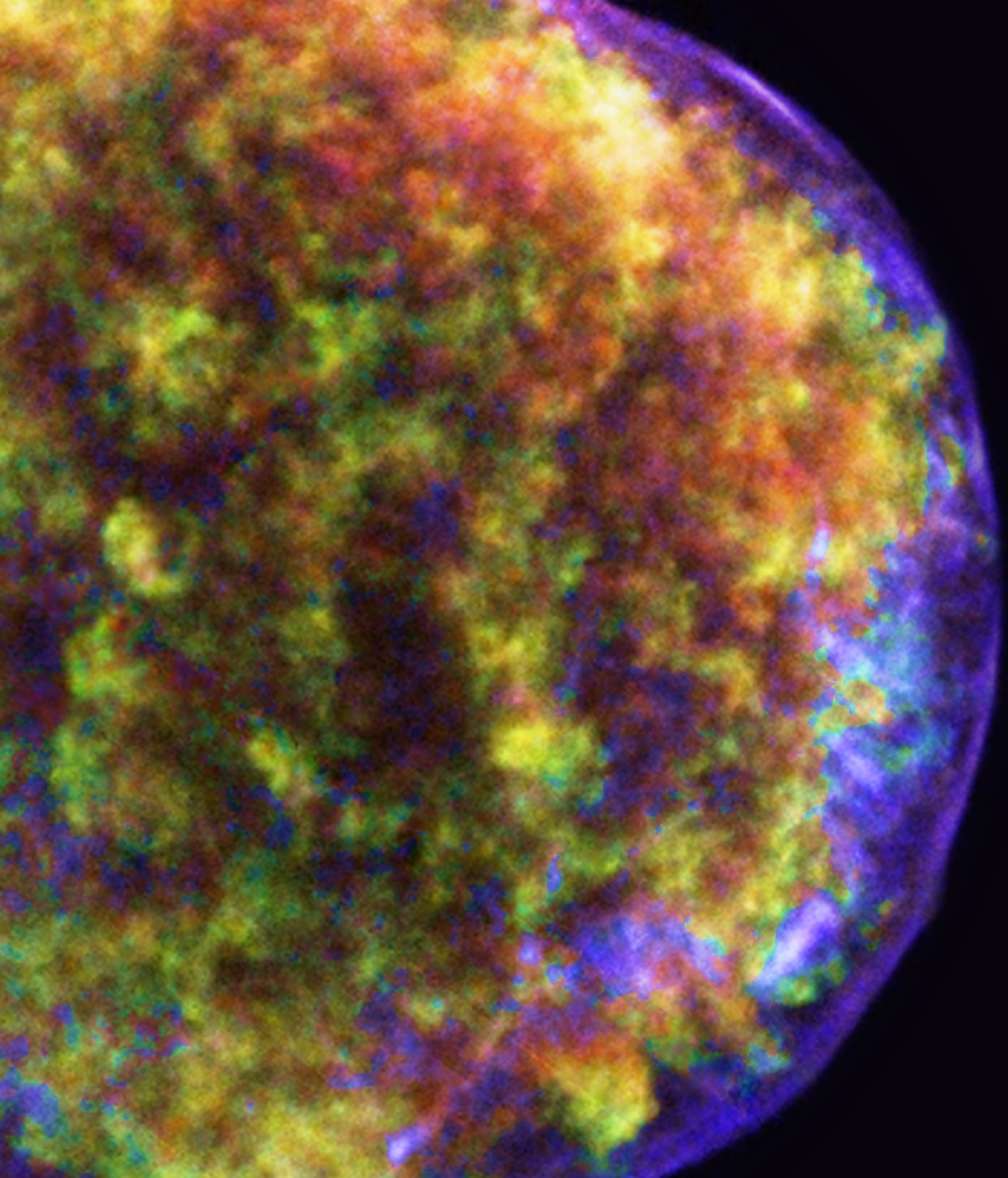


GALACTIC COSMIC RAY ACCELERATION WITH STEEP SPECTRA

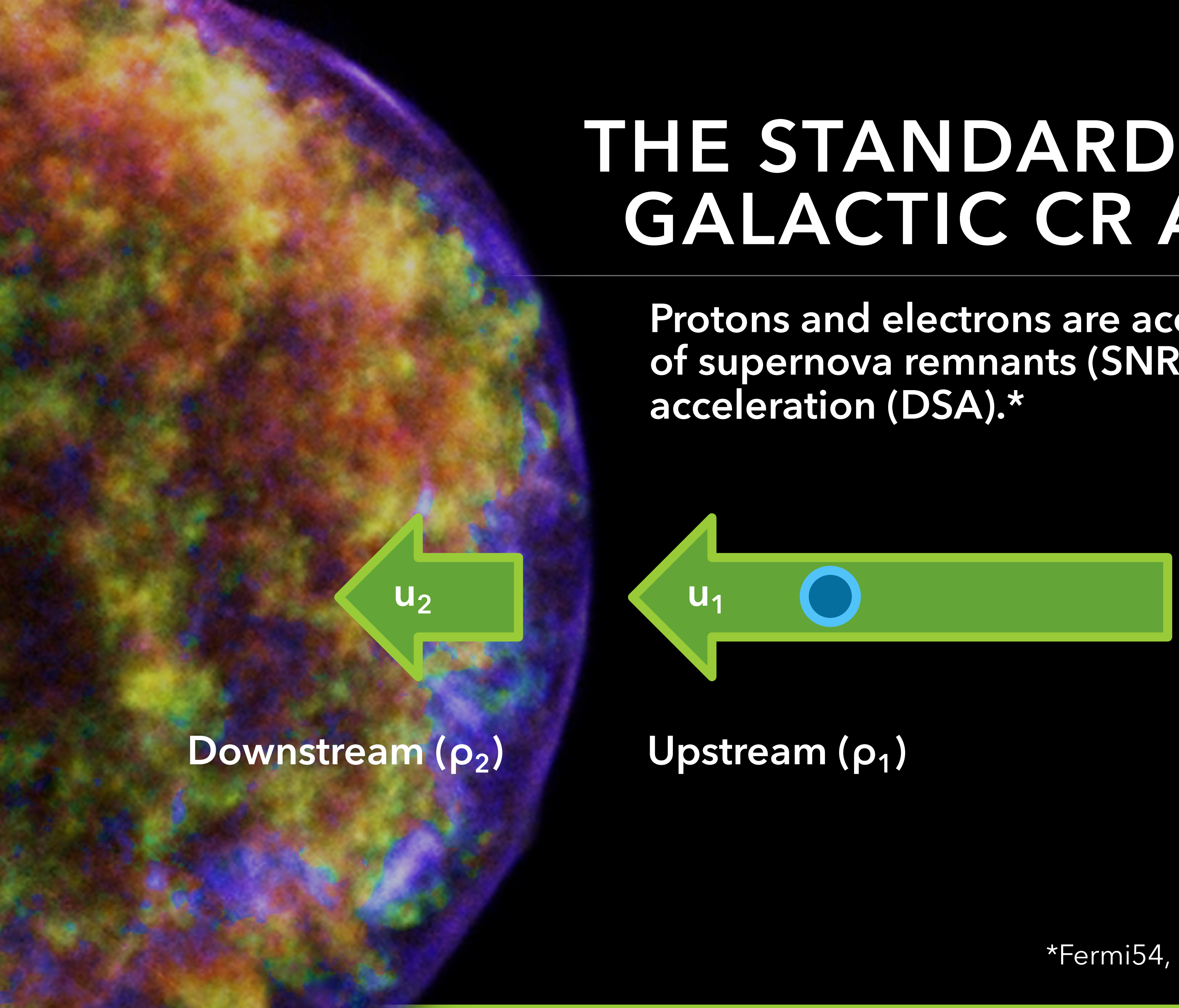
REBECCA DIESING &
DAMIANO CAPRIOLI

ICRC | JULY 20, 2021

Image: Tycho Supernova Remnant; Credit: Chandra X-Ray Observatory

THE STANDARD PARADIGM OF GALACTIC CR ACCELERATION

Protons and electrons are accelerated at the forward shocks of supernova remnants (SNRs) via diffusive shock acceleration (DSA).*



Downstream (ρ_2)

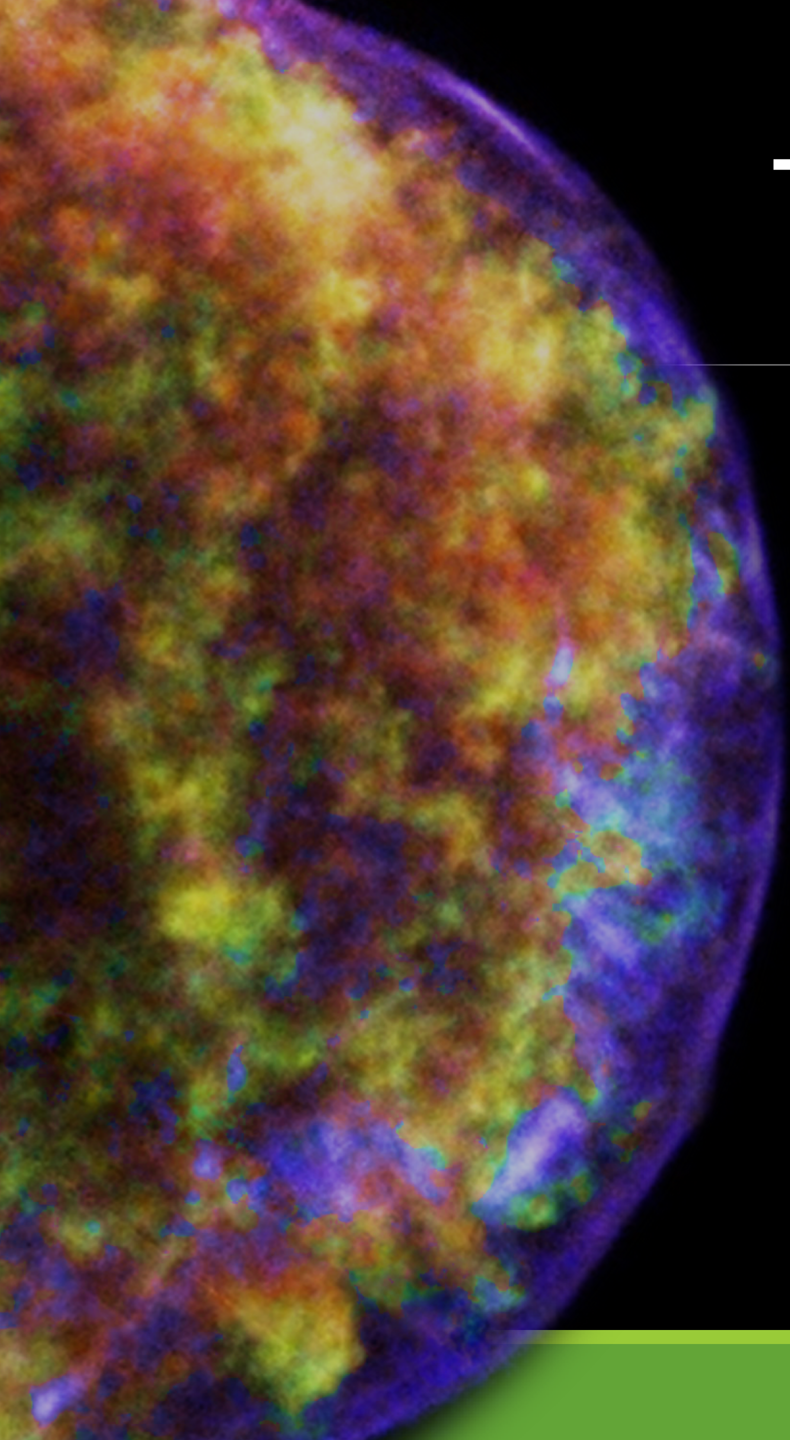
Upstream (ρ_1)

$$R \equiv \frac{\rho_2}{\rho_1} = \frac{u_1}{u_2}$$

For strong shocks, R = 4.

*Fermi54, Krymskii77, Axford+77, Bell78, Blandford+78

THE STANDARD PARADIGM OF GALACTIC CR ACCELERATION



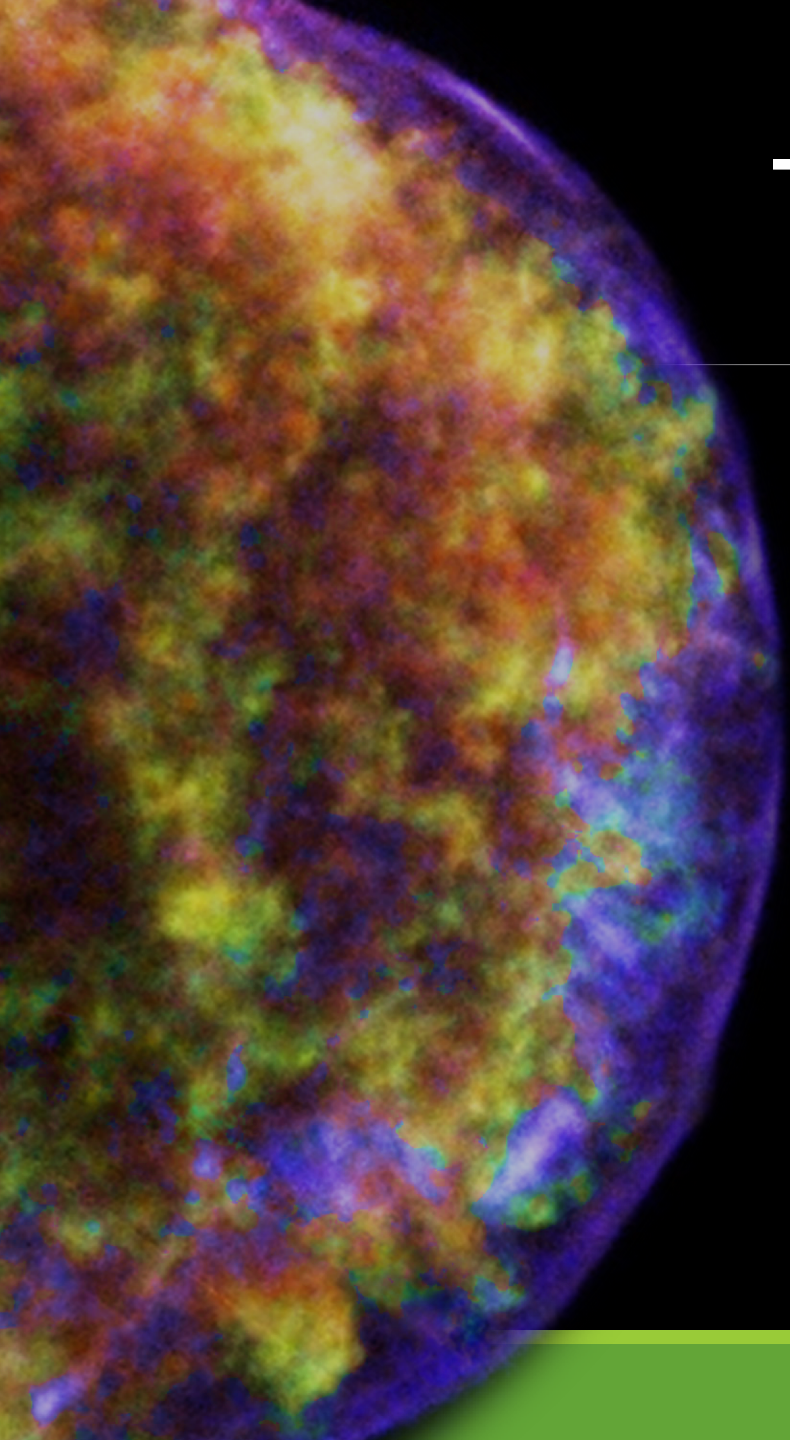
DSA predicts power law distributions of CRs.*

$$\Phi \propto p^{-q_{\rm p}}$$

$$q_{\rm p} = \frac{3R}{R-1}$$

For strong shocks, $q_p = 4$.

*Fermi54, Krymskii77, Axford+77, Bell78, Blandford+78



THE STANDARD PARADIGM OF GALACTIC CR ACCELERATION

DSA predicts power law distributions of CRs.*

$$\Phi \propto E^{-q}$$

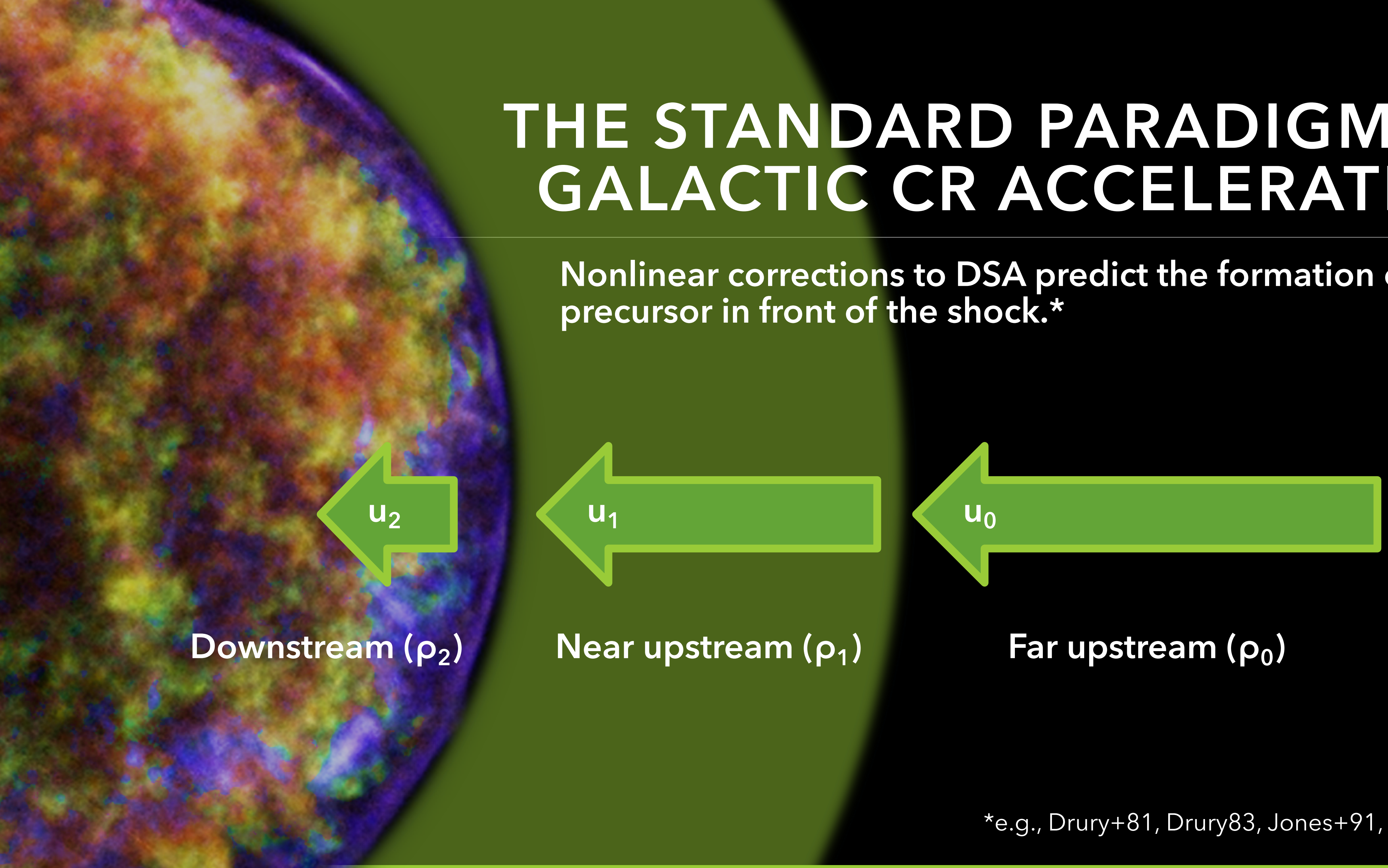
$$q = \frac{R+2}{R-1}$$

For strong shocks, q = 2.

*Fermi54, Krymskii77, Axford+77, Bell78, Blandford+78

THE STANDARD PARADIGM OF GALACTIC CR ACCELERATION

Nonlinear corrections to DSA predict the formation of a precursor in front of the shock.*



Downstream (ρ_2)

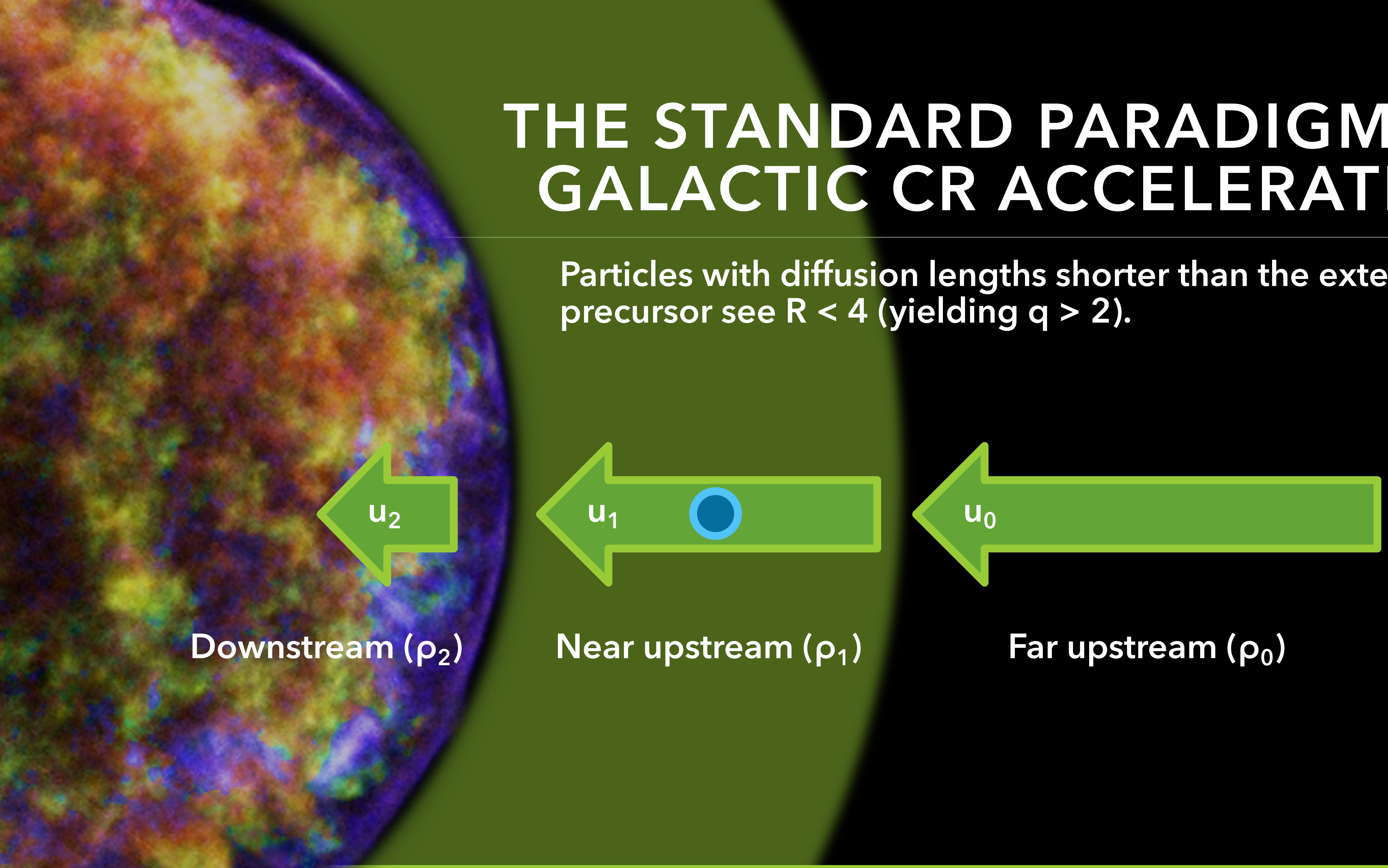
Near upstream (ρ_1)

Far upstream (ρ_0)

*e.g., Drury+81, Drury83, Jones+91, Malkov+01

THE STANDARD PARADIGM OF GALACTIC CR ACCELERATION

Particles with diffusion lengths shorter than the extent of the precursor see $R < 4$ (yielding $q > 2$).



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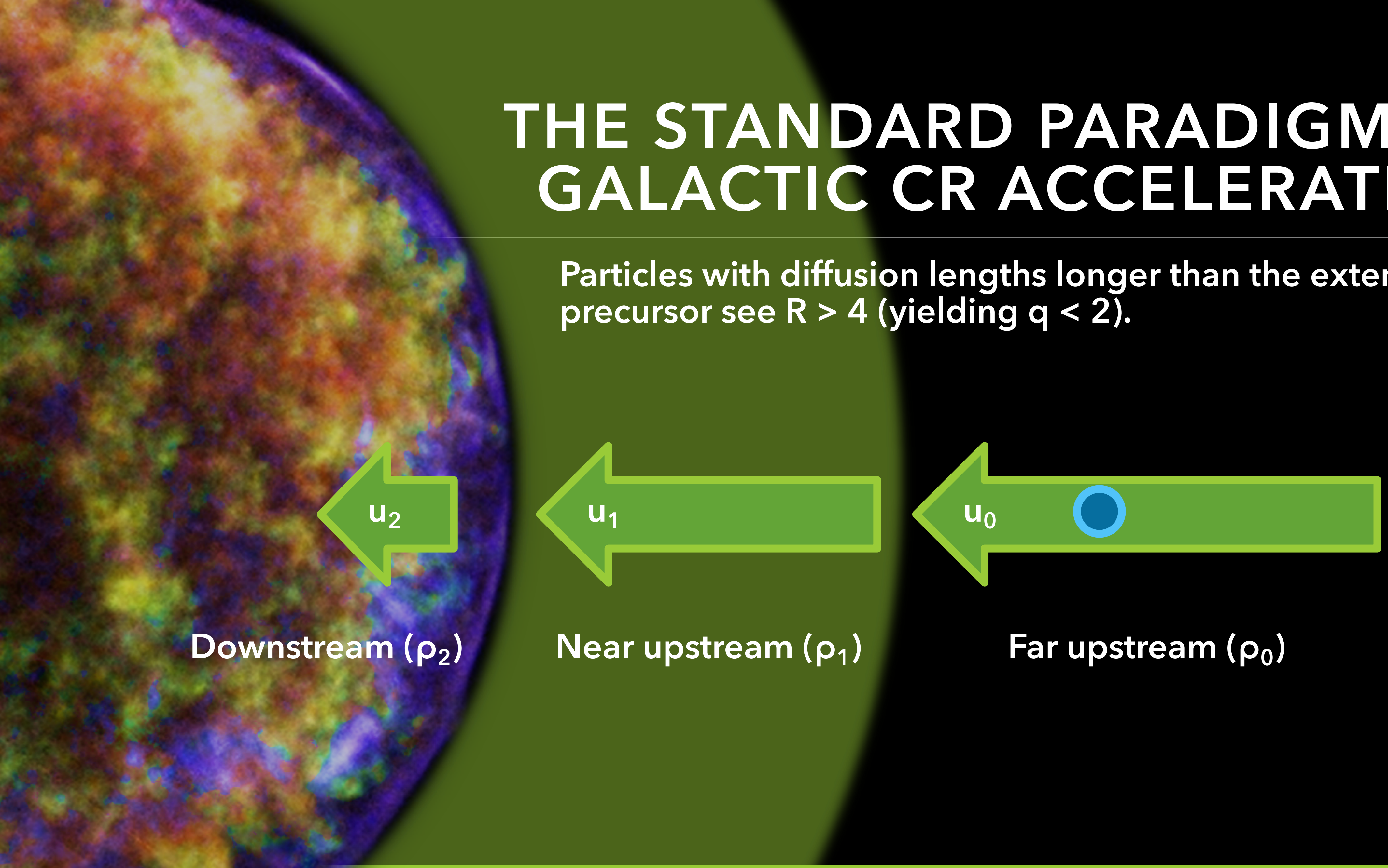


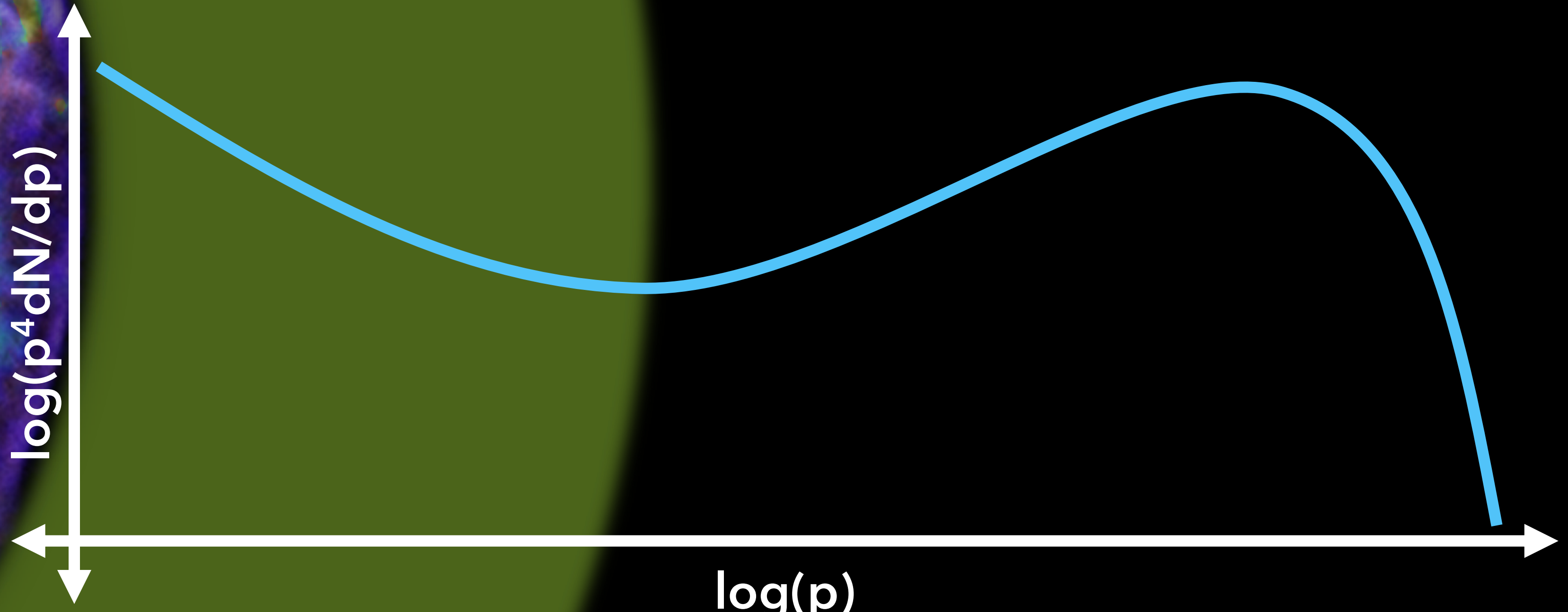
Downstream (ρ_2)

Near upstream (ρ_1)

Far upstream (ρ_0)

THE STANDARD PARADIGM OF GALACTIC CR ACCELERATION

Nonlinear DSA predicts concave spectra, with $q_p < 4$ ($q < 2$) for momenta above ~1 GeV/c.



THE PROBLEM WITH DSA

Observations point toward CR acceleration with spectra *steeper* than E^{-2} (i.e., $q > 2$).

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1. **ɣ-ray emission from Galactic SNRs suggest $2.2 \lesssim q \lesssim 2.6$.**
   e.g., Caprioli11, Giordano+12, Saha+14, Aharonian+19

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2. **Radio emission from young extragalactic SNe (radio SNe) suggest $q \approx 3$.**
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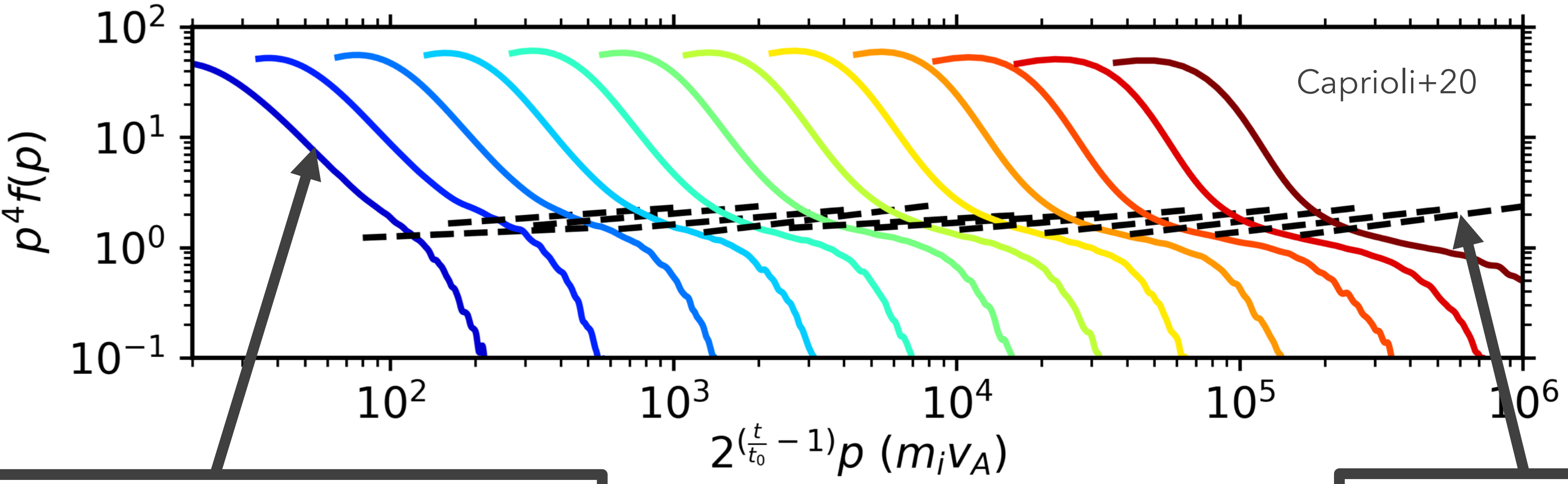
3. **Observations of Galactic CRs require $2.3 \lesssim q \lesssim 2.4$.**
   e.g., Evoli+19

STEEP SPECTRA IN SIMULATIONS

Kinetic simulations performed in Haggerty+20 and Caprioli+20 naturally reproduce steep spectra (see also talk by D. Caprioli, ID: 1345).

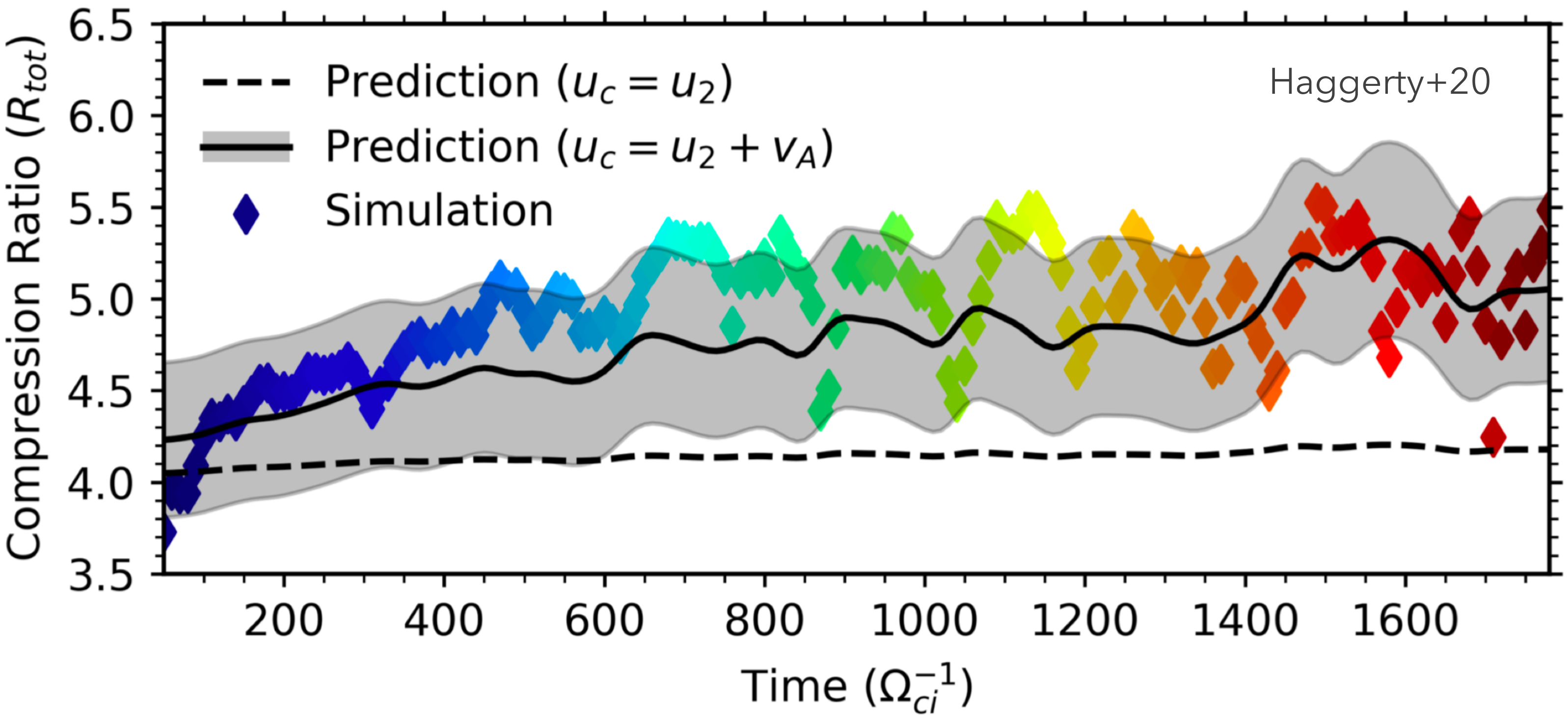


Simulated particle spectra (color scale denotes time)

Nonlinear DSA prediction

ENHANCED COMPRESSION RATIOS

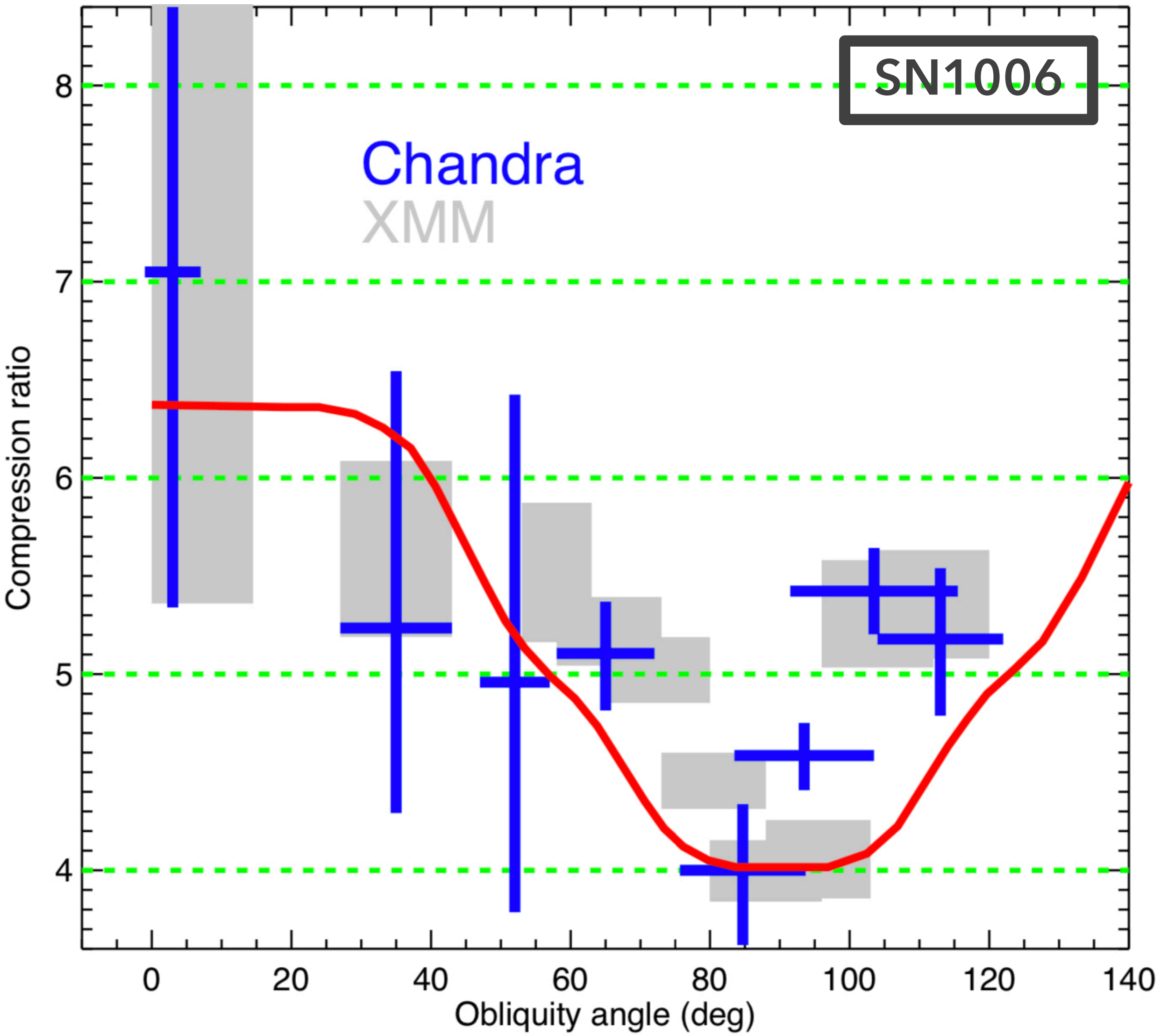
Intriguingly, Haggerty+20 and Caprioli+20 also find fluid compression ratios significantly *larger* than 4.



ENHANCED COMPRESSION RATIOS

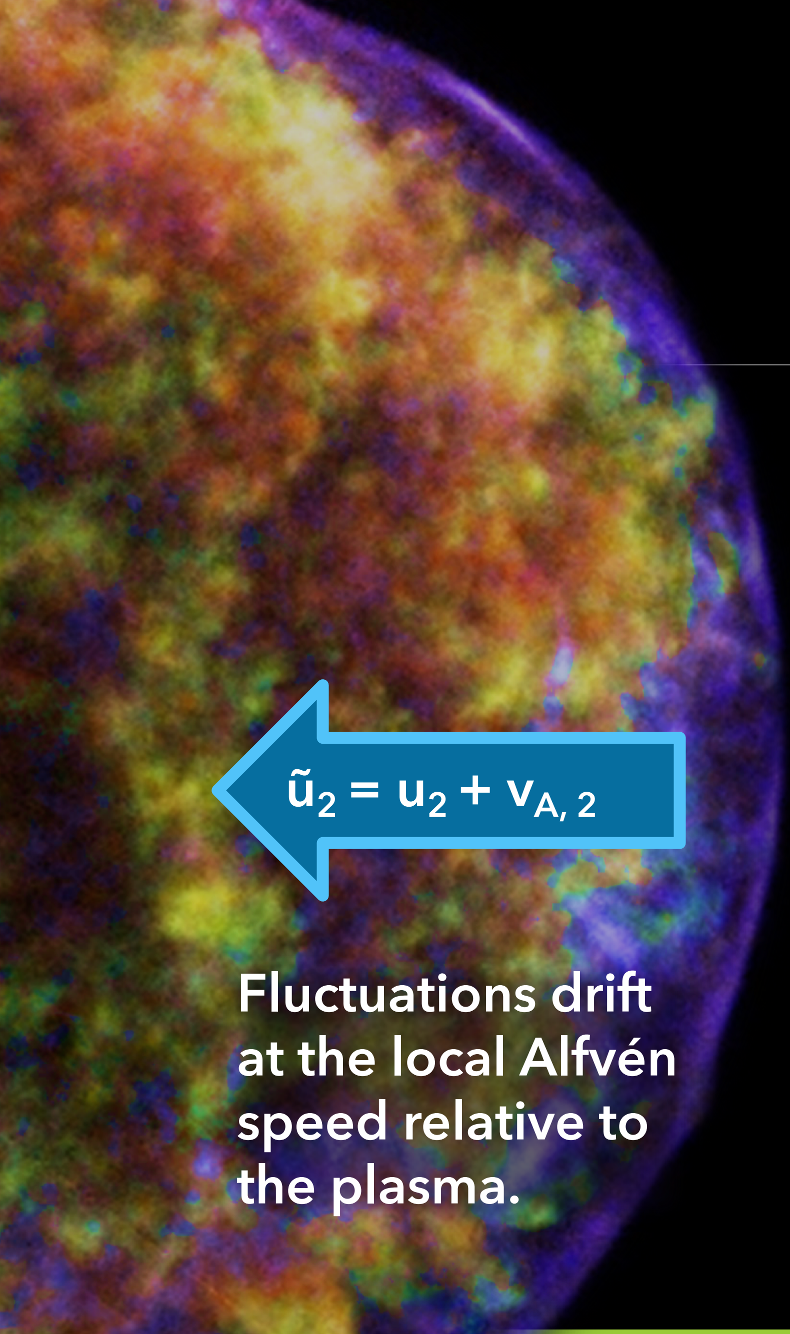
Observations also point towards large compression ratios: 6 < R < 7 in Tycho (Warren+05), 4 < R < 7 in SN1006 (Giuffrida+21, submitted)

Giuffrida+21, submitted

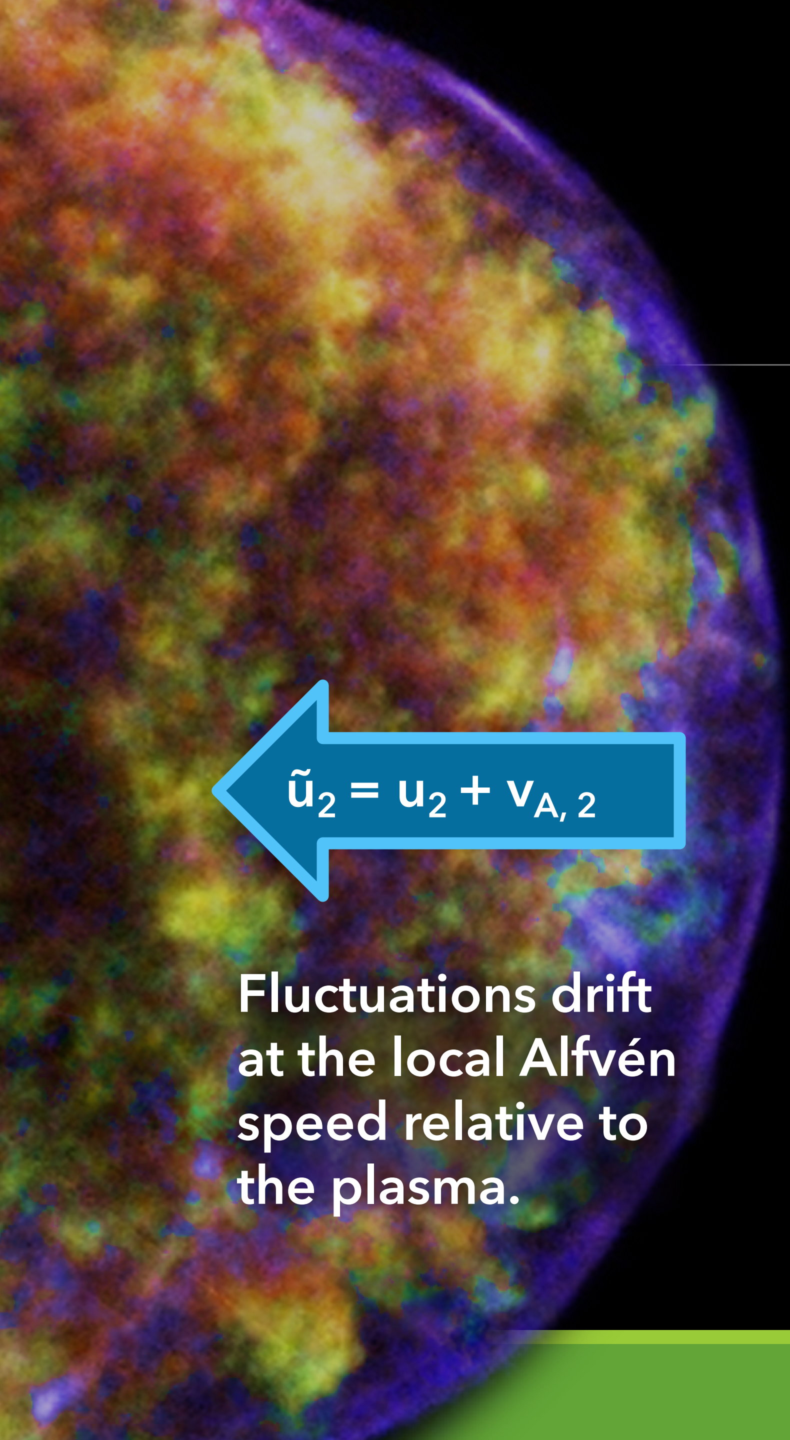


THE "POSTCURSOR"

Magnetic fluctuations generated by CR-driven instabilities in the upstream retain their inertia over a non-negligible distance when advected into the downstream.



Fluctuations drift at the local Alfvén speed relative to the plasma.



THE "POSTCURSOR"

Magnetic fluctuations generated by CR-driven instabilities in the upstream retain their inertia over a non-negligible distance when advected into the downstream.

$\tilde{u}_2 = u_2 + v_{A,2}$

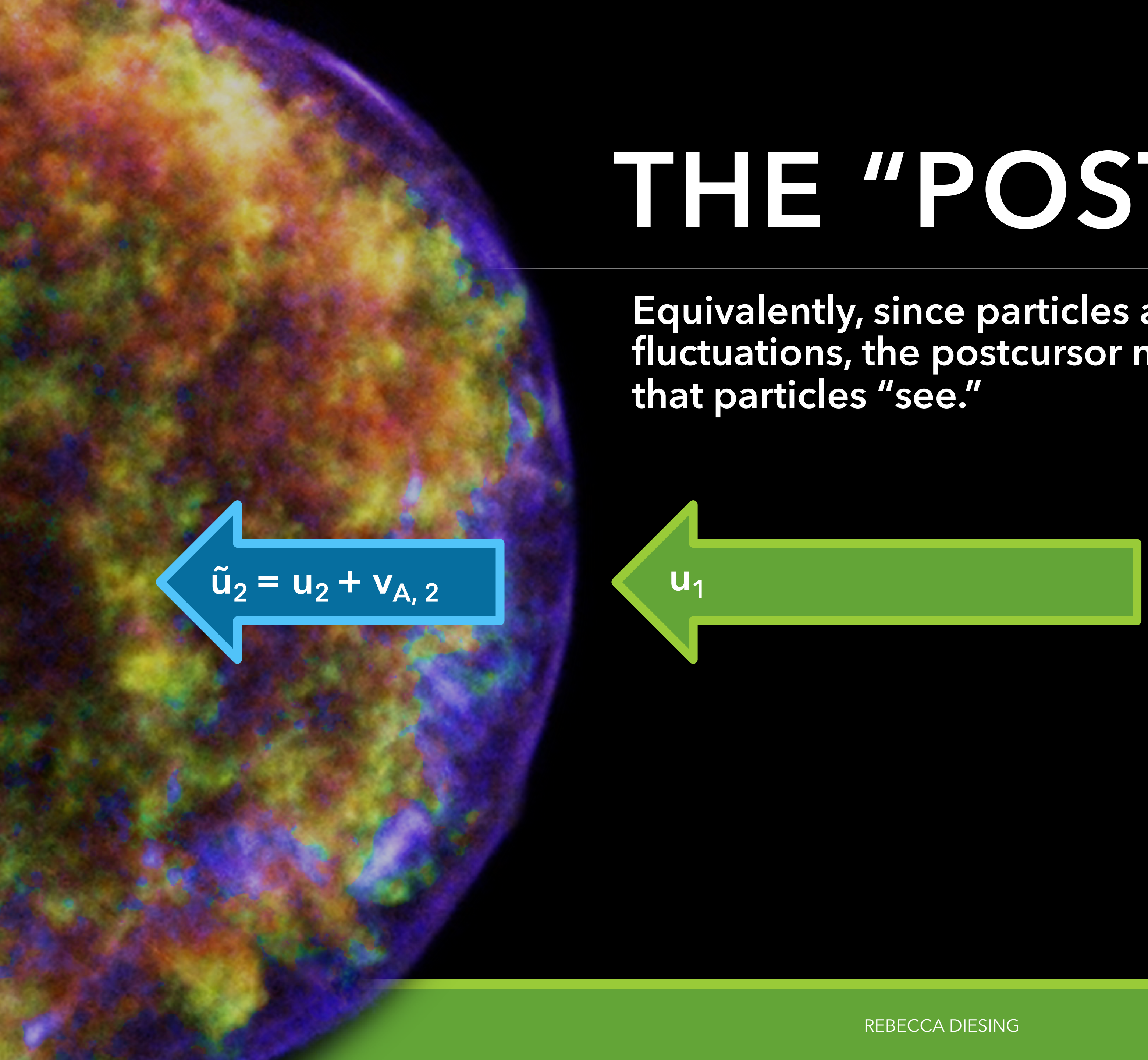
u_1

Fluctuations drift at the local Alfvén speed relative to the plasma.

CRs isotropize these magnetic fluctuations → a *postcursor* of drifting magnetic fluctuations and CRs enhances escape from the acceleration region, raising the fluid compression ratio while steepening the CR spectrum.

THE "POSTCURSOR"

Equivalently, since particles are scattered by magnetic fluctuations, the postcursor modifies the compression ratio that particles "see."



$$\tilde{R} = \frac{u_1}{u_2 + v_{\mathrm{A},2}}$$

THE “POSTCURSOR”

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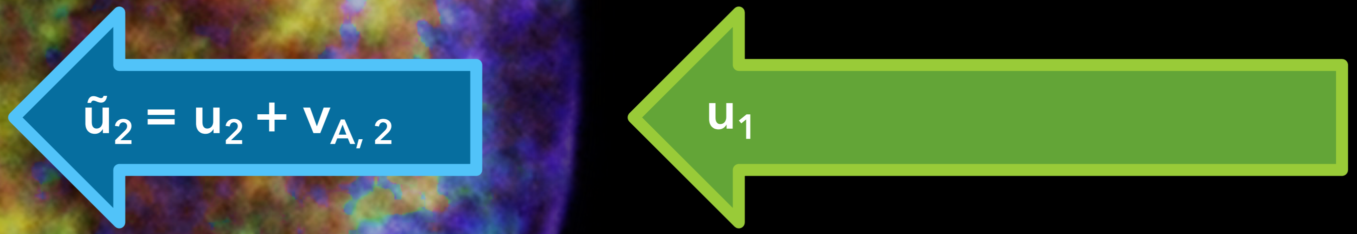


$$\tilde{R} = \frac{u_1}{u_2 + v_{A,2}}$$

Efficient CR acceleration and thus B-field amplification yield $0.5 < v_{A,2}/u_2 < 1$ and spectra steeper than E^{-2}.

THE POSTCURSOR

The postcursor paradigm predicts a physical relationship between CR acceleration efficiency, the magnetic pressure fraction, and q.

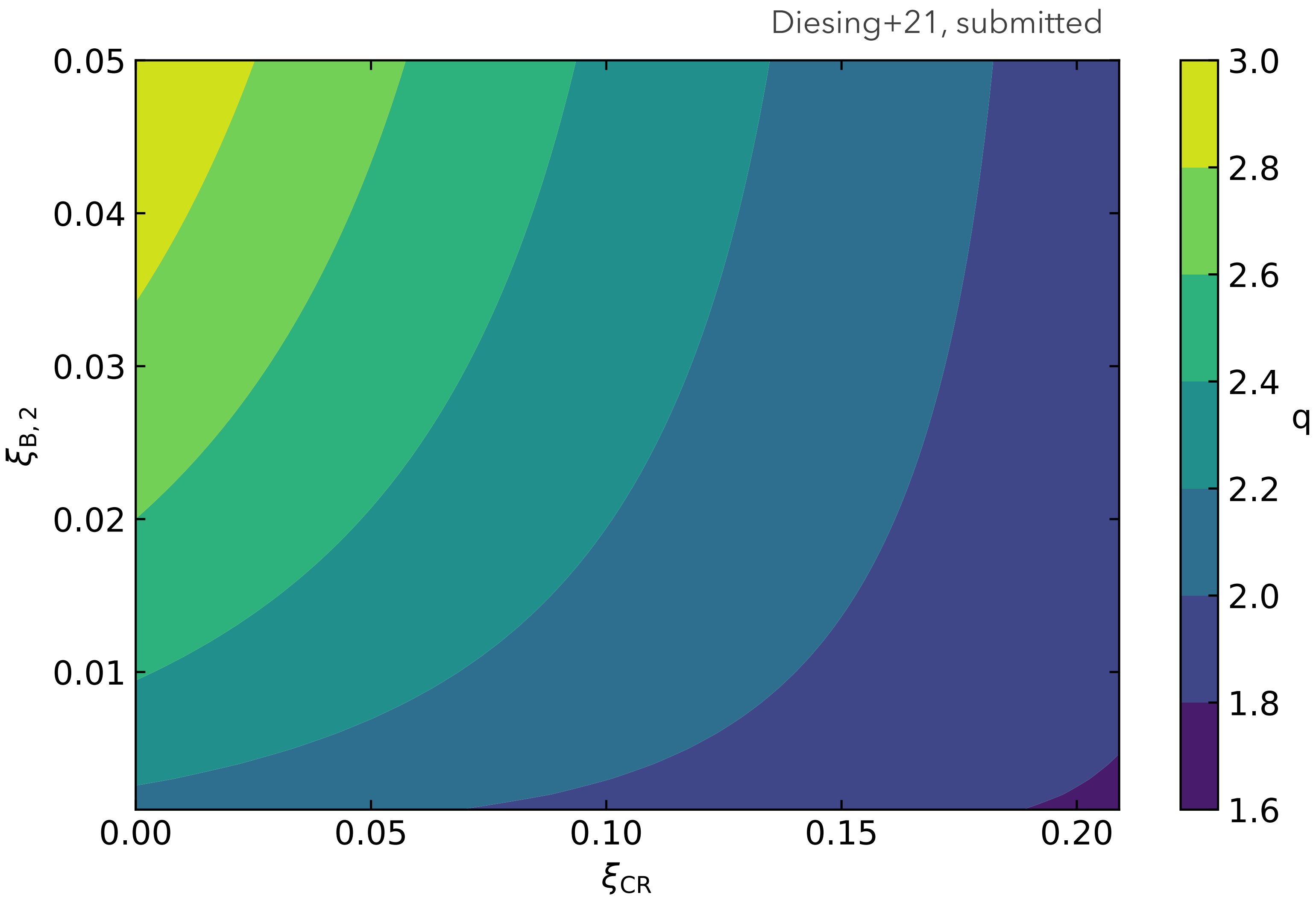
$$q_\mathrm{p} = \frac{3R}{R-1-\alpha} = \frac{3R}{R-1-\sqrt{2R\xi_{\mathrm{B},2}}}$$

$\alpha =$ $v_{A,2}/u_2$

Magnetic pressure fraction = $B^2/(8\pi\rho_0 v_{sh}^2)$

THE POSTCURSOR

The postcursor paradigm predicts a physical relationship between CR acceleration efficiency, the magnetic energy density downstream, and q.


Diesing+21, submitted

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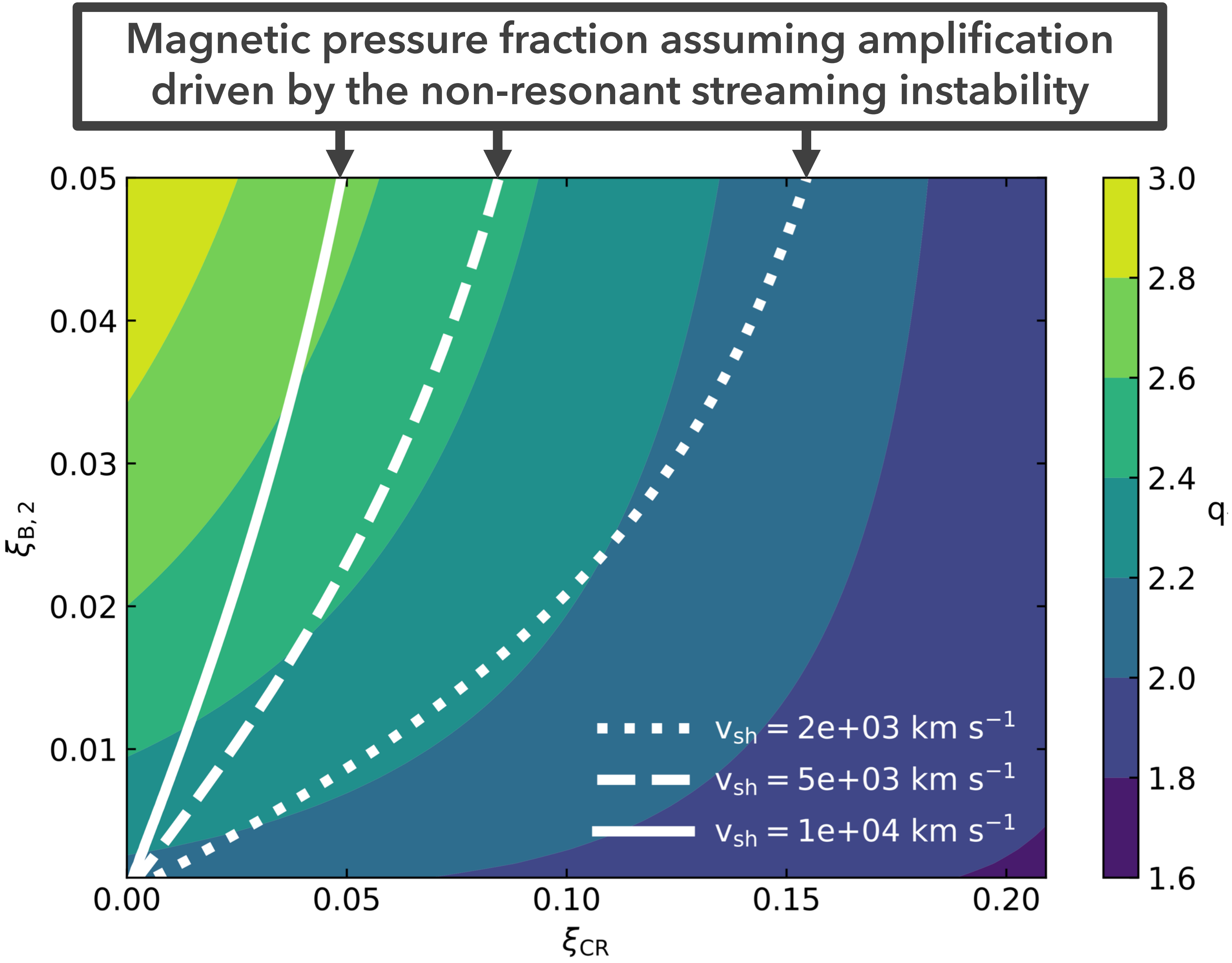
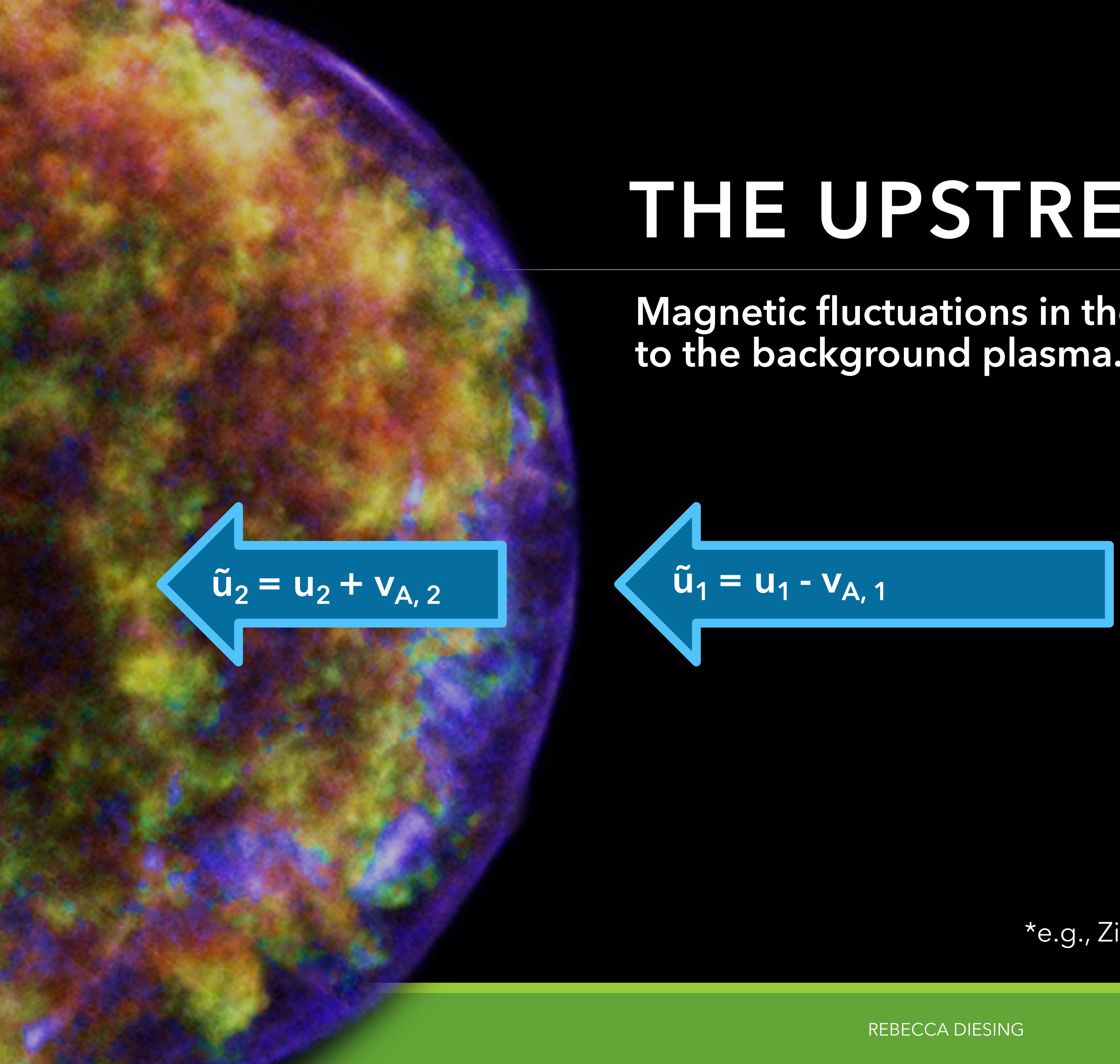

Magnetic pressure fraction assuming amplification driven by the non-resonant streaming instability

THE UPSTREAM REVISITED

Magnetic fluctuations in the upstream also drift with respect to the background plasma.*



$\tilde{u}_2 = u_2 + v_{A,2}$

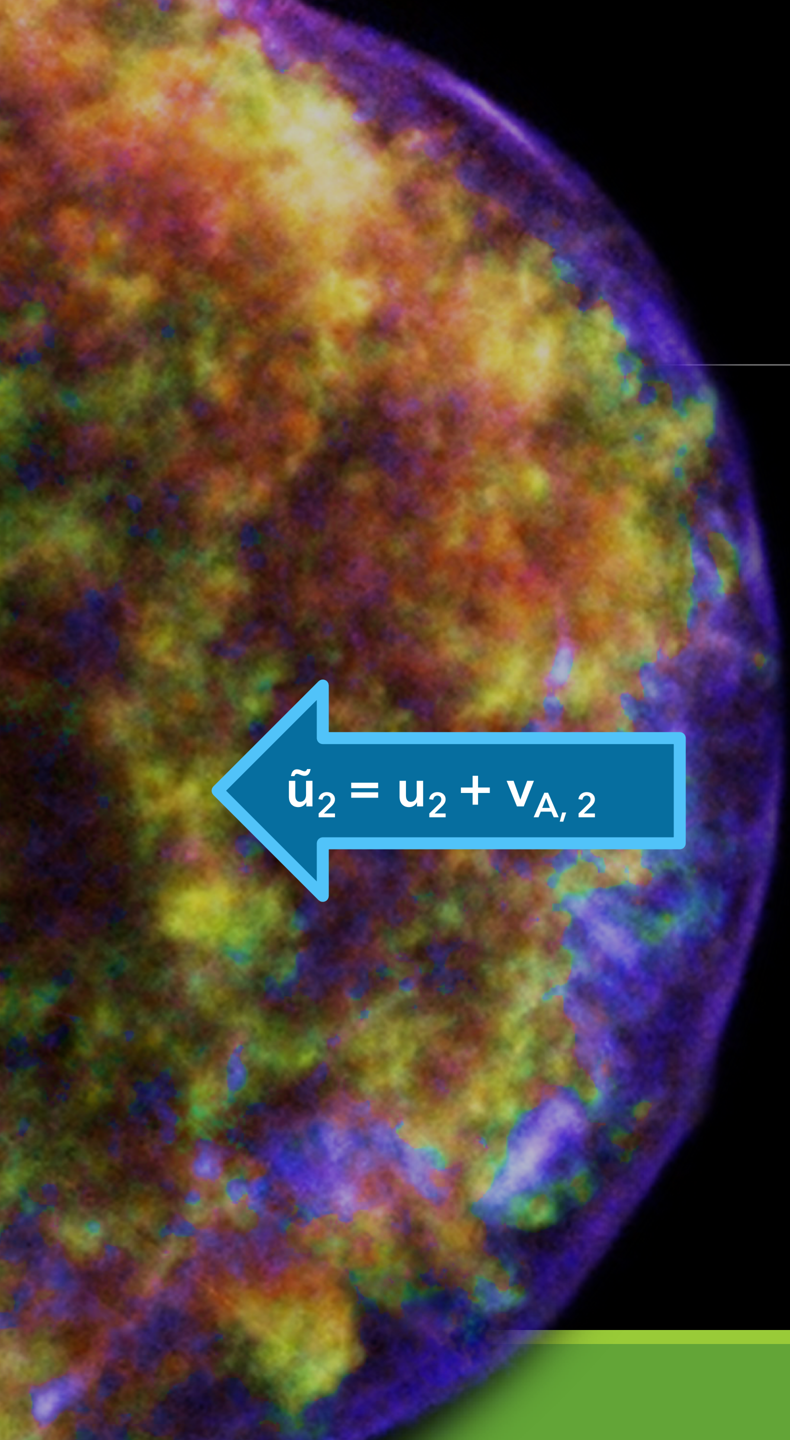
$\tilde{u}_1 = u_1 - v_{A,1}$

Because escaping particles drive magnetic field amplification in the upstream, these fluctuations move against the fluid (away from the shock).

*e.g., Zirakshvili+08, Caprioli11,12, Kang+13, Slane+14

THE UPSTREAM REVISITED

Magnetic fluctuations in the upstream also drift with respect to the background plasma.*



$\tilde{u}_2 = u_2 + v_{A,2}$

$\tilde{u}_1 = u_1 - v_{A,1}$

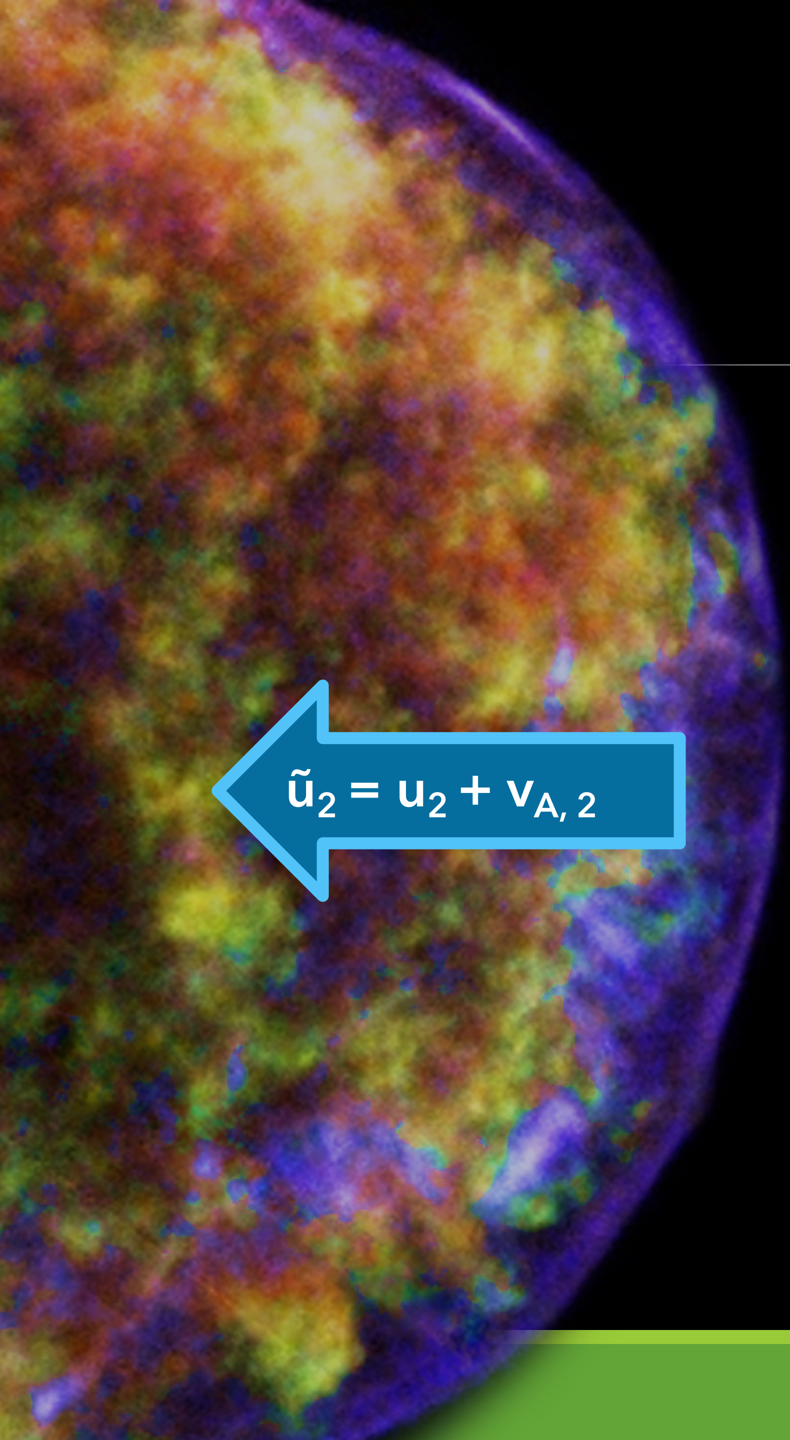
$$\tilde{R} = \frac{u_1 - v_{A,1}}{u_2 + v_{A,2}}$$

As a result, CRs “feel” and even smaller compression ratio, further steepening their spectra.

*e.g., Zirakshvili+08, Caprioli11,12, Kang+13, Slane+14

THE UPSTREAM REVISITED

Magnetic fluctuations in the upstream also drift with respect to the background plasma.*



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$\tilde{u}_1 = u_1 - v_{A,1}$

$$\tilde{R} = \frac{u_1 - v_{A,1}}{u_2 + v_{A,2}}$$

However, since magnetic fluctuations are compressed in the downstream, this effect remains subdominant to the postcursor.

*e.g., Zirakshvili+08, Caprioli11,12, Kang+13, Slane+14

PREDICTING q

Since q depends on the Alfvén speed which depends on CR-driven magnetic field amplification, quantifying the steepening due to the postcursor from first principles requires a self-consistent calculation.

PARTICLE ACCELERATION

Calculate the CR proton spectrum by solving the Parker transport equation.

Assume a fraction η of particles crossing the shock are injected into DSA.

$$\underbrace{\boxed{\tilde{u}(x)\frac{\partial f(x,p)}{\partial x}}}_{\text{Advection}} = \underbrace{\boxed{\frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right]}}_{\text{Diffusion}} + \underbrace{\boxed{\frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f(x,p)}{\partial p}}}_{\text{Adiabatic compression}} + \underbrace{\boxed{Q(x,p)}}_{\text{Injection}}$$

MODELING CR ACCELERATION

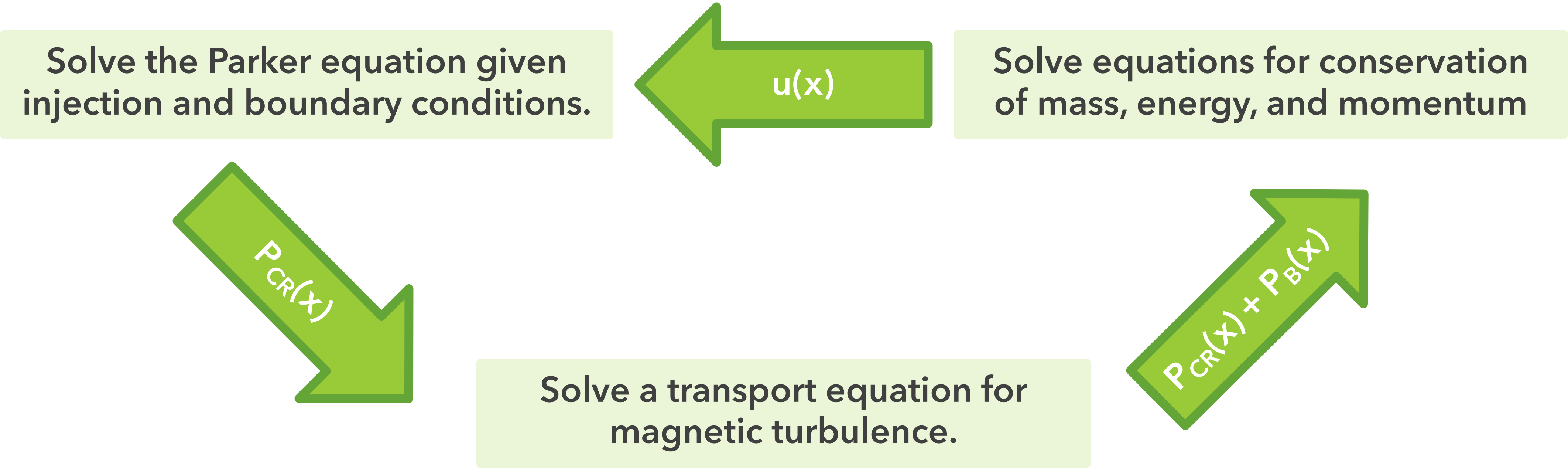
Calculate the CR proton spectrum by solving the Parker transport equation.

To include a postcursor, we consider ũ(x), the velocity of magnetic scattering centers.

$$\underbrace{\tilde{u}(x)\frac{\partial f(x,p)}{\partial x}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right]}_{\text{Diffusion}} + \underbrace{\frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f(x,p)}{\partial p}}_{\text{Adiabatic compression}} + \underbrace{Q(x,p)}_{\text{Injection}}$$

MODELING CR ACCELERATION

Use CRAFT (method paper in prep.), a semi-analytic model of non-linear DSA which self-consistently accounts for particle acceleration and magnetic field amplification.



Solve the Parker equation given injection and boundary conditions.

$u(x)$

Solve equations for conservation of mass, energy, and momentum

$P_{CR}(x)$

$P_{CR}(x) + P_B(x)$

Solve a transport equation for magnetic turbulence.

See also Amato+06, Caprioli+10; Caprioli12.

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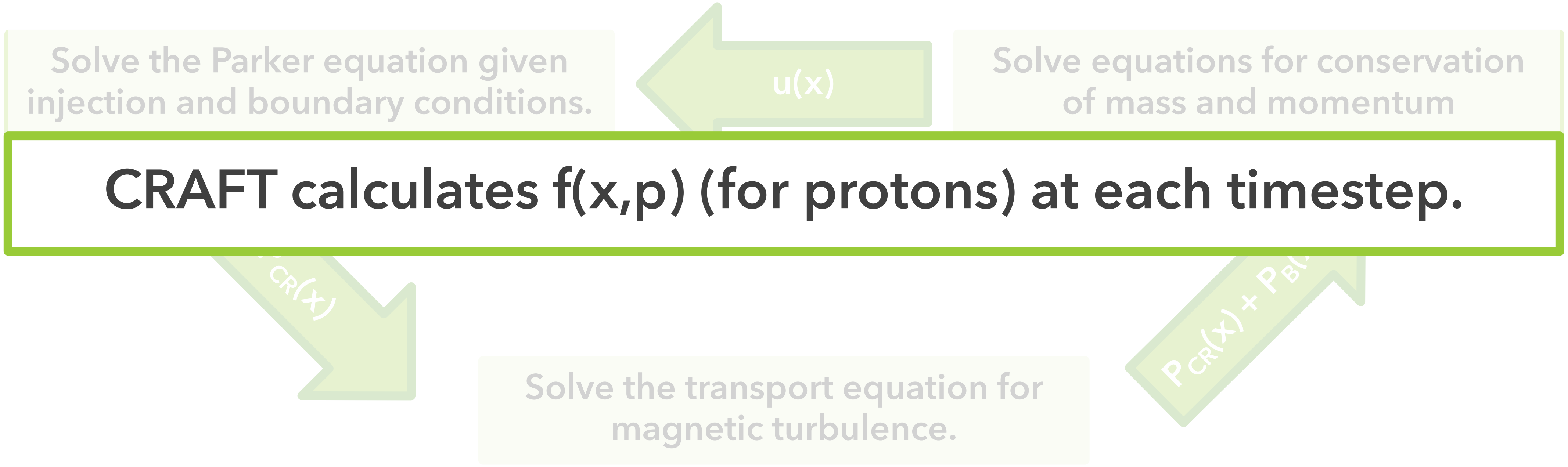


Solve the Parker equation given injection and boundary conditions.

Solve equations for conservation of mass and momentum

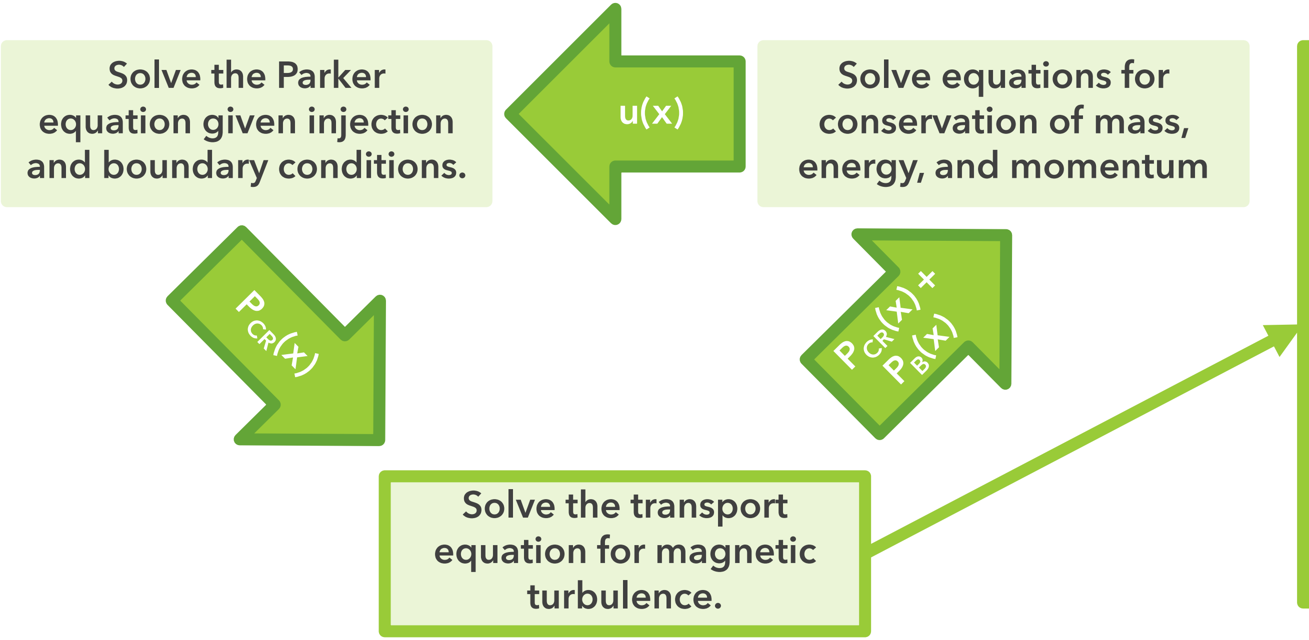
CRAFT calculates f(x,p) (for protons) at each timestep.

Solve the transport equation for magnetic turbulence.

See also Amato+06, Caprioli+10; Caprioli12.

MAGNETIC FIELD AMPLIFICATION

We model magnetic field amplification by assuming contributions from both the resonant streaming instability* and the non-resonant hybrid instability.**



Solve the Parker equation given injection and boundary conditions.

Solve equations for conservation of mass, energy, and momentum

Solve the transport equation for magnetic turbulence.

$$P_{\rm B1,res} = \frac{P_{\rm CR,1}}{4M_{\rm A,0}}$$

$$P_{\rm B1,Bell} = \frac{v_{\rm sh}}{2c}\frac{P_{\rm CR,1}}{\gamma_{\rm CR}-1}$$

$$P_{\rm B,1} = \sqrt{P^2_{\rm B1,res} + P^2_{\rm B1,Bell}}$$

*e.g., Kulsrud+69, Skilling75, Bell78, Lagage+83; **Bell04

See contribution by G. Zacharegkas (ID: 1356)

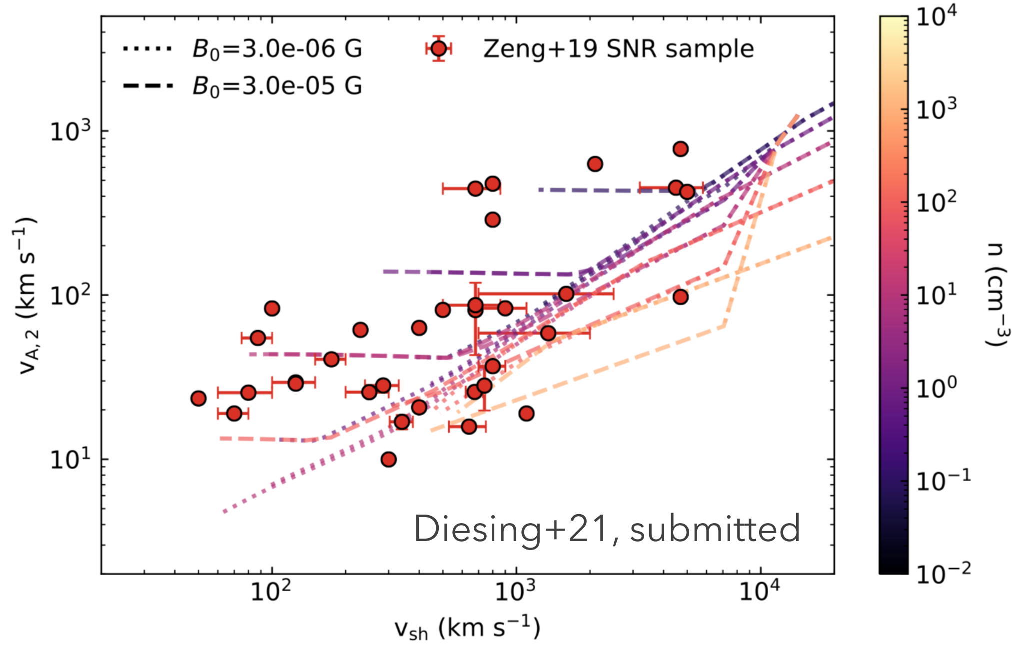
MAGNETIC FIELD AMPLIFICATION

Our model reproduces the magnetic fields inferred for young SNRs* and as well as the observed relationship between shock velocity and downstream Alfvén speed.

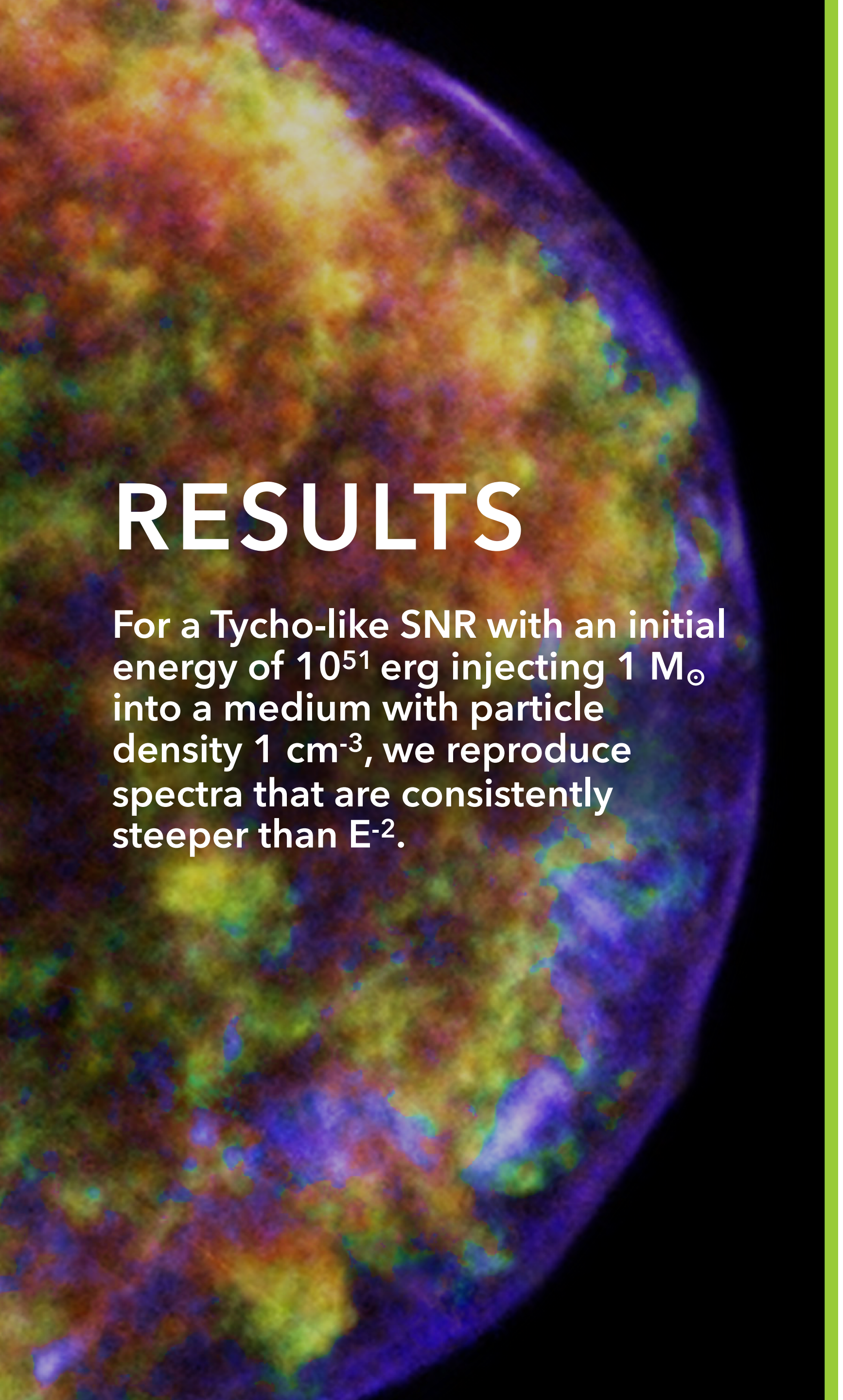
$$P_{\mathrm{B1,res}} = \frac{P_{\mathrm{CR,1}}}{4M_{\mathrm{A,0}}}$$

$$P_{\mathrm{B1,Bell}} = \frac{v_{\mathrm{sh}}}{2c}\frac{P_{\mathrm{CR,1}}}{\gamma_{\mathrm{CR}} - 1}$$

$$P_{\mathrm{B,1}} = \sqrt{P^2_{\mathrm{B1,res}} + P^2_{\mathrm{B1,Bell}}}$$

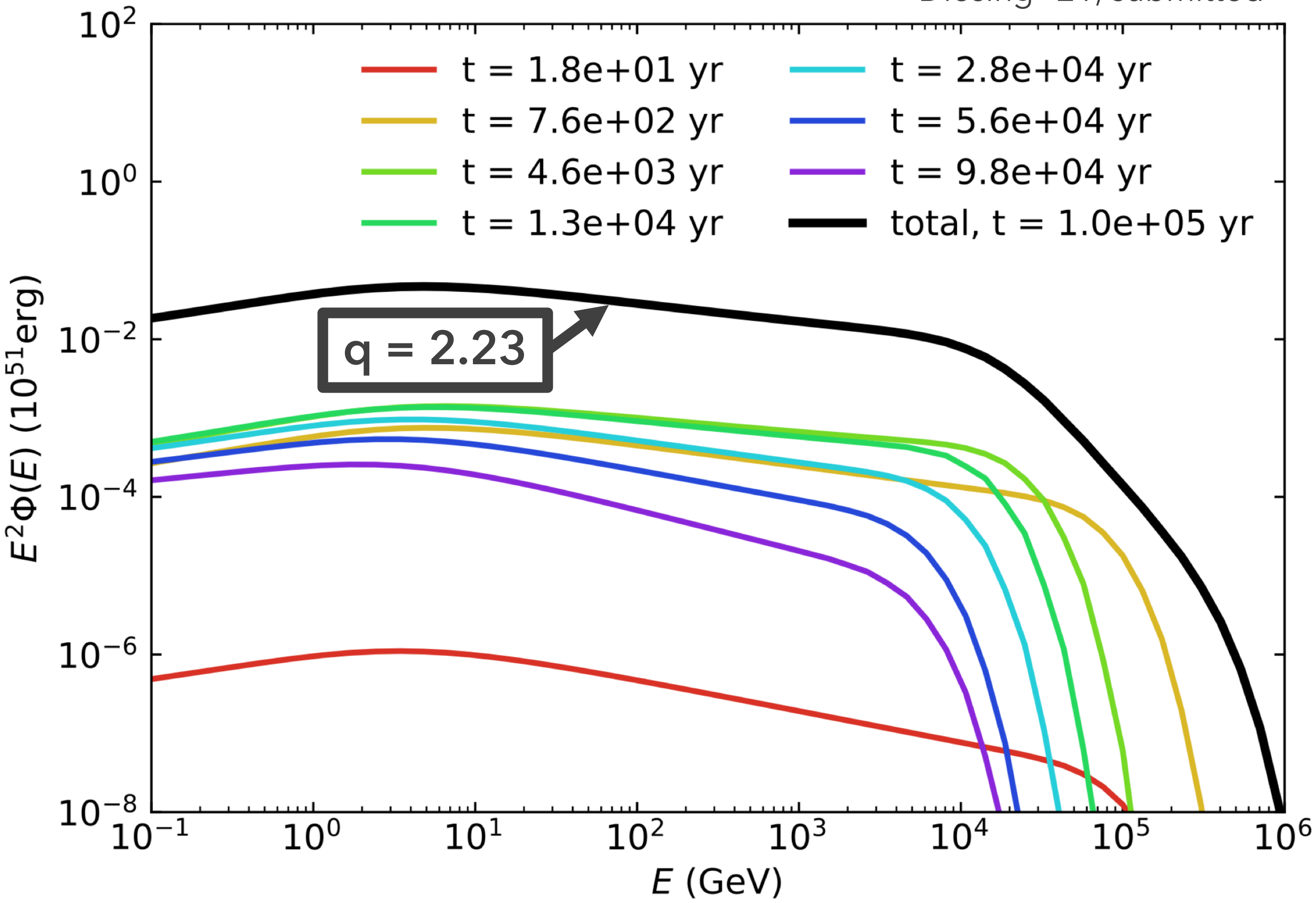


*e.g., Vink+03, Volk+05, Parizot+06, Caprioli+08, Ressler+14, Petruk+21



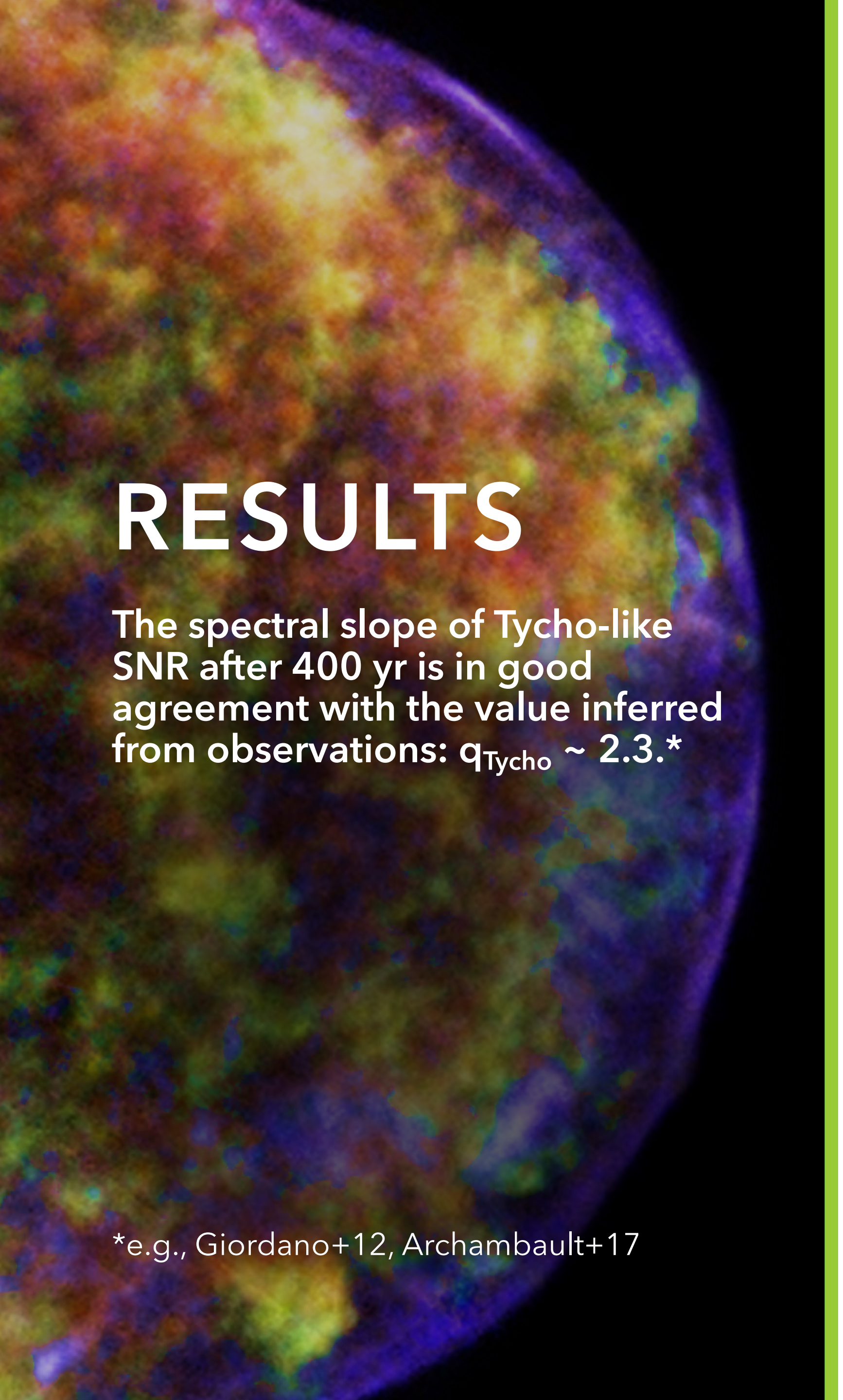
RESULTS

For a Tycho-like SNR with an initial energy of 10^{51} erg injecting 1 $M_\odot$ into a medium with particle density 1 cm^{-3}, we reproduce spectra that are consistently steeper than E^{-2}.



q = 2.23

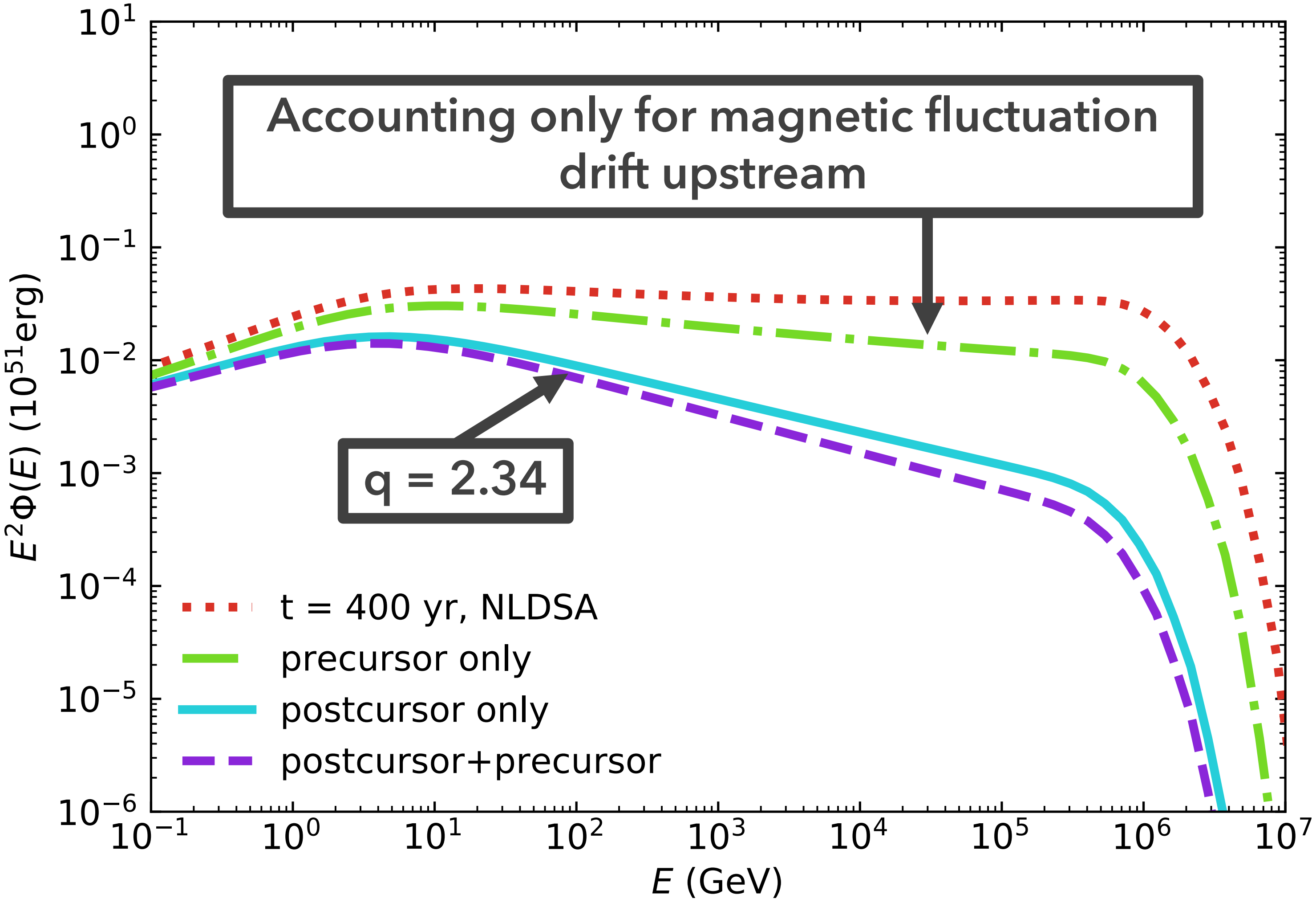
Diesing+21, submitted



RESULTS

The spectral slope of Tycho-like SNR after 400 yr is in good agreement with the value inferred from observations: q_{Tycho} ~ 2.3.*

*e.g., Giordano+12, Archambault+17



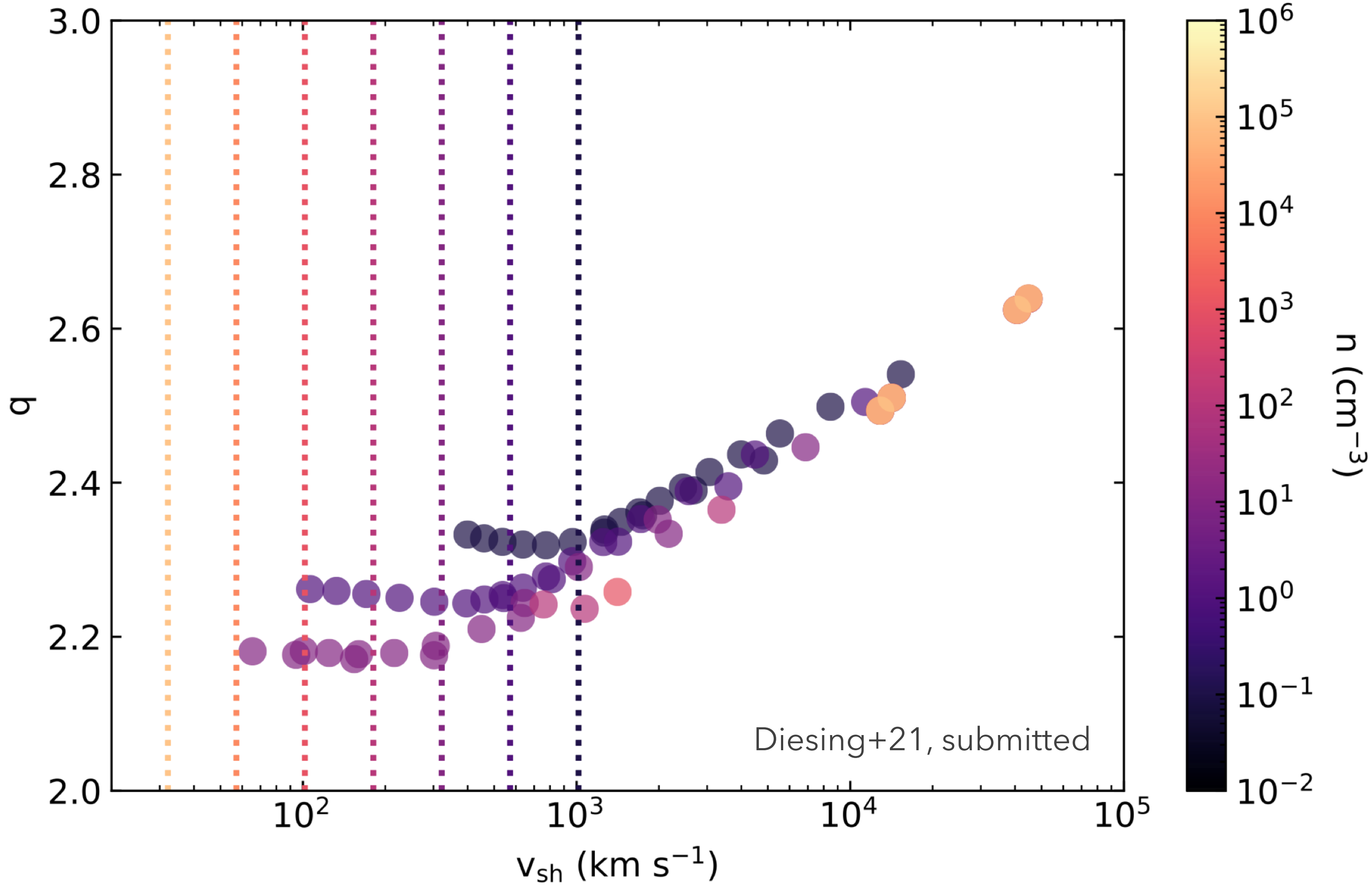
Diesing+21, submitted

Accounting only for magnetic fluctuation drift upstream

q = 2.34

RESULTS

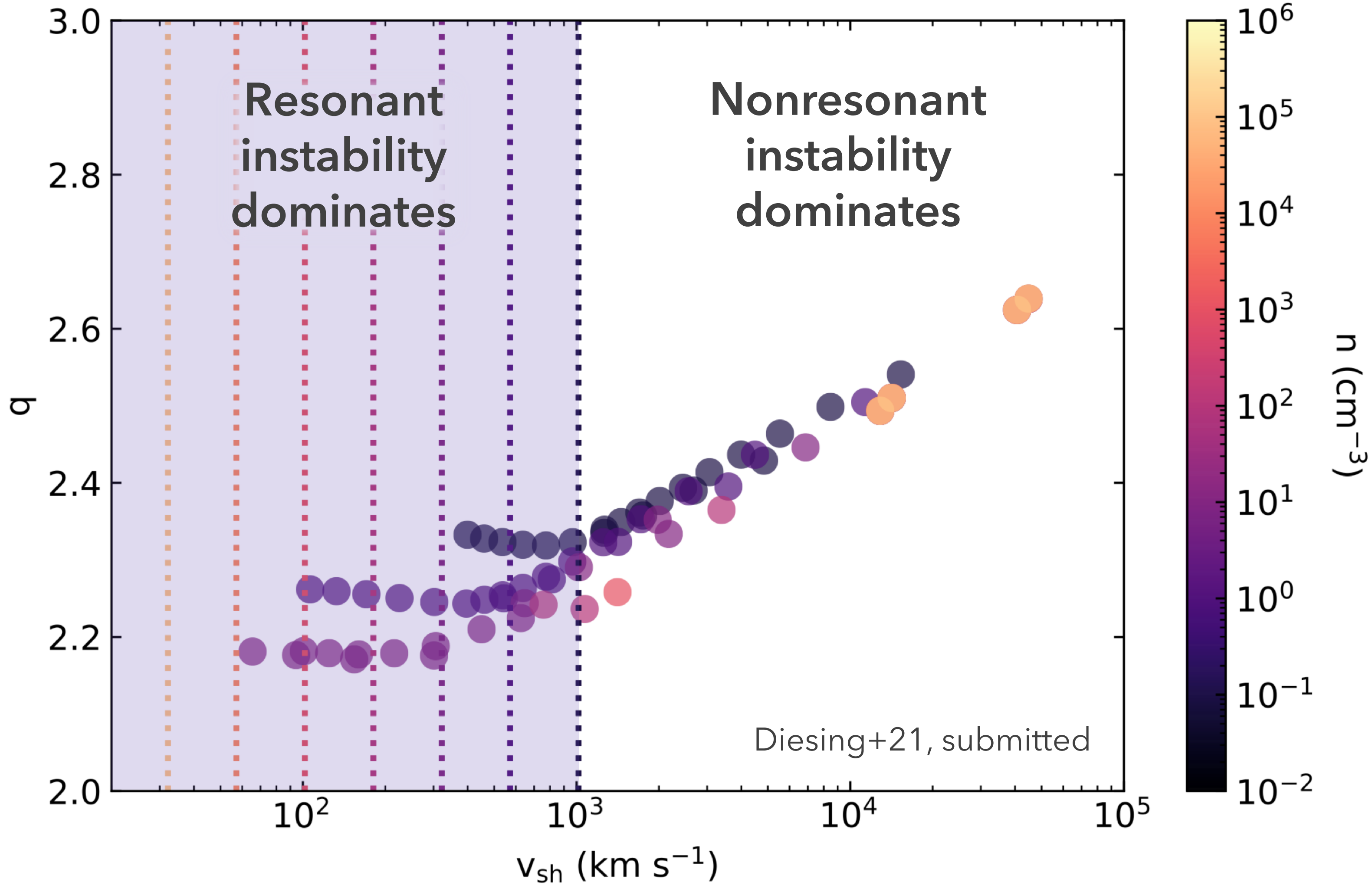
Young, fast remnants exhibit steeper spectra, up to q = 2.7 for a 3 μG ambient magnetic field.



RESULTS

Young, fast remnants exhibit steeper spectra, up to q = 2.7 for a 3 μG ambient magnetic field.

This relationship disappears for slow shocks, i.e., when the resonant instability dominates.

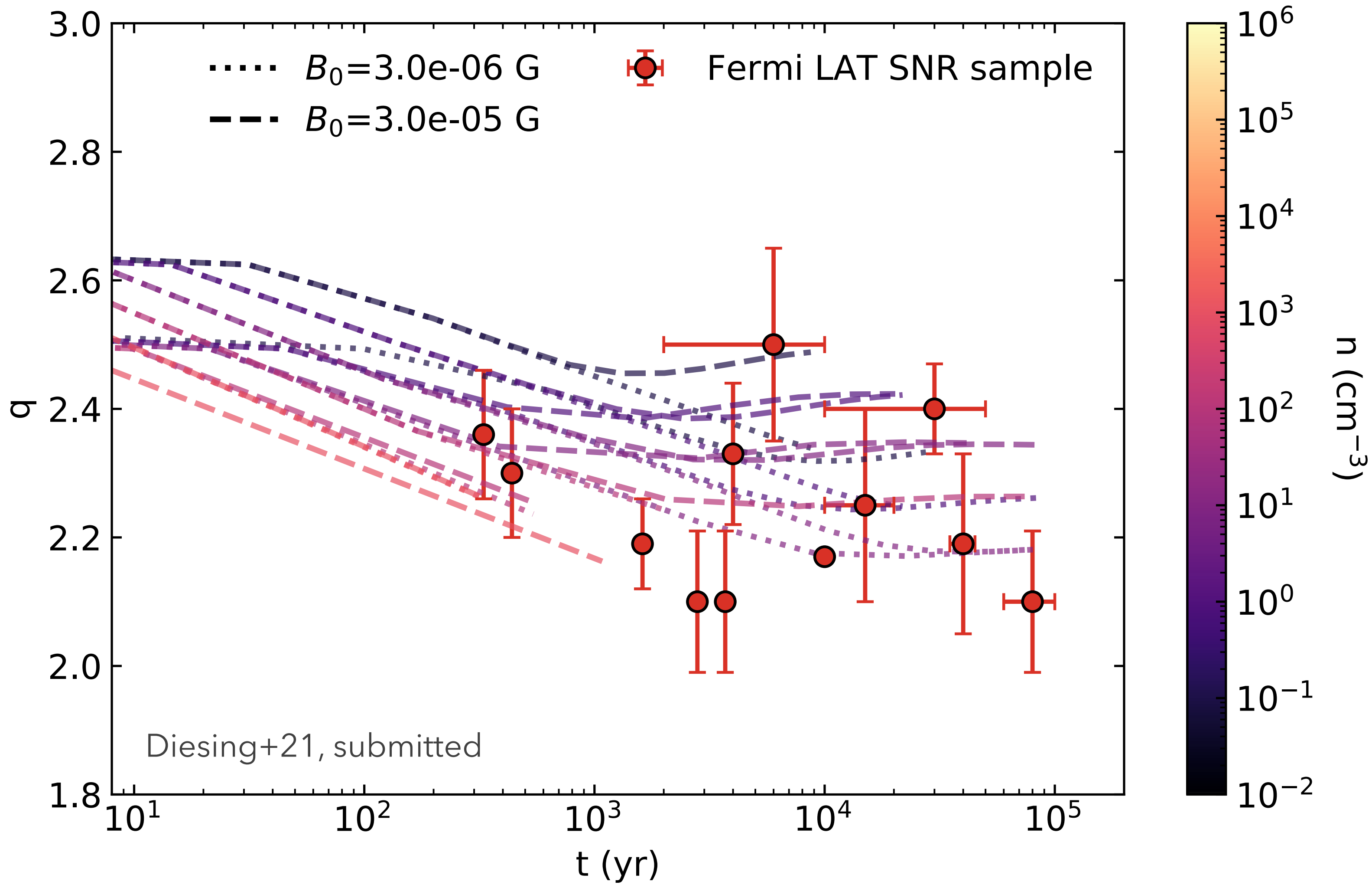


Diesing+21, submitted

COMPARISON TO OBSERVATIONS:

GALACTIC SNRS

Our modeled spectra produce good agreement with the spectra of Galactic SNRs (see Caprioli11).

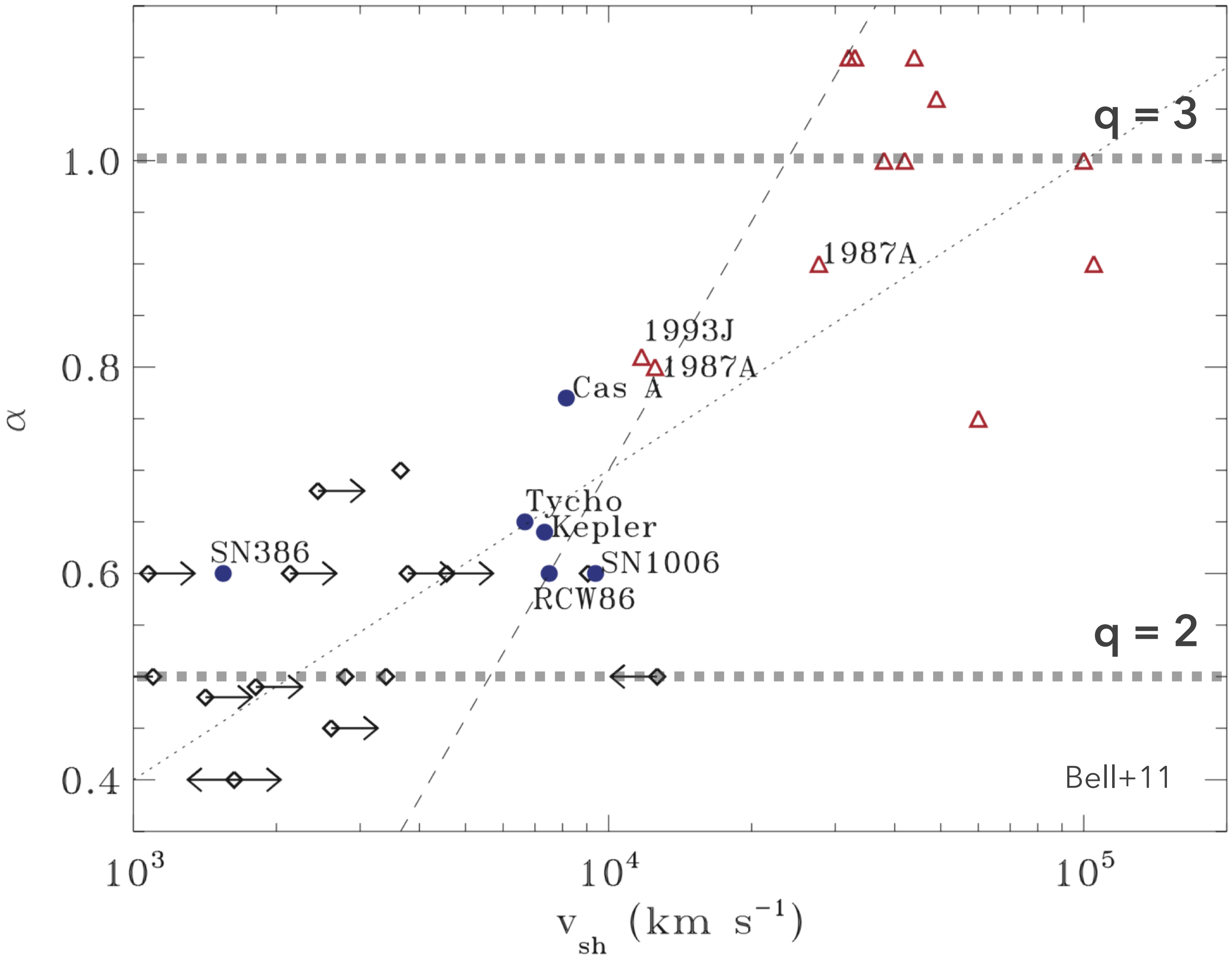


COMPARISON TO OBSERVATIONS:

RADIO SNE

Young, fast supernovae are inferred to have very steep spectra (q ~ 3).*

*e.g., Chevalier+06, Chevalier+17, Soderberg+10, Soderberg+12, Bell+11 Kamble+16, Terreran+19



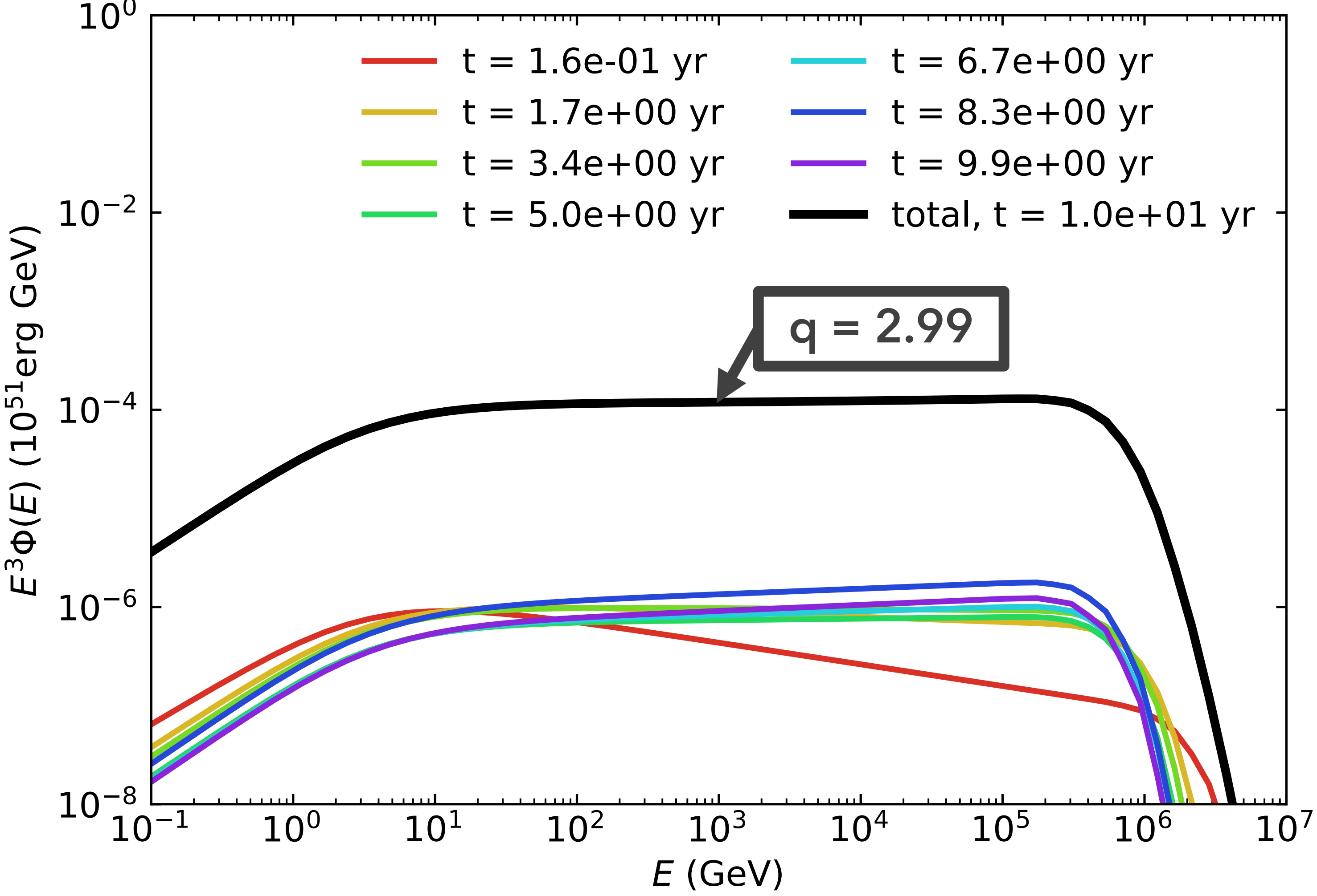
COMPARISON TO OBSERVATIONS:

RADIO SNE

Our toy-model radio supernova (i.e., a young, fast SNR expanding into a dense wind) yields a spectrum ∝ E^{-3}, consistent with observations.*

*e.g., Chevalier+06, Chevalier+17, Soderberg+10, Soderberg+12, Bell+11 Kamble+16, Terreran+19

Diesing+21, submitted



ULTRA-FAST OUTFLOWS

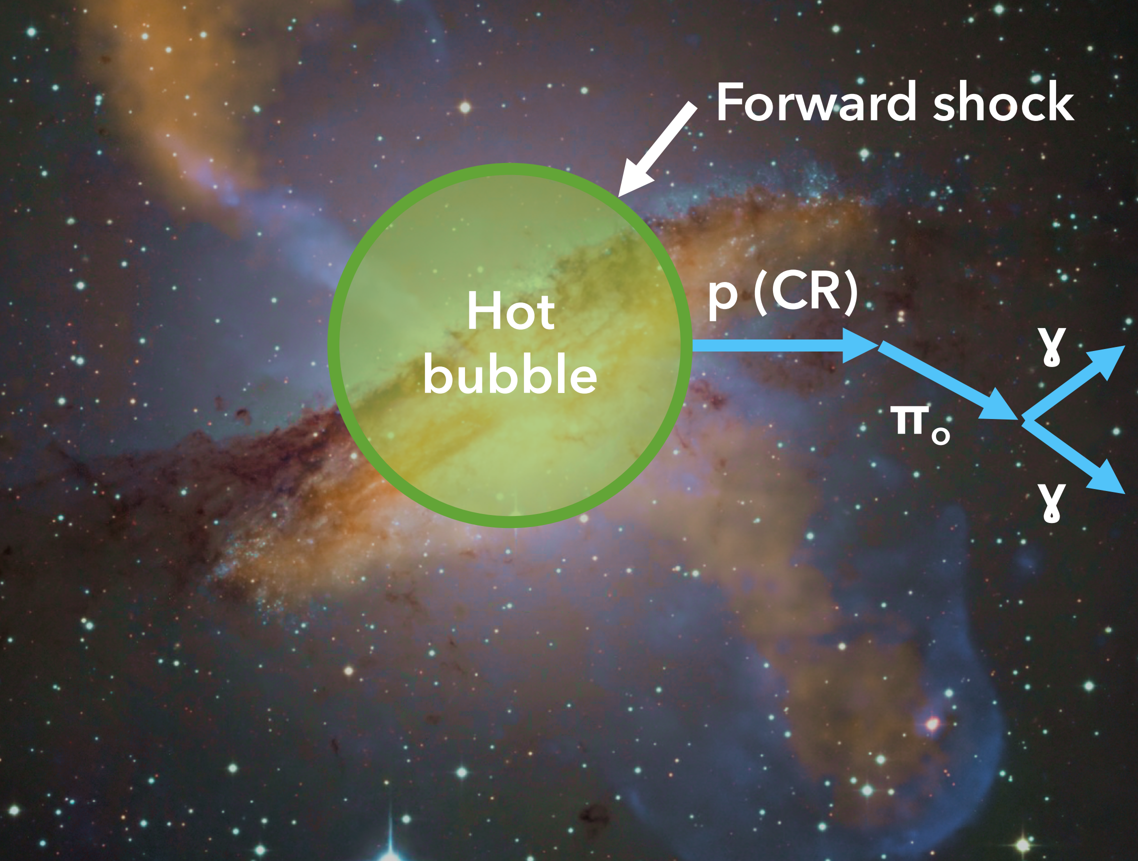
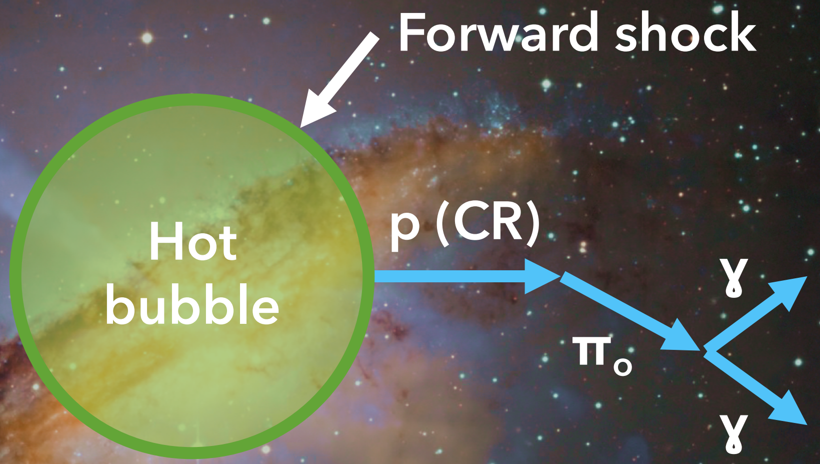


Image: Centaurus A; Credit: ESO/WFI (optical); MPFIR/ESO/APEX/A. Weiss et al. (submillimeter); NASA/CXC/CFA/R. Kraft et al. (x-ray)

ULTRA-FAST OUTFLOWS

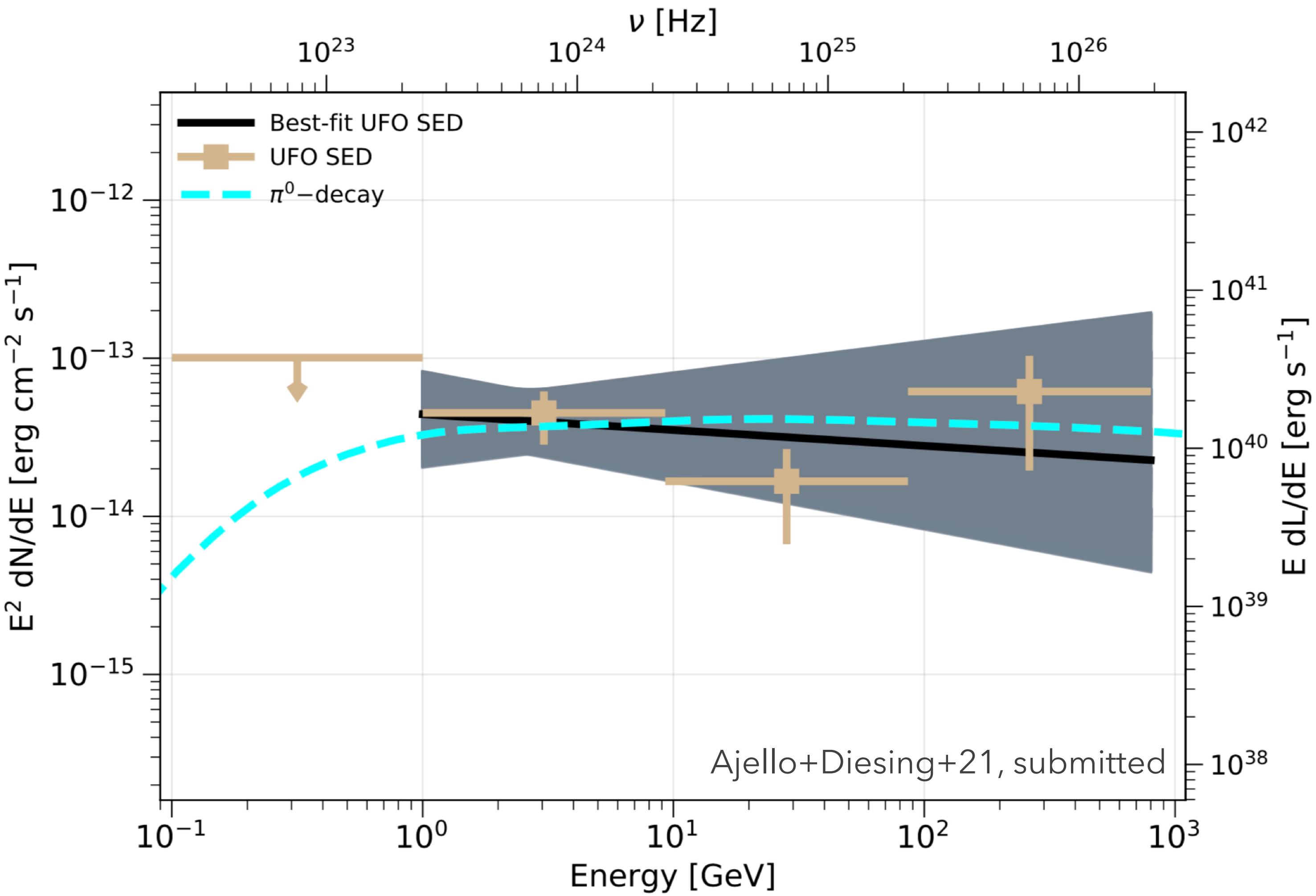


Fermi-LAT detected γ-rays from UFOs in a stacked sample of AGN.*
*Ajello+Diesing+21, submitted; see also contribution by C. Karwin (ID: 109)

Image: Centaurus A; Credit: ESO/WFI (optical); MPFIR/ESO/APEX/A. Weiss et al. (submillimeter); NASA/CXC/CFA/R. Kraft et al. (x-ray)

ULTRA-FAST OUTFLOWS

CRAFT was able to reproduce the stacked ɣ-ray SED.



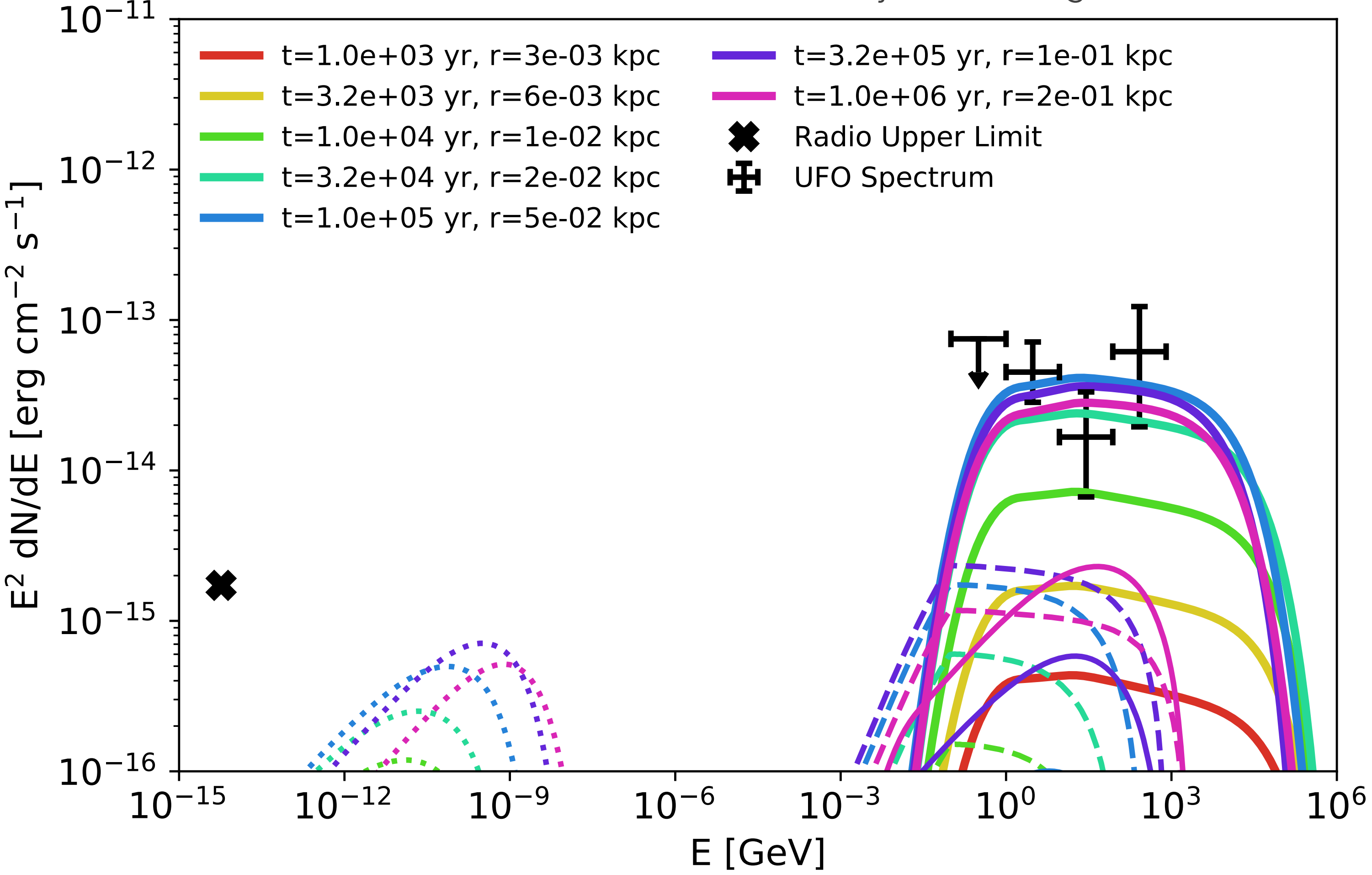
Ajello+Diesing+21, submitted

ULTRA-FAST OUTFLOWS

CRAFT was able to reproduce the stacked ɣ-ray SED.

CRAFT can also predict a UFO's multiwavelength emission as a function of time.

Ajello+Diesing+21, submitted



SUMMARY

1. **We modeled CR acceleration in SNRs while self-consistently accounting for the effect of a *postcursor*, or downstream region in which magnetic fluctuations and CRs drift away from the shock with respect to the background fluid.**

2. **We find that the presence of a postcursor substantially steepens CR spectra, with q ~ 2.3 for a "typical" SNR.**
   This steepening is enhanced in faster shocks.

3. **Our model reproduces the modestly steep spectra of Galactic SNRs (q ~2.3) and the very steep spectra of radio SNe (q ~ 3).**
   This result implies that the presence of a postcursor may resolve the tension between DSA predictions and observations.

For more information, please see Diesing+21 (arXiv:2107.08520).