COSMIC RAY ACCELERATION

LECTURE 2: ADVANCED TOPICS

P. BLASI

INAF/OSSERVATORIO ASTROFISICO DI ARCETRI
& GRAN SASSO SCIENCE INSTITUTE, CENTER FOR ADVANCED STUDIES

SPSAS-HighAstro, 29-30 May 2917, Sao Paulo, Brazil

NON LINEAR THEORY OF DSA

WHY DO WE NEED A NON LINEAR THEORY?

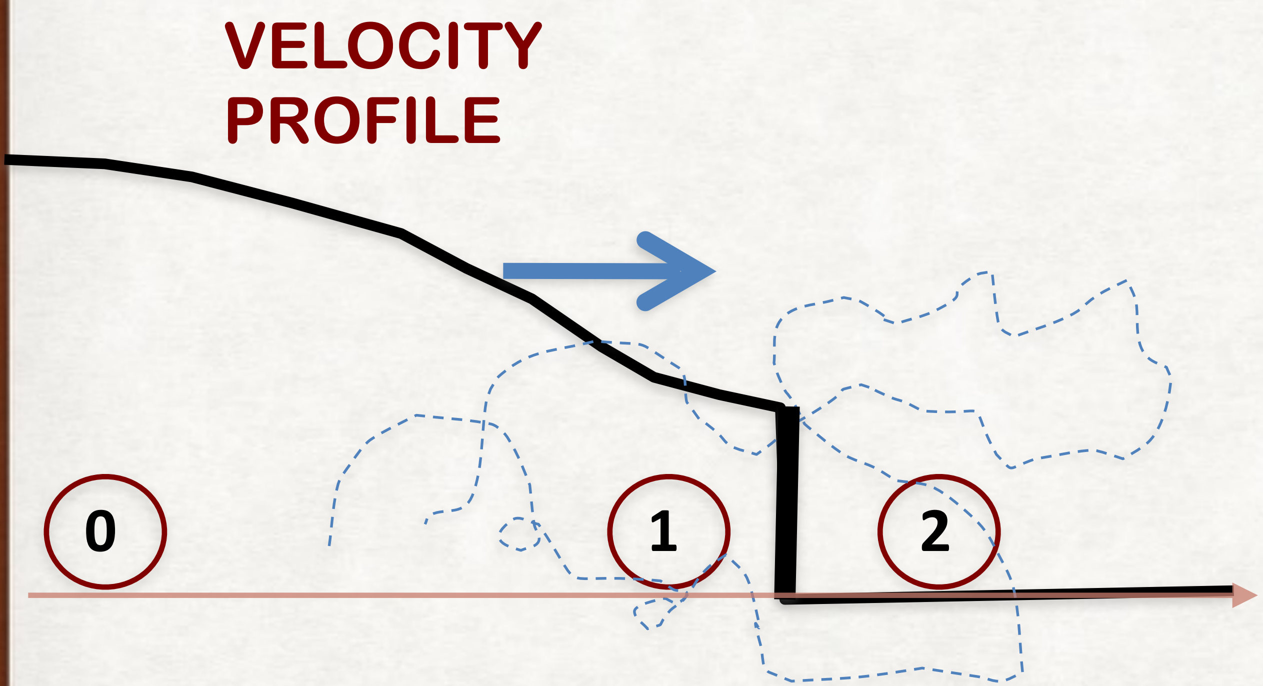
TEST PARTICLE THEORY PREDICTS ENERGY DIVERGENT SPECTRA

THE TYPICAL EFFICIENCY EXPECTED OF A SNR (~10%) IS SUCH THAT TEST PARTICLE THEORY IS A BAD APPROXIMATION

THE MAX MOMENTUM CAN ONLY BE INTRODUCED BY HAND IN TEST PARTICLE THEORY

SIMPLE ESTIMATES SHOW THAT EMAX IS VERY LOW UNLESS CR TAKE PART IN THE ACCELERATION PROCESS, BY AFFECTING THEIR OWN SCATTERING

DYNAMICAL REACTION OF ACCELERATED PARTICLES



Particle transport is described by using the usual transport equation including diffusion and advection

But now dynamics is important too:

$$\rho_0 u_0 = \rho_1 u_1$$

Conservation of Mass

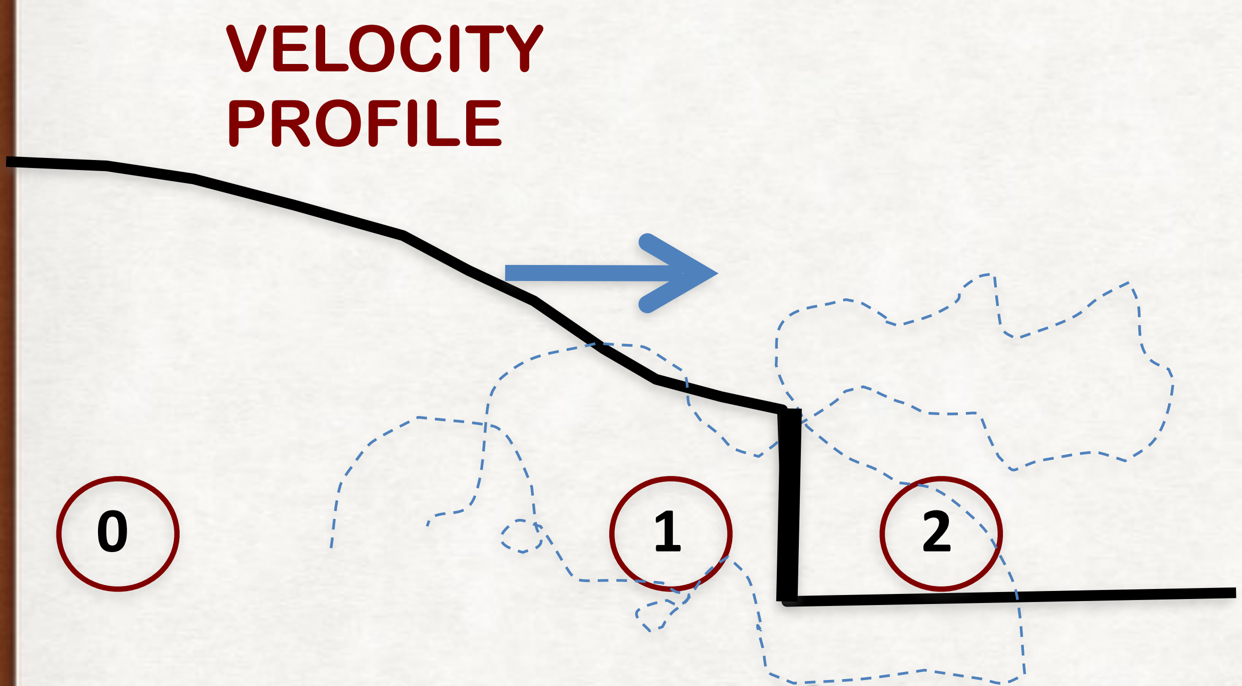
$$\rho_0 u_0^2 + P_{g,0} = \rho_1 u_1^2 + P_{g,1} + P_{c,1}$$

Conservation of Momentum

Conservation of Energy

$$\frac{1}{2}\rho_0 u_0^3 + \frac{P_{g,0} u_0 \gamma_g}{\gamma_g - 1} - F_{esc} = \frac{1}{2}\rho_1 u_1^3 + \frac{P_{g,1} u_1 \gamma_g}{\gamma_g - 1} + \frac{P_{c,1} u_1 \gamma_c}{\gamma_c - 1}$$

FORMATION OF A PRECURSOR - SIMPLIFIED



$$\frac{\partial}{\partial x}[\rho u] = 0 \rightarrow \rho(x)u(x) = \rho_0 u_0$$

$$\frac{\partial}{\partial x}\left[P_g + \rho u^2 + P_{CR}\right] = 0$$

$$P_g(x) + \rho u^2 + P_{CR} = P_{g,0} + \rho_0 u_0^2$$

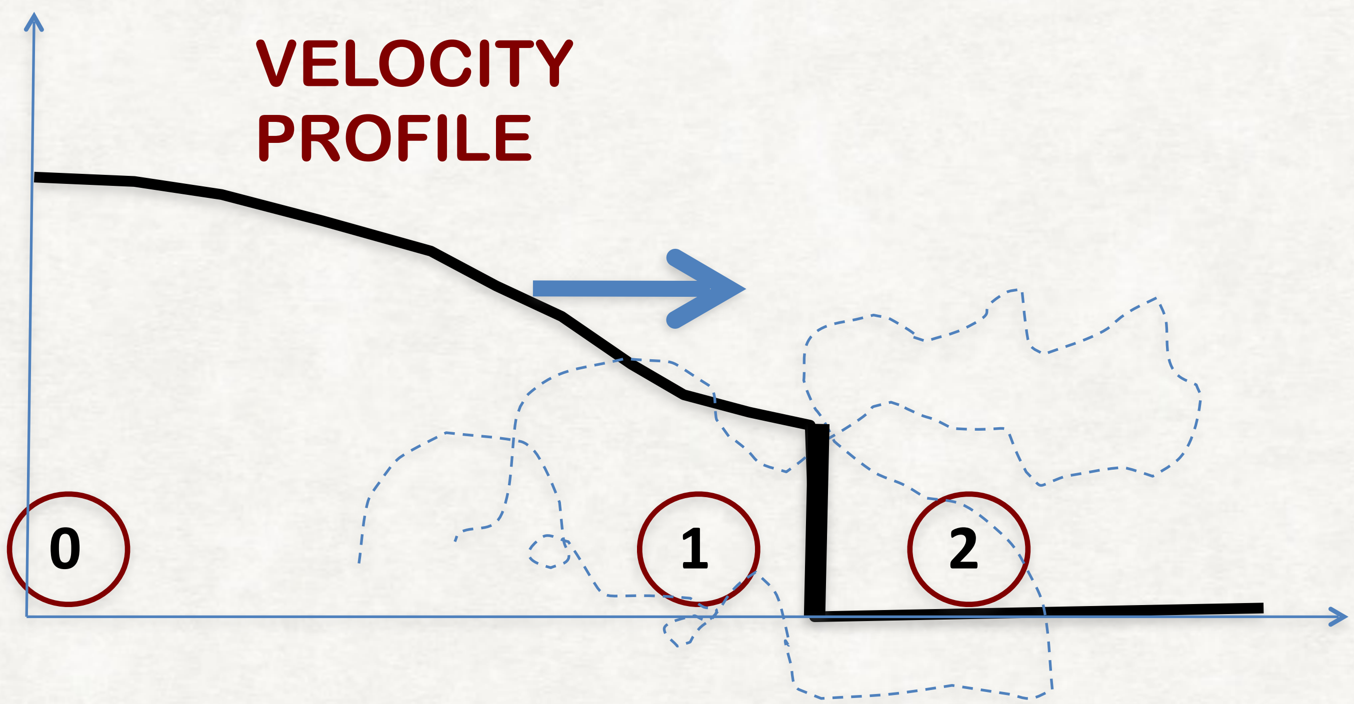
AND DIVIDING BY THE RAM PRESSURE AT UPSTREAM INFINITY:

$$\frac{P_g}{\rho_0 u_0^2} + \frac{u}{u_0} + \frac{P_{CR}}{\rho_0 u_0^2} = \frac{P_{g,0}}{\rho_0 u_0^2} + 1 \quad \Longrightarrow \quad \frac{u}{u_0} \approx 1 - \xi_{CR}(x)$$

WHERE WE NEGLECTED TERMS OF ORDER $1/M^2$

$$\xi_{CR}(x) = \frac{P_{CR}(x)}{\rho_0 u_0^2}$$

BASIC PREDICTIONS OF NON LINEAR THEORY



COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

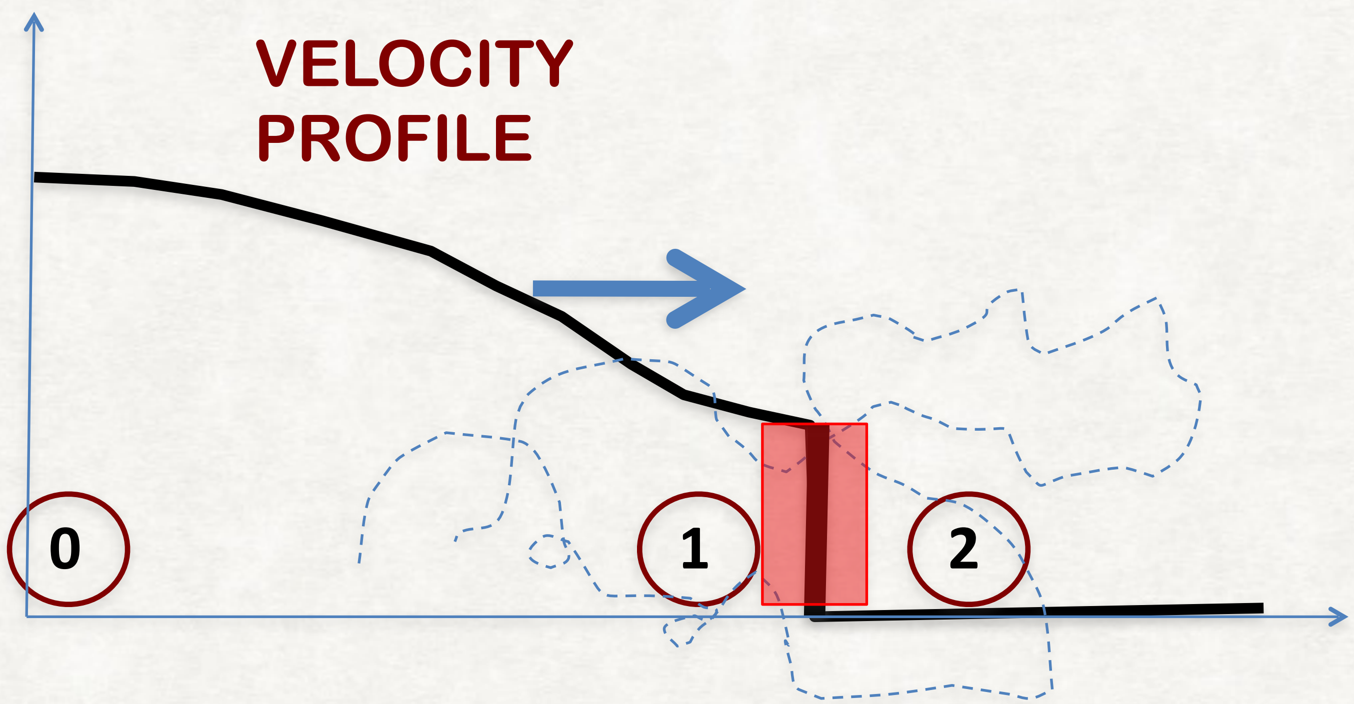
GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT

PB+2010

BASIC PREDICTIONS OF NON LINEAR THEORY



COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

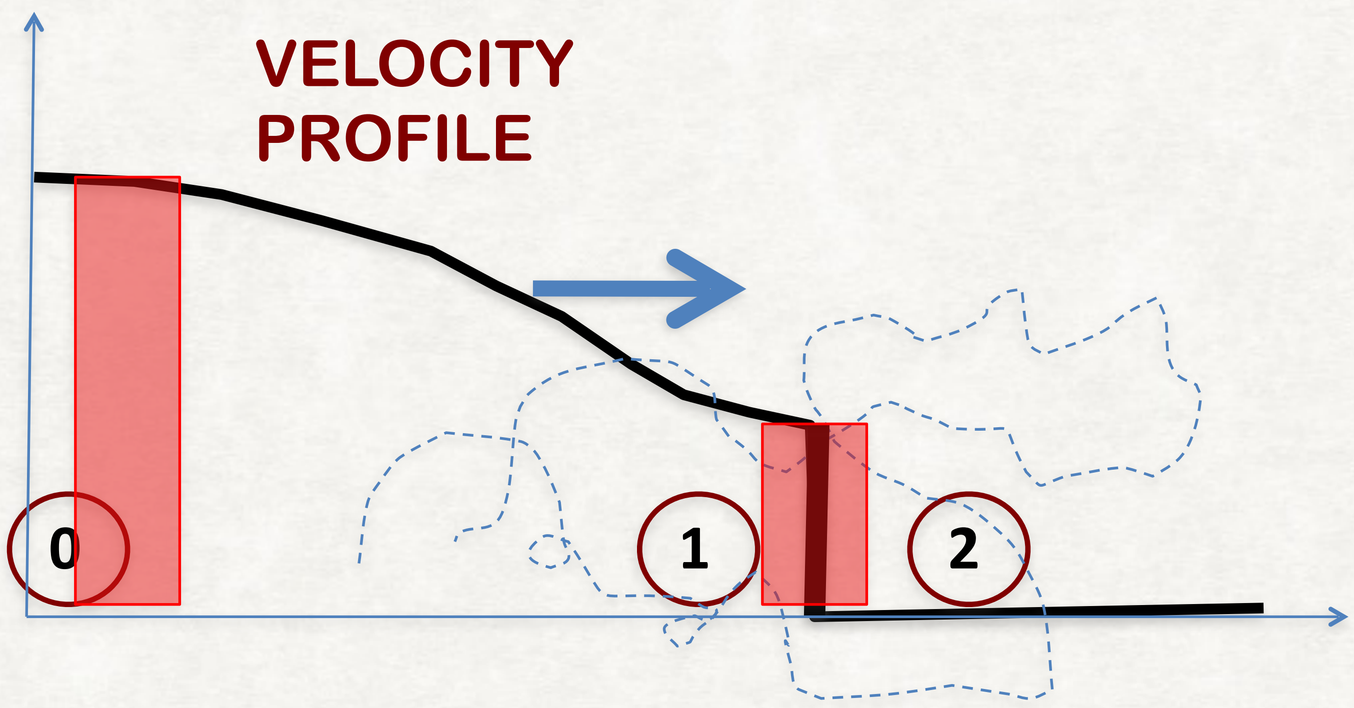
GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT

PB+2010

BASIC PREDICTIONS OF NON LINEAR THEORY



COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

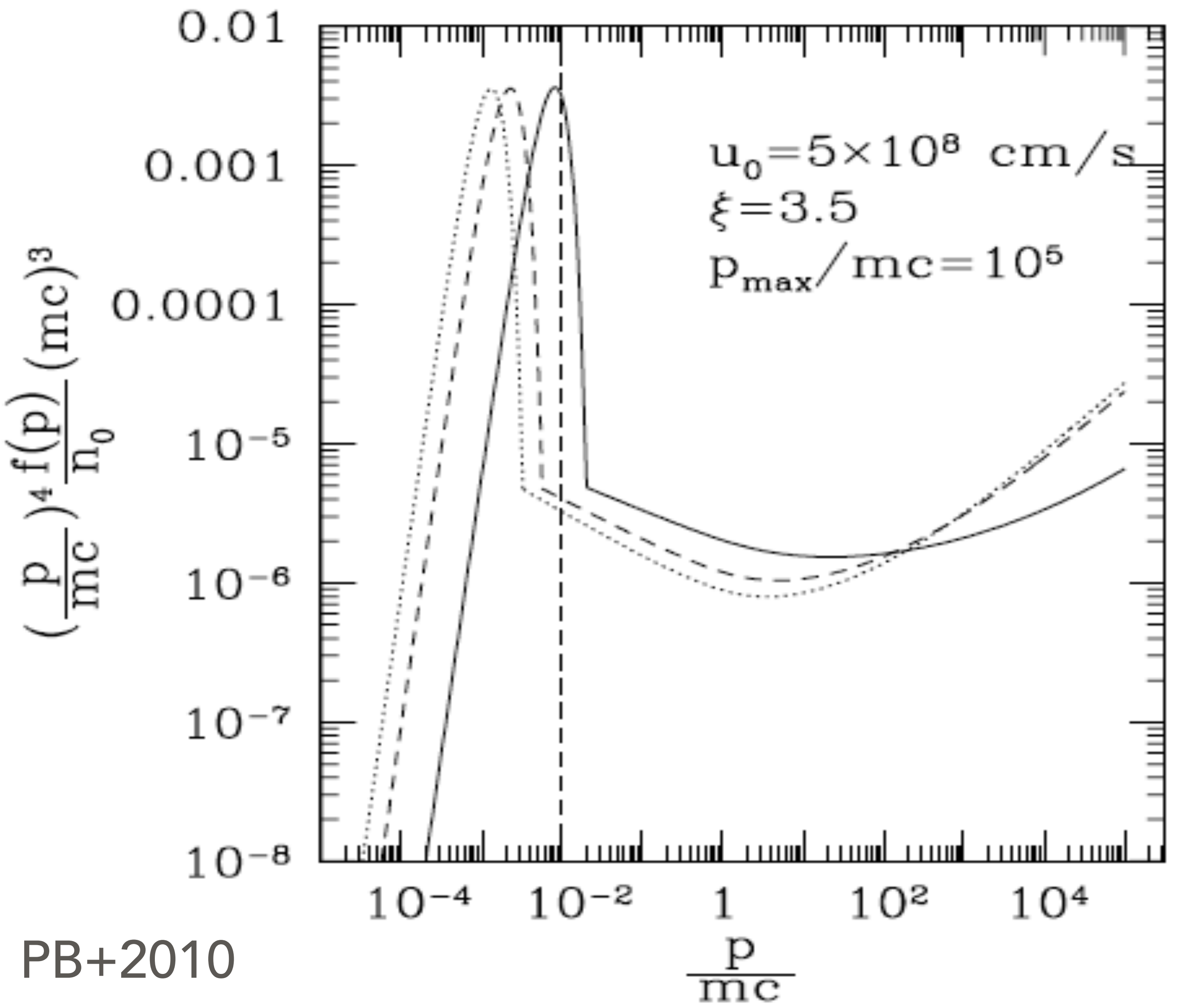
GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT

PB+2010

BASIC PREDICTIONS OF NON LINEAR THEORY



PB+2010

COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

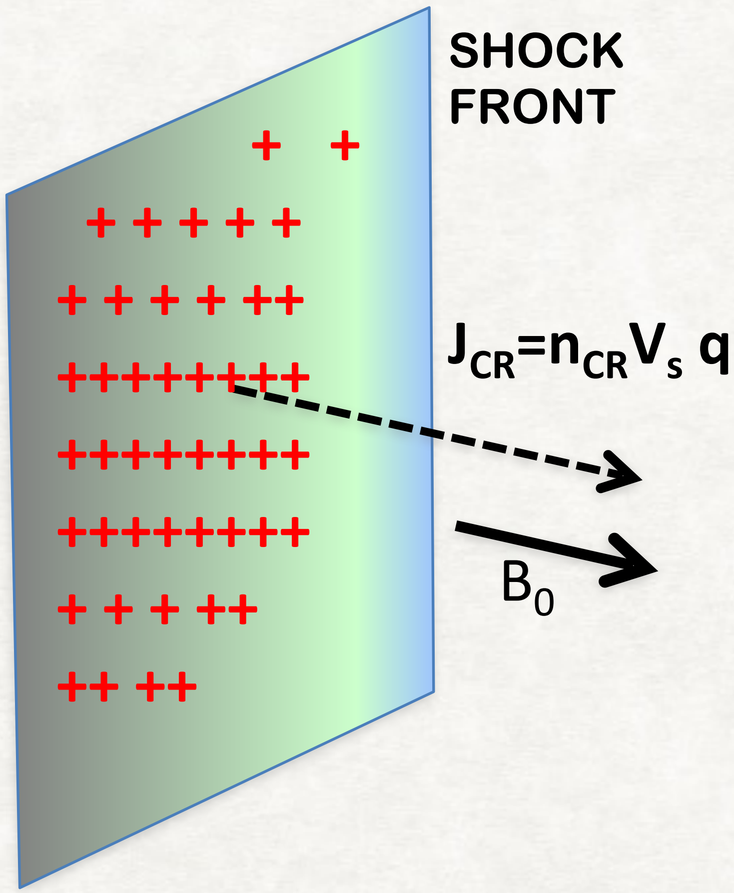
SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT

BASICS OF CR STREAMING INSTABILITY



THE UPSTREAM PLASMA REACTS TO THE UPCOMING CR CURRENT BY CREATING A RETURN CURRENT TO COMPENSATE THE POSITIVE CR CHARGE

THE SMALL INDUCED PERTURBATIONS ARE UNSTABLE (ACHTERBERG 1983, ZWEIBEL 1978, BELL 1978, BELL 2004, AMATO & PB 2009)

CR MOVE WITH THE SHOCK SPEED (>> V_A). THIS UNSTABLE SITUATION LEADS THE PLASMA TO REACT IN ORDER TO SLOW DOWN CR TO <V_A BY SCATTERING PARTICLES IN THE PERP DIRECTION (B-FIELD GROWTH)

STREAMING INSTABILITY - THE SIMPLE VIEW

CR streaming with the shock leads to growth of waves. The general idea is simple to explain:

$$n_{CR} m v_D \rightarrow n_{CR} m V_A \Rightarrow \frac{dP_{CR}}{dt} = \frac{n_{CR} m (v_D - V_A)}{\tau} \qquad \frac{dP_w}{dt} = \gamma_W \frac{\delta B^2}{8\pi} \frac{1}{V_A}$$

and assuming equilibrium:

$$\gamma_W = \sqrt{2}\, \frac{n_{CR}}{n_{gas}} \frac{v_D - V_A}{V_A} \Omega_{cyc}$$

And for parameters typical of SNR shocks:

$$\gamma_W \simeq \sqrt{2}\, \xi_{CR} \left(\frac{V_s}{c}\right)^2 \frac{V_s}{V_A} \Omega_{cyc} \sim \mathcal{O}(10^{-4} \;\; seconds^{-1})$$

BRANCHES OF THE CR INDUCED STREAMING INSTABILITY

A CAREFUL ANALYSIS OF THE INSTABILITY REVEALS THAT THERE ARE TWO BRANCHES

RESONANT	NON RESONANT
MAX GROWTH AT K=1/LARMOR	MAX GROWTH AT K>>1/LARMOR

THE MAX GROWTH CAN ALWAYS BE WRITTEN IN THE FORM

$$\gamma_{max} = k_{max} v_A$$

WHERE THE WAVENUMBER IS DETERMINED BY THE TENSION CONDITION:

$$k_{max} B_0 \approx \frac{4\pi}{c} J_{CR} \rightarrow k_{max} \approx \frac{4\pi}{c B_0} J_{CR}$$

THE SEPARATION BETWEEN THE TWO REGIMES IS AT $k_{MAX}\, r_L=1$

IF WE WRITE THE CR CURRENT AS $J_{CR} = n_{CR}(> E) e v_D$

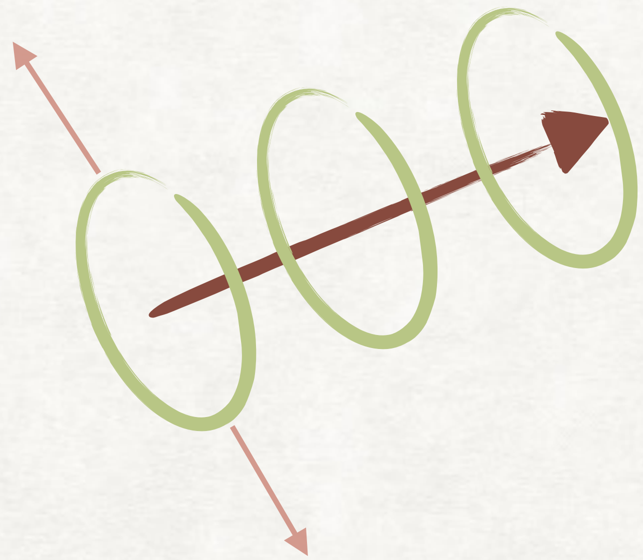
WHERE E IS THE ENERGY OF THE PARTICLES DOMINATING THE CR CURRENT, WE CAN WRITE THE CONDITION ABOVE AS

$$\frac{U_{CR}}{U_B} = \frac{c}{v_D} \qquad U_{CR} = n_{CR}(> E)E \qquad U_B = \frac{B^2}{4\pi}$$

IN CASE OF SHOCKS **VD=SHOCK VELOCITY** AND THE CONDITION SAYS THAT THE NON-RESONANT MODES DOMINATED WHEN THE SHOCK IS VERY FAST AND ACCELERATION IS EFFICIENT —- *FOR TYPICAL CASES THIS IS ALWAYS THE CASE*

BUT RECALL! THE WAVES THAT GROW HAVE K MUCH LARGER THAN THE LARMOR RADIUS OF THE PARTICLES IN THE CURRENT —> NO SCATTERING BECAUSE EFFICIENT SCATTERING REQUIRES RESONANCE!!!

THE EASY WAY TO SATURATION OF GROWTH



The current exerts a force of the background plasma

$$\rho \frac{dv}{dt} \sim \frac{1}{c} J_{CR} \delta B$$

which translates into a plasma displacement:

$$\Delta x \sim \frac{J_{CR}}{c\rho} \frac{\delta B(0)}{\gamma_{max}^2} exp(\gamma_{max} t)$$

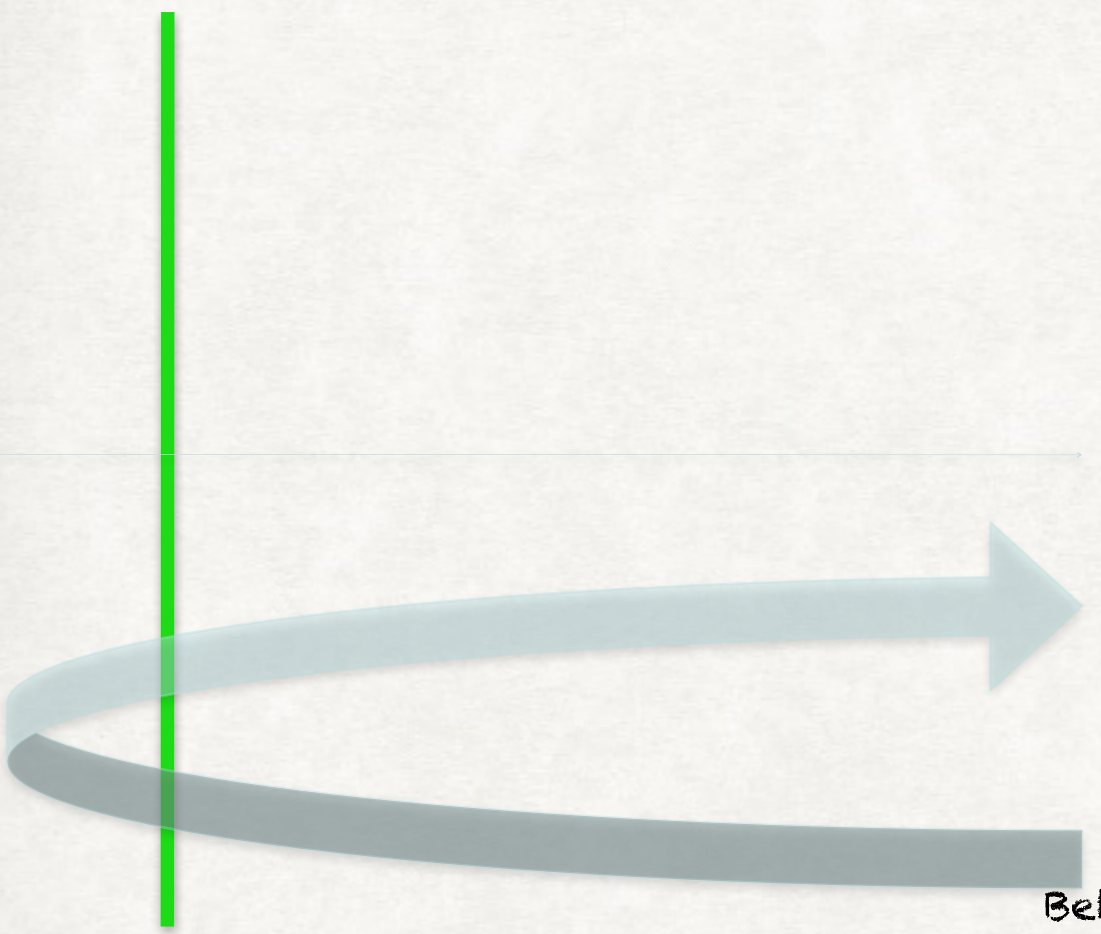
which stretches the magnetic field line by the same amount…

The saturation takes place when the displacement equals the Larmor radius of the particles in the field **δ**B … imposing this condition leads to:

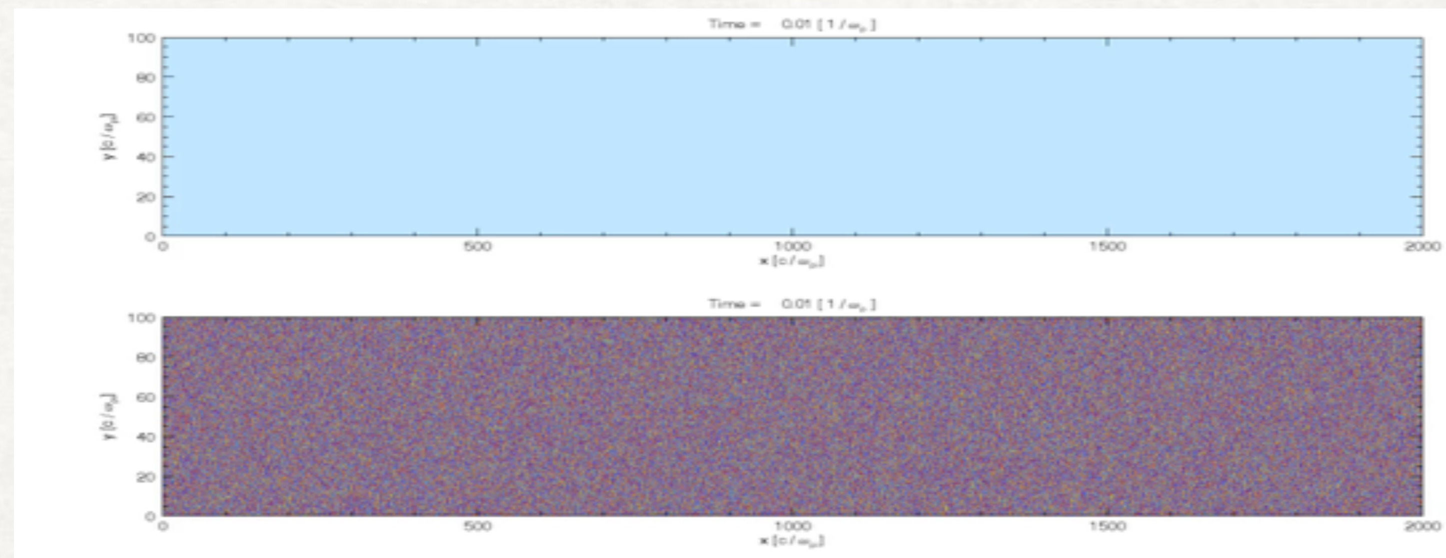
$$\frac{\delta B^2}{4\pi} = \frac{\xi_{CR}}{\Lambda} \rho v_s^2 \frac{v_s}{c} \qquad \Lambda = \ln(E_{max}/E_{min})$$

specialized to a shock and a spectrum E^{-2}

A QUALITATIVE PICTURE OF ACCELERATION

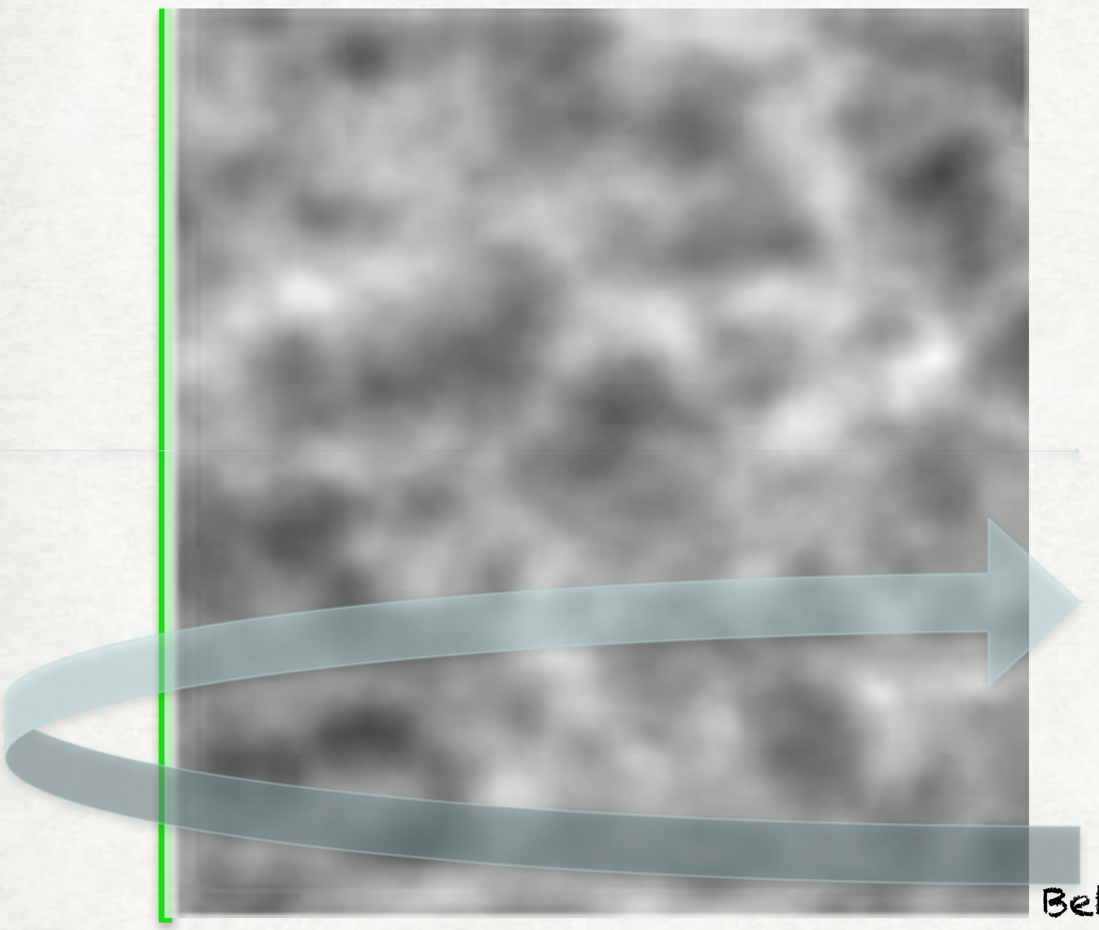


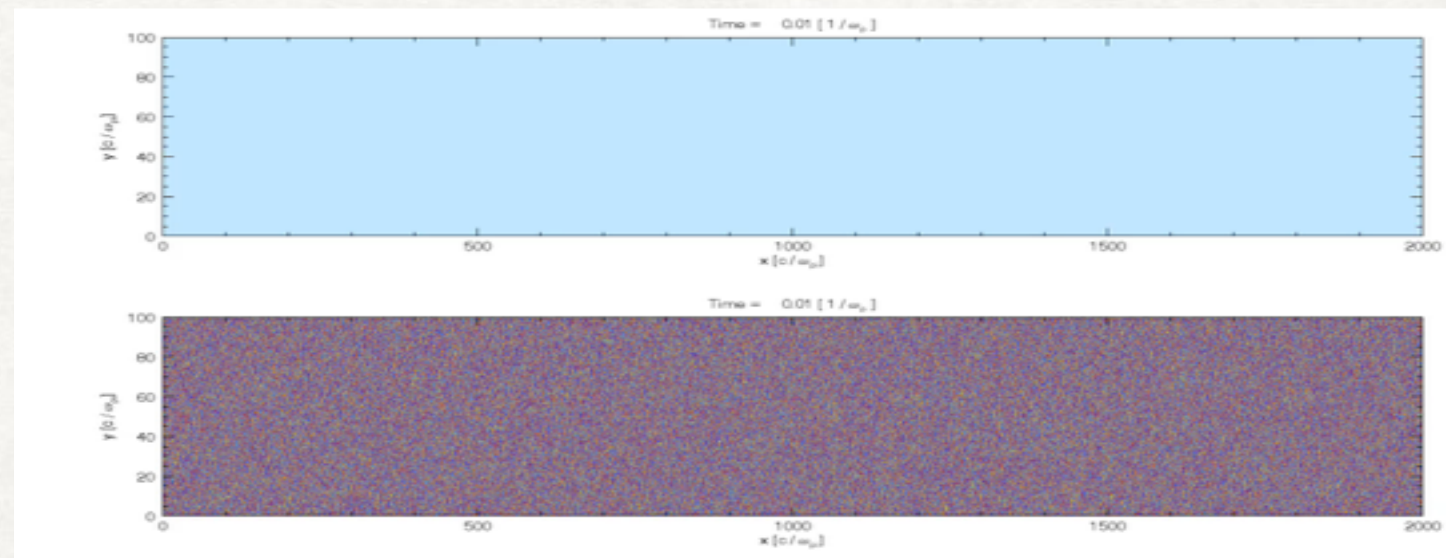
Bell & Schure 2013
Cardillo, Amato & PB 2015



Caprioli & Spitkovsky 2013

A QUALITATIVE PICTURE OF ACCELERATION

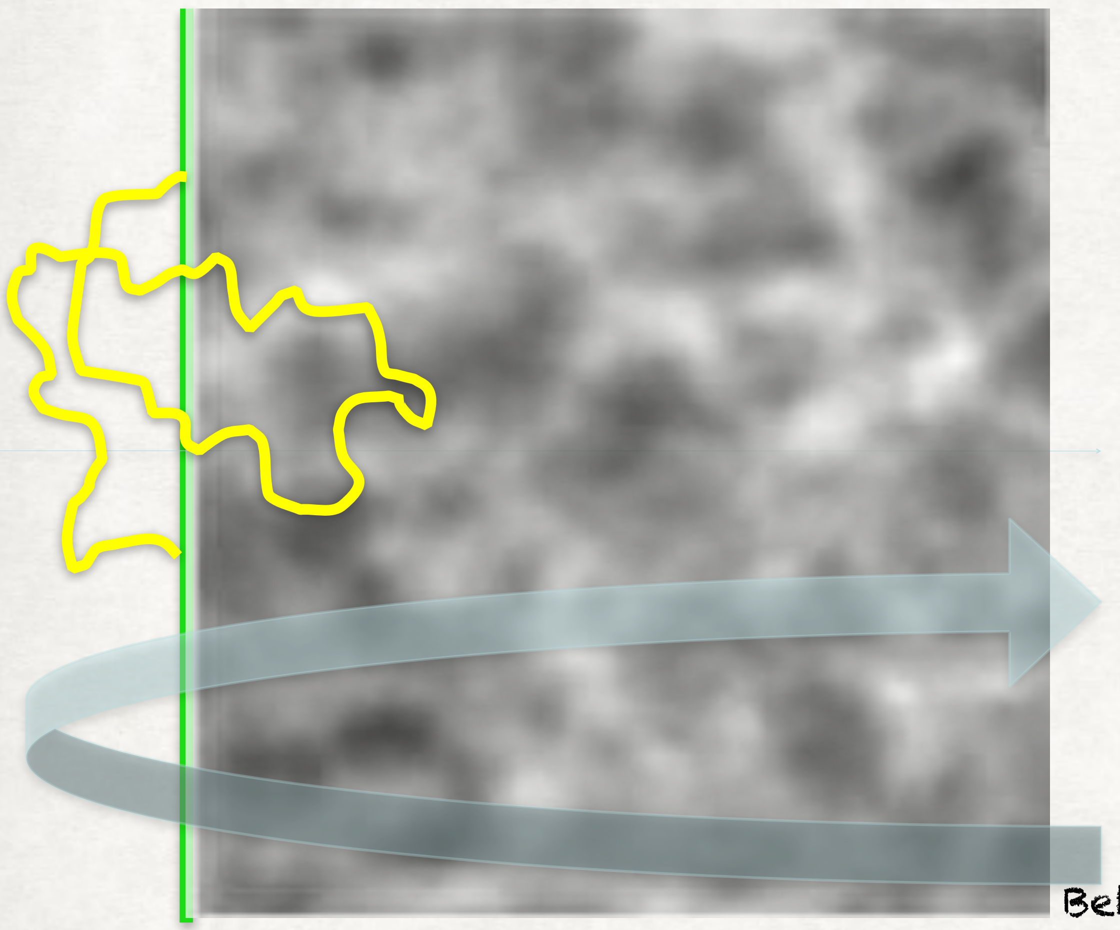


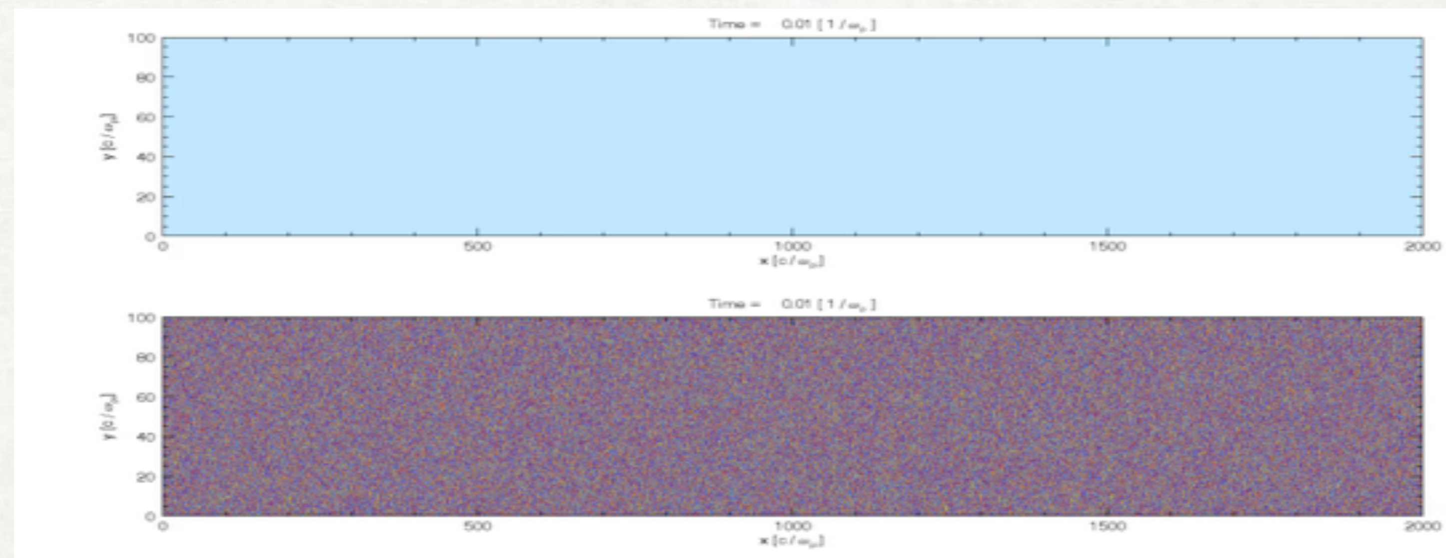


Caprioli & Spitkovsky 2013

Bell & Schure 2013
Cardillo, Amato & PB 2015

A QUALITATIVE PICTURE OF ACCELERATION

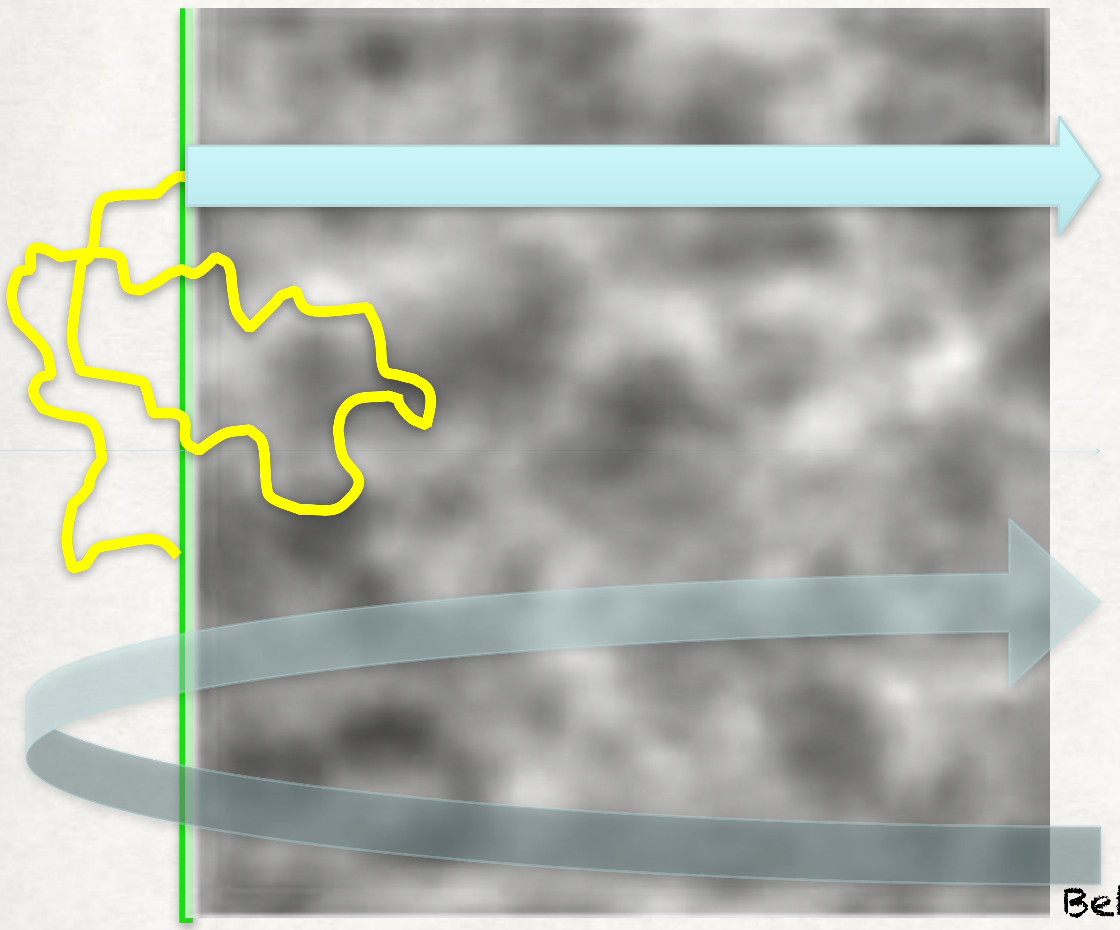


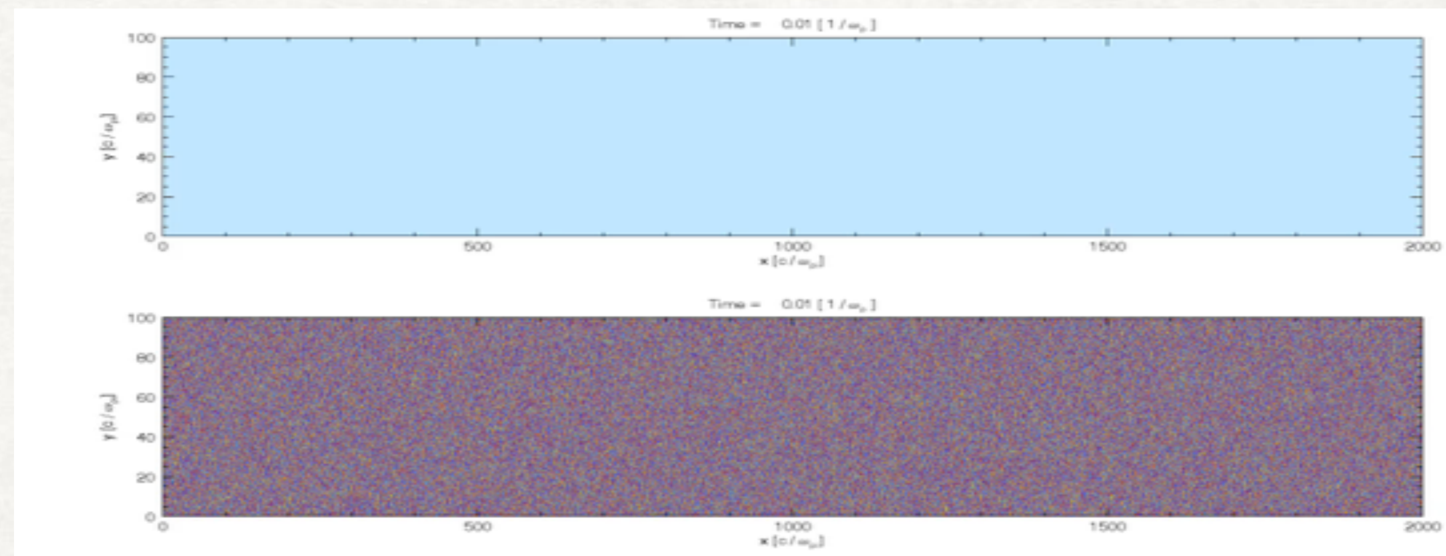


Caprioli & Spitkovsky 2013

Bell & Schure 2013
Cardillo, Amato & PB 2015

A QUALITATIVE PICTURE OF ACCELERATION

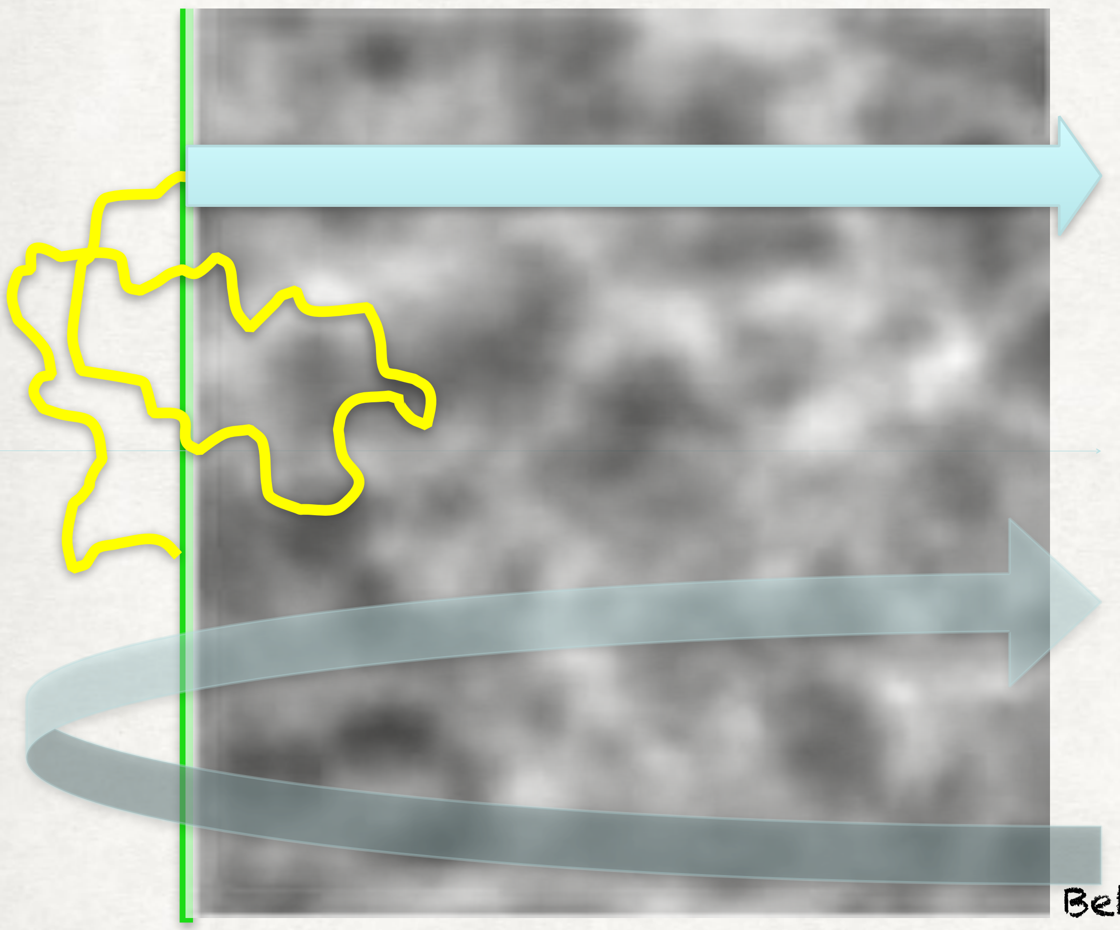


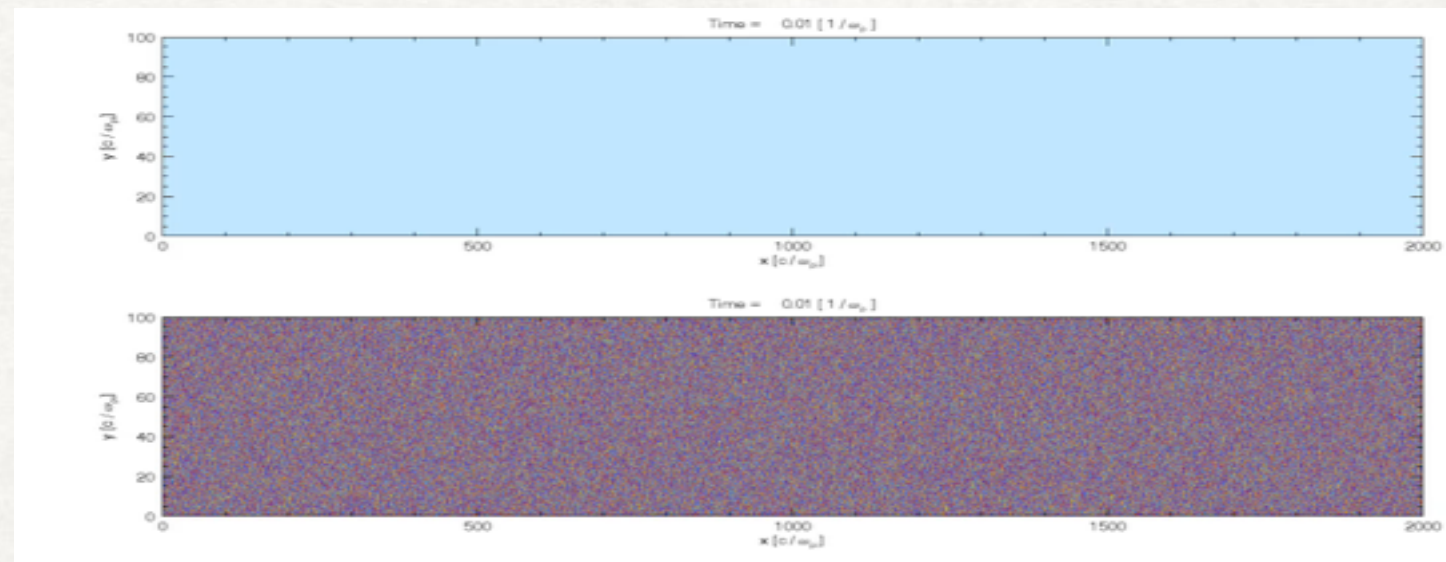


Caprioli & Spitkovsky 2013

Bell & Schure 2013
Cardillo, Amato & PB 2015

A QUALITATIVE PICTURE OF ACCELERATION





Caprioli & Spitkovsky 2013

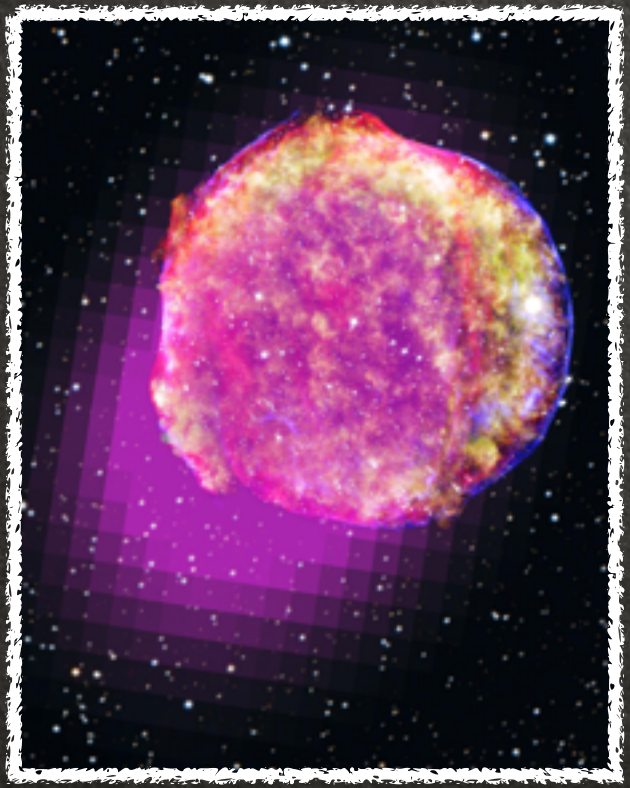
Bell & Schure 2013
Cardillo, Amato & PB 2015

IMPLICATIONS FOR MAXIMUM ENERGY

Supernovae of type Ia

Explosion takes place in the ISM with spatially constant density

$$E_{max} \approx 130\ TeV \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_{\odot}}\right)^{-2/3}\left(\frac{E_{SN}}{10^{51} erg}\right)\left(\frac{n_{ISM}}{cm^{-3}}\right)^{1/6}$$



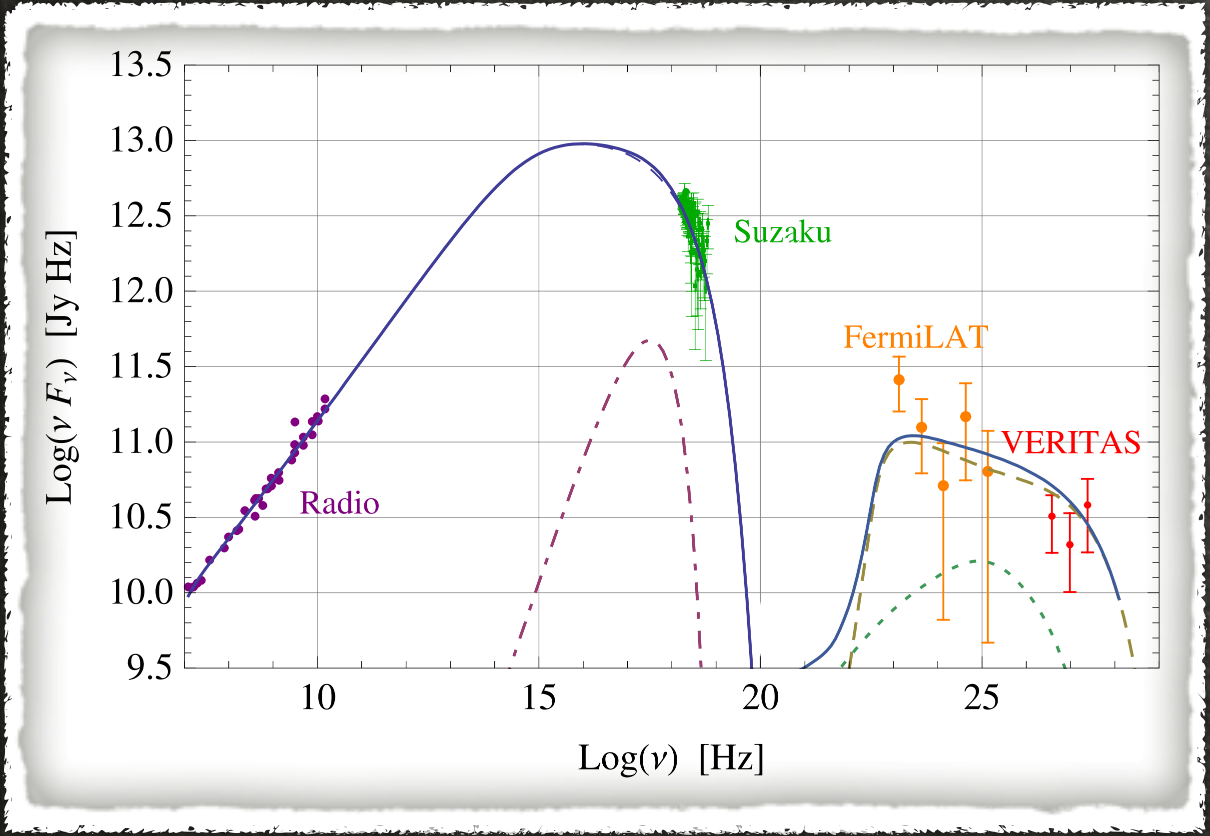
Supernovae of type II

IMPLICATIONS FOR MAXIMUM ENERGY

Supernovae of type Ia

Explosion takes place in the ISM with spatially constant density

$$E_{max} \approx 130\ TeV \left(\frac{\xi_{CR}}{0.1}\right) \left(\frac{M_{ej}}{M_\odot}\right)^{-2/3} \left(\frac{E_{SN}}{10^{51} erg}\right) \left(\frac{n_{ISM}}{cm^{-3}}\right)^{1/6}$$



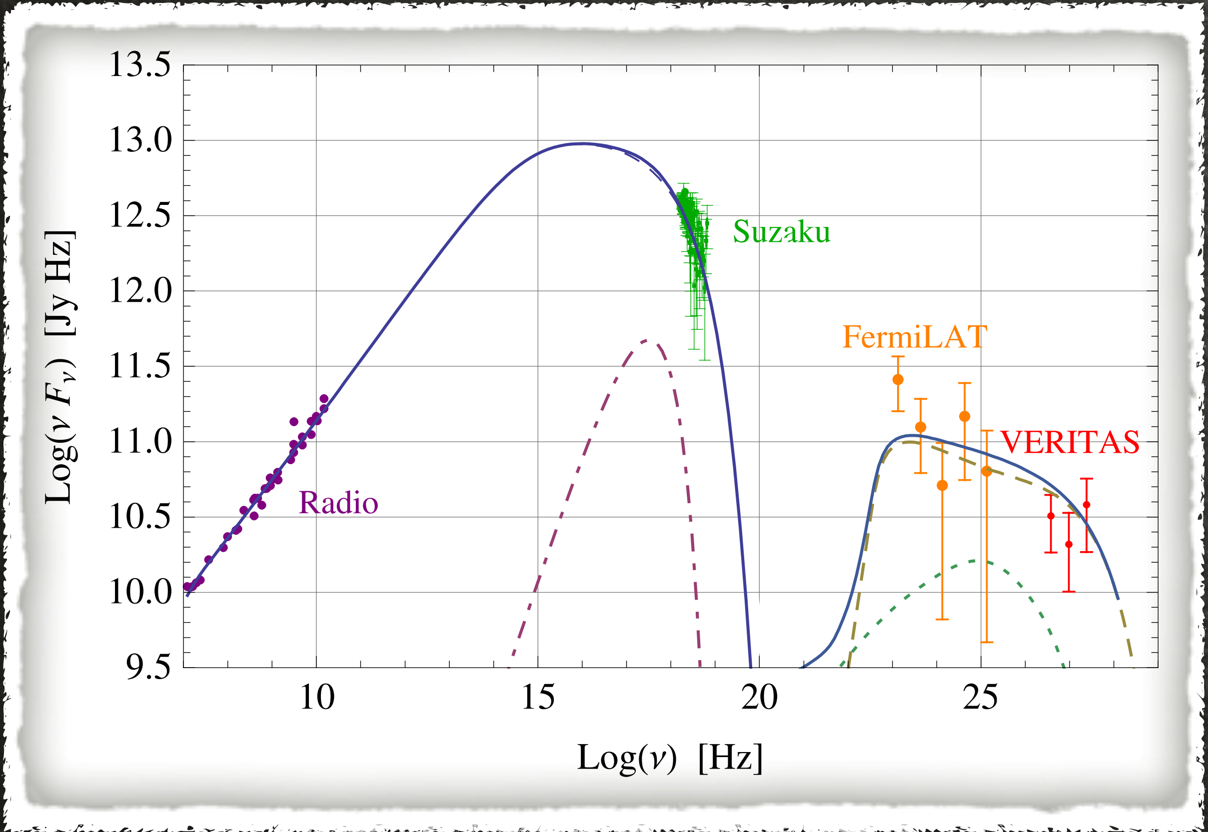
Supernovae of type II

IMPLICATIONS FOR MAXIMUM ENERGY

Supernovae of type Ia

Explosion takes place in the ISM with spatially constant density

$$E_{max} \approx 130\ TeV \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-2/3}\left(\frac{E_{SN}}{10^{51} erg}\right)\left(\frac{n_{ISM}}{cm^{-3}}\right)^{1/6}$$



Supernovae of type II

In most cases the explosion takes place in the dense wind of the red super-giant progenitor

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_W}$$

The Sedov phase reached while the shock expands inside the wind

$$R = M_{ej} v_W / \dot{M}$$

This corresponds to typical times of few tens of years after the SN explosion !!!

$$E_{max} \approx 1\ PeV \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-1}\left(\frac{E_{SN}}{10^{51} erg}\right) \times \left(\frac{\dot{M}}{10^{-5} M_\odot yr^{-1}}\right)^{1/2}\left(\frac{v_{wind}}{10 km/s}\right)^{-1/2}$$

X-ray rims and B-field amplification

TYPICAL THICKNESS OF FILAMENTS: ~ 10^{-2} pc

The synchrotron limited thickness is:

$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

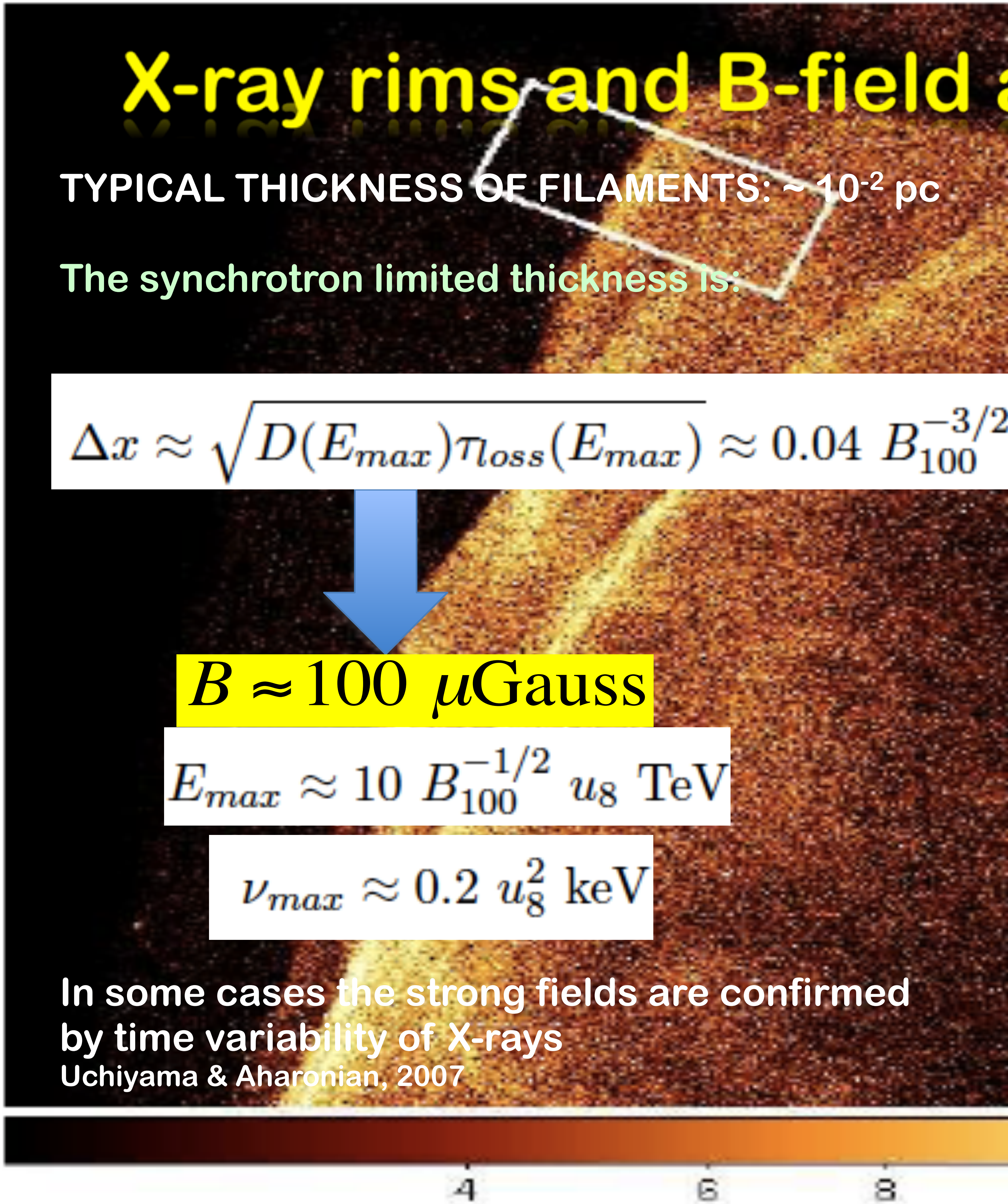
$$B \approx 100\ \mu\mathrm{Gauss}$$

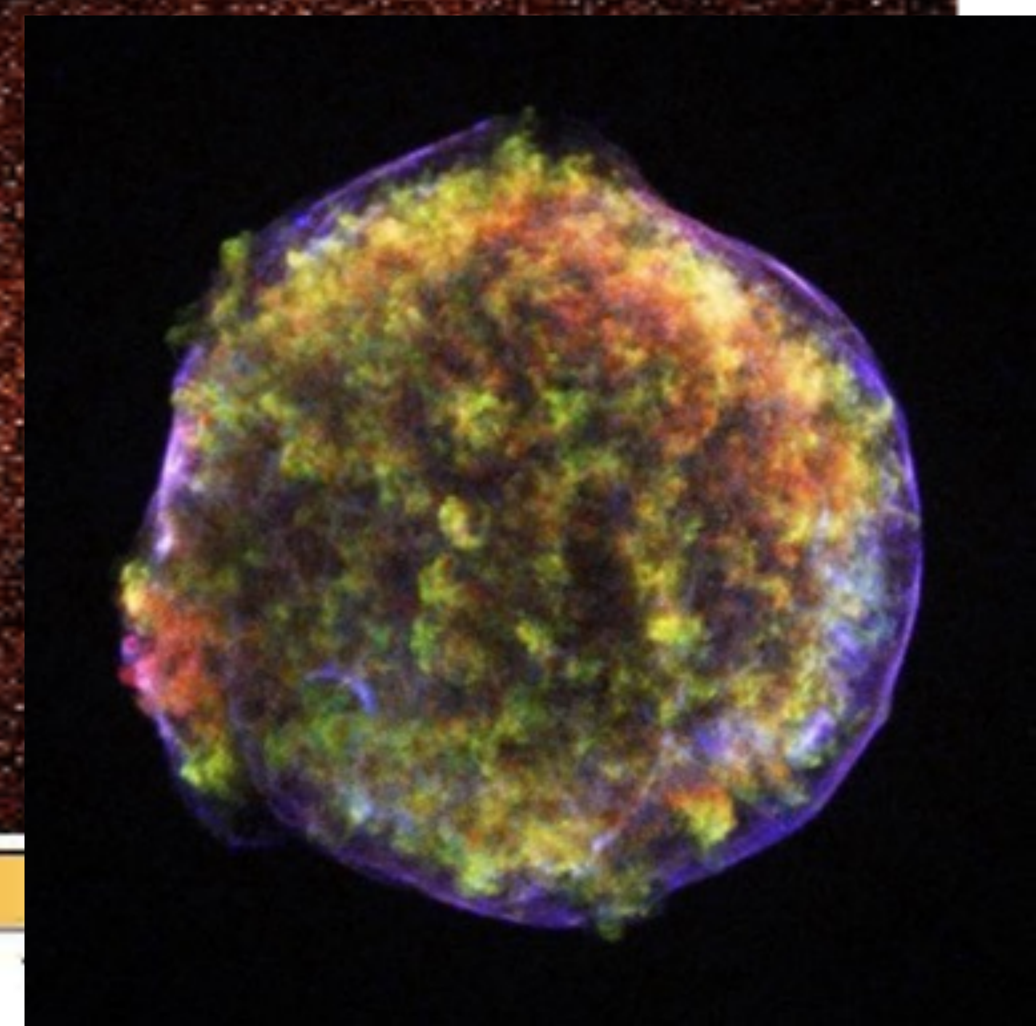
$$E_{max} \approx 10\ B_{100}^{-1/2}\ u_8\ \mathrm{TeV}$$

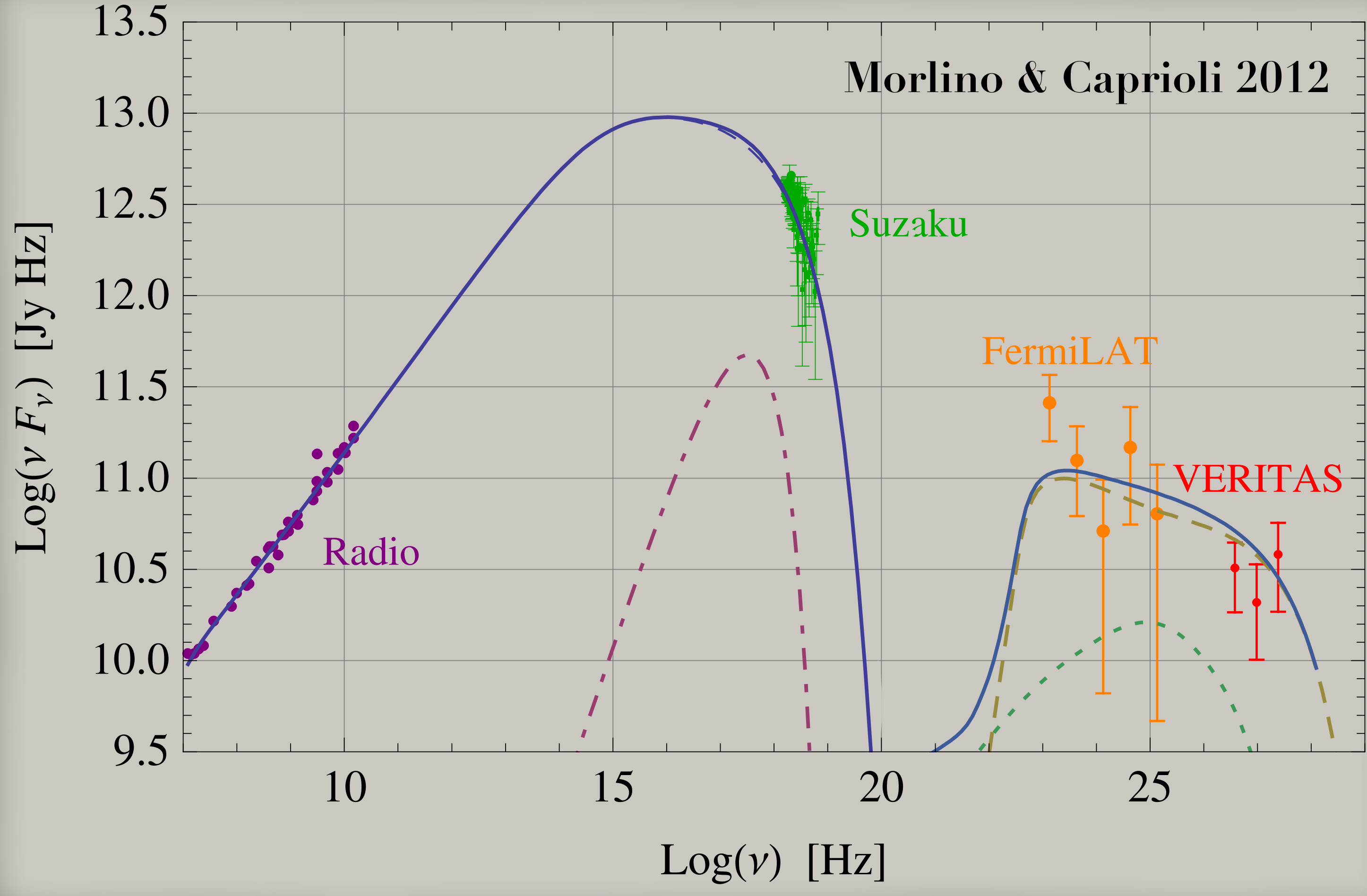
$$\nu_{max} \approx 0.2\ u_8^2\ \mathrm{keV}$$

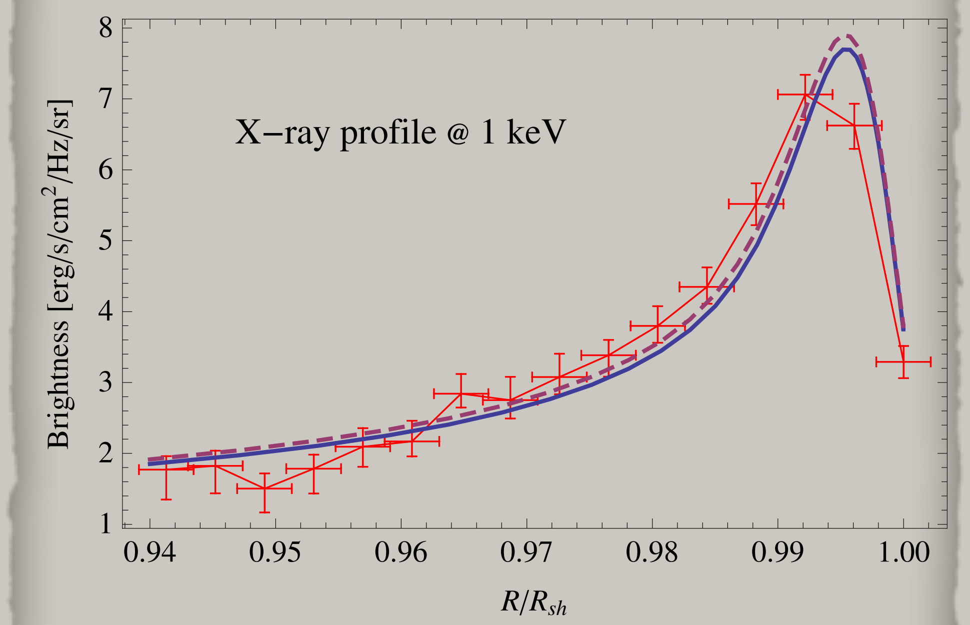
In some cases the strong fields are confirmed by time variability of X-rays

Uchiyama & Aharonian, 2007



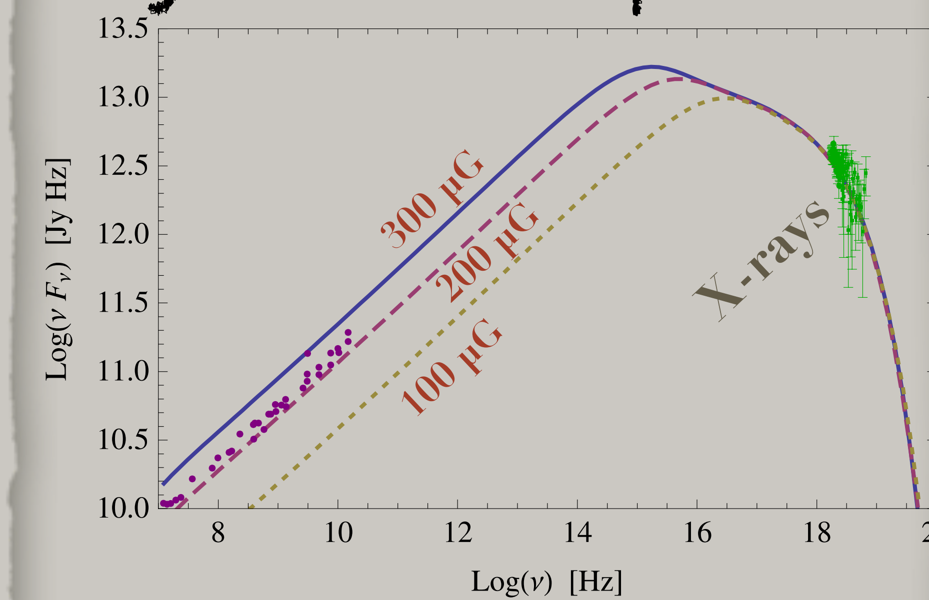






X-Ray Morphology

Synchrotron spectra



SPECTRUM AND MORPHOLOGY APPEAR TO BE WELL DESCRIBED BY EFFICIENT CR ACCELERATION

THE MAXIMUM ENERGY IS IN THE RANGE OF A FEW HUNDRED GeV

DSA IN THE PRESENCE OF NEUTRAL HYDROGEN

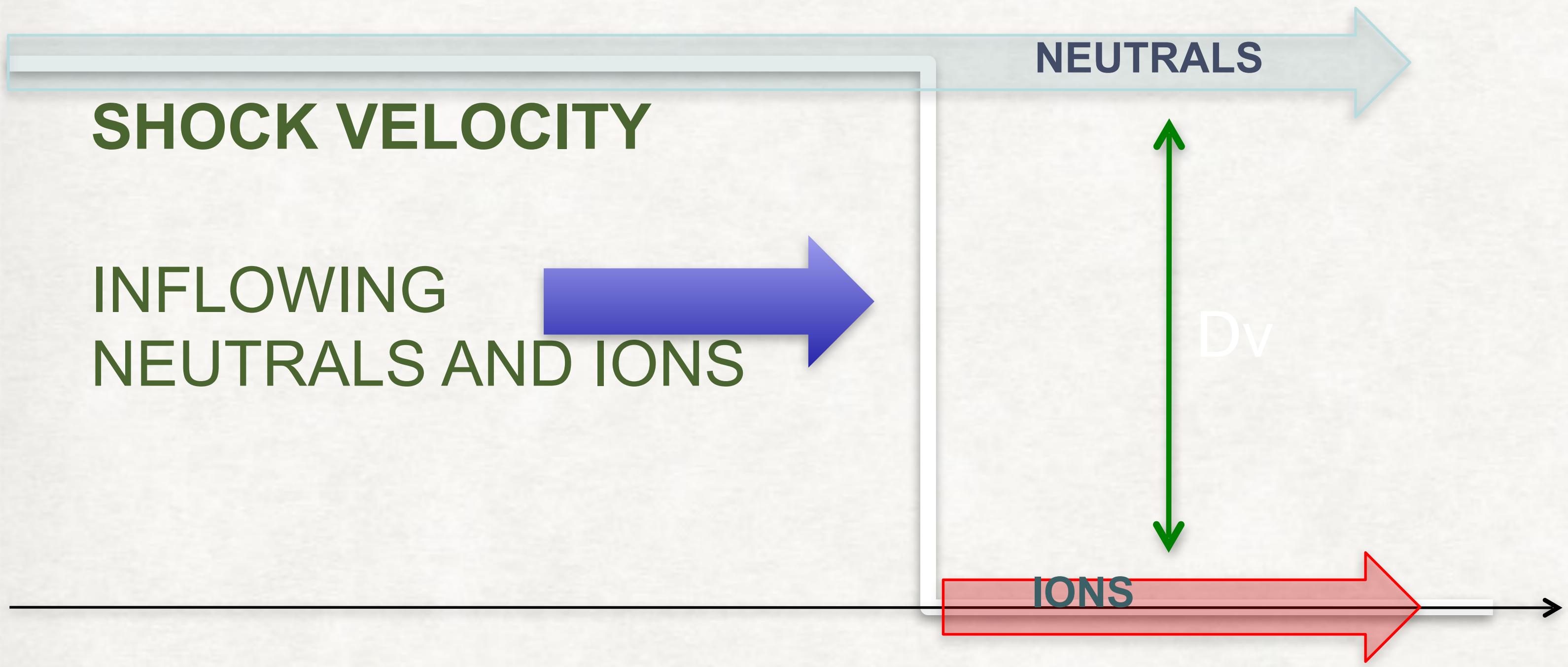
THE COLLISIONLESS NATURE OF MOST ASTROPHYSICAL SHOCKS LEADS TO THE RELEVANT QUESTION 'WHAT DO NEUTRAL ATOMS DO AT THE SHOCK?' (see case of pick up ions at the solar wind termination shock)

PARTIALLY IONIZED PLASMAS ARE THE NORM, AT LEAST IN THE ORDINARY ISM WHERE SN TYPE Ia EXPLODE BUT ALSO IN THE SURROUNDINGS OF SOME TYPE II SN

1) SHOCK MODIFICATION INDUCED BY NEUTRALS IN THE ABSENCE OF ACCELERATED PARTICLES
   a) Neutral return flux
   b) Spectra of test particles accelerated at neutrals-mediated collisionless shocks

2) NON LINEAR THEORY OF DSA IN THE PRESENCE OF NEUTRALS
   a) Shock modification induced by neutrals vs CR modification
   b) Narrow and broad Balmer lines in the presence of efficient CR acceleration
   c) Application to some SNR where Balmer emission is observed

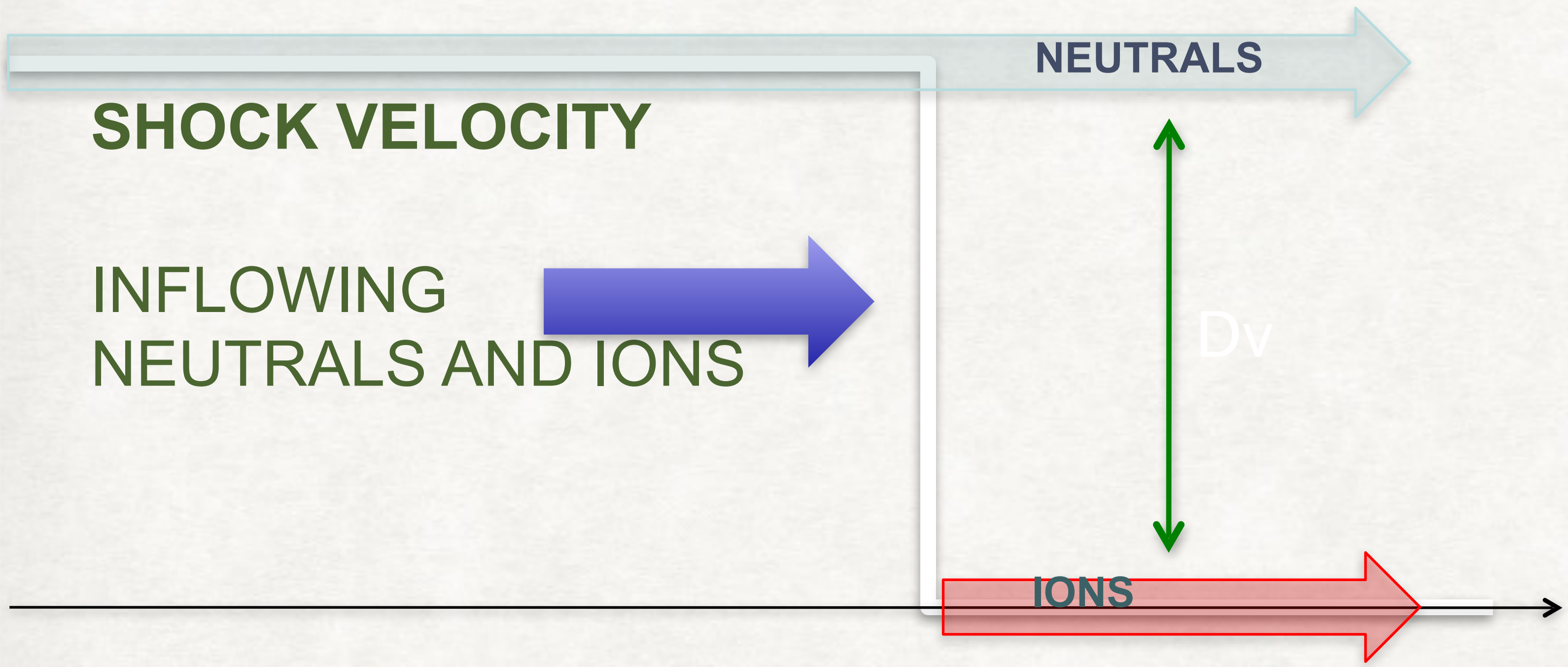
SNR IN PARTIALLY IONIZED PLASMAS



AT ZERO ORDER NOTHING HAPPENS TO NEUTRALS

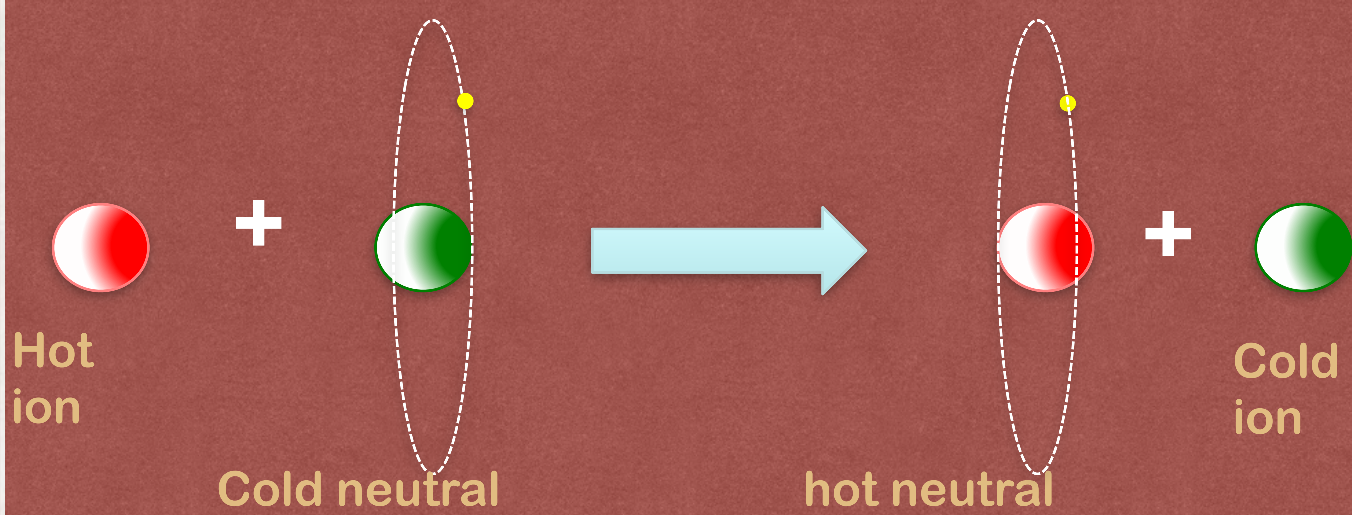
IONS ARE HEATED UP AND SLOWED DOWN

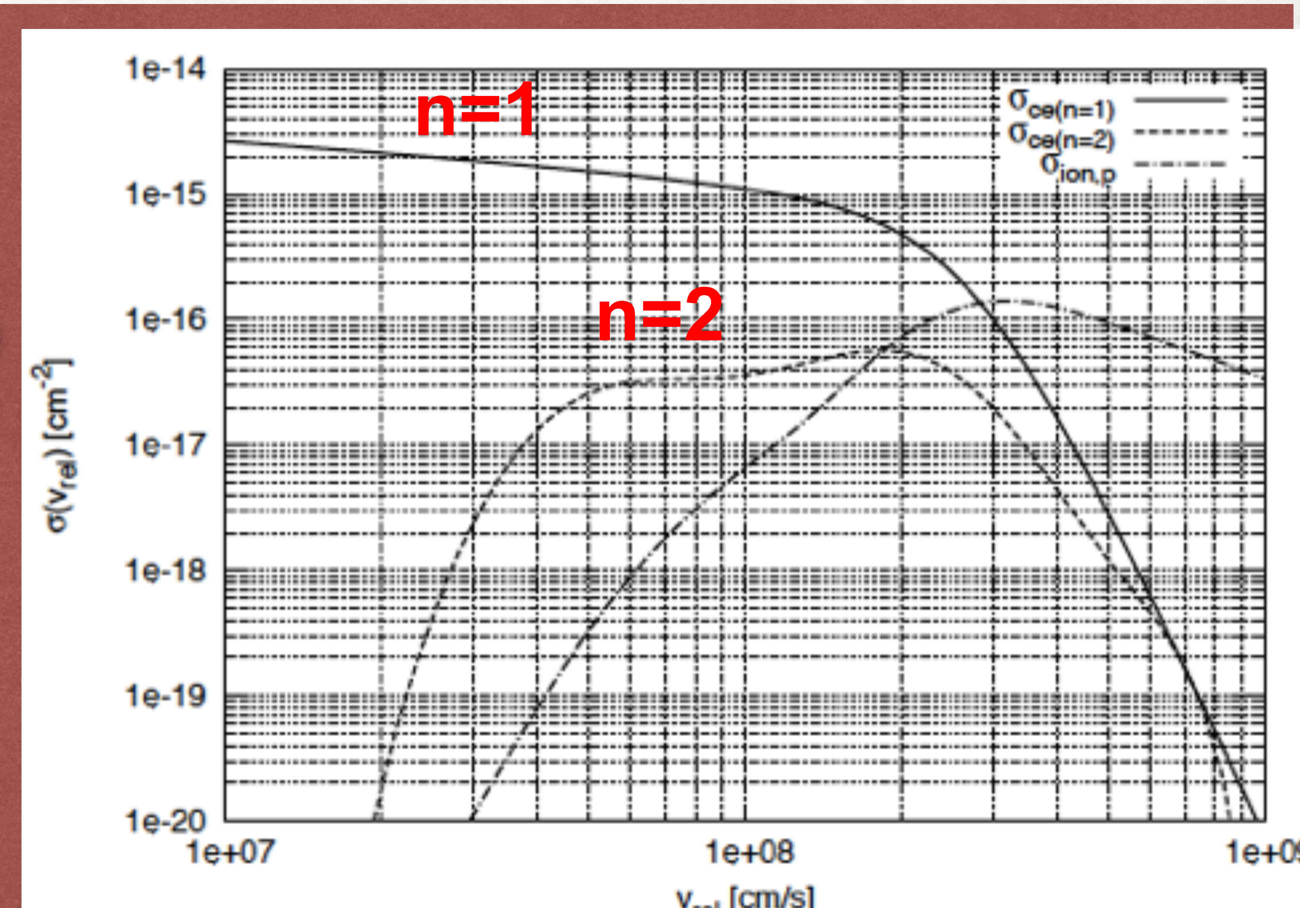
SNR IN PARTIALLY IONIZED PLASMAS



AT ZERO ORDER NOTHING HAPPENS TO NEUTRALS

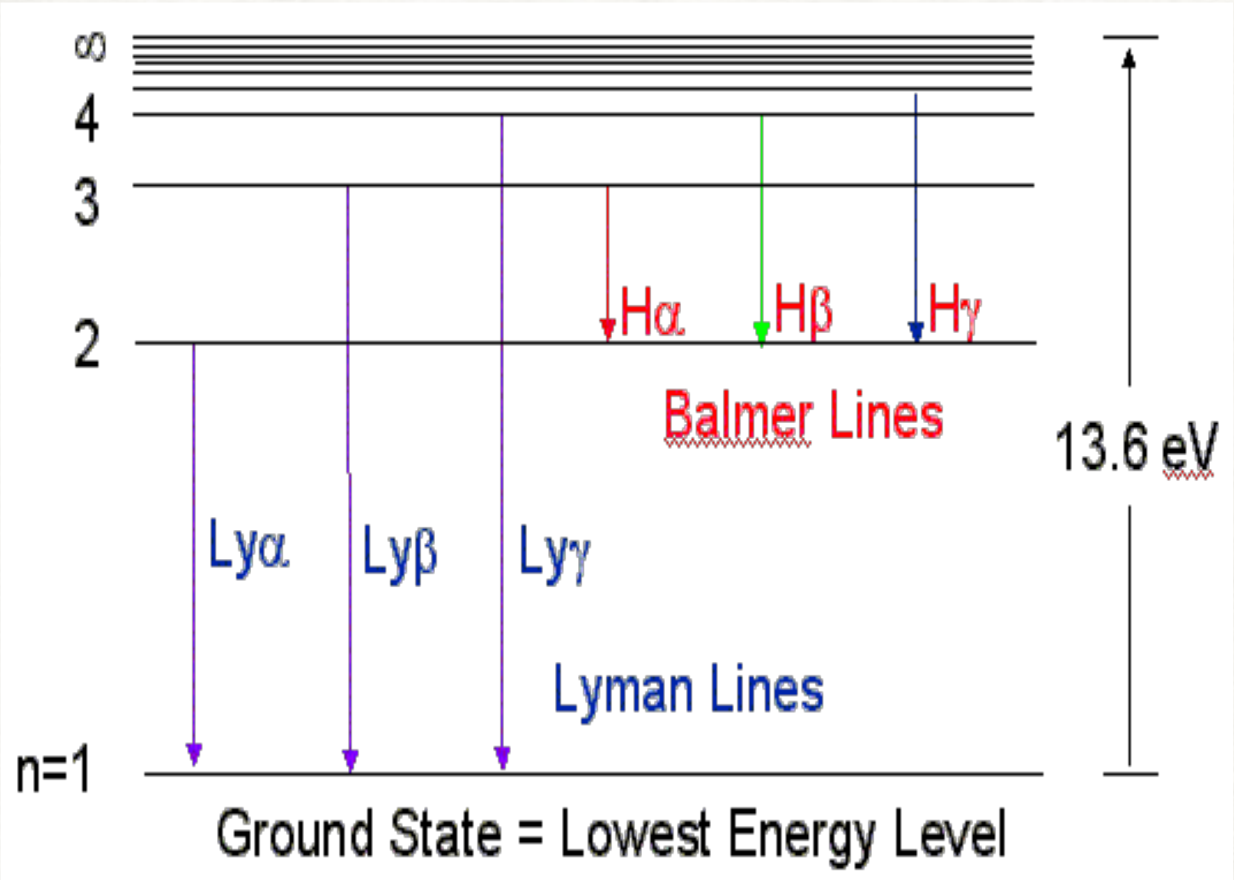
IONS ARE HEATED UP AND SLOWED DOWN





BASIC PHYSICS OF BALMER SHOCKS

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



Ha LINES ARE PRODUCED AFTER EXCITATION OF H ATOMS TO THE n=3 AND DE-EXCITATION TO n=2

IF EXCITATION OCCURS BEFORE THE ATOM SUFFERS A CHARGE EXCHANGE → NARROW BALMER LINE (ION T UPSTREAM)

IF H IS EXCITED AFTER CHARGE EXCHANGE DOWNSTREAM → BROAD BALMER LINE (ION T DOWNSTREAM)

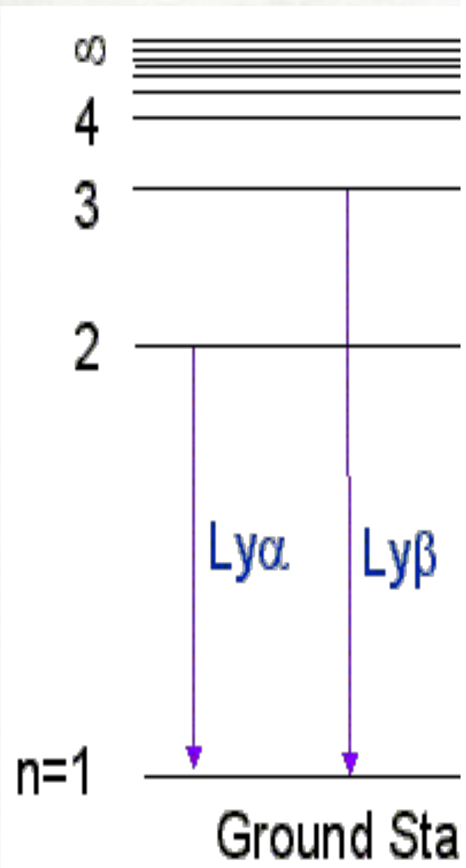
THE WIDTH OF THE BROAD Ha LINES TELLS US ABOUT THE ION TEMPERATURE DOWNSTREAM OF THE SHOCK

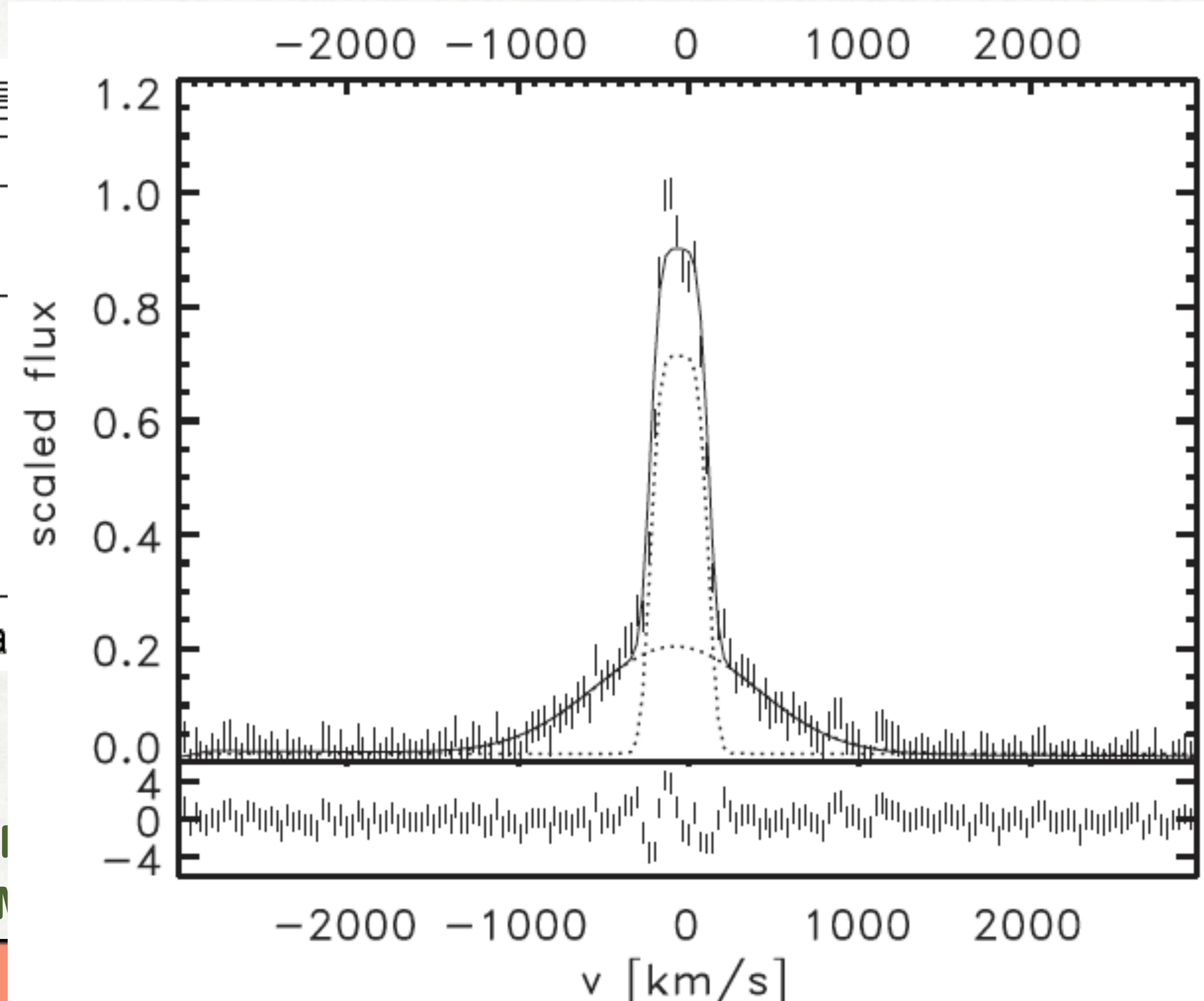
$$W_{narrow} \propto \sqrt{T_0}$$

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

BASIC PHYSICS OF BALMER SHOCKS

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



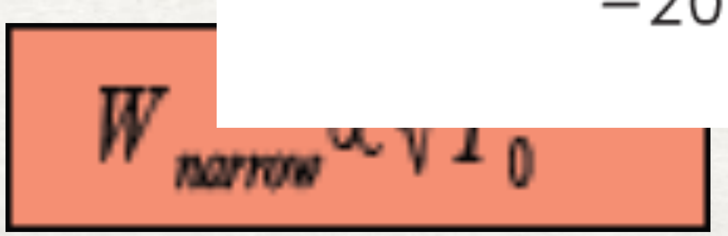


CED AFTER
TO THE n=3

EFORE THE
EXCHANGE
NE (ION T

R CHARGE
→ BROAD
STREAM)

THE WIDTH OI … MPERATURE
DOWNSTREAM

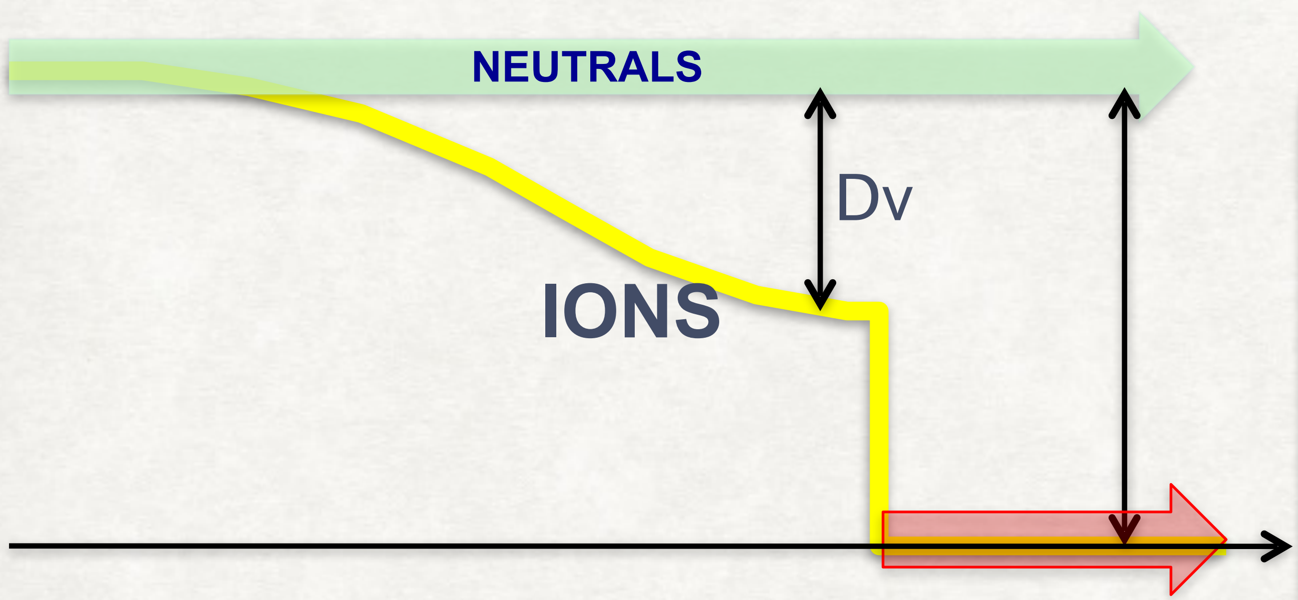


BALMER LINE WIDTHS IN CR MODIFIED SHOCKS

IN THE PRESENCE OF PARTICLE ACCELERATION TWO THINGS HAPPEN:

LOWER TEMPERATURE DOWNSTREAM

A PRECURSOR APPEARS UPSTREAM



BROAD BALMER LINE GETS NARROWER

NARROW BALMER LINE GETS BROADER

[redacted]

BALMER SHOCKS WITH NO CR

PB, Morlino, Bandiera, Amato & Caprioli, 2012

IONS ARE TREATED AS A PLASMA WITH GIVEN DENSITY AND A THERMAL DISTRIBUTION

NEUTRAL ATOMS ARE DESCRIBED USING A BOLTZMAN EQUATION WITH SCATTERING TERMS DESCRIBING CHARGE EXCHANGE AND IONIZATION

$$v_z \frac{\partial f_N(z,v)}{\partial z} = f_i(z,v)\beta_N(z,v) - f_N(z,v)\beta_i(z,v)$$

$$\beta_i(z,v) = \int d^3w \; v_{rel}\left[\sigma_{ce}(v_{rel}) + \sigma_{ion}(v_{rel})\right] f_i(z,w)$$

$$\beta_N(z,v) = \int d^3w \; v_{rel}\sigma_{ce}(v_{rel}) f_N(z,w)$$

PARTIAL SCATTERING FUNCTIONS METHOD

PB+ 2012

WE INTRODUCE THE FUNCTIONS:

$$f_N^{(k)}(z, v_{\parallel}, v_{\perp})$$

THEY REPRESENT THE DISTRIBUTION FUNCTIONS OF NEUTRALS THAT SUFFERED 0, 1, 2, …., k CHARGE EXCHANGE REACTIONS AT GIVEN LOCATION. THEY SATISFY:

$$v_{\parallel} \frac{\partial f_N^{(0)}}{\partial z} = -\beta_i f_N^{(0)}$$

$$v_{\parallel} \frac{\partial f_N^{(k)}}{\partial z} = \beta_N^{(k-1)} f_i - \beta_i f_N^{(k)}$$

k=1,2,…

WE SOLVE THESE EQUATIONS ANALYTICALLY AND THE TOTAL SOLUTION CAN BE WRITTEN AS:

$$f_N(z, v_{\parallel}, v_{\perp}) = \sum_{k=0}^{\infty} f_N^{(k)}(z, v_{\parallel}, v_{\perp})$$

SHOCKS IN PARTIALLY IONIZED MEDIA WITH NO CR

PB, Morlino, Bandiera, Amato & Caprioli, 2012

IONS AND NEUTRALS ARE CROSS-REGULATED THROUGH MASS, MOMENTUM AND ENERGY CONSERVATION:

Flux conservation:

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

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

$$\frac{\partial}{\partial z}\left[\frac{1}{2}\rho_i u_i^3 + \frac{\gamma_g}{\gamma_g - 1} P_i u_i + F_{en}\right] = 0$$ **ENERGY FLUX**

$$F_{mass} = m_p \int d^3v\, v_z f_N$$

$$F_{mom} = m_p \int d^3v\, v_z^2 f_N$$

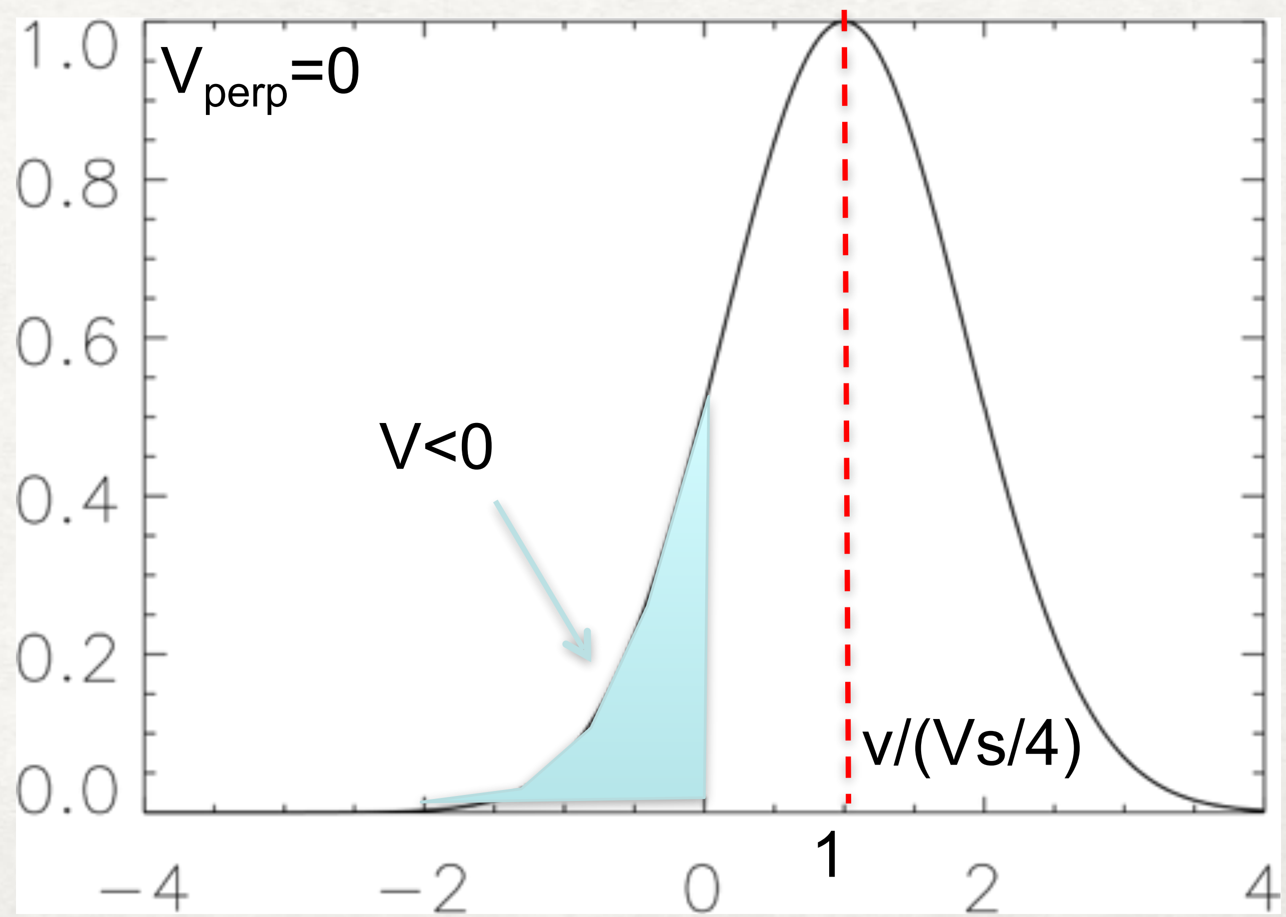
$$F_{en} = \frac{m_p}{2} \int d^3v\, v_z \left(v_z^2 + v_\perp^2\right) f_N$$

NEUTRAL RETURN FLUX

PB et al. 2012

NEUTRALS
AND IONS

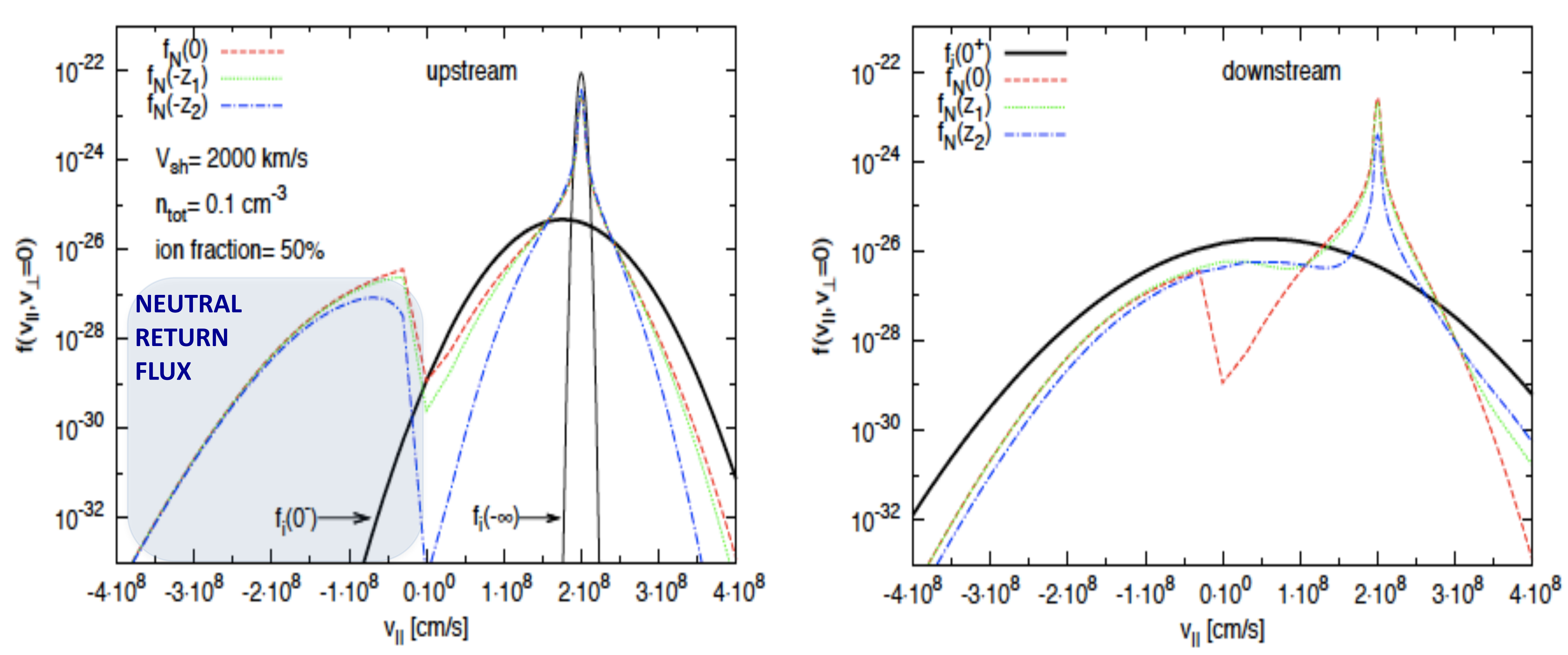
A NEUTRAL ATOM CAN CHARGE EXCHANGE WITH AN ION WITH V<0, THEREBY GIVING RISE TO A NEUTRAL WHICH IS NOW FREE TO <u>RETURN UPSTREAM</u>



THIS NEUTRAL RETURN FLUX LEADS TO ENERGY AND MOMENTUM DEPOSITION UPSTREAM OF THE SHOCK!

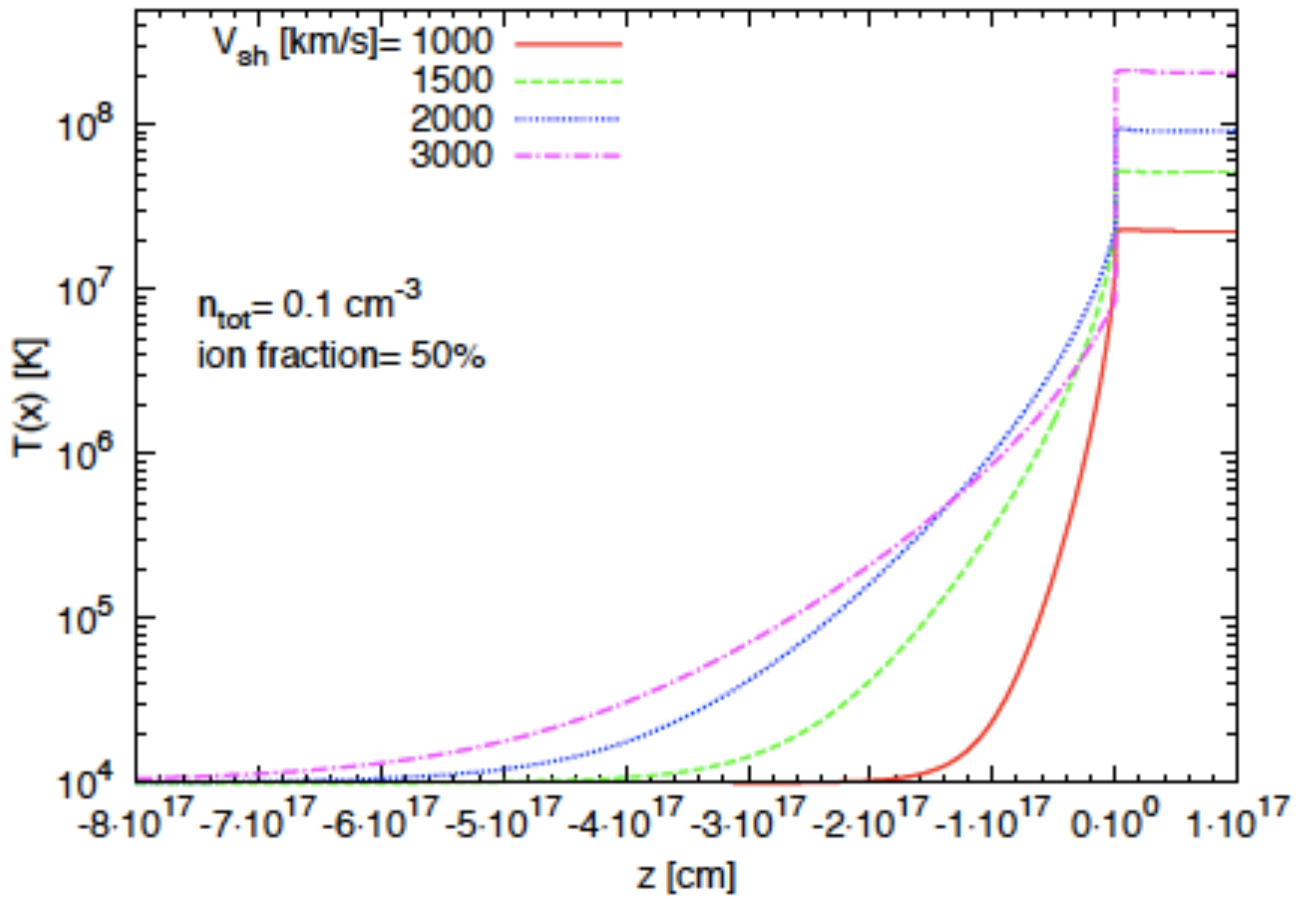
DISTRIBUTION FUNCTIONS IN PHASE SPACE

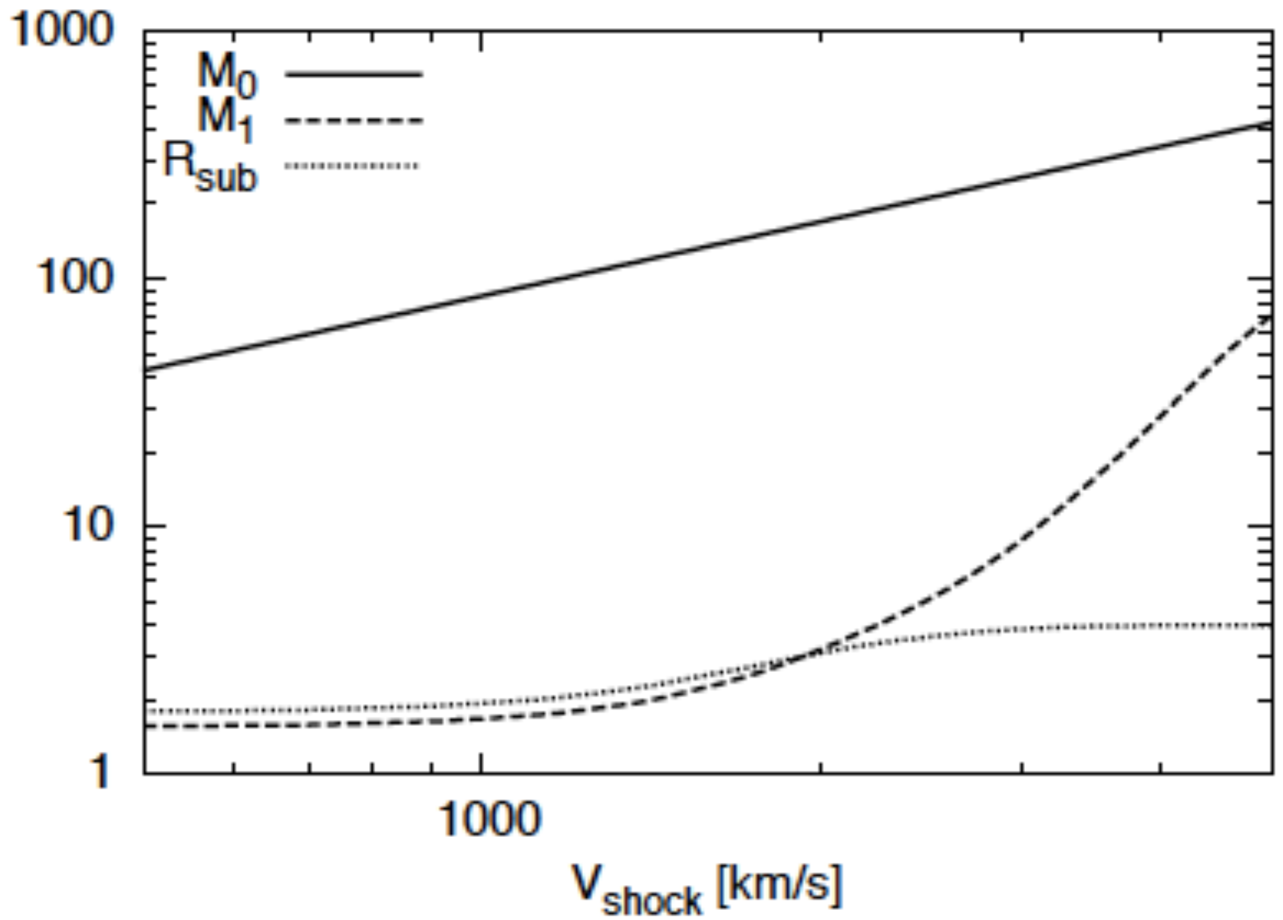
PB+ 2012



THE DISTRIBUTION FUNCTIONS OF NEUTRALS ARE NOT MAXWELLIAN IN SHAPE THOUGH THEY APPROACH A MAXWELLIAN AT DOWNSTREAM INFINITY

NEUTRAL INDUCED PRECURSOR



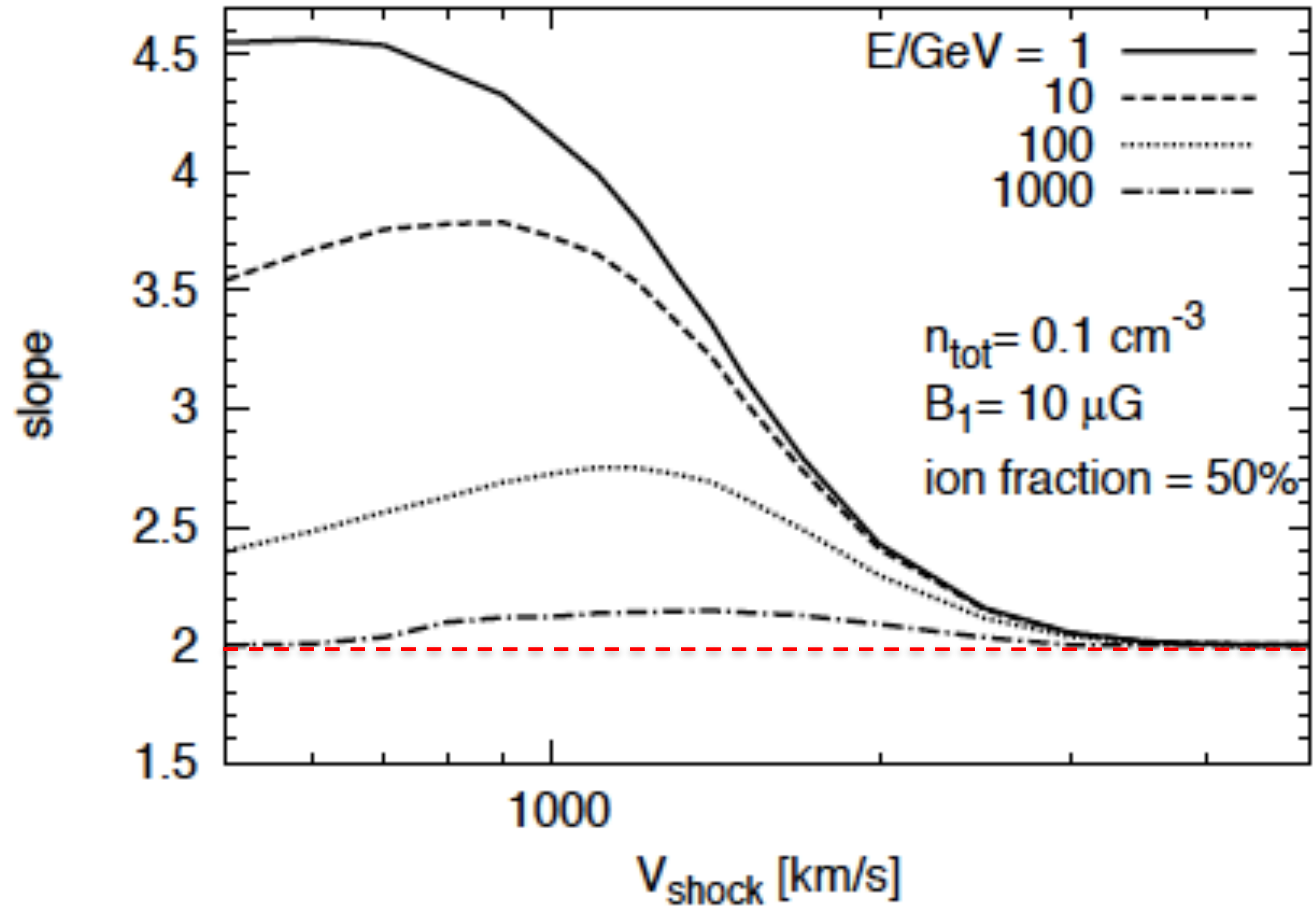


PB+ 2012

EVEN FOR A STRONG SHOCK (M>>1) THE EFFECTIVE MACH NUMBER OF THE PLASMA IS DRAMATICALLY REDUCED DUE TO THE ACTION OF THE NEUTRAL RETURN FLUX

ACCELERATION OF TEST PARTICLES

PB+ 2012



LIMITS ON ACCELERATORS OF UHECRS

IN THE NON RELATIVISTIC CASE ONE CAN WRITE A GENERIC EXPRESSION:

$$\frac{1}{3}\frac{E(eV)}{300 Z B}\frac{c}{u} = \xi R \quad \xi < 1$$

THIS IMPLIES THAT:

$$\epsilon_B = \frac{B^2}{4\pi} > 9.8 \times 10^{-8}\frac{E(eV)^2}{Z^2\beta^2\xi^2 R^2}$$

THE SOURCE ENERGETIC MUST BE AT LEAST AS LARGE AS THE MAGNETIC ONE:

$$L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.8 \times 10^{46} erg/s \left(\frac{E}{Z 10^{20} eV}\right)^2 \left(\frac{\xi}{0.1}\right)^{-2} \beta^{-1}$$

PROBABLY THE ONLY NON RELATIVISTIC SOURCES THAT MAY SATISFY THIS BOUND ARE LARGE SCALE STRUCTURE FORMATION SHOCKS AND ONLY MARGINALLY, ALTHOUGH NOTICE THE ROLE OF Z

CAVEAT ON DEFINITIONS

THE SO-CALLED HILLAS CRITERION FOR THE MAXIMUM ENERGY IS SOMEWHAT DIFFERENT:

$$\frac{E(eV)}{300B} < R \qquad \xi < 1$$

WITH THIS DEFINITION THE CONDITION ON LUMINOSITY BECOMES LESS SEVERE:

$$L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.6 \times 10^{45} erg/s \left(\frac{E}{Z 10^{20} eV}\right)^2 \beta$$

BUT LESS CLOSE TO WHAT IS FOUND IN ACTUAL CALCULATIONS. THE ‘TRUE’ CASE IS SOMEWHERE IN BETWEEN…

CLEARLY THIS DISTINCTION IS IMMATERIAL IN THE CASE OF RELATIVISTIC ACCELERATORS

THIS RESULT CAN BE GENERALIZED TO THE CASE OF RELATIVISTIC SOURCES WITH LORENTZ FACTOR G (Waxman 2005)

B' → MAGNETIC FIELD IN THE COMOVING FRAME

E'=E/Γ → PARTICLE ENERGY IN THE COMOVING FRAME

THE CONDITION FOR MAXIMUM ENERGY IS:

$$\frac{2\pi}{c}\frac{E'}{ZeB'} = \frac{2\pi}{c}\frac{E}{ZeB'\Gamma} < T_{dyn} \approx \frac{r}{c\Gamma}$$

WHICH IMPLIES:

$$B' > \frac{E}{ZeB'r} \rightarrow \epsilon'_B = \frac{B'^2}{4\pi} > \left(\frac{E}{ZeB'r}\right)^2 /4\pi$$

AND FINALLY THE SOURCE ENERGY INPUT MUST SATISFY:

$$L > 4\pi r^2 c\Gamma^2 \epsilon'_B = c\Gamma^2 (2\pi E/Ze)^2 \approx 10^{47}\Gamma^2 \left(\frac{E}{Z\ 10^{20} eV}\right)^2 erg/s$$

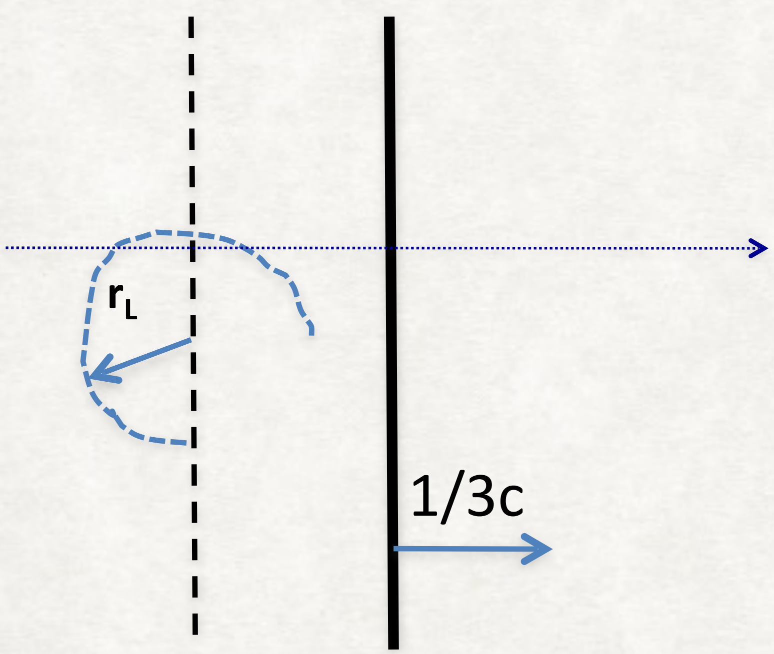
THIS IS HUGE AND ONLY THE UPPER END OF THE AGN AND GRB APPEAR TO SATISFY THIS BOUND, ALTHOUGH NOTICE THE ROLE OF Z

ACCELERATION AT RELATIVISTIC SHOCKS

Contrary to the case of non relativistic shocks, no universal spectrum of accelerated particles exist

In the small pitch angle scattering (SPAS) assumption, one obtains $E^{-2.23}$ at high energy, but this result neglects many complications

IF THE MAGNETIC FIELD UPSTREAM IS ORIENTED AT AN ANGLE >1/G, THEN THE SHOCK IS PERPENDICULAR:



COMOVING FRAME

IN THE FRAME OF THE DOWNSTREAM PLASMA THE SHOCK MOVES AT c/3

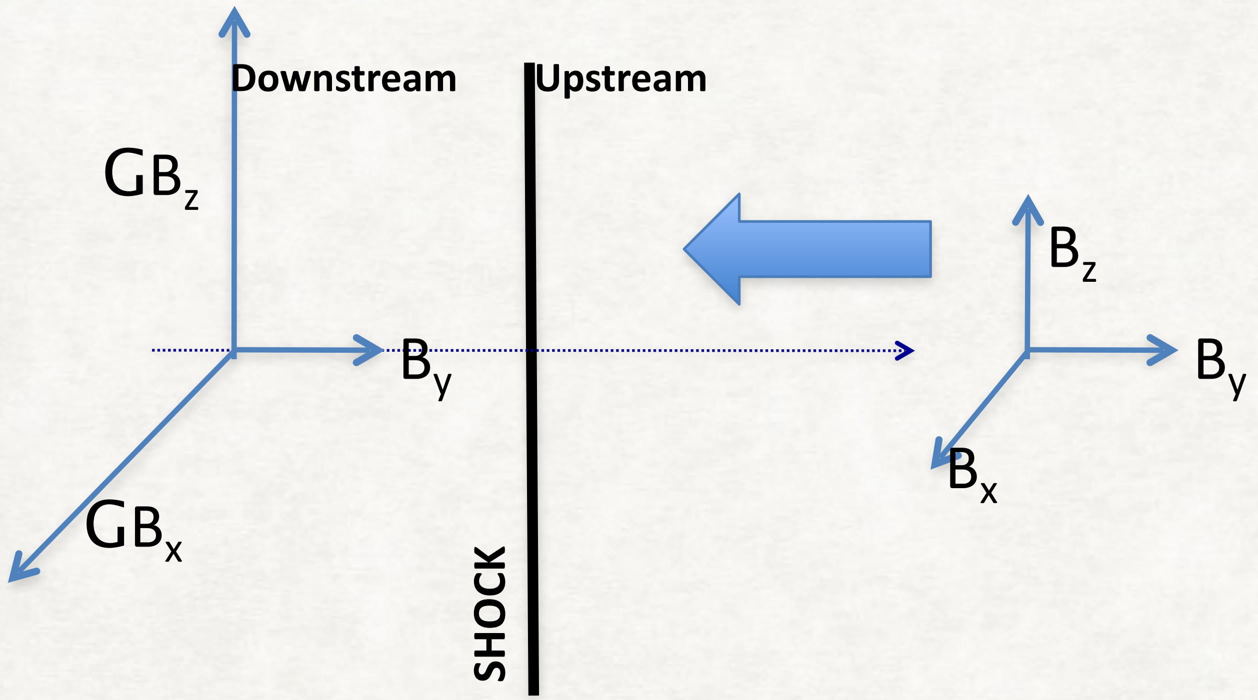
IN A LARMOR TIME THE SHOCK MOVES:

$$\frac{1}{3}c\frac{2\pi r_L}{c} = \frac{2\pi}{3}r_L > r_L$$

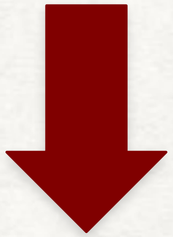
PARTICLES ARE TRAPPED DOWNSTREAM !

DOWNSTREAM SCATTERING MAY IMPROVE THIS SITUATION and INCREASE THE RETURN PROBABILITY

ACCELERATION AT RELATIVISTIC SHOCKS



EVEN IF THE TURBULENT FIELD UPSTREAM WERE ISOTROPIC, THE SHOCK COMPRESSION WOULD MAKE THE SHOCK QUASI-PERP



ACCELERATION IS INHIBITED AND THE SPECTRA OF ACCELERATED PARTICLES ARE TYPICALLY VERY STEEP **(Lemoine and Ravenue 2006)**

DESPITE THE SIMPLE PREDICTIONS OF SPAS CALCULATIONS, THE COMPRESSION OF THE B-FIELD LEADS TO TYPICAL SPECTRA $E^{-2.7}$ RATHER THAN $E^{-2.23}$

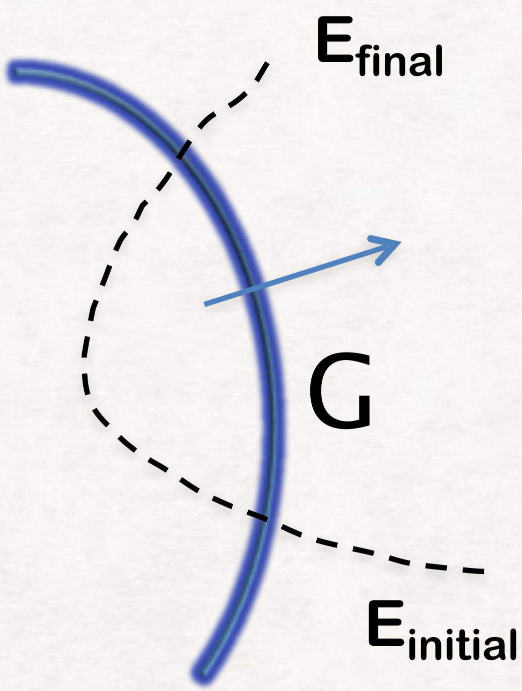
ACCELERATION AT RELATIVISTIC SHOCKS

THE CONCEPT OF SMALL OR LARGE ANGLE SCATTERING IS RELATIVE TO THE CRITICAL PARTICLE DEFLECTION 1/G

THE REGIME OF SPAS CAN BE BROKEN AND THIS LEADS TO SPECTRA THAT ARE IN GENERAL FLATTER (HARDER) THAN IN THE SPAS LIMIT

MAGNETIC FIELD PRESSURE AND EQUATION OF STATE OF THE PLASMA BEHIND THE SHOCK (FOR INSTANCE DUE TO DIFFERENT LEVELS OF THERMALIZATION OF PROTONS AND ELECTRONS) ALSO LEAD TO CHANGES IN THE SPECTRAL SLOPE

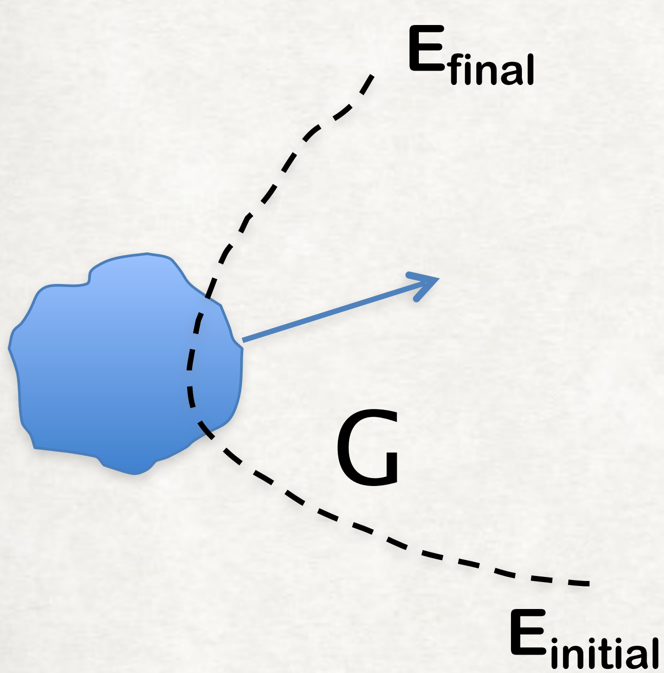
ACCELERATION AT RELATIVISTIC SHOCKS

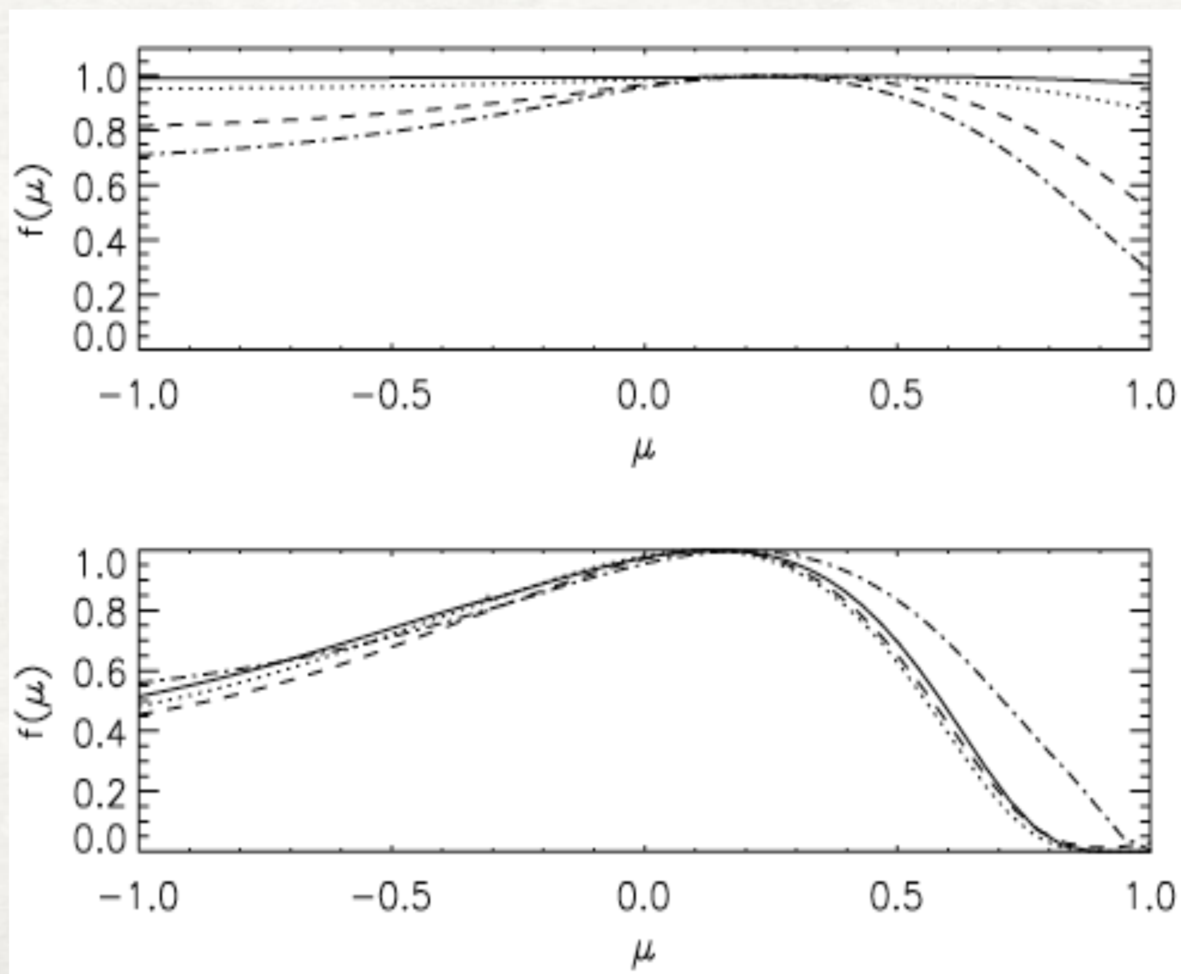


At the first particle-shock encounter, the particle distribution is isotropic in the lab frame and the particle reflection (if it happens) leads to an increase in particle energy $E_{final} = 4\Gamma^2 E_{initial}$

BUT AFTER THE FIRST ENCOUNTER THE PARTICLE DISTRIBUTION IN THE LAB FRAME IS CONCENTRATED WITHIN A CONE OF APERTURE $1/\Gamma \rightarrow \Delta E/E\sim 2$

THE SPETCRUM OF ACCELERATED PARTICLES HAS A LOW ENERGY CUTOFF AT $\Gamma^2 E_0$ WHERE E_0 = INJECTION





PARTICLE DISTRIBUTION FUNCTIONS IN THE SHOCK FRAME FOR DIFFERENT SHOCK SPEEDS (PB & Vietri 2005)

WHERE ARE THESE RELATIVISTIC SHOCKS?

CERTAINLY GRBs AND AGN ARE THE BEST SUSPECTS…

BUT THE LIMITS DERIVED ABOVE ON LUMINOSITY LEAD TO CONCLUDE THAT ONLY THE AGN IN THE UPPER PART OF THE LUMINOSITY FUNCTION COULD WORK (UNLESS Z>>1, IN WHICH CASE THE REQUIRED L BECOMES MUCH SMALLER!)

IN AGN THE FASTEST SHOCKS HAVE Γ~10-30

IN GRB THE NECESSARY CONDITIONS APPEAR TO BE FULFILLED…
AND Γ~200.

THE ISSUES THAT RISE ARE ABOUT ACCELERATION

B-FIELD

→ **LARGE SCALE OR WITH LARGE COHERENCE SCALE**
The shock is quasi-perp, steep spectra, inefficient acceleration

→ **SMALL SCALE (SKIN DEPTH)**
Canonical spectra, but slow return → low E_{max}

A FEW THINGS THAT YOU MISTAKINGLY THINK YOU UNDERSTOOD

--- NAMELY: WHAT IS LEFT TO DO ...---

☑ **We know how to calculate the spectrum of accelerated particles**

- *it may be affected by wave helicity if V_W is high*
- *it is affected by non-linear effects that have not yet been taken into account*
- *it is affected by the geometry of the large scale field, if any*

☑ **We know how to calculate the spectrum of particles escaping a source**

- *the flux of escaping CRs is one of the least known quantities in CR physics*
- *where is the escape boundary, or is there one?*
- *how is escape regulated by self-generation?*
- *how is the escapee flux linked to the time dependence of the shock evolution?*

☑ **We know the power spectrum of waves in the acceleration region**

- *we usually assume Bohm diffusion with some justification based upon the spectrum E^{-2}*
- *not clear what is the interaction between modes on the long term (PIC only follow beginning)*
- *damping of the modes?*

☑ **We know the contribution of SNR to the CR spectrum**

- *acceleration depends on environment*
- *different SNe explode in different environs and with different parameters*
- *what if different SNe have different E_{max}?*