COSMIC RAY SPECTRUM IN SN Ia REMNANTS

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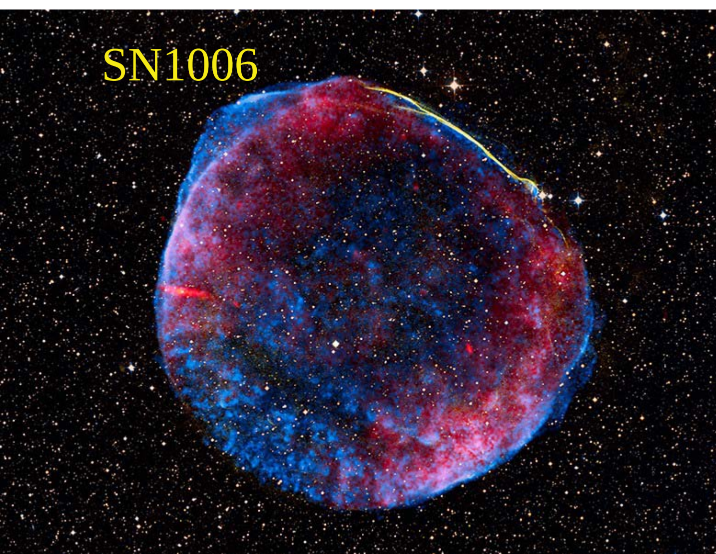
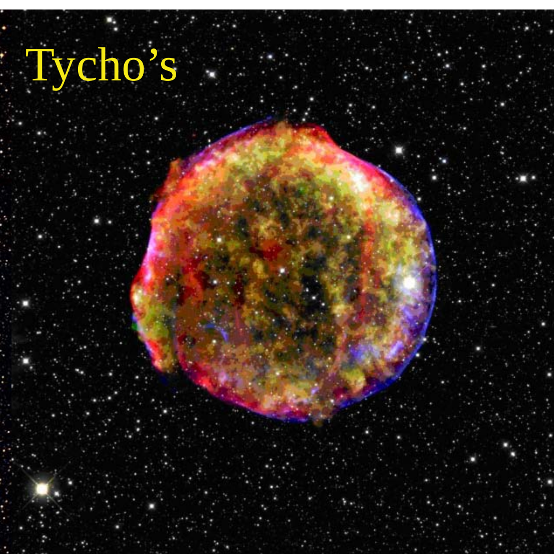
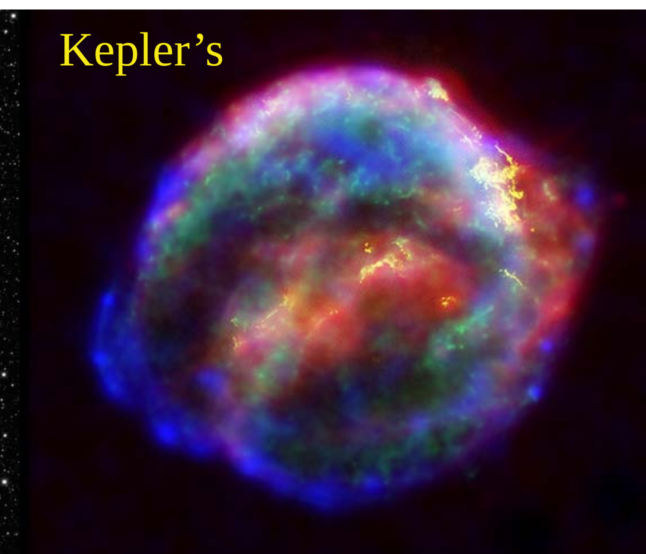
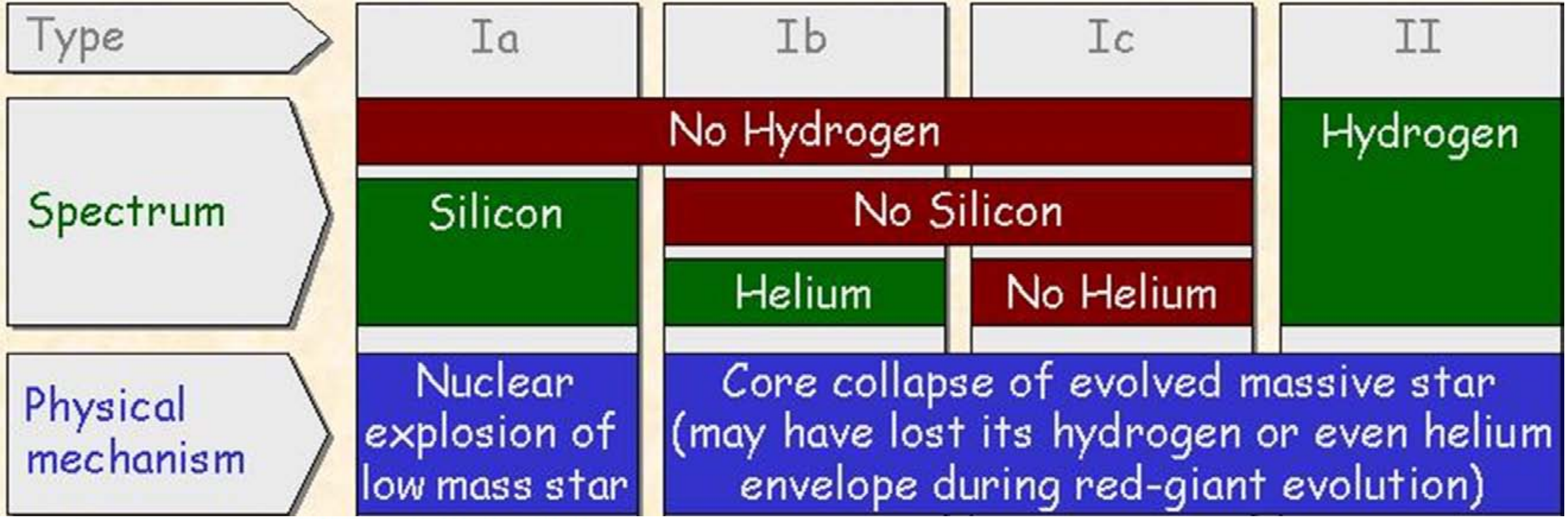
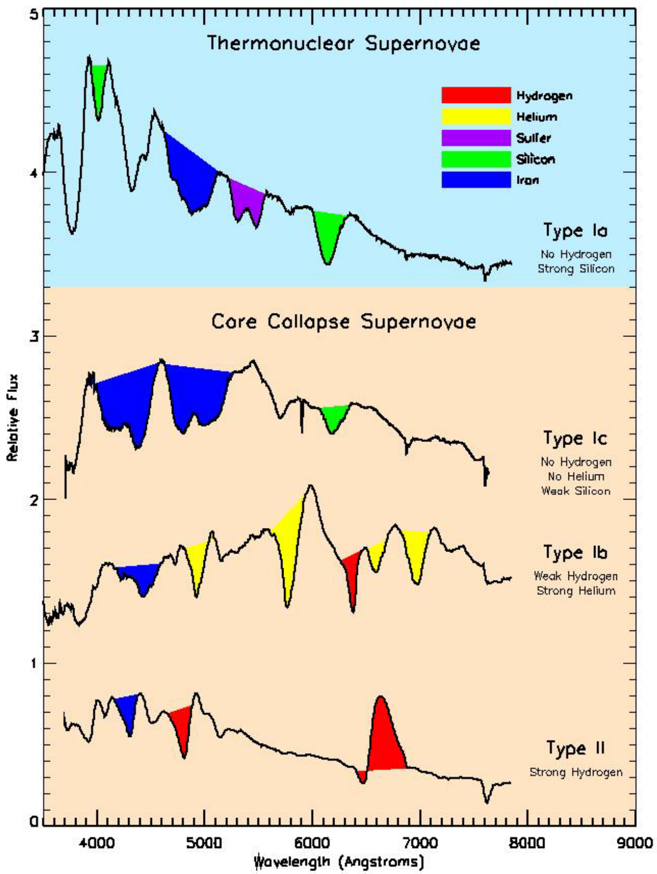










SN Ia (15%): low mass progenitor

→ WD in close binary system

explosion into uniform ISM

Si lines, no H lines

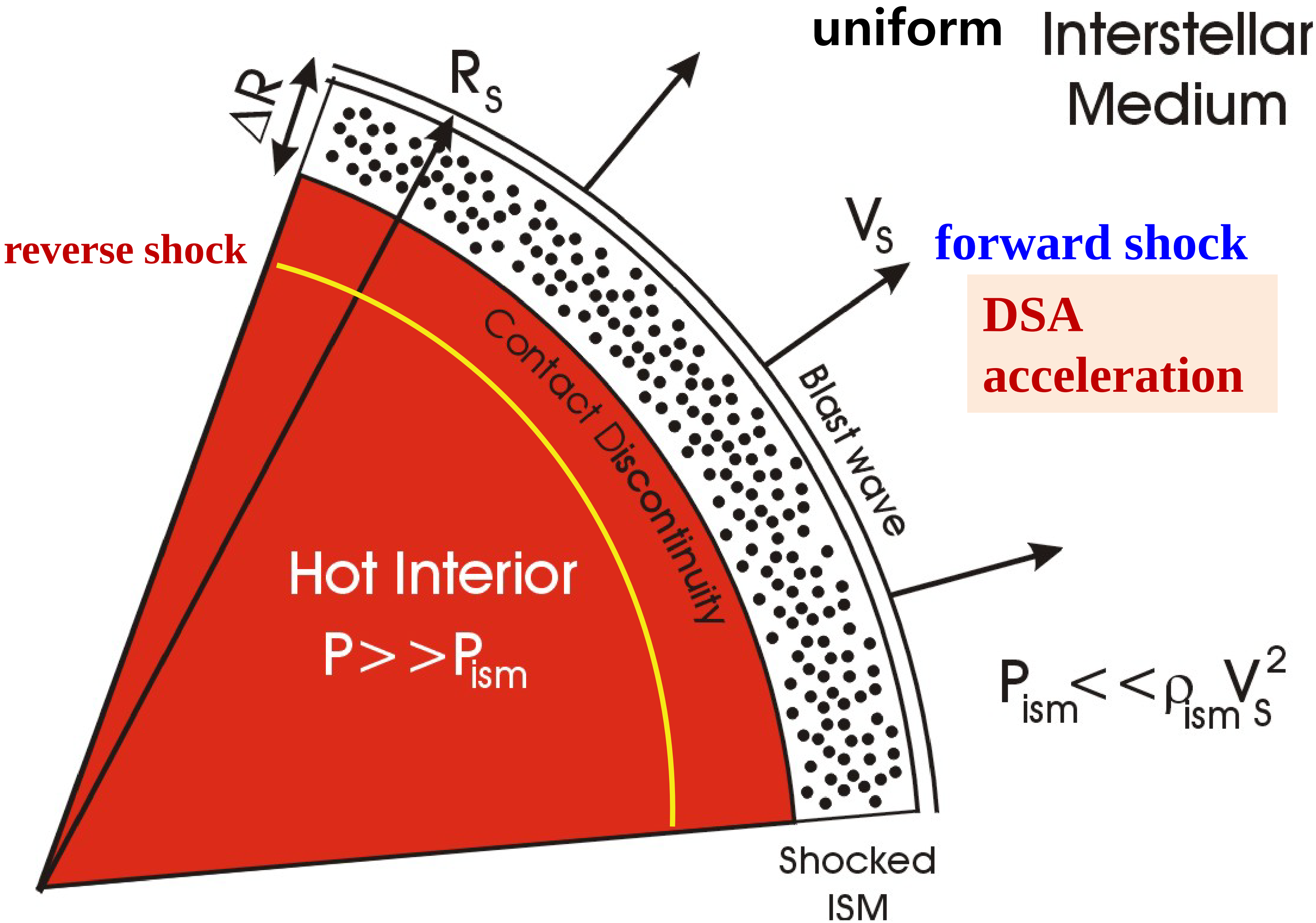
Core collapse SN: explosion into stellar wind bubble

II (70%) : massive progenitors with H envelope

Ib (15%): more massive progenitors that lost H envelope (no H lines)

Ic: most massive progenitors that lost both He and H envelopes (no H & He lines)

Supernova Remnant = Blast wave from SN Ia explosion

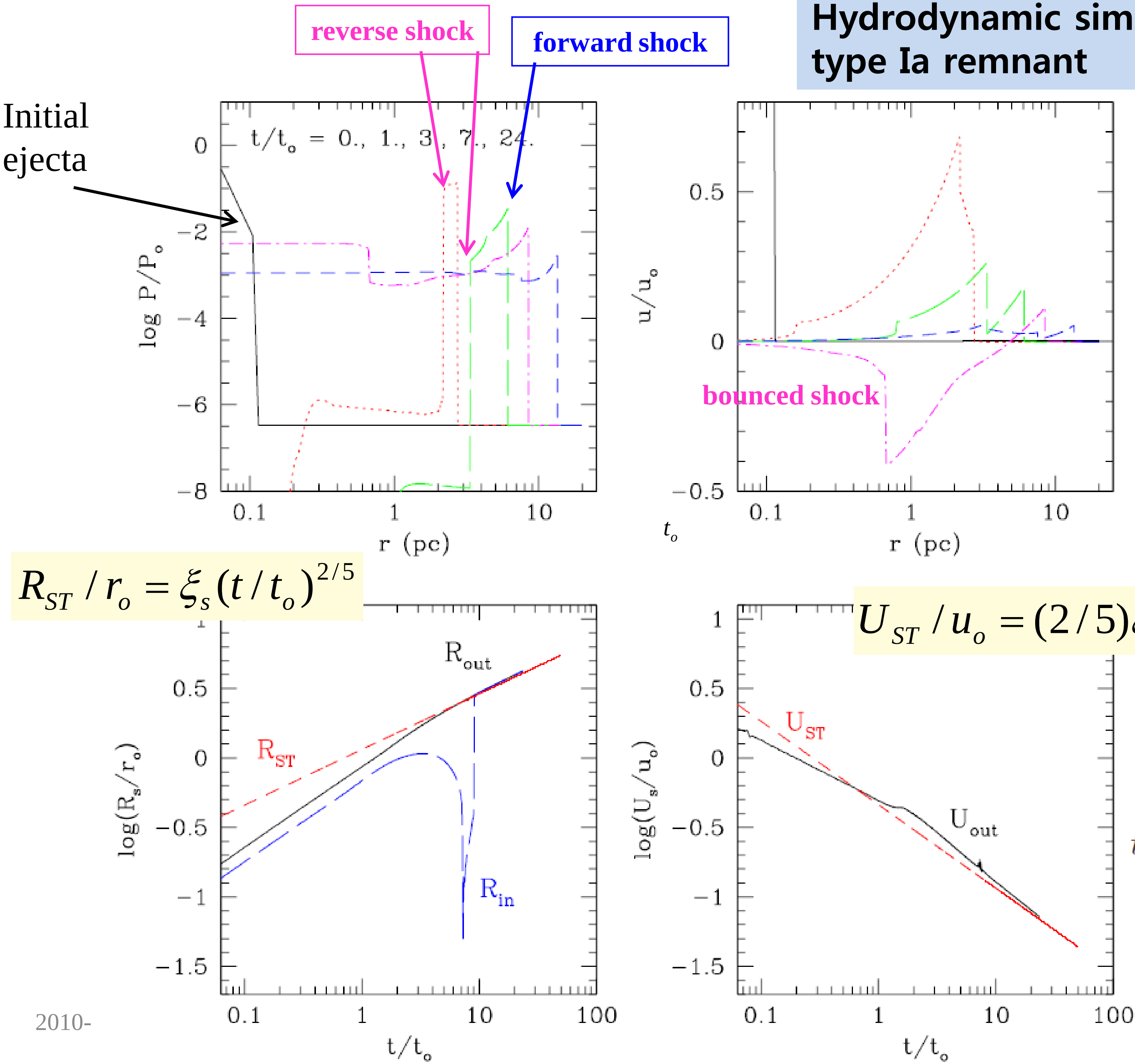


Phases of Shell-type SNRs

- **Supernova explosion** – ejecta $V \sim 10^4$ km/s
- **Free expansion** - ejecta mass > swept-up mass
- **Adiabatic or Sedov** – swept-up mass > ejecta mass
- **Snow-plow or Cooling** – shock front cools, interior also cools
- **Disappearence** – remnant slows to speed of the random velocities in the surrounding medium, merges with ISM

CR acceleration occurs mostly during free expansion and early Sedov stages (t< several 1000 years)

Hydrodynamic simulation of type Ia remnant



$$R_{ST}/r_o = \xi_s (t/t_o)^{2/5}$$

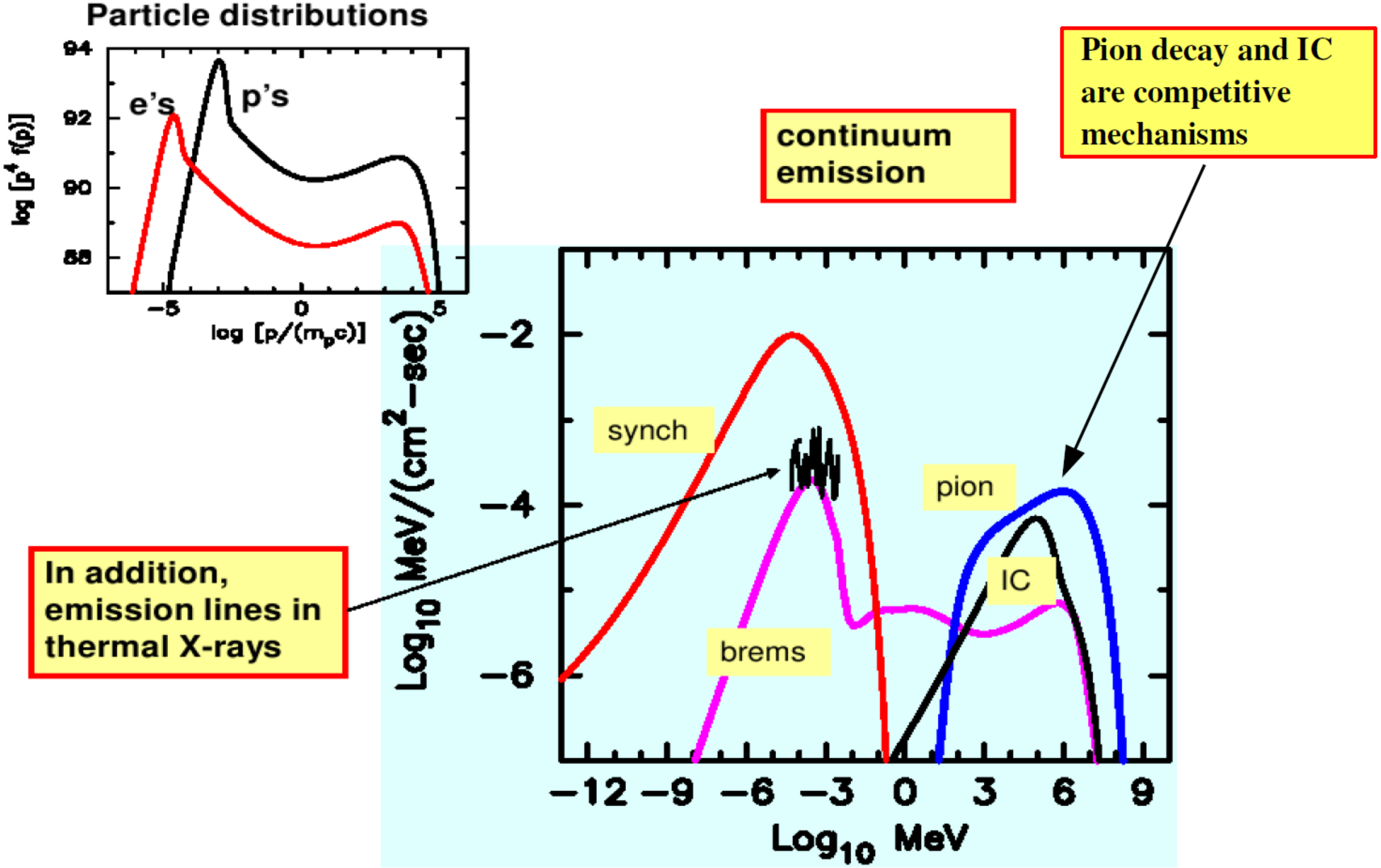
$$U_{ST}/u_o = (2/5)\xi_s (t/t_o)^{-3/5}$$

Sedov-Taylor similarity solution

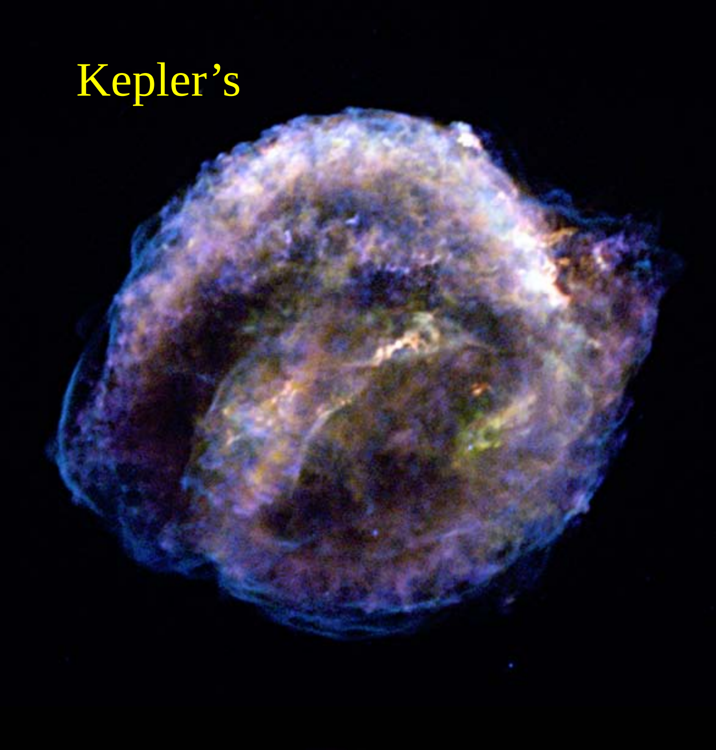
$$t_o = (\rho_o r_o^5/E_o)^{1/2}$$

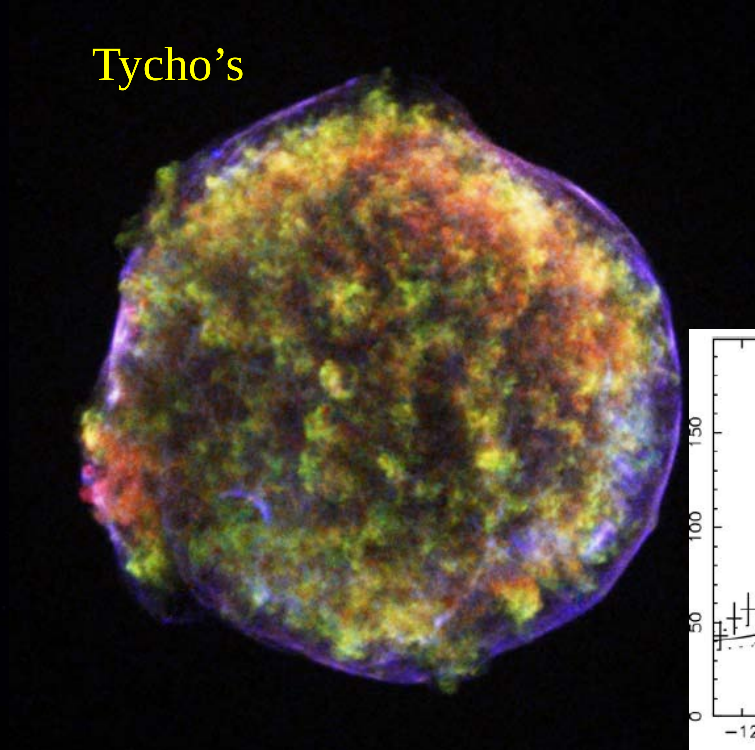
Broadband spectrum of SNRs

- CR e + B field → Synchrotron (radio – X-ray)
- thermal & nonthermal bremsstrahlung
- CR p + p→ π^0 decay → 100 GeV γ-ray
- CR e + CMBR → Inverse Compton scattering →TeV γ-ray

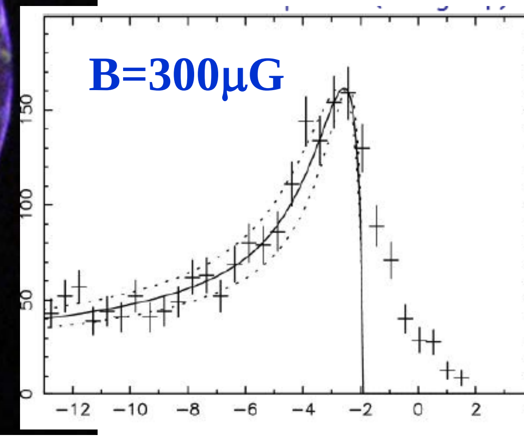


Provide observational evidence and constraints for CR acceleration.



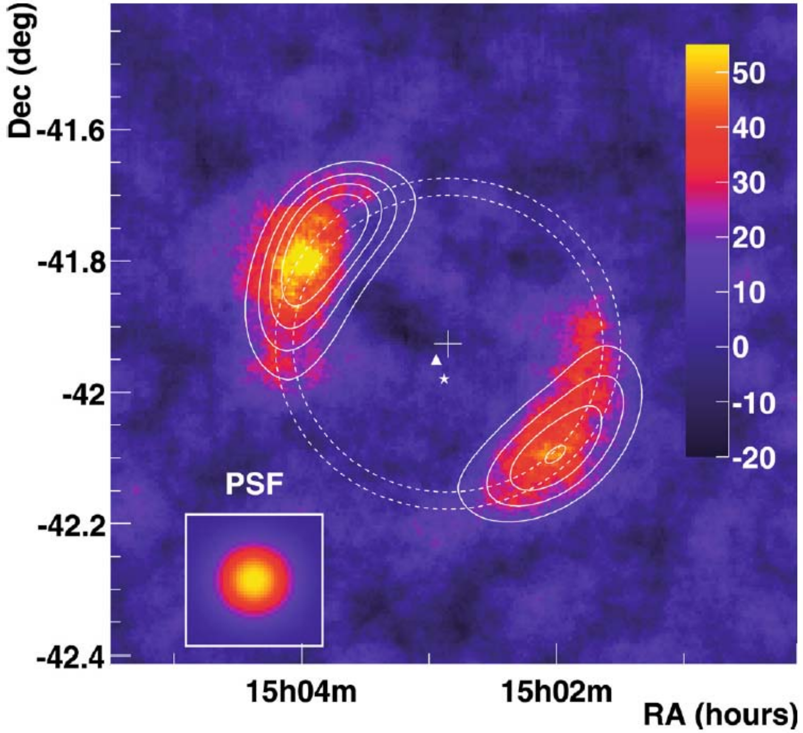


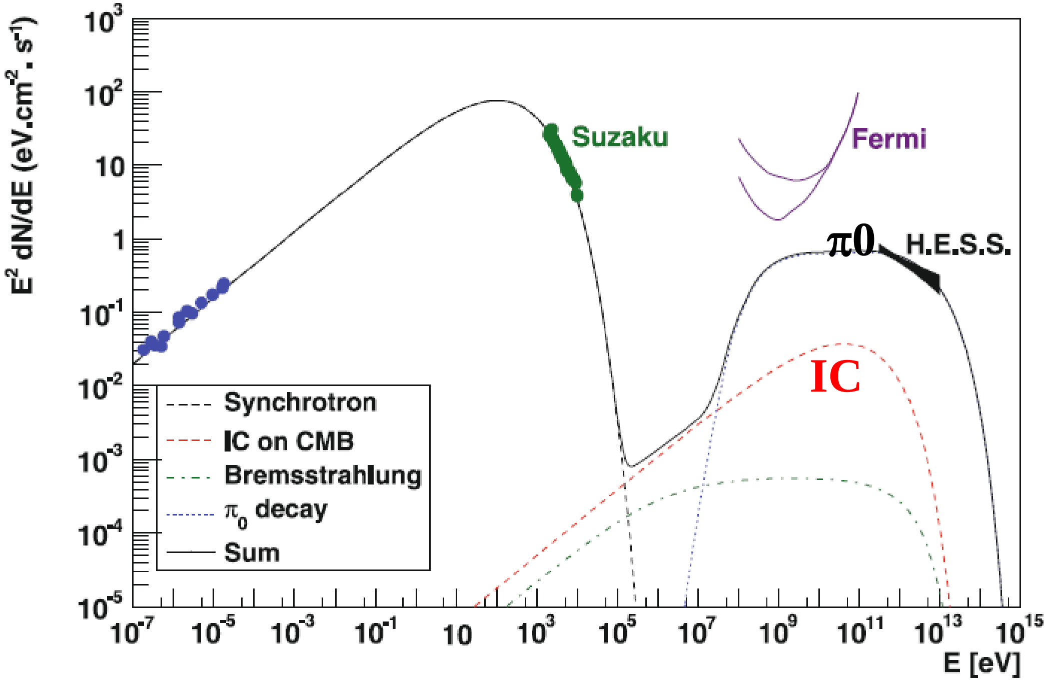
Chandra X-ray Images of SN Ia Remnants



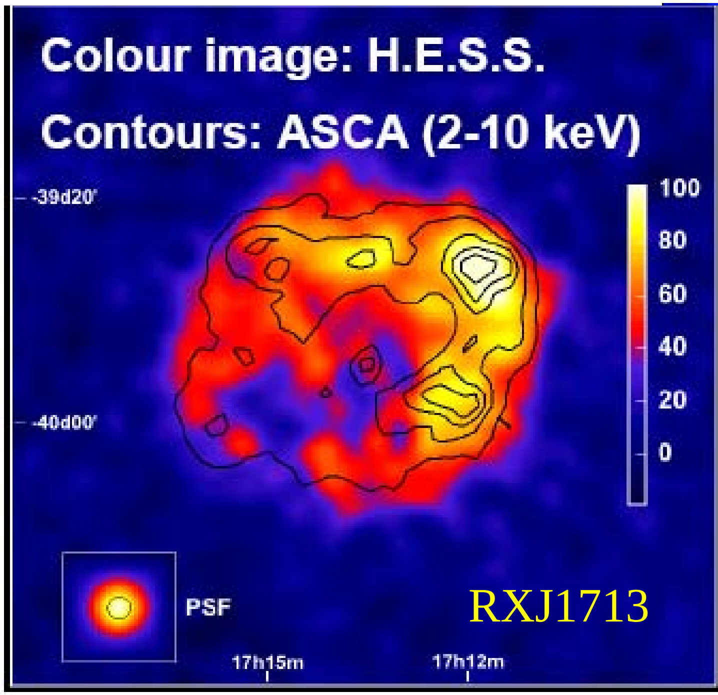
- **thin filaments of nonthermal X-ray indicating fast synchrotron cooling**
- **spectrum: synchrotron continuum**
- **B ~ a few 100 μG (mag. field amplificat.,** Bell & Lucek 2000, Bell 2004)
- **CR electrons with E_{ele} ~ a few 100 TeV**

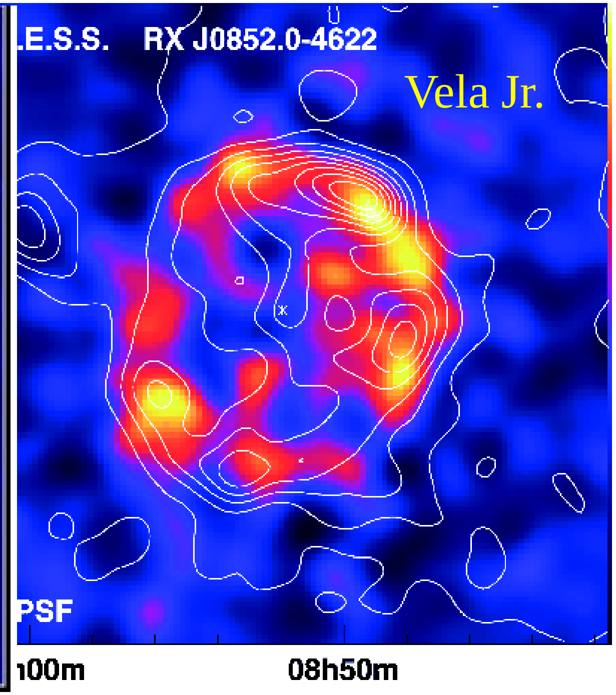
HESS γ-ray image of SN 1006
Acero et al. 2010

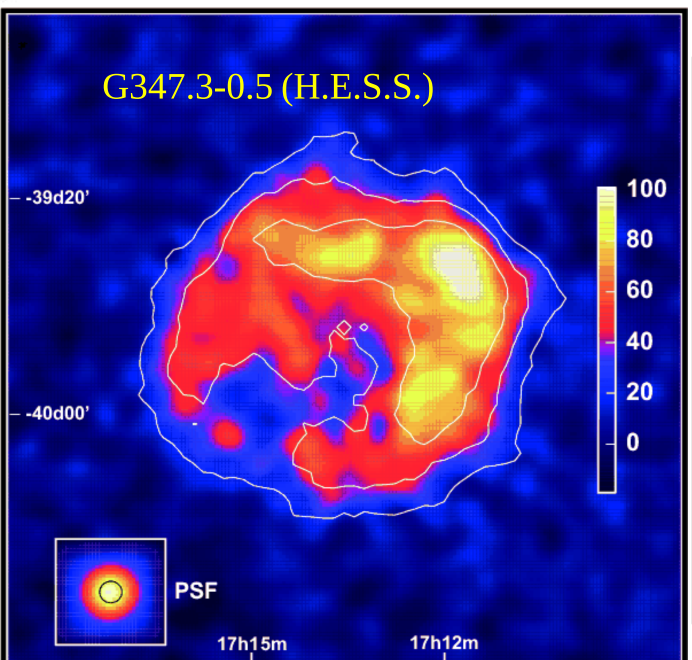


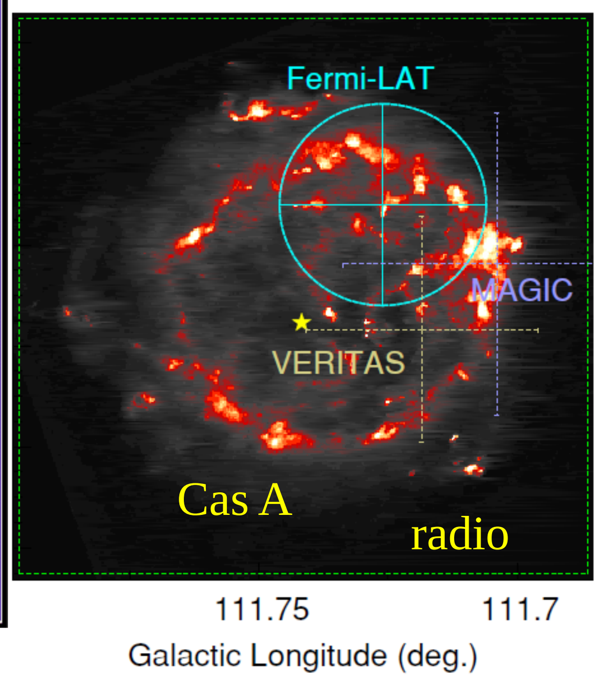


Model fitting → π0 gamma dominates over IC scattering









H.E.S.S. TeV image

Remnants from Core collapse SNe

- **RXJ1713**
- **Velar Jr.**
- **G347.3**

Leptonic (electron IC) vs. Hadronic (p-p coll.→π^0 decay) for TeV γ-ray ?

Evidence for the acceleration of protons.

NLDSA modeling of SNRs: Ne(E), Np(E) → Nonthermal radiation from CRs

proton max. E.: diffusive shock acceleration

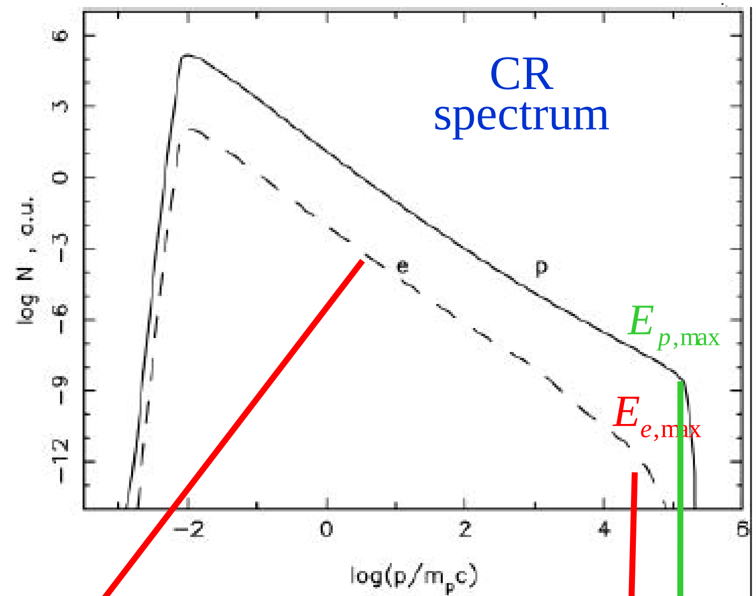
$$t_{acc} \propto \frac{\kappa_p(p)}{u_s^2} \propto \frac{E_p}{Bu_s^2} = t_{age} \Rightarrow E_{p,\max} \propto Bu_s^2\, t_{age}$$

electron max. E.: synchrotron cooling

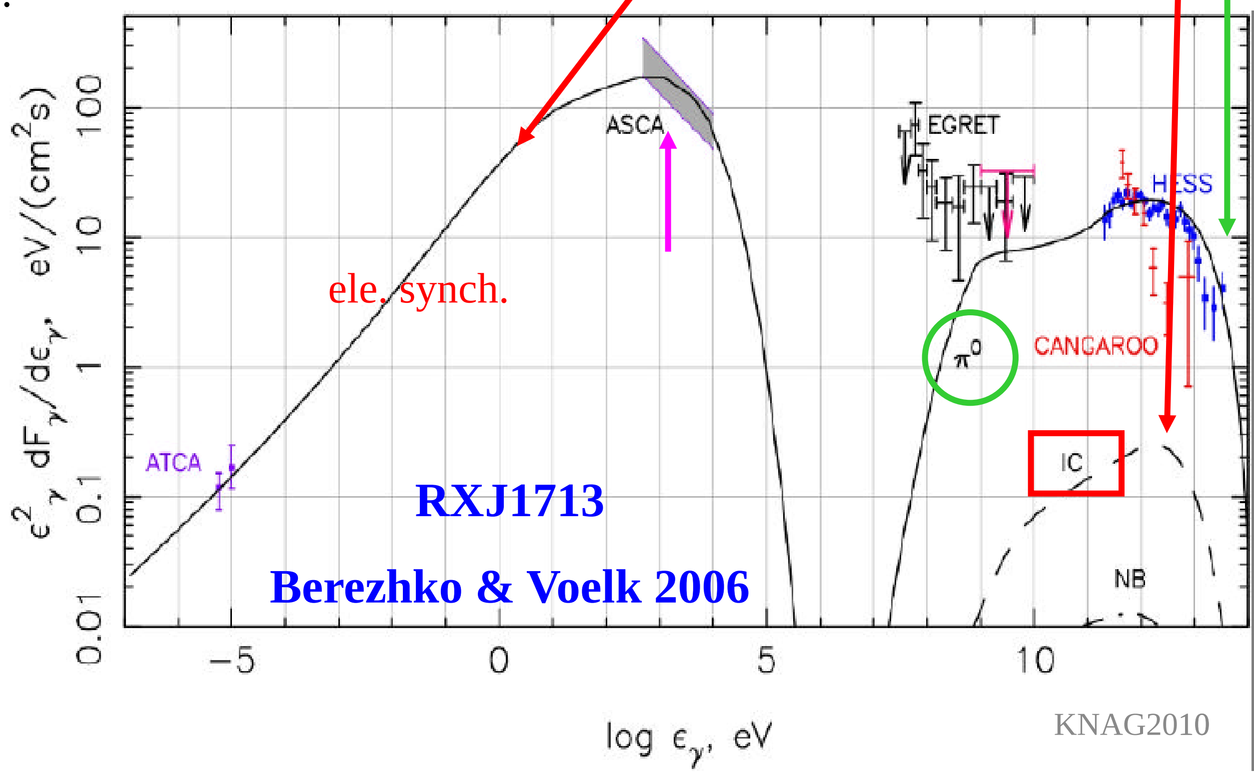
$$t_{acc} \propto \frac{\kappa_e(p)}{u_s^2} \propto \frac{E_e}{Bu_s^2} = t_{sync} \propto \frac{1}{E_e B^2} \Rightarrow E_{e,\max} \propto B^{-1/2}\, u_s$$

synchrotron roll-off frequency:

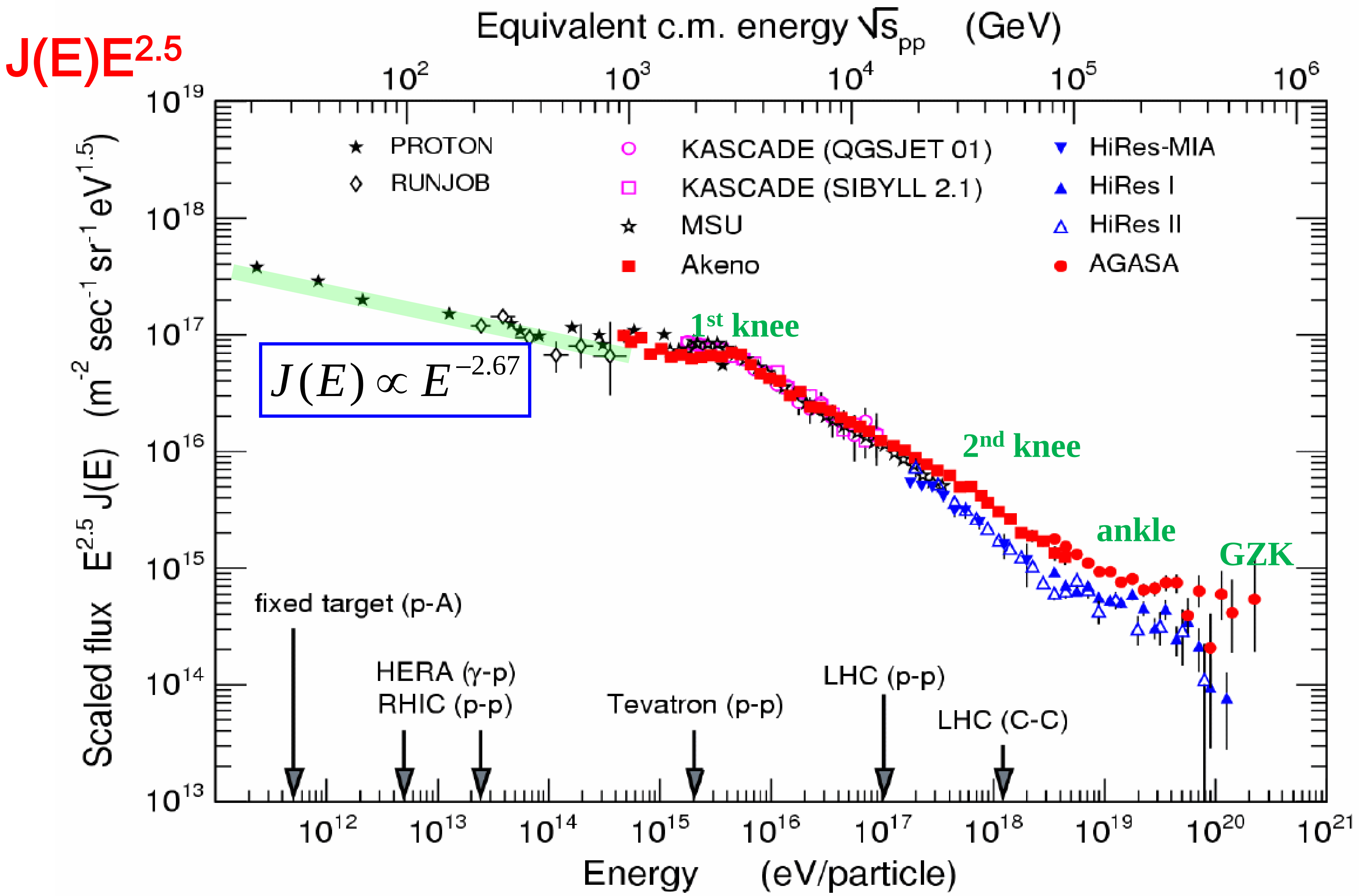
$$\nu_{roll} \propto BE_{e,\max}^2 \propto u_s^2$$

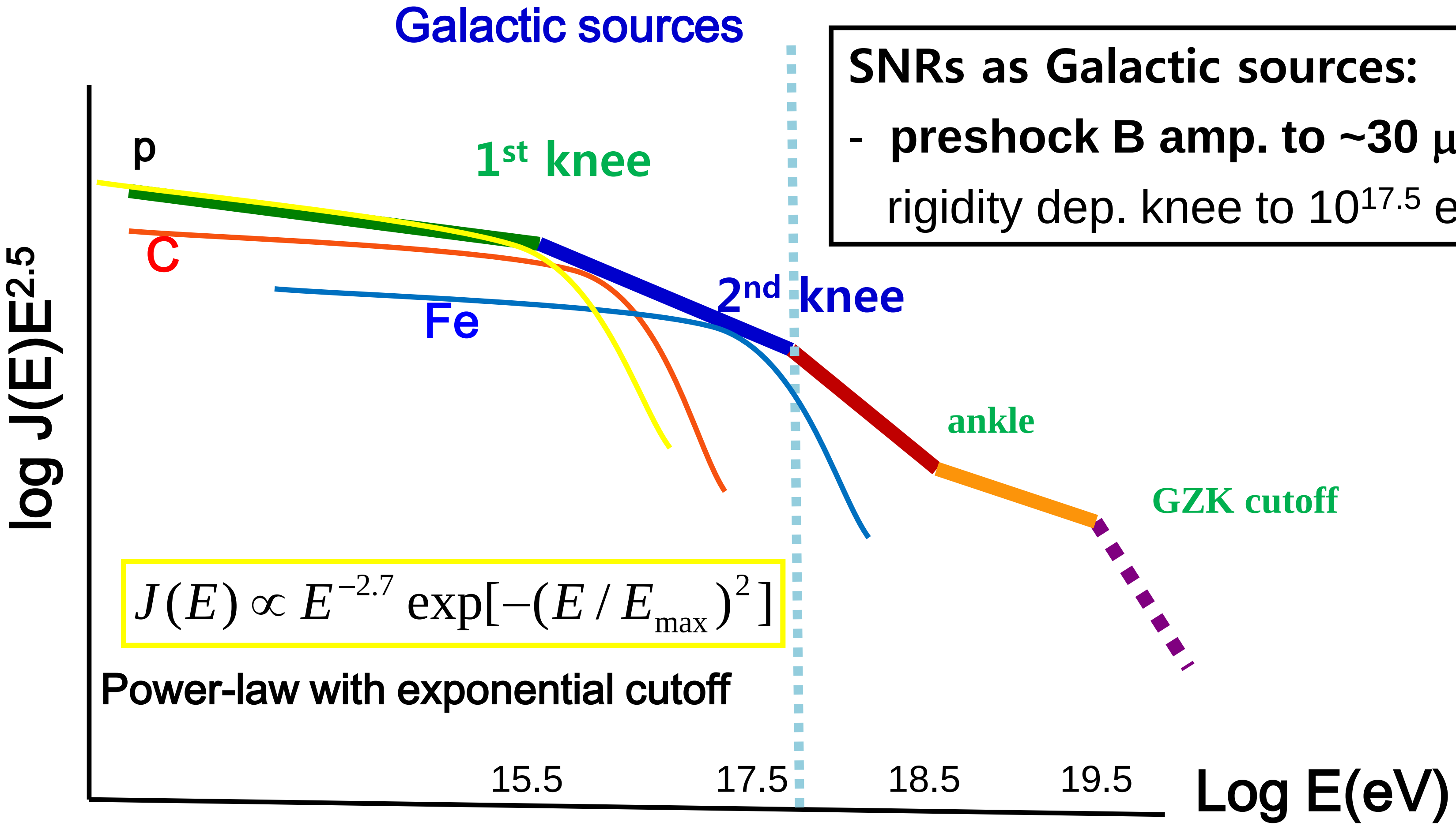


Provide observational evidence and constraints for CR acceleration at SNRs.



Observed CR spectrum near Knee: $J(E) \propto E^{-2.67}$





$$J(E) \propto E^{-2.7} \exp[-(E/E_{max})^2]$$

SNRs as Galactic sources:

- **preshock B amp. to ~30 μG**

  rigidity dep. knee to $10^{17.5}$ eV

$$\text{if } \Lambda(E) \propto E^{-0.6} \Rightarrow N(E) \propto E^{-2.3} \exp[-(E/E_{max})^2]$$

Source spectrum

(Ave et al 2009)

$$E_{max} \approx Z \cdot 10^{15.5} \text{eV} \left(\frac{B_0}{30\mu G}\right)$$

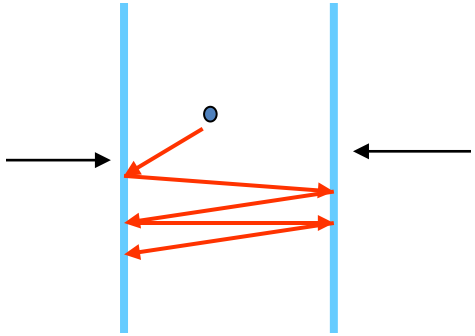
for typical SNIa remnants

" Fermi first order process"

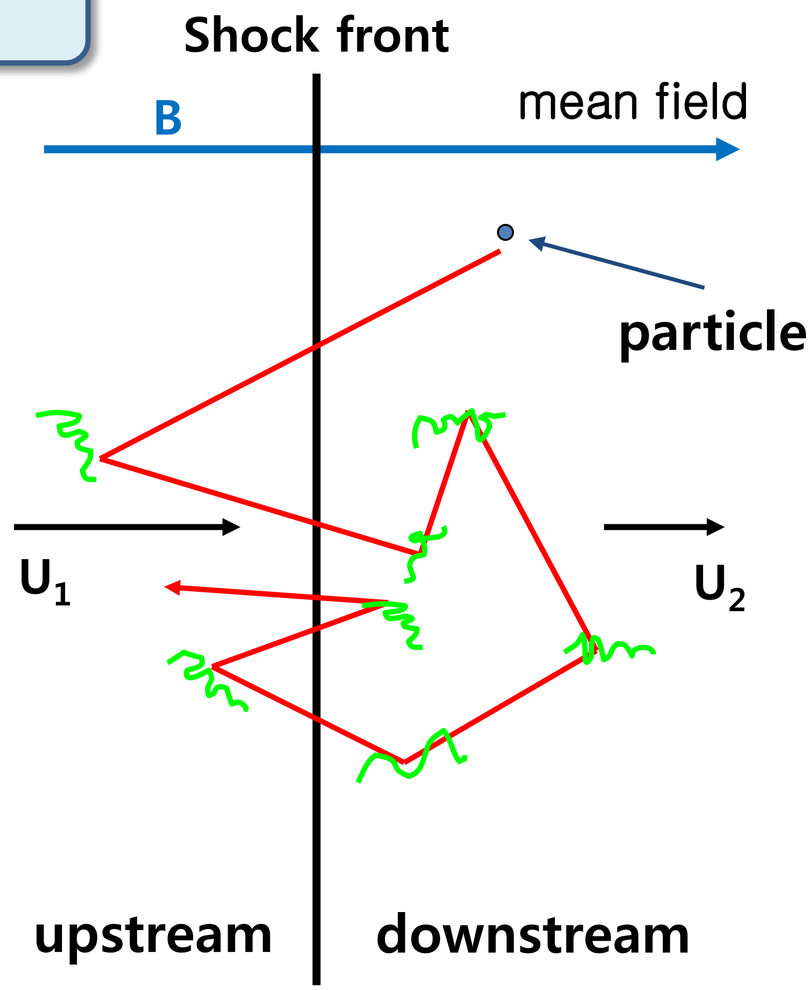
Diffusive Shock Acceleration in quasi-parallel shocks

Alfven waves in a converging flow act as converging mirrors
→ particles are scattered by waves
→ cross the shock many times

$$\frac{\Delta p}{p} \sim \frac{u_1 - u_2}{v} \text{ at each shock crossing}$$



converging mirrors



shock rest frame

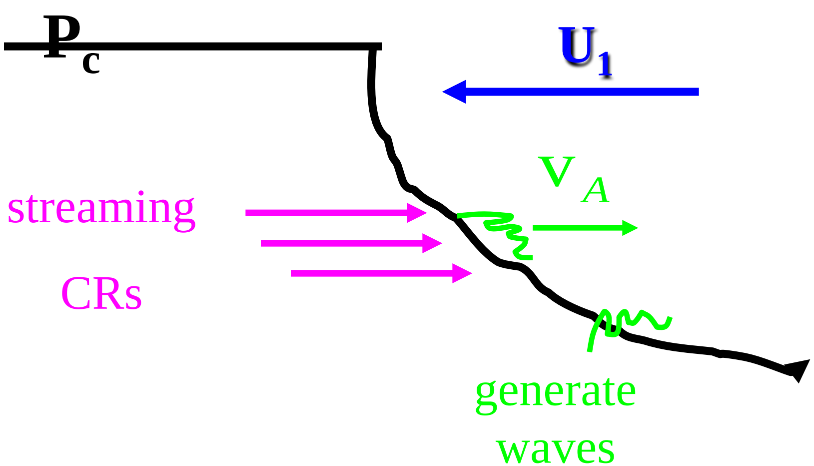
Diffusion-Convection Eq with wave drift & dissipation

$$\frac{\partial f}{\partial t} + (u+u_w)\frac{\partial f}{\partial x} = \frac{1}{3}\frac{\partial}{\partial x}[(u+u_w)]\, p\frac{\partial f}{\partial p} + \frac{\partial}{\partial x}[\kappa(x,p)\frac{\partial f}{\partial x}] + Q(x,p)$$

where $u_w = \mathrm{v}_A$ in upstream, $u_w = 0$ in downstream,

$\mathrm{v}_A = \mathrm{B}/\sqrt{4\pi\rho}$ is Alfven speed.

$W = -\mathrm{v}_A \frac{\partial P_c}{\partial r}$: Gas heating due to wave disspation



- **Waves drift upstream with** $\mathrm{v}_A = u_w$
- **Wave dissipate energy & heat the gas.**
- **CRs are scattered and isotropized in the wave frame rather than the gas frame** $\Rightarrow u + u_w$

→smaller Δu

→ less efficient acceleration

Prediction of DSA theory in test particle limit

(when non-linear feedback due to CR pressure is insignificant)

$$\frac{\Delta \mathrm{p}}{\mathrm{p}} \sim \frac{\mathrm{u}_1 - \mathrm{u}_2}{\mathrm{v}}, \quad p_{\mathrm{esc}} = \frac{\mathrm{u}_2}{\mathrm{v}} (\text{escape prob.}) \Rightarrow f(p) \propto p^{-q}$$

$$q_{test} = \frac{3u_1}{u_1 - u_2} \rightarrow 4 \text{ for strong shocks}$$

$$f(p) \propto p^{-4} \Rightarrow N(E) \propto E^{-2}$$

Considering Alfvenic drift in the precursor

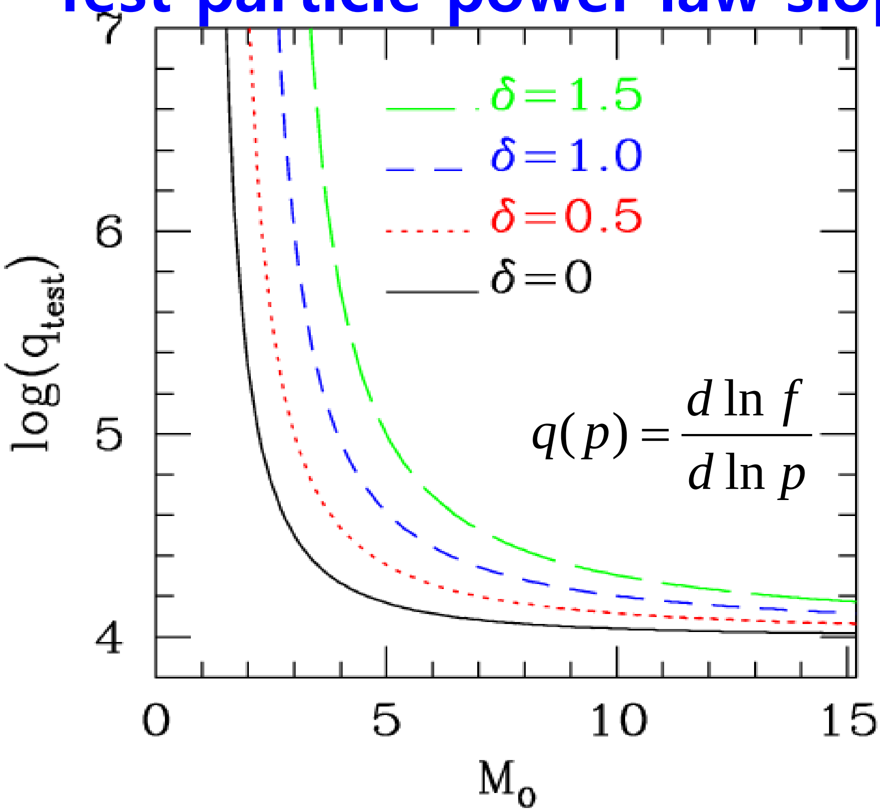
$$q_{test} = \frac{3(u_1 - \upsilon_A)}{u_1 - \upsilon_A - u_2} > 4, \quad \text{softer than } p^{-4}$$

If DSA is efficient → shock structure is modified by CR pressure.

$$q(p) \approx \frac{3(U(p) - \upsilon_A)}{U(p) - \upsilon_A - u_2}$$

U(p) is the precursor velocity that particles with *p* experience.

Test-particle power-law slope with Alfvenic Drift effect



$$q_{test} = \frac{3(u_1 - v_A)}{(u_1 - v_A - u_2)}$$

$$\delta = \frac{v_A}{c_s} = \frac{B/\sqrt{4\pi\rho}}{\sqrt{\gamma \cdot P/\rho}}$$

for coronal phase of ISM:

$T_0 = 10^6$ K, $n_H = 3\times10^{-3}$ cm^{-3},

$c_s \approx 150$ km/s

$v_A \approx 170$ km/s for $B = 5\mu$G

$\delta \sim 1$

For $V_s \le 2.3\times10^3$ km/s ($M_s \le 15$): **test-particle slope can be softer than 4 in the hot phase of ISM**

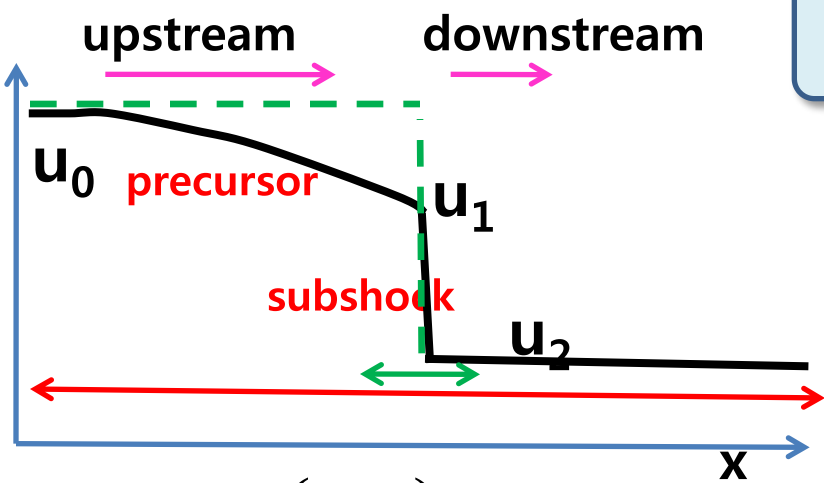
Recall $J(E) \propto E^{-2.7}$: all ptl spectrum at Earth (TRACER)

with mean propagation length $\Lambda \propto E^{-0.6}$

source spectrum at SNRs : $N(E) \propto E^{-\alpha}$, $\alpha = q - 2 \approx 2.3\text{-}2.4$ (Ave et al 2009)

Also γ-ray spectrum favors $\alpha \approx 2.3$ in some SNRs (eg. Cas A, *Fermi* LAT 2009)

CR modified shock structure



for $\kappa(p) = \kappa^* p^{\alpha}$

momentum dependent

- Particles with different p experience different Δu.
- Alfven waves drift w. r. t. bulk plasma

$$l_{diff}(p_{\min}) = \frac{\kappa(p_{\min})}{u_s}$$ → feel σ_s

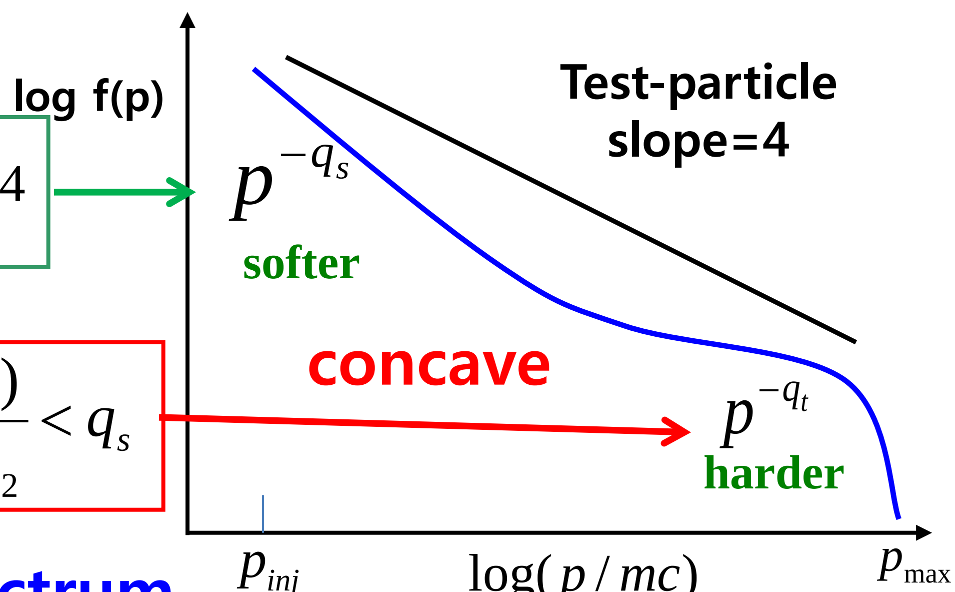
$$l_{diff}(p_{\max}) = \frac{\kappa(p_{\max})}{u_s}$$ → feel σ_t

across the subshock

$$q_s = \frac{3 \cdot (u_1 - v_A)}{u_1 - v_A - u_2} > 4$$

across the total shock

$$q_t = \frac{3 \cdot (u_0 - v_A)}{u_0 - v_A - u_2} < q_s$$



Alfvenic drift → softer spectrum

Phenomenological Model for Thermal Leakage Injection

Injection momentum

$$p_{inj} \approx 1.17 m_p u_2 (1 + \frac{1.07}{\varepsilon_B}) = Q_{inj}\, p_{th}$$

$$p_{th} = \sqrt{m_p k_B T_2}$$

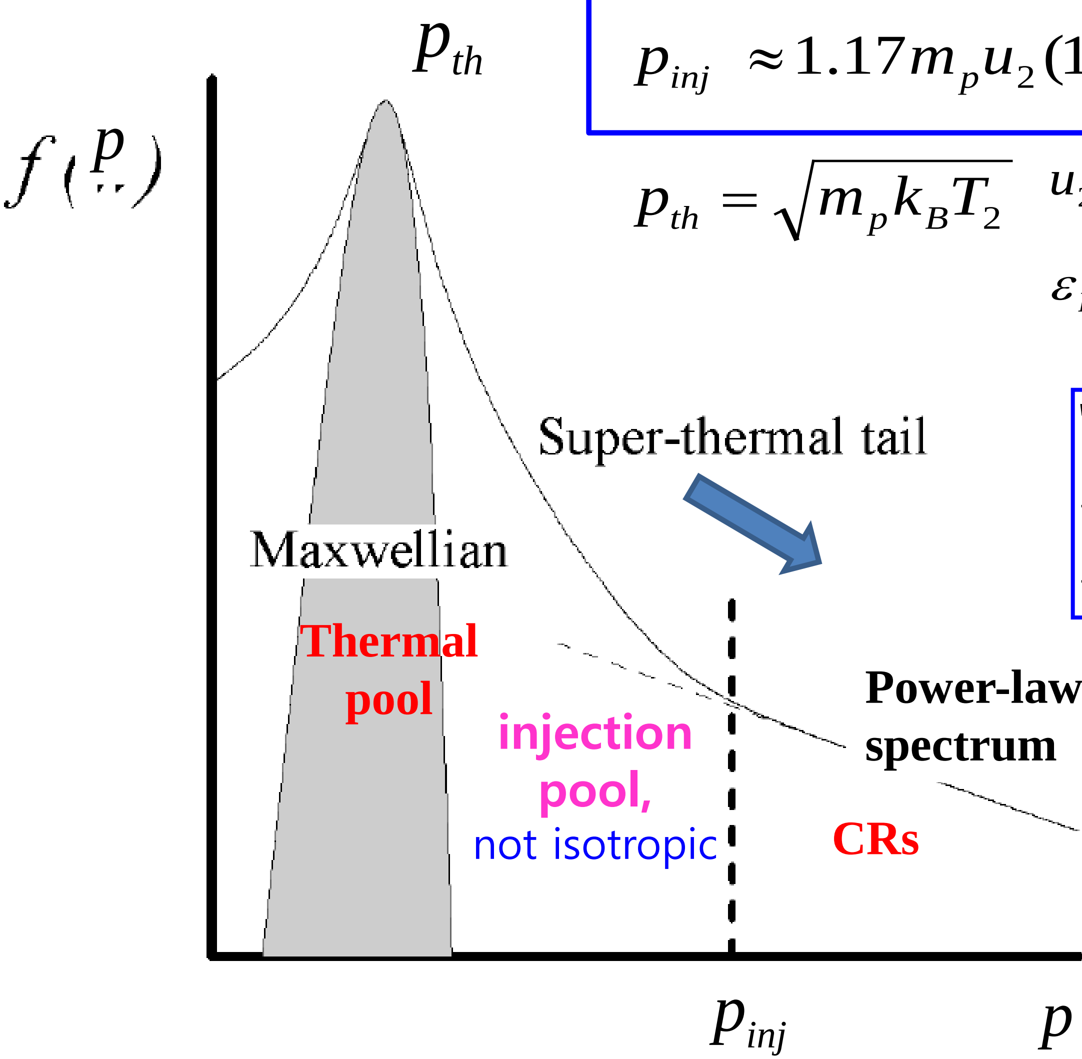
$u_2(M_0) =$ postshock vel

$$\varepsilon_B = \frac{B_0}{B_\perp} = \frac{\text{mean field}}{\text{turbulent field}}$$

"*effective*" p_{inj} depends on M_0 & ε_B

$\rightarrow$ more turbulent $B_\perp$: smaller ε_B

$\rightarrow$ weaker shock : larger u_2



$$f(p) = f_0 \cdot (p / p_{inj})^{-q_s}$$

$$f_0 = \frac{n_2}{\pi^{1.5} p_{th}^3} \exp(-Q_{inj}^2)$$

Thermal Maxwell

CRASH code in 1D spherical geometry

in a co-expanding frame which expands with the forward shock.

$$\frac{\partial\tilde{\rho}}{\partial t}+\frac{1}{a}\frac{\partial(\upsilon\tilde{\rho})}{\partial x}=-\frac{2}{ax}\tilde{\rho}\upsilon$$

$$\frac{\partial(\tilde{\rho}\upsilon)}{\partial t}+\frac{1}{a}\frac{\partial(\tilde{\rho}\upsilon^2+\tilde{P}_g+\tilde{P}_c)}{\partial x}=-\frac{2}{ax}\tilde{\rho}\upsilon^2-\frac{\dot{a}}{a}\tilde{\rho}\upsilon-\ddot{a}x\tilde{\rho}$$

$$\frac{\partial(\tilde{\rho}\tilde{e}_g)}{\partial t}+\frac{1}{a}\frac{\partial(\tilde{\rho}\tilde{e}_g\upsilon+\tilde{P}_g\upsilon+\tilde{P}_c\upsilon)}{\partial x}=-\frac{\upsilon}{a}\frac{\partial\tilde{P}_c}{\partial x}-\frac{2}{ax}(\tilde{\rho}\tilde{e}_g\upsilon+\tilde{P}_g\upsilon)$$

$$-2\frac{\dot{a}}{a}\tilde{\rho}\tilde{e}_g-\ddot{a}x\tilde{\rho}\upsilon-\tilde{L}(x,t)$$

Diffusion Convection Equation for $f(r,p,t)$

$$\frac{\partial\tilde{g}}{\partial t}+\frac{\upsilon-u_w}{a}\frac{\partial\tilde{g}}{\partial x}=[\frac{1}{3ax}\frac{\partial}{\partial x}(x^2(\upsilon-u_w))+\frac{\dot{a}}{a}](\frac{\partial\tilde{g}}{\partial y}-4\tilde{g})+3\frac{\dot{a}}{a}\tilde{g}+\frac{1}{a^2x^2}\frac{\partial}{\partial x}(x^2\kappa\frac{\partial\tilde{g}}{\partial x})$$

$x=r/a$: co-moving coordinate, a = expansion factor, $y=\ln p$

Numerical Tool: CRASH Code (Kang et al. 2001)

Bohm type diffusion: $\kappa(p) \propto p$

- **wide range of diffusion length scales to be resolved:** $l_{diff} = \kappa(p)/u_s$

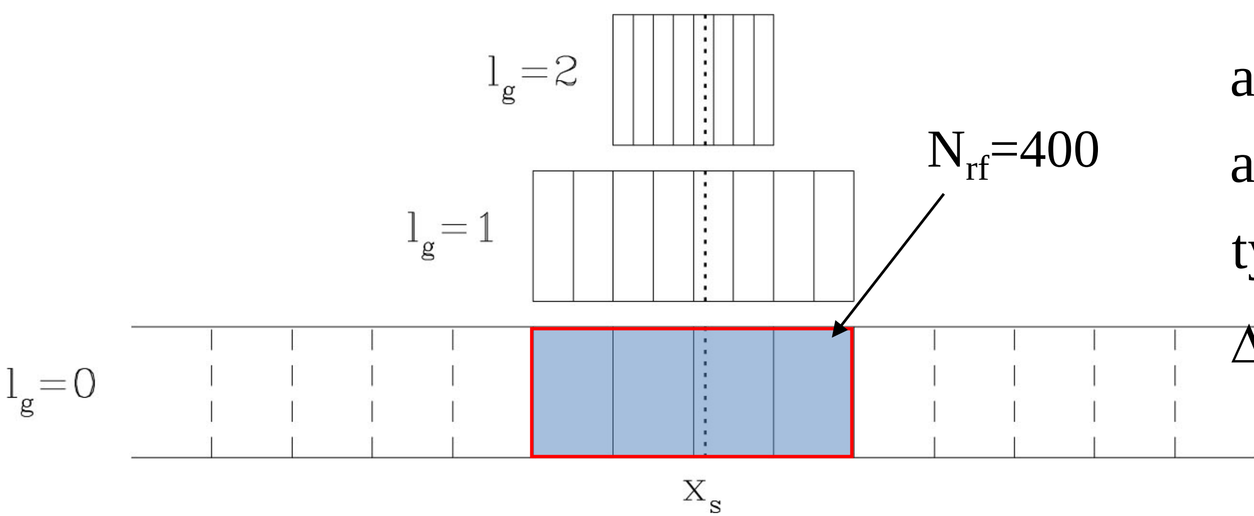
from p_{inj}/mc(~10^{-2}) to outer scales for the highest p_{max}/mc (~10^{6})

1) Shock Tracking Method (Le Veque & Shyue 1995)

- **tracks the subshock as an exact discontinuity**

2) Adaptive Mesh Refinement (Berger & Le Veque 1997)

- **refines region around the subshock with multi-level grids**



a factor of two refinement at each grid level,

typically $l_{g,\max} = 8-10$

$\Delta x_{10} = \Delta x_0 / 1024$

Co-expanding with the shock

Model Parameters for Type Ia Supernova Remnants

- Initial Conditions for the uniform ISM

$$r_s = \xi_s t^{2/5}, \quad u_s = \frac{2}{5}\xi_s t^{-3/5}, \text{ Sedov Similarity Solution at } t = 0.5$$

- Supernova Ia parameters: $E_o = 10^{51}\,\text{erg}, \quad M_{SN} = 1.4 M_{sun}$
- Bohm-type Diffusion

$$\kappa(\text{p}) = \left(\frac{3.0\times10^{22}}{B}\text{cm}^2/\text{s}\right)\frac{p}{mc} \quad \text{with } B = 5-30\mu\text{G}$$

- thermal leakage injection model $\varepsilon_B = 0.2\text{-}0.25$

Table 1. Model Parameters

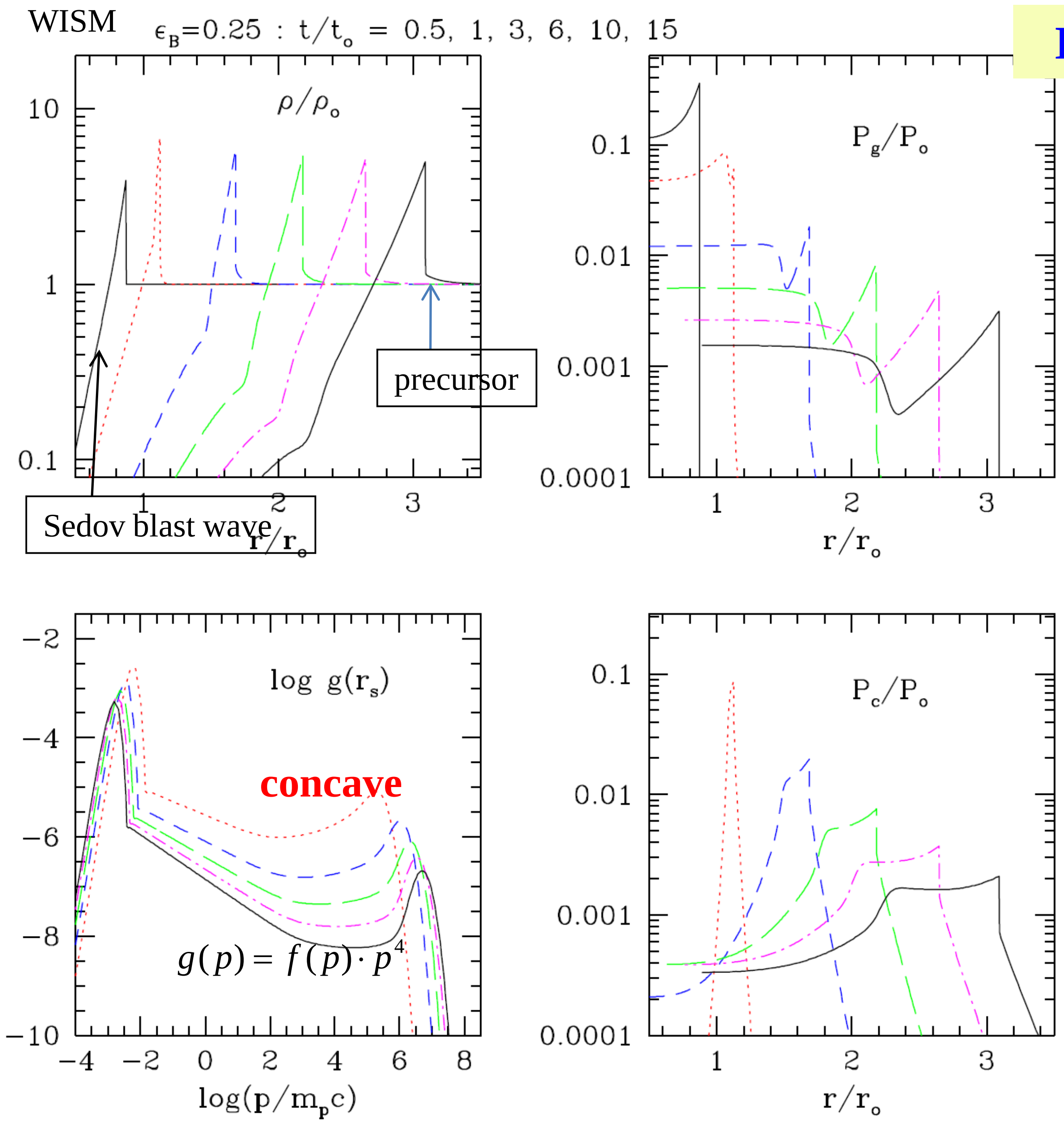
Model[a]	n_H (ISM) (cm^{-3})	T_0 (K)	E_0 (10^{51} ergs)	B_μ (μG)	r_o (pc)	t_o (years)	u_o (10^4 km s^{-1})	P_o (10^{-6}erg cm^{-3})
WISM	0.3	3.3×10^4	1.	30	3.19	255.	1.22	1.05
MISM	0.03	10^5	1.	30	6.87	549.	1.22	1.05×10^{-1}
HISM	0.003	10^6	1.	5	14.8	1182.	1.22	1.05×10^{-2}

The shock Mach number is the key parameter that determines CR acceleration.

Warm-phase ISM: high Mach number shock, efficient acceleration

intermdiate-phase ISM:

Hot-phase ISM: low Mach number shock, inefficient acceleration



Efficient Acceleration Case

$n_{ISM} = 0.3\,\mathrm{cm}^{-3}$

$B_0 = 30\,\mu\mathrm{G}$

$p_{max} = 10^6\ \mathrm{GeV/c}$

$\rho_2 / \rho_0 \approx 8$

$\rho_1 / \rho_0 \approx 2$

Normalization Constants

$r_o = 3.19\mathrm{pc},$

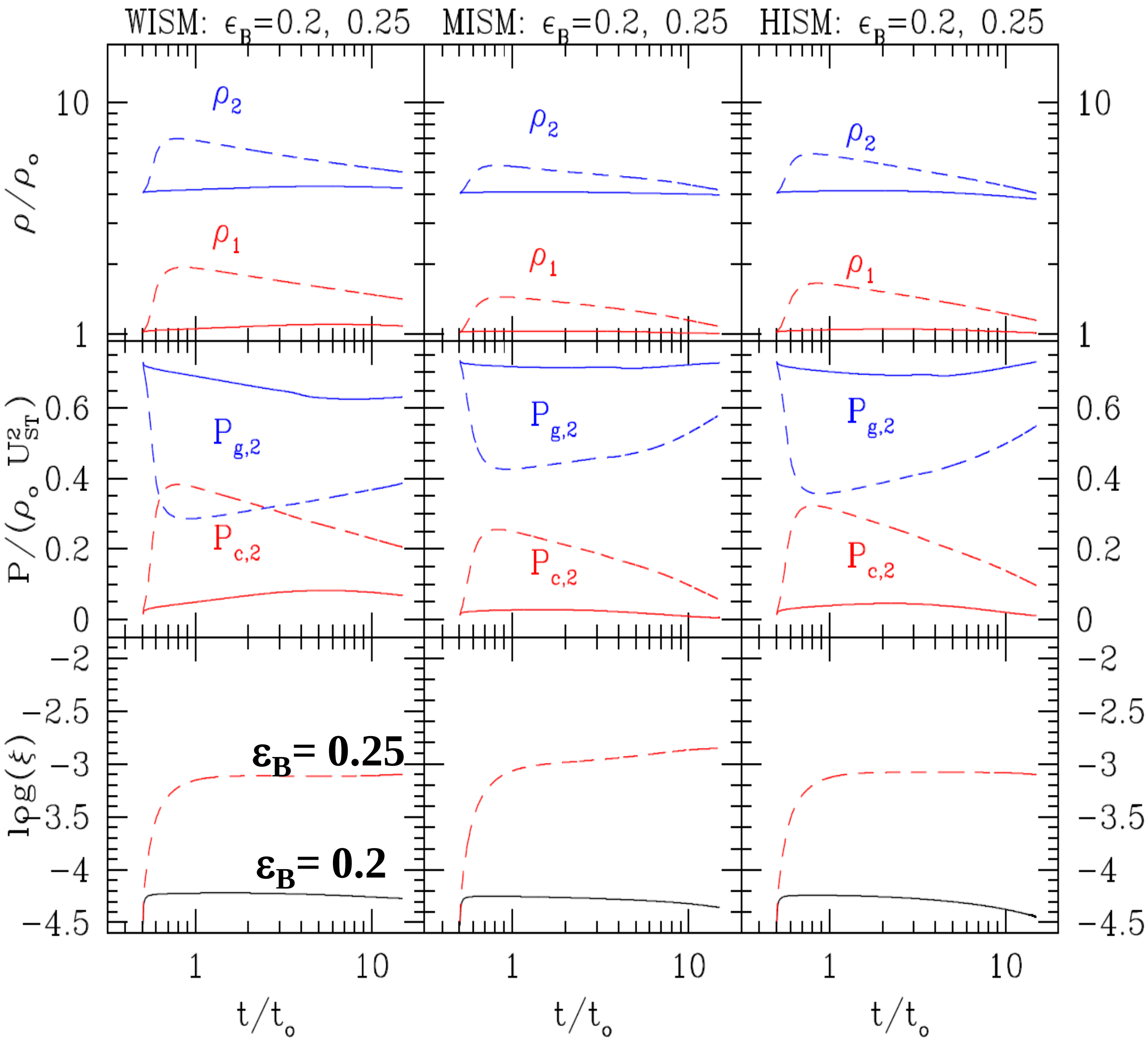
$t_o = 255\ \mathrm{yrs},$

$u_o = 1.22 \times 10^4\ \mathrm{km/s}$

$\rho_o = 7.0 \times 10^{-25}\,\mathrm{g/cm}^3,$

$P_o = 1.05 \times 10^{-6}\ \mathrm{erg/cm}^3,$

warm ISM: $n_H = 0.3\,\mathrm{cm}^{-3},\ T_o = 3 \times 10^4\ \mathrm{K},\ \ M_s \approx 300$



WISM vs. HISM
ε_B= 0.2 vs. 0.25

efficient case (dashed lines)

$\xi \approx 10^{-3}$ $(\varepsilon_B = 0.25)$

$\rho_2 / \rho_0 \approx 4-8$

$P_c / \rho_0 u_s^2 \approx 0.1-0.4$

inefficient case (solid line)

$\xi \approx 10^{-4}$ $(\varepsilon_B = 0.2)$

$\rho_2 / \rho_0 \approx 4-6$

$P_c / \rho_0 u_s^2 < 0.05$

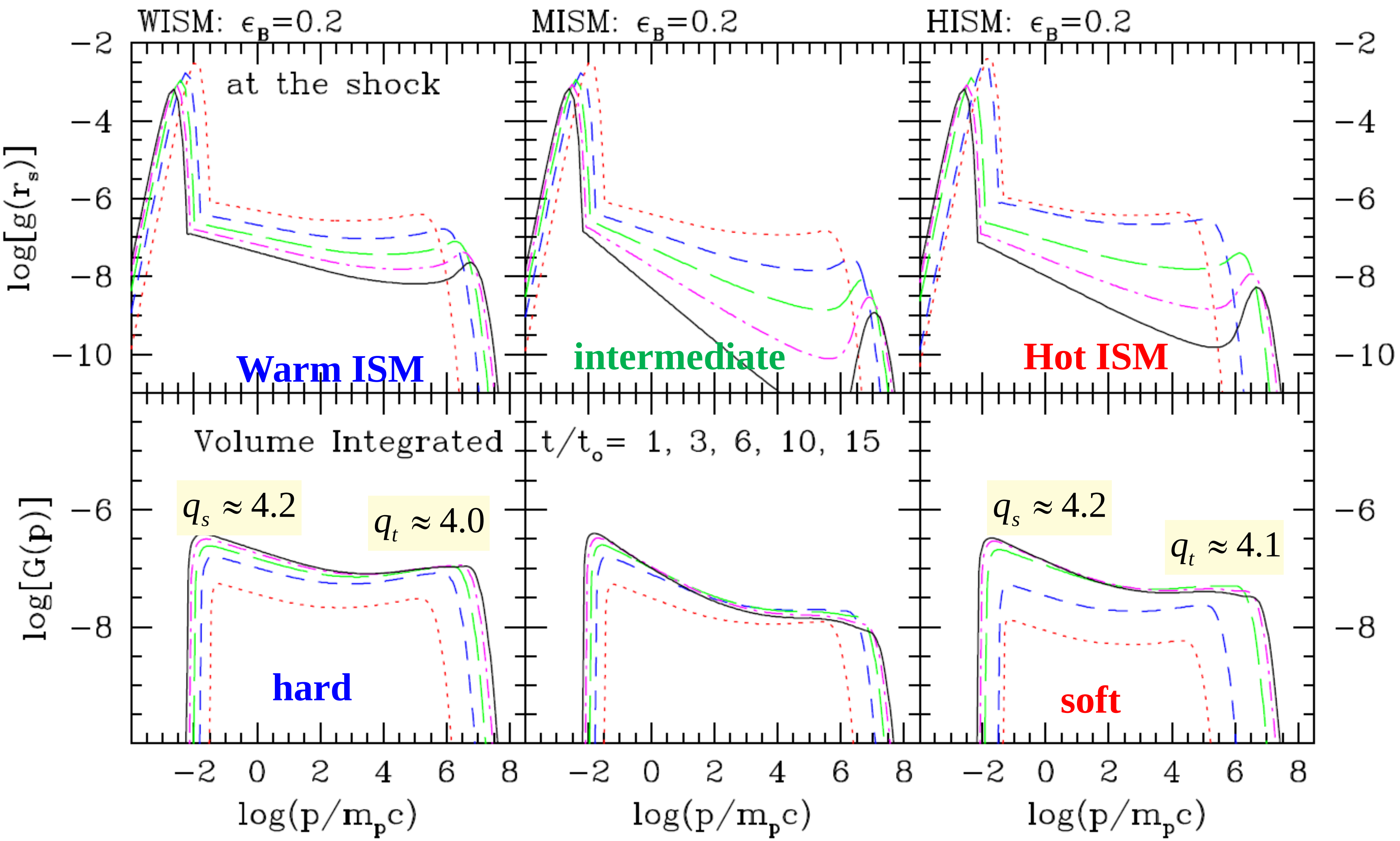
test-particle-like

CR injection fraction

$$\xi(t) = \frac{\int 4\pi r^2 \mathrm{d}r \int 4\pi f(p,r,t) p^2 \mathrm{d}p}{\int 4\pi r_s^2 n_0 u_s \mathrm{d}t}$$

CR spectrum at shock & Volume integrated spectrum

Inefficient solutions: low injection rate, test-particle

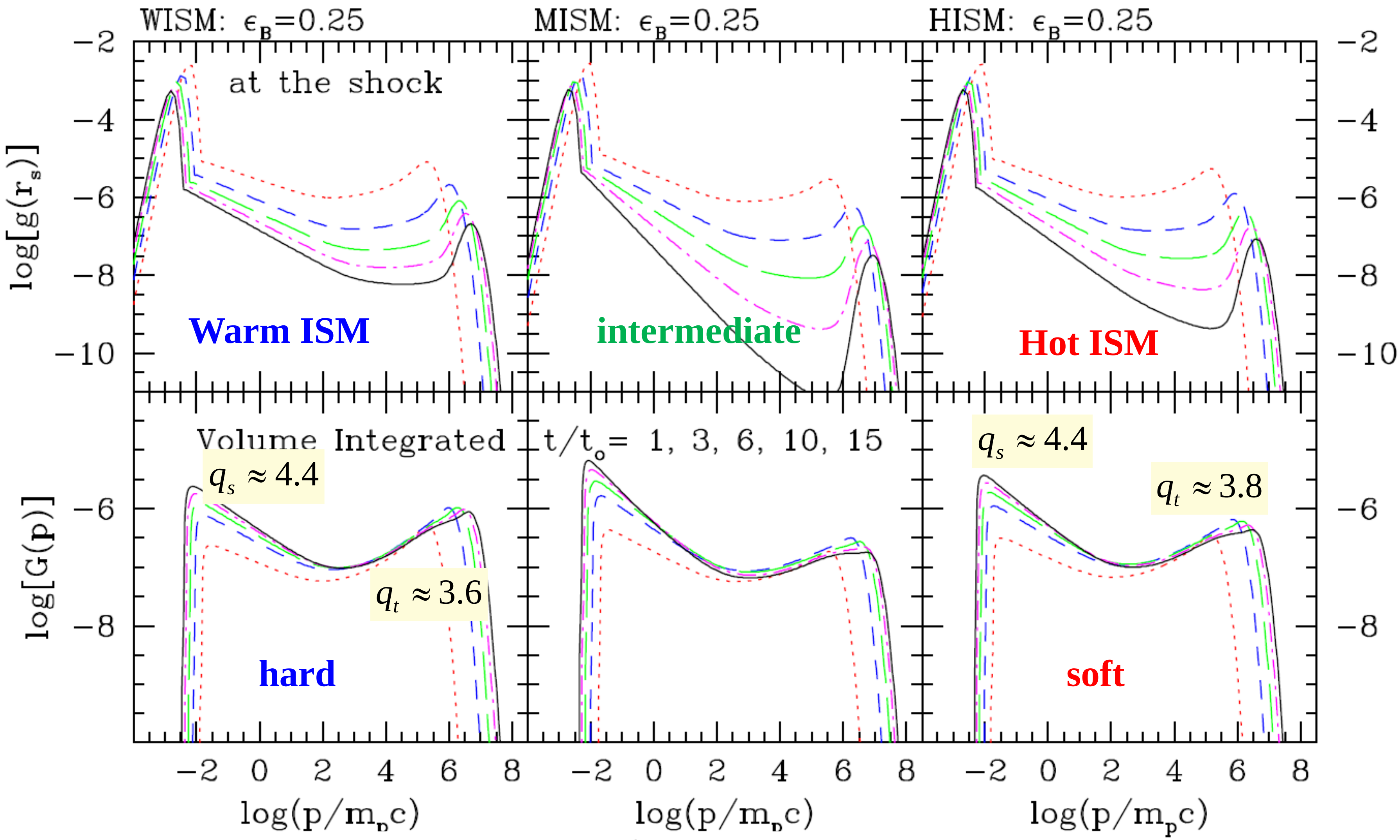


$$g(r_s, p) = f(r_s, p)p^4, \; G(p) = \int 4\pi r^2 g(r,p)dr$$

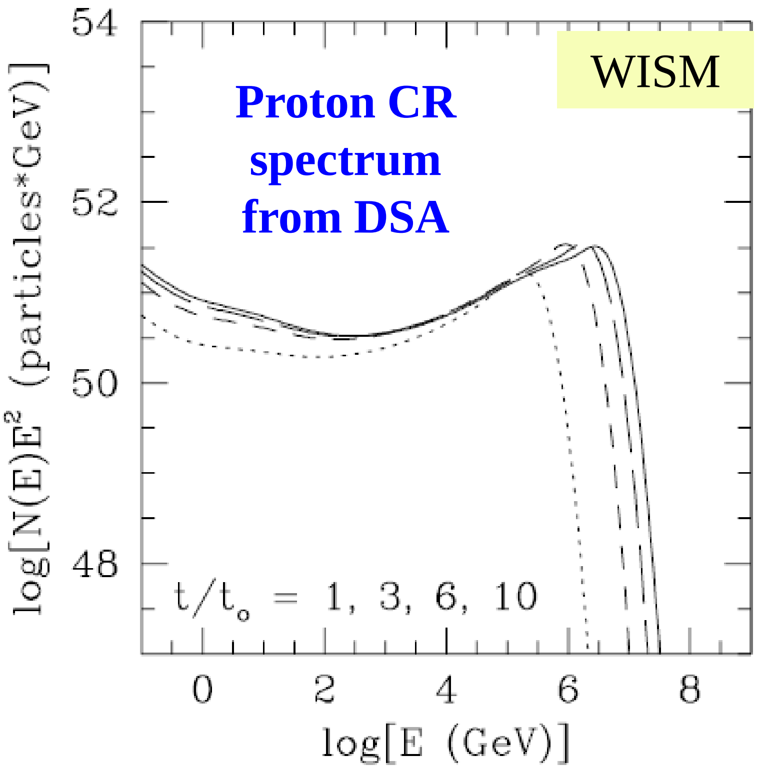
$$q_t = \frac{3\cdot(u_0 - v_A)}{u_0 - v_A - u_2} < q_s$$

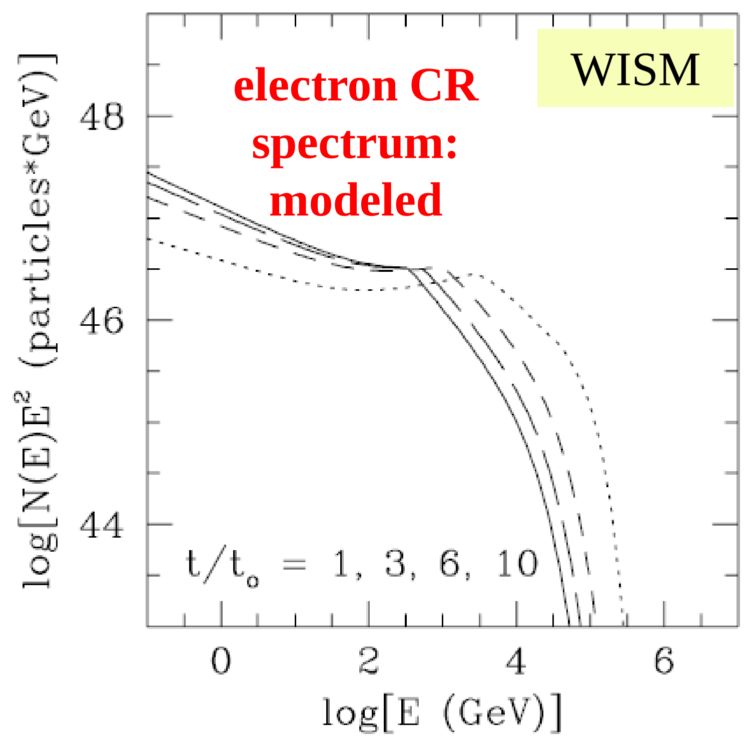
CR spectrum at shock & Volume integrated spectrum

Efficient solutions: high injection rate, modified



$$g(r_s, p) = f(r_s, p)p^4,\ G(p) = \int 4\pi r^2 g(r, p)dr$$





$$f_e(p,r,t) = K_{e/p} f_p(p,r,t) \left(\frac{p_{e,1}}{p}\right) \exp(-p/p_{ec}).$$

$$t_r = -p\left(\frac{dt}{dp}\right)_{rad}$$

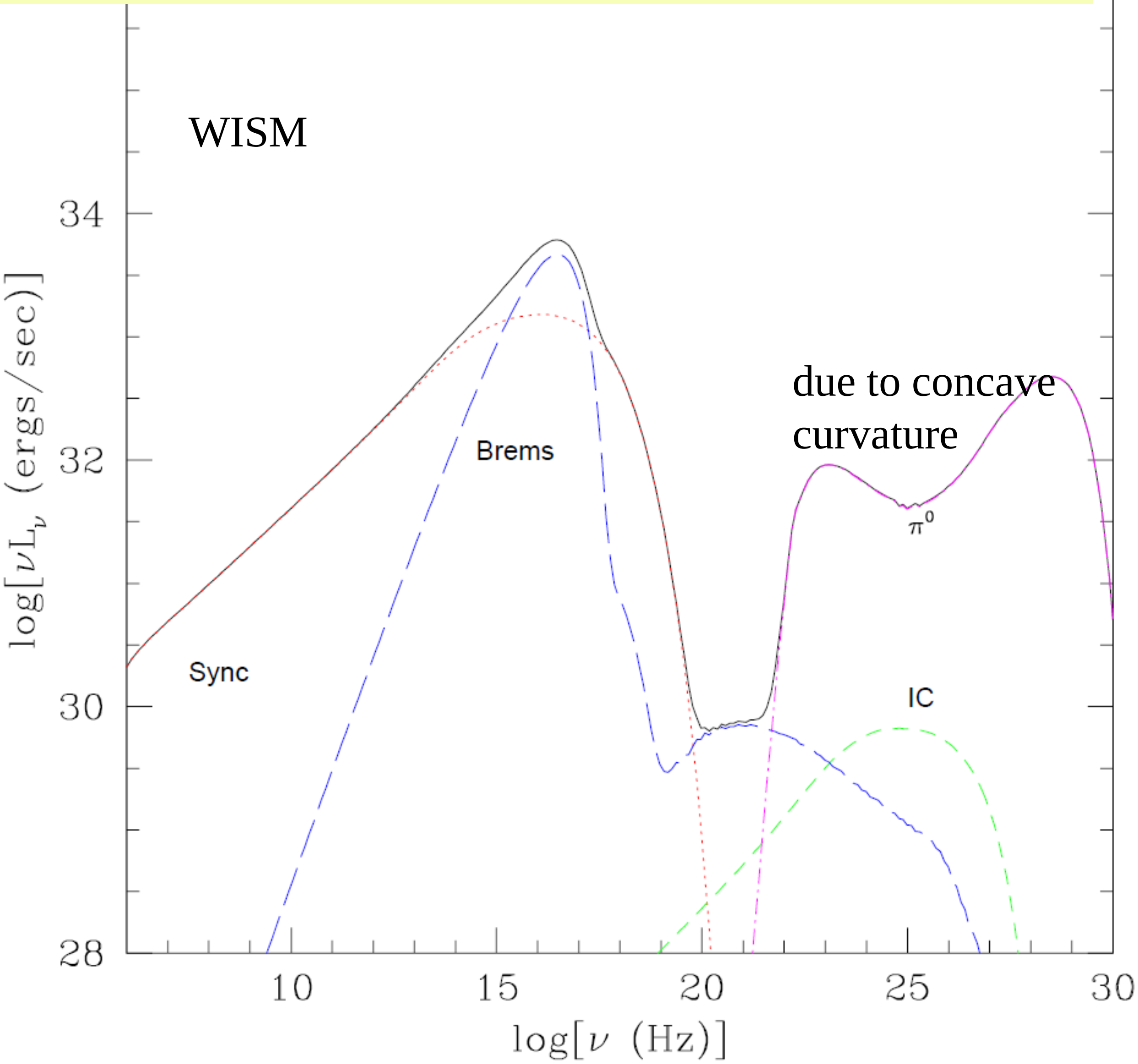
$t_{rad} = t_{acc} \Rightarrow p_{ec}$ electron cutoff momentum

$t_{rad} = t_{age} \Rightarrow p_{e,1}$ electron break momentum

$$t_a = p\left(\frac{dt}{dp}\right)_{DSA}$$

$K_{e/p} \approx 10^{-4}$

Warm ISM model with efficient injection



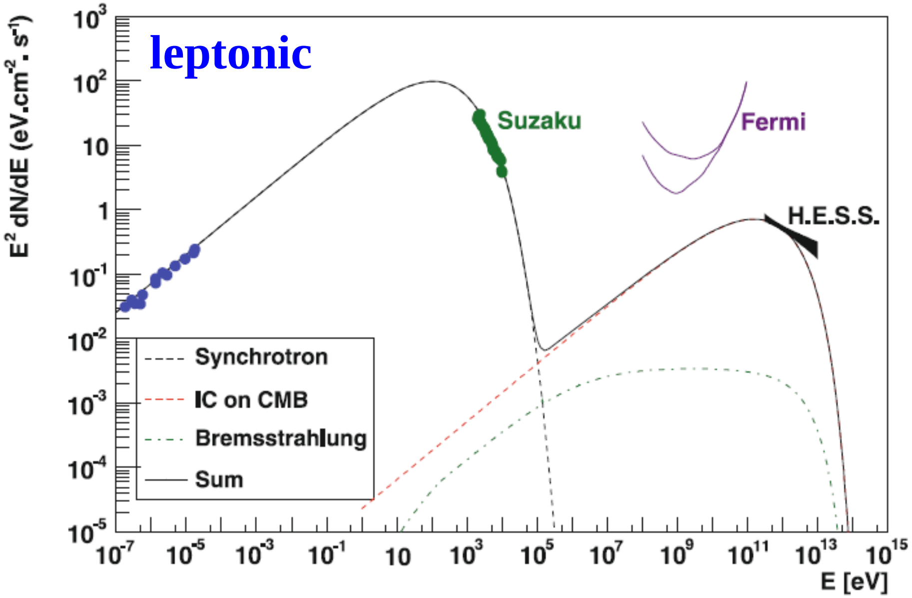
In Type Ia SNRs, π0 decay γ –rays dominate over Electron IC scattering.

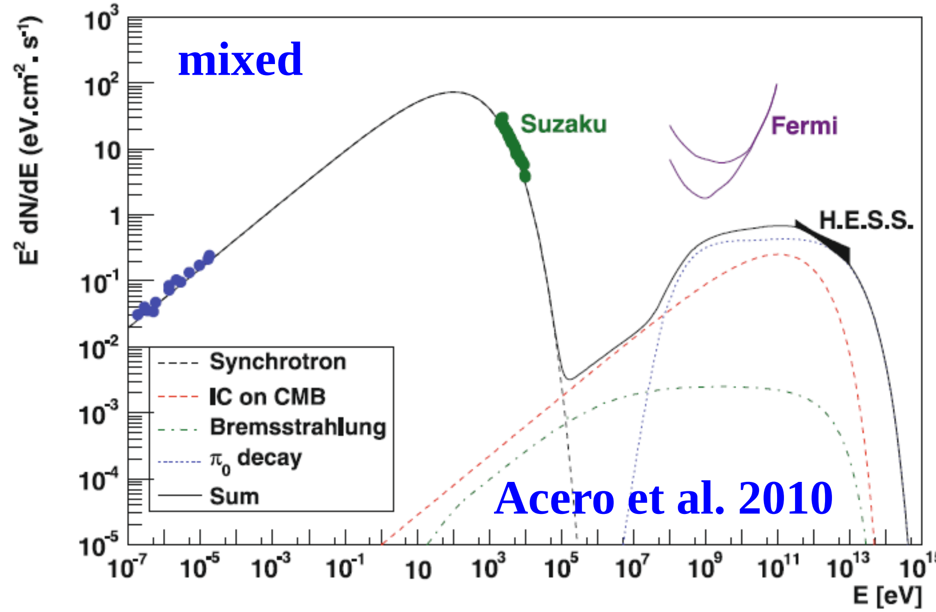
$$K_{e/p} = 10^{-4}$$

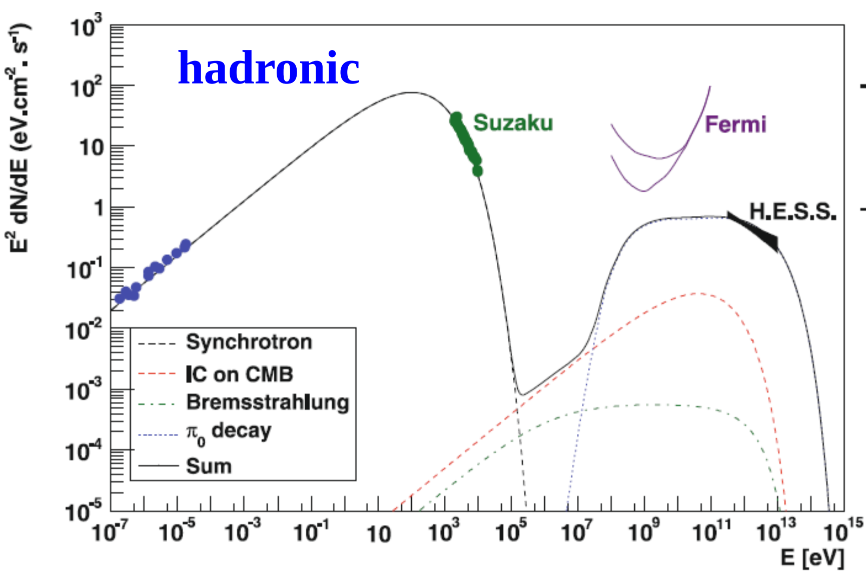
Edmon, Kang, Jones, Ma 2010

warm ISM: $n_H = 0.3\,\text{cm}^{-3}$, $T_o = 3\times10^4$ K, $M_s \approx 300$

Nonthermal radiation from SN1006 (Type Ia): HESS observation







Model	$E_{\mathrm{cut,e}}$ [TeV]	$E_{\mathrm{cut,p}}$ [TeV]	W_{e} [10^{47} erg]	W_{p} [10^{50} erg]	B [μG]
Leptonic	10	–	3.3	–	30
Hadronic	5	80	0.3	3.0	120
Mixed	8	100	1.4	2.0	45

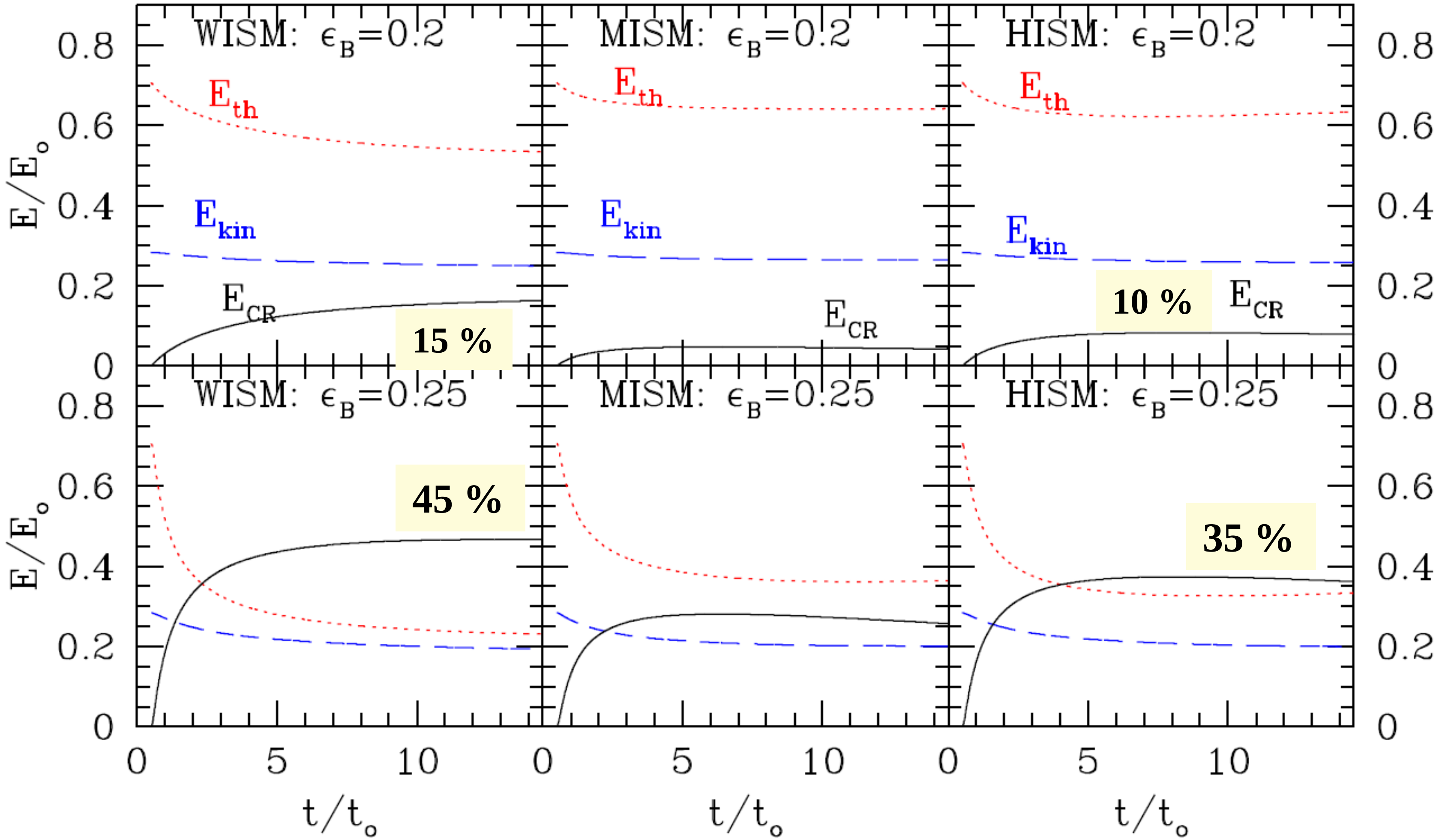
$$N_p(E) \propto E^{-2.0}$$

$$N_e(E) \propto E^{-2.1}$$

Purely leptonic model does not fit well the observed TeV spectrum.
Mixed or Hadronic models give better fit.

Confirmation of CR proton acceleration at SNR

Energy Conversion



Warm ISM: high Mach number, E_{CR}/Eo=15-45 %

Hot ISM : low Mach number, E_{CR}/Eo=10-35 %

SUMMARY

- With amplified B field, Galactic CRs up to $E_{\max} \approx Z \cdot 10^{15.5}\mathrm{eV}(\frac{B}{30\mu G})$ can be accelerated by SNRs.
- Alfvenic drift softens the CR spectrum. $q_{test} = \frac{3(u_1 - \mathrm{v}_A)}{u_1 - \mathrm{v}_A - u_2} > 4$
- The shock Mach number is the key parameter that determines CR acceleration.
- SNRs inside hot-phase ISM:

  for $\varepsilon_{\mathrm{B}} \sim 0.2: \ \xi \approx 10^{-4}, \ N(E) \propto E^{-2.3}, \ E_{CR}/E_0 \approx 5-10\%$

  can reconcile with observed $J(E) \propto E^{-2.7}$
- SNRs inside warm-phase ISM: too efficient !

  for $\varepsilon_{\mathrm{B}} \sim 0.2: \ \xi \approx 10^{-4}, \ N(E) \propto E^{-1.8}, \ E_{CR}/E_0 \approx 35\%$
- If $K_{e/p} \sim 10^{-4}$, $B_1 = 30\mu G$, $B_2 \sim 150\text{-}200\mu G$, $\pi 0$ decay γ–rays dominate over electron IC scattering.

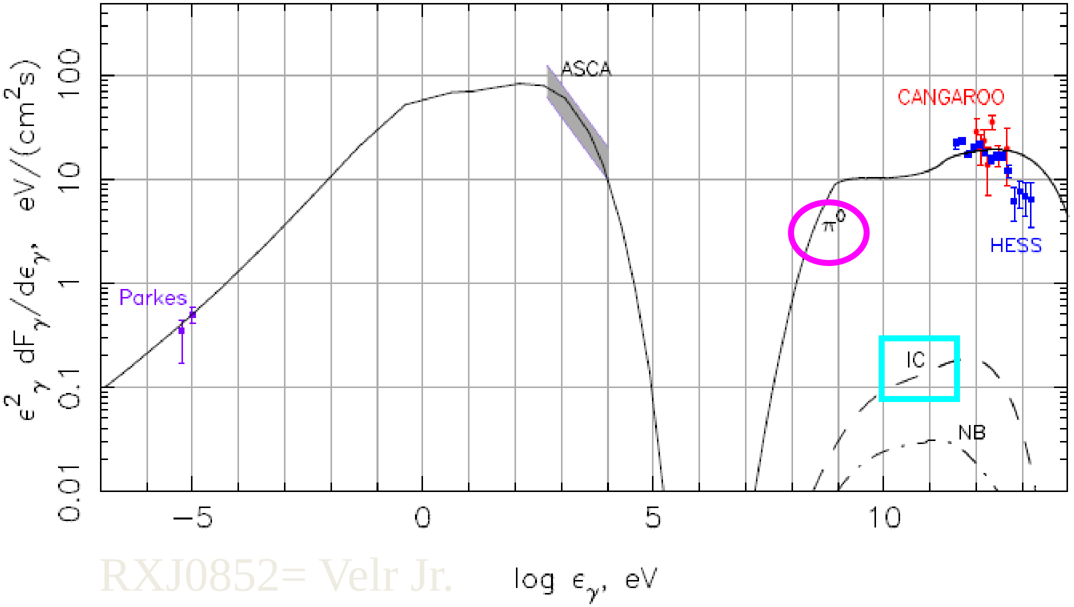


Figure 2: Calculated spectral energy distribution for Vela Jr. for the 1 kpc solution as function of photon

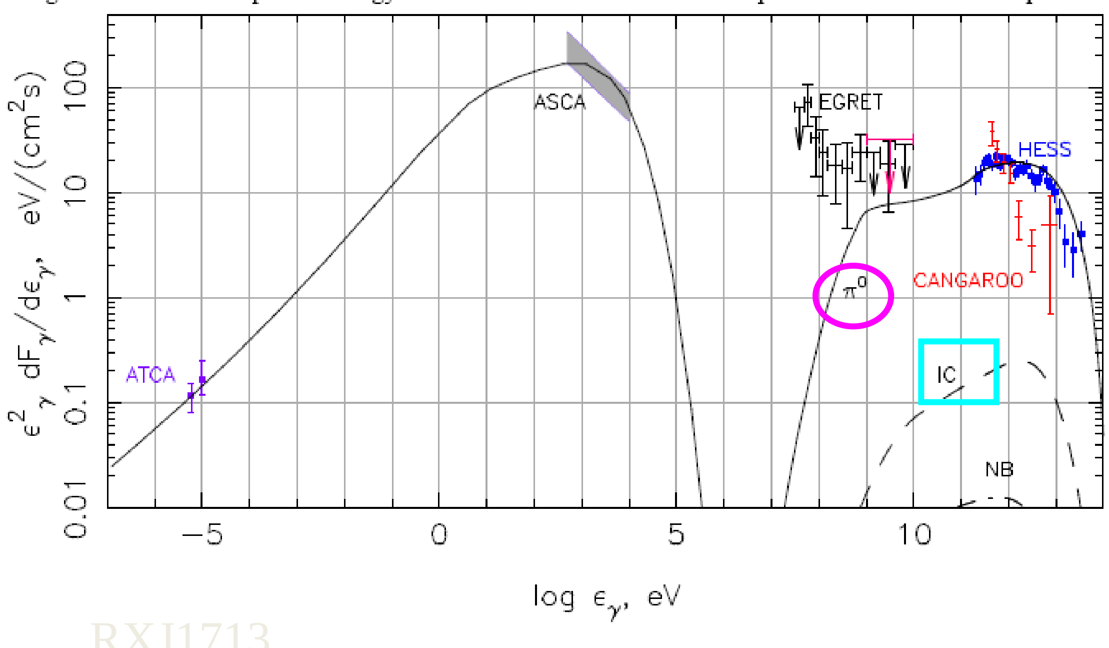


Figure 1: Spatially integrated spectral energy distributions of RX J1713-3946 [7]. The ATCA radio data, ASCA X-ray data, EGRET spectrum of 3EG J1714-3857, CANGAROO data and H.E.S.S. data from ([2]),

from radio, X-ray, 10 TeV

Hadronic model for γ-ray

$t \approx 4000\, yrs$

$B_d \approx 130\mu G, B_u \approx 65\mu G$

$12 < n_{ISM} < 40 cm^{-3}$

$E_{\max} \approx 700$ TeV

$E_{SN} \approx 2\times 10^{51}$ ergs

$t \approx 1600\, yrs$

$B_d \approx 130\mu G, B_u \approx 65\mu G$

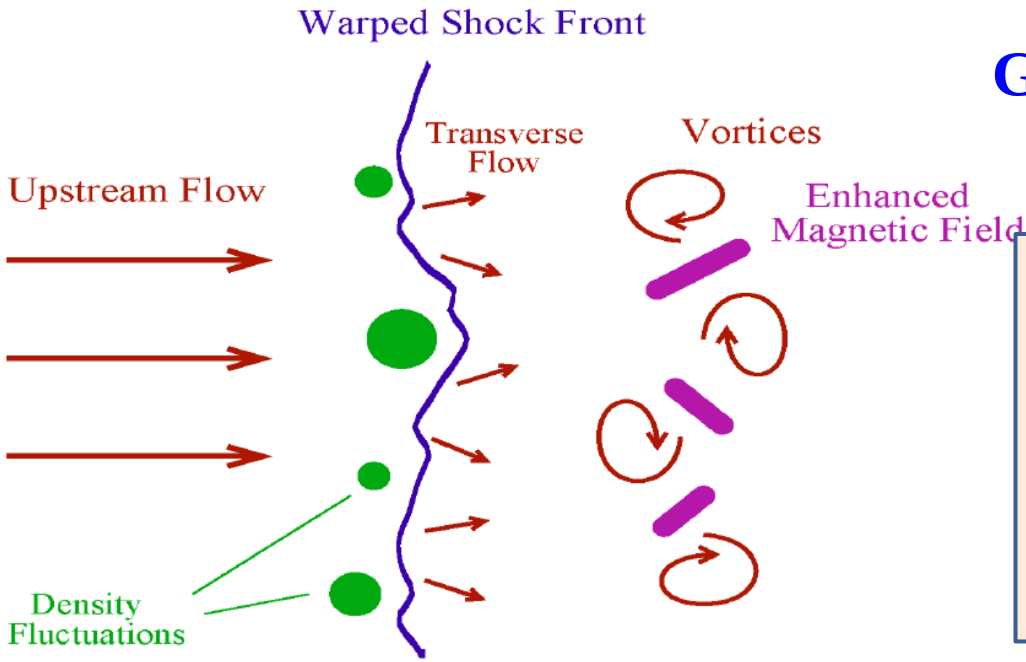
$n_{ISM} \approx 300 cm^{-3}$

$\sigma \approx 6.3$ (CR modified)

$E_{\max} \approx 100$ TeV

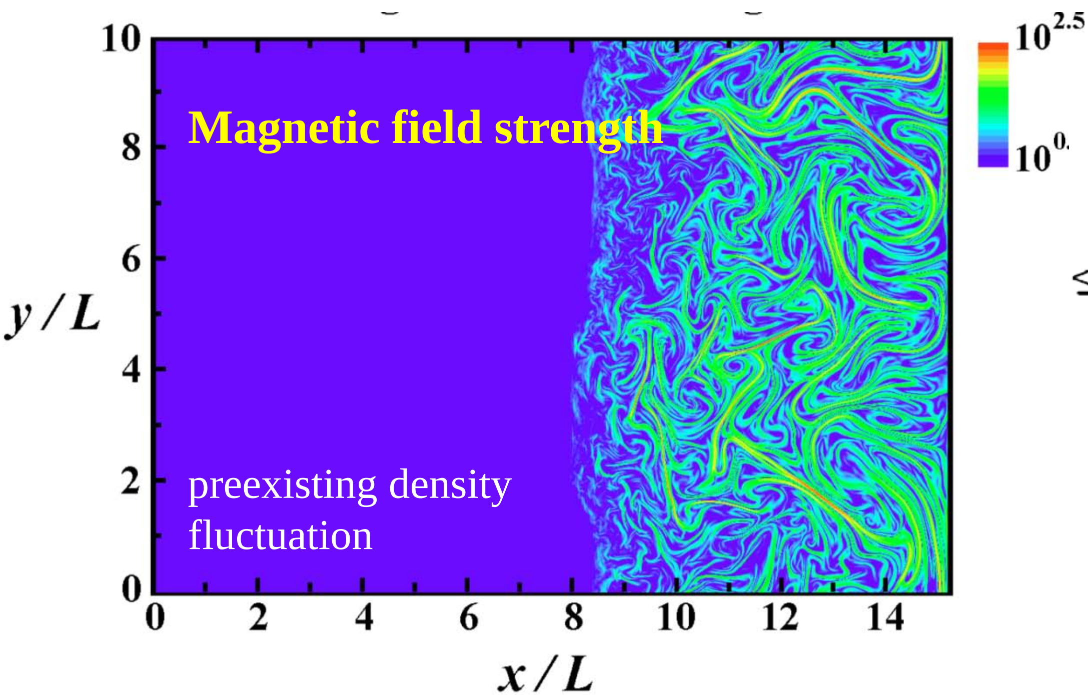
$E_{SN} \approx 1.8\times 10^{51}$ ergs

γ-ray detection only in high density environment (wind driven shell or molecular clouds)

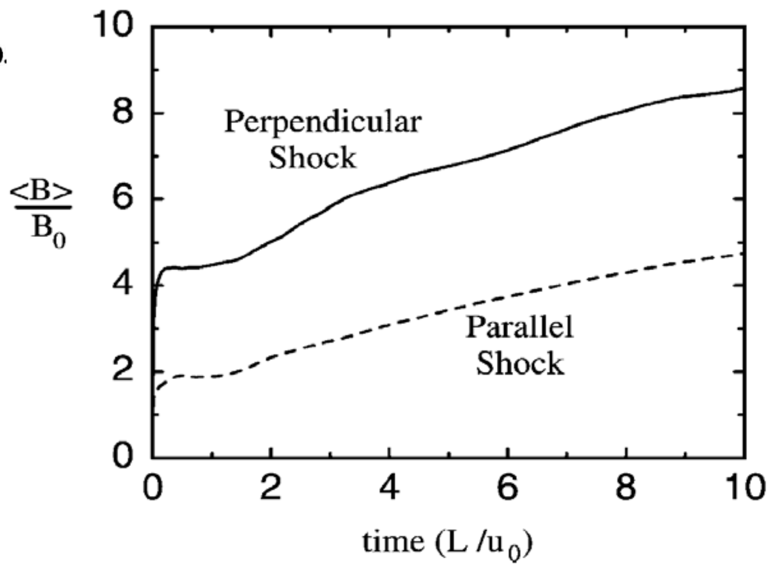


Giacalone &. Jokipii 2007
MHD simulations

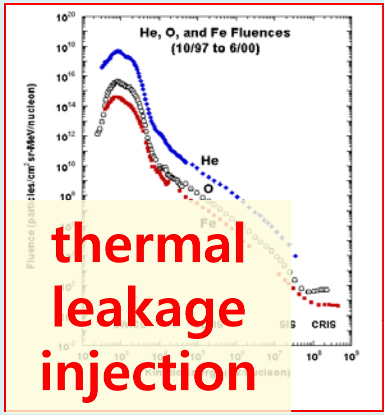
upstream density fluctuations
→warped shock front
→ vortices generated
→ turbulent amplification

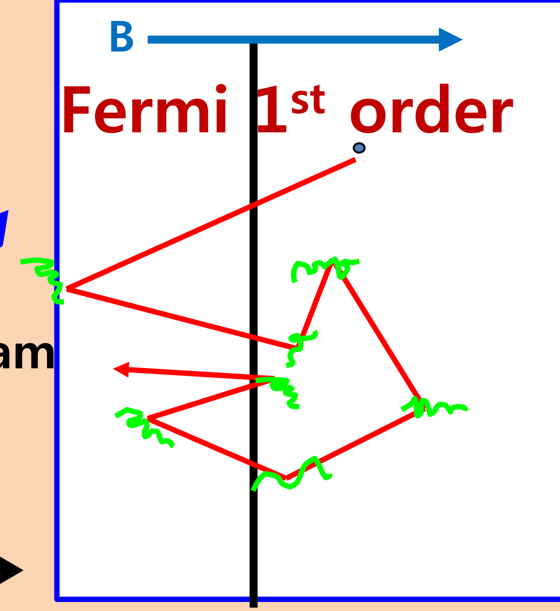


Amplified field downstream of shock



Key Physics of DSA





Shock front

upstream

downstream

U_1

U_2

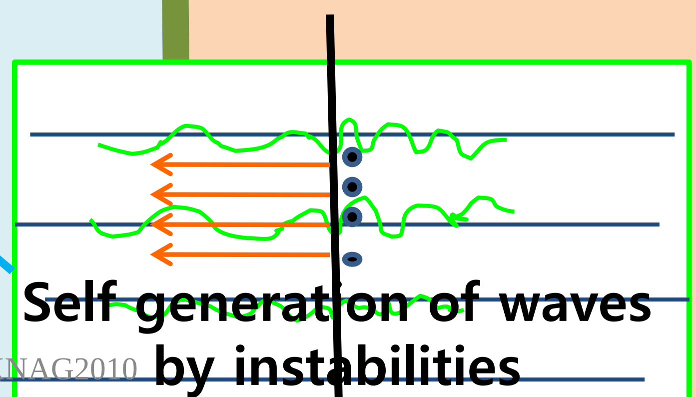
Preexisting upstream turbulence ?

streaming HE particles

Turbulent amplification of B in downstream

-Scattering by self-excited waves
→Bohm Diffusion: κ(p) up to p_{max} ?
- Amplification of B field
- Dissipation of waves

Escape of CRs from upstream



$$B_2 \approx 100 - 300\ \mu\text{G}$$

$$K_{e/p} \approx (1-5)\times 10^{-4}$$

SNR	B_{dw} (μG)	K_{ep}	B_{dw} (μG)	K_{ep}
RX J1713	100	8 · 10^-5	126	1 · 10^-4
SN1006	97	5 · 10^-4	150	4 · 10^-4
Tycho	270	9 · 10^-5	350 – 412	5 · 10^-4
Kepler			340	1.3 · 10^-4
Cas A			250 – 390	
RCW 86			75 – 145	

Morlino et al.

Berezhko & Voelk