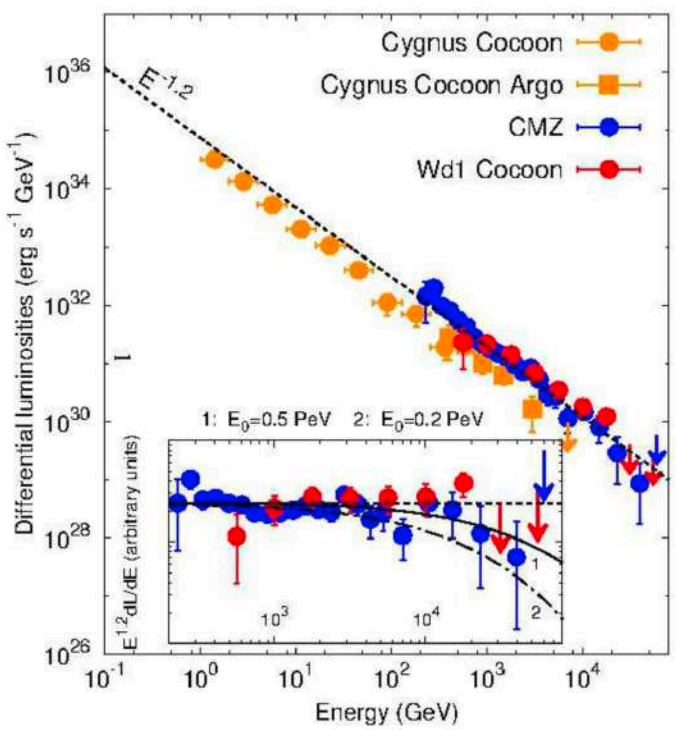
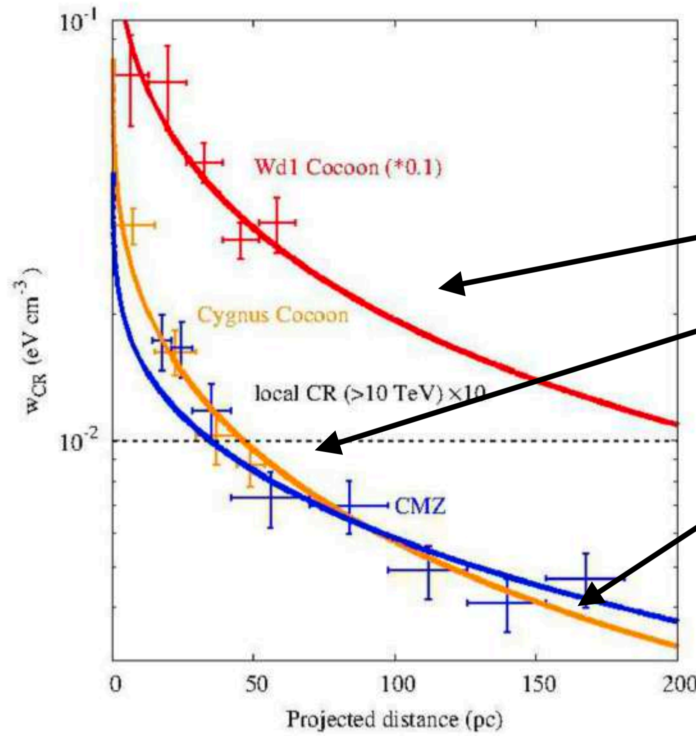
III. Massive stars and interstellar bubbles

Pierre Cristofari

ISAPP 2026

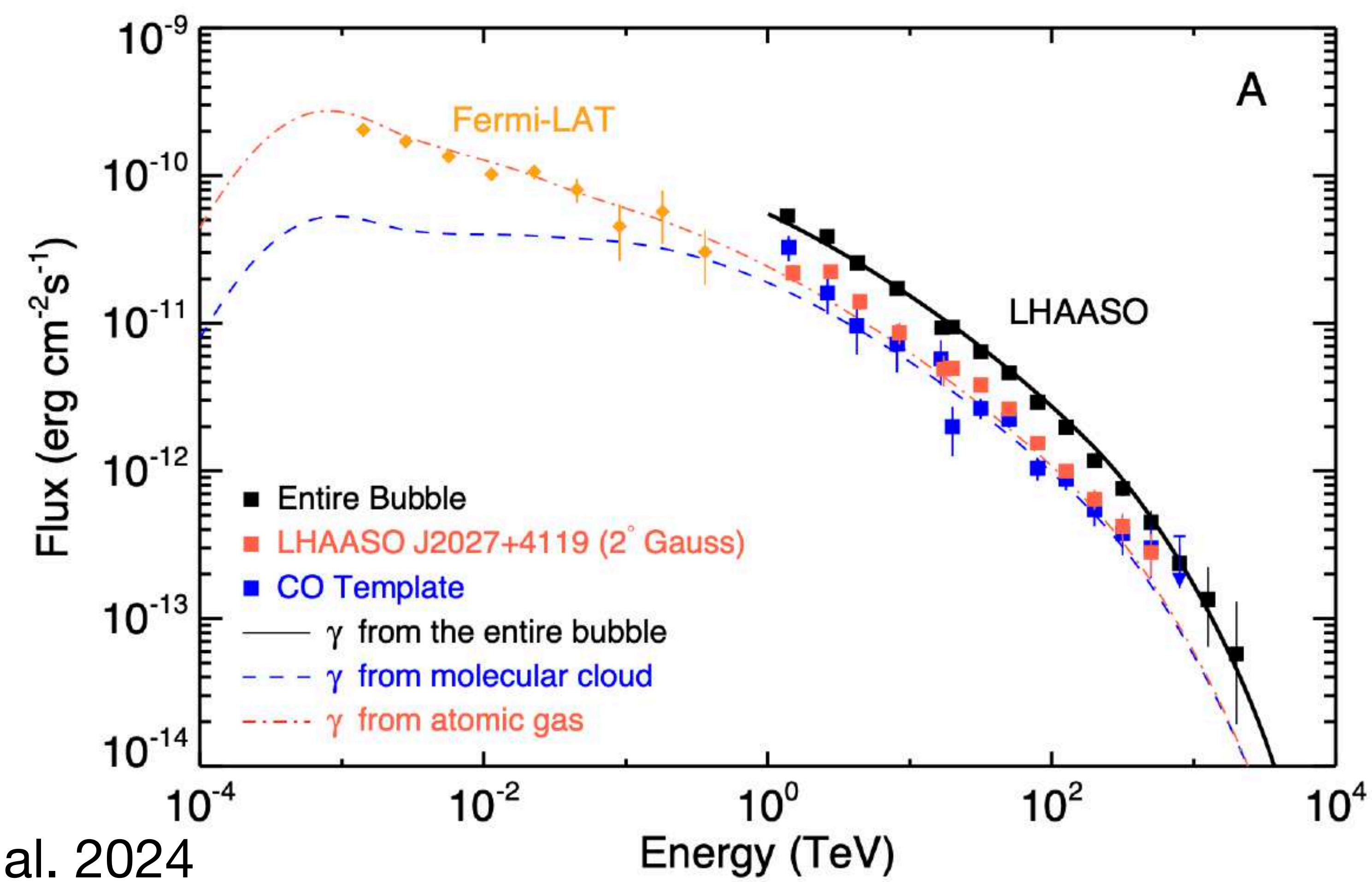
Massive stars and stellar clusters





1/R profile as expected in continuous injection from sources

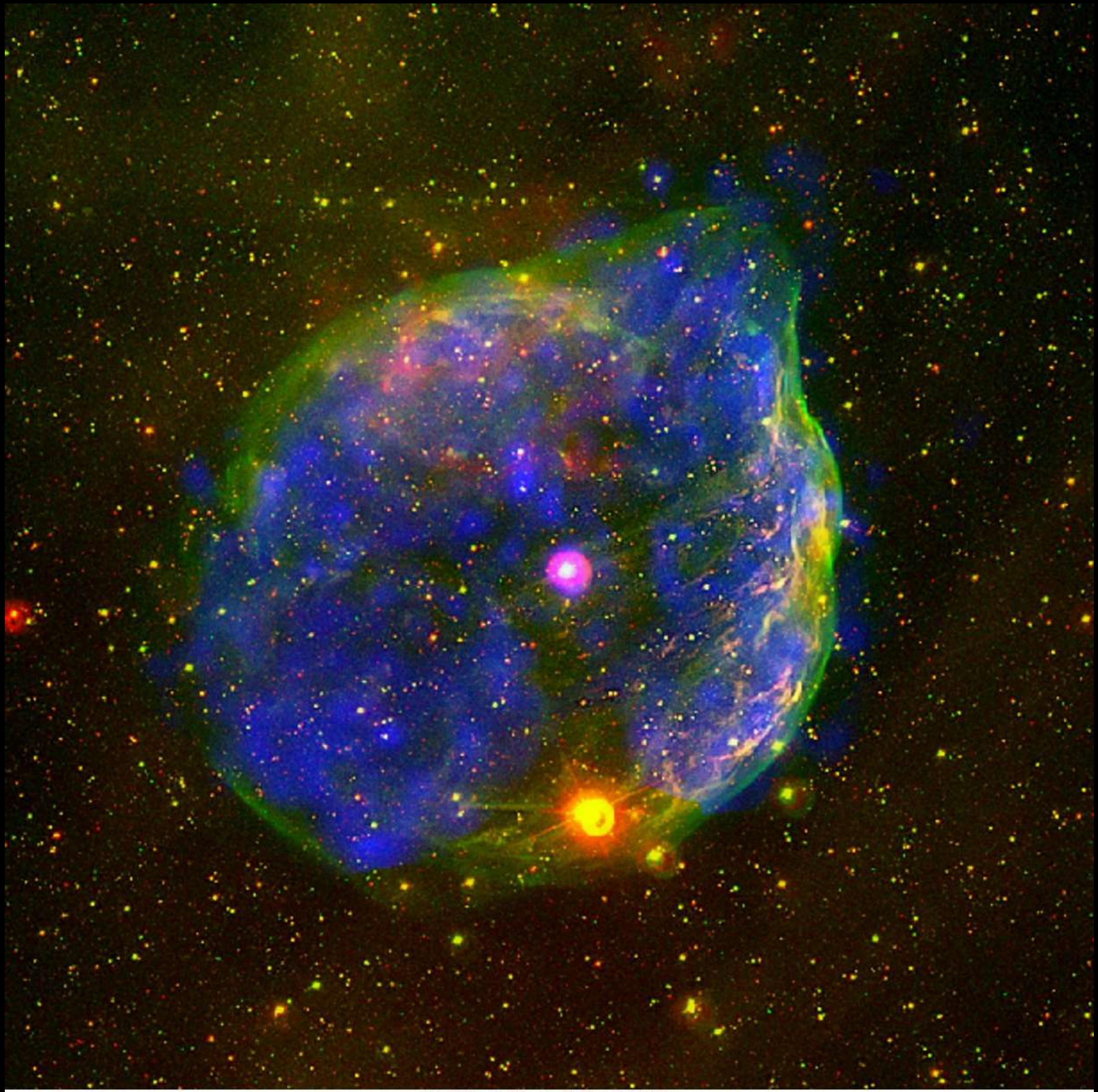
Aharonian et al. 2019, Yang et al. 2021



LHAASO Cao et al. 2024

PeV photons!

S308 Wolf Rayet bubble (XMM) Toala et al.



S308, a Wolf-Rayet Bubble Imaged by XMM-Newton in its Full Glory

Image courtesy of J.A. Toala and M.A. Guerrero (IAA-CSIC), Y.-H. Chu and R.A. Gruendl (UIUC), S.J. Arthur (CRyA - UNAM), R.C. Smith (NOAO/CTIO), and S.L. Snowden (NASA/GSFC) and G.Ramos-Larios (IAM)

European Space Agency

Crescent nebula (cygnus, XMM Newton) Toala et al.

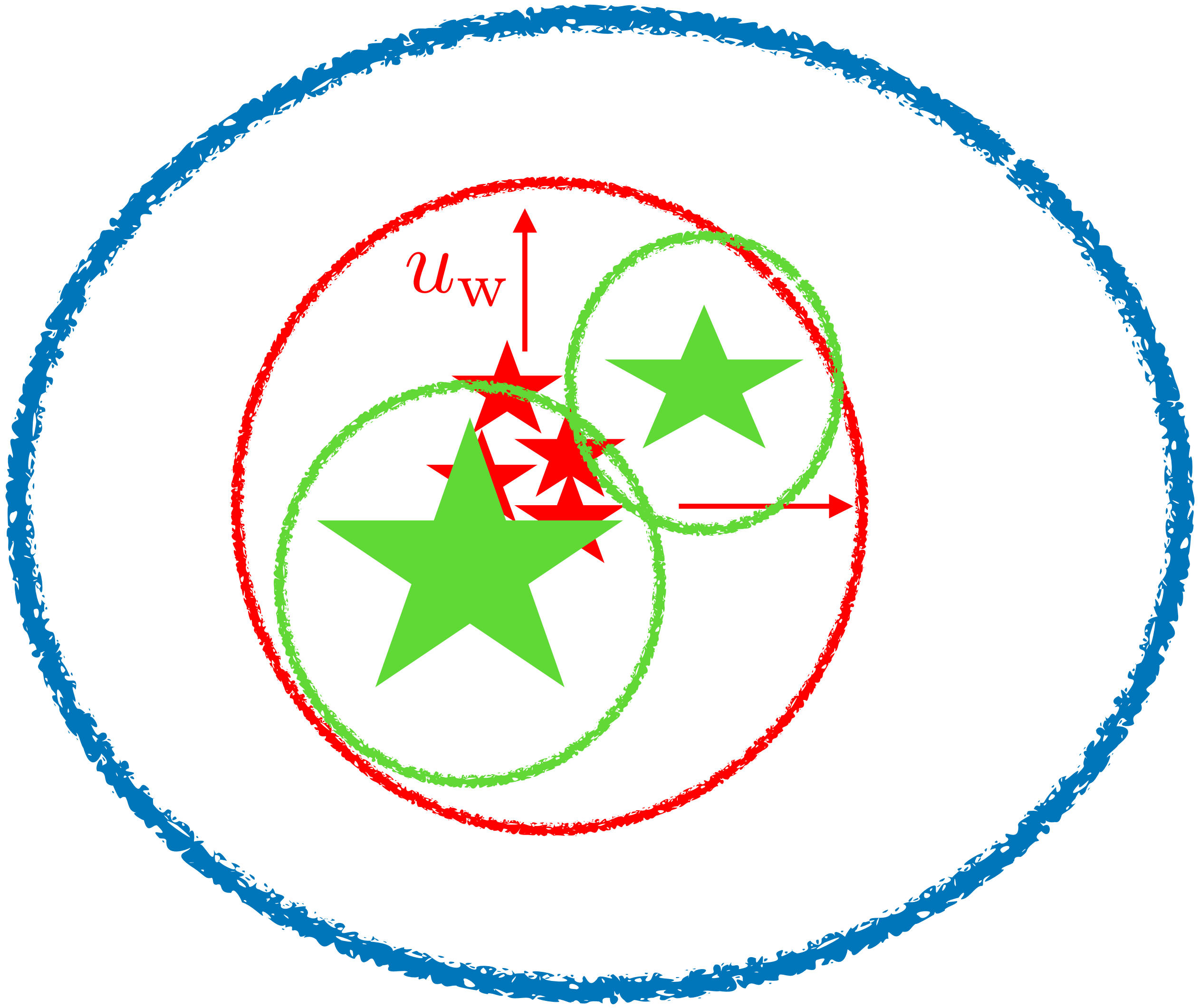
Young massive star (>25Msol), Red giant

Bubble nebula (NGC 7635) Hubble

(>45Msol) (intially 60Msol)

O star

Massive stars, OB associations, stellar winds, wind bubbles, supperbubbles?



2. Explosion of massive stars

Mechanical energy from supernovae

3. Combined effets

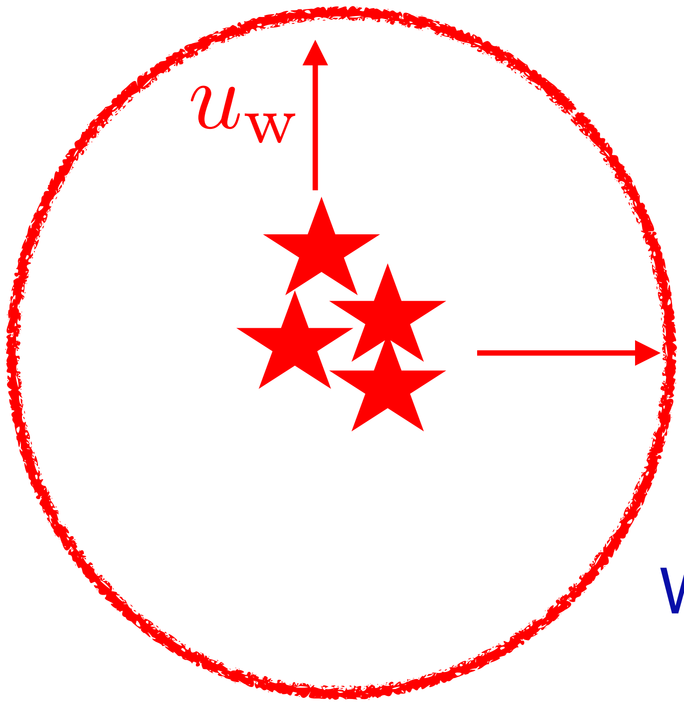
Winds + SNe: superbubbles?

Interior: hot, tenuous, and very turbulent medium shaped by winds+ repeated explosions?

1. First few millions years

Mechanical energy output dominated by winds

Where does the acceleration takes place: SNR shocks? Winds termination shocks? Turbulence? All of it? Other (compact) objects inside?



Consider one star (group of stars gathered) in ISM

Mass-loss rate and veolcity: $\dot{M}_w, u_w$

Wind kinetic power: $L_w = \dot{M} u_w^2 / 2$

Mass conservation:

$$\nabla(\rho_w u_w) = 0$$

Density profile:

$$\rho_w = \frac{\dot{M}_w}{4\pi u_w R^2}$$

Winds lauched from transfer momenty of stellar photon to matter

Star luminosity-> increases with mass -> powerful winds around massive stars

Momentum carried by wind ≈ Momentum carried by stellar photons

$$\dot{M}_w u_w \approx \frac{1}{2}\frac{L_\star}{c}$$

$$L_w \approx \frac{L_\star}{4}\frac{u_w}{c} \sim 3\times 10^{36} \left(\frac{L_\star}{3\times 10^5 L_\odot}\right)\left(\frac{u_w}{3000\mathrm{km/s}}\right) \mathrm{erg/s}$$

Total energy output over the lifetime of the star $\tau_\star \sim 1 - 10\times 10^6 \mathrm{yr}$ (Very massive stars

$$E_w \approx L_w \tau_\star \sim 4\times 10^{50} \left(\frac{L_\star}{3\times 10^5 L_\odot}\right)\left(\frac{u_w}{3000\mathrm{km/s}}\right)\left(\frac{\tau_\star}{4\mathrm{Myr}}\right) \mathrm{erg}$$

$$E_w \approx L_w \tau_\star \sim 4 \times 10^{50} \left(\frac{L_\star}{3 \times 10^5 L_\odot}\right) \left(\frac{u_w}{3000 \mathrm{km/s}}\right) \left(\frac{\tau_\star}{4 \mathrm{Myr}}\right) \mathrm{erg}$$

$$\sim 10^{51} \mathrm{erg}$$

≈ on the order of total explosion energy of a SN explosion, thus expected to impact the ambient ISM

Number of these massive stars?

O stars $N \sim 10^4 - 10^5$

Wolf Rayet $N \sim 10^3 - 10^4$

→ $L_{w,\mathrm{tot}} \sim N L_w \sim 10^{41} - 10^{42} \mathrm{erg/s}$

Mechanical power to inflate interstellar bubbles

SNR power?

$\nu_{\mathrm{SN}} \sim 3/\mathrm{century}$ → $L_{\mathrm{SN,tot}} \sim 10^{42} \mathrm{erg/s}$

Evolution of interstellar bubbles

1. Free expansion: CSM matter pushed by the wind and accumulates in dense shell at Rsh. The wind expands freely and since the shell is highly supersonic, a forward shock forms.

$$R_{\rm FS} \sim u_w t$$

$$M_{\rm sw} = \frac{4\pi}{3}\rho_0 R_{\rm FS}^3 \sim \dot{M}_w t$$

$$\Longrightarrow \quad \tau_{\rm FE} \left(\frac{3\dot{M}_w}{4\pi\rho_0 u_w^3}\right)^{1/2}$$

2. When mass of gas swept-up is comparable to mass carried by the wind, the expansion decelerates

$$\tau_{\rm FE} \sim 15 \left(\frac{\dot{M}_w}{10^{-6} M_\odot/{\rm yr}}\right)^{1/2} n_0^{-1/2} \left(\frac{u_w}{3000{\rm km/s}}\right)^{-3/2} {\rm yr}$$

$$\tau_{\rm FE} << \tau_\star$$

Almost instantenous: FE can be neglected!

3. Adiabatic phase:

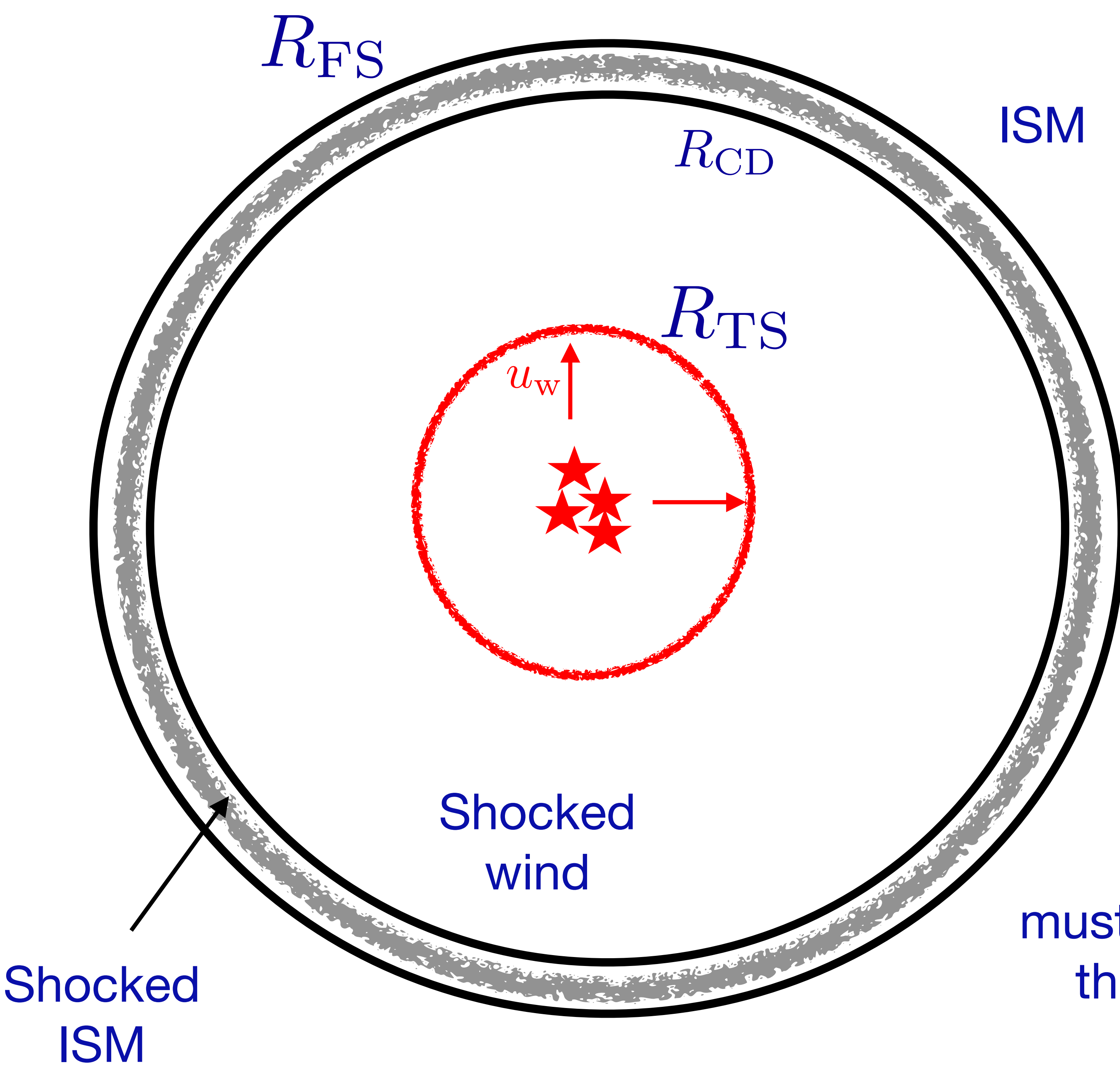
Shocked ISM becomes very hot $T_b \sim 10^6 - 10^8{\rm K}$

Cavity inside the bubble

$$P_{\rm ram} = \rho_w u_w^2 = \frac{\dot{M} u_w}{4\pi r^2} \sim P_b$$

At some point the wind cannot expand freely -> reverse (termination) shock

Evolution of interstellar bubbles



Contact discontinuity: pressure and velocity continuous but density can jump abruptly

Thickness of the shell of shocked ISM:

$$\Delta R = R_{\rm FS} - R_{\rm CD}$$

$$M_{\rm shell} \sim 4\pi R_{\rm FS} \Delta R \times 4\rho_0$$

must be equal to total mass $\frac{4\pi}{3} R_{\rm FS}^3 \rho 0$ that has been shocked

$$\Delta R = 0.08 R_{\rm FS}$$

$R_{\rm FS} \approx R_{\rm CD}$ Thin-shell approximation

Evolution of interstellar bubbles

3. Adiabatic expansion: (radiative losses can be neglected)

Wind kinetic power is dissipated at the TS (internal energy and pressure). This contributes to push onto the shell

Possible to look for a scale free solution (Zeldovich et al. 2002):

$$R_{\rm FS} \sim a \left(\frac{L_w}{\rho_0}\right)^{1/5} t^{3/5}$$

$$u_s = \frac{dR_{\rm FS}}{dt} = \frac{3}{5}\frac{R_{\rm FS}}{t} = \frac{3}{5} a \left(\frac{L_w}{\rho_0}\right)^{1/5} t^{-2/5}$$

Very high Temperature:

$$kT = \frac{3}{16}\mu m_H u_s^2 \sim 44\, a^2 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{2/5} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-2/5} \left(\frac{t}{10^4\,{\rm yr}}\right)^{-4/5} {\rm eV}$$

→ Plasma emitting in UV/X-ray domain

Cooling depends on temperature: $\tau_{\rm cooling}$

End adiabatic phase: $t_{\rm age} \sim \tau_{\rm cooling}$

Evolution of interstellar bubbles

$$10^5\mathrm{K} \lesssim T \lesssim 10^{7.5}\mathrm{K}$$

Cooling function:

$$\Lambda(T) = \Lambda_0 T^{-1/2} \sim 1.6 \times 10^{-19} T^{-1/2}\ \mathrm{erg\,cm^3\,s^{-1}}$$

Raymond et al. 1988

Fully inonized plasma nH, ne ~1.2 nH (to account for presence of Helium)

$$L \equiv n_H n_e \Lambda(T) \sim 1.2\, n_H^2 \Lambda(T)$$

Dense shell cools first

Thermal energy density of fully ionized plasma: $\epsilon_{\rm th} \sim 2.33/2 n_H kT$

$$\tau_c = \frac{\epsilon_{\rm th}}{\mathcal{L}} = \frac{2.3\,(kT)^{3/2}}{3.2\,n_0 \Lambda_0 k^{1/2}} \sim 2.5 \times 10^4 \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{kT}{0.1\,\mathrm{keV}}\right)^{3/2}\ \mathrm{yr}$$

$$\tau_{\rm AD} \sim 8.6 \times a^{15/11} \left(\frac{L_w}{10^{36}\,\mathrm{erg/s}}\right)^{3/11} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{-8/11}\ \mathrm{kyr}$$

$$\tau_{\rm AD} << \tau_\star$$

Adiabatic phase can also be neglected!

Evolution of interstellar bubbles

Partially radiative phase: dense shell cools but at TS, still pretty adiabatic

Interior density is low enough so that the cooling happens on longer timescales

Most of the life of bubbles happens in this partially radiative phase.

Let us assume that all kinetic energy accross FS is radiated, the rate of energy loss is:

$$L_{\rm rad} = (4\pi R_s^2)\left(\frac{1}{2}\rho_0 u_s^3\right)$$

Constant in time if $R_{\rm FS} \propto t^{3/5}$

Possible to define an effective injected power constant in time:

$$L_{\rm eff} = L_w - L_{\rm rad}$$

Still valid: $R_{\rm FS} \sim a \left(\frac{L_w}{\rho_0}\right)^{1/5} t^{3/5}$

Castor et al. 1975

a=0.76 (instead of 0.88 in FE)

$$R_{\rm FS} \sim 26 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{1/5} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-1/5} \left(\frac{t}{\rm Myr}\right)^{3/5} \quad {\rm pc}$$

$$u_{\rm FS} \sim 15 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{1/5} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-1/5} \left(\frac{t}{\rm Myr}\right)^{-2/5} \quad {\rm km/s}$$

Evolution of interstellar bubbles

Total energy of system: $$E_{\rm tot} \sim (L_w - L_{\rm rad})t = \left[1 - 2\pi \left(\frac{3}{5}\right)^3 a^5\right] L_w t$$

Cold dense expanding shell + Thermal energy of interior

$$E_k = \frac{1}{2} M_{\rm sh} u_{\rm FS}^2 = \frac{2\pi}{3} \left(\frac{3}{5}\right)^2 a^5 L_w t$$

$$E_{\rm th} = \left(\frac{3}{2} P\right) \left(\frac{4\pi}{3} R_{\rm FS}^3\right)$$

$$P = 4.5 \times 10^{-12} \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{2/5} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{3/5} \left(\frac{t}{\rm Myr}\right)^{-4/5} \ {\rm erg/cm^3}$$

$$R_{\rm FS} \sim 26 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{1/5} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-1/5} \left(\frac{t}{\rm Myr}\right)^{3/5} \ {\rm pc}$$

$$u_{\rm FS} \sim 15 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{1/5} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-1/5} \left(\frac{t}{\rm Myr}\right)^{-2/5} \ {\rm km/s}$$

All this valid until when? Forward shock is still stong?

$$\mathcal{M}_s \sim 1.5 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{1/5} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-1/5} \left(\frac{T_0}{10^4\,{\rm K}}\right)^{-1/2} \left(\frac{t}{\rm Myr}\right)^{-2/5}$$

$$\tau_{\rm RAD} \sim 1{\rm Myr}$$

The internal structure of Interstellar bubbles

At the FS, the shell becomes very dense and thin because of cooling

If cooling is very efficient, we can consider temperature constant across shock transition

Momentum + mass conservation:

$$\rho_1 u_1^2 + \rho_1 c_{s,0}^2 = \rho_2 u_2^2 + \rho_2 c_{s,0}^2$$

$$\rho_1 u_1 = \rho_2 u_2$$

$$(r - \mathcal{M}^2)(r-1) = 0$$

Solution r=1 : (no shock wave..)

$$r = \mathcal{M}^2$$

Compression can be very large!

In fact also magnetic field compressed at the shock

$$B_2 = r B_1 \qquad \frac{B_2^2}{8\pi} \propto r^2$$

$$\rho_2 u_2^2 \propto r$$

For large compression, the magnetic pressure dominates

For highly supersonic and superAlfvenic shock, momentum conservation gives: $\rho_1 u_1^2 \sim r^2 \frac{B_1^2}{8\pi}$

$u_1 \gg c_{s,0}$ $\qquad u_1 \gg v_{A,0}$

$$r \sim \left(\frac{8\pi\rho_1 u_1^2}{B_1^2}\right)^{1/2} = \sqrt{2}\,\mathcal{M}_A \gg 1$$

Compression factor is bounded

The internal structure of Interstellar bubbles

The shocked wind is extremely hot-> the sound speed high enough that pressure equilibrates across the cavity on a timescale shorter than the bubble age -> interior pressure uniform

Thermal conduction at the interface between the hot cavity and the cold dense shell -> evaporation of shell material into the bubble, where it mixes with the shocked wind.

The boundary between shocked ISM and shocked wind is not sharp: Heat flow is proportional to the temperature difference:

$$F_h = -K \frac{\partial T}{\partial z}$$

Thermal conductivity

At equilibrium: Heat flow balance by mechanical flow..

$$T \sim 1.0 \times 10^6 \left(\frac{L_w}{10^{36}\,\mathrm{erg/s}}\right)^{8/35} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{2/35} \left(\frac{t}{\mathrm{Myr}}\right)^{-6/35} \mathrm{K}$$

$$n \sim 1.3 \times 10^{-2} \left(\frac{L_w}{10^{36}\,\mathrm{erg/s}}\right)^{6/35} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{19/35} \left(\frac{t}{\mathrm{Myr}}\right)^{-22/35} \mathrm{cm}^{-3}$$

If only shocked wind:

$$n \sim \frac{\dot{M}_w t}{\frac{4\pi}{3} R_s^3} \sim 4 \times 10^{-4} \mathrm{cm}^{-3}$$

Evaporated matter largely conrtibutes to density inside the bubble!

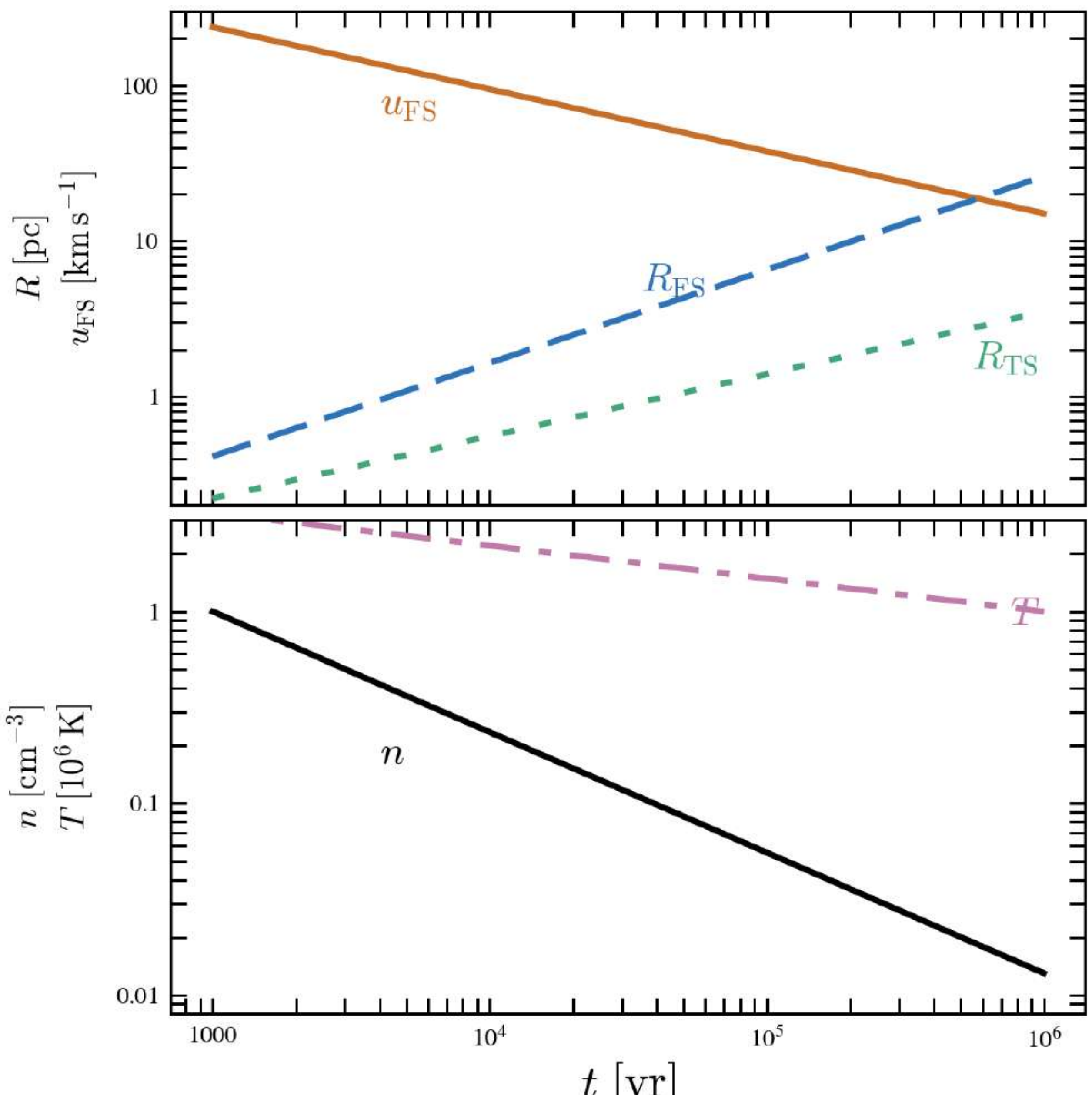
The wind termination shock

$$R_{\rm TS} \sim 3.5 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{3/10} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-3/10} \left(\frac{u_w}{3000\,{\rm km/s}}\right)^{-1/2} \left(\frac{t}{\rm Myr}\right)^{2/5} \ {\rm pc}$$

$$R_{\rm FS} \sim 26 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{1/5} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-1/5} \left(\frac{t}{\rm Myr}\right)^{3/5} \ {\rm pc}$$

$$u_{\rm TS} = \frac{dR_{\rm TS}}{dt} \sim 1.4 \left(\frac{L_w}{10^{36}\,{\rm erg/s}}\right)^{3/10} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-3/10} \left(\frac{u_w}{3000\,{\rm km/s}}\right)^{-1/2} \left(\frac{t}{\rm Myr}\right)^{-3/5} \ {\rm km/s}$$

Shock moving very slow! But fluid coming in at 3000 km/s



Bubble inflated by a cluster of massive stars

Average quantities can be obtained with analogous reasoning with N stars

$$\mathcal{P}_{\rm tot} = \langle L_w \rangle N_* \sim$$

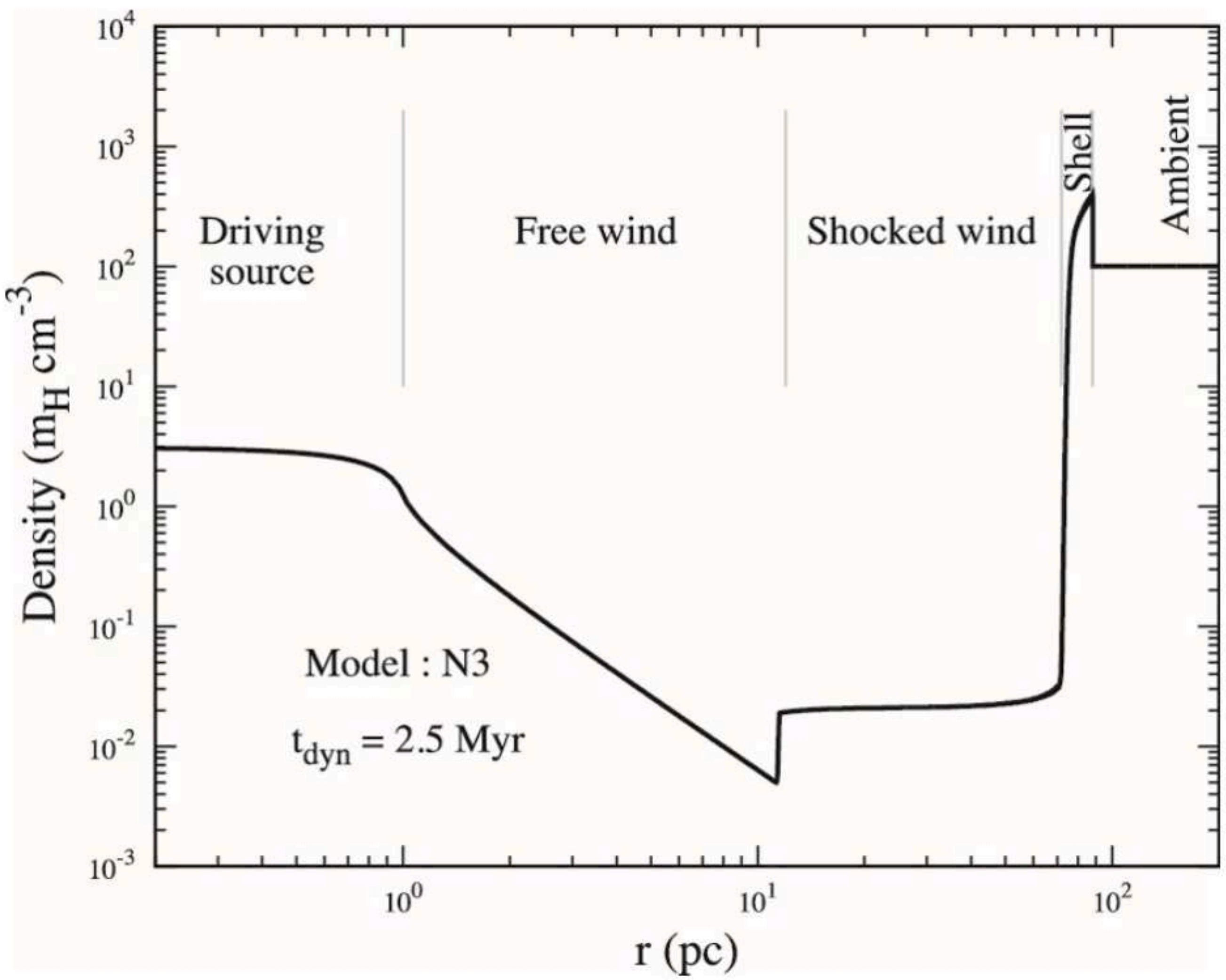
$$R_{\rm FS} \sim 2.6 \times 10^2 \left(\eta \frac{N_*}{100}\right)^{1/5} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-1/5} \Big($$

$$u_{\rm FS} \sim 15 \left(\eta \frac{N_*}{100}\right)^{1/5} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-1/5} \left(\frac{t}{10\,\rm Myr}\right)^{-2}$$

$$T \sim 2.0 \times 10^6 \left(\eta \frac{N_*}{100}\right)^{8/35} \left(\frac{n_0}{\rm cm^{-3}}\right)^{2/35} \left(\frac{}{10}\right.$$

$$n \sim 7.0 \times 10^{-?} \left(\eta \frac{N_*}{100}\right)^{6/35} \left(\frac{n_0}{\rm cm^{-3}}\right)^{19/35} \left(\frac{t}{10\,\rm M}\right.$$

$$R_{\rm TS} \sim 35 \left(\eta \frac{N_*}{100}\right)^{3/10} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-3/10} \left(\frac{u_w}{3000\,\rm km/s}\right) \left(\frac{t}{10\,\rm Myr}\right) \rm pc$$

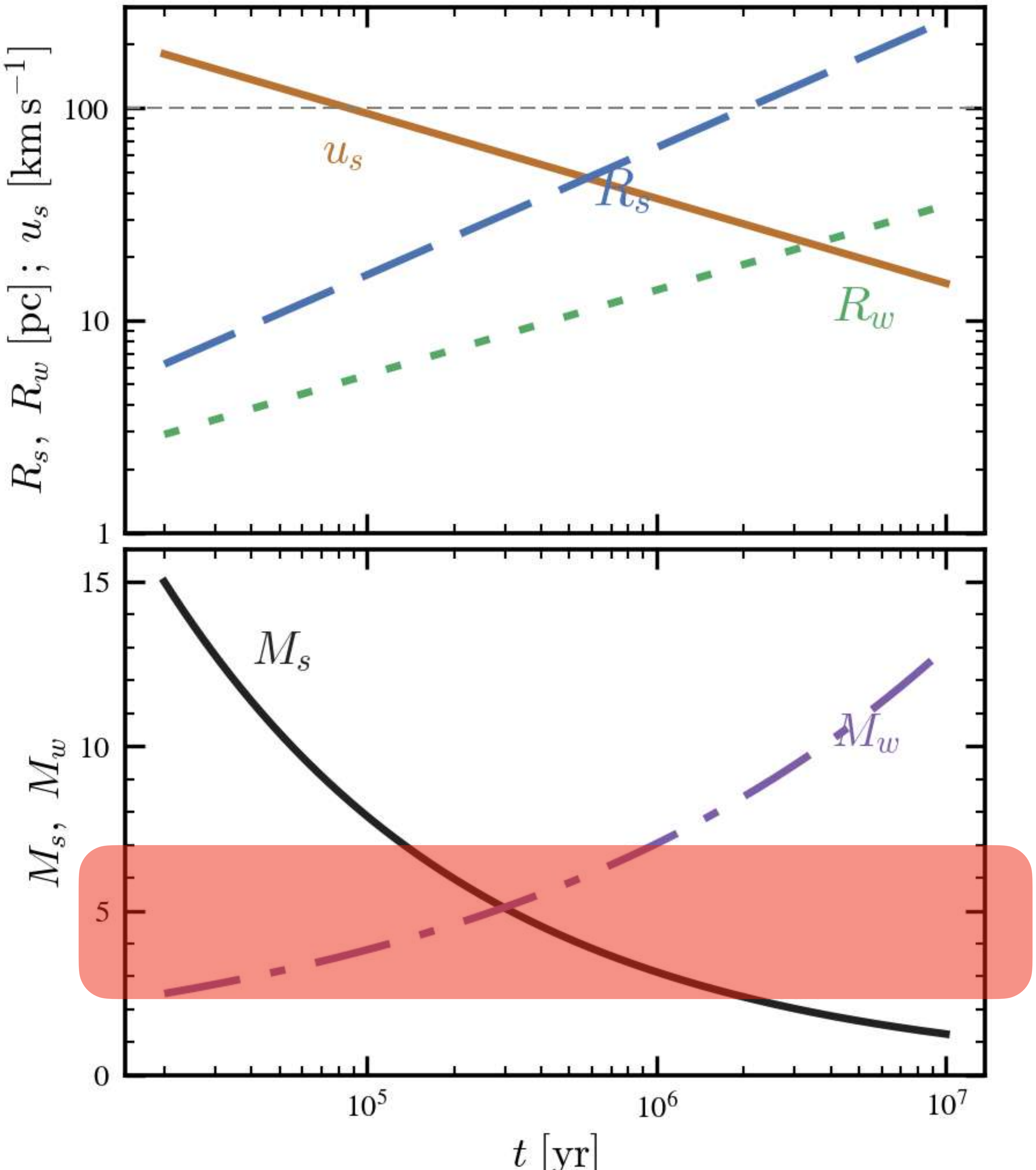


Gupta et al. (2018) numerical sim.

$$\mathcal{M}_{\rm TS} = \frac{u_w - \dot{R}_{\rm TS}}{c_{s,w}} \sim \frac{u_w}{c_{s,w}} \sim 13 \left(\frac{\eta N_*}{100}\right)^{1/5} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-3/10} \left(\frac{u_w}{3000\ \rm km/s}\right) \left(\frac{R_c}{3\ \rm pc}\right)^{-2/3} \left(\frac{t}{10\ \rm Myr}\right)^{4/15}$$

Correction factor to match more accurate studies $\eta \sim 0.22$

Bubble inflated by a cluster of massive stars

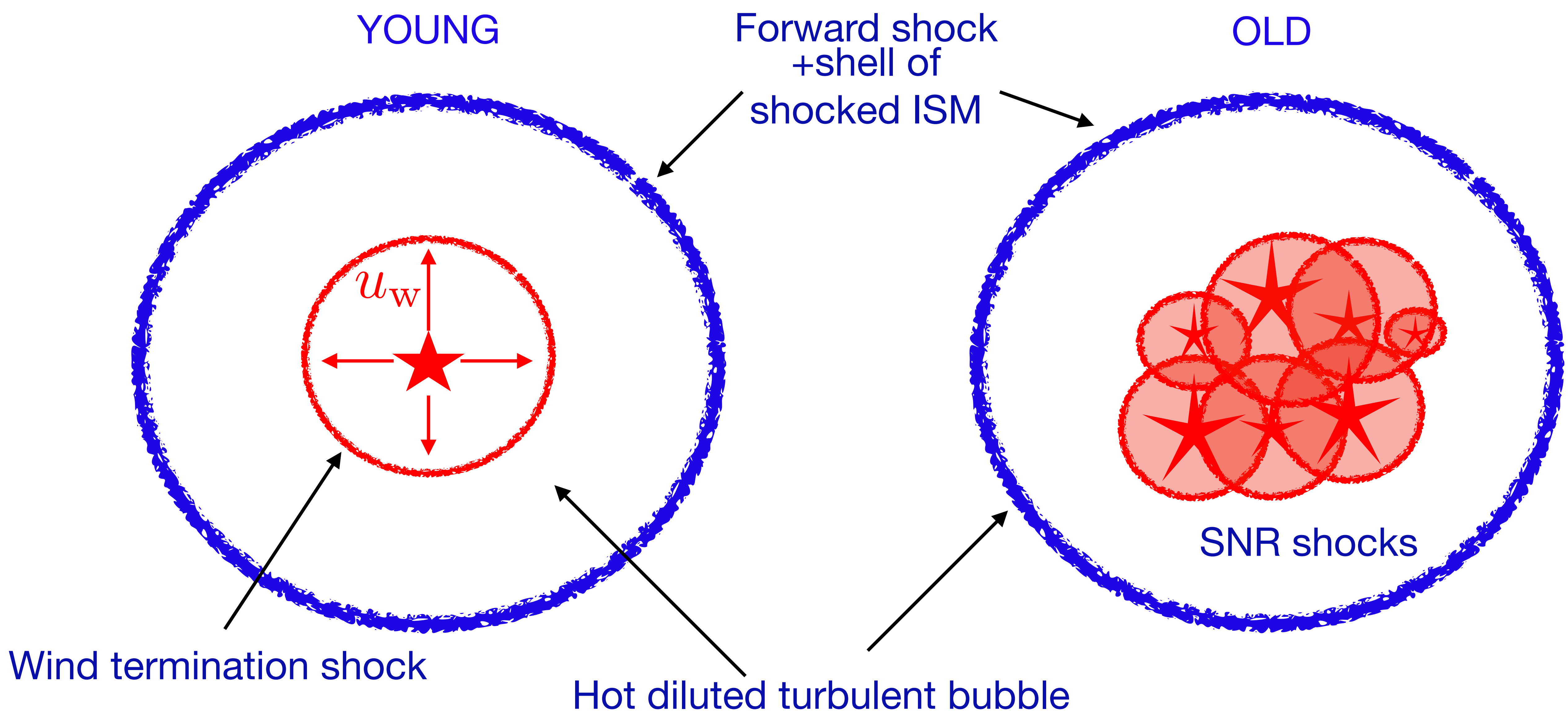


$$\alpha = \frac{3r}{r-1} = \frac{4\mathcal{M}^2}{\mathcal{M}^2 - 1}$$

$$\alpha = 4.1 - 4.4 \rightarrow \mathcal{M} \sim 3 - 7$$

CRs from stellar clusters and interstellar bubbles

Cassé & Paul 1980,1982; Volk& Forman 1982, Cesarsky & Montmerle 1983; Webb et al. 1985, Bykov et al. 2001 ++, Parizot et al. 2004, Ferrand & Marcowith 2010, Morlino et al. 2021, Vieu et al. 2022, 2023, 2024, Härer et al. 2025 ..



Castor et al. 1975, Weaver et al. 1977, MacCray&Kafatos 1987, MacLow&McCray 1988, Koo&McKee 1992

Particle acceleration?

Where are particles accelerated? Mechanism?
Maximum energy of accelerated particles?
Spectrum of accelerated particles?

Maximum energy: Hillas criterion in the turbulent bubble

$$E_{\rm max} \sim \left(\frac{e}{c}\right) BuL$$

$$E_{\rm max} \simeq 3 \left(\frac{B}{100\,\mu{\rm G}}\right) \left(\frac{U}{1000\,{\rm km/s}}\right) \left(\frac{L}{\rm pc}\right) {\rm PeV}$$

Not well constrained

$$P_B = \frac{B^2}{8\pi} < P_{\rm ram} = \rho_w u_w^2$$

$$E_{\rm max} < 1 \left(\eta \frac{\mathcal{P}_{\rm tot}}{3\times 10^{51}\,{\rm erg/Myr}}\right)^{18/35} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{9/70} \left(\frac{t}{10\,{\rm Myr}}\right)^{4/35} {\rm PeV}$$

Particle acceleration at the WTS?

$$u\frac{\partial f}{\partial R} = \frac{1}{R^2}\frac{\partial}{\partial R}\left(R^2 D \frac{\partial f}{\partial R}\right) + \frac{p}{3R^2}\frac{d(uR^2)}{dR}\frac{\partial f}{\partial p}$$

Analytical solution hard to find (D= const, not physical) → Numerical solving
Iterative methods

Particle spectrum at termination shocks

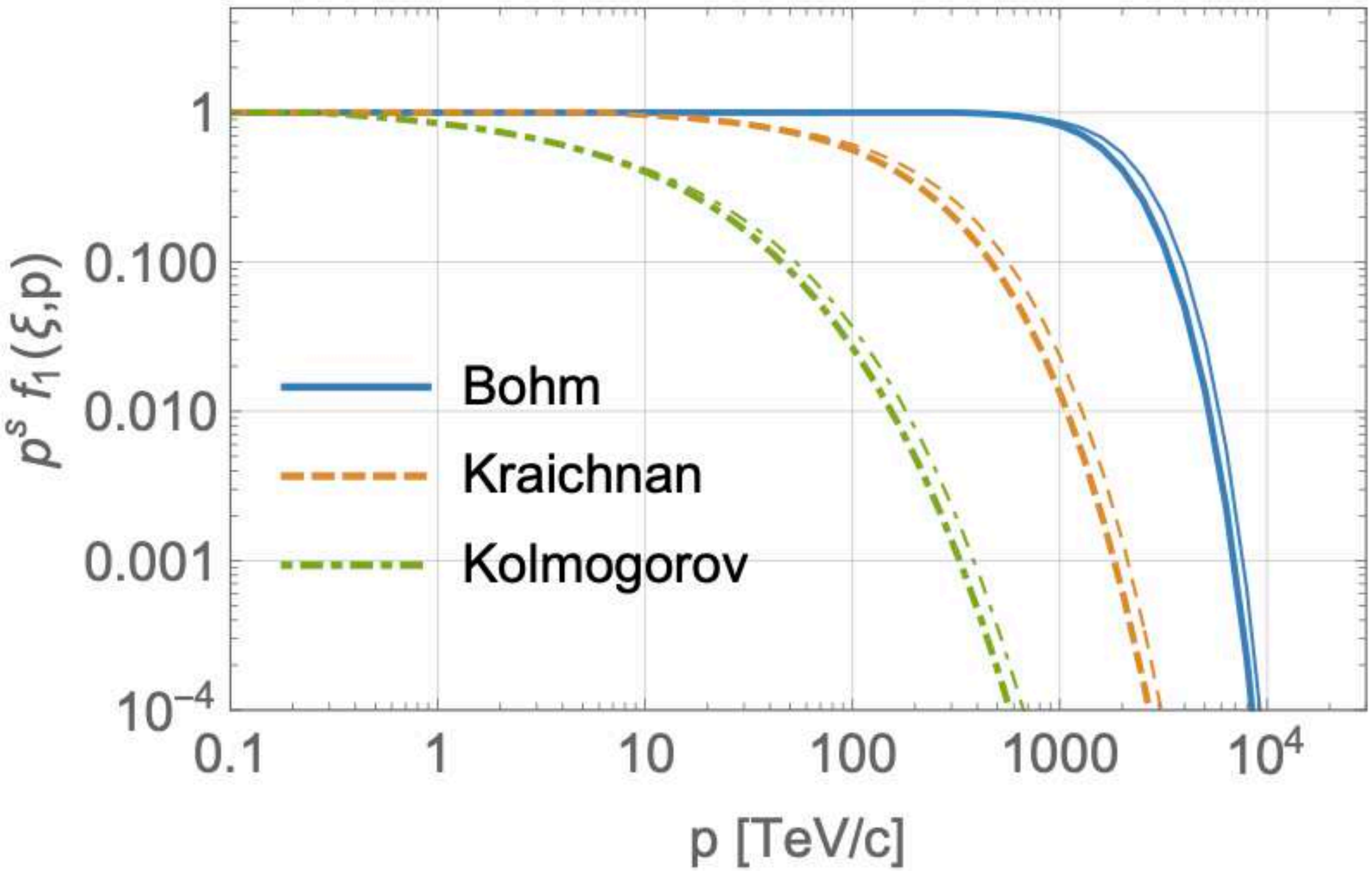


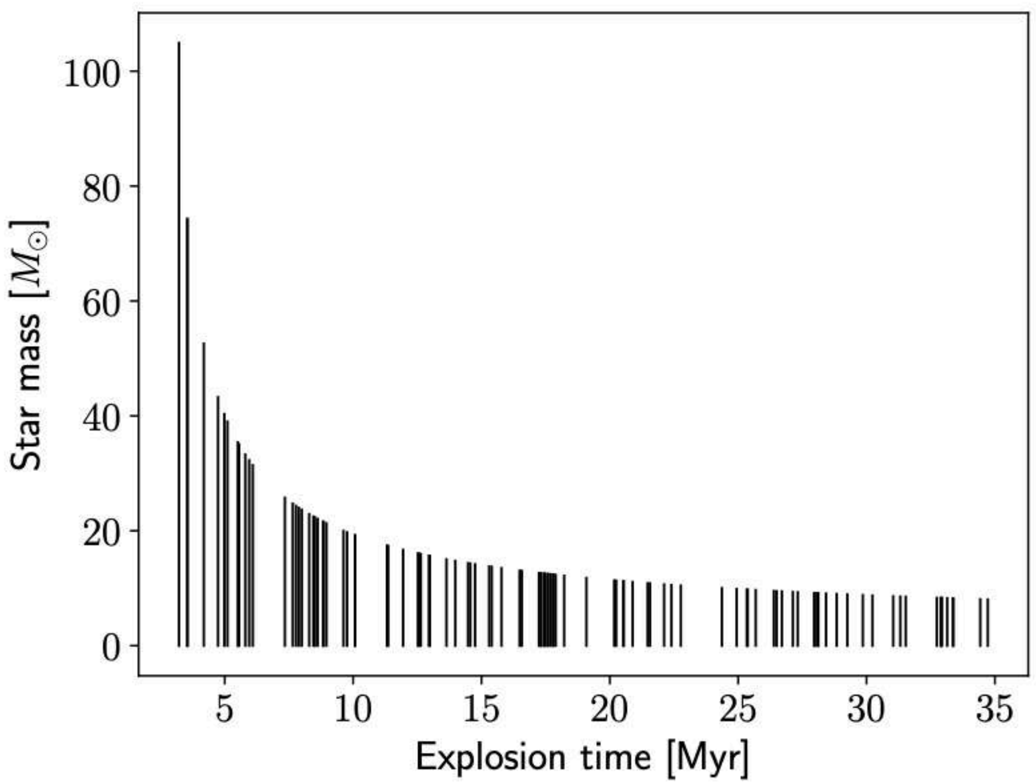
Figure 4. Thick lines: distribution function of CR at the shock for different diffusion coefficients. Thin lines: corresponding escaping flux. The results refer to the benchmark case described in the text.

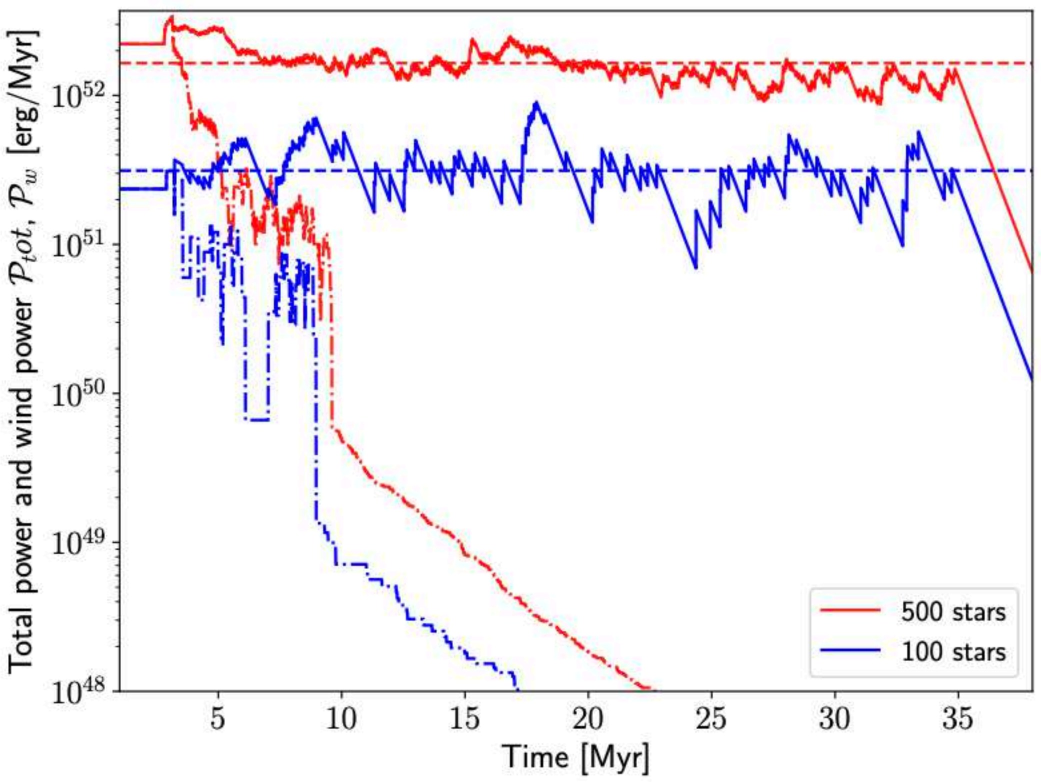
Morlino et al. 2021

A complex environment

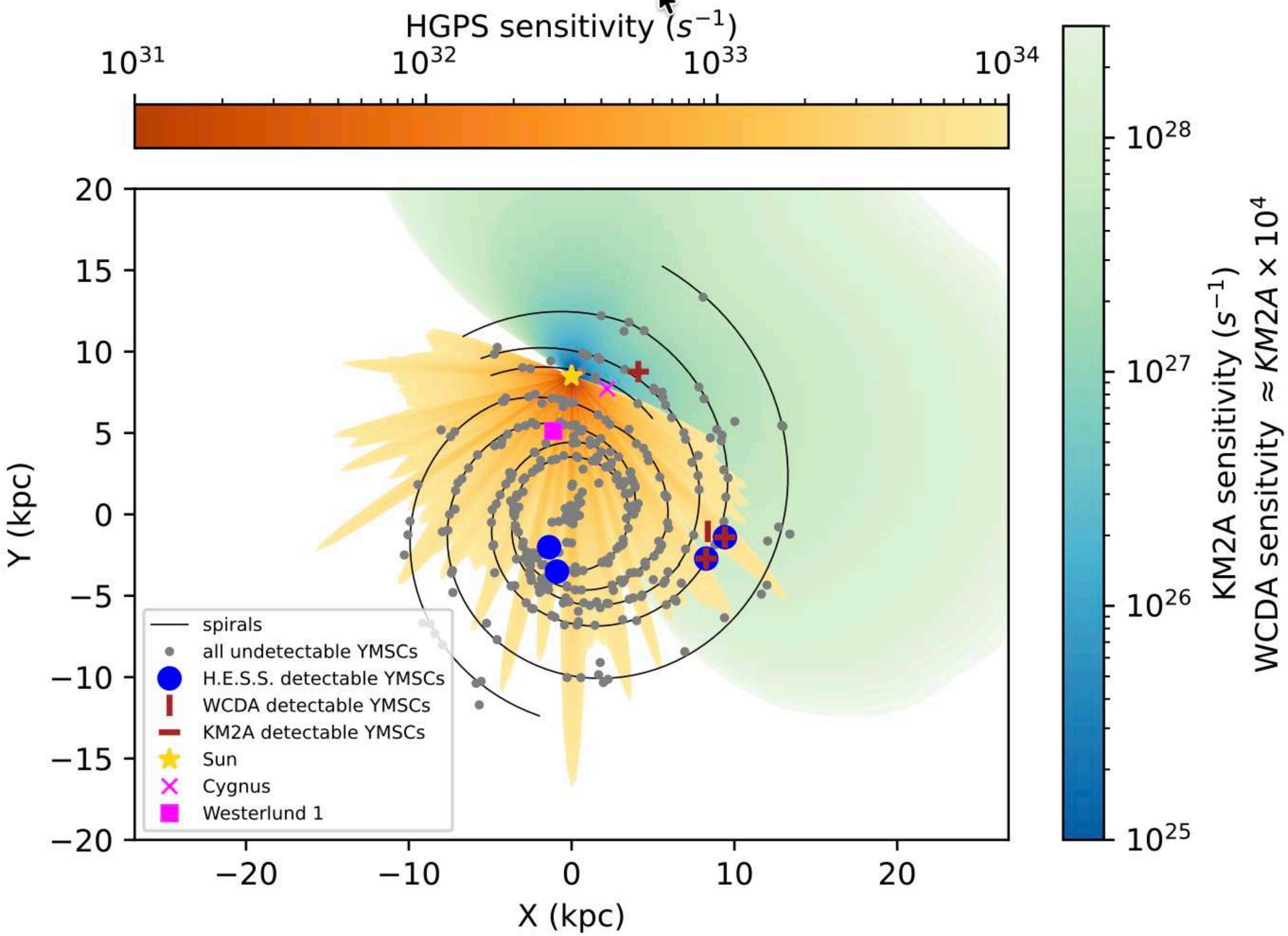
A lot can happen: acceleration, reacceleration (turbulence), reacceleration at various shocks

Stochasticity, not easy to account for (Vieu, Gabici et al. 2022)





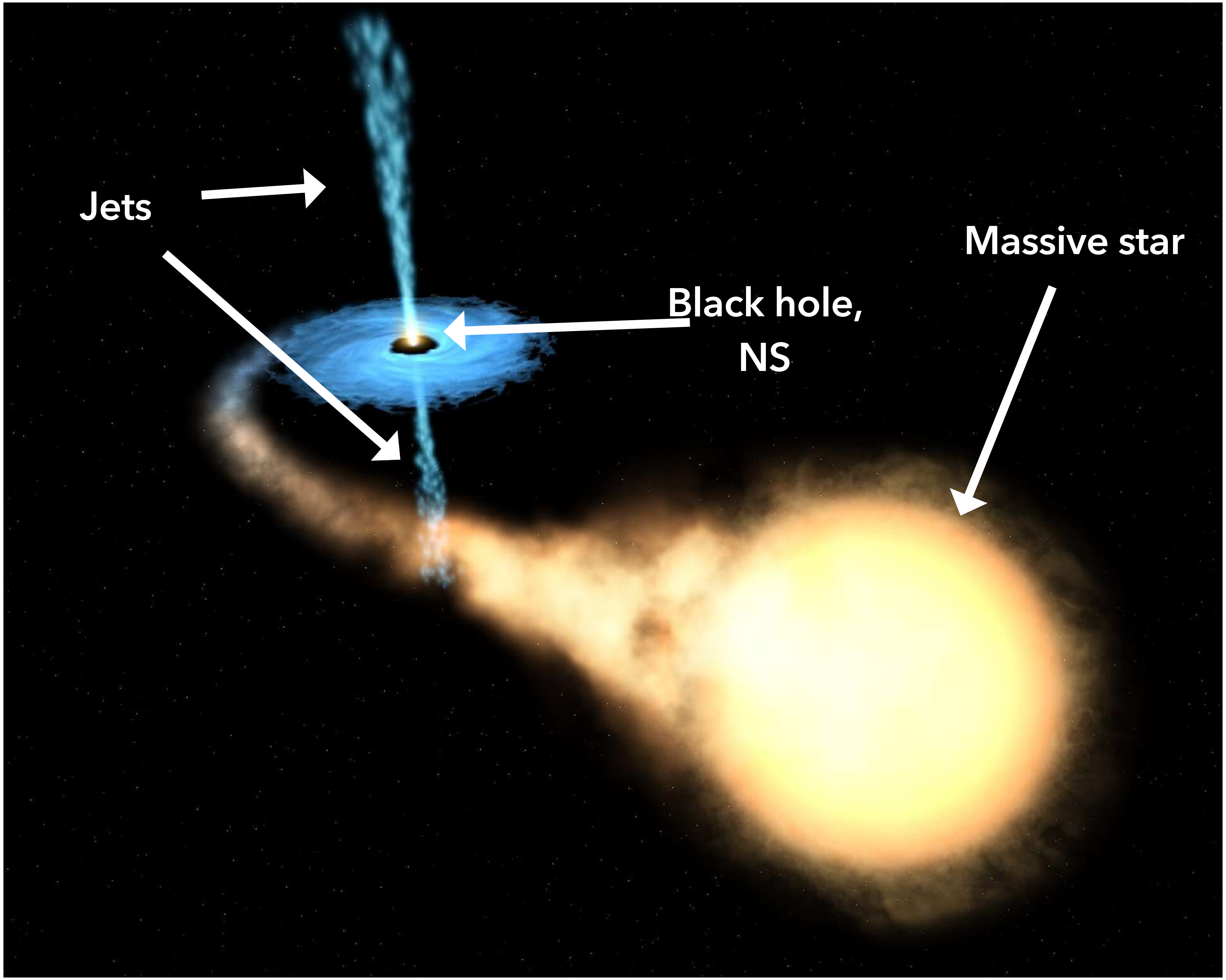
Population of young massive star clusters in the TeV range



Confronting population of simulated population to actual detected population (HESS, LHAASO)

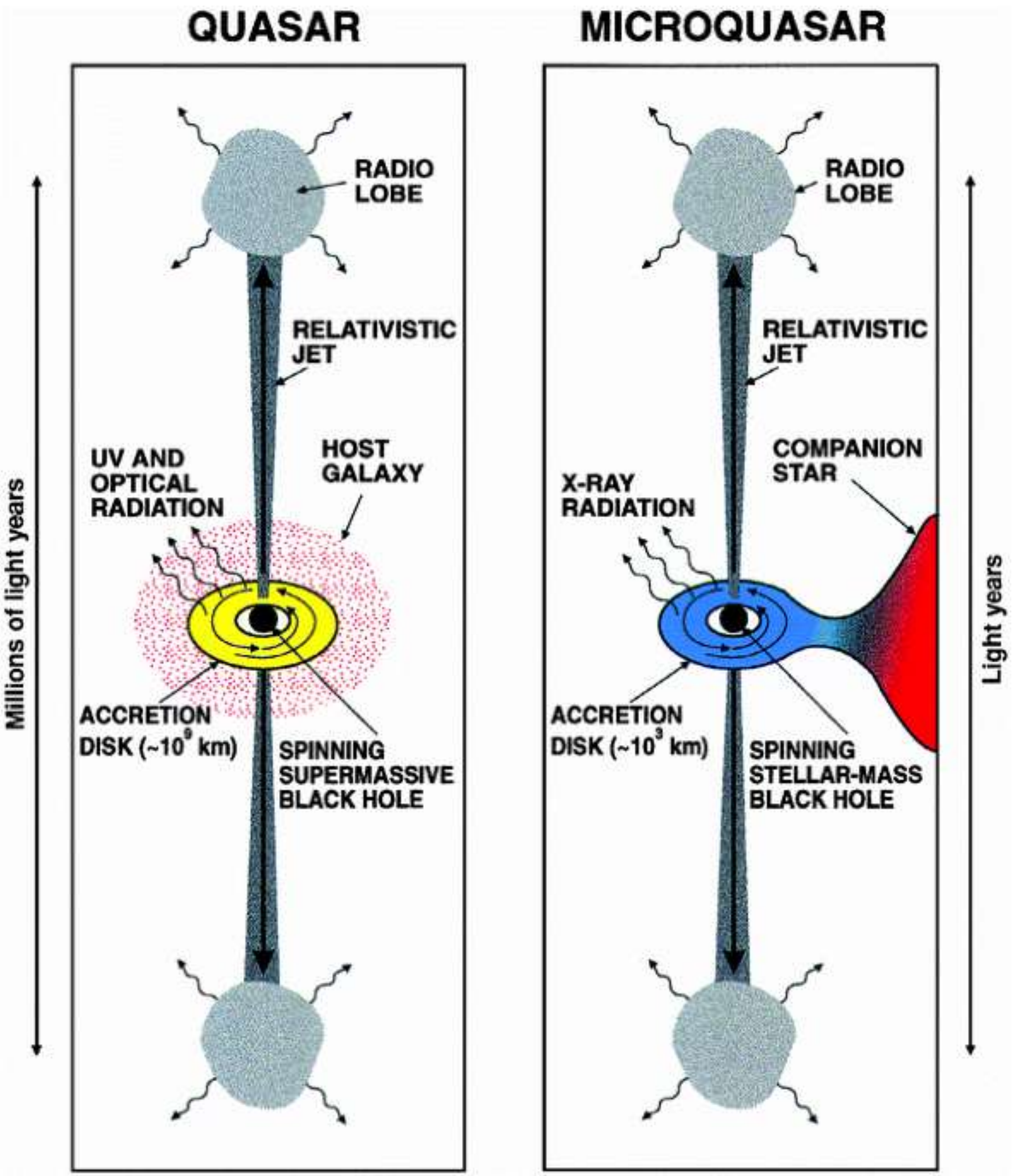
Menchiari et al. 2022, 2023, Batzofin 2026

Microquasars



Wiki, ESA/NASA GROJ1655-40 (artist view)

Particle acceleration at microquasars



Mirabel and Rodriguez 1998

Jet velocity: $\beta = \frac{v_j}{c} \sim 0.1 - 0.9$

Jet power: $L_j \sim 10^{36} - 10^{40} \mathrm{erg/s}$

Magnetic field (jet base): $B \sim 10^4 - 10^6 \mathrm{G}$

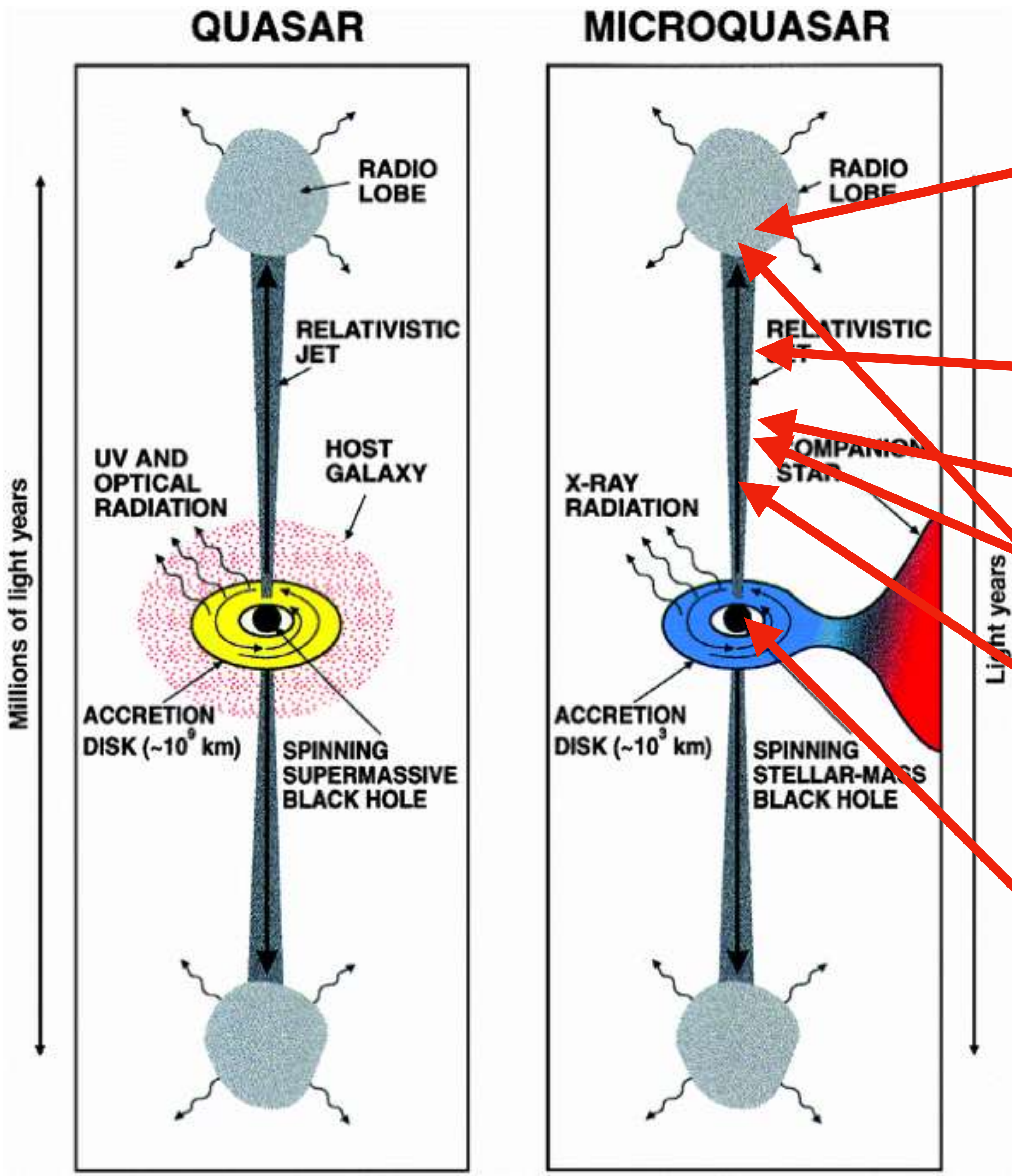
$B \propto R^{-1...2}$

Size: $R \sim 10^7 - 10^{19} \mathrm{cm}$

Complex to model!

Bosch-Ramon & Khangulyan 2009, Romero et al. 2017

Particle acceleration at microquasars



Mirabel and Rodriguez 1998

Termination shocks (forward, reverse)
Diffusive shock acceleration

Jet recollimation shocks (jet confined by external pressure creating standing shocks)
Diffusive shock acceleration

Jet: internal shocks
Diffusive shock acceleration

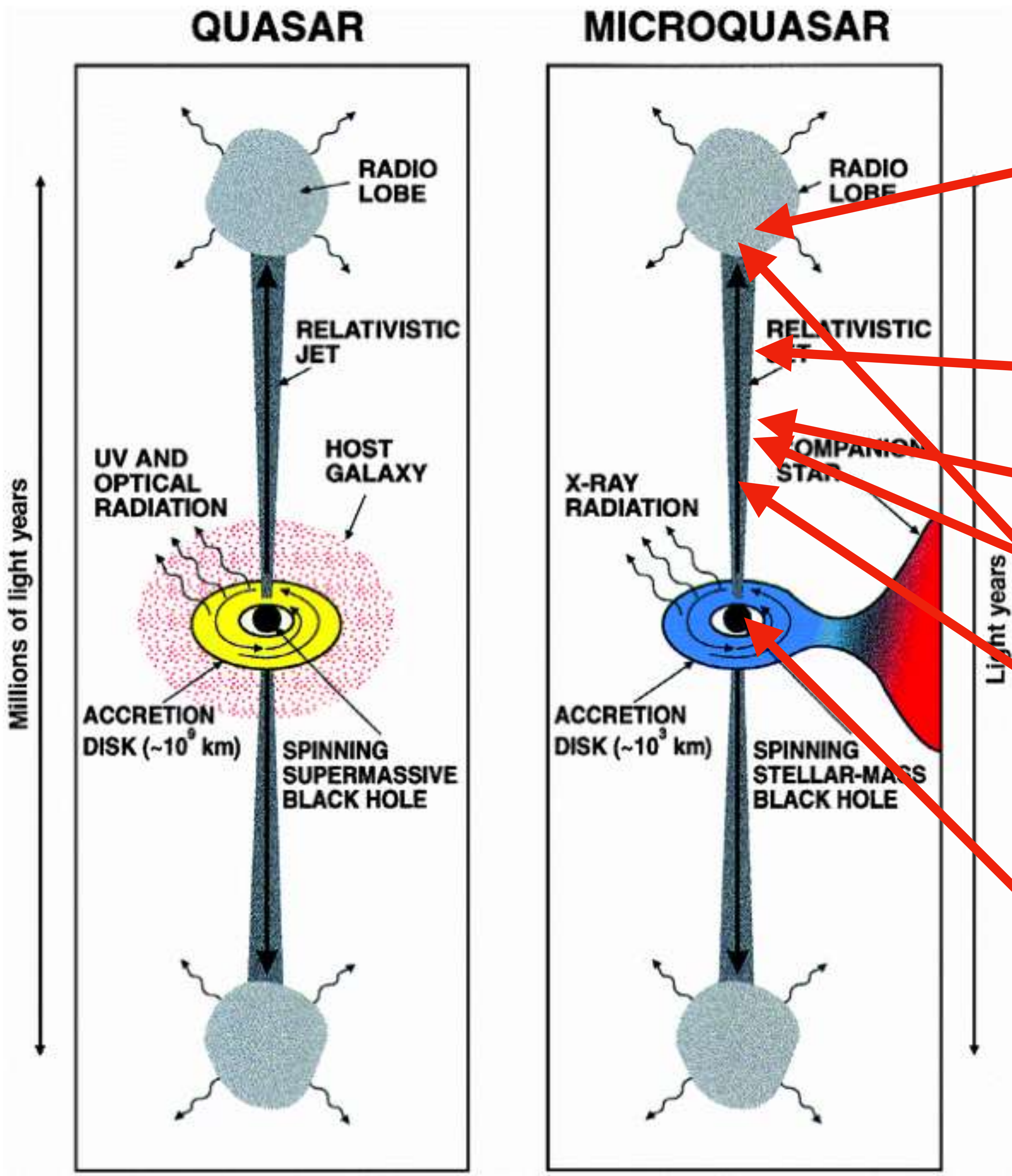
Jet boudaries
Shear acceleration

Turbulence everywhere
Turbulent acceleration (Fermi2)

Jet base: Highly magnetized, strong radiation field
Magnetic reconnection, gap acceleration, turbulent acceleration (Fermi 2)

Bosch-Ramon & Khangulyan 2009, Romero et al. 2017

Particle acceleration at microquasars



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Mirabel and Rodriguez 1998

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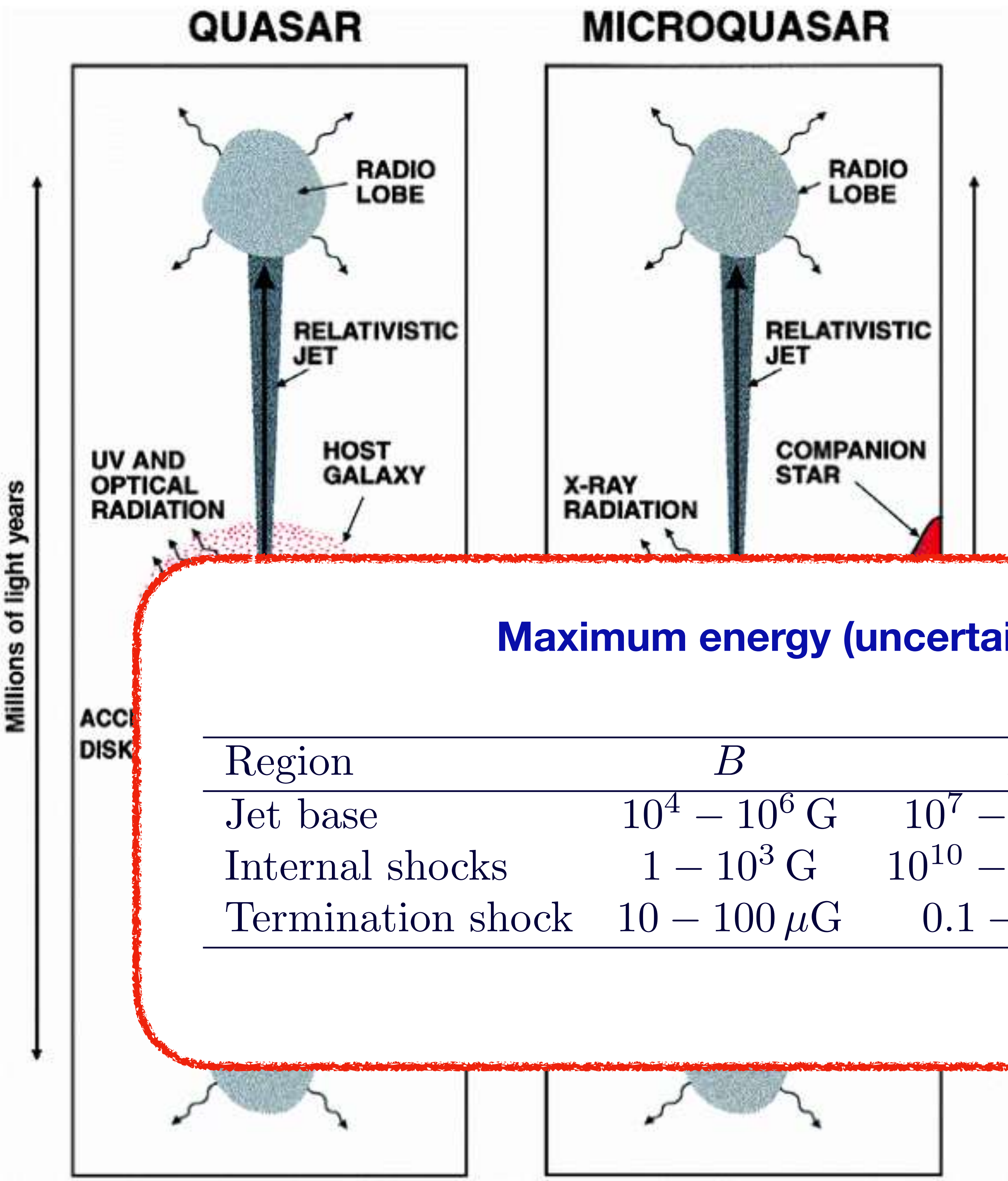
Particle acceleration at microquasars



Mirabel and Rodriguez 1998

Maximum energy (Hillas?)

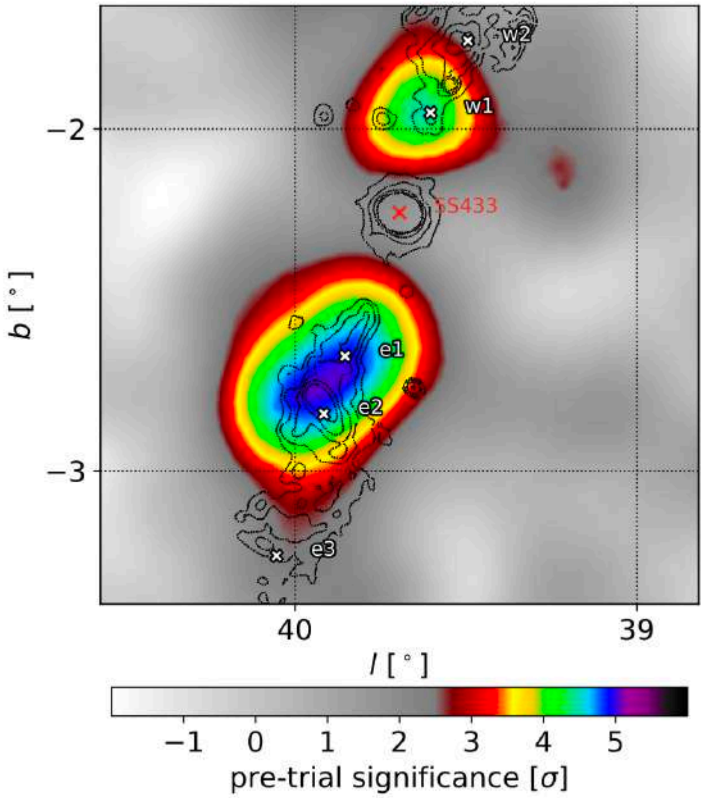
$$E_{\rm max}^{\rm termination} \sim 10\, Z\beta \left(\frac{B}{100\,\mu{\rm G}}\right)\left(\frac{R}{1\,{\rm pc}}\right) {\rm PeV}$$

Maximum energy (uncertain) but PeV- multi PeV ok

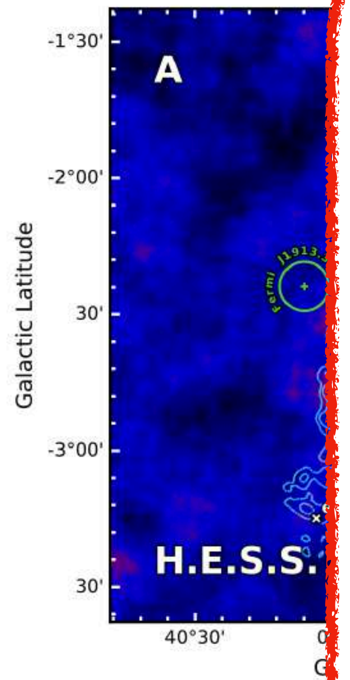
Region	B	R	$E_{\rm max}^{\rm Hillas}$
Jet base	$10^4 - 10^6$ G	$10^7 - 10^9$ cm	$0.03 - 300\, Z\beta$ PeV
Internal shocks	$1 - 10^3$ G	$10^{10} - 10^{13}$ cm	$3 \times 10^{-4} - 300\, Z\beta$ PeV
Termination shock	$10 - 100\,\mu$G	$0.1 - 10$ pc	$0.9 - 900\, Z\beta$ PeV

Bosch-Ramon & Khangulyan 2009, Romero et al. 2017

Microquasars: the case of SS433



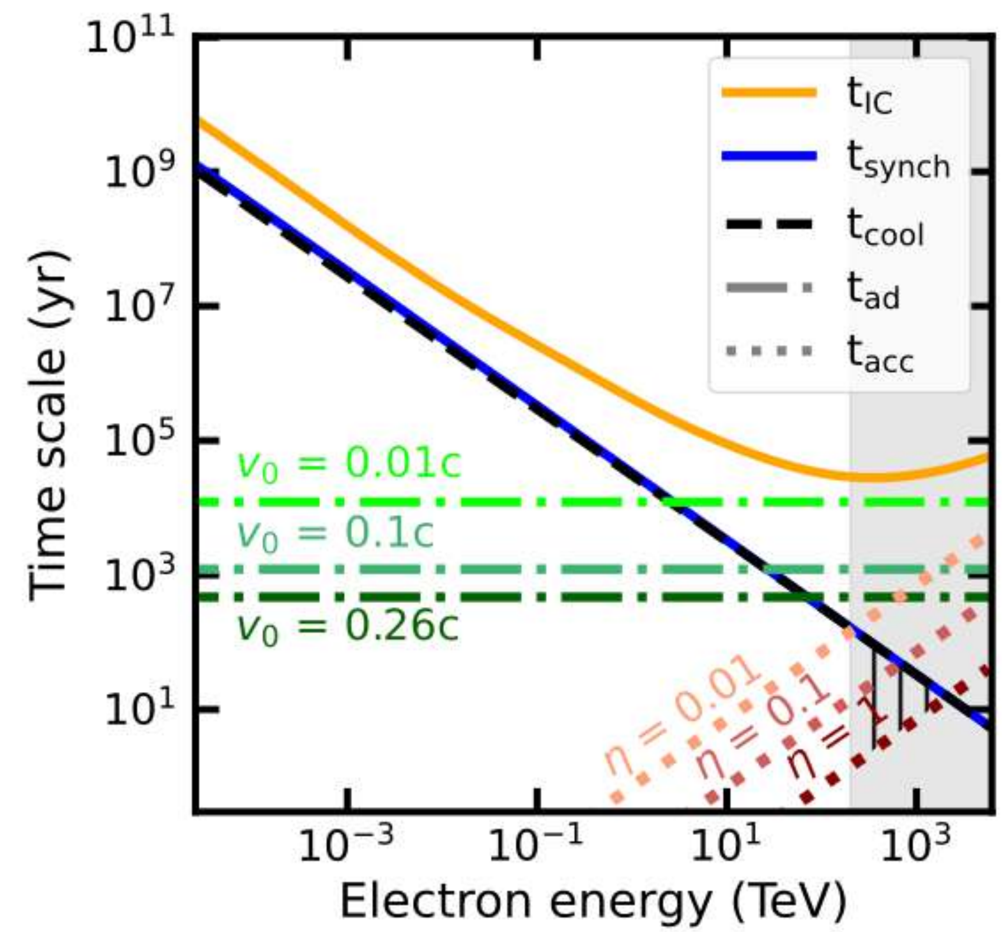
HAWC 2018



HES

Acceleration / cooling of electrons

$$t_{\rm cool} = \frac{3 m_e c}{4 \sigma_T \gamma \left(U_B + U_{\rm rad}\right)}$$



Aharonian et al. 2024

HAWC/H.E.S.S.S: electrons?

energy dependent emission on pc scale jets. Fast cooling due to intense stellar radiation field +magnetic field (GeV range : jet precession)

LHAASO: electrons + protons

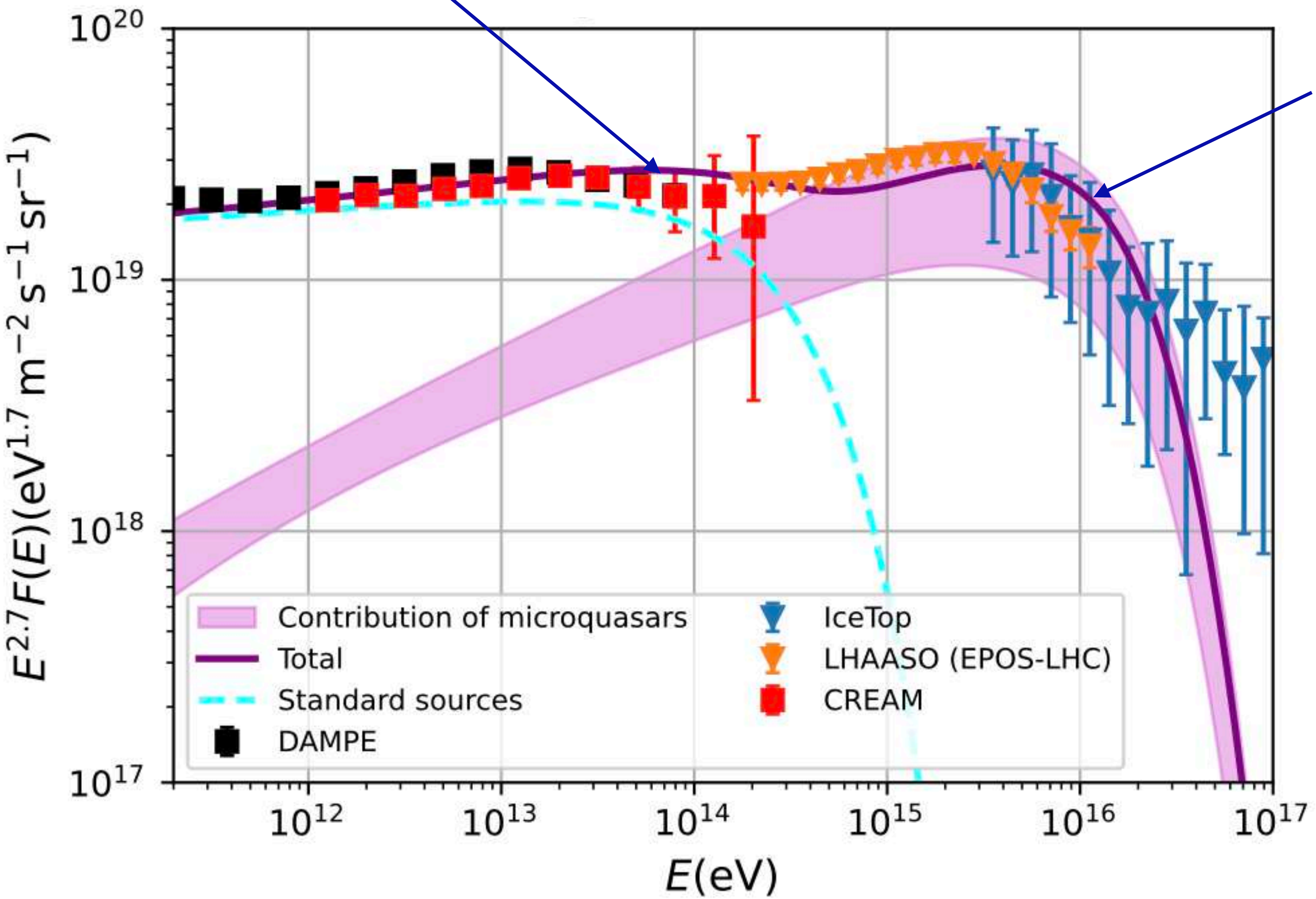
Particle acceleration: DSA? At which shocks (internal, forward, recollimation shocks?)? Fermi II? Shear acceleration? Magnetic reconnection?

Bosch-Ramon 2006, 2011, Orelanna et al. 2007, Vila&Romero 2010, Khangulyan et al. 2024, Bykov et al. 2024, Peretti et al. 2025, Fujita et al. 2026 + many more

Mixed contribution: microquasars + other « standard » sources

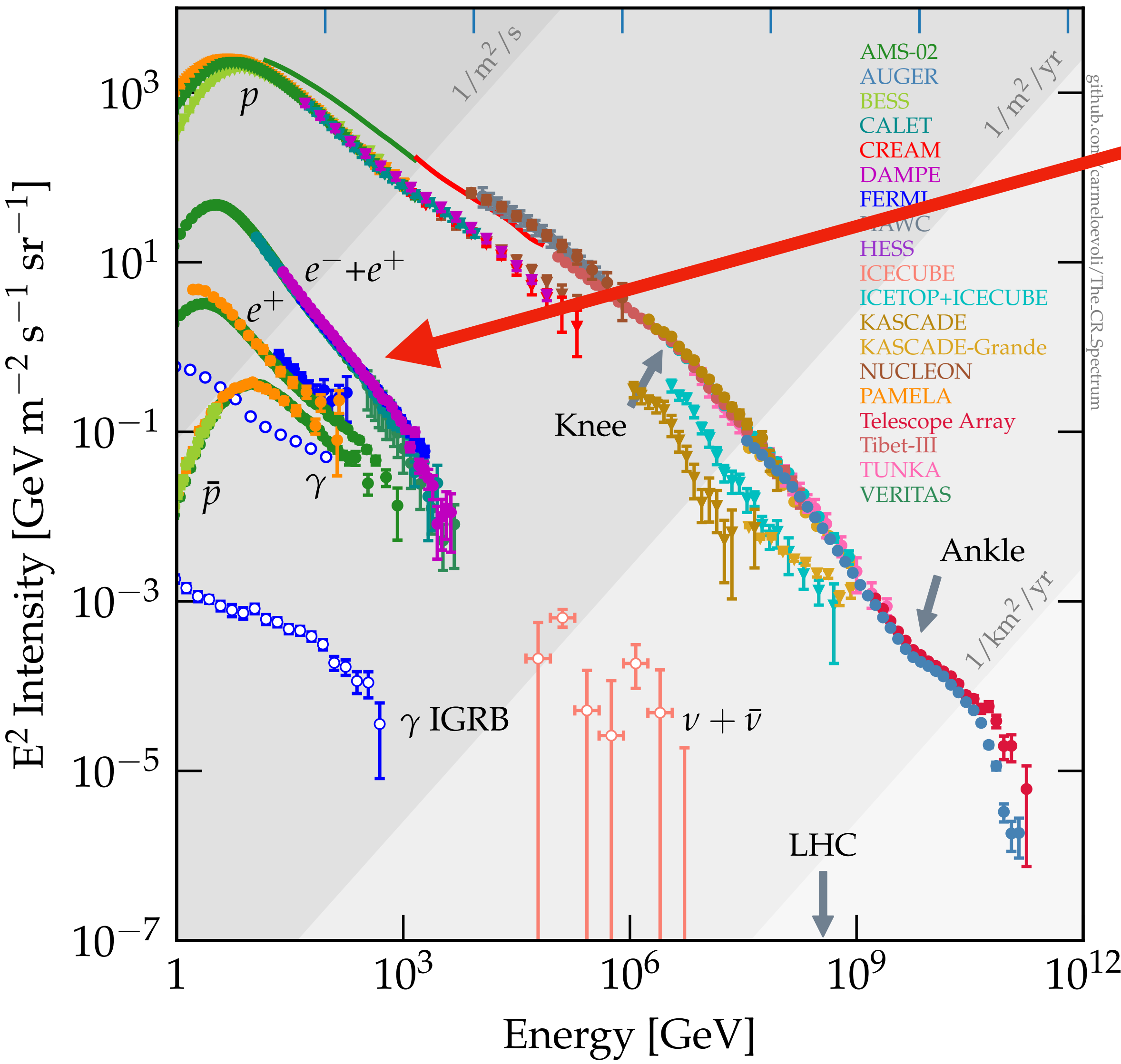
Massive stars, SNRs?

10 Powerful microquasars



Kaci et al. 2025

Cosmic ray electrons



Spectrum steeper than protons

$$\propto E^{-3.1}$$

$$\frac{\partial N}{\partial t} = \nabla \cdot (D \nabla N) + \frac{\partial}{\partial E}(b(E)N) + Q$$

$$D(E) \sim 10^{28} \left(\frac{E}{10\,\mathrm{GeV}}\right)^{\delta} \mathrm{cm^2\,s^{-1}} \qquad \delta \sim 0.3 - 0.6$$

$$\left(\frac{dE}{dt}\right)_{\mathrm{syn}} = -\frac{4}{3}\sigma_T c U_B \gamma^2$$

$$\left(\frac{dE}{dt}\right)_{\mathrm{IC}} = -\frac{4}{3}\sigma_T c U_{\mathrm{rad}} \gamma^2$$

$$U_B \sim 0.2 - 0.6 \ \mathrm{eV\ cm^{-3}}$$

$$U_{\mathrm{CMB}} \sim 0.26 \ \mathrm{eV\ cm^{-3}}$$

TeV electrons (IC and syn roughly same order

$$t_{\mathrm{cool}} = \frac{1}{bE} \sim 3 \times 10^5 \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-1} \mathrm{yr}$$

$$\tau_{\mathrm{esc}} \sim 10 \times 10^6 \mathrm{yr}$$

TeV electrons are local!

Nearby sources: $l_{\mathrm{diff}} \sim \sqrt{4Dt_{\mathrm{cool}}} \sim 1\mathrm{kpc}$

Not too close, constraint from anisotropy:

$$\delta \sim \frac{3D}{c}\frac{|\nabla N|}{N} \qquad \delta \lesssim 10^{-3}$$

$$r \gtrsim 3 \times 10^{20} - 10^{21} \ \mathrm{cm} \sim 100 - 300 \ \mathrm{pc}$$

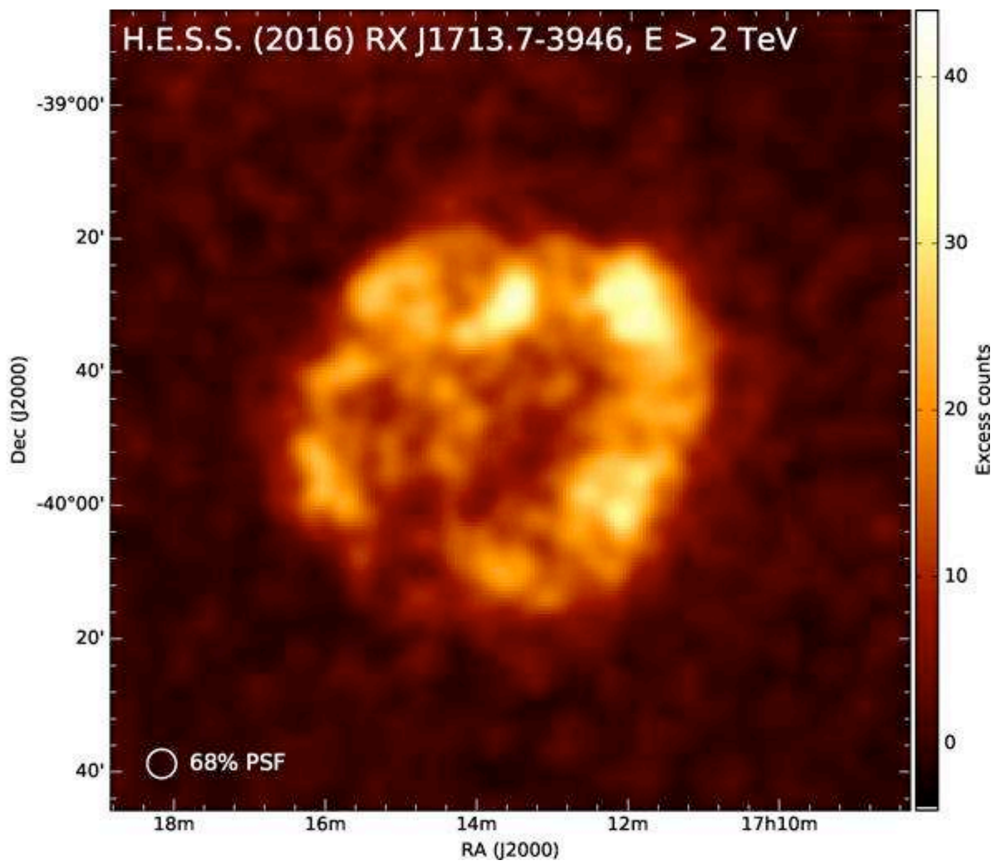
$$100 \ \mathrm{pc} \lesssim \mathrm{dist} \lesssim 1 \ \mathrm{kpc}$$

Cosmic ray electrons: good candidates

Supernova remnants

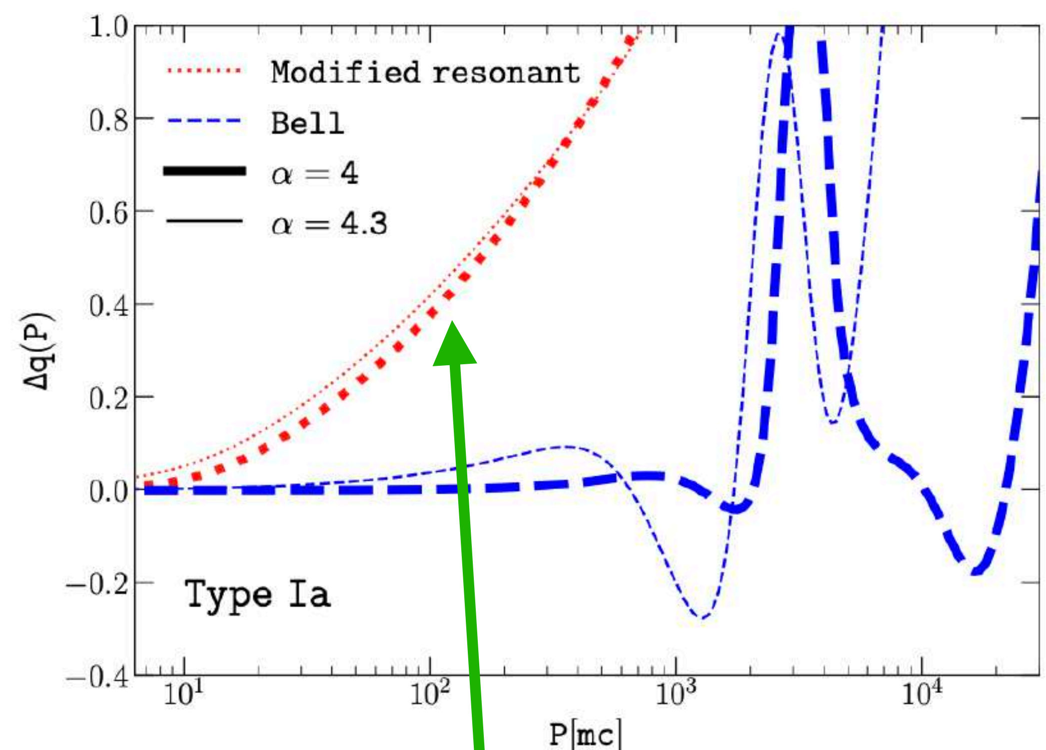
DSA proceeds the same way for protons and electrons (injection different, and losses different)

Discussion on RXJ1713-3946?
(Protons, electrons?)



HESS Aharonian et al. 2016

Accelerated and trapped particles (electron suffer loses)

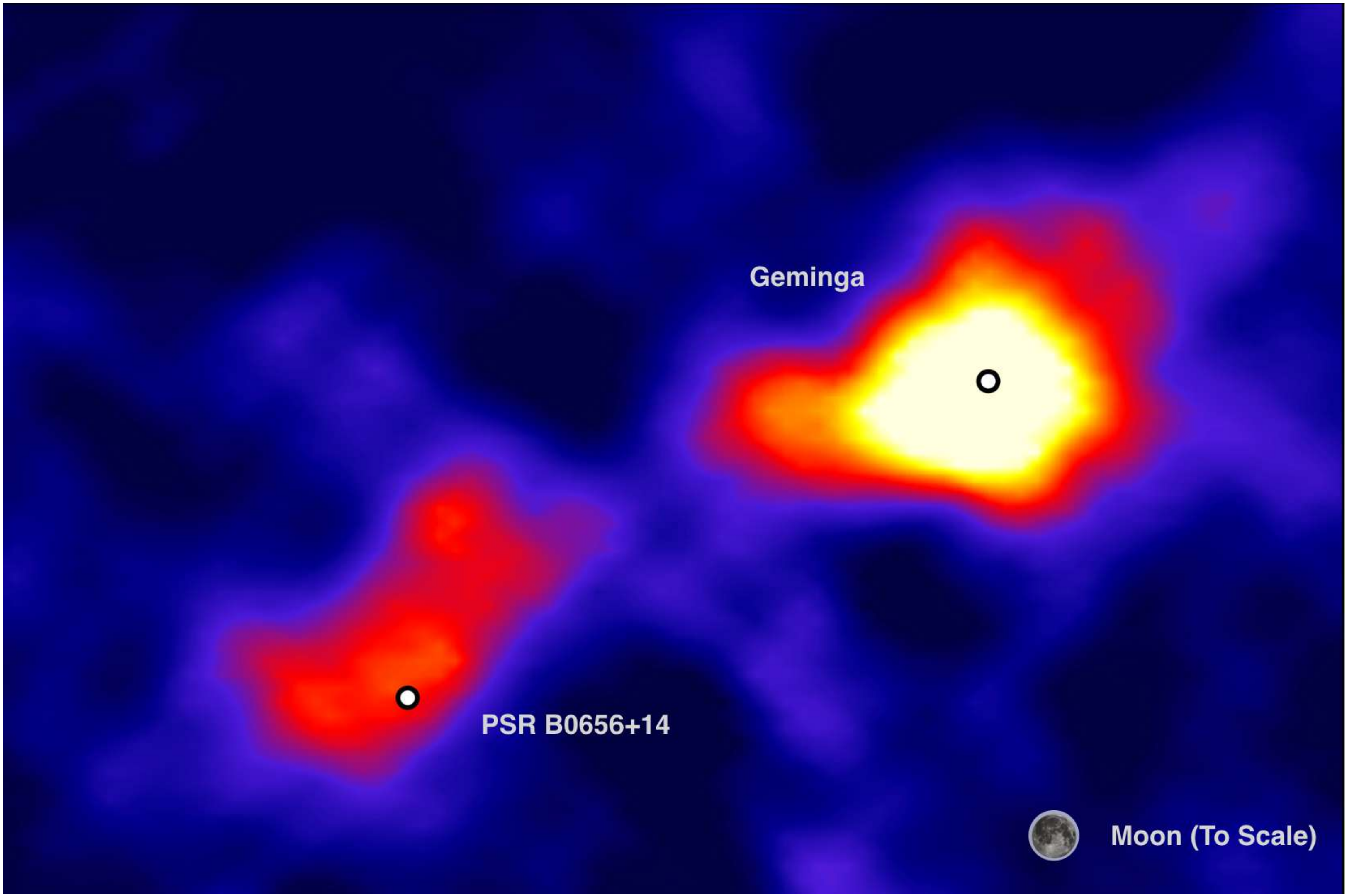


Difference of slope beteween electrons and protons

PC, Blasi, Caprioli 2021

Cosmic ray electrons: good candidates

Pulsars, Pulsar winds, and halos



HAWC 2018

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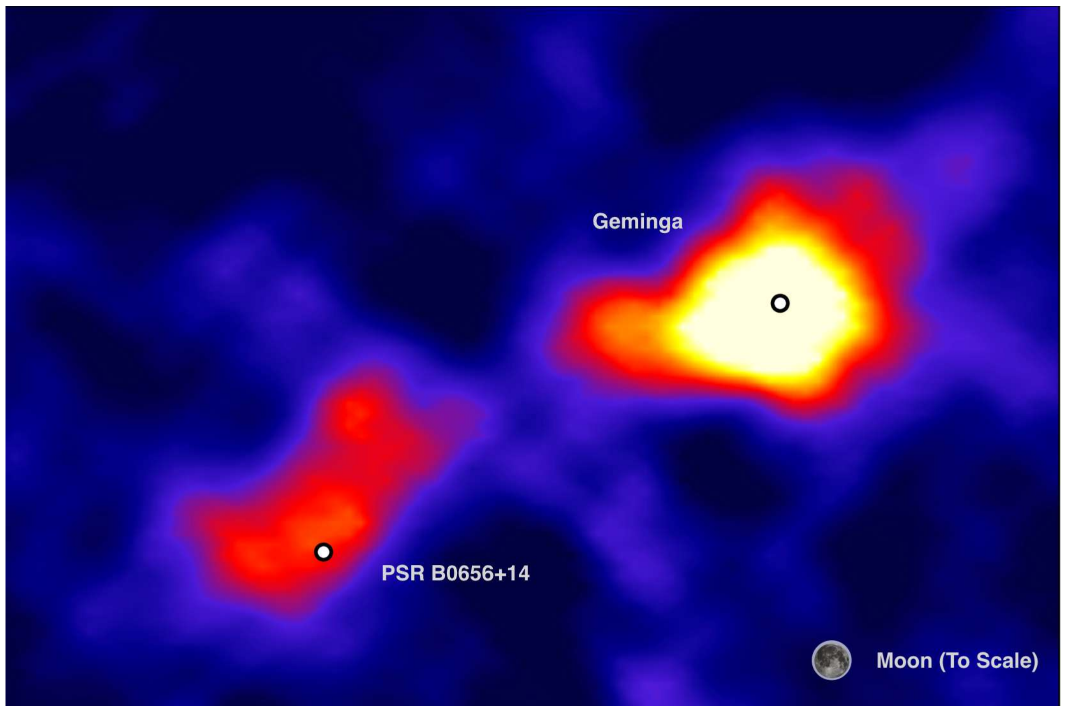


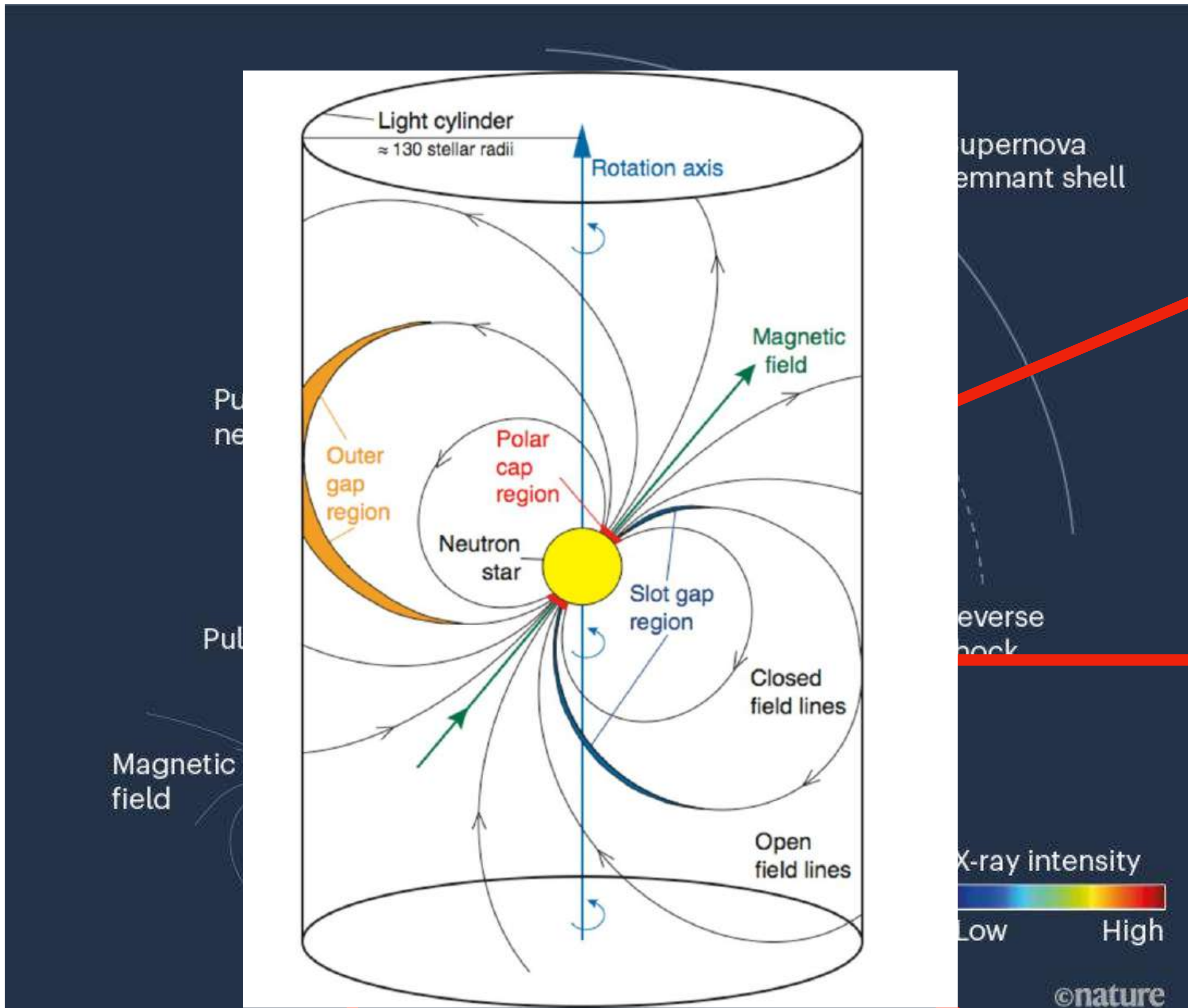
Dist≈250 pc
Age≈300 kyr
Radio quiet pulsar
One of brightest GeV

$$\dot{E} \sim 3 \times 10^{34} \mathrm{erg/s}$$

Link between pulsar magnetospheres
Acceleration electron/positrons
CR electrons/positrons
TeV halos
CR diffusion and escape

HAWC 2018

Particle acceleration around pulsars



Nebula /Halo

Turbulent acceleration / Fermi 2

Termination shock

DSA

Ultra-relativistic wind (e±) , high magnetized

Stipped wind (regions alternating +B, -B, +B, -B)

Relativistic reconnection

Pulsar magnetosphere (polar cap, slot gap, outer gap equatorial current sheet)

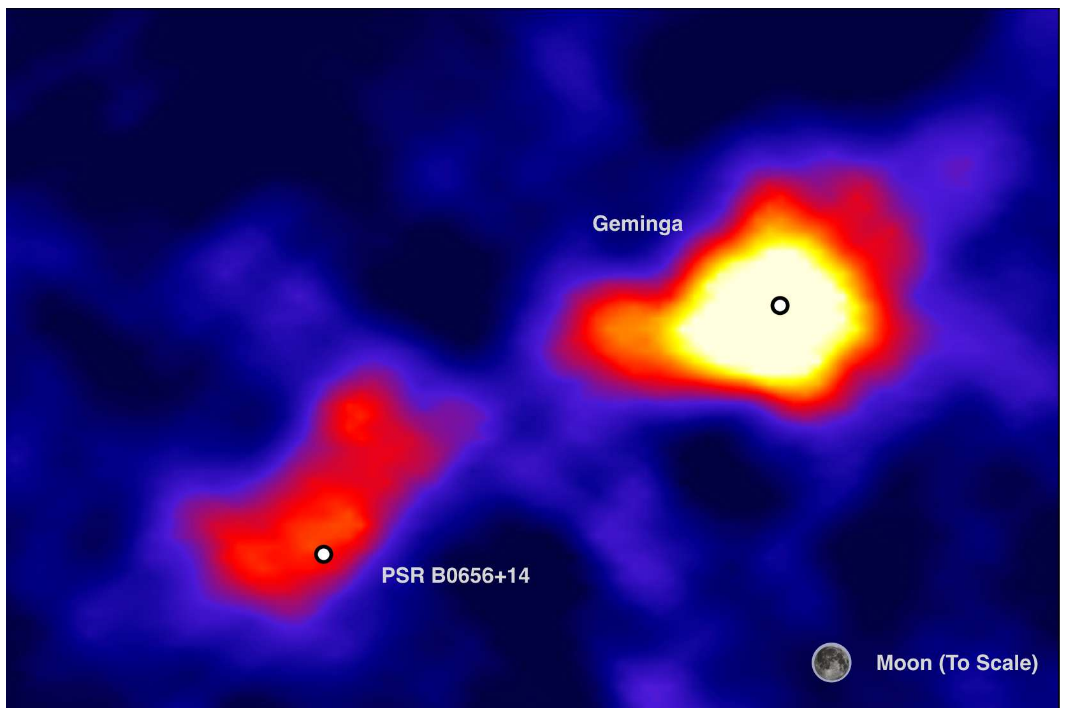
Electrostatic acceleration in gaps

Cosmic ray electrons: good candidates

Pulsars, Pulsar winds, and halos

$$D_{\rm Geminga} \sim 10^{26} - 10^{27} {\rm cm}^2/{\rm s} \ll D_{\rm ISM} \sim 10^{28} - 10^{29} {\rm cm}^2/{\rm s}$$

2-3 orders smaller (at ~10 TeV)



HAWC 2018

$$\frac{{\rm d}E}{{\rm d}t} \propto -E^2 \qquad \tau_{\rm cooling} \propto \frac{1}{E}$$

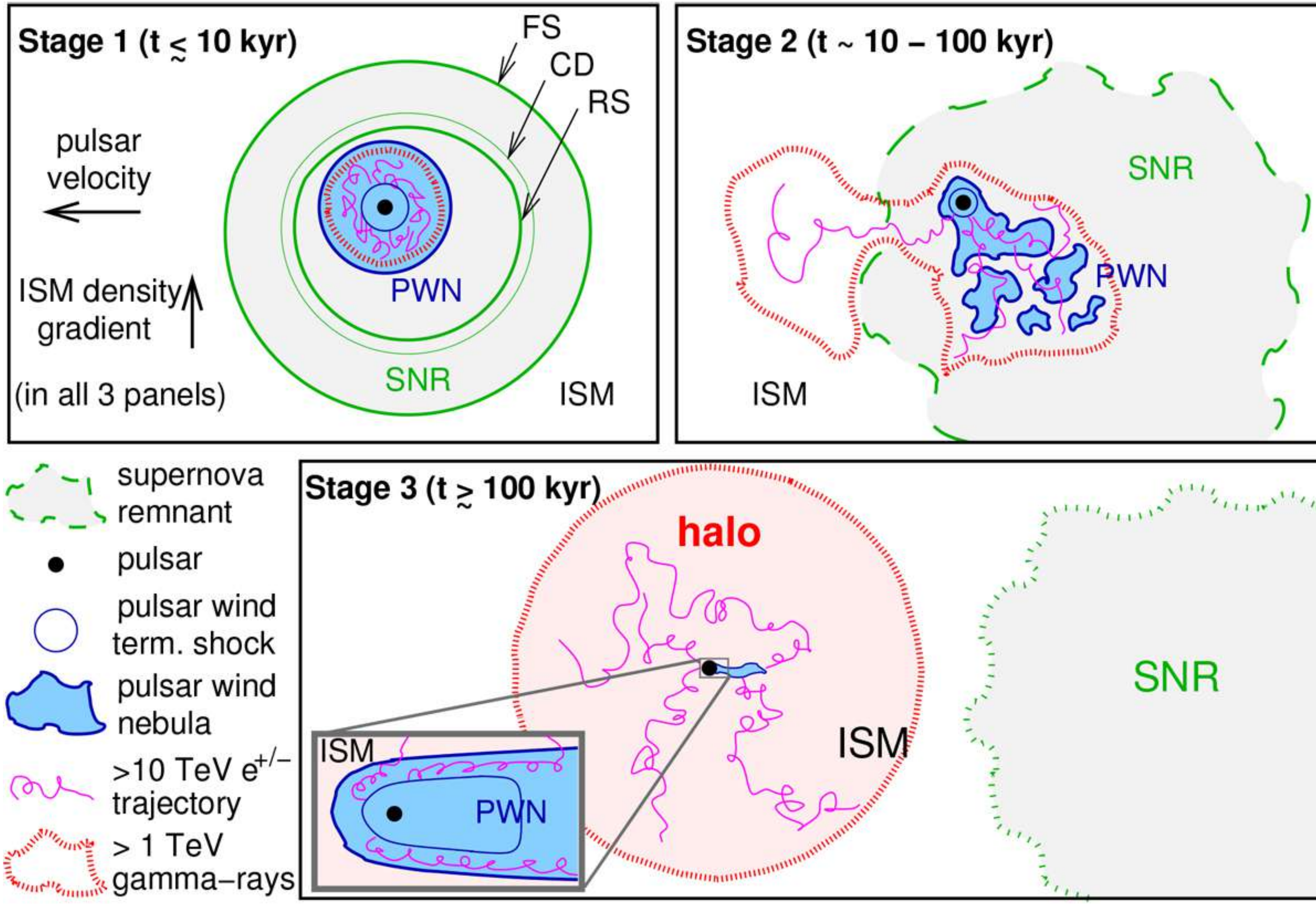
$$U_{\rm rad} + U_B \sim 1\ {\rm eVcm}^{-3}$$

$$t_{\rm cool} \approx 3 \times 10^5 \left(\frac{1\ {\rm TeV}}{E}\right)\ {\rm yr}$$

$$r_{\rm diff} \sim \sqrt{4Dt}$$

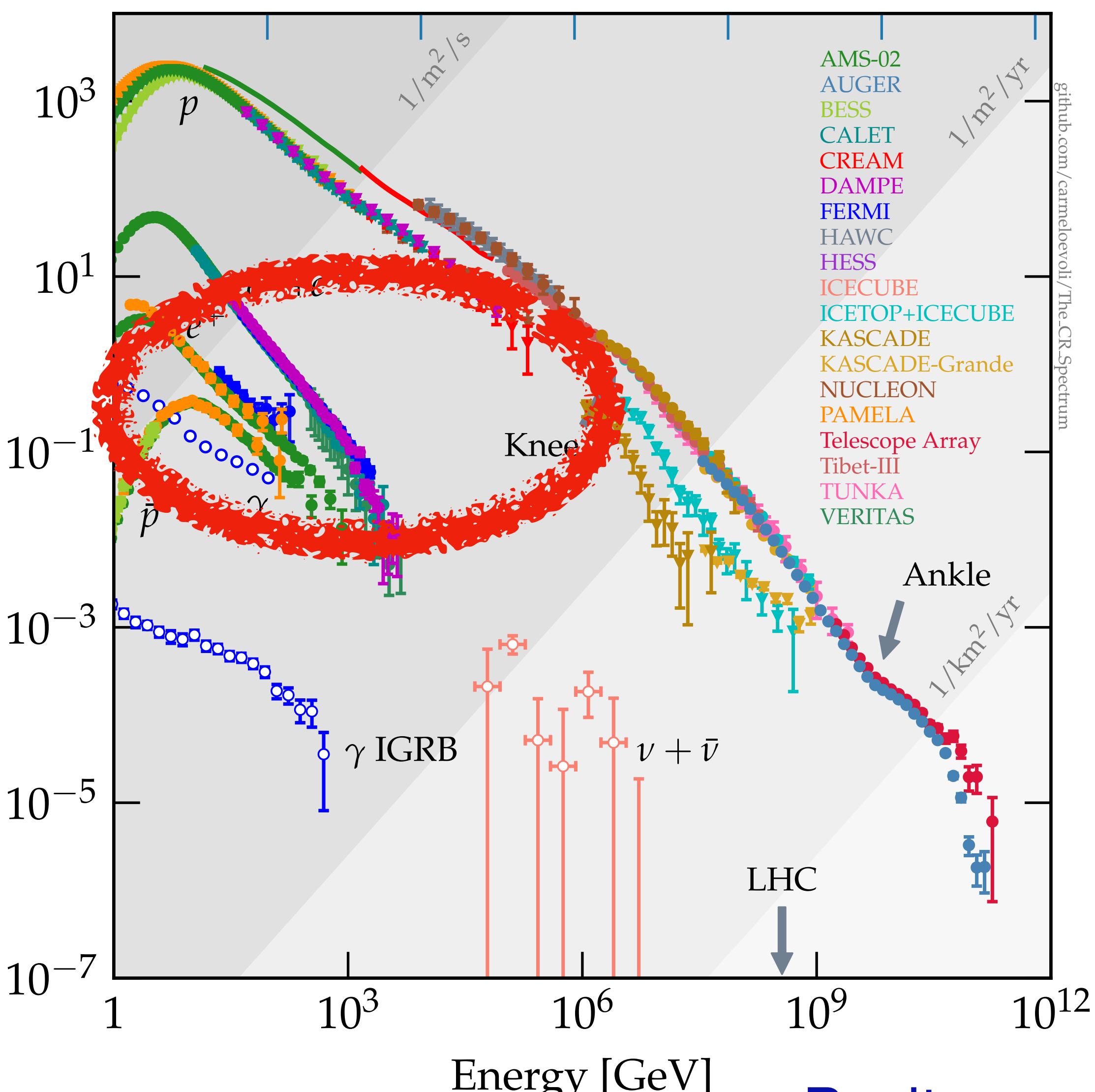
Important: Diffusion coefficient is energy dependent: extrapolation to GeV no easy! $D(E) \propto \left(\frac{E}{E_0}\right)^{\delta}$

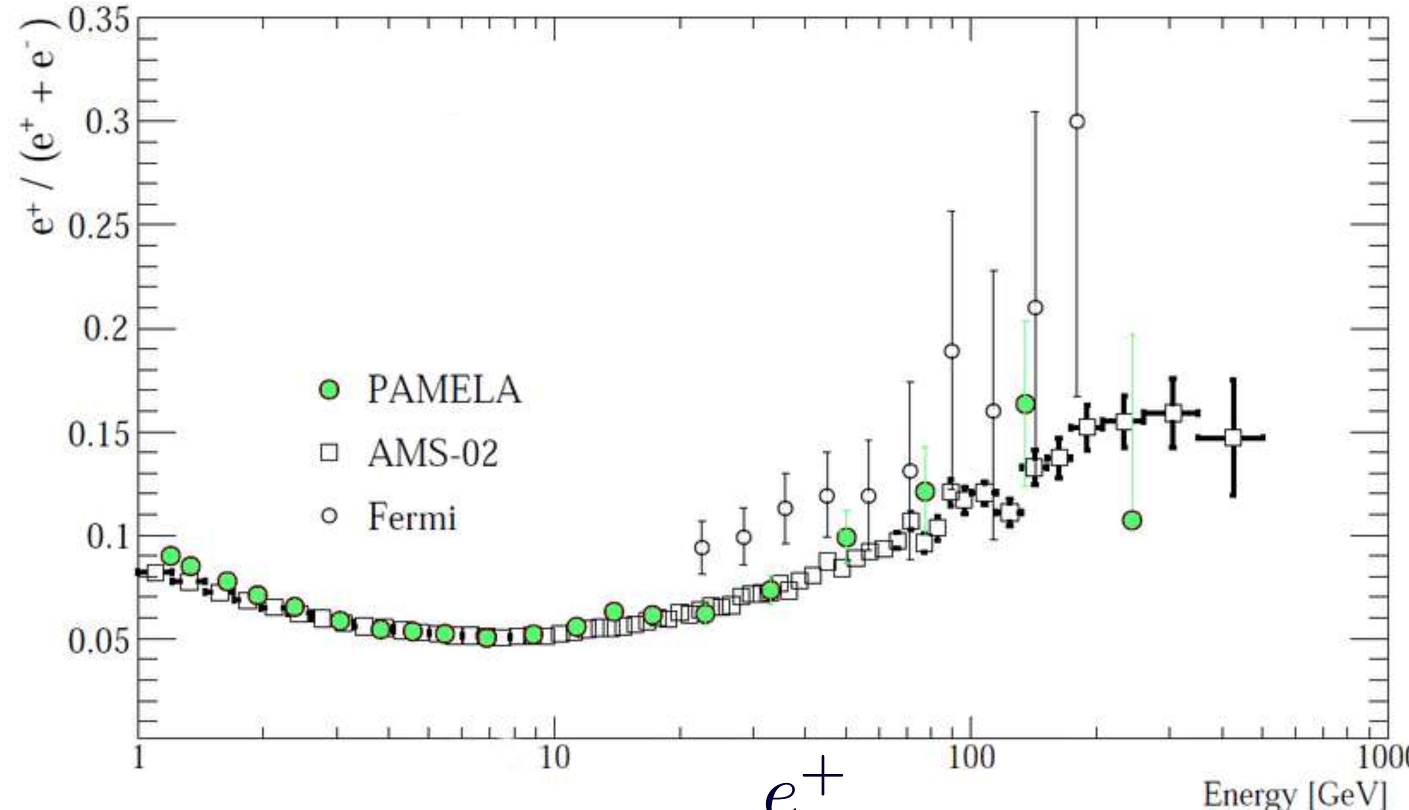
How is diffusion suppressed? Mechanism?
Is this only close to source? (Usual picture) or Local Bubble?



Giacinti et al. 2020

The positron excess





$$\Phi = \frac{e^+}{e^- + e^+}$$

Unexpected if sources inject same electrons and positrons the same way

Positron produced in secondary CR interactions?

$$p + p \to \pi^{\pm} + \pi^0 + X$$

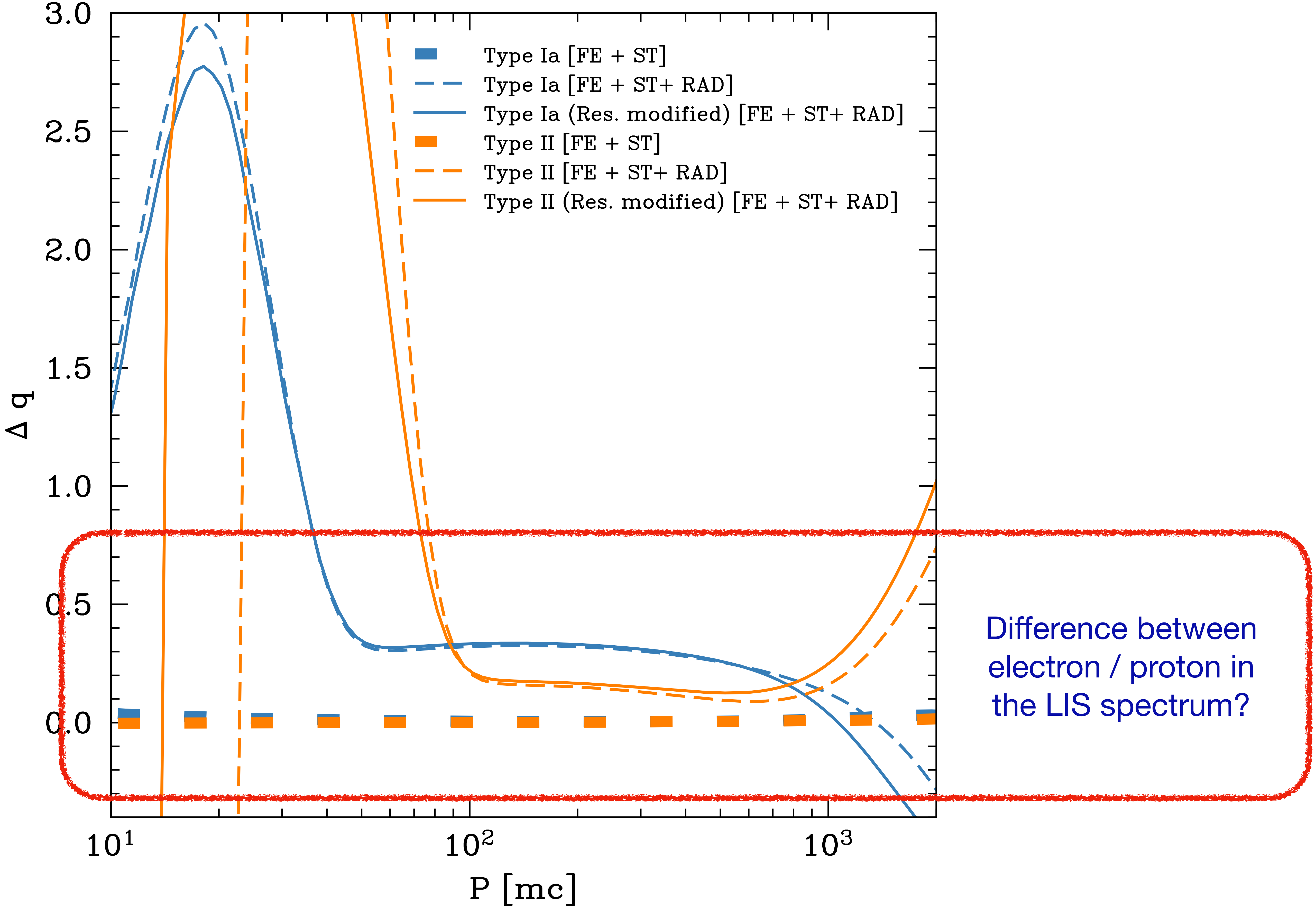
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Possible with pulsars
Possible with SNRs
other exotic explanations?

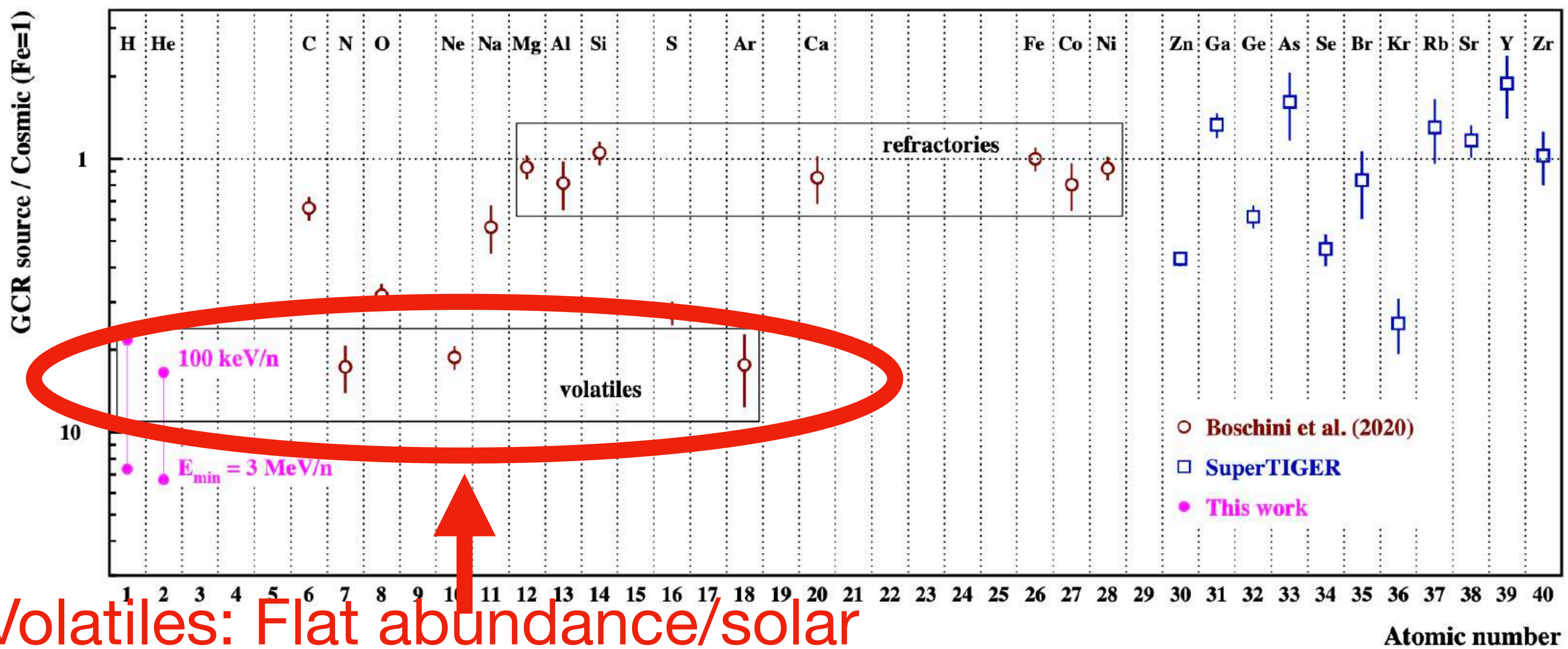
Adriani et al. 2009, Aguilar et al. 2013, Hooper et al. 2009, Blasi 2009, Profumo 2012

SNR radiative phase (protons+ electrons?)



Explaining the CR composition

CR abundances relative to solar composition (Voyager/AMS/SuperTIGER)



Volatiles: Flat abundance/solar ratio, A/Q ~2 for all elements

Injection from hot medium (superbubbles?)

Tatischeff et al. 2021

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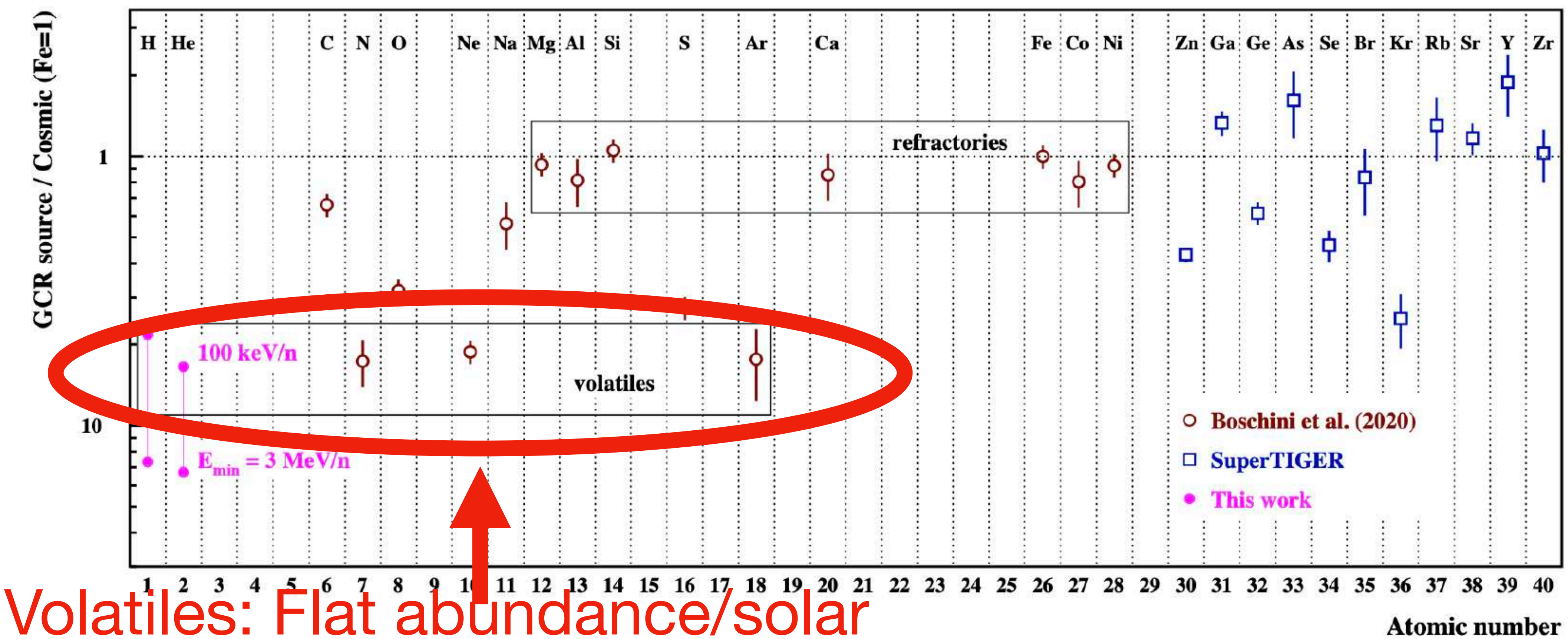

Volatiles: Flat abundance/solar ratio, A/Q ~2 for all elements
Injection from hot medium (superbubbles?)

	Model 1	Model 2	Model 3	Model 4	Model 5
GCR gas source of SC compo.	70% WNM, 30% WIM	SB	SB	60% SB, 28% WNM, 12% WIM	60% SB, 28% WNM, 12% WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated wind	Winds in SB	Accelerated winds
SB temperature $\log(T_{SB})^a$	–	6.50 ± 0.2	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	26.0 ± 13.2	17.9 ± 9.7	27.0 ± 13.2	22.8 ± 10.6
W.-R. wind contribution $x_w{}^c$	10.3%	48.9%	(5.1 – 6.1)%	$(55.6^{+1.3}_{-0.3})$%	(7.3 – 7.9)%
χ^2_{min}(GCR dust source)^d	24.6	26.9	25.9	26.0	24.8
χ^2_{min}(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	23.2 ± 9.4	20.2 ± 7.2	24.6 ± 10.2	24.4 ± 9.2
W.-R. wind contribution $x_w{}^c$	10.3%	48.9%	5.9%	56.0%	7.7%
χ^2_{min}(GCR dust source)^d	24.6	28.0	26.9	26.4	25.0
χ^2_{min}(GCR gas source)^e	24.7	32.3	13.2	32.4	18.3

Tatischeff et al. 2021

Explaining the CR composition

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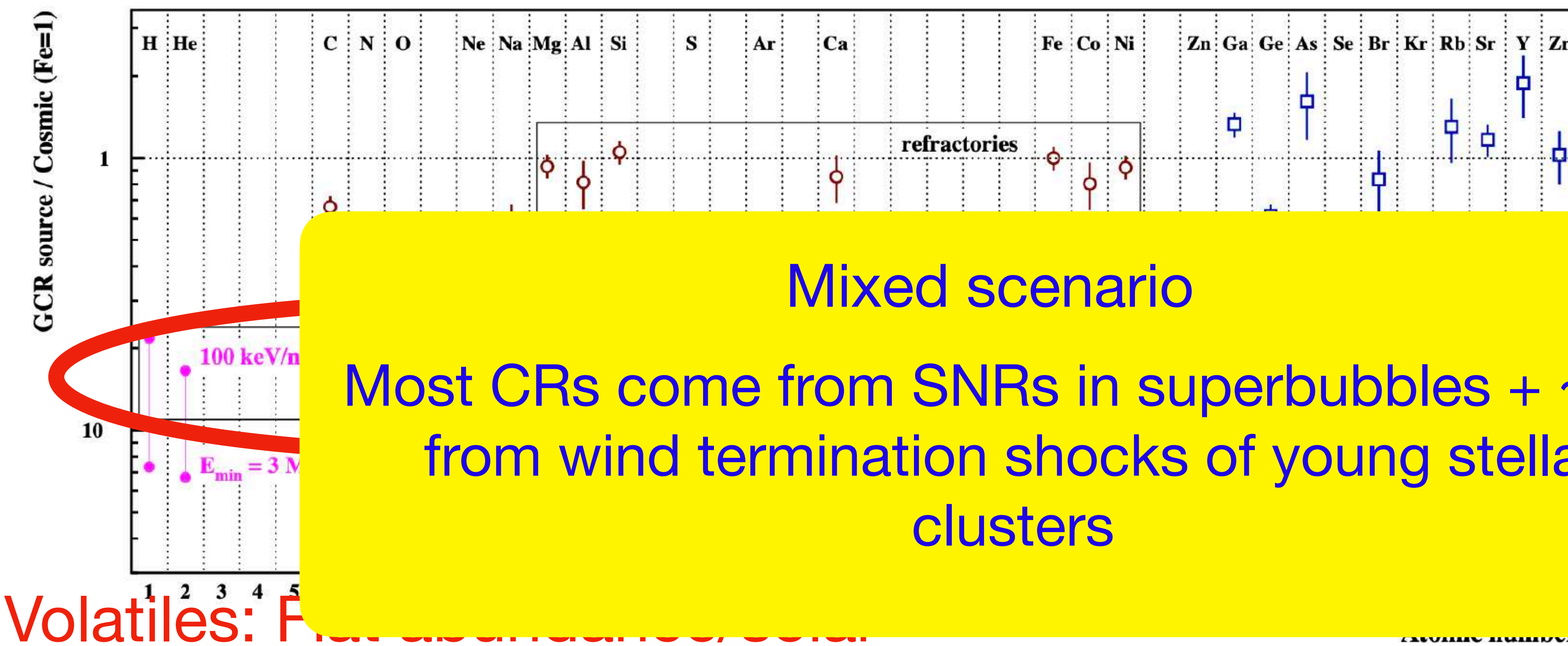

Mixed scenario

Most CRs come from SNRs in superbubbles + ~5% from wind termination shocks of young stellar clusters

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Tatischeff et al. 2021

Diffusive shock acceleration of dust grains

1. Cosmic ray air showers?

ON THE HYPOTHESIS OF DUST GRAIN ORIGIN OF COSMIC RAYS AIR SHOWERS

(Research Note)

V. S. BEREZINSKY and O. F. PRILUTSKY
P. L. Lebedev Physical Institute of the U.S.S.R., Academy of Sciences, Moscow, U.S.S.R.

(Received 5 January, 1973)

It is shown that relativistic and subrelativistic dust grains accumulate large electric charges as a result of the interaction with photons and interstellar gas atoms. The developing electrostatic forces break up the grains. The relativistic dust grains break effectively within the solar system and, therefore, cannot give rise to the observed extensive air showers.

The hypothesis of the dust grain origin of cosmic rays has been repeatedly put forward (Herlofson, 1956; Spitzer, 1949). Recently Hayakawa (1972) took advantage of this hypothesis to overcome the difficulties in explanating extensive air showers with energies $E > 3 \times 10^{19}$ eV.

We would like to remark that, when colliding with photons and interstellar gas atoms, a relativistic dust grain accumulates a large electric charge which causes it to break up. The relativistic dust grains with Lorentz factors $\gamma > 30-50$ are split up within the solar system due to interaction with the solar photons. Subrelativistic dust grains with velocities $v > 0.1$ c are split up due to interaction with interstellar gas atoms.

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1973Ap&SS..21..475B

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Diffusive shock acceleration of dust grains

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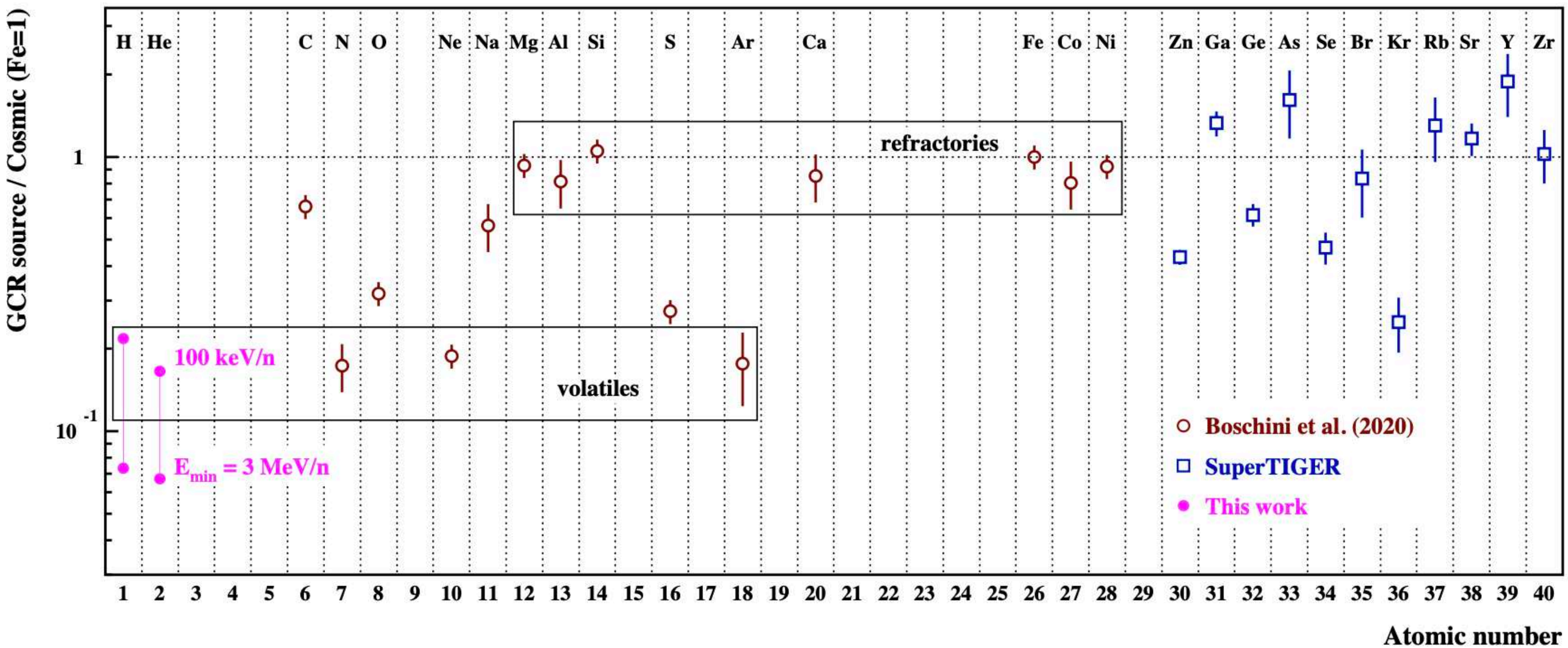

Lodders+ 2009,Nieva+ 2012, Murphy+2016 Boschini+ 2020,2021, Tatischeff+2021

Diffusive shock acceleration of dust grains

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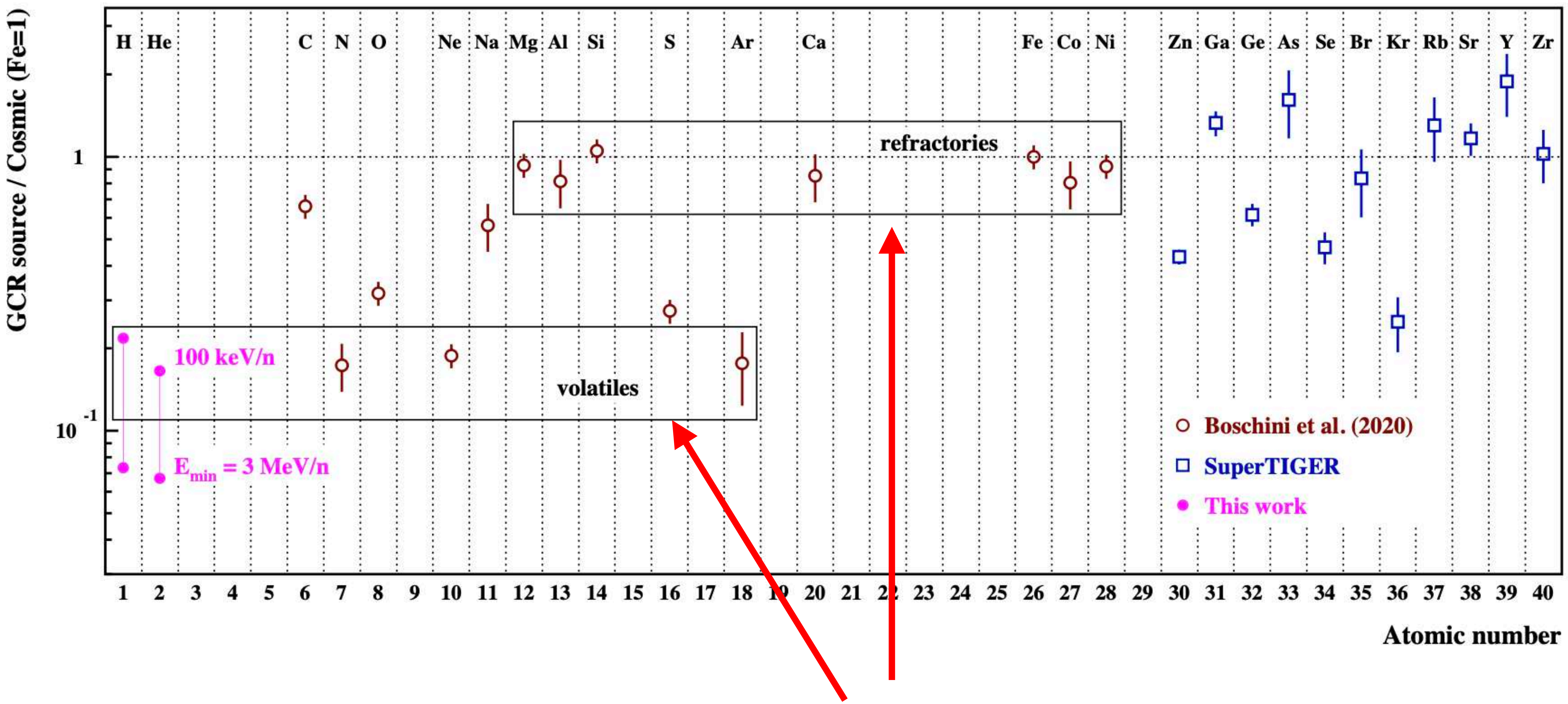

Preferential acceleration of dust grains?

Lodders+ 2009,Nieva+ 2012, Murphy+2016 Boschini+ 2020,2021, Tatischeff+2021

Diffusive shock acceleration of dust grains

Galactic Cosmic rays from Supernova Remnants: II Shock Acceleration of Gas and Dust

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ellison1997.pdf

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ABSTRACT

We present a quantitative model of galactic cosmic ray (GCR) origin and acceleration, wherein a mixture of interstellar and/or circumstellar gas and dust is accelerated by a supernova remnant (SNR) blast wave. The gas and dust are accelerated simultaneously, but differences in how each component is treated by the shock leaves a distinctive signature which we believe exists in the cosmic ray composition data. A re-examination

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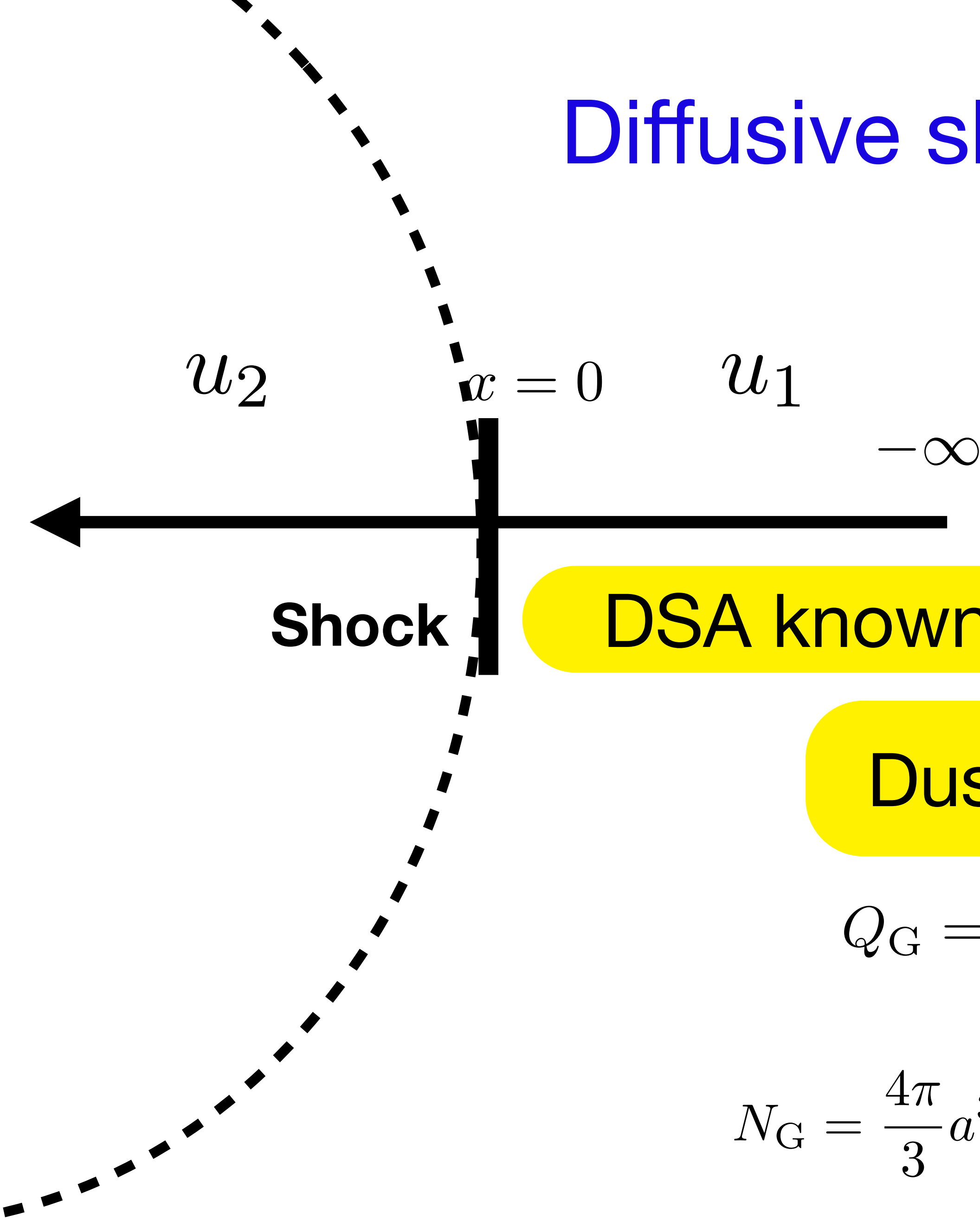
Diffusive shock acceleration (DSA) of dust grains

$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f(x,p)}{\partial p} = -Q(x,p)$$



DSA known to be efficient for protons/electrons/ions

Dust grains: big ions

Ellison et al. 1997

$$Q_{\mathrm{G}} = \frac{q}{e} \approx 700\left(\frac{a}{10^{-5}\mathrm{cm}}\right)\left(\frac{\phi}{10\mathrm{V}}\right)$$

$$N_{\mathrm{G}} = \frac{4\pi}{3}a^3 n_d \sim 4\times 10^8\left(\frac{a}{10^{-5}\mathrm{cm}}\right)^3\left(\frac{n_d}{10^{23}\mathrm{cm}^{-3}}\right)$$

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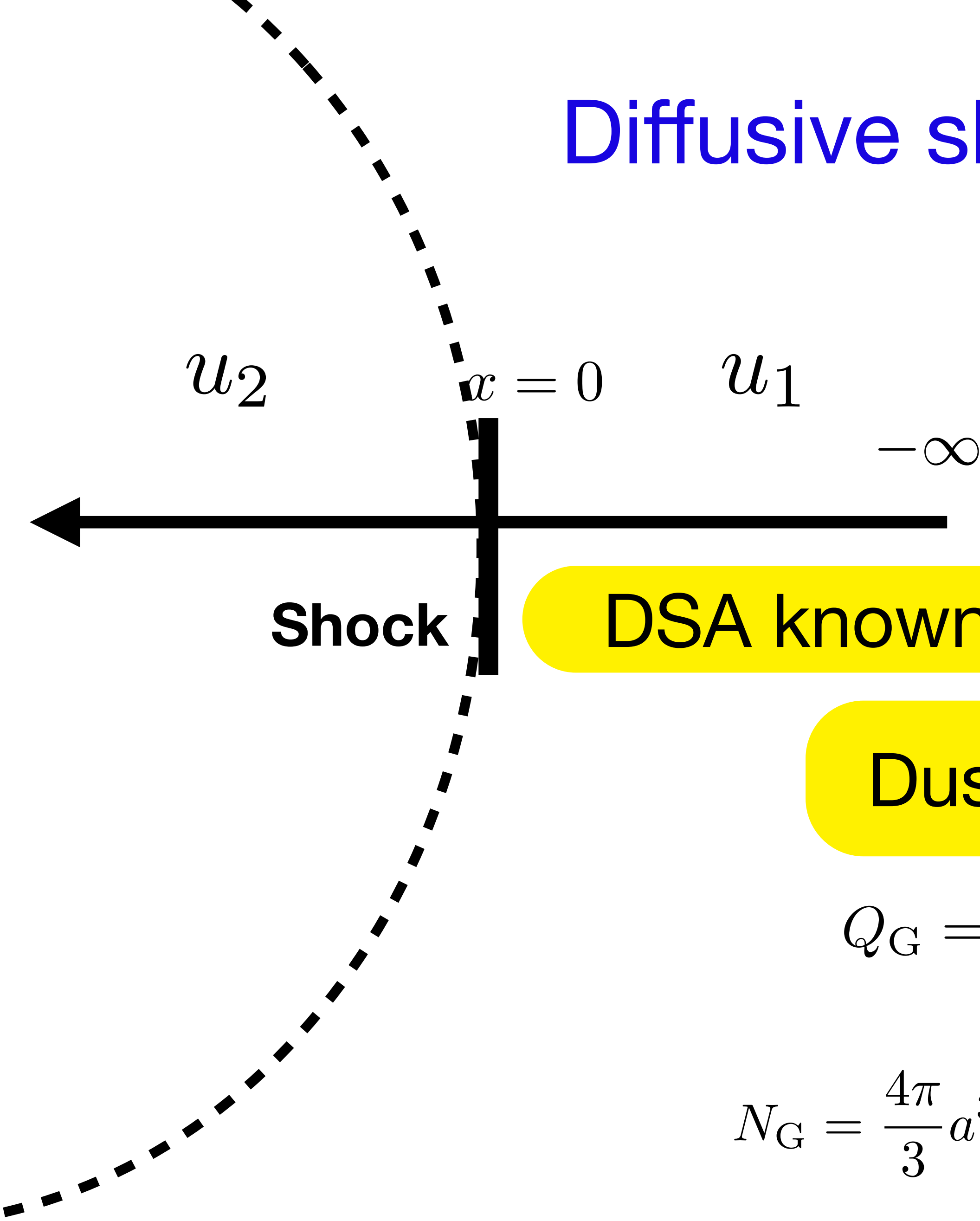

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New: Grain distribution in size, shock velocity, grain-grain collisions, etc.

This work

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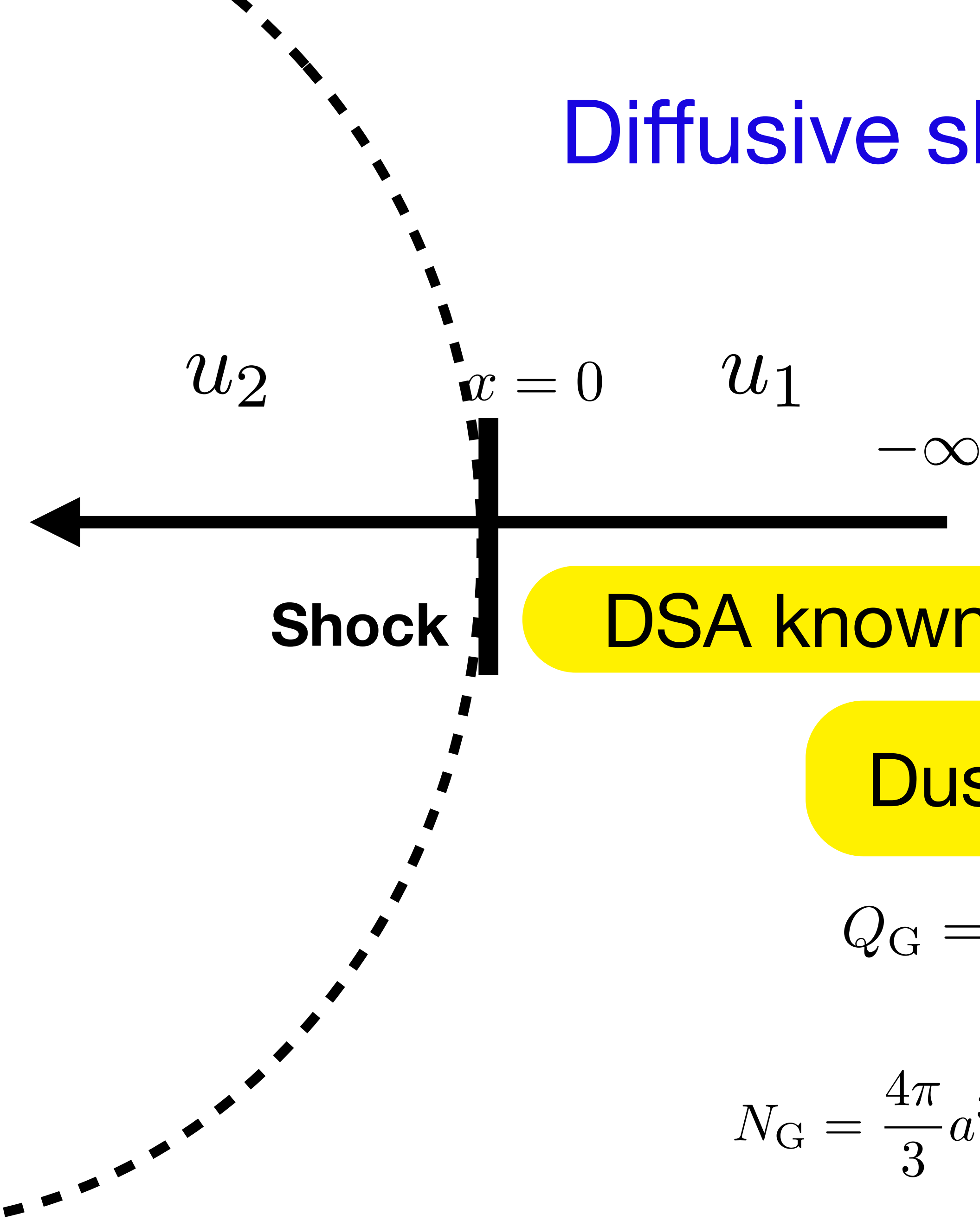

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$$s=\frac{3r}{r-1}$$

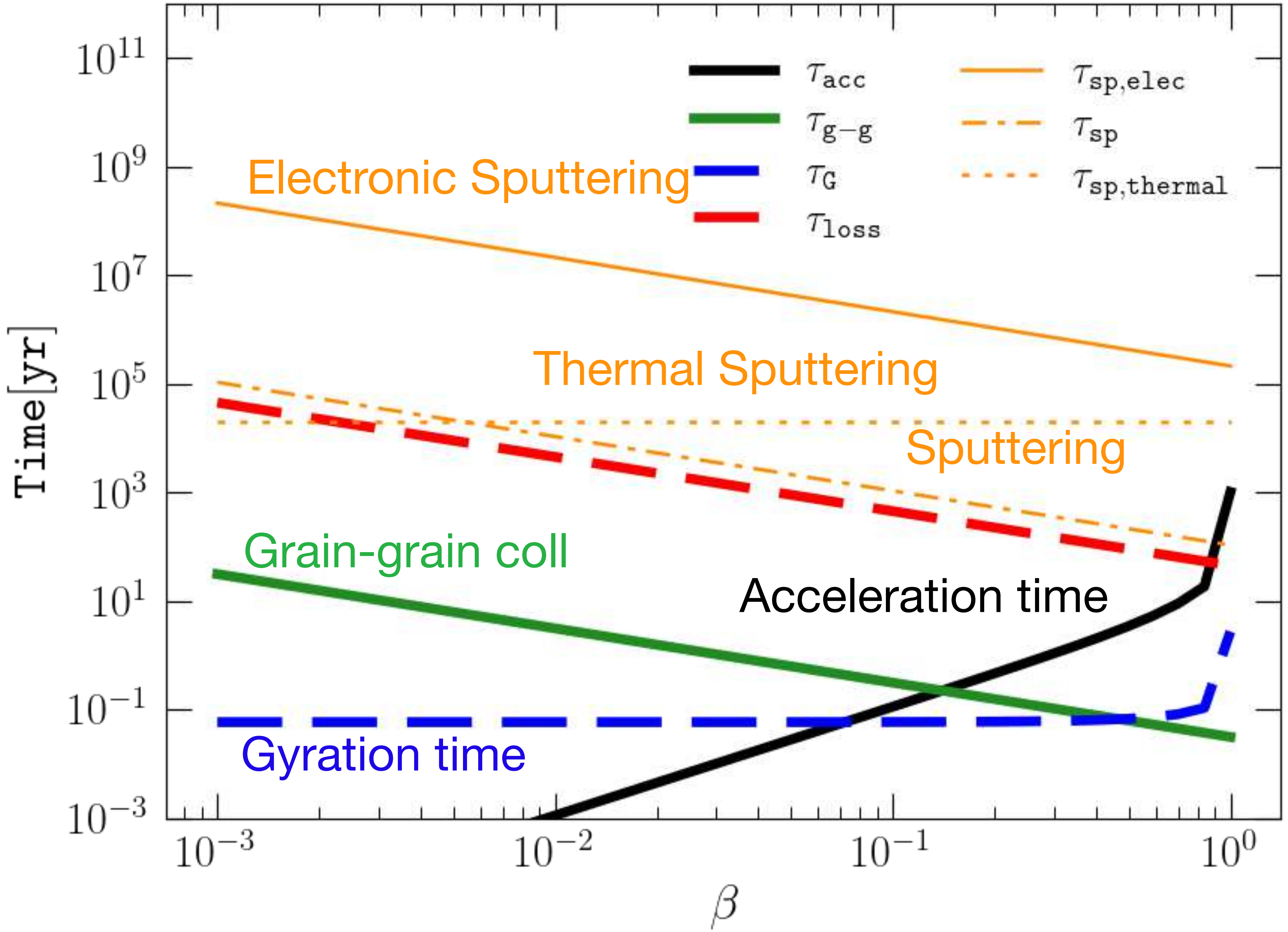
New: Grain distribution in size, shock velocity, grain-grain collisions, etc.

This work

$$f_0^a(p)=A^a\left(\frac{p}{p_0}\right)^{-s}\exp\left[-\frac{p}{p^a_{\rm max}}\right]$$

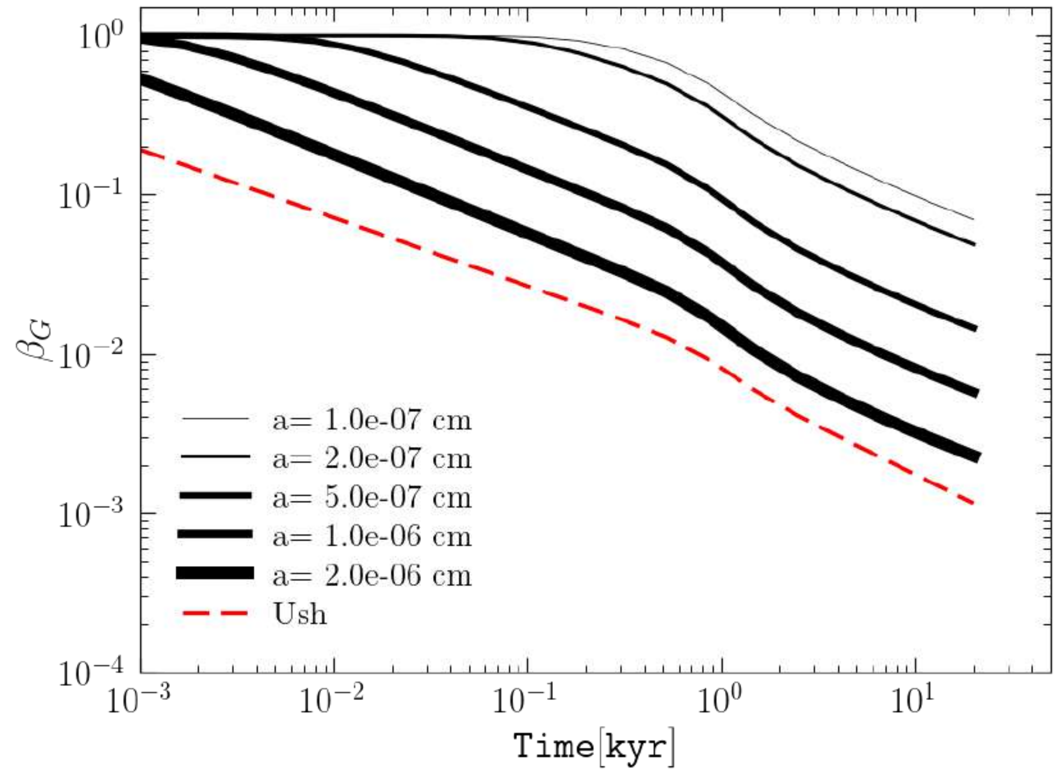
Usual question on particle acceleration: Efficiency? Maximum momentum? + Survival of grains?

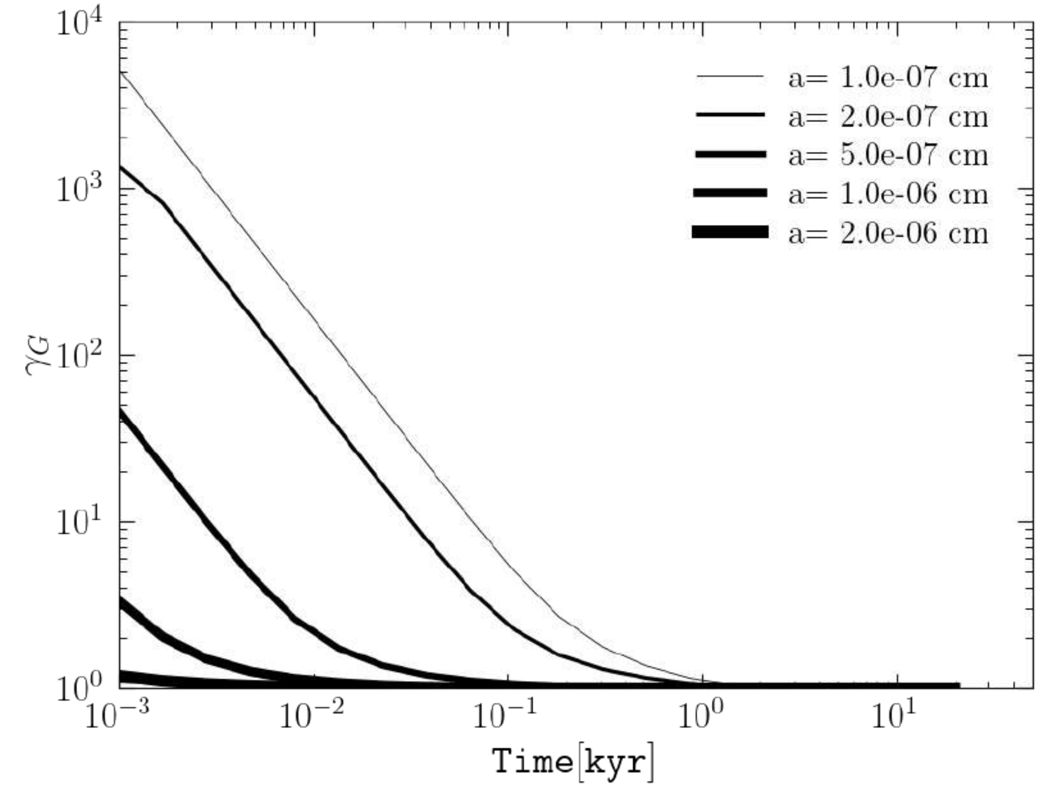
Maximum momentum of accelerated dust grains

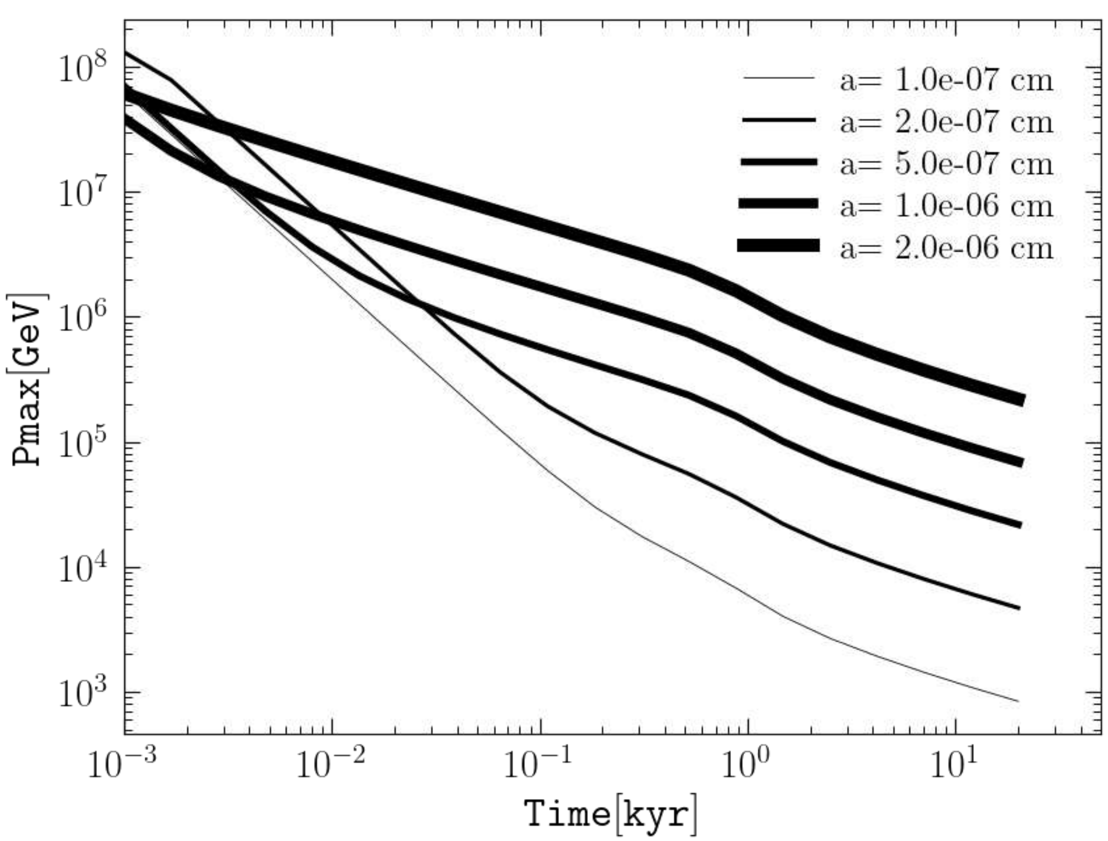


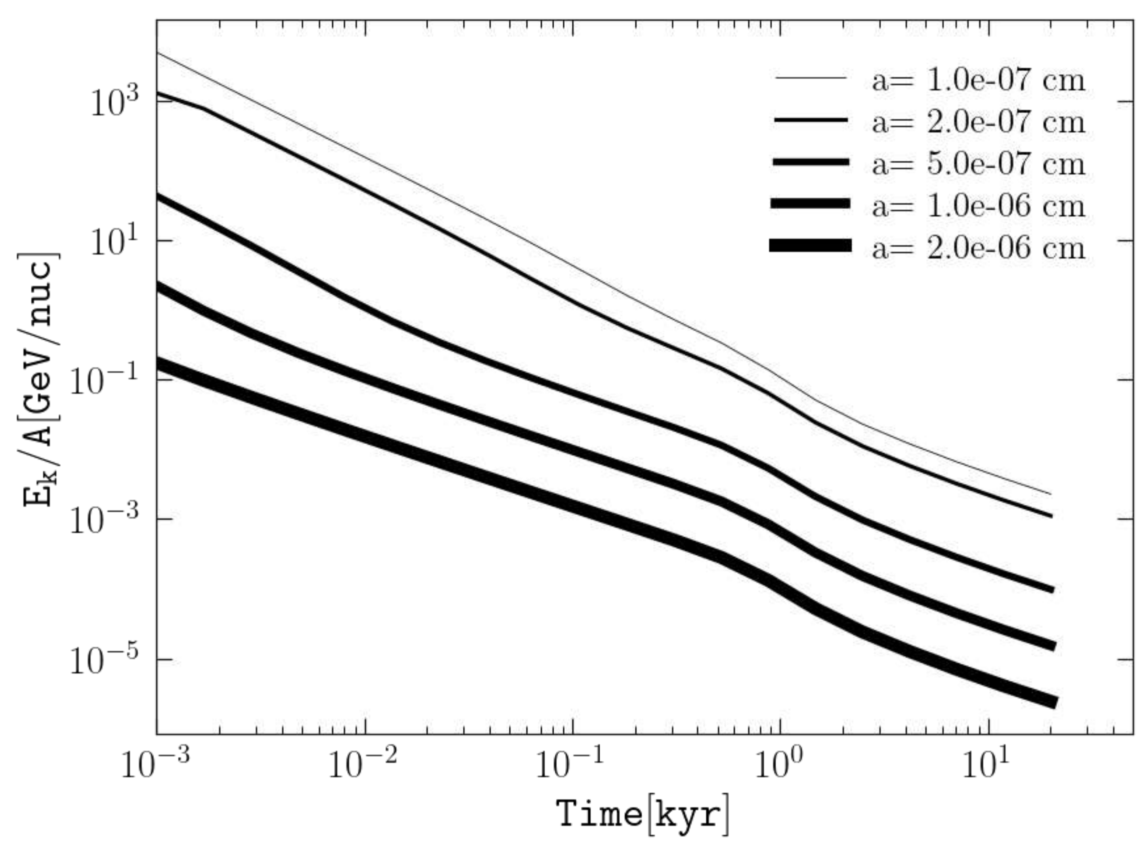
Maximum momentum of accelerated dust grains

Time evolution for a type Ia SNR



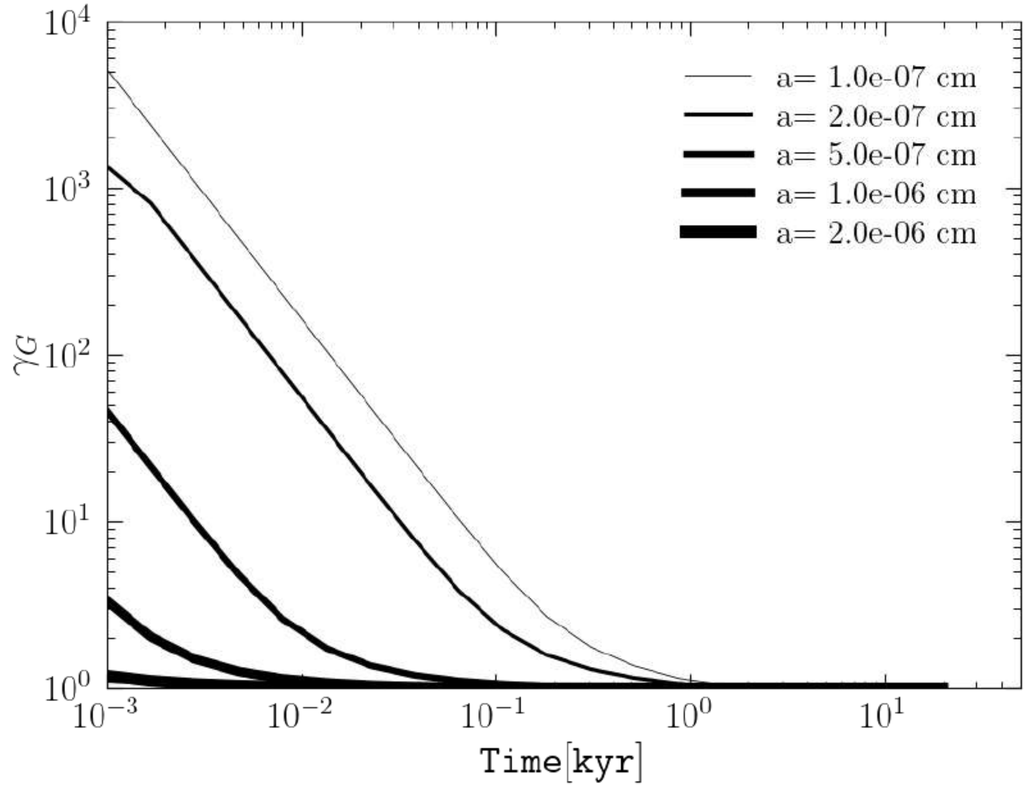




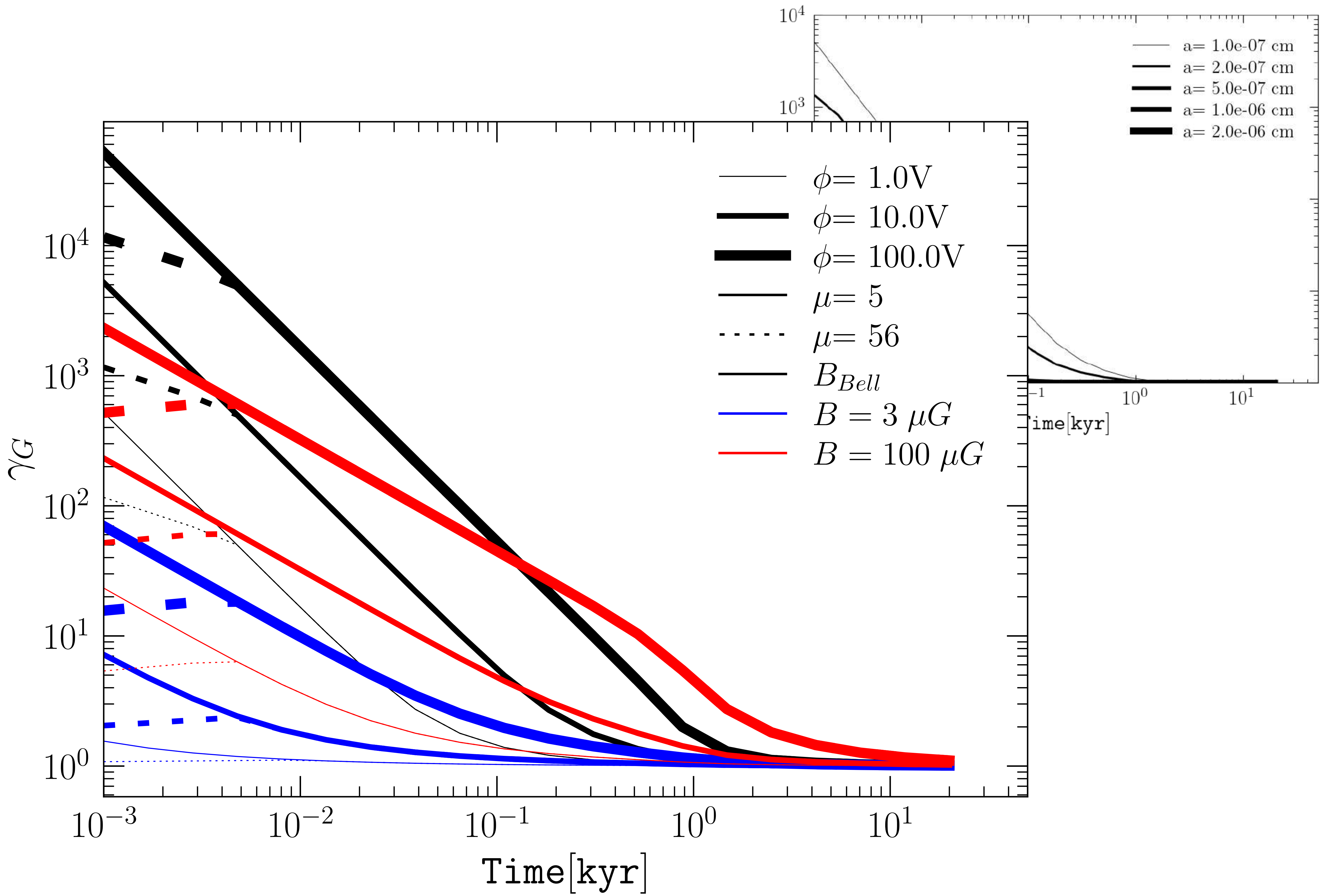


Maximum momentum of accelerated dust grains

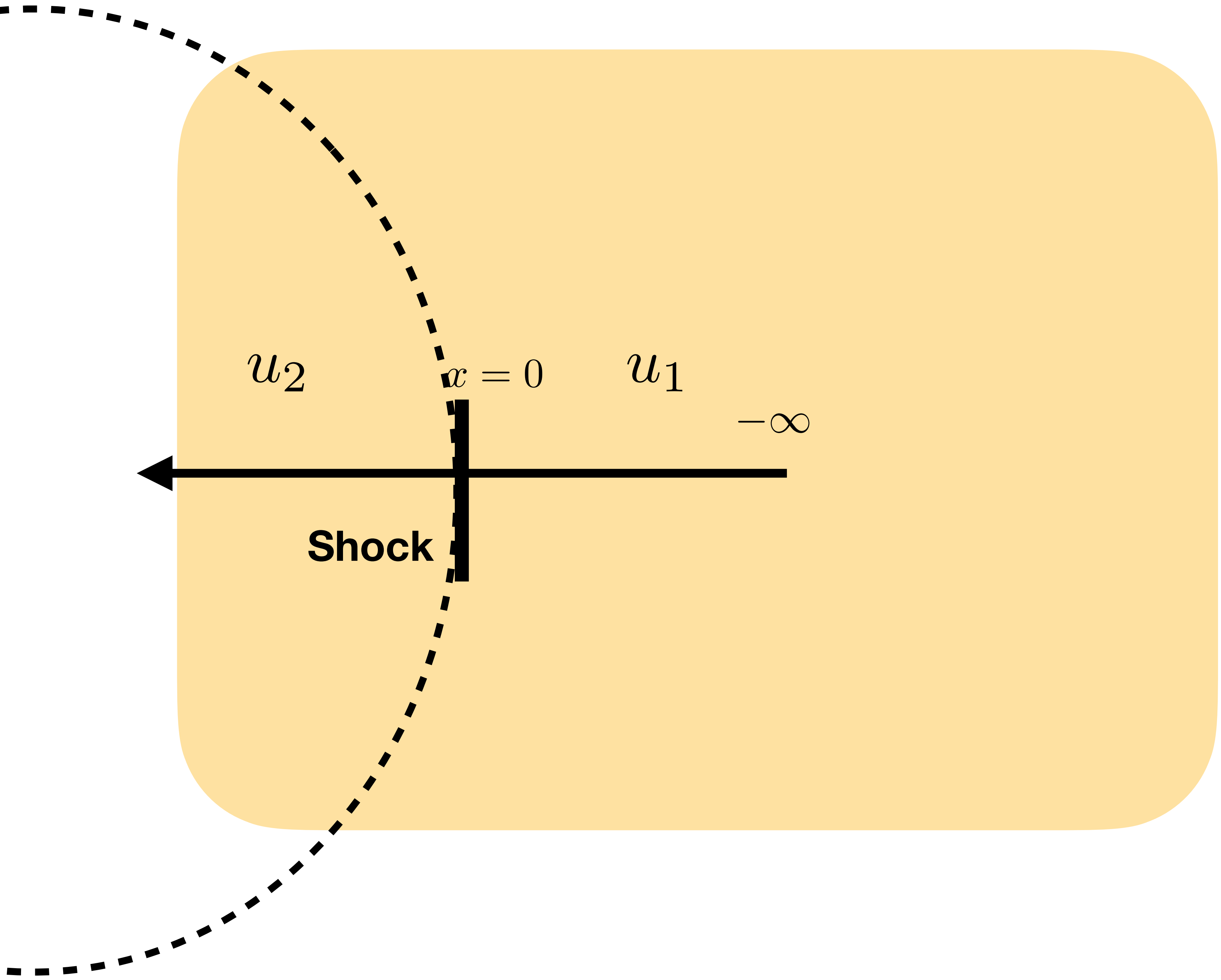
Time evolution for a type Ia SNR



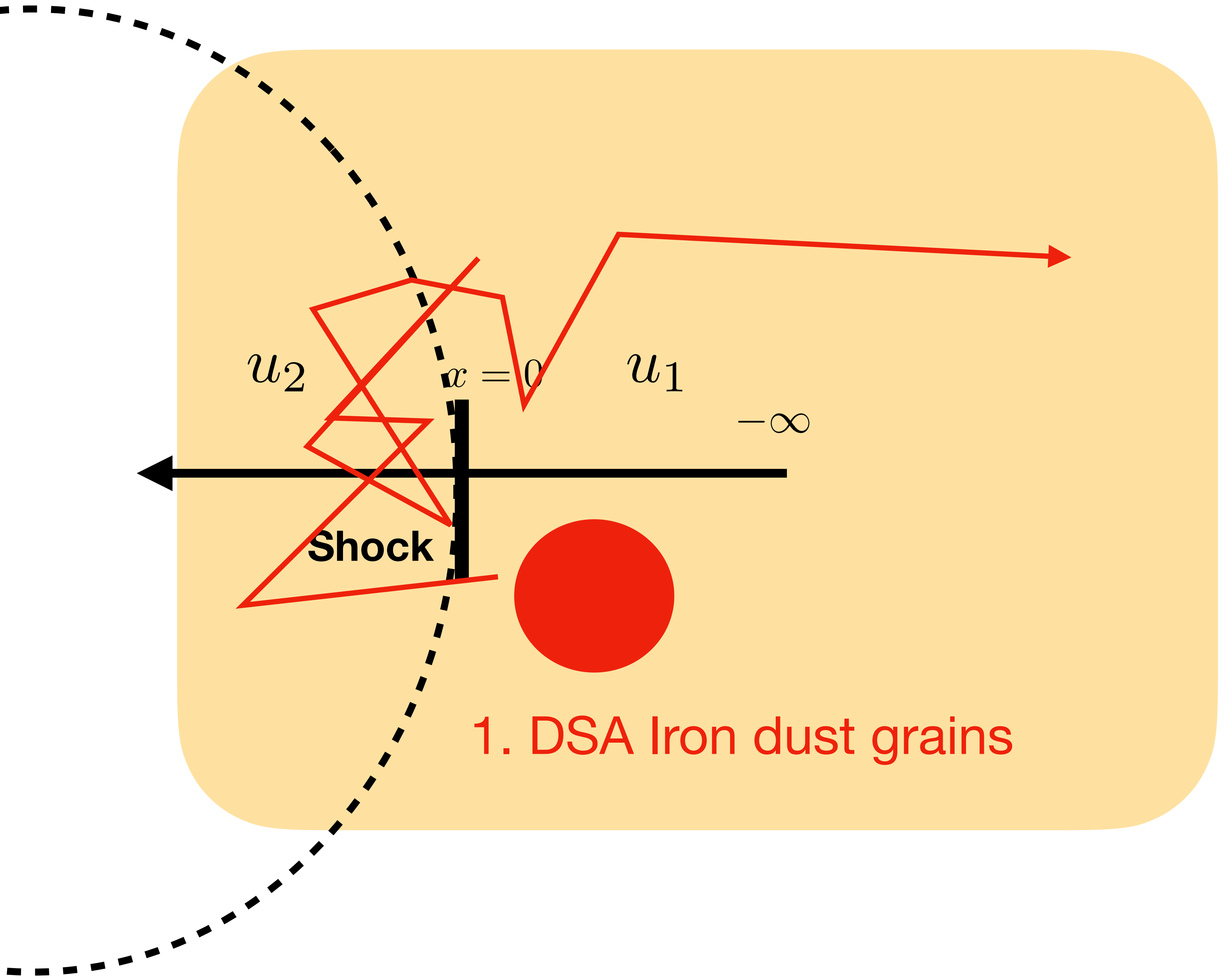
Maximum momentum of accelerated dust grains



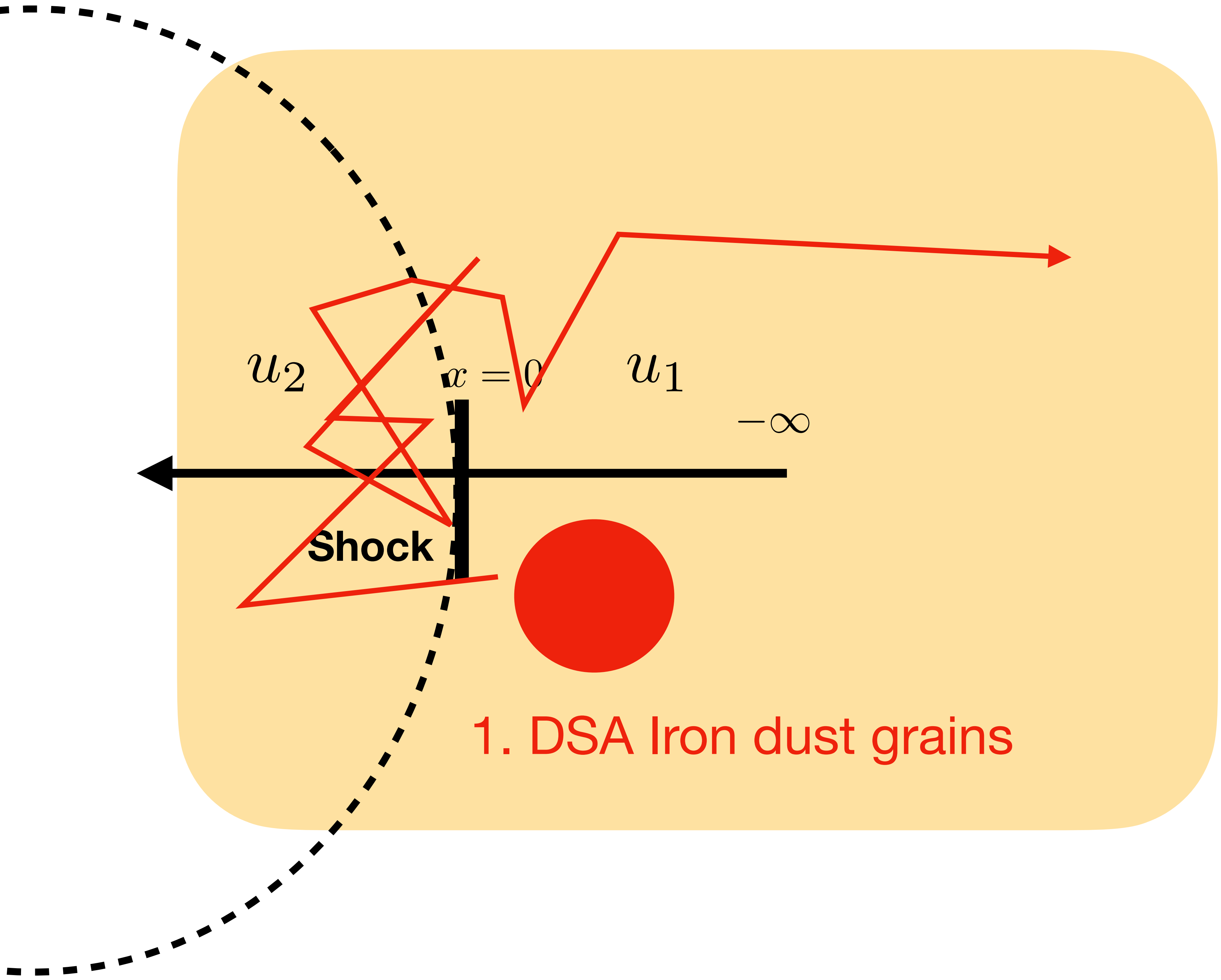
Rigidity of iron dust grains



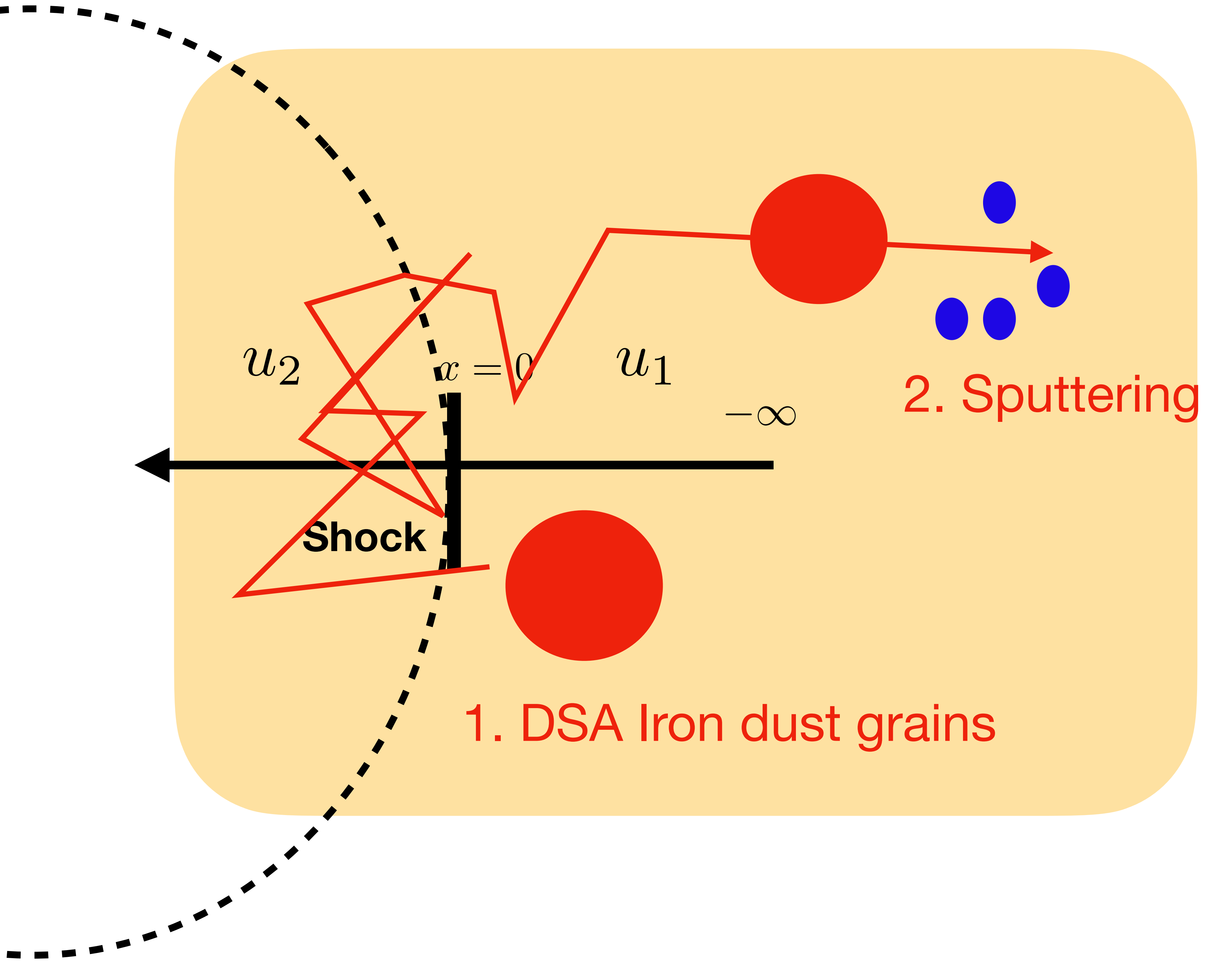
Rigidity of iron dust grains



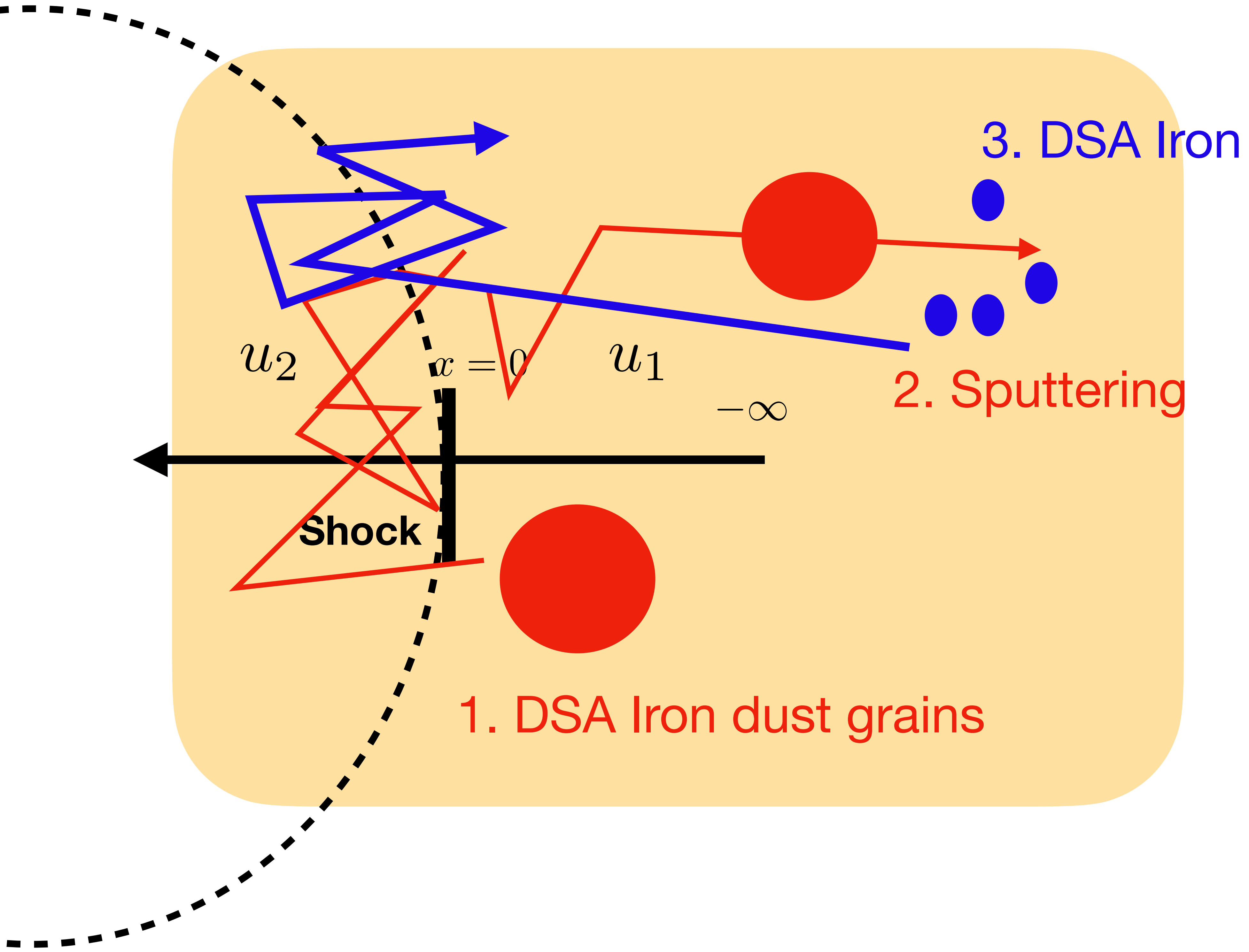
Rigidity of iron dust grains



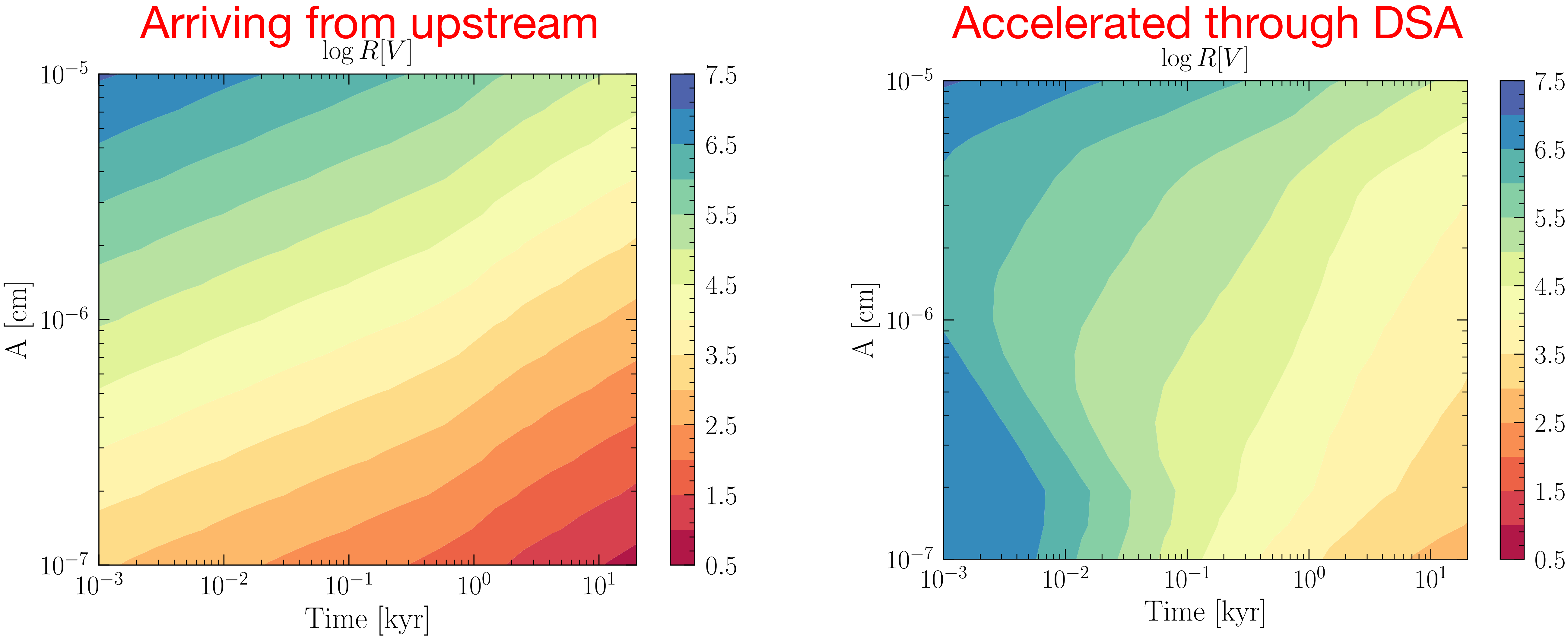
Rigidity of iron dust grains



Rigidity of iron dust grains

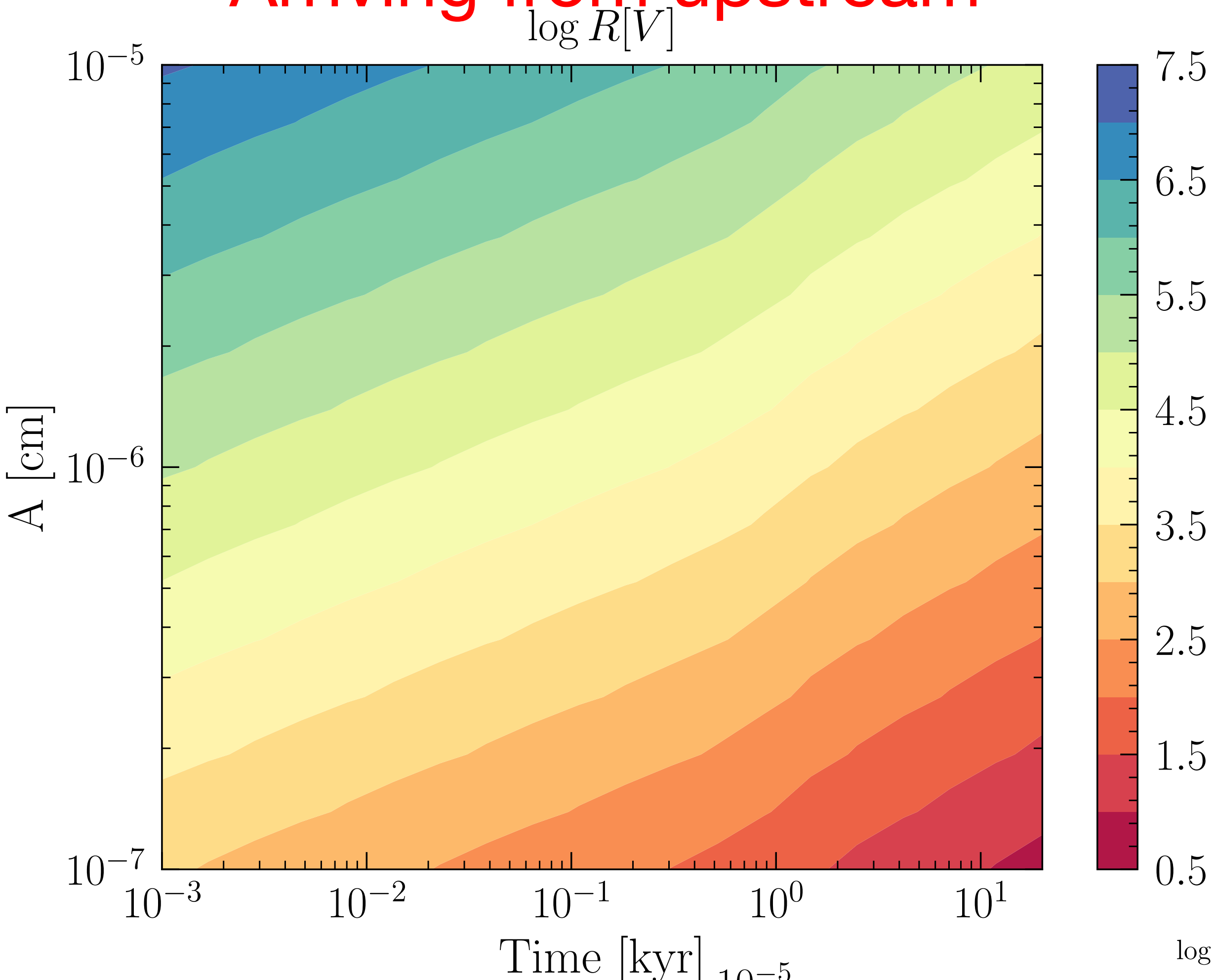


Rigidity of iron dust grains

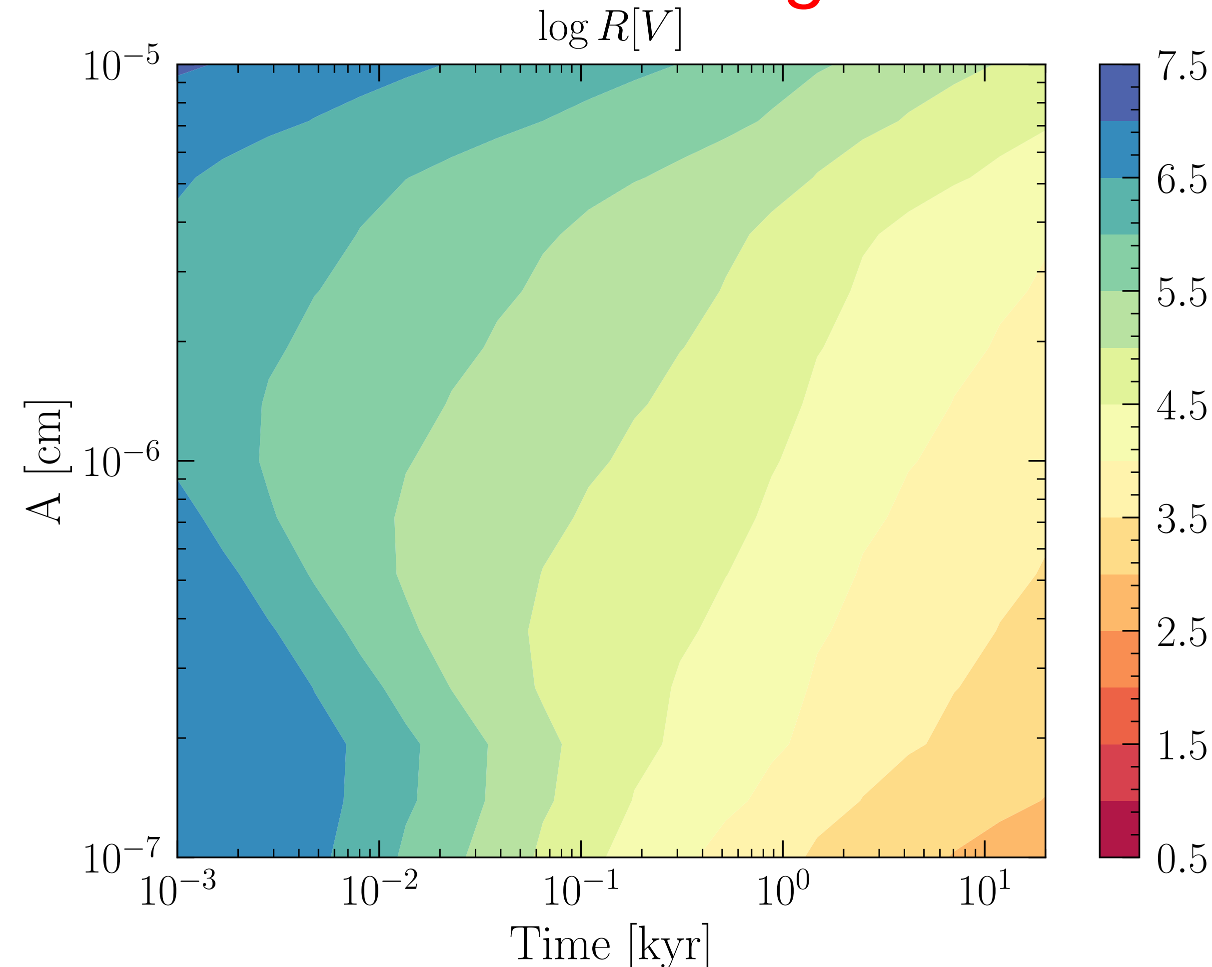


Rigidity of iron dust grains

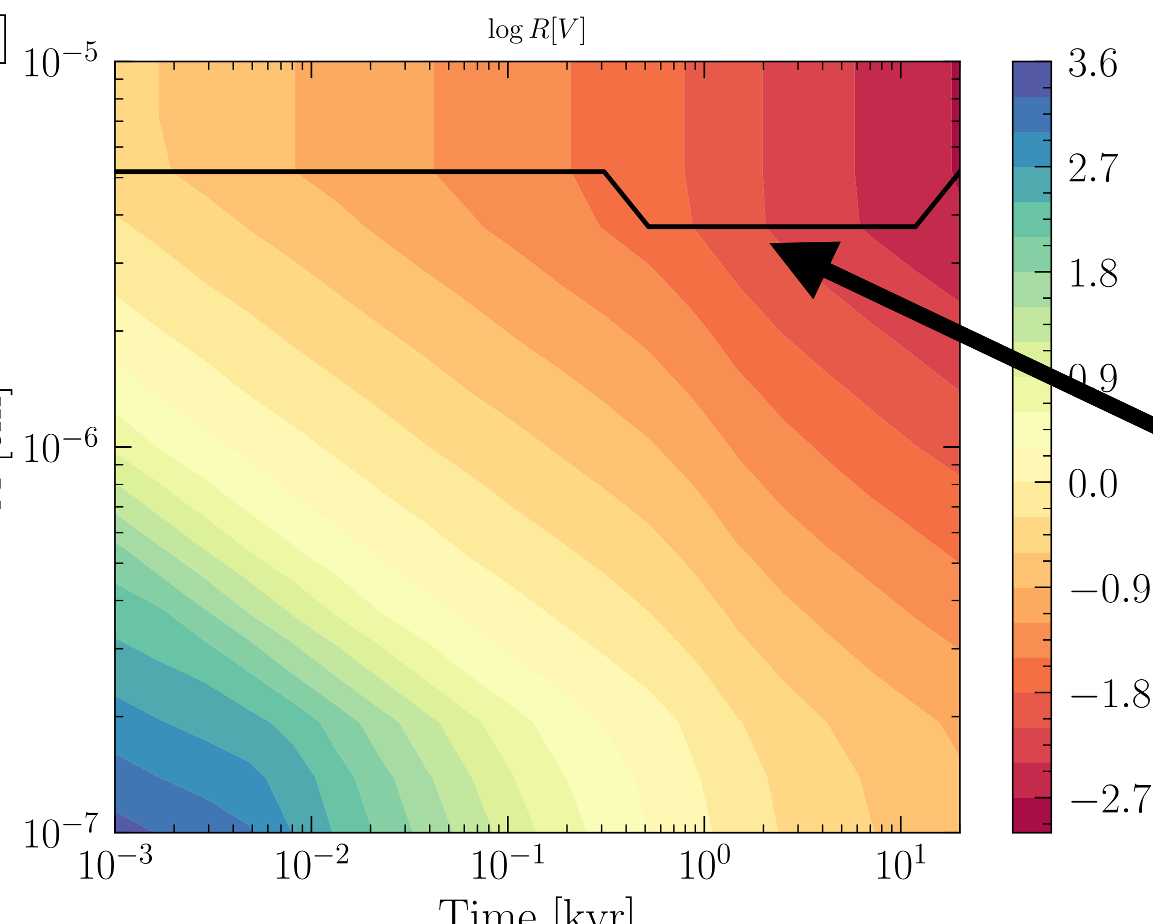
Arriving from upstream



Accelerated through DSA



Rigidity of Iron (sputtered from grains)



Minimum rigidity required for proton to enter DSA

$$p_{\rm inj} \sim 3p_{\rm th}$$

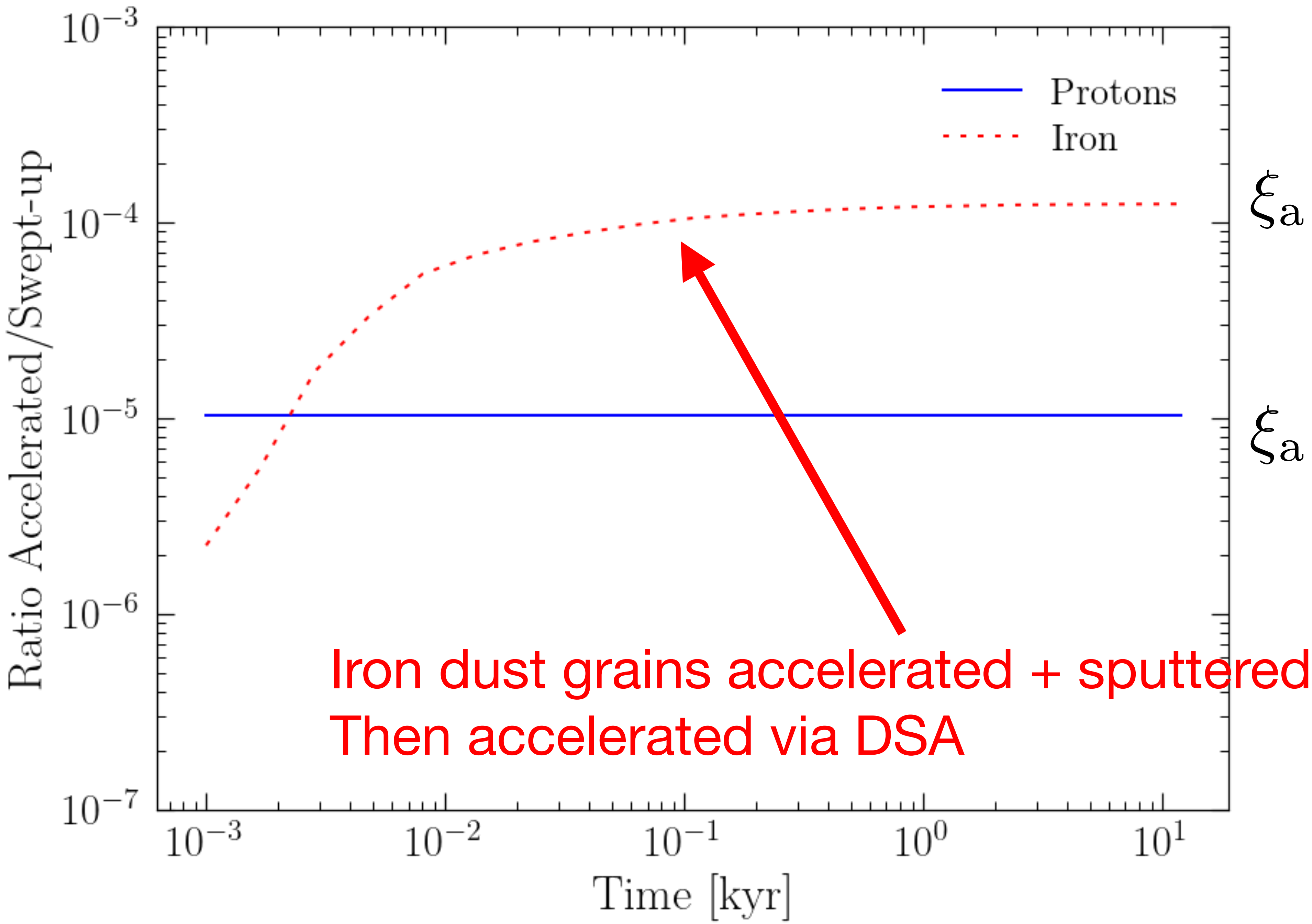
Ratio Iron/proton accelerated

Protons:

$$N_{\rm p}(p) \propto \xi_{\rm CR} n_0$$

Dust grains:

$$N^a(p) \propto \xi_{\rm a} n(a) {\rm d}a$$



Efficiency for smaller grain

$\xi_{\rm a} = 10^{-2}$

$\xi_{\rm a} = 10^{-5}$

Diffusive shock acceleration of dust grains

Conclusions

1. **DSA at SNR shock waves can energize dust grains up to Lorentz factor 10^3 - 10^4 (smaller grains)**

2. **The importance of the charging of grains (survival + Pmax)**

3. **Survival of dust grains in the ISM/ sputtering?**

4. **The distribution of grains in the SNR surroundings**

5. **The enhanced refractory/volatile ratio could be explained if efficiency sufficient**

Consensual pictures

Supernova remnants

must play a role in producing Galactic of CRs, but face issues (exact spectrum accelerated and injected, efficiency)

could be pevatrons (rare and unusual events, or specific environments?)

Massive stars, star clusters, winds

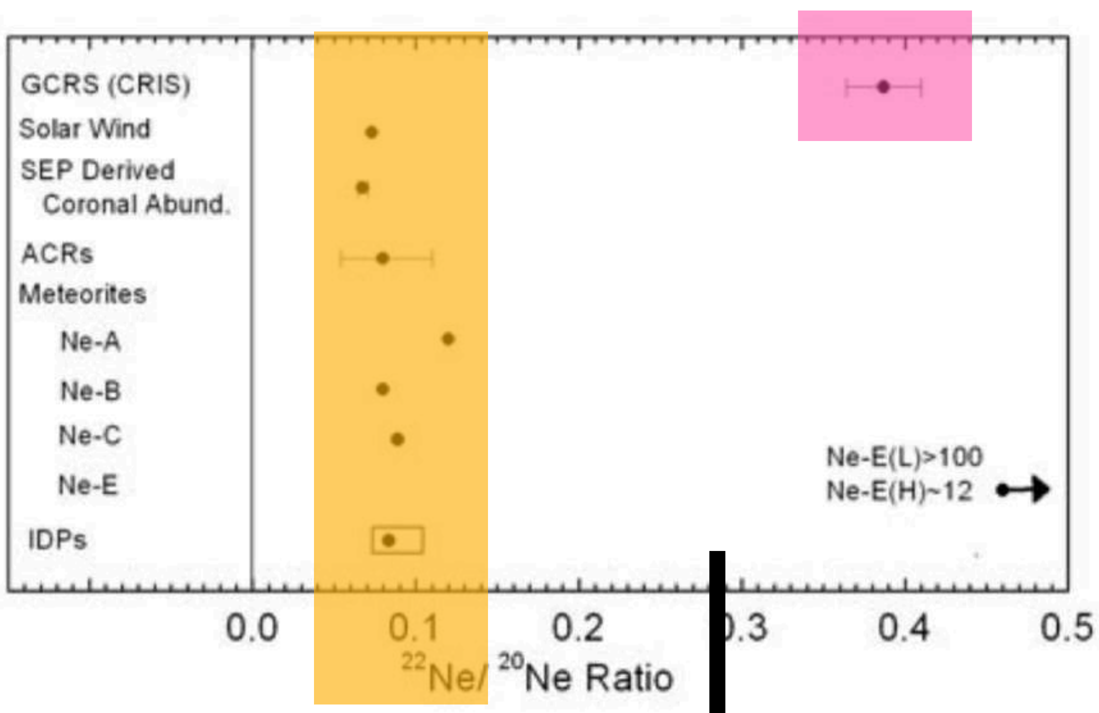
play a role in producing Galactic of CRs

needed to account for CR composition

pevatrons, but efficient enough?

The ^{22}Ne/^{20}Ne ratio

Local ISM (today + 4.5 Gyr ago)



Stellar winds termination shocks

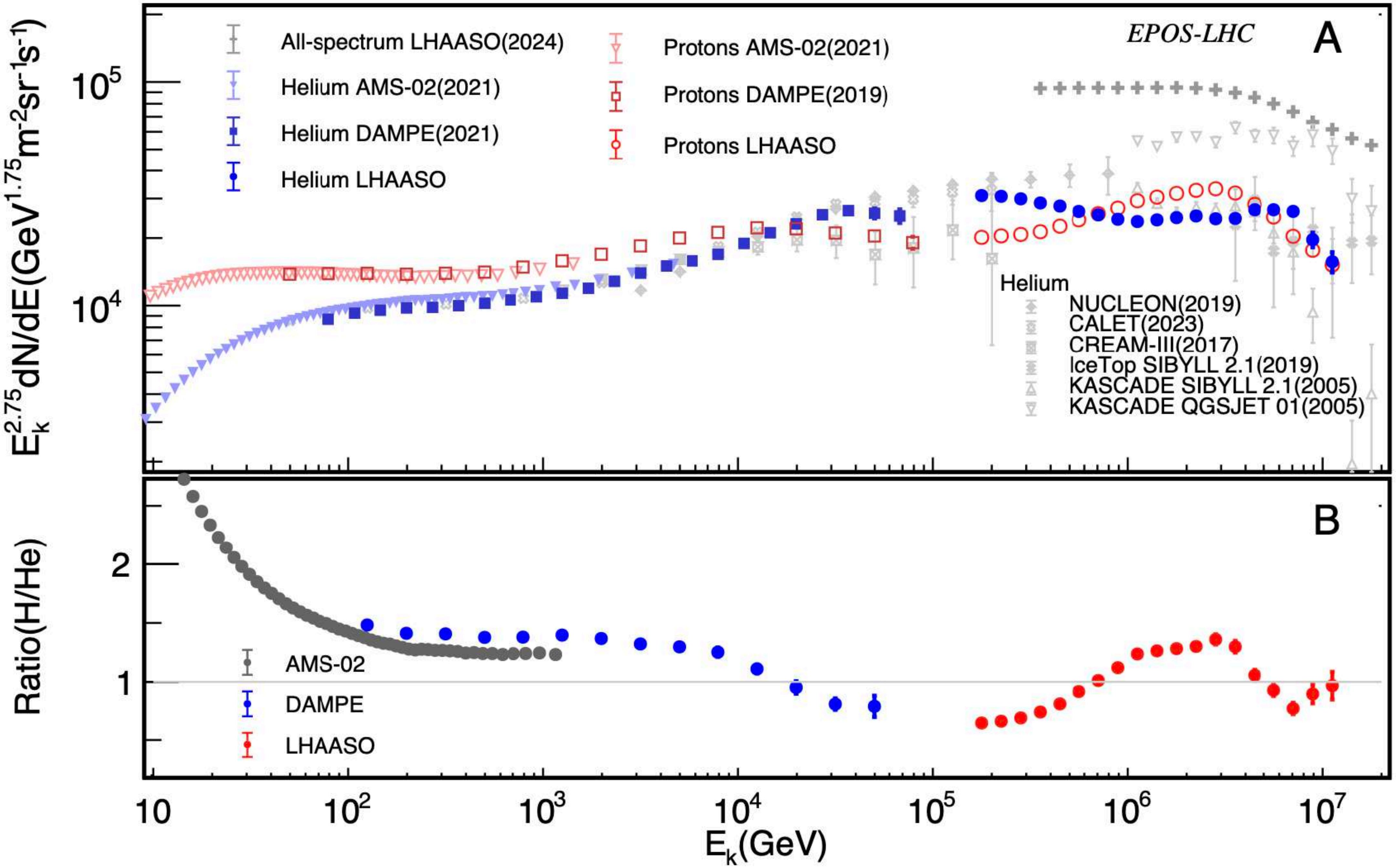
Wolf-Rayet winds (^{22}Ne enriched)

Binns et al. 2005, Prantzos 2012, Tatischeff et al. 2018

Microquasars

definitely pevatrons
contribution lower energy?
superpevatrons?

The proton and Helium « knee »



Complex behavior (not like the smooth all-particle spectrum)
Interpretation: Several sources of Galactic cosmic rays (not only one)

LHAASO Cao et al. 2026

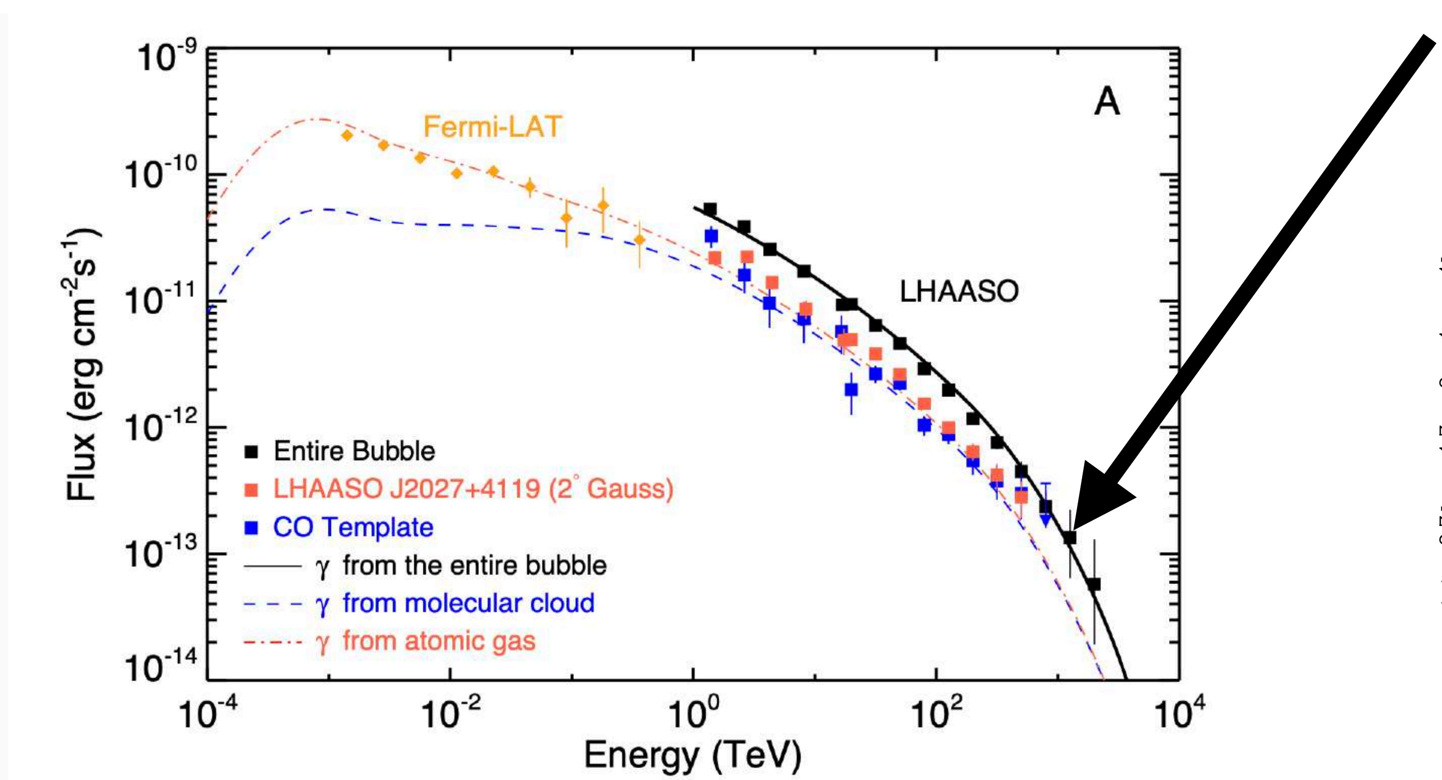
Summary

Supernova remnants, massive stars, star clusters, superbubbles, wind termination shocks, unusual objects

Several open problems (spectrum? Efficiency? Escape around sources?) for all of these candidates: interesting even if not pevatrons!

What does it mean to be a pevatron?

Very sensitive instruments can detect very few PeV particles important for CR: Efficient pevatrons-superpevatrons



Cygnus cocoon LHAASO 2024