Particle acceleration in winds of stellar clusters

Giovanni Morlino

INAF/Osservatorio astrofisico di Arcetri

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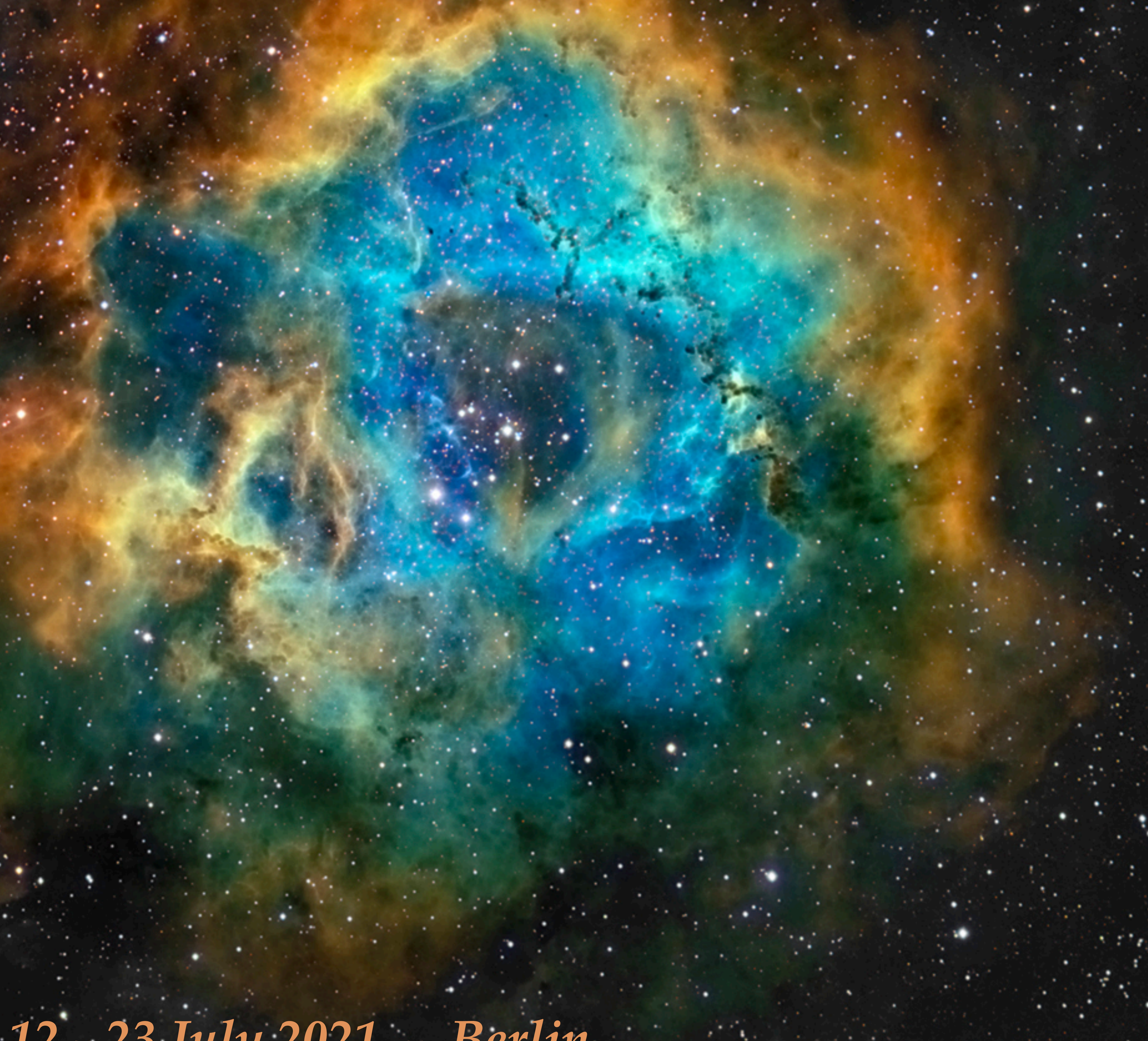


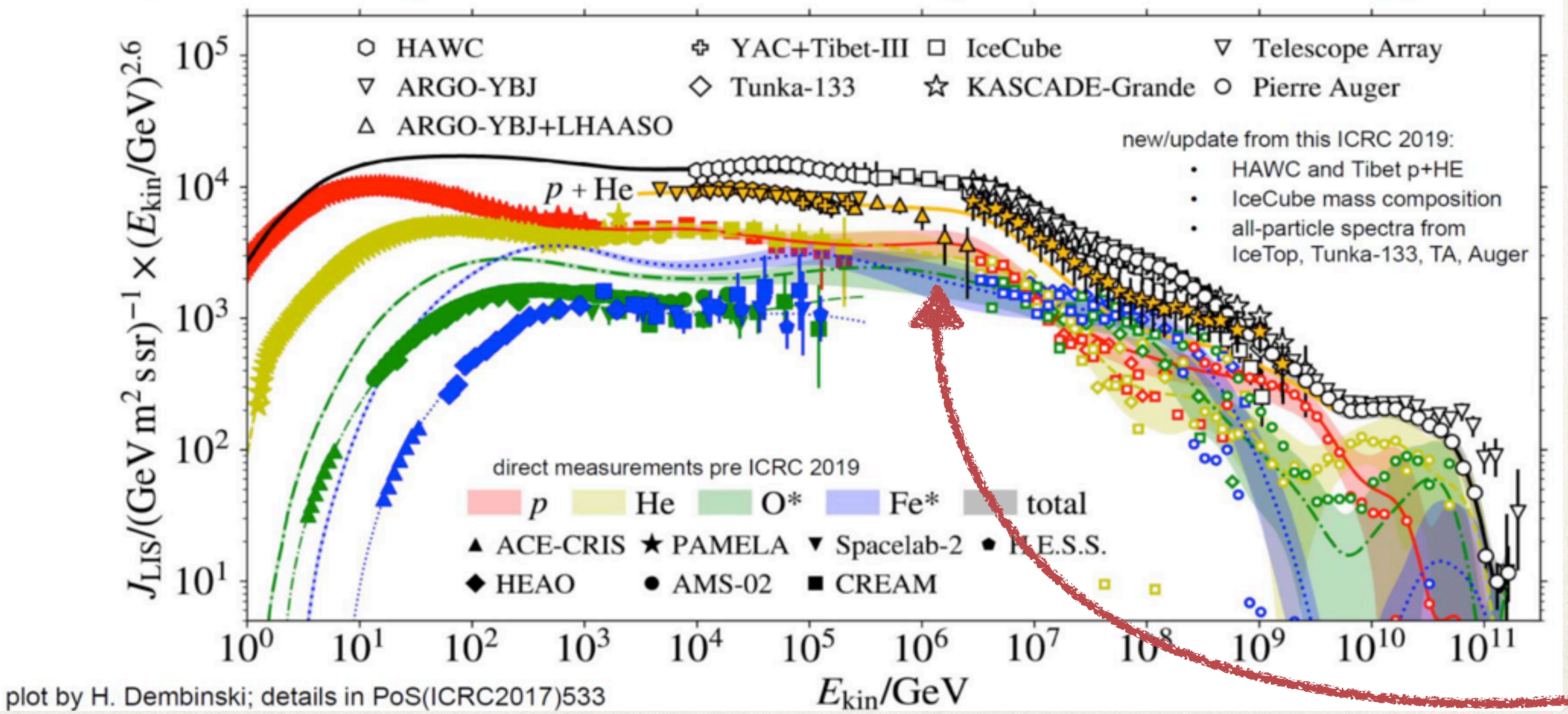
NGC 2237-9 The Rosette Nebula

Mainly based on:
G. Morlino, P. Blasi, E. Peretti & P. Cristofari, 2021, MNRAS 749

Where does PeV particles come from?

In spite of big efforts of the last years, the origin of CRs is still unclear

- The SNR paradigm is the most accepted scenario but
  - problem in reaching the maximum energy close to ~PeV for protons [see Cristofari, Blasi, Amato, 2020]
  - issue concerning the chemical abundances (e.g. ^{20}Ne/^{22}Ne) [see Prantzos, 2012, A&A 538]



It is worth exploring other possible candidates for the production of cosmic rays

Galactic CR protons should be accelerated up to ~PeV to explain the knee in the CR spectrum

Possible role of stellar winds

WINDS FROM SINGLE STARS

Pros.

- Winds from massive stars inject into the Galaxy a kinetic energy comparable to SNRs [Cesarsky & Montmerle, 1983]
- Long-living systems (age ~ Myr)
- Large size (bubble can reach several tens of pc)

Cons.

- Small velocity ($v_w \lesssim 3000$ km/s)
- Small mass ejecta: $\dot{M} \lesssim 10^{-5} M_\odot \, \mathrm{yr}^{-1}$
- Small magnetic field in the free wind region $\rightarrow$ large diffusion coefficient

WIND FROM MASSIVE YOUNG STELLAR CLUSTERS

- #stars >~ 10^3 $\Rightarrow \dot{M} \gtrsim 10^{-4} M_\odot \, \mathrm{yr}^{-1}$
- presence of strong wind turbulence -> possibility to generate magnetic turbulence

Massive stellar cluster detected in gamma-rays

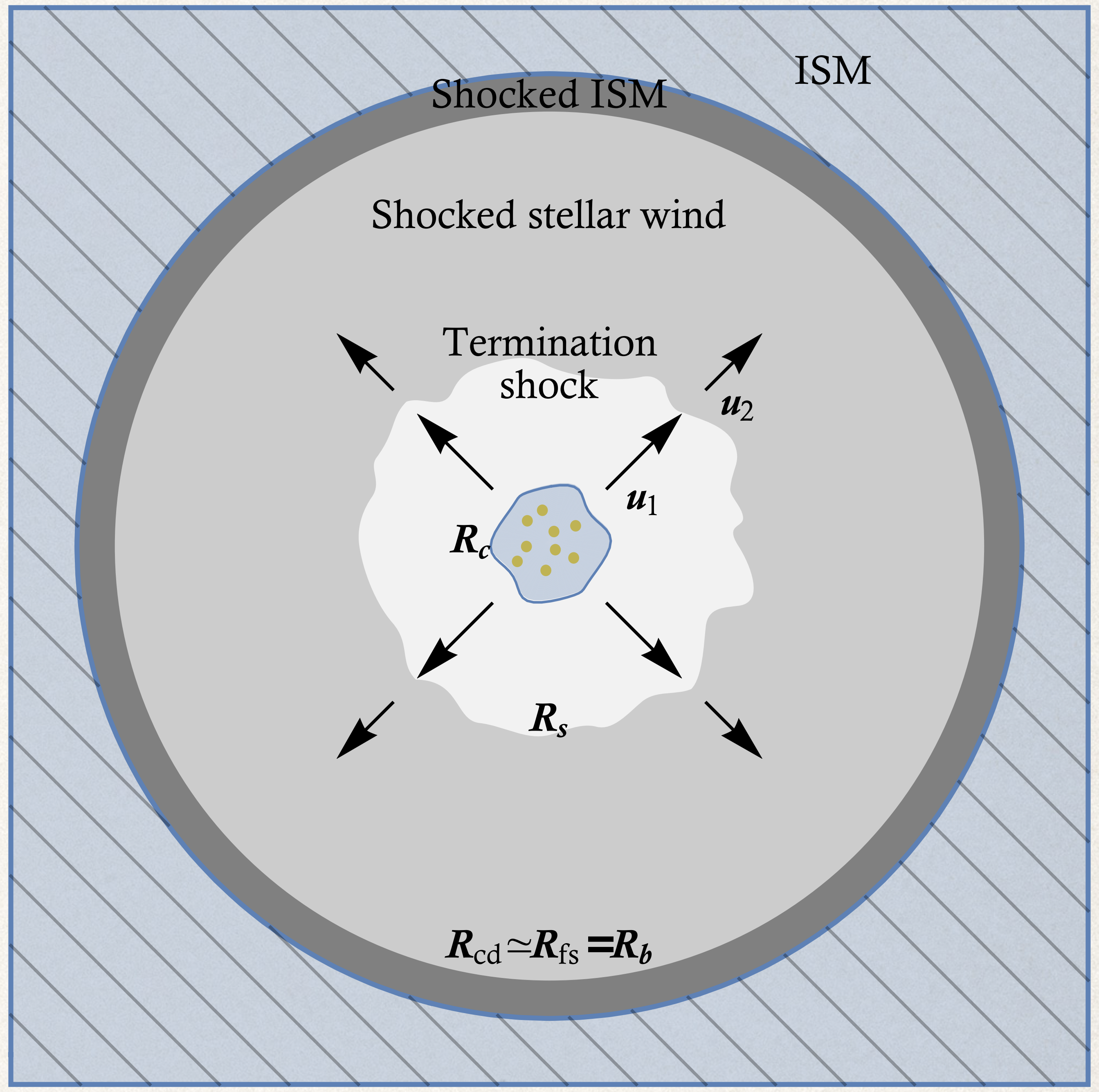
Recently, several young massive stellar clusters have been associated with gamma-rays sources

Name	log M/M$_{sun}$	r_c/pc	D/kpc	age/Myr	L_w/ 10^{38} erg s^{-1}	Reference
Westerlund 1	4.6 ± 0.045	1.5	4	4-6	10	Abramowski A., et al., 2012, A&A, 537, A114
Westerlund 2	4.56 ±0.035	1.1	2.8 ± 0.4	1.5-2.5	2	Yang, de Oña Wilhelmi, Aharonian, 2018, A&A, 611, A77
Cyg. OB2	4.7±0.3	5.2	1.4	3-6	2	Ackermann M., et al. 2011, Science, 334, 1103
NGC 3603	4.1 ± 0.10	1.1	6.9	2-3	?	Saha, L. et al 2020, ApJ, 897, 131
BDS 2003	4.39	0.2	4	1	?	Albert A., et al., 2020, arXiv:2012.15275
W40	2.5	0.44	0.44	1.5	?	Sun, X.-N. et al. 2020, A&A, 639, A80
30 Dor (LMC) NGC 2070/RCM 136	4.8-5.7 4.34-5	multiple sub-clusters	50	1 5	?	H. E. S. S. Collaboration et al., 2015, Science, 347, 406

The wind-bubble system

The stellar wind blow a hot bubble in the ISM [Weaver et al., 1977, ApJ 218]

- The hot bubble spend the majority of its life (~few Myr) the in adiabatic phase
- The shocked ISM collapse to a thin shell ($t_{\rm cool} \sim 10^4\, yr$)
- The termination shock is almost stationary

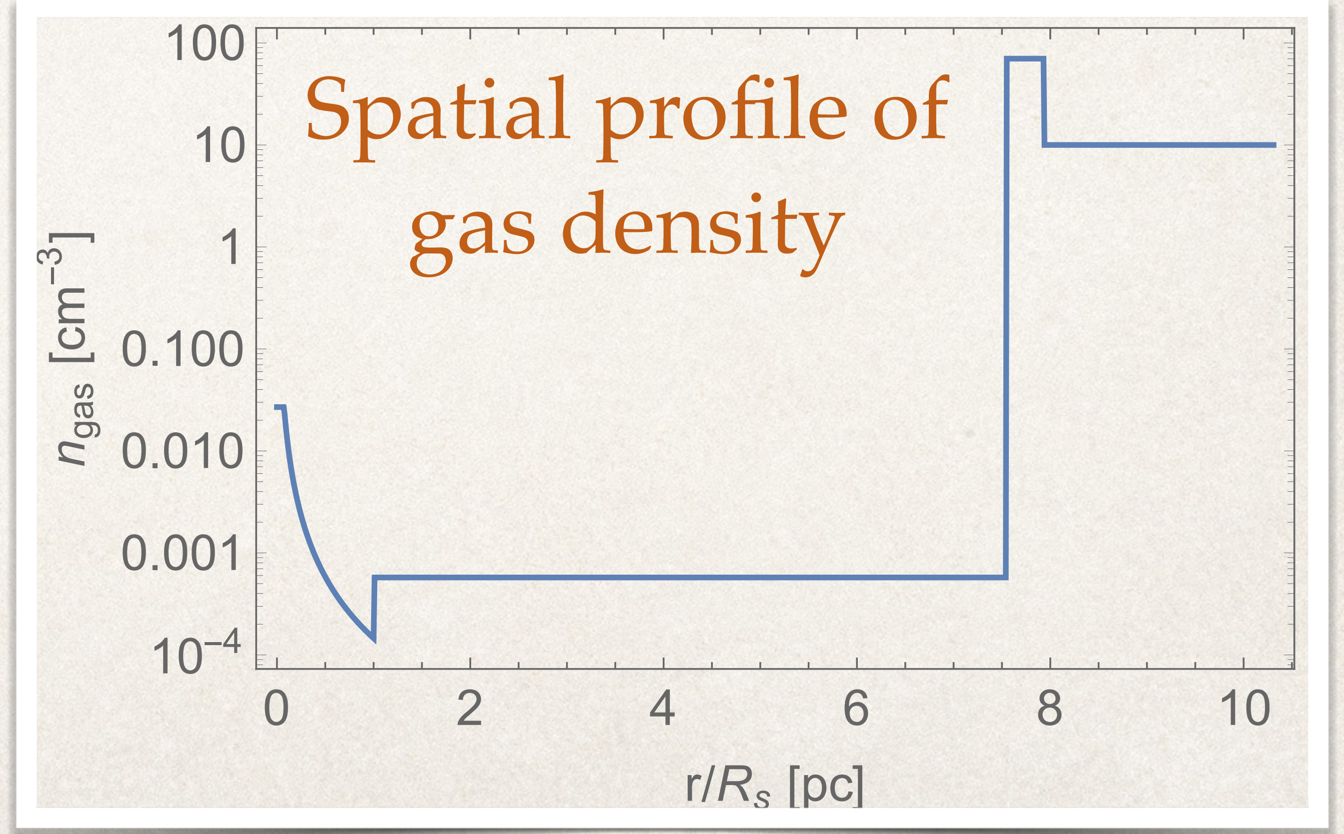


Bubble radius:

$$R_b \simeq 55\ \mathrm{pc} \left(\frac{\dot{M}}{10^{-4} M_\odot/yr}\right)^{1/5} \left(\frac{v_w}{1000\,\mathrm{km/s}}\right)^{2/5} \left(\frac{\rho_0/m_p}{\mathrm{cm}^{-3}}\right)^{-1/5} \left(\frac{t_{\rm age}}{\mathrm{Myr}}\right)^{3/5}$$

Radius of termination shock:

$$R_s \simeq 20\ \mathrm{pc} \left(\frac{\dot{M}}{10^{-4} M_\odot/yr}\right)^{3/10} \left(\frac{v_w}{1000\,\mathrm{km/s}}\right)^{1/10} \left(\frac{\rho_0/m_p}{\mathrm{cm}^{-3}}\right)^{-3/10} \left(\frac{t_{\rm age}}{\mathrm{Myr}}\right)^{2/5}$$



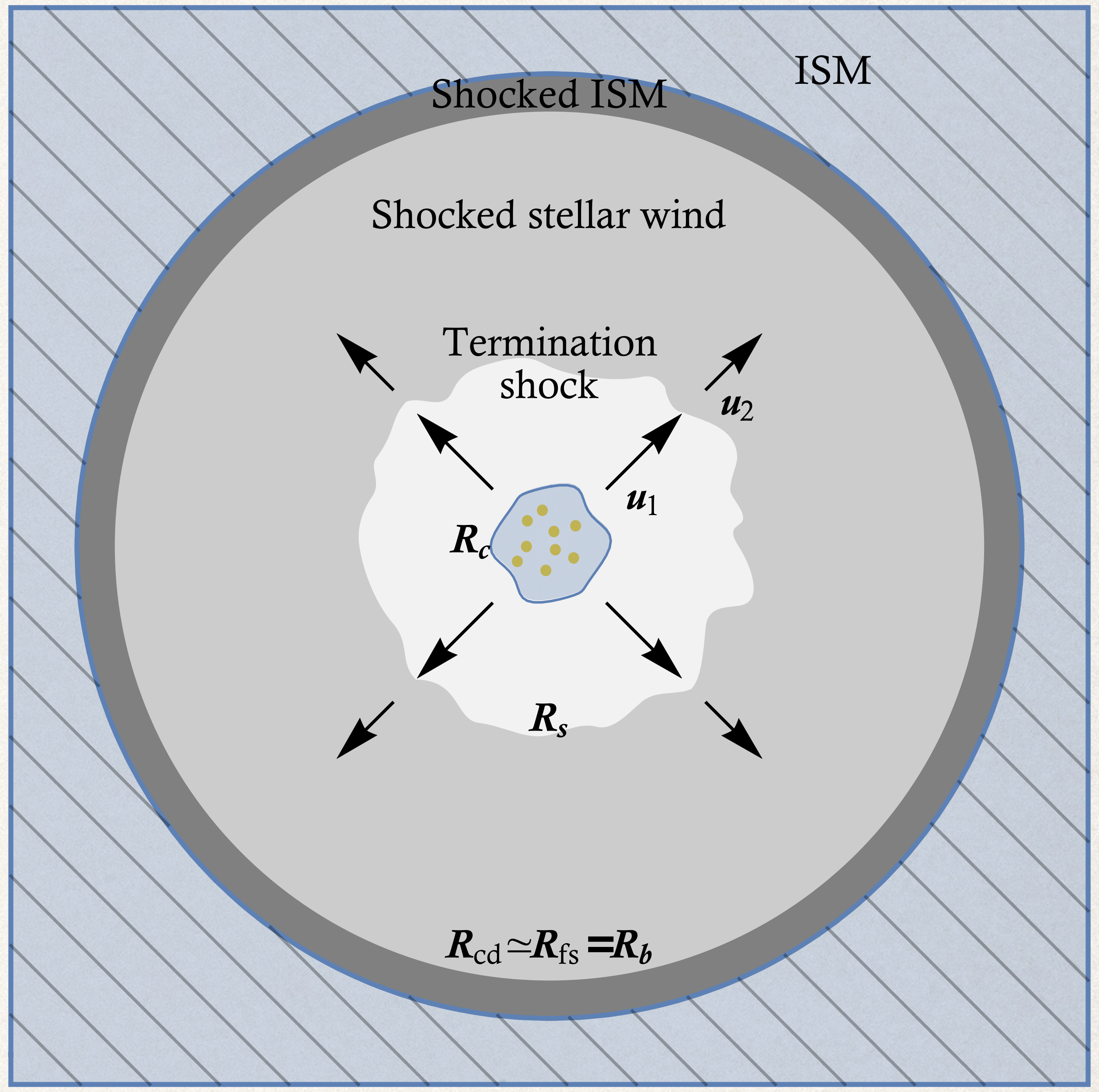
$$u_{ts} \simeq v_w \sim 2000 - 3000\,\mathrm{km/s}$$

$$u_{fs} = \frac{dR_b}{dt} \simeq 10 - 30\,\mathrm{km/s}$$

Particle acceleration at the termination shock

Time-stationary transport equation in spherical geometry:

$$\frac{\partial}{\partial r}\left[r^2 D(r,p)\frac{\partial f}{\partial r}\right] - r^2 u(r)\frac{\partial f}{\partial r} + \frac{d\left[r^2 u\right]}{dr}\frac{p}{3}\frac{\partial f}{\partial p} + r^2 Q(r,p) = 0$$



- Arbitrary diffusion coefficient $D(\mathrm{r},p)$
- Injection only at the termination shock $\quad Q(r,p) \propto \delta(p - p_{\mathrm{inj}})\,\delta(r - R_s)$
- Wind velocity profile:

$$u(r) = \begin{cases} u_1 = v_w & \text{for } r < R_s\,, \\ \dfrac{u_1}{\sigma}\left(\dfrac{R_s}{r}\right)^2 & \text{for } R_s < r < R_b\,, \\ 0 & \text{for } r > R_b\,; \end{cases}$$

With respect to SNRs the geometry is "reversed"

Solution of the transport equation

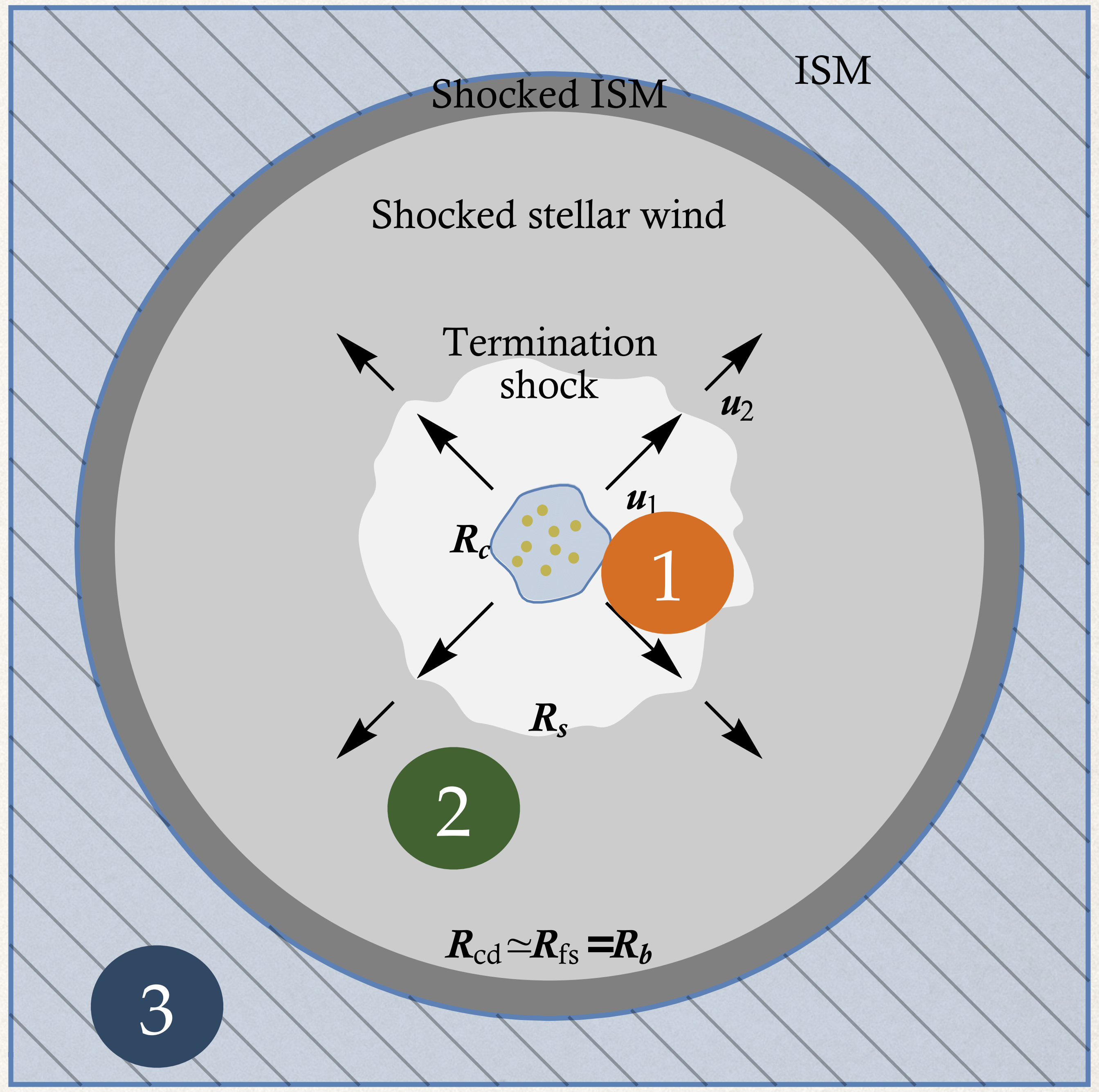
Time-stationary transport equation in spherical geometry:

$$\frac{\partial}{\partial r}\left[r^2 D(r,p)\frac{\partial f}{\partial r}\right] - r^2 u(r)\frac{\partial f}{\partial r} + \frac{d\left[r^2 u\right]}{dr}\frac{p}{3}\frac{\partial f}{\partial p} + r^2 Q(r,p) = 0$$

Boundary conditions:

1. No net flux at the cluster center: $r^2[D\partial_r f - uf]_{r=R_c} = 0$

2. Matching the Galactic distribution: $f(r \to \infty, p) = f_{\rm gal}(p)$



- The equation is solved in regions 1, 2 and 3 and than matched at R_s and R_b using the flux conservation

- For generic expression of $D(r,p)$ and $u(r)$ the solution is not analytical, but can be expressed in an implicit form that can be solved by iterations.

Diffusion coefficient

Time-stationary transport equation in spherical geometry:

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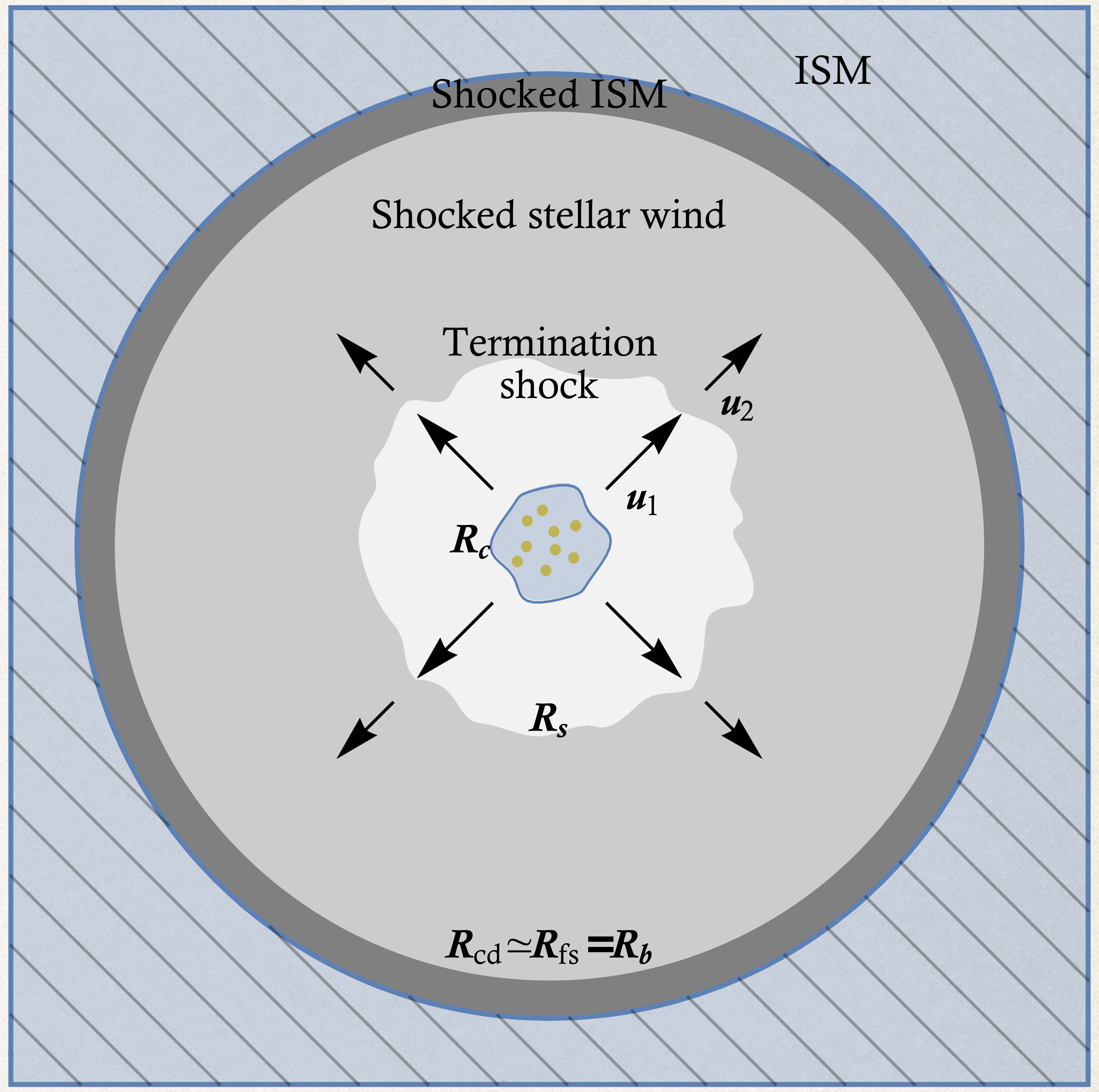

Wind-wind collision and non-stationarity can produce high level of HD turbulence

Assuming that a fraction η_B of kinetic wind energy is converted into magnetic energy

$$\frac{\delta B}{4\pi} 4\pi r^2 v_w = \frac{1}{2}\eta_B \dot{M} v_w^2 \Rightarrow \delta B(R_s) \gtrsim \mu G$$

The type of turbulent cascade can result into different diffusion coefficients

$$\begin{cases} D_{\rm Kol}(E) = \frac{v}{3} r_L (\delta B)^{1/3} L_c^{2/3} \\ D_{\rm Kra}(E) = \frac{v}{3} r_L (\delta B)^{1/2} L_c^{1/2} \\ D_{\rm Bohm}(E) = \frac{v}{3} r_L (\delta B) \end{cases}$$

L_c is the injection scale of turbulence, assumed of the order of the cluster size (~pc)

Bohm diffusion can be realised if there are multiple injection scales

Solution: particle distribution at the shock

$$\boxed{f_s(p) = s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\; e^{-\Gamma_2(p)}}$$

Solution: particle distribution at the shock

Standard power-law for plane shocks

$$s = \frac{3u_1}{u_1 - u_2}$$

$$f_s(p) = \boxed{s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s}}\; e^{-\Gamma_1(p)}\;\; e^{-\Gamma_2(p)}$$

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Where:

$$\Gamma_1(p) = s\int_{p_{\rm inj}}^{p} \frac{\Lambda_1(1,p')}{f_s(p')}dp' \quad \Rightarrow \quad \Gamma_1(p) \gg 1 \Rightarrow p \gg p_{\max 1} : \frac{D_1(p_{\max 1})}{u_1} = R_s$$

$p_{\max}$ due to the upstream: the effective plasma speed decreased reducing the energy gain

$$\Lambda_1(\xi,p) = -\frac{2}{3}\int_0^{\xi} f_1(\xi',p)\frac{d\ln(p^3 f_1)}{d\ln p}\xi' d\xi' \quad \Rightarrow$$

Non-linear term:
f_s depends on f_1 (upstream)

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Standard power-law for plane shocks

$$s = \frac{3u_1}{u_1 - u_2}$$

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Non-linear term:
f_s depends on f_1 (upstream)

$$\Gamma_2(p) = s\frac{u_2}{u_1}\int_{p_{inj}}^{p} \frac{dp'/p'}{e^{\alpha_2(p',R_b)} - 1} \Rightarrow \Gamma_2(p) \gg 1 \Rightarrow p \gg p_{\max 2} : \frac{D_2(p_{\max 2})}{u_2} = R_s\left(1 - \frac{R_s}{R_b}\right)$$

$p_{\max}$ due to the escape from the downstream

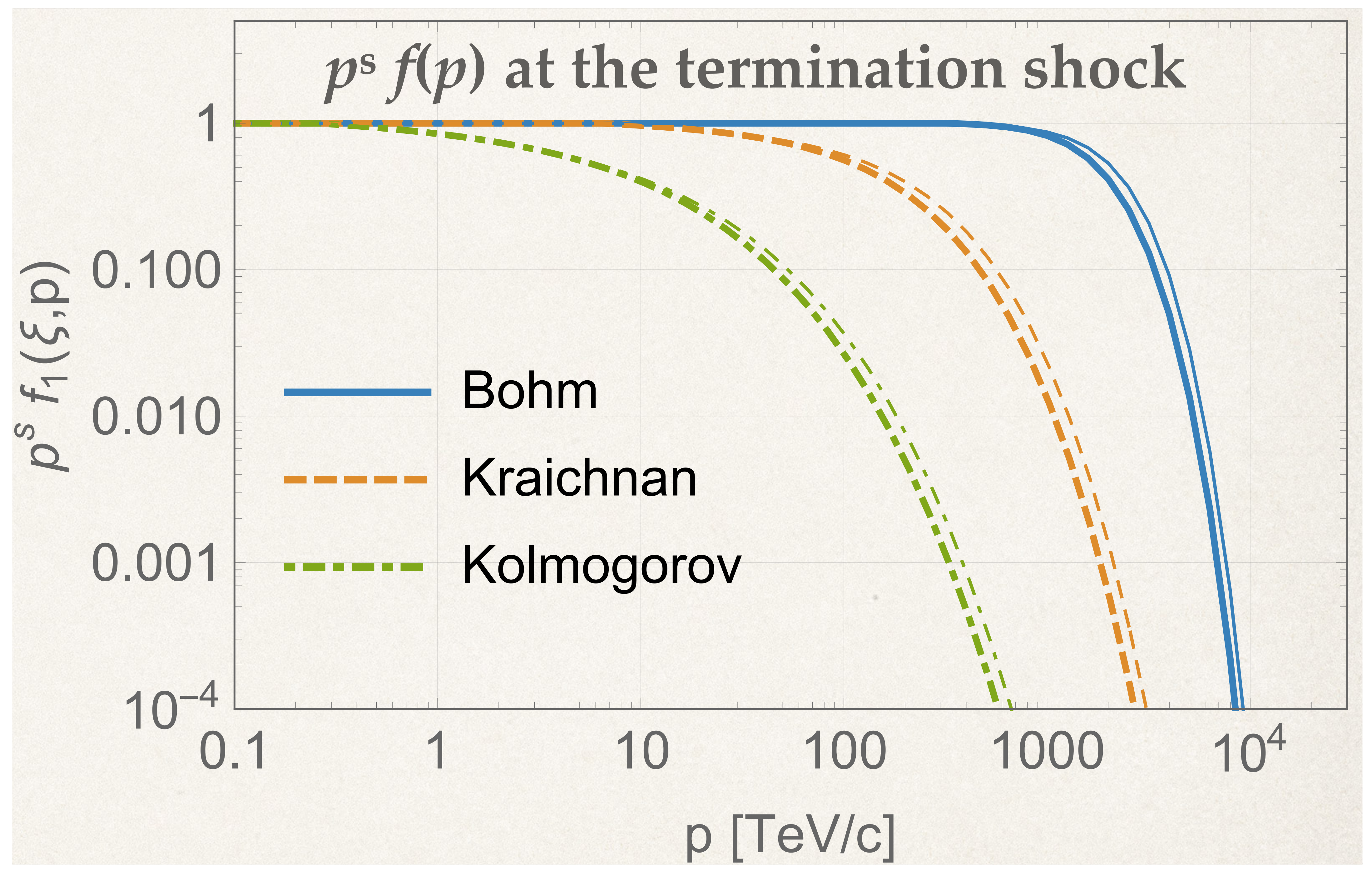
Impact of diffusion coefficient

For fixed values of all parameters, the diffusion coefficient has a strong impact on the cutoff shape and effective maximum energy

Typical values for massive stellar clusters

$$\begin{cases} \dot{M} = 10^{-4}\, M_\odot\, \mathrm{yr}^{-1} \\ v_w = 3000\ \mathrm{km/s} \\ L_{\rm CR} = 0.1\, L_w \\ \eta_B = 0.1 \end{cases}$$

PeV energies can be reached in very powerful stellar clusters if the diffusion is close to *Bohm*



Determining the diffusion properties inside the bubble is fundamental

Solution: spatial profile of CR distribution

Region 1 (cold wind):

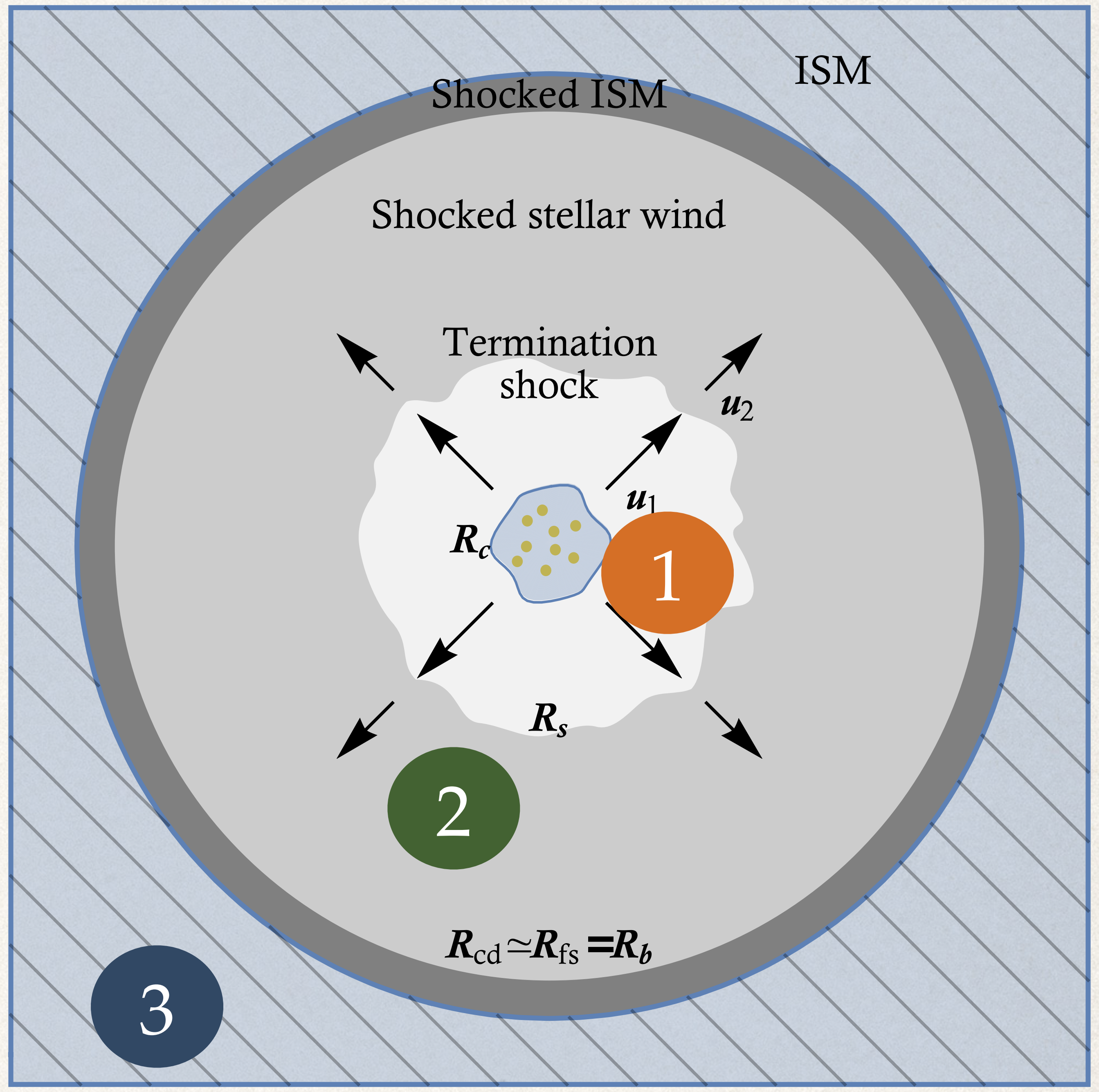
$$f_1(\xi,p) = f_s(p)\ \exp\left\{-\int_\xi^1 \alpha_1\left[1+\frac{\Lambda_1(\xi',p)}{\xi'^2 f_1(\xi',p)}\right]d\xi'\right\}$$

Region 2 (shocked wind):

$$f_2(\xi,p) = f_s(p)\, e^{\alpha_2}\frac{1+\beta\left[e^{\alpha_2(1)-\alpha_2(\xi)}-1\right]}{1+\beta\left[e^{\alpha_2(1)}-1\right]} + f_{\rm gal}(p)\frac{\beta\left[e^{\alpha_2(\xi)}-1\right]}{1+\beta\left[e^{\alpha_2(1)}-1\right]}$$

Region 3 (unperturbed ISM):

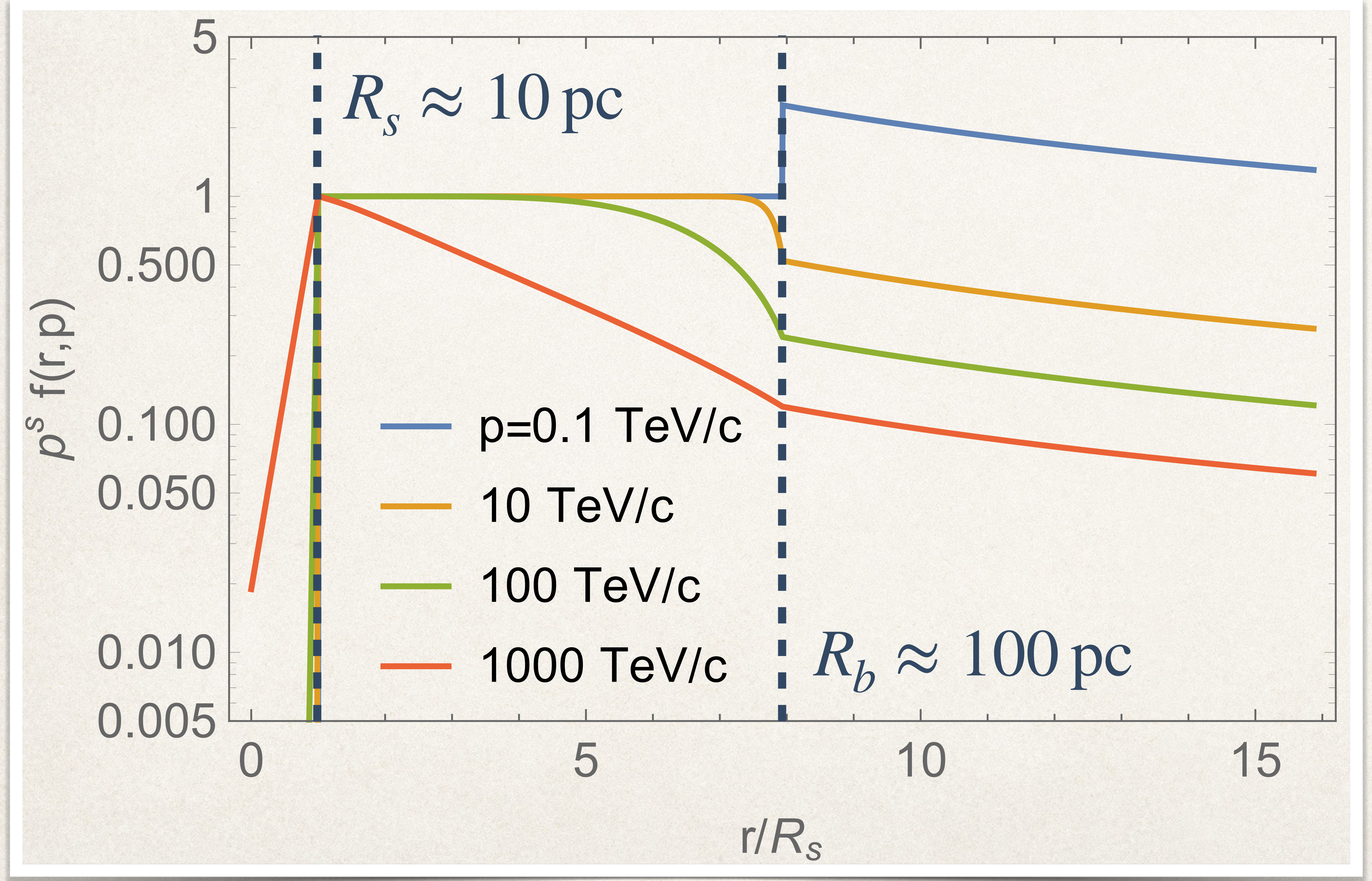
$$f_3(\xi,p) = f_2\left(R_b/R_s,p\right)\frac{1}{\xi} + f_{\rm gal}(p)\left(1-\frac{1}{\xi}\right)$$

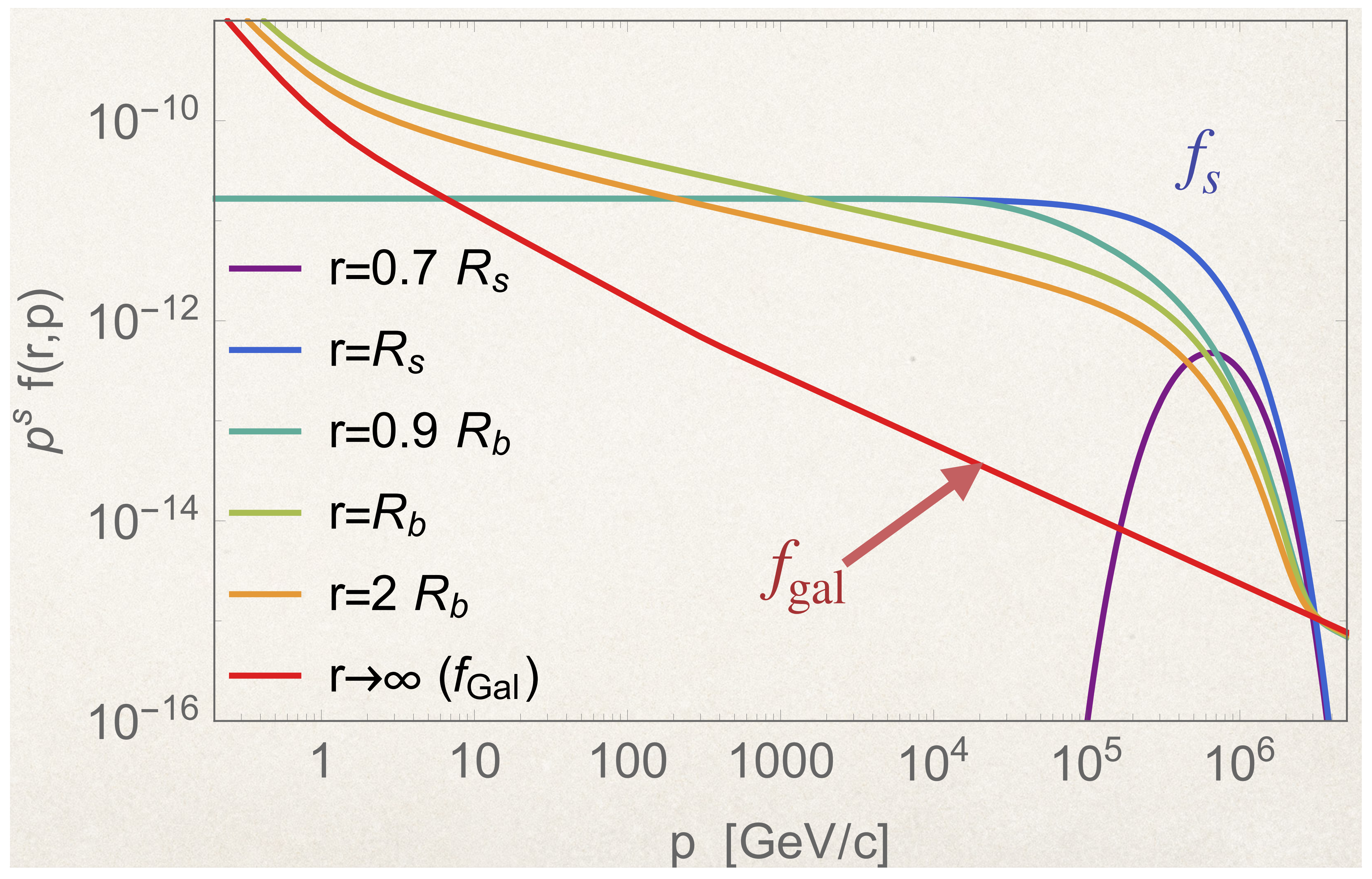


where: $\xi = \dfrac{r}{R_s}$; $\alpha_1(\xi,p) = \dfrac{u_1 R_s}{D_1(\xi,p)}$; $\alpha_2(\xi,p) = \dfrac{u_2 R_s}{D_2(p)}\left(1-\dfrac{1}{\xi}\right)$; $\beta(p) = \dfrac{D_{\rm gal}(p) R_s}{u_2 R_b^2}$;

Solution: spatial profile of CR distribution

- For $r < R_s$ the distribution is suppressed except when $E \gtrsim E_{max}$
- Distribution inside the bubble is flat for $E \ll E_{max}$
  - $\neq 1/r$ inferred from FermiLAT data by Aharonian et al., 2019, Nat. Astr.3, 561
- For $E \lesssim 100 GeV$ the distribution outside the bubble is larger than the one inside it
  - possible signature in the gamma-ray emission (to be investigated)





Possible role of self-generated magnetic field

Similarly to what is thought to happen for SNR shocks, streaming CRs could amplify the turbulent magnetic field ahead of the shock through resonant or non-resonant modes

Resonant modes

$$\left(\frac{\delta B_{\rm res}}{B_1}\right)^2 \simeq \frac{\pi}{2}\frac{\xi_{\rm CR}}{p_{\rm max}/m_p c}\frac{v_w}{v_A} = \frac{\pi}{2}\frac{\xi_{\rm CR}}{p_{\rm max}/m_p c}\frac{1}{\sqrt{2\eta_B}}$$

➡ $\delta B_{\rm res} > B_1$ only if $\eta_B \lesssim 10^{-4}$ ➡ $\boxed{\delta B_{\rm res} \ll \mu G}$

Non-resonant modes

Allowed to grow only if energy density in CR current > energy density of pre-existing magnetic field

➡ $$\eta_B \lesssim \frac{6\,\xi_{\rm CR}}{\log(p_{\rm max}/m_p c)}\frac{v_w}{c} \sim 10^{-4}$$ ➡ $\boxed{\delta B_{\rm non-res} \ll \mu G}$

CR self-amplification is not efficient

Conclusions

Context:

- Several massive stellar clusters have been associated to gamma-ray sources, suggesting that they could contribute to the bulk of Galactic component of cosmic rays.
- **Where those particles are accelerated?**

Method:

- We investigated the spectrum of protons accelerated at the termination shock of stellar winds, developing a technique to solve the transport equation in spherical symmetry able to account for *space-dependent* wind velocity and *space-* and *energy-dependent* particle diffusion.

Results:

- We show that the maximum energy can reach the PeV for very massive stellar cluster under the assumption that few percent of the wind kinetic energy is converted into magnetic turbulence and that diffusion is close to *Bohm*.
- The spatial profile of the accelerated particles is also presented and discussed
  - important to predict the morphology of gamma-ray emission
  - f_{CR} inside the bubble is flat at low energies; the $\sim 1/r$ shape inferred from some analysis is difficult to recover