Modifications to diffusive shock acceleration in the presence of density gradients

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AG2026, GARCHING, 09.09.2026

Galactic Cosmic Rays

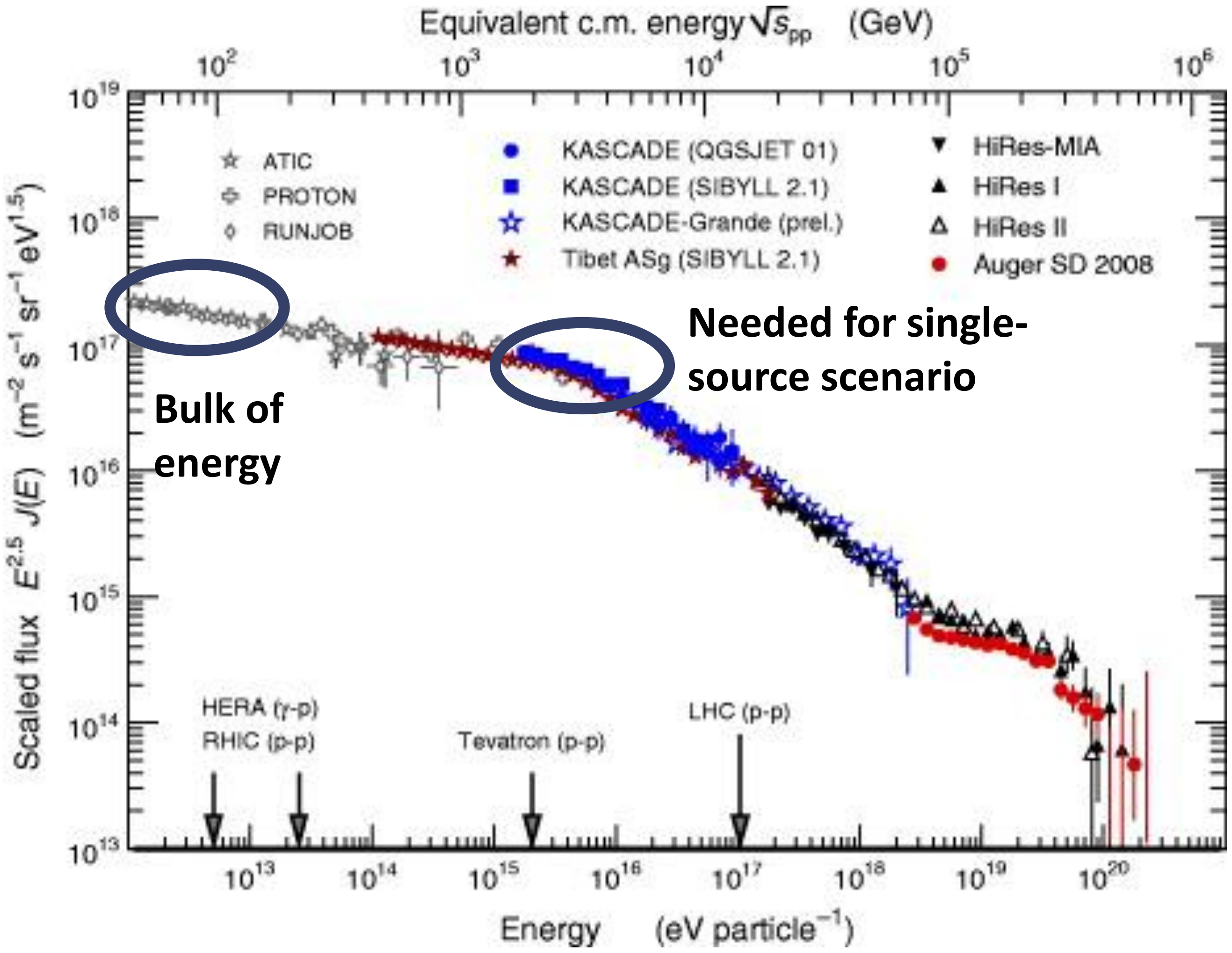
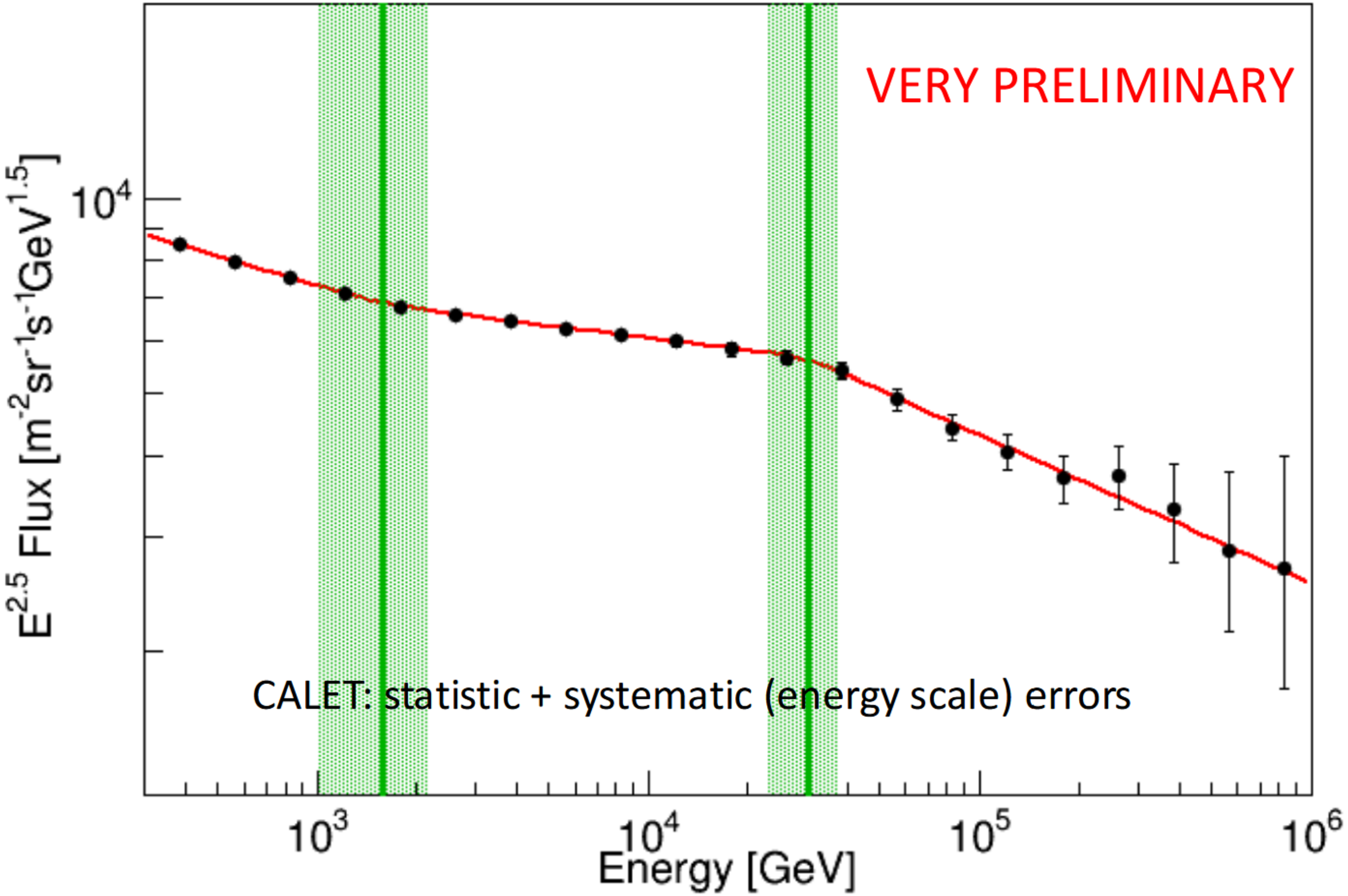


Figure: The cosmic ray spectrum (Blümer et al. 2019)

What are the sources?
How get particles accelerated?

Measured CR spectra

$$\Phi(E) = C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left[1+\left(\frac{E}{E_0}\right)^{S}\right]^{\frac{\Delta\gamma}{S}}\left[1+\left(\frac{E}{E_1}\right)^{S_1}\right]^{\frac{\Delta\gamma_1}{S_1}}$$



Fitting Parameters

$\gamma = -2.65 \pm 0.03$

$E_0 = 1.57 \pm 0.58$ TeV
$\Delta\gamma = 0.09 \pm 0.03$
$s = 6.6$ (Fix)

$E_1 = 30.6 \pm 7.4$ TeV
$\Delta\gamma_1 = -0.17 \pm 0.04$
$s_1 = 10$ (Fix)

Yosui Akaike ICRC 2025 – The Astroparticle Physics Conference, Geneva, Switzerland

Cosmic Rays Species

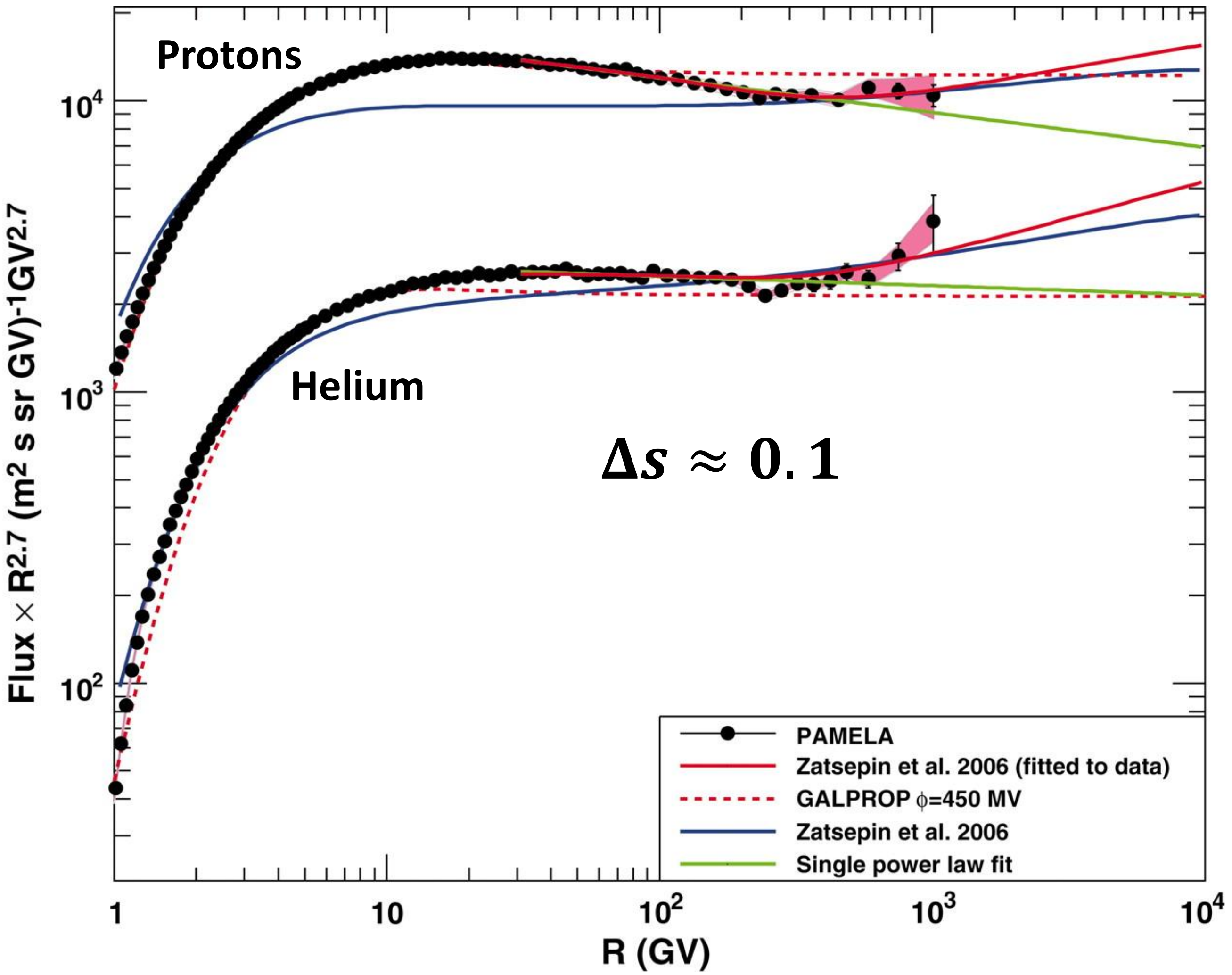


Figure: Proton and Helium spectra (PAMELA collab. 2011)

The acceleration should only be rigidity dependent!

- **Propagation effect (spallation)?**
- **Different sources (a local Helium accelerator)?**

Why SNRs?

- Known to inject enough energy in the Galaxy
- Known accelerators of non-thermal electrons
- Known accelerators of hadrons
- Viable acceleration mechanism known

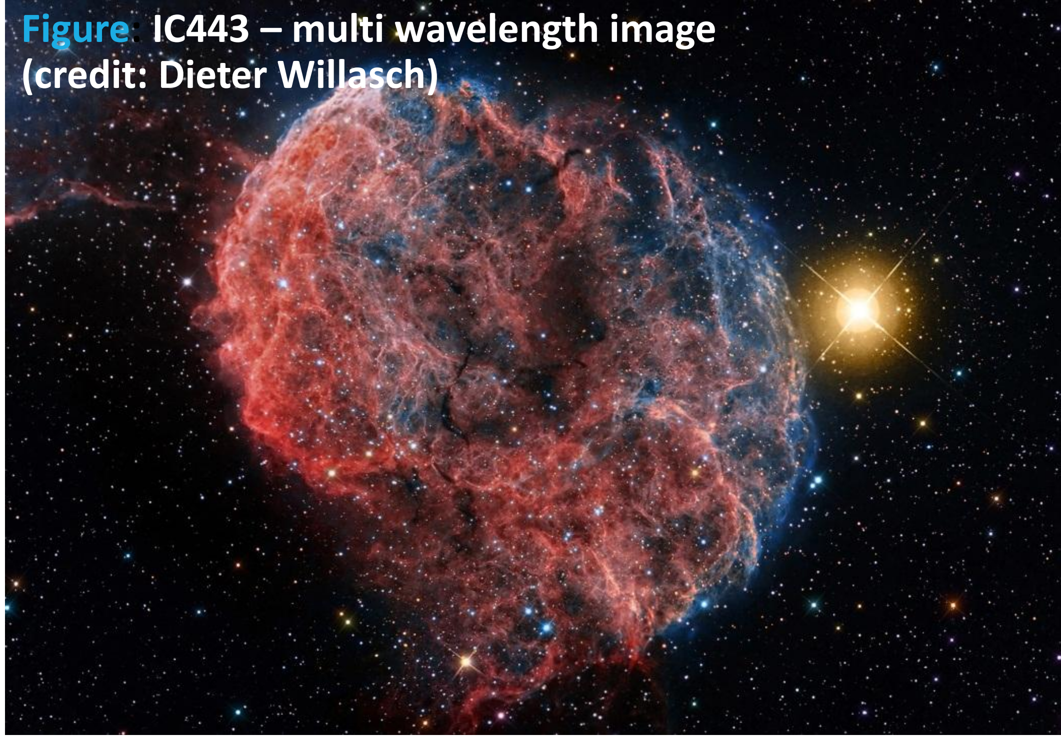


Figure: IC443 – multi wavelength image (credit: Dieter Willasch)

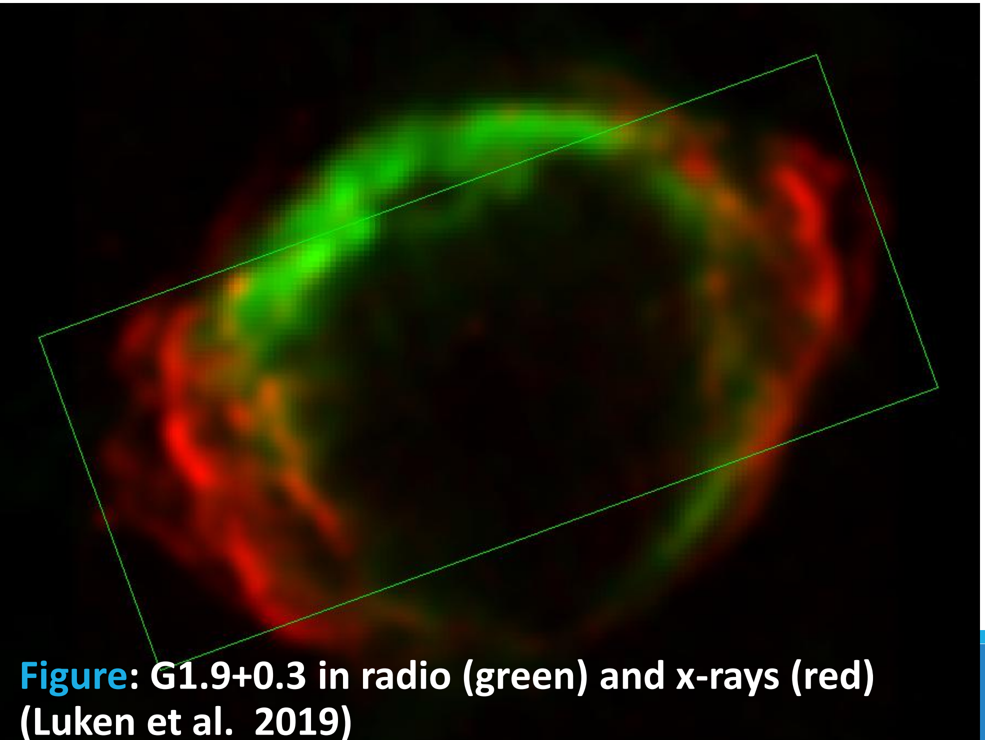


Figure: G1.9+0.3 in radio (green) and x-rays (red) (Luken et al. 2019)

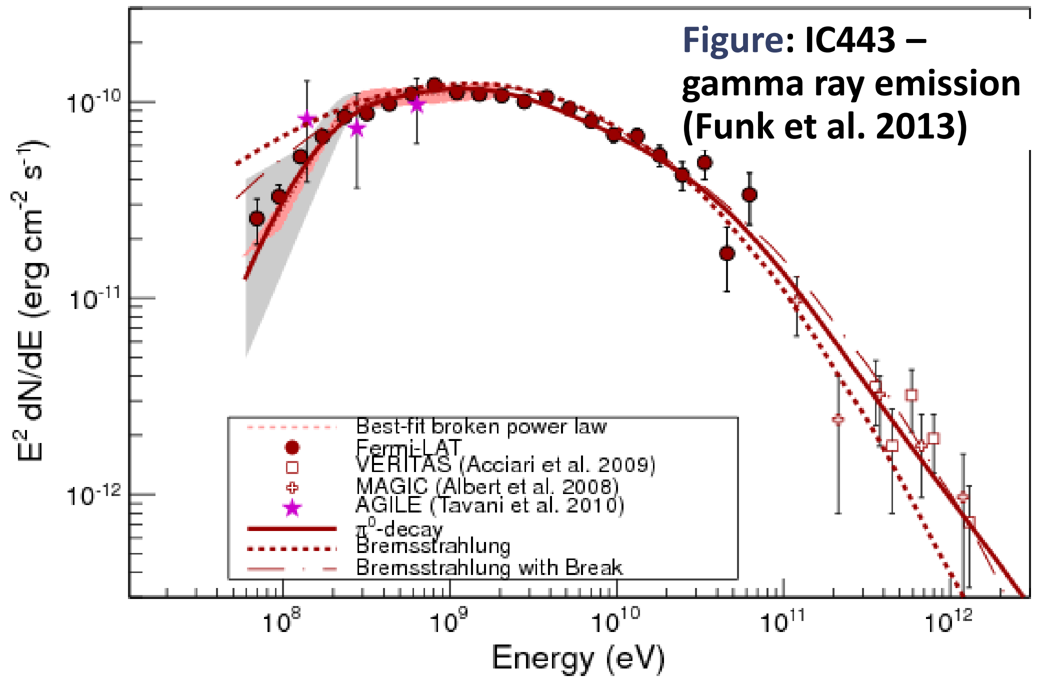


Figure: IC443 – gamma ray emission (Funk et al. 2013)

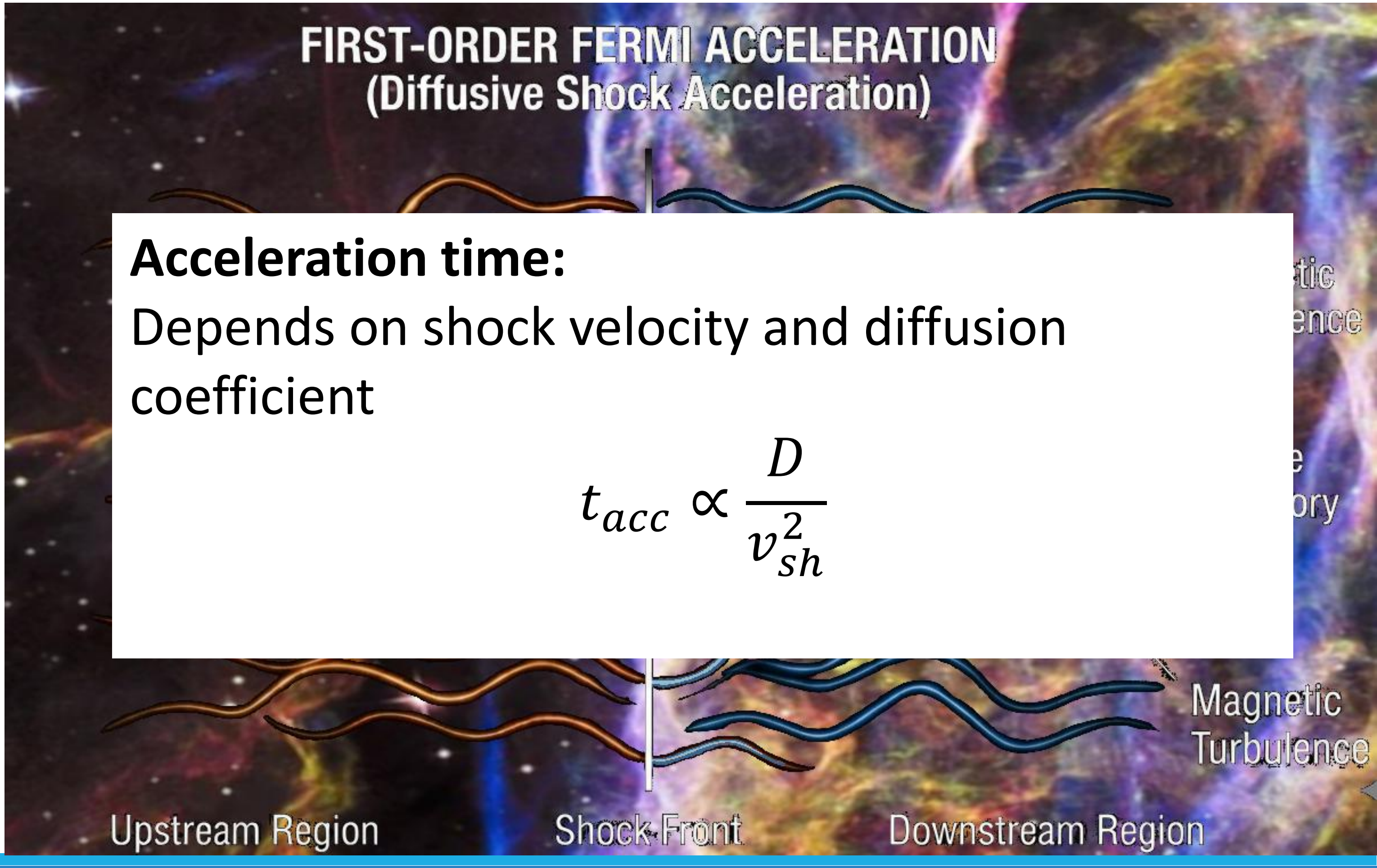
Diffusive shock acceleration

Ingredients:

- The Hydro evolution of the specific SNR
- The distribution of CRs
- The distribution of magnetic disturbances that scatter the CRs

→non-thermal, power-law spectra

$$N(p) \propto p^{-{r+2}/{r-1}}$$
$$N(p) \approx p^{-2}$$



Acceleration time:

Depends on shock velocity and diffusion coefficient

$$t_{acc} \propto \frac{D}{v_{sh}^2}$$

Other modifications

Basic idea of most: $r \neq 4 \; \rightarrow s \neq -2$

- *Alfvenic drift:* Scattering centers have sizable velocity with respect to the shock
  $\rightarrow v_u = v_{sh} + v_A, v_d = \frac{1}{4} v_{sh} + xV_A$
- *Weak shocks:* For massive stars, r<4 in the shocked wind → soft spectra (e.g. Das et al. 2023, 2025)
- *Magnetic pressure:* Magnetic pressure can limit gas-compression. More relevant in radiative shocks.
- *Energy transfer to turbulence:* $\gamma = 2 + 4\Phi$ for strong shocks, with $\Phi = {}^{E_{turb}}/_{E_{CR}} \ll 1$ (e.g. Bell 2019)

Realistic environments

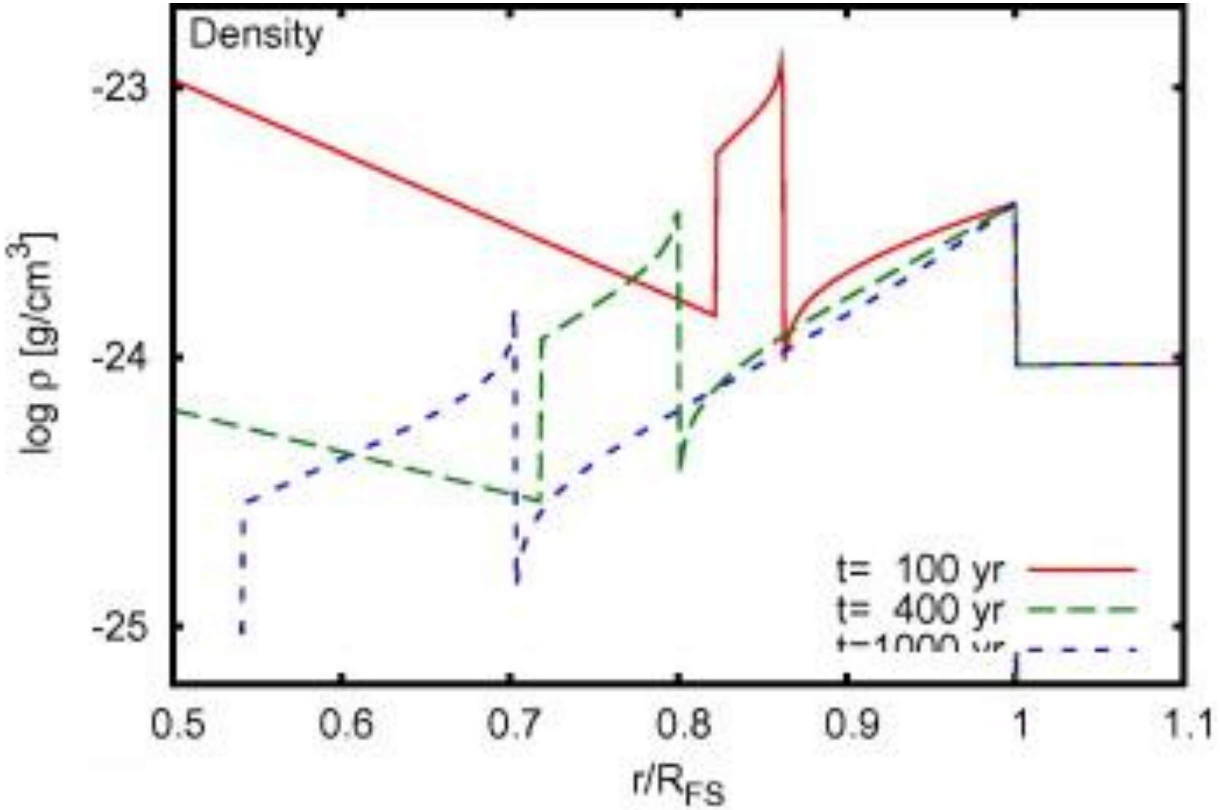


Figure: Density structure of a Type-Ia SNR (Telezhinsky et al. 2012)

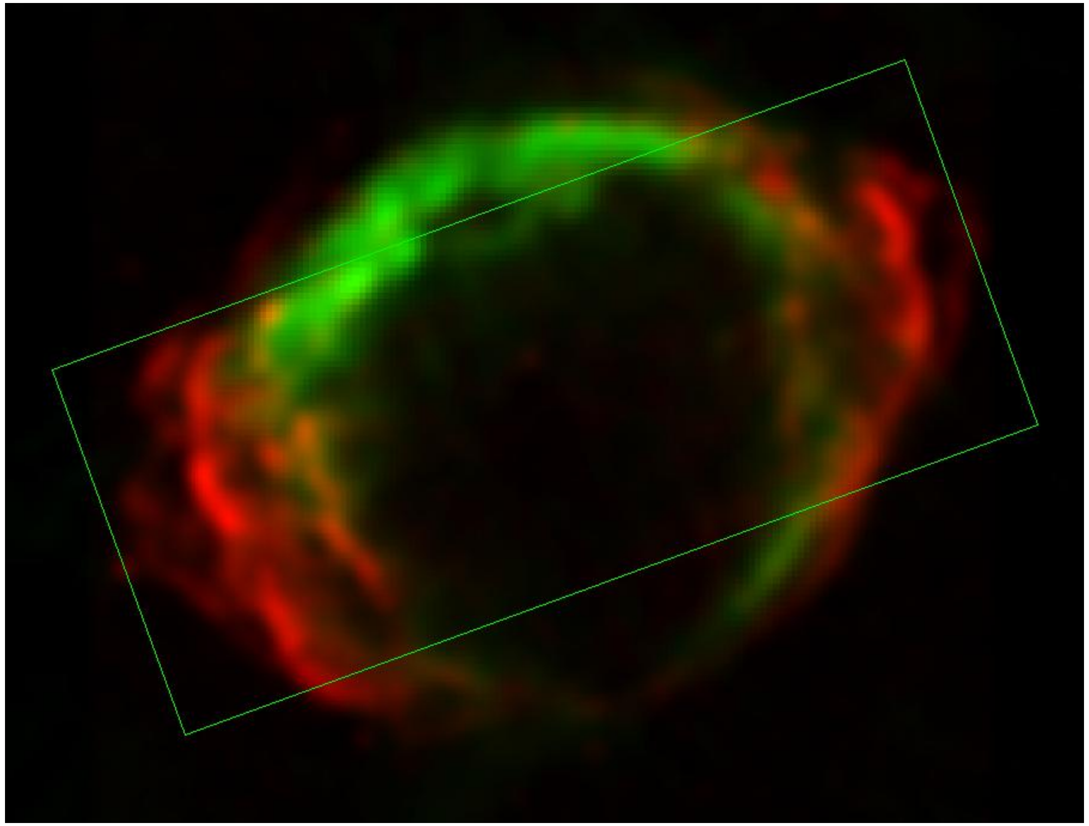


Figure: G1.9+0.3 in radio (green) and x-rays (red) (RB et al. 2019)

Realistic environments

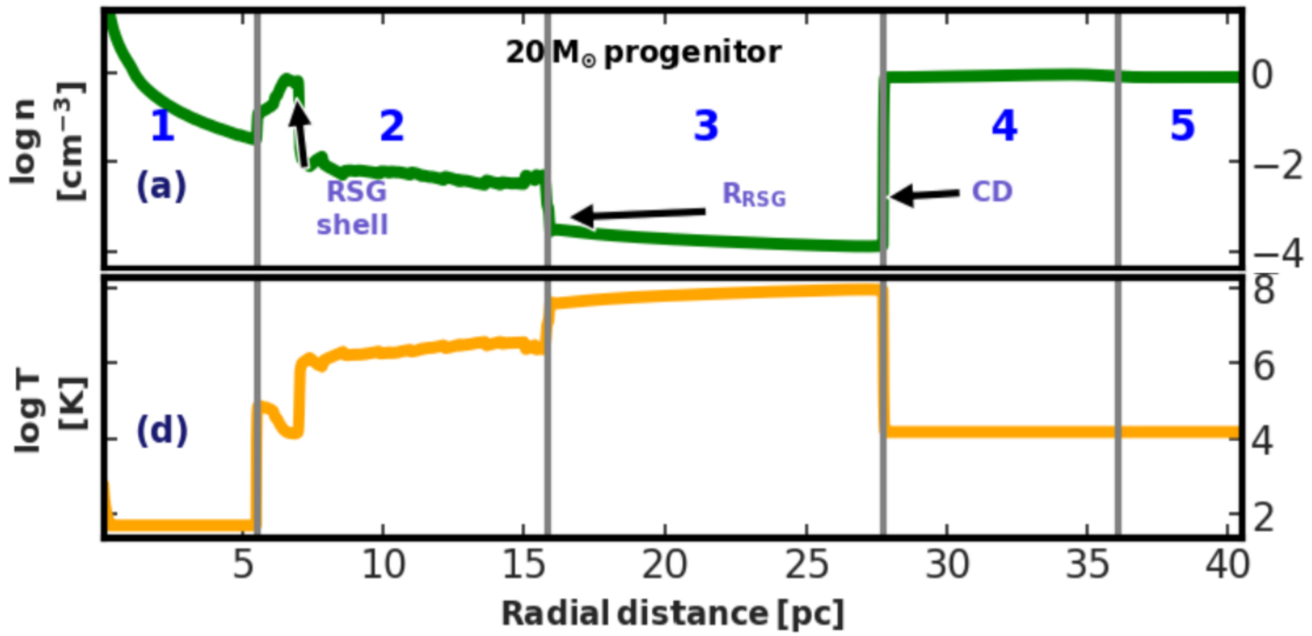
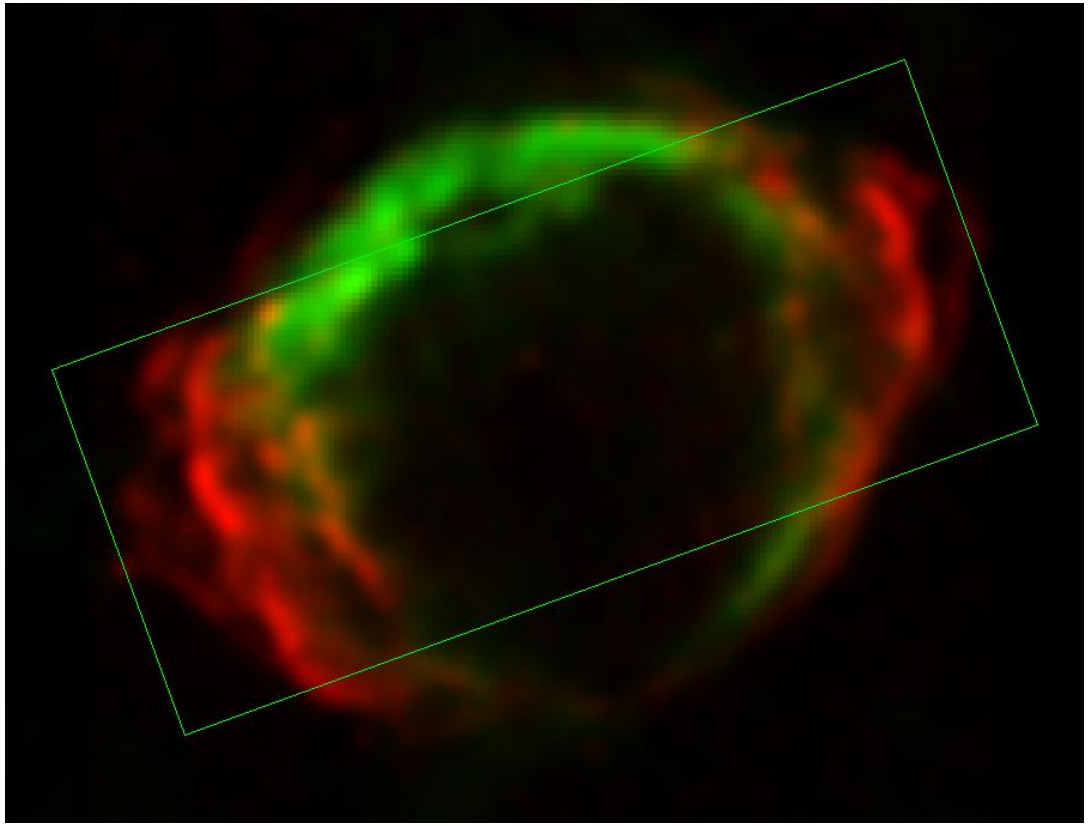


Figure: Density structure around a 20 M_{sol} star (Das et al. 2022)



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Varying abundancies

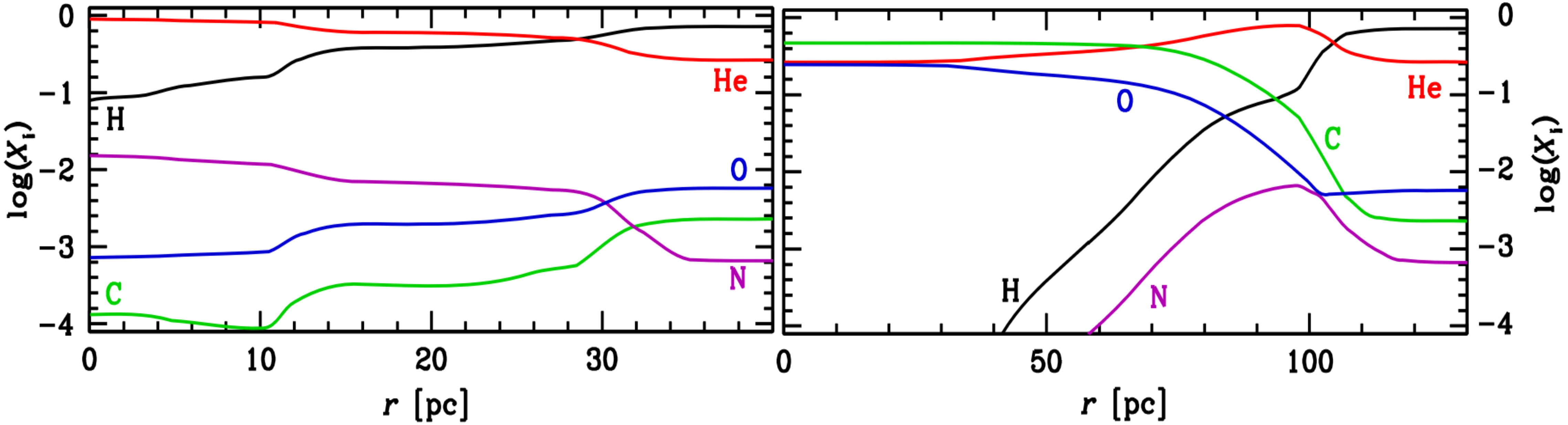


Figure: Abundancy around a 25M_{sol} (left) and 85M_{sol} (right) star. (Georgy et al. 2013)

Abundancies of CR species can vary way stronger than the overall density profile!

Disclaimer

1 PHYSICS

1.1 History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.

(Weinersmith, 2017)

We have it all figured out besides the

- Magnetic turbulence
- Particle energization
- (Hydrodynamics)

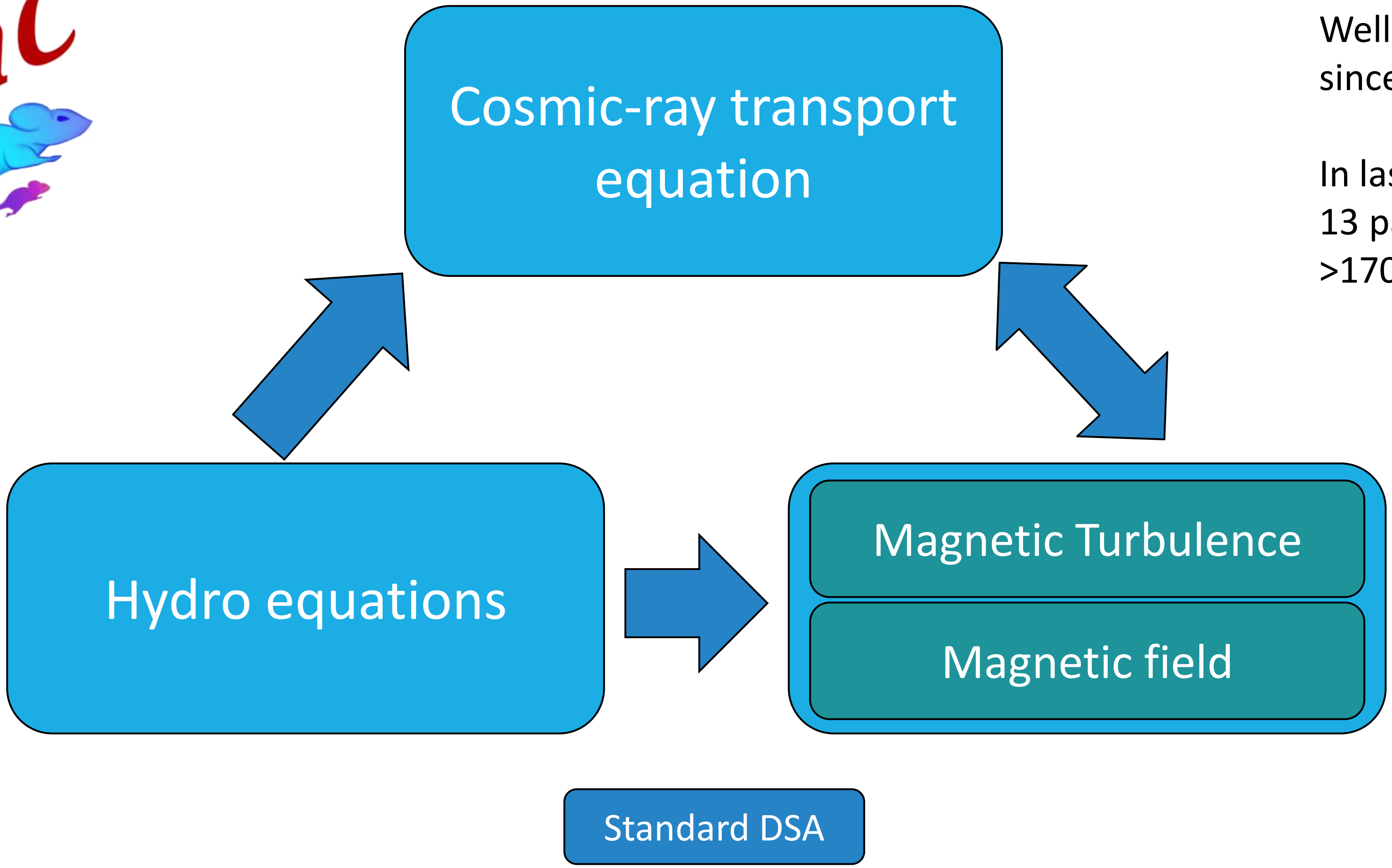
The Simplifications – CR-Scattering

Wave-modes scattering CRs not fully clear – a necessary assumptions in all models:

- Alfven waves (e.g. Skilling 1975)
- Bell's mode waves (Lucek & Bell 2000)
- Fast-mode waves (Yan & Lazarian 2004)
- Mirror-scattering (Bell 2025)
- Resonant curvature scattering (Kempski 2025)

→ Type of turbulence/instability will ultimately affect the time-evolution of CR-acceleration

RATPaC – Radiaion Acceleration Transport PArallel Code



Well-tested code in development since 2012

In last 5 years:
13 papers
>170 citations

RATPaC – The Equations

$$\frac{\partial N}{\partial t} = \underbrace{\nabla D_r \nabla N}_{\text{Diffusion}} - \underbrace{\nabla v N}_{\text{Advection}} - \frac{\partial}{\partial p}\Big(\underbrace{N\dot{p}}_{\text{Cooling}} - \underbrace{\frac{v}{3}Np}_{\text{Acceleration}}\Big) + \underbrace{Q}_{\text{Injection}}$$

$$\frac{\partial E_W}{\partial t} = -\underbrace{(v\nabla_r E_W + c\nabla_r v E_W)}_{\text{Advection + Compression}} + \underbrace{k^3 \nabla_k D_k \nabla_k \frac{E_W}{k^3}}_{\text{Cascading}} + \underbrace{2(\Gamma_g - \Gamma_d)E_W}_{\text{Growth + Damping}}$$

$$\frac{\partial}{\partial t}\begin{pmatrix} \varrho \\ \boldsymbol{m} \\ E \end{pmatrix} + \nabla \begin{pmatrix} \varrho \boldsymbol{v} \\ \boldsymbol{m}\boldsymbol{v} + (P)\boldsymbol{I} \\ (E+P)\boldsymbol{v} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix} \qquad \frac{\rho \boldsymbol{v}^2}{2} + \frac{P}{\gamma - 1} = E$$

The equations are solved:

- One dimensional
- Spherically symmetric
- Monoenergetic injection
- Including Synchrotron and inverse-Compton cooling for electrons
- On a comoving, expanding grid for turbulence and CRs → no free escape boundary

Varying abundancies

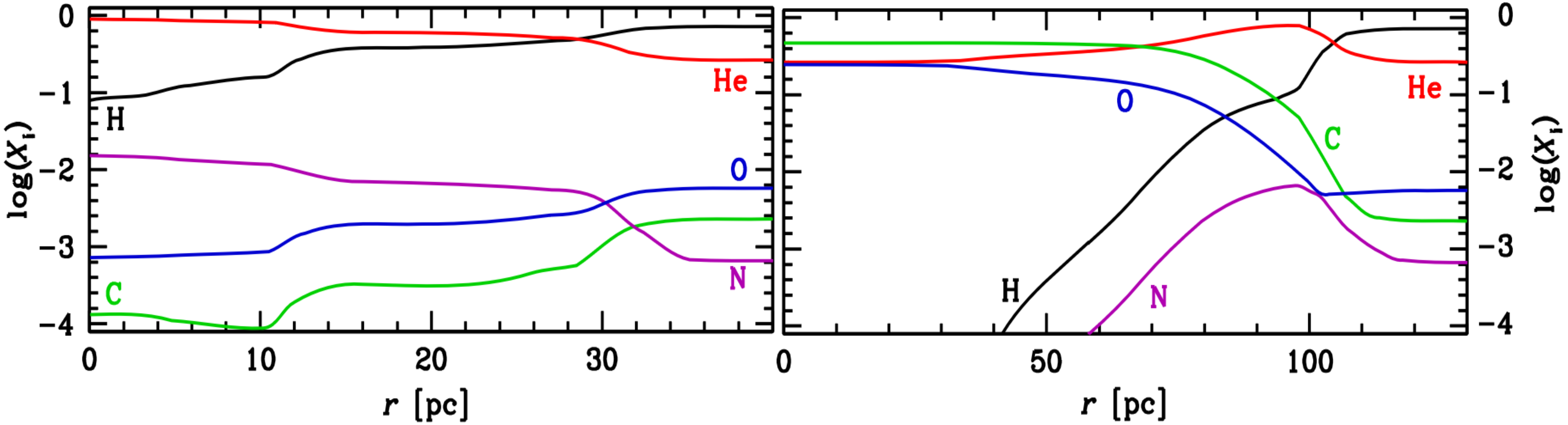
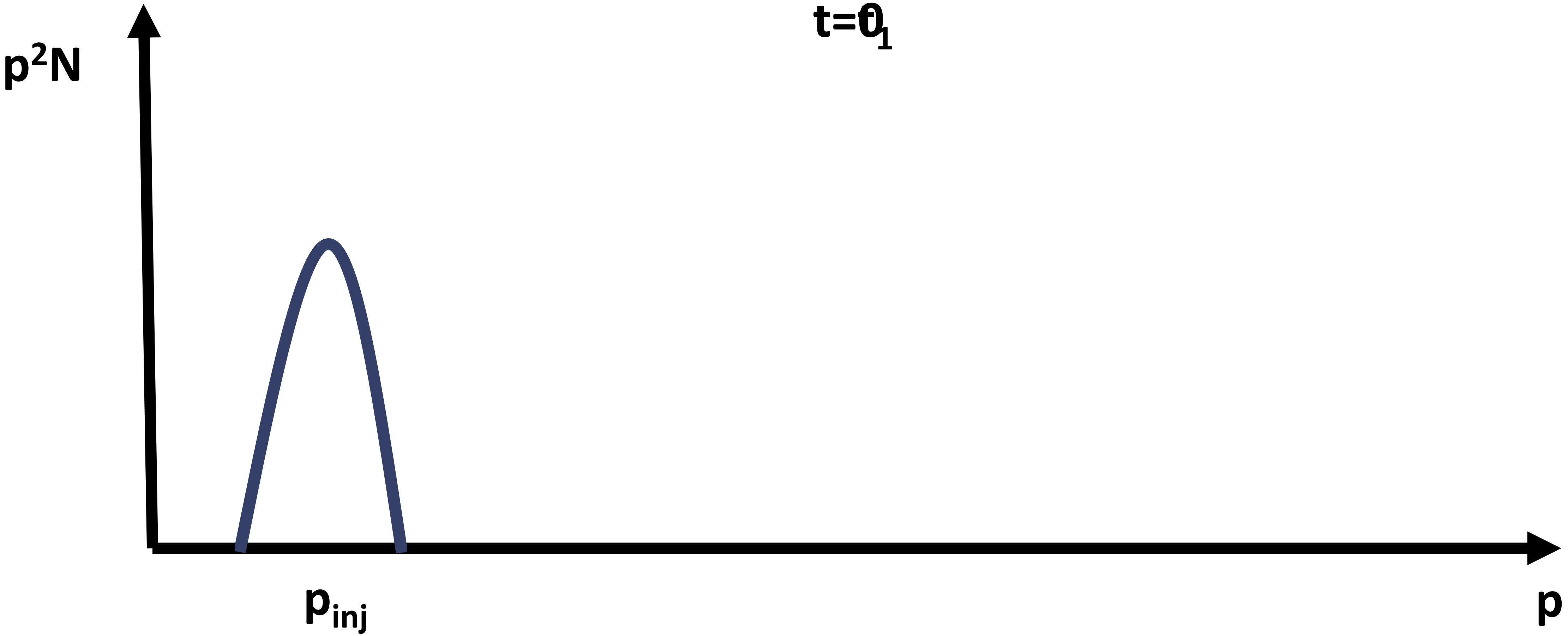


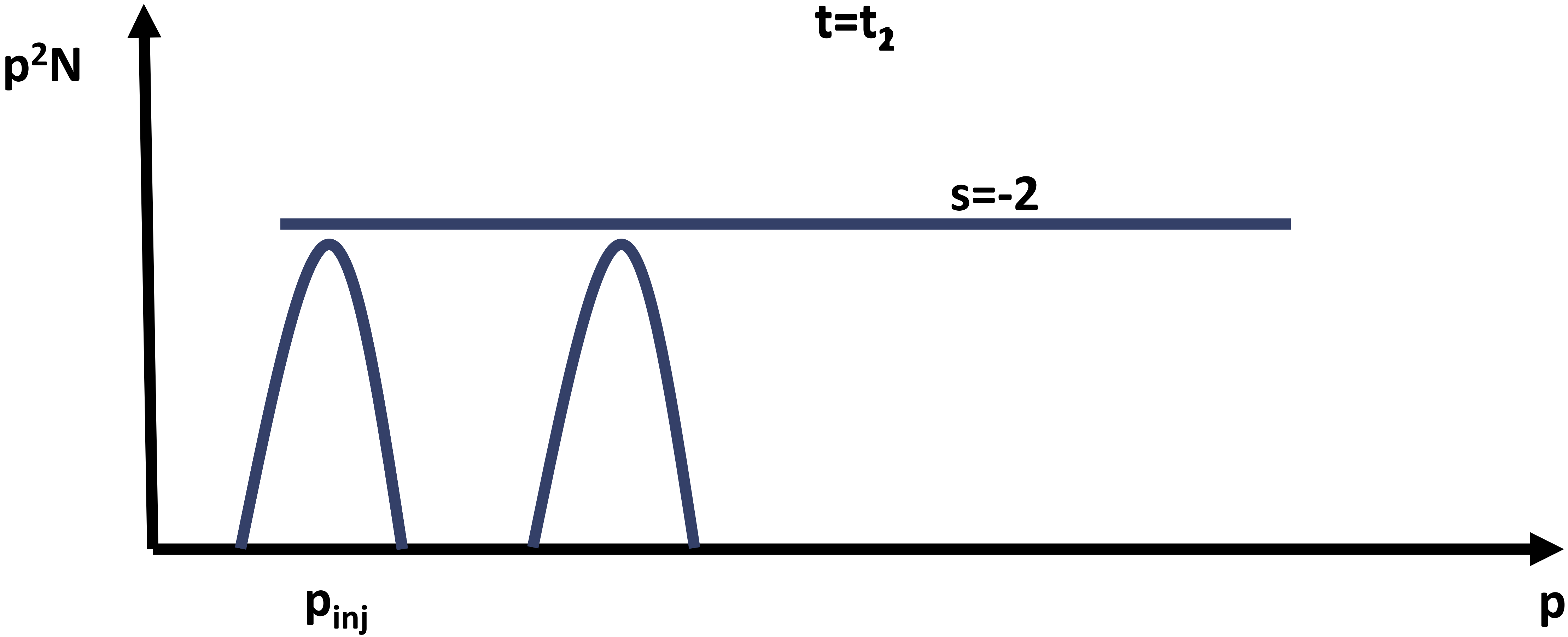
Figure: Abundancy around a 25M_{sol} (left) and 85M_{sol} (right) star. (Georgy et al. 2013)

Abundancies of CR species can vary way stronger than the overall density profile!

DSA in the face of gradients



DSA in the face of gradients



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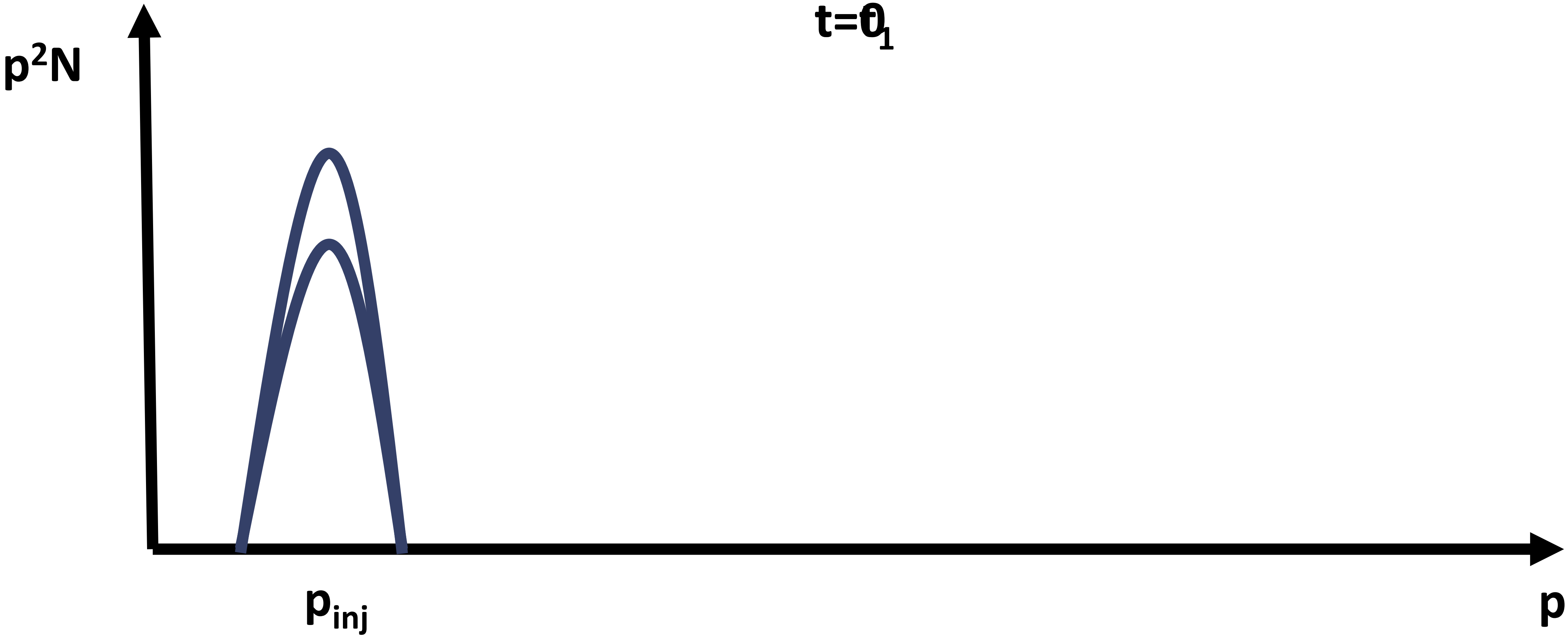

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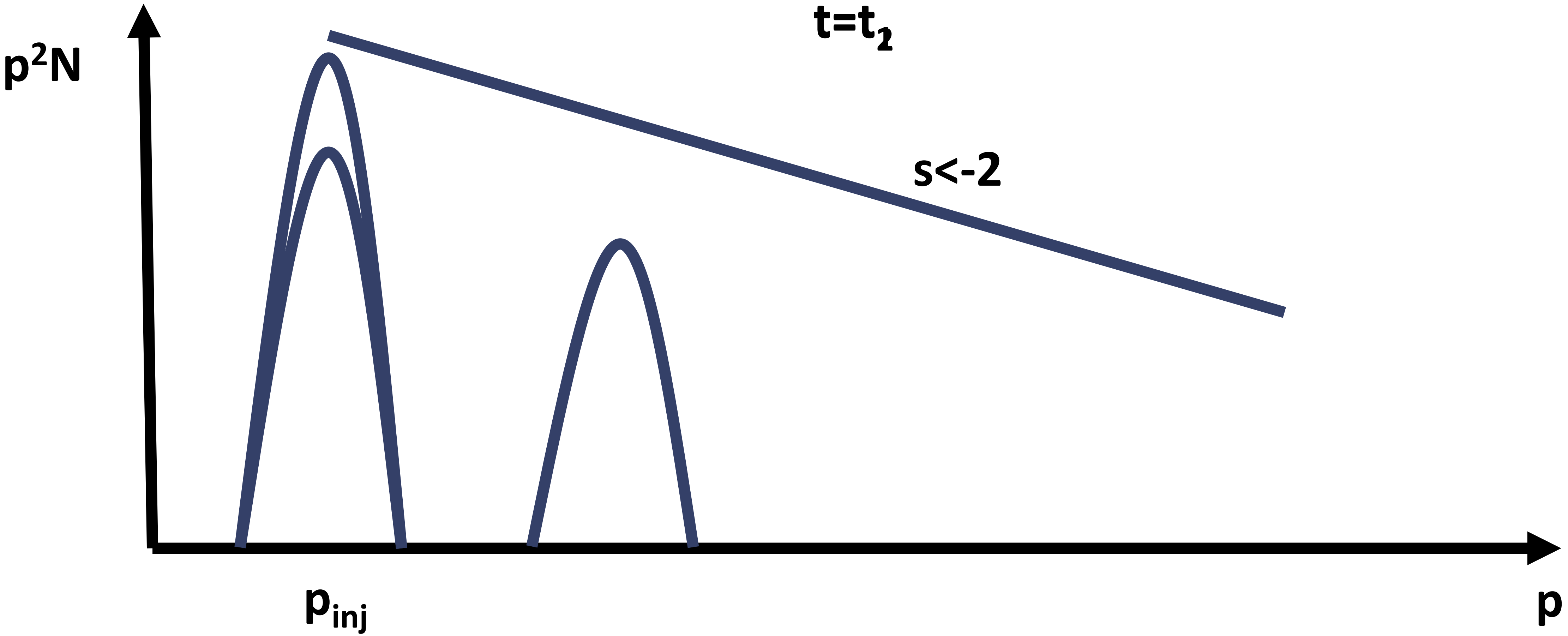


DSA in the face of gradients

$$\frac{\partial N(p,r,t)}{\partial t} - \nabla(D\nabla \mathrm{N} - uN) - \frac{\partial}{\partial p}\left(\frac{\nabla u}{3} Np\right) = Q(p,r,t)$$

…

$$N(p) \propto Q(p_0, t) p^{-(r+2)/(r-1)}$$

$$\rightarrow N(p) \propto p^{-\frac{r+2}{r-1} \pm \frac{\tau_{acc}}{t_{gra}}} \quad \text{with}$$

τ_{acc} - acceleration time
τ_{gra} - time scale of density change

Problem: What is the escape flux?

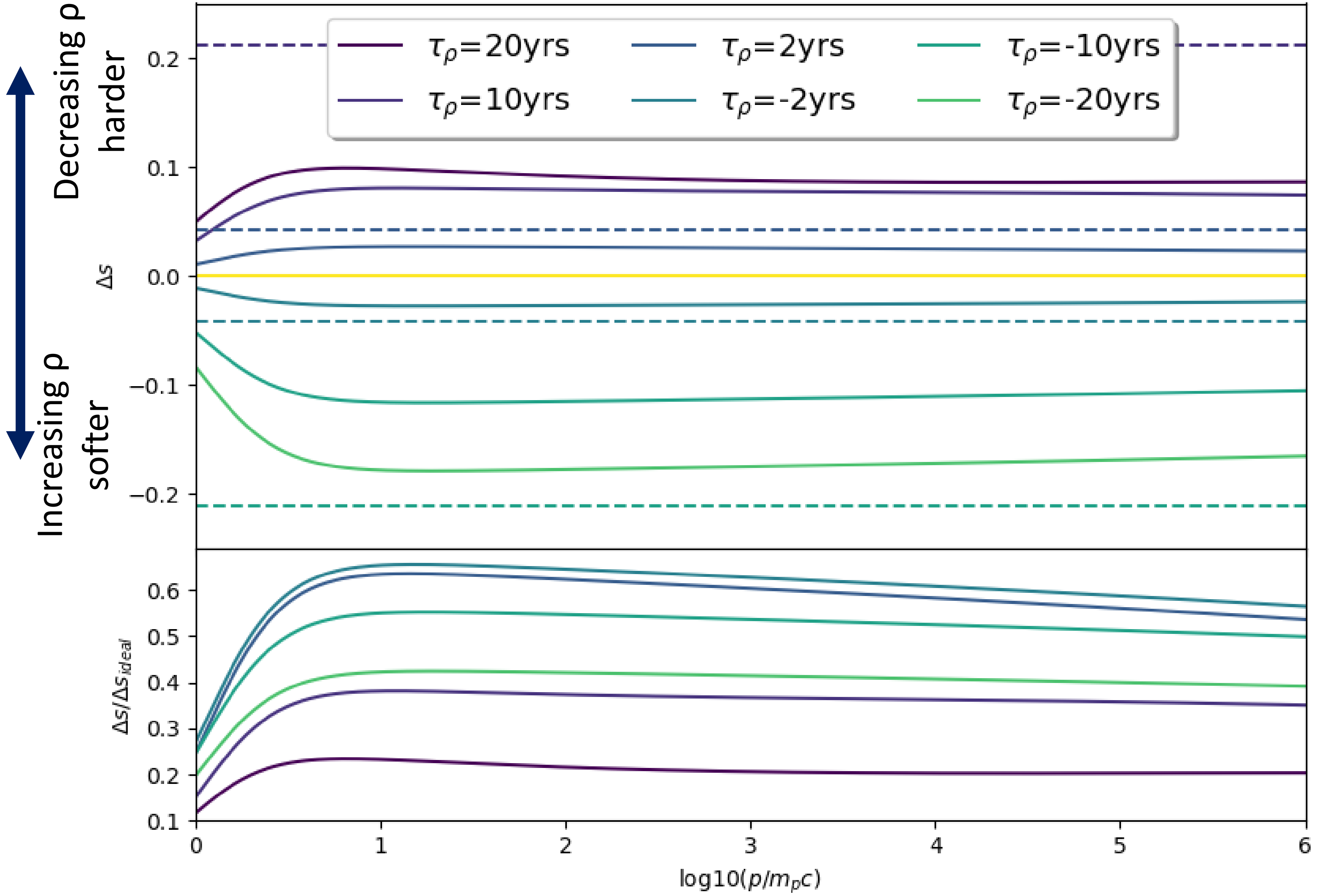
A Toymodel

$$\frac{\partial N(r,p,t)}{\partial t} = \nabla D_r \nabla N - \nabla v N - \frac{\partial}{\partial p}\left(N\dot{p} - \frac{v}{3}Np\right) + Q$$

A Toymodel setup:

- Constant shock velocity
- Constant downstream flow-velocity
- Exponential upstream density: $\rho_u = \rho_0 \exp\left(\pm\frac{\mathrm{t}}{\tau_{grad}}\right)$
  (mimics one species with strongly varying abundancy)
- Kolmogorov or constant diffusion coefficient

A Toymodel – energy-independent diffusion

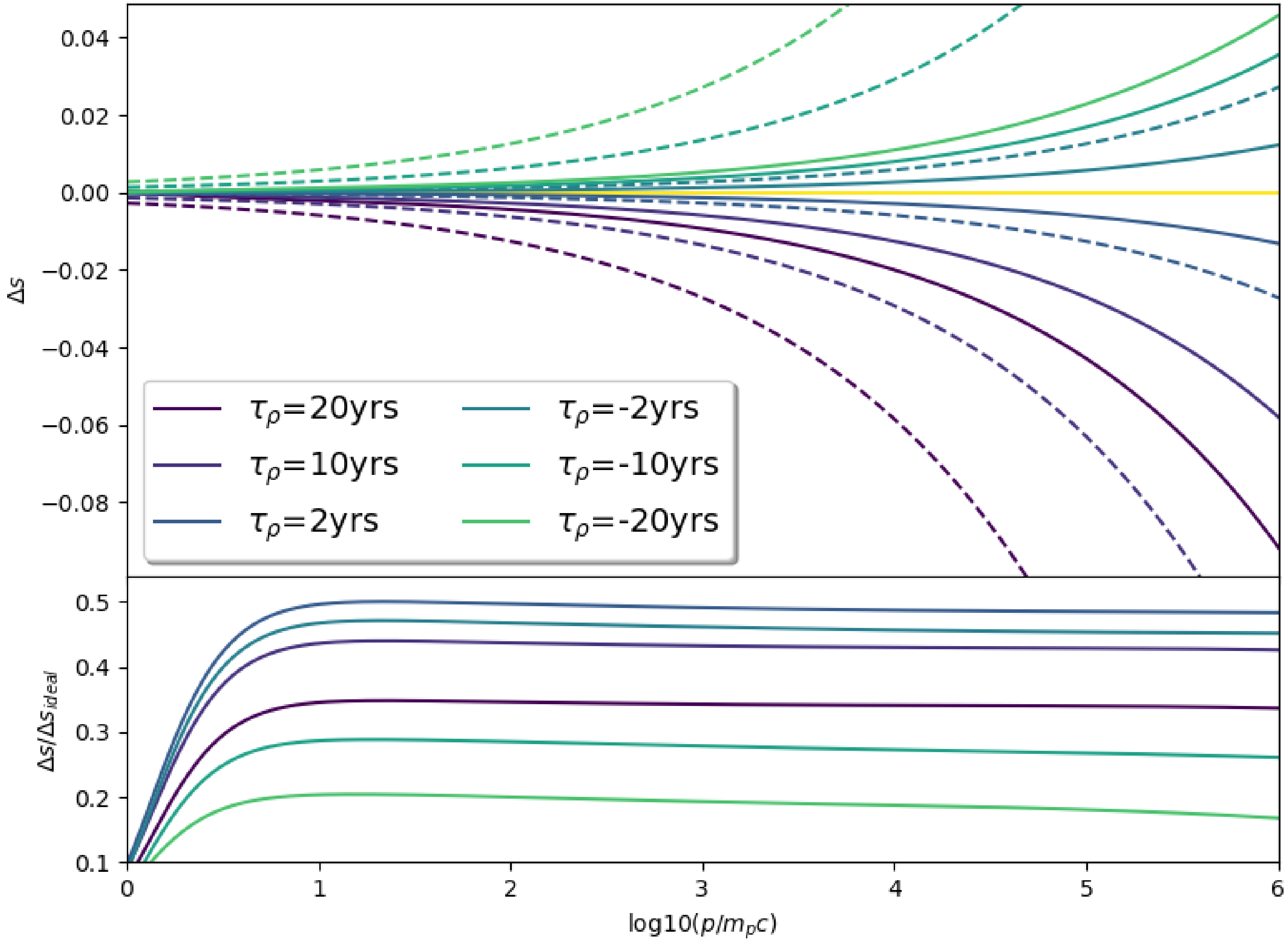


- **The effect is clearly visible in simulations**
- **Strong gradients weaken the effect with respect to naive expectations**

A Toymodel – Kolmogorov Diffusion

Decreasing ρ
harder

Increasing ρ
softer



- **The effect is stronger at higher energies (larger τ_{acc})**

Use-cases – Fe60 in the local bubble

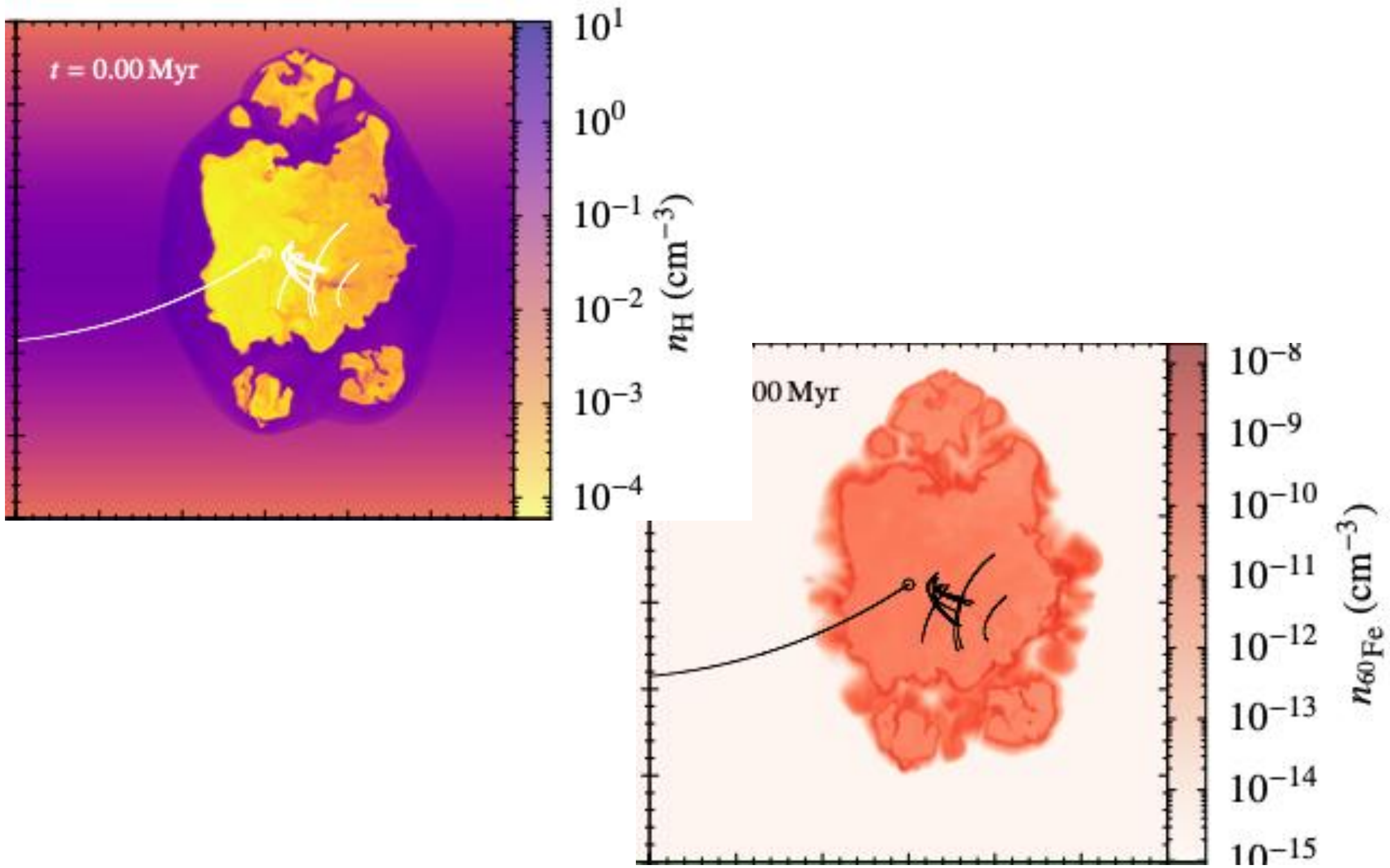


Figure: The local bubble (Schulreich et al. 2023)

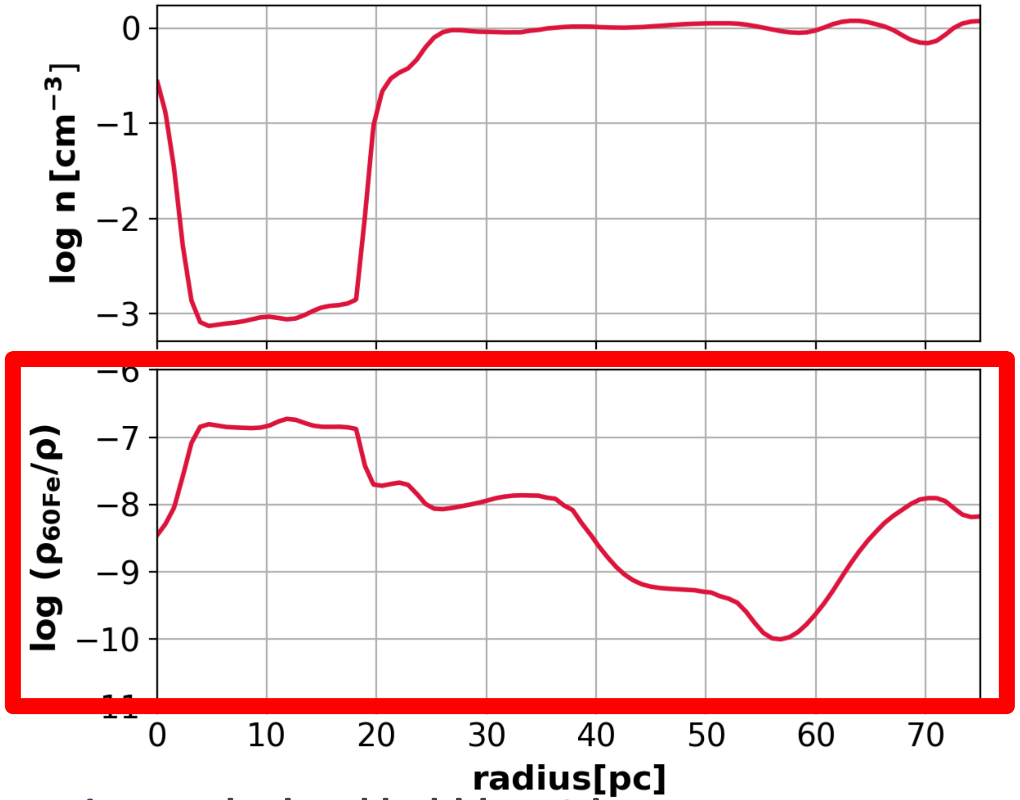
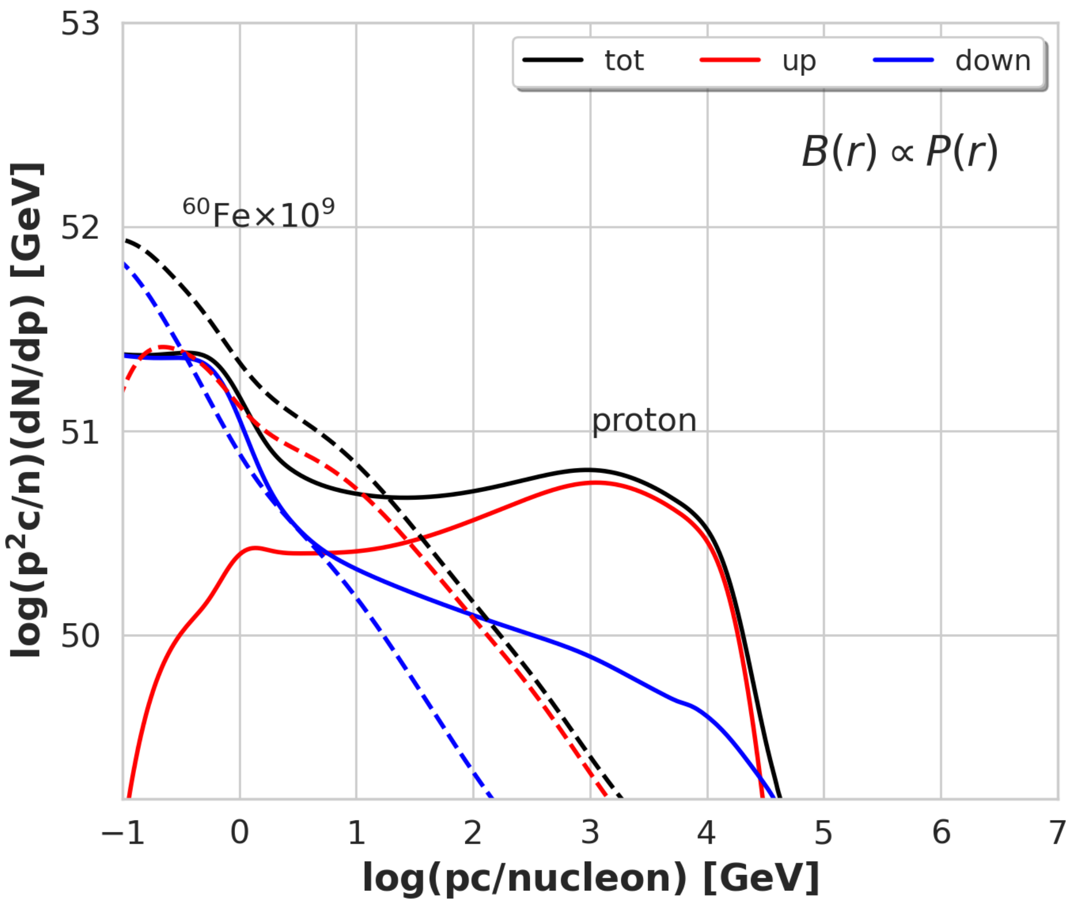


Figure: The local bubble – 1d cones (Shi et al et al. 2025)

Use-cases – Fe60 in the local bubble

The effect persists in „long“ simulations with realistic CSM



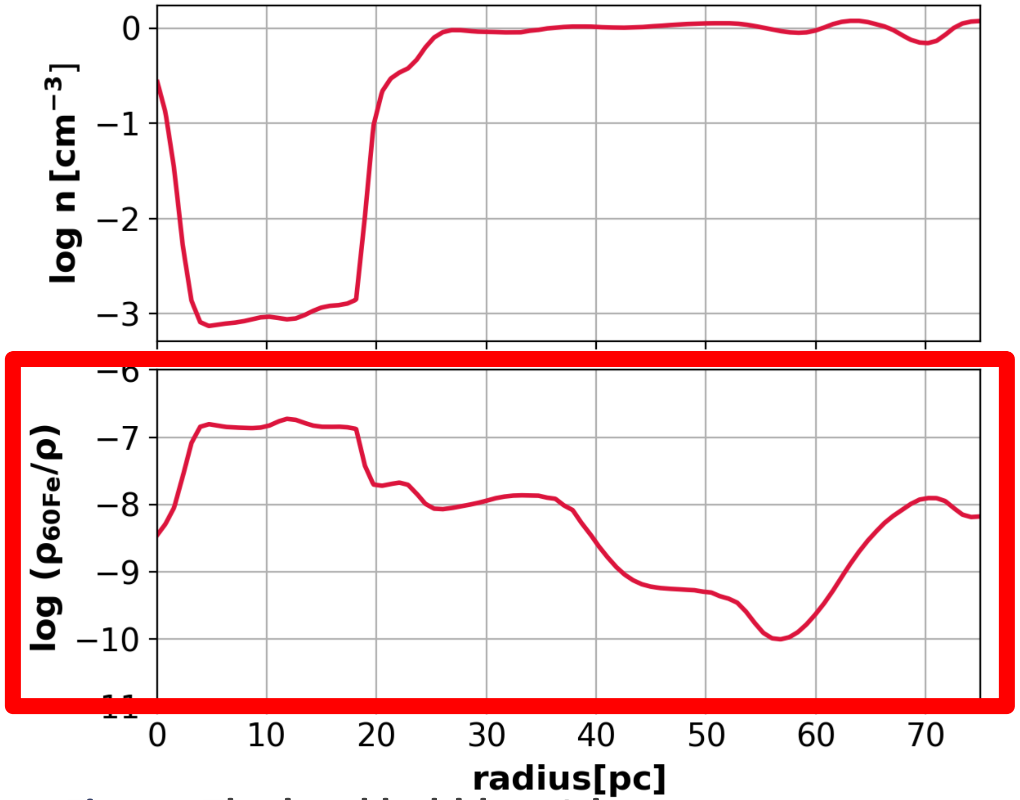


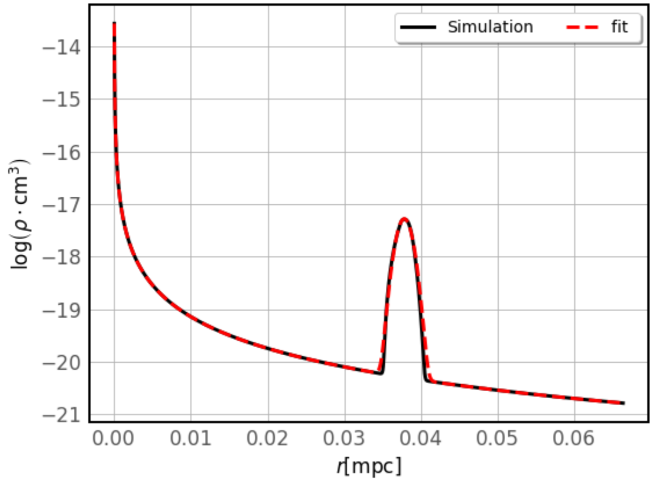
Figure: The local bubble – 1d cones (Shi et al et al. 2025)

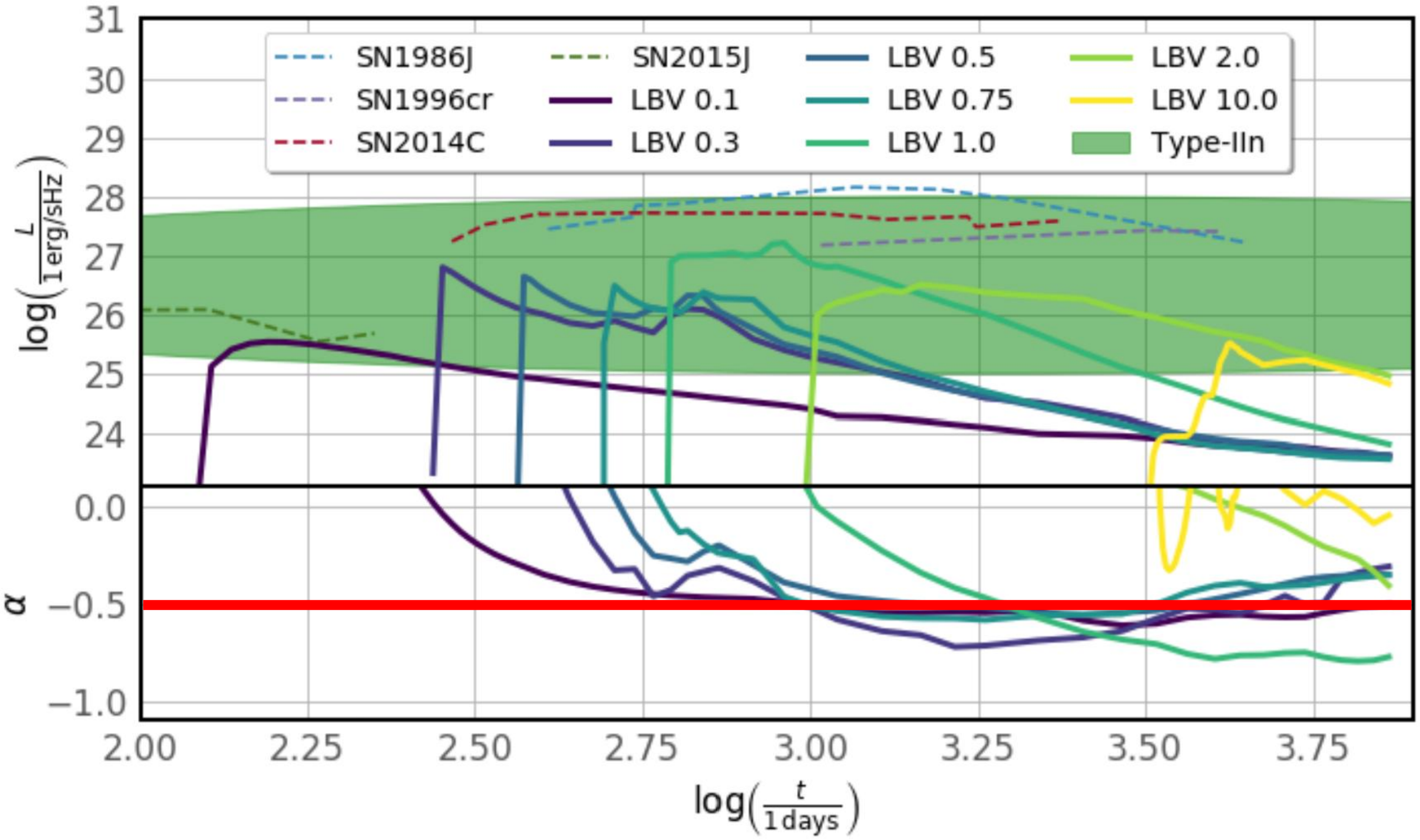
Use-cases – radio SNe

Figure(top): Radio luminosity at 4GHz.
Figure(right): Radio spectral-index 4GHz (RB+2026b)

Use-case:

- **SN shock running into dense shell**
- **Spectral softening followed by hardening**





Use-cases – CC-SNe

Probably a Wolf-Rayet phase required for strong gradients!

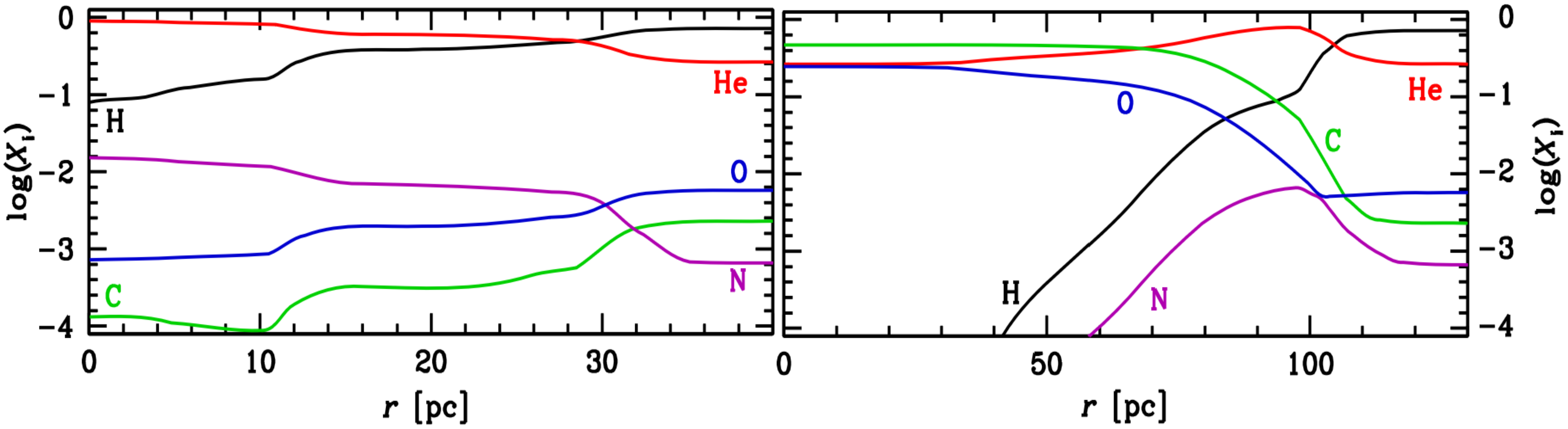


Figure: Abundancy around a 25M_{sol} (left) and 85M_{sol} (right) star. (Georgy et al. 2013)

Summary

- The universal power-law of DSA can be modified by many processes

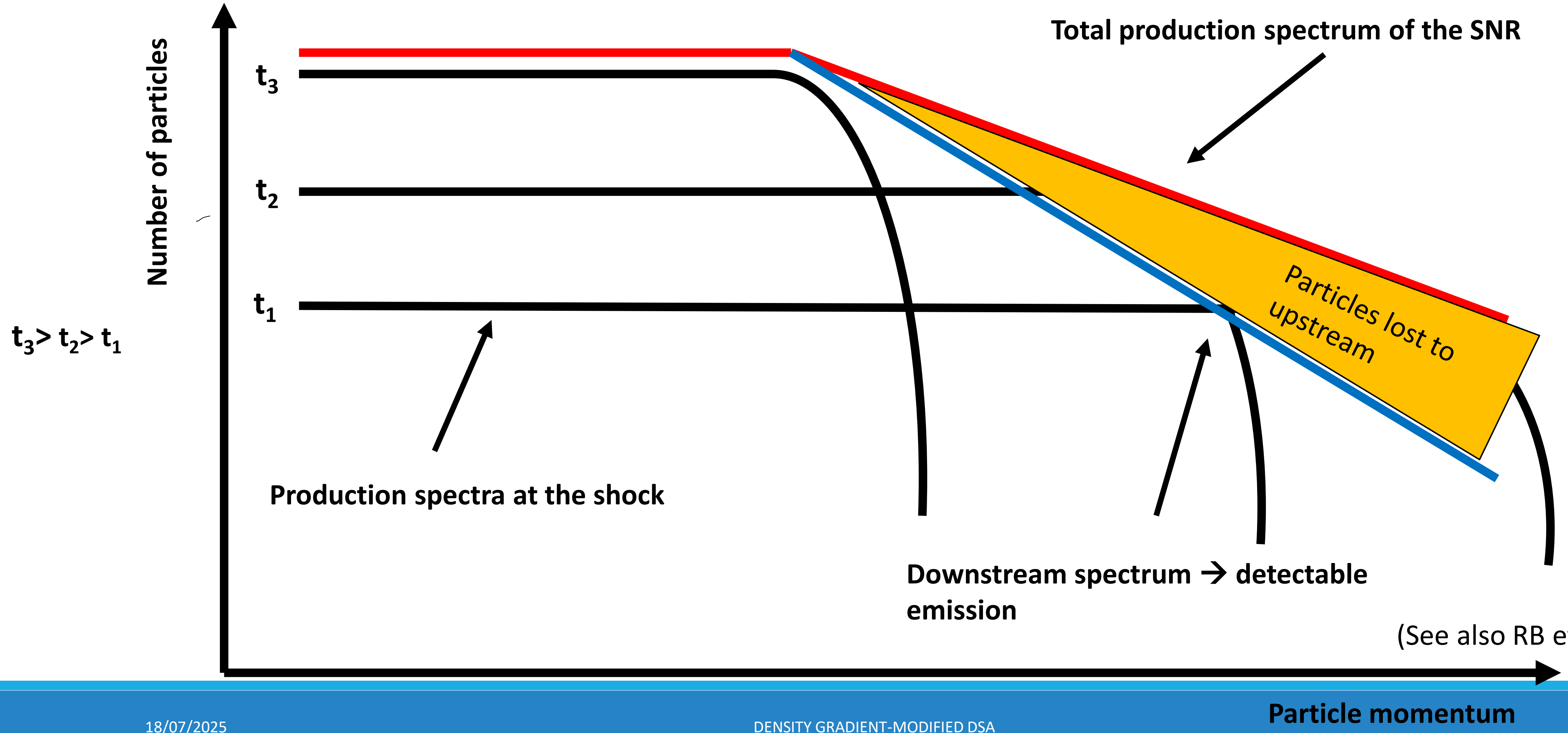
- Density gradients are present everywhere around astrophysical shocks
- If $\tau_{acc} > \tau_{grad}$, injection modifies the particle spectrum to

$$N(p) \propto p^{-2 \pm \frac{\tau_{acc}}{t_{gra}}}$$

- Different particle species have different abundancy distributions → Spectral indices can differ between species
- Spectral difference between Protons and Helium of ≈0.1 might explained by wind-bubble structure around massive stars → a possible tracer for (near) source structure!

Thanks for your attention!

Superposition of spectra – total CR production and escape



(See also RB et al. 2020, 2021)

Non-linear modification

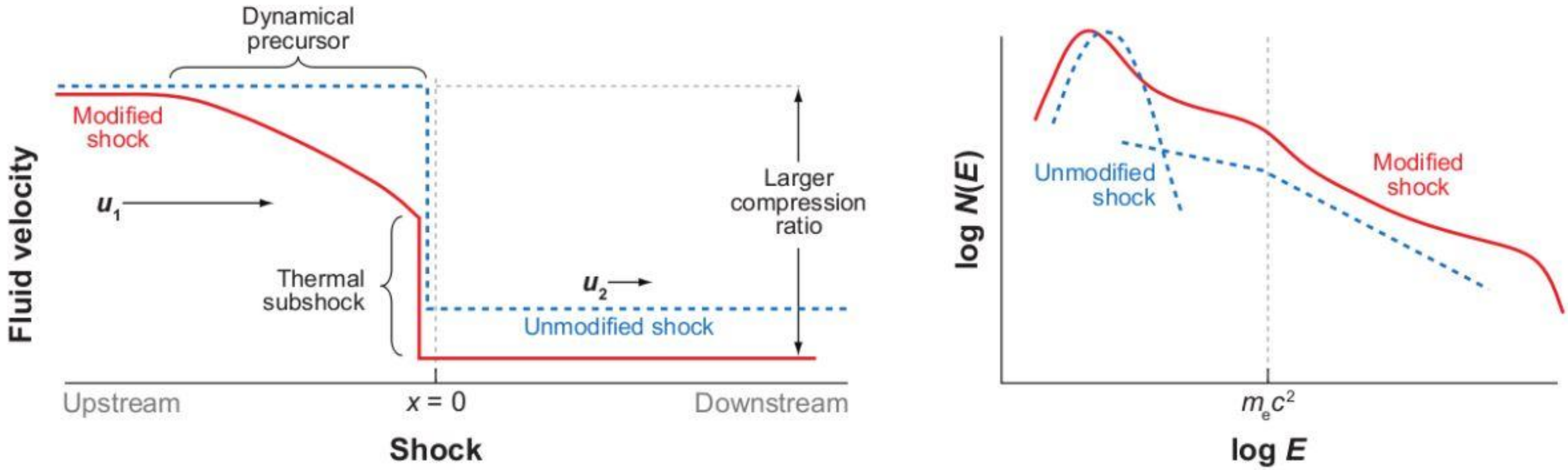


Figure: DSA vs. NDSA-spectra (Reynolds 2013)

A Toymodel - Results