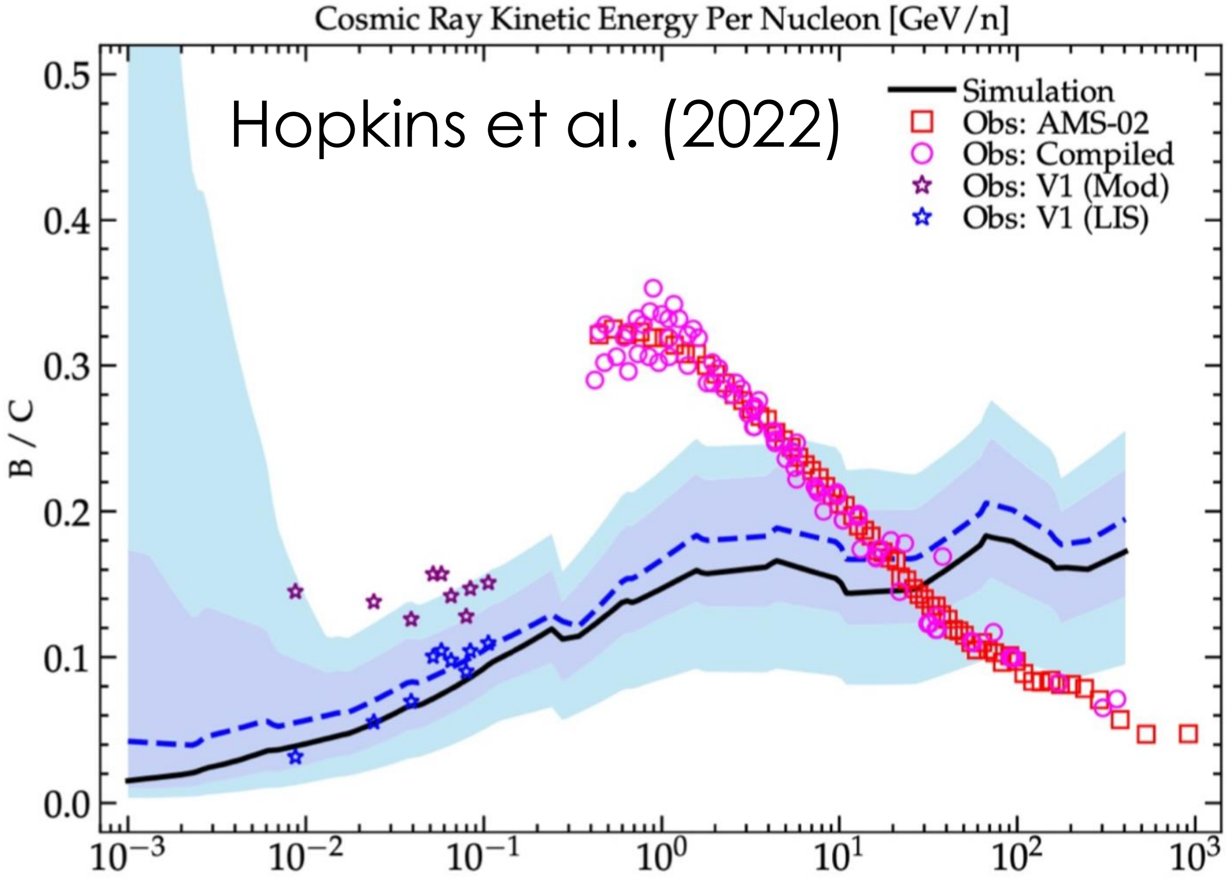




Weber et al. (2025)

Spallation reactions & energy dependence of CR transport





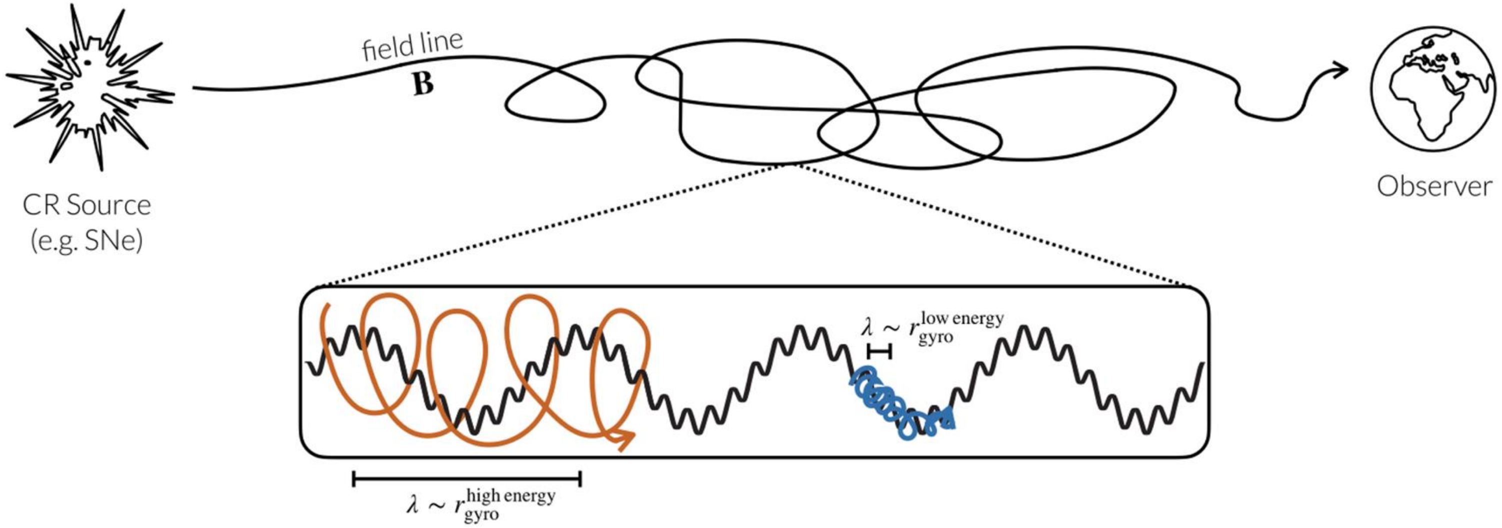
$$\frac{n_B}{n_C} \approx \bar{n}_H \beta c \sigma_{C \to B}\, \tau$$

$$\kappa \propto \tau^{-1} \propto E^{0.33}$$

$$\frac{n_B}{n_C} = 0.65\beta \left(\frac{R}{GV}\right)^{-0.33}$$

$$R \equiv r_g B = \frac{p_\perp c}{Ze}$$

observations



extrinsic & self-confinement

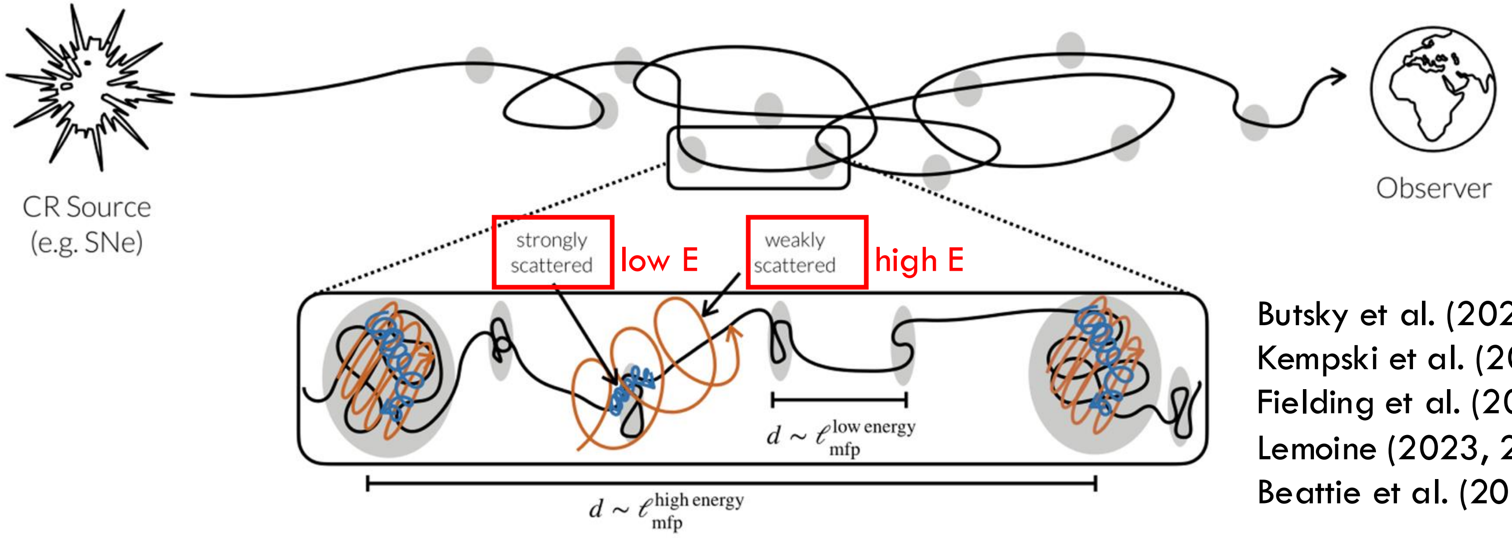
$\kappa \sim v_($

$f_V \sim 1$

$\delta B/B \ll 1$

$l_{\rm mfp} \propto R_{\rm GV}^{\delta}$

$\delta \lesssim 0$



Butsky et al. (2024)
Kempski et al. (2023)
Fielding et al. (2023)
Lemoine (2023, 2025)
Beattie et al. (2025)

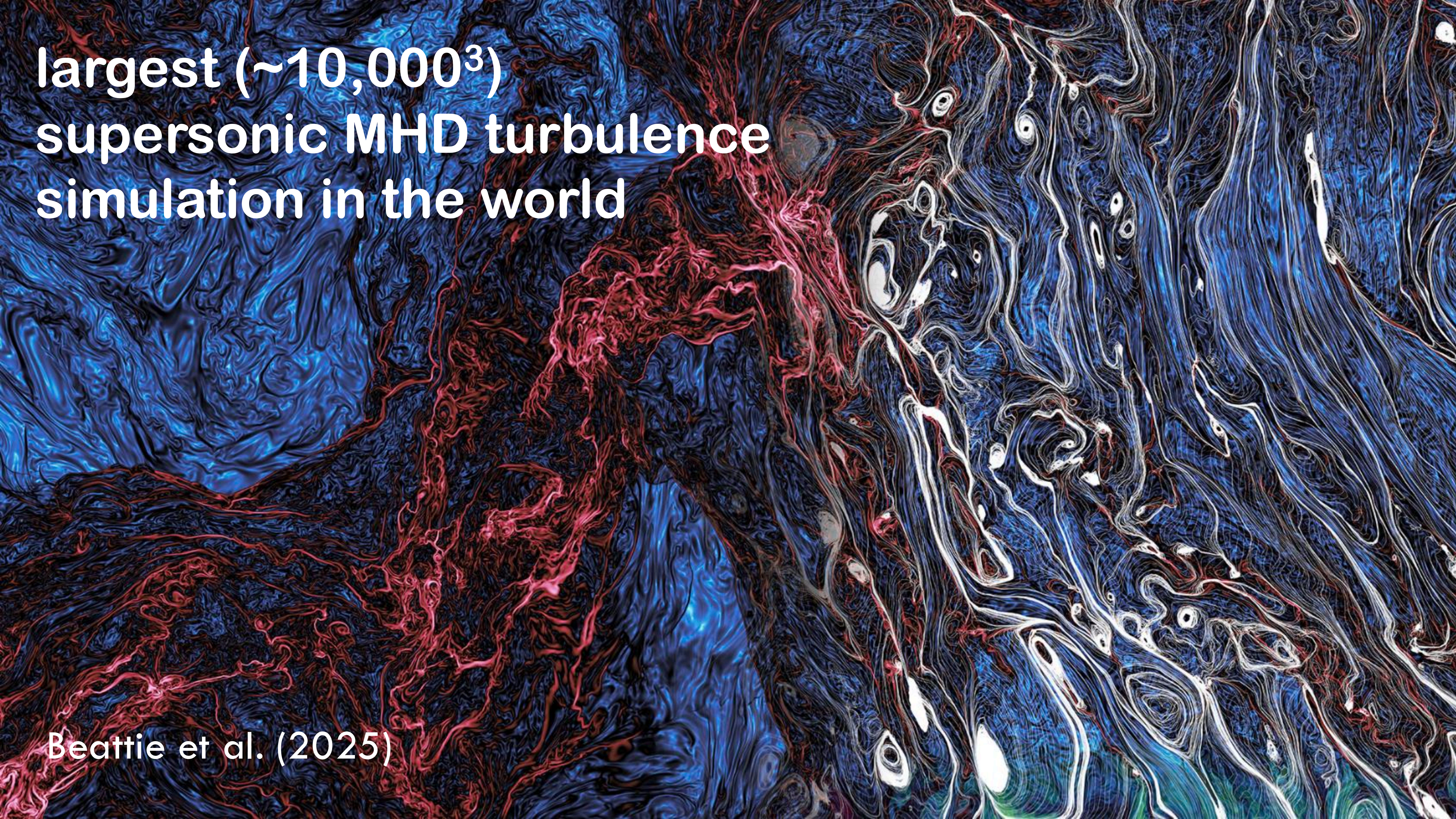
$f_V \ll 1$

$\delta B/B \sim 1$

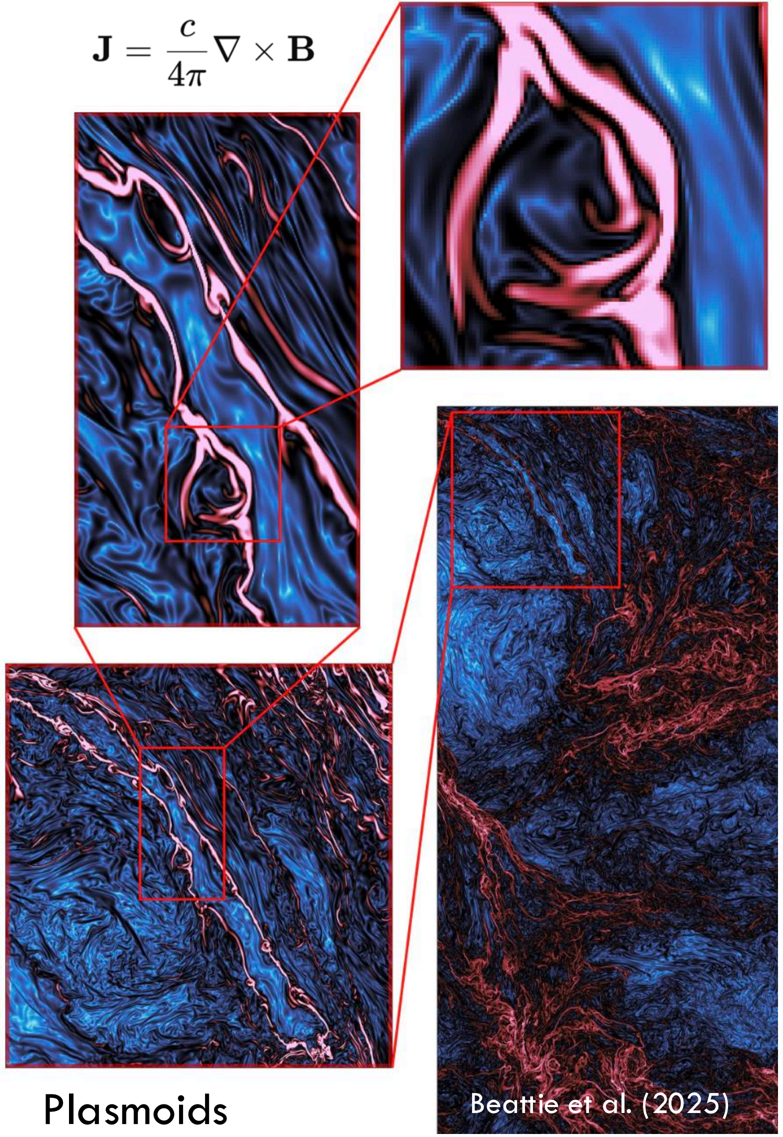
$l_{\rm mfp} \propto R_{\rm GV}^{\delta}$

$\delta > 0$

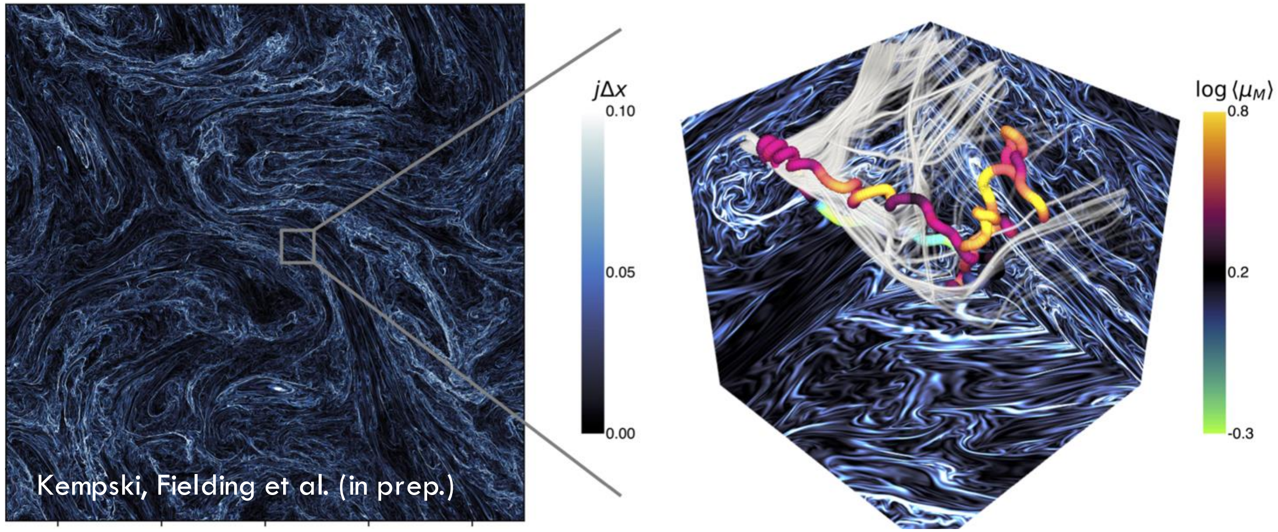
scattering on **spatially intermittent turbulence**


largest (~10,000^3)
supersonic MHD turbulence
simulation in the world
Beattie et al. (2025)

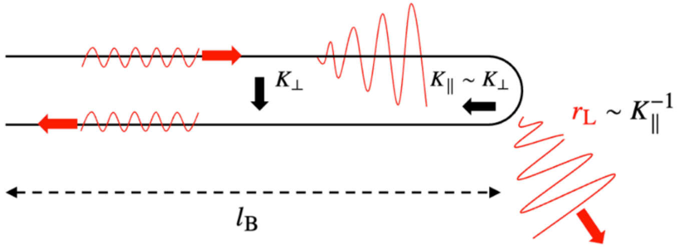
~10,000³ subsonic MHD turbulence

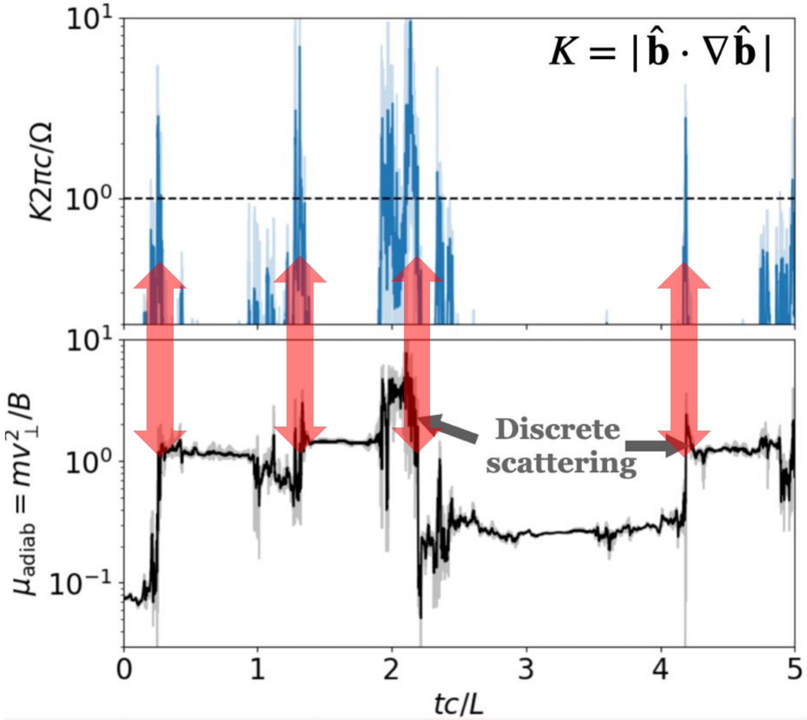


Plasmoids



$\mathscr{M} \approx 0.5$ $\delta B/B_0 \approx 2$





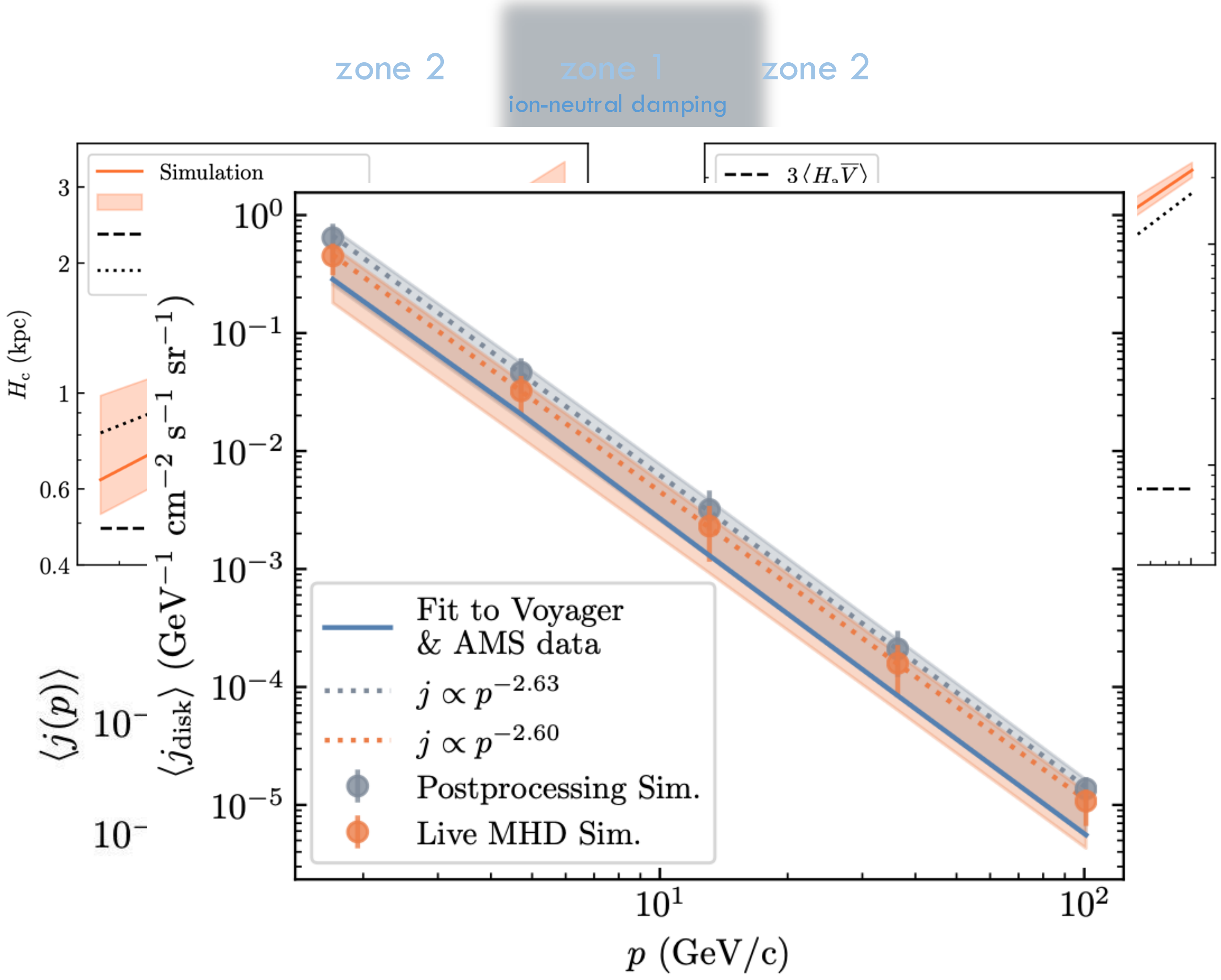
low-volume-filling

spatially intermittent structures

required for

strong CR scattering in the ISM

energy-dependent & physically-motivated CR transport



standard self-confinement model

1-zone model assumes $H_c(p) = const$

$$\kappa/H_c \sim v_{obs} \propto p^{0.4-0.6}$$

2-zone model predicts $H_c(p) \neq const$

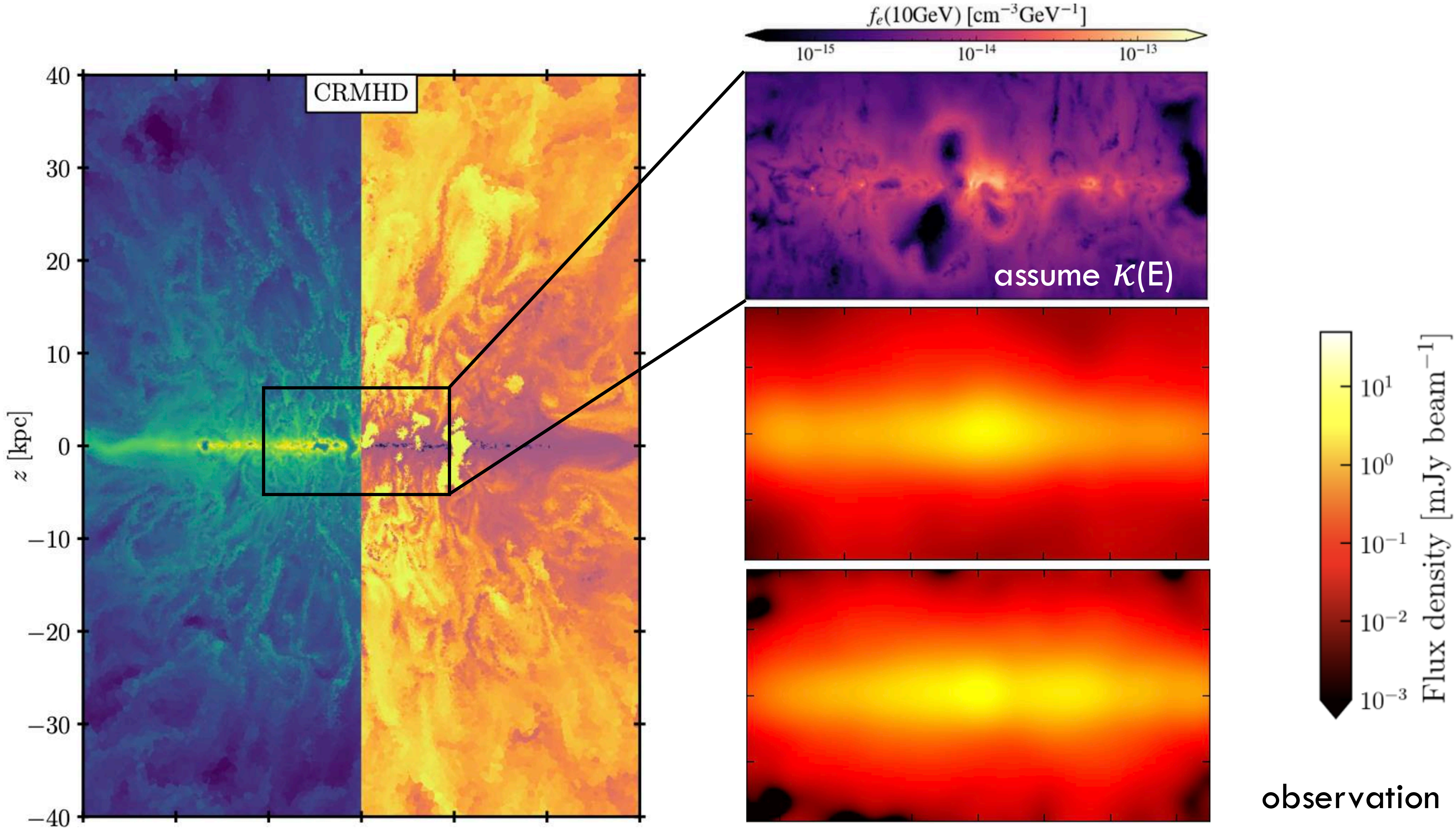
$$\kappa/H_c \sim v_{c,eff} \propto p^{\gamma_{inj}/3-1} \propto p^{0.43}$$

agrees with observations!

effective CR speed has the right scaling with CR energy

c.f. Hopkins et al. (2022)

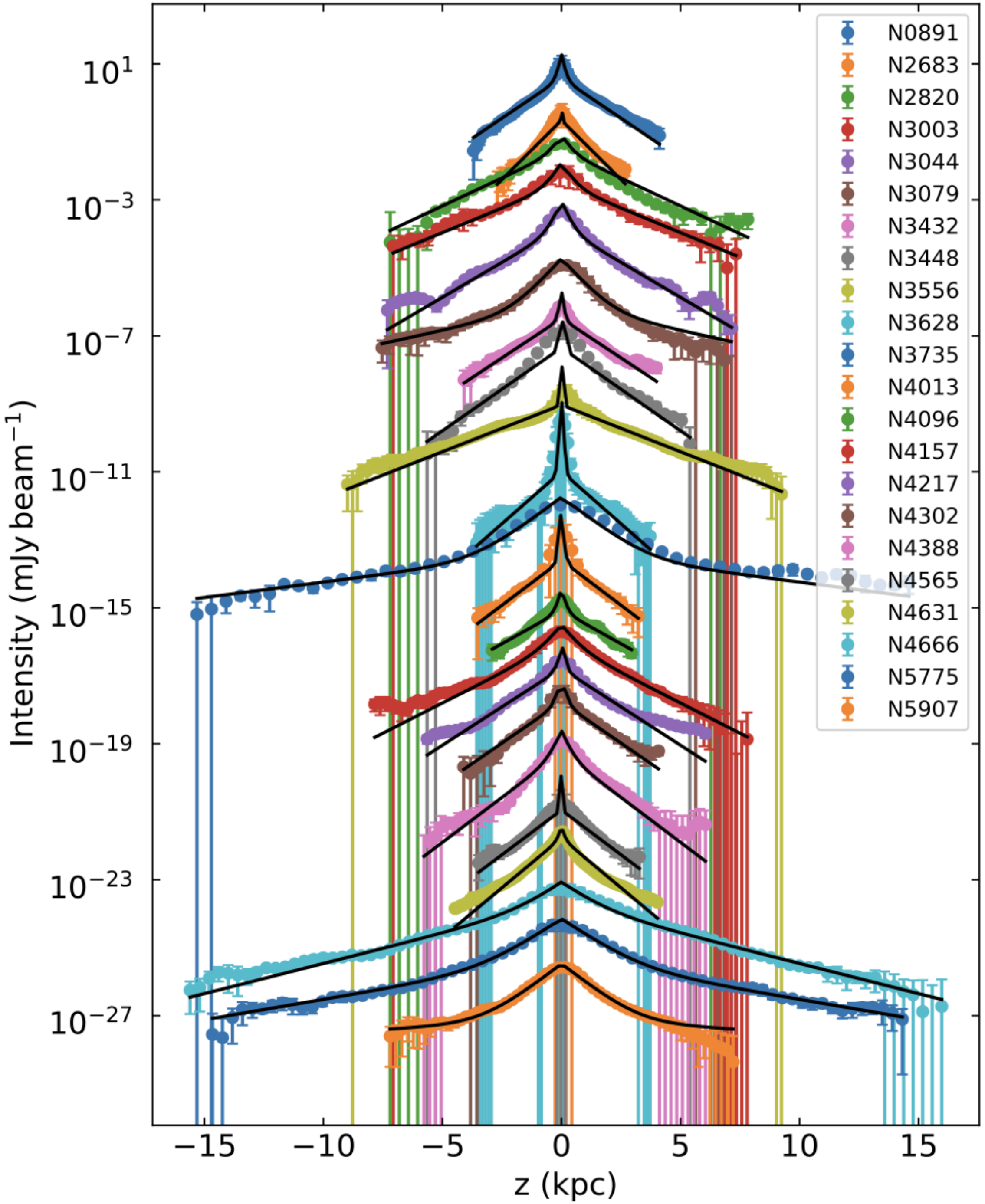
Armillotta et al. (2025); see also Linzer et al. (2025) for e^- spectra

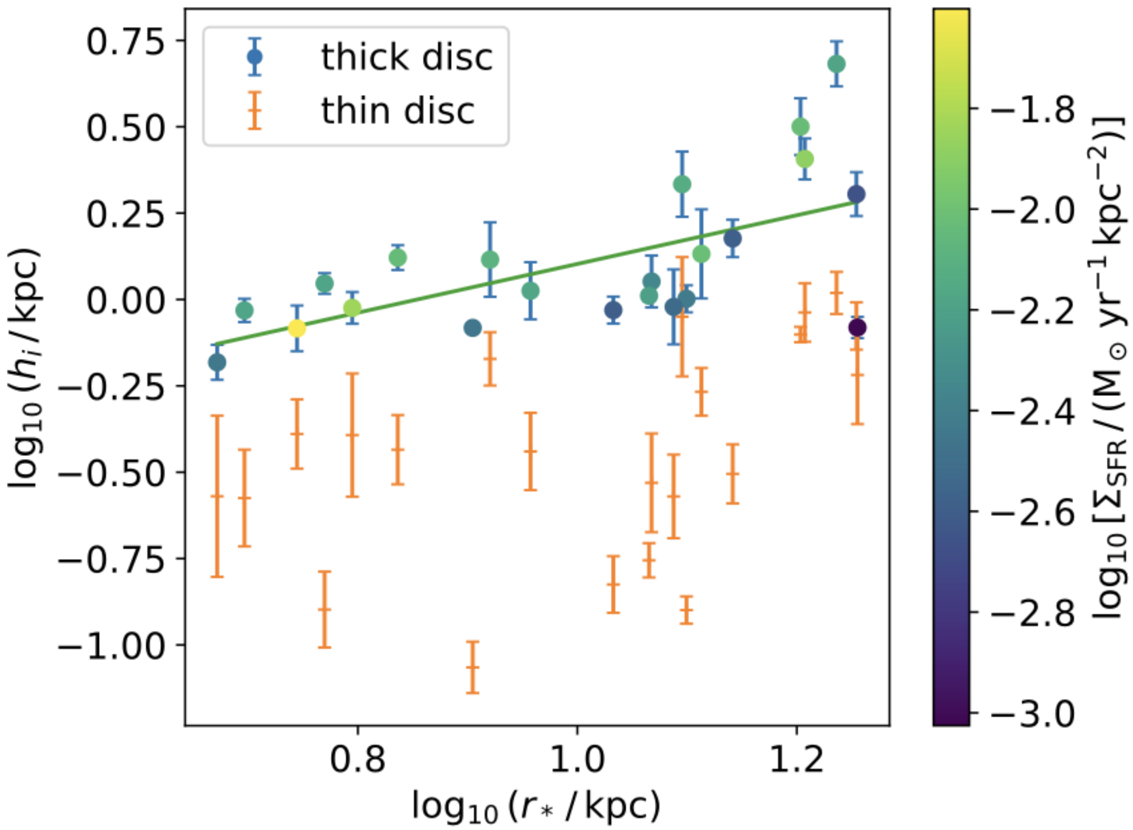


Thomas et al. (2024)

Chiu et al. (2024)

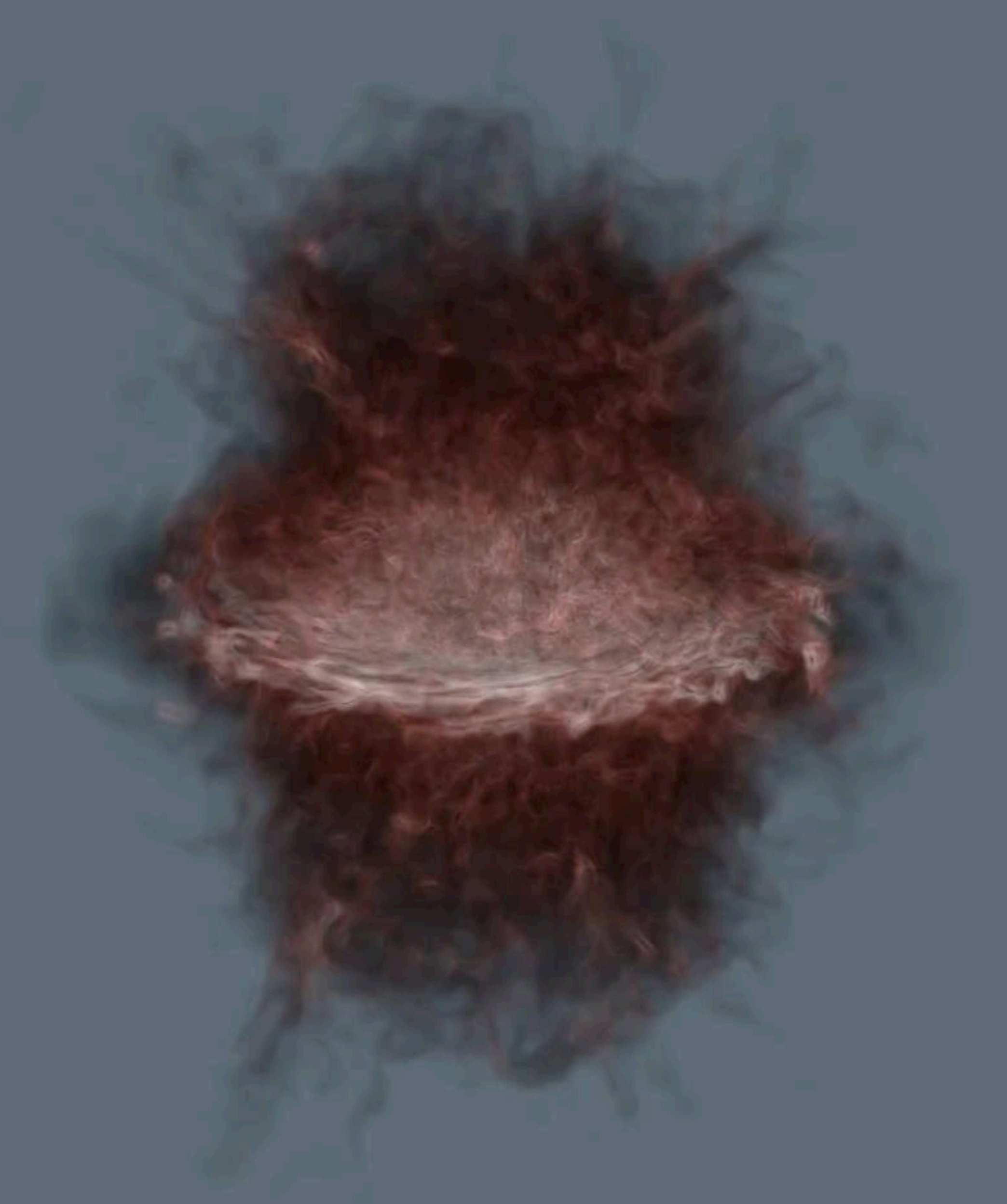
CHANG-ES catalog of edge-on disk galaxies



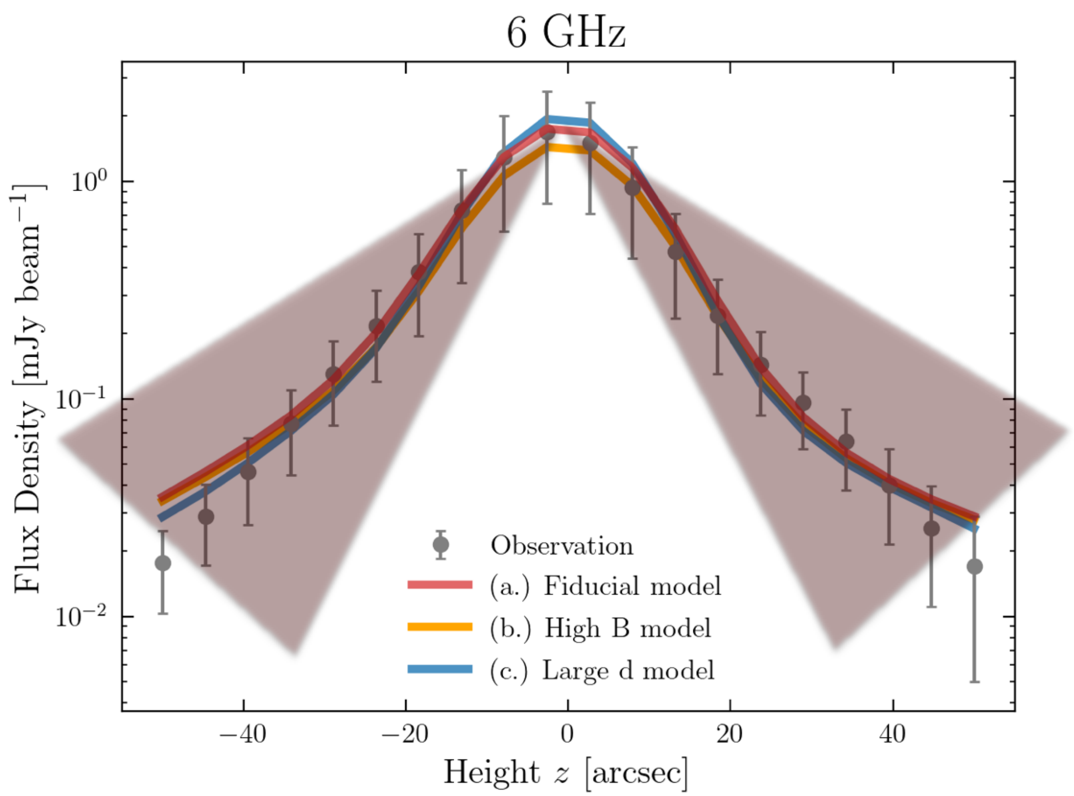


agrees with steady-state 1D solution of Quataert et al. (2022)

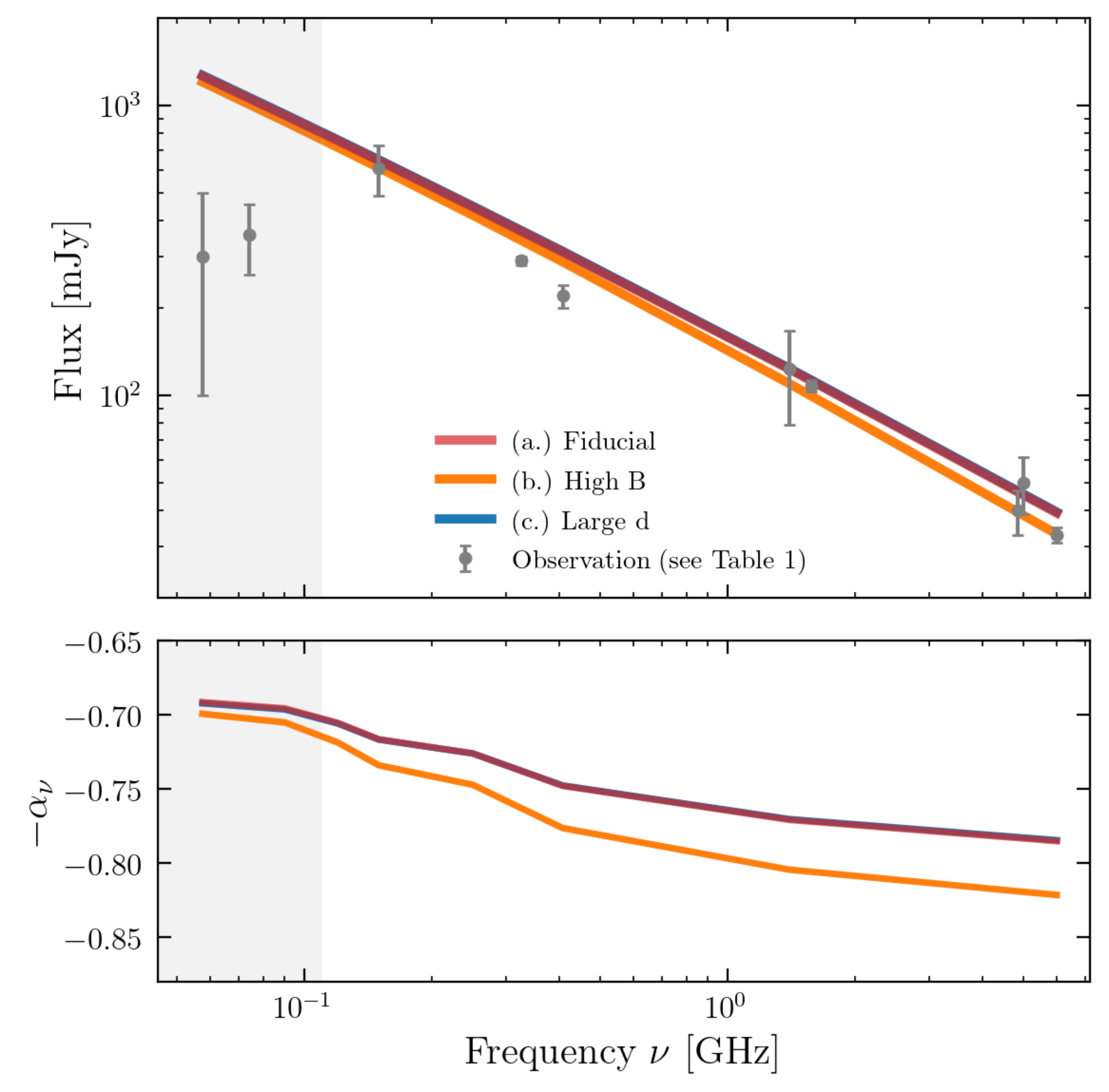
Heesen et al. (2025)



Thomas et al. (2024)



Chiu, Ruszkowski, Thomas, Werhahn, Pfrommer (2024)



$\alpha_\nu = (\alpha_e - 1)/2$

freely cooling: $\alpha_e = \alpha_{inject}$; $\alpha_{inject} \sim 2.1$

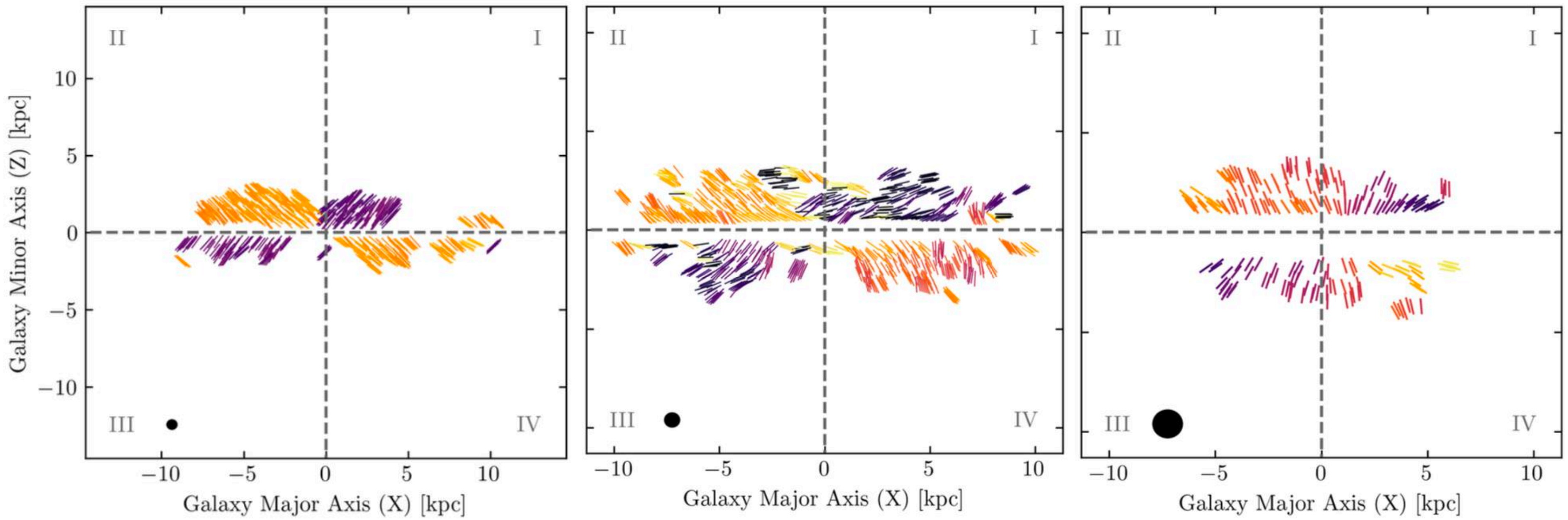
steady-state: $\alpha_e = \alpha_{inject} + \alpha_{steady}$

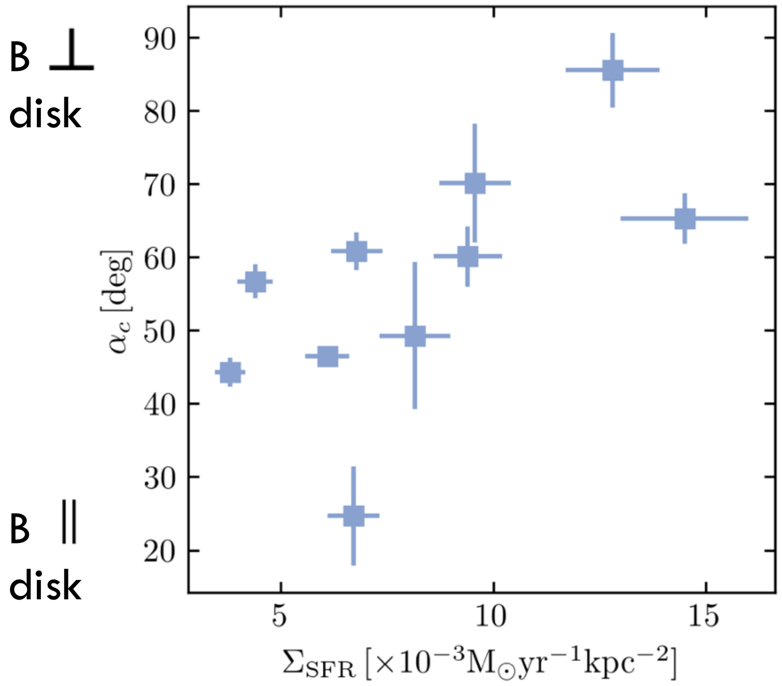
freely cooling:		$\alpha_\nu \sim 0.55$
diffusion-dominated:	$\alpha_{steady} \sim 0.3$;	$\alpha_\nu \sim 0.7$
IC/synch-dominated:	$\alpha_{steady} = 1.0$;	$\alpha_\nu = 0.95$

see also other work on spectrally-resolved CR transport

Yang & Ruszkowski (2017)
Werhahn et al. (2021a,b,c)
Girichidis et al. (2022)
Hopkins et al. (2022)
Krumholz et al. (2022)
Böss et al. (2023)
Baldacchino-Jordan et al. (2025)
Armillotta et al. (2025)
Linzer et al. (2025)

Chiu, Ruszkowski, Thomas, Werhahn, Pfrommer (2024)

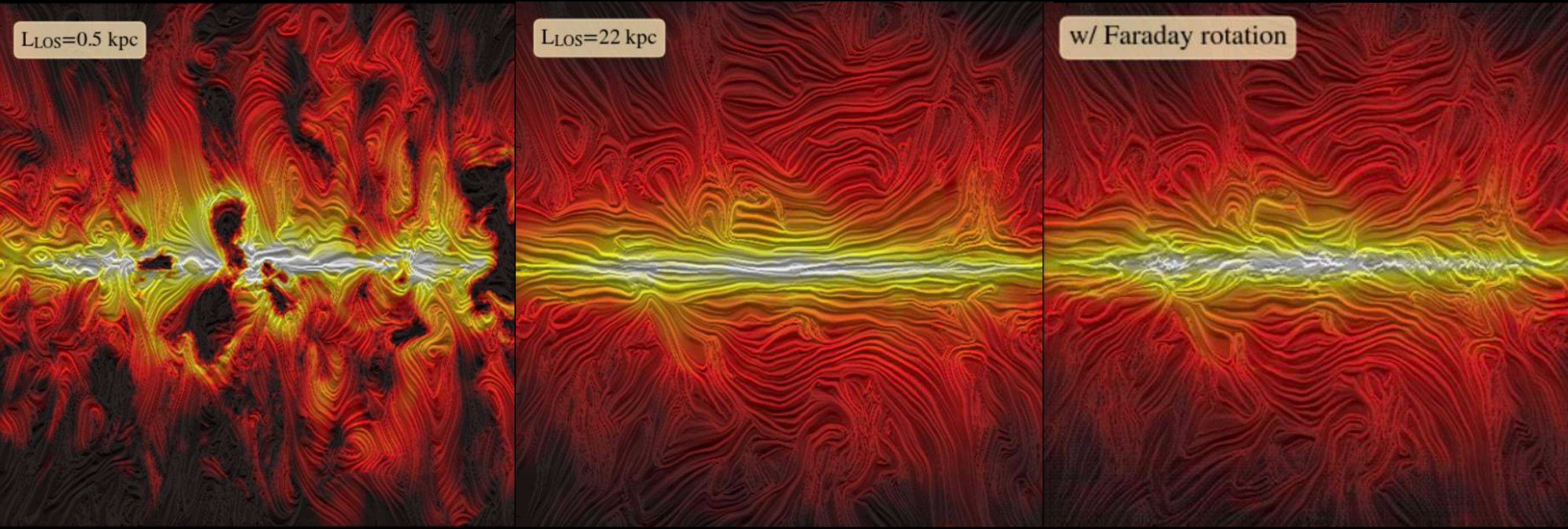




most galaxies exhibit **X-ray shaped B-fields**

B-fields more vertical for higher SFR surface density

Stein et al. (2025)



X-ray shaped B-fields

Chiu, Ruszkowski, Thomas, Werhahn, Pfrommer (2024)

Contents lists available at ScienceDirect
High Energy Density Physics
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Preliminary study for the laboratory experiment of cosmic-rays driven magnetic field amplification

Chun-Sung Jao[*,a,1], Sergei Vafin[a,b,1], Ye Chen[a,1], Matthias Gross[a], Mikhail Krasilnikov[a], Gregor Loisch[a], Timon Mehrling[c], Jacek Niemiec[d], Anne Oppelt[a], Alberto Martinez de la Ossa[e], Jens Osterhoff[c], Martin Pohl[a,b,1], Frank Stephan[a]

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ARTICLE INFO

Keywords:
Laboratory astrophysics
Beam-plasma instability
Magnetic field amplification
Radio-frequency electron gun
Field-emission-based quasi continuous-wave electron beam

ABSTRACT

To understand astrophysical magnetic-field am... experiment of a non-resonant strea... (PITZ). This non-resonant ... candidate for ... shock...

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Transport of High-energy Charged Particles through Spatially Intermittent Turbulent Magnetic Fields

L. E. Chen[1], A. F. A. Bott[1], P. Tzeferacos[1,2], A. Rigby[1], A. Bell[1], R. Bingham[3,4], C. Graziani[5], J. Katz[6], M. Koenig[7,8], C. K. Li[9], R. Petrasso[9], H.-S. Park[10], J. S. Ross[10], D. Ryu[11], T. G. White[1,12], B. Reville[13], J. Matthews[1], J. Meinecke[1], F. Miniati[1], E. G. Zweibel[14], S. Sarkar[1], A. A. Schekochihin[1], D. Q. Lamb[2], D. H. Froula[6], and G. Gregori[1,2]
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[5] Argonne Natior... ...Computer Science Division, Argonne, IL, USA
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[8] Gradu... ...565-0871, Japan
[9] Massachuse... ...02139, USA
[10] Lawrenc...
[11] Departm...
[13] Sch...
[14] Departments of A...
Received 202...

Identifying the sourc... stochastic, spatially... particle propagatio... diffusive transport... regime of interes... intermittency of...

Unified Astrono... (1733); Magne... (813); Particl...

nature COMMUNICATIONS
ARTICLE
DOI: 10.1038/s41467-018-02953-2
OPEN

Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma

P. Tzeferacos[1,2], A. Rigby[1], A. F. A. Bott[1], A.R. Bell[1], R. Bingham[3,4], A. Casner[5], F. Cattaneo[2], E.M. Churazov[6,7], J. Emig[8], F. Fiuza[9], C.B. Forest[10], C. Graziani[2], J. Katz[12], M. Koenig[13], C.-K. Li[14], J. Meinecke[1], R. Petrasso[14], H.-S. ... J.S. Ross[8], D. Ryu[15], D. Ryutov[8], T.G. White[1], B. Reville[16], F. Minia... D.H. Froula[12] & G. Gregori[1,2]

... density of these fields is typically ... of the plasma in which they are ... dynamics of the luminous matter. ... magnetic fields is through the ... level consistent with current ... lent dynamo mechanism has ... tremely hard to re-create in ... ed colliding plasma flows ... to near equipa...

SCIENCE ADVANCES | RESEARCH ARTICLE
PHYSICS

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Strong suppression of heat conduction in a laboratory replica of galaxy-cluster turbulent plasmas

Jena Meinecke[1], Petros Tzeferacos[1,2,3,4], James S. Ross[5], Archie F. A. Bott[1,6], Scott Feister[2,7], Hye-Sook Park[5], Anthony R. Bell[1,8], Roger Blandford[9], Richard L. Berger[5], Robert Bingham[8,10], Alexis Casner[11], Laura E. Chen[1], John Foster[12], Dustin H. Froula[4], Clement Goyon[5], Daniel Kalantar[5], Michel Koenig[13], Brandon Lahmann[14], Chikang Li[14], Yingchao Lu[3], Charlotte A. J. Palmer[1,15], Richard D. Petrasso[14], Hannah Poole[1], Bruce Remington[5], Brian Reville[16], ... Reyes[3], ... Alexandra Rigby[1], Dongsu Ryu[17], George Swadling[5], Alex Zylstra[5,18], Fr... Subir Sarkar[1], Alexander A. Schekochihin[1,19,20], Donald Q. Lamb[2], Gianl...

In conventional gases and plasmas, it is known that heat fluxes are proportional... collisions between particles mediating energy flow from hotter to colder regio... conduction given by Spitzer's theory. However, this theory breaks down in ma... sional plasmas, although modifications are difficult to predict from first princip... nature of the problem. Understanding heat transport is important in astroph... axy clusters, where observed temperature profiles are explicable only in the... heat conduction compared to Spitzer's theory. To address this problem, we... tem in a laser laboratory experiment. Our data show a reduction of heat tra... more, leading to large temperature variations on small spatial scales (as is...

Time-resolved turbulent dynamo in a laser plasma

Archie F. A. Bott[a,b,1], Petros Tzeferacos[a,c,d,e], Laura Chen[a], Charlotte A. J. Palmer[a,f], Alexandra Rigby[a], Anthony R. Bell[a], Robert Bingham[g,h], Andrew Birkel[i], Carlo Graziani[j], Dustin H. Froula[d,e], Joseph Katz[e], Michel Koenig[k,l], Matthew W. Kunz[b], Chikang Li[i], Jena Meinecke[a], Francesco Miniati[a], Richard Petrasso[i], Hye-Sook Park[m], Bruce A. Remington[m], Brian Reville[n], J. Steven Ross[m], Dongsu Ryu[o], Dmitri Ryutov[m], Fredrick H. Séguin[i], Thomas G. White[p], Alexander A. Schekochihin[a], Donald Q. Lamb[c], and Gianluca Gregori[a,c]

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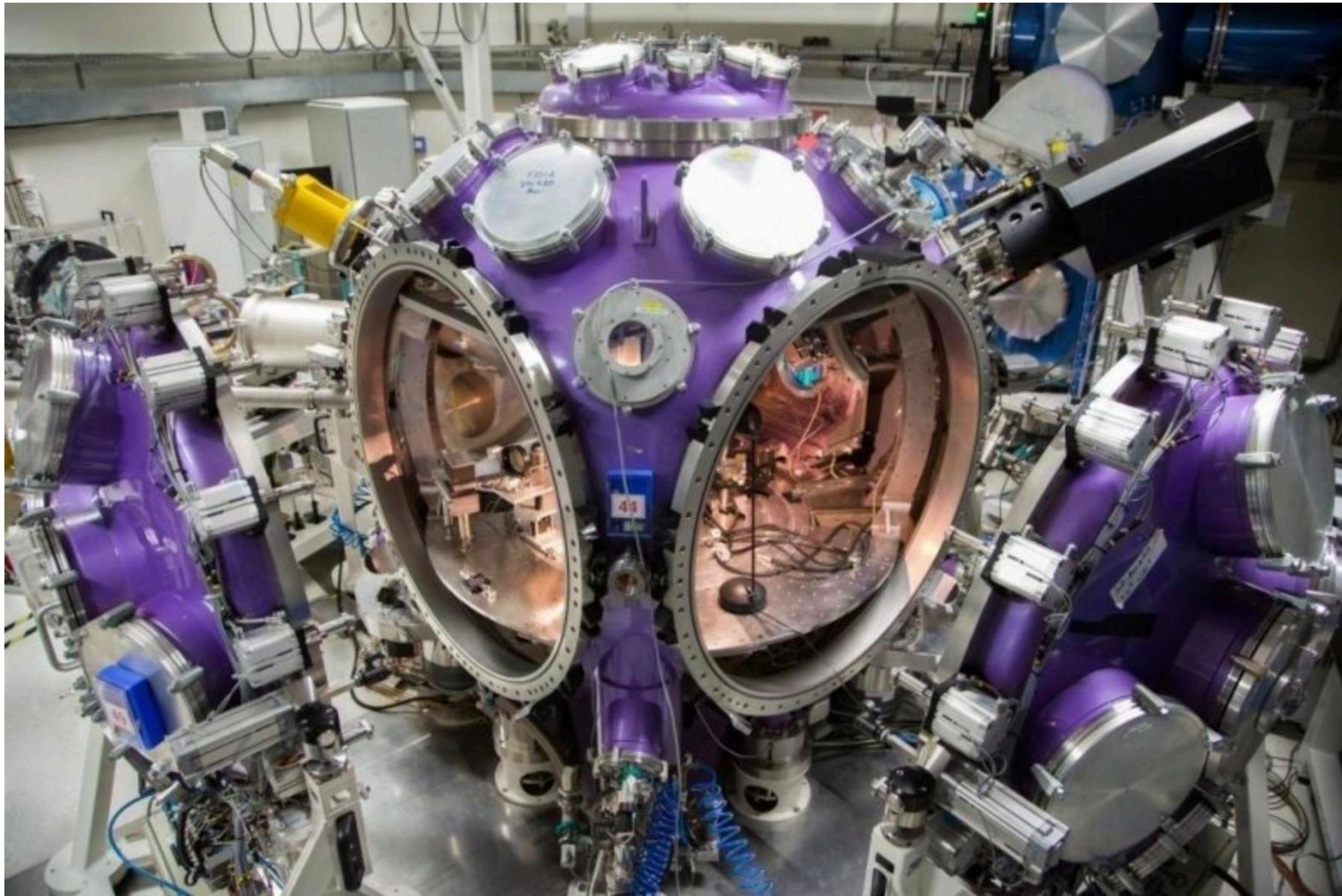
Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved January 14, 2021 (received for review July 27, 2020)

Understanding magnetic-field generation and amplification in turbulent plasma is essential to account for observations of magnetic fields in the universe. A theoretical framework attributing the origin and sustainment of these fields to the so-called fluctuation dynamo was recently validated by experiments on laser facilities...

MHD, the fluctuation dynamo can operate only if the magnetic Reynolds number $\mathrm{Rm} \equiv u_L L/\eta$—where L is the length scale of driving stochastic motions, u_ℓ the characteristic velocity of motions at a given scale ℓ, and η the resistivity of the plasma—is above some critical threshold Rm_c (26). The precise value of...

LULI2000 = Laboratoire pour l'Utilisation des Lasers Intenses



Summary

(stellar) CR feedback

New CR acceleration mechanisms

CR transport processes are crucially important for controlling star formation & galactic wind properties

CR may play an important role in open star cluster formation and clustered SN feedback

Impact of CRs in CGM can be dramatic and depends critically on CR transport physics

CR wind models are broadly consistent with radio observations of galaxies

CR transport is fundamentally important

We need a complete **CR transport** theory

We need to test it in **laboratory** settings