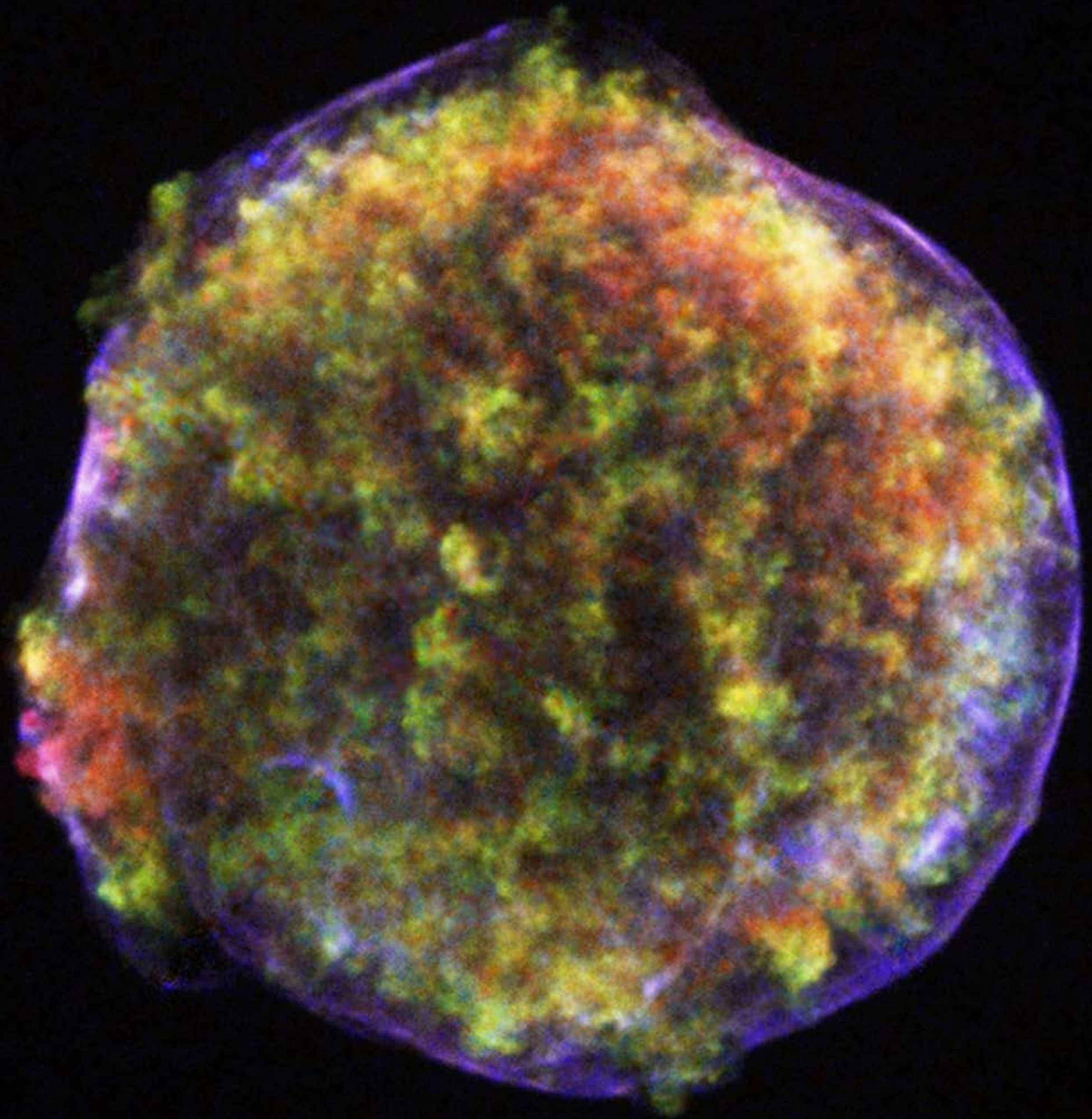


HOW COSMIC RAYS SHAPE SUPERNOVA REMNANTS

REBECCA DIESING

SUPERNOVA REMNANTS II

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

MOTIVATION

Feedback from active galactic nuclei, stellar winds, and supernovae plays a crucial role in galaxy formation.

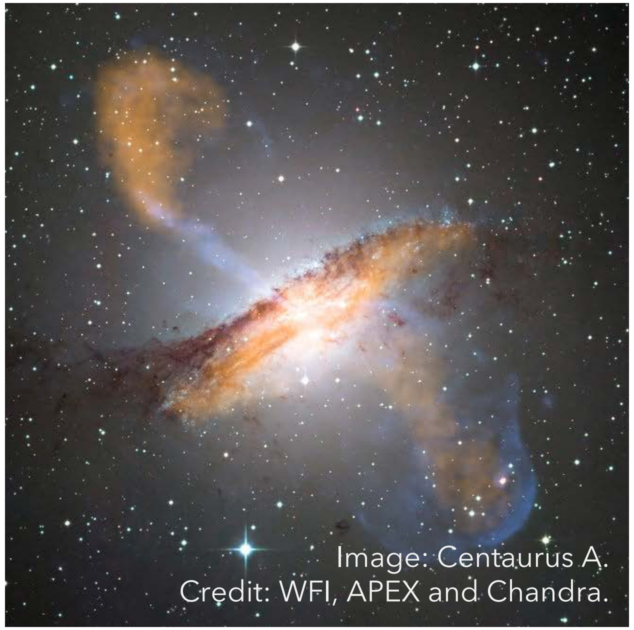


Image: Centaurus A.
Credit: WFI, APEX and Chandra.

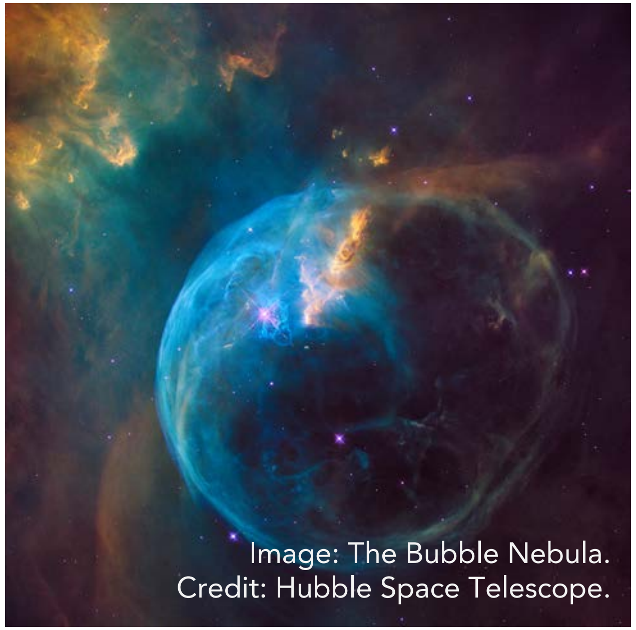


Image: The Bubble Nebula.
Credit: Hubble Space Telescope.

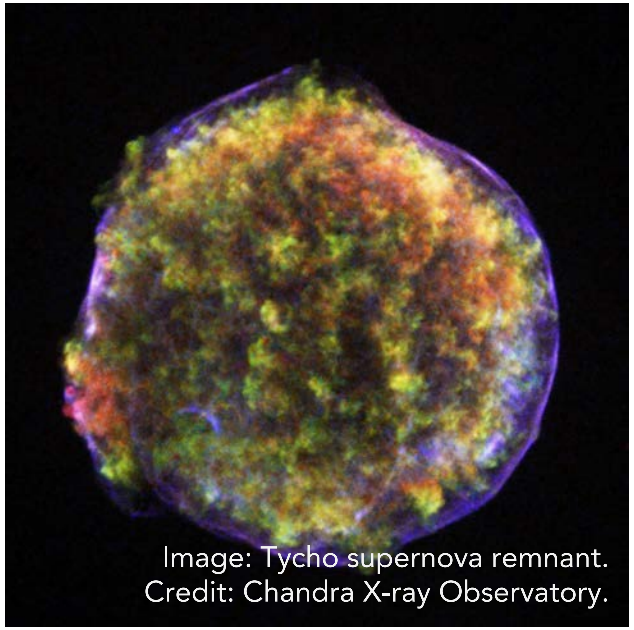


Image: Tycho supernova remnant.
Credit: Chandra X-ray Observatory.

These objects inject energy and momentum into the interstellar medium.

MOTIVATION

To produce galaxies consistent with observations, models typically boost the momentum yield calculated for single supernova remnants (SNRs) by a factor of 3-5.

THE ROLE OF COSMIC RAYS

Cosmic rays (CRs) are produced at SNR blast waves via diffusive shock acceleration. Their effect is two-fold:

1. Acting as a relativistic fluid, CRs suffer less adiabatic loss than thermal gas; at late times they dominate the internal pressure.

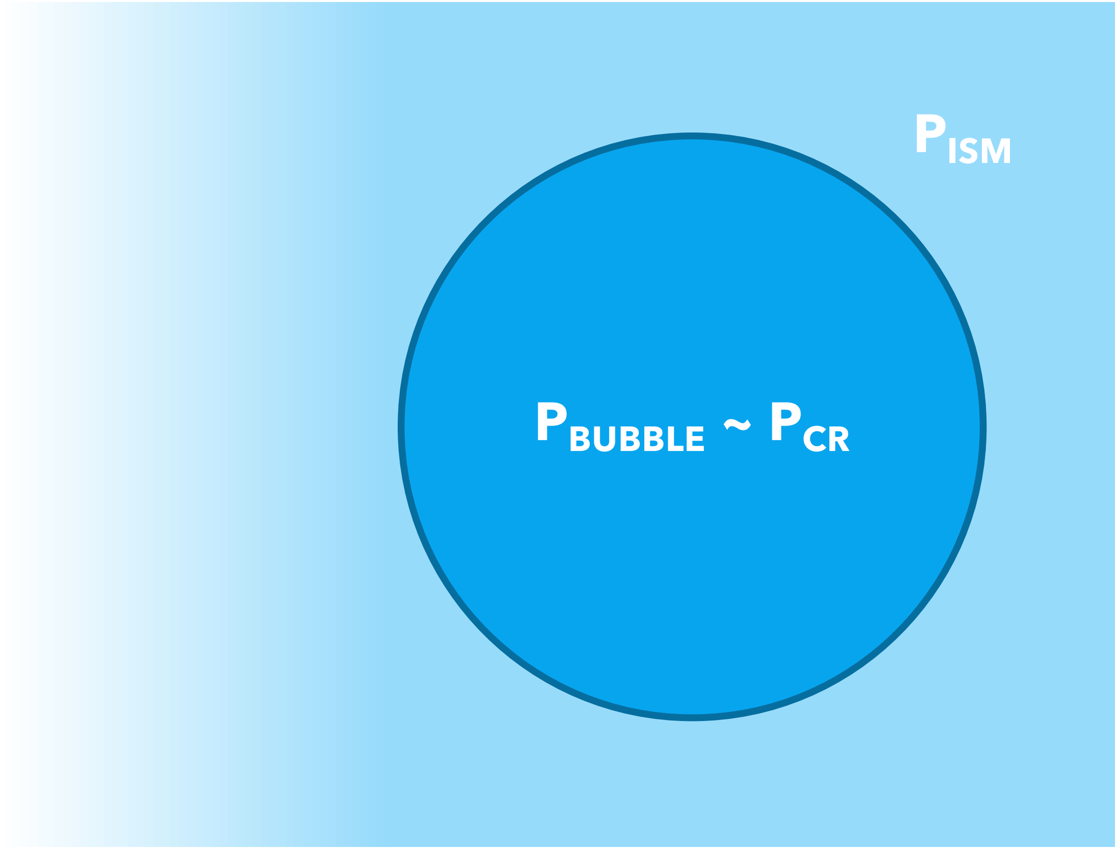
THE ROLE OF COSMIC RAYS

Cosmic rays (CRs) are produced at SNR blast waves via diffusive shock acceleration. Their effect is two-fold:

1. Acting as a relativistic fluid, CRs suffer less adiabatic loss than thermal gas; at late times they dominate the internal pressure.
2. CR energy is not radiated at late times, but rather continues to support expansion.

A SIMPLE ESTIMATE

After the thermal gas radiates away its energy, cosmic rays push the remnant outward.



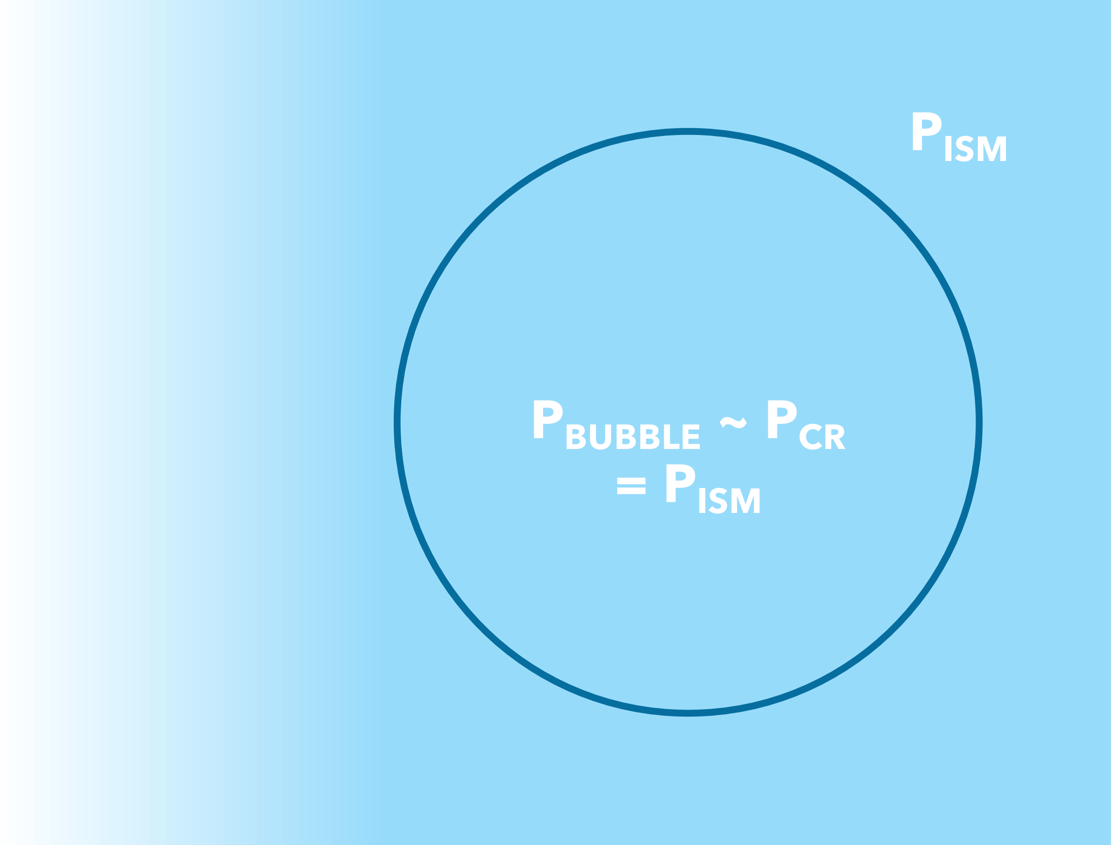
A SIMPLE ESTIMATE

After the thermal gas radiates away its energy, cosmic rays push the remnant outward.

Momentum becomes constant when pressures equilibrate:

$$\frac{\xi E_{\mathrm{SN}}}{V} = n_{\mathrm{ISM}} k T$$

CR acceleration efficiency



A SIMPLE ESTIMATE

Assume ejecta mass is negligible and estimate the final SNR mass:

$$M_f \approx n_{\rm ISM} \mu m_p V = \frac{\xi E_{\rm SN} \mu m_p}{kT}$$

Assume final SNR velocity is of order the ISM sound speed:

$$v_f = c_s = \sqrt{\frac{\gamma k T}{\mu m_p}}$$

A SIMPLE ESTIMATE

Momentum deposited is simply the final mass times the final velocity:

$$p_{\rm dep} = M_f v_f \approx \xi E_{\rm SN} \sqrt{\frac{\gamma \mu m_p}{kT}}$$

Assuming γ = 5/3 and μ = 1.4:

$$p_{\rm dep} \approx 9.44 \times 10^5 \frac{\xi}{0.1} \frac{E_{\rm SN}}{10^{51}{\rm erg}} \left(\frac{T}{8000{\rm K}} \right)^{-1/2} M_\odot {\rm km\ s}^{-1}$$

A SIMPLE ESTIMATE

WITH COSMIC RAYS

$$p_{\rm dep} \approx 9.44 \times 10^5 \frac{\xi}{0.1} \frac{E_{\rm SN}}{10^{51}{\rm erg}} \left(\frac{T}{8000{\rm K}}\right)^{-1/2} M_\odot {\rm km\ s}^{-1}$$

WITHOUT COSMIC RAYS

$$p_{\rm dep} \approx 2.8 \times 10^5 M_\odot {\rm km\ s}^{-1}$$

Factor of ~3 lower than SNRs with CRs

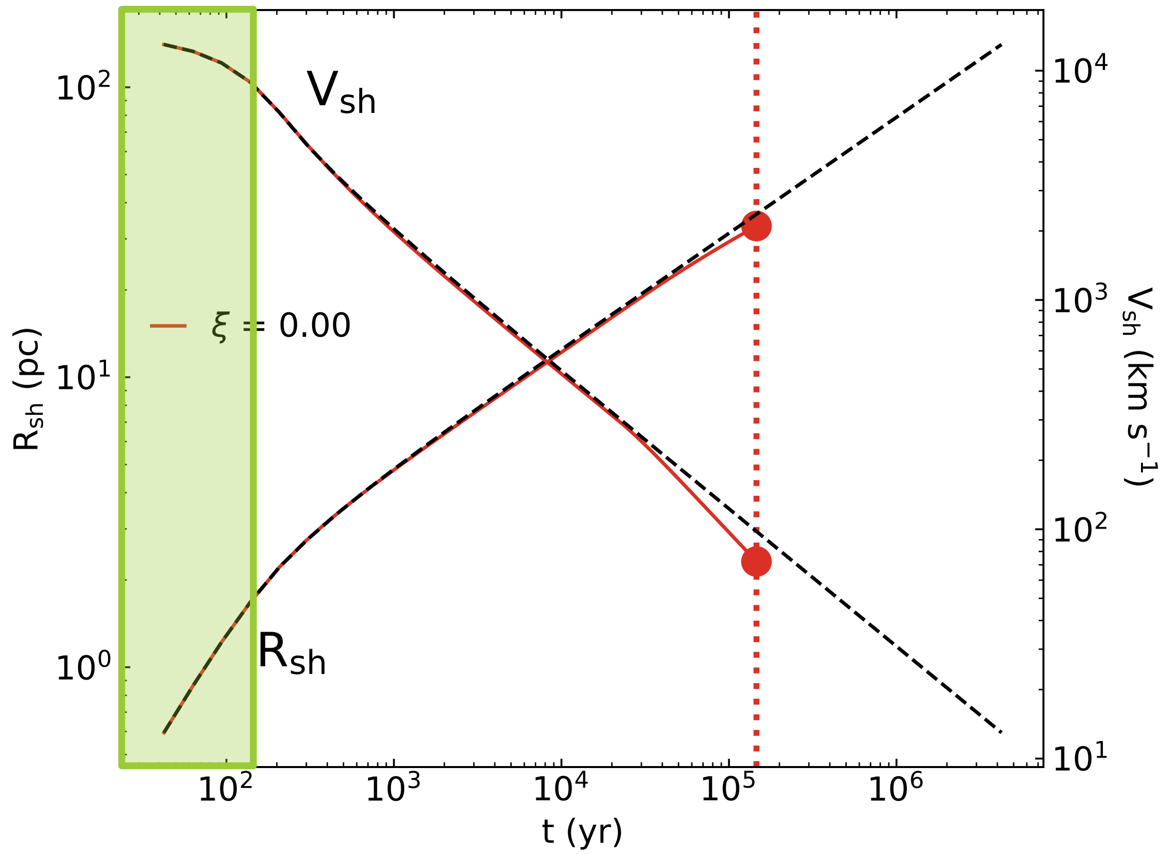
A MORE DETAILED CALCULATION

1. EJECTA-DOMINATED STAGE

Energy is conserved and swept up mass < ejecta mass.

CR contribution to expansion is negligible.

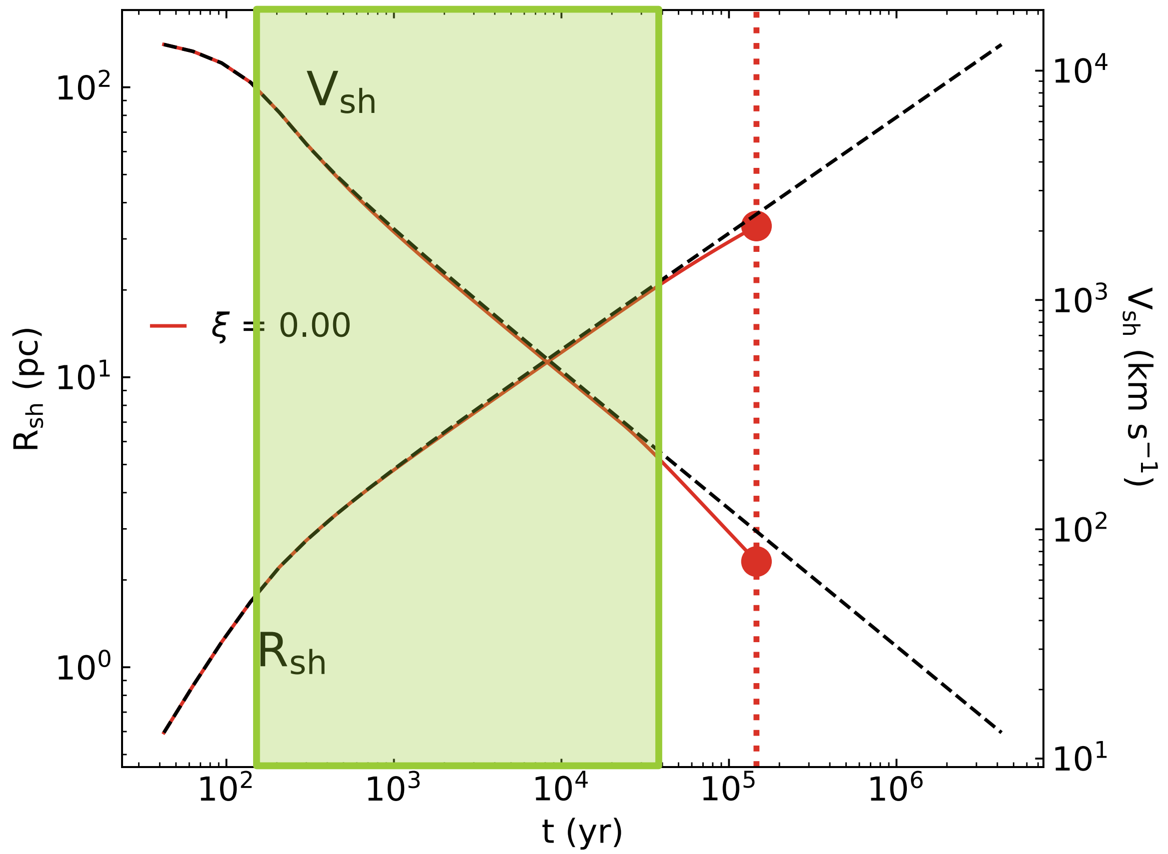
Use analytic approximation from Truelove & McKee 1999 (dashed line).



2. SEDOV-TAYLOR STAGE

Energy is conserved and swept up mass > ejecta mass.

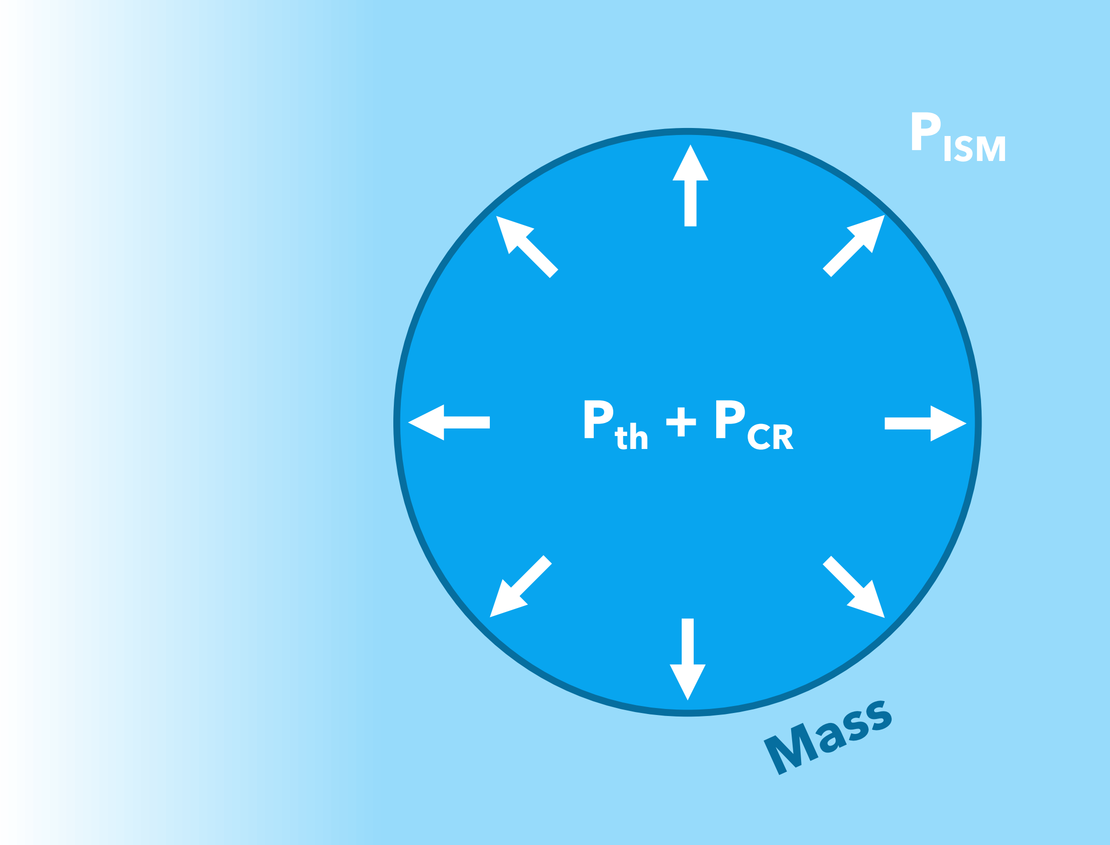
Use thin-shell approximation.



THIN SHELL APPROXIMATION

Assume mass is confined to a thin shell.

Shell expands due to pressure inside the hot bubble.



THIN SHELL APPROXIMATION

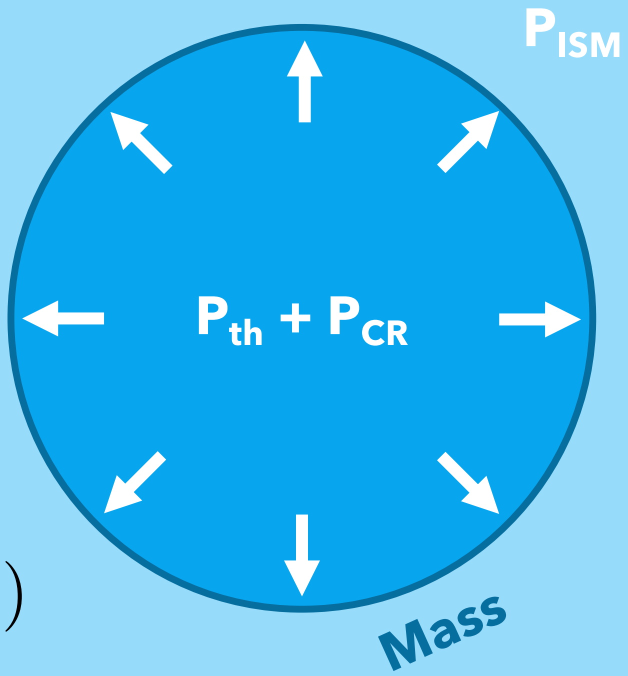
Enforce conservation laws:

$$M(R_{sh}) = M_{ej} + \frac{4\pi}{3} R_{sh}^3 \rho_{\rm ISM}$$

Effective adiabatic index depends on ξ

$$E = E_{SN}$$

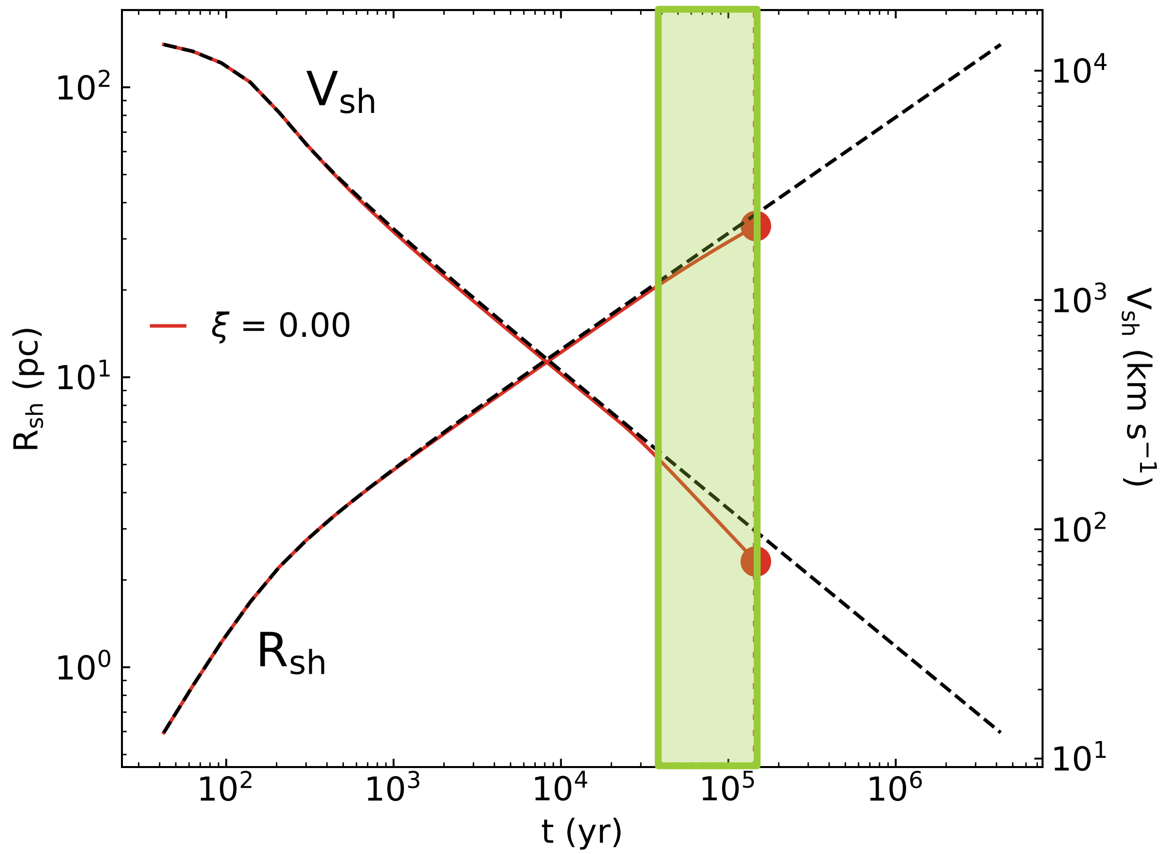
$$\frac{2}{\gamma_{\rm eff}+1}\frac{d(Mv_{sh})}{dt} = 4\pi R_{sh}^2 (P_{th} + P_{\rm CR} - P_{\rm ISM})$$



3. RADIATIVE STAGE

$T \lesssim 10^6$ K → thermal gas radiates away energy.

Use modified thin-shell approximation.



MODIFIED THIN SHELL APPROXIMATION

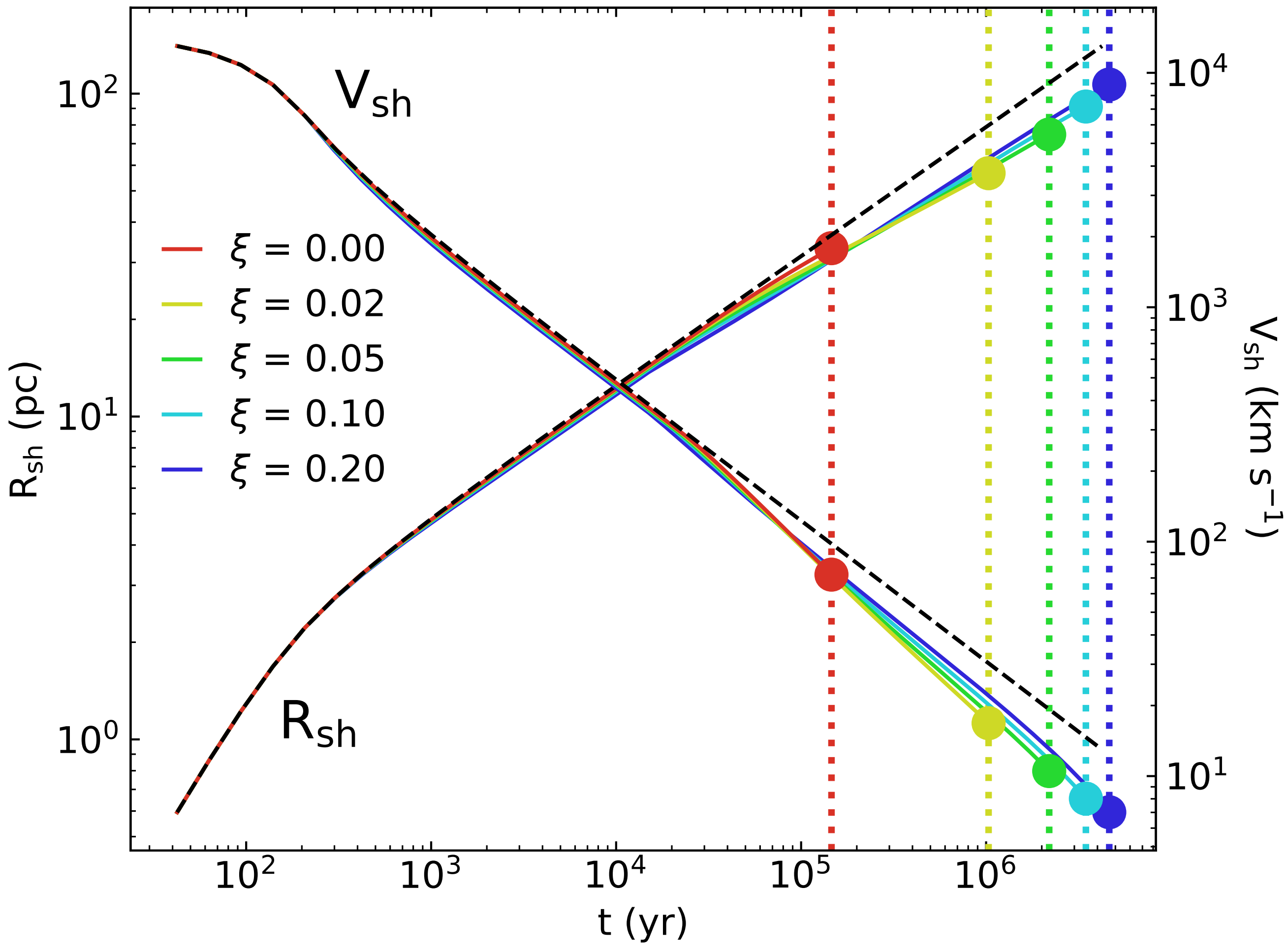
Enforce new conservation laws:

$$M(R_{sh}) = M_{ej} + \frac{4\pi}{3} R_{sh}^3 \rho_{\rm ISM}$$

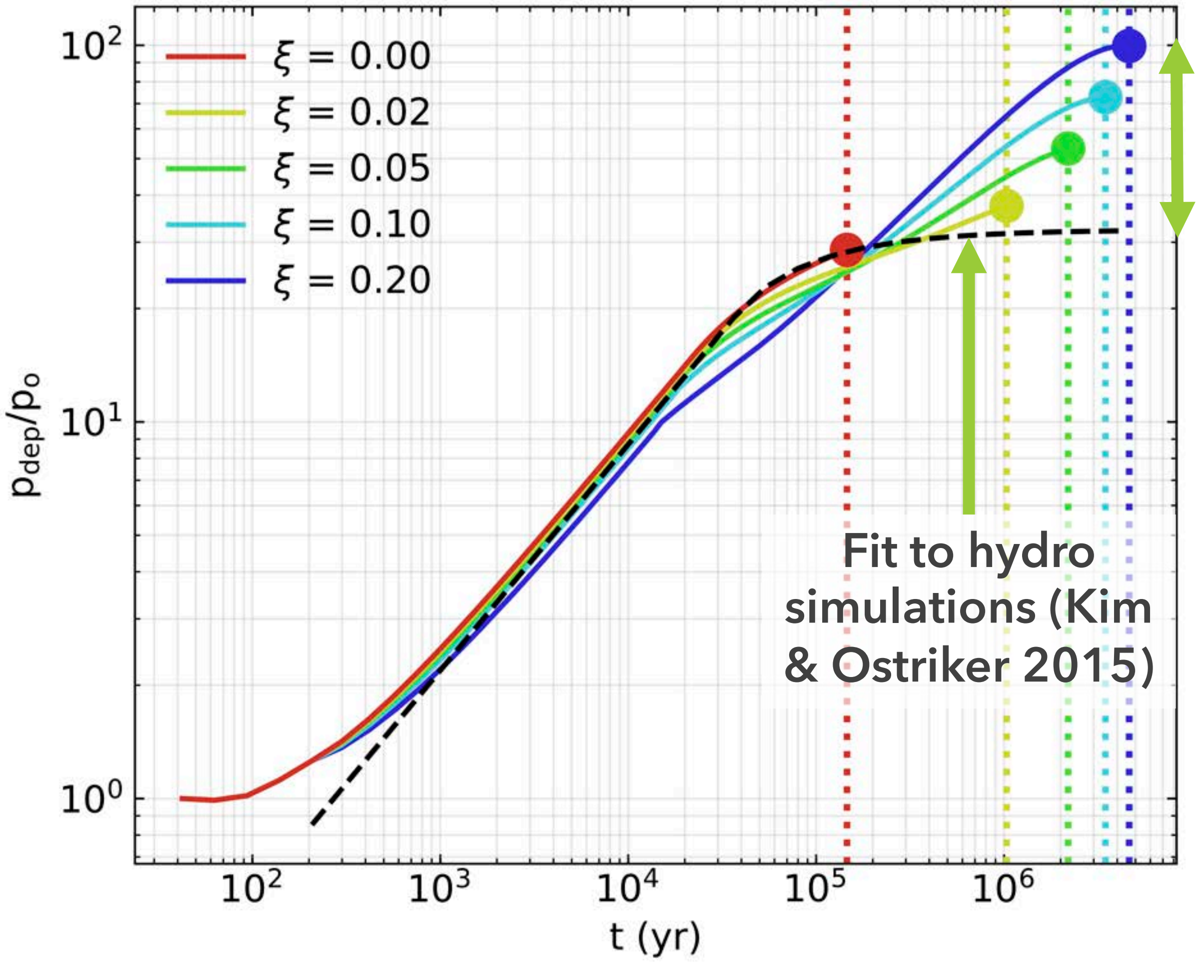
$$E(R_{sh}) = E_{SN} - \int_{t_{\rm rad}}^{t} d\tau 2\pi \chi_{th} \rho v_{sh}^3 R_{sh}^2$$

$$\frac{2}{\gamma_{\rm eff}+1} \frac{d(M v_{sh})}{dt} = 4\pi R_{sh}^2 (P_{th} + P_{\rm CR} - P_{\rm ISM})$$

RADIUS & VELOCITY EVOLUTION



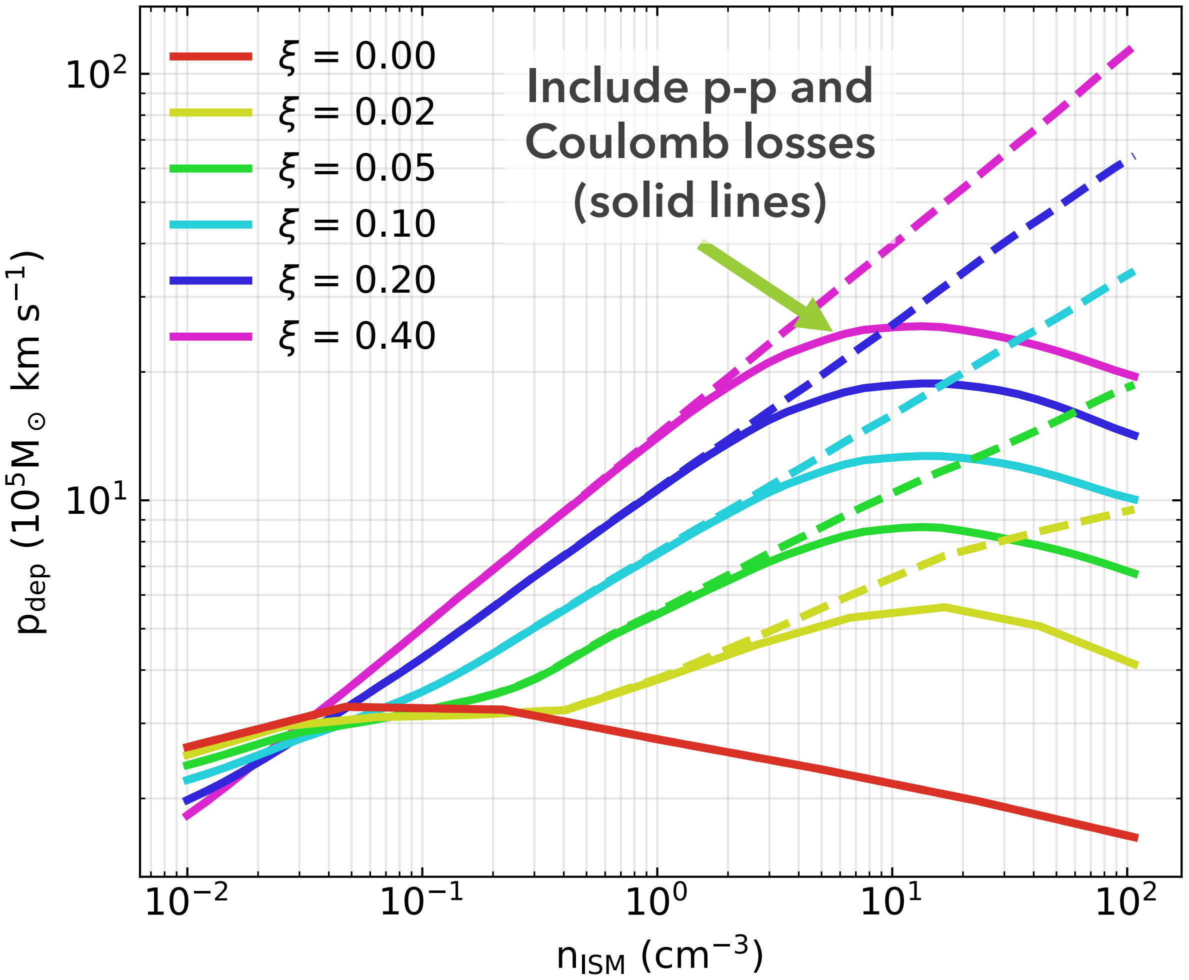
MOMENTUM EVOLUTION



Factor of ~2-3 increase

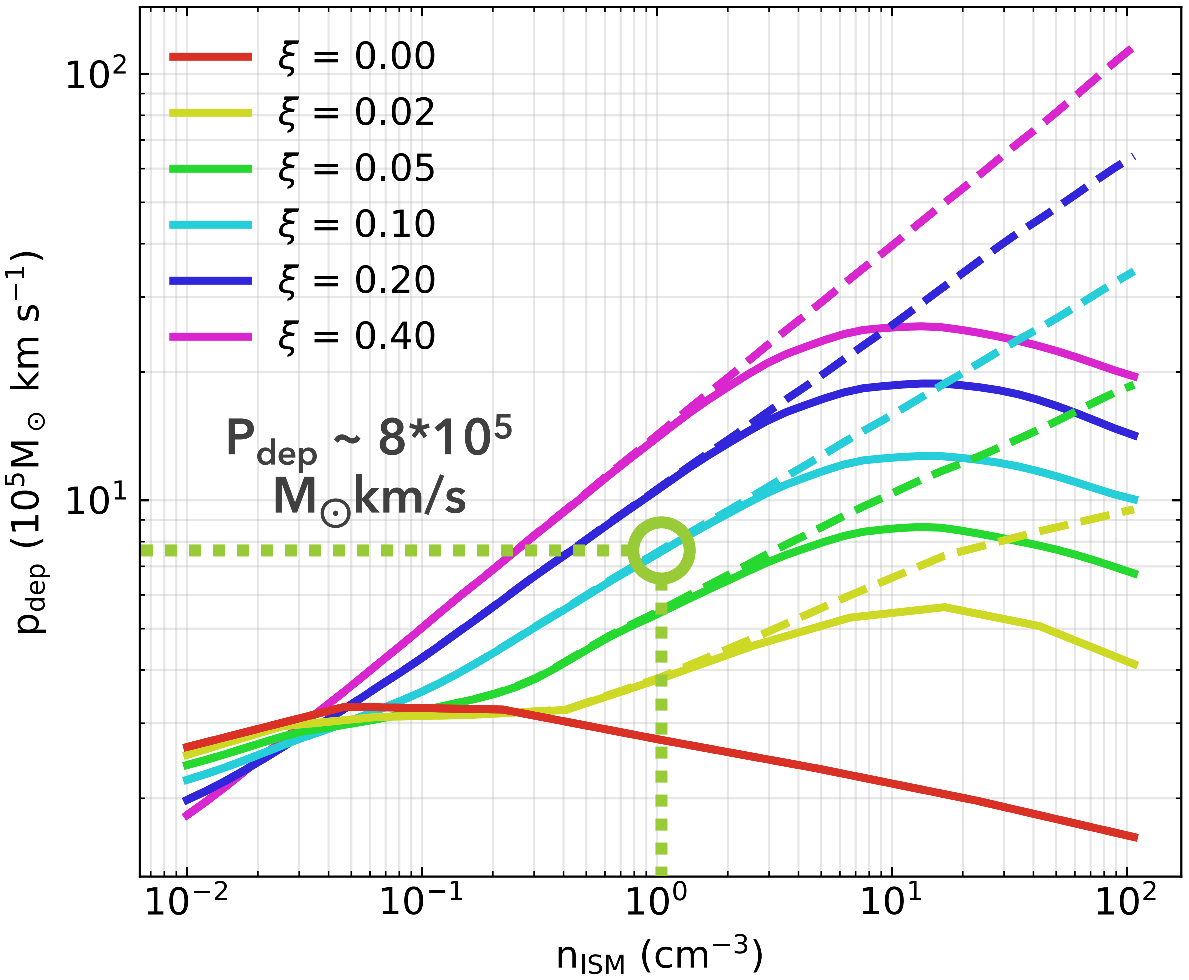
EFFECT OF ISM DENSITY

(keeping pressure constant)



EFFECT OF ISM DENSITY

(keeping pressure constant)



CONCLUSIONS

1. **This work represents the first semi-analytical calculation—in the thin-shell approximation limit—of SNR evolution through the Sedov-Taylor and radiative stages.**

   Our approach accurately reproduces the main features of hydro simulations (w/o CRs).

1. **The presence of cosmic rays prolongs the expansion of SNRs, resulting in 2-3 times more momentum deposition in the ISM.**

   This boost becomes more pronounced in dense environments.

2. **Galaxy formation simulations that include supernova feedback via sub-grid models should account for the additional contribution of the CRs accelerated at SNR shocks.**

For more information, please see Diesing & Caprioli 2018.