SNRS IN THEIR GOLDEN YEARS

NONTHERMAL SIGNATURES OF RADIATIVE SUPERNOVA REMNANTS

Rebecca Diesing, Minghao Guo, Chang-Goo Kim, James Stone, & Damiano Caprioli

IAS | INSTITUTE FOR ADVANCED STUDY

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Image: Cygnus Loop. Credit: Petri Kehusmaa/Telescope Live

FEEDBACK IS CRUCIAL TO GALAXY FORMATION

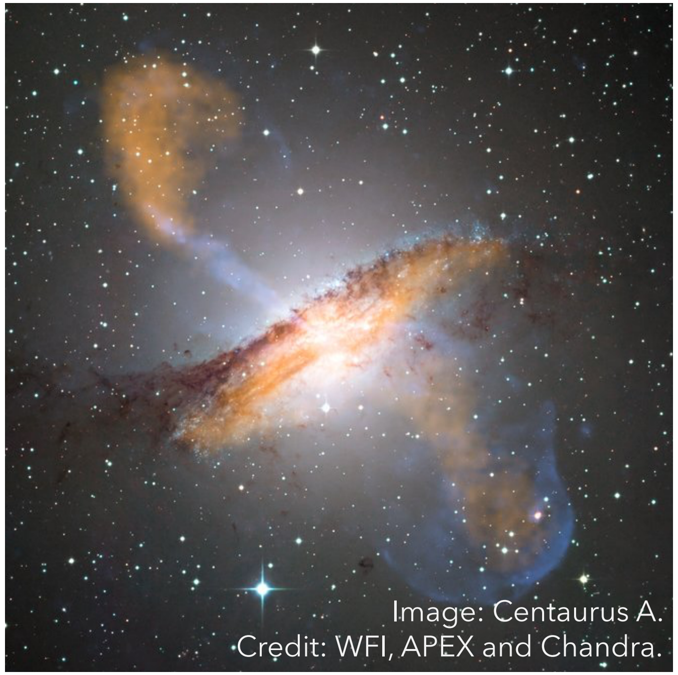


Image: Centaurus A.
Credit: WFI, APEX and Chandra.


Image: The Bubble Nebula.
Credit: Hubble Space Telescope.

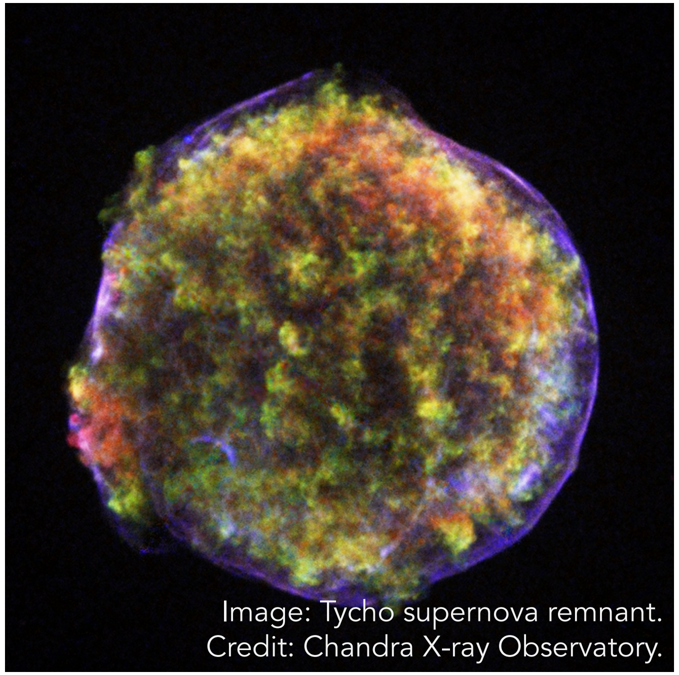


Image: Tycho supernova remnant.
Credit: Chandra X-ray Observatory.

SUPERNOVA REMNANTS ARE DOMINANT FEEDBACK SOURCES IN LOW-MASS GALAXIES

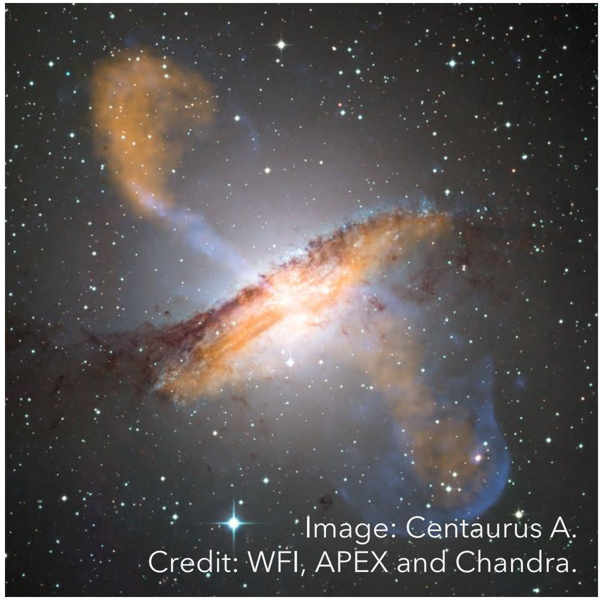


Image: Centaurus A.
Credit: WFI, APEX and Chandra.

Image: The Bubble Nebula.
Credit: Hubble Space Telescope.

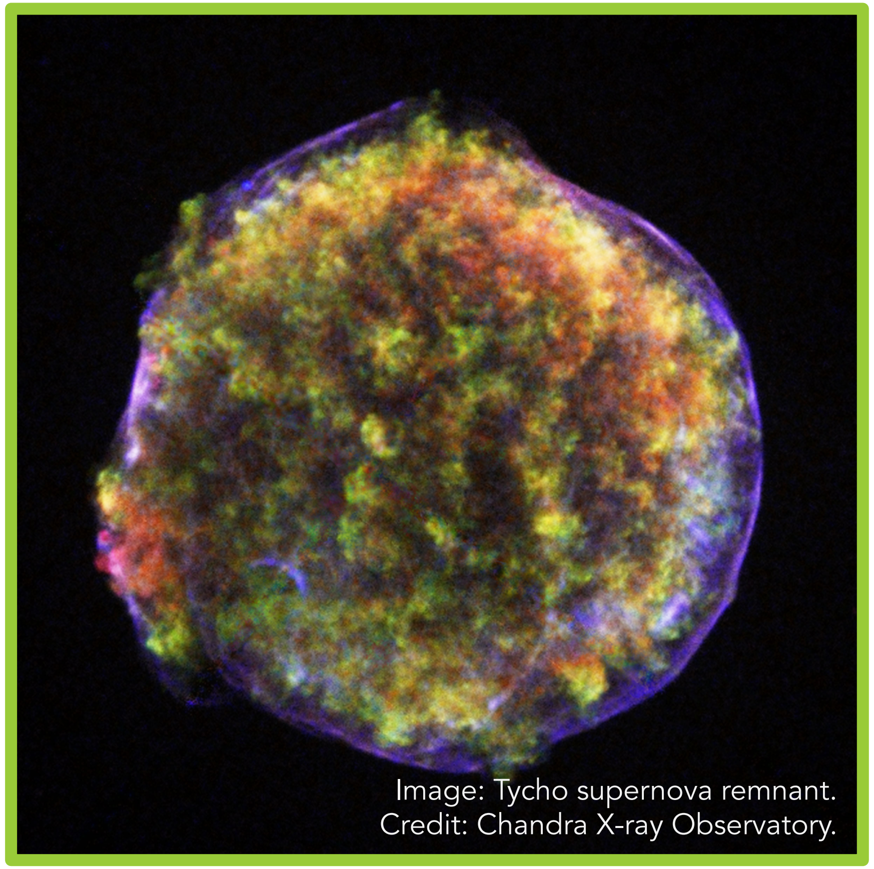
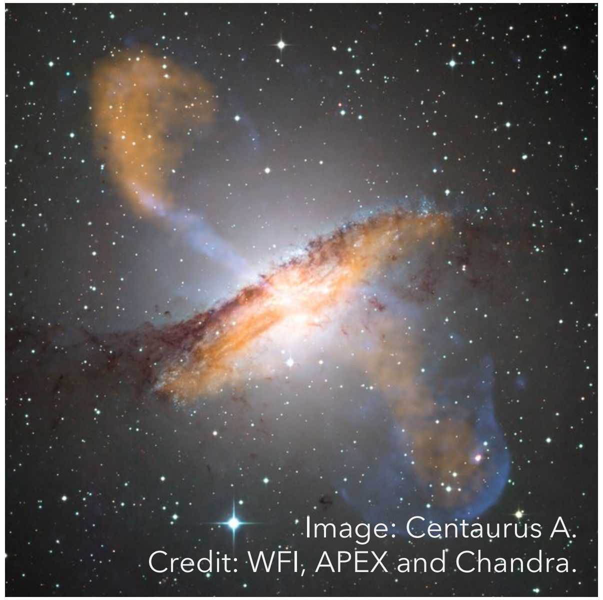
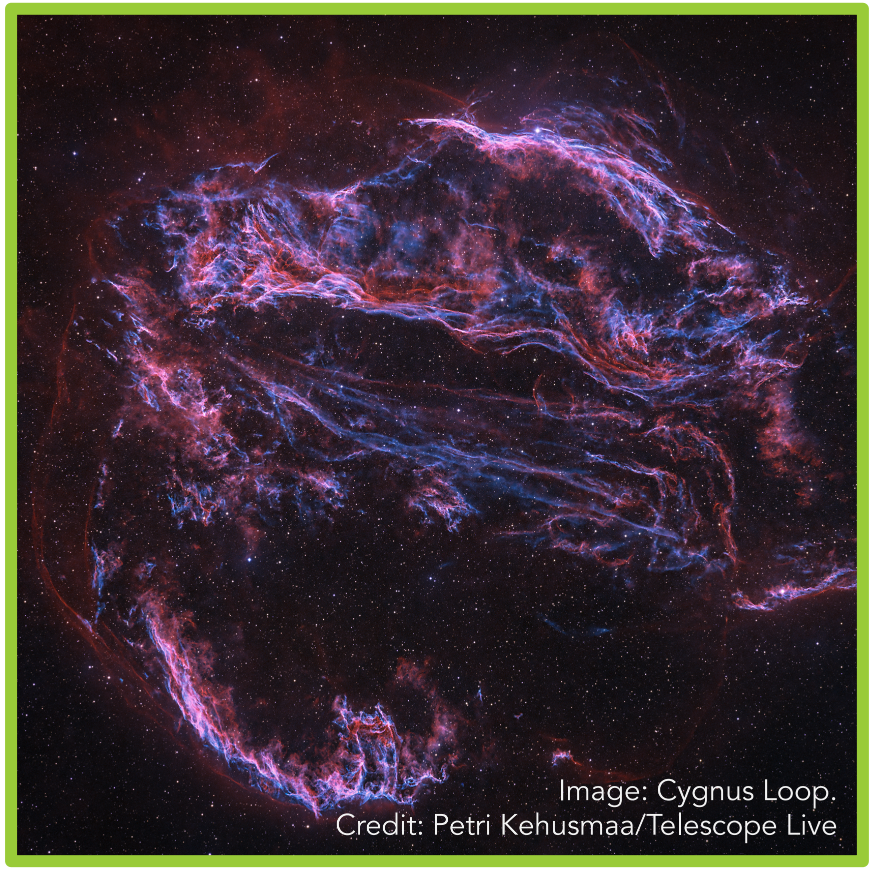


Image: Tycho supernova remnant.
Credit: Chandra X-ray Observatory.

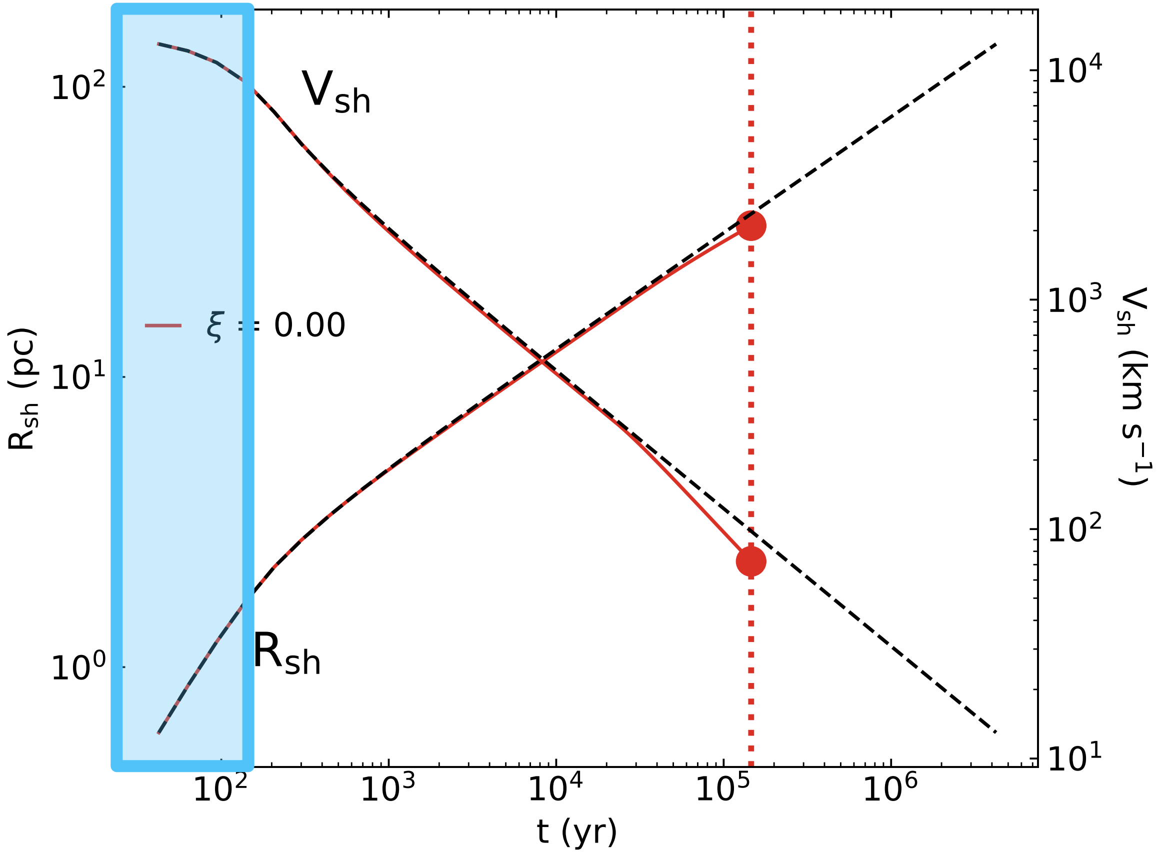
SNRS DEPOSIT ENERGY AND MOMENTUM AT THE ENDS OF THEIR LIVES





THE THREE STAGES OF SNR EVOLUTION

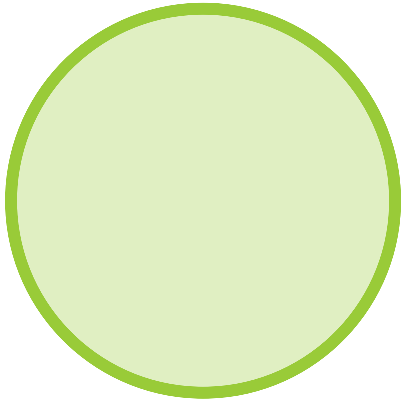
1. Ejecta-dominated ($t < 10^3$ yr).

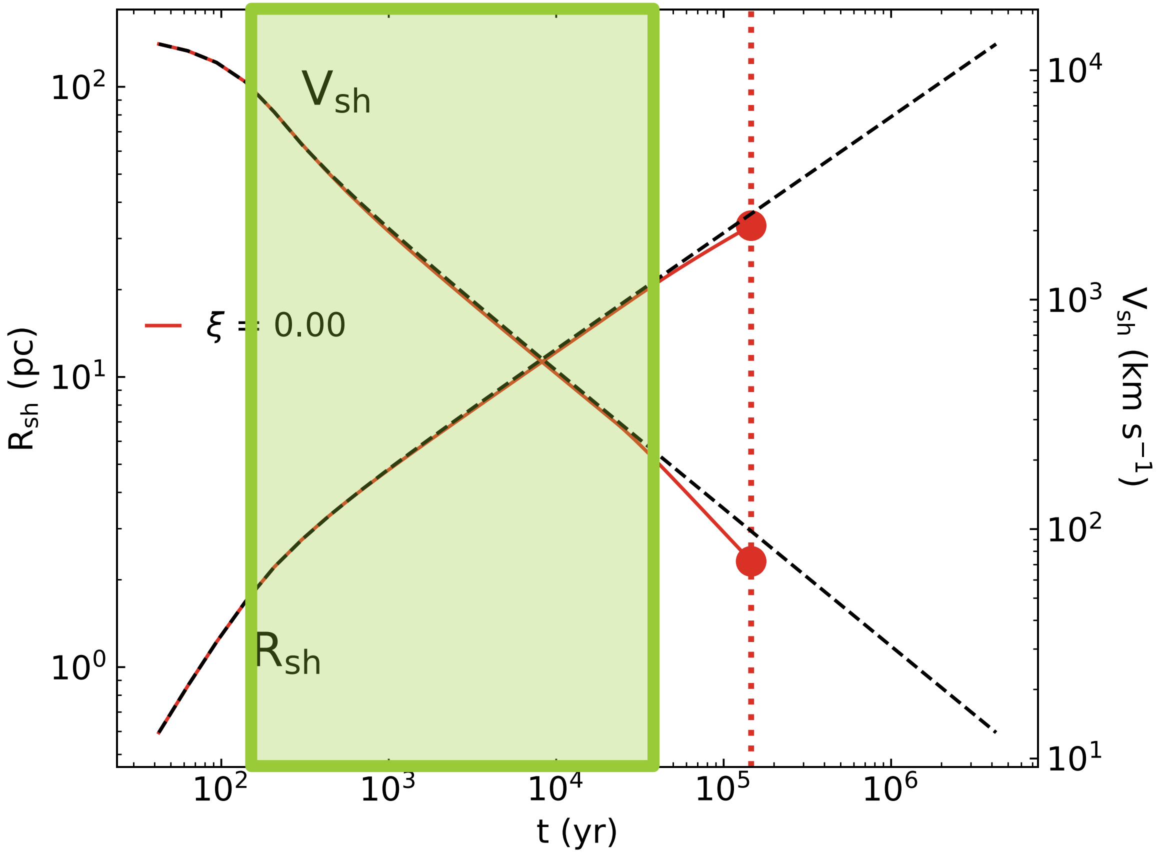


Energy is conserved and swept-up mass < ejecta mass.

THE THREE STAGES OF SNR EVOLUTION

2. Sedov-Taylor ($t < 10^4$ yr).



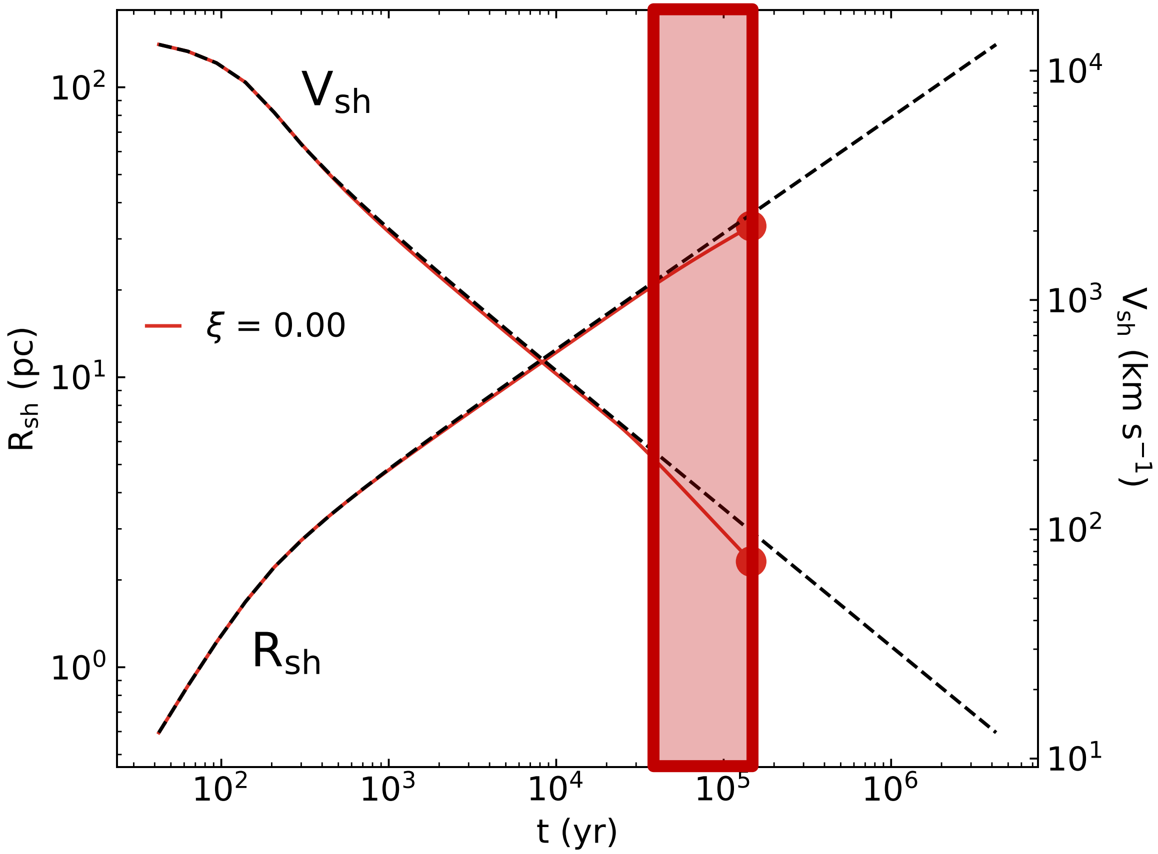


Energy is conserved and swept-up mass >> ejecta mass.

THE THREE STAGES OF SNR EVOLUTION

3. Radiative (t > 10^4 yr).

Post-shock temperature < 10^6 K → radiative cooling becomes efficient; thermal gas loses energy.

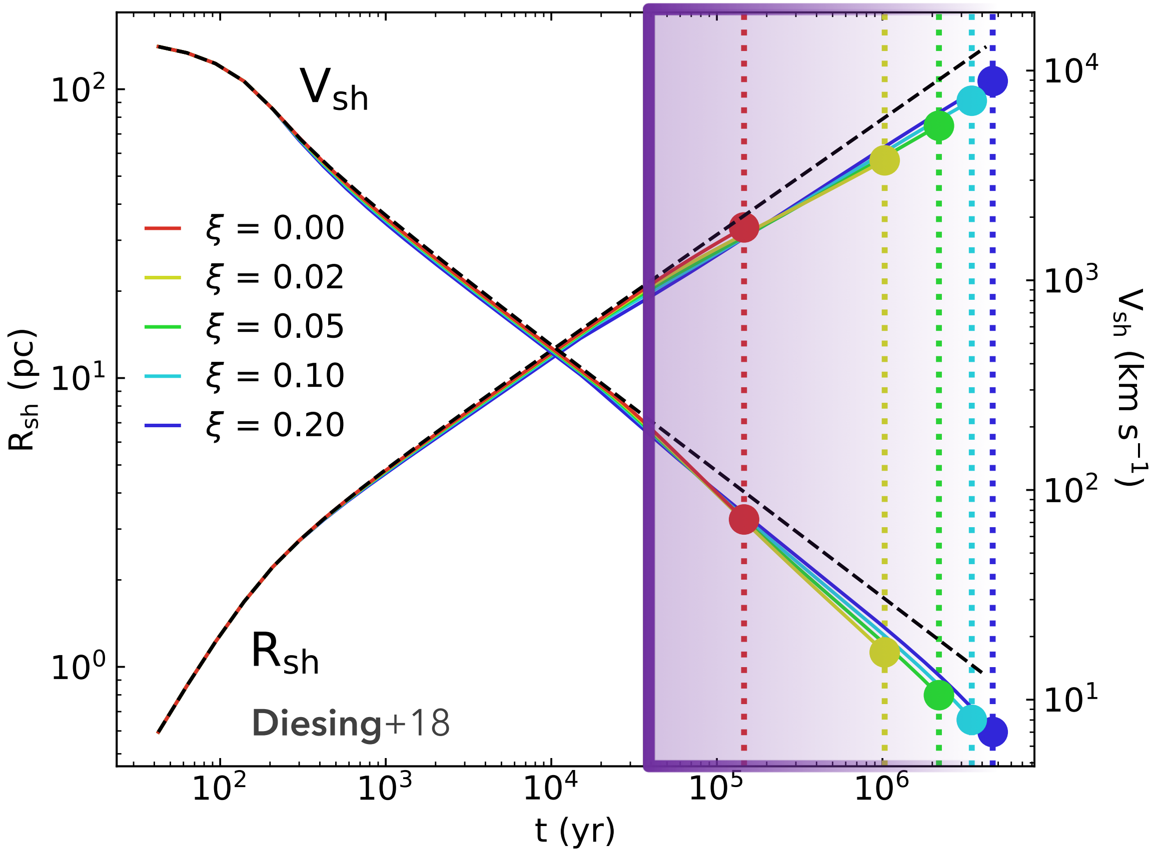


COSMIC RAYS MAY CHANGE THIS PICTURE

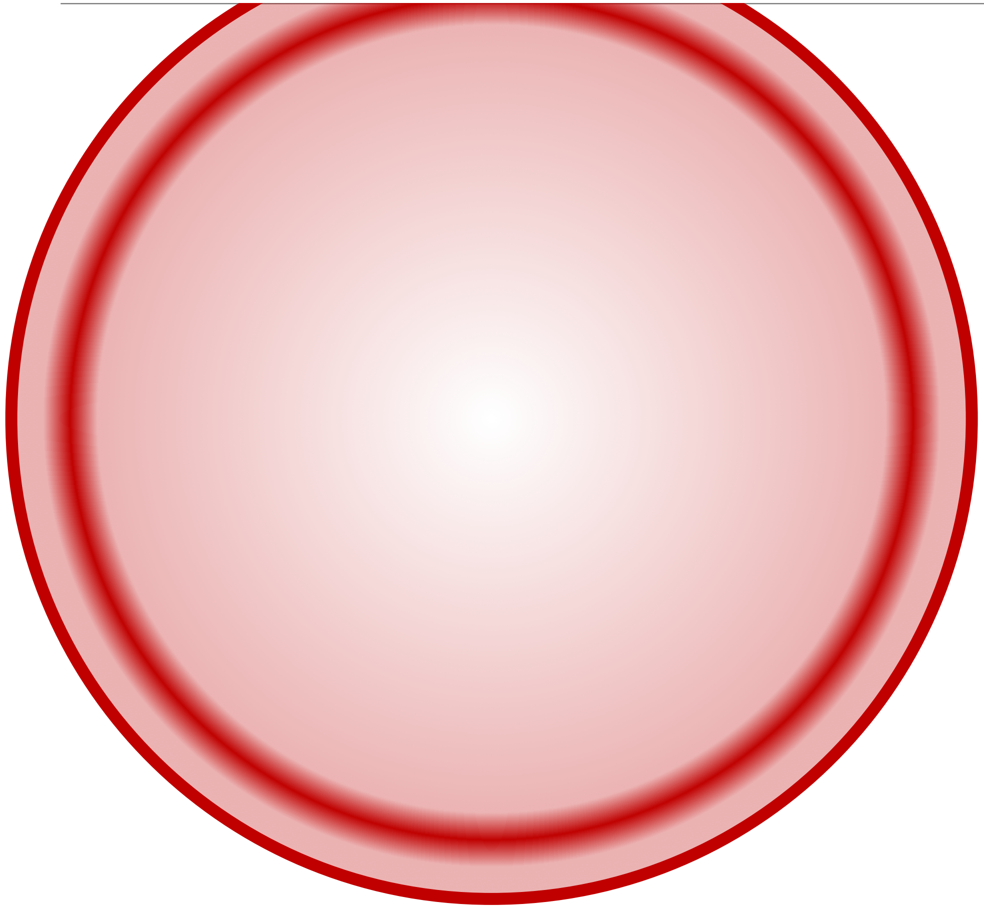
3. Radiative (t > 10^4 yr).

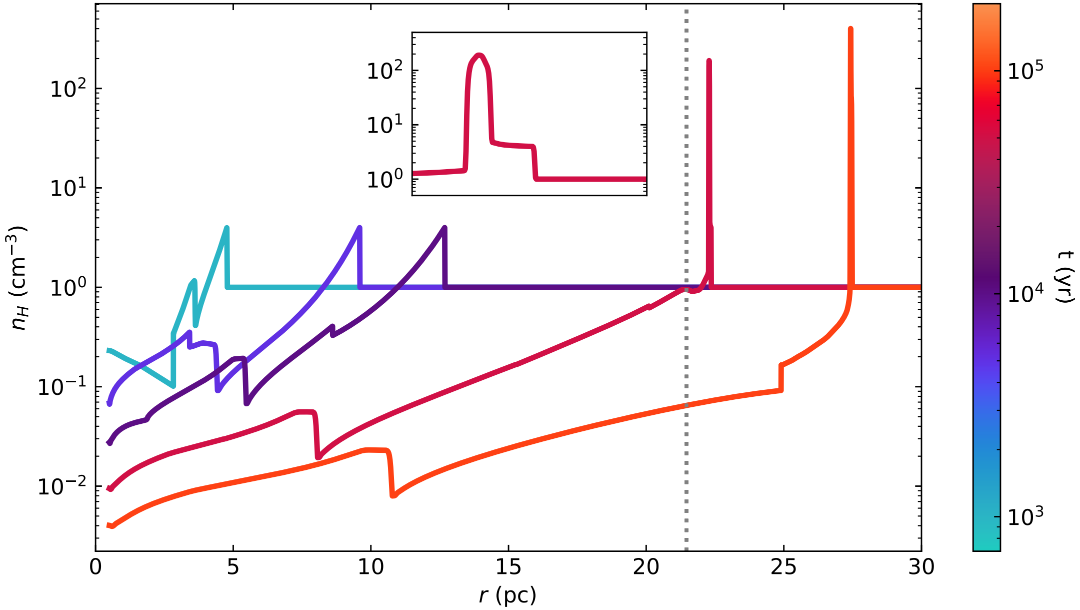
Post-shock temperature < 10^6 K → radiative cooling becomes efficient; thermal gas loses energy.

But CRs serve as an additional source of pressure.

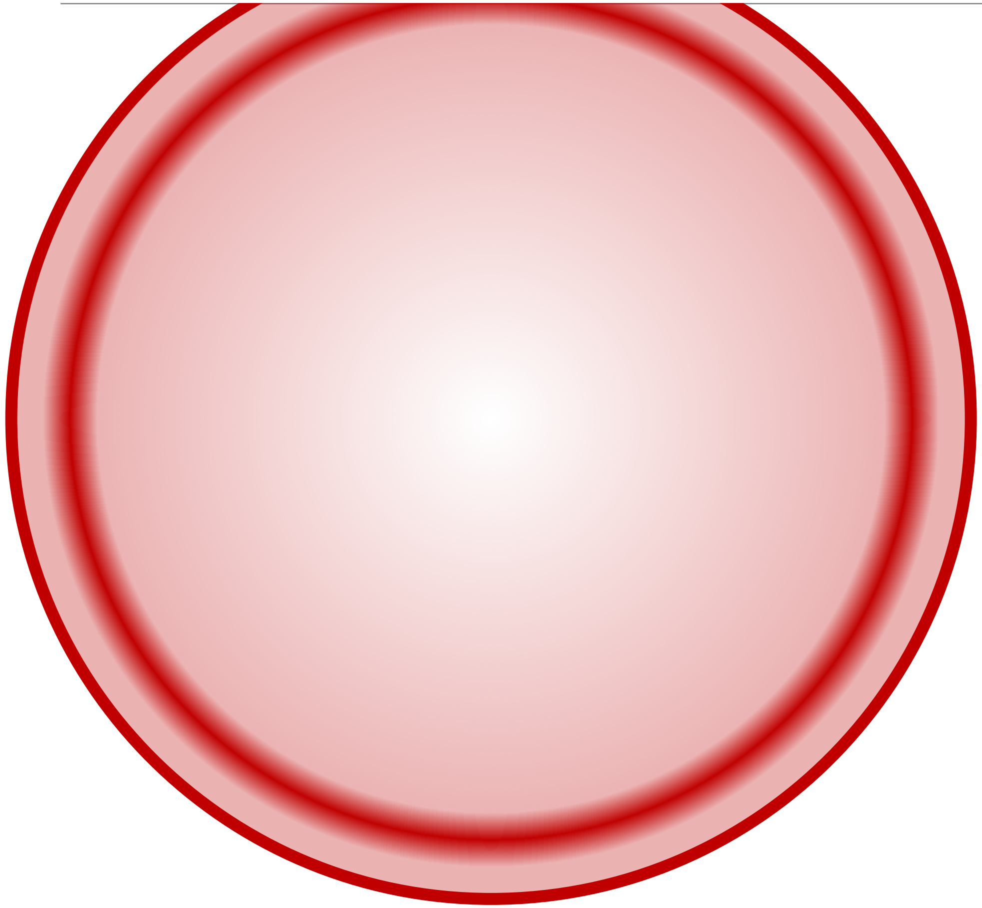


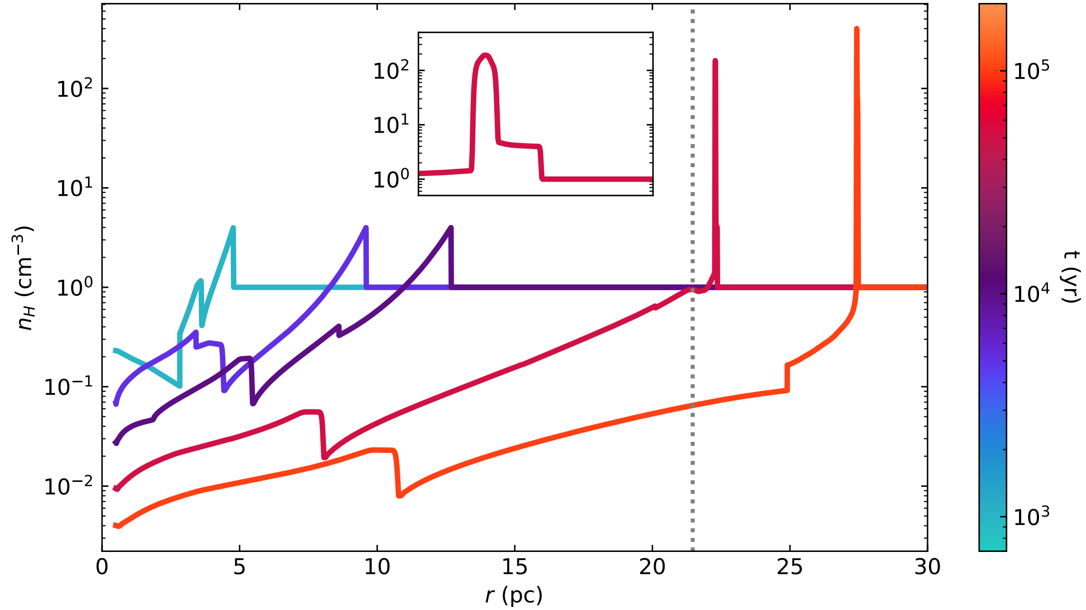
WITHOUT COSMIC RAYS, A SHELL FORMS





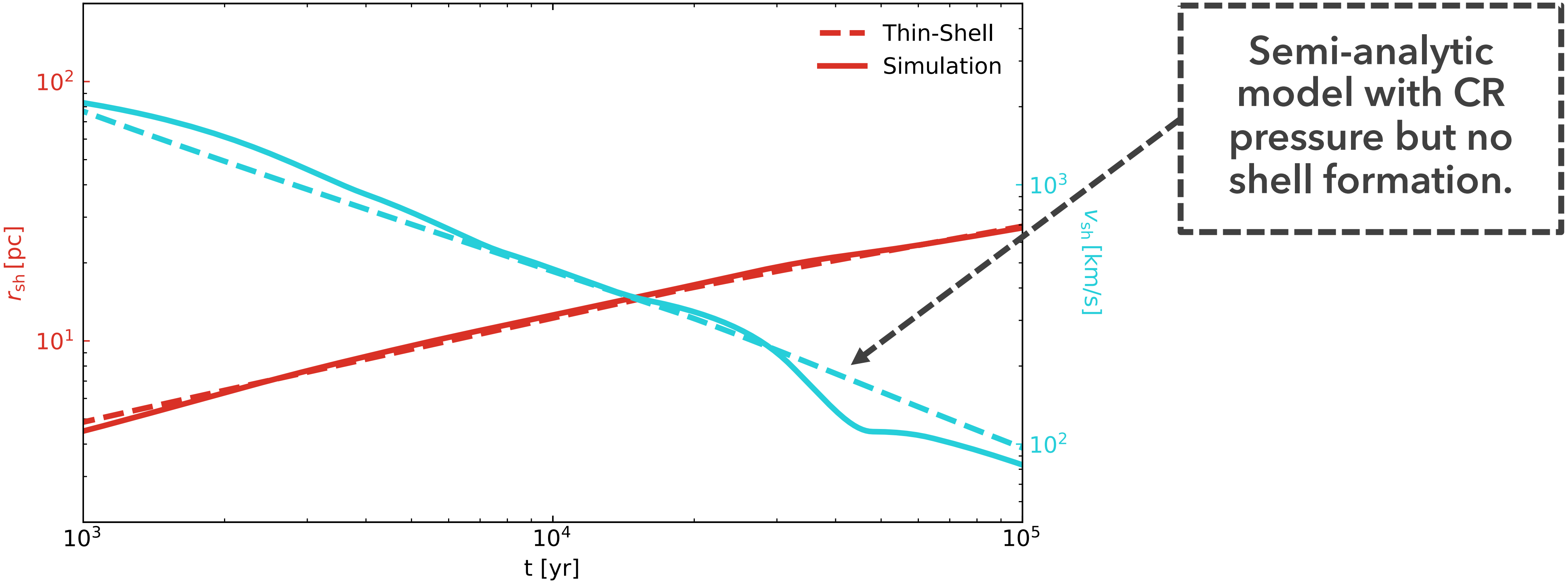
WITHOUT COSMIC RAYS, A SHELL FORMS



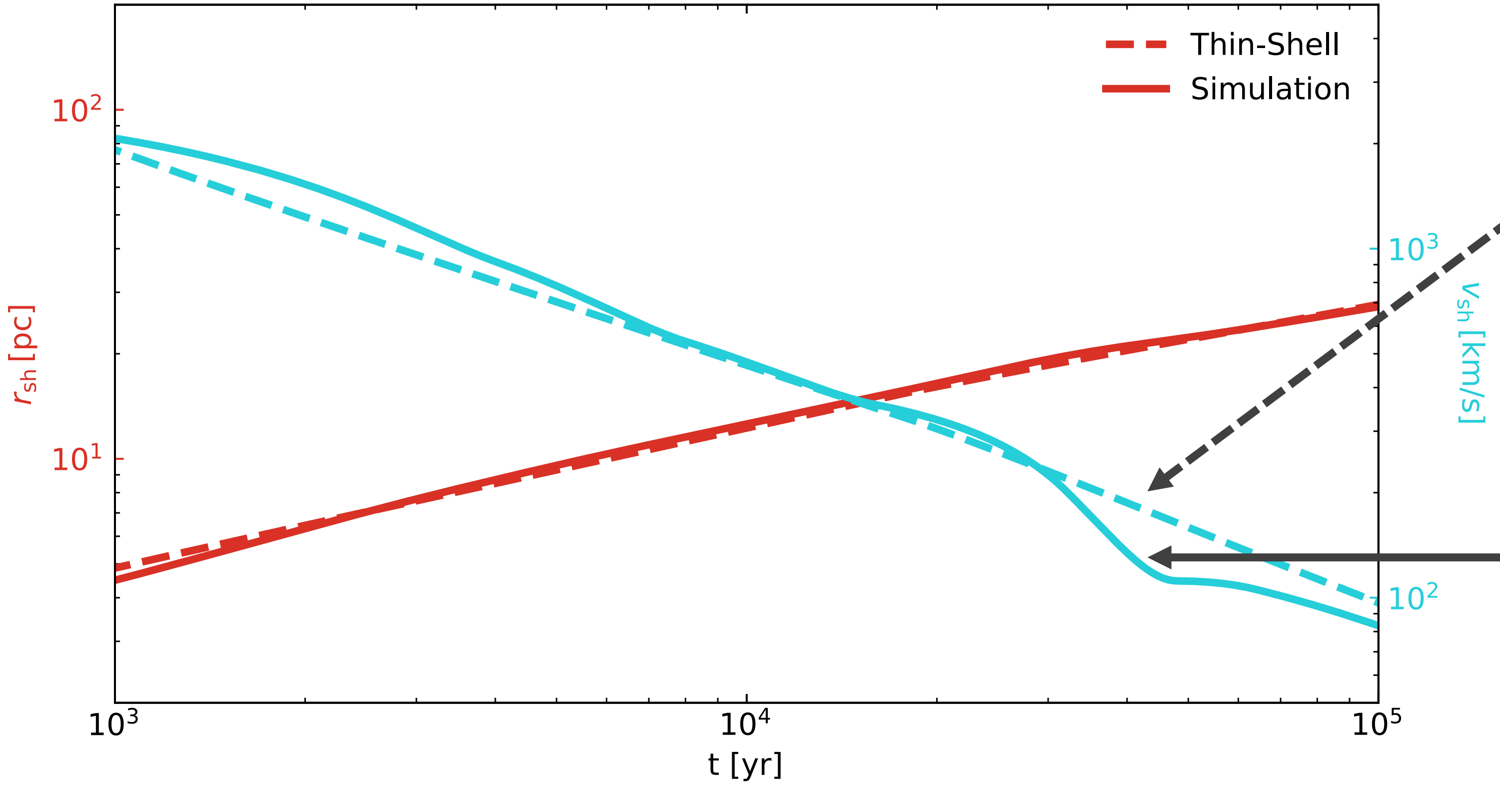


Radiative shells may be significant sources of nonthermal emission.

MODELING SNR EVOLUTION



MODELING SNR EVOLUTION



Semi-analytic model with CR pressure but no shell formation.

Hydrodynamic model with no CR pressure that forms a shell.

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

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

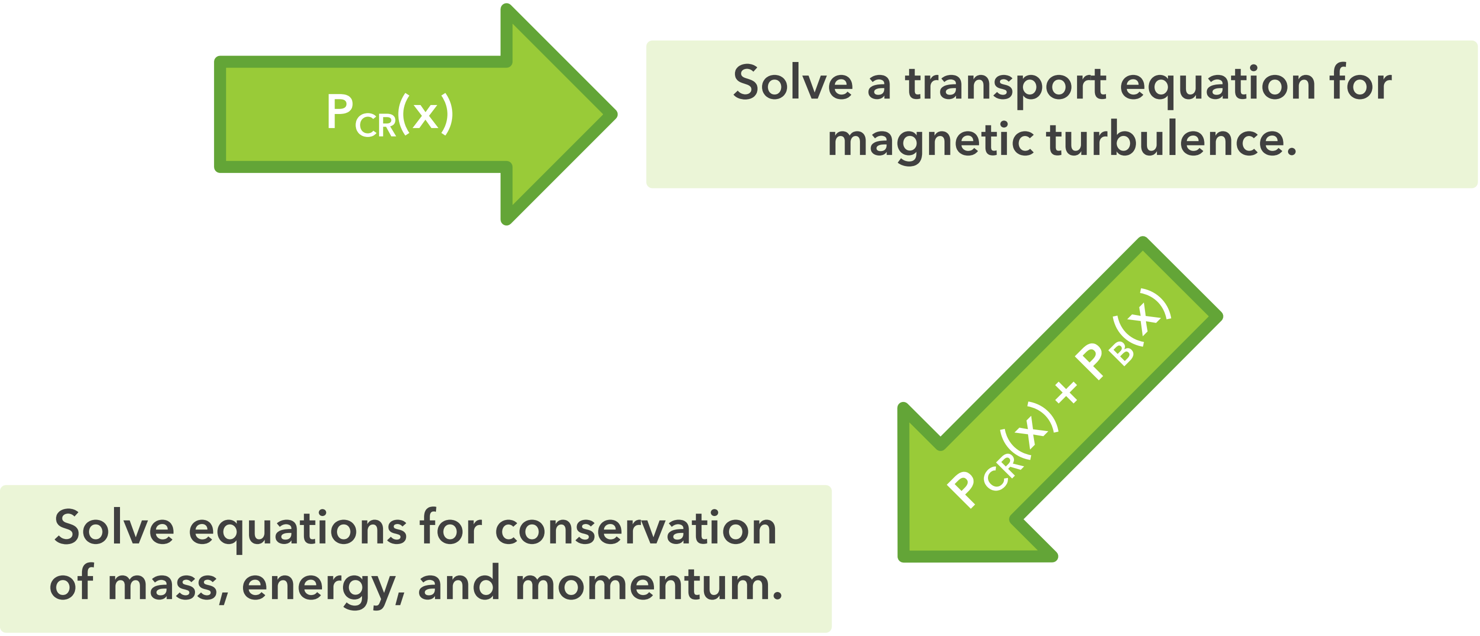
$P_{CR}(x)$ →

Solve a transport equation for magnetic turbulence.

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

MODELING CR ACCELERATION

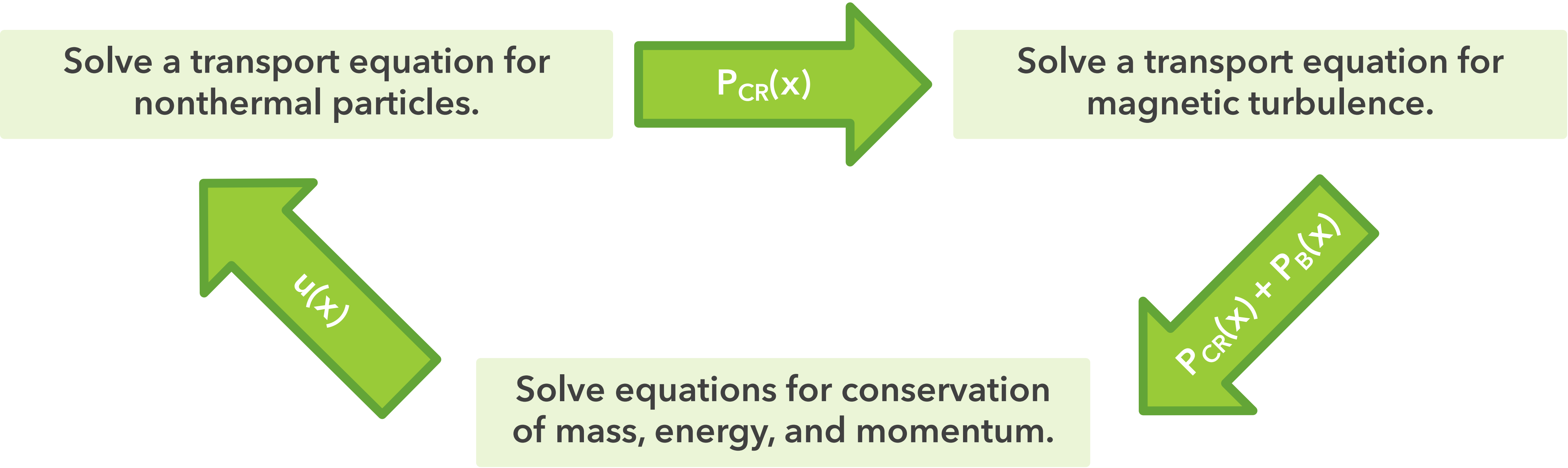
Use a semi-analytic model of non-linear DSA which self-consistently accounts for particle acceleration and magnetic field amplification.



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.



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

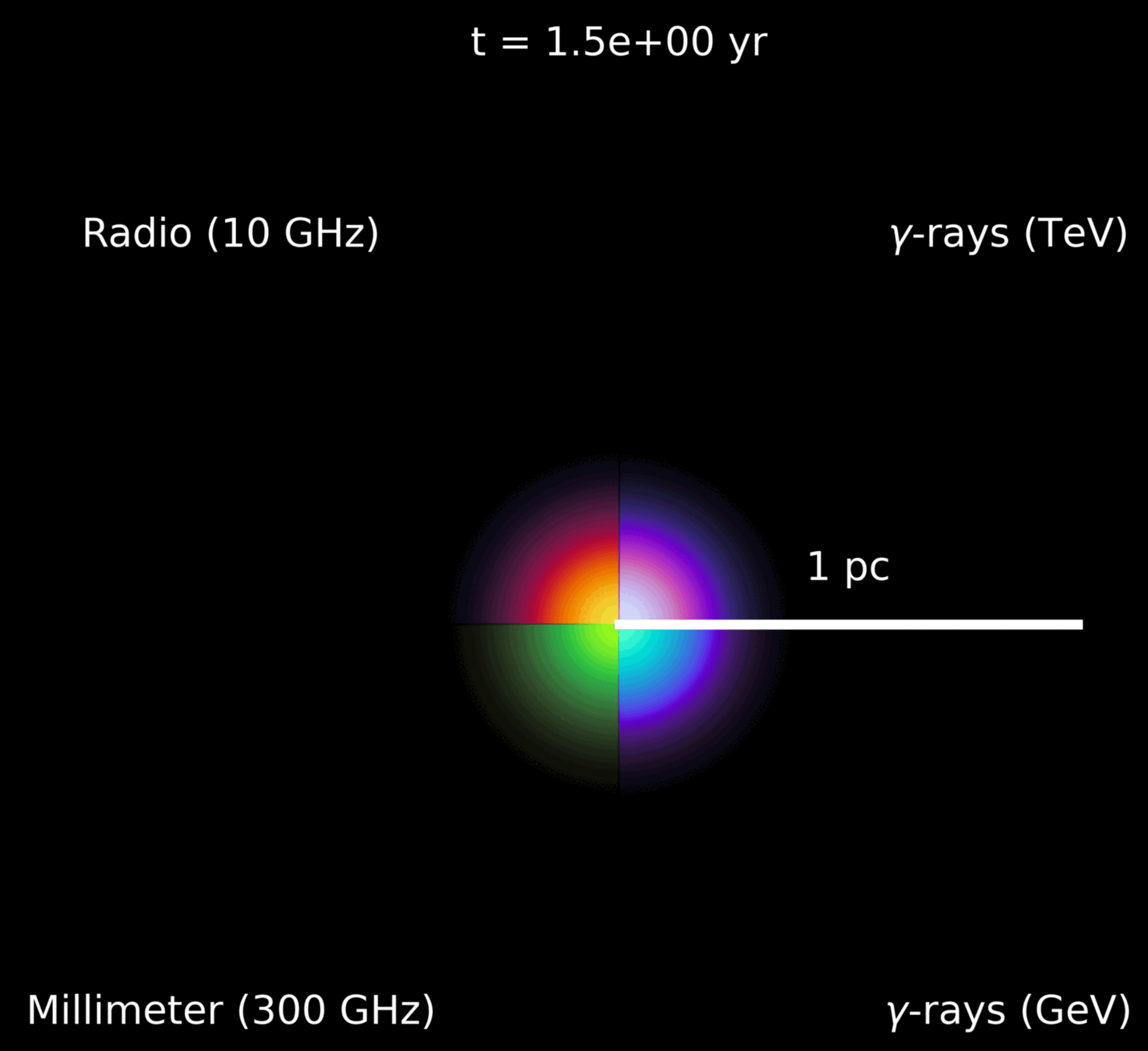
Solve a transport equation for

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.

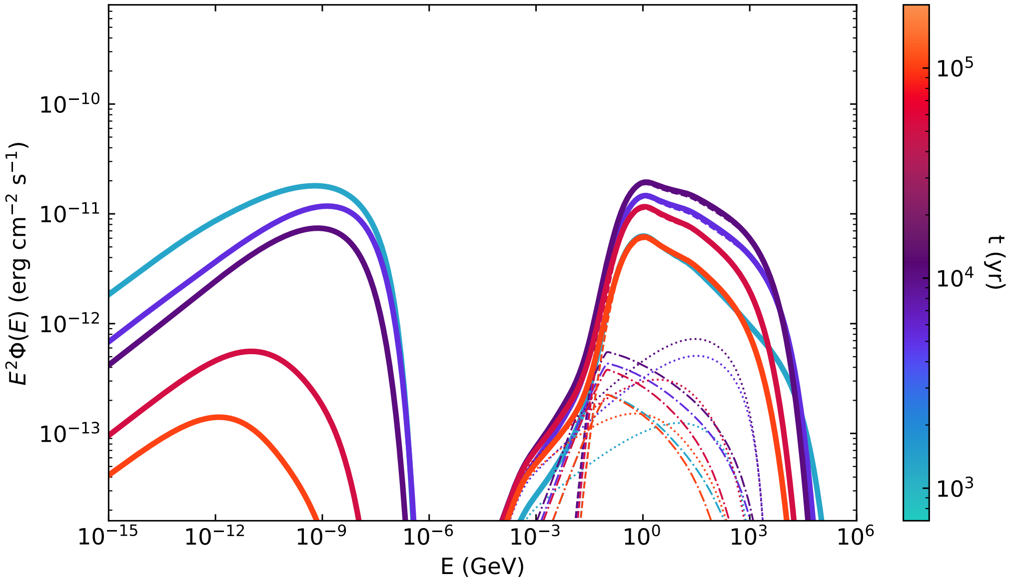
See also Amato+06, Caprioli+10; Caprioli12.

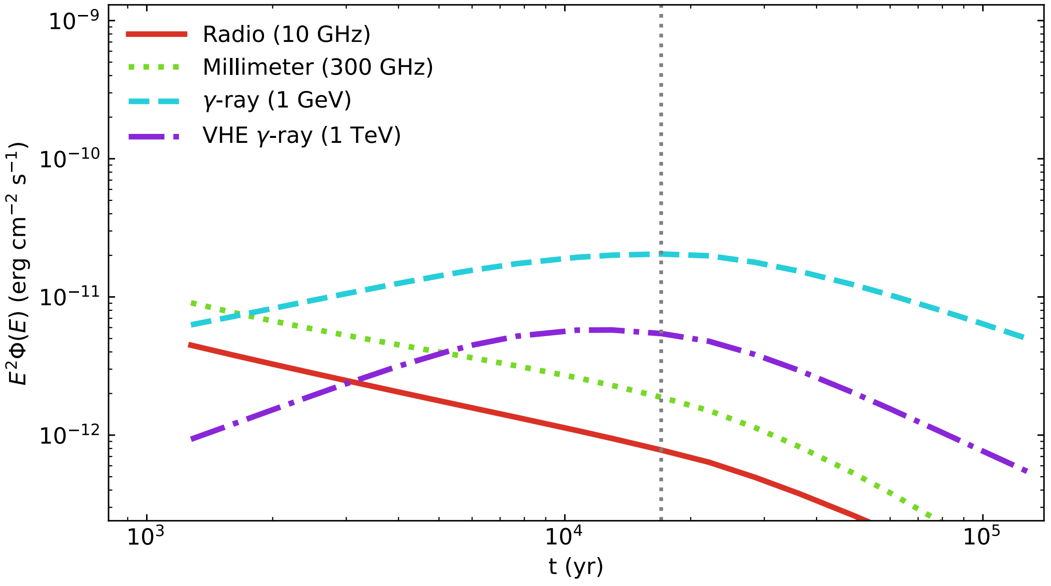
FROM PARTICLE ACCELERATION TO MULTI-WAVELENGTH EMISSION



SEMI-ANALYTIC MODEL (NO SHELL FORMATION)

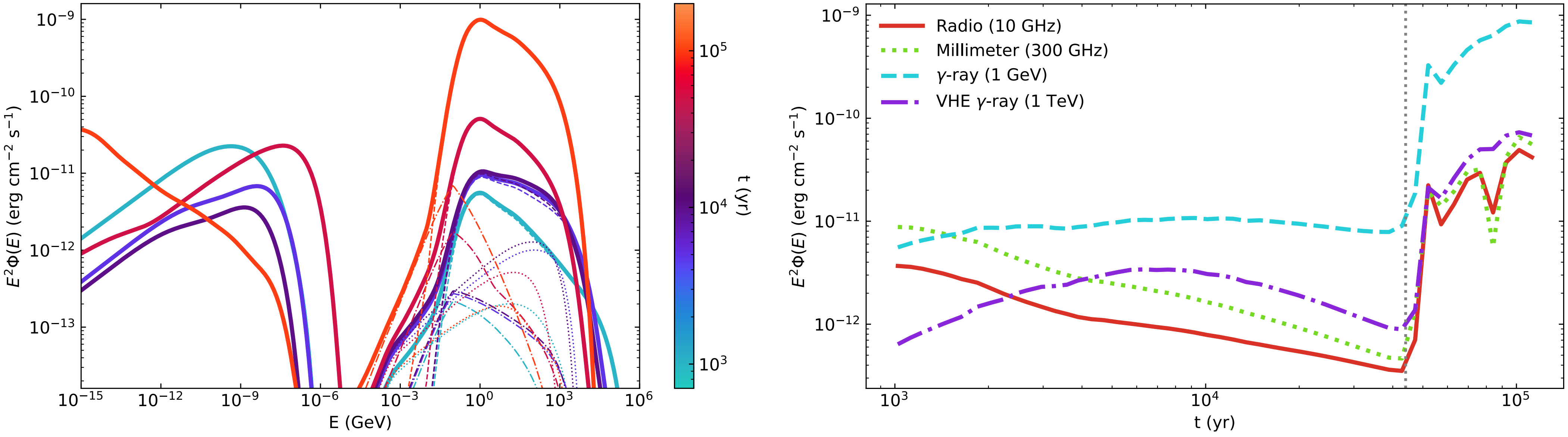
After the onset of the radiative stage, non-thermal emission (from radio to gamma-rays) drops precipitously.

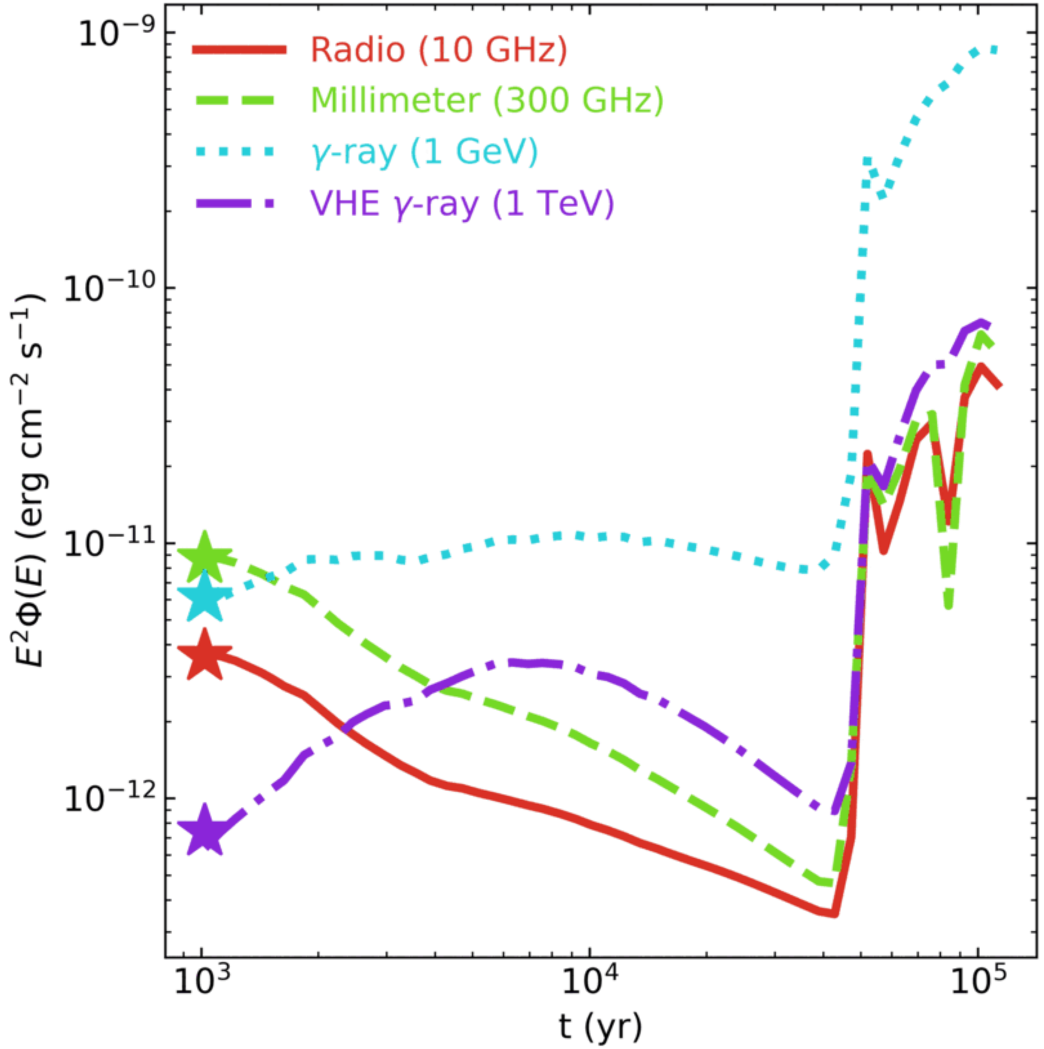


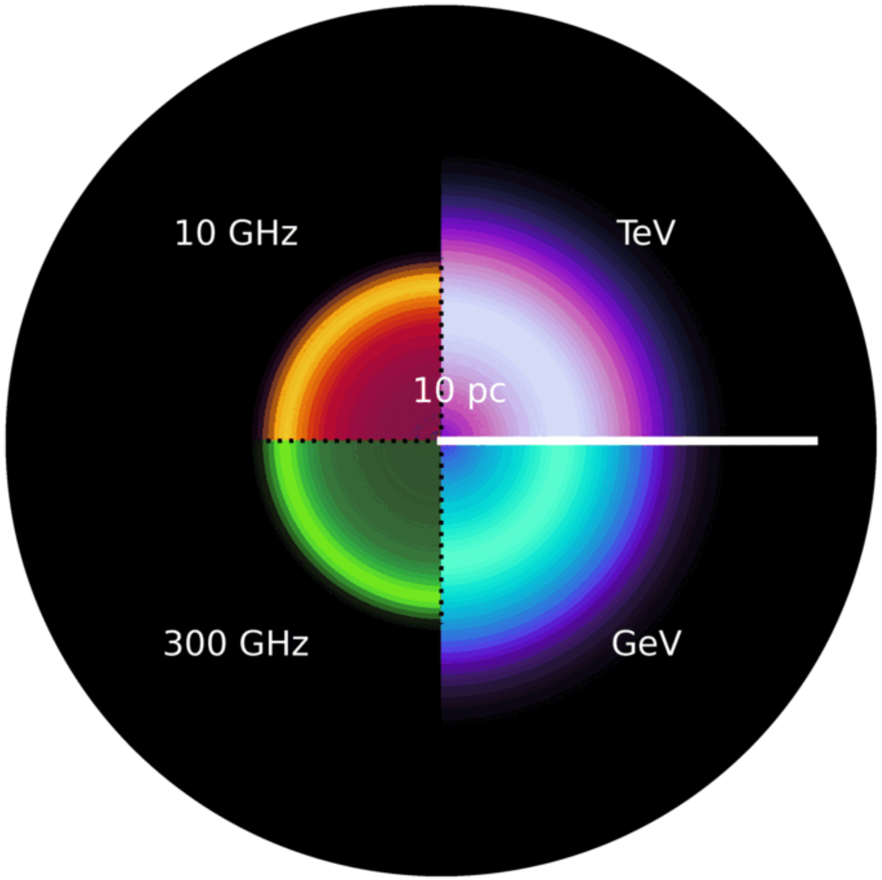


HYDRODYNAMIC MODEL (SHELL FORMATION)

After the onset of the radiative stage, non-thermal emission (from radio to gamma-rays) rises by up to two orders of magnitude.

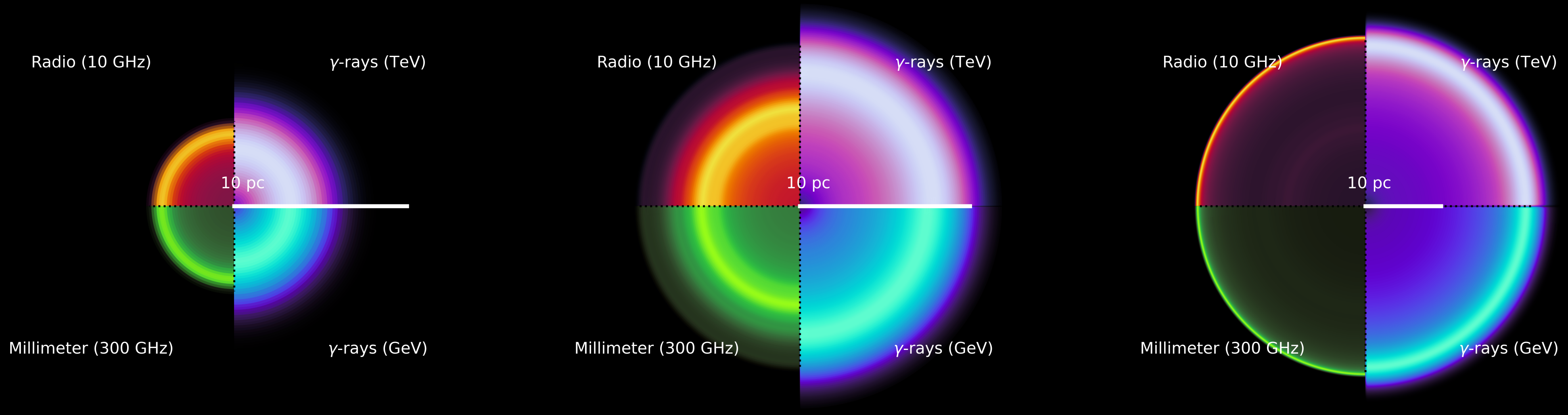



Radio (10 GHz)
Millimeter (300 GHz)
γ-ray (1 GeV)
VHE γ-ray (1 TeV)
$E^2\Phi(E)$ (erg cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^3
10^4
10^5
t (yr)


10 GHz
TeV
10 pc
300 GHz
GeV

IF SHELLS FORM, WE SHOULD SEE THEM IN RADIO

CTA will also be able to resolve them.



$t = 10^3$ yr $\quad$ $t = 5\times10^3$ yr $\quad$ $t = 5\times10^4$ yr

Note that, based on 3D simulations (Guo+24, in prep.), complete shells should form even if the SNR expands into an inhomogeneous medium.

SUMMARY

1. In the standard picture of SNR evolution, cosmic rays accelerated at the forward shock interact with the dense shell formed at the onset of the radiative stage.
2. As a result, old SNRs can be ~100 times brighter in nonthermal emission than their younger counterparts.
3. Current-generation radio telescopes (and next-generation gamma-ray telescopes) can resolve this non-thermal emission in nearby radiative SNRs, allowing us to distinguish between shell formation and molecular cloud interactions.
4. The lack of complete shell detections in the literature may be evidence for shell disruption by magnetic fields and/or cosmic rays.

For more information, see Diesing+24 (submitted)

Image: Cygnus Loop. Credit: Petri Kehusmaa/Telescope Live