PARTICLE ACCELERATION AT SHOCKS PROPAGATING IN PARTIALLY IONIZED PLASMA

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LECTURE III

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SUMMARY OF PAST LECTURES

- DSA in test-particle limit
  - *$f(E) \propto E^{-2}$ slope in tension with observations in gamma-rays*
  - *$E_{max} << PeV$*

- Non-linear DSA (efficient acceleration)
  - *Magnetic field amplification → OK with observations*
  - *Shock modification → larger compression ratio*
  - *Spectra harder than E^{-2} → NOT OBSERVED*

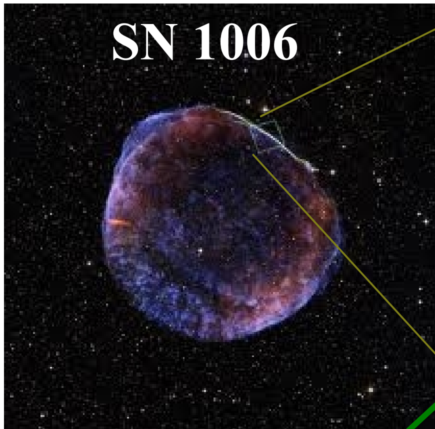
    (But the effects of scattering centers can produce steeper spectra)

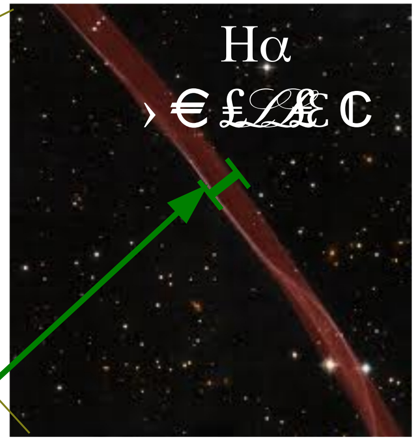
ADDING MORE PIECES OF REAL PHYSICS:

- ISM is not homogeneous
  - *Hydrodynamical instabilities*

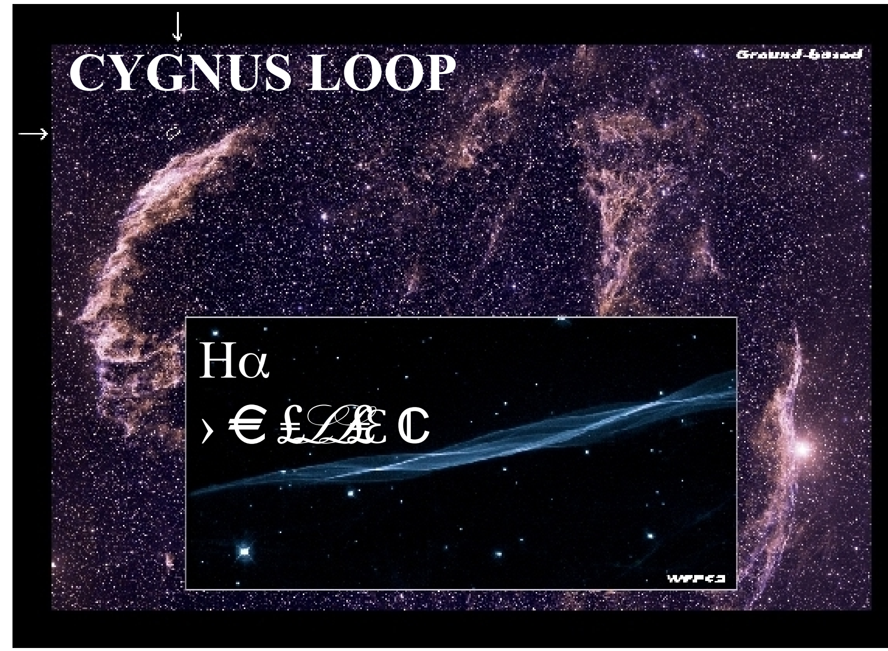
- ISM can be partially ionized
  - *Which is the role of neutral particles?*

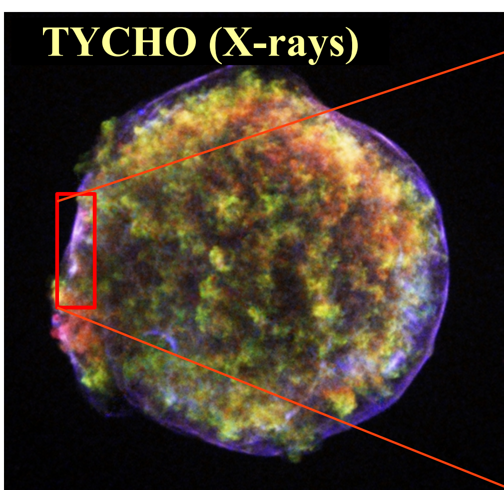
Balmer-Dominated Shocks



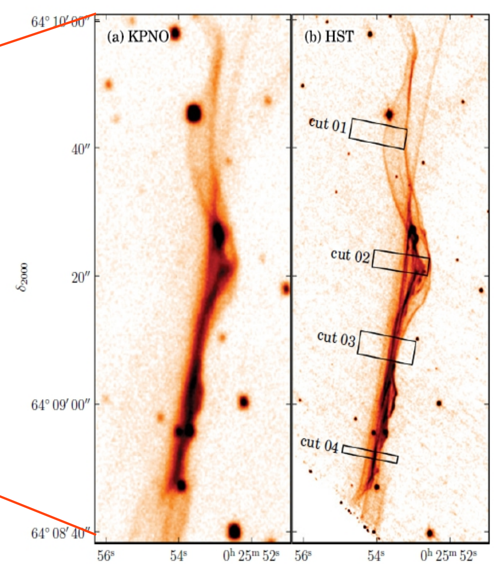


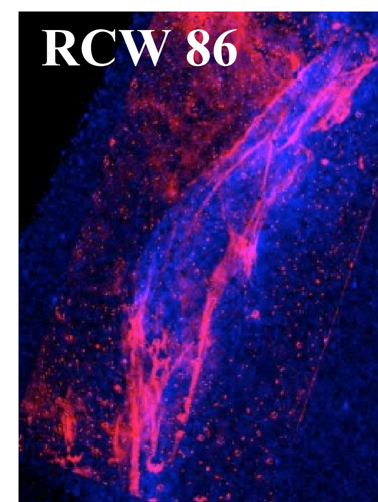
Thickness ~ 10" → 3×10^{17} cm
Hα resolution ~ 0.7" → 2×10^{16} cm





Hα emission





Close up view of SN 1006

[Nikolic et al. (2013)]

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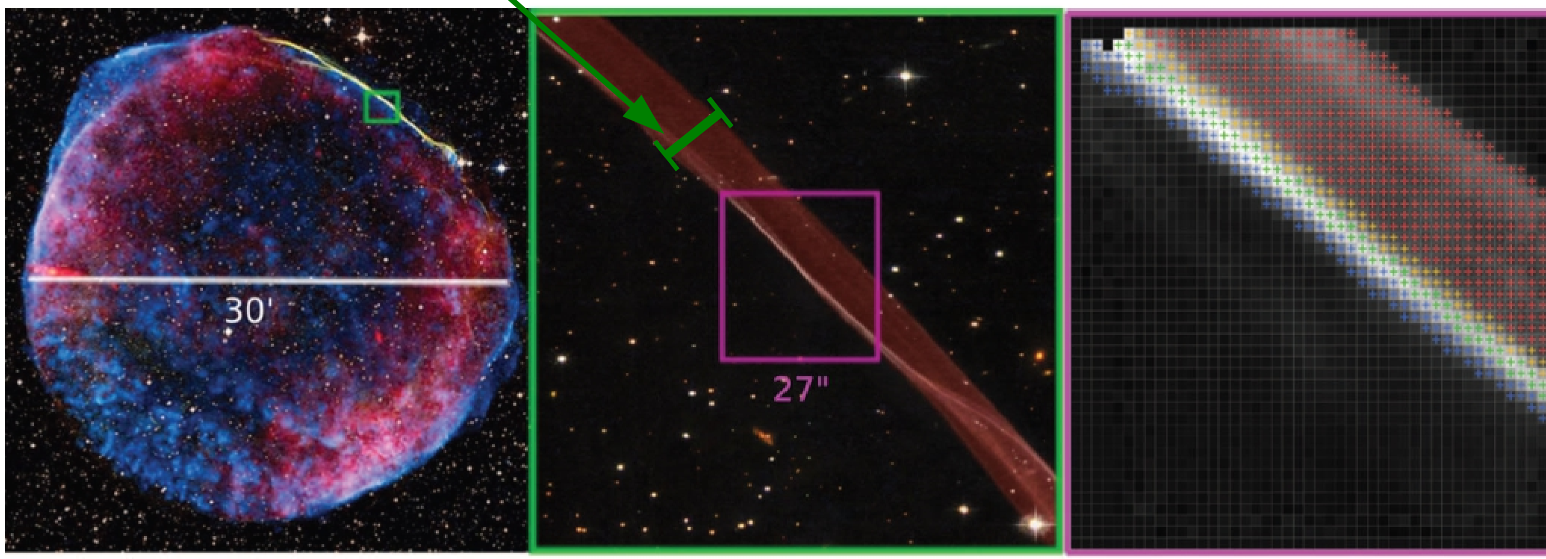
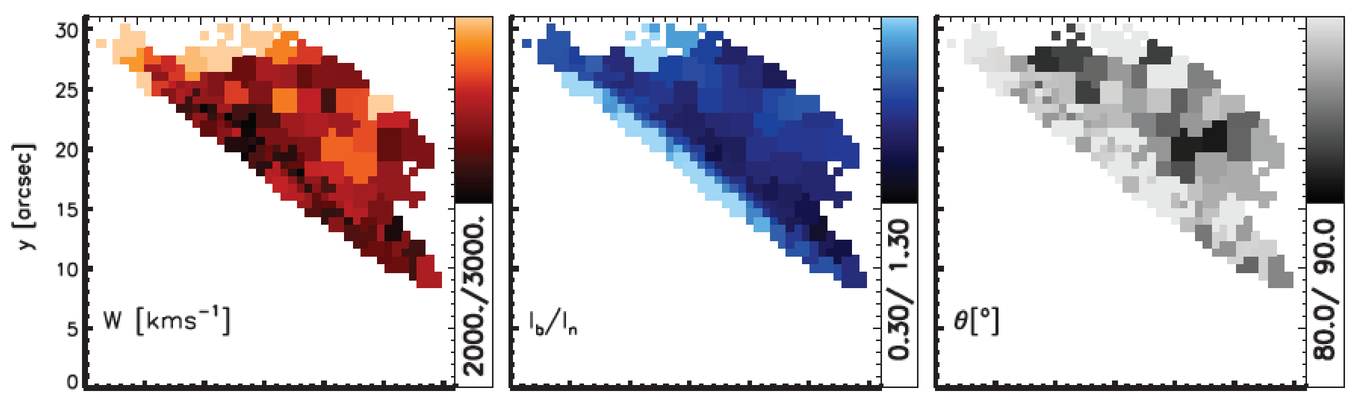
Hα resolution ~ 0.7" → 2×10^{16} cm

Image obtained using an integral-field spectrograph VIMOS at VLT

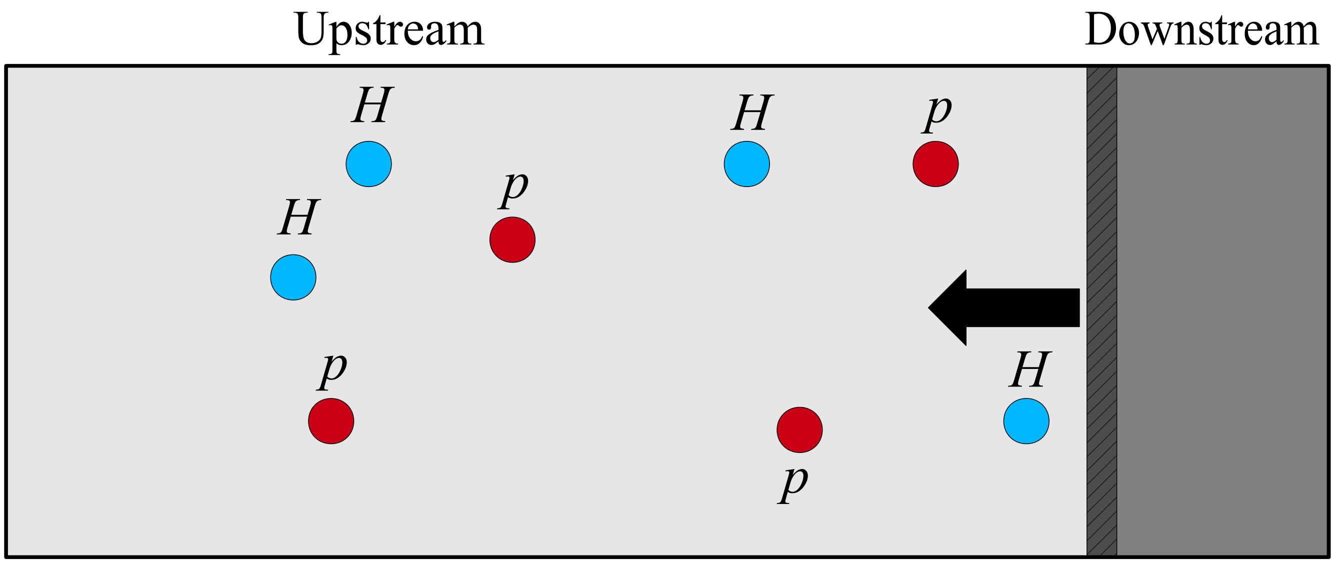


For each pixel you can get a Balmer spectrum



Basic physics of Balmer shocks

[Chevalier & Raymond(1978); Chevalier et al (1980)]



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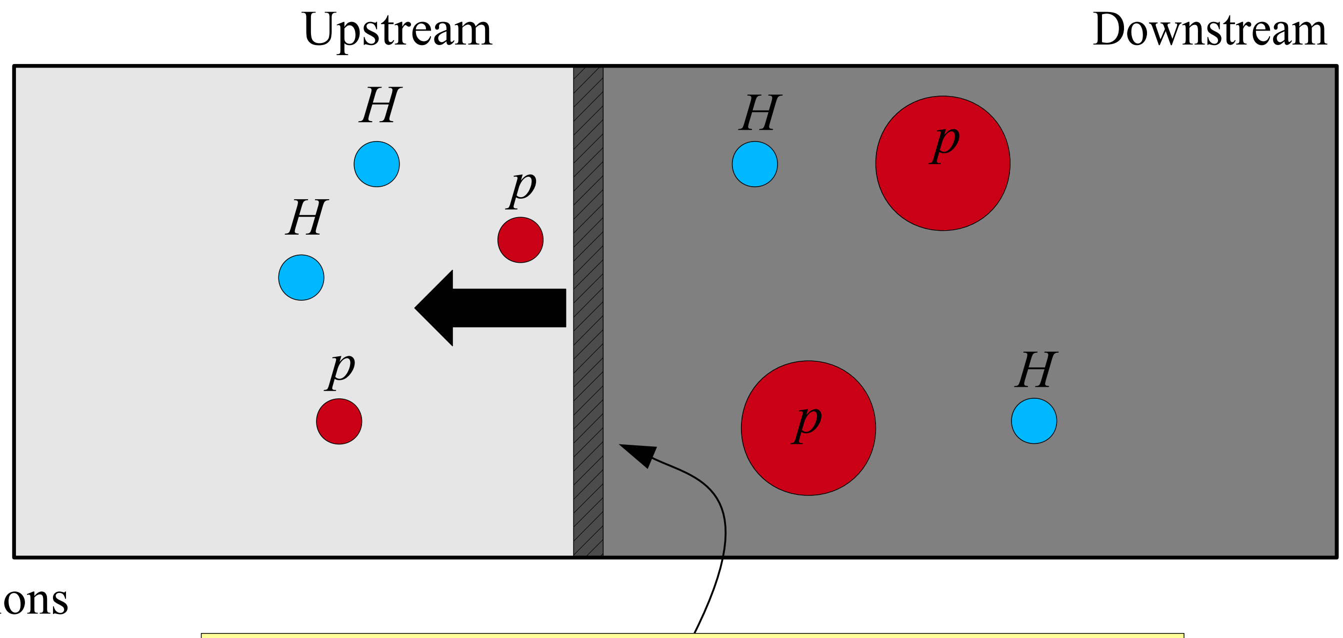

• Collisionless shocks heats up only ions

Shock thickness:

$$\lambda \approx \xi r_{L,th} \approx 10^{10} \left(\frac{B}{\mu G} \right)^{-1} \left(\frac{T}{10^8 K} \right)^{1/2} cm \ll \lambda_{coll}$$

Collisional length scale
(ionization or charge-exchange):

$$\lambda_{coll} \approx \frac{u_{sh}}{(n \sigma_{coll} v_{rel})} \approx 10^{15-16} cm \left(\frac{n}{1 cm^{-3}} \right)^{-1}$$

Collisionless shocks are mediated by electromagnetic plasma processes
→ At zeroth order the neutral component does not feel the shock discontinuity

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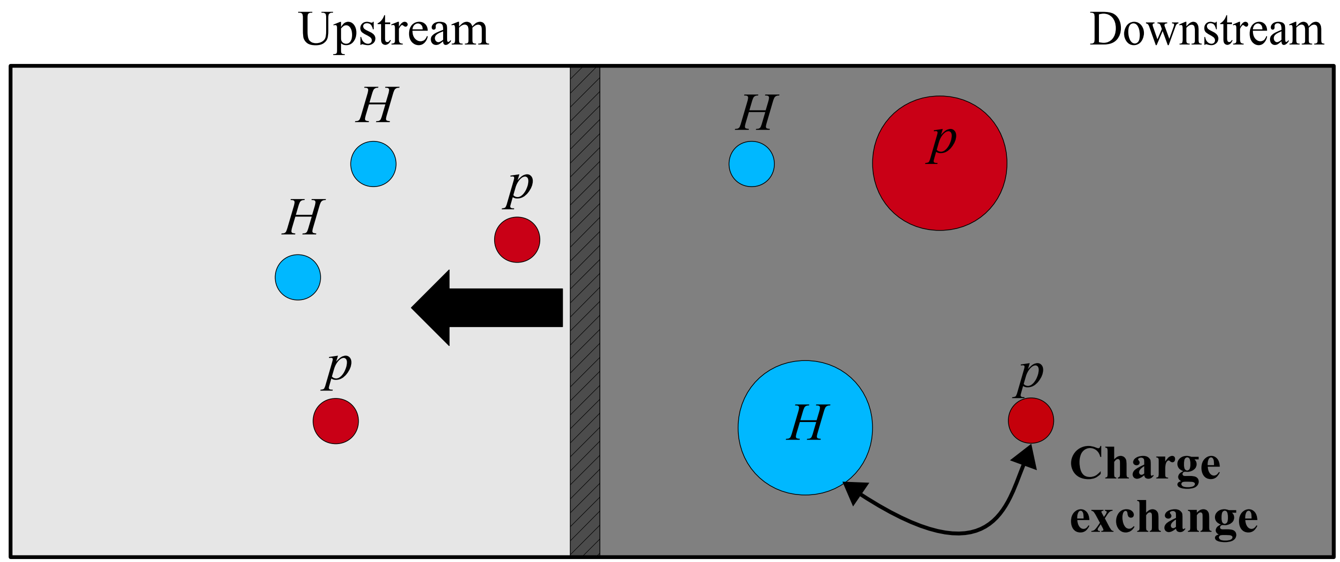
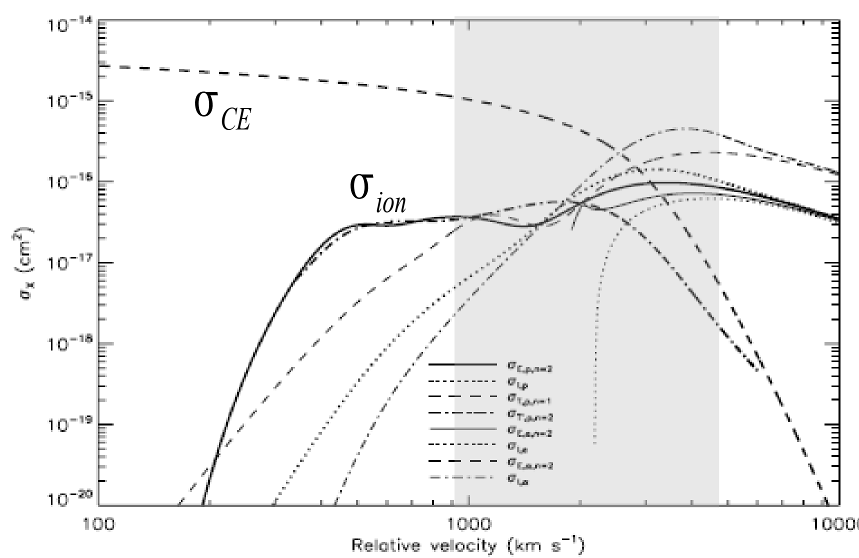
[Chevalier & Raymond(1978); Chevalier et al (1980)]



- Collisionless shocks heats up only ions

- Charge exchange can occur before ionization is completed because $\sigma_{ce} > \sigma_{ion}$ → a new population of hot hydrogen arises



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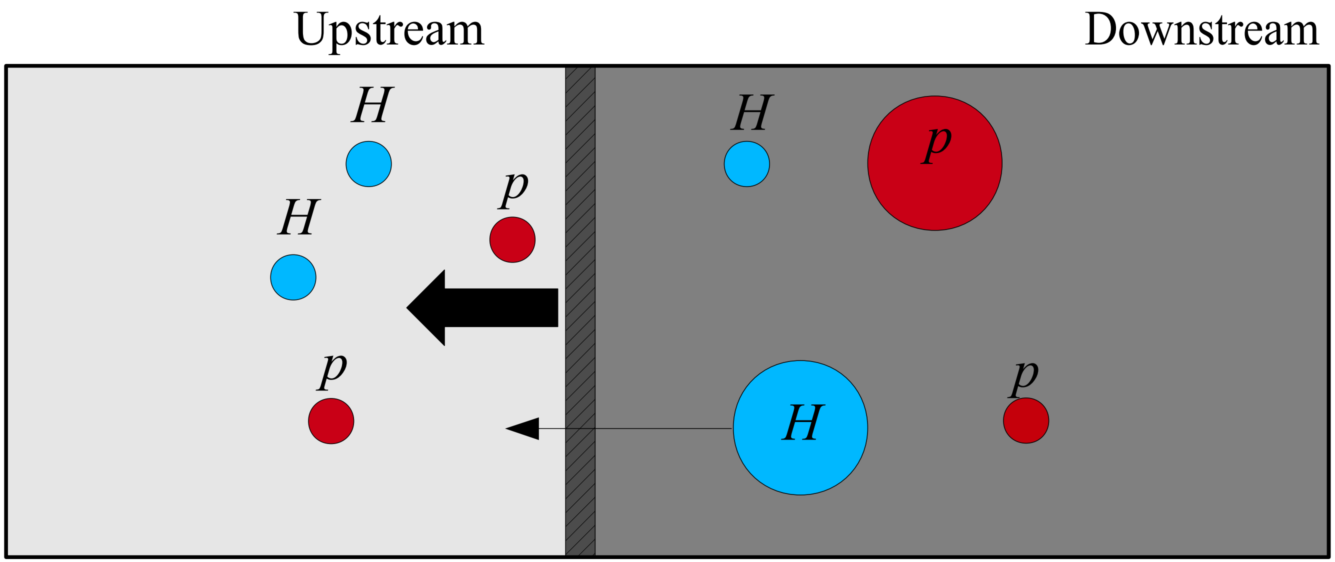

• Collisionless shocks heats up only ions

• Charge exchange can occur before ionization is completed because $\sigma_{ce} > \sigma_{ion}$ → a new population of hot hydrogen arises

• Hot hydrogen atoms can recross the shock and transfer momentum and energy upstream → formation of a *neutral precursor*

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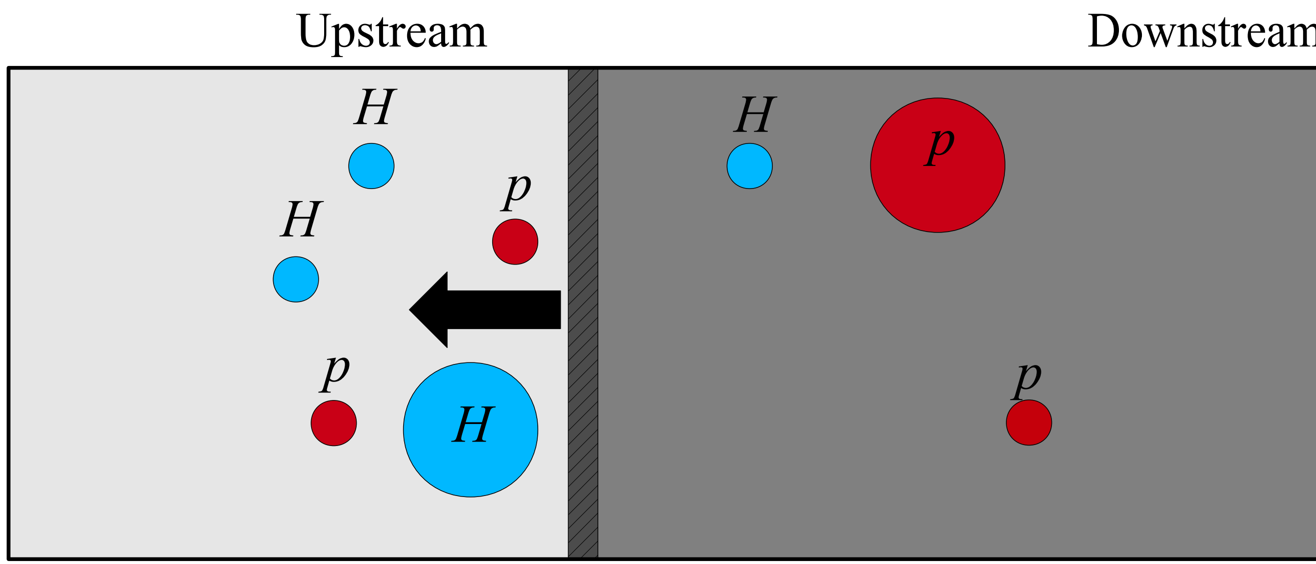

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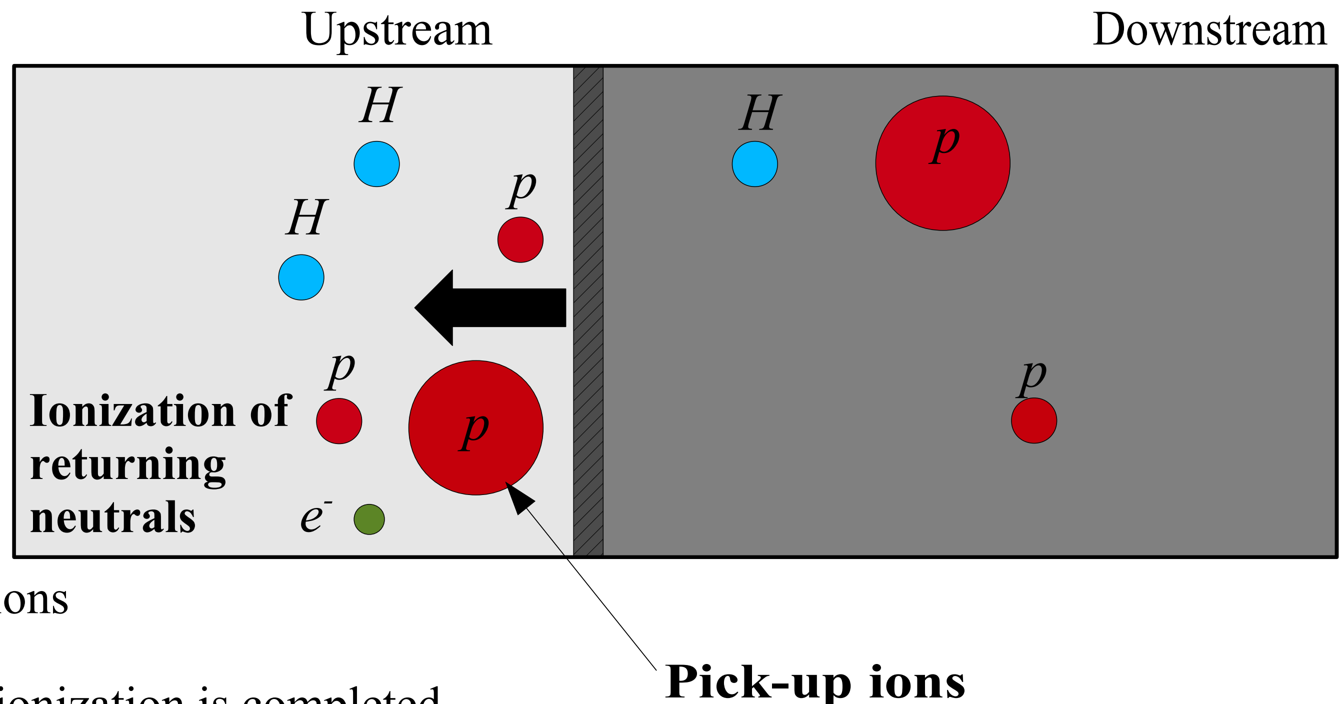

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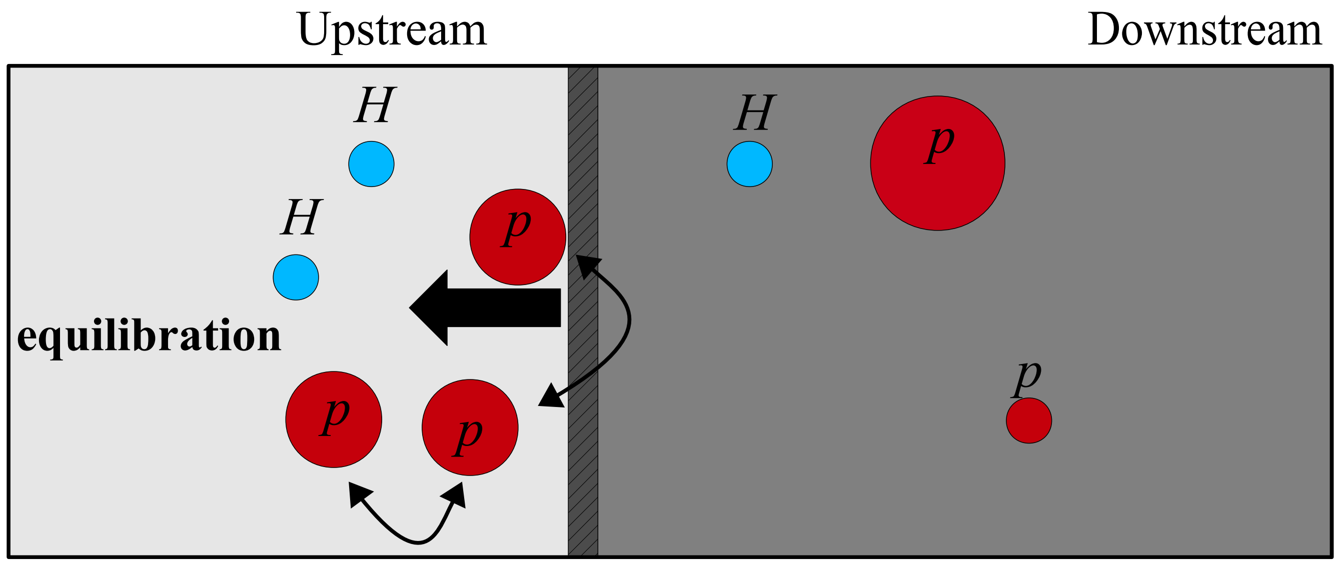

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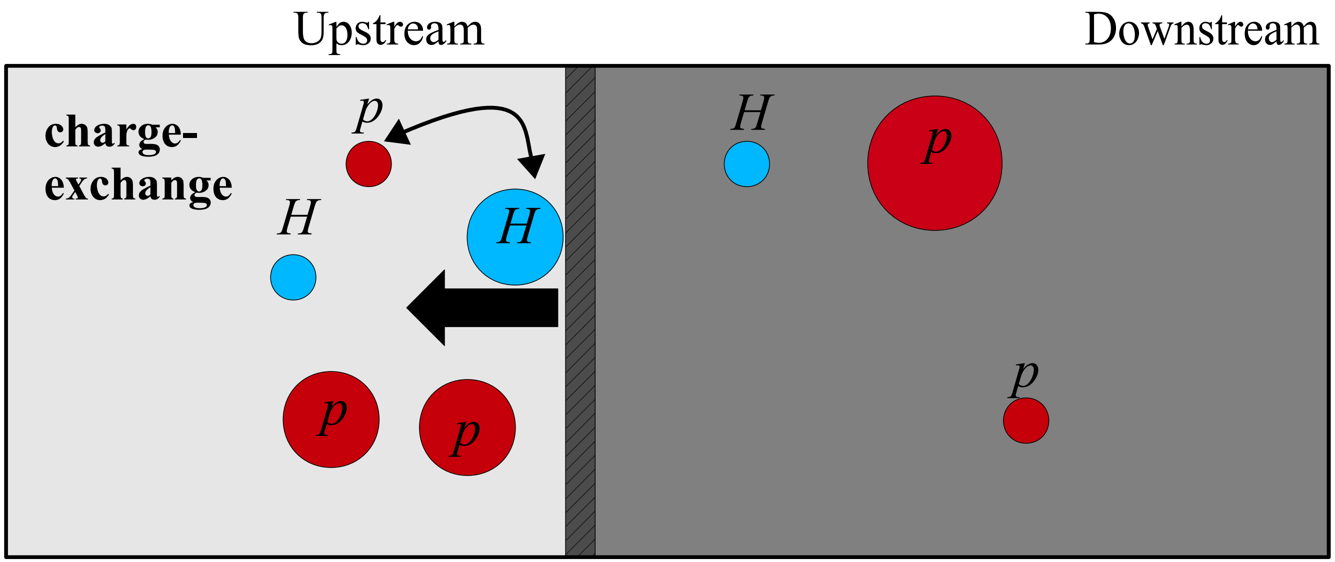

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• Charge-exchange with protons in the precursor generate a third population of warm hydrogen

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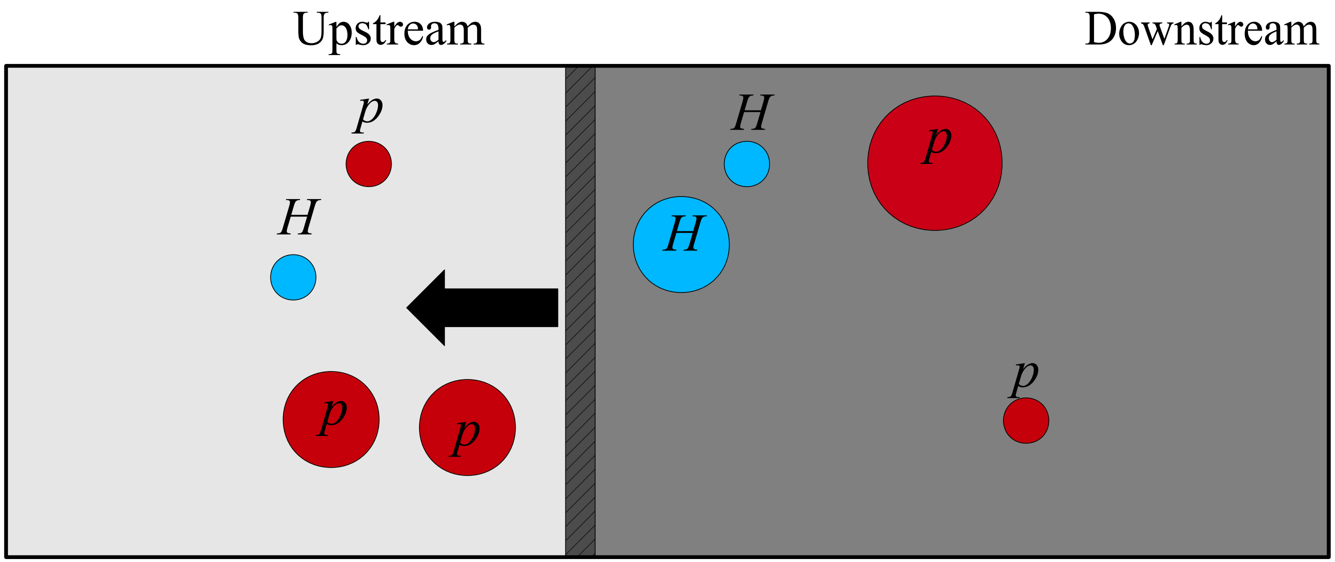

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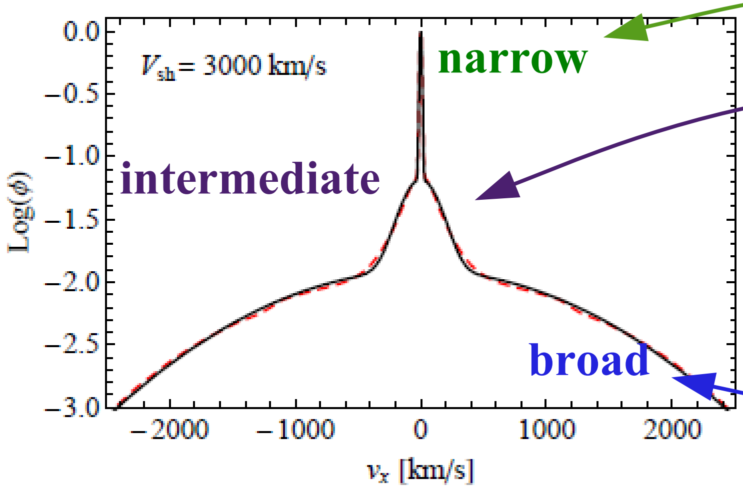
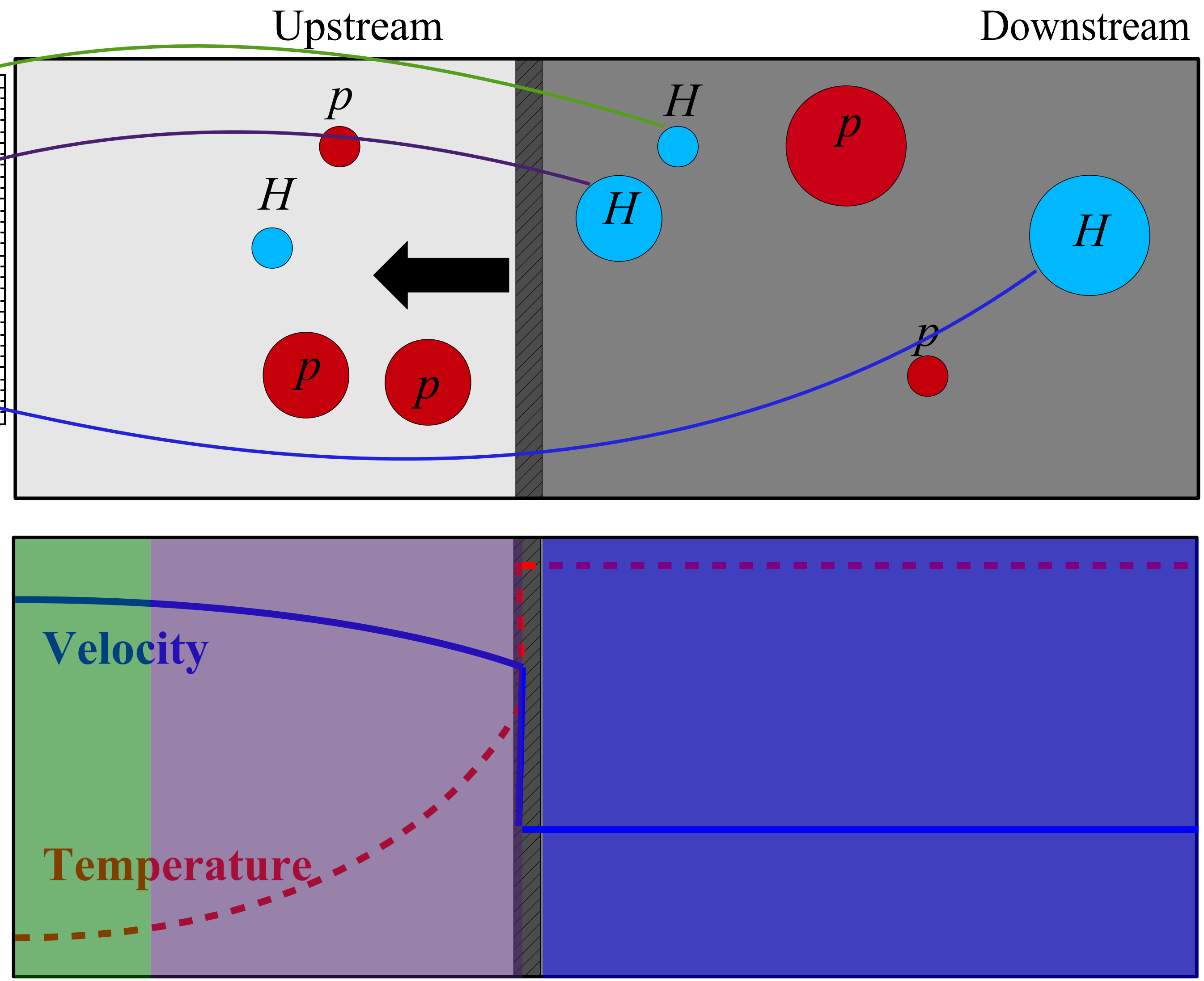




$W_{narrow} \propto \sqrt{T_0}$

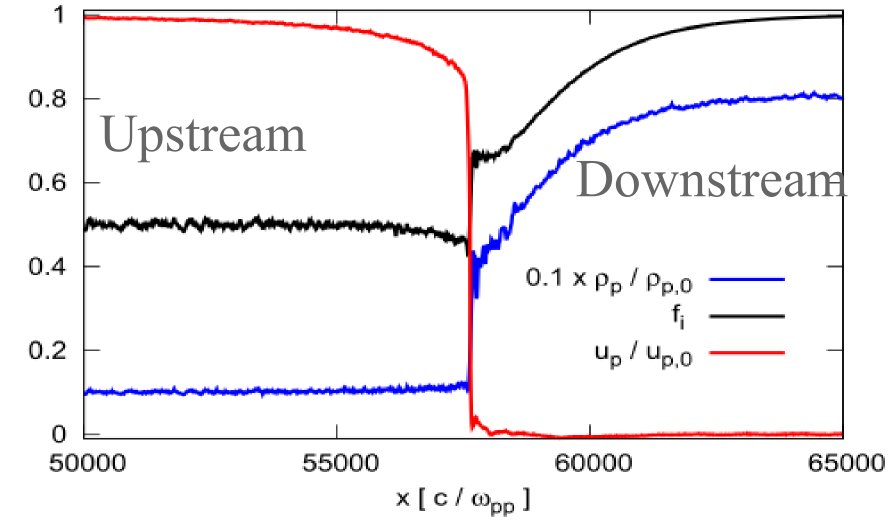
$W_{inter} \propto \sqrt{T_{pr}}$

$W_{broad} \propto \sqrt{T_2} \sim V_{sh}$

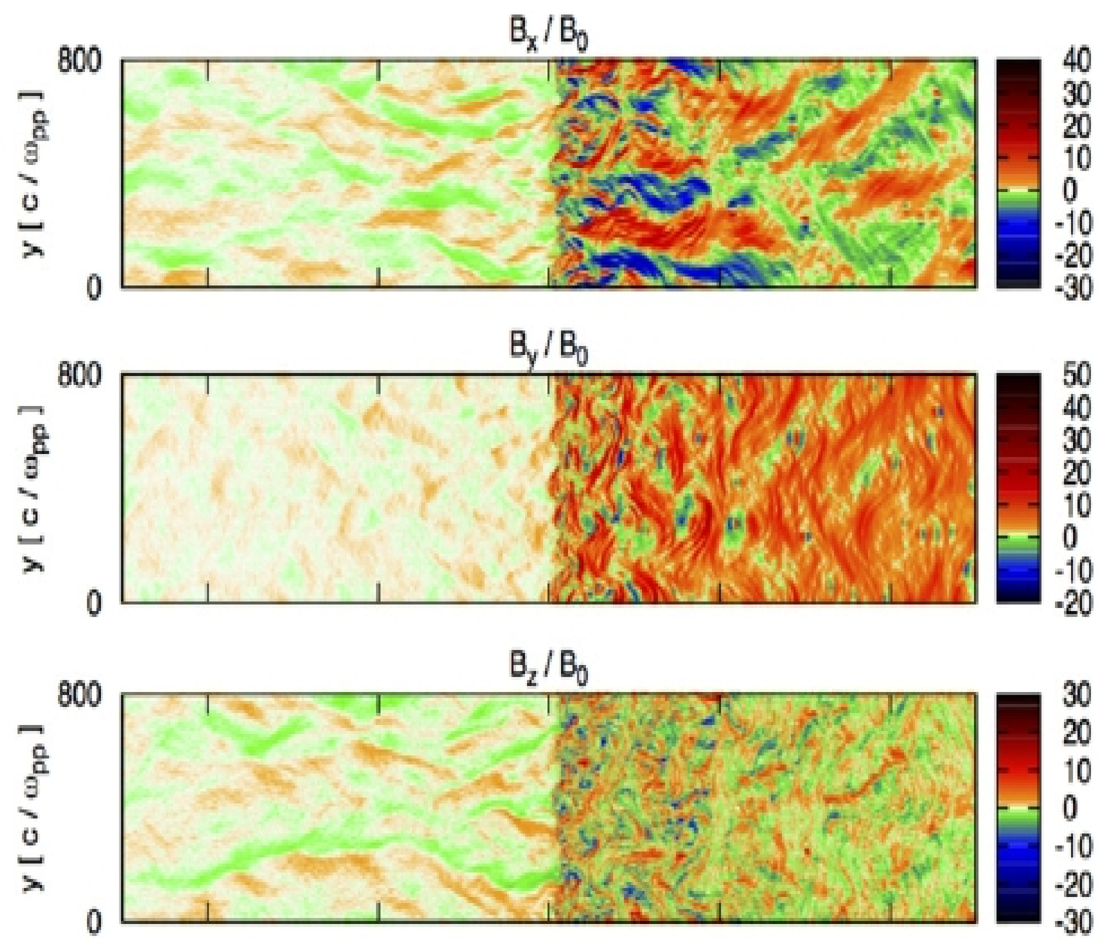
Results from simulations

[Results from Y. Ohira (2016), ApJ 817, 137]

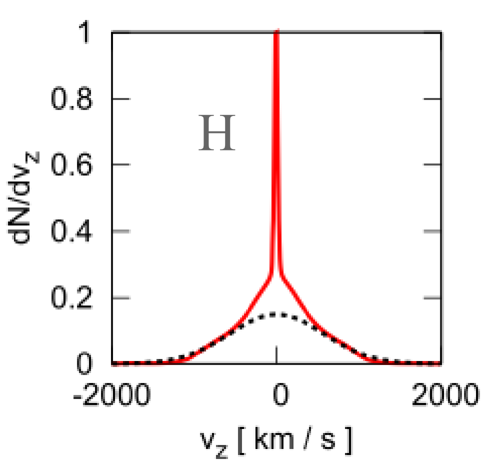
Shock structure

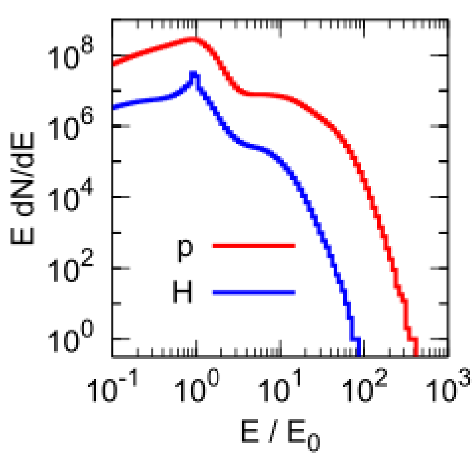


Magnetic field amplification



Particles' distributions





CR acceleration in presence of neutrals: test-particle regime

The compression ratio is a function of particle energy:

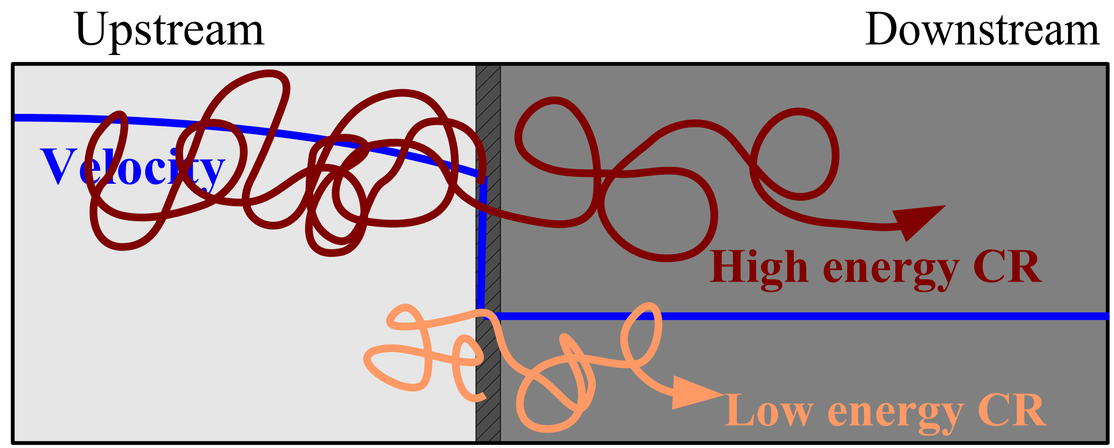
$$r(E) = \frac{u_1(E)}{u_2(E)}$$

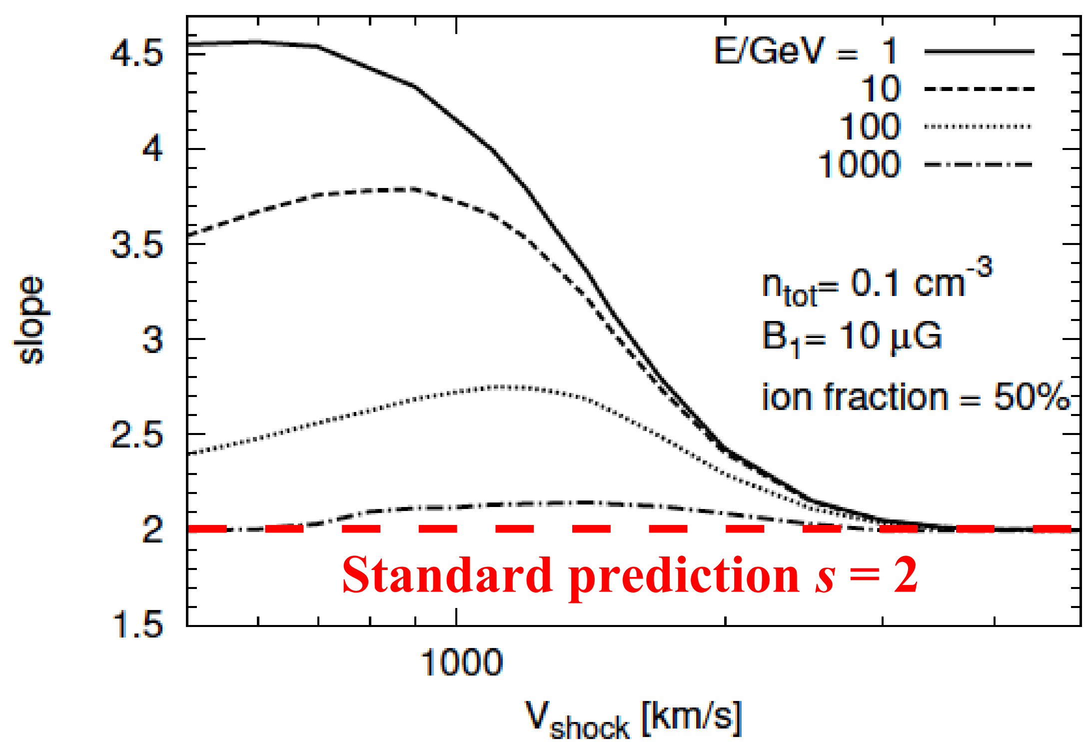
↓

<u>Slope of CR spectrum</u>

$$s(E) = \frac{r+2}{r-1}$$

→ For $V_{sh} < 3000$ km/s and large neutral fraction the CR spectrum can be very steep

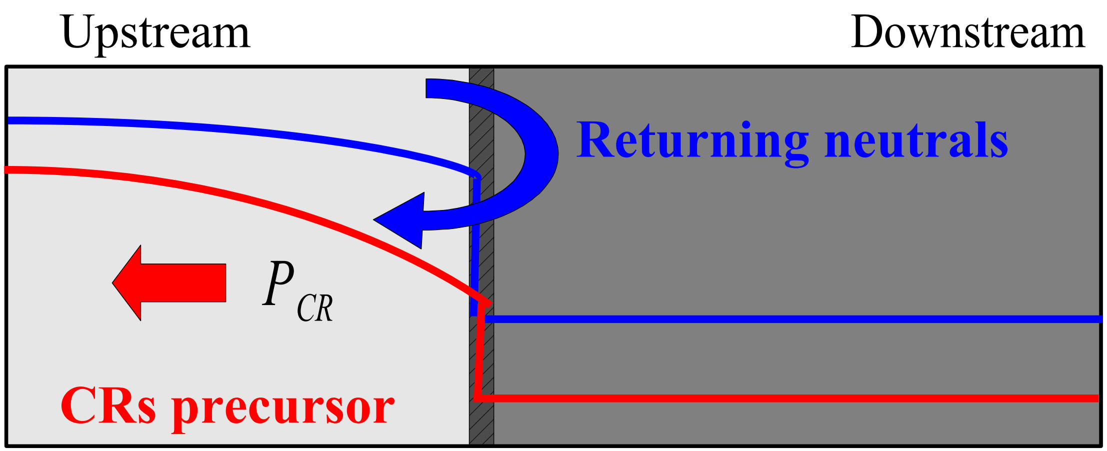


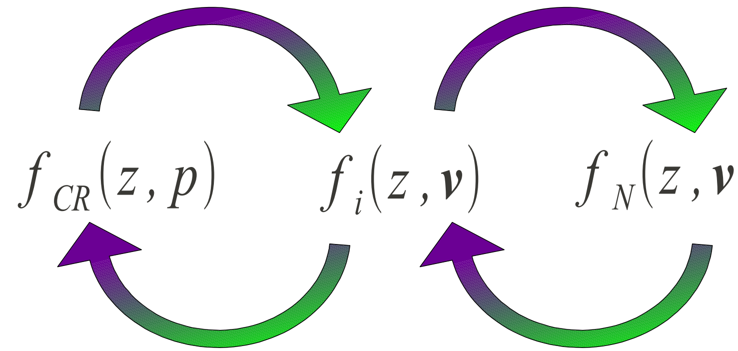


[Blasi, G.M., Bandiera, Amato & Caprioli 2012, *ApJ* 755, 121]

Acceleration of CRs in presence of neutrals: the semi-analytical approach

[G.M., Blasi, Bandiera, Amato, & Caprioli, 2013. *ApJ* 768, 148]





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Boltzmann equation for neutrals

$$v_z \frac{\partial f_N}{\partial z} = f_i \beta_N - f_N \beta_i$$

Transport equation for CRs

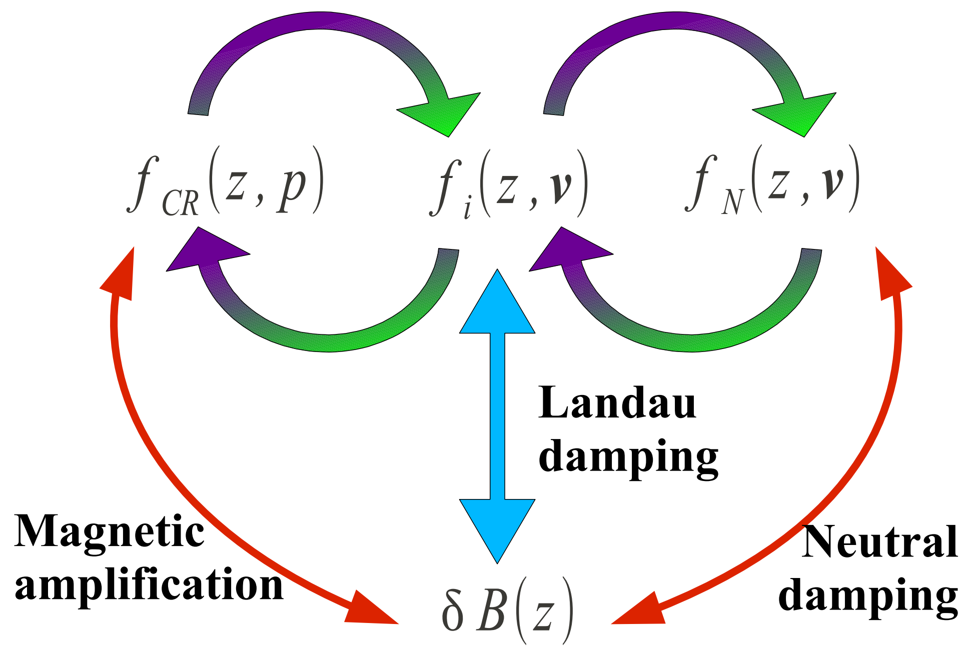
$$\frac{\partial}{\partial z}\left[D(z,p)\frac{\partial f_{CR}}{\partial z}\right] - u\frac{\partial f_{CR}}{\partial z} + \frac{1}{3}\frac{du}{dz}\, p\frac{\partial f_{CR}}{\partial p} = 0$$

Fluid equations couple CRs + neutrals + ions

$$\frac{\partial}{\partial z}\left[\rho_i u_i + F_{mass}\right] = 0$$

$$\frac{\partial}{\partial z}\left[\rho_i u_i^2 + P_i + P_{CR} + F_{mom}\right] = 0$$

$$\frac{\partial}{\partial z}\left[\frac{1}{2}\rho_i u_i^3 + \frac{\gamma}{\gamma-1} P_i u_i + F_{en}\right] = -u\frac{\partial P_{CR}}{\partial z}$$



Transport equation for magnetic field

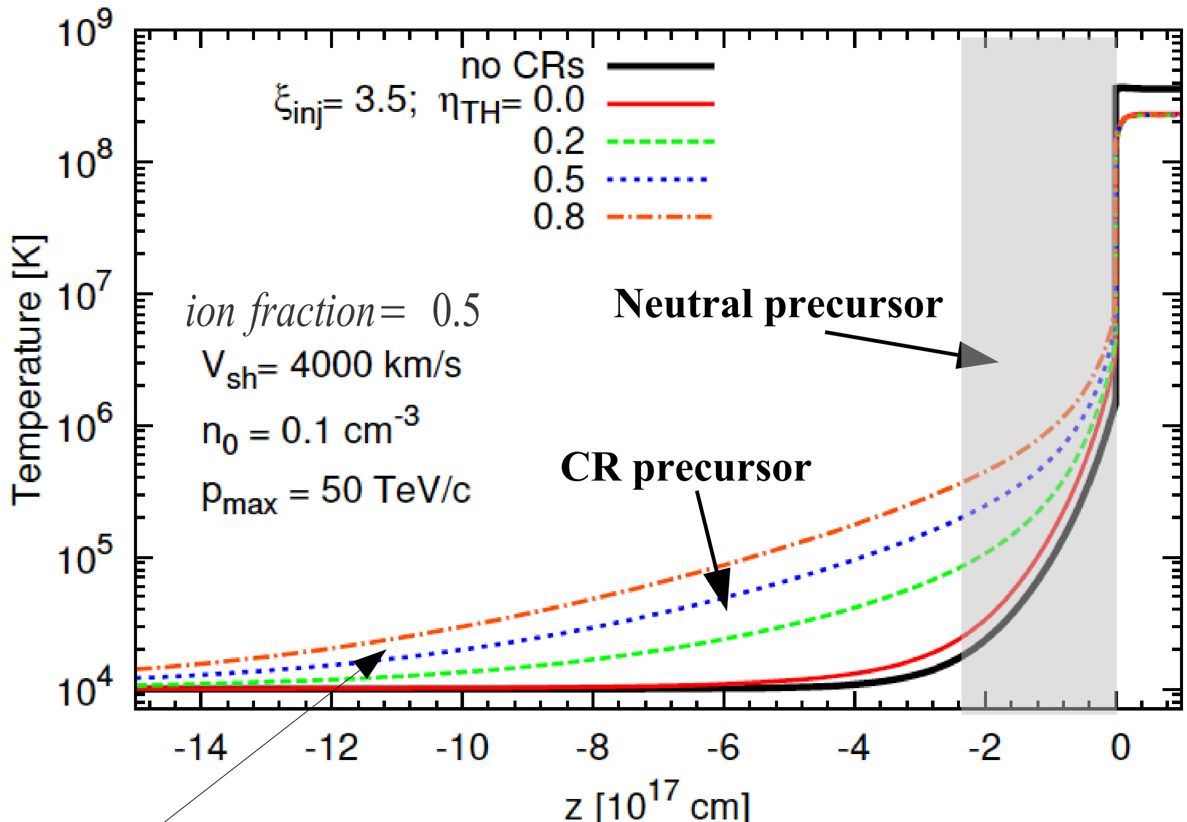
$$\frac{\partial F_w}{\partial z} = u\frac{\partial P_w}{\partial z} + P_w\left[\sigma_{CR}(k,z) - \Gamma(k,z)\right]$$

Electrons:

$$u_e = u_i; \quad n_e = n_i; \quad T_e = \beta\, T_p$$

Neutral-precursor vs CR-precursor

Temperature profile for acceleration efficiency $\epsilon_{CR} \sim 40\%$



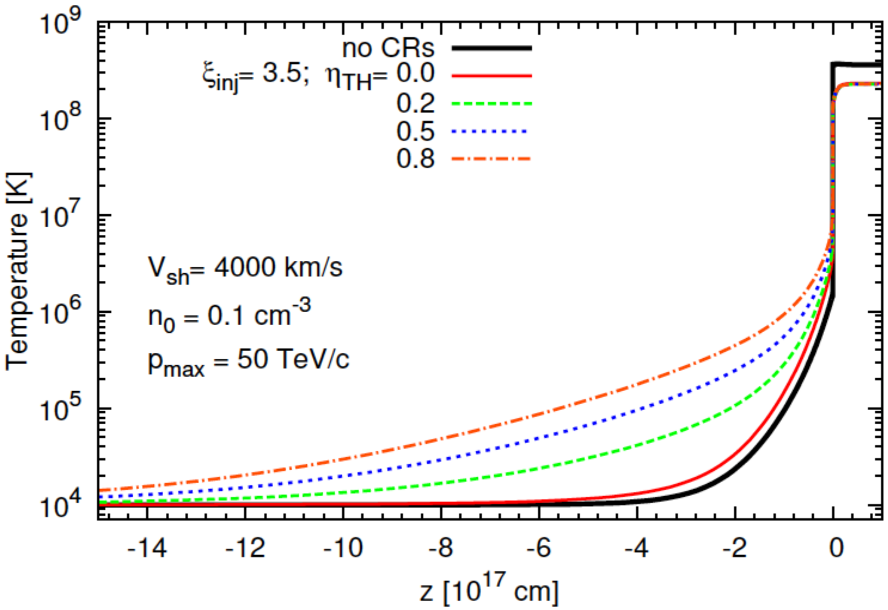
Downstream temperature decreases

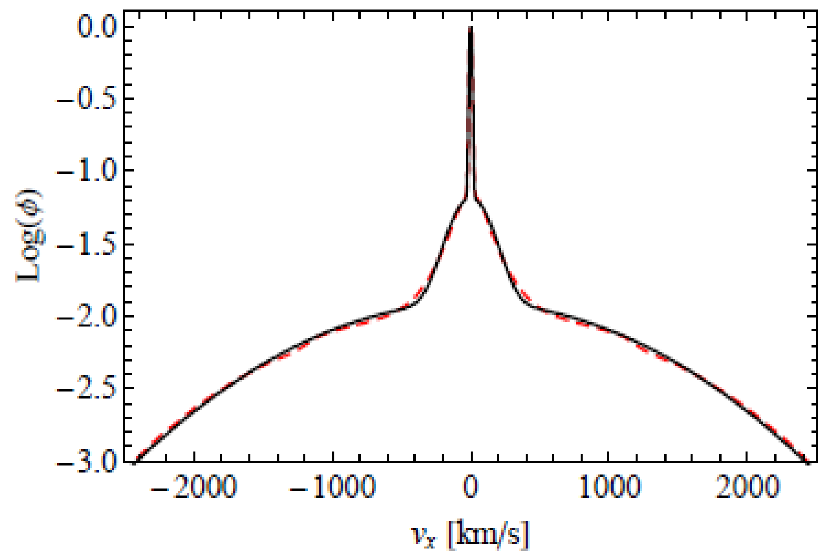
Heating in the upstream depends on the amount of magnetic turbulence damped

Transport Eq. for magnetic field $$\frac{\partial F_w}{\partial z} = u \frac{\partial P_w}{\partial z} + P_w \left[\sigma_{CR}(k,z) - \Gamma(k,z) \right]$$

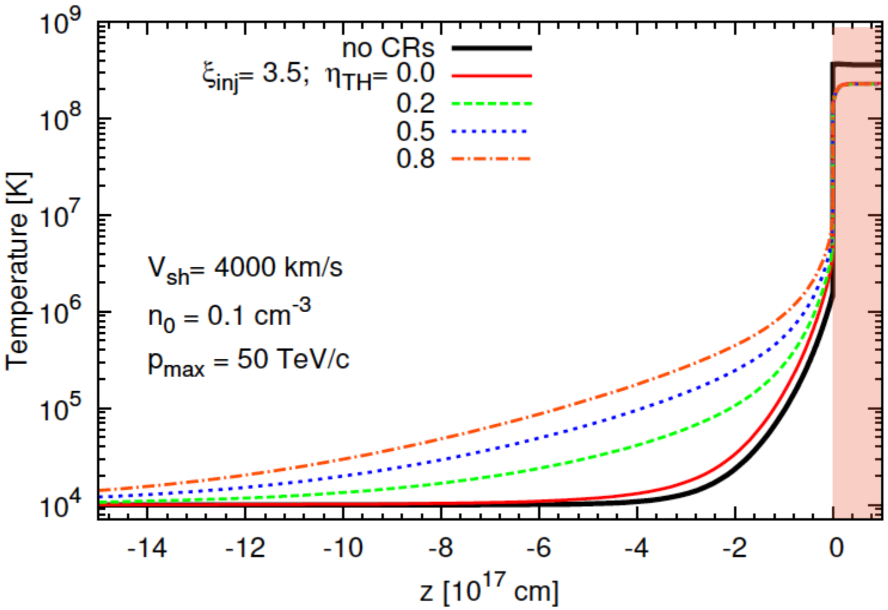
Damping rate $$\Gamma(k,z) = \eta_{TH} \sigma_{CR}(k,z)$$

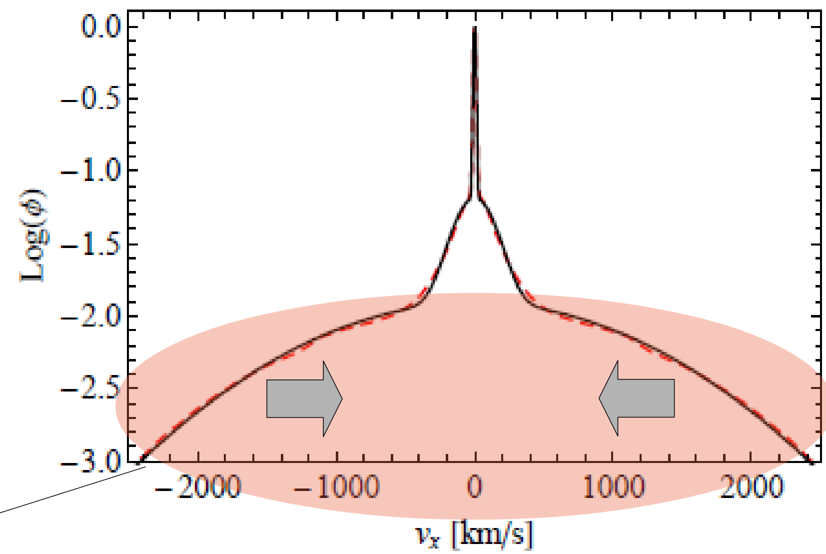
Width of H lines vs. acceleration efficiency



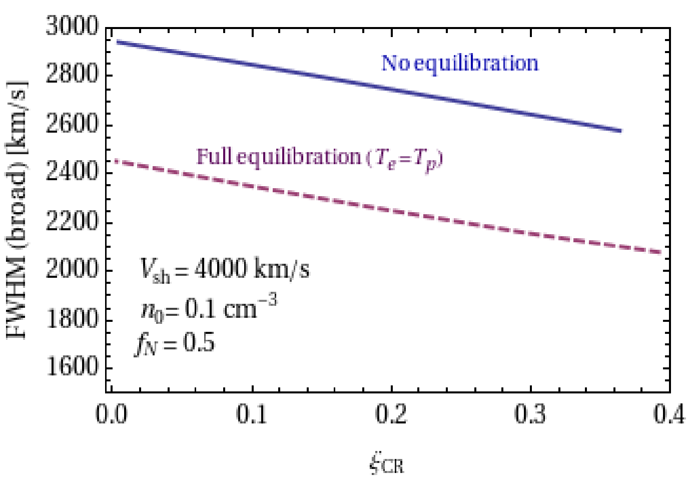


Width of Hα lines vs. acceleration efficiency

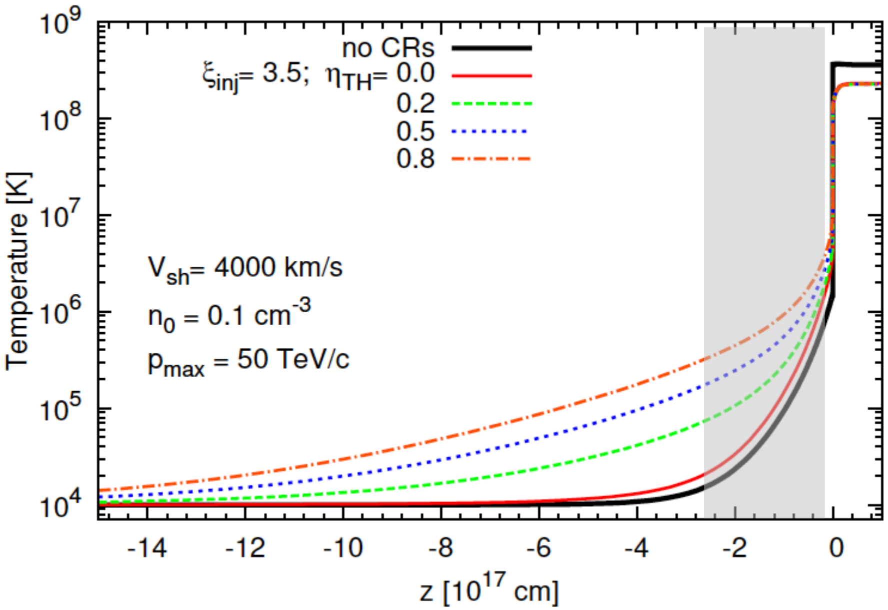


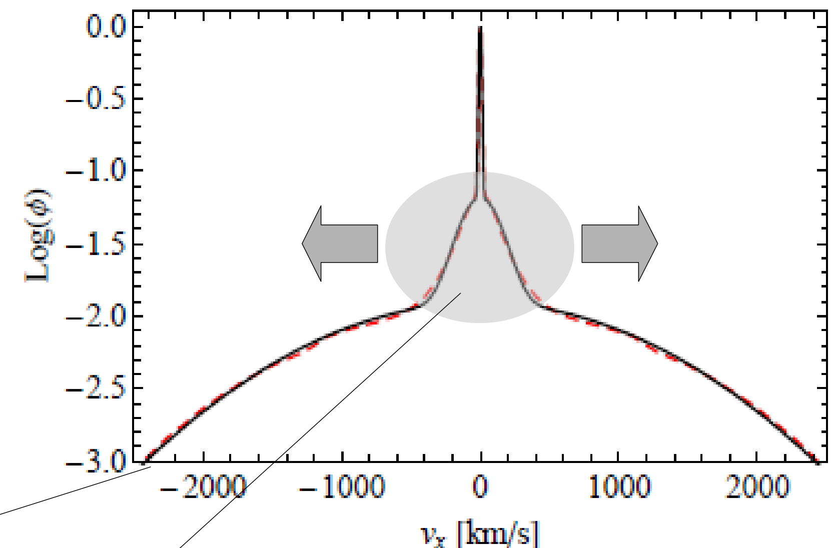


FWHM of broad line
→ *T* of downstream



Width of Hα lines vs. acceleration efficiency





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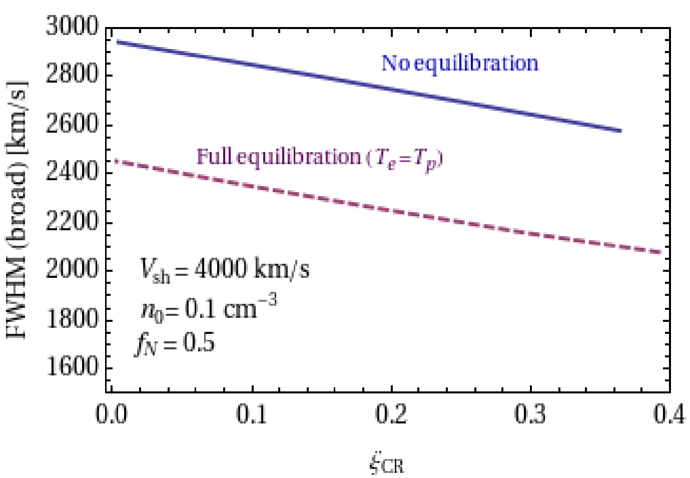
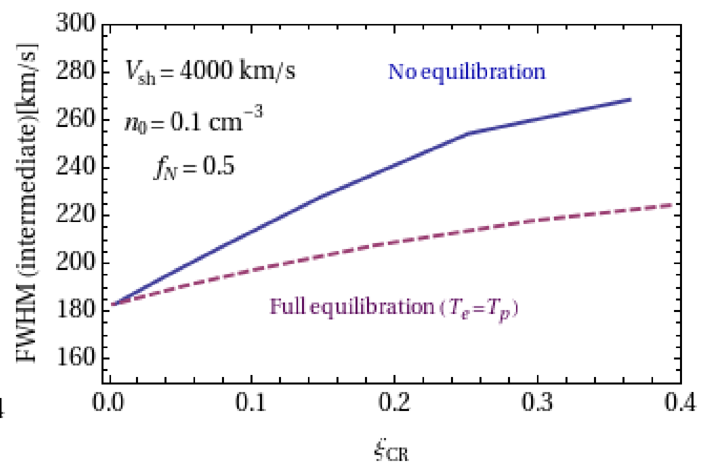
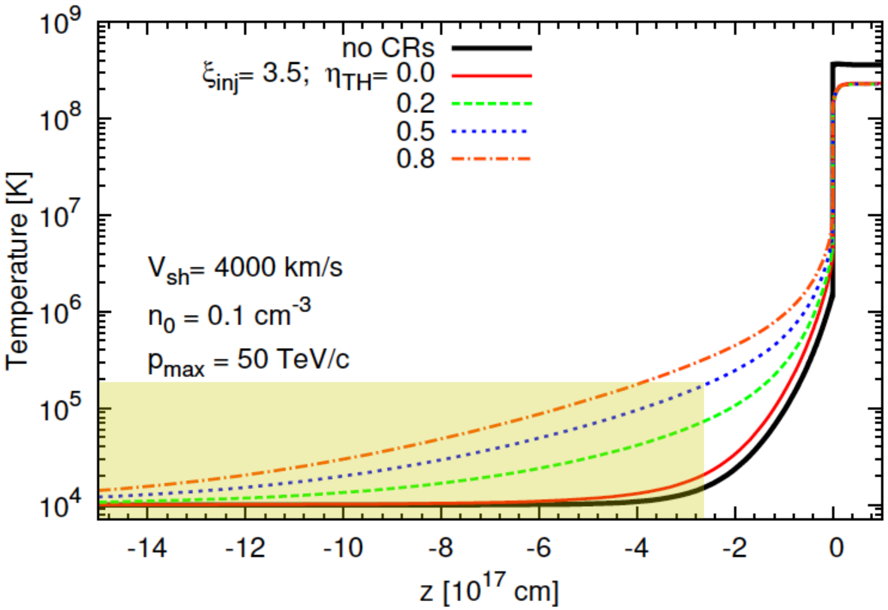
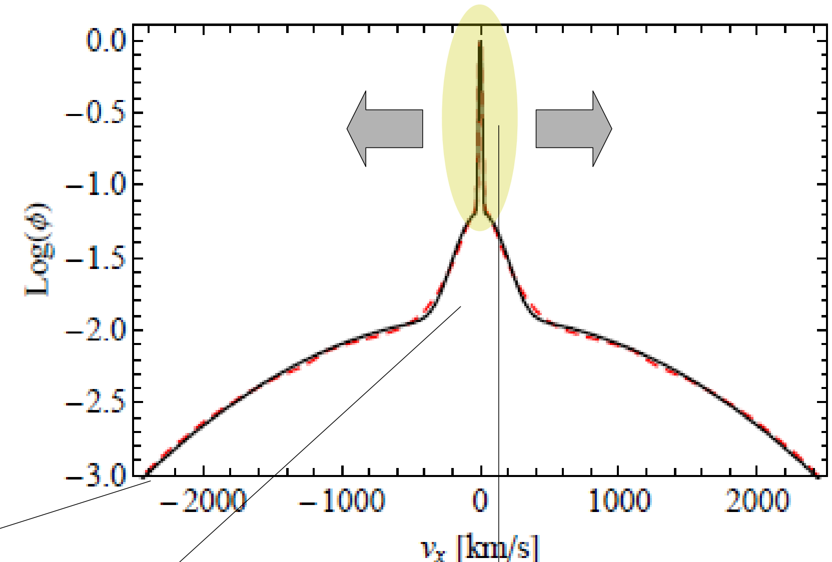


FWHM of intermediate line
→ *T* of neutral precursor



Width of Hα lines vs. acceleration efficiency

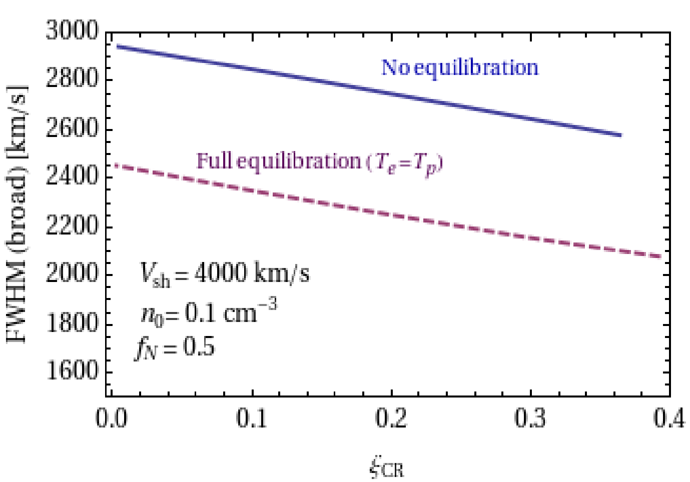


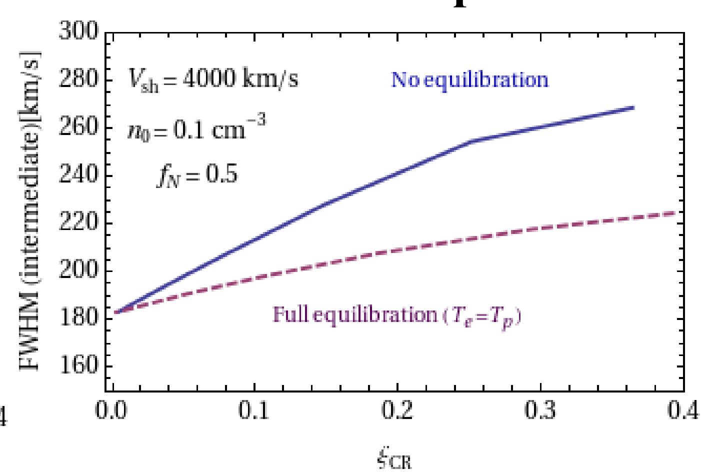


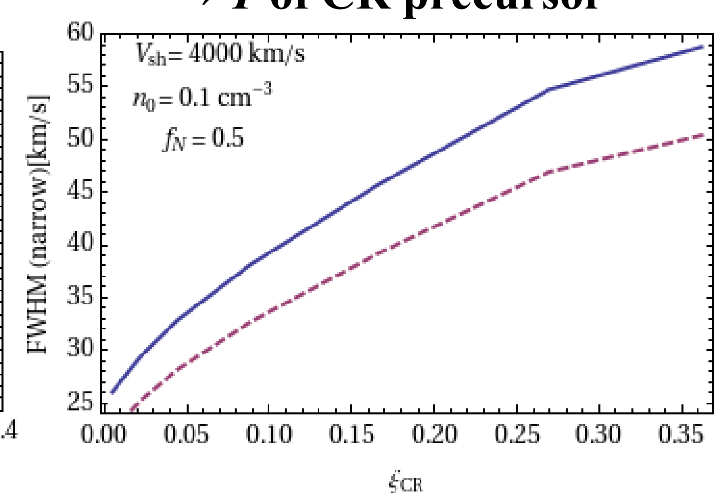
FWHM of broad line → *T* of downstream

FWHM of intermediate line → *T* of neutral precursor

FWHM of narrow line → *T* of CR precursor

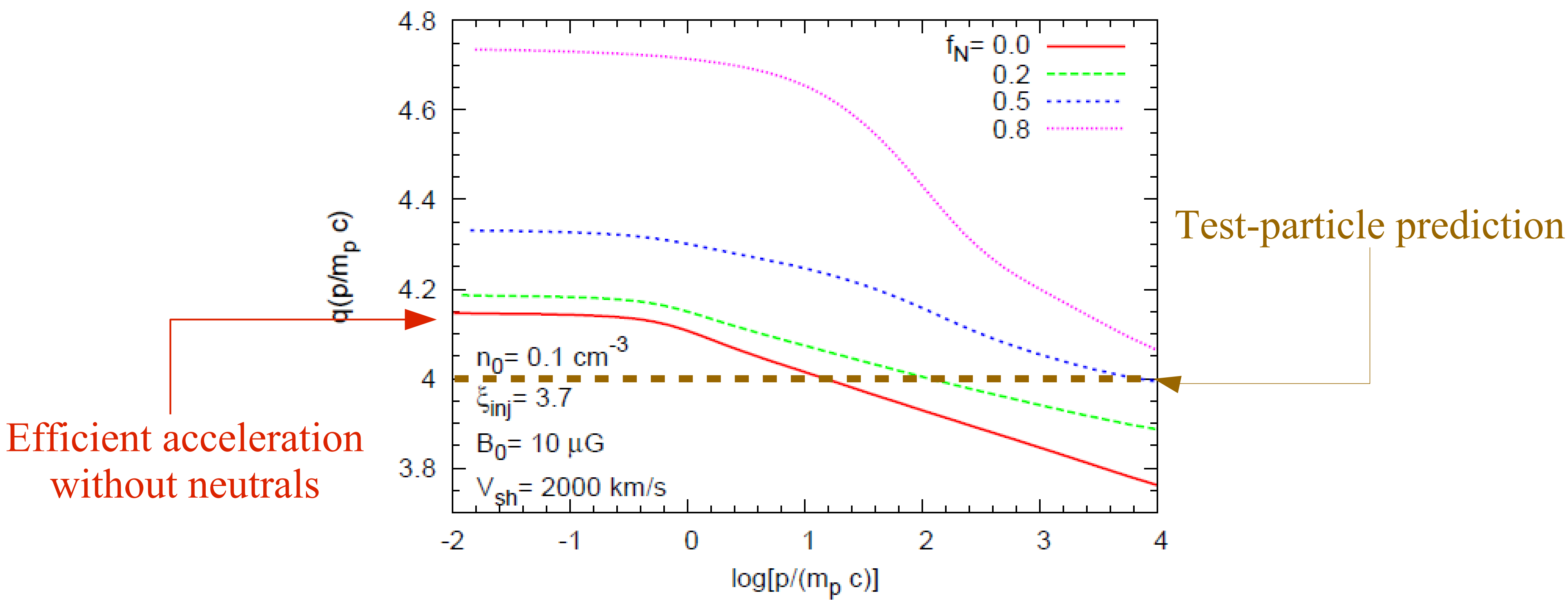






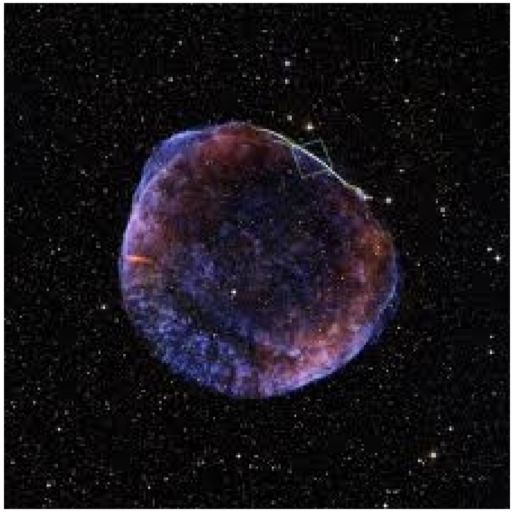
Spectrum of CR in presence of neutrals: efficient acceleration

Slope of accelerated particles $f_{CR}(p) \propto p^{-q(p)}$



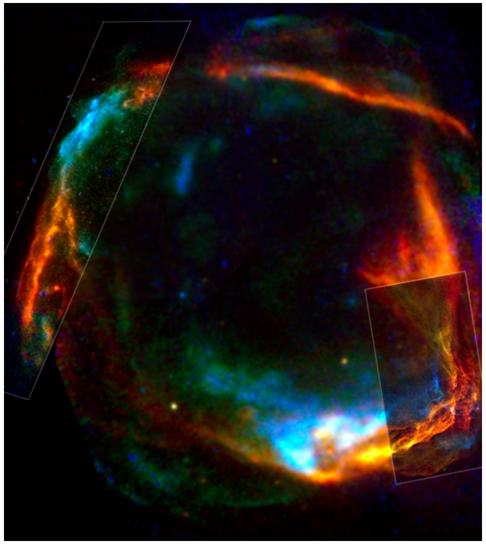
Application to single SNRs

SN 1006

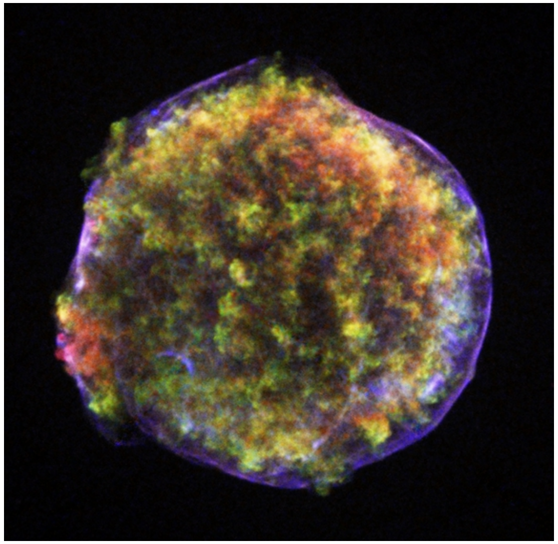


SNR 0509-67.5

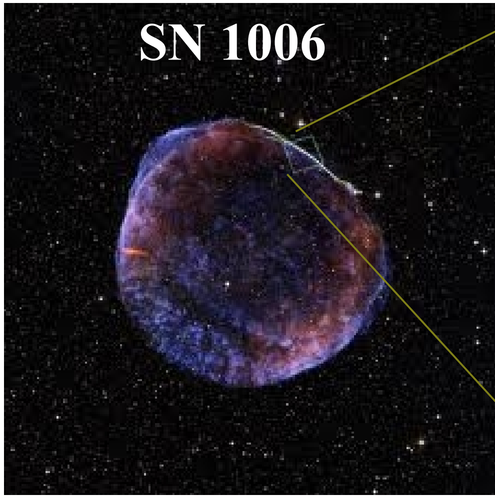
RCW 86

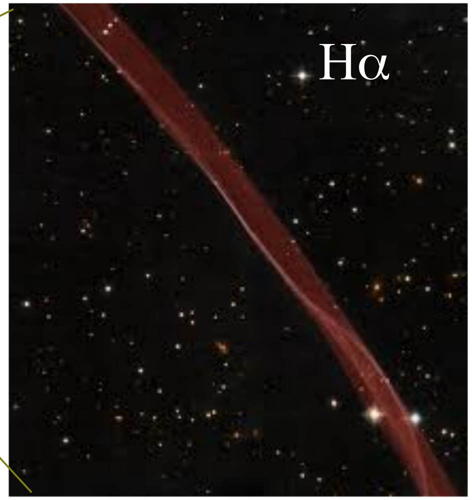


TYCHO

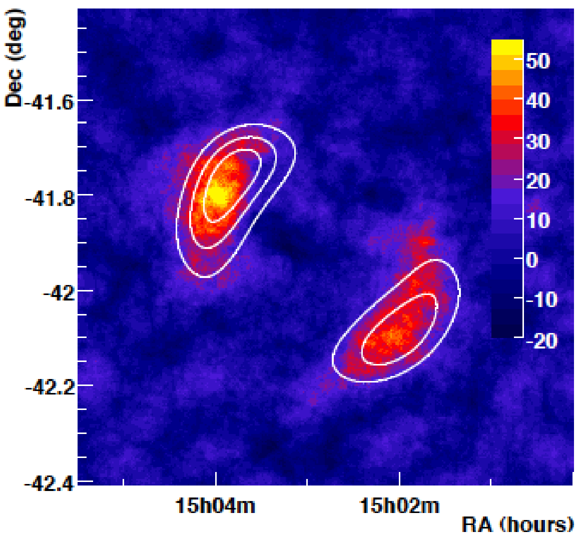


NW rim of SN 1006: the unmodified case



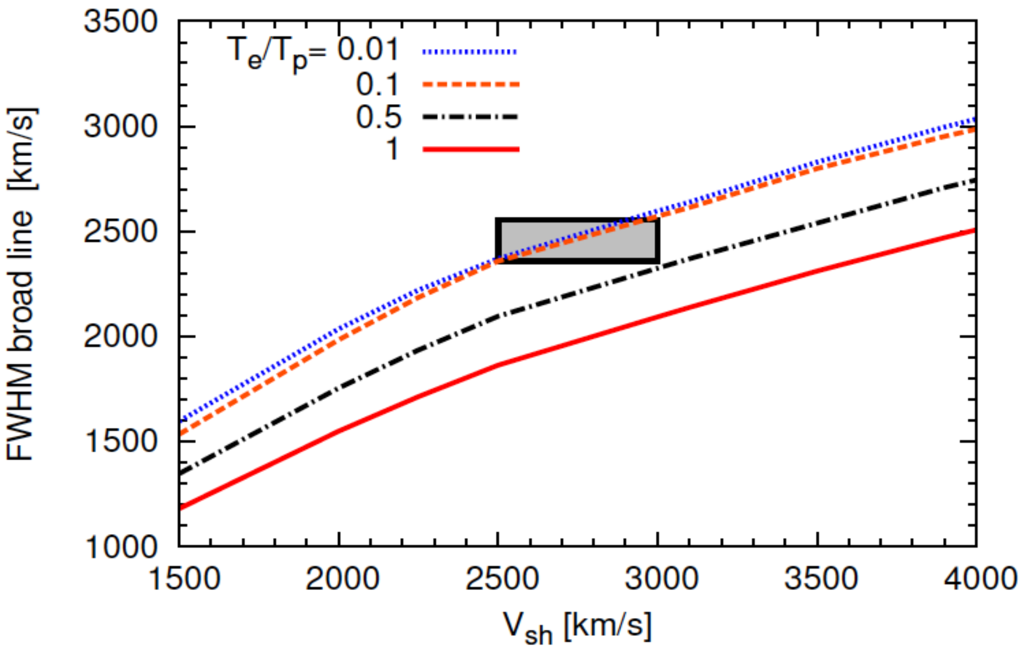


SN 1006 in TeV (HESS)



In the NW region where Balmer emission is stronger there are no indications of efficient CR acceleration:

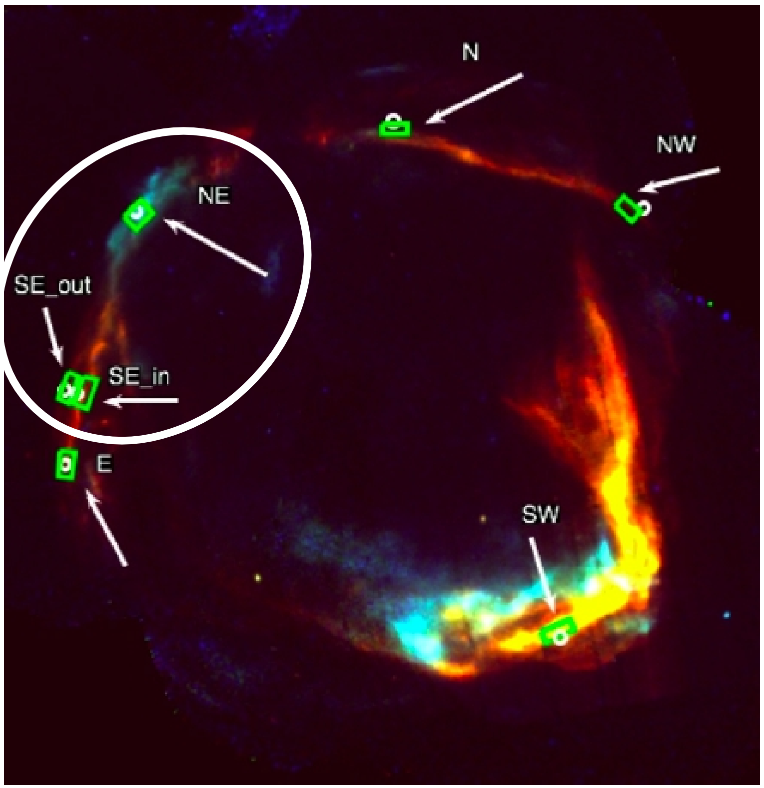
- absence of non thermal X-rays
- no gamma-ray emission
- larger distance between contact discontinuity and forward shock
- **FWHM of narrow line = 21 km/s**
  → $T_{ISM} = 10^4$ K
  → no need of CR-precursor

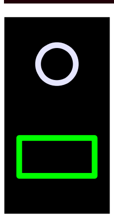


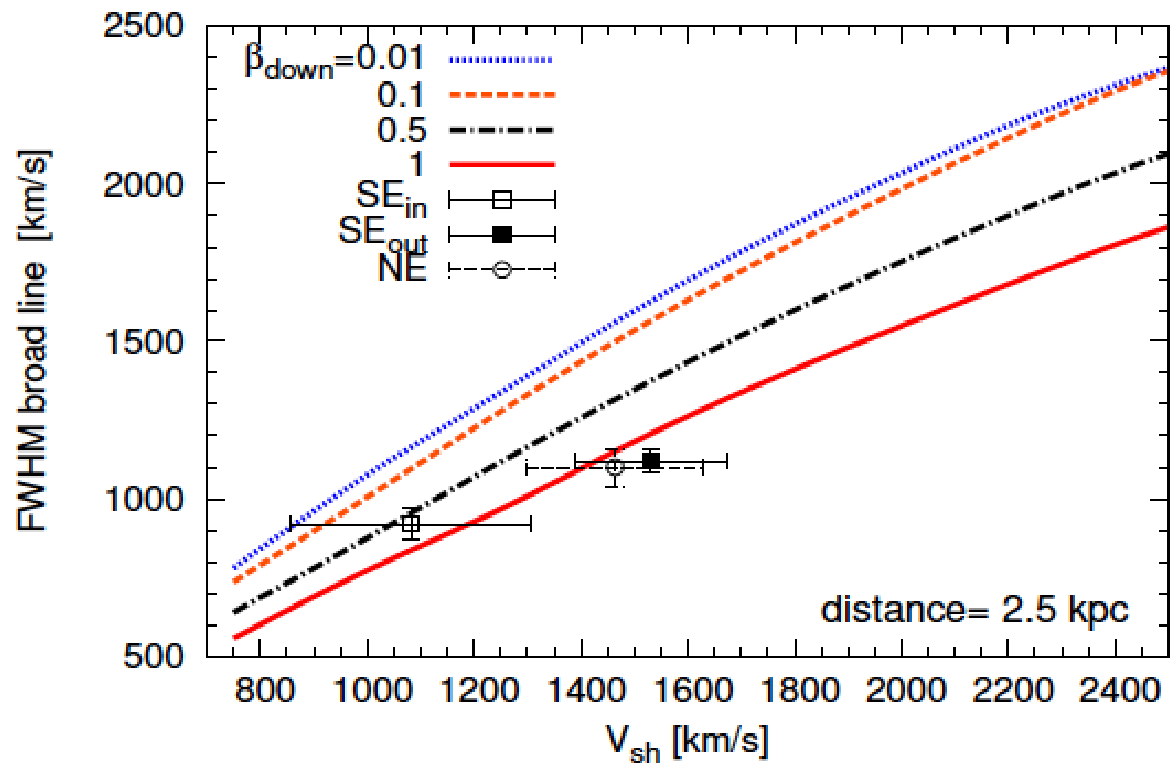
RCW 86: anomalously narrow broad line

[G.M., Bandiera, Blasi, Amato, A&A, 2014]

[From Helder, Vink, & Bassa, 2011, ApJ 737, 85]





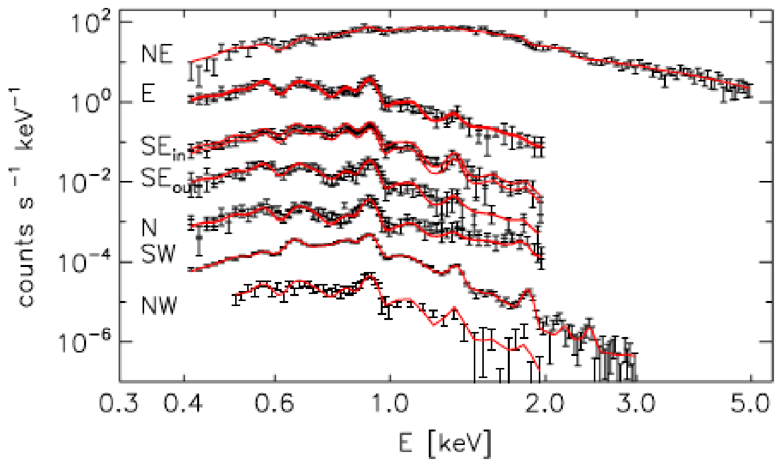


Distance: 2 kpc < *d* < 3 kpc
d ~ 2.5 the most quoted value

RCW 86: anomalously narrow broad line

[G.M., Bandiera, Blasi, Amato, A&A, 2014]

Helder et al. also inferred the electron temperature from the X-ray spectrum

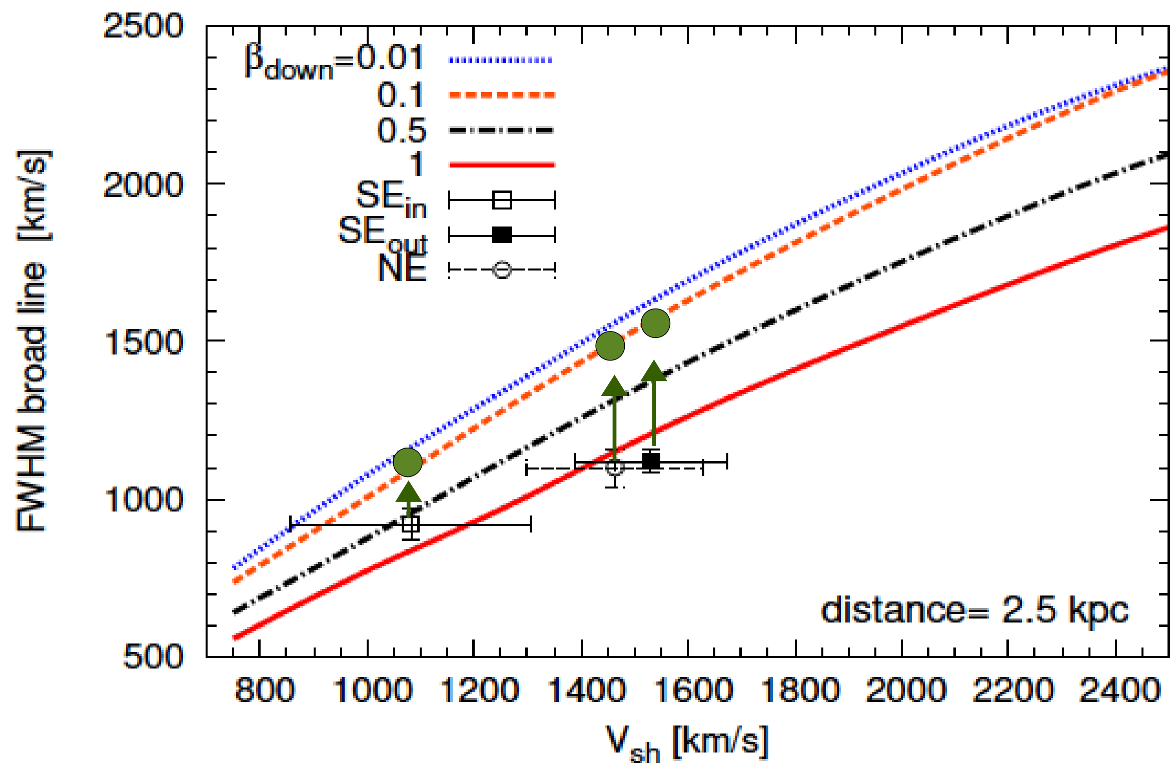


	NE	SE_{in}	SE_{out}
T_e (keV)	37^{+29}_{-19}	0.9±0.1	0.6±0.1

For the SE_{out} region $T_e < 0.7$ keV (right downstream of the shock)

For d= 2.5 kpc, combining the FWHM and the T_e we get

$$\epsilon_{CR} > 15\%$$



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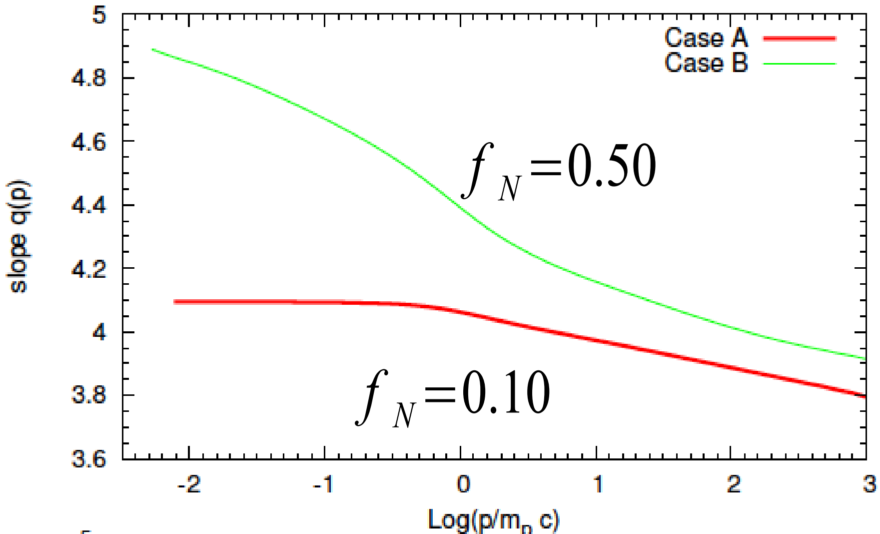
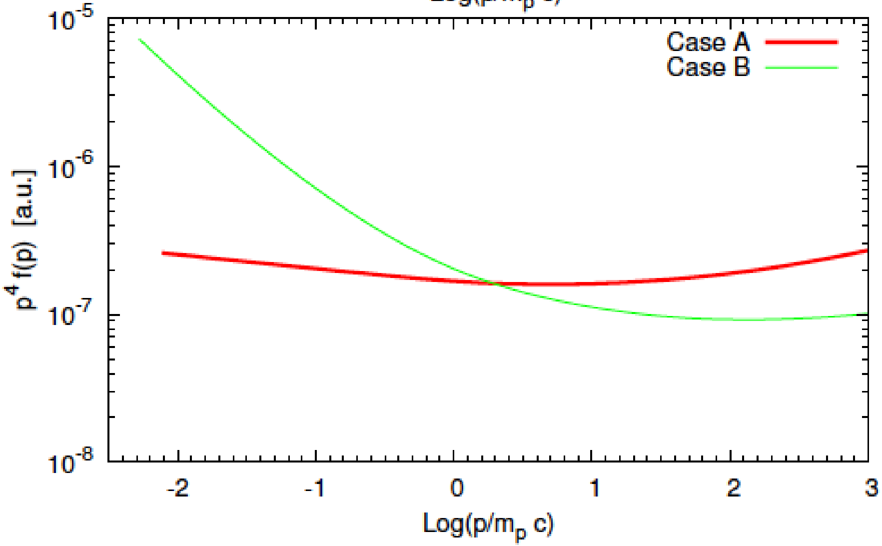
Spectrum of accelerated CRs

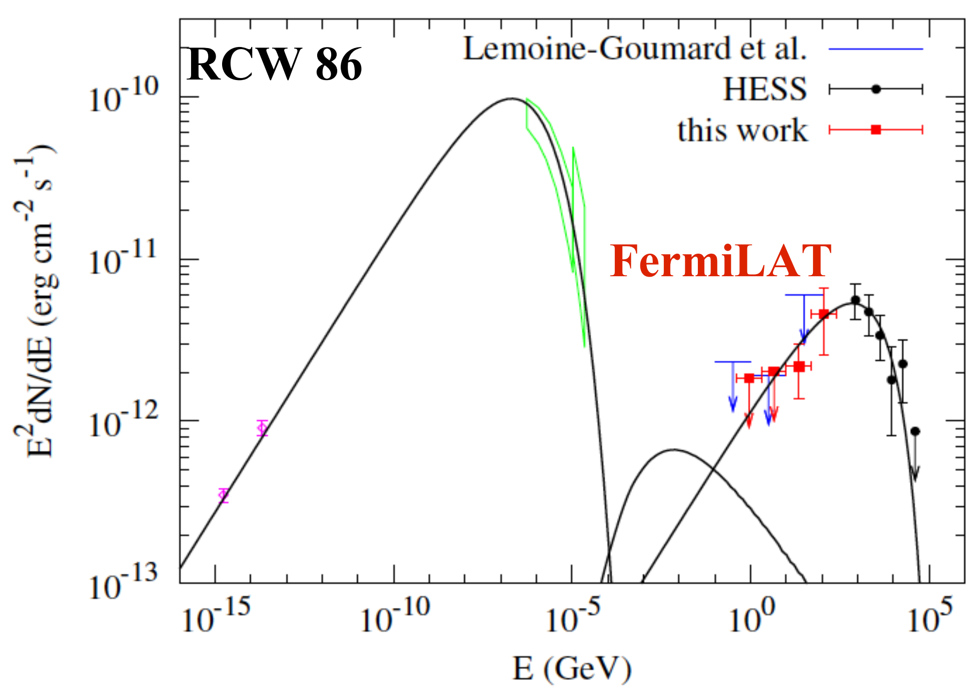




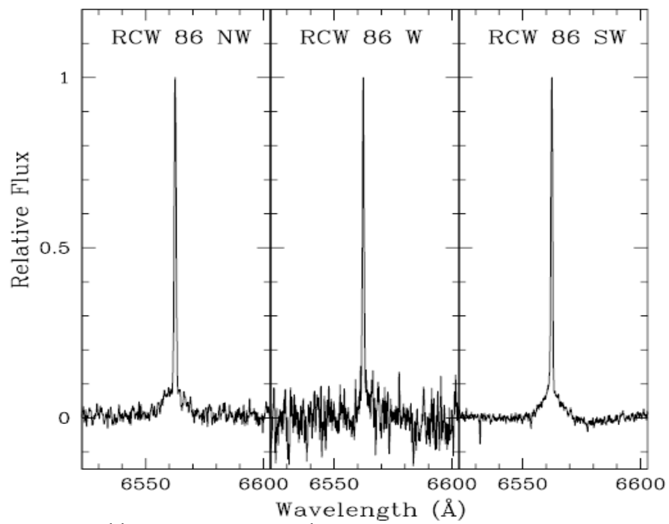
Caveat

Efficient acceleration does not imply hard spectrum and large energies

For f_N >> 10% the spectrum is very steep and the large part of the energy is in suprathermal particles $E < 1$ GeV



Narrow H Lines with Unusual Broad Width



From Sollerman at al., 2003

SNR	Shock velocity (km s^{-1})	Narrow component *FWHM* (km s^{-1})
Cygnus Loop	300–400	28–35
RCW 86 SW	580–660	32 ± 2
RCW 86 W	580–660	32 ± 5
RCW 86 NW	580–660	40 ± 2
Kepler D49 & D50	2000–2500	42 ± 3
0505-67.9	440–880	32–43
0548-70.4	700–950	32–58
0519-69.0	1100–1500	39–42
0509-67.5	–	25–31
Tycho	1940–2300	44 ± 4
SN 1006	2890 ± 100	21 ± 3

The H FWHM of narrow lines measured from Balmer Shocks gives an estimate of upstream temperature

$$W_n = \sqrt{8 \ln 2 \frac{k T_0}{m_H}} = 21\, km/s \left(\frac{T_0}{10^4 K} \right)^{1/2}$$

Measured FWHM in some SNRs:

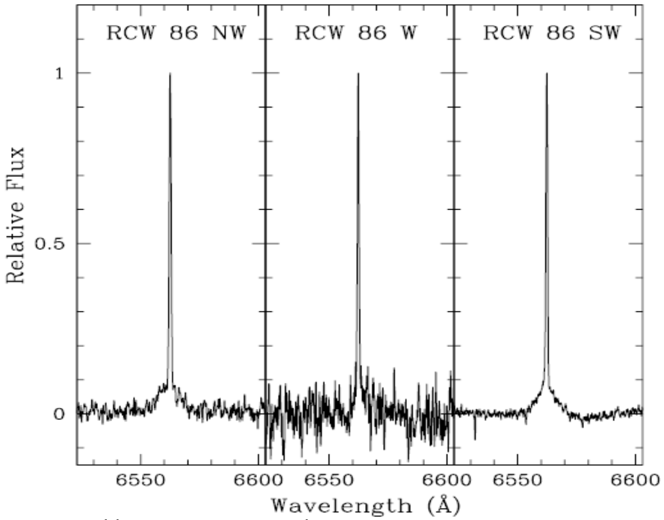
$$W_n \sim 30-50\, km/s \rightarrow T \sim 2-6\, 10^4\, K$$

But for *T*>10^4 K Hydrogen is expected to be completely ionized

→ We need a mechanism able to heat the neutral ISM component in a time less than the ionization time

→ a CR precursor could be able to heat the neutrals

Narrow Hα Lines with Unusual Broad Width



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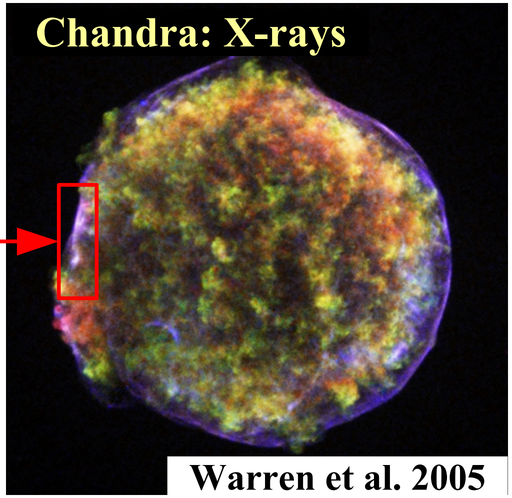
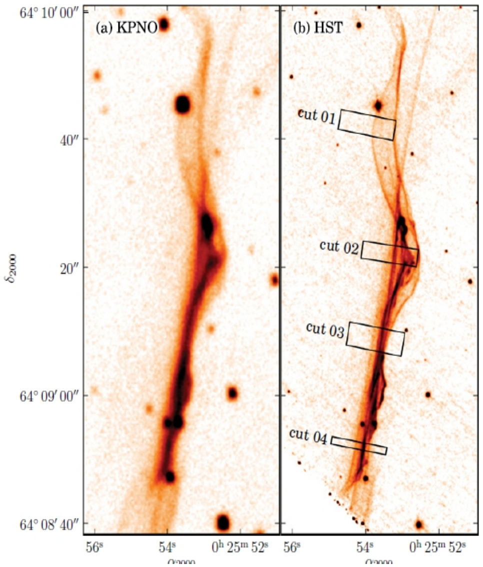
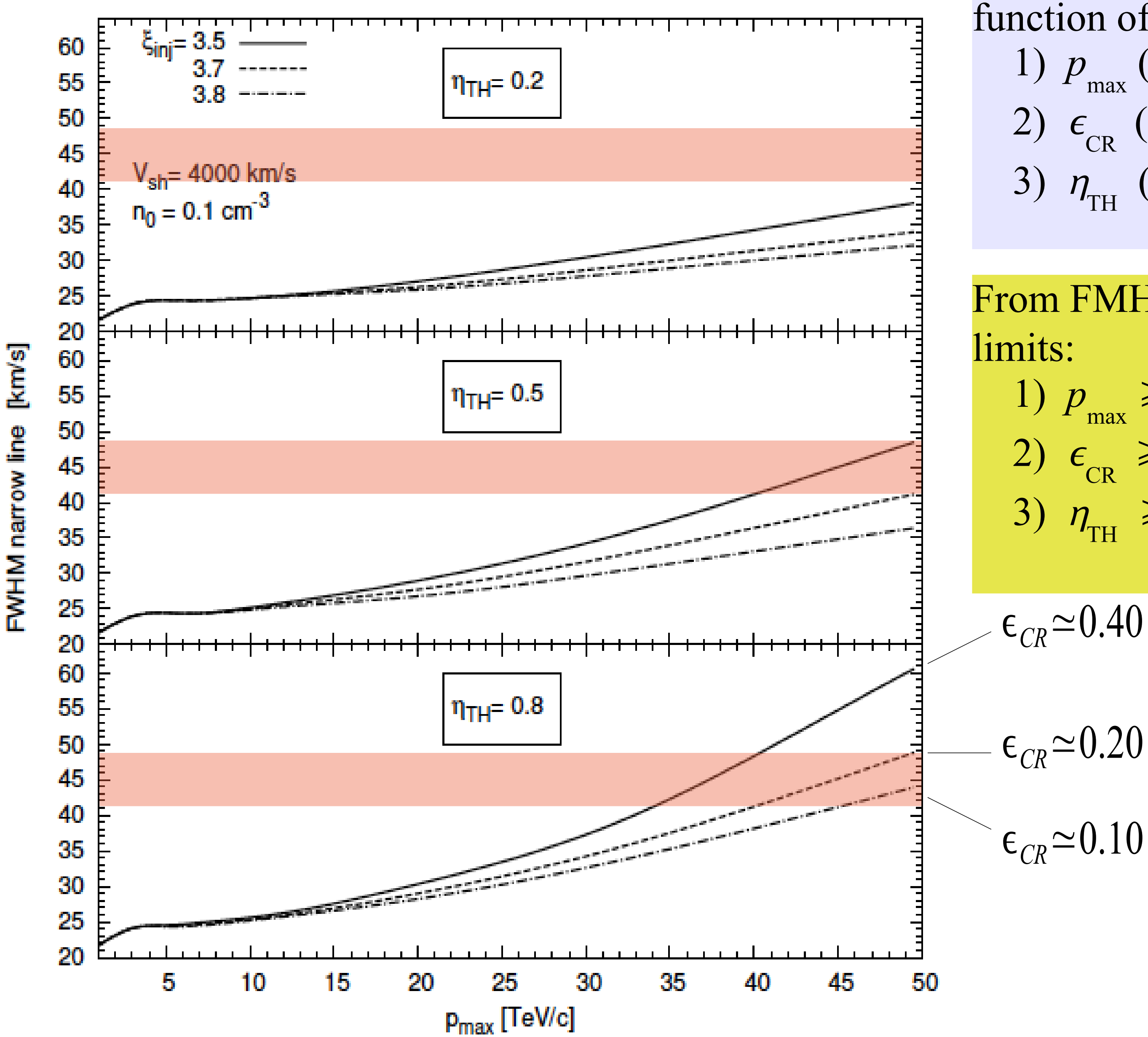


Knot g



Tycho's SNR:
Narrow Hα Lines with Unusual Broad Width

FWHM of narrow component



The width of narrow line is an increasing function of:

1) p_{max} (→ Length of CR-precursor)
2) ϵ_{CR} (→ acceleration efficiency)
3) η_{TH} (→ magnetic damping)

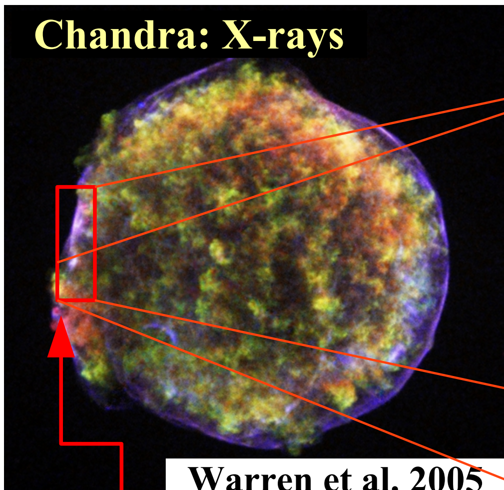
From FMHW= 44±4 we can estimate lower limits:

1) $p_{max} \geqslant 50$ TeV/c
2) $\epsilon_{CR} \geqslant 0.1$
3) $\eta_{TH} \geqslant 0.2$

Assuming Bohm diffusion in the amplified magnetic field

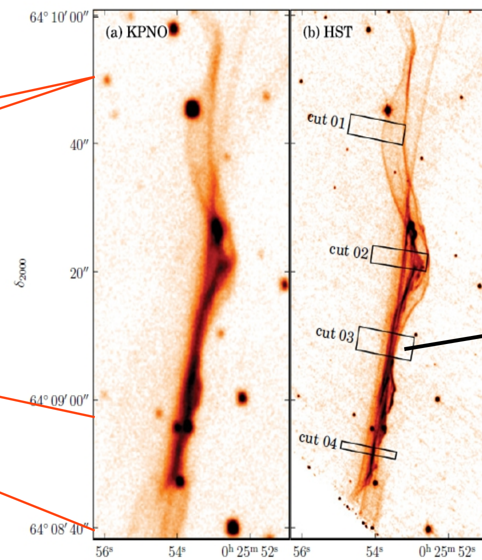
Tycho's SNR:
Precursor in Balmer-Dominated Shocks

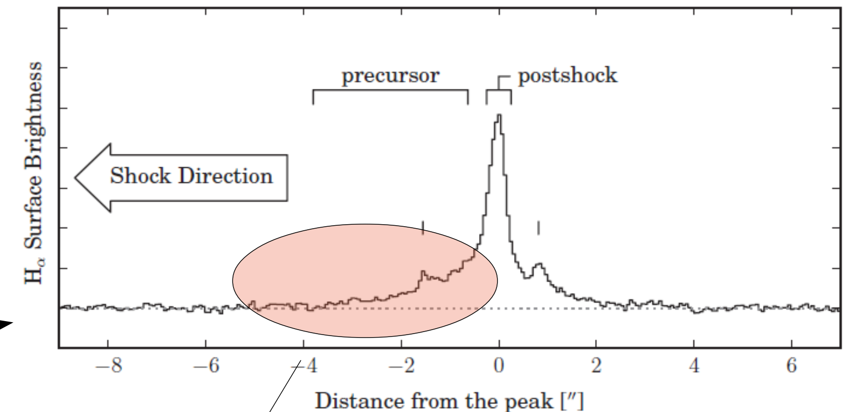
Lee et al., 2010
(Observation with the Hubble Space Telescope)



Knot g

Hα emission



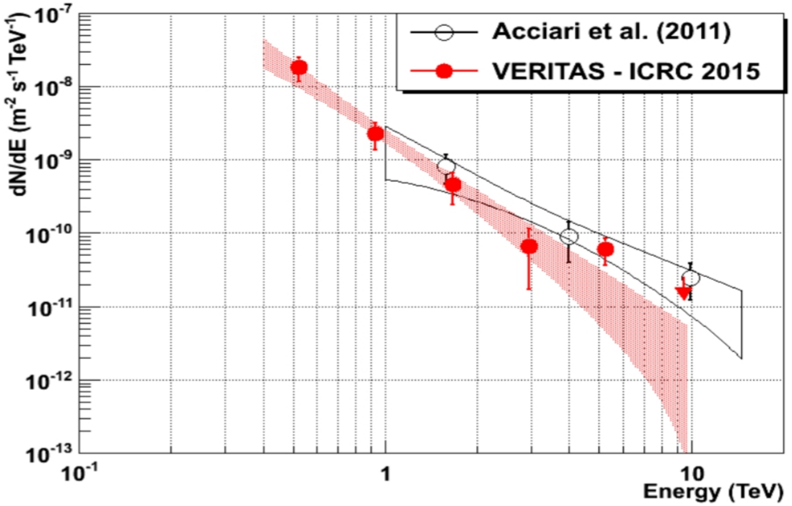


1) Evidence of Hα emission from the precursor which contribute up to 30-40% of the total narrow Hα emission:
→ different temperature and/or different bulk speed between ions and neutrals in the precursor region

2) The *knot g* in Tycho remnant is associated with non-thermal X-ray emission
→ the shock may accelerate particles efficiently

Tycho revised:
leaving the *spherical-cow* approximation

1) The new VERITAS data show a cut-off with maximum energy ~ 10 TeV



2) Williams et al. (2013) found evidence for an overall gradient in the ambient density surrounding Tycho, with densities › 3 − 10 times higher in the northeast region with respect to the southwest region.

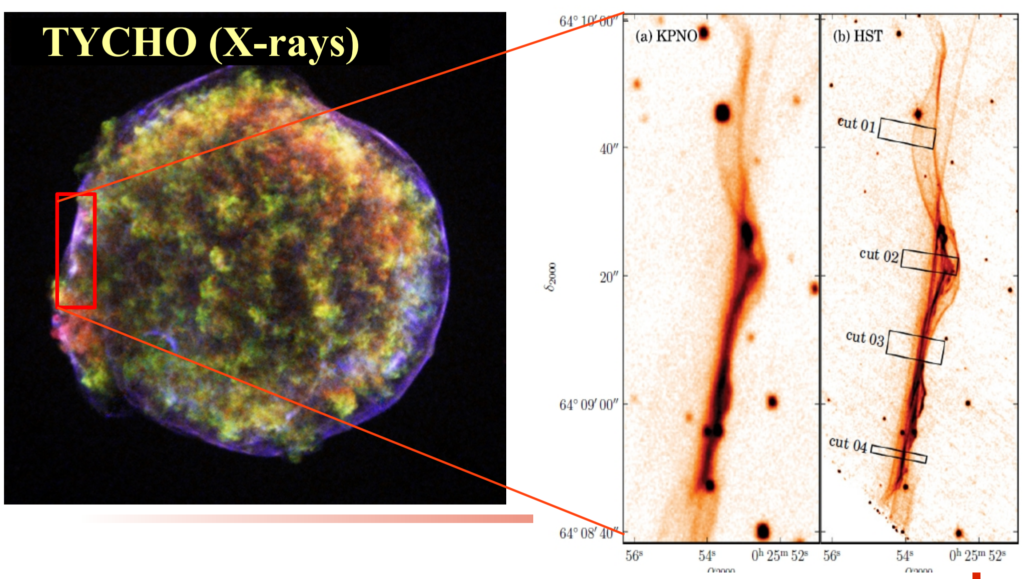
3) Variations in the proper motion of the shock observed in radio (Reynoso et al., 1997) and X-ray studies (Katsuda et al. , 2010) return an average shock speed (For distance between 2 and 3 kpc)

V_{sh} › 4000 − 5000 km/s (southwest)

› 2000 − 3000 km/s (northeast)

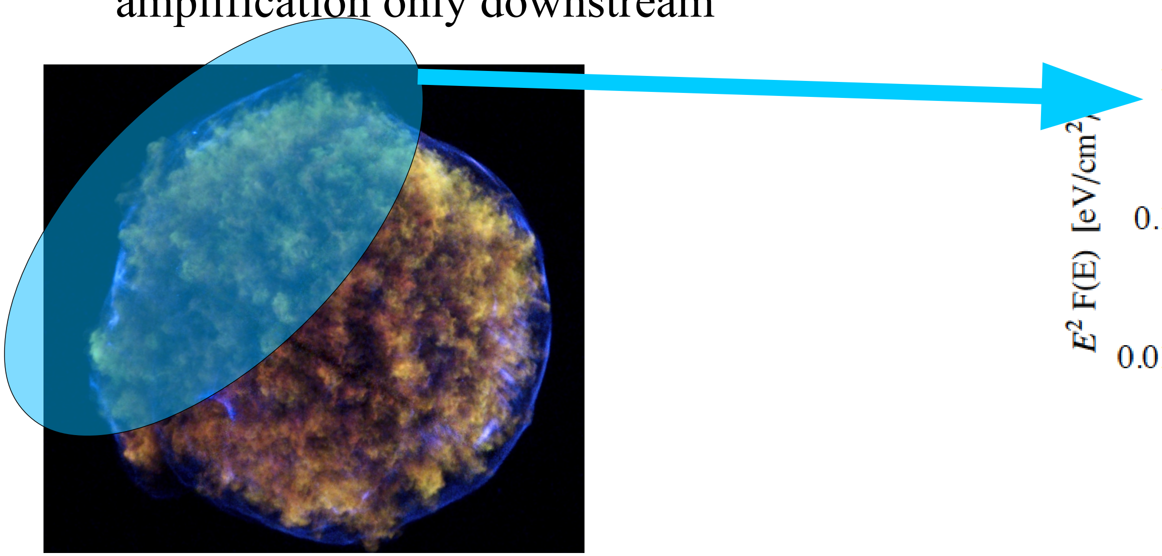
4) The NE part shows a strong Hα emission (estimated neutral fraction > 50%)

Hα emission

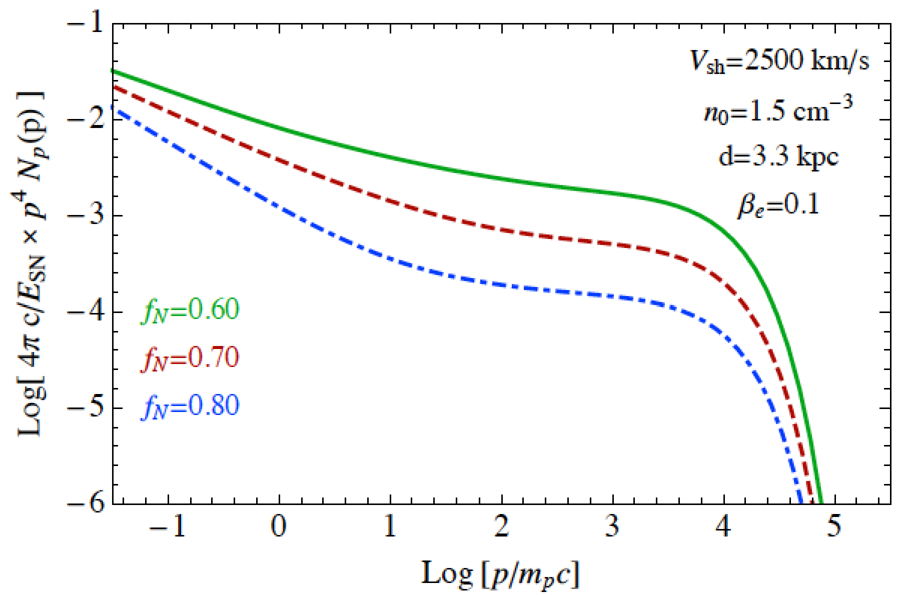


Results for Tycho

- We include amplification due to Bell-instability
- The emission in gamma-ray is mainly due to the NW region where the shock is slower and the ISM is denser
- The presence on neutrals produces steep spectra
- In this framework is not easy to explain the X-ray rims:
  - In SE magnetic amplification is enough
  - In NW we also need some further amplification only downstream



Proton spectrum



γ-ray emission