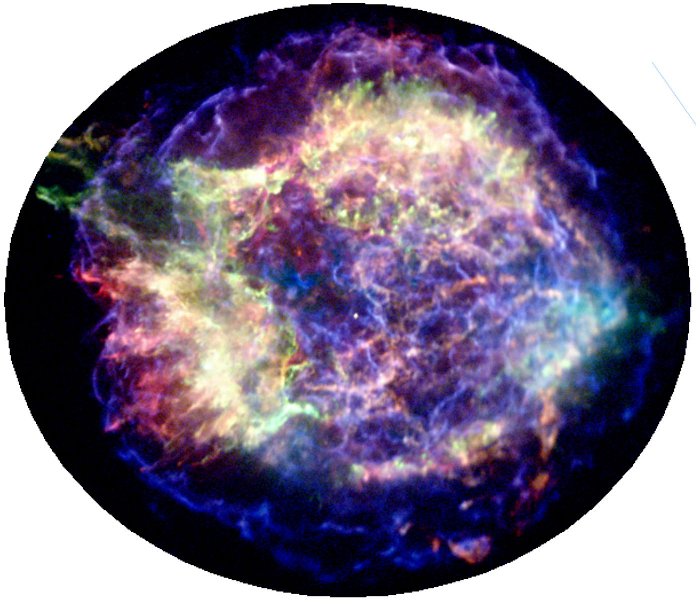
ON THE MECHANISMS OF PARTICLE ACCELERATION IN ASTROPHYSICAL SOURCES

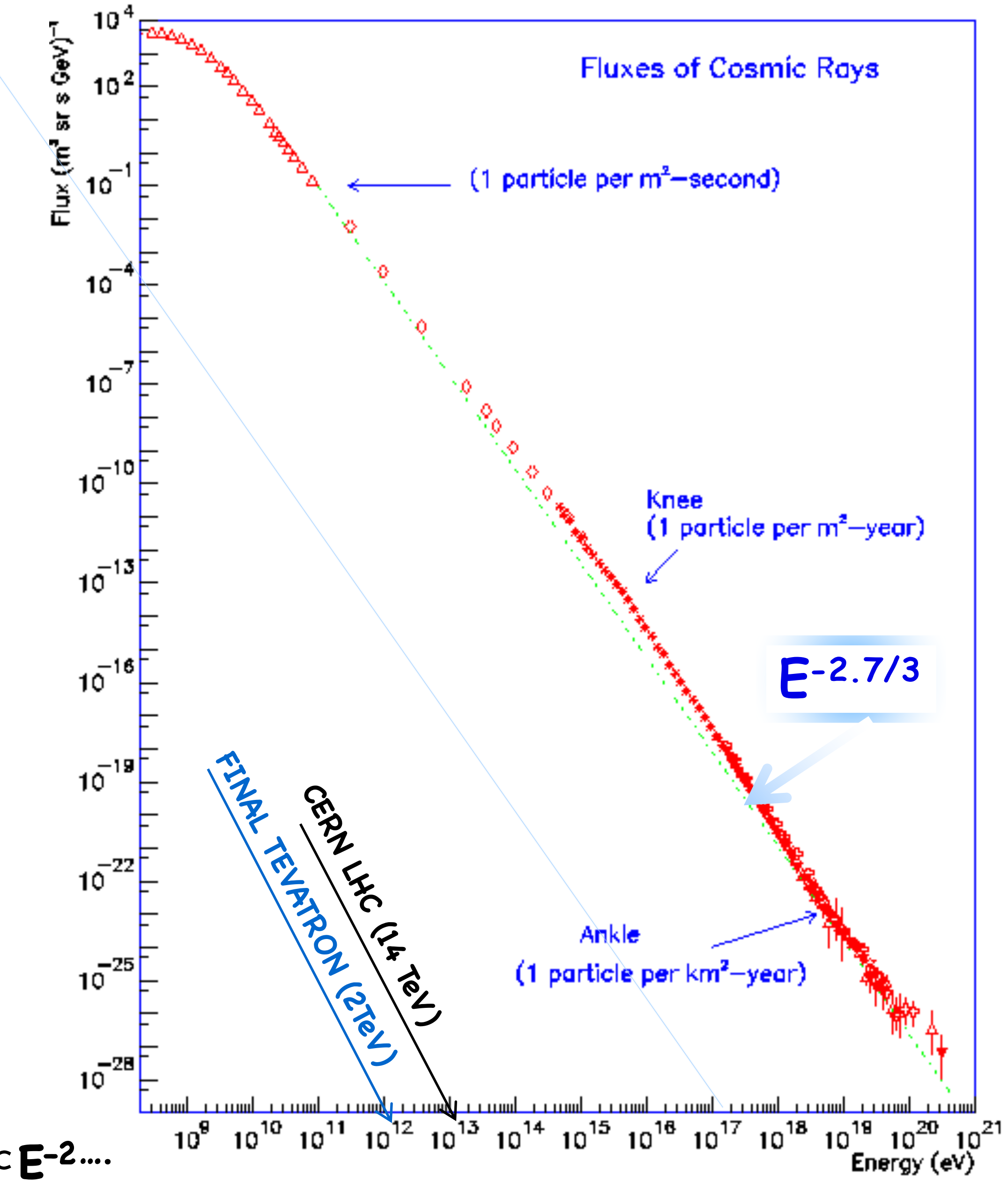
Elena Amato

INAF-Osservatorio
Astrofisico di Arcetri

WHAT WE NEED TO EXPLAIN



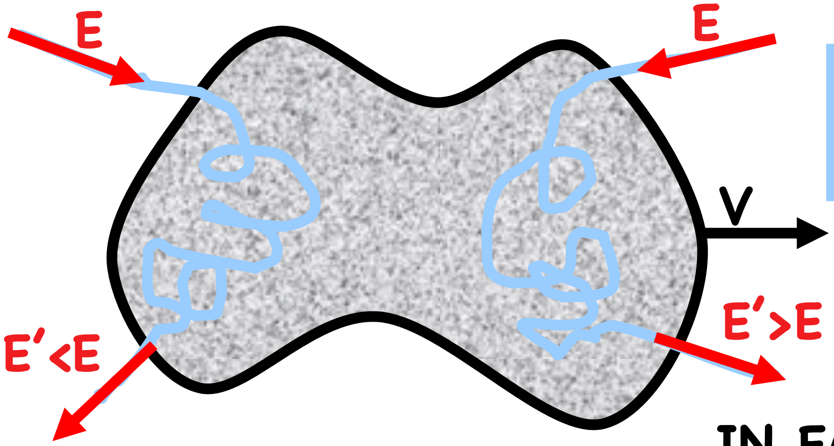
Combined IR, optical and X-ray data



MOST OF THE TIMES: $N(E) \propto E^{-2}$....

DIFFUSIVE SHOCK ACCELERATION

(2ND ORDER TEST PARTICLES)



PARTICLE GAINS ENERGY SOMETIMES
LOSES ENERGY SOME OTHERS

ELASTIC SCATTERING

IN EACH COLLISION: $\Delta E \approx \frac{V}{v} E$

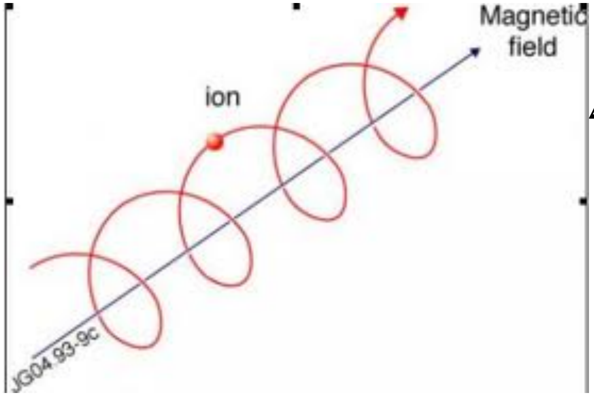
AVERAGE ENERGY GAIN $G = \frac{\Delta E}{E} \approx \left(\frac{V}{c}\right)^2$

INITIALLY THOUGHT IN CONNECTION WITH CLOUDS BUT LATER UNDERSTOOD TO WORK WITH MAGNETIC PERTURBATIONS:

- $V \approx V_A$
- SLOW PROCESS UNLESS RELATIVISTIC TURBULENCE
- NO HOPE OF REACHING HIGH ENERGY

INTERACTION OF A COSMIC RAY WITH AN ALFVÉN WAVE

$$\begin{cases} \vec{B}_0 &= B_0 \hat{z} \\ \delta\vec{B} &= \delta B \sin(kz-\omega t)\hat{x} \end{cases}$$



$$\Delta p_z = e\int_0^\tau dt \left(\frac{\vec{v}\wedge\vec{B}}{c}\right)_z$$

$$\tau = \frac{2\pi}{kv_z-\omega}$$

INTERACTION MOST EFFECTIVE AT RESONANCE: ✦r_L

$$\frac{1}{\tau_s} = D_\alpha = \lim_{t\to\infty}\left\langle\frac{\Delta\theta\Delta\theta}{t}\right\rangle = 2\pi^2\Omega_L\left(\frac{\delta B}{B_0}\right)^2 = 2\pi^2\frac{v}{r_L}\frac{k_{\rm res}W(k_{\rm res})}{B_0^2}$$

$$D_{zz} = \frac{1}{3}v\lambda = \frac{1}{3}v^2\tau_s$$

$$D_{pp} = \frac{1}{3}\frac{<\Delta p\Delta p>}{\tau_s} = \frac{1}{3}\frac{V_A^2}{v^2}\frac{p^2}{\tau_s}$$

$$\boxed{D_{pp} \approx \frac{1}{9}\frac{V_A^2 p^2}{D_{zz}}}$$

DIFFUSION IN MOMENTUM SPACE
INEVITABLY ASSOCIATED WITH SPATIAL DIUFFUSION

FERMI II AND CR REACCELERATION

THE CR TRANSPORT EQUATION (NO LOSSES)

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial z} = Q + \frac{\partial}{\partial z}\left(D_{zz}\frac{\partial f}{\partial z}\right) + \frac{1}{3}\left(\frac{du}{dz}\right)p\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

WHEN SOLVED THROUGH CODES LIKE GALPROP (Trotta et al 06) **OR DRAGON** (Di Bernardo et al 10) **RE-ACCELERATION FOUND TO BE VERY RELEVANT**

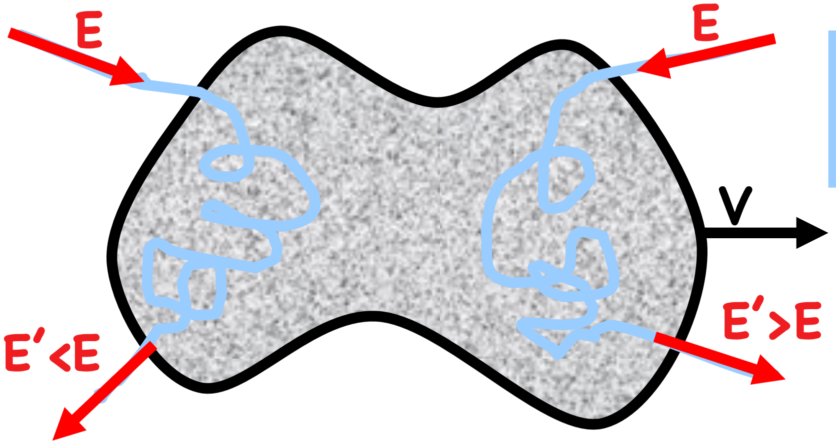
ABOUT 50% OF THE TOTAL CR POWER FROM THIS PROCESS
(Drury & Strong 17)

CRs WOULD RESULT IN A MAJOR SOURCE OF DAMPING OF INTERSTELLAR TURBULENCE

HOWEVER, CAN THIS PLAY ANY ROLE IN CLOUDS?

DIFFUSIVE SHOCK ACCELERATION

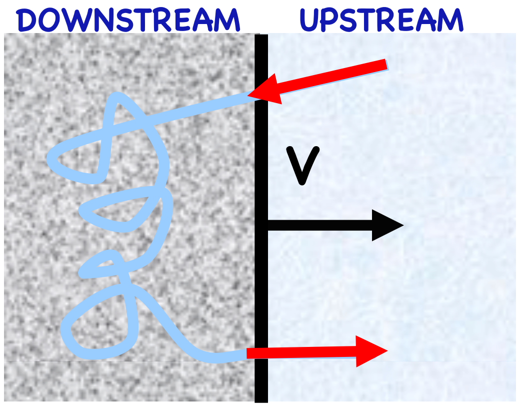
(1ST ORDER TEST PARTICLES)



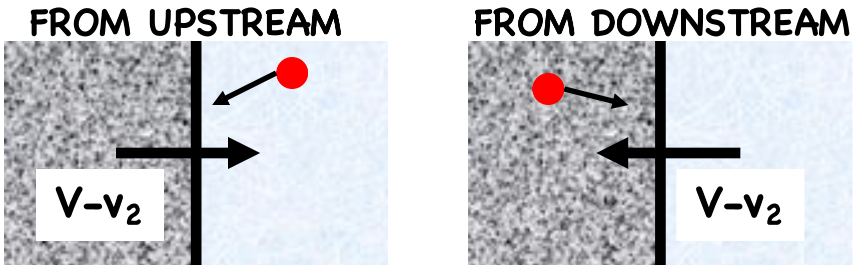
PARTICLE GAINS ENERGY SOMETIMES
LOSES ENERGY SOME OTHERS

AVERAGE ENERGY GAIN $G = \frac{\Delta E}{E} \approx \left(\frac{V}{c}\right)^2$

AT A SHOCK



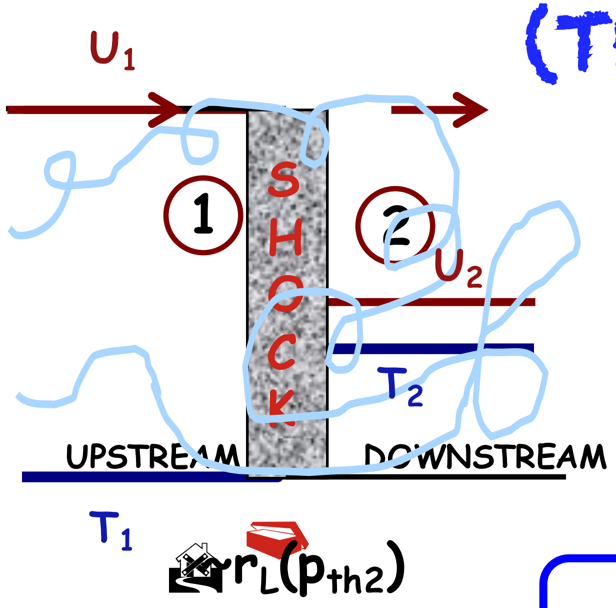
- PARTICLE GAINS ENERGY EACH TIME IT CROSSES THE SHOCK
- FUNDAMENTAL ASSUMPTION: ISOTROPIZATION ON BOTH SIDES OF THE SHOCK



ENERGY GAIN PER CYCLE $G = \frac{\Delta E}{E} \approx \frac{V}{c}$

DIFFUSIVE SHOCK ACCELERATION

(TEST PARTICLES)



ENERGY GAIN PER CROSSING $\frac{\Delta E}{E} = \frac{4(u_1 - u_2)}{3v}$

ESCAPE PROBABILITY $P_{\rm esc} = 4u_2/v$

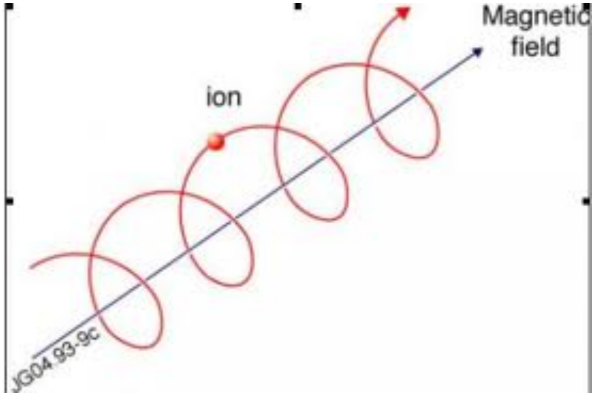
POWER LAW SPECTRA $\gamma_e = 1 + \frac{P_{\rm esc}}{\Delta E/E} = \frac{2+R}{R-1}$

ONLY DEPENDENT ON COMPRESSION RATIO!

INDEPENDENT OF SCATTERING PROPERTIES!!!

FOR STRONG SHOCKS: $u_1/u_2=4$ 🌬 ■=4 🌧 ■=2

PARTICLE ISOTROPIZATION



COLLISIONLESS PLASMA…
WAVE-PARTICLE INTERACTIONS!!!

PITCH ANGLE DIFFUSION: $D_\alpha = \frac{\pi}{8}\Omega_L \left(\frac{\delta B}{B_0}\right)^2$

->SPATIAL DIFFUSION $D(p) = \frac{4}{3\pi}\left(\frac{B_0}{\delta B}\right)^2 c r_L$

$$t_{\mathrm{acc}1} = \frac{E}{dE/dt} = \frac{t_{\mathrm{diff}}}{\Delta E/E} = \frac{3v}{4(u_1 - u_2)}\frac{4D_1}{u_1 v}$$

ACCELERATION TIME DEPENDS ON TURBULENCE LEVEL

$$t_{acc} = \frac{3}{u_1 - u_2}\left\{\frac{D_1}{u_1} + \frac{D_2}{u_2}\right\}$$

MAXIMUM ACHIEVABLE ENERGY DEPENDS ON TURBULENCE LEVEL

$$t_{acc}(E_{\mathrm{MAX}}) = \min\left(t_{age}, t_{loss}\right)$$

✓IF δB SAME RESPONSIBLE FOR CR CONFINEMENT IN THE GALAXY: E_{max}~GeV

✓IF δB ~B_0, E_{max}~10^3-10^4 GeV (Lagage & Cesarsky 83)

- **AMPLIFIED B IS REQUIRED TO REACH THE KNEE**

PARTICLE DIFFUSION AND WAVE GROWTH

IF CR ARE ISOTROPIZED BY THE WAVES...

BEFORE SCATTERING: $P_{CR}=n_{CR}m$[redacted]v_d

AFTER SCATTERING: $P_{CR}=n_{CR}m$[redacted]v_A

→

$$\frac{dP_{CR}}{dt} = \frac{n^*_{CR} m\gamma_{CR}(v_d - v_A)}{\tau}$$

FOR RESONANT ALFVÉN WAVES

$$\tau^{-1} = D_\alpha = \frac{\pi}{8}\Omega\left(\frac{\delta B}{B_0}\right)^2$$

$$\frac{dP_{CR}}{dt} = \frac{dP_w}{dt} = \frac{1}{v_A}\frac{dE_w}{dt} = \frac{1}{v_A}2\gamma_w\frac{\delta B^2}{8\pi}$$

MOMENTUM HAS GONE TO THE WAVES

$$\gamma_w = \frac{\pi}{4}\frac{n^*_{CR}}{n_i}\Omega_0\frac{(v_d - v_A)}{v_A}$$

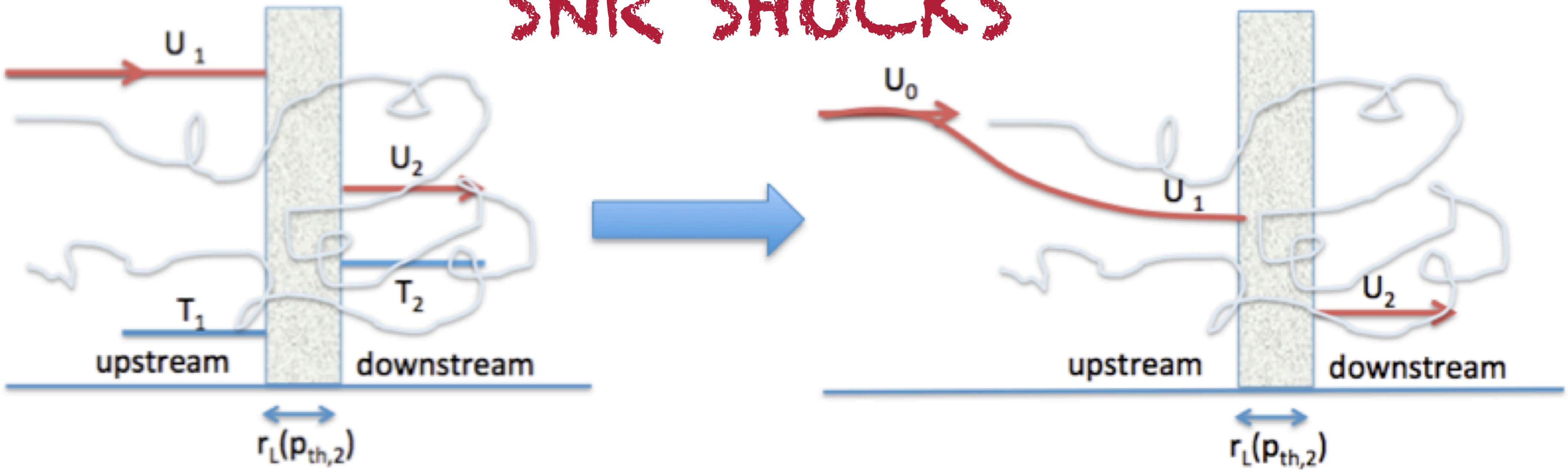
with

$$n^*_{CR} = n_{CR}\left(p > \frac{eB}{ck}\right)$$

SUPERALFVÉNIC STREAMING OF CRs → WAVE GROWTH

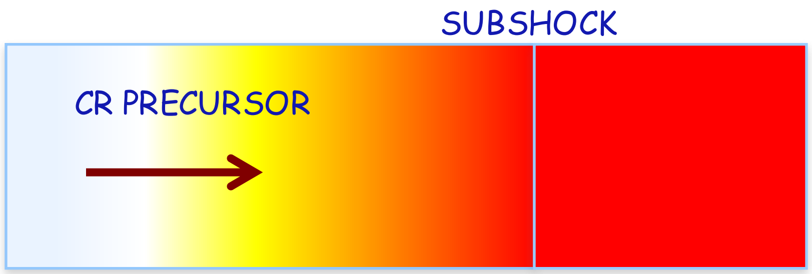
+ EFFICIENT ACCELERATION → SHOCK MODIFICATION!!!!

EFFICIENT ACCELERATION AT SNR SHOCKS



- ✧ CR STREAMING INDUCES PRESSURE GRADIENT UPSTREAM
- ✧ A PRECURSOR IS FORMED: FLUID PROGRESSIVELY SLOWS DOWN
- ✧ CR ESCAPE MAKES SHOCK RADIATIVE

$R_{TOT}>4$ WHILE $R_{SUB}<4$



DENSITY OF ACCELERATED PARTICLES

DIFFERENT ENERGY PARTICLES HAVE DIFFERENT DIFFUSION LENGTHS

➔EXPERIENCE DIFFERENT R (<4 AT LOW EN, >4 AT HIGH EN)

➔SPECTRUM BECOMES CONCAVE (STEEP AT LOW EN. FLAT AT HIGH)

BASIC PREDICTIONS OF NL-DSA

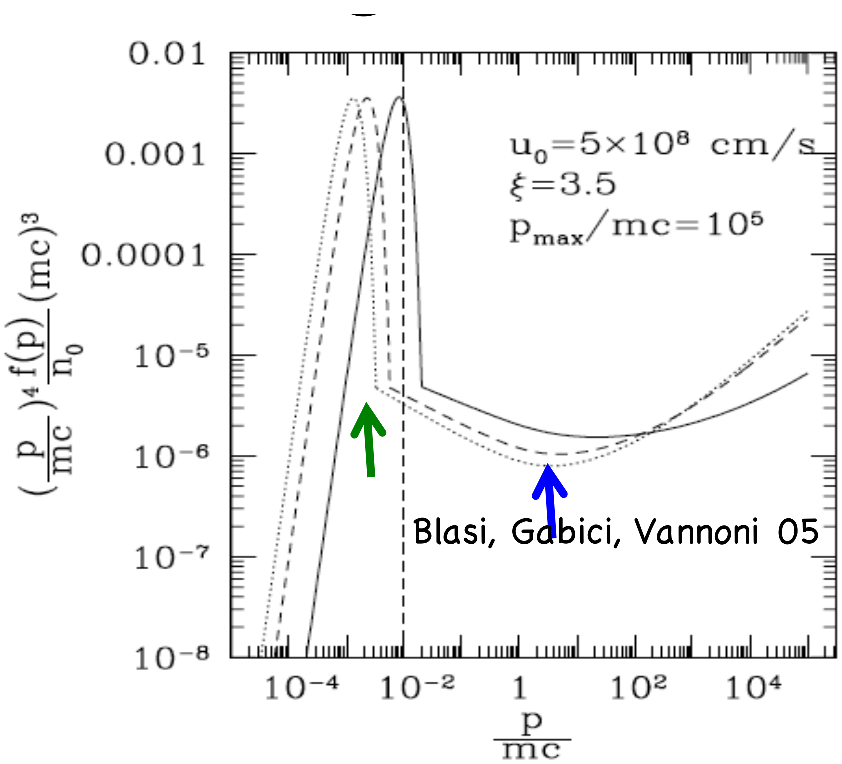
- **BACK-REACTION OF CRs**
- **MAGNETIC FIELD AMPLIFICATION**
- **BACK-REACTION OF AMPLIFIED FIELD**

TWO-FLUIDS: Drury & co.

MONTECARLO: Ellison & co.

FINITE DIFFERENCE: Berezhko, Volk & co.

KINETIC: Amato & Blasi 05,06; Blasi+ 08
Caprioli+ 08,09,10,11



Blasi, Gabici, Vannoni 05

HINTS OF EFFICIENT ACCELERATION:

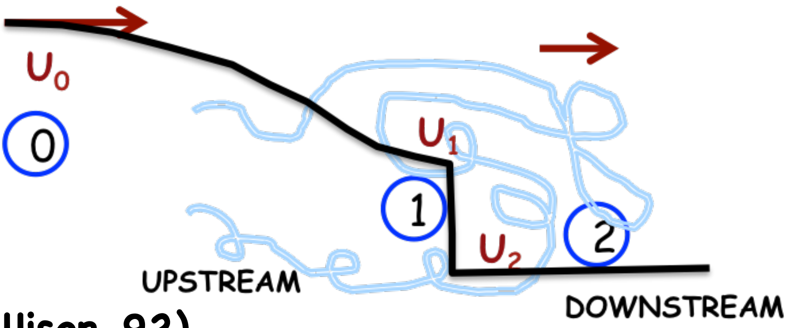
- **COMPRESSION RATIO > 4:**

CD VS SHOCK IN TYCHO (Warren+ 05) AND SN1006 (Cassam-Chenaii+ 08) AND EMISSION PROFILES (Morlino+ 10)

- **T_2 IS LOWER THAN EXPECTED: IN RCW86**

T_2~1/10 T_{RH} (Helder+ 09, Morlino+ 13)

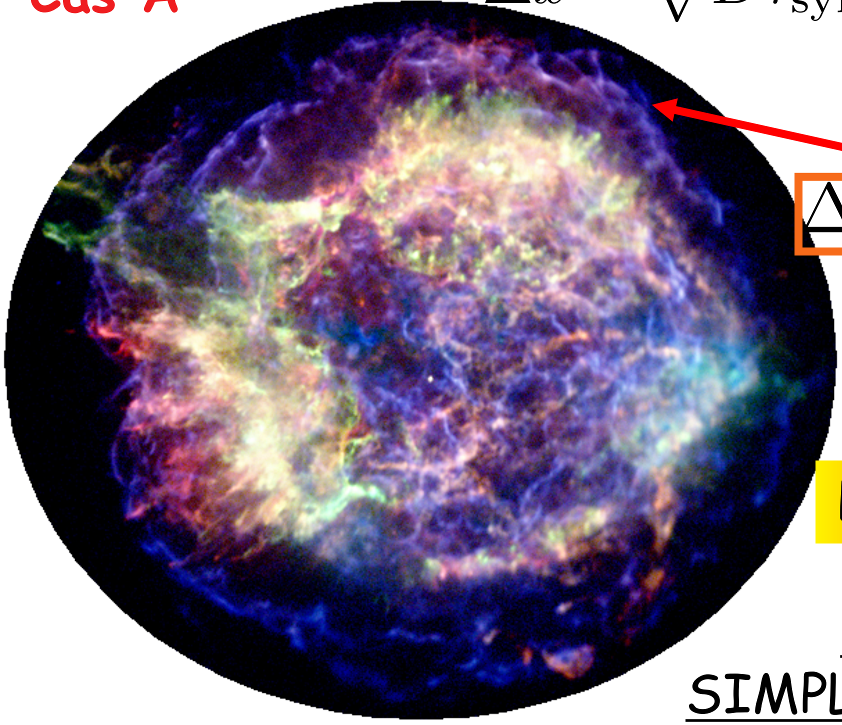
- **CONCAVE SPECTRA: RADIO SNRs (Reynolds & Ellison 92) AND SED FITTING OF SN1006 AND RCW86 (Vink 12)**
- **B-FIELD LARGELY AMPLIFIED**



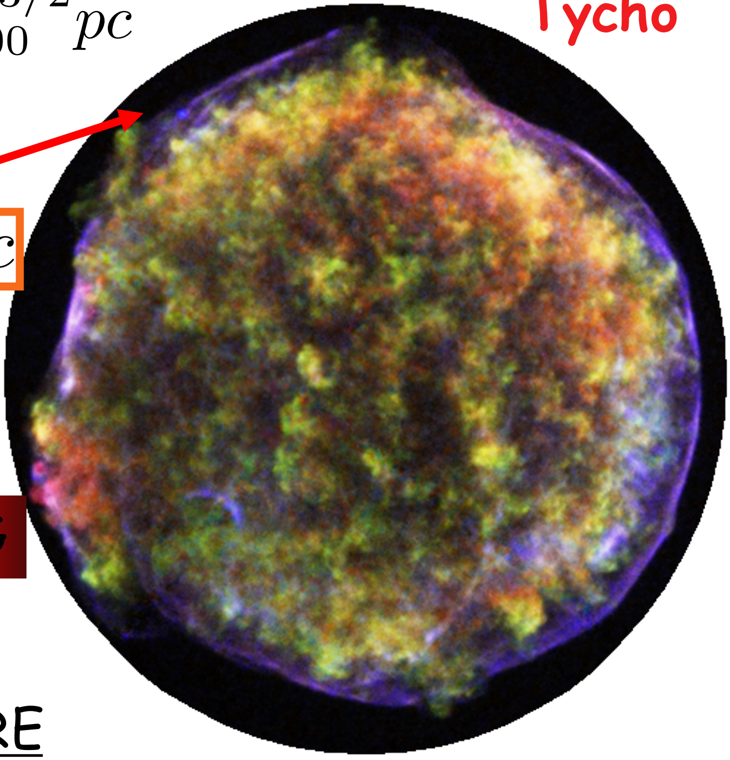
AMPLIFIED MAGNETIC FIELDS

$$\Delta x = \sqrt{D\tau_{\rm sync}} = 0.04 B_{100}^{-3/2} pc$$

Cas A



Tycho



$\boxed{\Delta x \approx 0.01 pc}$

B~100-300μG

IN THE
SIMPLEST PICTURE

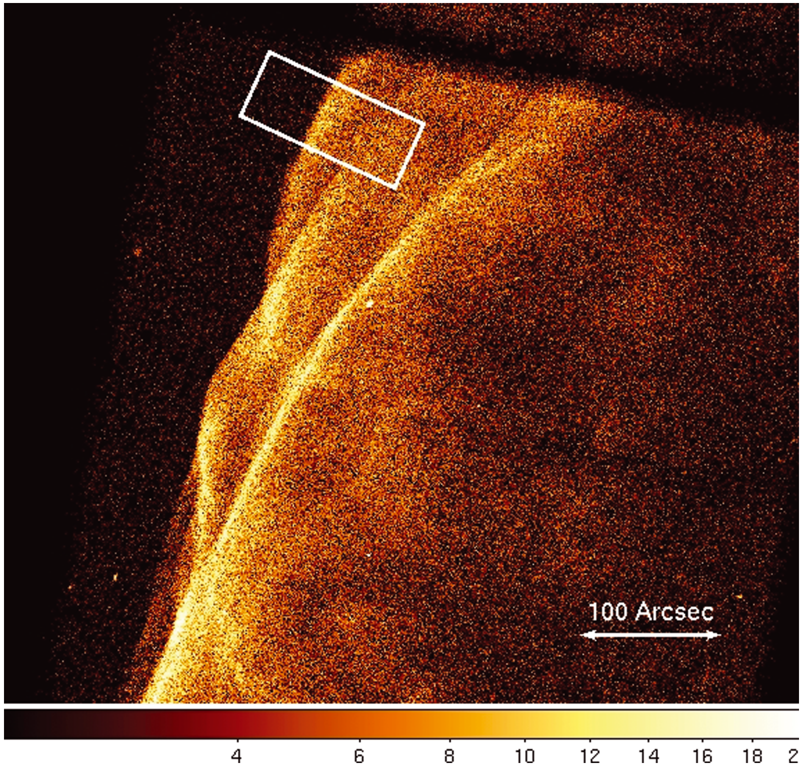
EFFICIENT PARTICLE ACCELERATION BECAUSE OF HIGH B-FIELD

HIGH B-FIELD BECAUSE OF EFFICIENT PARTICLE ACCELERATION

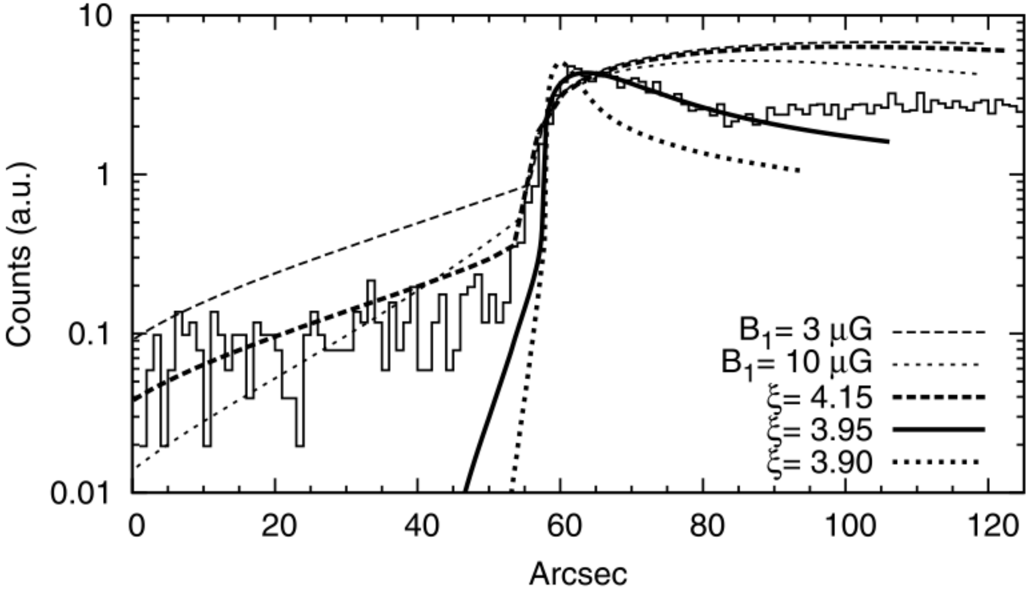
CAVEAT:

LARGE MAGNETIC FIELDS MIGHT HAVE DIFFERENT ORIGIN AND DO NOT IMPLY EFFICIENT SCATTERING...

AMPLIFICATION NEEDED IN THE UPSTREAM



REPRODUCING THE X-RAY SPATIAL EMISSION PROFILE IN SN1006



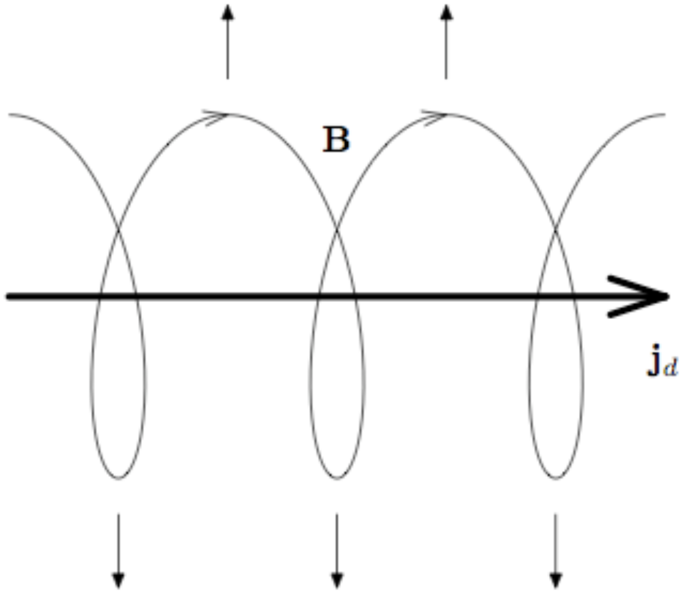
Morlino+ 10

CR AMPLIFIED FIELDS

"STANDARD" GROWTH RATE ONLY APPLIES WHEN $\boxed{J_{\rm CR} < c\frac{B_0}{r_{L0}}} \Longleftrightarrow \boxed{U_{\rm CR} < \frac{c}{v_S} U_B}$

OTHERWISE GROWTH OF RESONANT MODES IS SUPPRESSED
NON RESONANT MODES (Bell 04, Amato & Blasi 09) **BECOME DOMINANT**

- CR CURRENT INDUCES COMPENSATING CURRENT IN PLASMA
- $\vec{J}_{ret} \times \vec{B}$ INDUCES TRANSVERSE PLASMA MOTION
- RESULTING CURRENT ACTS AS A SOURCE OF B
- FOR RIGHT-HAND POLARIZED WAVES, FIELD LINES ARE STRETCHED: FIELD IS AMPLIFIED



VERY LARGE FIELD ON VERY SMALL SCALES

EFFICIENT FOR SCATTERING?

STRONGLY CURRENT DRIVEN REGIME

NON-RESONANT MODE ONLY EXISTS WHEN

$$\boxed{\frac{4\pi}{c} J_{CR} > \left|\frac{B_0}{r_{L,0}}\right|}$$

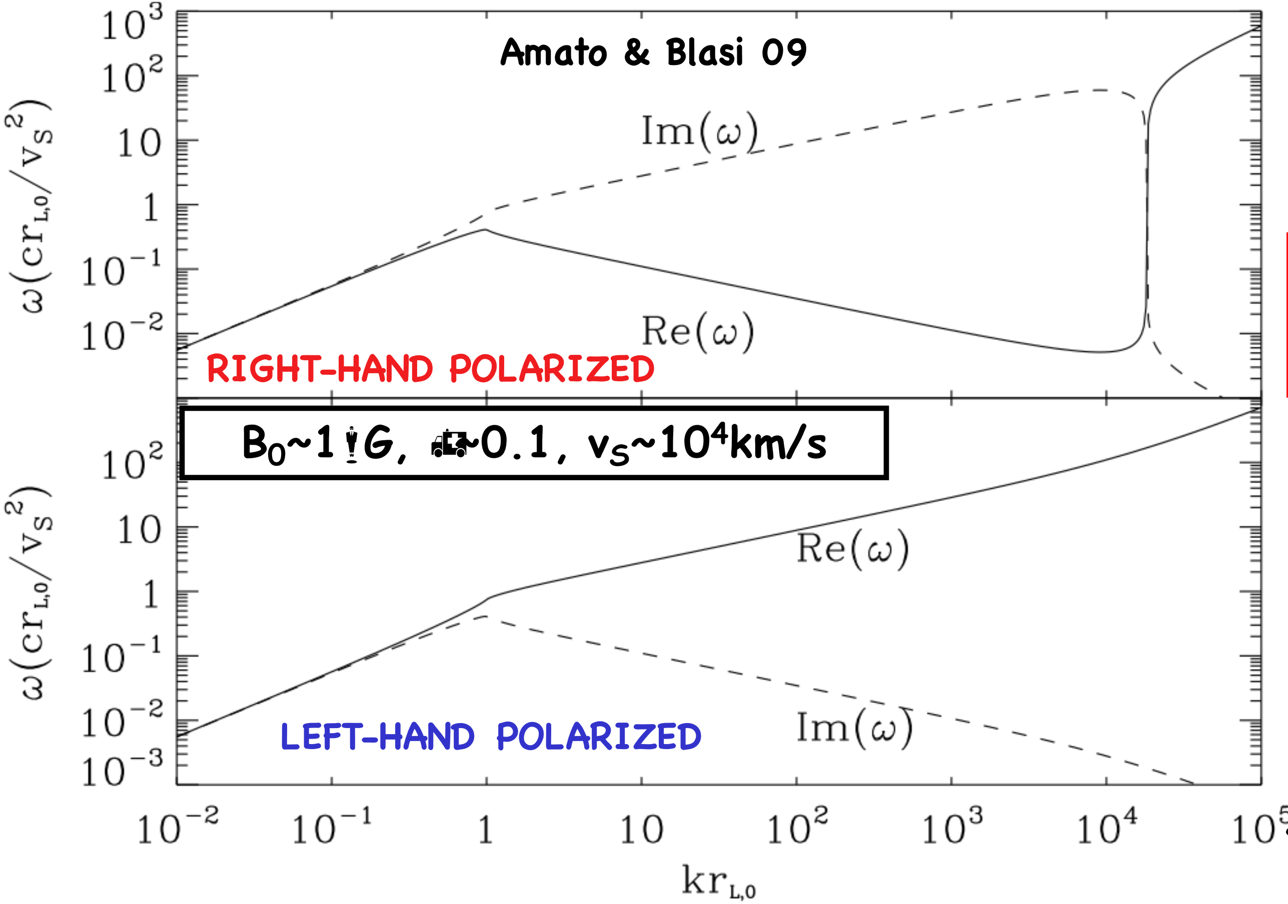
OR

$$\boxed{U_{CR}/U_B > c/v_S}$$

$$k_{max} = \frac{4\pi J_{CR}}{2cB_0} >> \frac{1}{r_{L,0}}$$

EQUILIBRIUM BETWEEN CURRENT AND MAGNETIC TENSION: LARGE BY DEFINITION

$$\Gamma_{max} \approx v_A k_{max} >> \frac{v_A}{r_{L,0}} >> \omega$$



B_0~1🕴G, 🚑~0.1, v_S~10^4km/s

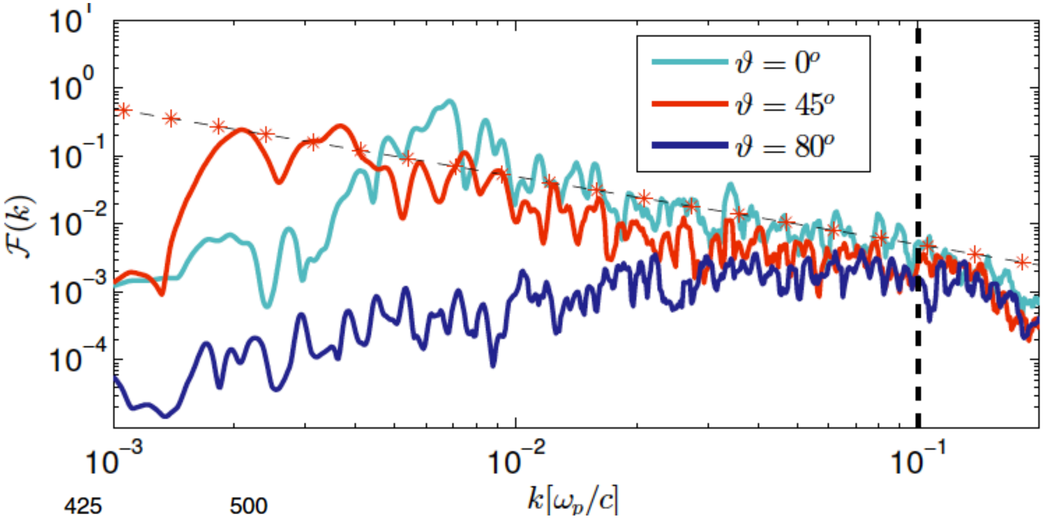
SHORT WAVELENGTH QUASI-STANDING WAVES

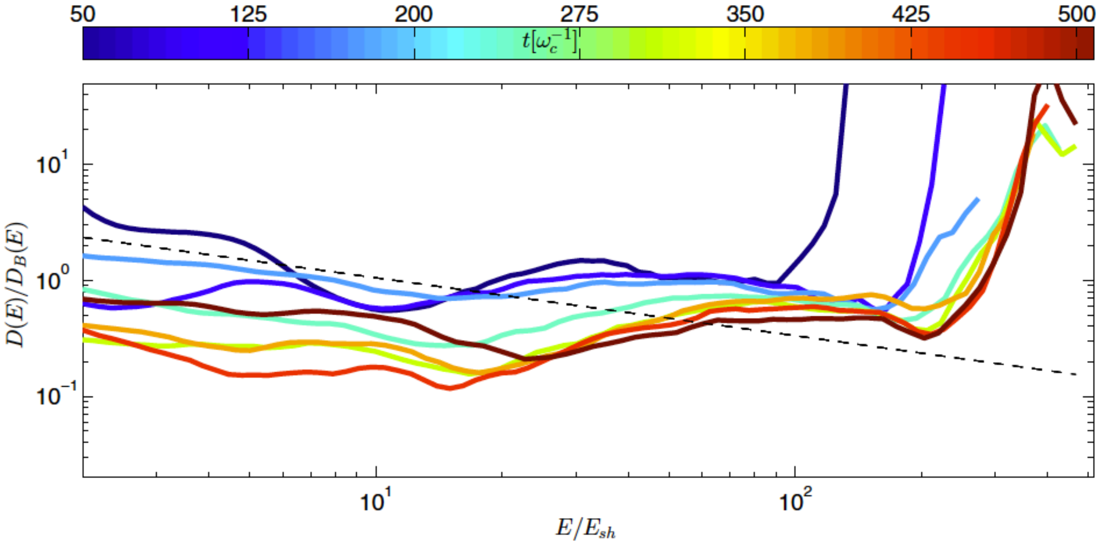
DAMPING STRONGLY SUPPRESSED

(Reville+07)

SATURATION & SCATTERING

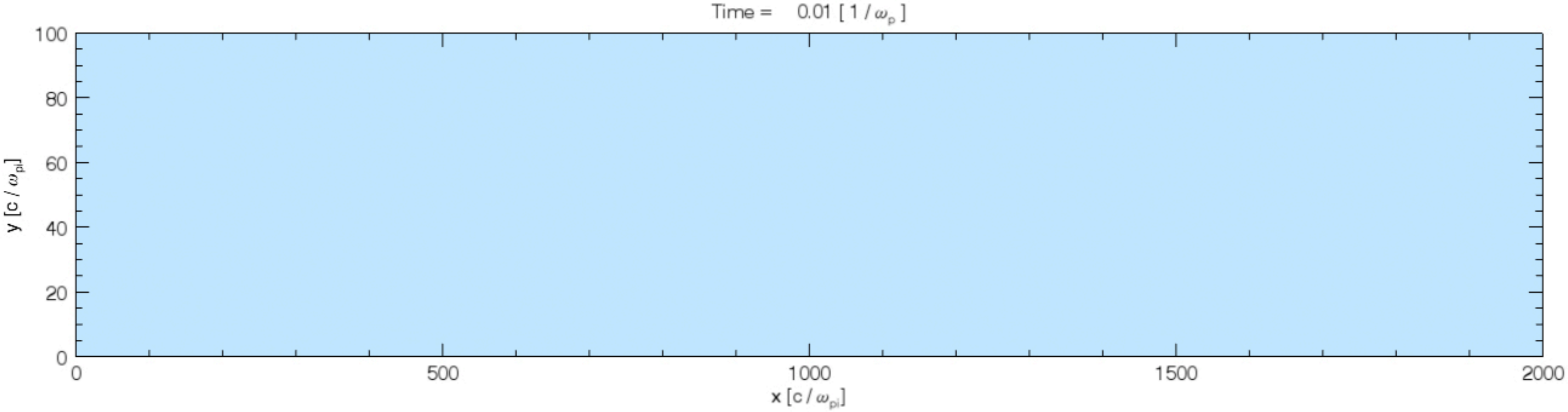
- B-FIELD EASILY AMPLIFIED TO FEW X 100 μG (Riquelme & Spitkovsky 09, Caprioli & Spitkovsky 14)
- EFFECTIVE INVERSE CASCADING PROVEN BY NUMERICAL WORK (Caprioli & Spitkovsky 14): SCALE GROWS QUICKLY AND SCATTERING IS IN BOHM REGIME

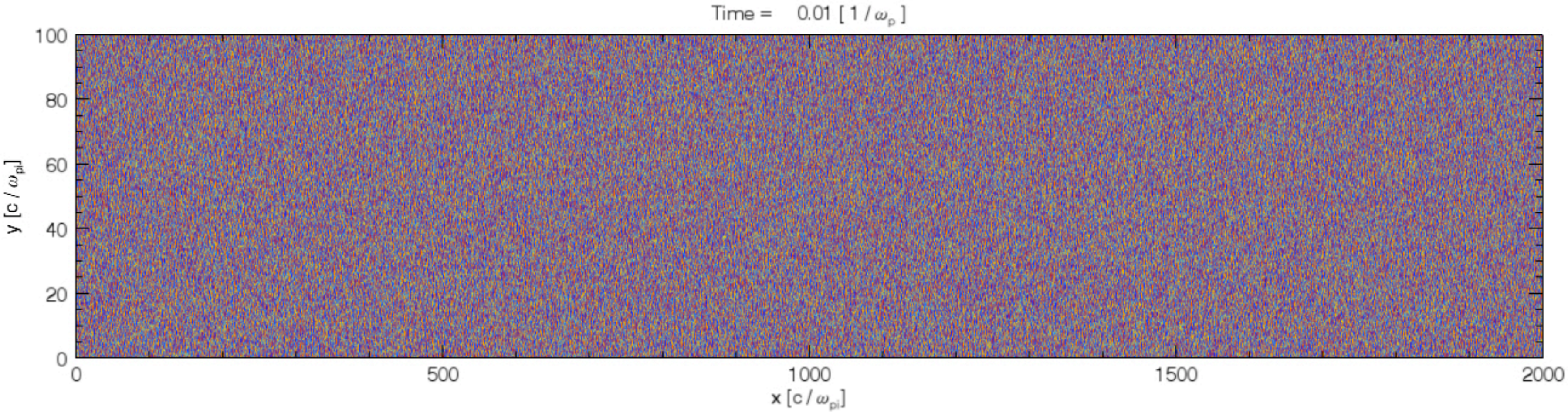




Caprioli & Spitkovsky 14

PARTICLE ACCELERATION AND MFA: PIC SIMULATIONS





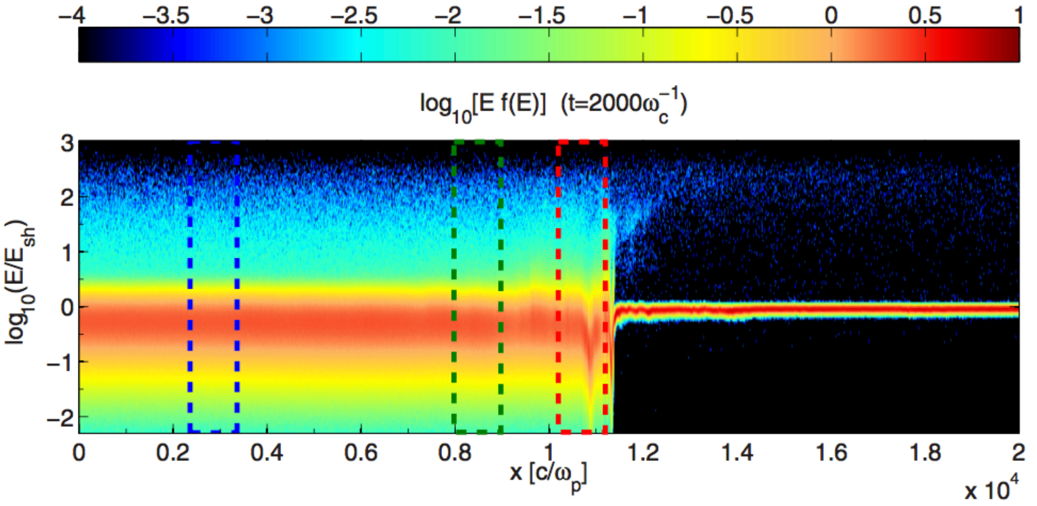
Caprioli & Spitkovsky 14

RESULTS FROM PIC SIMULATIONS

TURBULENCE IN THE UPSTREAM SEEDED BY THE CURRENT CARRIED BY THE ESCAPING PARTICLES

IF SHOCK MACH NUMBER LARGE ENOUGH, FASTEST INSTABILITY IS BELL'S

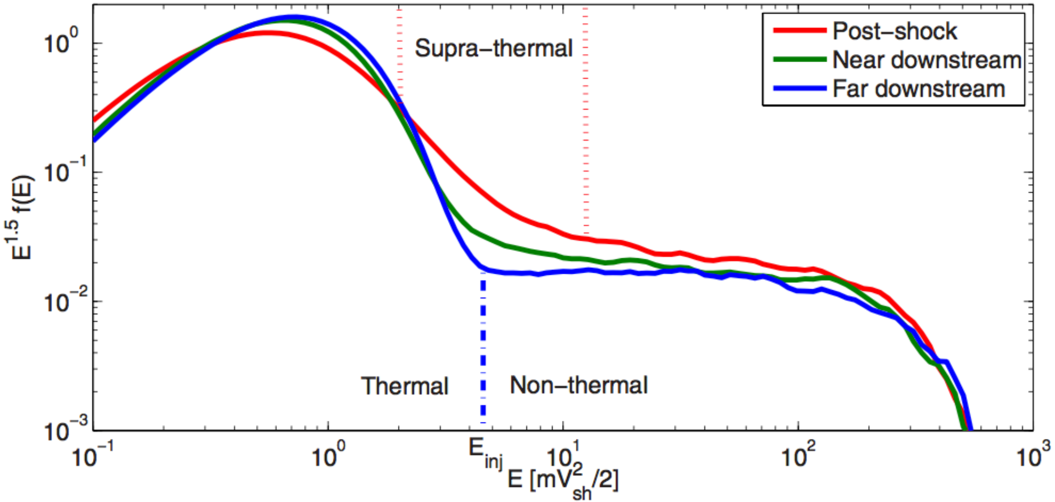
(Caprioli & Spitkovsky 14)



GROWING MODES ARE SMALL SCALE, BUT QUICKLY GROW TO LARGER SCALES.

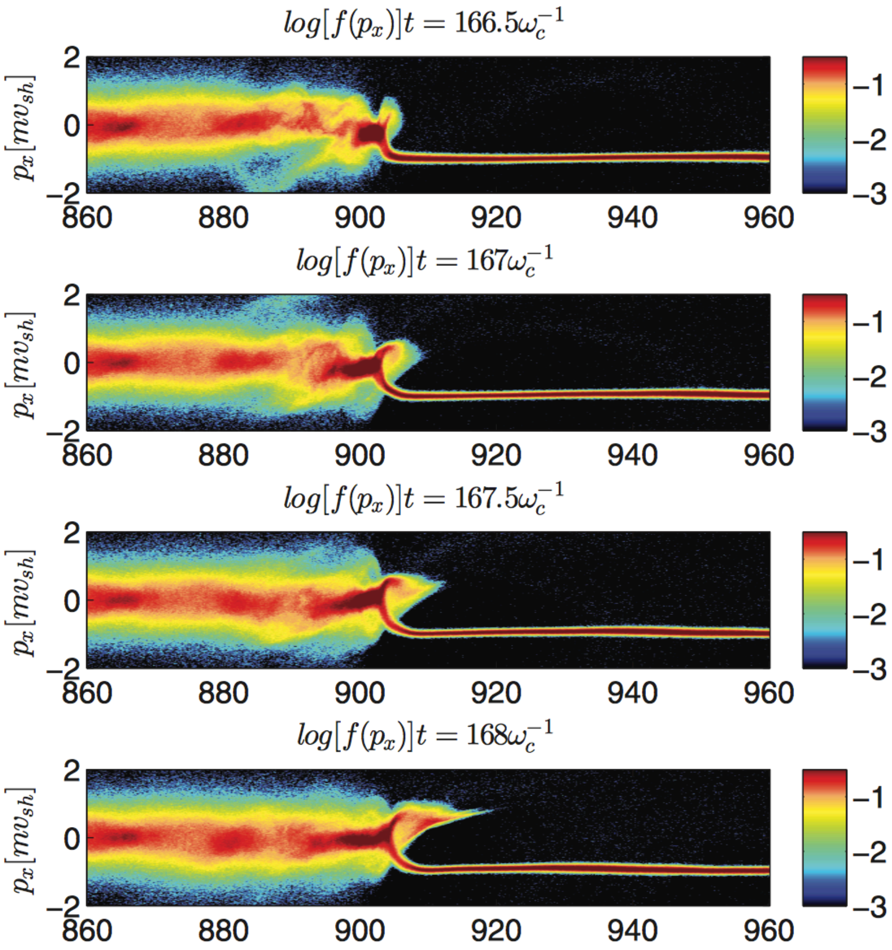
CLOSE TO SHOCK PARTICLES START BOHM DIFFUSION IN AMPLIFIED FIELD AND A PRECURSOR IS FORMED

SATURATION AT $(\delta B/B_0)^2 \approx M_A$

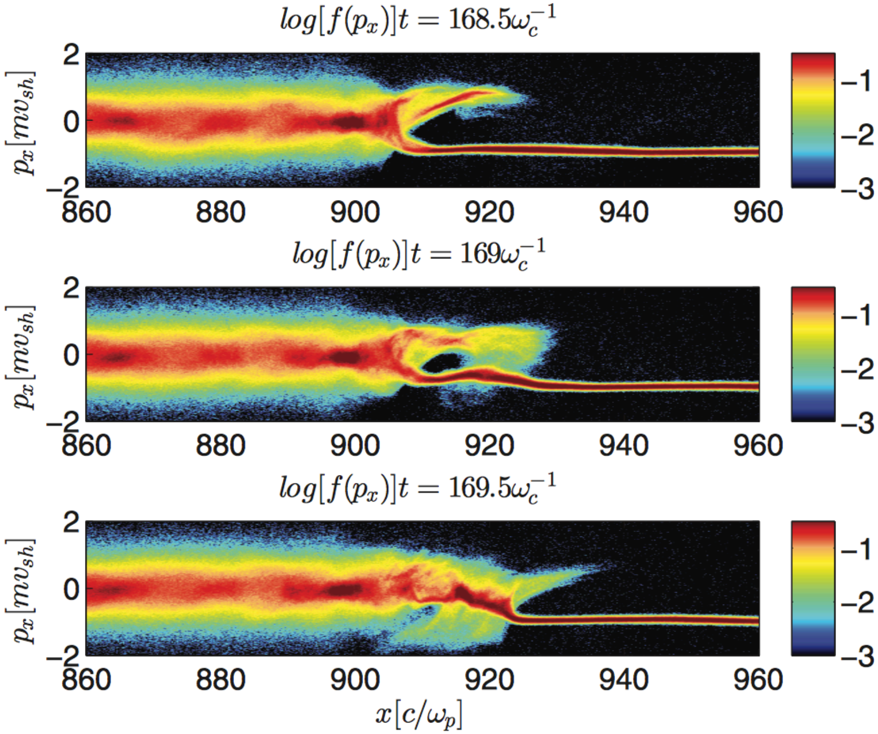


ACCELERATION EFFICIENCY 10-15%

PARTICLE INJECTION

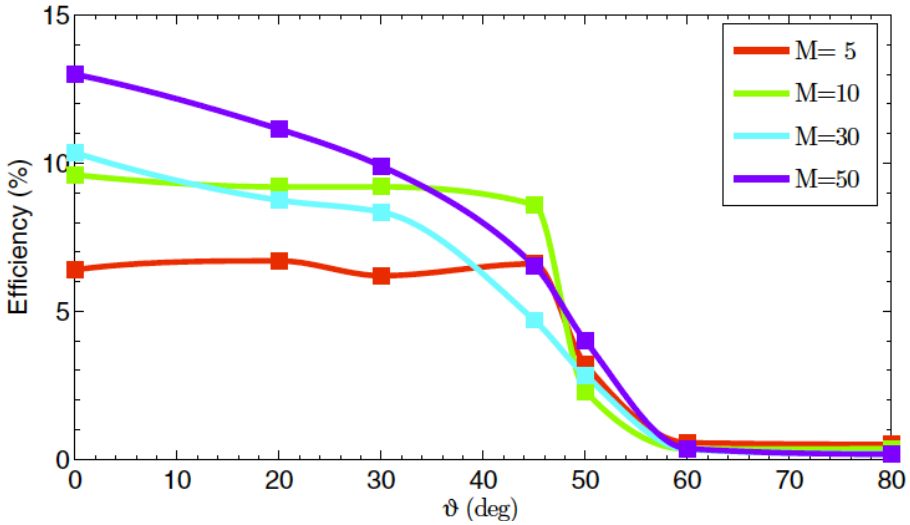


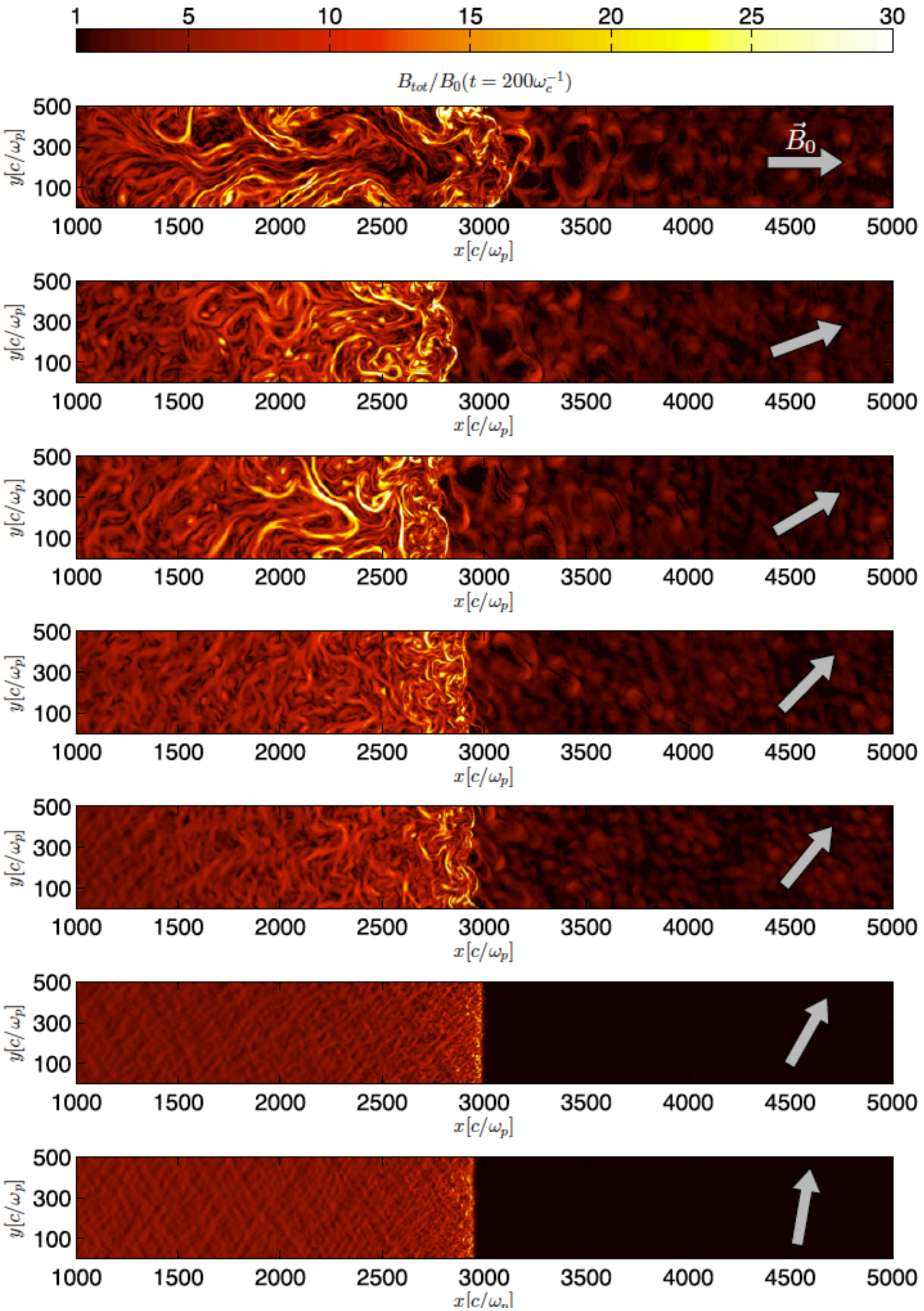
- SHOCK FRONT REFORMS QUASI-PERIODICALLY ON ION-CYCLOTRON TIME
- INJECTION BY CHANCE OF 1-FEW% OF THE IONS
- 10% EFFICIENCY



Caprioli + 15

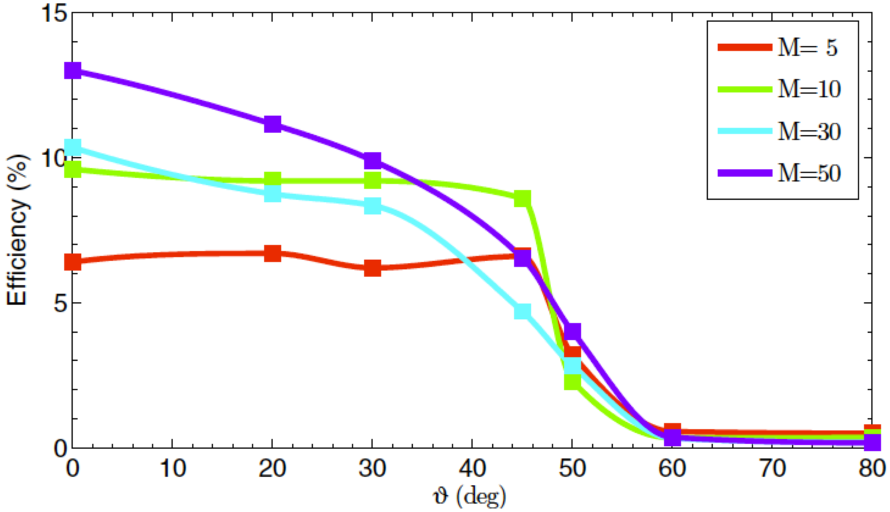
SHOCK OBLIQUITY AND MAGNETIC TURBULENCE



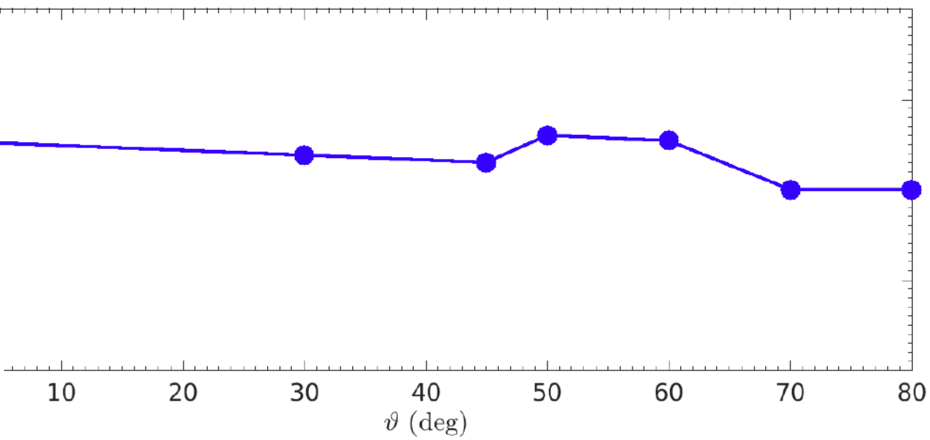


Caprioli & Spitkovsky 14

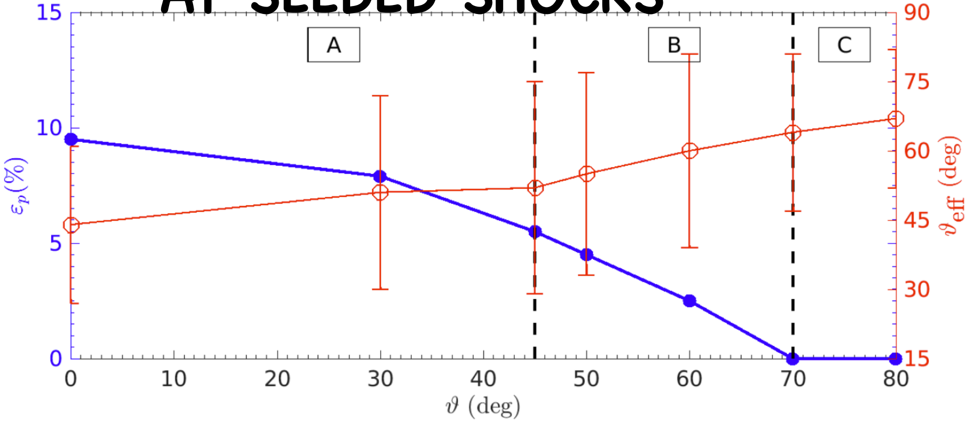
SEEDED SHOCKS



REACCELERATION EFFICIENCY



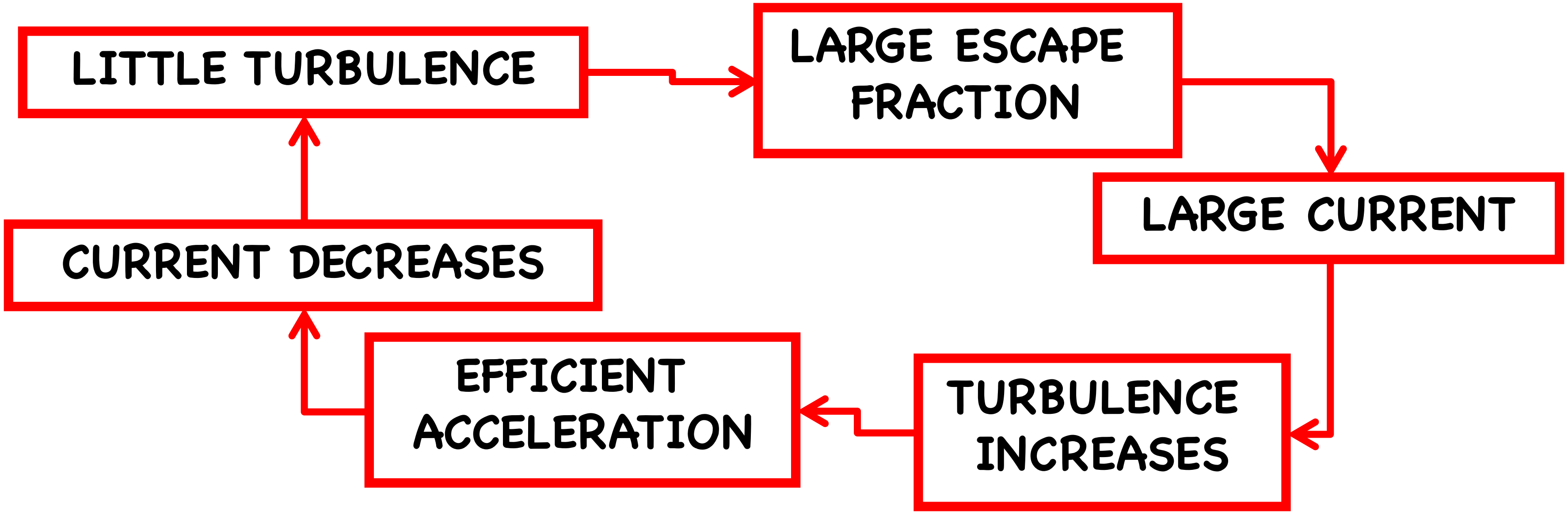
ACCELERATION EFFICIENCY AT SEEDED SHOCKS



Caprioli + 18

RELEASED SPECTRUM

- MFA DUE TO CURRENT OF ESCAPING PARTICLES
- GROWTH RATE PROPTO J_{CR} WHICH DEPENDS ON SPECTRUM AT THE SHOCK, P_{MAX} AND V_S



LITTLE TURBULENCE

LARGE ESCAPE FRACTION

LARGE CURRENT

TURBULENCE INCREASES

EFFICIENT ACCELERATION

CURRENT DECREASES

RELEASED PARTICLE SPECTRUM:

$$\begin{cases} \Gamma_{CR} > 2 \text{ IF } \Gamma_{SRC} > 2 \\ \Gamma_{CR} = 2 \text{ IF } \Gamma_{SRC} \leq 2 \end{cases}$$

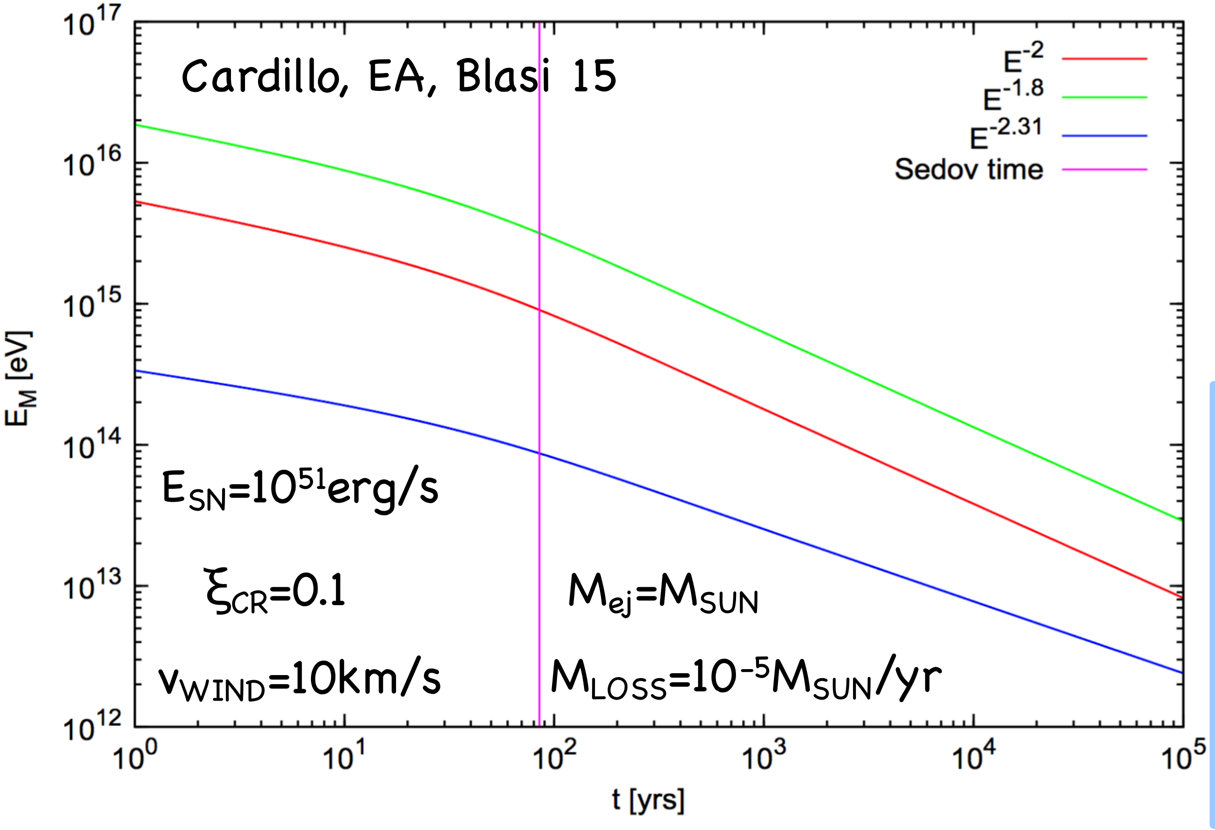
MAXIMUM ENERGY

TYPE I

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

TYPE II

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

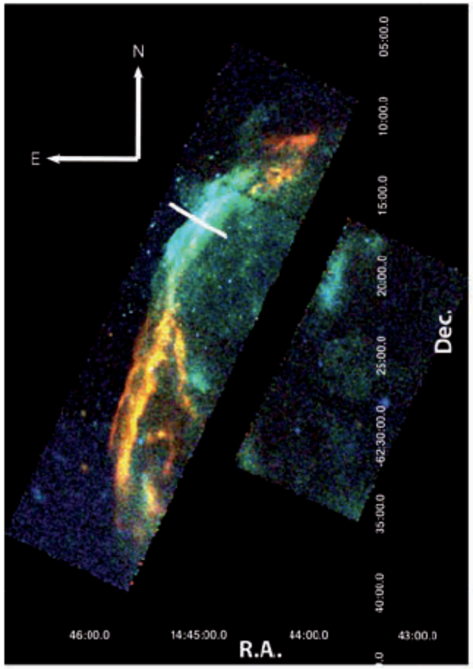


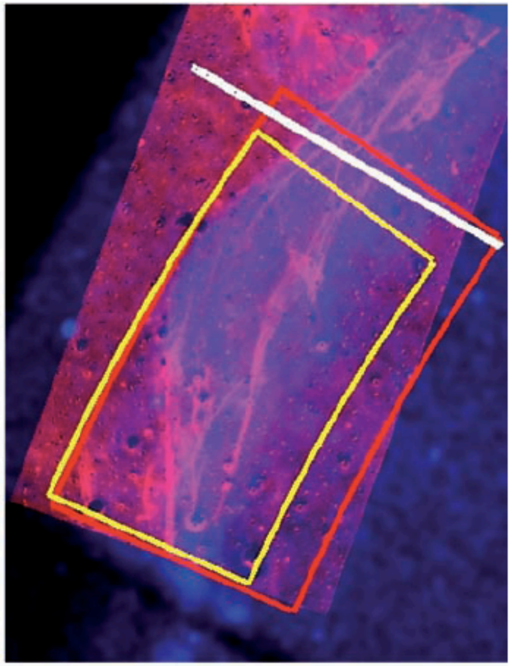
WITH Γ_{CR} >2, P_{max}=PeV REQUIRES

- **RARE** (<1/1000 yr^{-1})
- **EXTREME EVENTS** ($E_{SN}>10^{52}$erg)
- **EXTREME EFFICIENCY** (ξ_{CR}>30%)

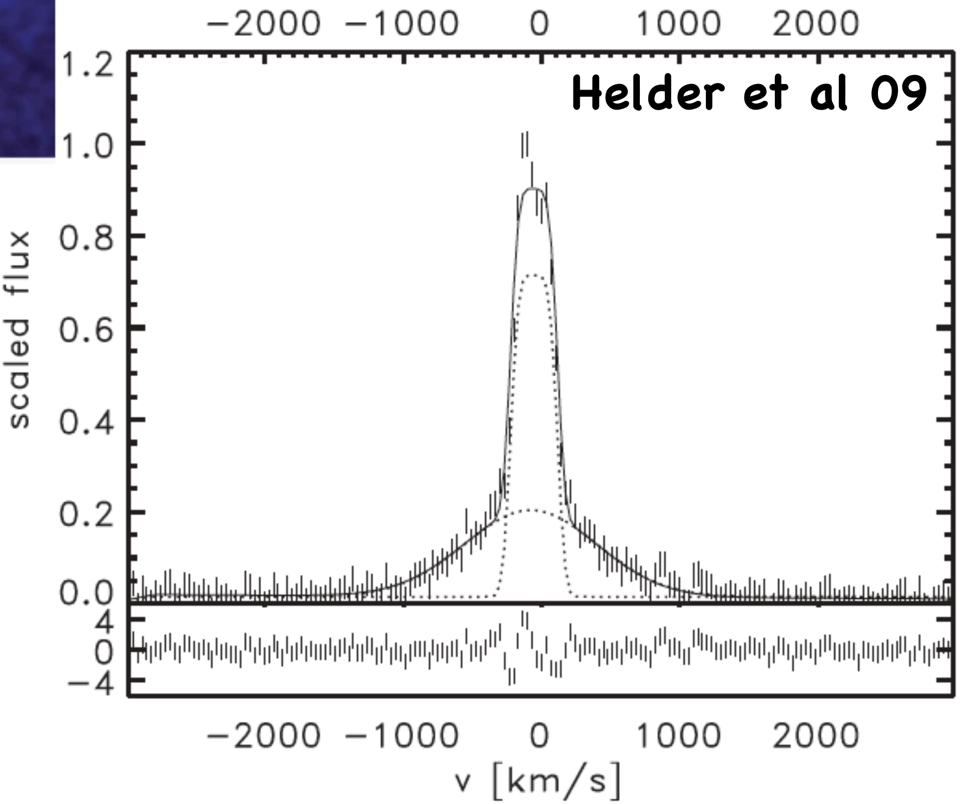
SHOCKS IN PARTIALLY IONIZED PLASMAS

BALMER DIAGNOSTICS





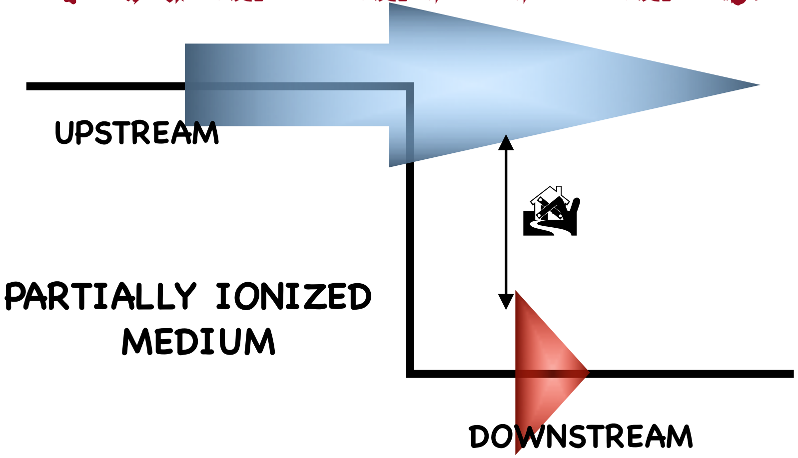
IN RCW 86
⇒50% DEDUCED FROM
BALMER LINES STUDY
(Helder et al 09): $T_{i,2}$ vs V_s



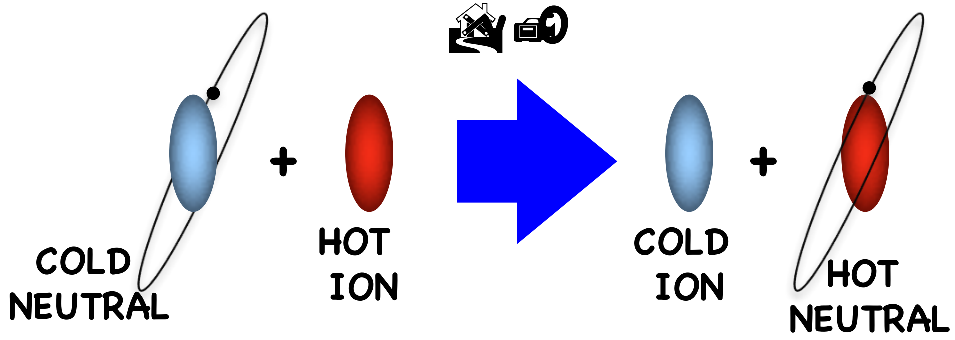
BALMER DOMINATED SHOCKS
(Chevalier & Raymond 78,
Heng & McCray 07, Heng et al 07,
van Adelsberg et al 08)

- ISM IS NOT FULLY IONIZED
- NEUTRAL ATOMS EMIT BALMER LINES
- BROAD AND NARROW COMPONEN TELL DIFFERENT STORIES

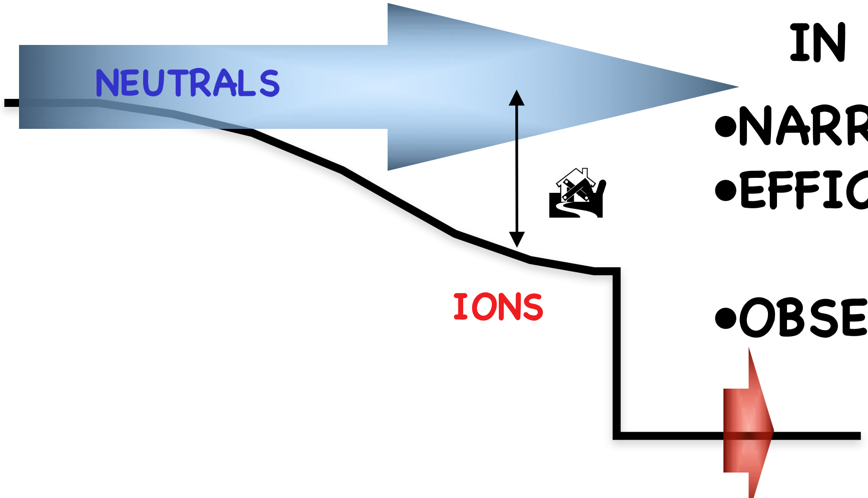
THE EFFECT OF NEUTRALS



CHARGE EXCHANGE WHERE 🏚📹



- •BROAD BALMER LINE 📹 DOWNSTREAM T_{ION}
- •EFFICIENT CR ACCELERATION 🌬 LOWER T_{ION} 🎭NARROWER BROAD LINE
- •IN RCW86 🚚50-60 % INFERRED FROM NARROW BROAD LINES (Helder et al. 09)



IN MODIFIED SHOCKS CE IN PRECURSOR

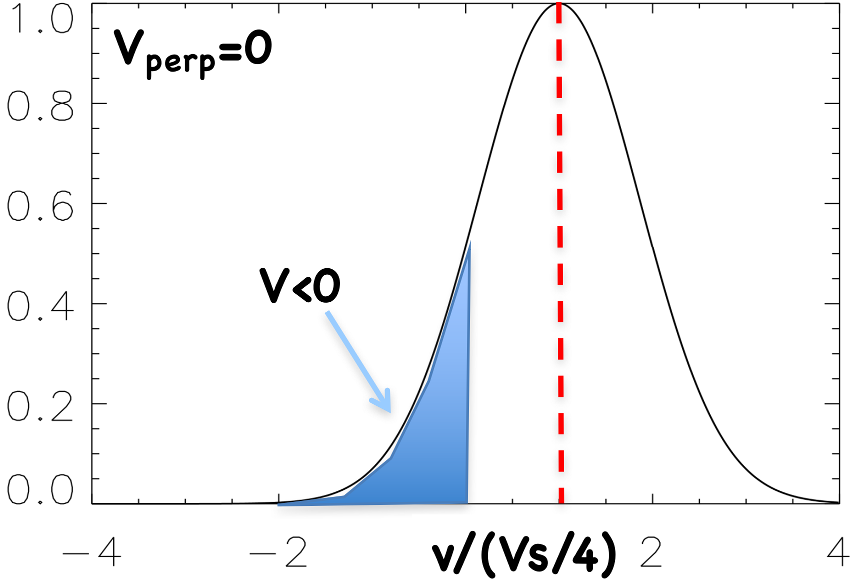
- •NARROW BALMER LINE 📹 UPSTREAM T_{ION}
- •EFFICIENT CR ACCELERATION 🌬 HIGHER T_{ION} 🎭 BROADER NARROW LINE
- •OBSERVED IN RCW86 (Sollerman et al 03, Helder et al 09)

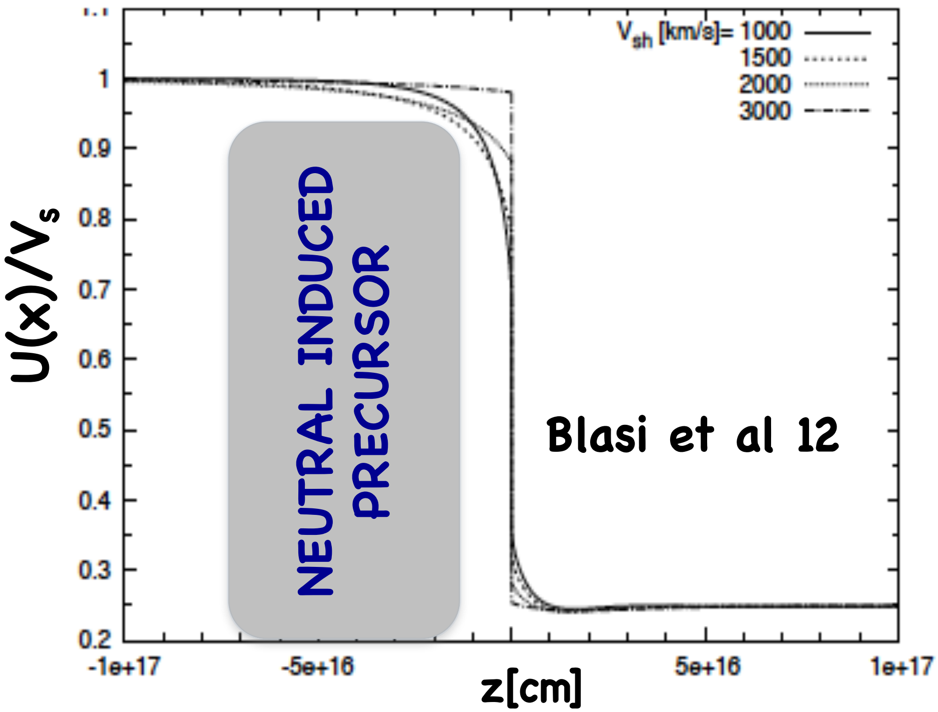
A DIFFERENT PRECURSOR

CE DOWNSTREAM WITH COUNTERSTREAMING IONS

NEUTRAL RETURN FLUX

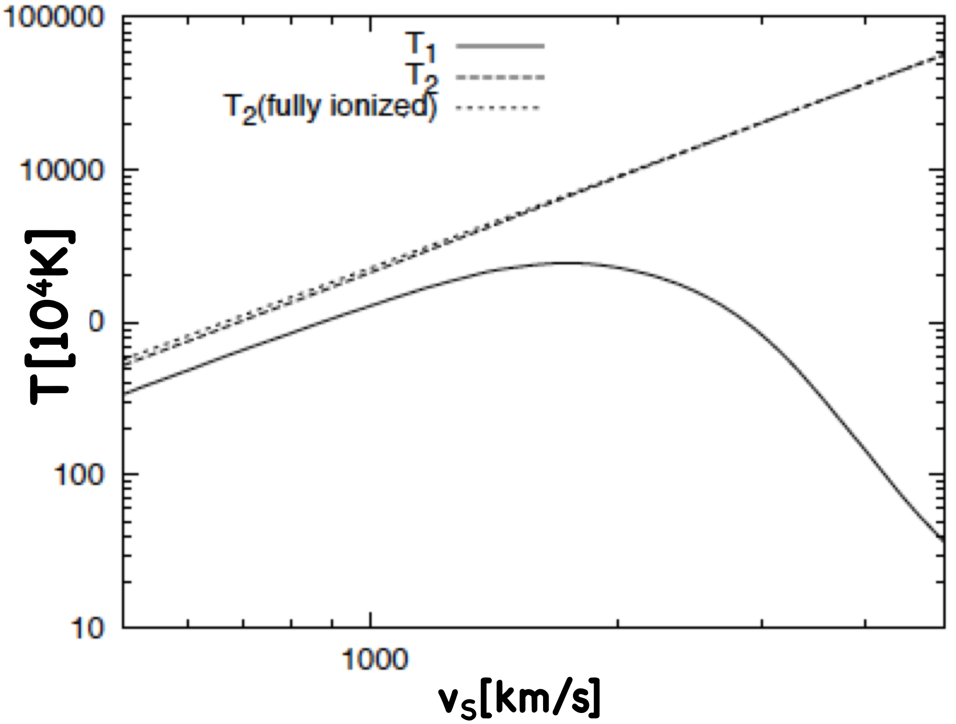
ENERGY AND MOMENTUM DEPOSITION UPSTREAM





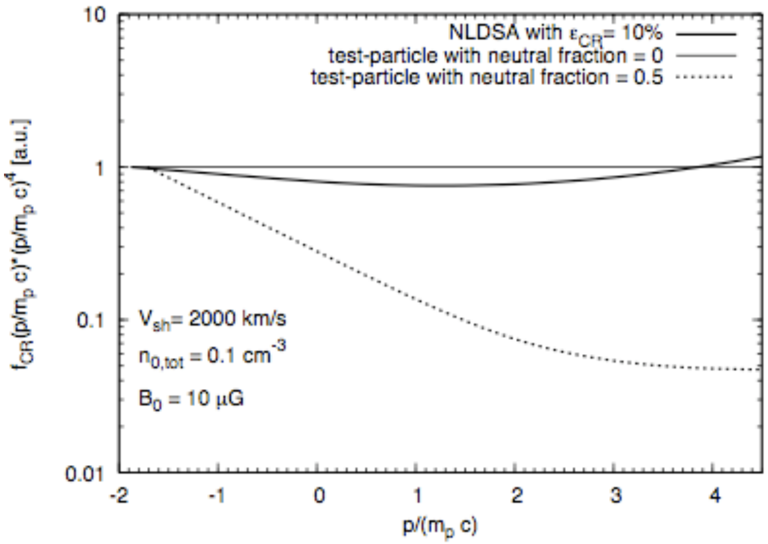
NEUTRAL INDUCED PRECURSOR

Blasi et al 12

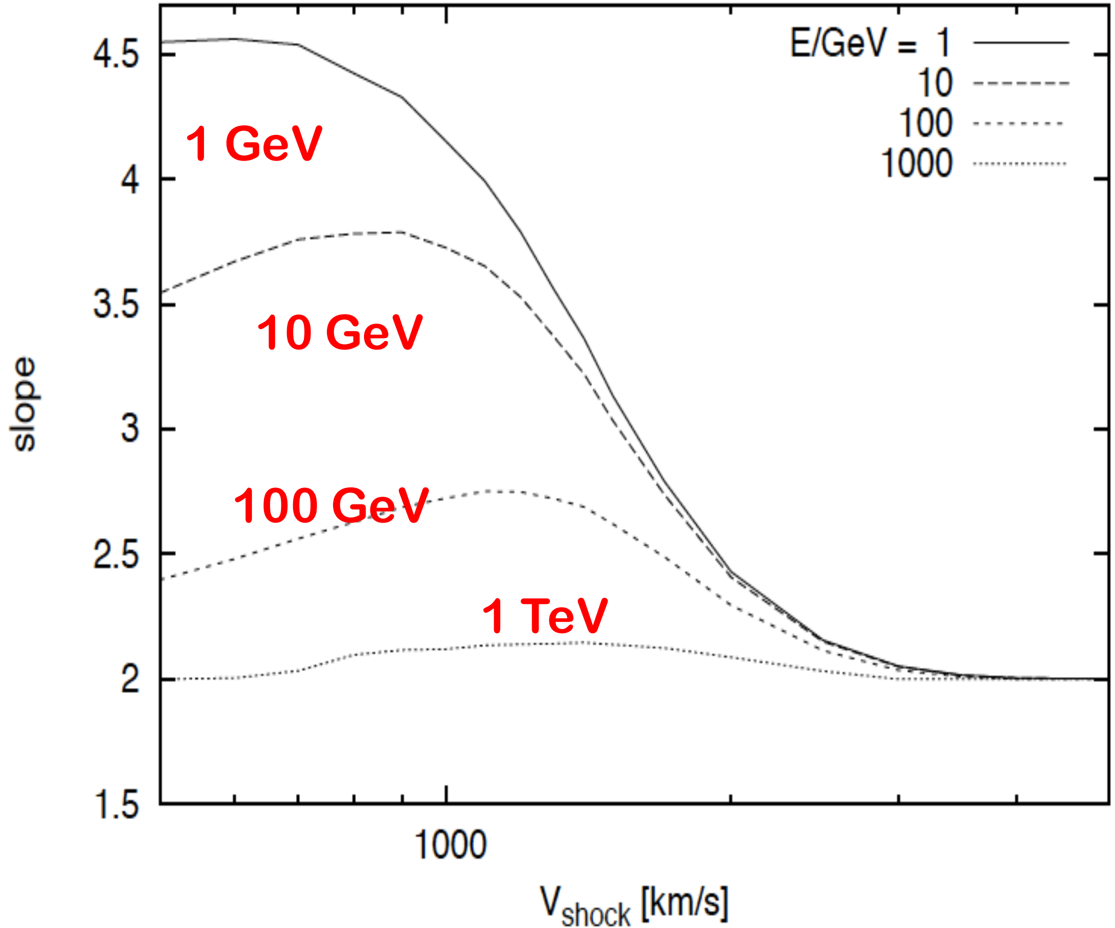


TEST PARTICLE SPECTRA IN THE PRESENCE OF NEUTRALS

SPECTRA ARE ALWAYS STEEPER THAN 2 EVEN FOR HIGH MACH NUMBER SHOCKS



Blasi+ 12,
Morlino+ 13,14



SUMMARY

A COMBINATION OF THEORY, OBSERVATIONS AND SIMULATIONS ARE UNVEILING THE PHYSICS OF PARTICLE ACCELERATION AT SNR SHOCKS:

- DIFFUSIVE SHOCK ACCELERATION IN THE EFFICIENT REGIME
- TURBULENCE SELF-GENERATION
- PARTICLE INJECTION
- MAXIMUM ENERGY
- RELEASED PARTICLE SPECTRUM
- SHOCKS IN PARTIALLY NEUTRAL PLASMAS

AND A QUESTION

IS ANY OF THIS USEFUL FOR THIS COMMUNITY?