UNIVERSITY OF COPENHAGEN

Niels Bohr Institutet

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Exploring galactic wind superbubbles by multimessenger observations

ICRC 2021 contribution – 21 July 2021 discussion

Peretti E.*, Morlino G., Blasi P., Cristofari P. & Ahlers M.

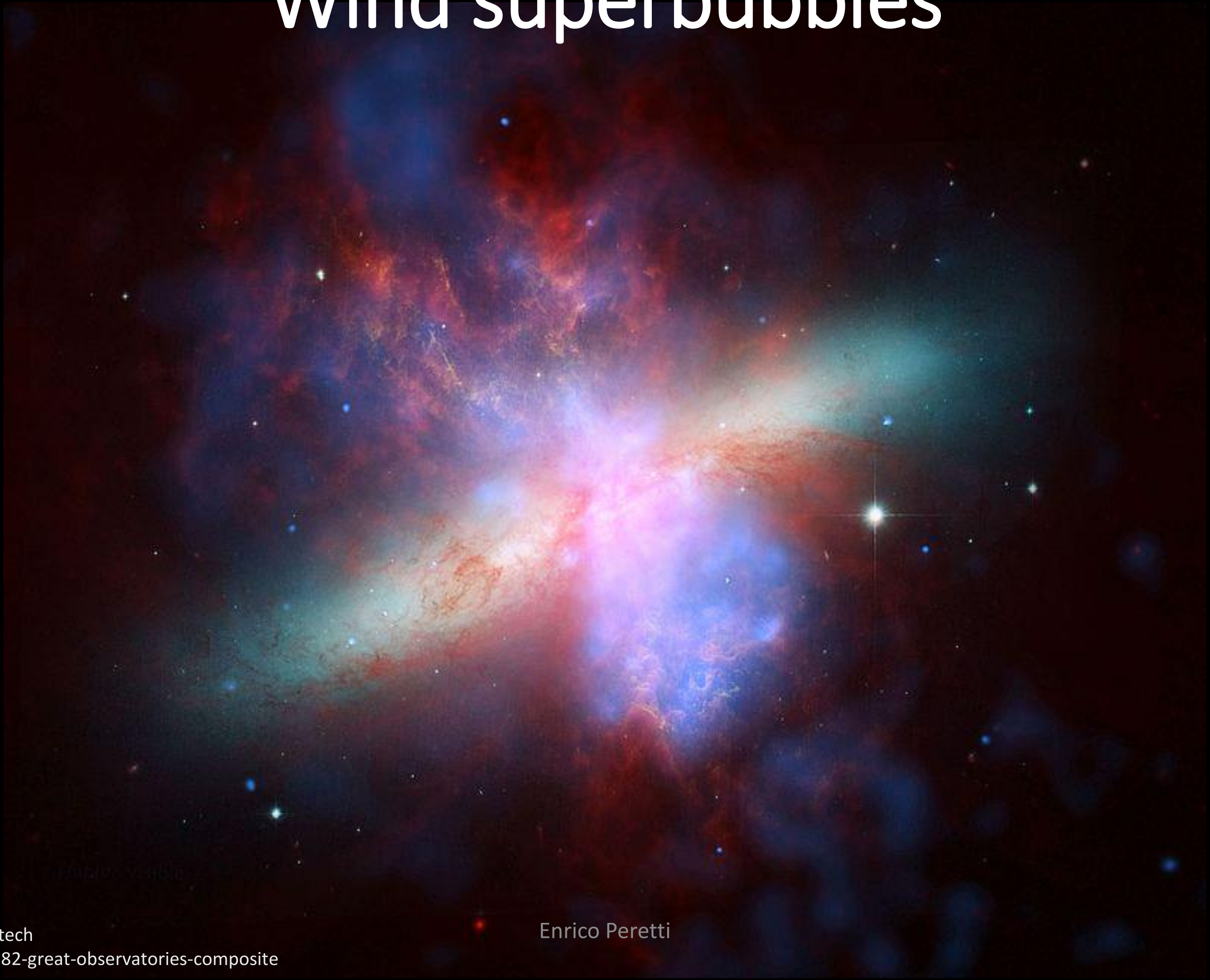
The Niels Bohr International Academy

VILLUM FONDEN

Outline

- General properties
- Structure and evolution
- Acceleration and transport
- Particles, gamma rays and neutrinos
- Maximum energy and luminosity

Wind superbubbles

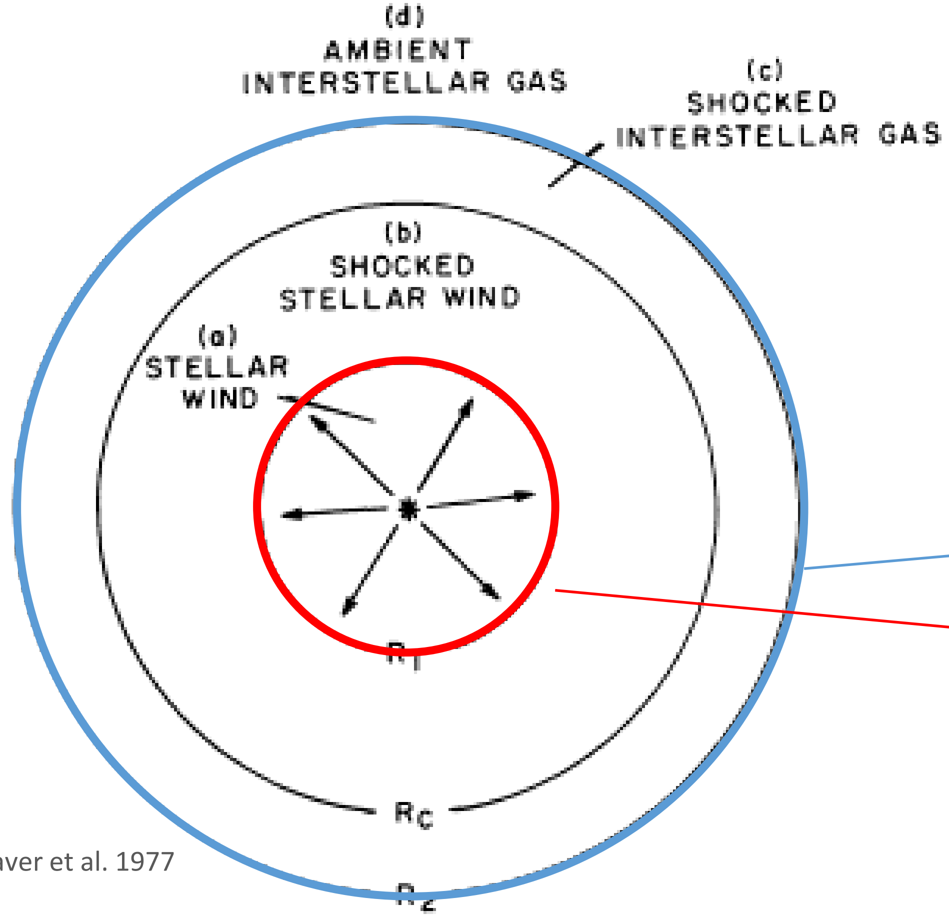


Credit image: NASA, ESA, CXC, and JPL-Caltech
https://sci.esa.int/web/hubble/-/39143-m82-great-observatories-composite

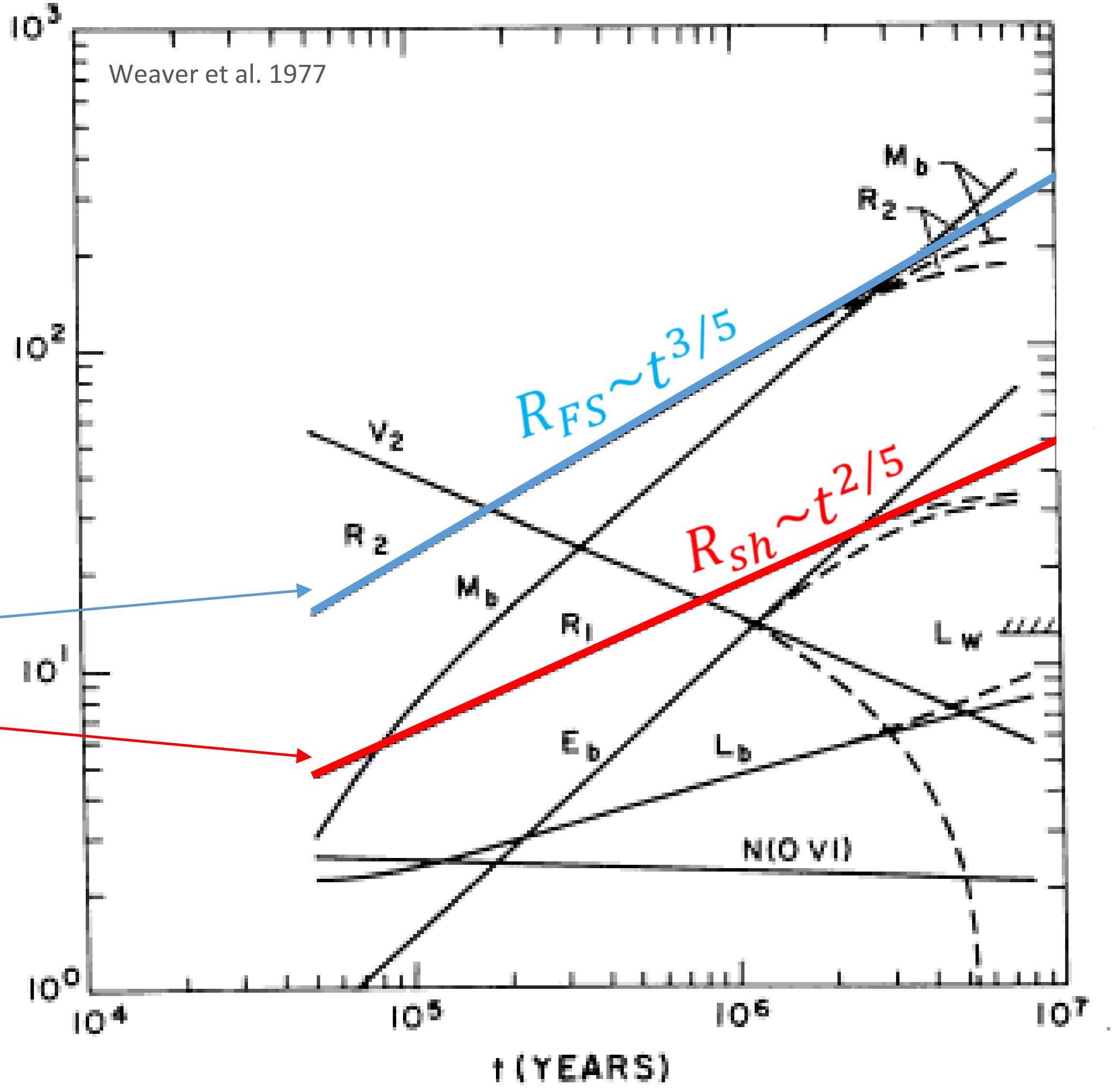
General properties

	AGN-driven	**Starburst-driven**
• Central engine:	Accretion disk - jet (?)	Supernovae
• Driving mechanism:	Radiation – Mechanical (?)	Mechanical
• Lifetime:	10—10^2 Myr	> 40 Myr
• Wind speed (ionized):	10^2 – 10^3 km/s (WA)	10^2 – 10^3 km/s (Hα)
• Mass loss rate:	0.1—10^4 $M_{\odot} yr^{-1}$	0.1—10^2 $M_{\odot} yr^{-1}$

Structure and evolution



Weaver et al. 1977

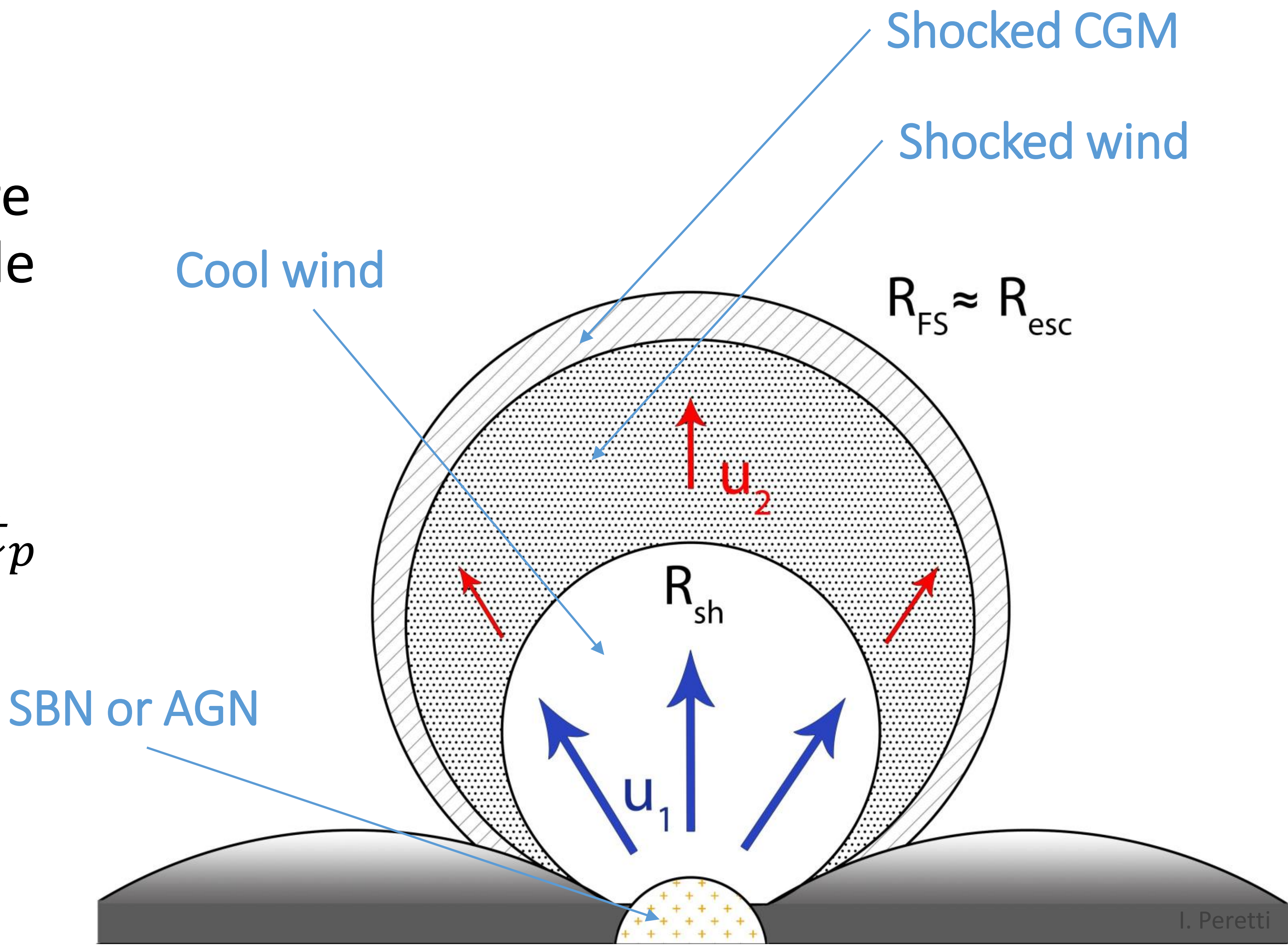


Structure and evolution

- Forward and reverse shocks are decoupled and the wind bubble inflates

- $R_{sh} \sim \begin{cases} (\dot{M} u_1 / 4\pi P_h)^{1/2} & t > t_p \\ t^{2/5} & t < t_p \end{cases}$

- $R_{FS} \sim t^{3/5}$



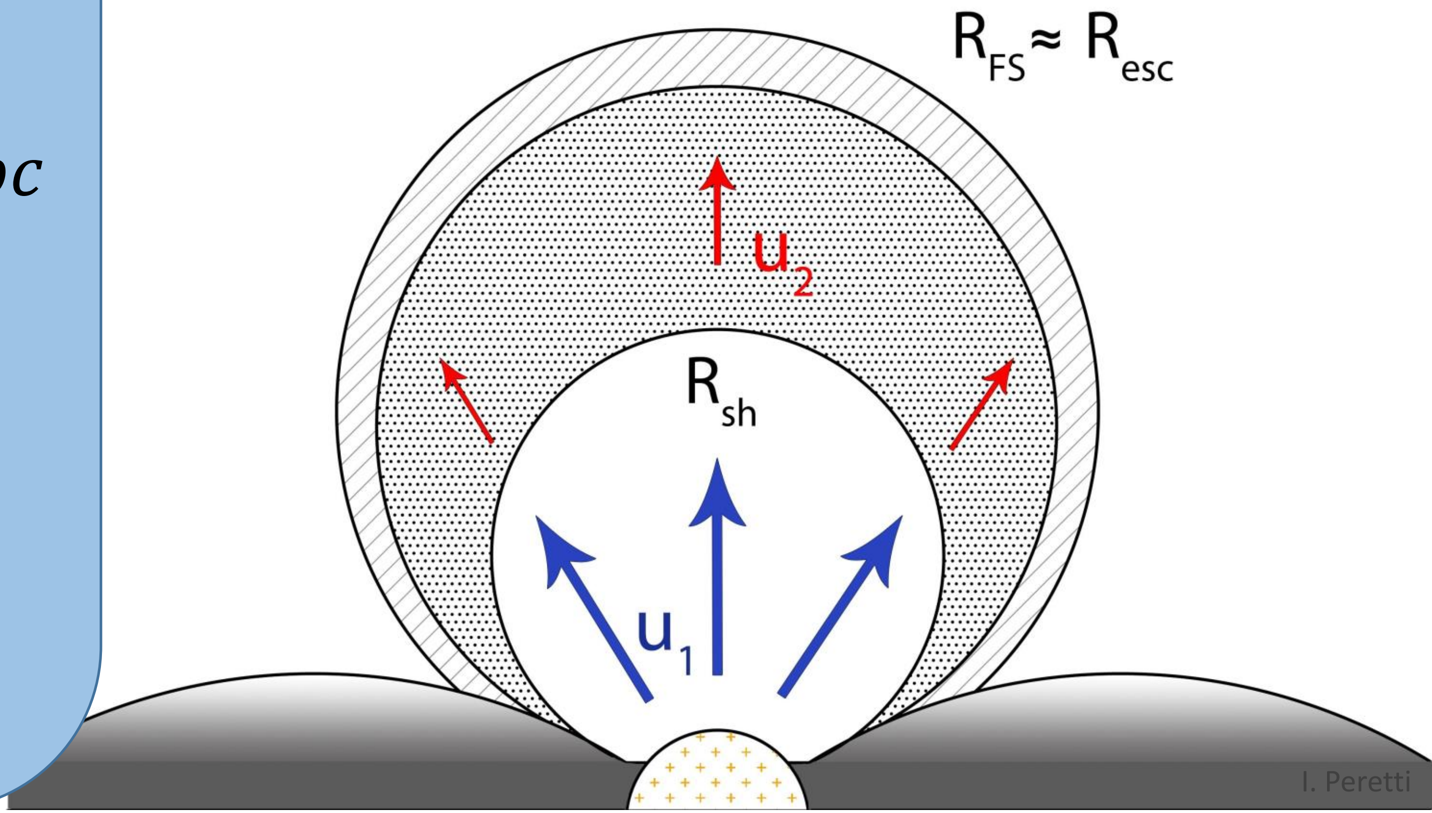
Structure and evolution

Shocks and Mach number

$$R_{sh} \approx 6.2\, \dot{M}_0^{1/2} u_{1,3}^{1/2} (P/k)_{h,4}^{-1/2}\ kpc$$

$$\mathcal{M}_{FS} = \dot{R}_{FS}/c_{s,h} \lesssim 5$$

$$\mathcal{M}_{sh} = u_1/c_{s,1} \gtrsim 10$$



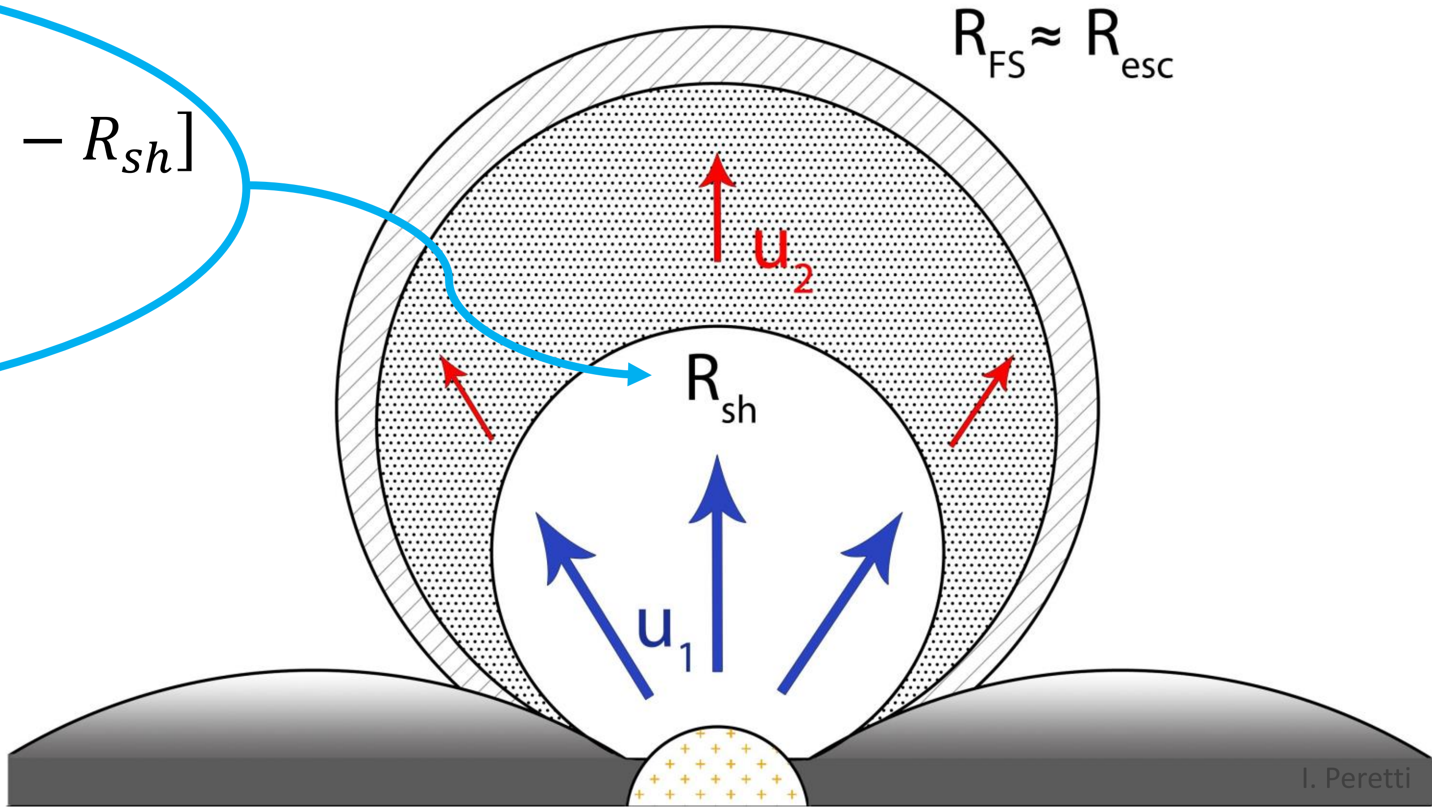
Particle acceleration and transport

$$r^2 Q(r,p)$$

Injection

$$Q(r,p) = {}^{n_1 u_1 \eta}/_{4\pi p^2}\ \delta[p - p_{inj}]\delta[R - R_{sh}]$$

$$P_{CR} \approx \xi_{CR} P_{RAM}$$

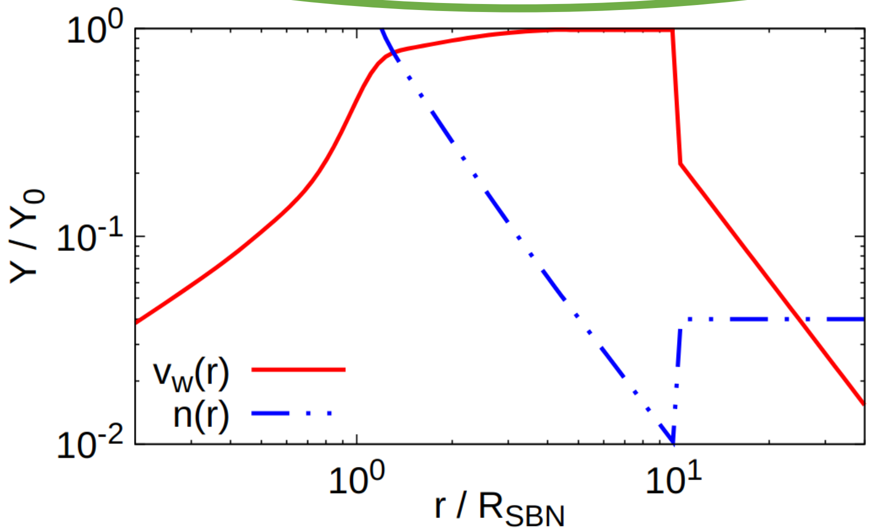


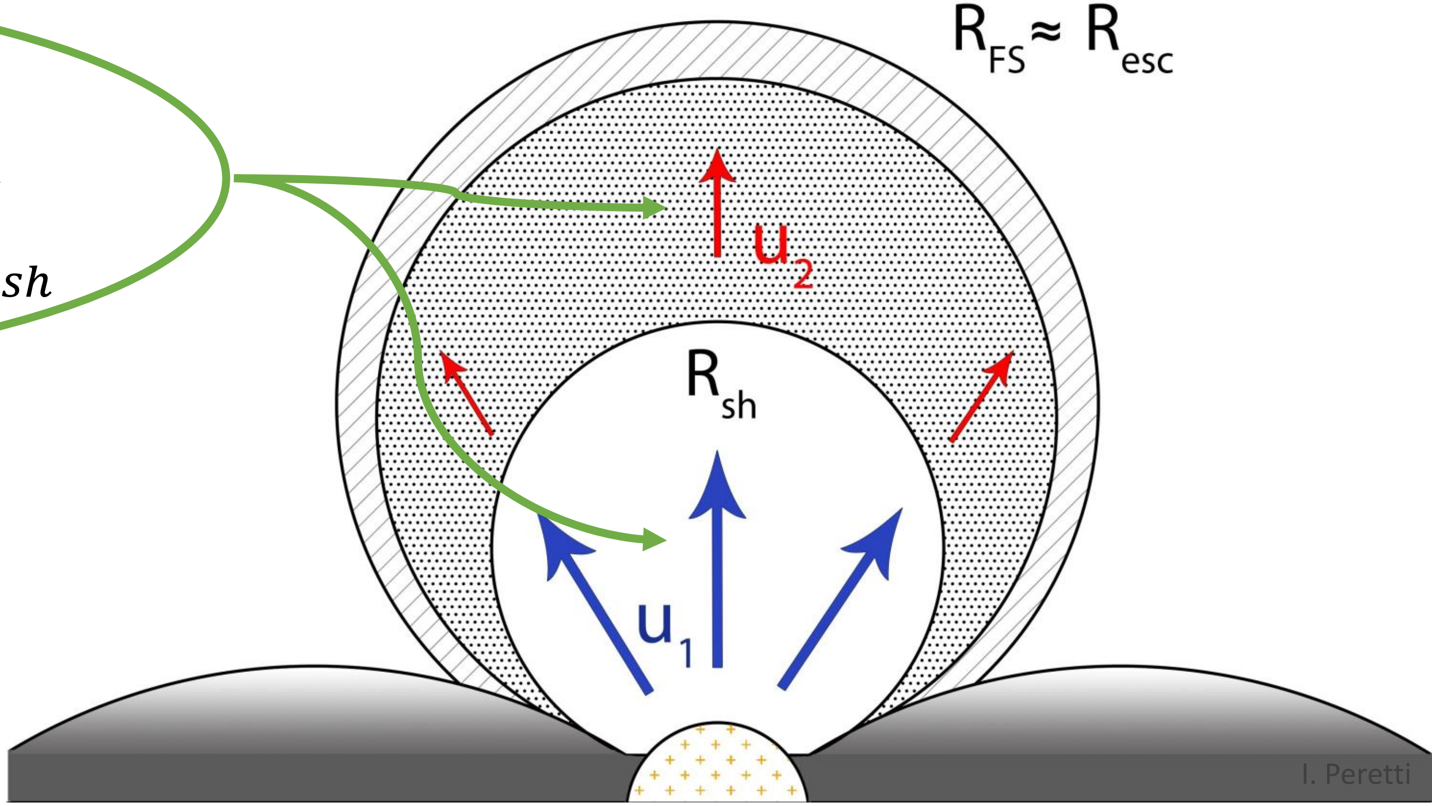
Particle acceleration and transport

$$r^2 u(r)\partial_r f = \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p)$$

Advection & Adiabatic losses

$$u(r) = \begin{cases} u_1(r) \approx u_1 & r < R_{sh} \\ u_2\left(R_{sh}/r\right)^2 & r > R_{sh} \end{cases}$$





Particle acceleration and transport

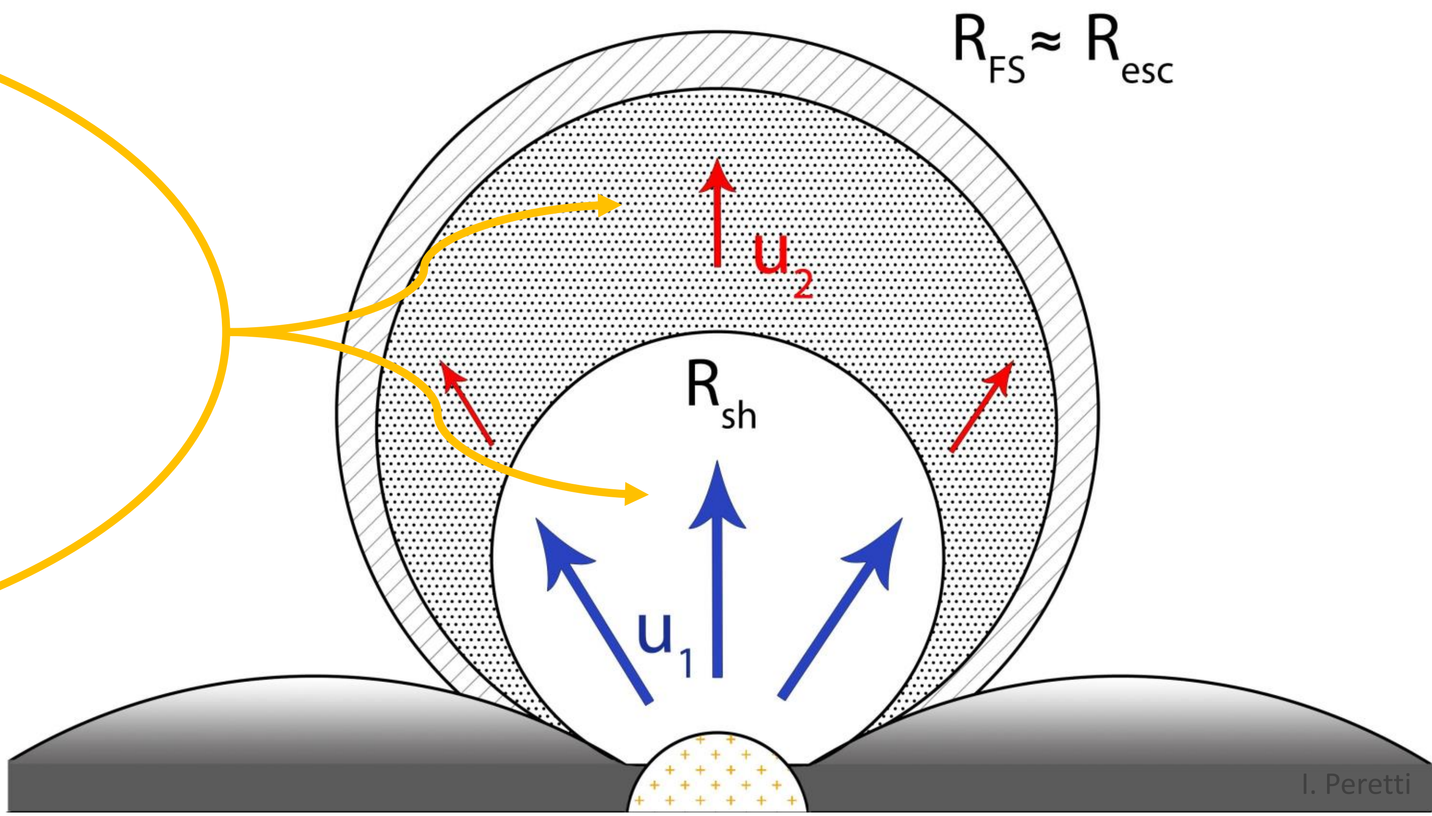
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p)$$

Diffusion

$$D(r,p) = {}^1/_3\, c\, r_L^{\delta} l_c^{1-\delta}$$

$$l_c \approx 10^2\ pc$$

$$U_{B,1} \approx \epsilon_B \rho u_1^2/2$$



Particle acceleration and transport

$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$

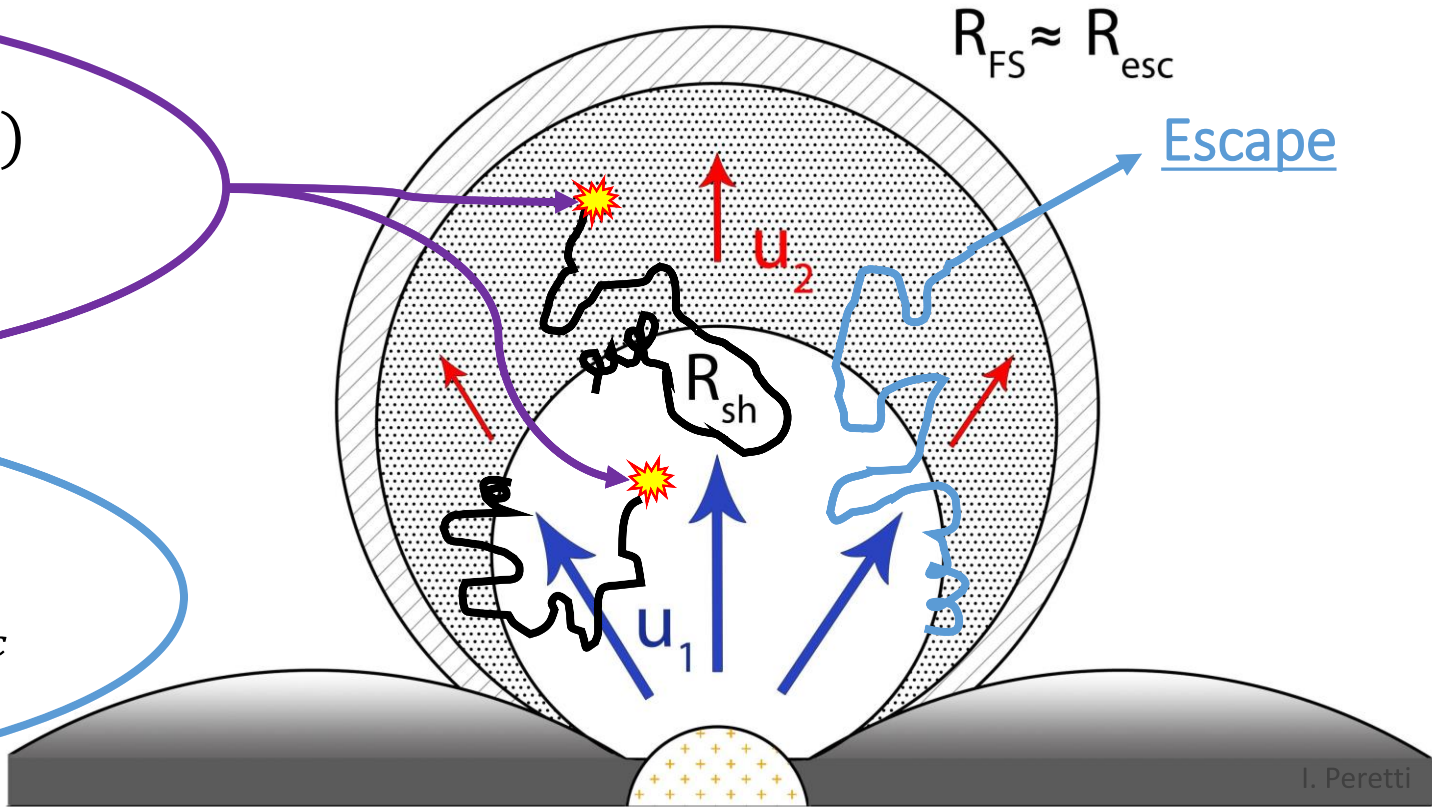
Energy losses

$$\Lambda(r,p) = n(r)\sigma_{pp}(p)v(p)f(r,p)$$

P-gamma timescale: negligible

Escape

$$j_{esc}(p) = -D(r,p)\partial_r f(r,p)|_{R_{esc}}$$

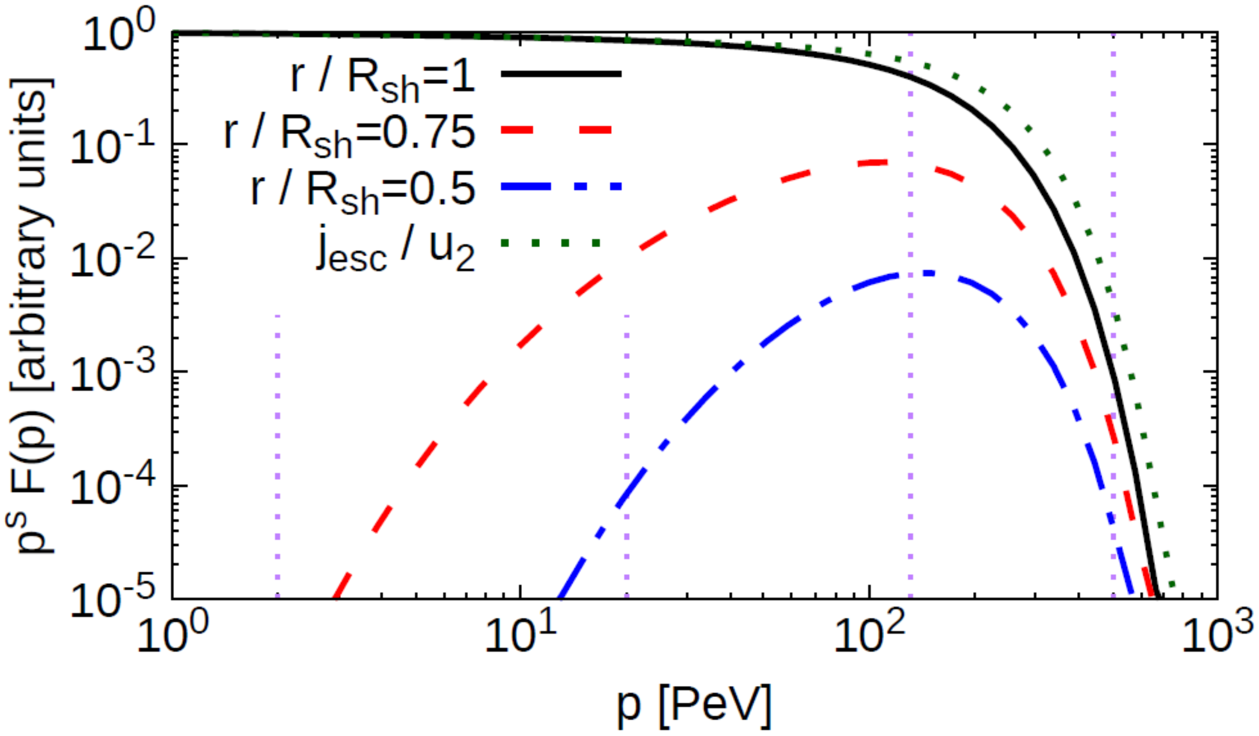


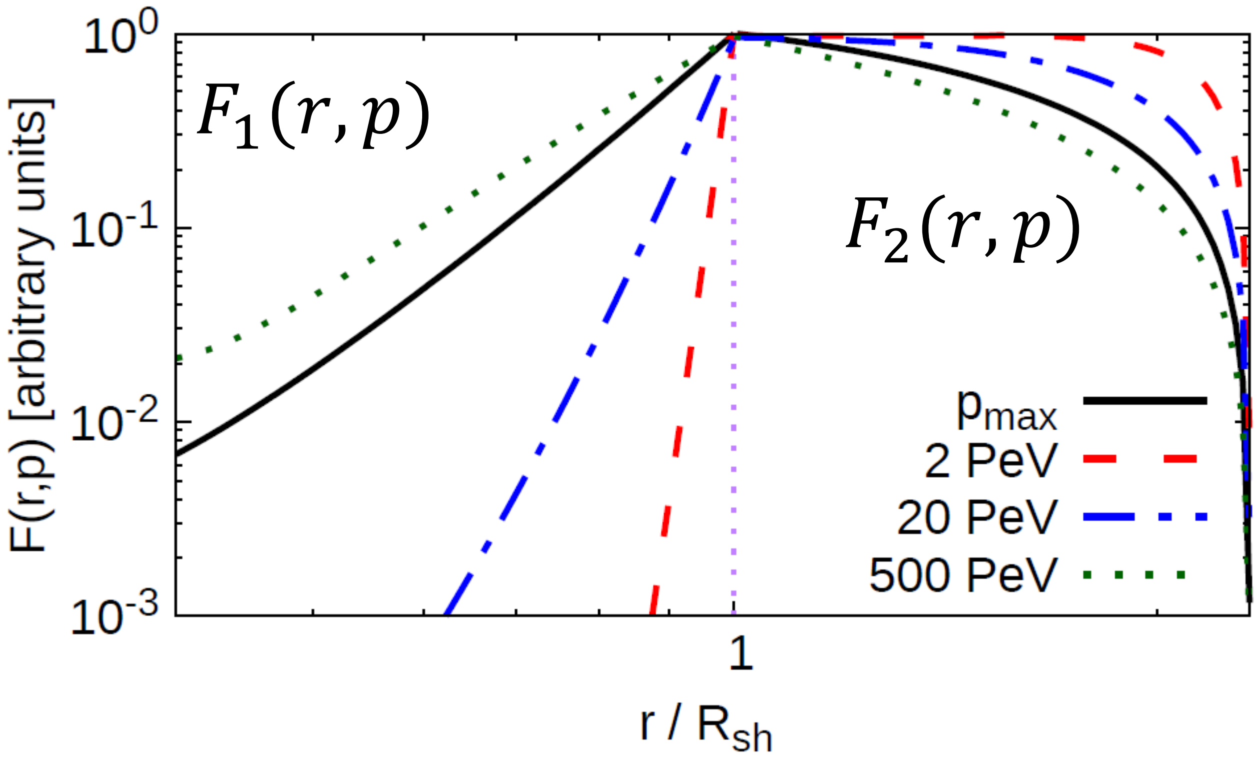
Properties of the solution

$$f_{sh}(p) = \frac{s\,\eta_{CR}\,n_1}{4\pi p_{inj}^3}(\frac{p}{p_{inj}})^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

- s → Slope DSA → $s = 3u_1/(u_1 - u_2) \gtrsim 4$
- η_{CR} → Test particle regime → $P_{CR} \approx \xi_{CR}\, P_{RAM}$
- $\Gamma_2(p)$ → Downstream HE cut off → $\frac{D_2}{\langle u_2 \rangle} \approx R_{esc} - R_{sh}$ (Hillas)
- $\Gamma_1(p)$ → Upstream HE cut off → $u_1 = u_1(p)$ + Losses (~~Hillas~~)

Accelerated particles in the system

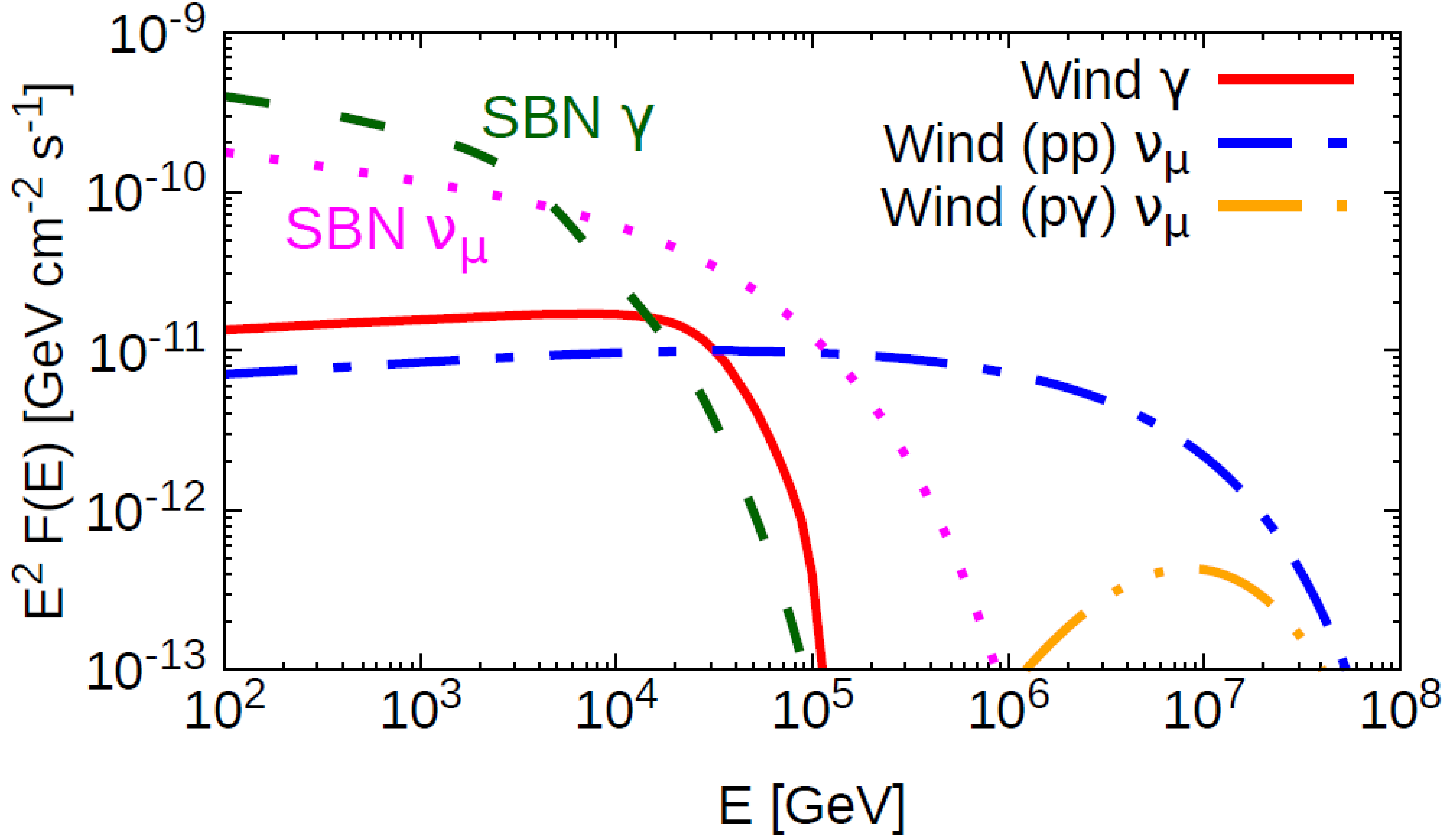




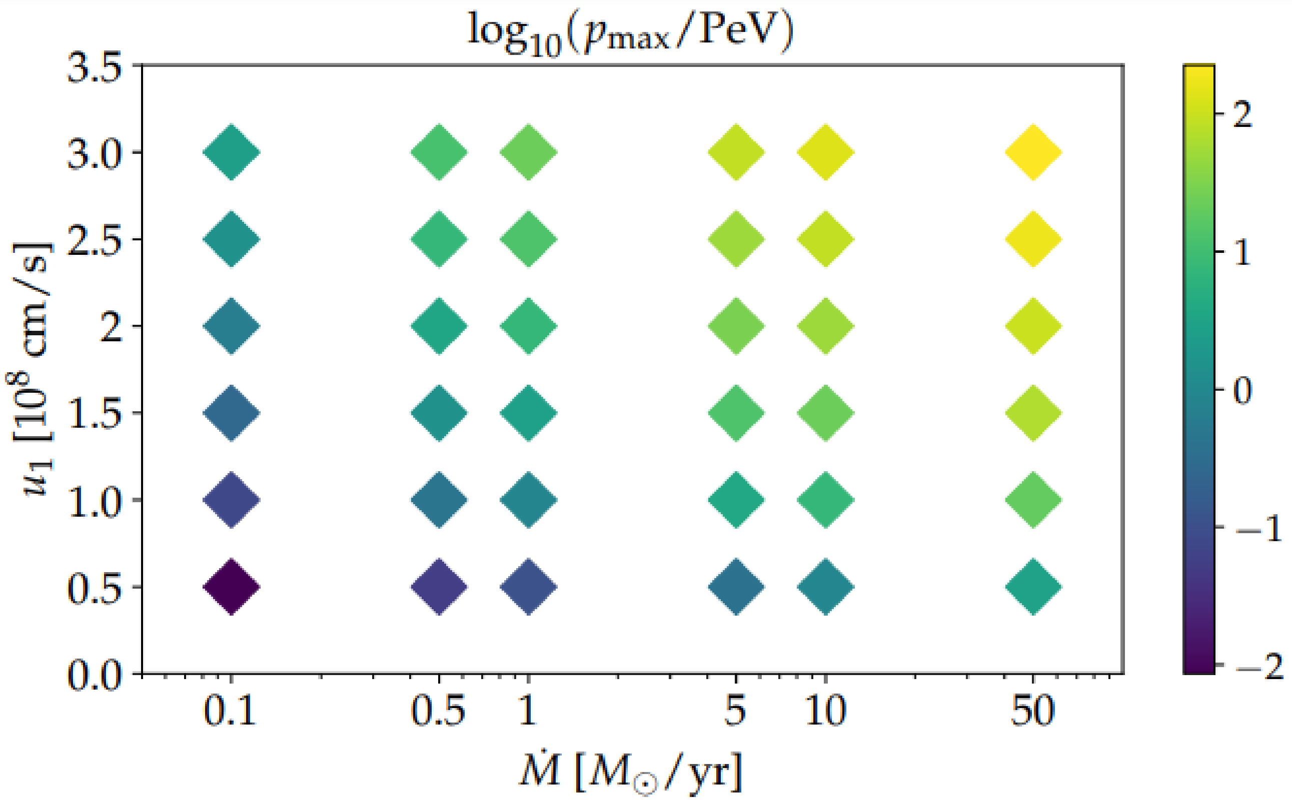
$$F_1(r,p) = f_{sh}(p)\, \exp[-\int_r^{R_{sh}} dr'/\lambda_D(r',p)]$$

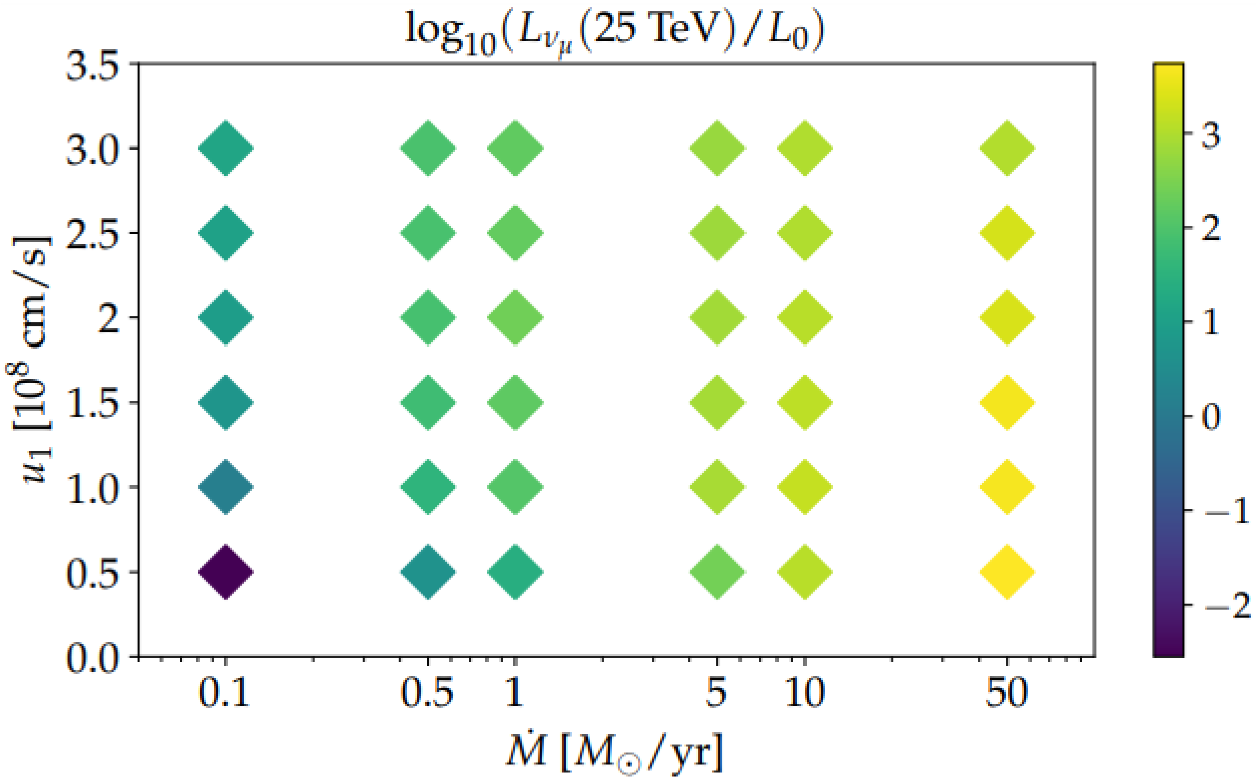
$$F_2(r,p) \propto f_{sh}(p)$$

Gamma rays and neutrinos

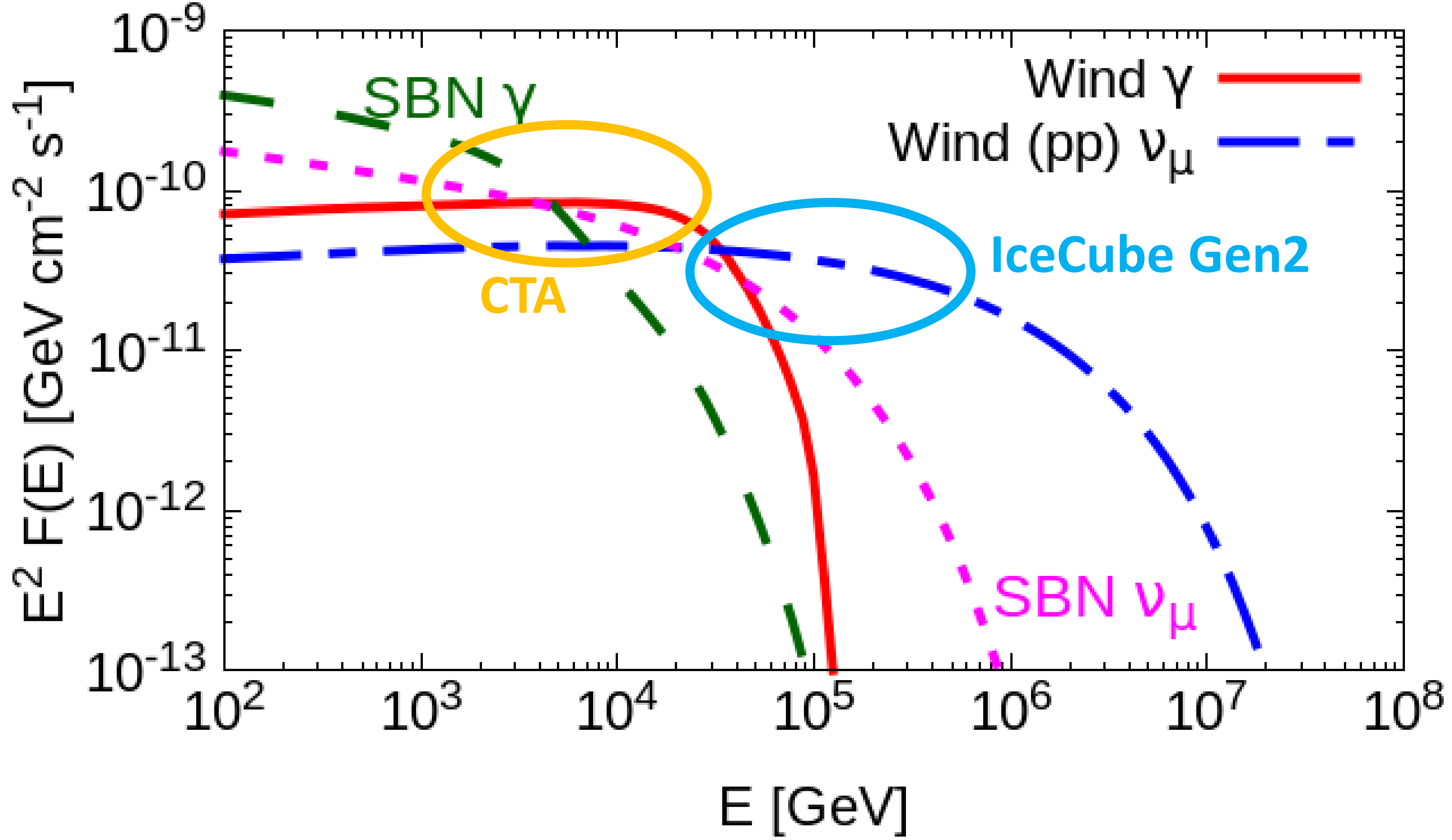


Maximum energy and luminosity





Observational perspectives



Outlooks and Conclusions

- Protons can be accelerated up to hundreds of PeV at the termination shock of wind superbubbles
- High multi-messenger potential: 1) gamma rays and neutrinos are copiously produced; 2) the escaping flux of protons and nuclei could contribute to the spectrum of cosmic rays observed at Earth
- The most nearby sources (D < 10 Mpc) could be accessible next generation detectors such as CTA and IceCube Gen2

Thanks for your attention!