Unveiling the presence of Cosmic Rays in supernova remnant using Blamer emission

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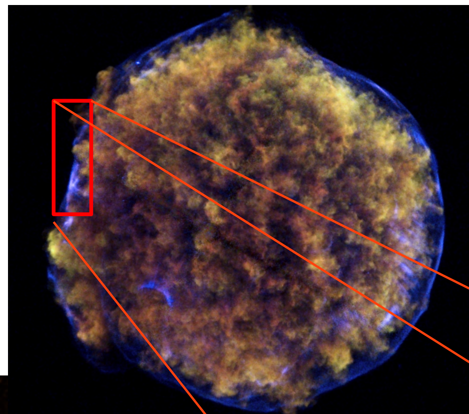
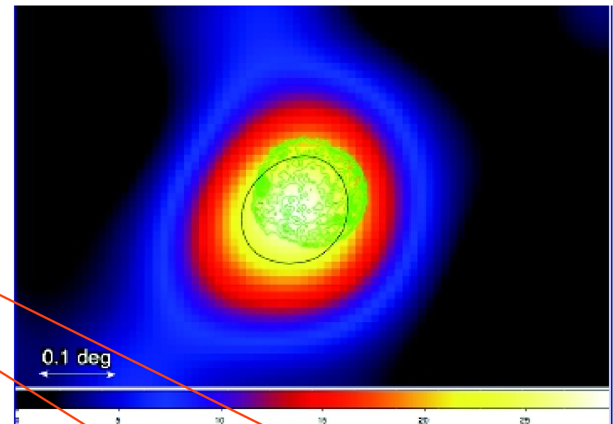
SN 1006
NASA/ESA/Hubble Heritage Team (STScI/AURA)

Multiwavelength spectrum of Tycho's SNR

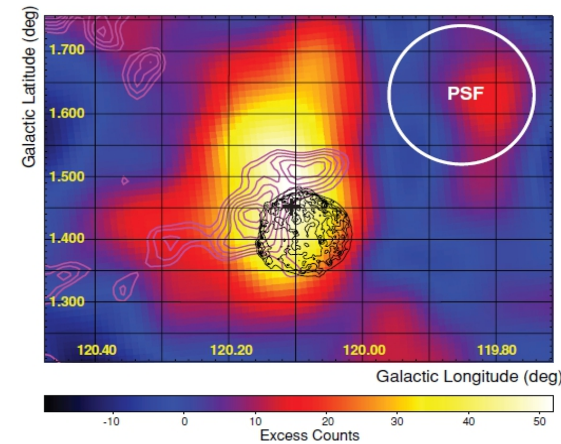
X-rays (Chandra)



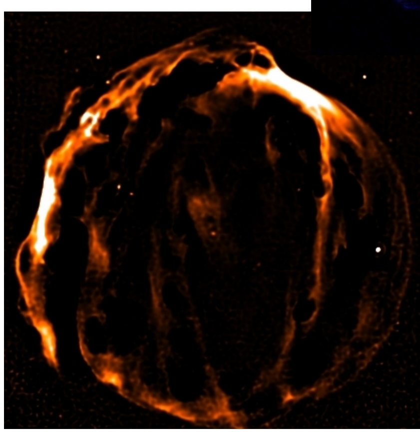
1-100 GeV from FermiLAT [Giordano et al. 2011]

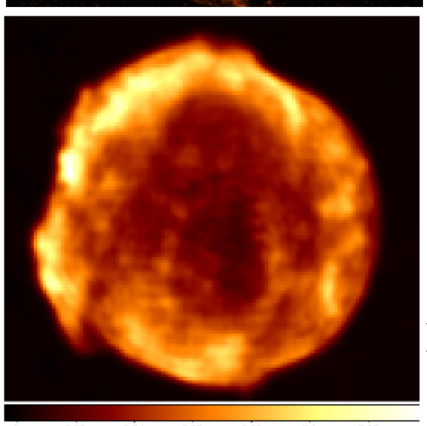


VERITAS map $E > 1$ TeV [Acciari et al. 2011]

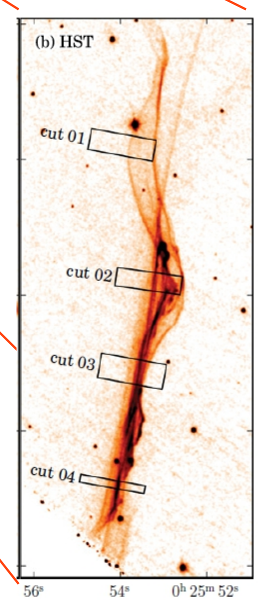


Spitzer image at 24 μm





Radio map at 1.5 GHz



Hα emission (with HST)

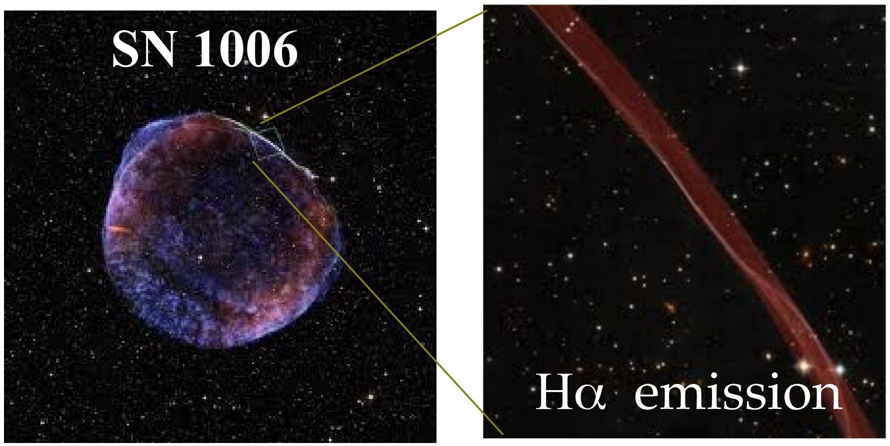
Importance of shocks

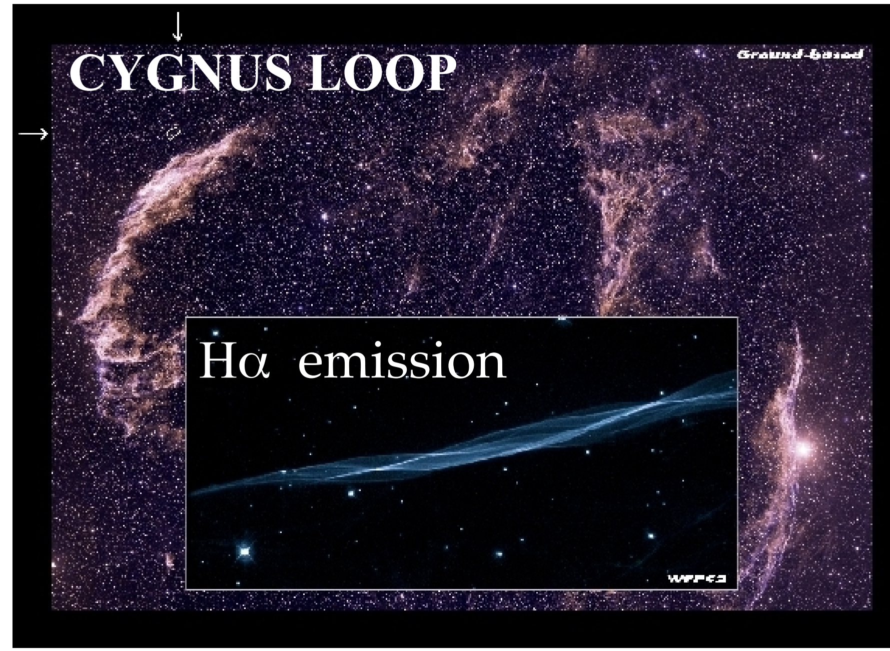
Almost all emission from SNRs is connected with processes occurring at its shocks

- Radio, non-thermal X-rays, gamma-rays ^ accelerated paricles
- Thermal X-rays ^ plasma heating due to shock compression
- Infrared emission ^ heating of ISM dust
- Lines from heavy elements ^ heating of ejecta from reverse shock
- **Balmer lines** ^ charge-exchange and excitation of neutral Hydrogen

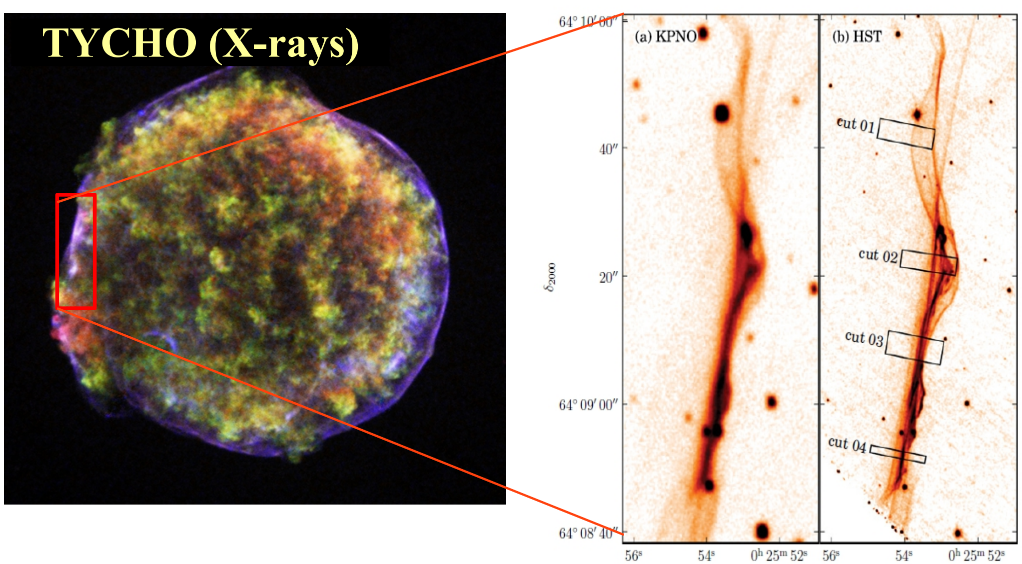
What can we learn from Balmer emission?

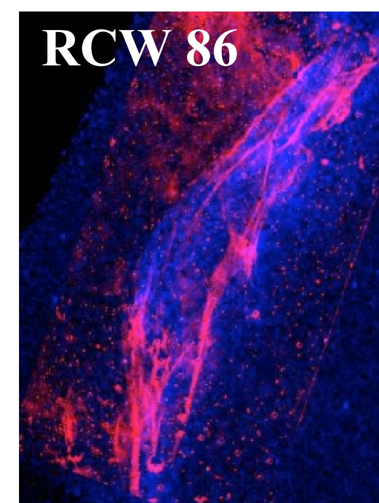
Balmer-Dominated Shocks





Hα emission





Balmer-Dominated Shocks

SN 1006 filament with HST

Filament thickness
$\sim 10'' \rightarrow 3\text{x}10^{17}$ cm

Hα resolution (HST)
$\sim 0.7'' \rightarrow 2\text{x}10^{16}$ cm

Shock transition
$\sim 10^{15}$ cm $\rightarrow 0.04''$

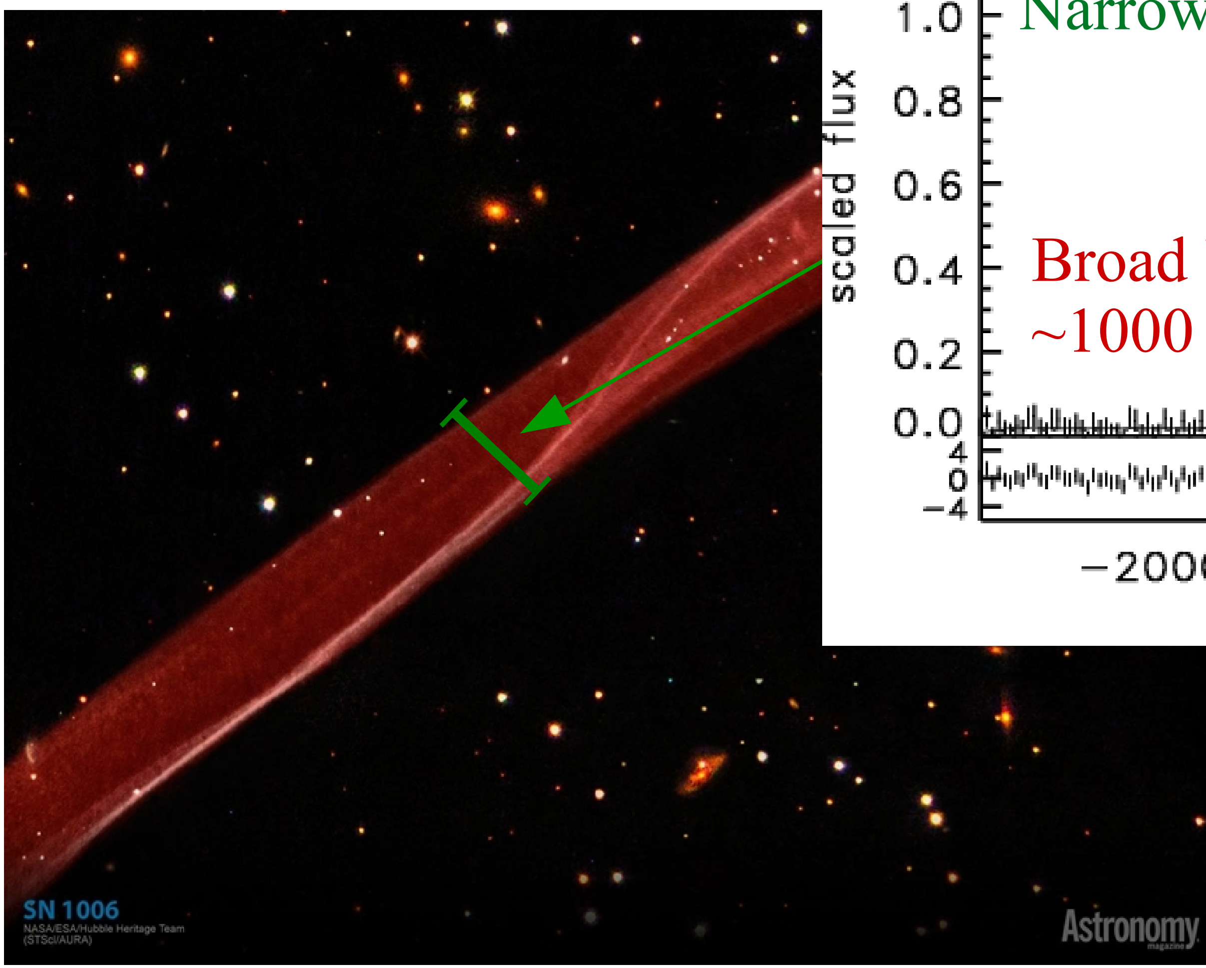
Compare with resolution in other wavelength:

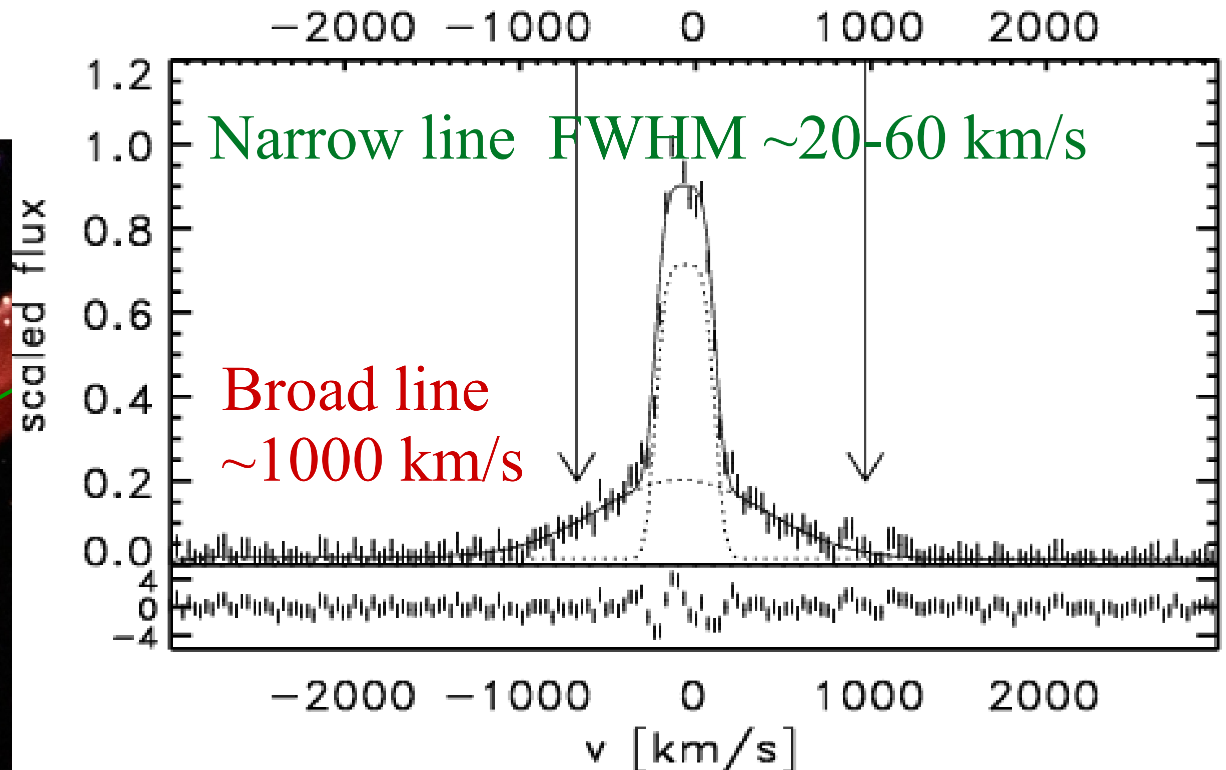
X-rays: ~1'' (Chandra)

γ-rays: ~few arcmin (CTA)

Balmer-Dominated Shocks

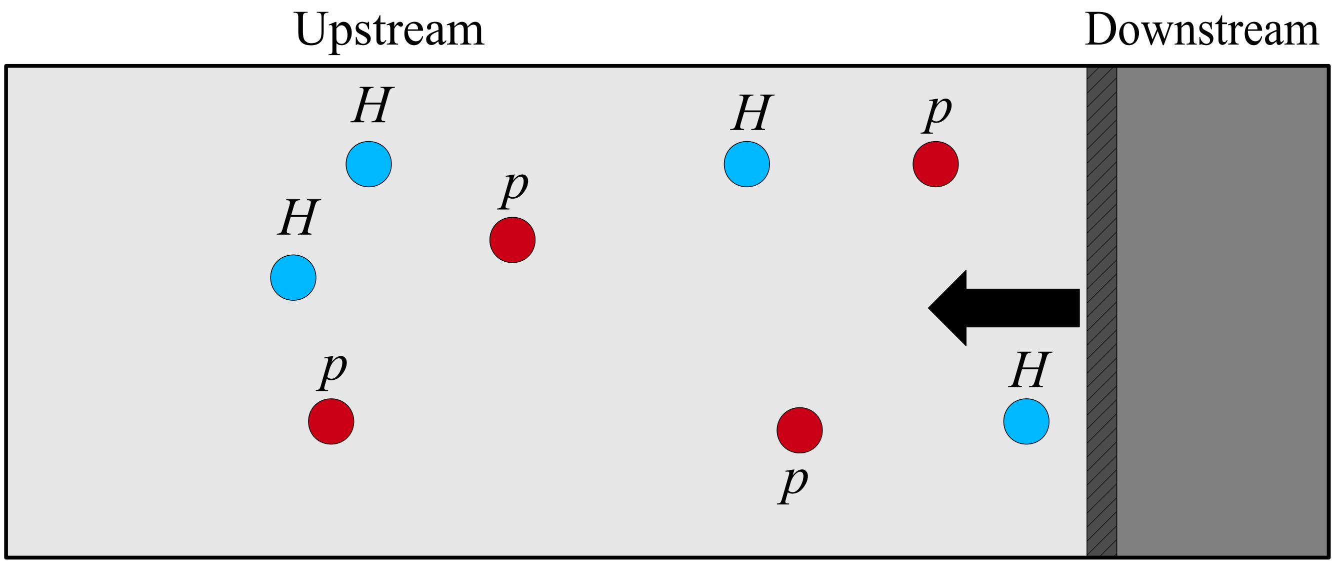
SN 1006 filament with HST





Basic physics of Balmer shocks

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



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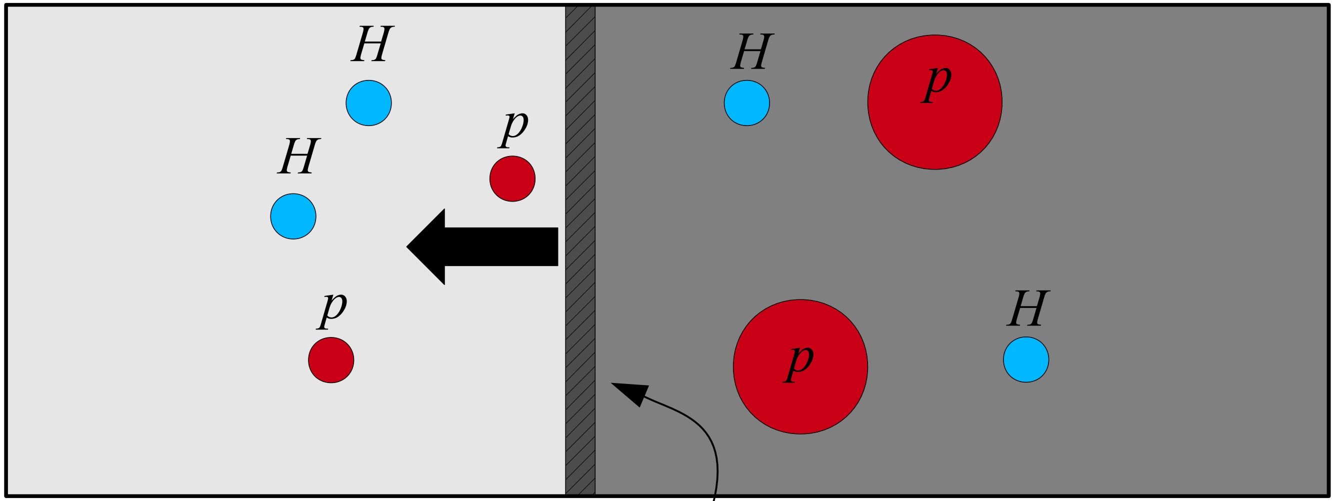


- Collisionless shocks heats up only ions

Shock thickness:

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

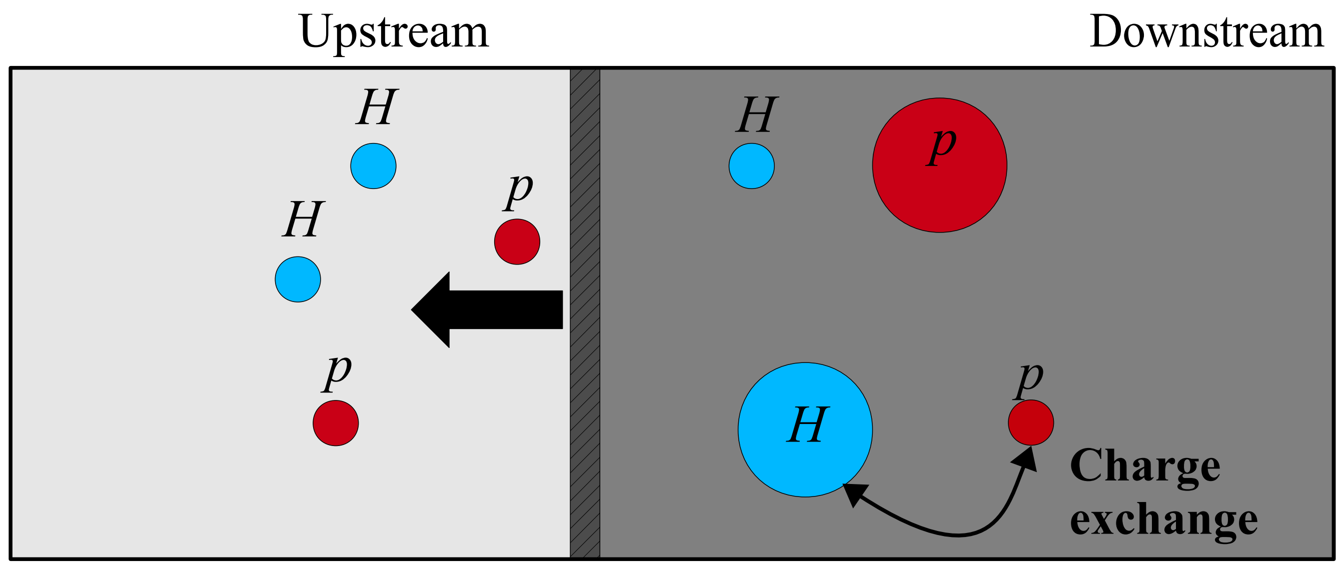
Collisional length scale (ionization or charge-exchange):

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

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

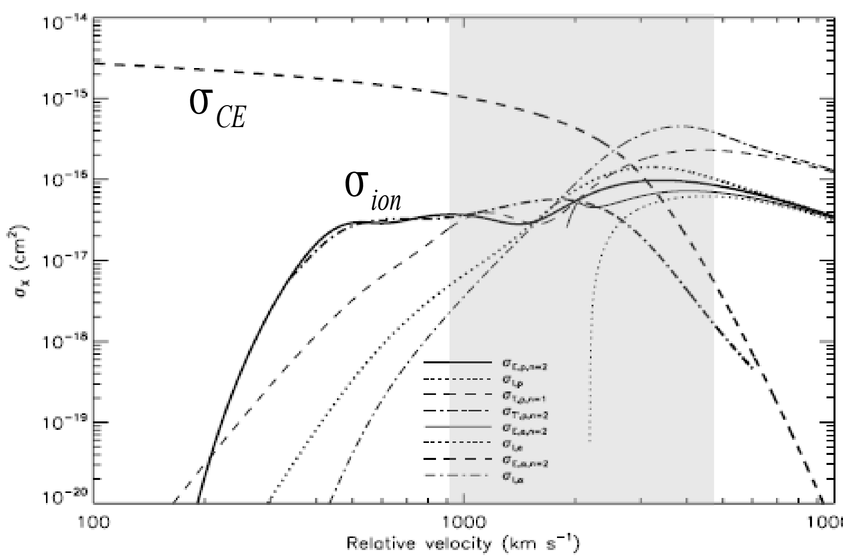
Basic physics of Balmer shocks

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

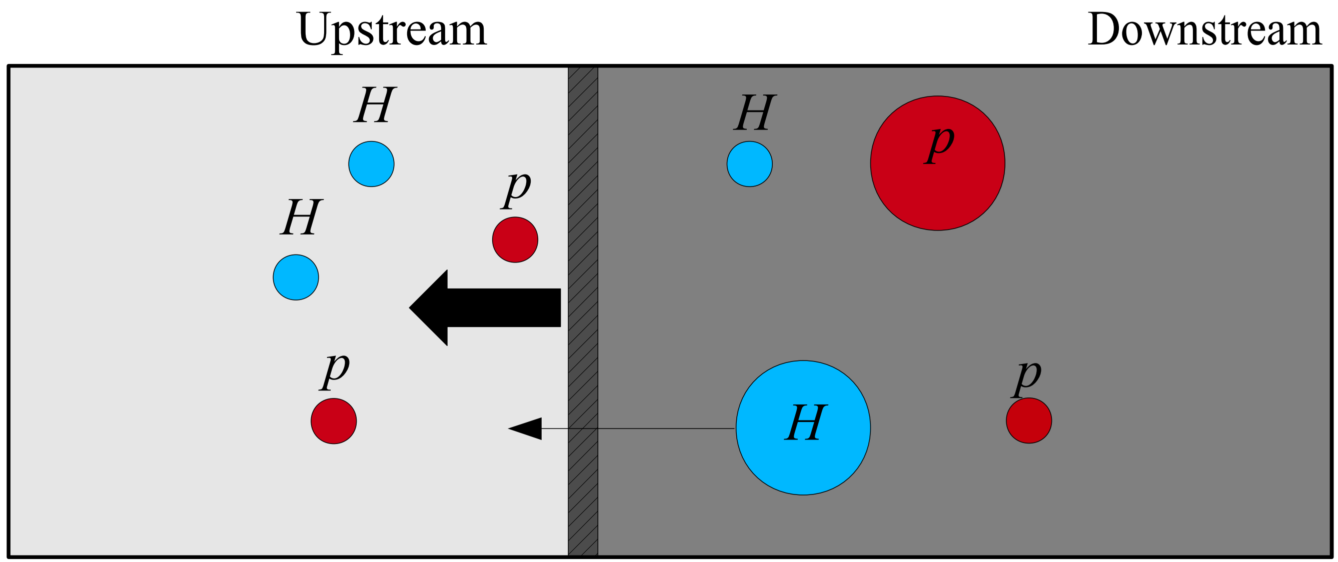


• Collisionless shocks heats up only ions

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



Basic physics of Balmer shocks

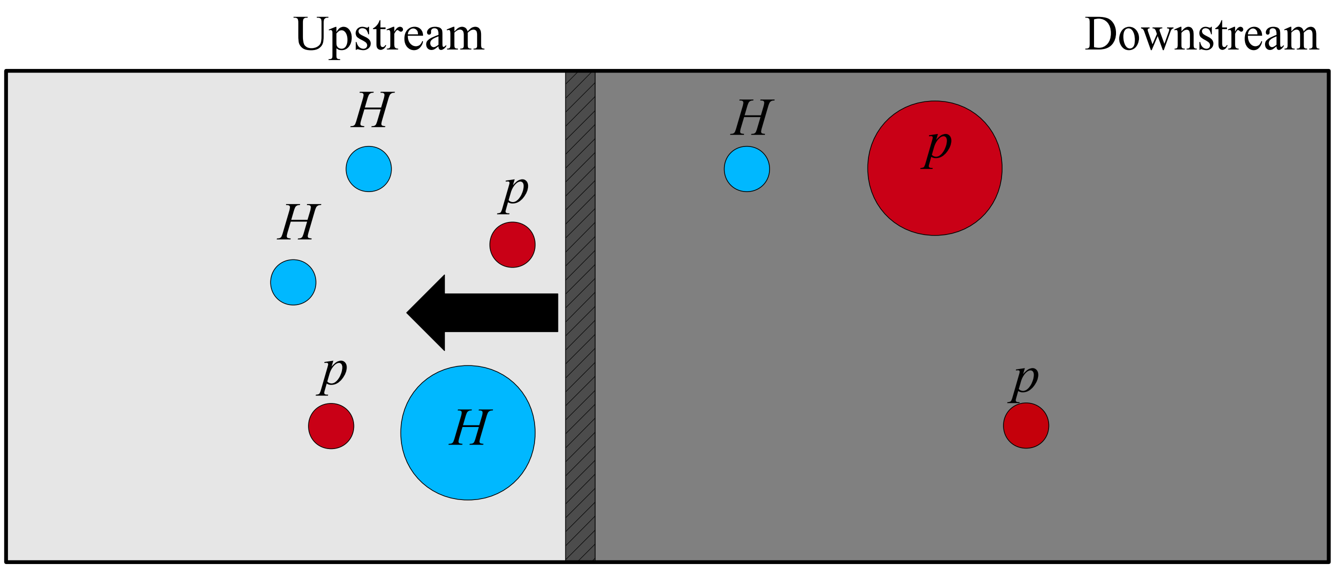


• Collisionless shocks heats up only ions

• 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*

Basic physics of Balmer shocks



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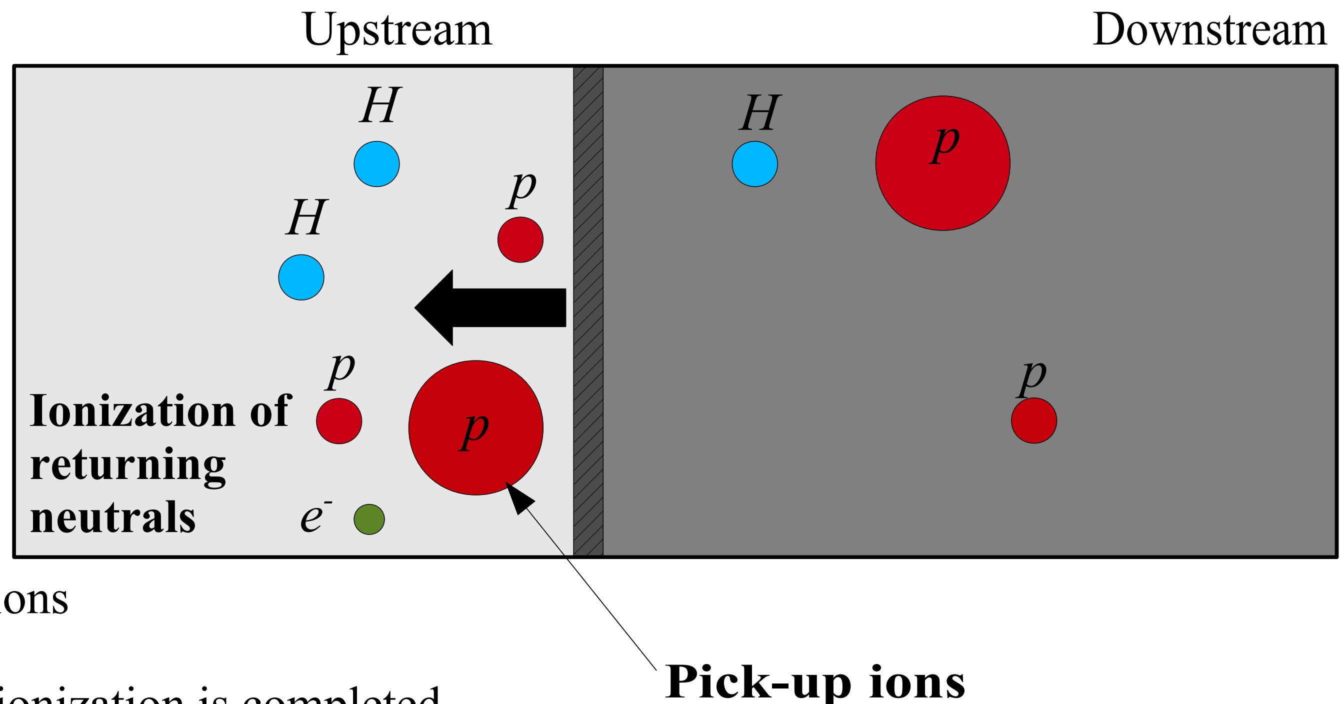

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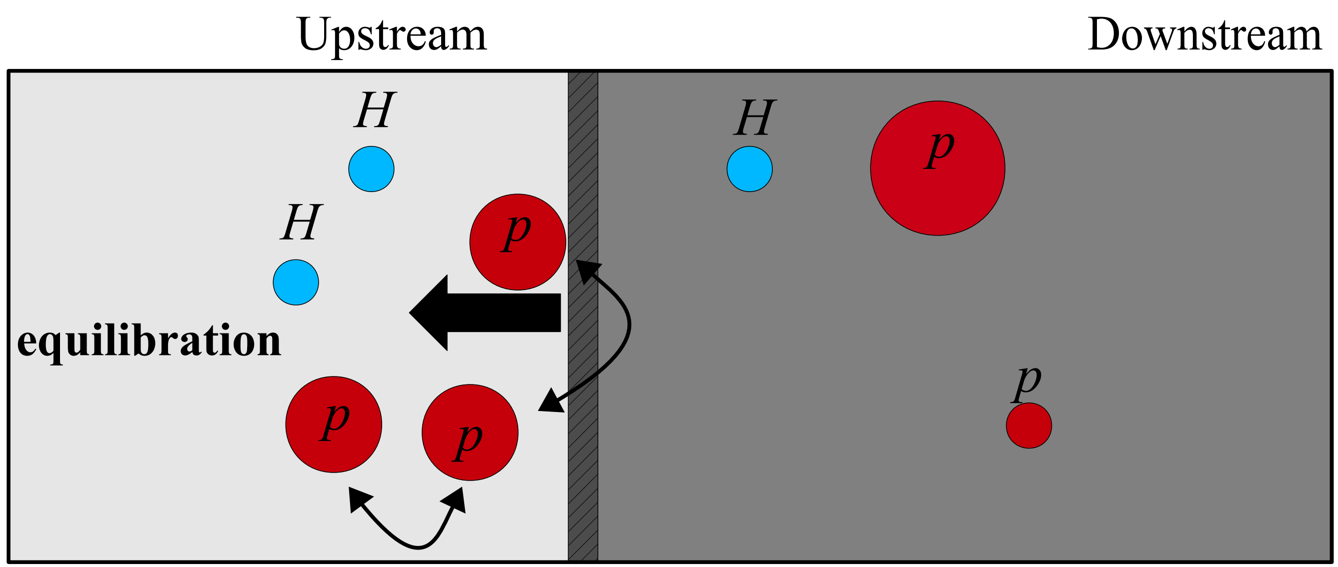

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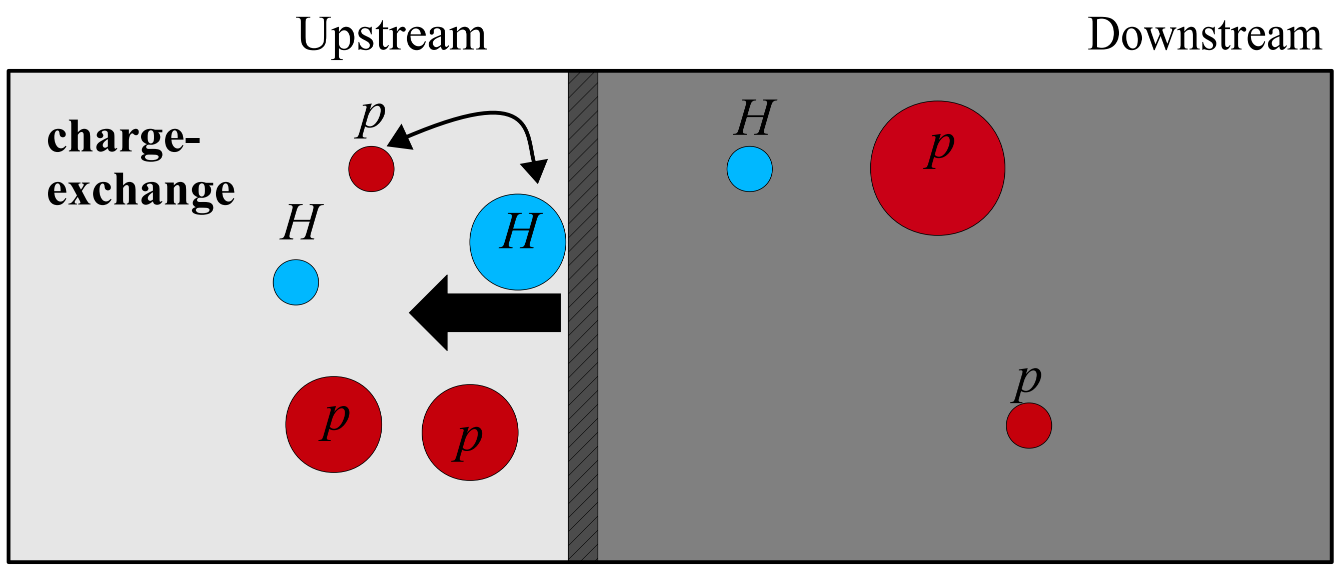
Basic physics of Balmer shocks



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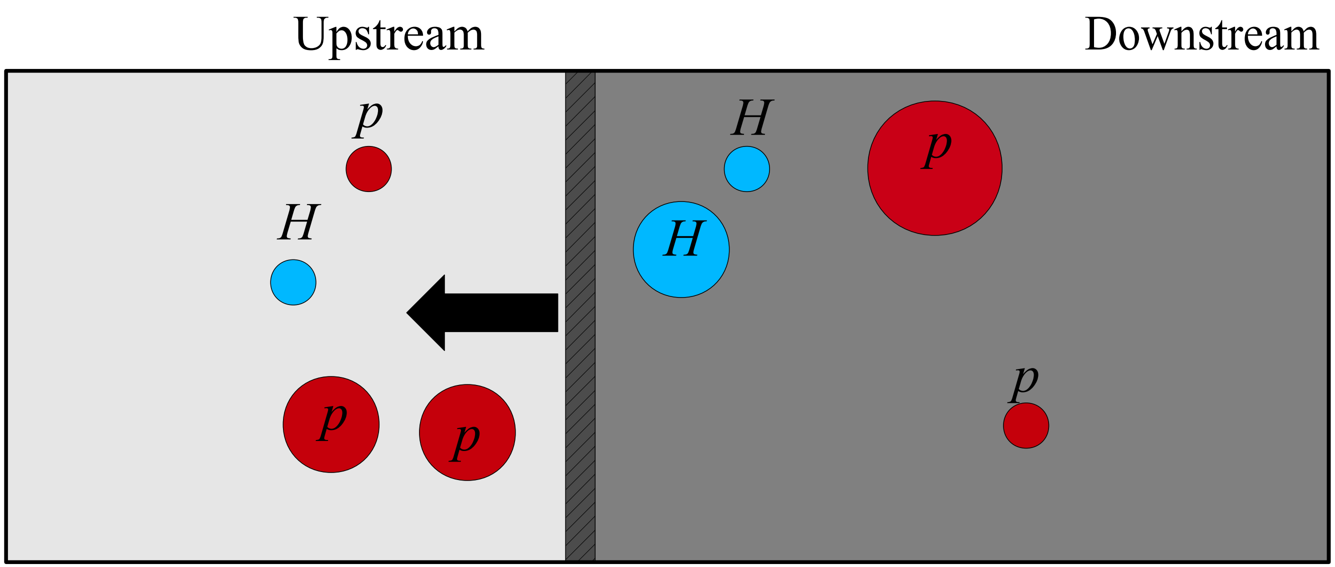
• Charge-exchange with protons in the precursor generate a third population of warm hydrogen

Basic physics of Balmer shocks



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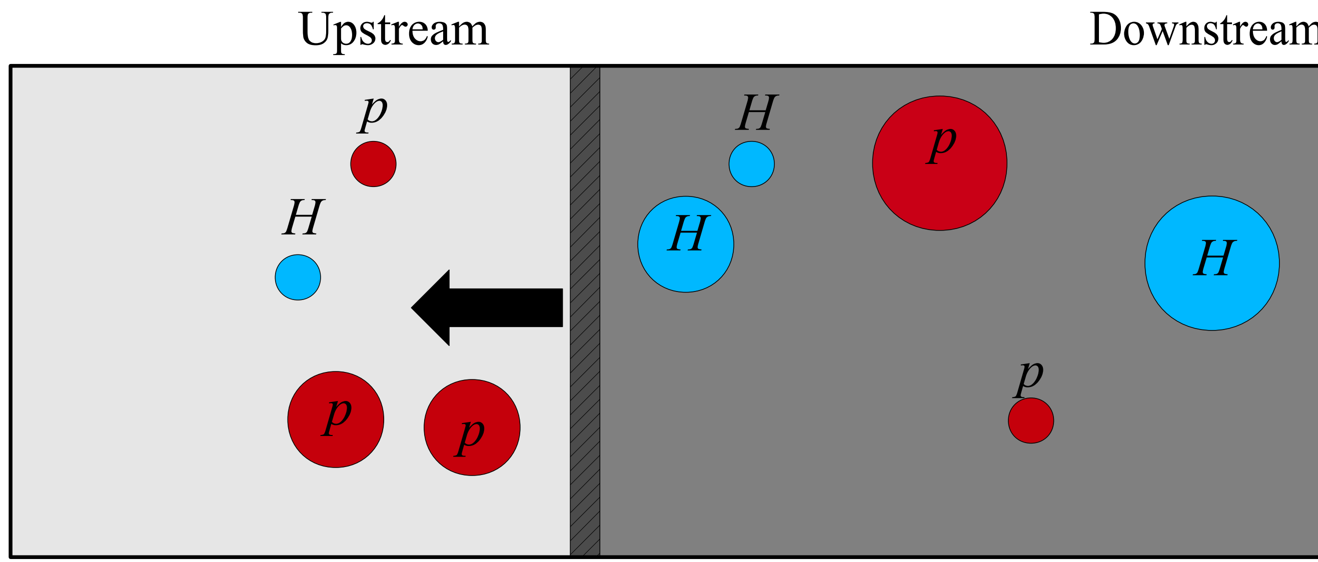
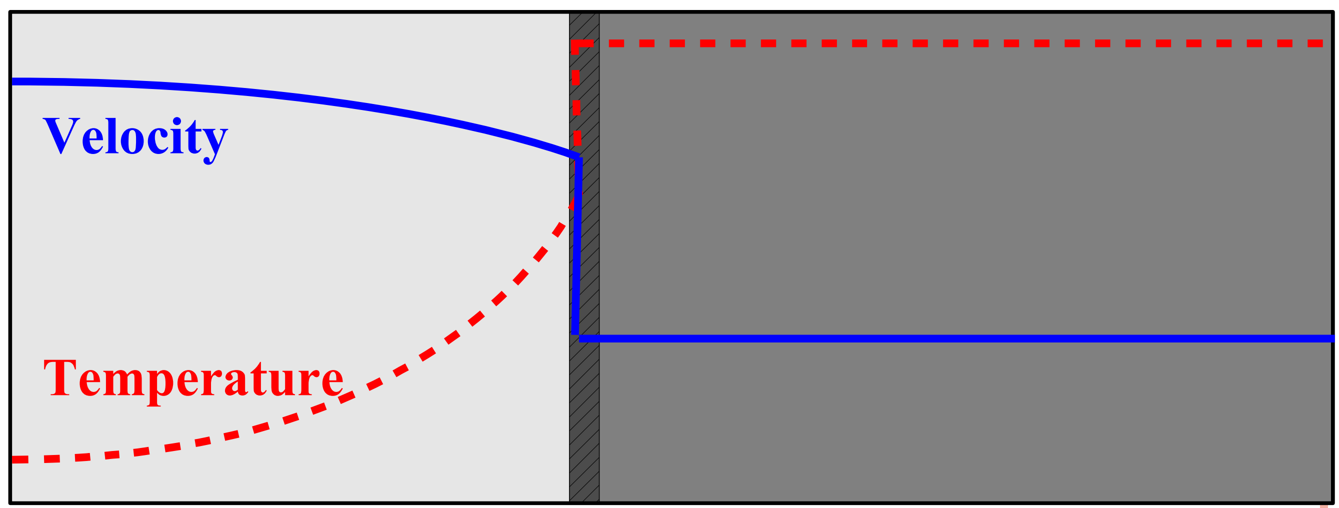
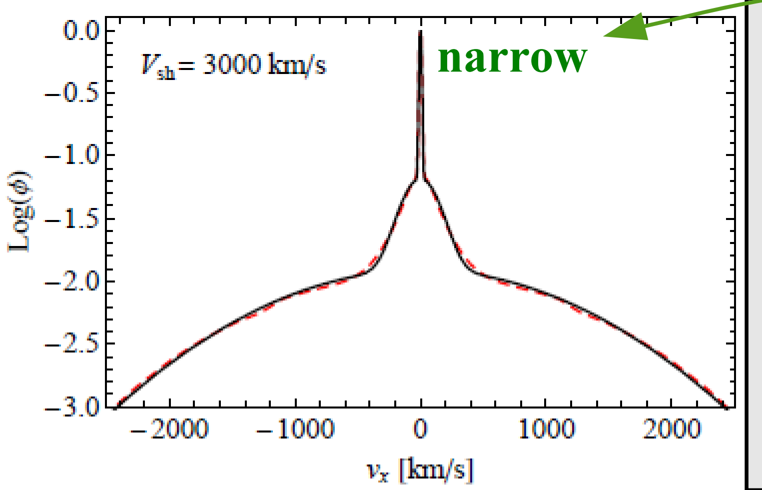
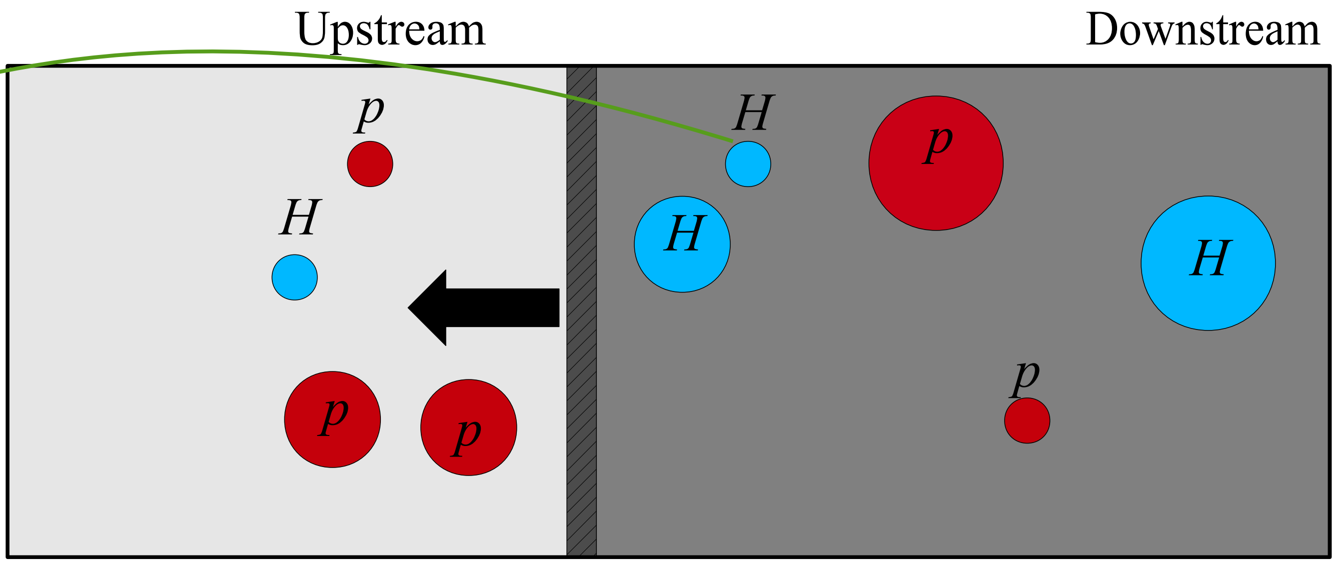


Formation of a *neutral-induced* precursor

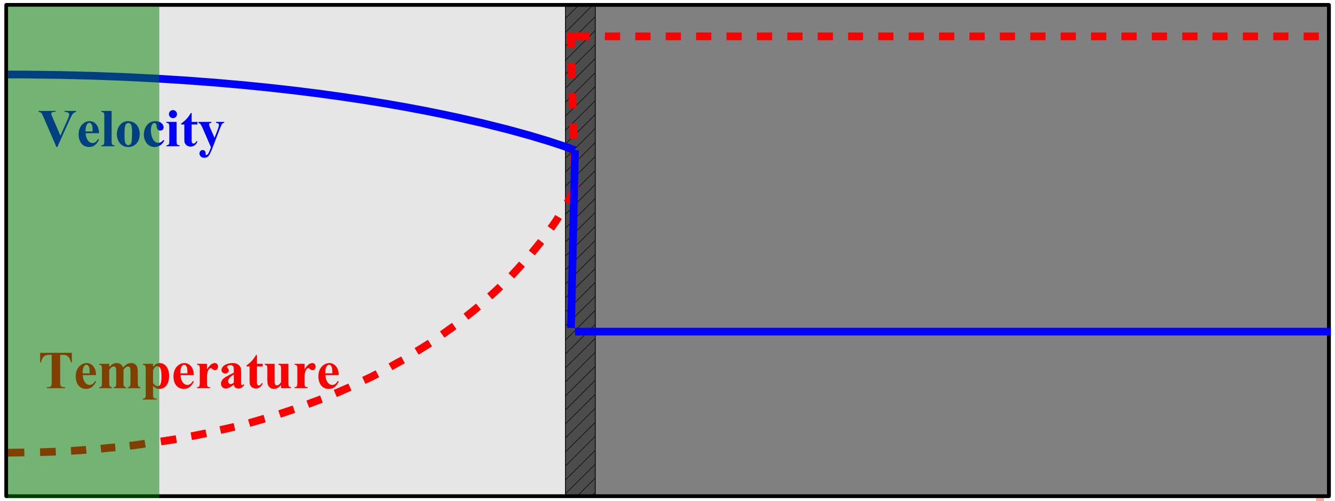


Basic physics of Balmer shocks

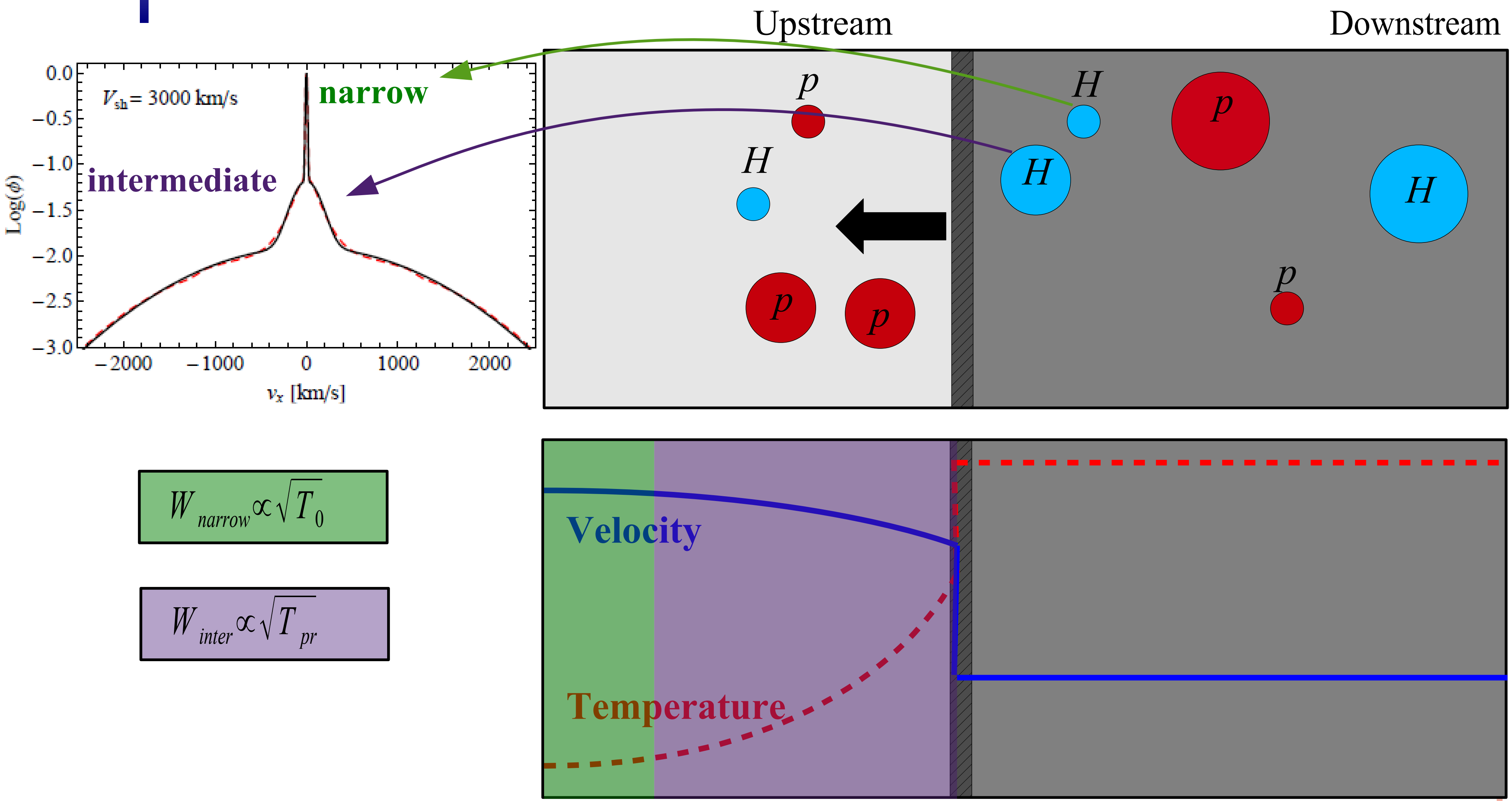




$$W_{narrow} \propto \sqrt{T_0}$$



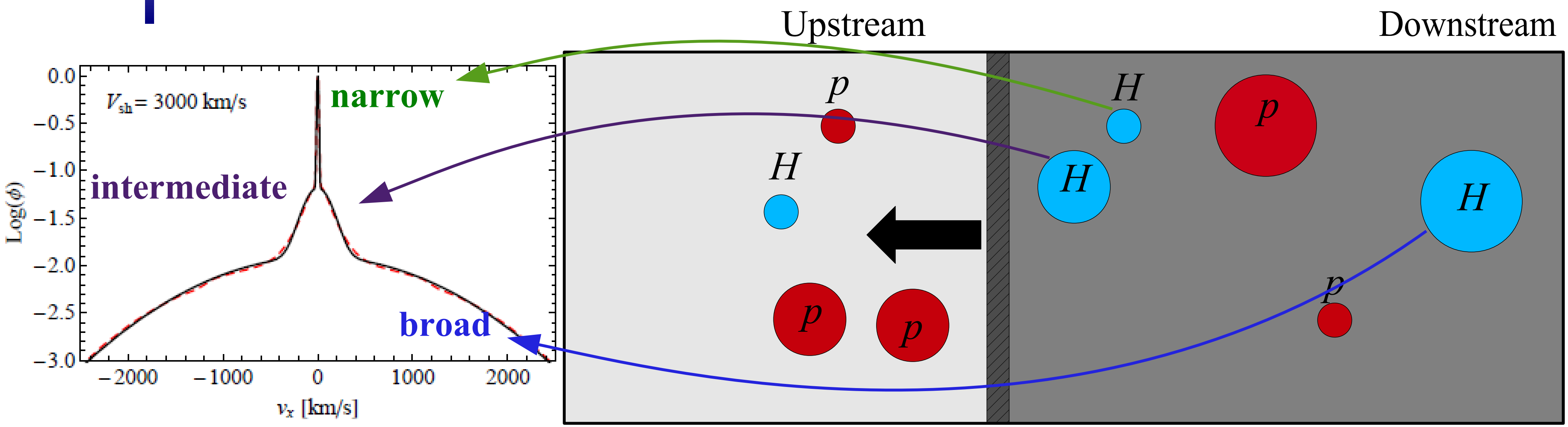
Basic physics of Balmer shocks



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

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

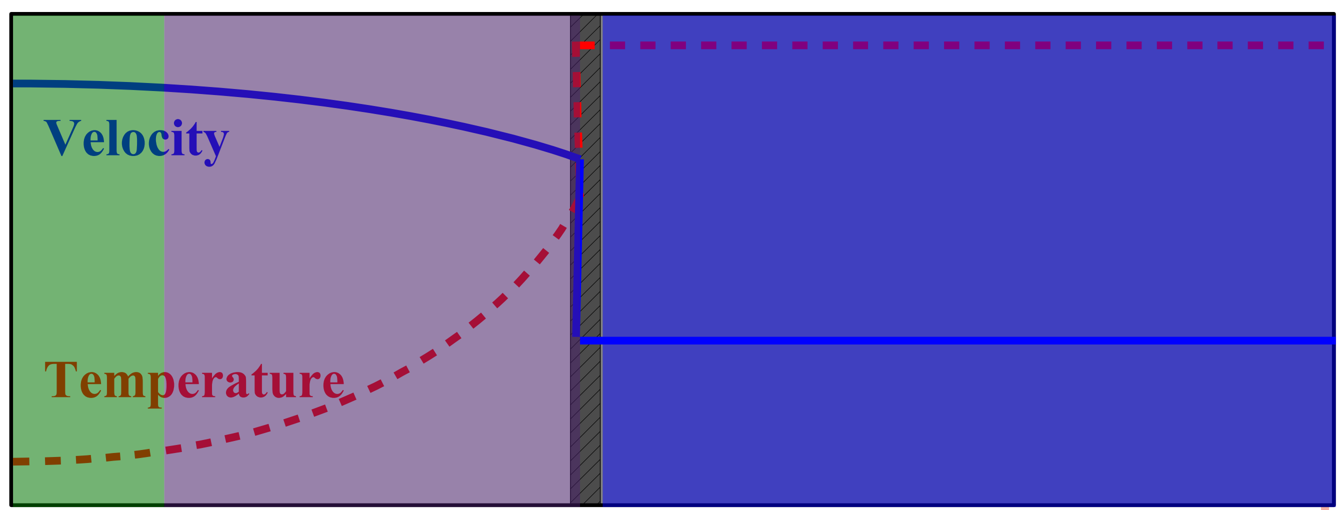
Basic physics of Balmer shocks



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

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

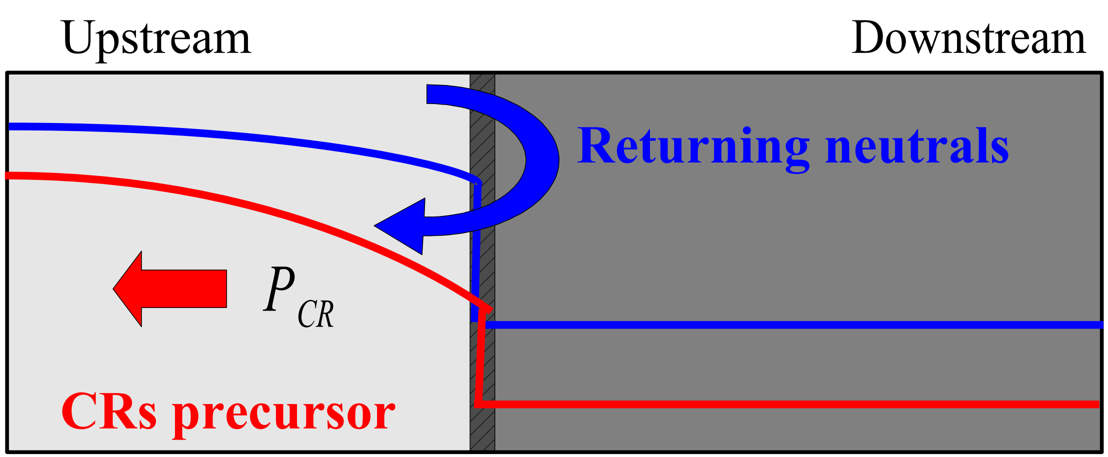
$$W_{broad} \propto \sqrt{T_2} \sim V_{sh}$$



Efficient acceleration of Cosmic Rays

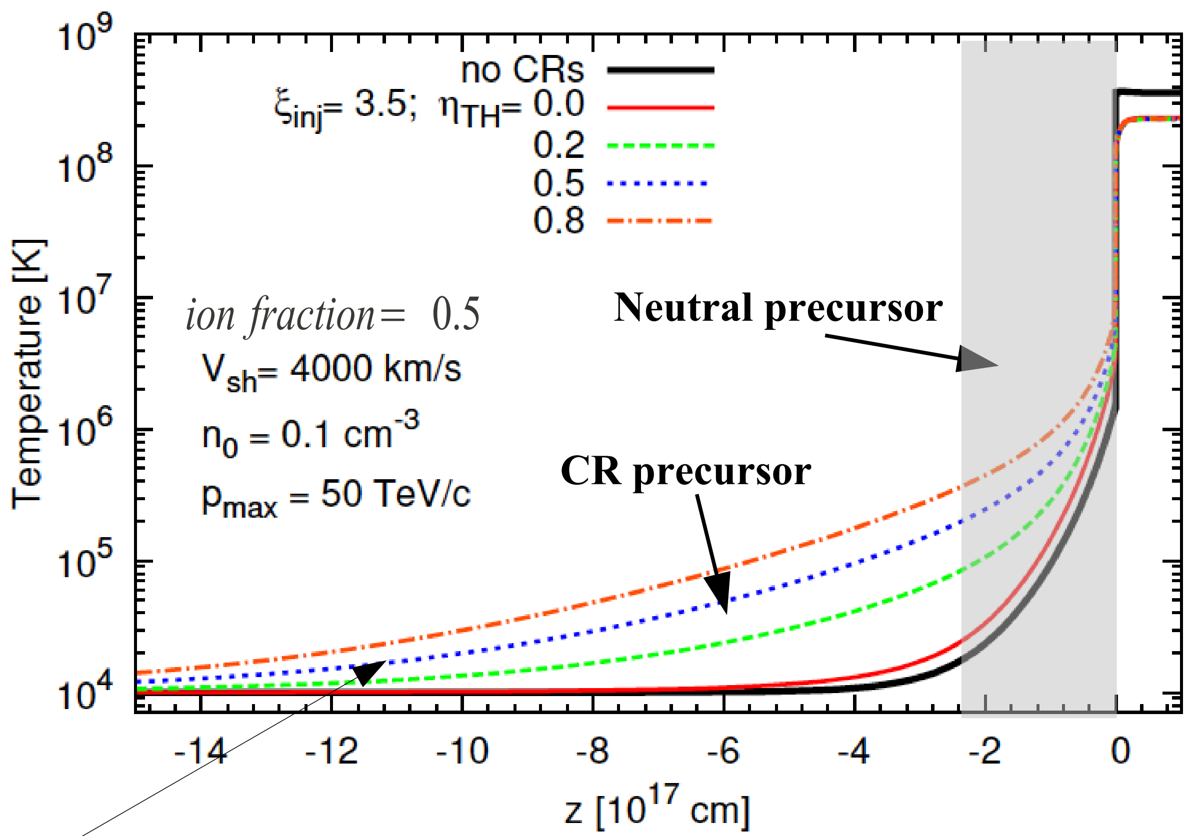
When the acceleration efficiency of non-thermal particles is large (~ 10%)

- CRs subtract energy from the thermal bath of the downstream
  → downstream temperature decreases
- CRs transfer a fraction of energy and momuntum upstream of the shock
  → the upstream plasma is accelerated and heated up



Neutral-precursor vs CR-precursor

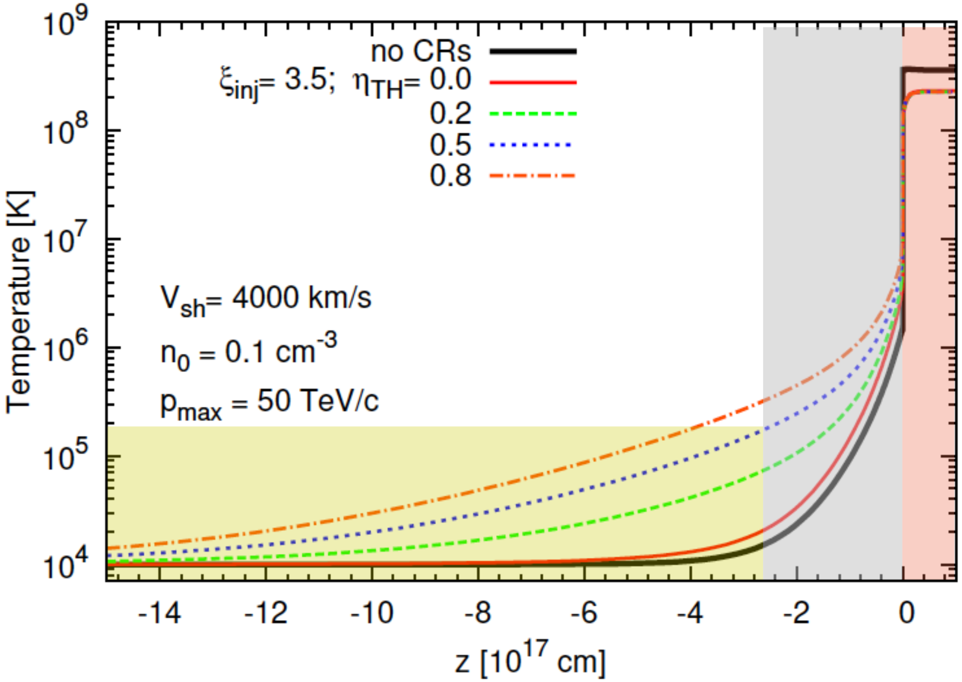
Temperature profile for acceleration efficiency $\epsilon_{CR} \sim 40\%$

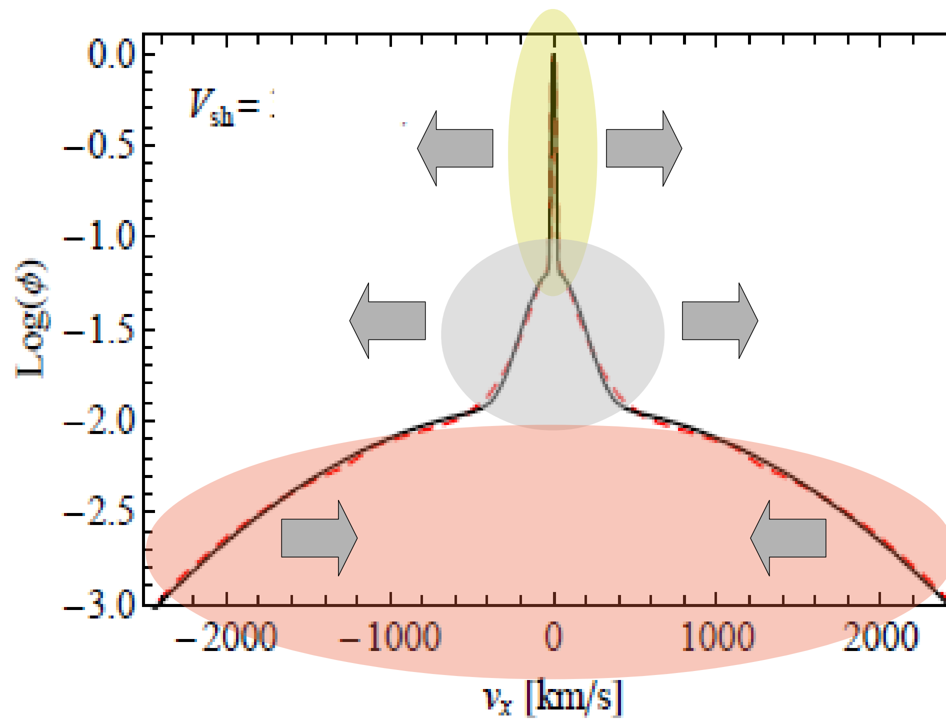


Downstream temperature decreases

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

Width of Hα lines vs. acceleration efficiency



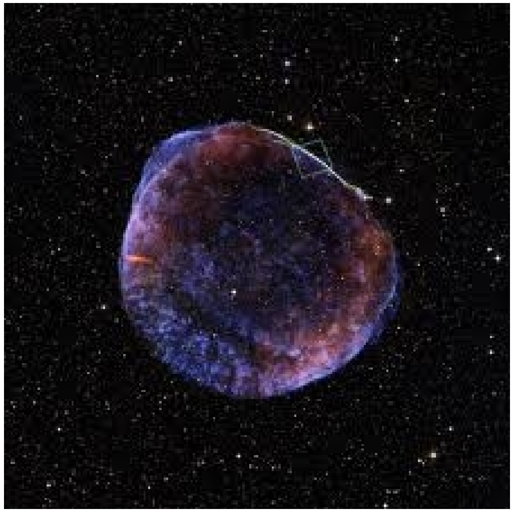


In the presence of efficient CR acceleration, the line widths are modified

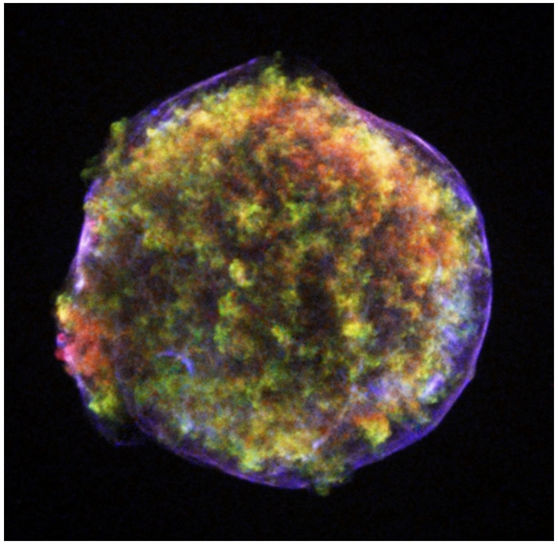
- Broad line narrows
- Intermediate line broads
- Narrow line broads

Application to single SNRs

SN 1006



TYCHO

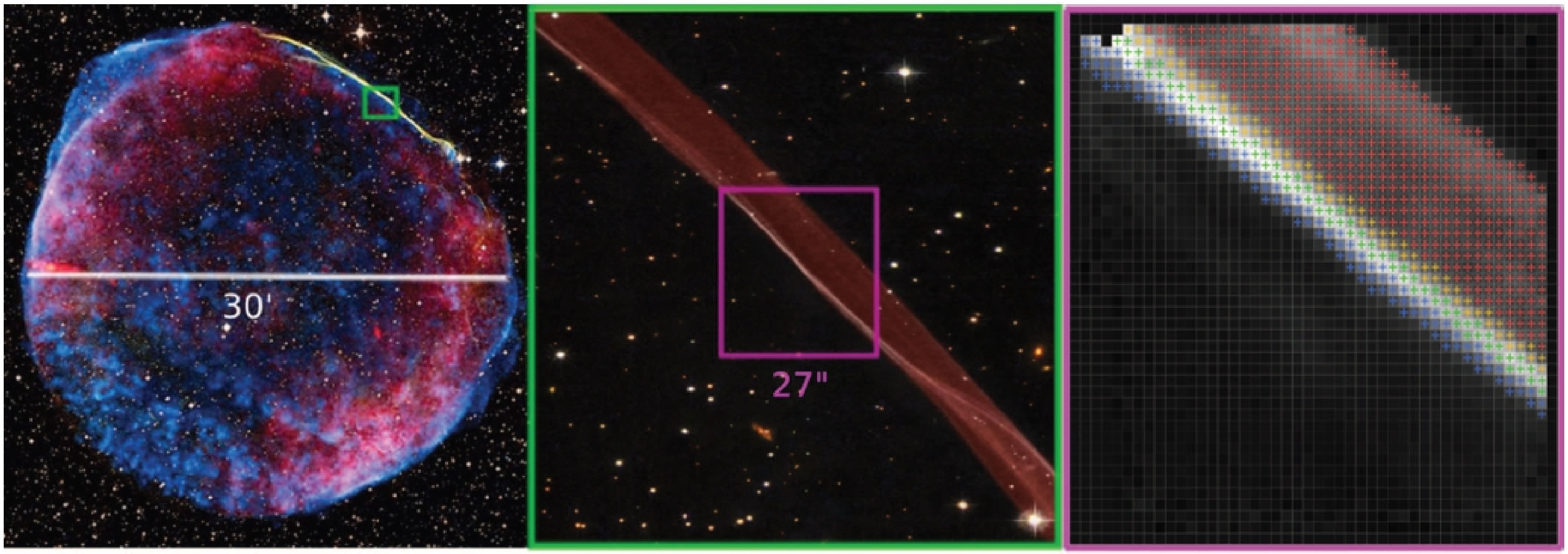


SN 0509 – 67.5 in LMC

Close up view of Balmer filament in SN 1006

[Nikolic et al. (2013)]

Image obtained using an integral-field spectrograph VIMOS at VLT



A Balmer filament is not planar nor spherical

→ density perturbations bent the filament
→ high spatial resolution needed to disentangle geometrical from physical properties

Close up view of Balmer filament in SN 1006

[Nikolic et al. (2013)]

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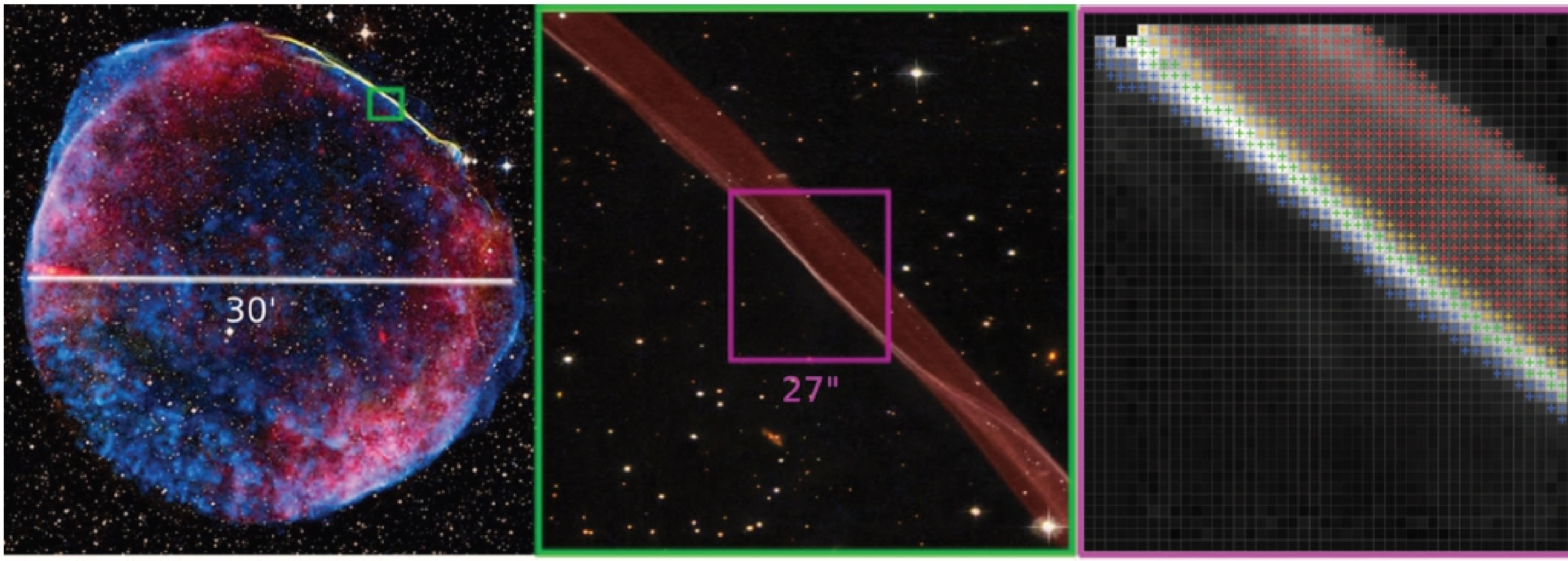
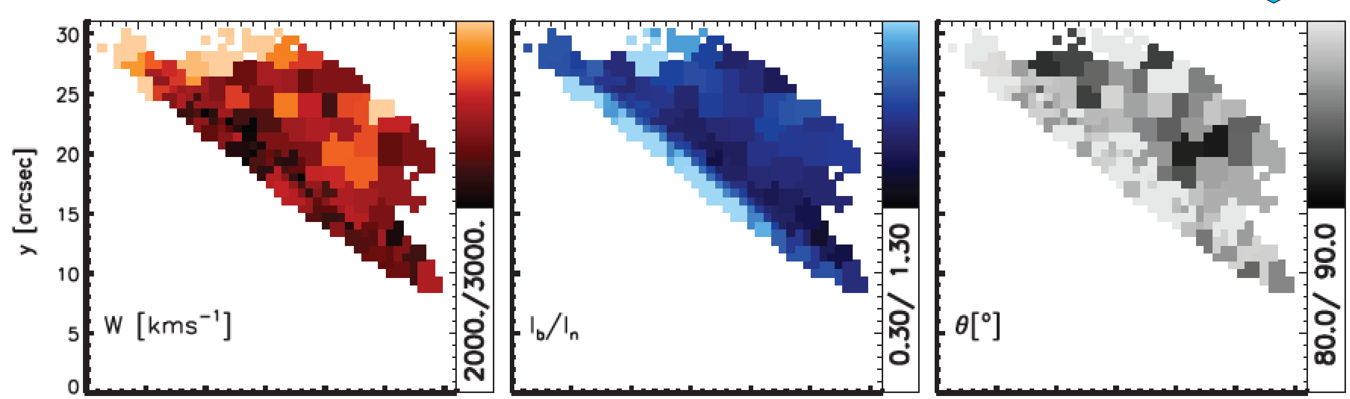
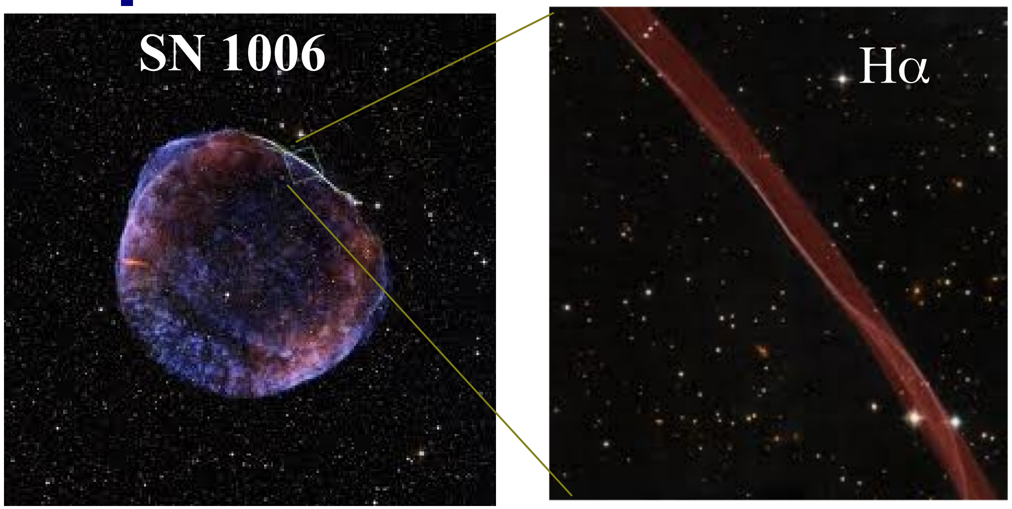


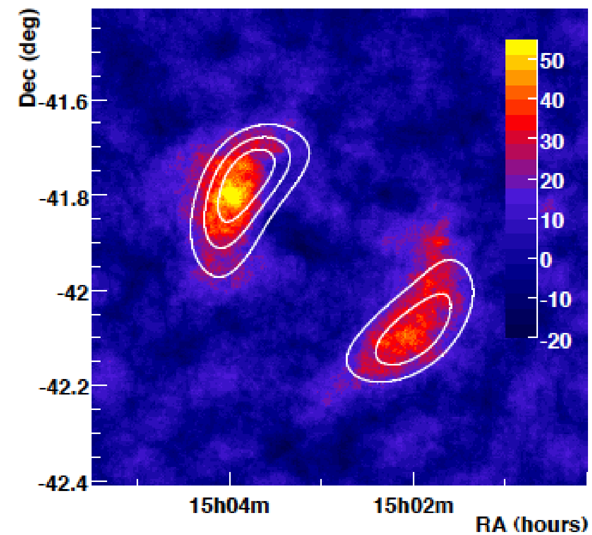
For each pixel one can get a separate Balmer spectrum



NW rim of SN 1006: the unmodified case

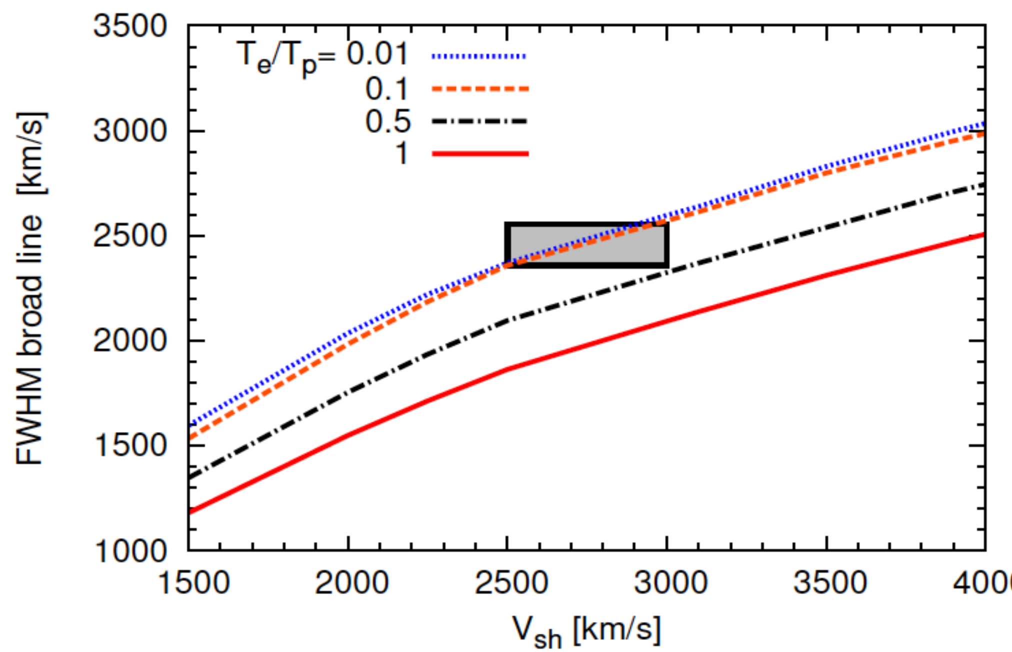


SN 1006 in TeV (HESS)

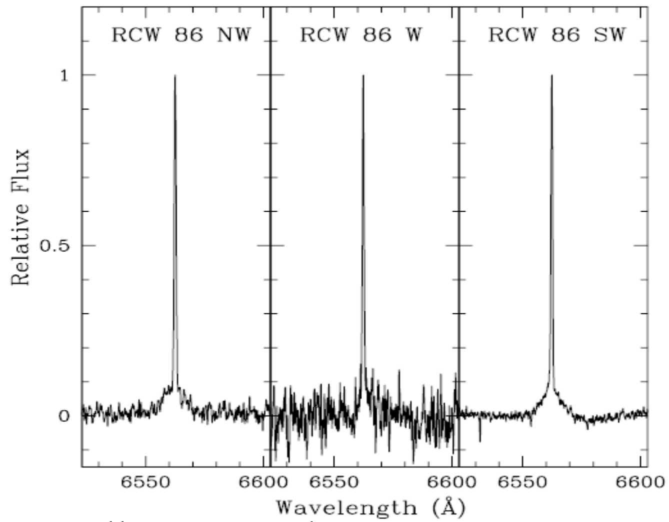


In the NW region where Balmer emission is stronger there are no indications of efficient CR acceleration:

- 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



Narrow Hα 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 Hα 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:

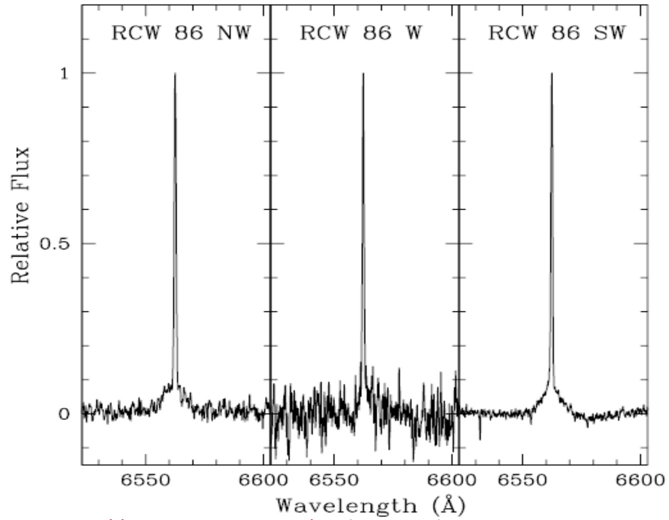
$$W_n \sim 30-50\, km/s \rightarrow T \sim 2-6\, 10^4 K$$

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 up the neutrals

Narrow Hα lines with unusual broad width



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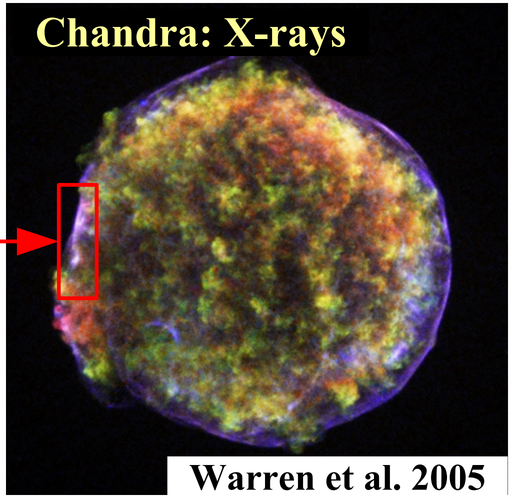

Knot g

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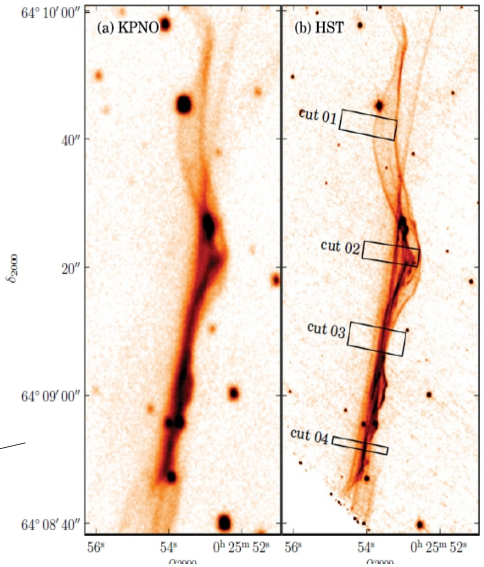
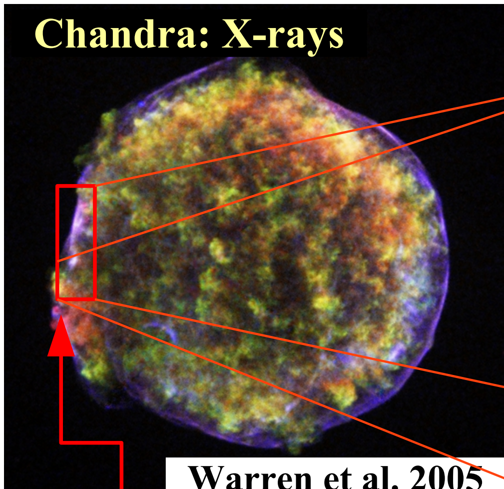
Value obtained integrating over the whole region



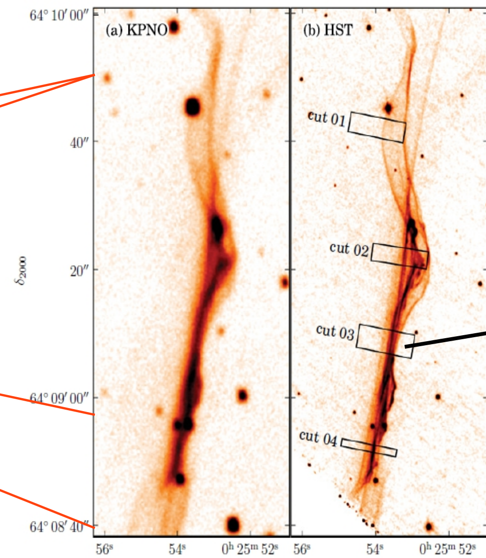
Tycho's SNR: Precursor in Balmer-Dominated Shocks

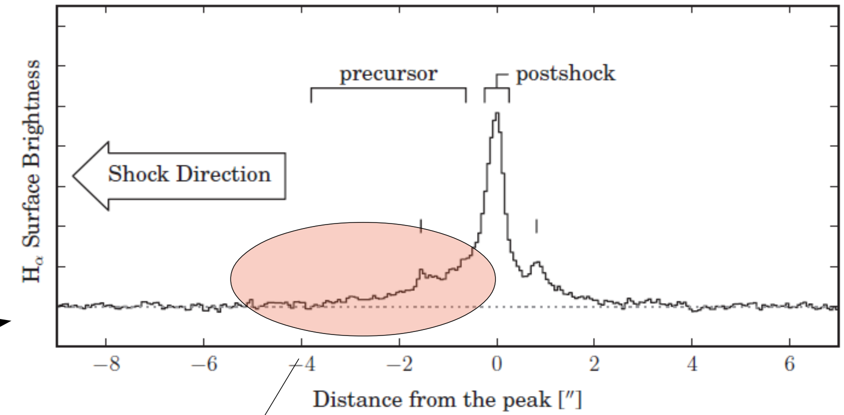
Lee et al., 2010
(Observation with the Hubble Space Telescope)



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

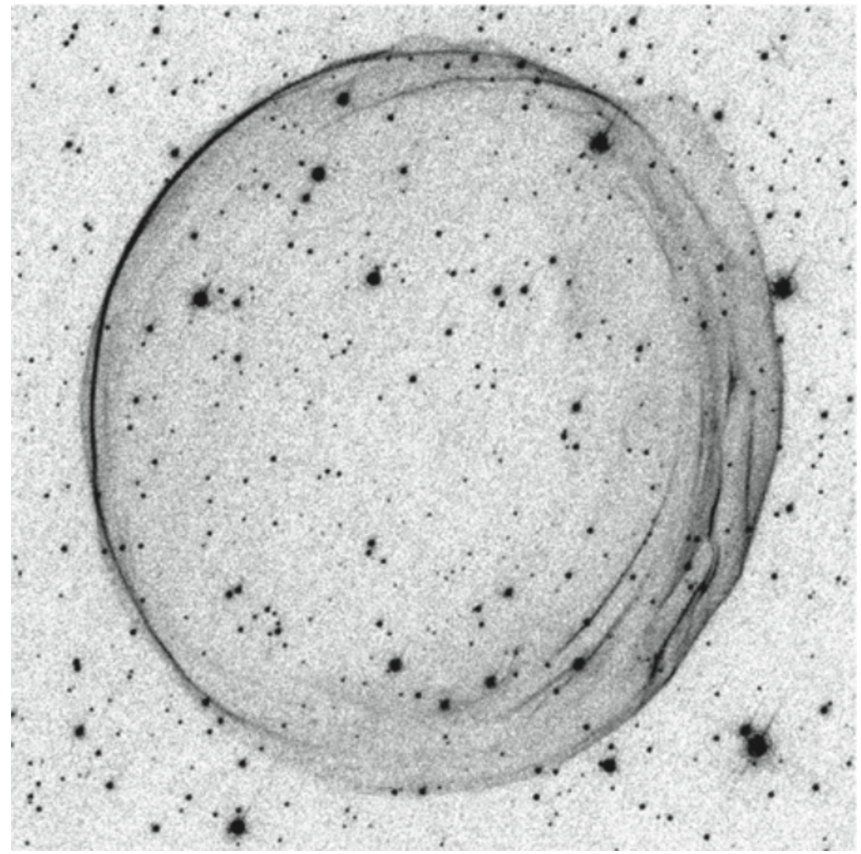
2) The *knot g* in Tycho remnant is associated with non-thermal X-ray emission

→ the shock may accelerate particles efficiently

SN 0509 – 67.5 in LMC

Radius ≈ 14.8 "
≈ 3.6 pc
Age: 400 ± 120 yr
(Rest et al. 2005)

Pure Balmer emiss.
HST image
(from Hovey et al. 2015)

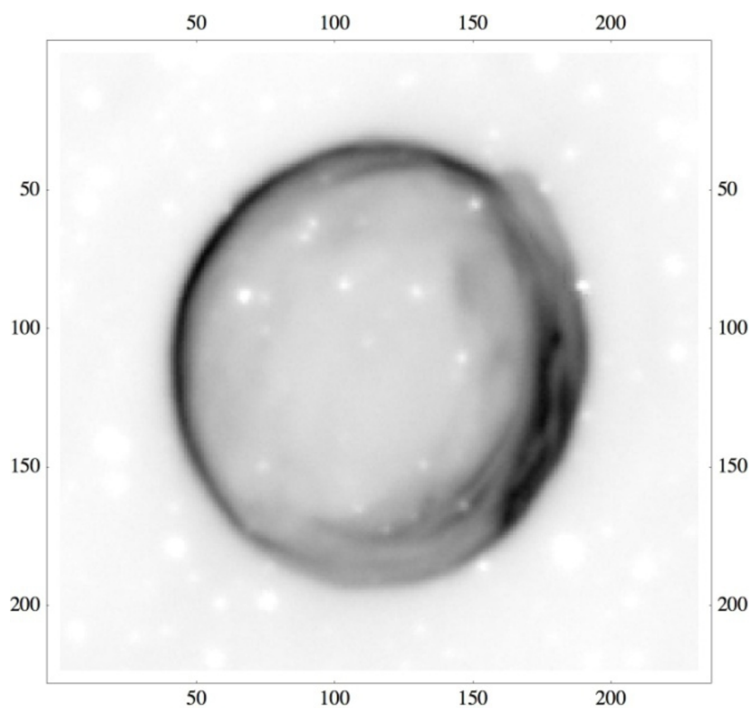


SN 0509 – 67.5 in LMC

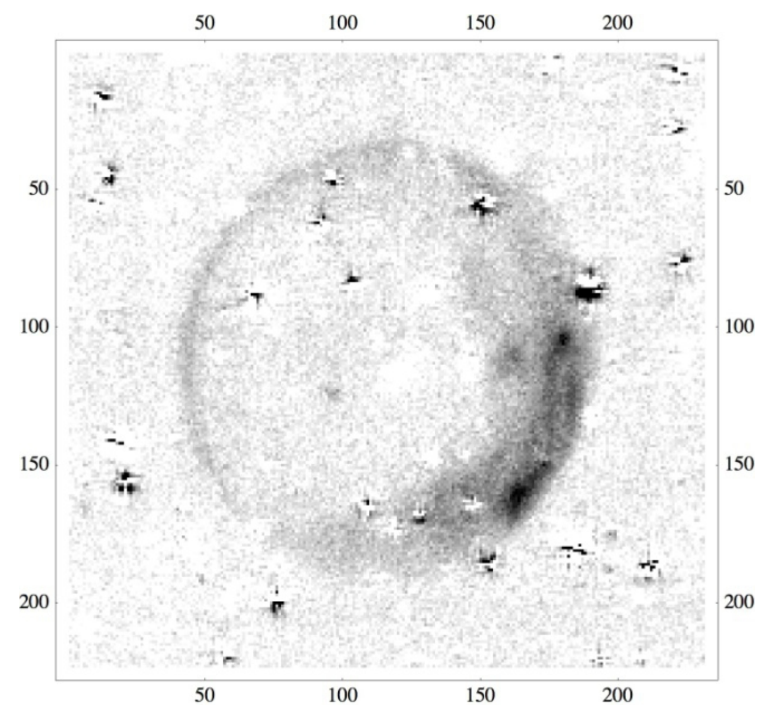
MUSE : Integral field spectrograph @ ESO - VLT

Wide-field mode:

Spatial sampling: 0.2 arcsec
Spectral resol.≈ 100 km/s @ Hα
Field of view: 1 x 1 arcmin^2



Narrow-line map



Broad-line map

(after stellar subtraction)

Conclusions & future prospectives

Balmer lines from SNR shocks can be used to :
1) Probe the ISM conditions

- Density, neutral fraction, turbulence level

2) Probe the shock physics

- Electron-ion interaction in the plasma
- CR acceleration efficiency
- Existence of CR precursor
  - Maximum energy of accelerated particles
  - Damping of magnetic turbulence

Better Hα line detection combined with measurements of shock proper motion will allow usa better determination of all those quantities.

MAVIS is the best instrument to reach these goals