Australian National University

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AND ROLAND CROCKER

COSMIC RAYS TRANSPORT IN STARBURST GALAXIES

REFERENCES… AND A WARNING

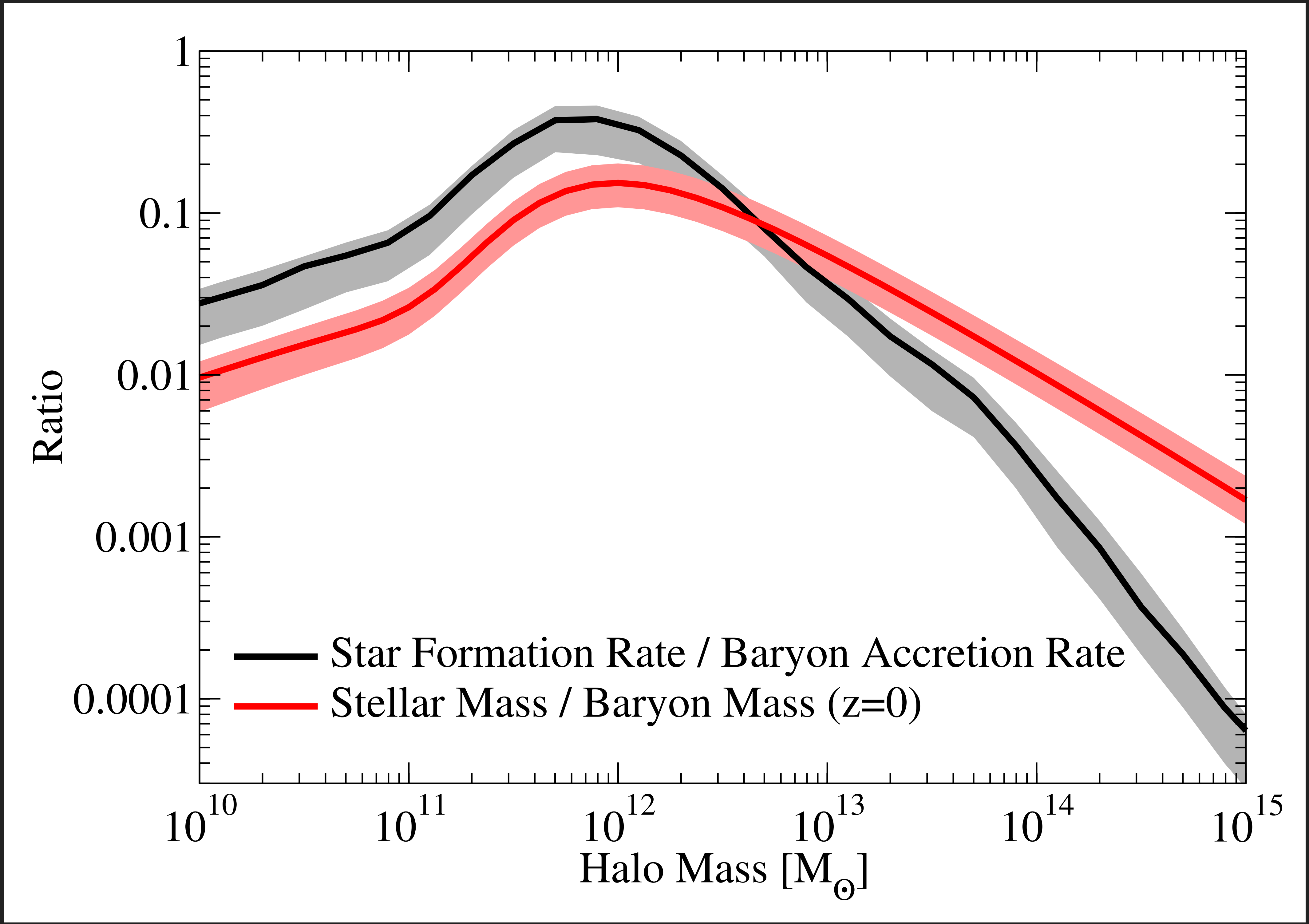
- This talk is mostly based on:
  - Krumholz, Crocker, Xu, Lazarian, Bedwell-Wilson, & Rosevear, 2020, MNRAS, 493, 2817
  - Crocker, Krumholz, & Thompson, 2020, in prep. (see next talk)
- A warning: this talk is being given by someone who probably knows a lot less about cosmic rays than many of the people in the audience.
  - However, I do know a few things about galaxies and the ISM, so I'm hoping we can learn from each other…

OUTLINE

- Introduction and motivation
- CR transport in star-forming gas
  - Magnetohydrodynamics of the neutral ISM
  - CR streaming and diffusion
- Implications: γ-ray spectra of local starbursts
- Conclusions and future work

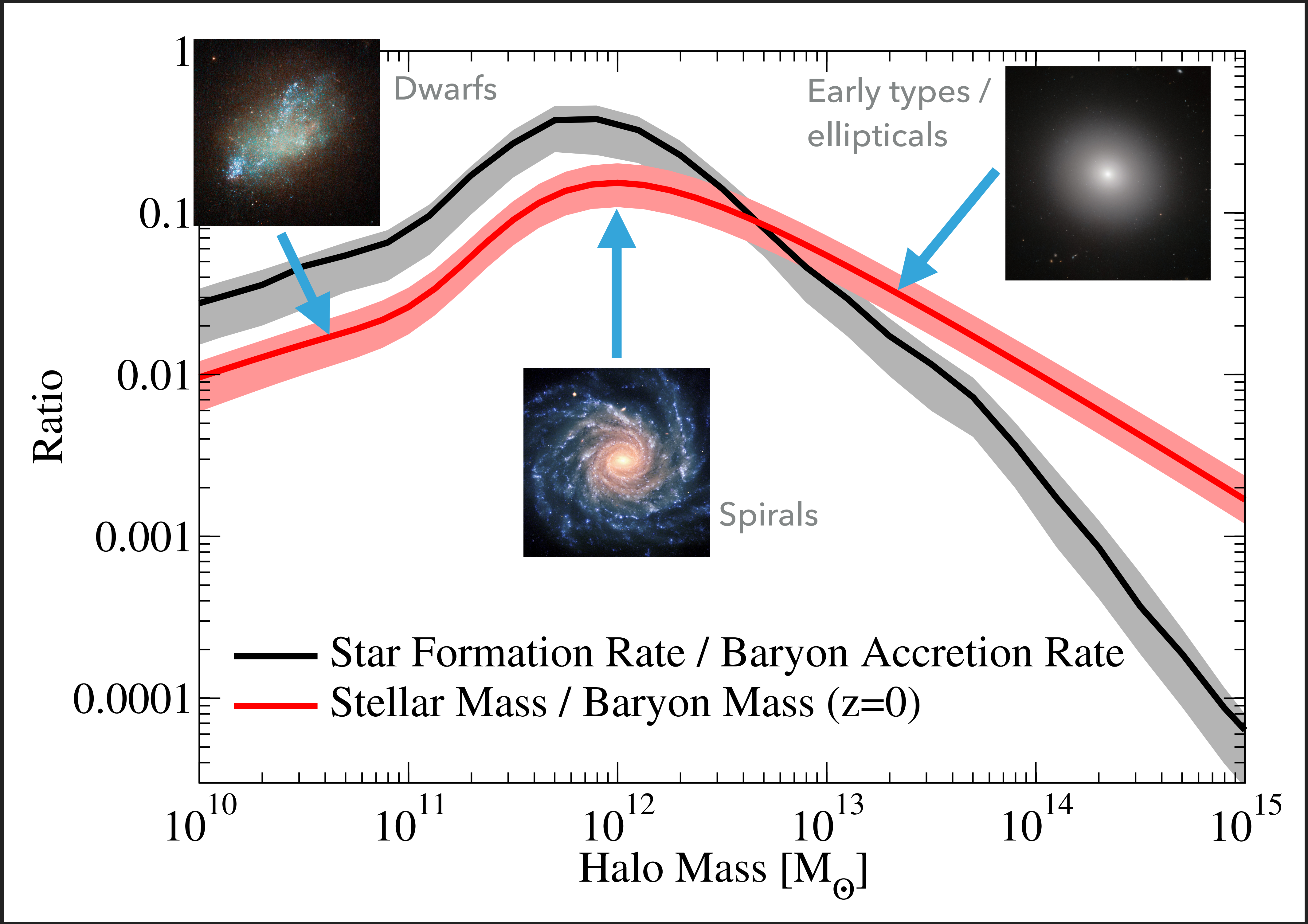
Left: theorist attempting to interpret observations

INTRODUCTION AND MOTIVATION



GALAXY FORMATION IS INEFFICIENT

Behroozi+ 2013



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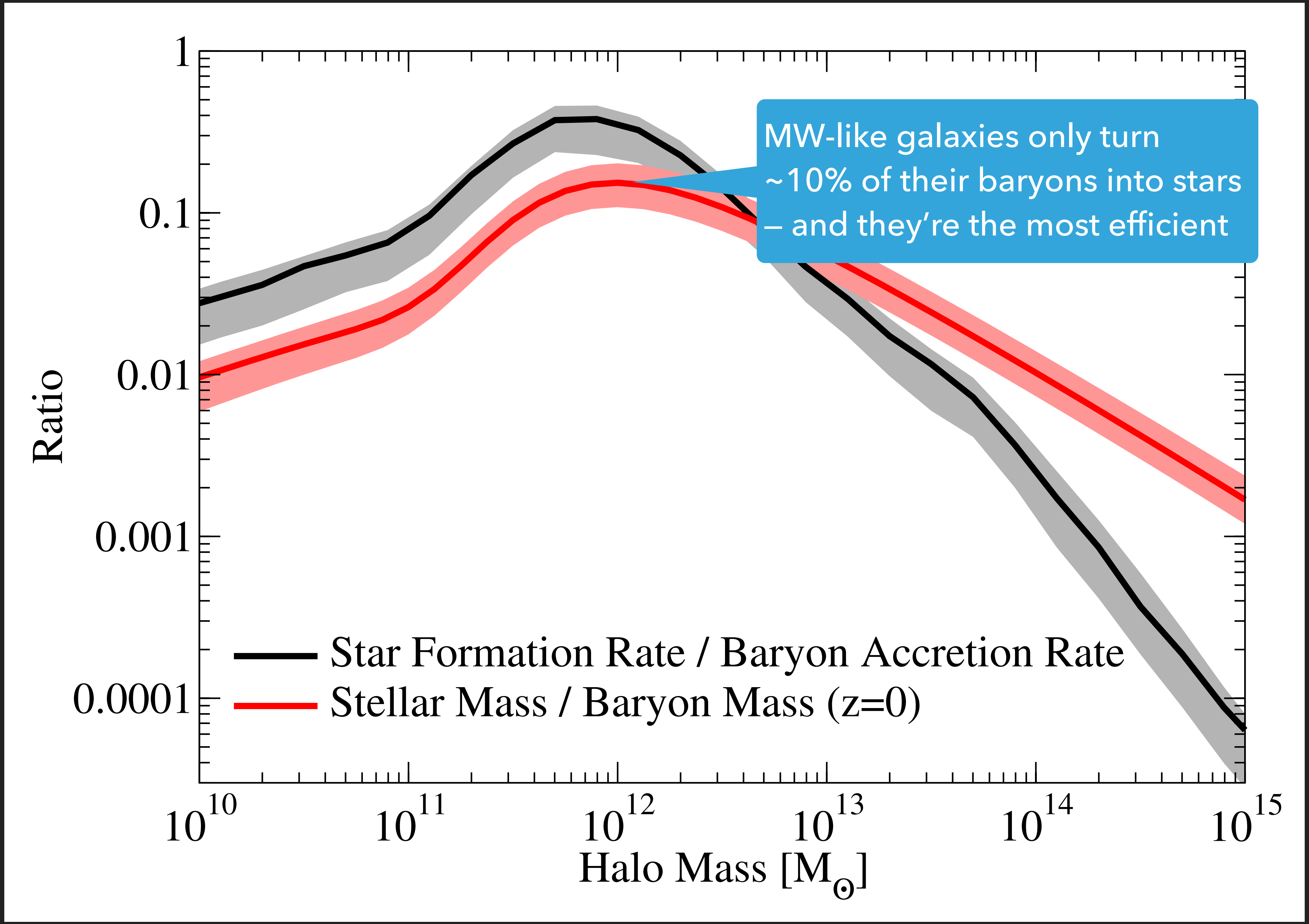

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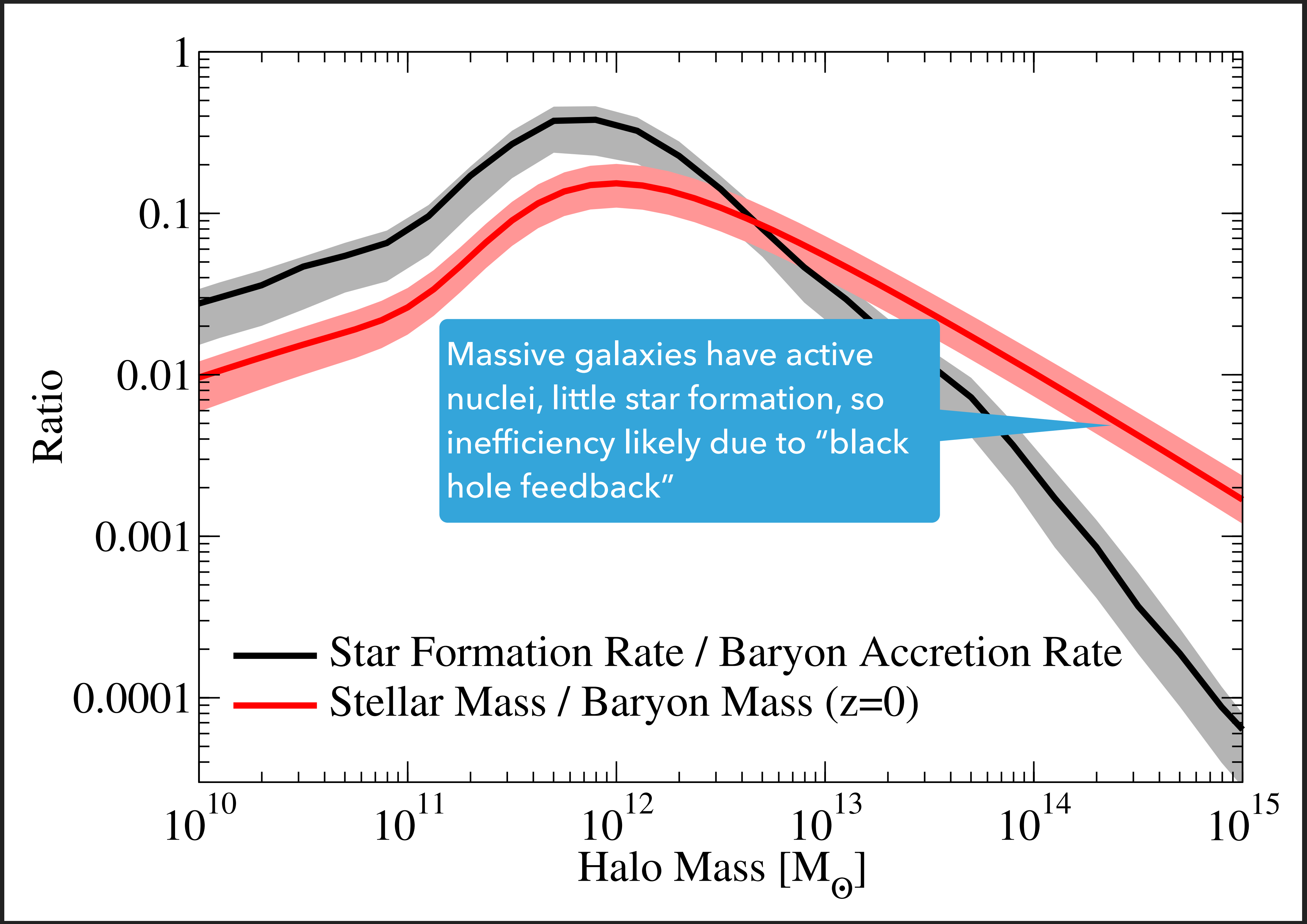

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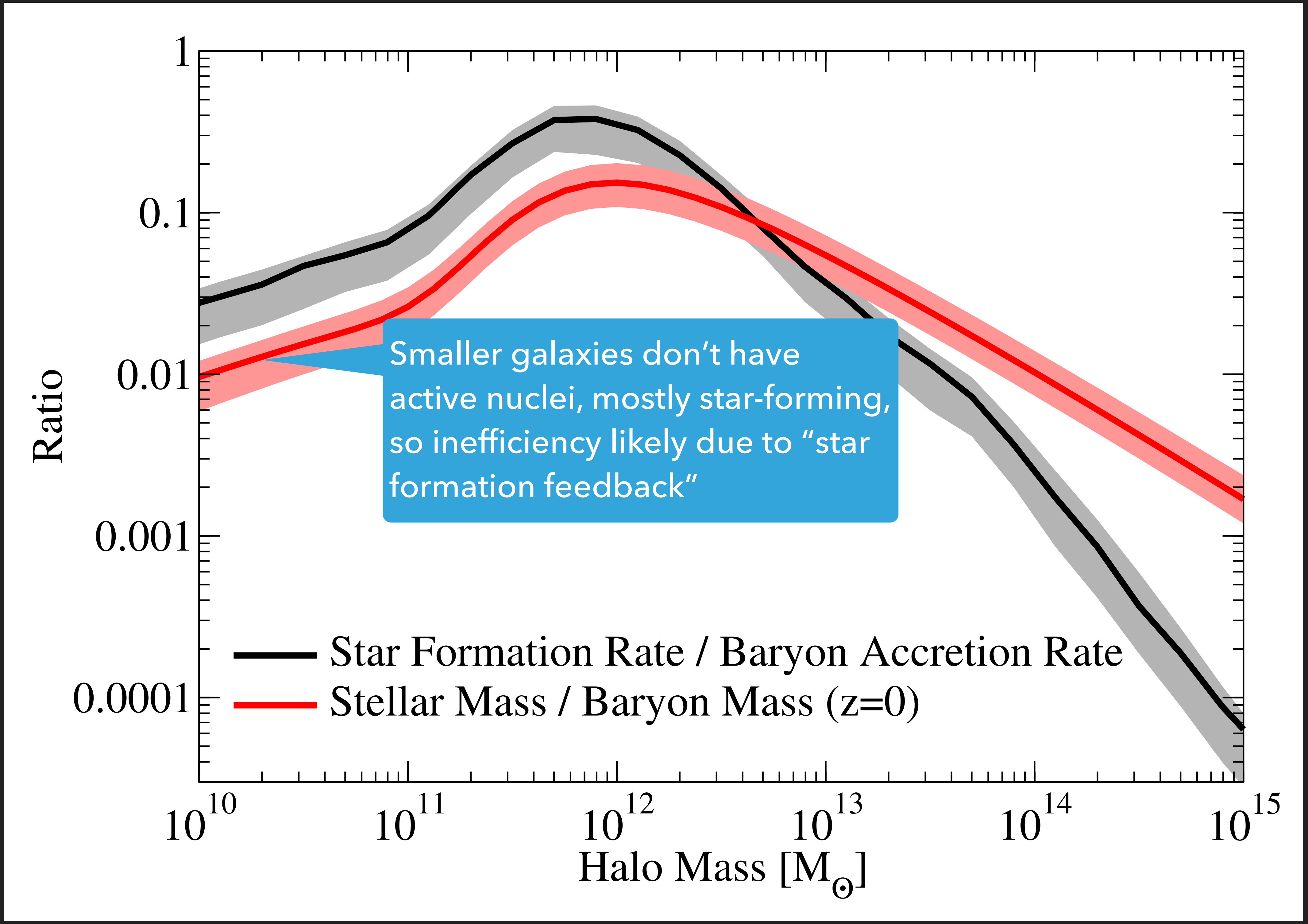

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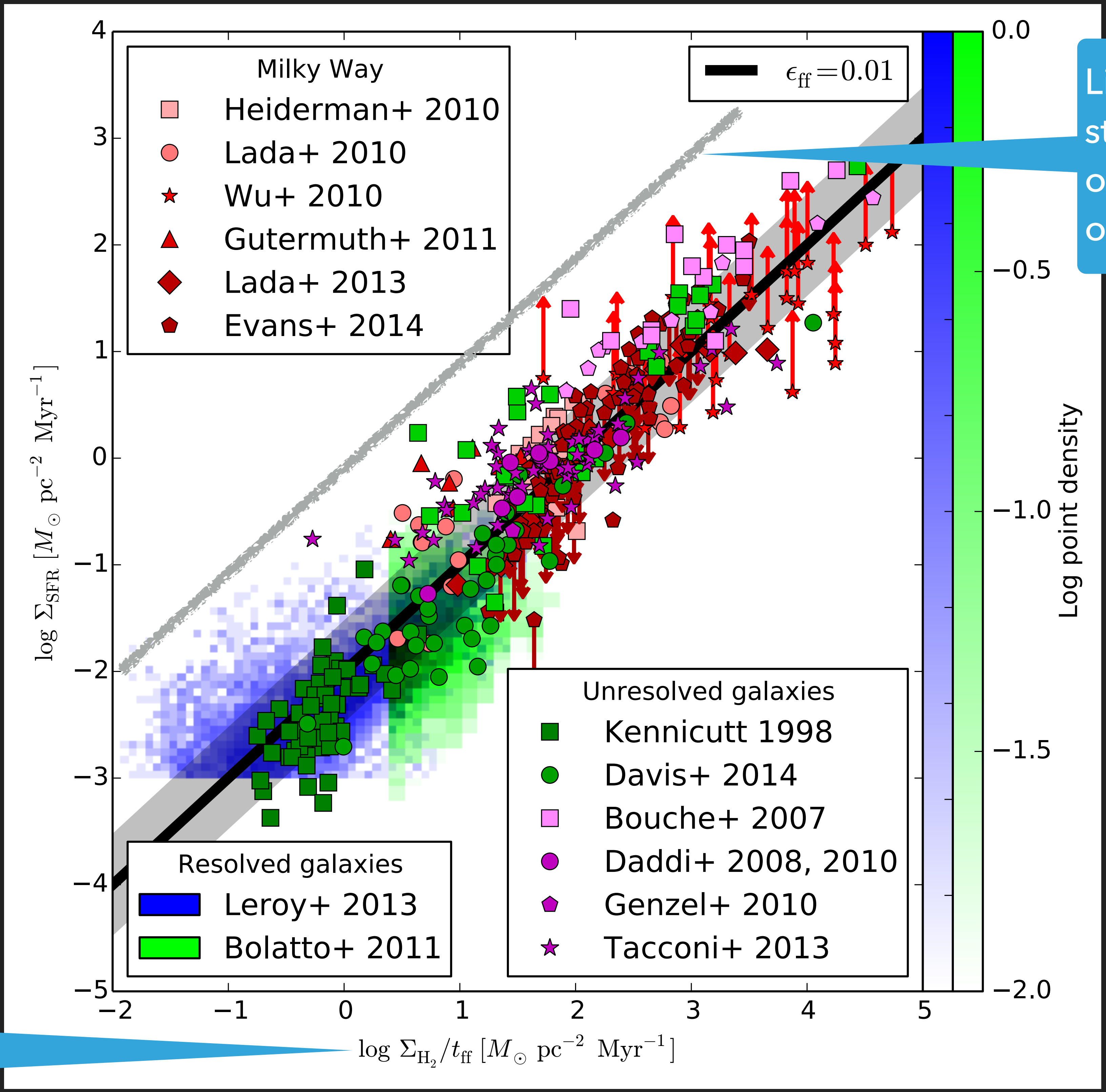


Limit of "efficient" star formation: 100% of gas consumed in one dynamical time

Low efficiency even for cold, molecular gas!

STAR FORMATION IS INEFFICIENT

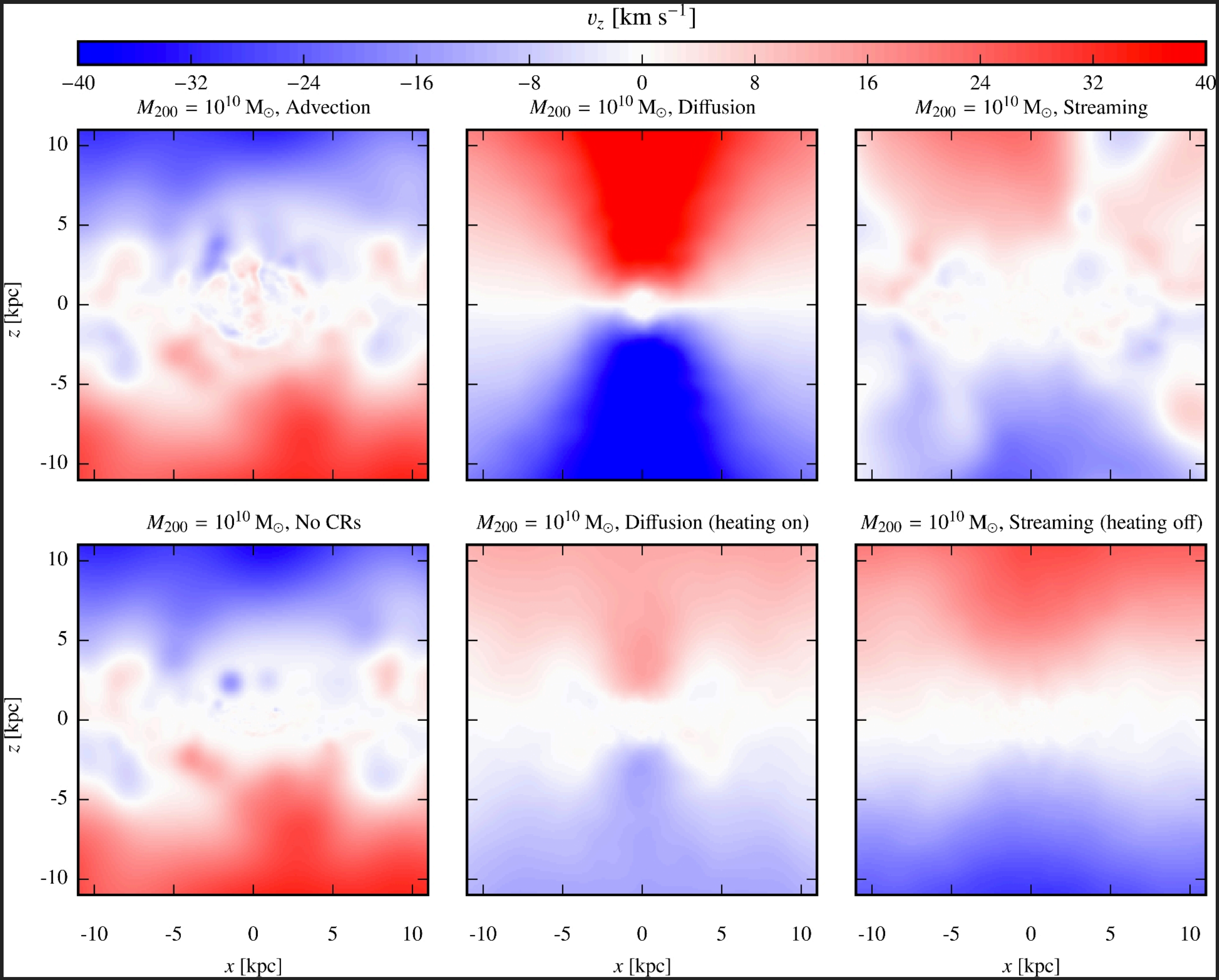
Krumholz 2014

STAR FORMATION FEEDBACK BUDGET

- Most important form of stellar feedback is supernovae
  - ~1 SN per $M_{SN} \sim 100\ M_\odot$ of stars formed, $E_{SN} \sim 10^{51}$ erg
  - Efficiency of energy release $\varepsilon_{SN} \sim E_{SN} / M_{SN} c^2 \sim 5 \times 10^{-6}$
- Energy deposited as heat in ISM, leading to blast wave
- Blast wave becomes radiative after ~10-100 kyr; >90% of energy lost, radial momentum for single SNe limited to $\sim 3 \times 10^5\ M_\odot$ km s^{-1} (Gentry+ 2017)
- Open question whether this is enough to explain efficiency

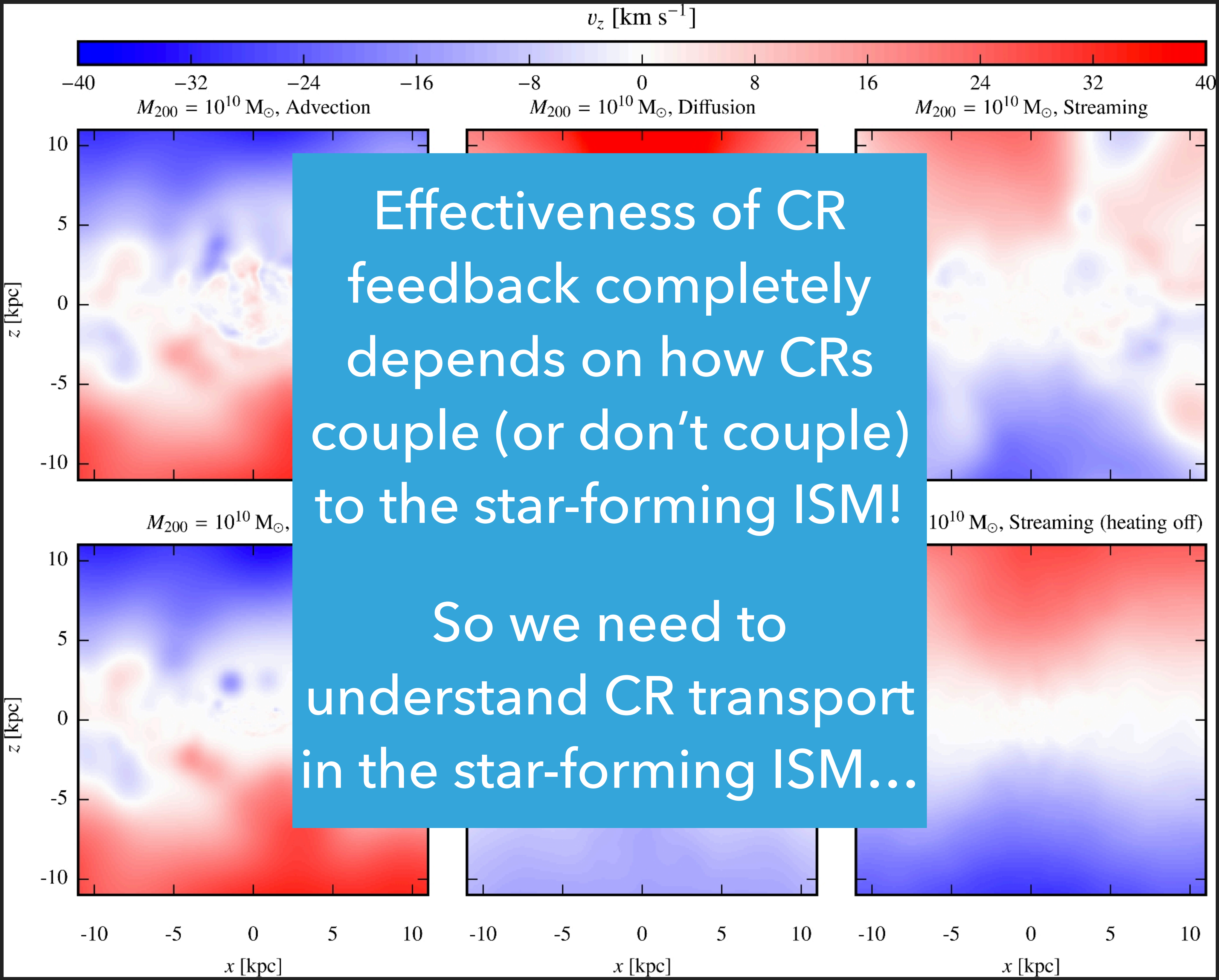
WHY THINK ABOUT COSMIC RAYS?

- SNe deposit ~10% of their energy in relativistic particles, mostly ~GeV protons: $E_{CR} \sim 10^{50}$ erg, $\varepsilon_{CR} \sim 5 \times 10^{-7}$
- 10× smaller energy budget, BUT escape time is also ~10× longer, so comparable energy density expected
- Consistent with observations: at MW midplane, CR energy density is ~1 eV cm^{-3}, comparable to midplane energy density in gas turbulent motions, magnetic fields



THE PROBLEM WITH CR FEEDBACK

Wiener+ 2017



Effectiveness of CR feedback completely depends on how CRs couple (or don't couple) to the star-forming ISM!

So we need to understand CR transport in the star-forming ISM…

THE PROBLEM WITH CR FEEDBACK

Wiener+ 2017

Left: probably not how it works, but who knows?

CR TRANSPORT IN THE STAR-FORMING ISM

CR TRANSPORT IN PLASMA: THE CONVENTIONAL PICTURE

- CRs gyrate around magnetic field lines, try to follow them; gyro radius for a 1 GeV CR is $r_g \sim 0.001$ AU $\sim 10^{-7}$ pc
- Alfvén waves with $\lambda \sim r_g$ scatter CRs, changing pitch angle and travel direction; scattering MFP is small
- Waves can be either extrinsic (generated by turbulent cascade from larger scales) or self-generated (via CR streaming instability)
- Net effect is that CR transport is effectively diffusive

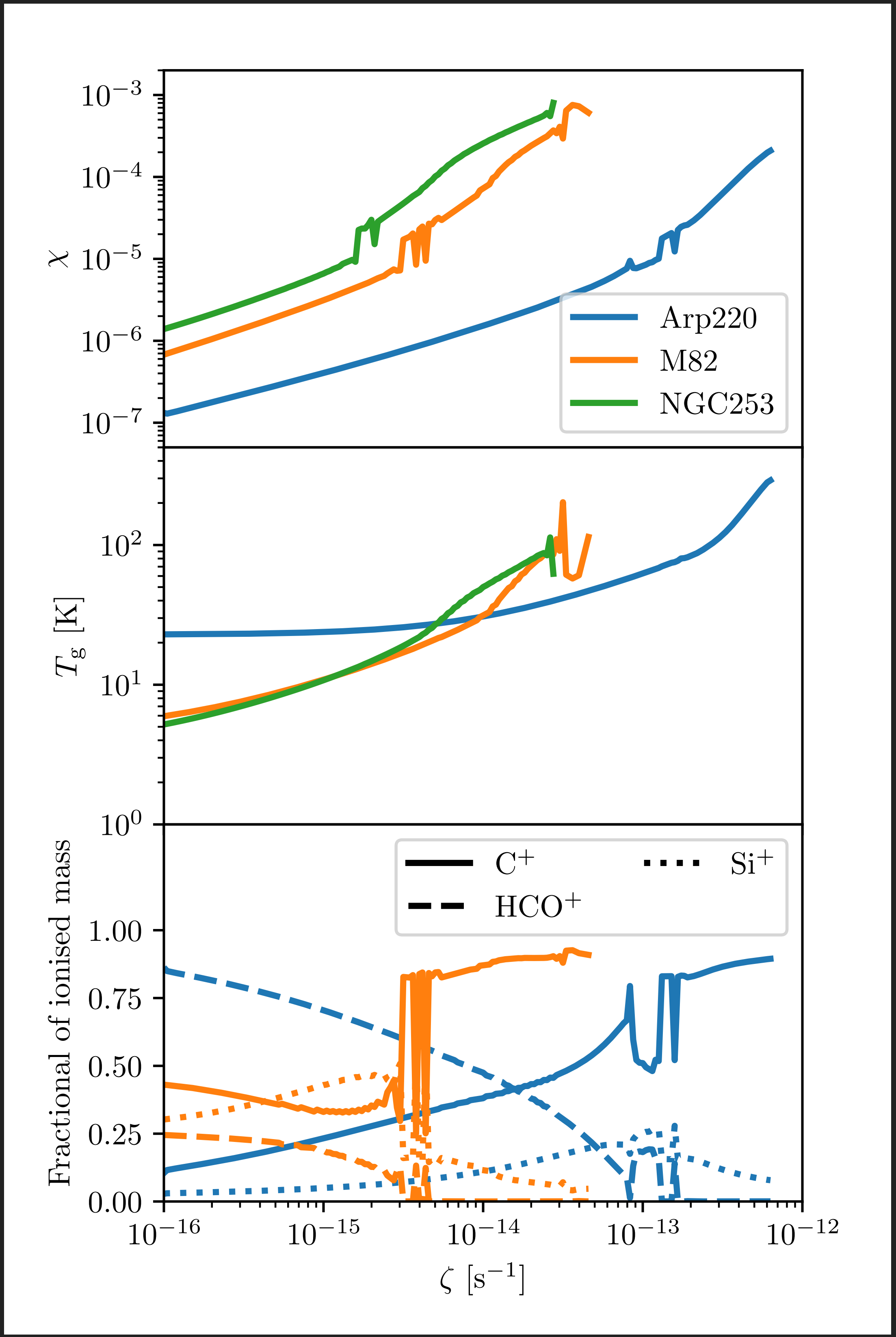
CHEMICAL STATE OF THE STAR-FORMING ISM

- In modern spirals and dwarfs, ISM at midplane is ~50% by volume and ~95% by mass neutral gas (mostly free atomic H), $n \sim$ few cm^{-3}
- Stars form only in the cold ($\lesssim 50$ K), molecular (mostly H_2) phase of the ISM where dust blocks UV light: $n \sim 10^2 - 10^5$ cm^{-3}, $N \gtrsim 10^{21}$ cm^{-2} (Krumholz, McKee, & Leroy 2011)
- The molecular phase dominates the midplane by both mass and volume in starburst galaxies

IONISATION STATE

- In atomic gas, main ions are C^+ (from FUV), H^+ (from X-ray); $\chi \sim 10^{-2}$
- Photons blocked in molecular regions, CRs dominate ionisation
  - $H_2 + CR \rightarrow H_2^+ + e^- + CR$
  - $He + CR \rightarrow He^+ + e^- + CR$
  - Various reaction chains then make HCO+, C+
- In molecular gas, $\chi \sim 10^{-6} - 10^{-4}$, depending on CR density

Krumholz+ 2020



A QUICK PRIMER ON TURBULENCE IN WEAKLY-IONISED MEDIA

- ν_{ni} = frequency with which neutral collides with an ion
- ν_{in} = frequency with which ion collides with a neutral

Coupled regime	Damping regime	Decoupled regime
$\nu \ll \nu_{ni} \ll \nu_{in}$	$\nu_{ni} \ll \nu \ll \nu_{in}$	$\nu_{ni} \ll \nu_{in} \ll \nu$
Fluid acts as if fully ionised; normal MHD waves exist	Ions try to move with B field, but collide with ions that don't → damping	Normal MHD in ions, pure HD in neutrals, two fluids act independently

→ Frequency / wavenumber

← Wavelength

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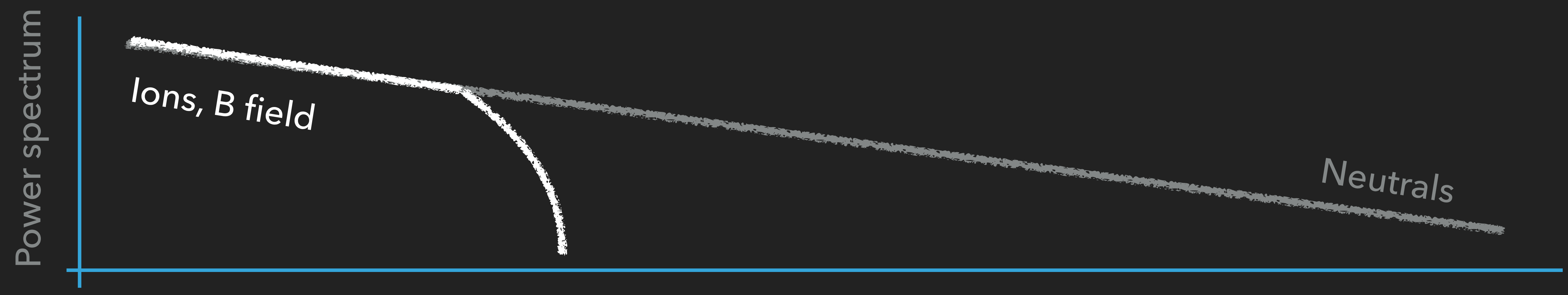

Coupled regime	Damping regime	Decoupled regime
$v \ll v_{ni} \ll v_{in}$	$v_{ni} \ll v \ll v_{in}$	$v_{ni} \ll v_{in} \ll v$
Fluid acts as if fully ionised; normal MHD waves exist	Ions try to move with B field, but collide with ions that don't → damping	Normal MHD in ions, pure HD in neutrals, two fluids act independently

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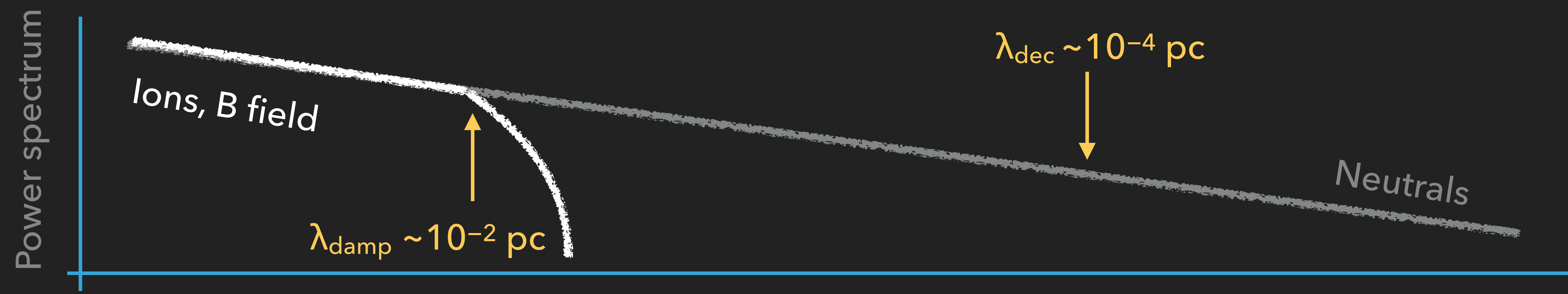

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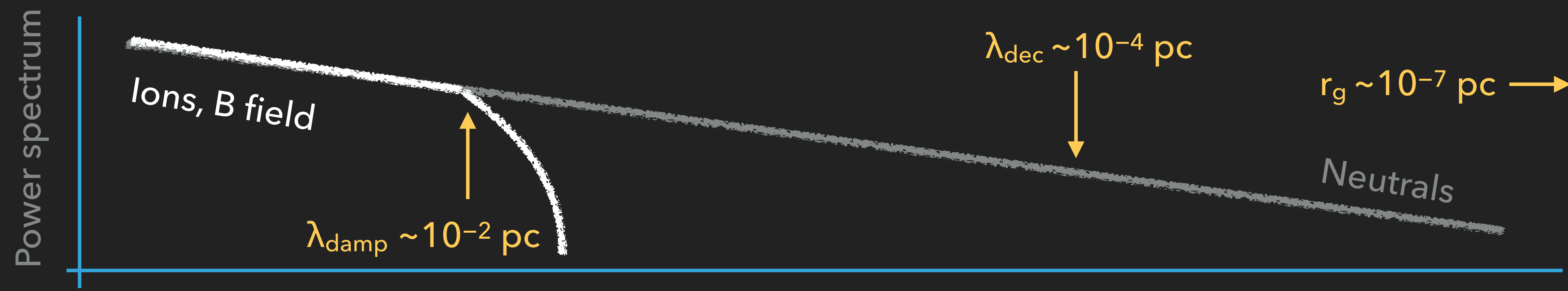

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IMPLICATIONS OF ION-NEUTRAL DAMPING

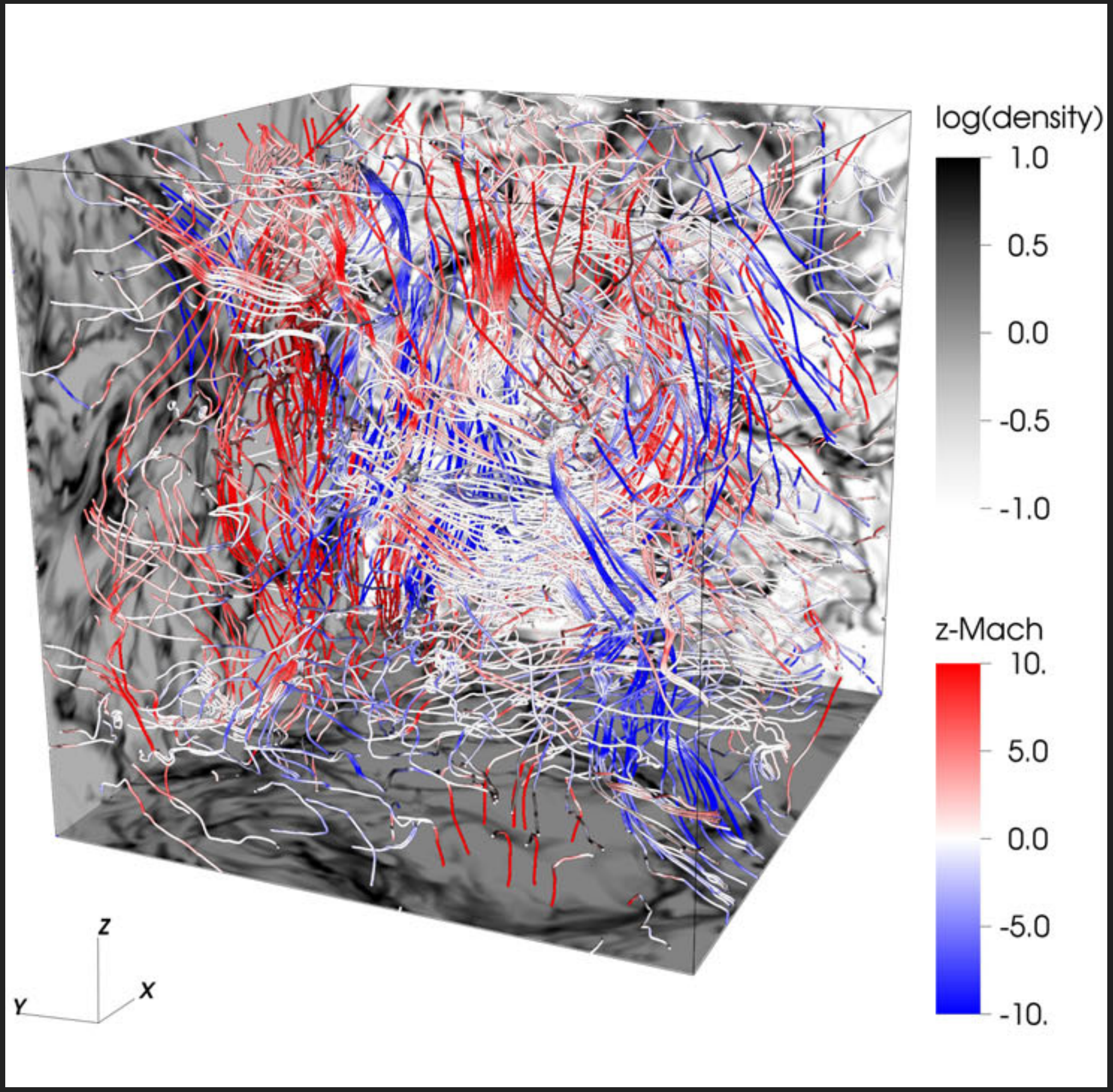
- CRs can only interact with self-generated turbulence, which only scatters them along field lines, not across them
- Level of turbulence set by competition between streaming instability growth and damping by ion-neutral collisions:

$$\Gamma_{\mathrm{CR}} = \frac{eB}{mc}\frac{n_{\mathrm{CR}}(>\gamma)}{n_i}\left(\frac{v_{\mathrm{st}}}{v_{\mathrm{A,i}}} - 1\right) \qquad \Gamma_{\mathrm{in}} = \gamma_{\mathrm{d}}\chi\rho_i$$

- Solve for streaming speed, find $v_{st} / v_{A,i} - 1 \ll 1$
  - For $E_{CR} \lesssim$ TeV in starburst-like H_2-dominated ISM
  - For $E_{CR} \lesssim$ 10 GeV in MW-like H-dominated ISM

MACROSCOPIC DIFFUSION: FIELD LINE RANDOM WALK (FLRW)

- CRs stream along field lines, but in turbulent medium field lines themselves constant moving
- Size of motions is coherence length of field $l_{coh} \sim h / M_A^3$; turbulent dynamo gives $M_A \sim 1 - 2$
- Acts like diffusion with coefficient $\kappa_{FLRW} \approx l_{coh} v_{st} \sim 10^{27} - 10^{28}$ cm^2 s^{-1} at energies up to TeV in starbursts / early disks, ~10 GeV in z = 0 spirals



Birnboim, Federrath & Krumholz 2018

Left: typical astrophysical model

IMPLICATIONS FOR γ-RAY SPECTRA

Left: typical astrophysical model… Australian version

IMPLICATIONS FOR ɣ-RAY SPECTRA

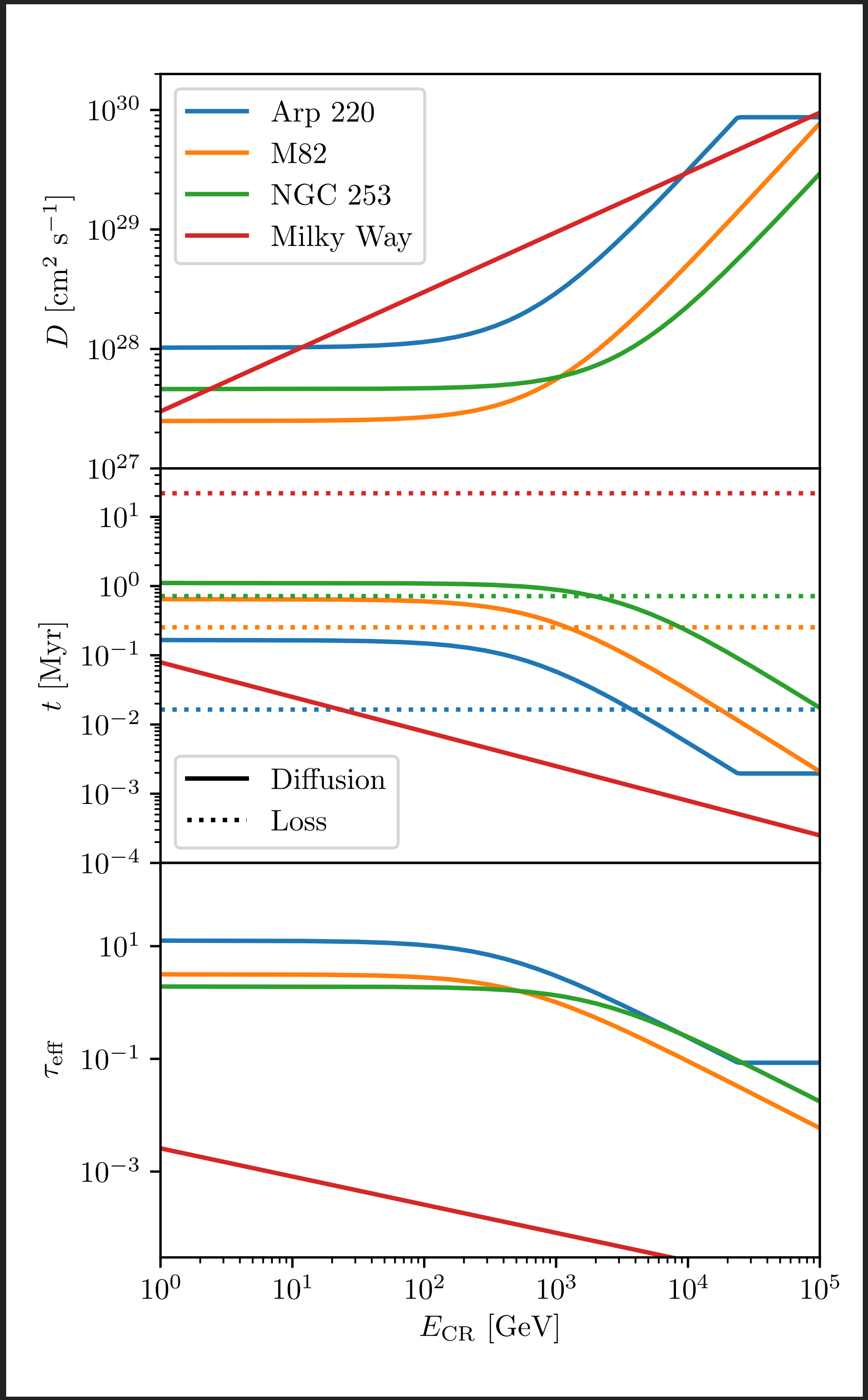
DIFFUSION MODEL FOR GALAXY SPECTRA

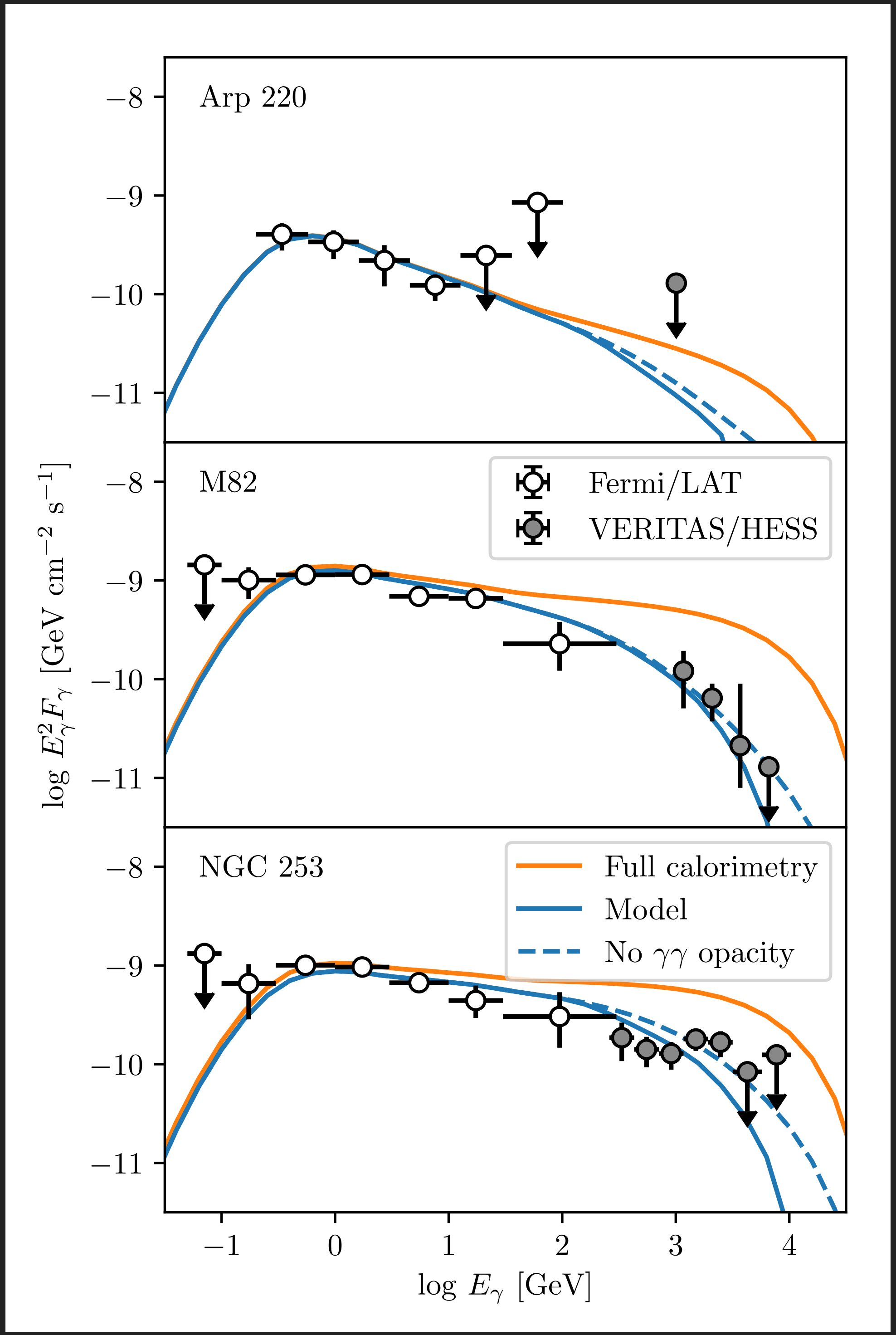
- Test by comparing to ɣ-ray spectra of starburst galaxies
- Simple diffusion model: $\frac{d}{dz}\left(-\kappa \frac{dU}{dz}\right) = -\frac{U}{t_{pp}} \approx -n\sigma_{pp}\eta_{pp}cU$
- Assuming CRs injected at z = 0 into exponential gas disc with scale height h, fraction of CRs that produce ɣ-rays depends only on

$$\tau_{\mathrm{eff}} = \frac{\sigma_{pp}\eta_{pp}\Sigma hc}{2\kappa\mu_p m_{\mathrm{H}}}$$

- Everything except κ is (almost) energy-independent, so energy-dependence of κ alone sets shape of ɣ-ray spectrum

PREDICTED OPTICAL DEPTHS AND SPECTRA





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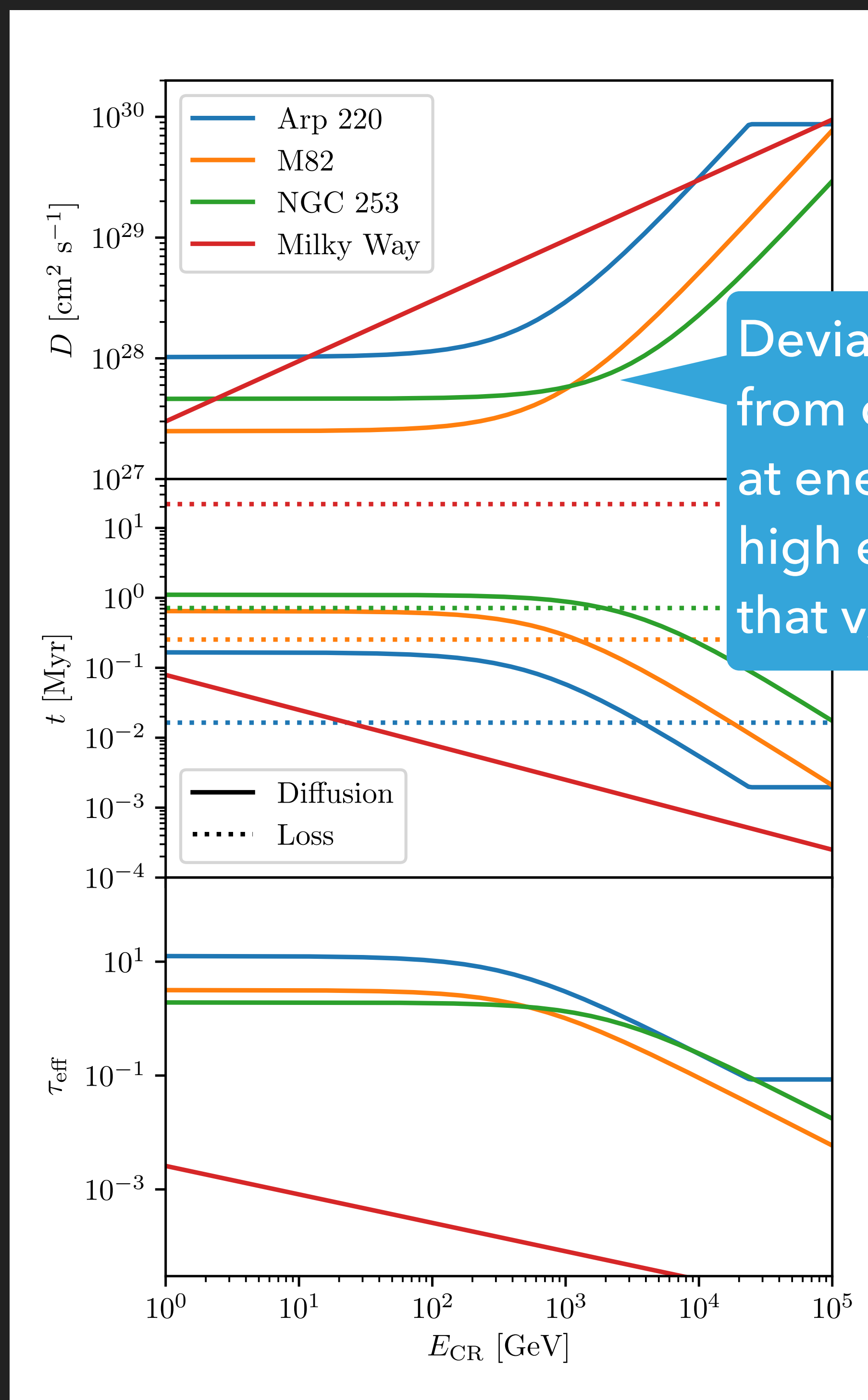
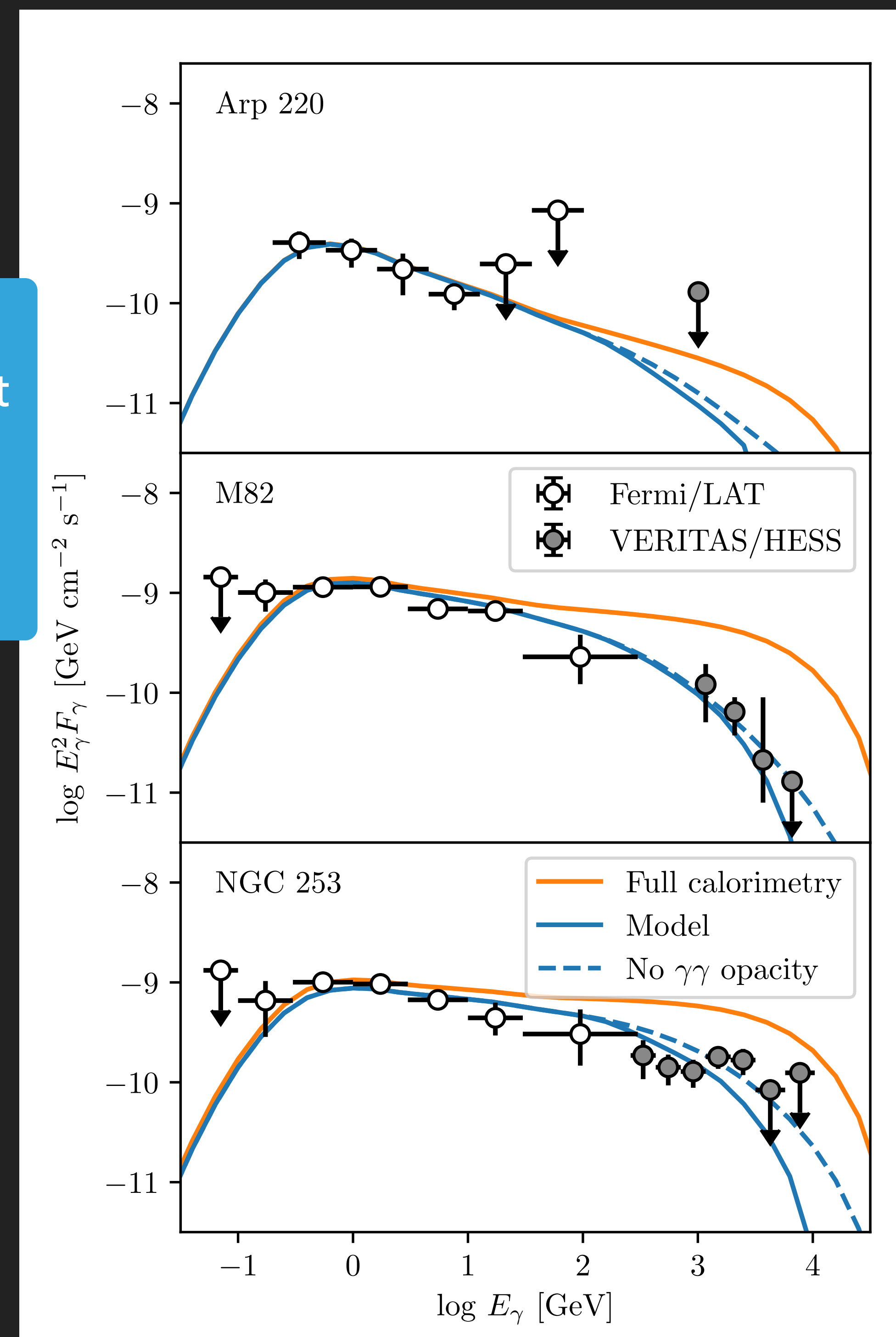


Deviation from constant at energies high enough that $v_{st} \gg v_{A,i}$



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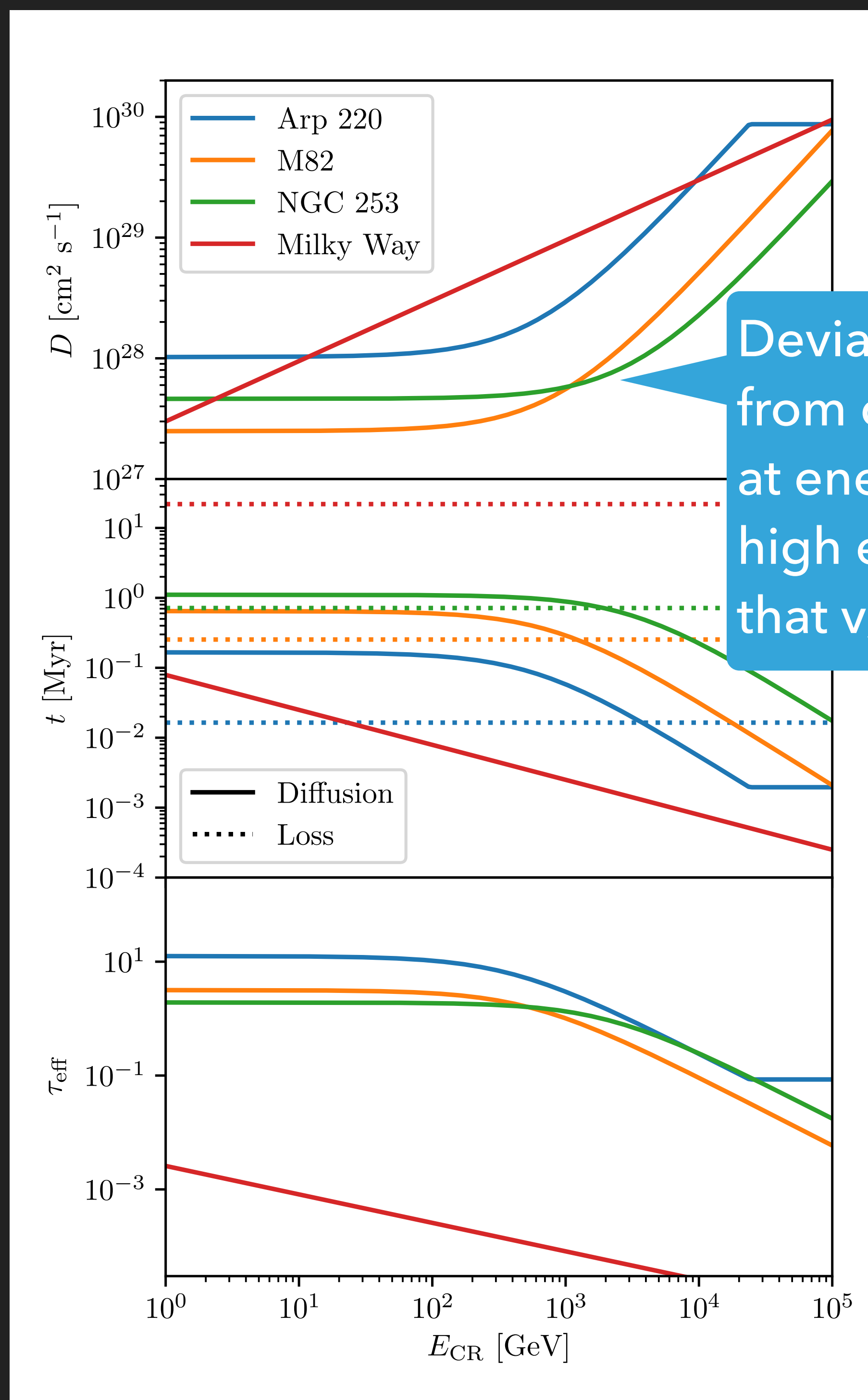

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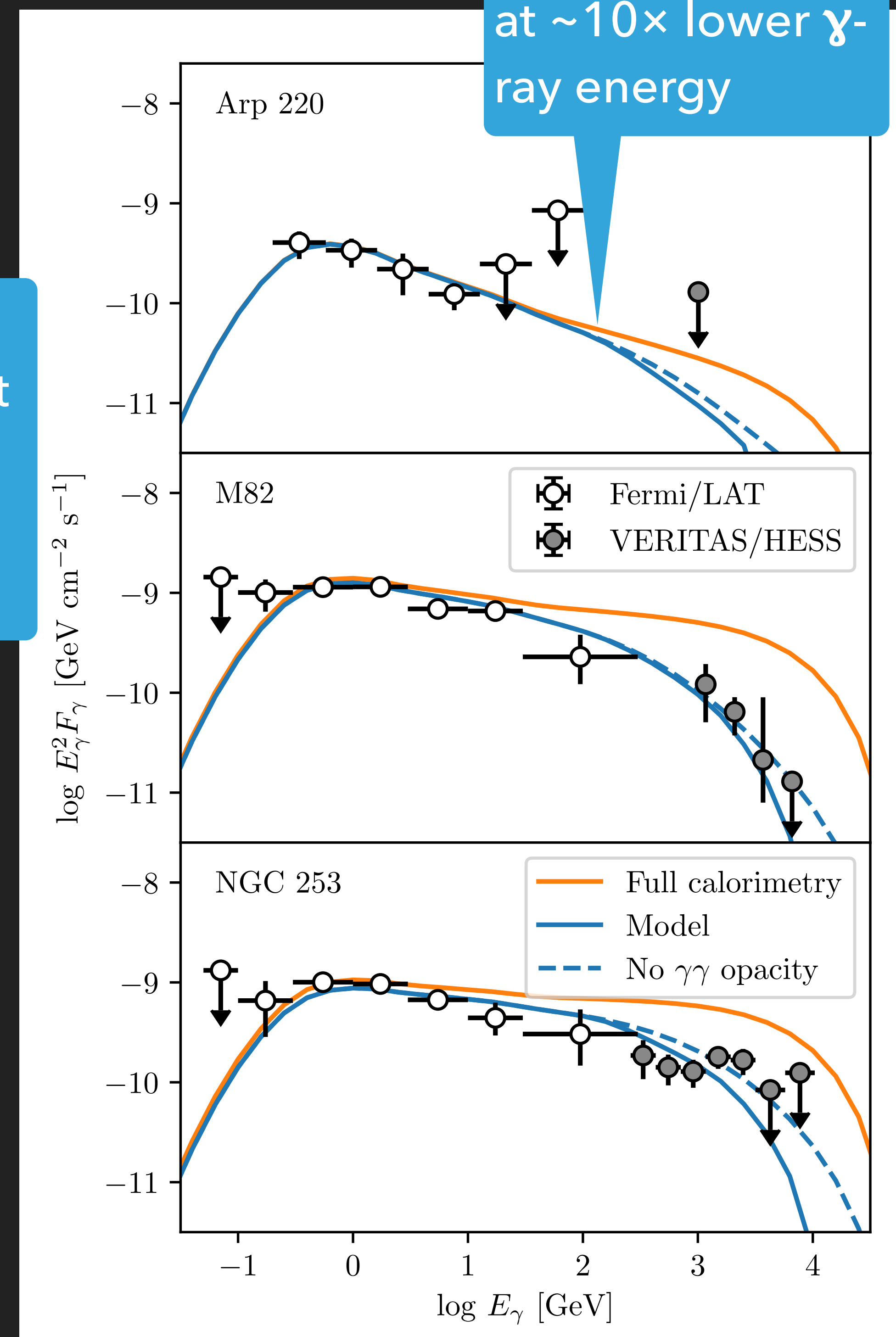

Corresponding deviation from full calorimetry at ~10× lower Ɣ-ray energy

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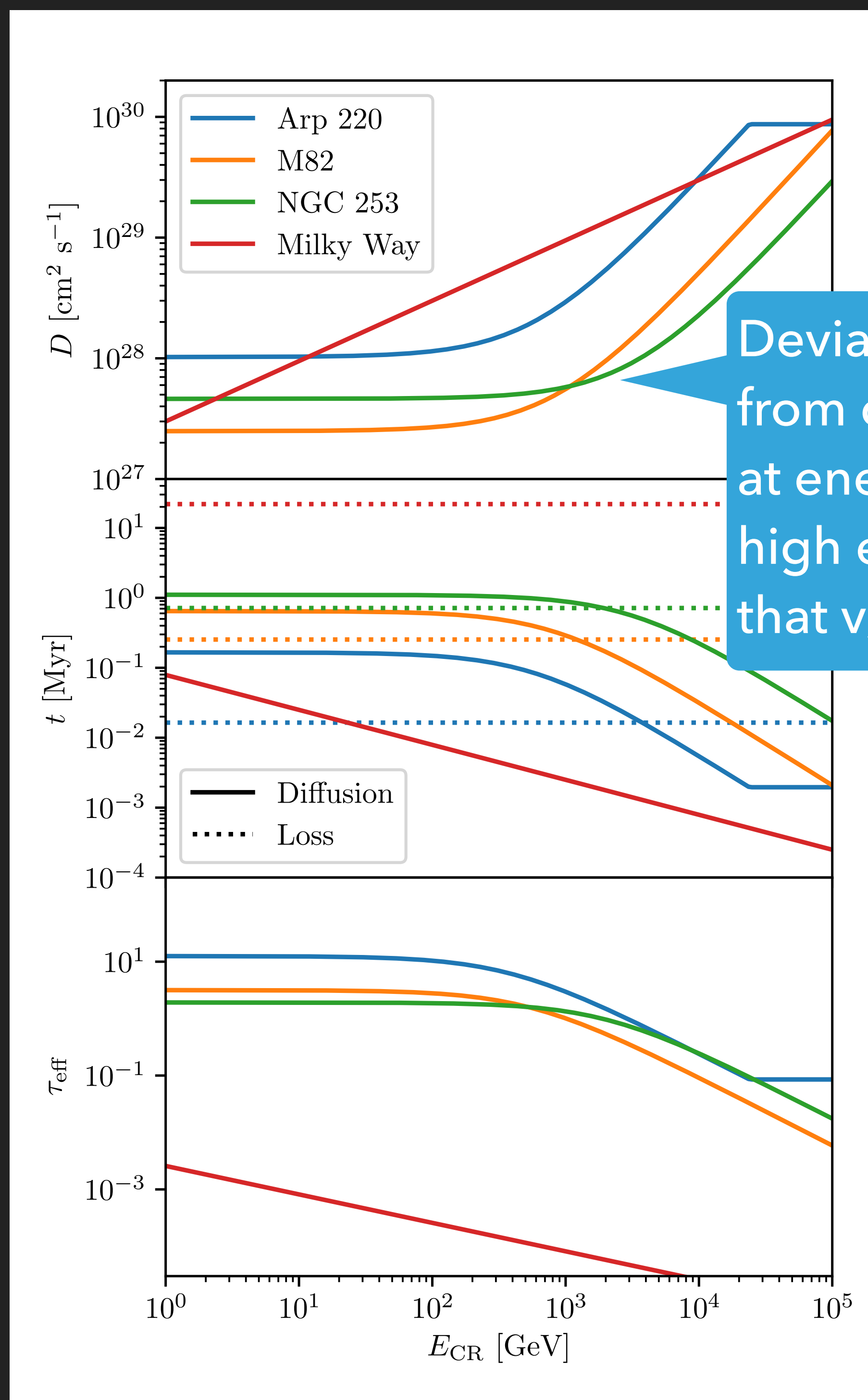

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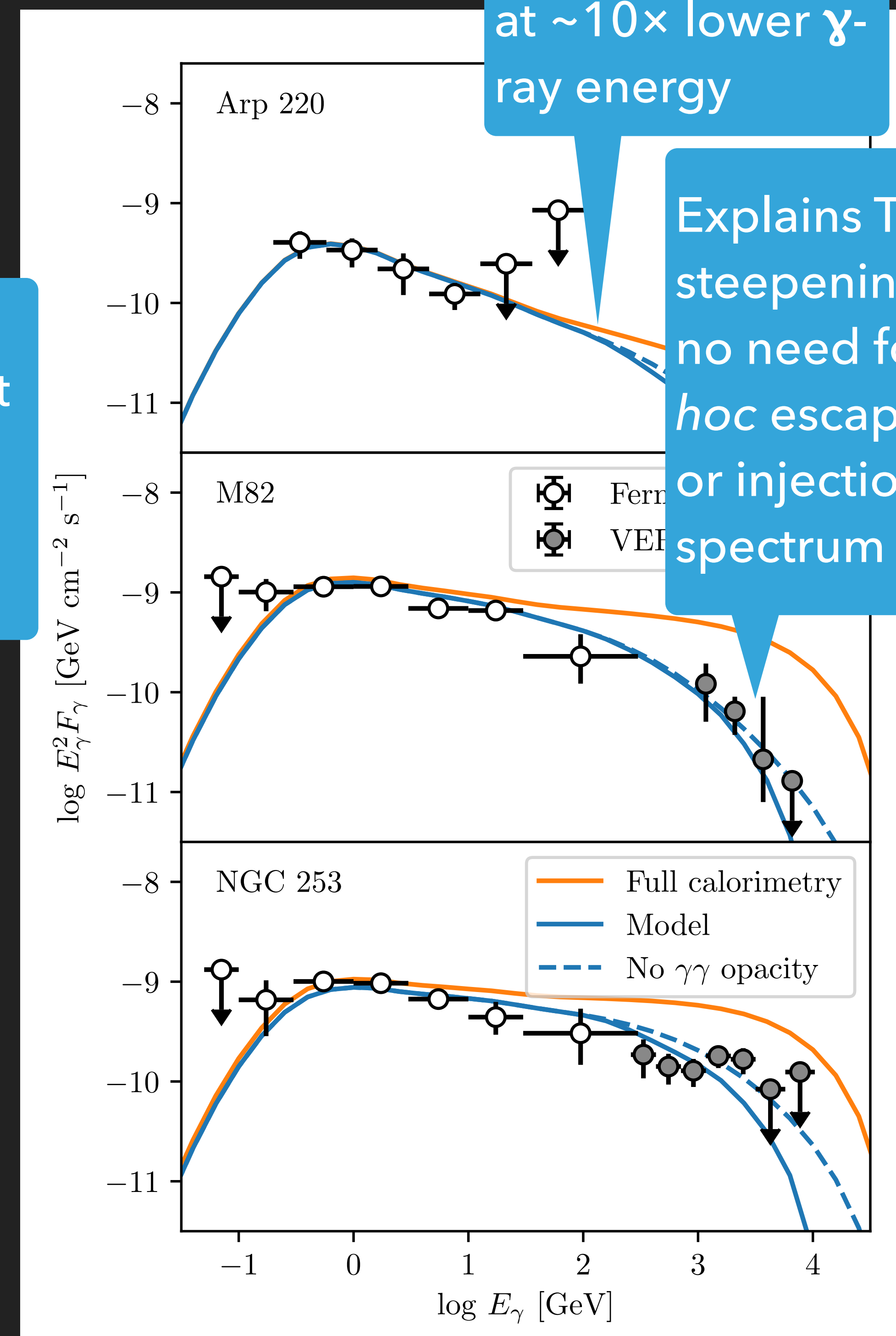

Corresponding deviation from full calorimetry at ~10× lower γ-ray energy

Explains TeV steepening with no need for *ad hoc* escape time or injection spectrum break

Left: typical audience at end of talk by theorist

CONCLUSIONS AND FUTURE WORK

SUMMARY I

- Role of CRs in galaxy evolution mostly set by microphysics of CR interaction with the star-forming, neutral ISM
- In this medium, ion-neutral decoupling means that
  - On small scales, CRs stream along field lines at $v_{A,i}$, independent of energy up to ~10 GeV - 1 TeV
  - On large scales, CR transport is via streaming + random walk of field lines in turbulent dynamo
- This picture naturally explains ɣ-ray spectral shapes of nearby starbursts, and why they differ from MW

OPEN QUESTIONS

- Low energy CRs and ionisation: ionisation in the natural ISM is dominated by sub-relativistic CRs. Are their dynamics different? Can we constrain CR ionisation rates in starbursts using γ-ray data from higher-energy CRs?
- Implications for spatial variation of CRs within MW, and for cosmological γ-ray background
- Can we detect high-energy breaks in γ-ray spectra in more galaxies using CTA, and, if so, do they match the predictions of this model?

Left: for no particular reason, here is a baby echidna

THE END