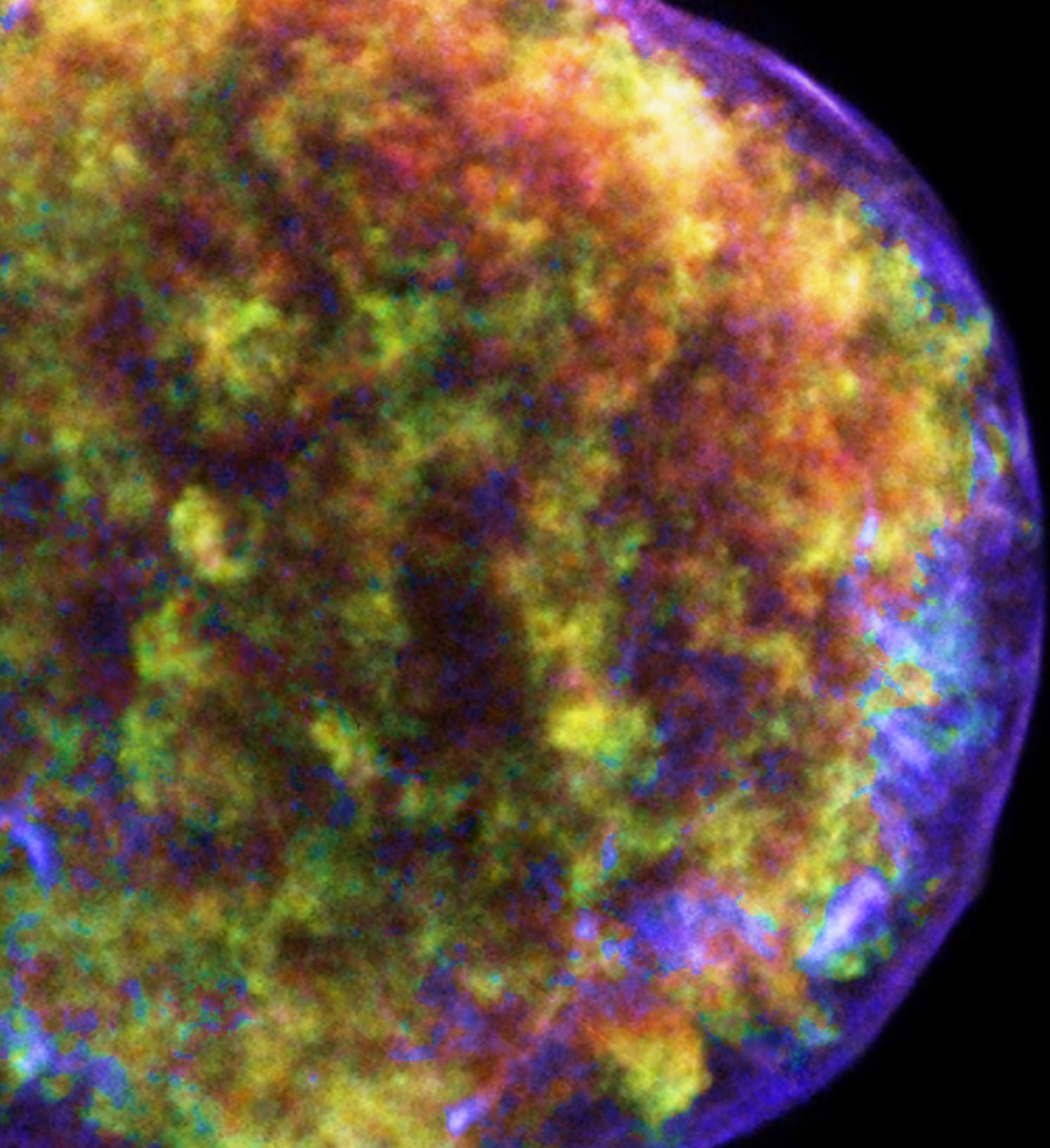


FROM MICROPHYSICAL THEORY TO MULTI-MESSENGER OBSERVATIONS:

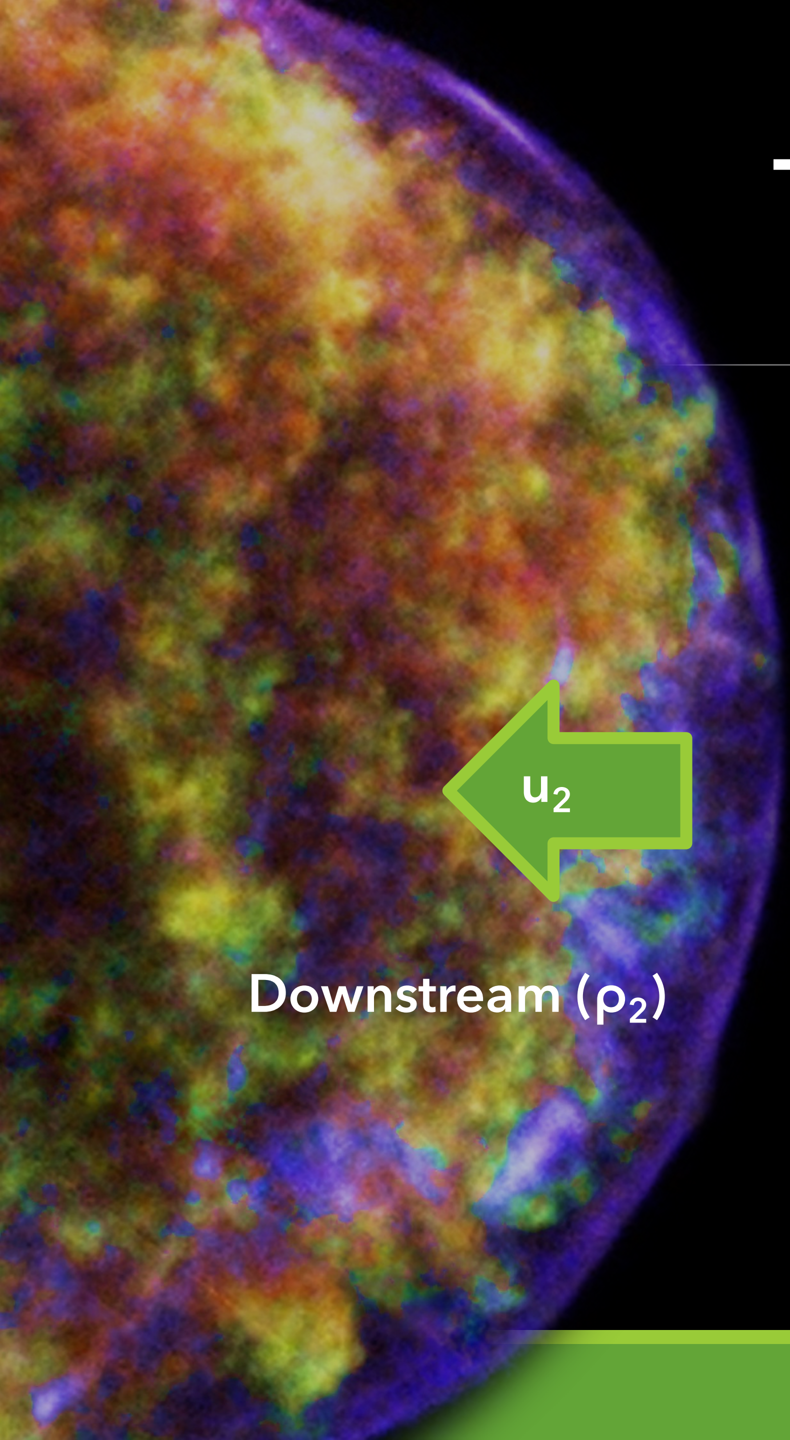
A SEMI-ANALYTIC APPROACH TO COSMIC RAY ACCELERATION

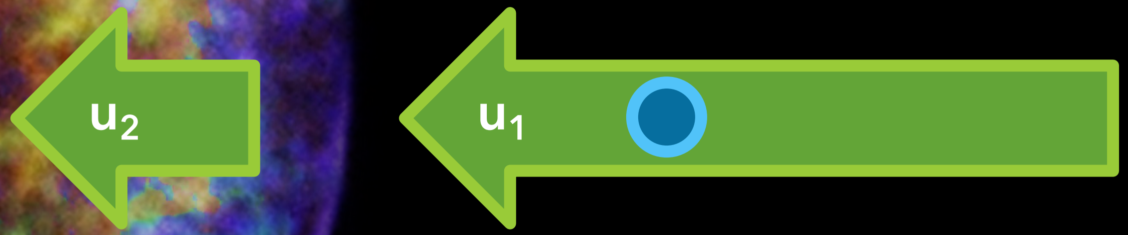
REBECCA DIESING

TEVPA | AUGUST 27, 2024

THE STANDARD PARADIGM OF SHOCK ACCELERATION

Protons and electrons are accelerated via diffusive shock acceleration (DSA).*





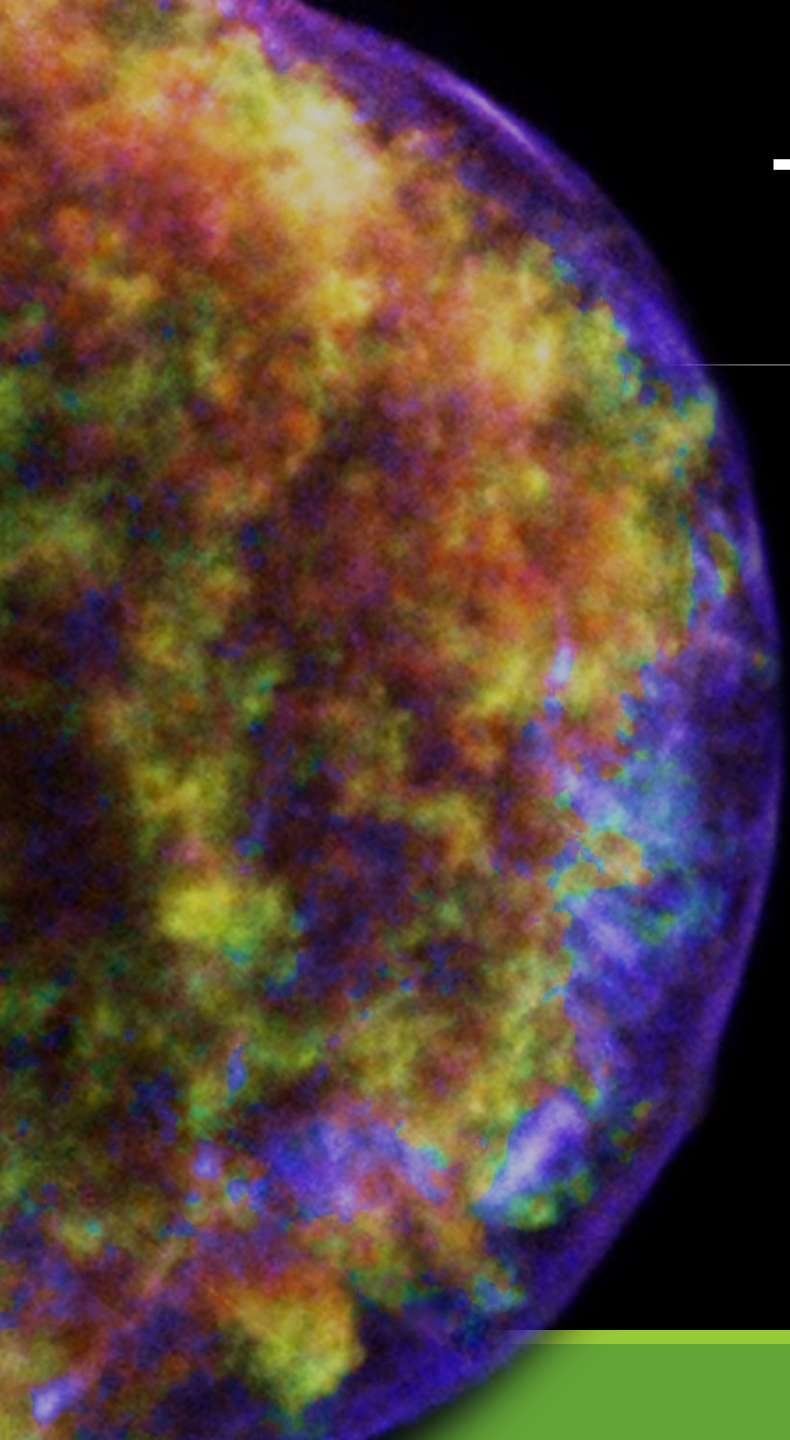
Downstream (ρ_2)

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 particles.*

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

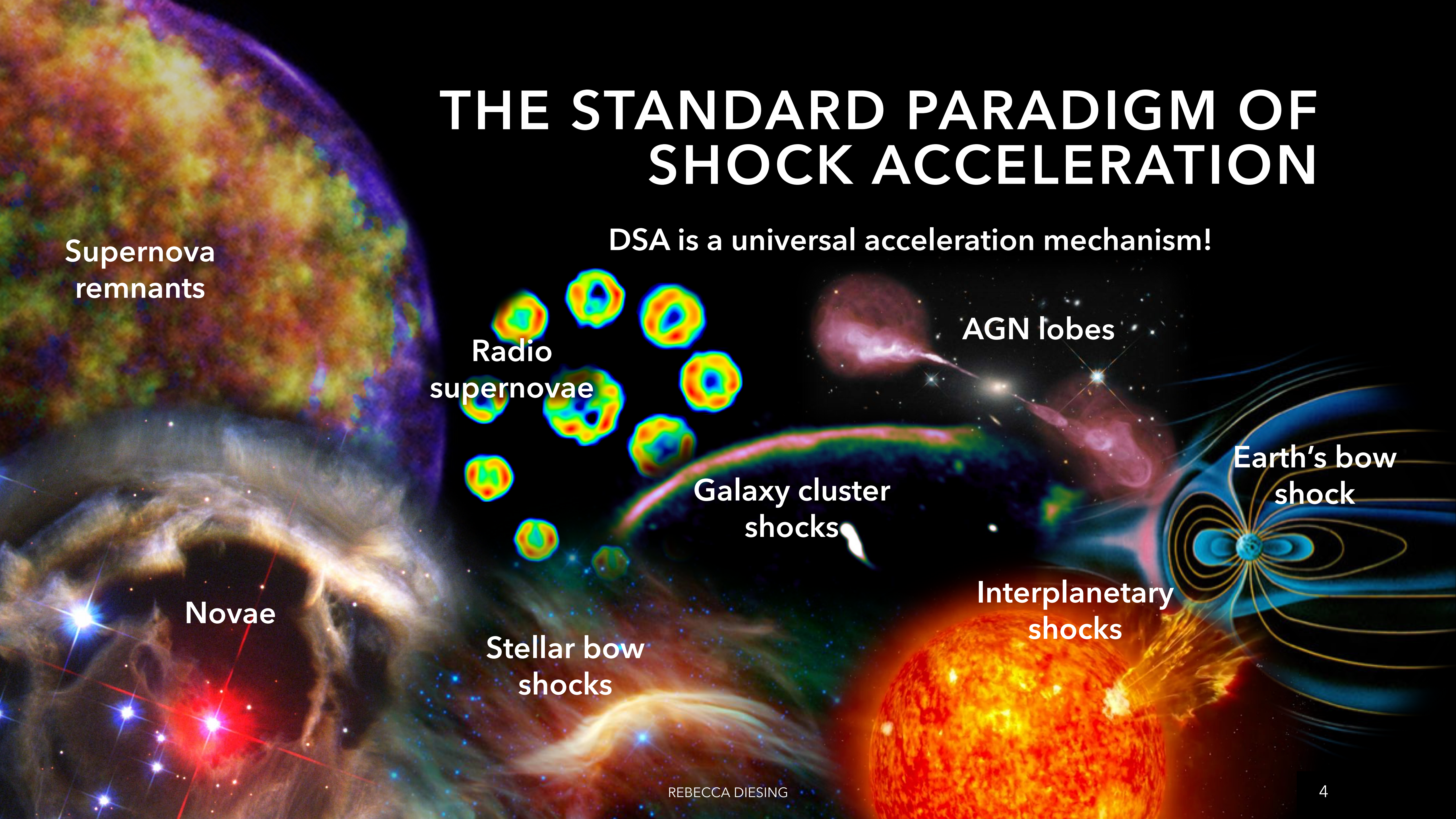
$$q = \frac{R+2}{R-1}$$

For strong shocks, **q = 2**.

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

THE STANDARD PARADIGM OF SHOCK ACCELERATION

DSA is a universal acceleration mechanism!



THE PROBLEM WITH DSA

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

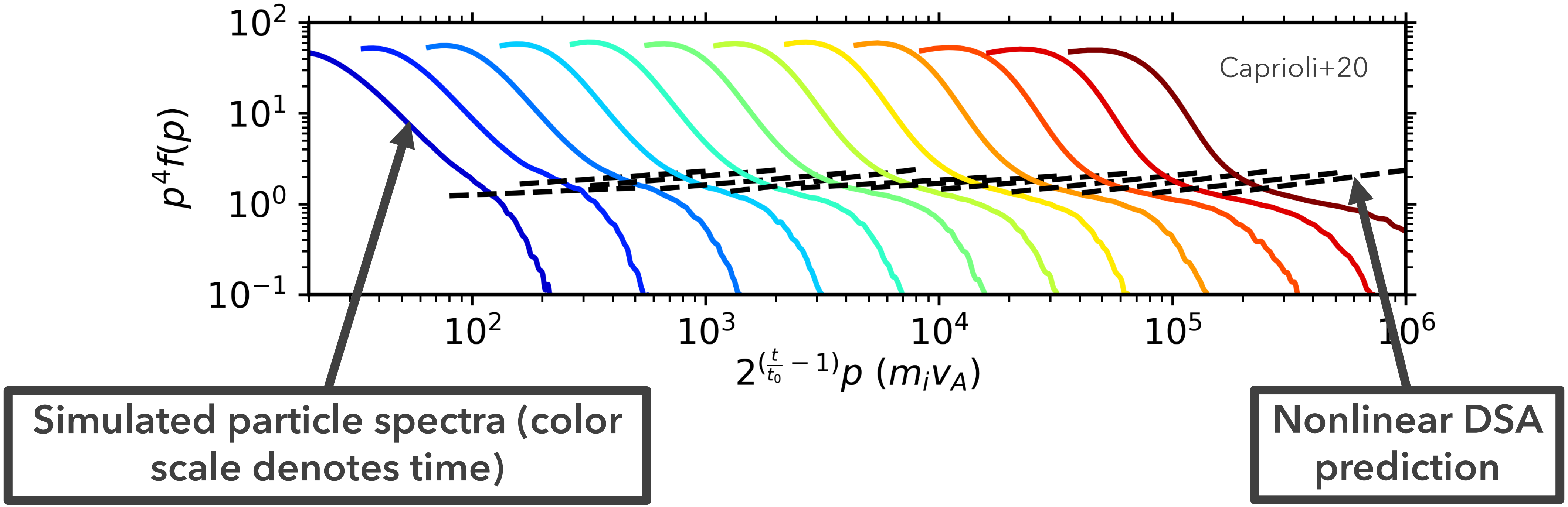
1. **ɣ-ray emission from Galactic SNRs suggest $2.2 \lesssim q \lesssim 2.6$.**
   e.g., Caprioli11, Giordano+12, Saha+14, Aharonian+19

2. **Radio emission from young extragalactic SNe (radio SNe) suggest $q \approx 3$.**
   e.g., Chevalier+06, Chevalier+17, Soderberg+10, Soderberg+12, Kamble+16, Terreran+19

3. **Observations of Galactic CRs require $2.3 \lesssim q \lesssim 2.4$.**
   e.g., Evoli+19

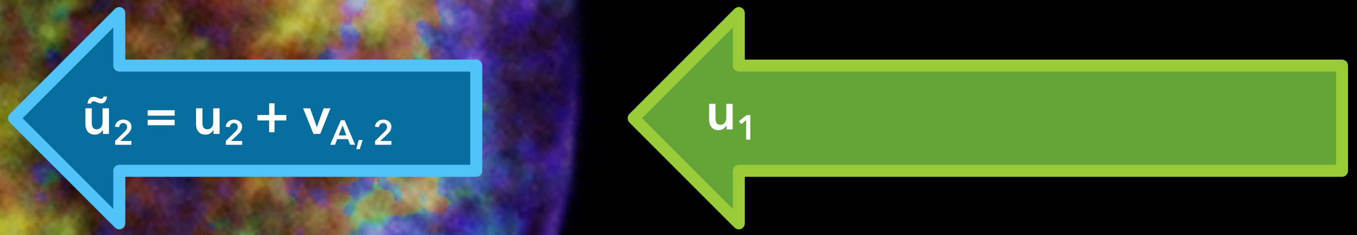
STEEP SPECTRA IN SIMULATIONS

Kinetic simulations performed in Haggerty+20 and Caprioli+20 naturally reproduce steep spectra.



THE “POSTCURSOR”

Magnetic fluctuations generated by cosmic rays (CRs) 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.

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.

MODELING CR 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.

$$\tilde{u}(x)\frac{\partial f(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right] + \frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f(x,p)}{\partial p} + Q(x,p)$$

Advection — Diffusion — Adiabatic compression — Injection

MODELING CR ACCELERATION

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

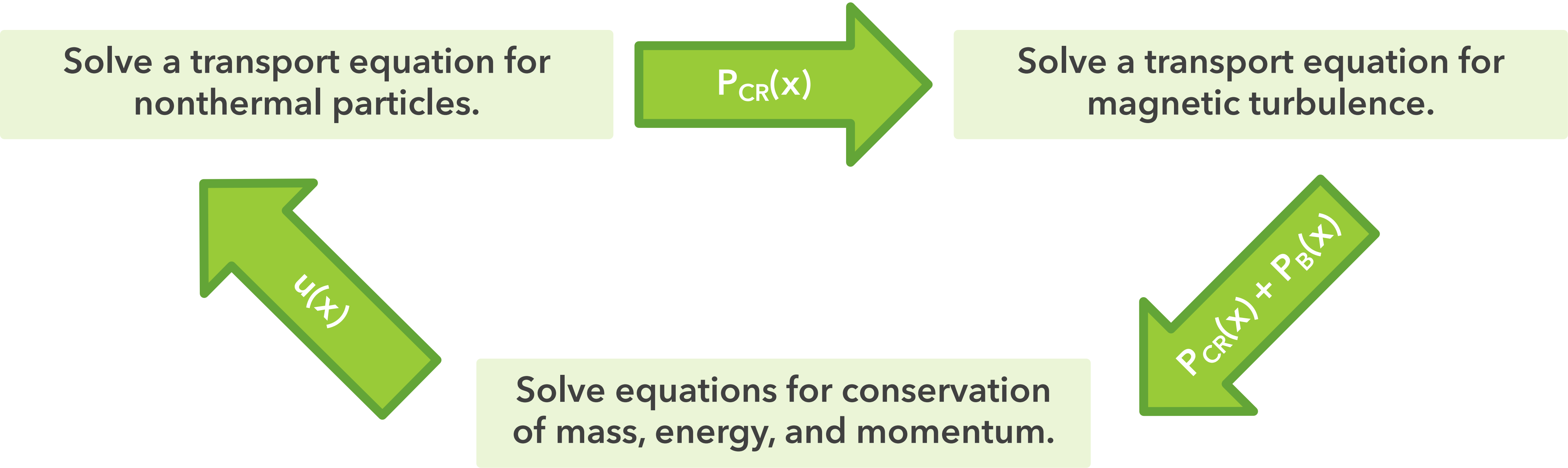
To include a postcursor, we consider ũ(x), the velocity of magnetic scattering centers.

$$\tilde{u}(x)\frac{\partial f(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right] + \frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f(x,p)}{\partial p} + Q(x,p)$$

Advection — Diffusion — Adiabatic compression — Injection

MODELING CR ACCELERATION

Use a semi-analytic model of non-linear DSA which self-consistently accounts for particle acceleration and magnetic field amplification.



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

MODELING CR ACCELERATION

Use a semi-analytic model of non-linear DSA which self-consistently accounts for particle acceleration and magnetic field amplification.

Solve a transport equation for

Solve a transport equation for

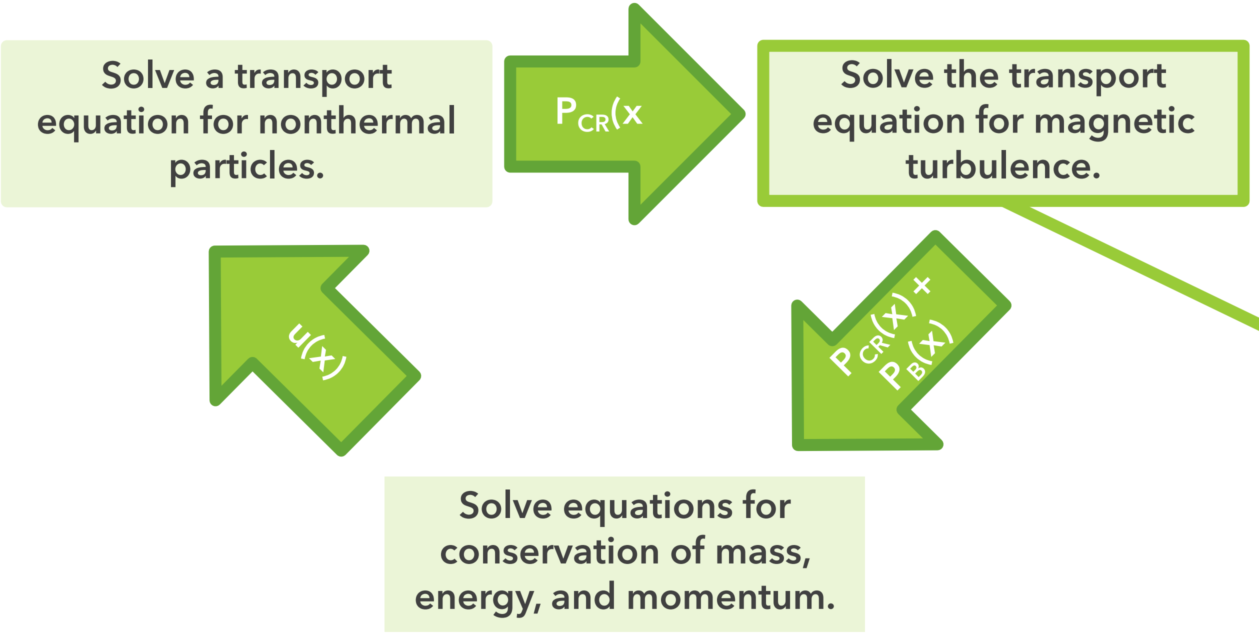
This model calculates the instantaneous proton spectrum, f(x,p), at each timestep. These spectra can be converted to electron spectra and weighted to account for energy losses.

Solve equations for conservation of mass, energy, and momentum.

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 (Bell) instability.**

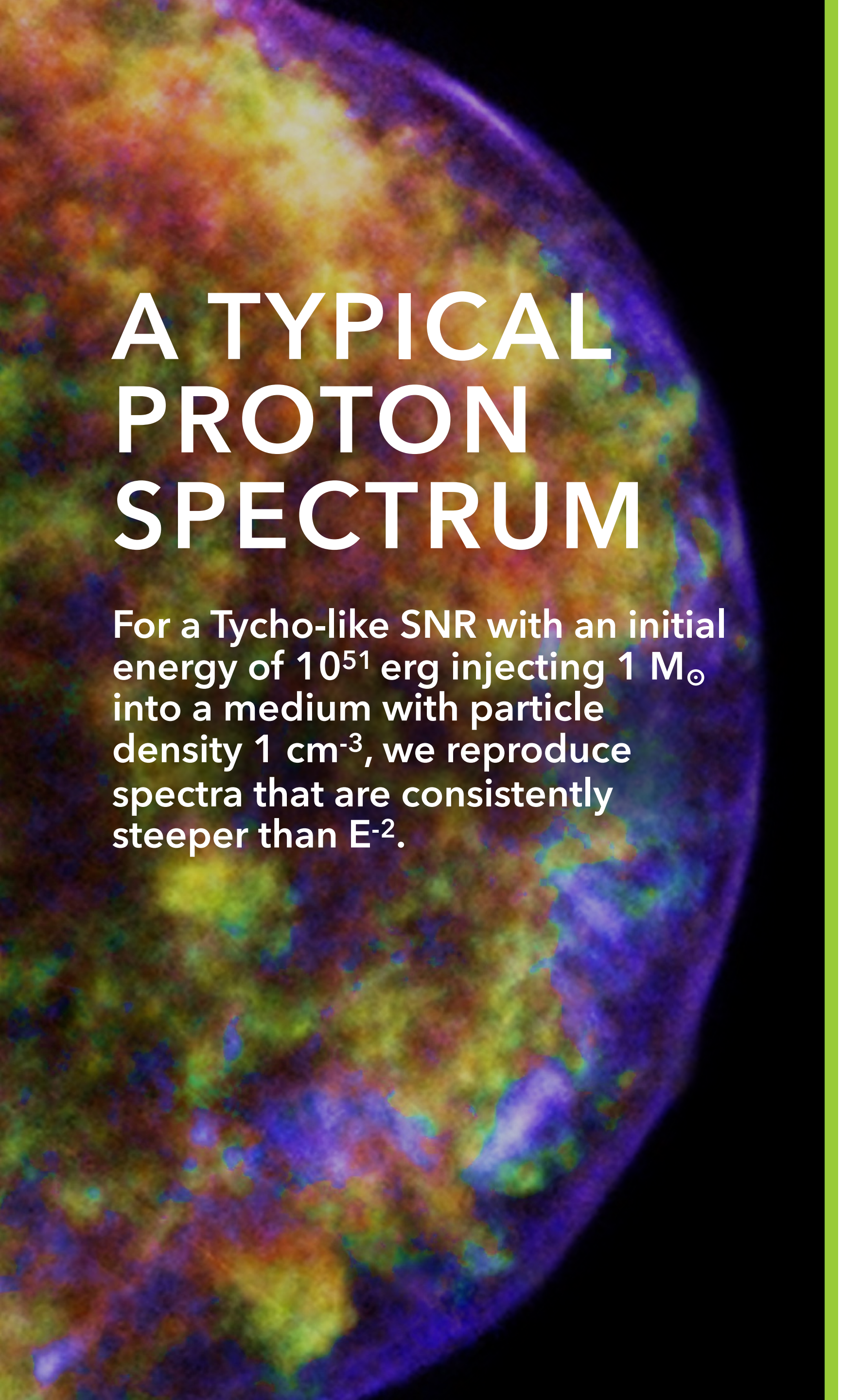


For fast shocks characteristic of SNRs, the Bell instability dominates

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

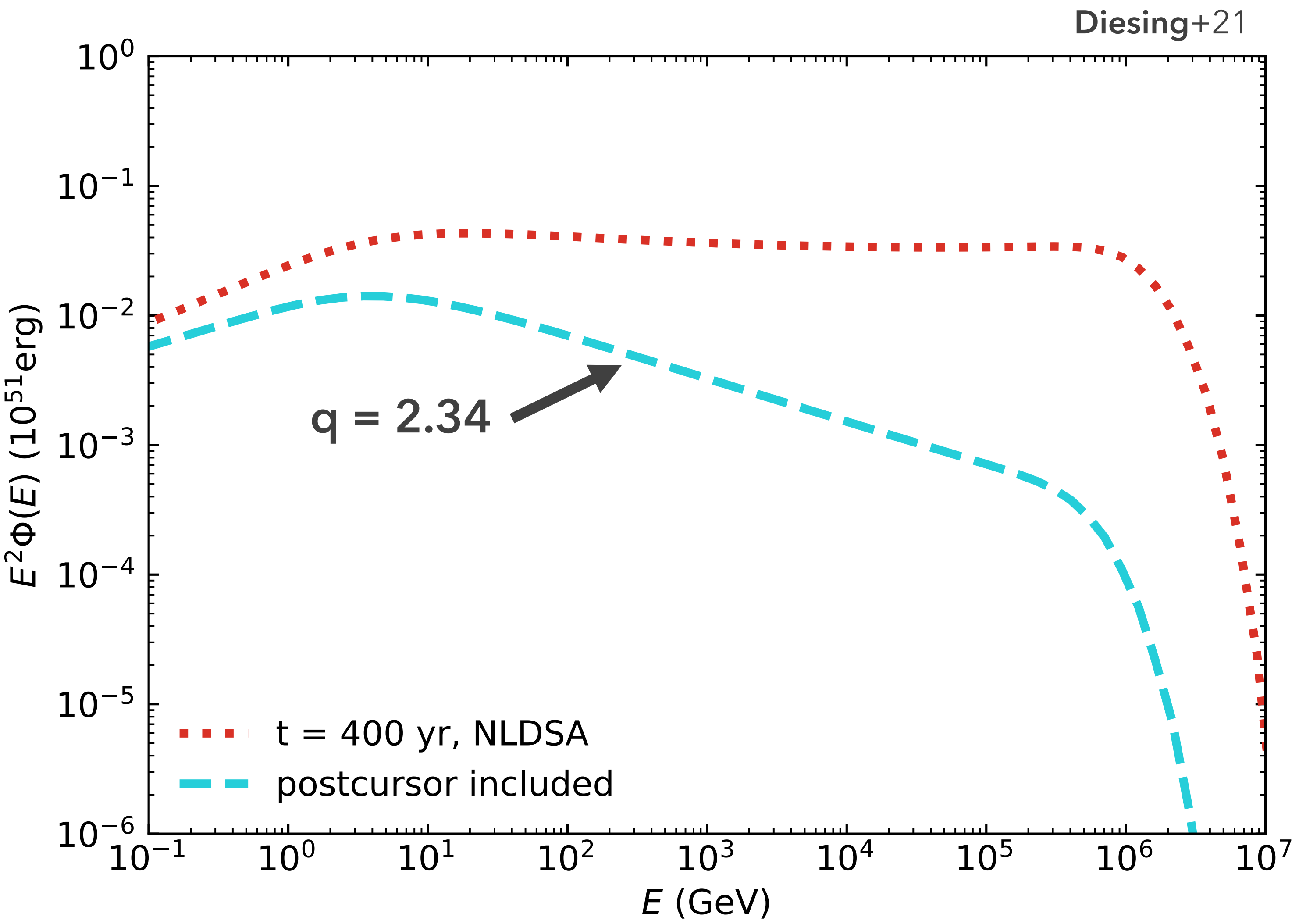
fast shocks → steep spectra

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



A TYPICAL PROTON SPECTRUM

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}.

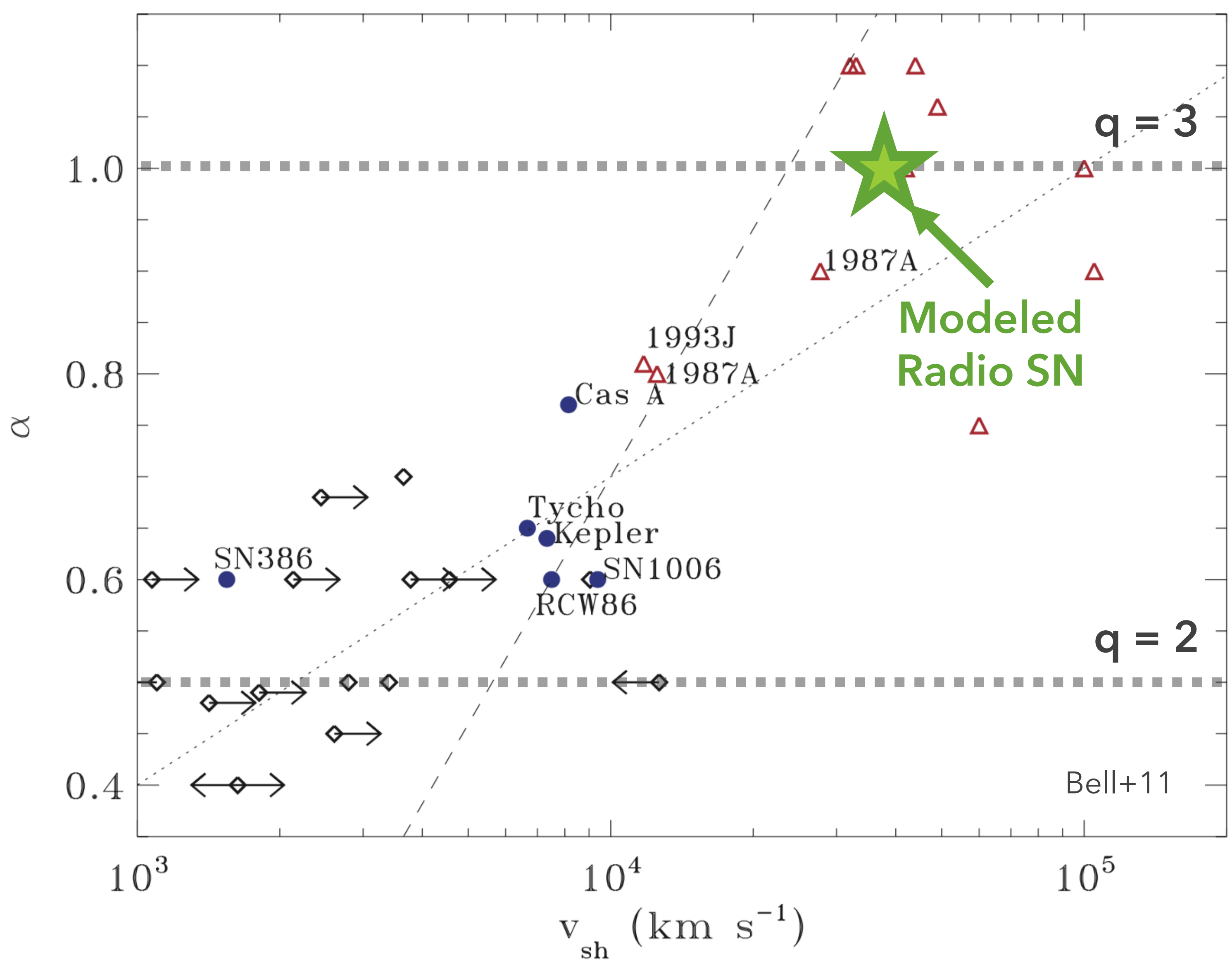


RADIO SUPERNOVAE

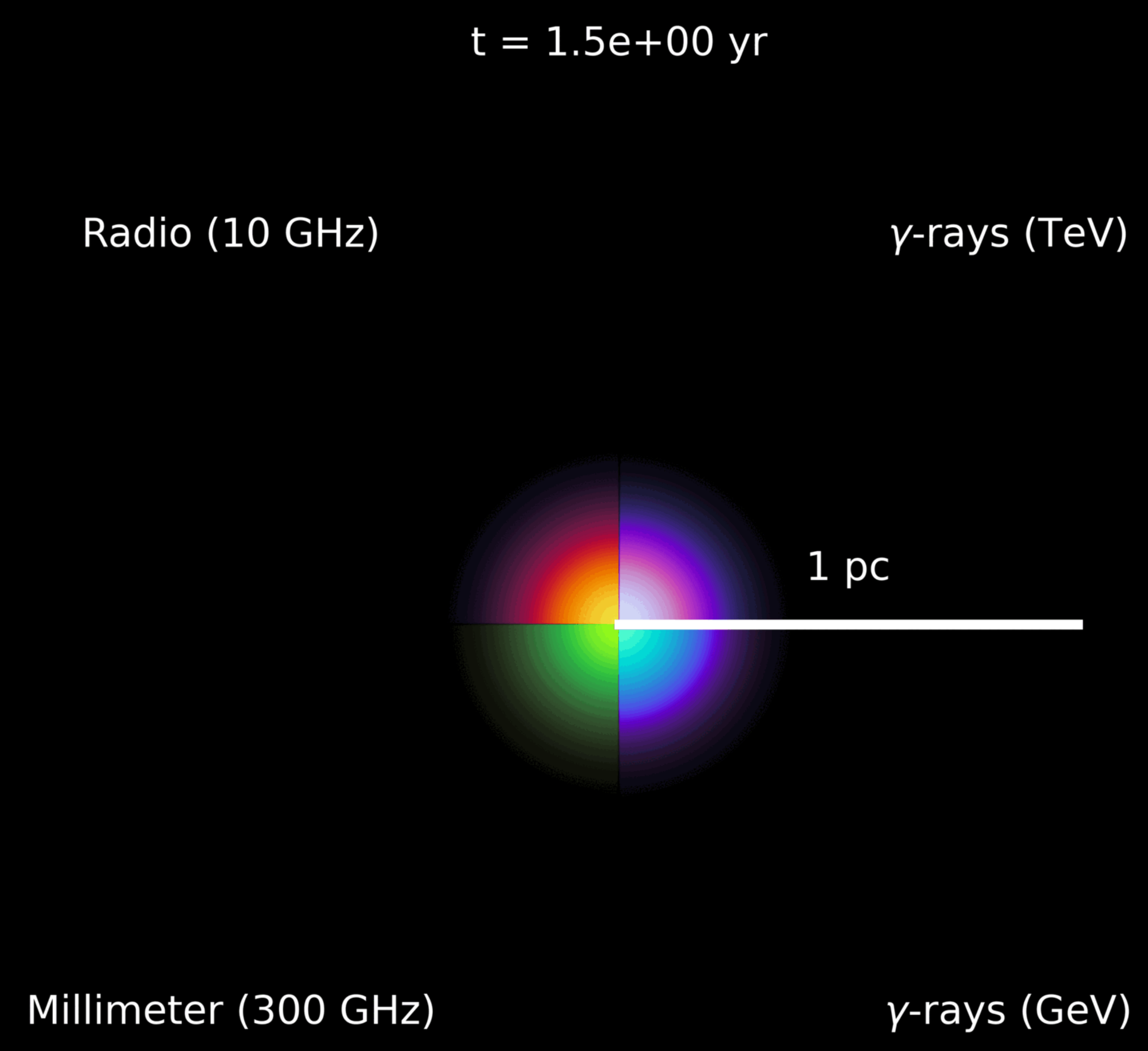
Young, fast supernovae are inferred to have very steep spectra (q ~ 3).*

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



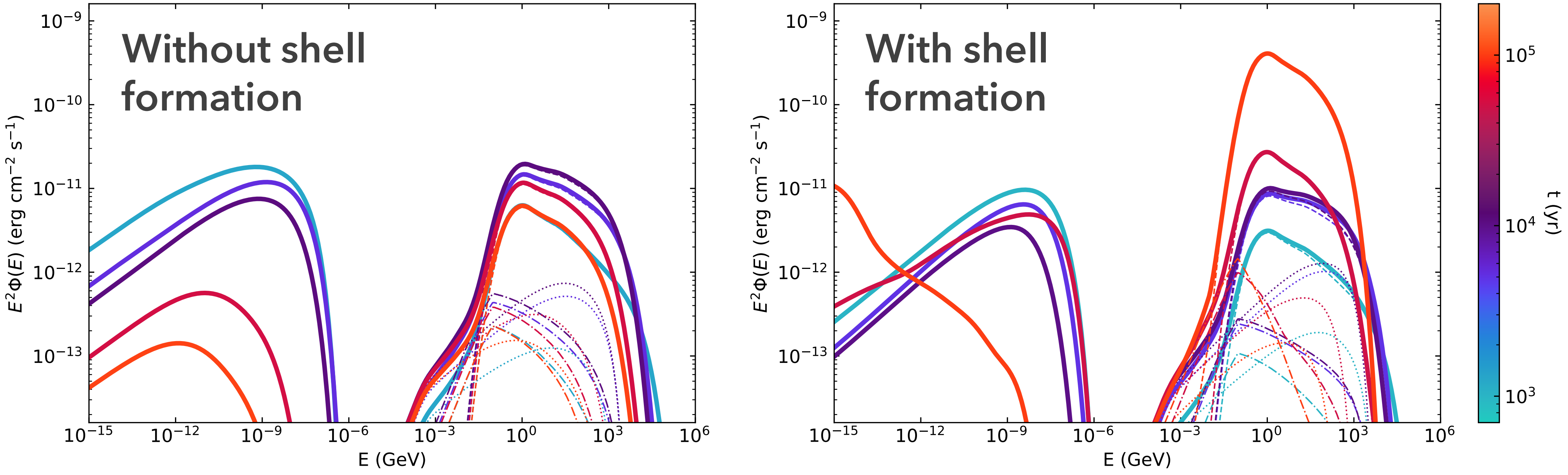
FROM PARTICLE ACCELERATION TO MULTI-WAVELENGTH EMISSION



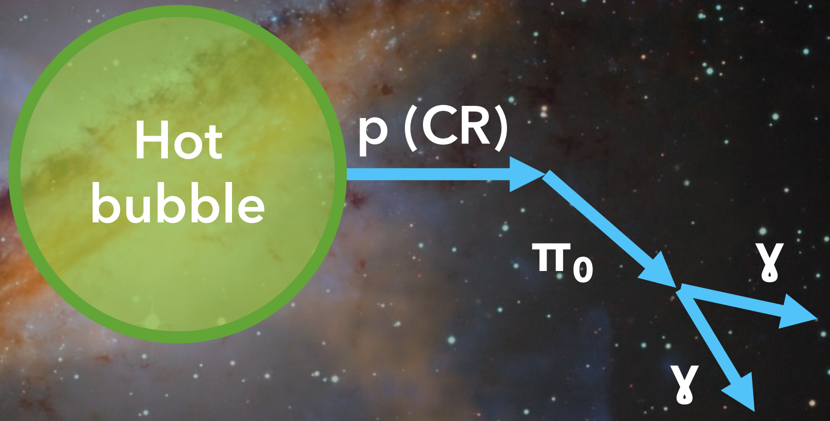
RADIATIVE SUPERNOVA REMNANTS

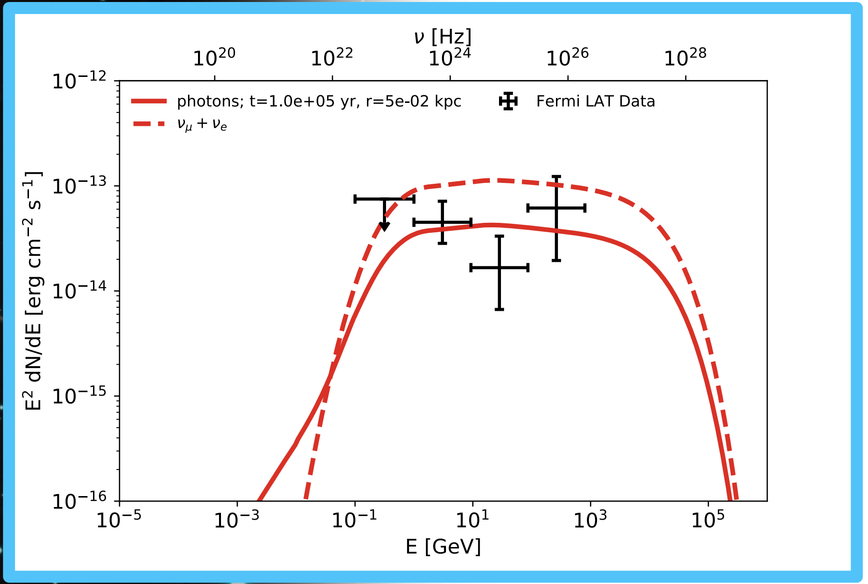
Hydrodynamic models predict the formation of a dense shell near the end of an SNR's life (after a few tens of thousands of years). This shell formation gives rise to observable nonthermal signatures, including a significant rebrightening.

Diesing+24 (in review)



AGN WINDS



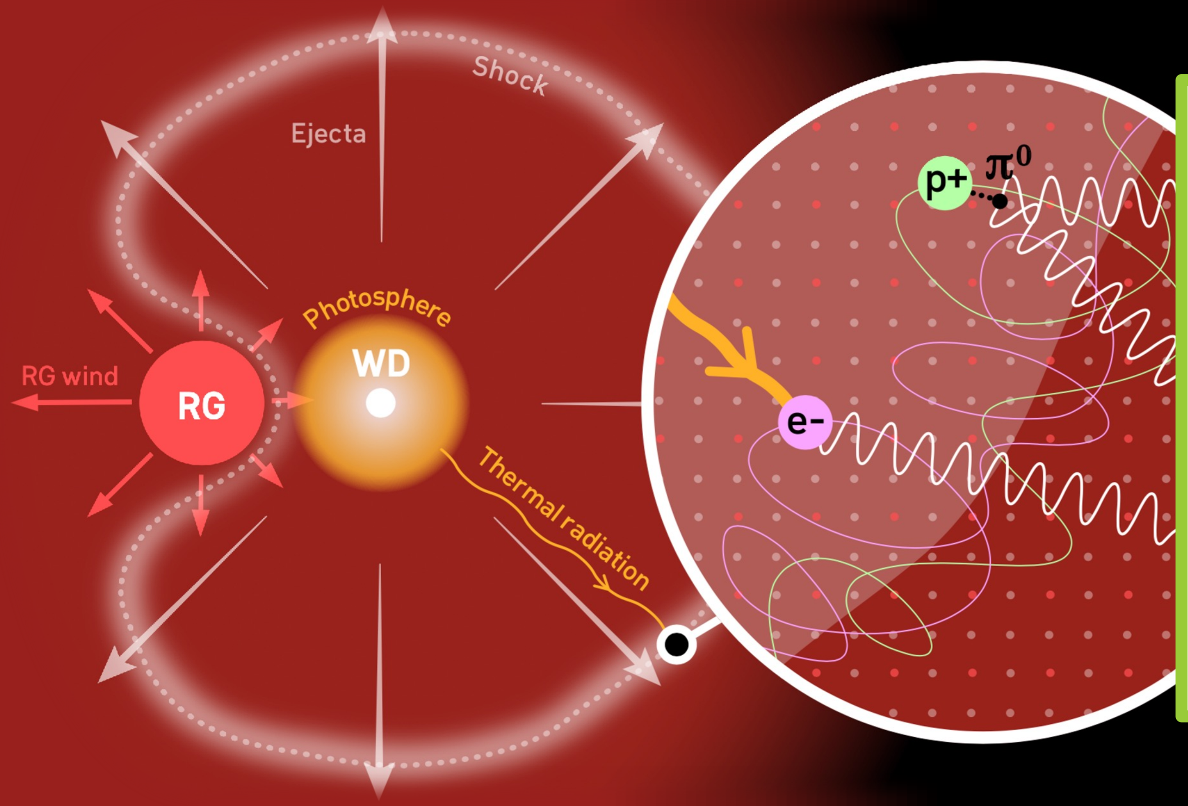


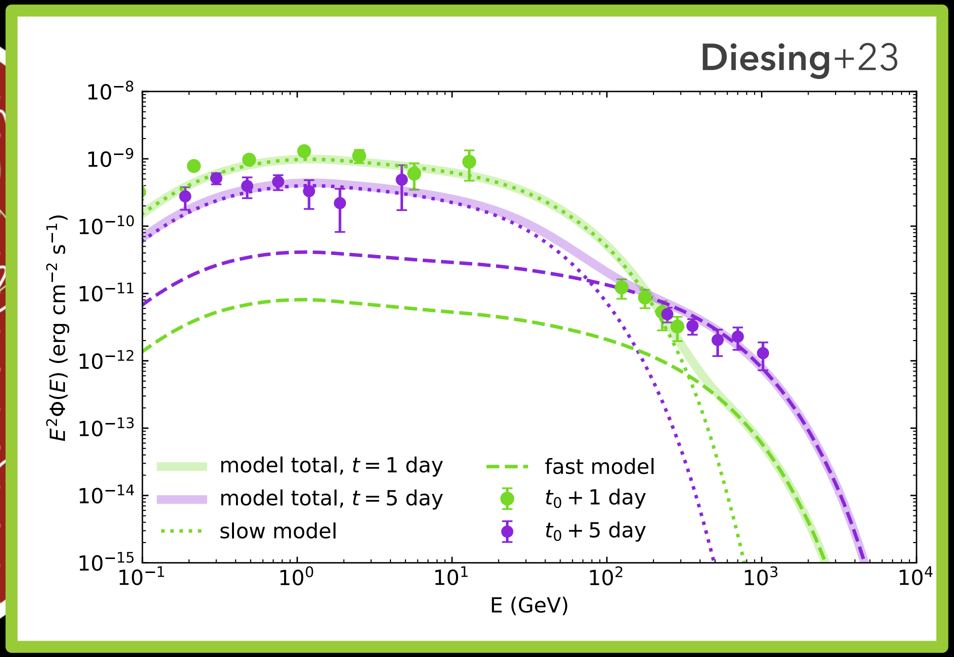
Fermi-LAT detected ɣ-rays from a stacked sample of AGN winds (Fermi-LAT collab.+Diesing+21). These outflows may also be a source of neutrinos.

Credit: ESO/WFI; MPFIR/ESO/APEX/A. Weiss et al. ; NASA/CXC/CFA/R. Kraft et al.

NOVAE

A self-consistent model for particle acceleration requires multiple shock components to fit the gamma-ray data from RS Ophiuchi.





Credit: MAGIC22

SUMMARY

1. We developed a fast, multi-zone framework for particle acceleration, including microphysical effects such as magnetic field amplification and shock modification.

2. The inclusion of these effects (e.g., the postcursor) may resolve key tensions between theory and observations.

3. Proper modeling of cosmic ray acceleration can reveal the evolution and environments surrounding supernova remnants, novae, winds blown by supermassive black holes, and more.