RECENT DEVELOPMENTS ON THE SNR-CR CONNECTION

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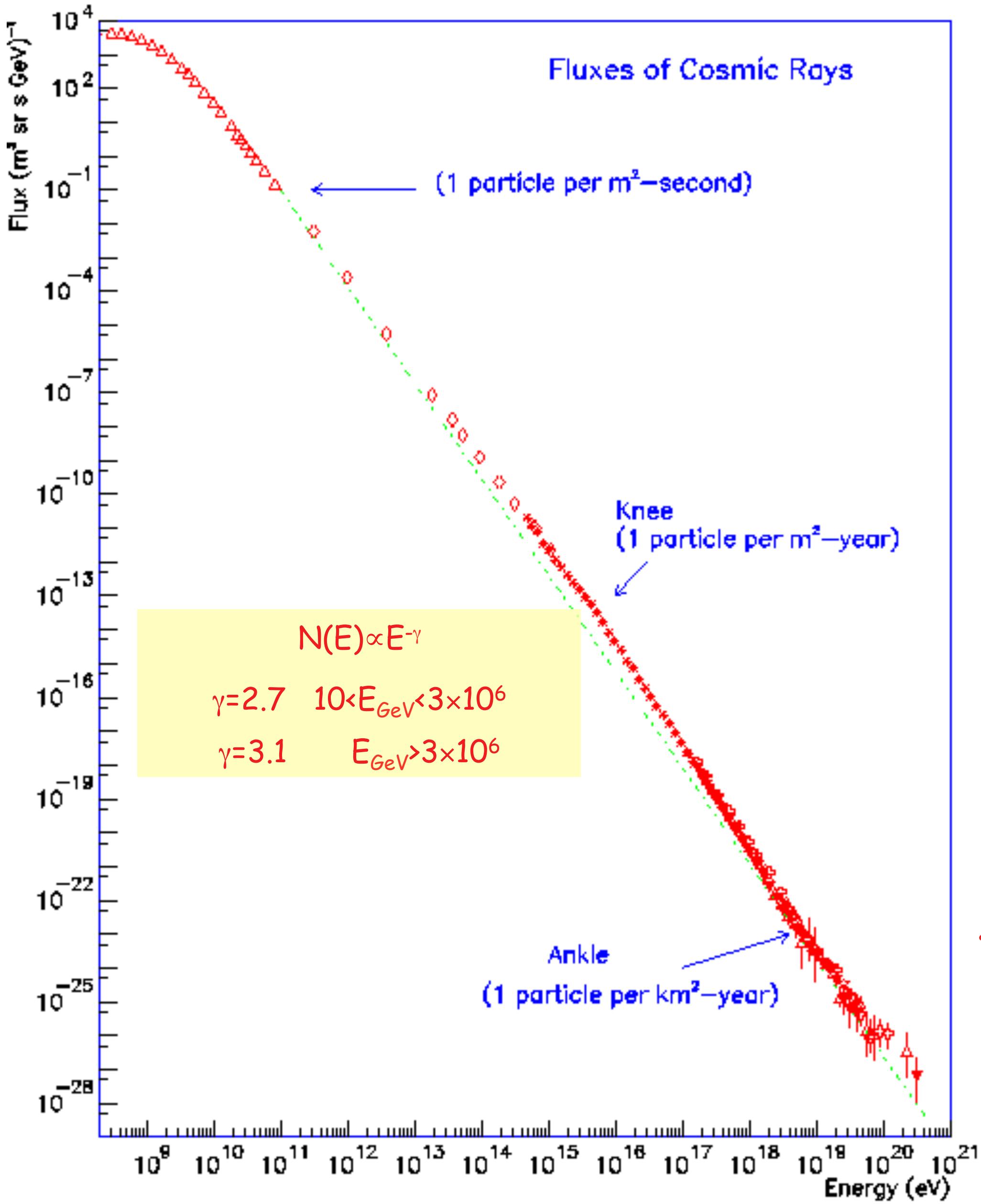
CRs – SNRs PARADIGM



ASSOCIATION WITH SNe
PROPOSED ALREADY IN THE '30s
ON ENERGETIC GROUNDS
(Baade and Zwicky, 1934)

$n_{CR} \sim 10^{-9} cm^{-3}$

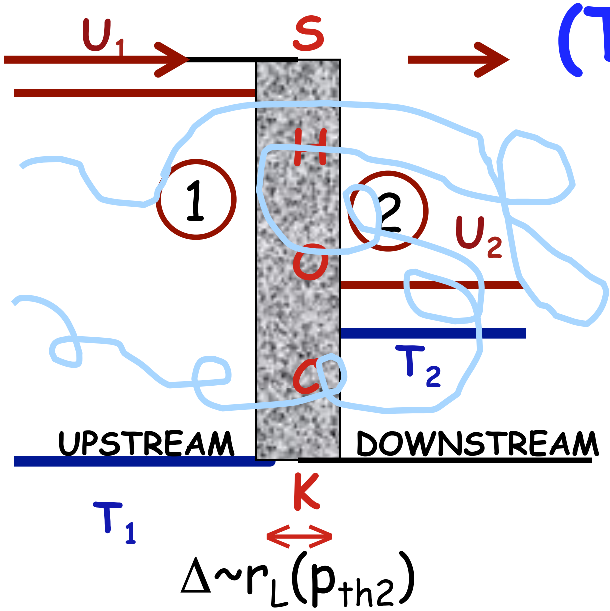
$L_{CR} \sim 3\times10^{40}$ erg s^{-1}

~ 10%(10^{51}erg/100yr)

ACCELERATION PROCESS
PROPOSED IN LATE '70s:
DIFFUSIVE SHOCK ACCELERATION
(Krymskii 77, Bell 78)

DIFFUSIVE SHOCK ACCELERATION

(TEST PARTICLES)



COLLISIONLESS SHOCKS
E.M. INSTABILITIES RESPONSIBLE FOR DISSIPATION AND ACCELERATION

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

POWER LAW SPECTRA $N(p) \propto p^{-\gamma_p}$ $\quad \gamma_p = \frac{3u_1}{u_1 - u_2}$

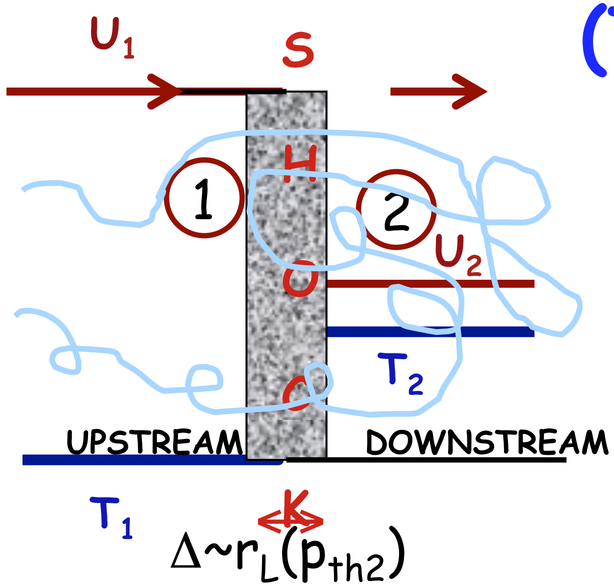
ONLY DEPENDENT ON COMPRESSION RATIO!

INDEPENDENT OF SCATTERING PROPERTIES!!!

FOR STRONG SHOCKS: $u_1/u_2=4 \Rightarrow \gamma_p=4 \Leftrightarrow \gamma_e=2$

MAXIMUM ENERGY IN DSA

(TEST PARTICLES)



E_{MAX} DOES DEPEND ON D(p)!!!

E_{MAX} IS SET BY: $\tau_{acc}(E_{MAX}) = \min(\tau_{age}, \tau_{loss})$

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

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

✓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

•10% EFFICIENCY IMPLIES SHOCK MODIFICATION

DIFFUSIVE SHOCK ACCELERATION

(WITH BACK REACTION)

- ✓ DYNAMICAL REACTION OF ACCELERATED PARTICLES
- ✓ SELF REGULATION OF THE INJECTION
- ✓ CR INDUCED B-FIELD AMPLIFICATION
- ✓ DYNAMICAL REACTION OF AMPLIFIED FIELD
- ✓ REVISED ACCELERATION TIME
- ✓ ESCAPE OF PARTICLES

$$\frac{\partial \rho}{\partial t} = -\frac{\partial(\rho u)}{\partial x}$$

MASS CONSERVATION

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x}\left[\rho u^2 + P_g + P_c + P_w\right]$$

MOMENTUM CONSERVATION

TWO-FLUIDS: Drury & co.

MONTECARLO: Ellison & co.

FINITE DIFFERENCE: Berezhko, Volk & co.

KINETIC: Amato & Blasi 05,06; Blasi et al.08, Caprioli et al 08,09,10,11

$$\frac{\partial}{\partial t}\left[\frac{\rho u^2}{2} + \frac{P_g}{\gamma_g - 1}\right] = -\frac{\partial}{\partial x}\left[\frac{\rho u^3}{2} + \frac{\gamma_g P_g u}{\gamma_g - 1}\right] - u\frac{\partial}{\partial x}\left[P_c + P_w\right] + \Gamma E_w$$

ENERGY CONSERVATION

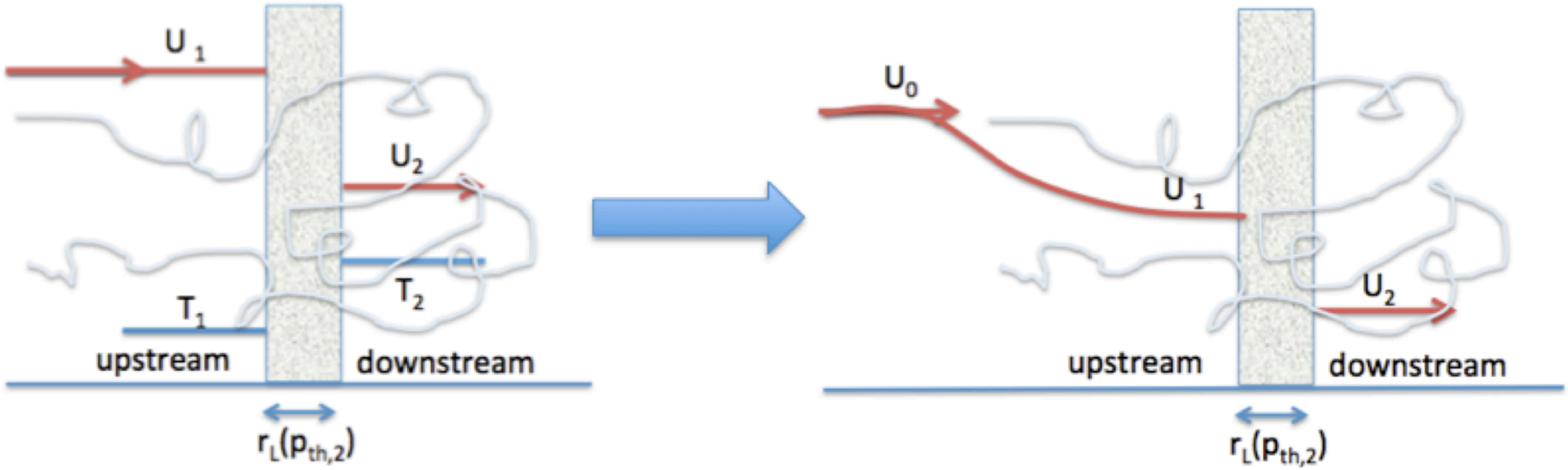
$$\frac{\partial F_w}{\partial x} = u\frac{\partial P_w}{\partial x} + \sigma E_w - \Gamma E_w$$

EVOLUTION OF WAVES

$$\frac{\partial f(t,x,p)}{\partial t} + \tilde{u}(x)\frac{\partial f(t,x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(t,x,p)}{\partial x}\right] + \frac{p}{3}\frac{\partial f(t,x,p)}{\partial p}\frac{d\tilde{u}(x)}{dx}$$

TRANSPORT EQUATION

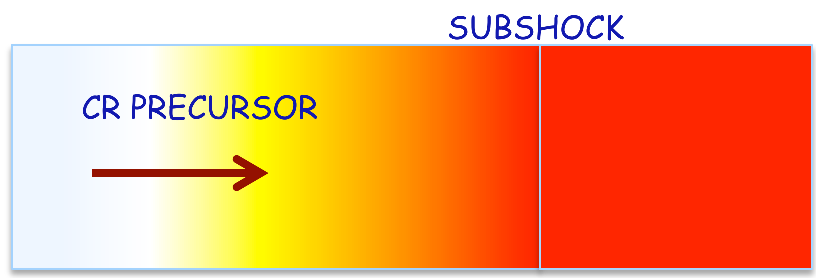
CR MODIFIED SHOCKS



✧ 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)

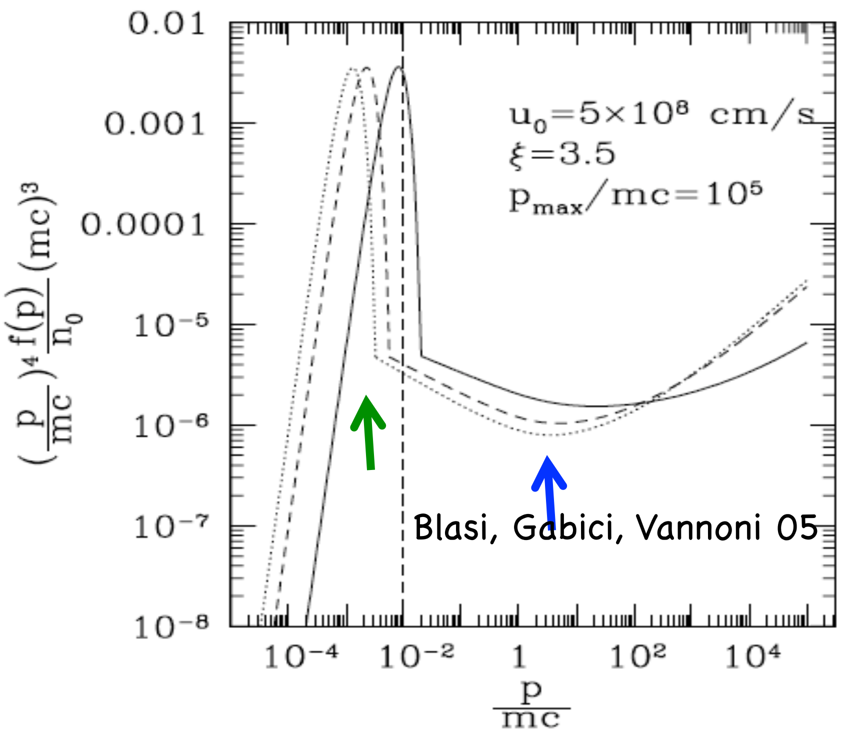
➔SPECTRUM BECOMES CONCAVE (STEEP AT LOW EN. FLAT AT HIGH)

BASIC PREDICTIONS OF NL-DSA

HINTS OF EFFICIENT ACCELERATION:

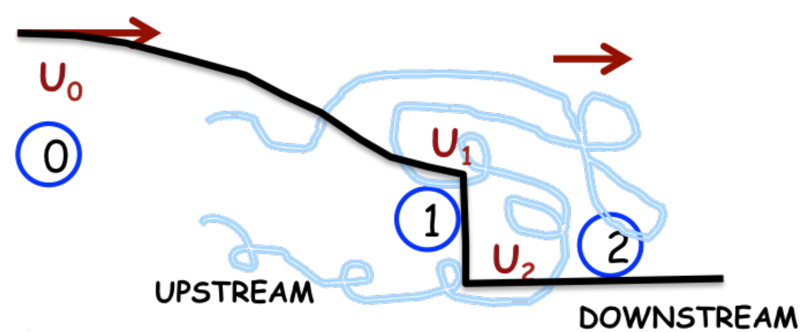
▪ **COMPRESSION RATIO > 4:**

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



▪ **T_2 IS LOWER THAN EXPECTED:**

IN RCW86 T_2~1/10 T_{RH} (Helder et al 09, 13;
Morlino et al 14)



▪ **CONCAVE SPECTRA:**

▪RADIO SNRs (Reynolds & Ellison 92)
AND SED FITTING OF SN1006 AND RCW86 (Vink 12)

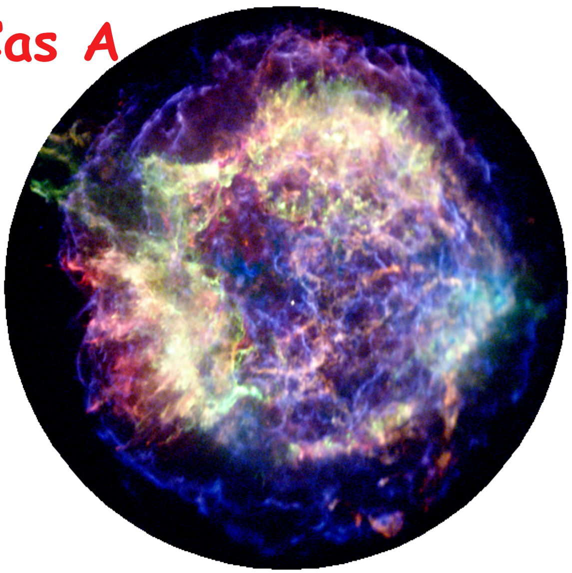
▪ **B-FIELD LARGELY AMPLIFIED**

EVIDENCE OF MFA

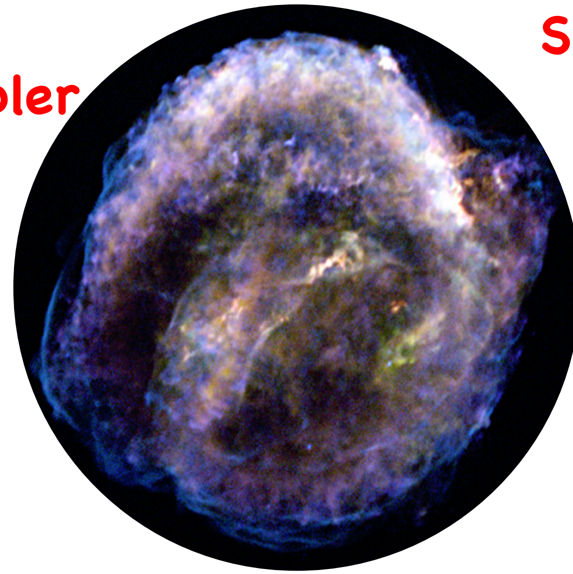
RELATIVISTIC ELECTRONS IN SNRs

(Ballet 06, Vink 12)

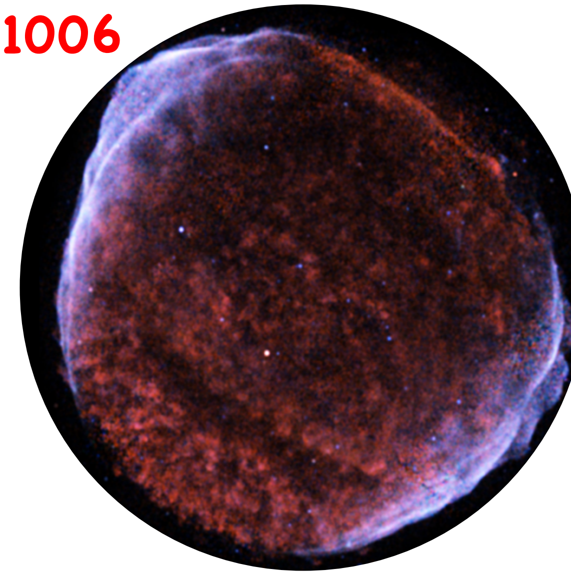
Cas A



Kepler



SN1006



VIRTUALLY ALL YOUNG REMNANTS SHOW X-RAY SYNCHROTRON FILAMENTS

LOSS LENGTH $\Delta x = \sqrt{D\tau_{\rm sync}} = 0.04 B_{100}^{-3/2} pc$ ⇒ **AMPLIFIED MAGNETIC FIELD**

INDIRECT EVIDENCE FOR EFFICIENT CR ACCELERATION ⇐

IN THE SIMPLEST PICTURE

THINNESS OF X-RAY RIMS → AMPLIFIED FIELD ⇄ EFFICIENT PARTICLE ACCELERATION

CAVEATS:

- DAMPING MAY BREAK FIRST IMPLICATION
- OTHER SOURCES OF AMPLIFIED FIELDS MAY BREAK SECOND
- AMPLIFIED FIELDS ARE NOT BOUND TO GUARANTEE EFFICIENT SCATTERING AND REACHING HIGH ENERGIES

DAMPING

RECENT STUDIES ON THE PROPERTIES OF X-RAY FILAMENTS

(Rettig & Pohl 12, Ressler et al 14, Tran et al 15)

SHOW THAT EVEN IN THE CASES WHEN DAMPING FITS THE RESULTS BETTER THAN LOSSES LARGE FIELDS ARE REQUIRED

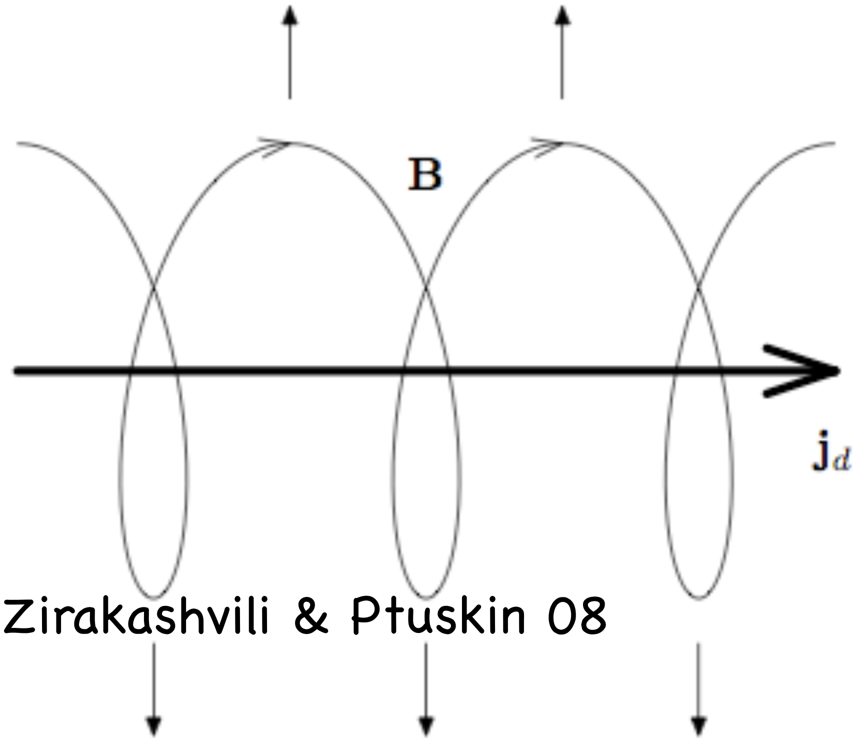
MANY MECHANISMS OF B-FIELD AMPLIFICATION

NON RESONANT STREAMING INSTABILITY

BASIC PHYSICAL PICTURE

CURRENT DRIVEN INSTABILITY

(Bell instability)



Zirakashvili & Ptuskin 08

IF $U_{CR}/U_B > c/v_S$

- 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

SEVERAL DIFFERENT STUDIES:

MHD: Bell 04,05; Reville et al 08, Zirakashvili et al 08

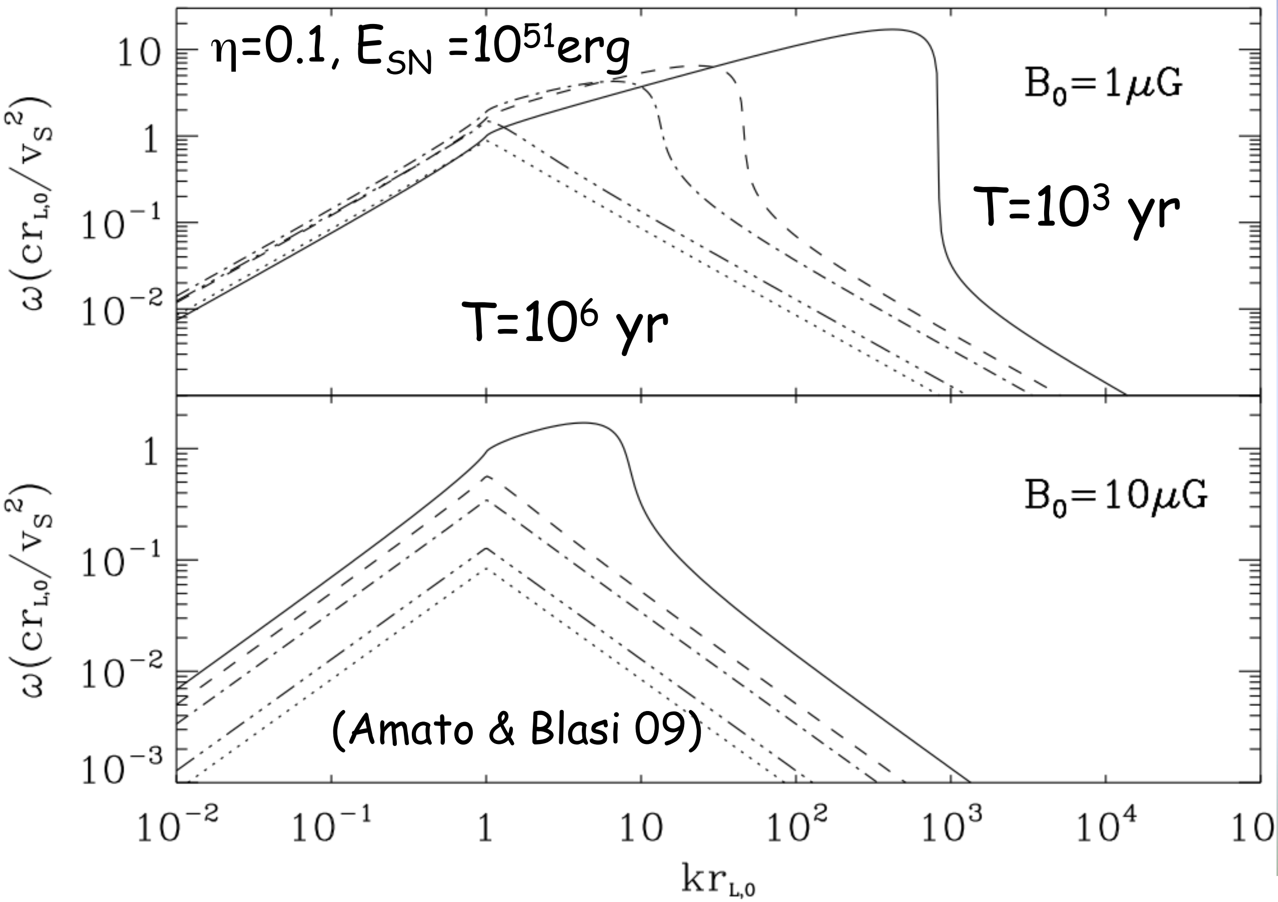
PIC: Niemec et al 08, Riquelme & Spitkovsky 09, Ohira et al 09

PROPERTIES OF BELL'S MODES

$U_{CR}/U_B > c/v_S$ FOR BELL'S MODES TO EXIST

$$\gamma_M = k_M v_A \qquad k_M B_0 \approx \frac{4\pi}{c} J_{CR}$$

DURING SEDOV-TAYLOR EVOLUTION OF A SNR



- THE NON-RESONANT MODE DISAPPEARS AFTER 5×10^3–10^4 YR FOR EXPANSION IN THE ISM
- EARLIER WHEN THE FIELD IS HIGHER OR THE ENVIRONMENT IS DENSER
- BELL MODES COULD BE IMPORTANT AT BEGINNING OF SEDOV PHASE
- WHEN IS E_{MAX} REACHED?

DO WE EXPECT TO SEE PEVATRONS IN THE SKY?

HYBRID SIMULATIONS' RESULTS

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

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

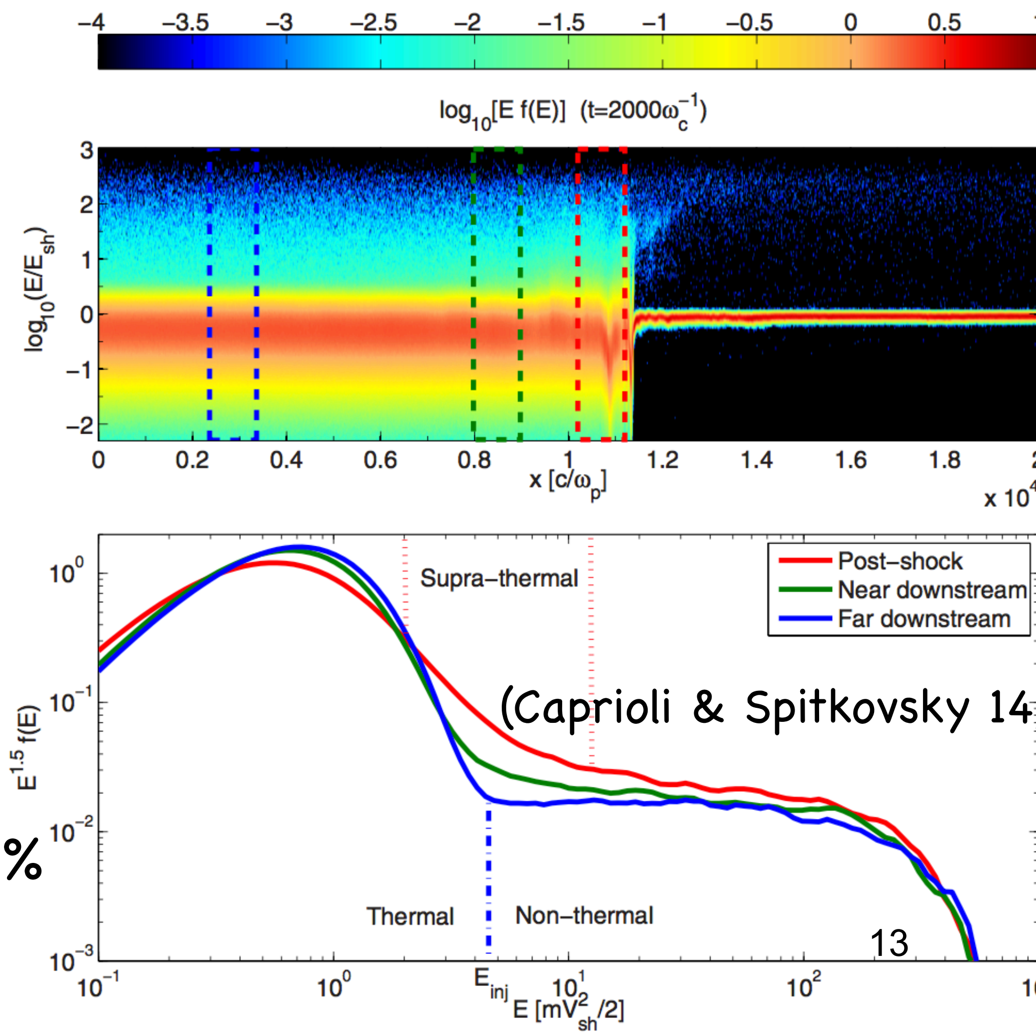
GROWING MODES ARE SMALL SCALE, BUT QUICKLY GROW TO LARGER SCALES.

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%

NO CONCAVE SPECTRA SO FAR

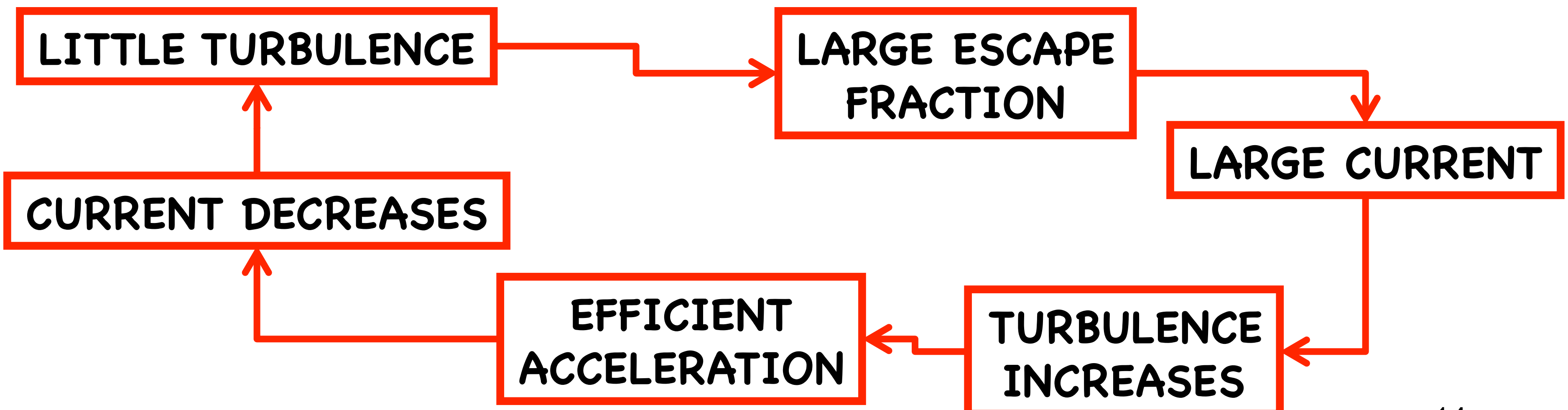


(Caprioli & Spitkovsky 14)

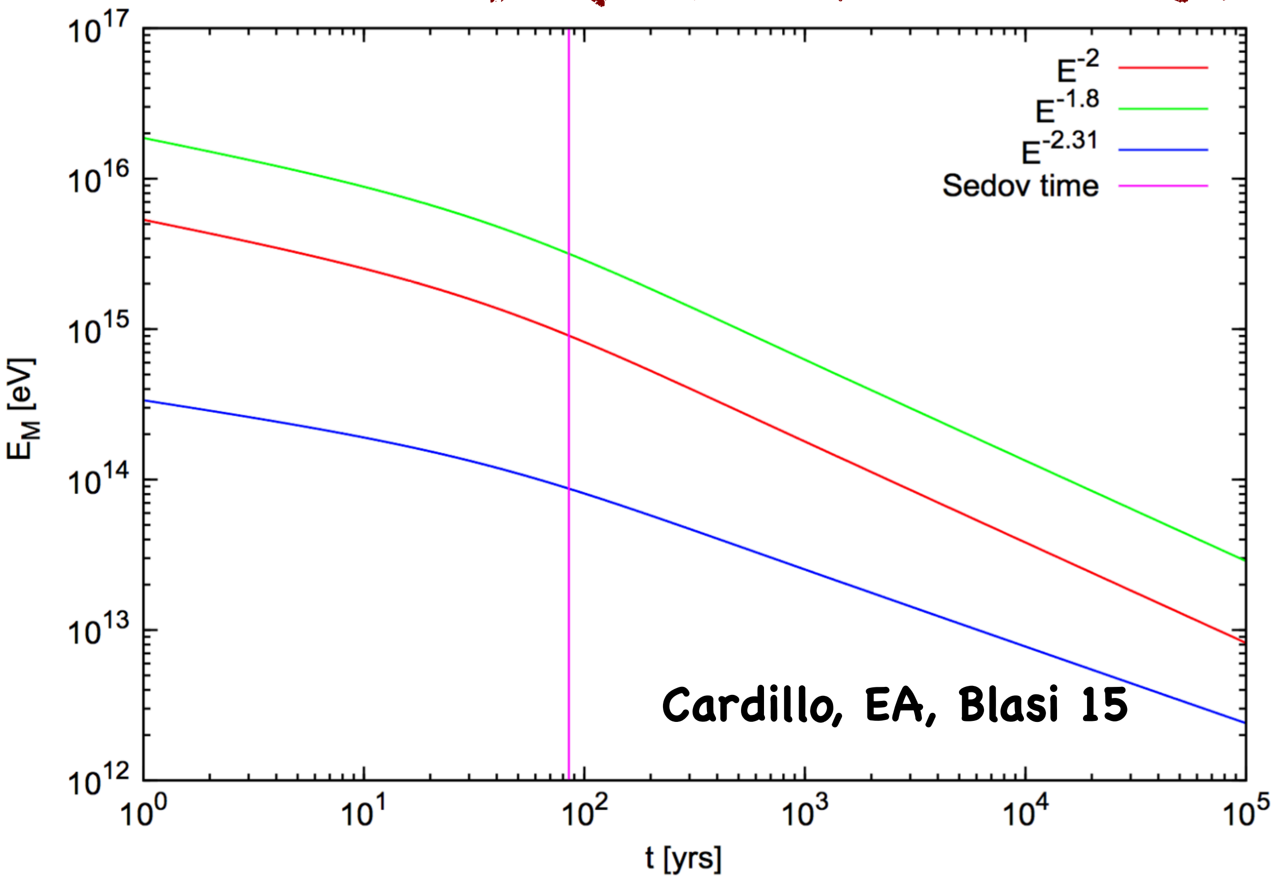
MAXIMUM ENERGY WITH BELL'S MFA

- MAGNETIC FIELD IS AMPLIFIED BY THE CURRENT OF ESCAPING PARTICLES
- GROWTH RATE IS PROPORTIONAL TO J_{CR} WHICH DEPENDS ON SPECTRUM AT THE SHOCK, MAXIMUM ENERGY AND SHOCK VELOCITY

SELF-REGULATING ACCELERATION AND ESCAPE



MAXIMUM ENERGY VS TIME FOR TYPE II SNe



$E_{SN}=10^{51}$erg/s

$\xi_{CR}=0.1$

$M_{ej}=M_{SUN}$

$M_{LOSS}=10^{-5}M_{SUN}/yr$

$v_{WIND}=10$km/s

- THE MAXIMUM ENERGY ALWAYS DECREASE WITH TIME
  (also check poster by Kantzas)

- THE RELEVANT VALUE IS THAT AT THE BEGINNING OF SEDOV PHASE DUE TO WEIGHING WITH PROCESSED MATERIAL

MAXIMUM PARTICLE ENERGY
(E^{-2} SPECTRUM)

TYPE I

$$m = 0, \quad k = 7$$

$$E_M \approx \frac{e}{\mathcal{N} c} \xi_{\rm CR} v_0^2 \sqrt{4\pi\rho R_0^2}$$

TYPE II

$$m = 2, \quad k = 9$$

$$E_M \approx \frac{2e}{\mathcal{N} c} \xi_{\rm CR} v_0^2 \sqrt{4\pi\rho R_0^2}$$

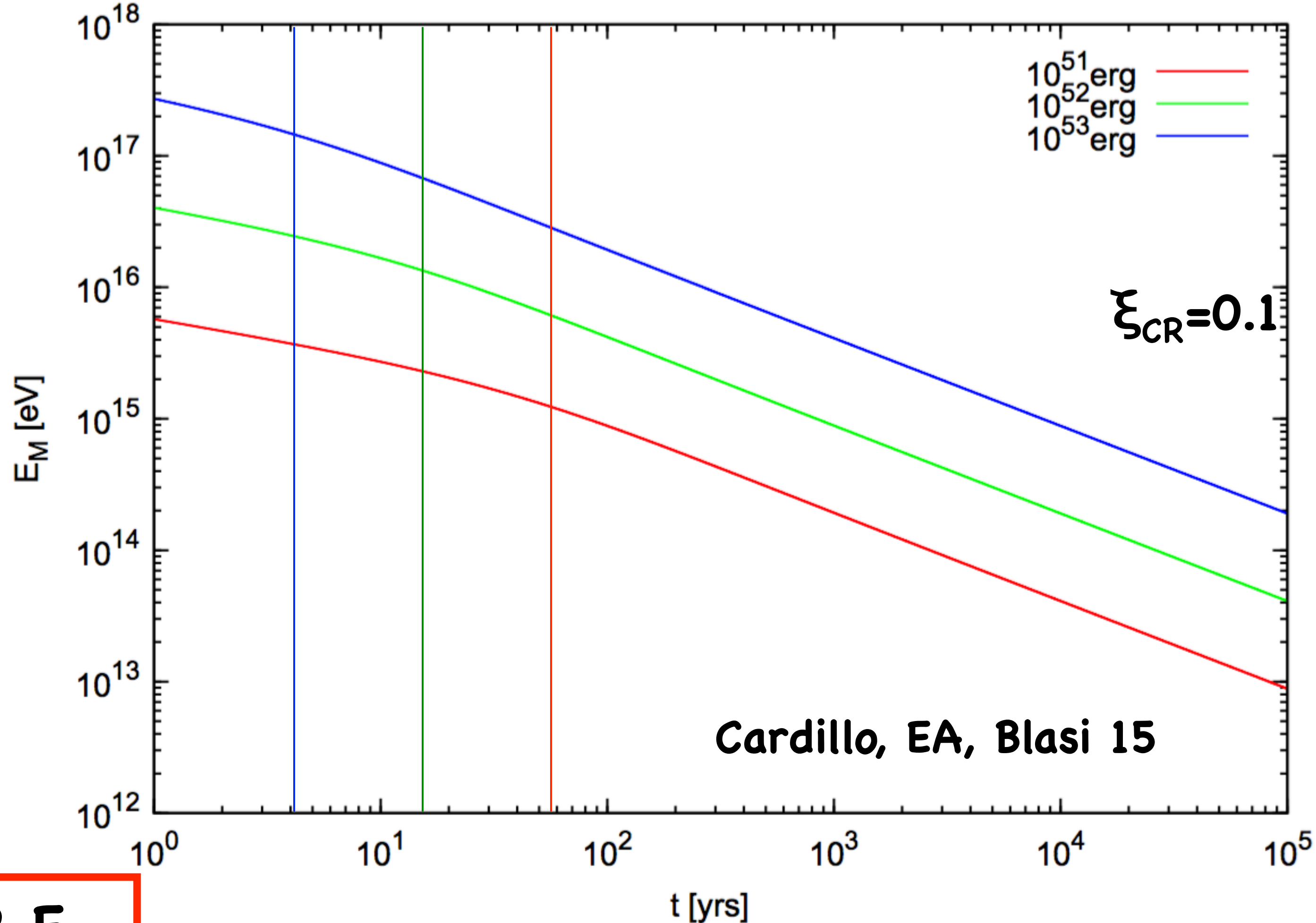
TYPE I

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

TYPE II

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

CHANGING THE EXPLOSION ENERGY



LARGER E_{SN}

- **EARLIER BEGINNING OF THE SEDOV PHASE**
- **LARGER E_M**

RELEASED SPECTRUM VS SOURCE SPECTRUM

$$N_{\rm esc}(E)dE = \frac{J_{\rm CR}}{e} 4\pi R^2 dt$$

RESULT DEPENDS ON DENSITY PROFILE OF EJECTA AND AMBIENT MEDIUM

$$\rho_{\rm ej} \propto R^{-k}$$

$$\rho_{\rm amb} \propto R^{-m}$$

TYPE I

$$m = 0, \quad k = 7$$

$$N_{\rm esc}(E) \propto \begin{cases} E^{-(5+4\epsilon)} & \text{ED phase;} \\ E^{-(2+\epsilon)} & \text{ST phase;} \end{cases}$$

TYPE II

$$m = 2, \quad k = 9$$

$$N_{esc}(E) \propto \begin{cases} E^{-(4+3\epsilon)} & \text{ED phase;} \\ E^{-(2+\epsilon)} & \text{ST phase;} \end{cases}$$

WITH $$\epsilon = \begin{cases} 0 & \beta \le 0 \\ \beta & \beta > 0 \end{cases}$$

AND ASSUMING: $$f_s(E) \propto E^{-(2+\beta)}$$

RELEASED SPECTRUM VS SOURCE SPECTRUM

TYPE I

$$N_{\rm esc}(E) \propto \begin{cases} E^{-(5+4\epsilon)} & \text{ED phase;} \\ E^{-(2+\epsilon)} & \text{ST phase;} \end{cases}$$

TYPE II

$$N_{esc}(E) \propto \begin{cases} E^{-(4+3\epsilon)} & \text{ED phase;} \\ E^{-(2+\epsilon)} & \text{ST phase;} \end{cases}$$

$$\epsilon = \begin{cases} 0 & \beta \leq 0 \\ \beta & \beta > 0 \end{cases}$$

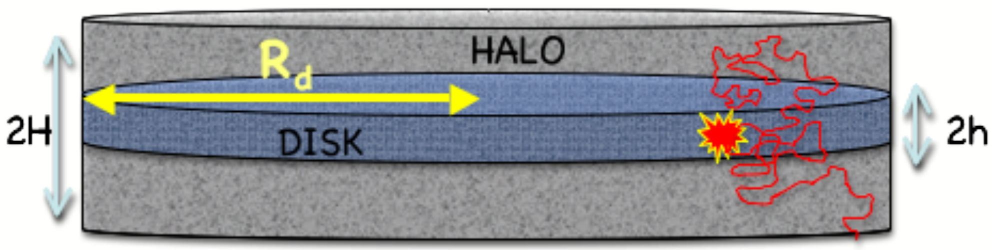
STEEP POWER LAW AT HIGH ENERGY DUE TO PARTICLES ACCELERATED IN THE EJECTA DOMINATED PHASE

IN SEDOV TAYLOR PHASE THE RELEASED SPECTRUM IS

- E^{-2} IF $N_{SOURCE} \approx E^{-2}$ OR FLATTER
- SAME AS N_{SOURCE} IF THIS IS STEEPER

WHAT CR SPECTRA SHOULD SNRS RELEASE?

CR INJECTION SPECTRUM



$$N_S(E) \propto E^{-\gamma_{inj}}$$

$$\tau_{ESC}(E) \approx \frac{H^2}{D(E)} \propto E^{-\delta_e}$$

$$N(E) = \frac{N_S(E)\mathcal{R}}{2\pi R_d^2 H}\tau_{ESC} \propto E^{-\gamma_{inj}-\delta_e}$$

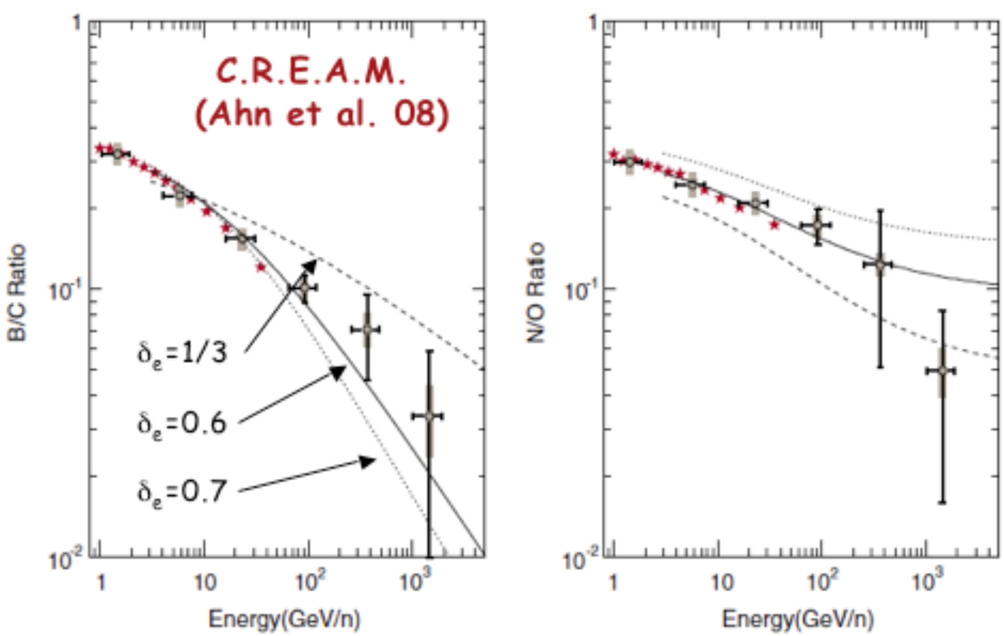
DIFFUSE PARTICLE SPECTRUM ONLY SENSITIVE TO $\gamma_{inj}+\delta_e$

SECONDARIES

$$N_{SEC}(E) = N(E)\mathcal{R}_{SP}\,\tau_{ESC} \propto E^{-\gamma_{inj}-2\delta_e}$$

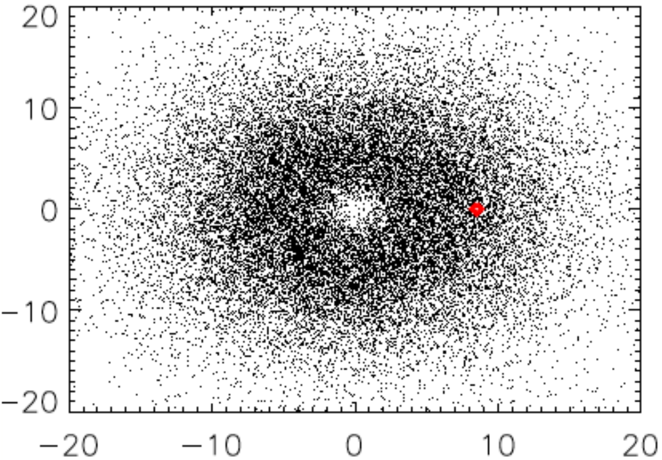
$$\frac{N_{SEC}(E)}{N(E)} \propto E^{-\delta_e}$$

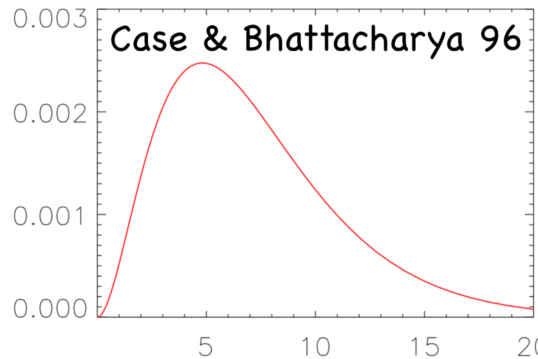
SECONDARY-TO-PRIMARY RATIOS SENSITIVE TO δ_e

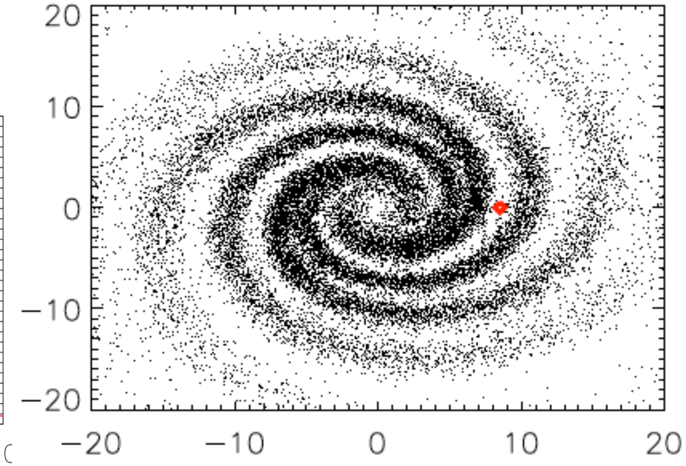


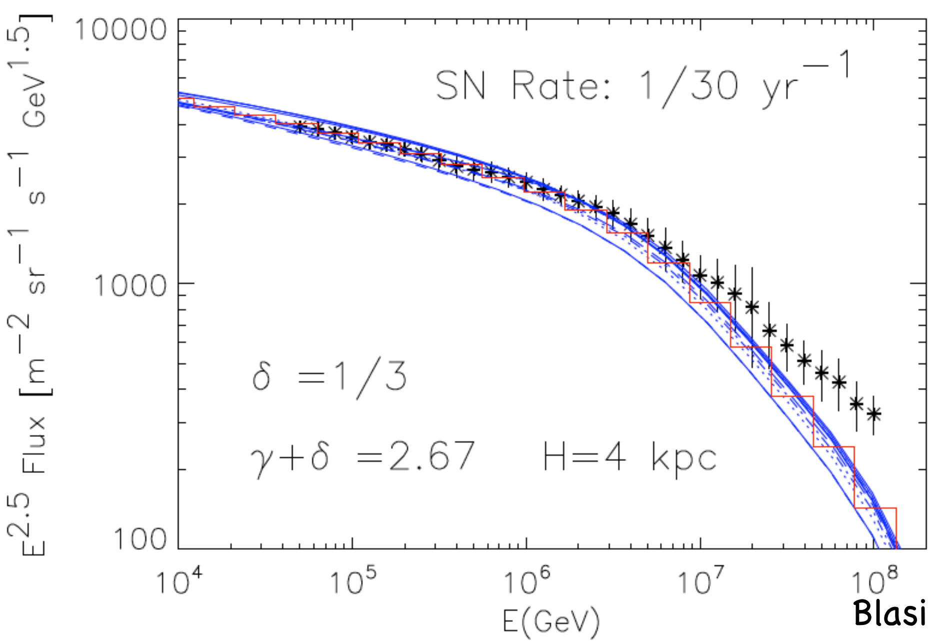
B/C RATIO → $1/3<\delta_e<0.7$

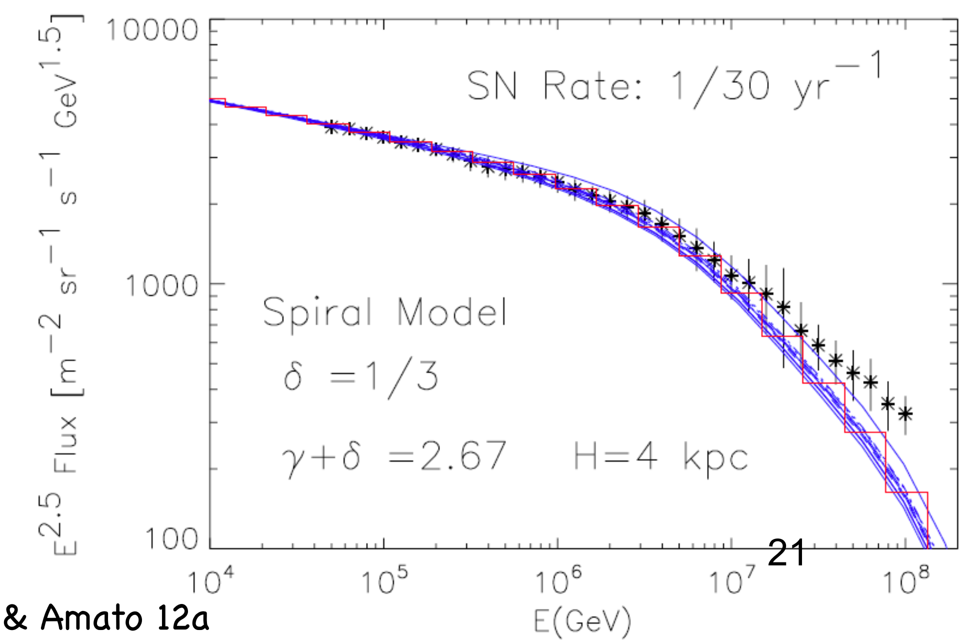
SPECTRA FROM DISCRETE SOURCES





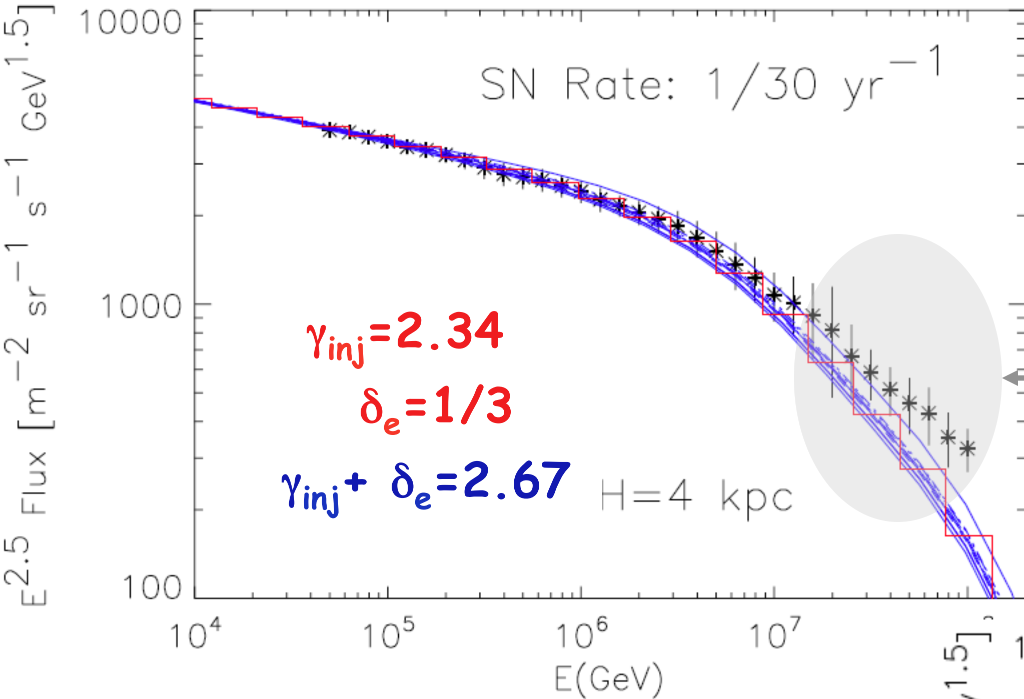






Blasi & Amato 12a

IMPACT OF THE DIFFUSION COEFFICIENT



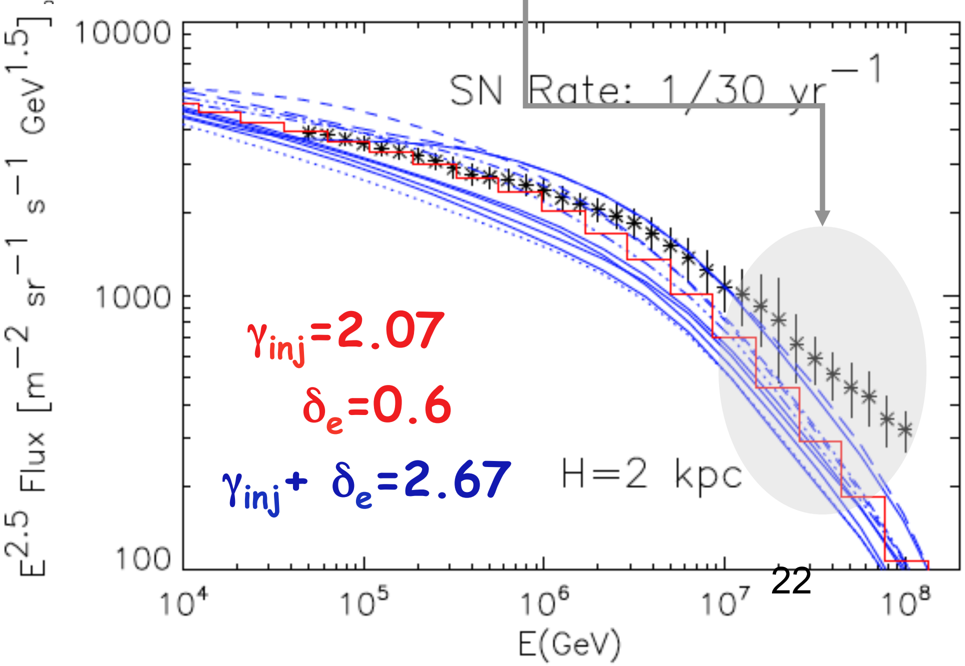
$N_{SRC}(E) \propto E^{-\gamma_{inj}}$ $D(E) \propto E^{\delta_e}$

B/C WAS TELLING US
$1/3 < \delta_e < 0.6$

CONTRIBUTION FROM EXTRAGALACTIC CRs

ONLY DIFFERENCE: FLUCTUATIONS ARE LARGER FOR FASTER DEPENDENCE
(Blasi & Amato 12a)

IMPOSSIBLE TO DISTINGUISH BETWEEN SOURCE SPECTRA BASED ON SPECTRUM AT EARTH ALONE

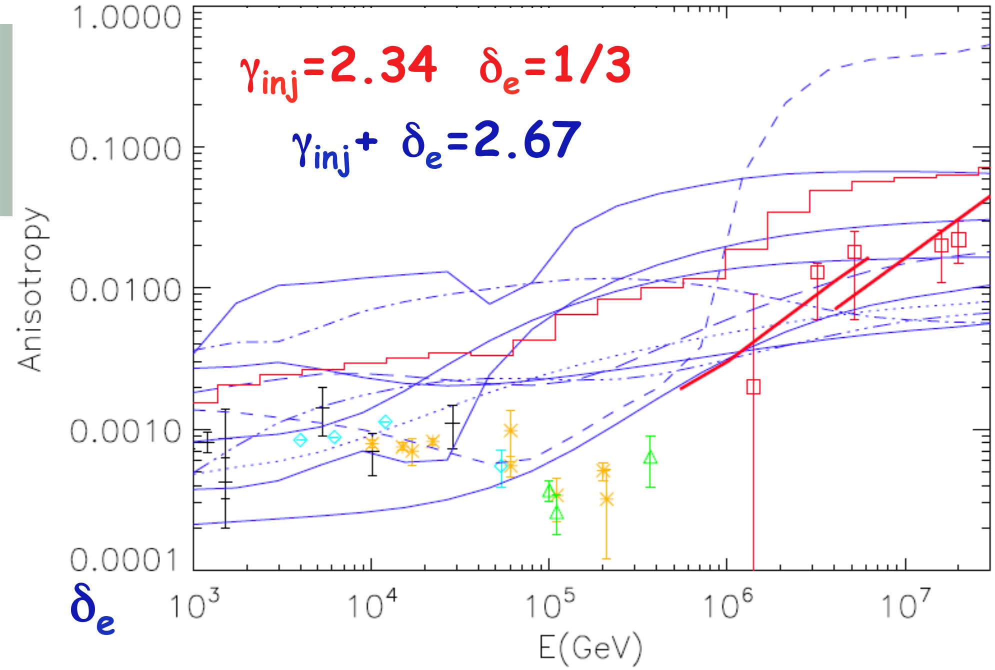


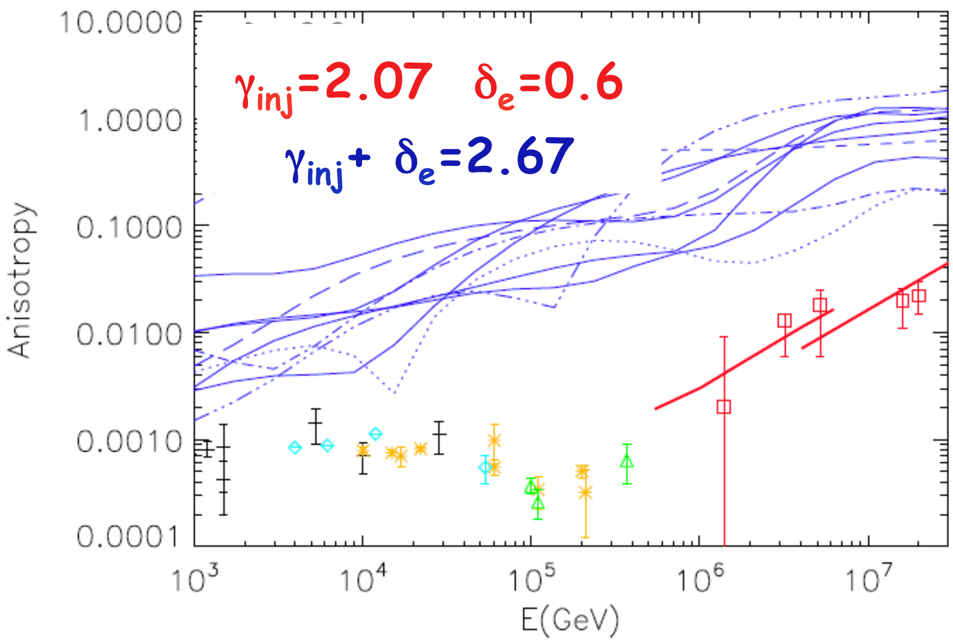
CONSTRAINTS FROM ANISOTROPY

CR SPECTRA AT EARTH → $\gamma_{inj} + \delta_e$

B/C RATIO → $1/3 < \delta_e < 0.7$

ANISOTROPY ALLOWS TO DISENTANGLE BETWEEN INJECTION AND PROPAGATION δ_e

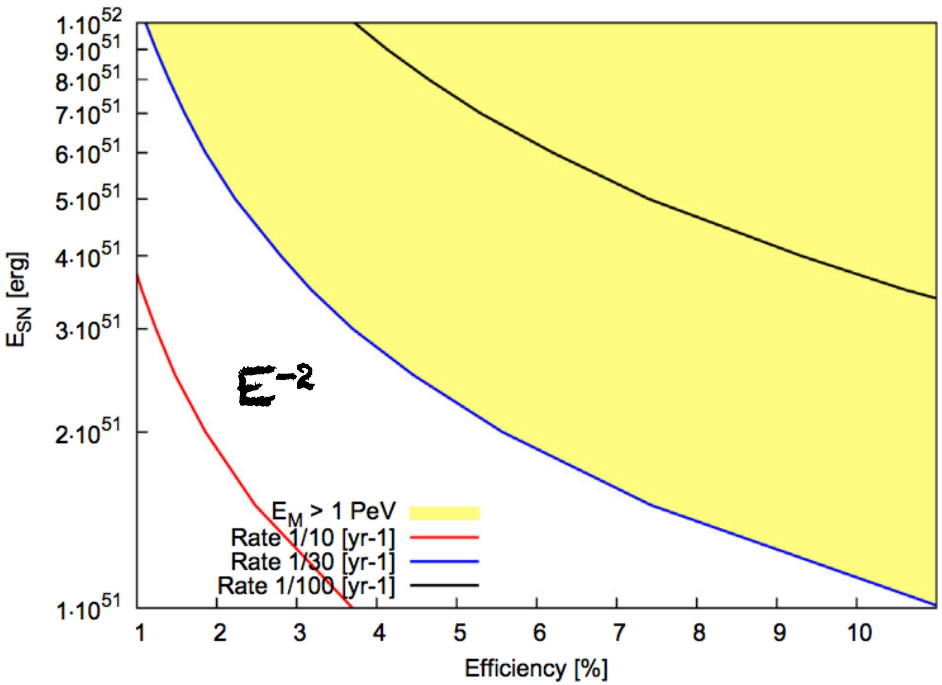




- **ANISITROPY IS TOO LARGE FOR δ=0.6** (Blasi & Amato 12, see also Ptuskin et al 07, Sveshnikova et al 13, Pohl & Eichler 13)
- **FOR δ=1/3 CONFIGURATIONS CLOSE TO DATA CAN BE FOUND**

STEEP INJECTION SPECTRUM IS IMPLIED

MAXIMUM ENERGY AND SOURCE SPECTRUM

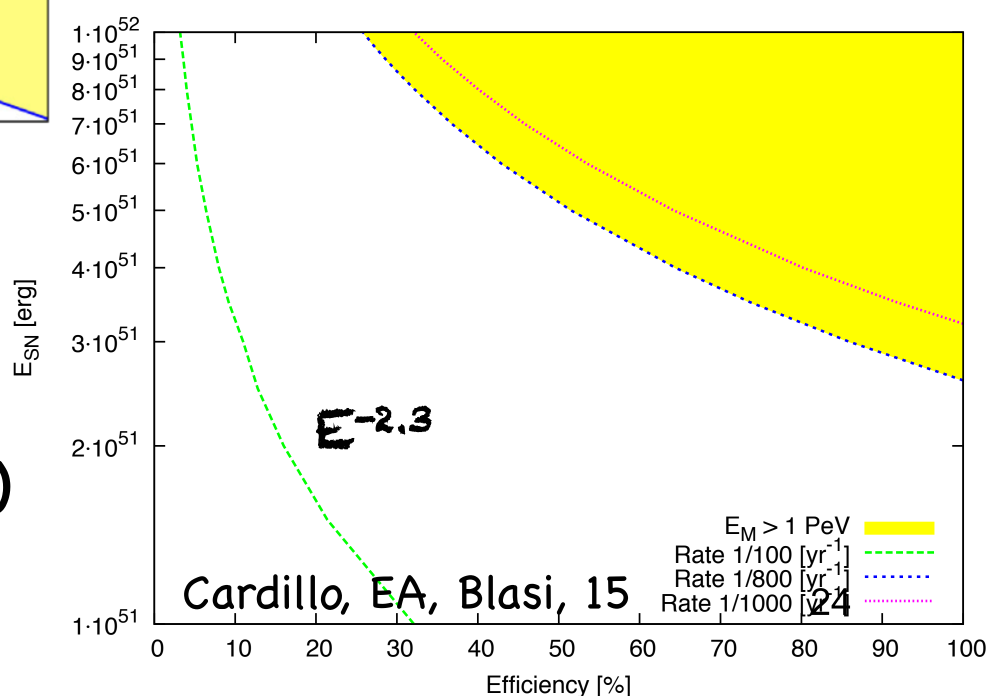


$$E_{\mathrm{MAX}} \propto \xi_{\mathrm{CR}} E_{\mathrm{SN}}$$

$$Flux \propto \xi_{\mathrm{CR}} E_{\mathrm{SN}} \mathcal{R}$$

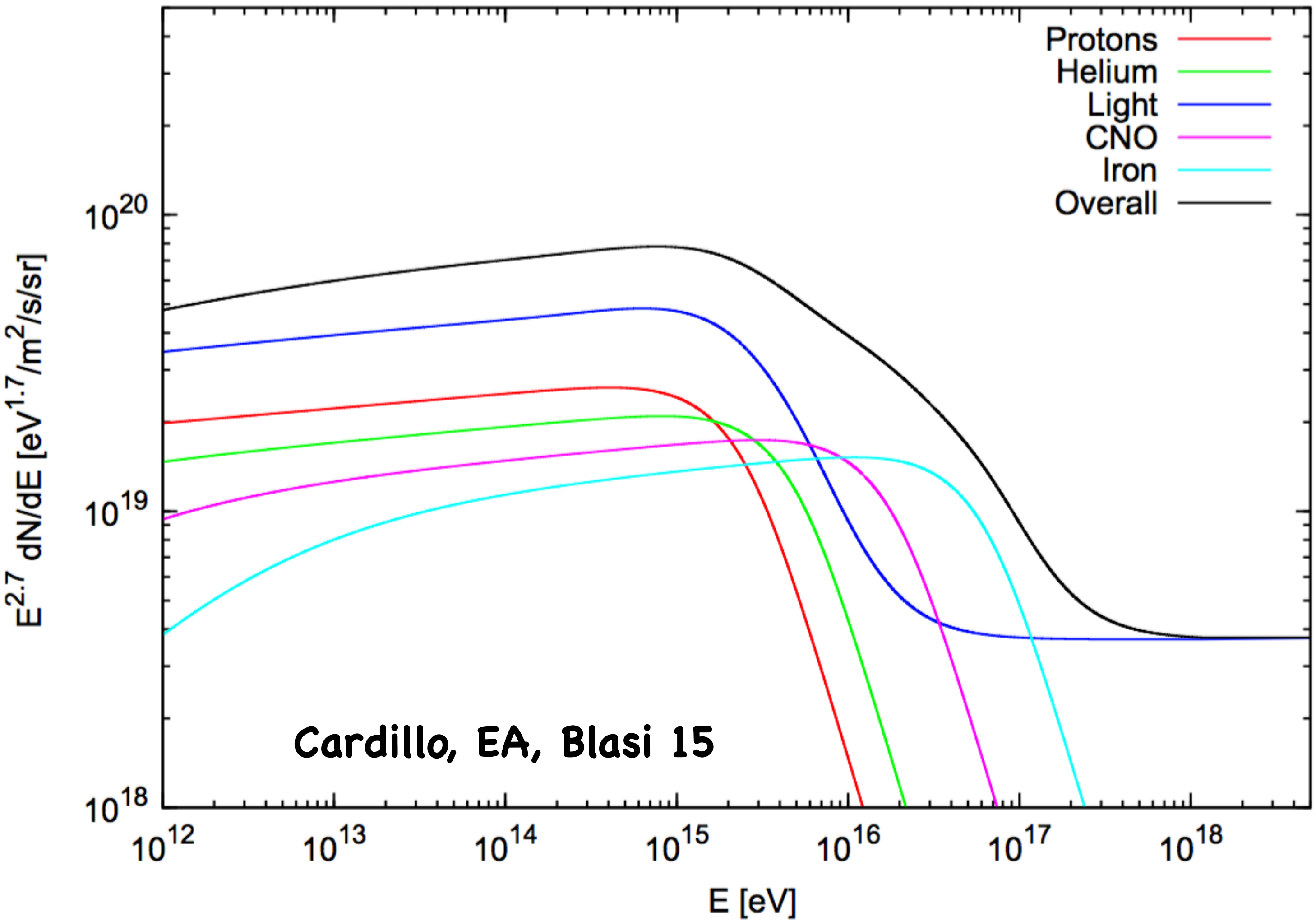
IN ORDER TO REACH THE KNEE WITH STEEP SOURCE SPECTRUM

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



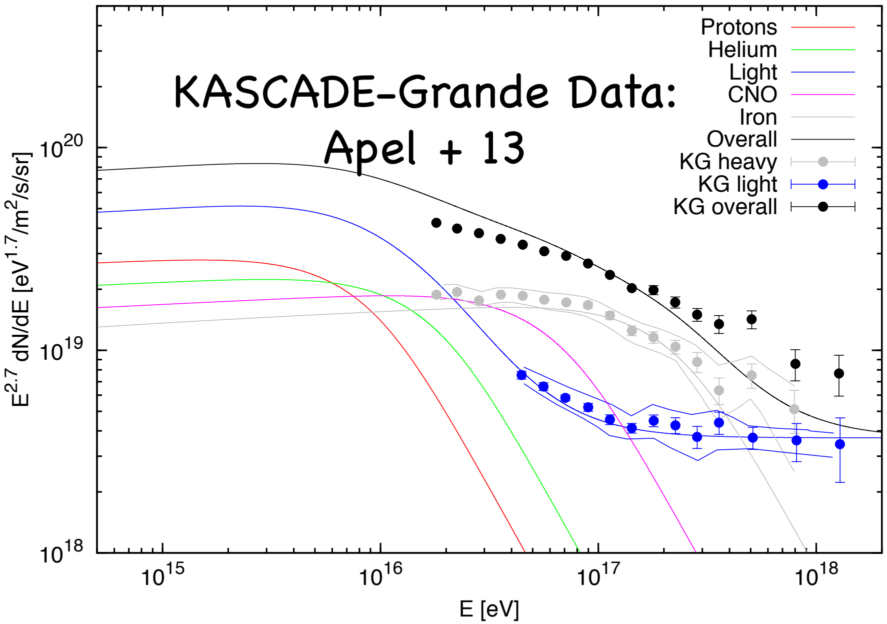
Cardillo, EA, Blasi, 15

HOW THE SPECTRUM LOOKS LIKE



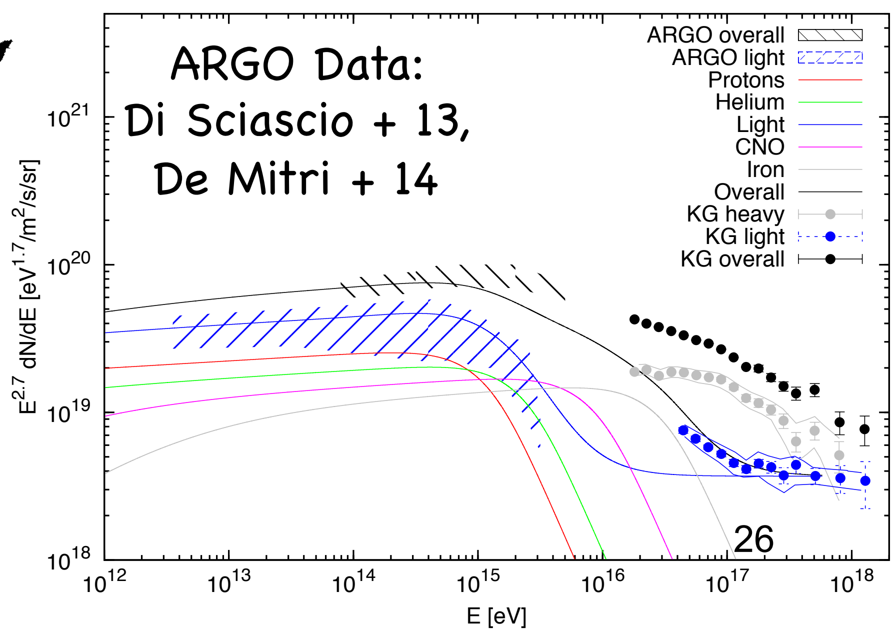
ABOVE THE MAXIMUM ENERGY THE SPECTRUM SHOULD SHOW A STEEPER POWER-LAW RATHER THAN A CUT-OFF, DUE TO PARTICLES ACCELERATED DURING EJECTA DOMINATED PHASE

BUT WHERE IS THE KNEE?



$\xi_{CR} \approx 15\%$ $E_{MAX} \approx 4PeV$
$R \approx 1/100\ yr^{-1}$ $E_{SN} \approx 2 \times 10^{51}$

$\xi_{CR} \approx 5.2\%$ $E_{MAX} \approx 500TeV$
$R \approx 1/15\ yr^{-1}$ $E_{SN} \approx 10^{51}$



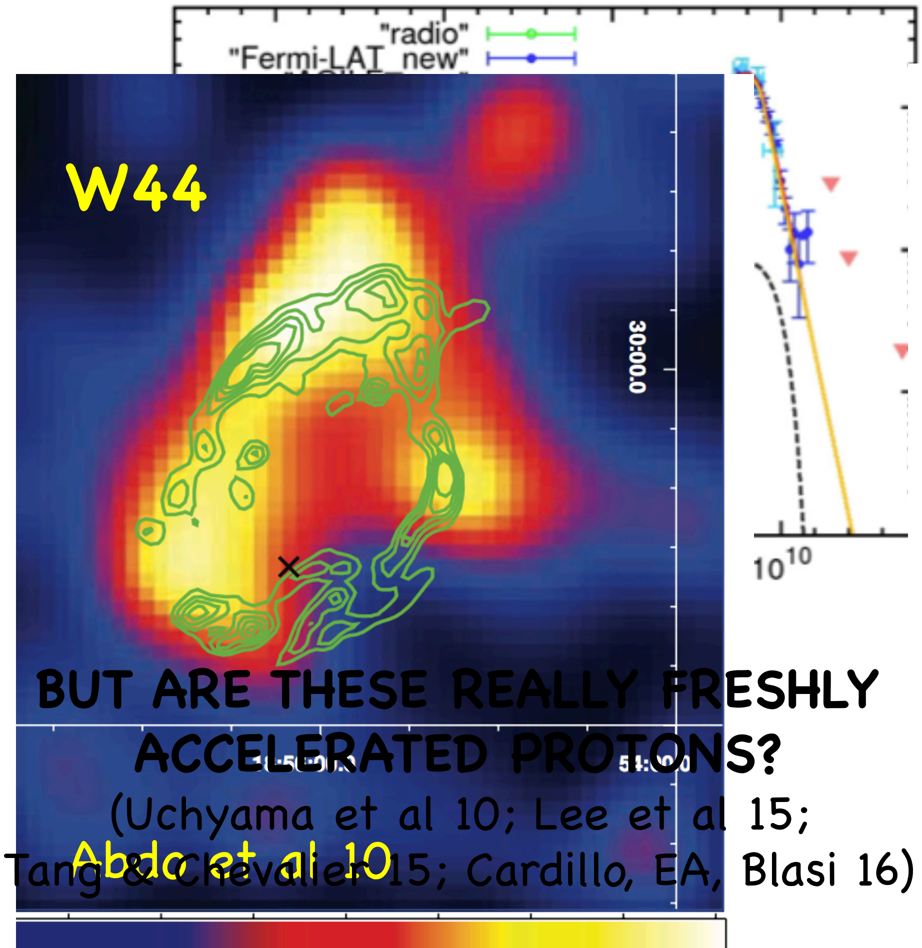
CLEARLY SOME INCONSISTENCY IN THE DATA:

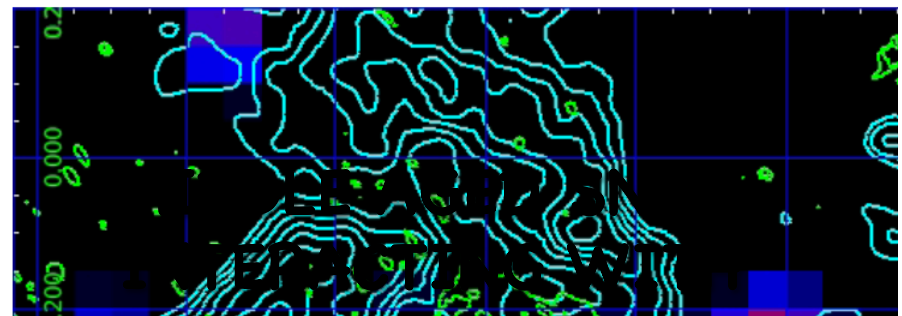
- THE ALL PARTICLE SPECTRUM IS THE SAME
- BUT THE PROTON SPECTRUM CUTS OFF AT 10 TIMES LOWER ENERGY

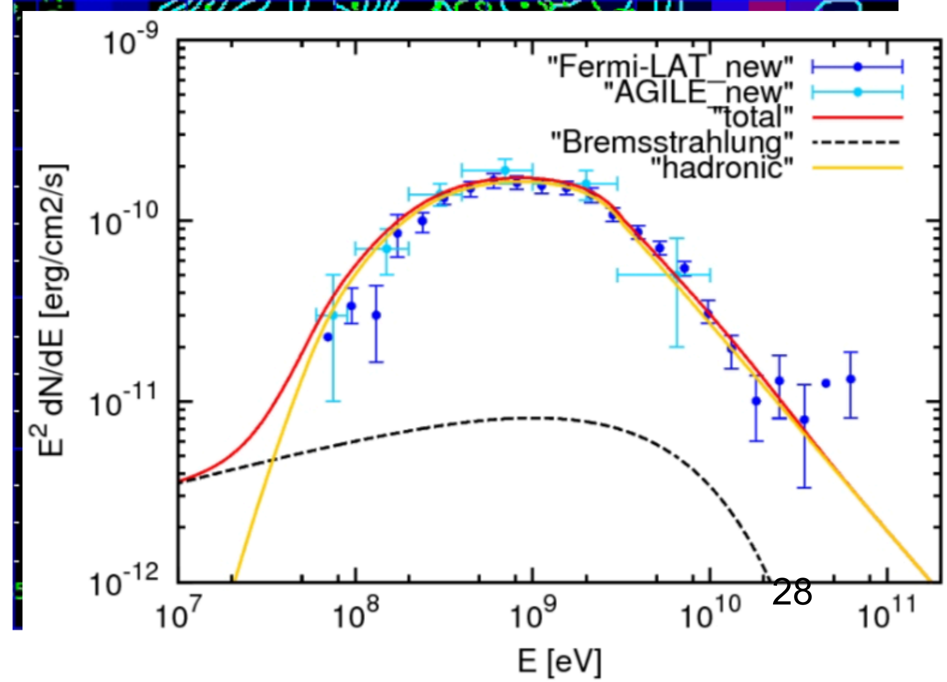
NEWS FROM THE GAMMA-RAY SKY

RELATIVISTIC PROTONS IN SNRs

(AGILE: Giuliani+ 11, Cardillo+ 14; FERMI: Abdo+ 10, Ackermann+ 11)





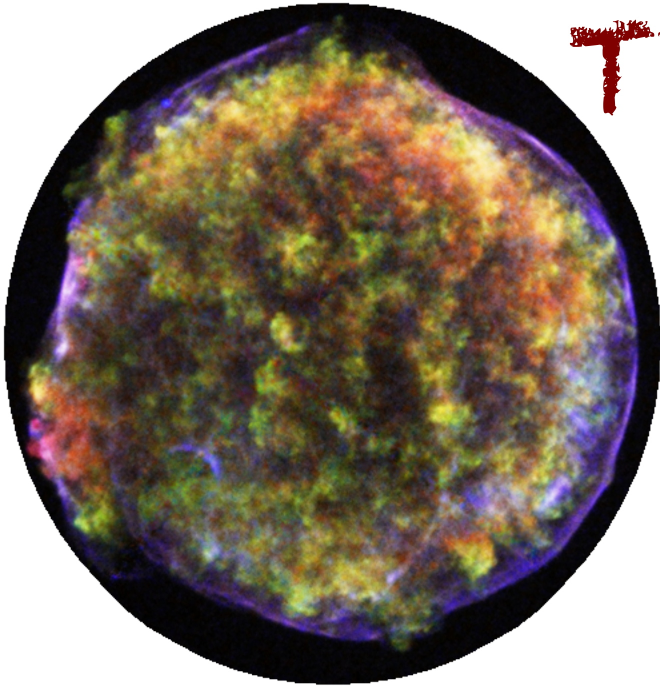


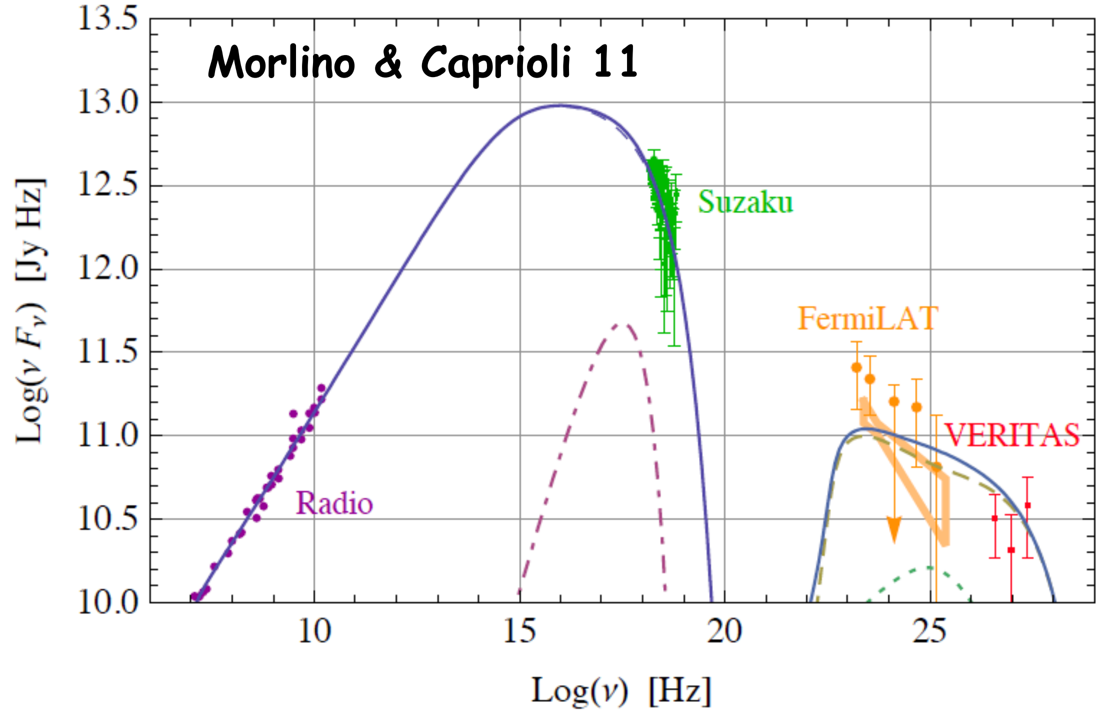
BUT ARE THESE REALLY FRESHLY ACCELERATED PROTONS?

(Uchyama et al 10; Lee et al 15; Tang & Chevalier 15; Cardillo, EA, Blasi 16)

SEE MARTINA CARDILLO'S TALK…

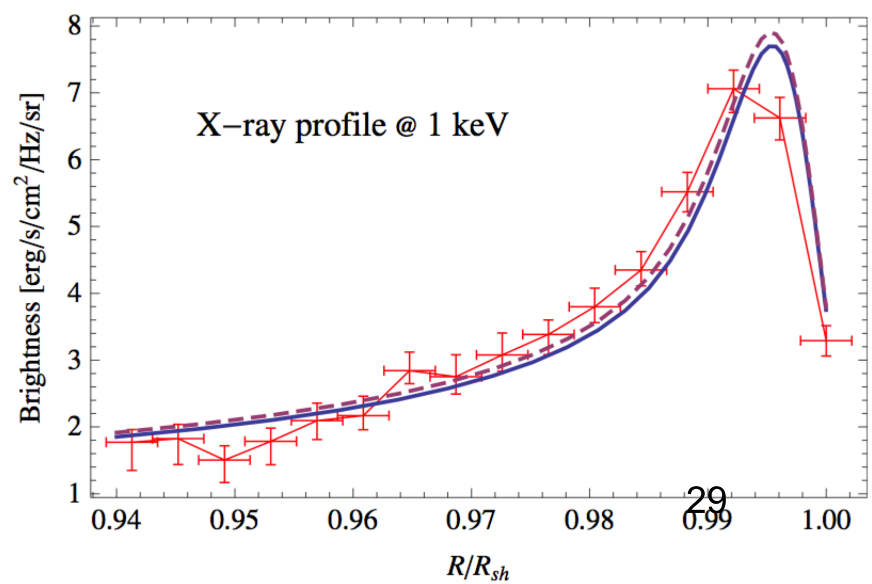
TYCHO





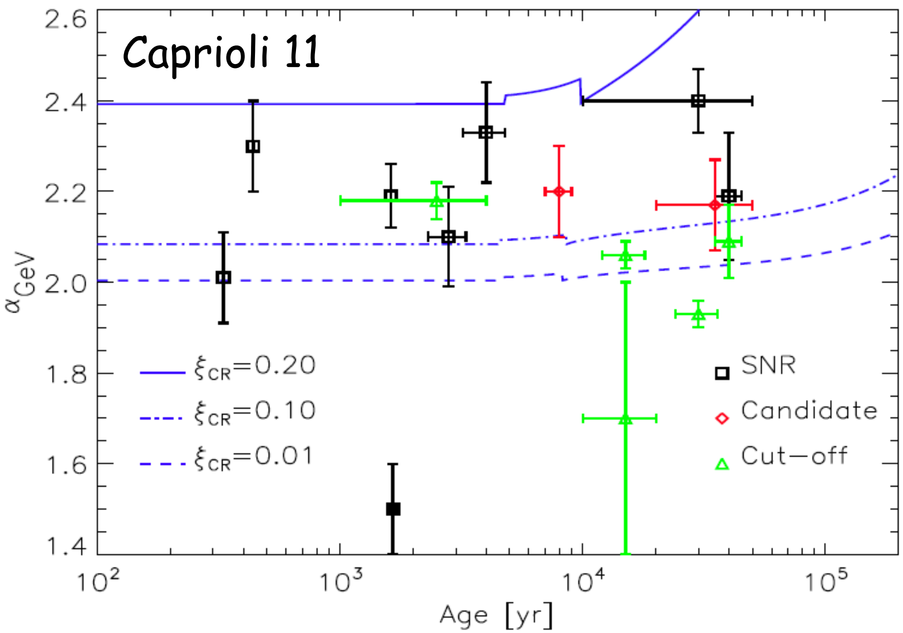
Broad band SED and morphology well reproduced assuming:

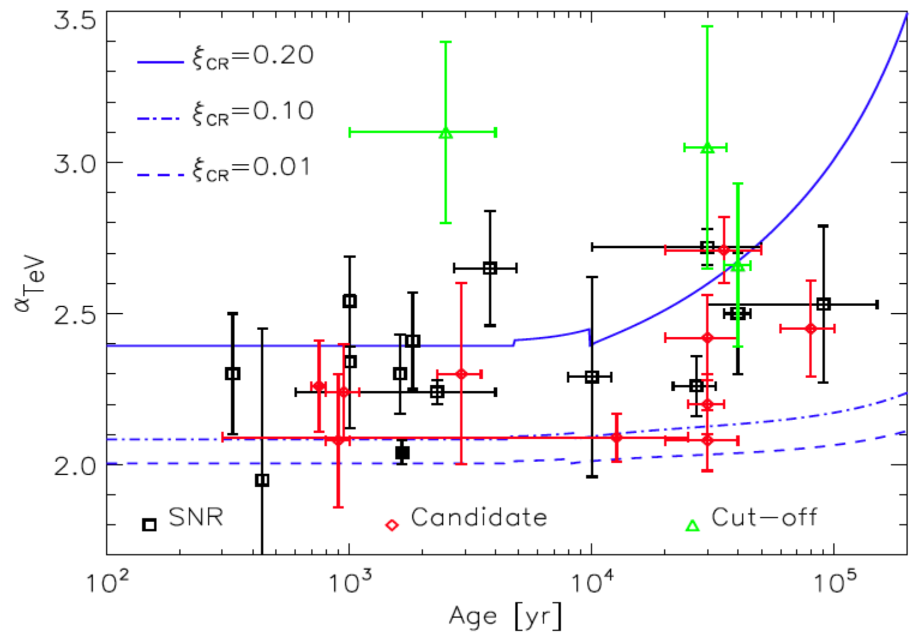
- E_{MAX} ≈500 TeV
- ξ_{CR} ≈10%
- Steep spectrum: $E^{-2.3}$



Discrepancy?

STEEP SOURCE SPECTRA



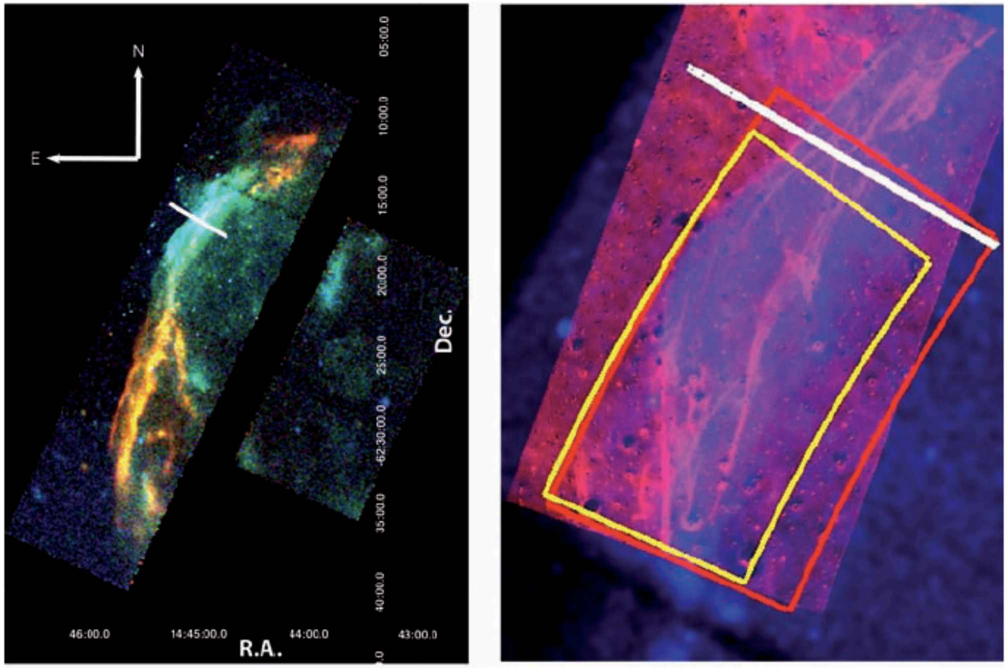


POSSIBLE EXPLANATION: RESULT OF MAGNETIC FIELD AMPLIFICATION (Zirakashvili & Ptuskin 08, Caprioli 11)

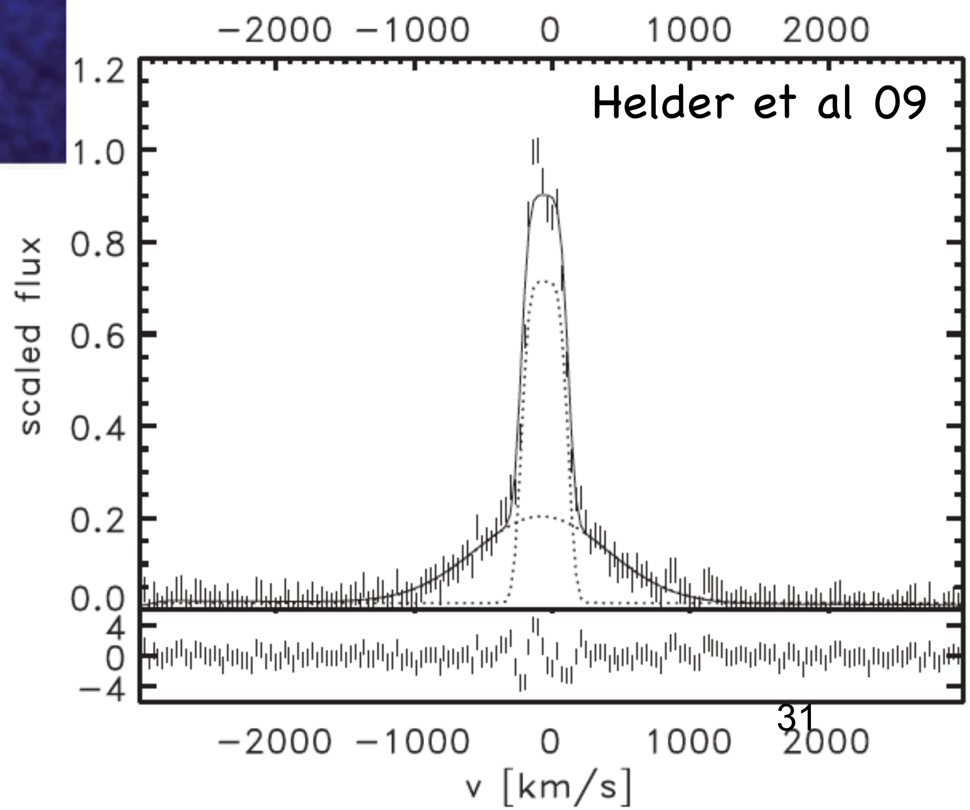
$$r' = \frac{u_1 + v'_{A,1}}{u_2 + v'_{A,2}} \Longrightarrow \alpha = \frac{r'+2}{r'-1} > 2$$

- CAVEAT: DEPENDS ON DETAILS OF THE TURBULENCE PROPERTIES
- ALSO OTHER WAYS...

NEWS FROM THE OPTICAL



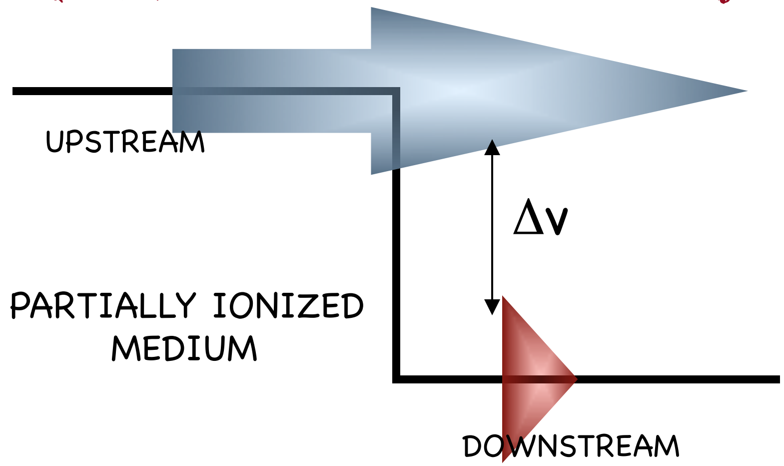
CR ACCELERATION EFFICIENCY CAN BE ESTIMATED FROM BALMER LINES STUDY (E.G. Helder et al 09): $T_{i,2}$ vs V_s



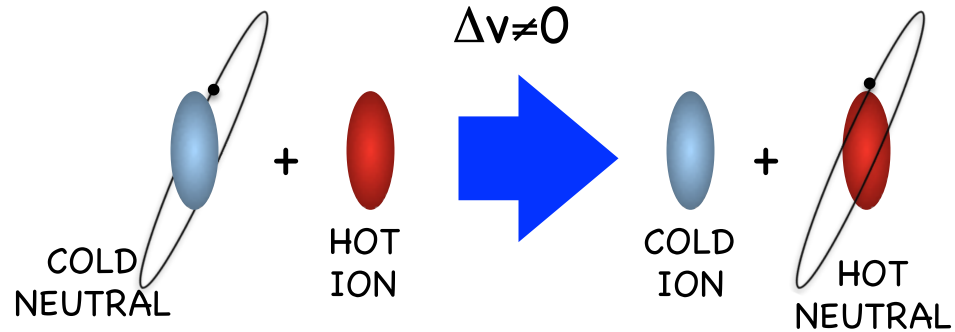
BALMER DOMINATED SHOCKS
(Chevalier & Raymond 78,
Heng & McCray 07, Heng et al 07,
van Adelsberg et al 08)

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

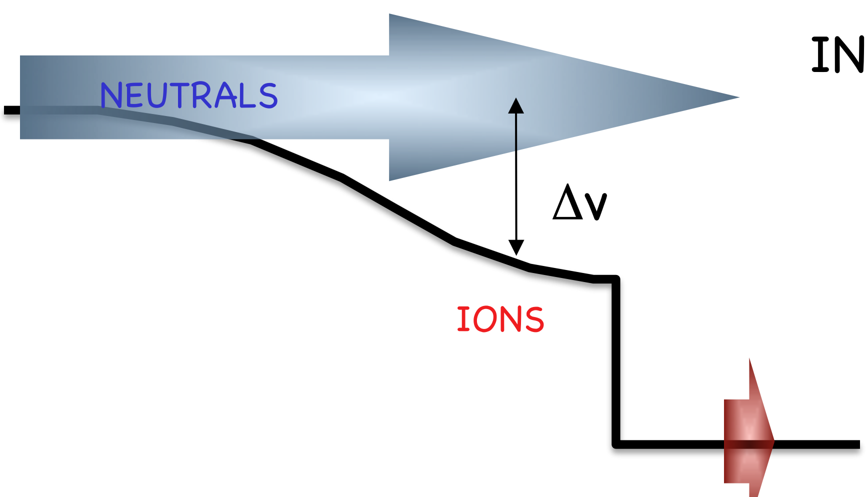
THE EFFECT OF NEUTRALS



CHARGE EXCHANGE WHERE $\Delta v \neq 0$



- BROAD BALMER LINE $\leftarrow$ DOWNSTREAM T_{ION}
- NARROW BALMER LINE $\leftarrow$ UPSTREAM T_{ION}
- EFFICIENT CR ACCELERATION $\Rightarrow$ LOWER DOWNSTREAM T_{ION} $\rightarrow$ NARROWER BROAD LINE



IN MODIFIED SHOCKS CE IN PRECURSOR

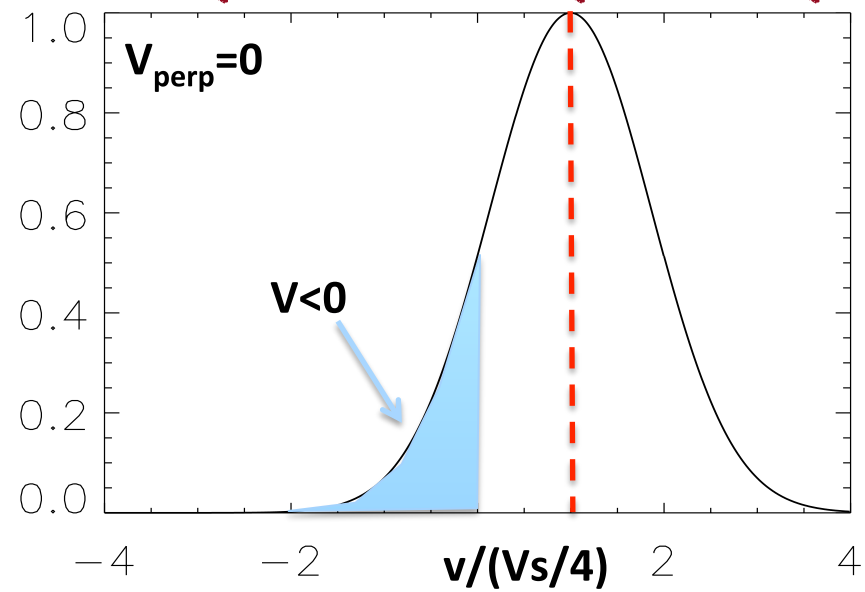
- EFFICIENT CR ACCELERATION $\Rightarrow$ HIGHER UPSTREAM T_{ION} $\rightarrow$ BROADER NARROW LINE
- IN RCW86 BOTH EFFECTS OBSERVED (Sollerman et al 03, Helder et al. 09)

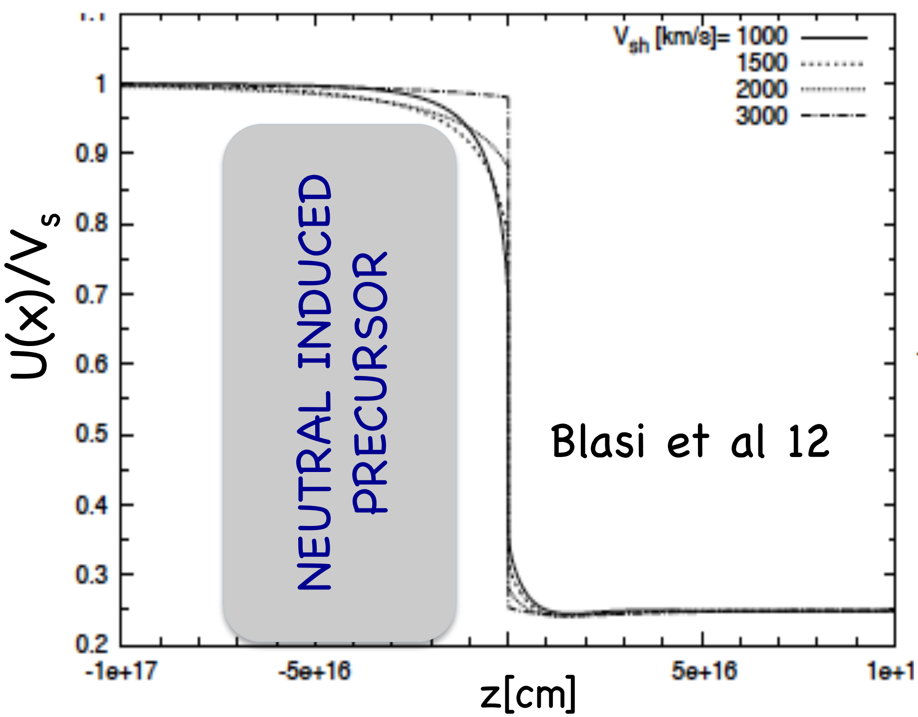
A DIFFERENT PRECURSOR

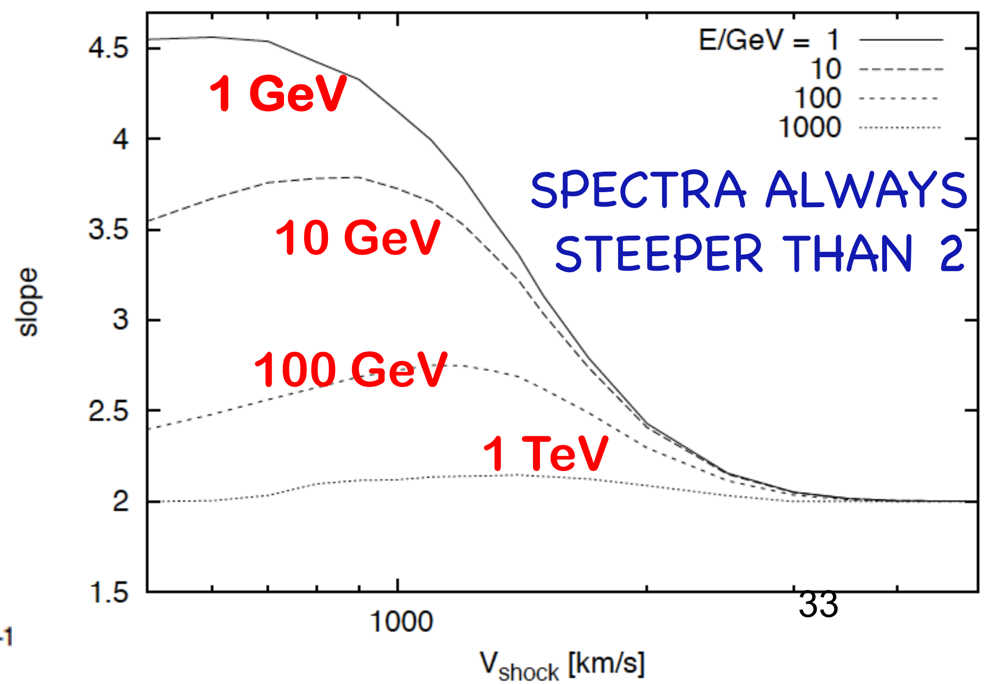
CE DOWNSTREAM WITH COUNTERSTREAMING IONS

NEUTRAL RETURN FLUX

ENERGY AND MOMENTUM DEPOSITION UPSTREAM



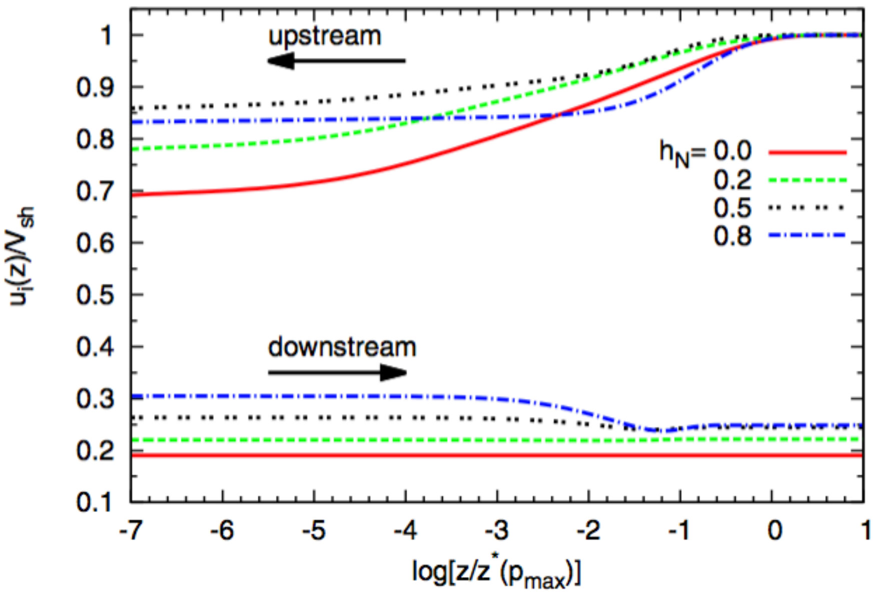


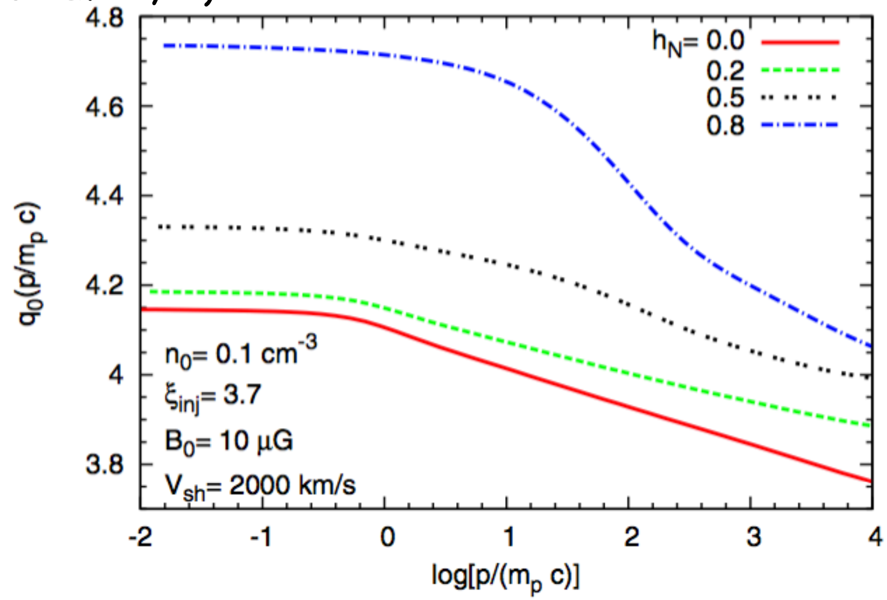


CR MODIFIED SHOCKS IN PARTIALLY IONIZED ISM

VARYING NEUTRAL FRACTION
SHOCK VELOCITY FIXED AT 2000 km/s

(Morlino et al 12,13)





CR PRECURSOR IS STRONGLY SUPPRESSED
q>4 EVEN AT 10 TeV IF IONIZATION IS <50%

INFERRED ACCELERATION EFFICIENCY OF 30% IN RCW86!!!!

(Morlino et al 14)

HOWEVER NO EFFECTS FOR FAST SHOCKS

SUMMARY

- WE LIKELY HAVE NOT SEEN CR ACCELERATION IN SNRs YET
- ACCUMULATING EVIDENCE THAT CR SOURCES ACCELERATE PARTICLES WITH STEEP SPECTRA
- NOT CLER HOW SNRs CAN REACH THE KNEE..
- CONFLICTING DATA ON WHERE THE KNEE IS
- NUMERICAL EXPERIMENTS FINALLY WITHIN REACH TO PROBE OUR THEORIES ON PARTICLE ACCELERATION
- THE GENERAL PICTURE OF NON-LINEAR SHOCK ACCELERATION AND A NUMBER OF SIMPLIFICATIONS PROVEN TO BE OK
- NEW PATHS FOR FINDING EVIDENCE OF CR ACCELERATION ARE JUST BEGINNING TO BE EXPLORED