Australian National University

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COSMIC RAYS AND THEIR ROLE IN GALAXY FORMATION

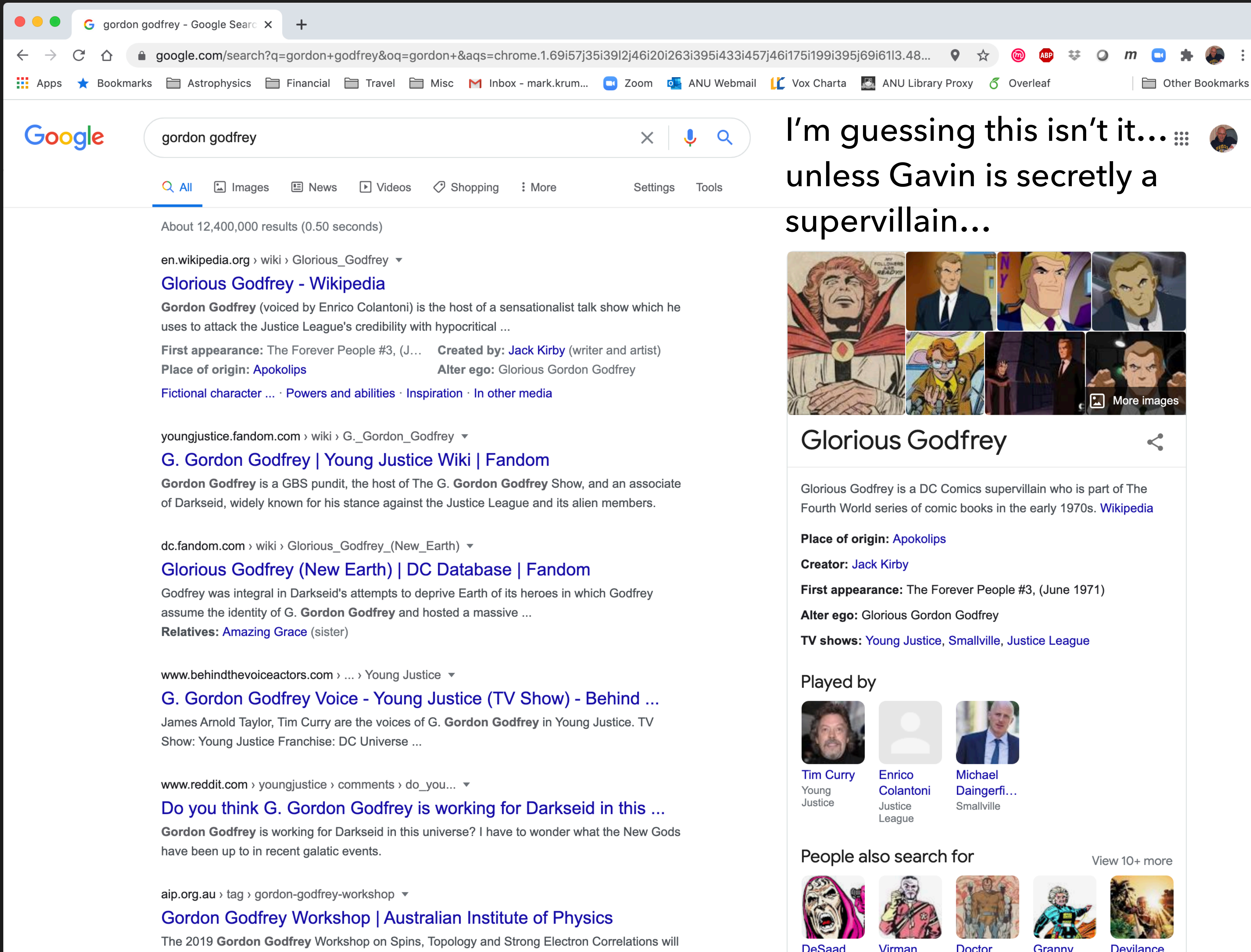
COLLABORATORS AND REFERENCES

- Collaborators:
  - Roland Crocker, Matt Roth (ANU)
  - Todd Thompson (Ohio State)
  - Silvia Celli (INFN)
  - Alex Lazarian, Siyao Xu (U. Wisconsin)
- References:
  - Krumholz, Crocker, Xu, Lazarian, Bedwell-Wilson, & Rosevear, 2020, MNRAS, 493, 2817
  - Crocker, Krumholz, & Thompson, 2020, submitted to MNRAS, arXiv:2006.15819 and arXiv:2006.15821
  - Roth, Krumholz, Crocker, & Celli, 2020, submitted to Nature

THE MOST IMPORTANT QUESTION

WHO IS GORDON GODFREY?

I'm guessing this isn't it… unless Gavin is secretly a supervillain…

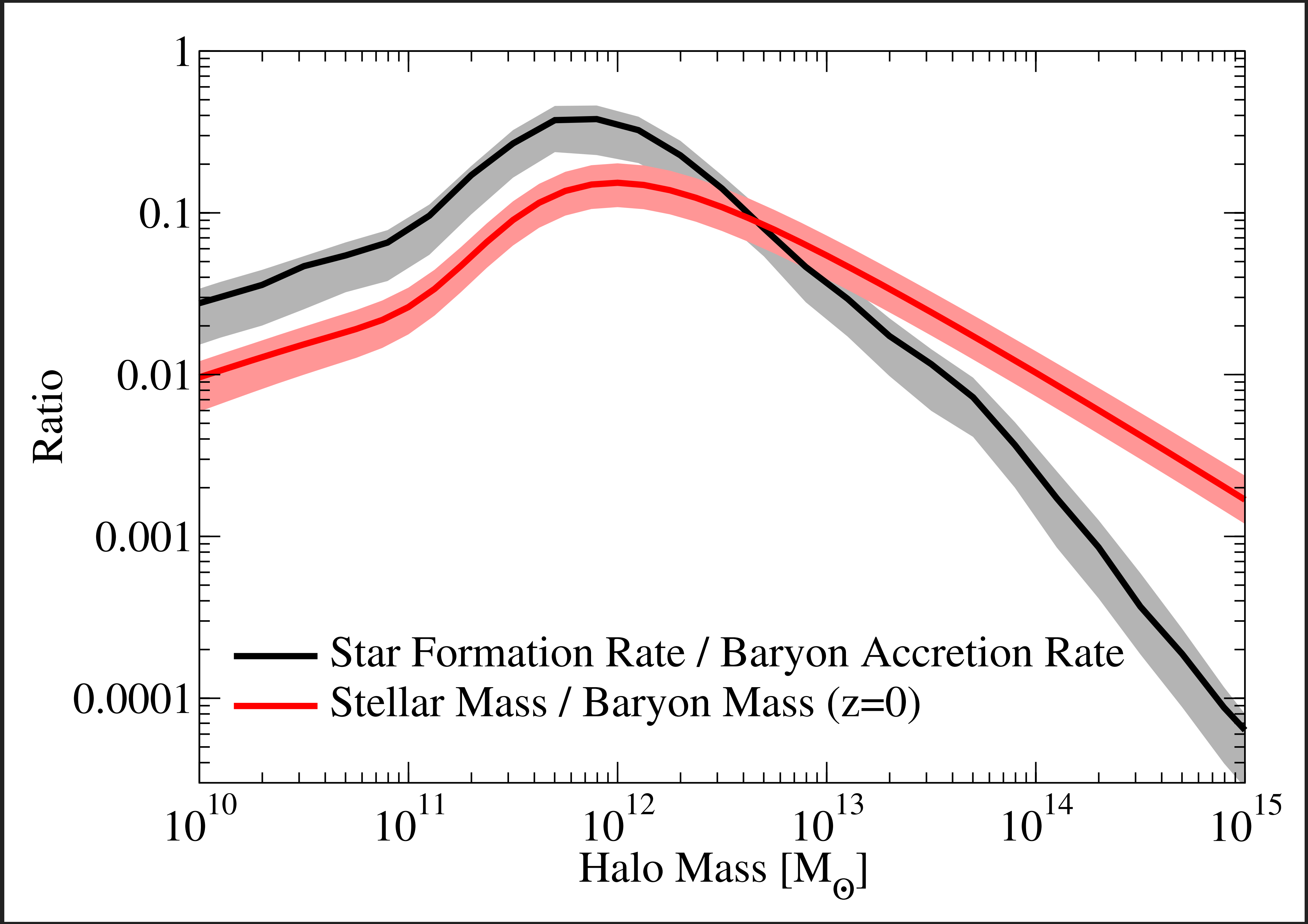


OUTLINE

- Introduction and motivation
- CR transport in star-forming gas
  - Magnetohydrodynamics of the neutral ISM
  - CR streaming and diffusion
- Models and tests
  - γ-ray spectra of local starbursts
  - The diffuse isotropic γ-ray background
  - CR stability limits and the star formation law
- Conclusions and future work

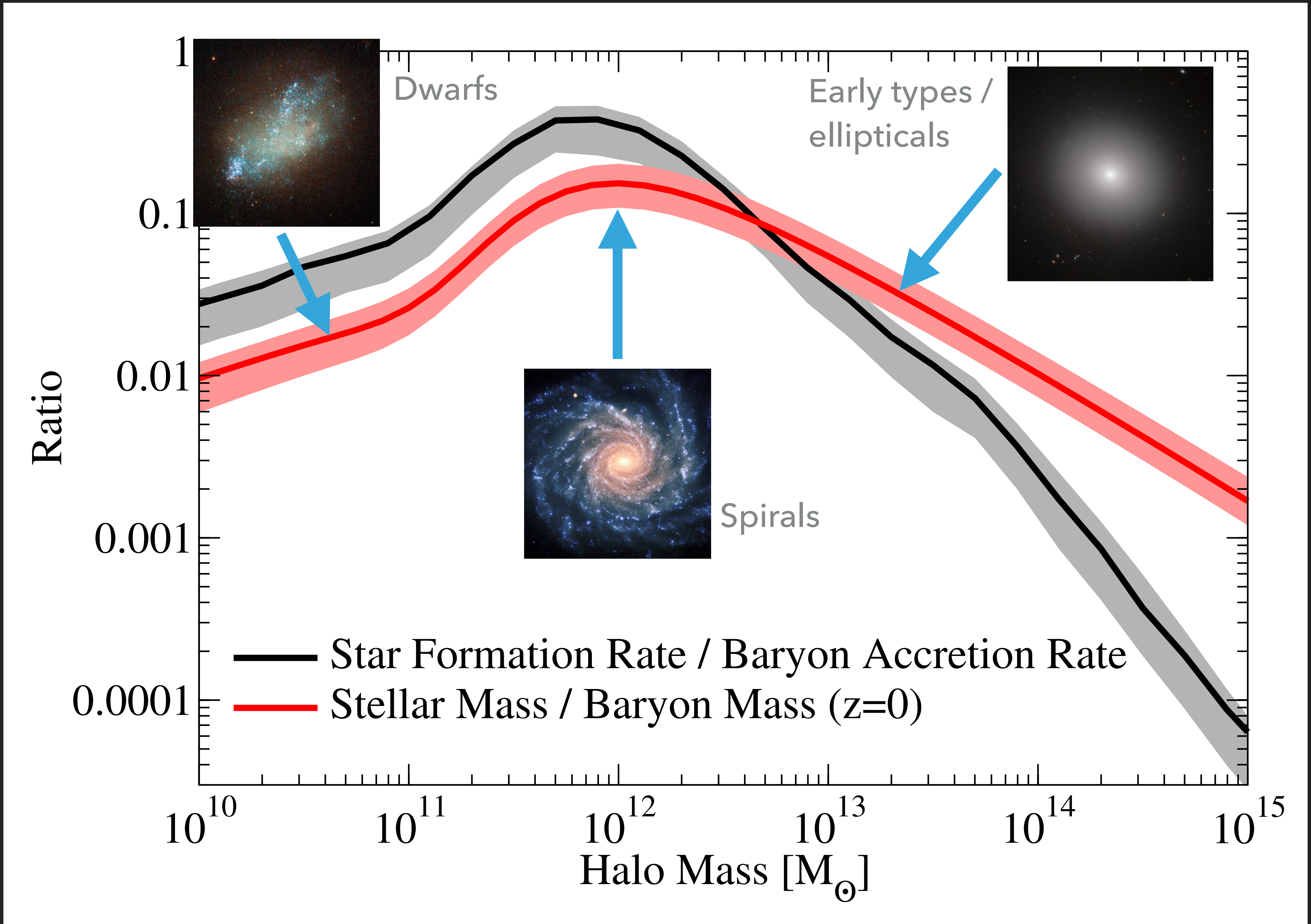
Left: theorist attempting to interpret observations

INTRODUCTION AND MOTIVATION



GALAXY FORMATION IS INEFFICIENT

Behroozi+ 2013



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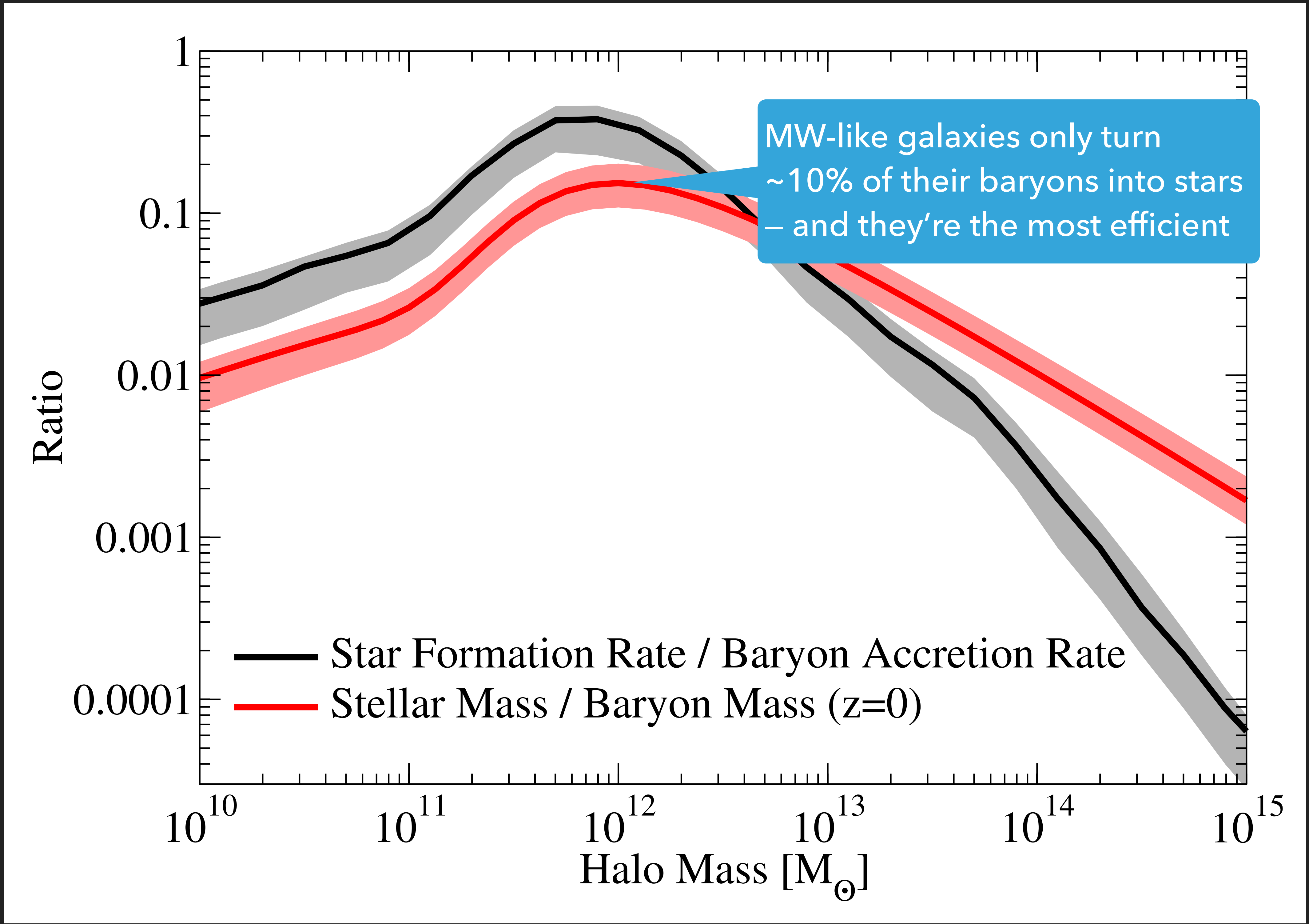

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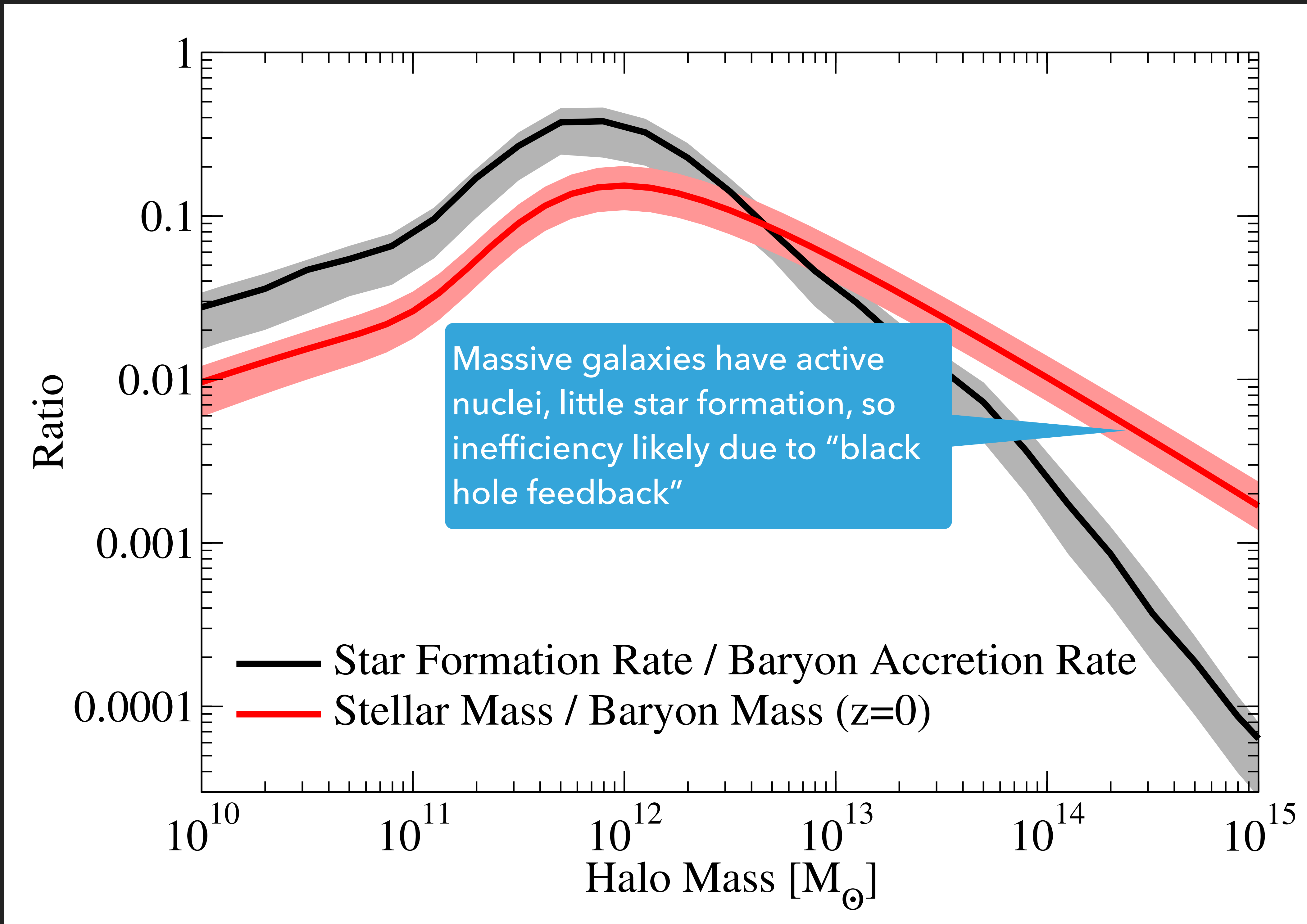

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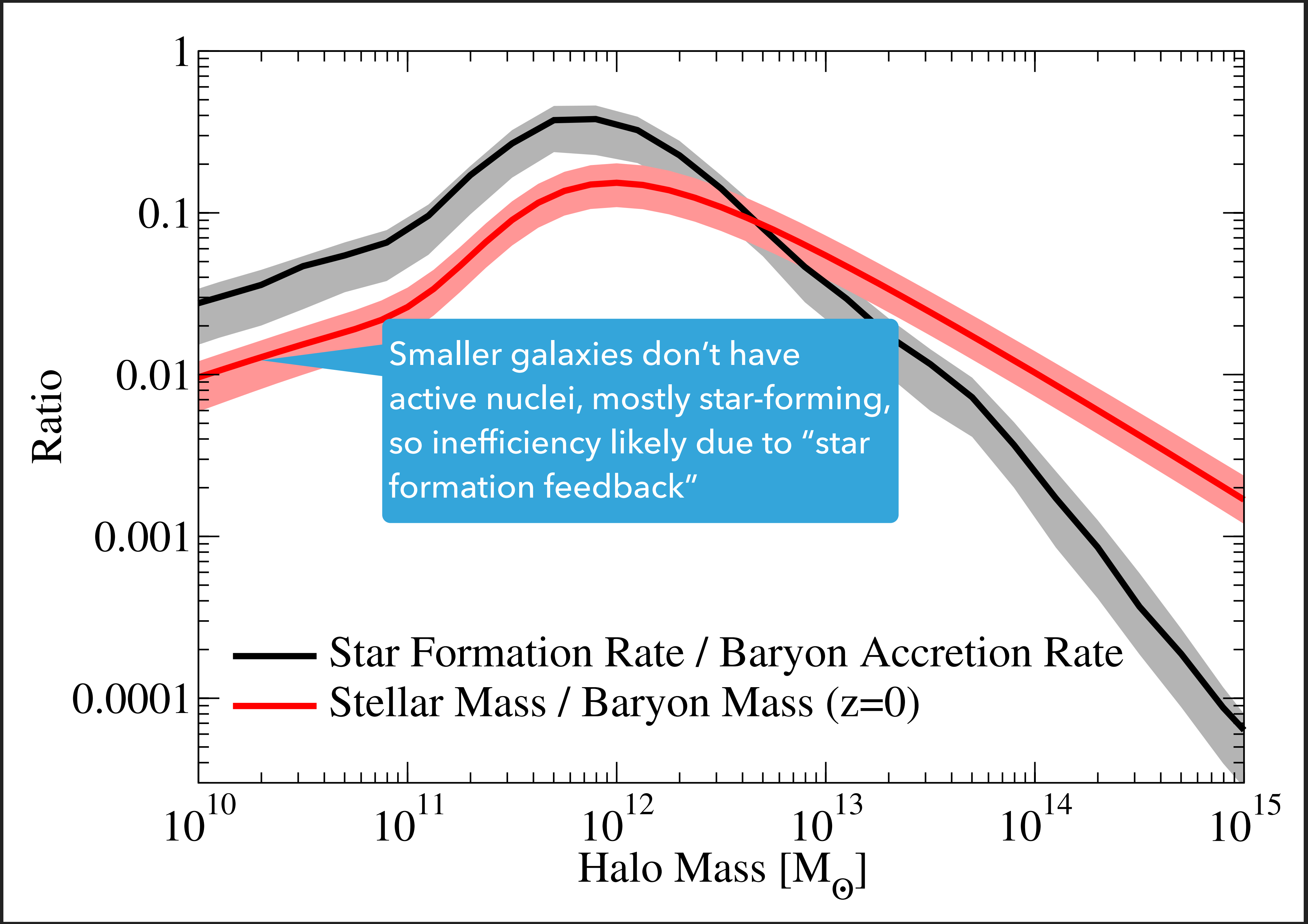

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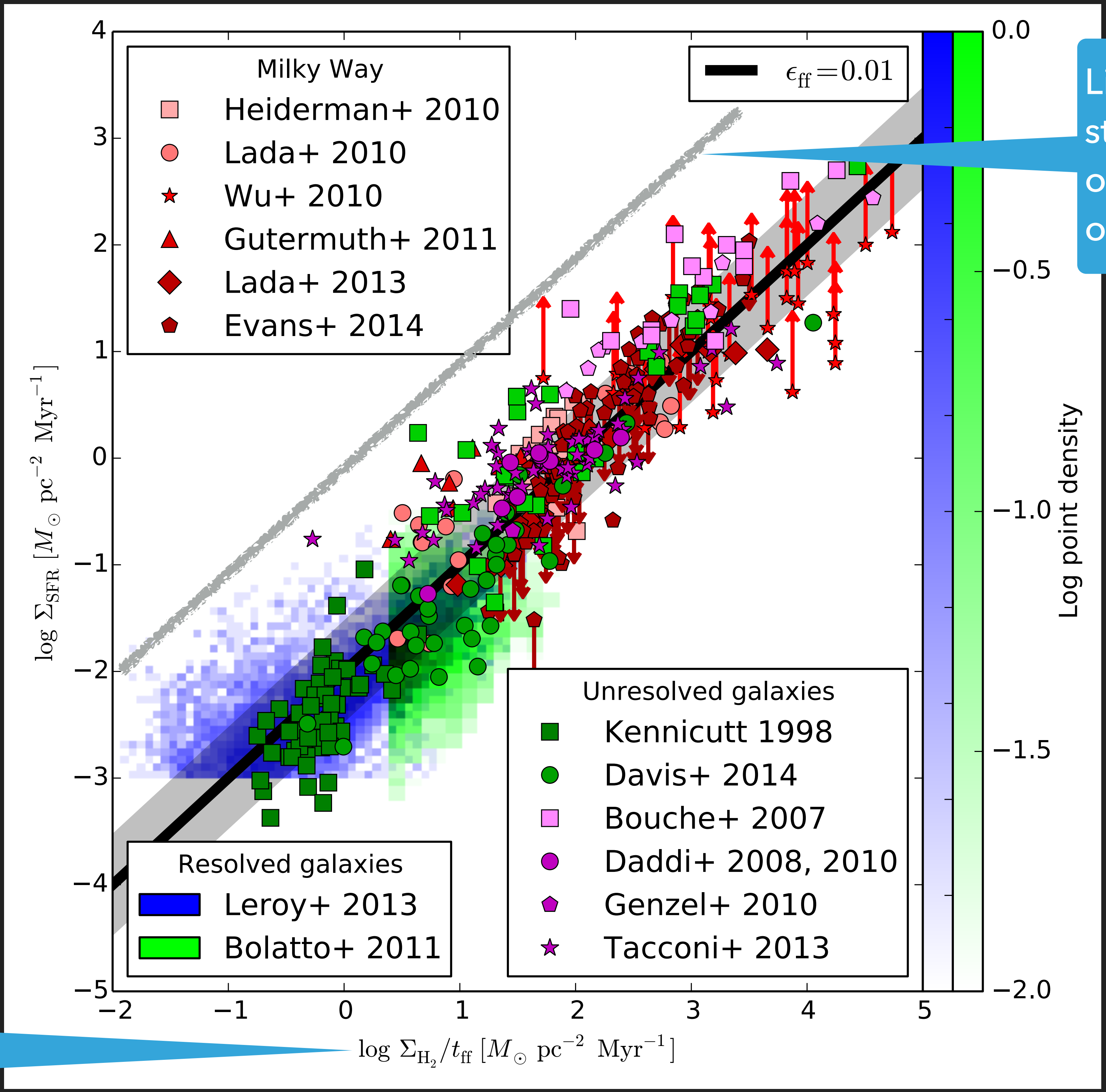


Limit of "efficient" star formation: 100% of gas consumed in one dynamical time

Low efficiency even for cold, molecular gas!

STAR FORMATION IS INEFFICIENT

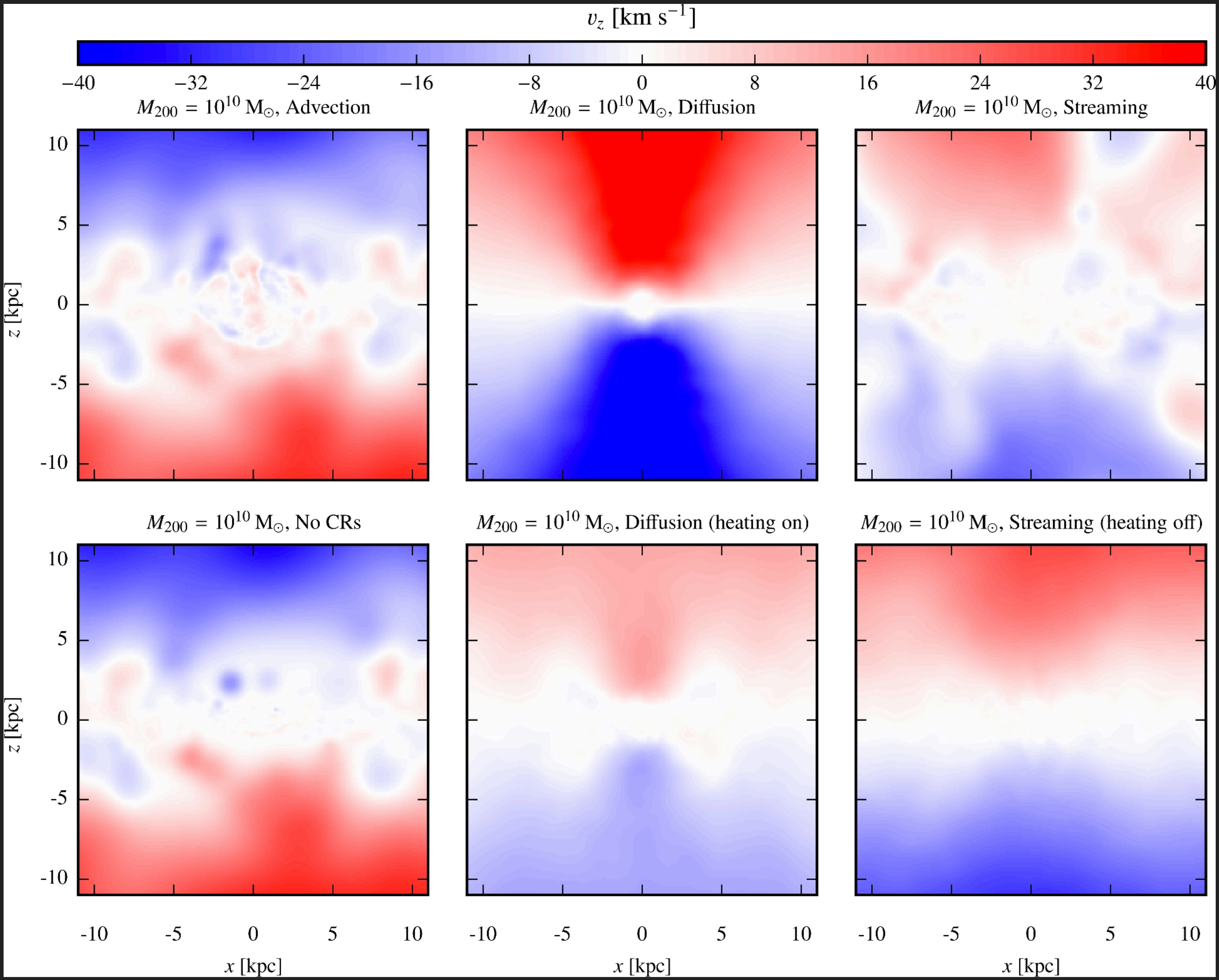
Krumholz 2014

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 ~3 $\times 10^5\ M_\odot$ km s^{-1} (Gentry+ 2017)
- Open question whether this is enough to explain efficiency

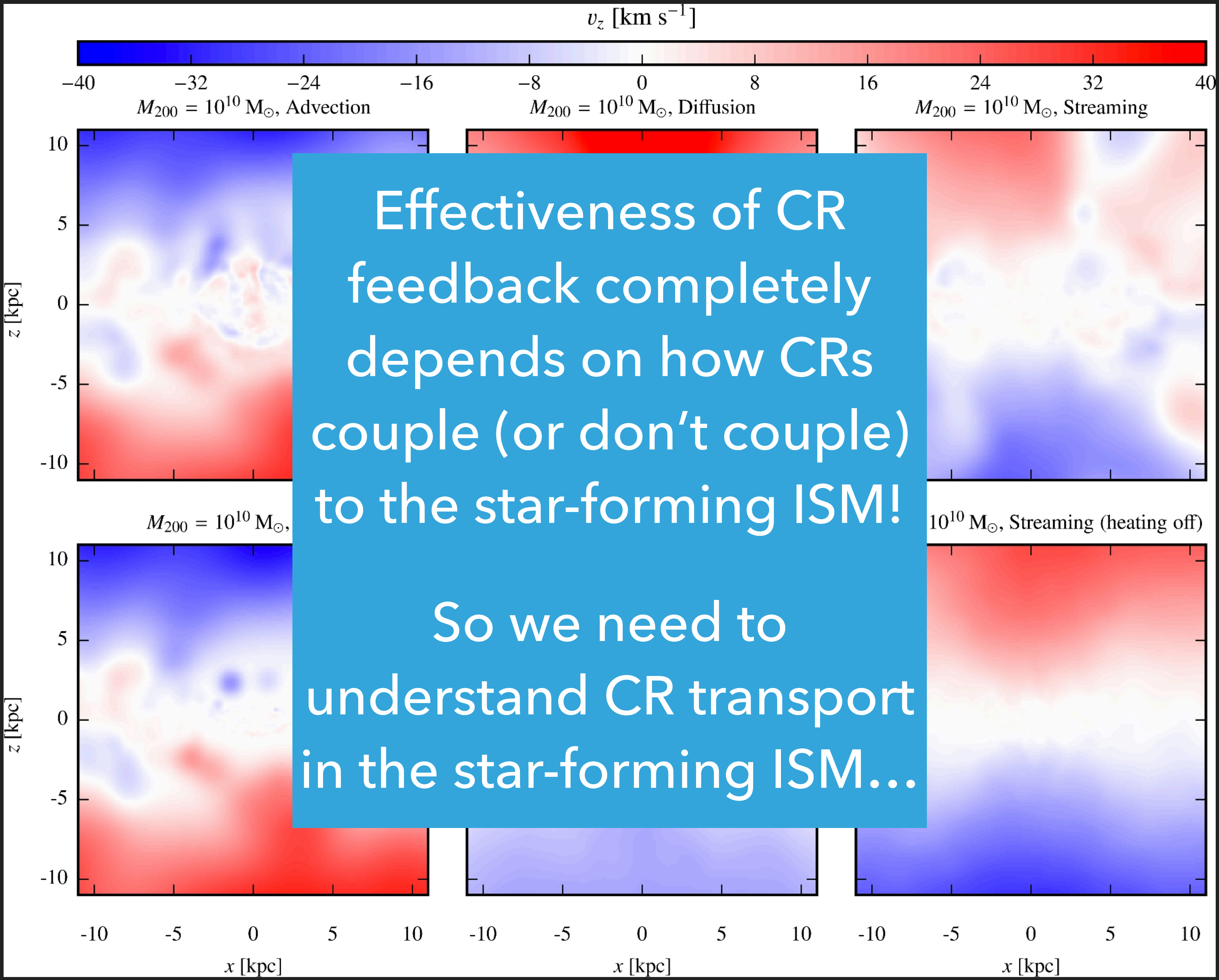
WHY THINK ABOUT COSMIC RAYS?

- 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

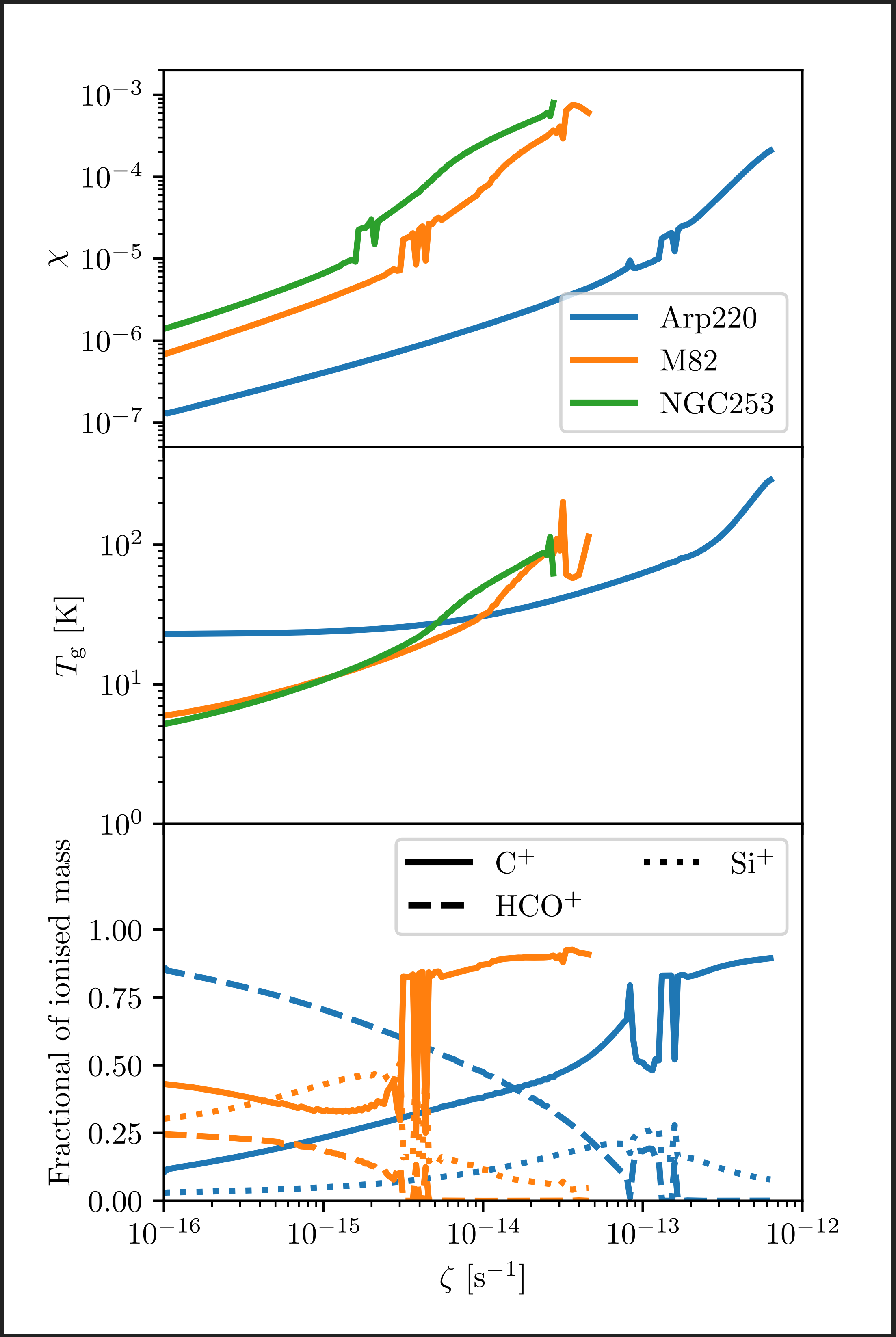
- CRs gyrate around magnetic field lines, try to follow them; gyro radius for a 1 GeV CR is $r_g \sim 0.001$ AU $\sim 10^{-7}$ pc
- Alfvén waves with $\lambda \sim r_g$ scatter CRs, changing pitch angle and travel direction; scattering MFP is small
- Waves can be either extrinsic (generated by turbulent 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 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 both local starburst galaxies and normal galaxies at $z \gtrsim 2$ (epoch of peak star formation)

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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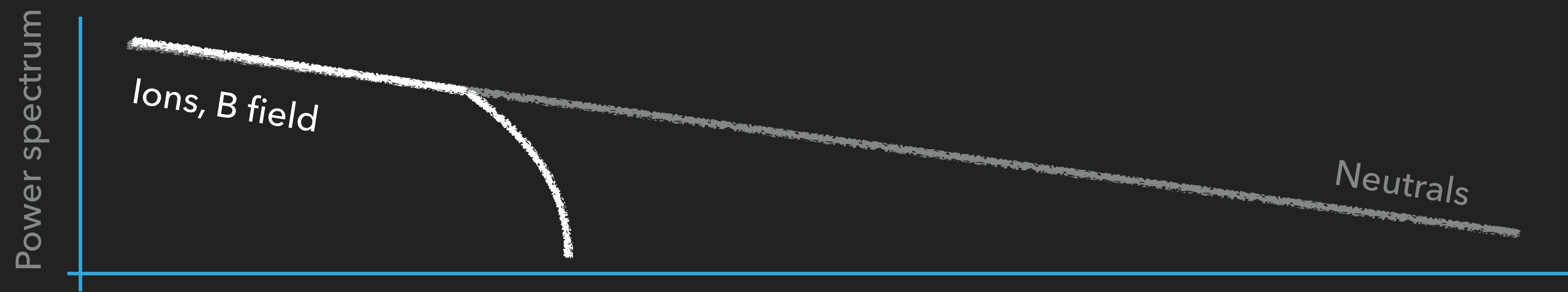

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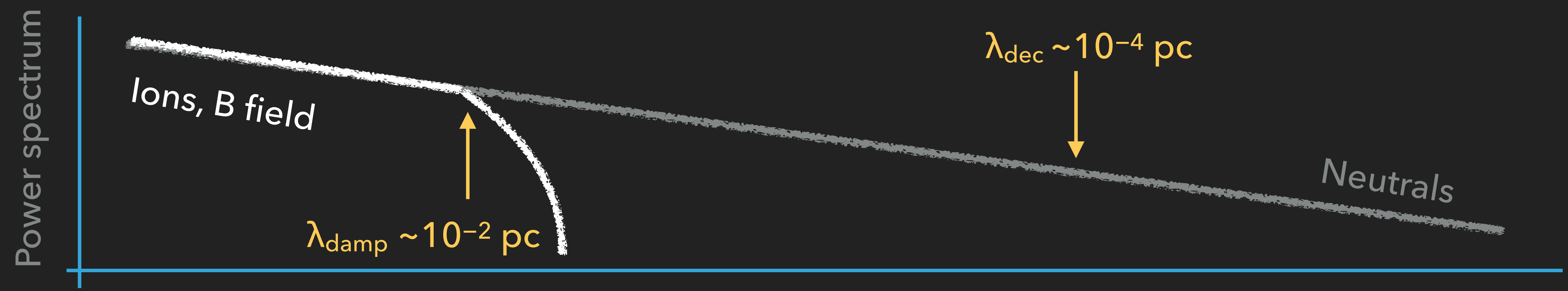

Coupled regime	Damping regime	Decoupled regime
$v \ll v_{ni} \ll v_{in}$	$v_{ni} \ll v \ll v_{in}$	$v_{ni} \ll v_{in} \ll v$
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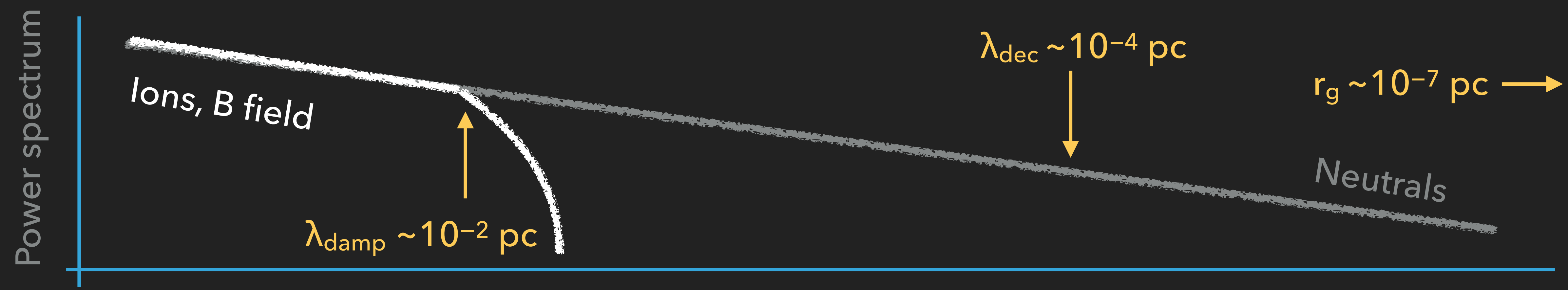

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IMPLICATIONS OF ION-NEUTRAL DAMPING

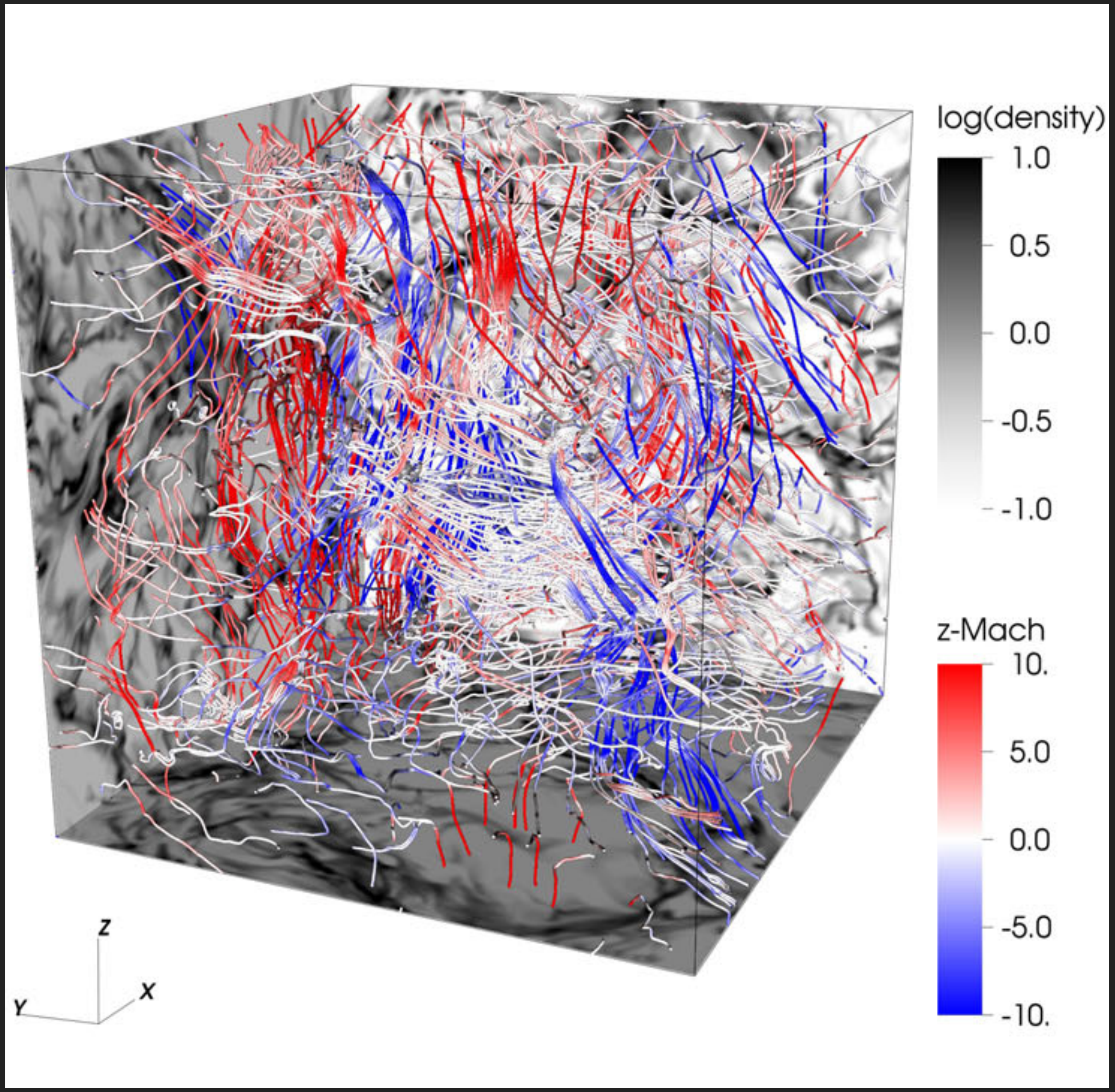
- CRs can only interact with self-generated turbulence, which only scatters them along field lines, not across them
- Level of turbulence set by competition between streaming instability growth and damping by ion-neutral collisions:

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

- Solve for streaming speed, find v_{st} / $v_{A,i}$ – 1 ≪ 1
  - For E_{CR} ≲ TeV in starburst-like H_2-dominated ISM
  - For E_{CR} ≲ 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 $M_A \sim 2$
- 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

MODELS AND TESTS

Left: typical astrophysical model… Australian version

MODELS AND TESTS

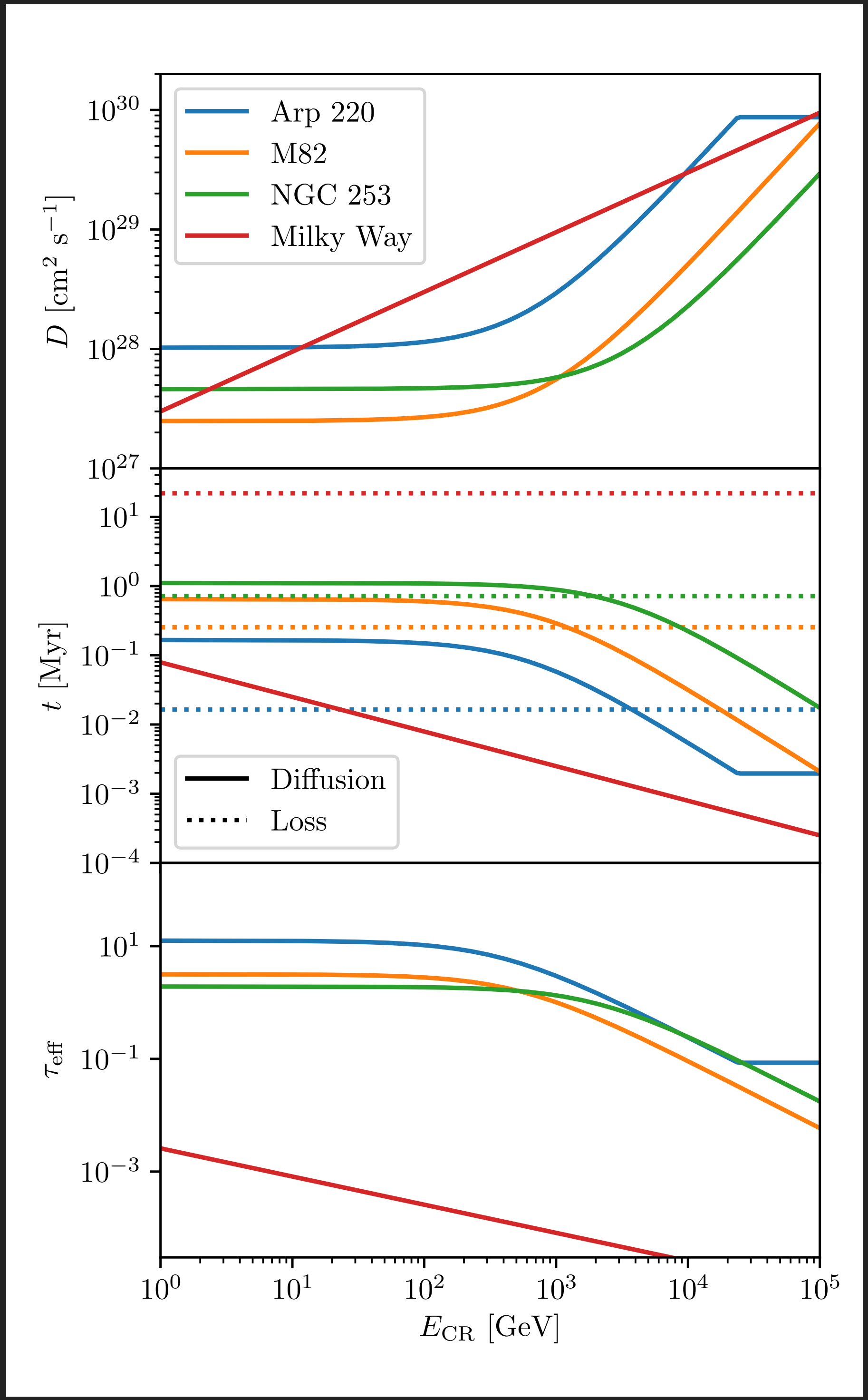
DIFFUSION MODEL FOR GALAXY SPECTRA

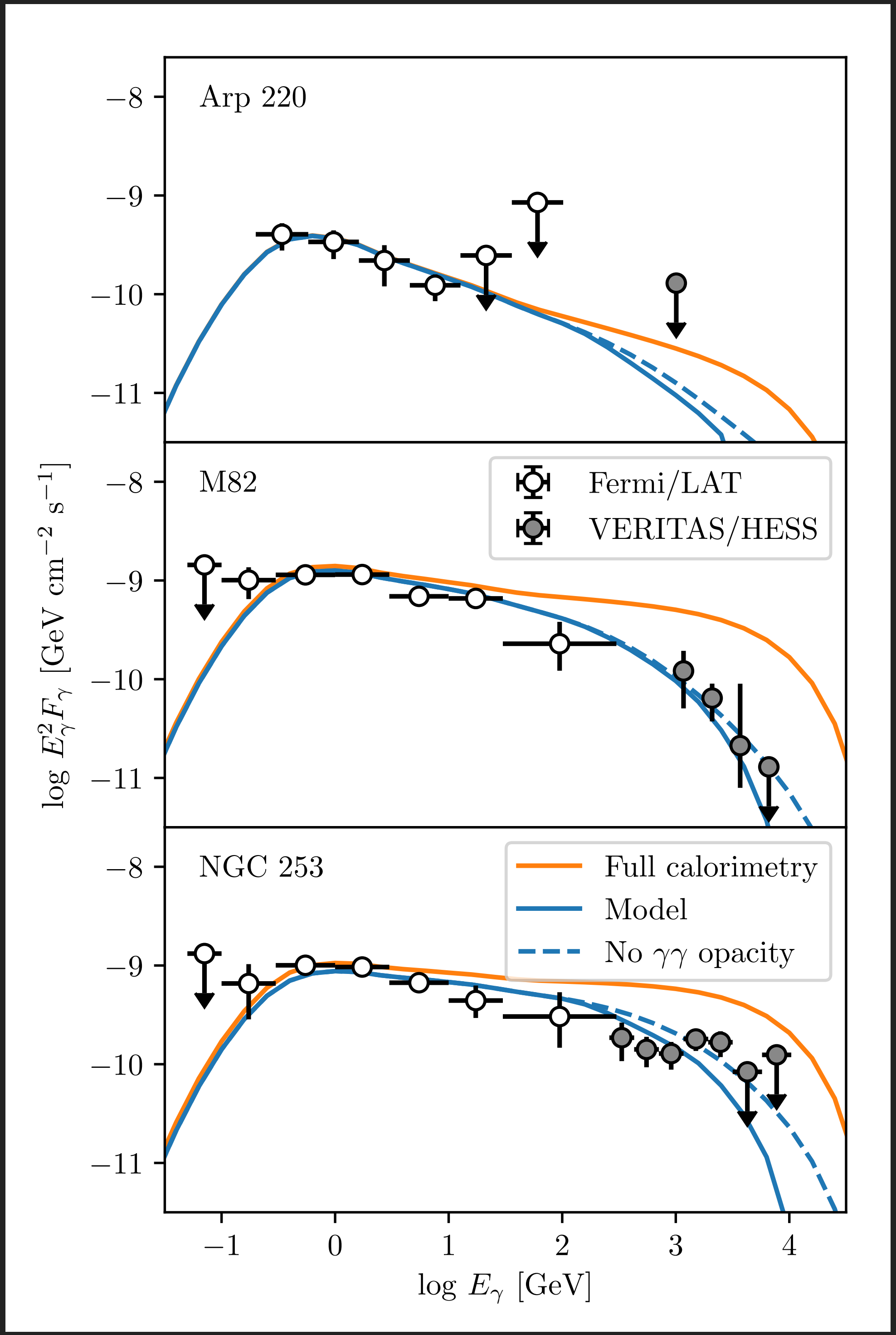
- Test by comparing to γ-ray spectra of starburst galaxies
- Simple diffusion model: $\frac{d}{dz}\left(-\kappa\frac{dU}{dz}\right) = -\frac{U}{t_{pp}} \approx -n\sigma_{pp}\eta_{pp}cU$
- Assuming CRs injected at z = 0 into exponential gas disc with scale height h, fraction of CRs that produce γ-rays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

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

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

PREDICTED OPTICAL DEPTHS AND SPECTRA





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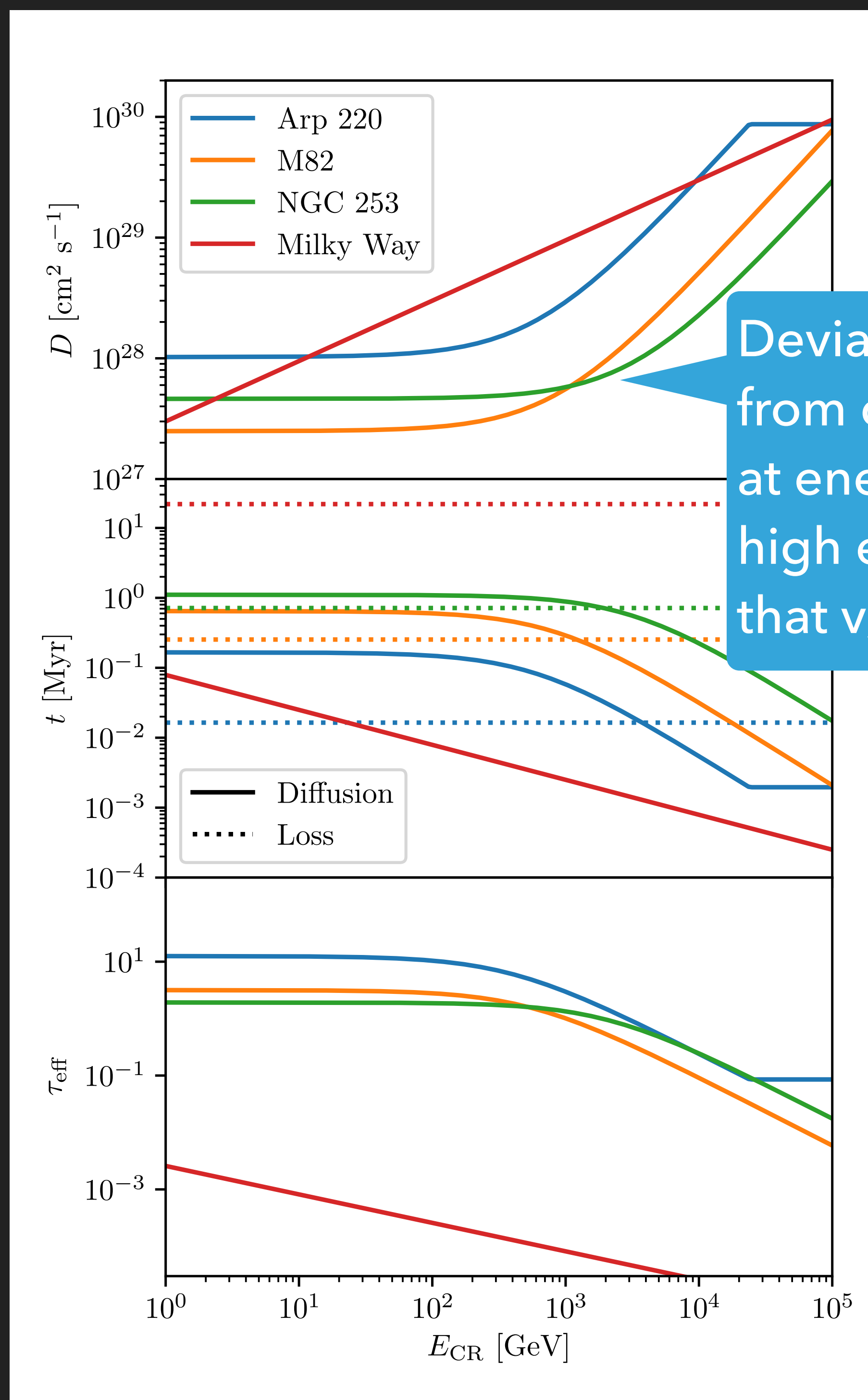
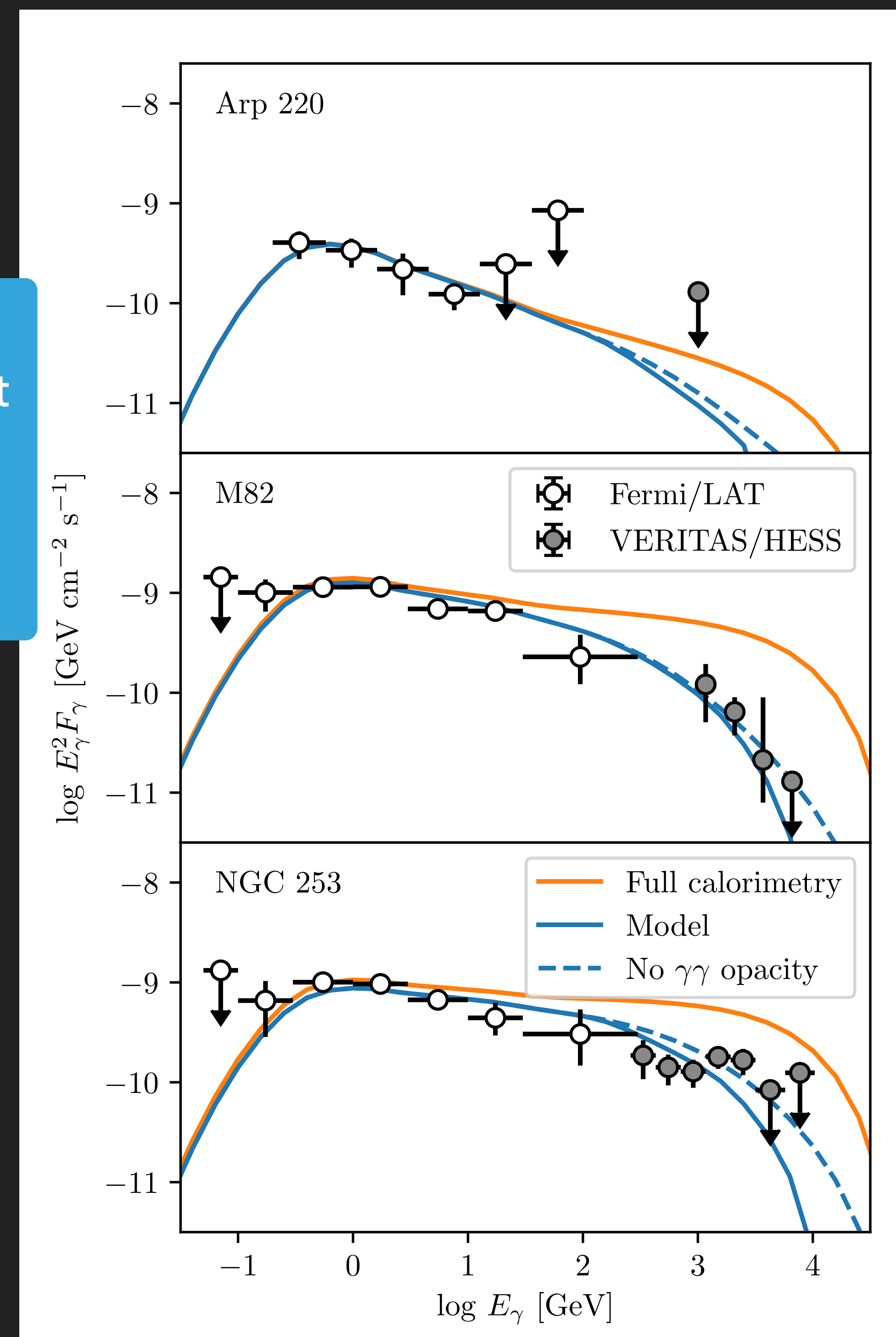


Deviation from constant at energies high enough that $v_{st} \gg v_{A,i}$



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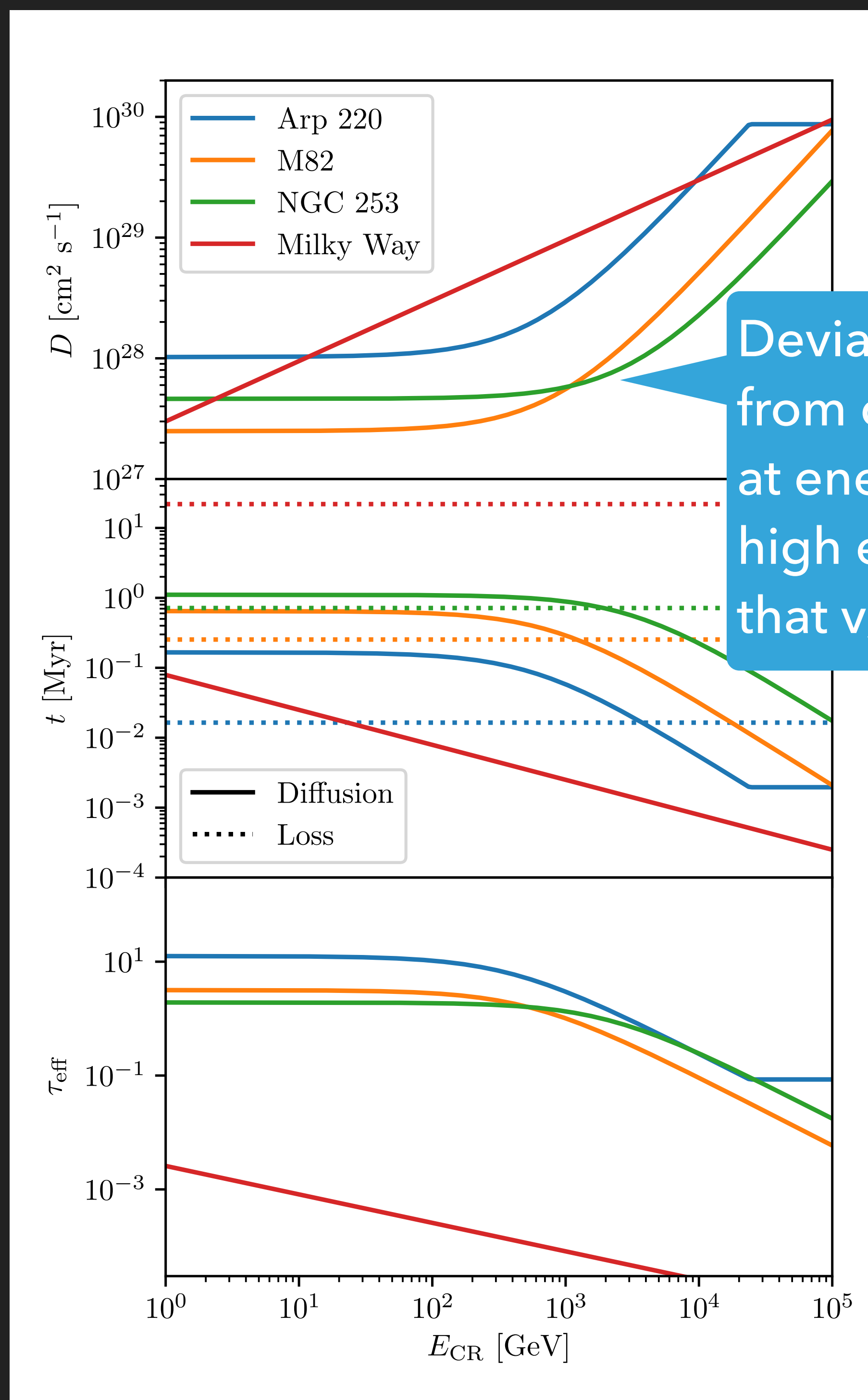

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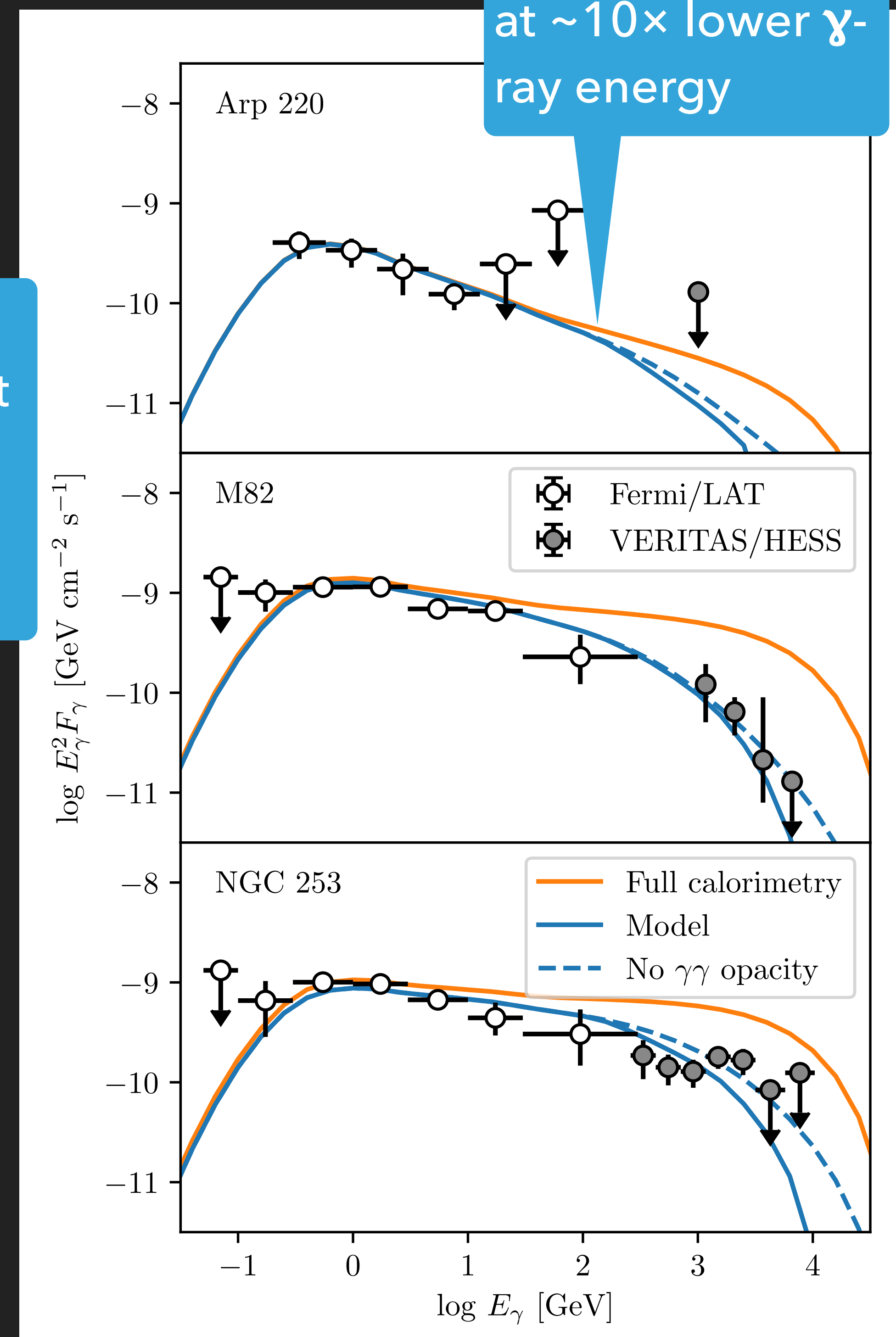

Corresponding deviation from full calorimetry at ~10× lower ɣ-ray energy

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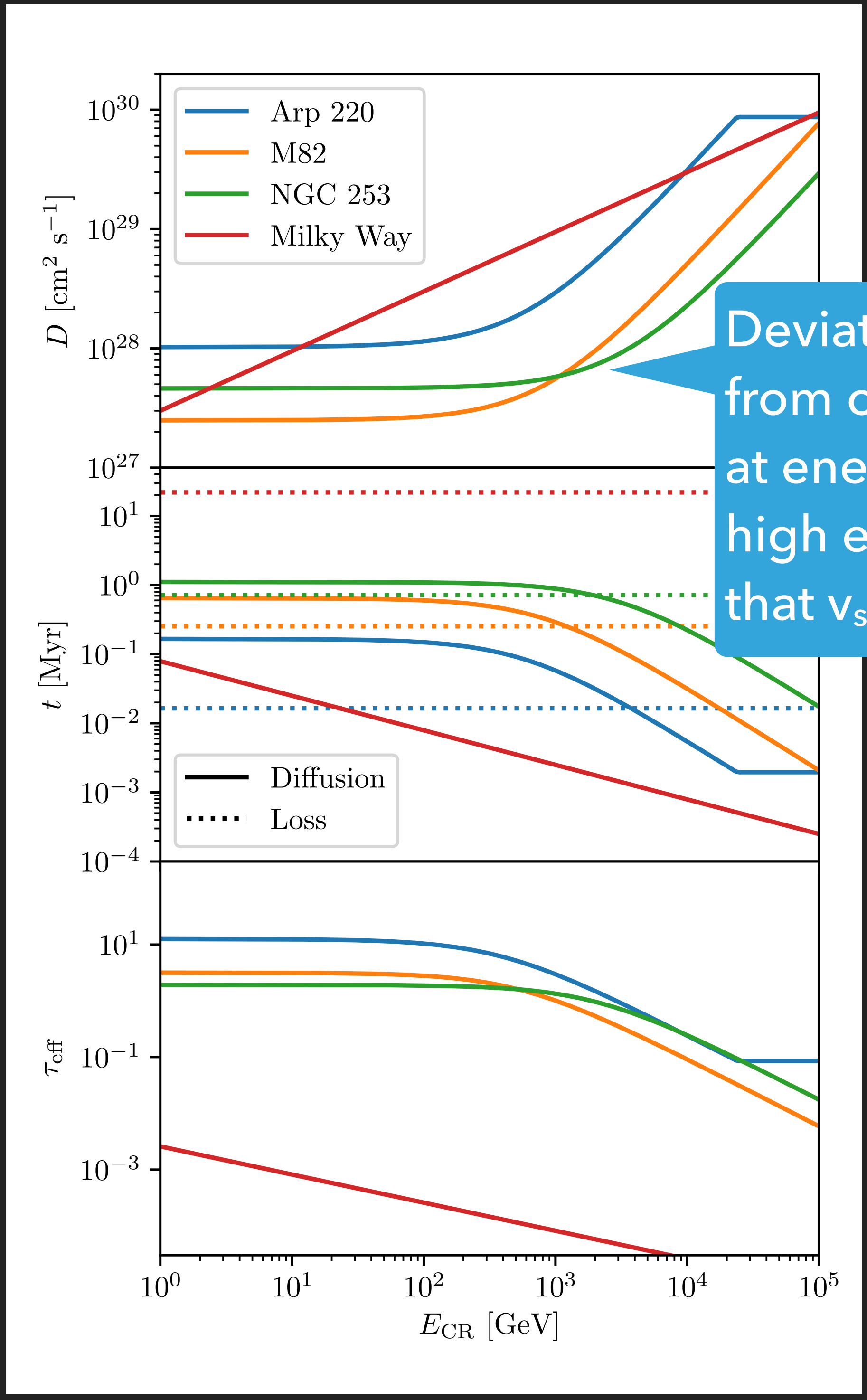

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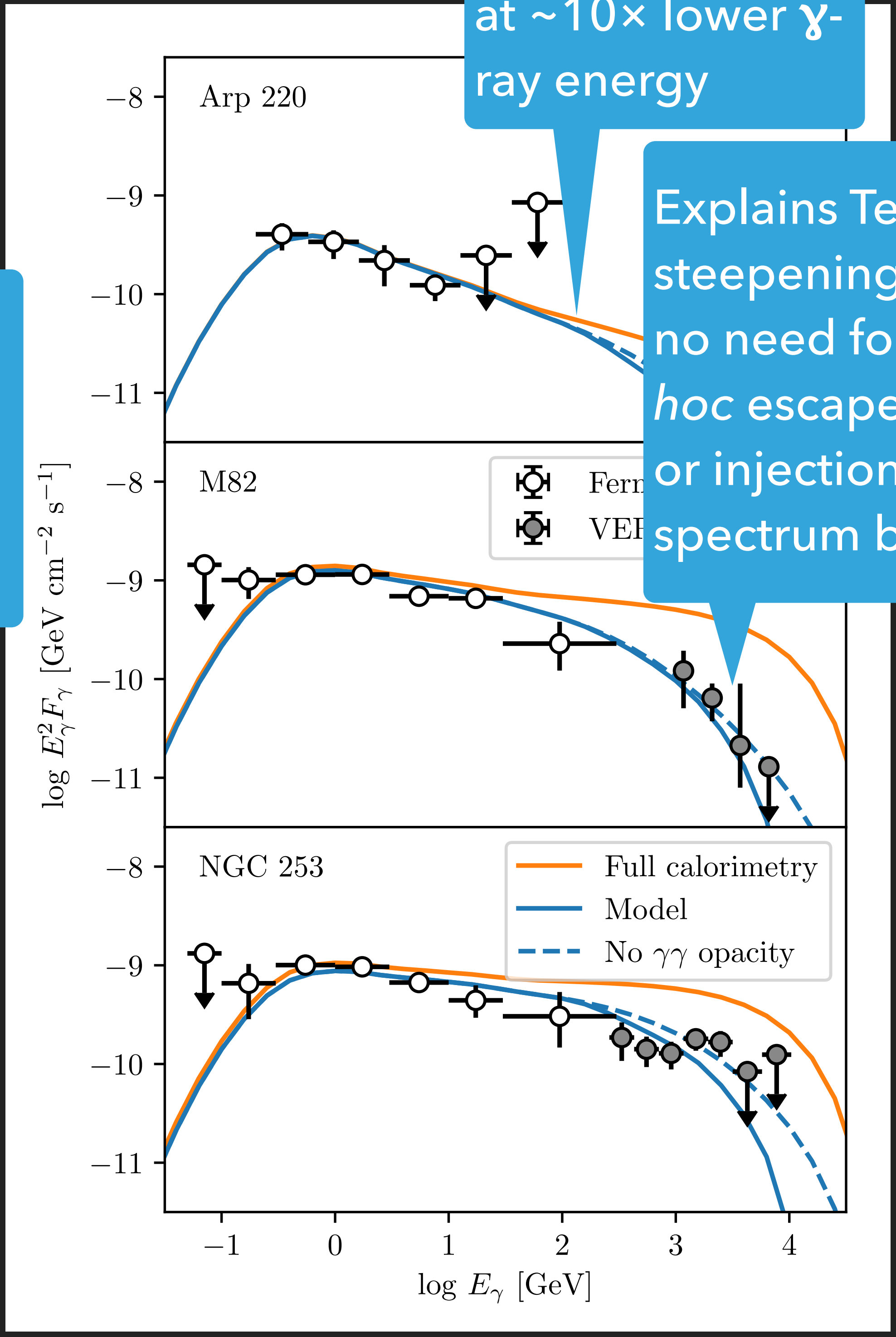
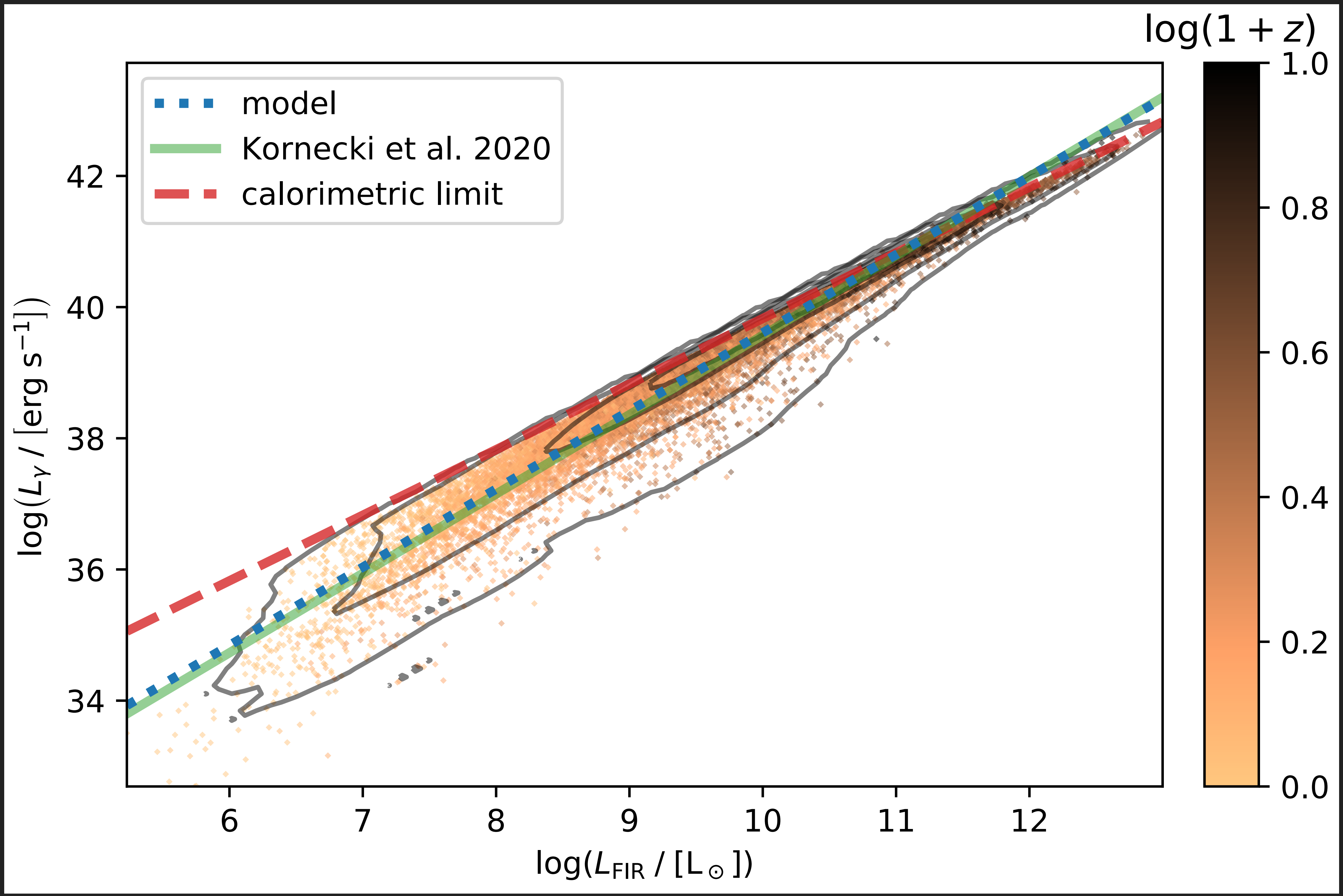


Corresponding deviation from full calorimetry at ~10× lower Ɣ-ray energy

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

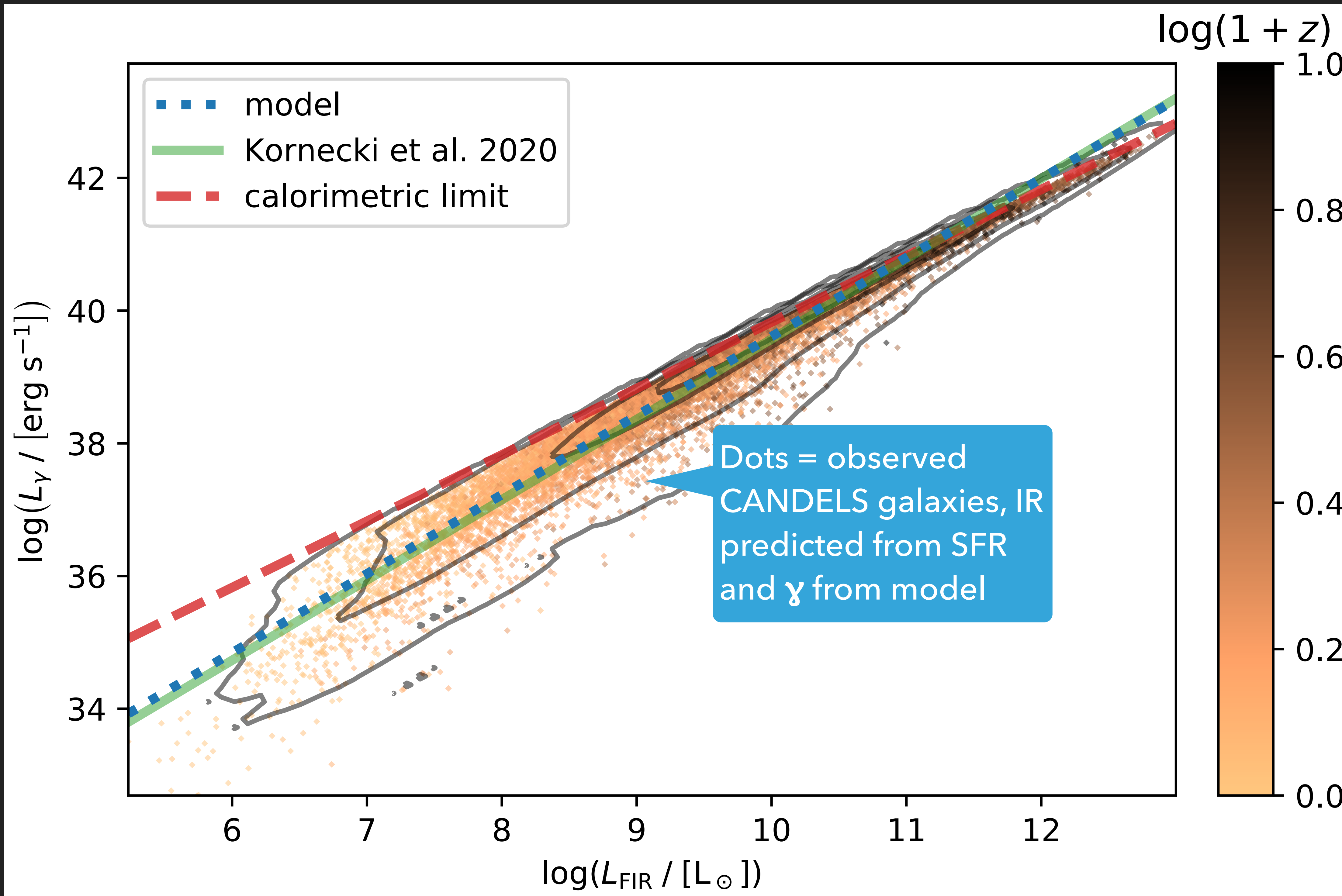
APPLICATION TO THE STAR-FORMING GALAXY POPULATION

- Only ~10 SFGs detected individually in γ-rays, but very complete surveys out to z > 2 exist in optical / UV / IR (e.g., CANDELS)
- Can apply model to predict γ-ray spectra of these galaxies, compute statistics of population and contribution to unresolved γ-ray background



THE IR-ɣ RELATION

Roth+ 2020



THE IR-γ RELATION

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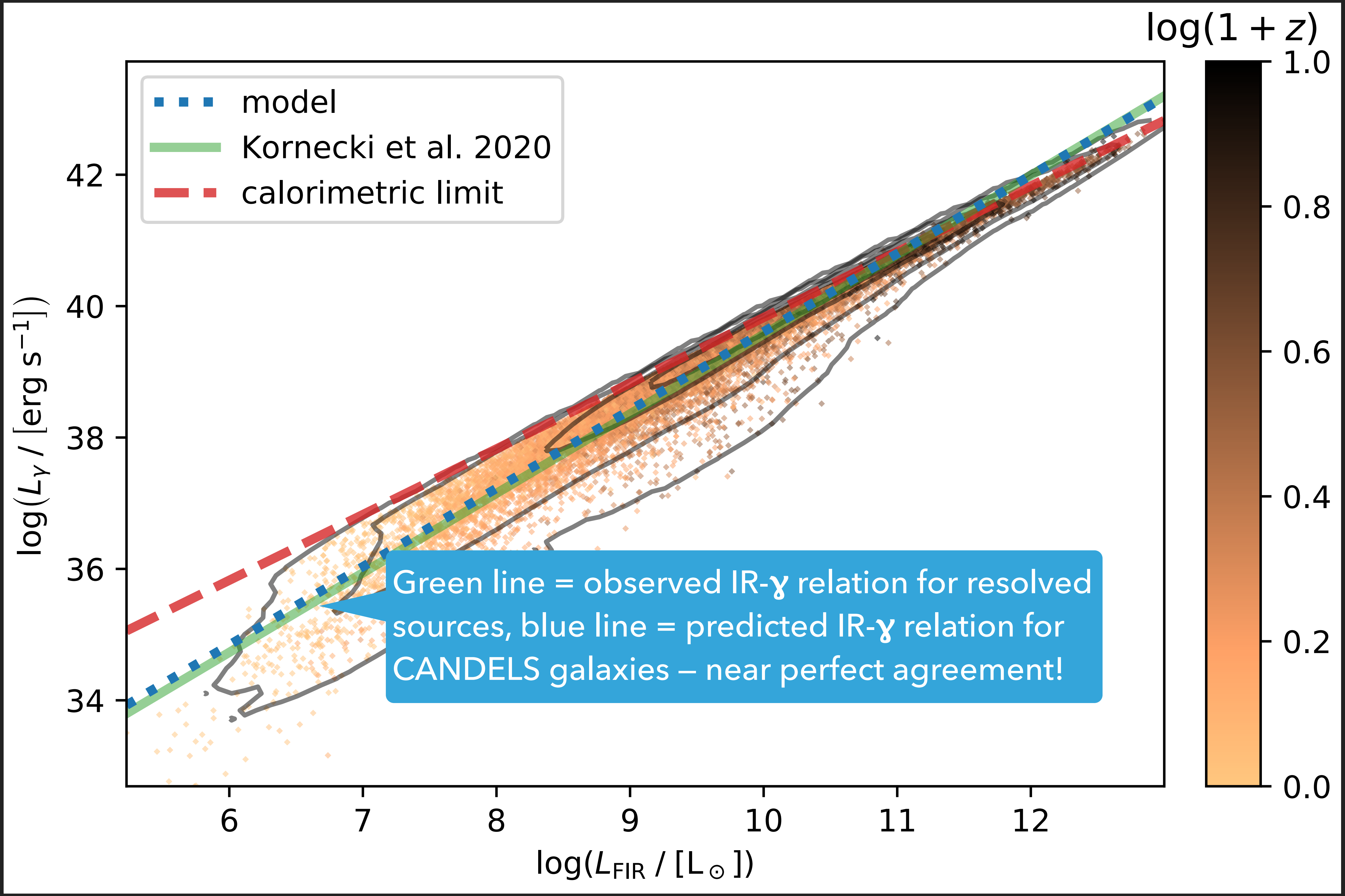

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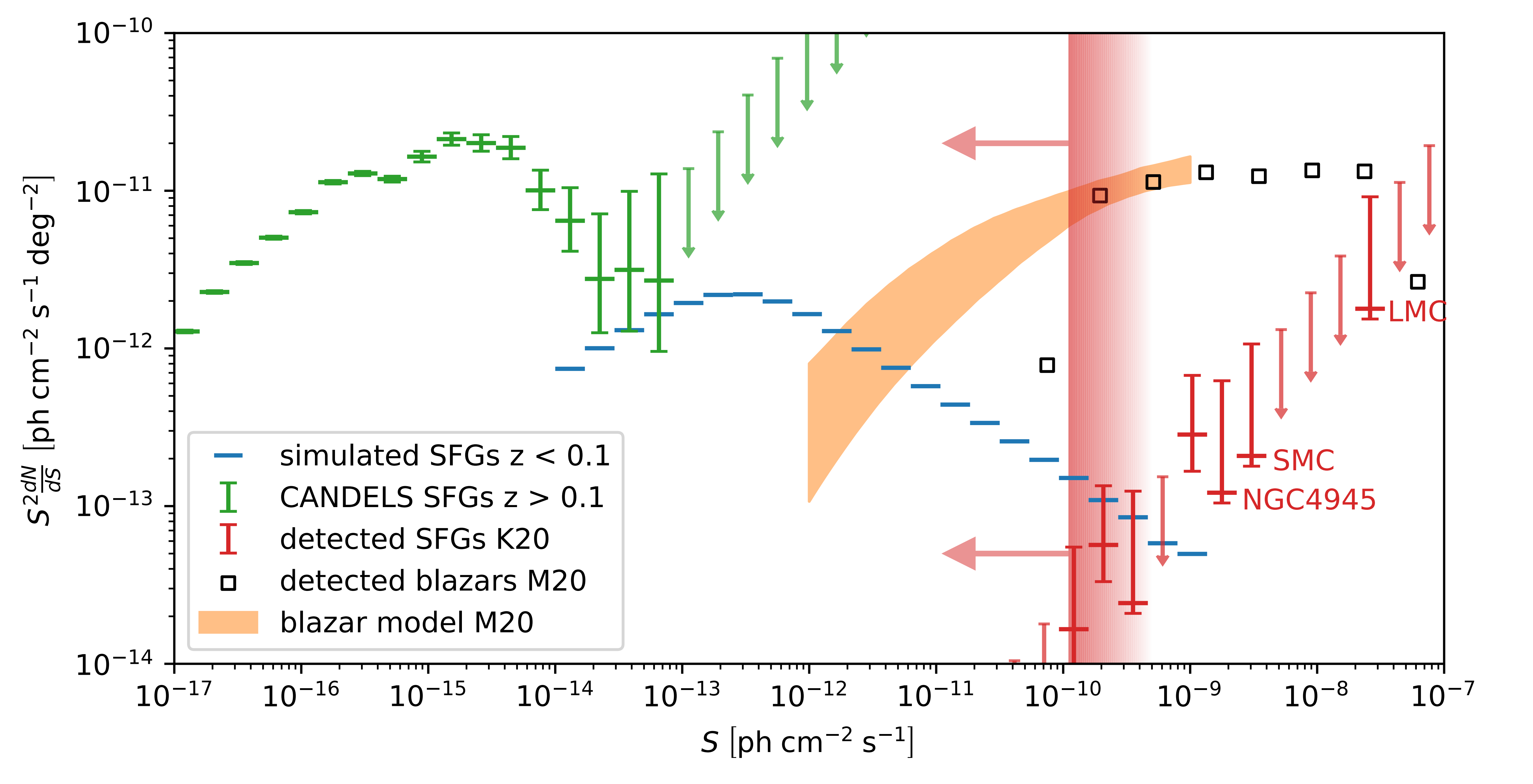
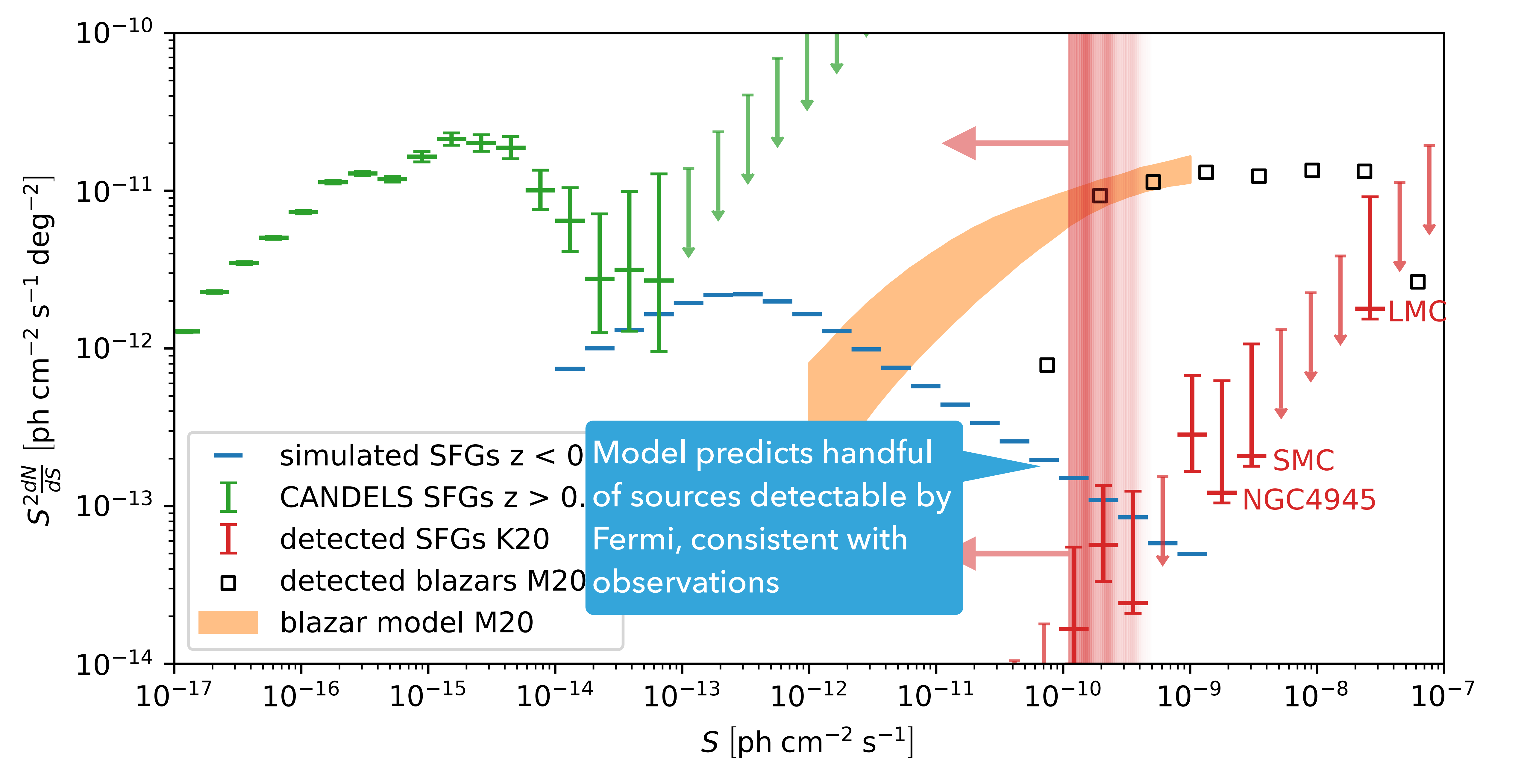


RESOLVED SOURCE NUMBER COUNTS

Roth+ 2020



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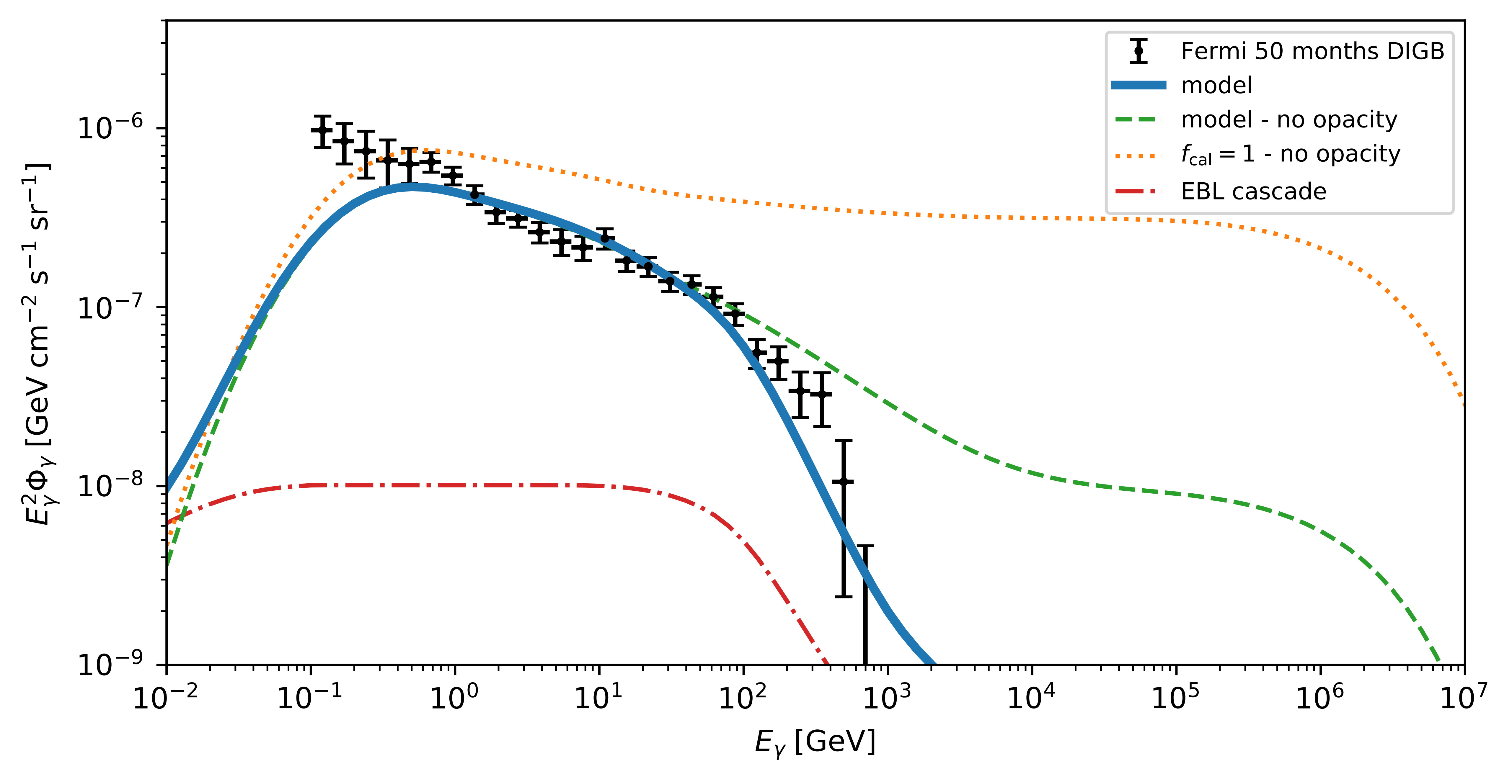
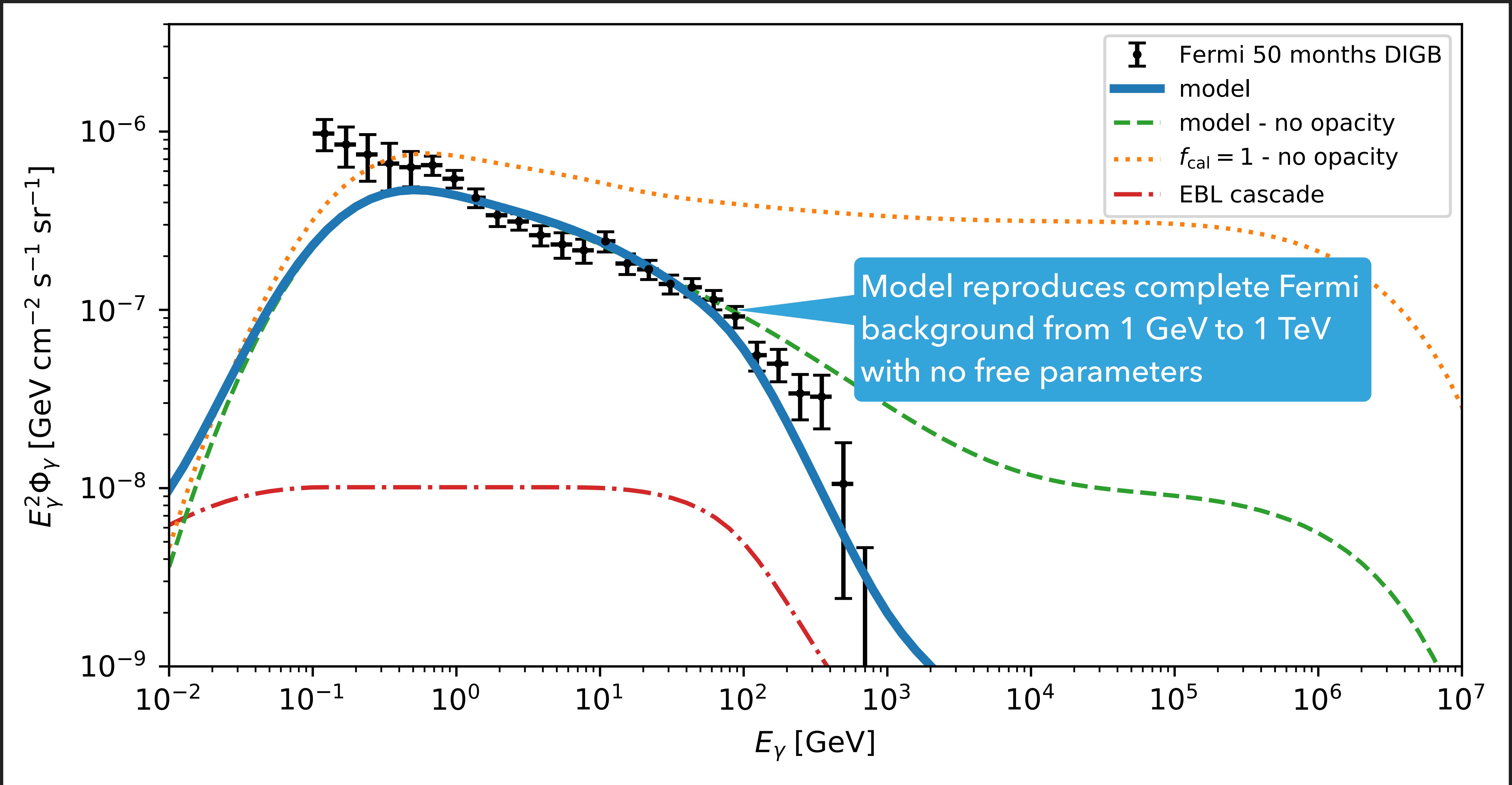


UNRESOLVED BACKGROUND

Roth+ 2020



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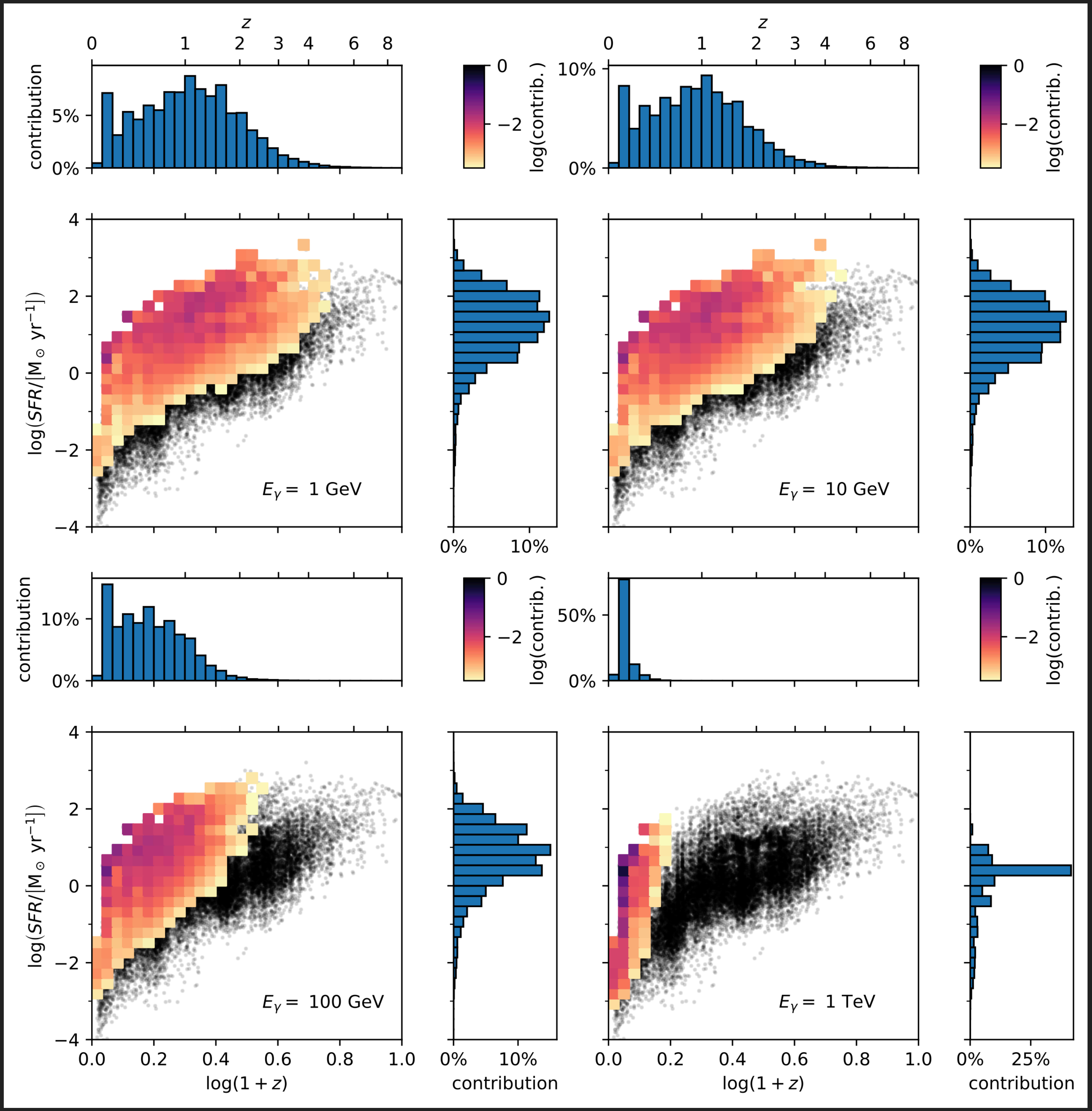

SOURCES OF THE UNRESOLVED BACKGROUND

IMPLICATIONS OF COSMIC RAY PRESSURE

- Calculations thus far assumed exponential gas disc
- However, this neglects effects of CR pressure; as CR flux is turned up, at some point pressure of CRs must begin to affect vertical density distribution
- Basic physics question: given gravity-confined column of gas, into which CRs are injected, is there are maximum CR flux beyond which hydrostatic equilibrium is impossible?
- For photon flux there is such a limit (Crocker+ 2018a,b)

A (NEARLY) TRIVIAL MODEL

- Require (1) energy conservation, (2) hydrostatic equil.

$$\frac{dF_c}{dz} = -\frac{u_c}{t_{pp}} + v_{A,i}\frac{dP_c}{dz}$$

$$\frac{dP_c}{dz} = -\frac{dP_{\rm turb}}{dz} - \frac{dP_{\rm mag}}{dz} - \rho g_z$$

- Add boundary conditions specifying CR flux injected at z = 0, CR flux → streaming at v_A as z → ∞

A (NEARLY) TRIVIAL MODEL

CR flux

CR energy density

CR pressure

$$\frac{dF_c}{dz} = -\frac{u_c}{t_{pp}} + v_{A,i}\frac{dP_c}{dz}$$

$$\frac{dP_c}{dz} = -\frac{dP_{\rm turb}}{dz} - \frac{dP_{\rm mag}}{dz} - \rho g_z$$

Gas ram pressure

Magnetic pressure

Gravity

A (NEARLY) TRIVIAL MODEL

Change in flux — pp losses — Streaming instability losses

$$\frac{dF_c}{dz} = -\frac{u_c}{t_{pp}} + v_{A,i}\frac{dP_c}{dz}$$

$$\frac{dP_c}{dz} = -\frac{dP_{\mathrm{turb}}}{dz} - \frac{dP_{\mathrm{mag}}}{dz} - \rho g_z$$

CR pressure gradient — Gas pressure gradient — Magnetic pressure grad — Gravity

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- System fully specified by a few dimensionless numbers:

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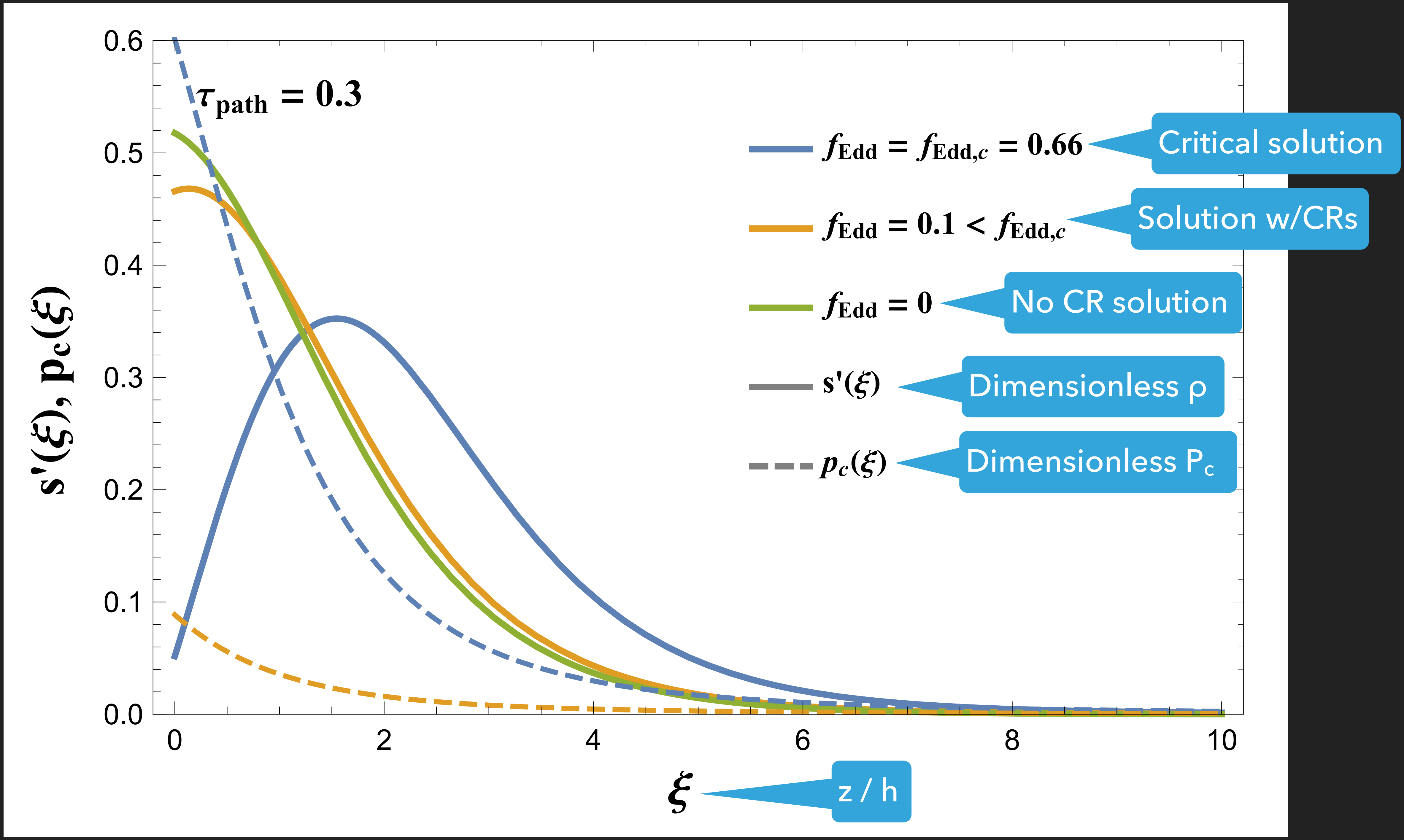
  - $f_{Edd} \approx (\tau_s / \beta_A)\ (F_{c,z=0} / \pi G c \Sigma^2)$: ``Eddington ratio": ratio of momentum flux carried by CRs at z = 0 to momentum flux provided by gravity

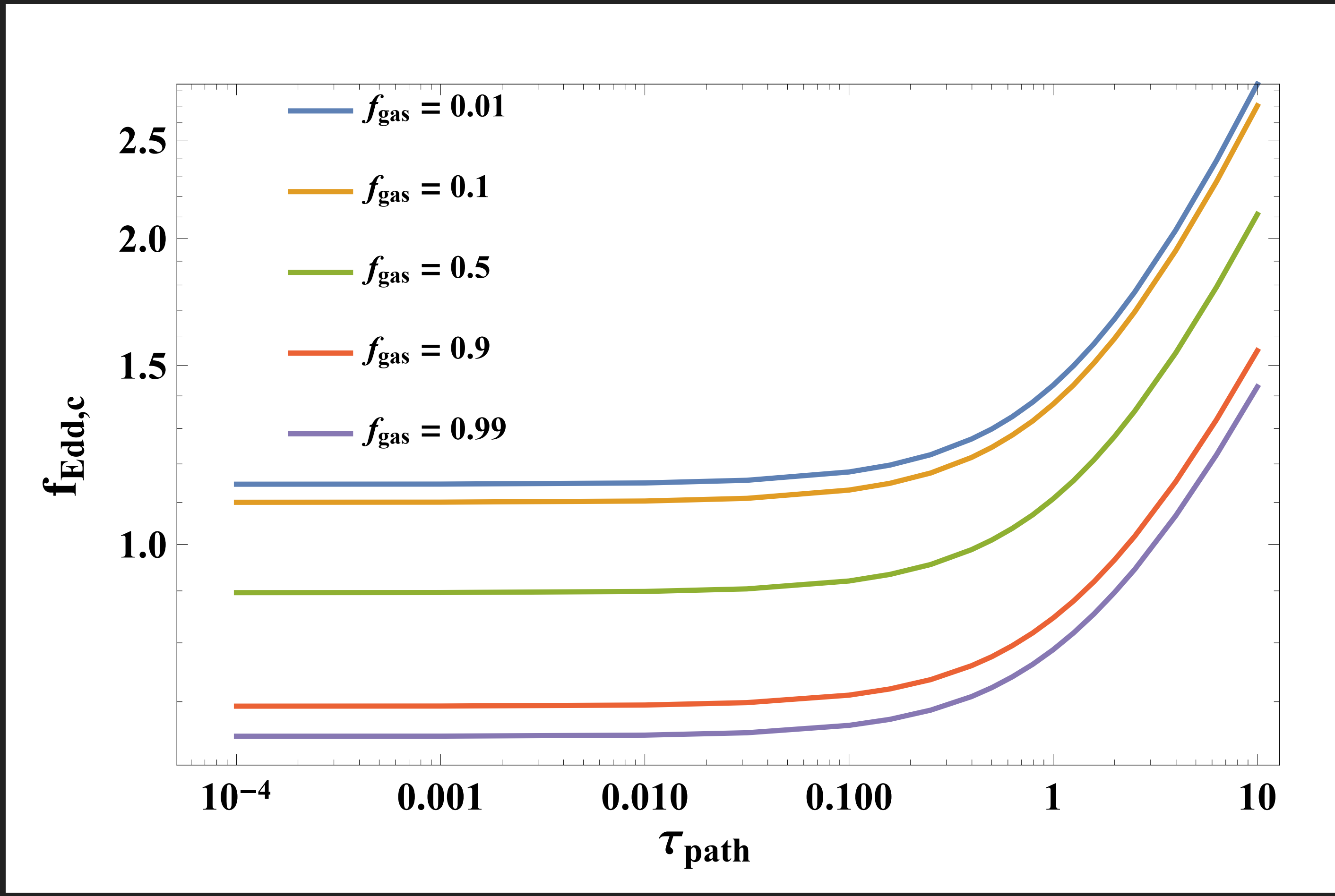


STRUCTURE OF SOLUTIONS

Crocker+ 2020

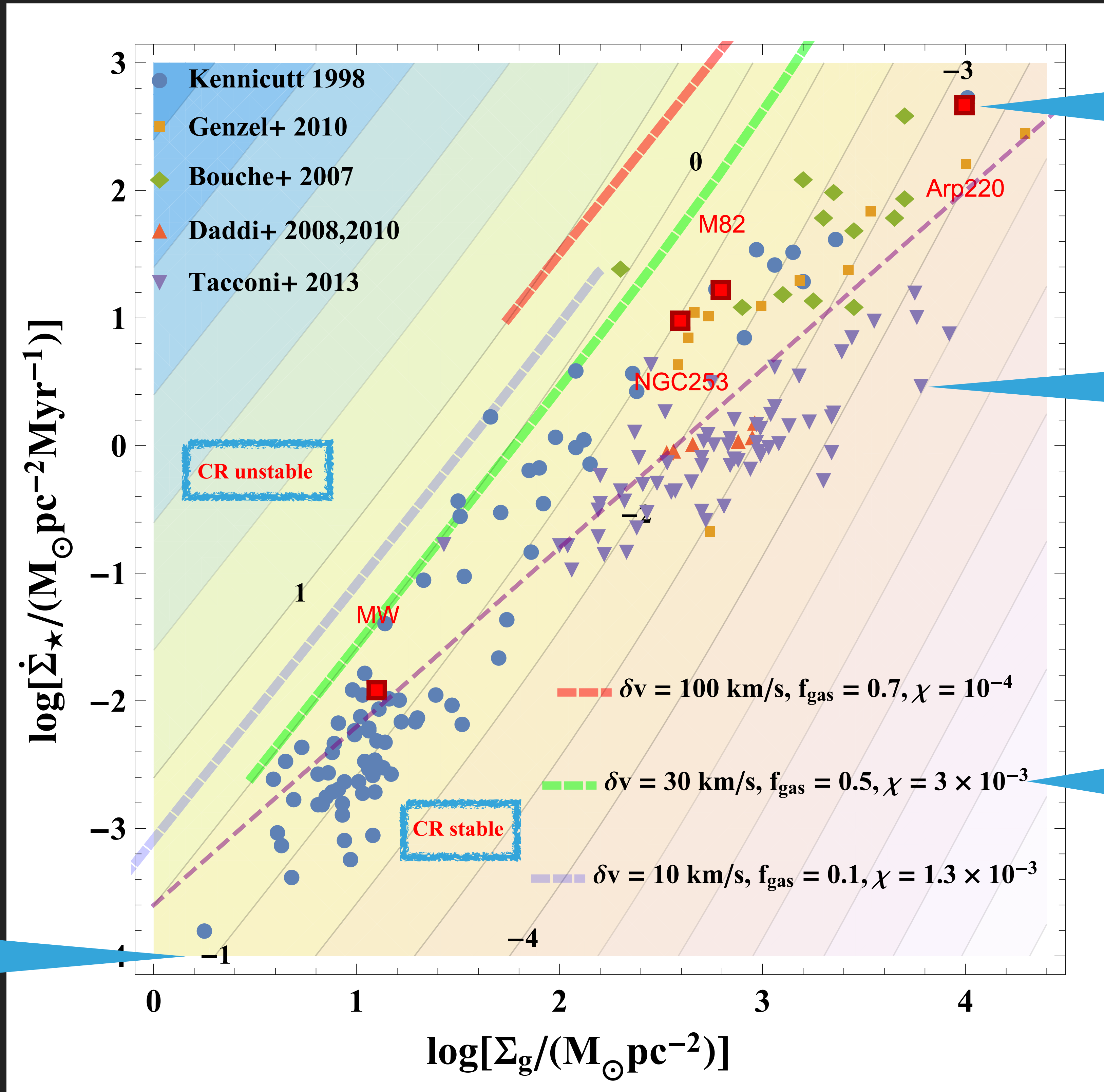
CRITICAL STABILITY LIMIT

- For any given τ_{path}, f_{gas}, there is a maximum f_{Edd} that allows both energy and hydrostatic balance
- Critical value is ~constant for small τ_{path}, rises linearly with τ_{path} for $\tau_{path} \gtrsim 1$
- More gas-poor systems more stable, because stars don't respond to CRs



ASTROPHYSICAL IMPLICATIONS

- τ_{path} is basically a proxy for gas surface density of a galaxy
- f_{Edd} is basically a proxy for galaxy star formation rate / unit area (since SF → SNe → CRs)
- Thus critical curve $f_{Edd}(\tau_{path}, f_{gas})$, plus a few auxiliary variables (e.g., ISM velocity dispersion → scale height), translates directly into parameter space of $(\Sigma_{gas}, \Sigma_{SFR})$
- Can compare to well known Kennicutt-Schmidt (KS) relation for observed galaxies in this space



Red points = local galaxies w/ measured ɣ-ray spectra

Points = various observed galaxy classes

Lines = critical curves for a few parameter sets

Contours = log (P_{cr} / P_{grav}) at midplane

CR STABILITY IN THE KS PLANE

Crocker+ 2020

CR STABILITY TAKEAWAYS

- CRs not dynamically important for starburst / high-redshift galaxies due to pp losses, which reduce CR pressure at midplane (and make these galaxies good calorimeters)
- CRs stability line is close to upper envelope of data distribution for low SFR dwarfs and local spirals
  - No a priori reason why it should have come out this way
  - Suggests that CR feedback may play a role in shaping KS plane: perhaps dwarf galaxies can't go to higher SFRs because they lose gas to CR-driven winds

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

SUMMARY II

- This picture of CR transport naturally explains γ-ray spectral shapes of nearby starbursts, and why they differ from MW
- Applied to the observed star-forming galaxy population, it naturally reproduces:
  - The observed IR-γ relation
  - The number of individually-resolved SFGs
  - The diffuse isotropic γ-ray background

SUMMARY III

- CRs injected by SN limit the stability of the ISM: too many and hydrostatic equilibrium becomes impossible
- Conditions under which this occurs can be represented in observed space of (Σ_{gas}, Σ_{SFR}); implications:
  - CRs dynamically unimportant in starbursts and high-z discs due to pp losses
  - CRs potentially very important in dwarfs and local spirals; may set upper edge of galaxy distribution in KS plane

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?
- What happens in unstable systems? If CR injection rate goes above stability limit, is the result a wind? Turbulence?
- Implications for spatial variation of CRs within MW
- Implications for other backgrounds: lower energy γ rays from CR electrons, neutrinos

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

THE END