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Collective acceleration inside superbubbles

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contents

1) **Superbubbles**
a particular environment for acceleration

2) **Multiple acceleration** by shocks
regular acceleration (Fermi 1)

3) **Transport in the bubble**
stochastic acceleration (Fermi 2) and escape

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1.1 Superbubbles: origin and basic properties

most massive stars live
and thus most SN explode
in OB associations
inside **superbubbles**

big

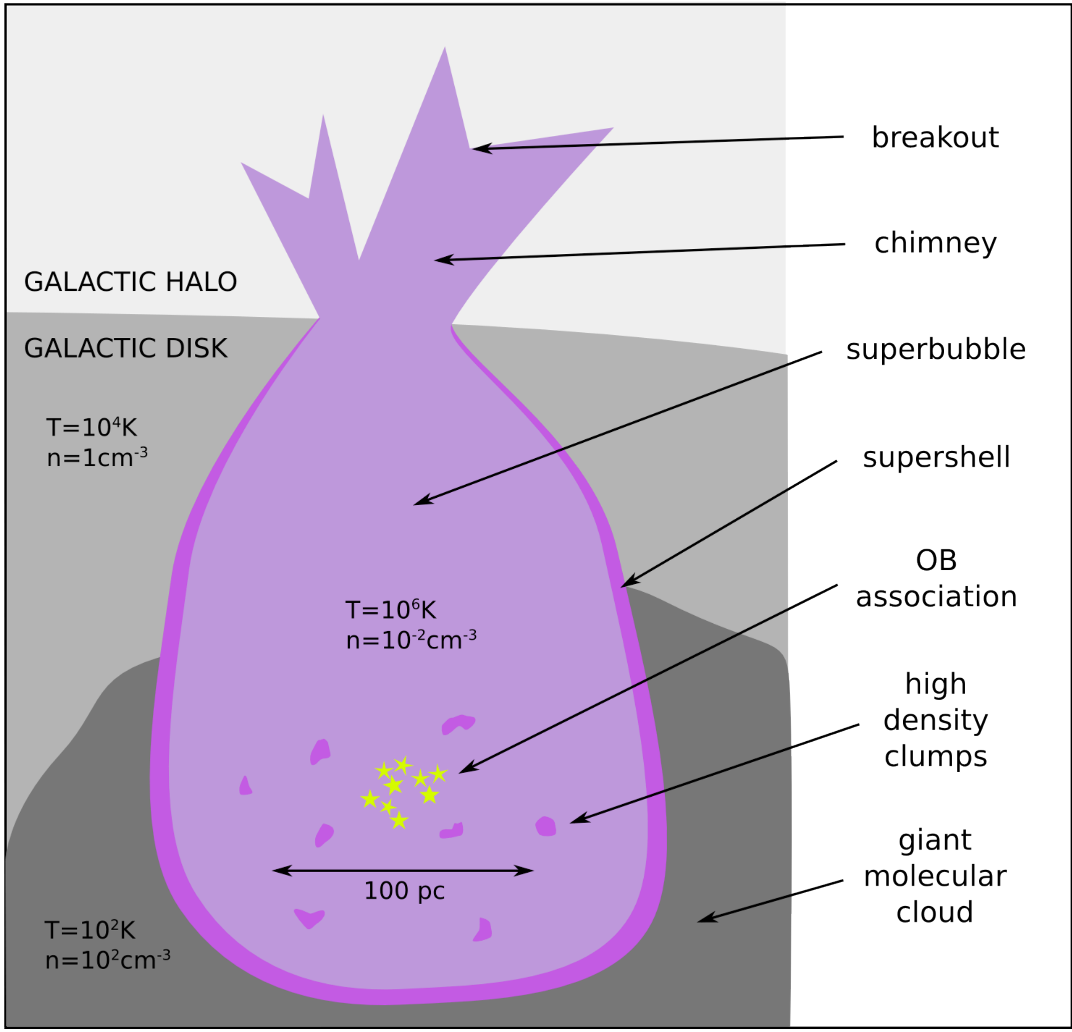
$$r_{SB} \simeq 270 \text{ pc} \times \left(\frac{L_{OB}}{10^{38} \text{ erg/s}}\right)^{1/5} \times \left(\frac{n_{ISM}}{1 \text{ cm}^{-3}}\right)^{-1/5} \times \left(\frac{t}{10^7 \text{ yr}}\right)^{3/5}$$

tenuous

$$n_{SB} \simeq 4\times10^{-3} \text{ cm}^{-3} \times \left(\frac{L_{OB}}{10^{38} \text{ erg/s}}\right)^{6/35} \times \left(\frac{n_{ISM}}{1 \text{ cm}^{-3}}\right)^{19/35} \times \left(\frac{t}{10^7 \text{ yr}}\right)^{-22/35} \times \left(1-\frac{r}{r_{SB}}\right)^{-2/5}$$

hot

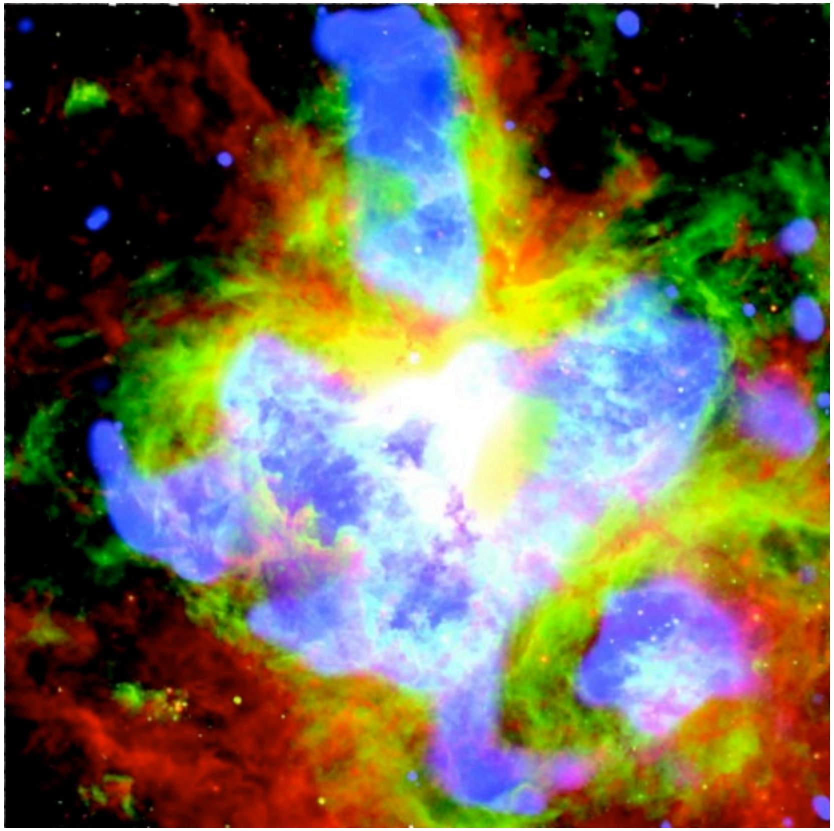
$$T_{SB} \simeq 3.5\times10^{6} \text{ K} \times \left(\frac{L_{OB}}{10^{38} \text{ erg/s}}\right)^{8/35} \times \left(\frac{n_{ISM}}{1 \text{ cm}^{-3}}\right)^{19/35} \times \left(\frac{t}{10^7 \text{ yr}}\right)^{-6/35} \times \left(1-\frac{r}{r_{SB}}\right)^{2/5}$$



[review: Parizot et al 2004; lecture: Marcowith 2007]

Superbubbles: observations

thermal emission

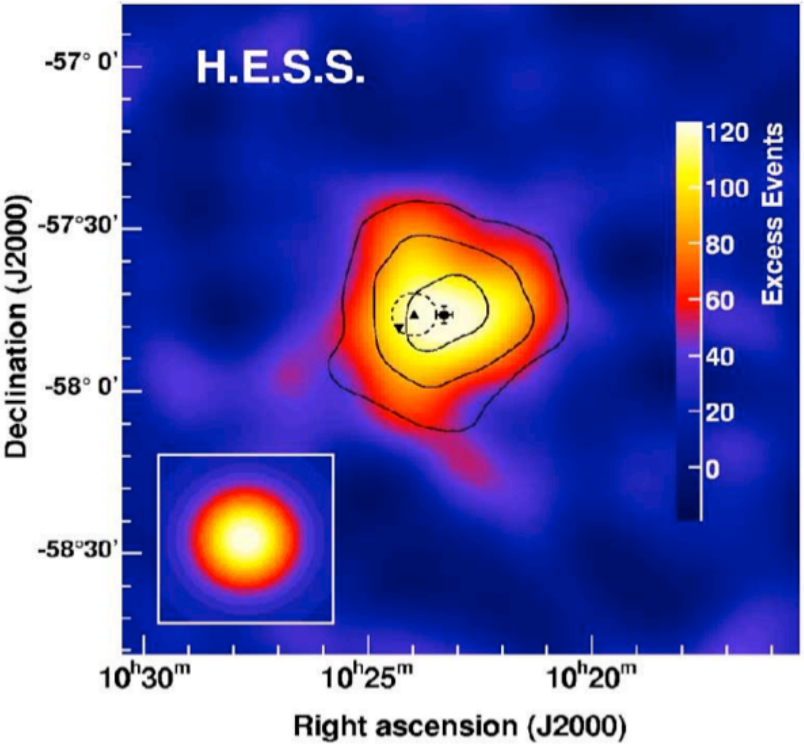


multi-wavelength image of 30 Doradus

colour	instrument	band	composition	object
blue	Chandra ACS	0.9-2.3 keV	10^6 K plasma	superbubble
green	MCELS	656 nm	10^4 K plasma	supershell
red	Spitzer IRAC	6.5-9.4 μm	dust, PAH	shell & cloud

[composite by Townsley et al 2006]

non-thermal emission

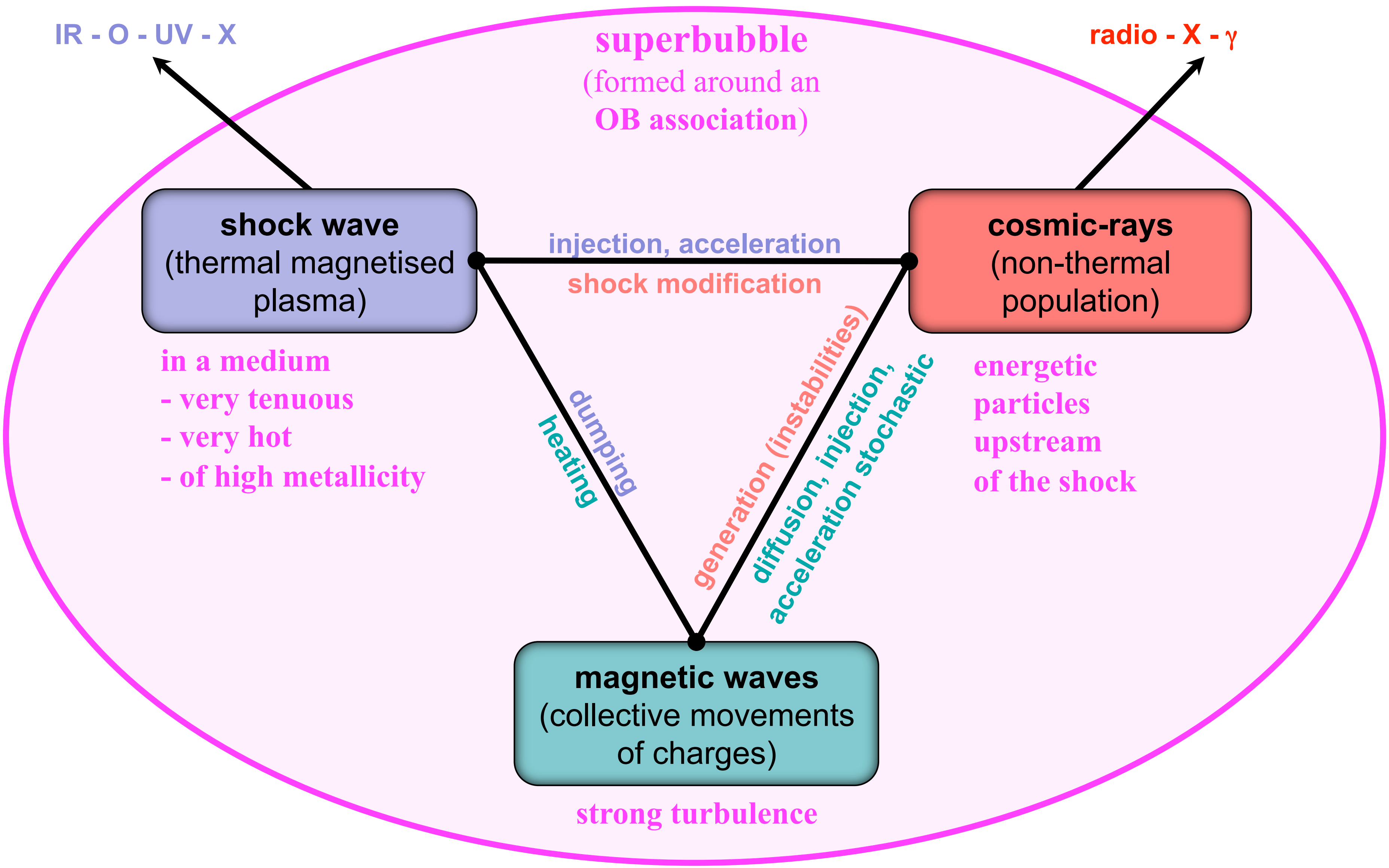


TeV emission from Westerlund 2

colliding winds?
collective winds?
multiple shocks?

[Aharonian et al 2007]

1.3 Acceleration: the coupled system, in context



[a model of acceleration inside superbubbles: Bykov 2001]

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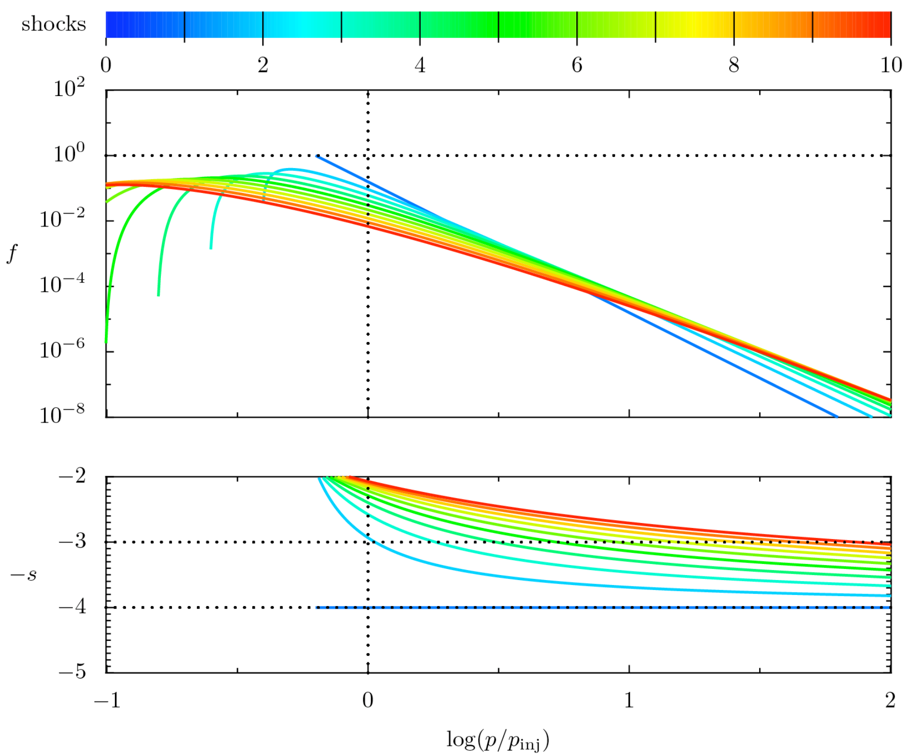
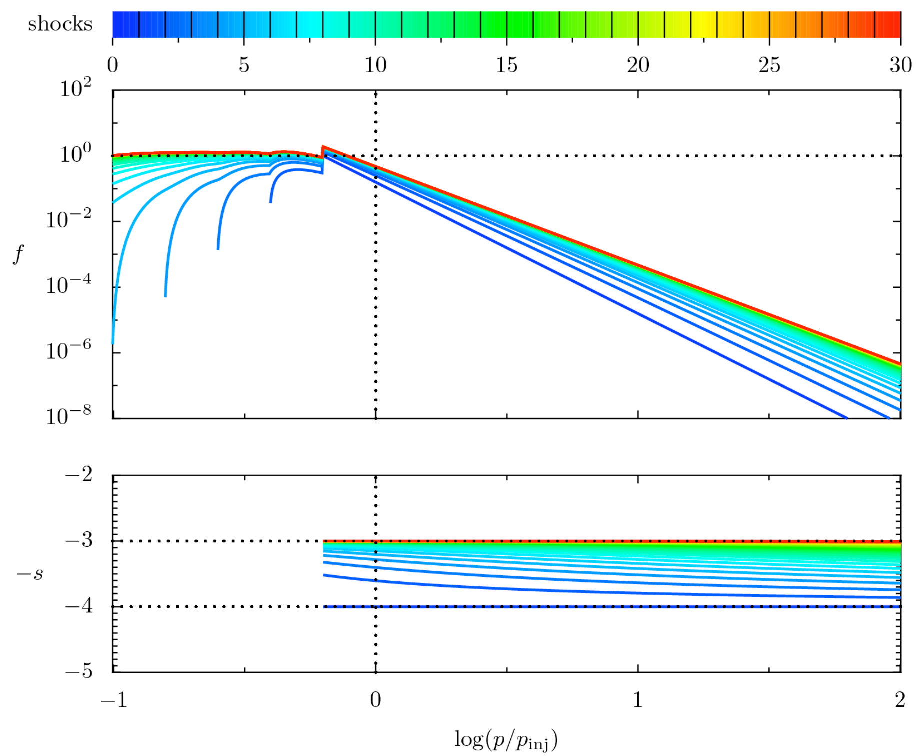
Multiple acceleration: linear regime





$$f_{(i)}(p) = \frac{k\, s_1^i}{p_{\rm inj}} \left(\frac{R^i\, p}{p_{\rm inj}}\right)^{-s_1} \frac{\left(\ln\left(\frac{R^i\, p}{p_{\rm inj}}\right)\right)^{i-1}}{(i-1)!} H\left(p - \frac{p_{\rm inj}}{R^i}\right)$$

contribution from injection at the first shock to the distribution downstream of the i-th shock (after decompression)

$$f_n(p) = \sum_{i=1}^{n} f_{(i)}(p) \qquad f_\infty(p > p_{\rm inj}) \propto p^{-3}$$

total distribution downstream of the n-th shock (with injection at each shock, and after decompression)

[Achterberg 1990, Schneider 1993, Pope & Melrose 1994]

2.2 Numerical simulations of shock acceleration

marcos code

hydrodynamic treatment

conservation laws:

$$\frac{\partial \vec{X}}{\partial t} + div\left(\vec{F}\left(\vec{X}\right)\right) = \vec{0}$$

Euler 1D :

$$\vec{X} = \begin{pmatrix} \rho \\ \rho u \\ e \end{pmatrix} \quad \vec{F}\left(\vec{X}\right) = \begin{pmatrix} \rho u \\ \rho u^2 + P \\ \left(e + P\right)u \end{pmatrix}$$

kinetic treatment

spectrum of particles:

$$\mathrm{n}\left(\mathrm{x,t}\right) = \int_p f\left(p,x,t\right) 4\pi p^2 \mathrm{d}p$$

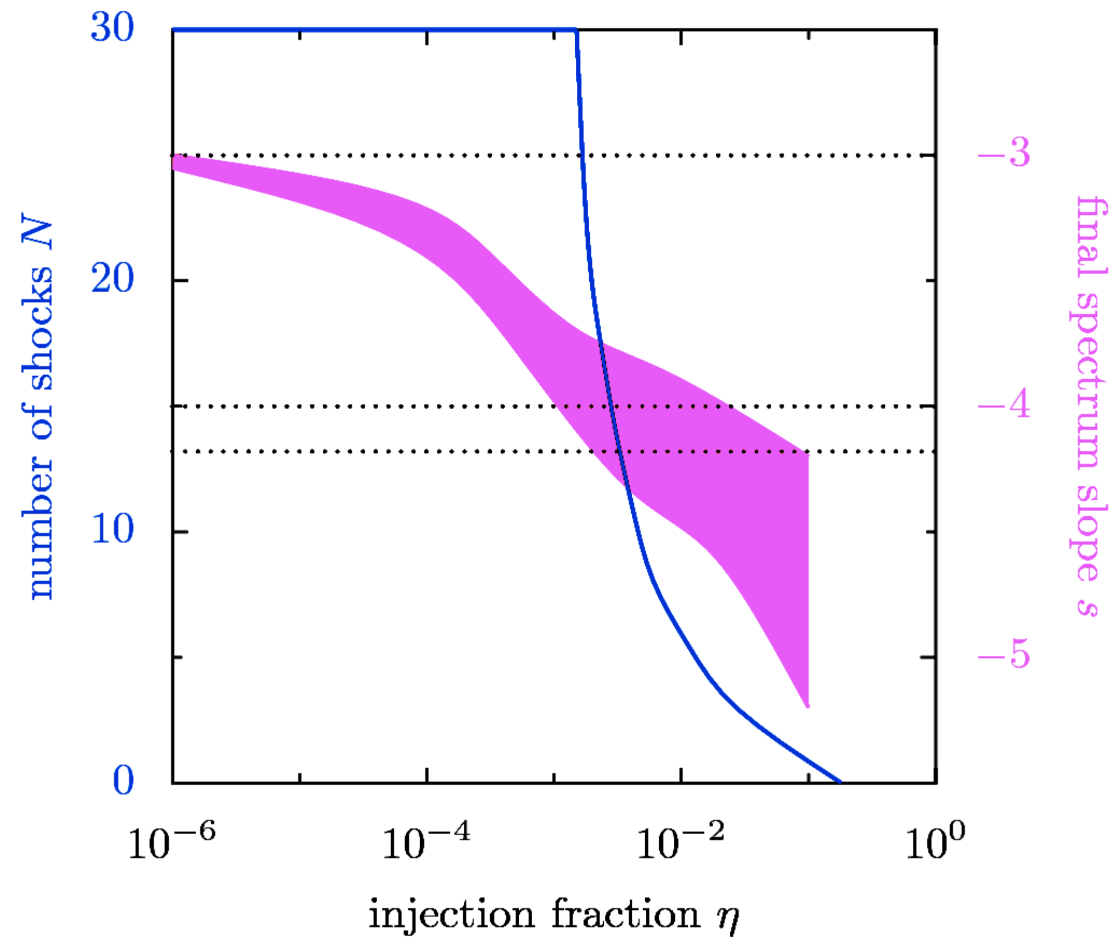
transport equation:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}\left(uf\right) = \frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right) + \frac{1}{3p^2}\frac{\partial p^3 f}{\partial p}\frac{\partial u}{\partial x}$$

[Falle & Giddings 1987, Ferrand, Downes, Marcowith 2008]

Multiple acceleration: non-linear regime

first investigation of time-dependent non-linear acceleration by a sequence of shocks



→ large range of indices, spectra can get very hard

[Ferrand, Downes, Marcowith 2008]

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Monte-Carlo simulations of CR production

Aim: investigate the time-dependent shape of the energy spectrum of CR protons produced inside SBs

Method: semi-analytical model of CR production and transport inside Monte-Carlo simulations of OB clusters timelines

process	Fermi 1	Fermi 2
what ?	regular acceleration	stochastic re-acceleration + escape
why ?	SN explosions	magnetic turbulence
where ?	at shock fronts	in the SB medium
when ?	quite discreetly (during early SNR stages)	continuously (between SN shocks)

Green function for Fermi 1

linear first order Fermi acceleration at shock fronts

CR distribution downstream of the shock: $f_{\mathrm{down}}\left(p\right) = \int_0^\infty G_1\left(p, p_0\right)\; f_{\mathrm{up}}\left(p_0\right)\; \mathrm{d}p_0$

Green function: $G_1\left(p, p_0\right) = \frac{s_1}{p_0}\left(\frac{p}{p_0}\right)^{-s_1} H\left(p - p_0\right)$

canonical slope: $s_1 = \frac{3r}{r-1}$

[reference review: Drury 1983]

+ adiabatic decompression: $f'_{\mathrm{down}}\left(p\right) = f_{\mathrm{down}}\left(Rp\right) \quad \text{where} \quad R = r^{1/3}$

[Melrose & Pope 1993, Ferrand et al 2008]

3.3 Green function for Fermi 2 and escape

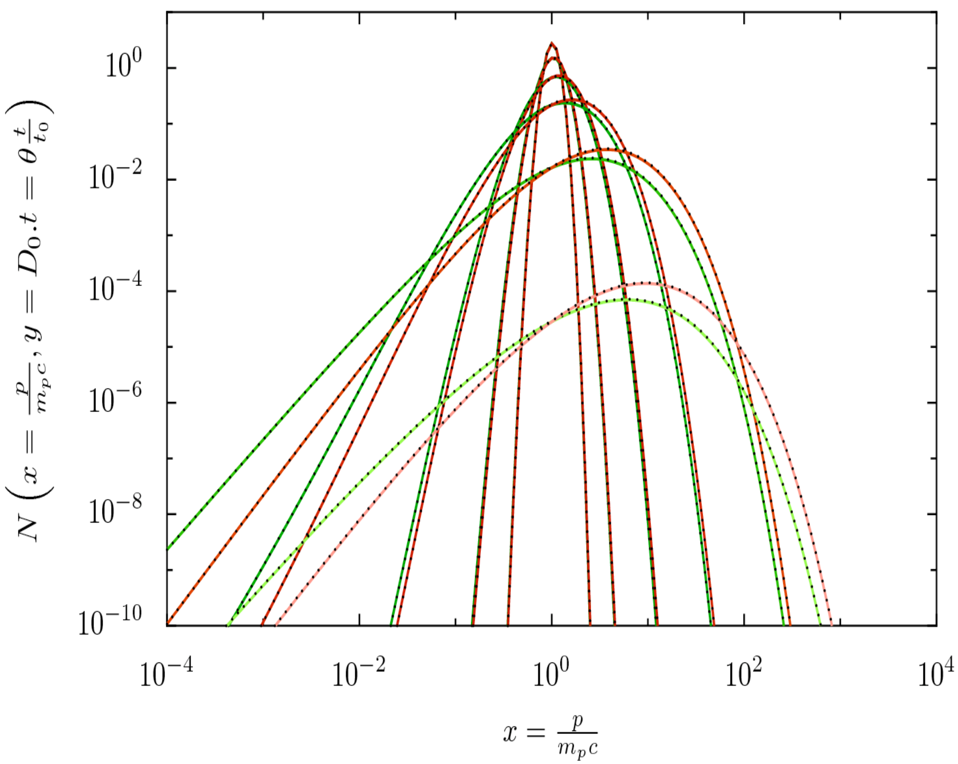
valid for any turbulence index 0<q<2

$$f_{\rm end}(p,t) = \int_0^\infty G_2(p,p_0,t)\; f_{\rm init}(p_0)\; {\rm d}p_0$$

$$\begin{aligned}
G_2(p,p_0,t) &= \frac{2-q}{p_0}\sqrt{\frac{p}{p_0}}\;\frac{\sqrt{z z_0 \xi}}{1-\xi} \\
&\times \exp\left(-\frac{(z+z_0)(1+\xi)}{2(1-\xi)}\right) \\
&\times {\rm I}\left(\frac{1+q}{2-q}, \frac{2\sqrt{z z_0 \xi}}{1-\xi}\right)
\end{aligned}$$

with

$$\begin{aligned}
z(p) &= \frac{2}{\sqrt{D_p^\star t_{\rm esc}^\star}}\;\frac{p^{2-q}}{2-q} \\
\xi(t) &= \exp\left(2(q-2)\,\frac{D_p^\star\, t}{\sqrt{D_p^\star t_{\rm esc}^\star}}\right)
\end{aligned}$$



[Becker et al 2006]

Diffusion scales

energy spectrum of magnetic turbulence : $W(k) \propto k^{-q}$

$$\frac{\delta B^2}{4\pi} = \int_{k_{\min}}^{k_{\max}} W(k)\, \mathrm{d}k$$

space diffusion and escape

momentum diffusion (stochastic acceleration)

$$D_x\,(p) = D_x^\star \times \left(\frac{p}{m_p c}\right)^{2-q}$$

$$t_{\rm esc}\,(p) = t_{\rm esc}^\star \times \left(\frac{p}{m_p c}\right)^{q-2}$$

$$t_{\rm esc}^\star \propto \eta_T\; B^{2-q}\; \lambda_{\max}^{1-q}\; x_{\rm acc}^2$$

$$D_p\,(p) = D_p^\star \times (m_p c)^2 \times \left(\frac{p}{m_p c}\right)^{q}$$

$$D_p^\star \propto \eta_T\; B^{4-q}\; \lambda_{\max}^{1-q}\; n^{-1}$$

[Casse 2002, Becker et al 2006]

Distribution of stars

Initial Mass Function (IMF):

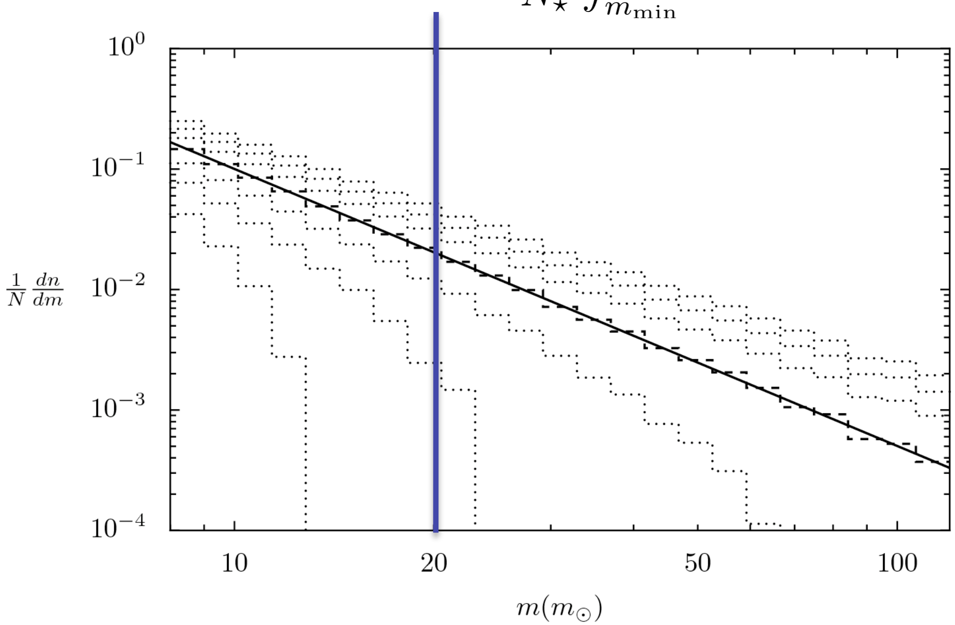
$$N_\star = \int_{m_{\min}}^{m_{\max}} \xi(m)\, \mathrm{d}m$$

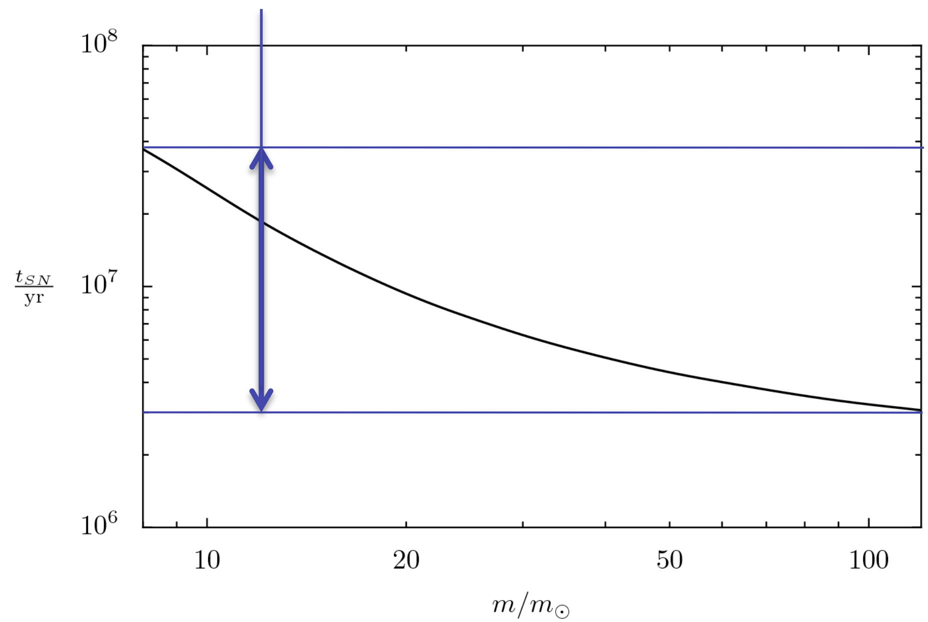
with $\xi(m) \propto m^{-2.3}$

massive stars burn strongly and die fast (3-37 Myrs)
→ live in groups

mean mass $\overline{m} = \frac{1}{N_\star} \int_{m_{\min}}^{m_{\max}} m\, \xi(m)\, \mathrm{d}m$

$\Delta t^{\star}_{\mathrm{OB}} \simeq 34$ Myr active life

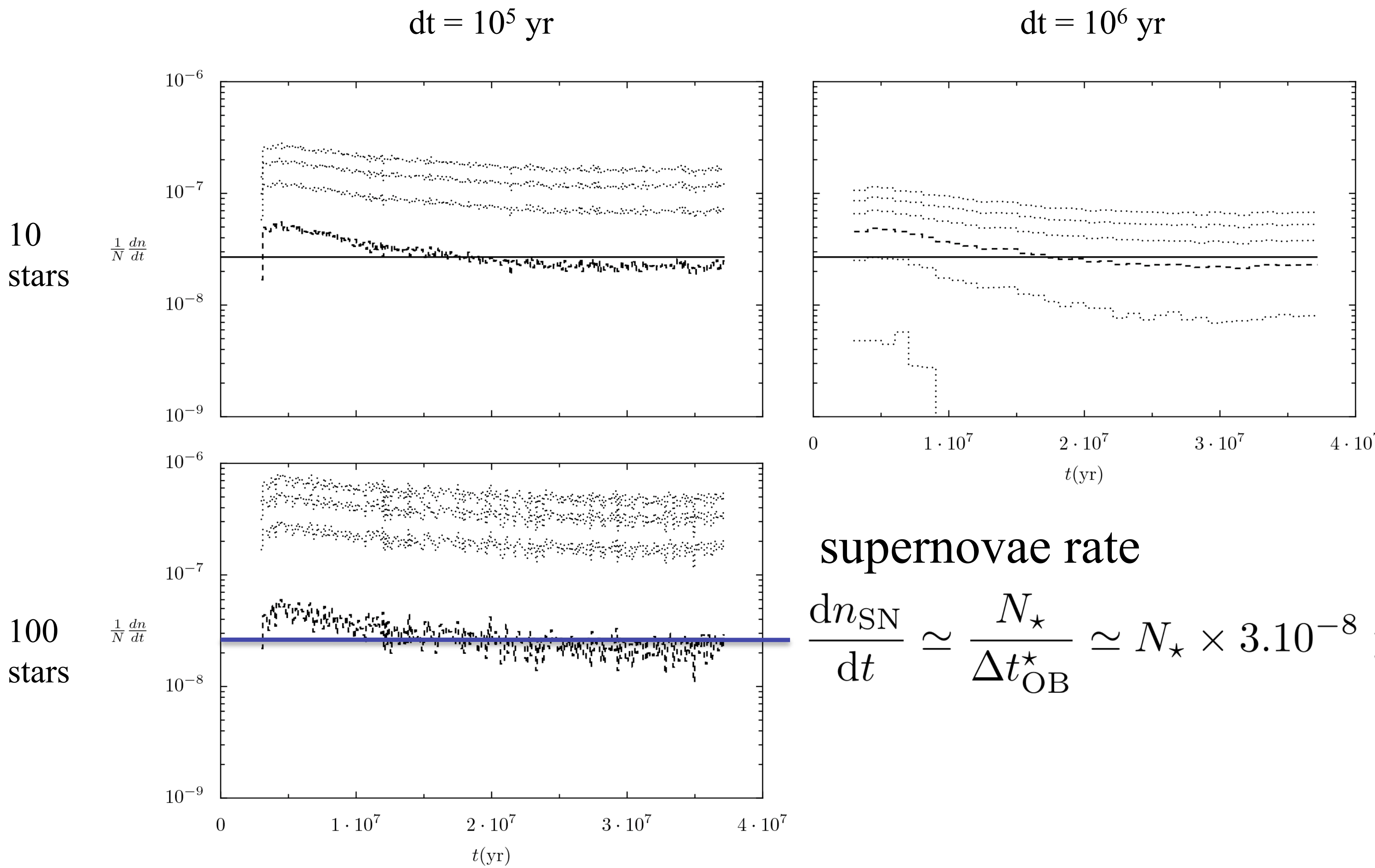




[IMF from Salpeter 1955, Kroupa 2002]

[data from Limongi and Chieffi 2006]

Distribution of supernovae



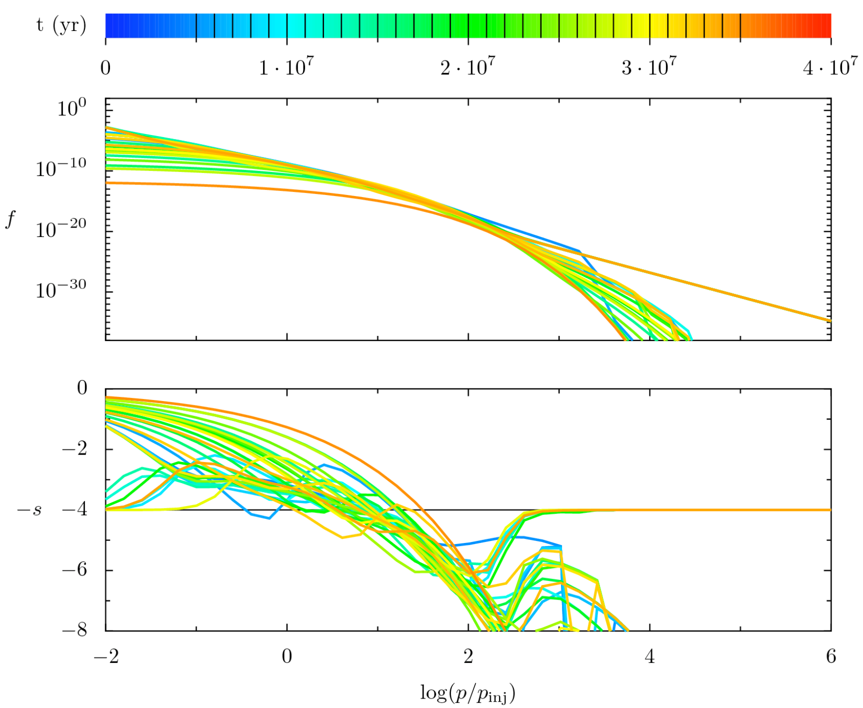
supernovae rate

$$\frac{dn_{\rm SN}}{\rm dt} \simeq \frac{N_\star}{\Delta t^\star_{\rm OB}} \simeq N_\star \times 3.10^{-8}\ \rm yr^{-1}$$

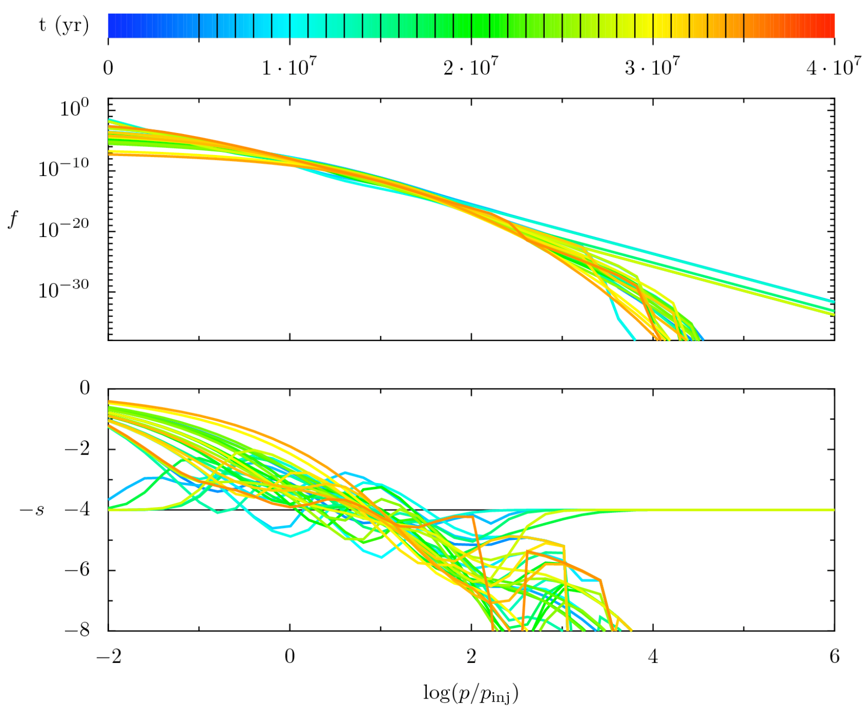
[compares well with Cerviño et al 2000]

Average spectra inside superbubbles

repeat until some average trend emerges:
- pick-up a random cluster following the IMF
- sample time by intervals dt = 10 000 yrs:
  - if SN: do instantaneous Fermi 1 (from 10 MeV to 1 PeV)
  - else: do Fermi 2 + escape since last SN



100 clusters of 10 stars



10 clusters of 100 stars

[Ferrand & Marcowith 2009, in prep]

Parametric study

many physical parameters, often poorly constrained → 720 runs

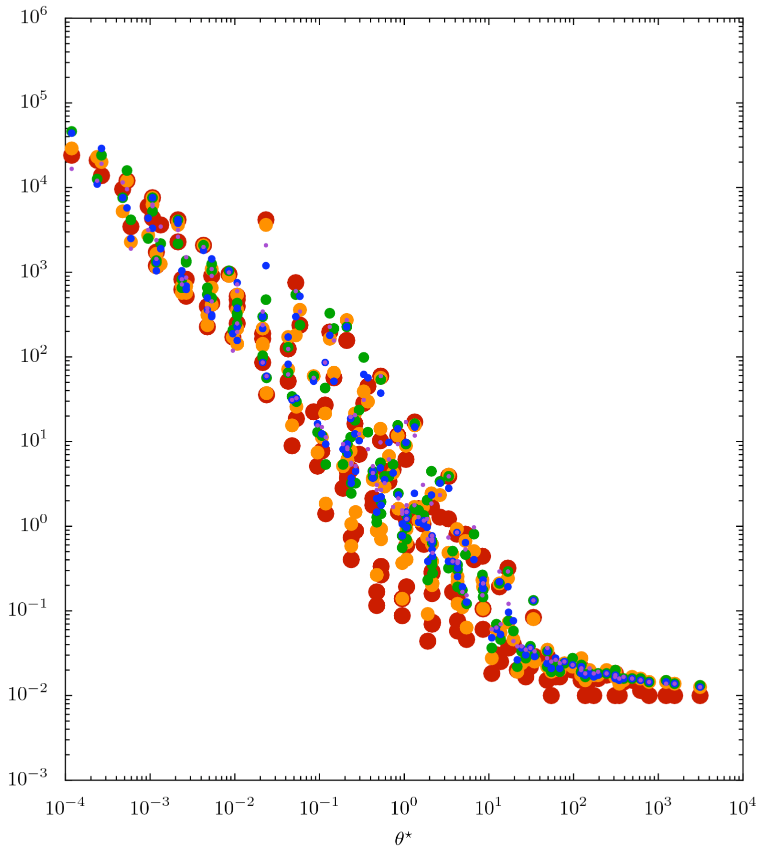
$N_\star = [10, 30, 70, 200, 500]$; $r = 4$

$B = [1, 10]\ \mu\text{G}$; $\eta_T = [1/5, 1]$; $q = [3/2, 5/3]$; $\lambda_{\max} = [10, 20, 40, 80]$ pc

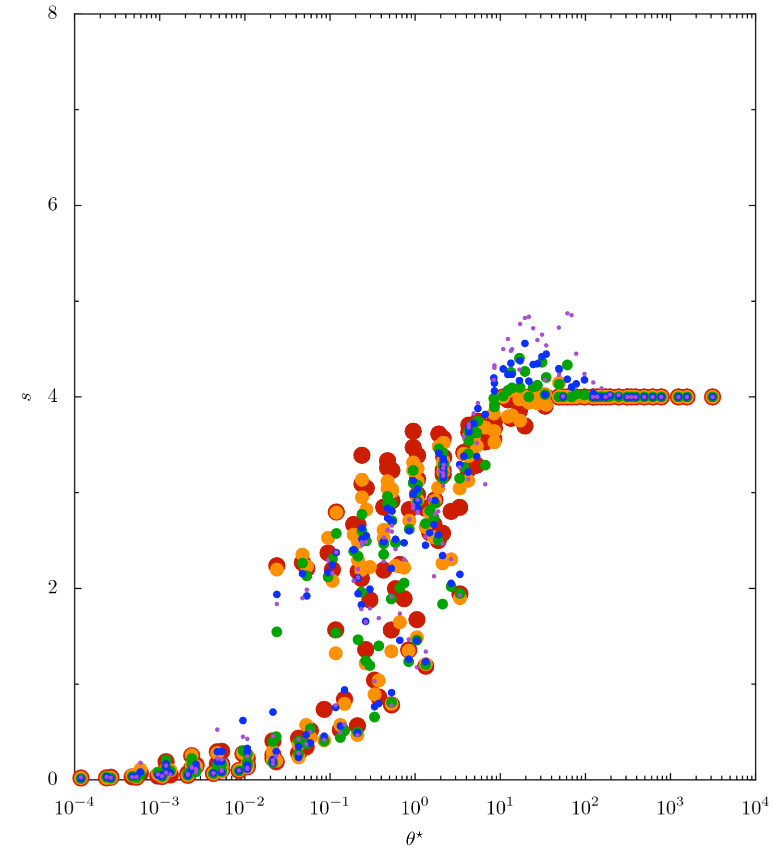
$n = [10^{-3}, 5.10^{-3}, 10^{-2}]\ \text{cm}^{-3}$; $x_{\text{acc}} = [40, 80, 120]$ pc

but one single dimensionless key parameter: $\theta^\star = (D_p^\star\, t_{\text{esc}}^\star)^{-1} \in [10^{-4}, 10^{+4}]$

hard-soft transition momentum



minimum index at 1 GeV



[Ferrand & Marcowith 2009, in prep]

Summary

i. CR spectra inside SBs are strongly **intermittent**

ii. sill, CR spectra have a distinctive two-parts shape resulting from **competition between acceleration and escape**: they are harder at the lowest energies and softer at the highest energies

iii. the momentum at which this spectral break occurs critically depends on the **SB parameters**, all their effects being summarized by a single dimensionless parameter

iv. for reasonable values of SB interior parameters, and especially for highly magnetized and turbulent SBs, very **hard spectra** (s<3) can be obtained over an important range of CR energies, at least up to the GeV domain

→ important implications
- on the in-situ **chemistry**
- on the high-energy **emission**