Cosmic Ray Acceleration at Supernova*e* Remnants

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Giacinti & Bell, To appear ; Bell et al. MNRAS 431, 415 (2013)

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Outline

I – Cosmic Ray Acceleration and escape at SNR shocks

→ ***How do CR escape SNR?***

→ ***Importance of magnetic field amplification***

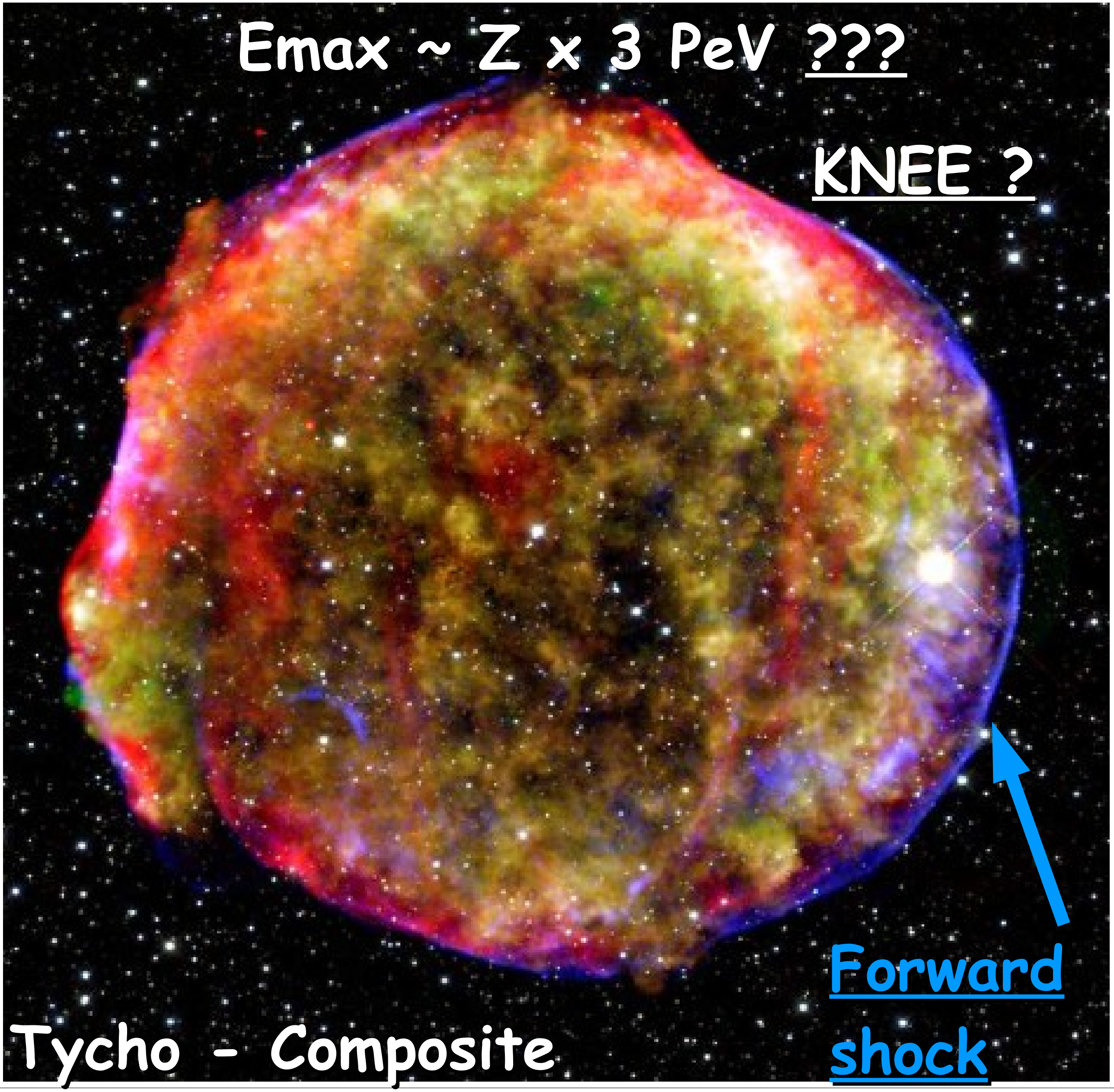
→ ***Can SNR accelerate CR to > 1 PeV ... when ?***

... *First few DECADES following the SN explosion ?*

II – SNe in dense winds as PeVatrons

Sources, acceleration mechanism

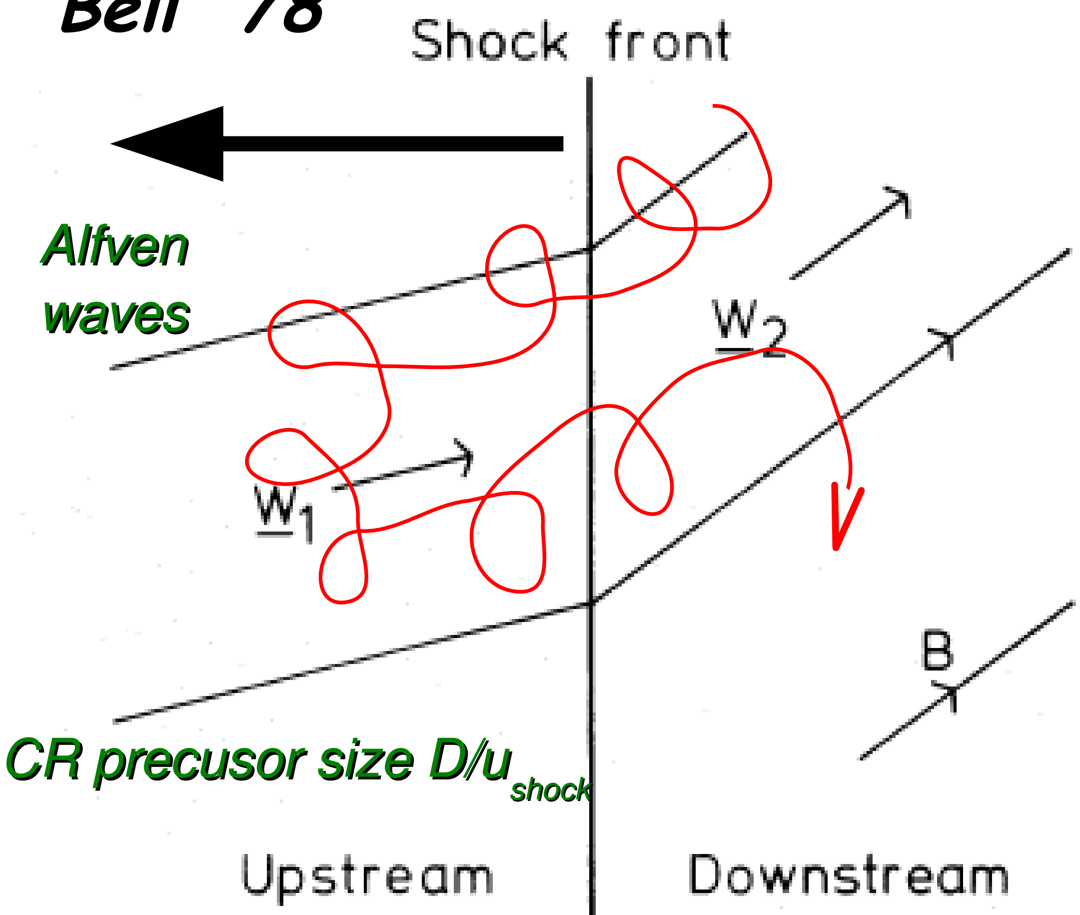
Supernova
remnant



Sources, acceleration mechanism

Diffusive shock acceleration (Krymskii '77; Axford *et al.* '77; Bell '78; Blandford & Ostriker '78)

Bell '78



$$\tau = \frac{4D_{upstream}}{u_{shock}^2} + \frac{4D_{downstream}}{(u_{shock}/4)^2} \approx \frac{8D_{upstream}}{u_{shock}^2}$$

E_{max} for : $\tau = R/u_{shock}$

$D_{Bohm} = cR_g/3$

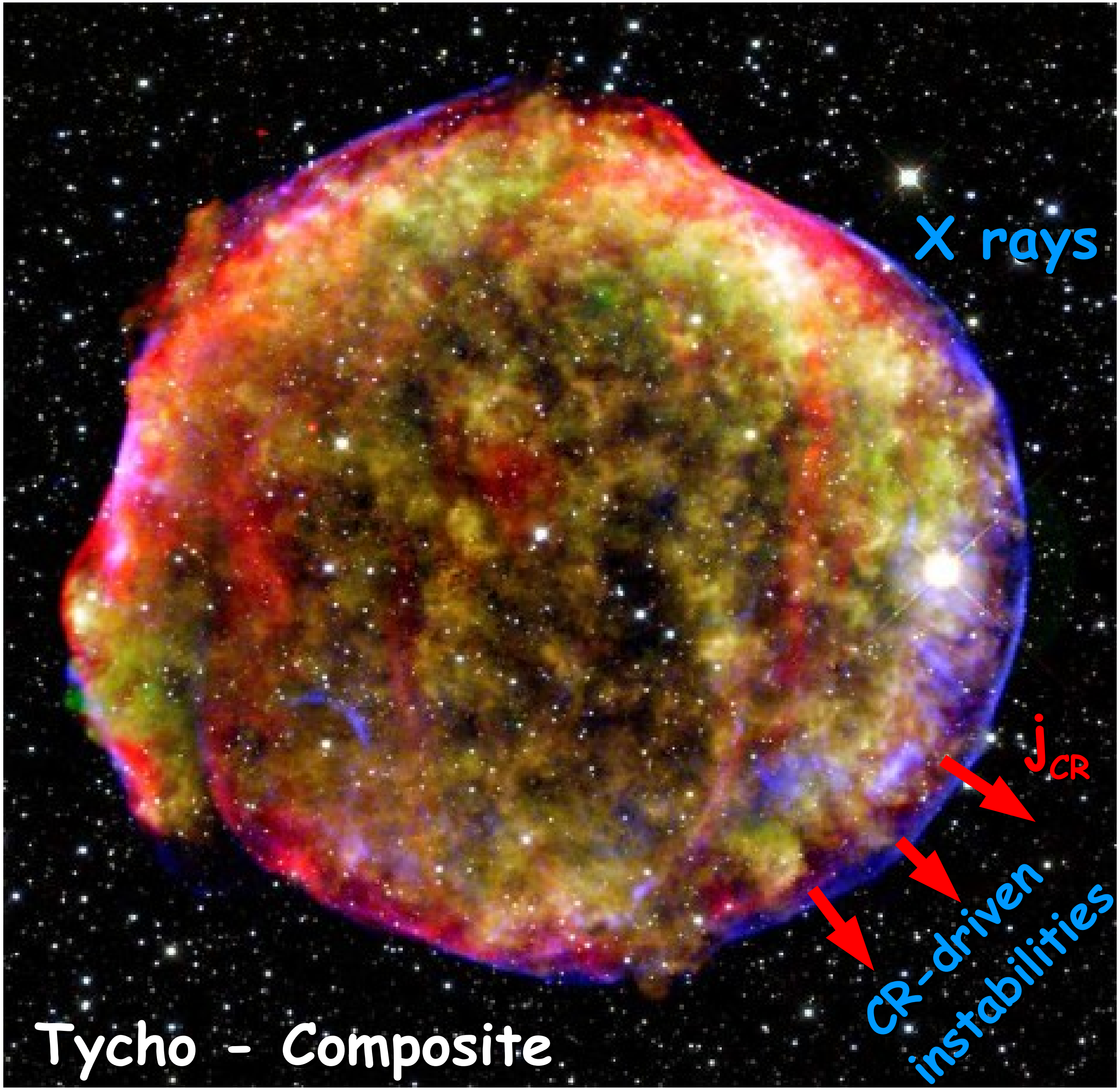
$$E_{max} = \frac{3}{8} u_{shock} BR$$

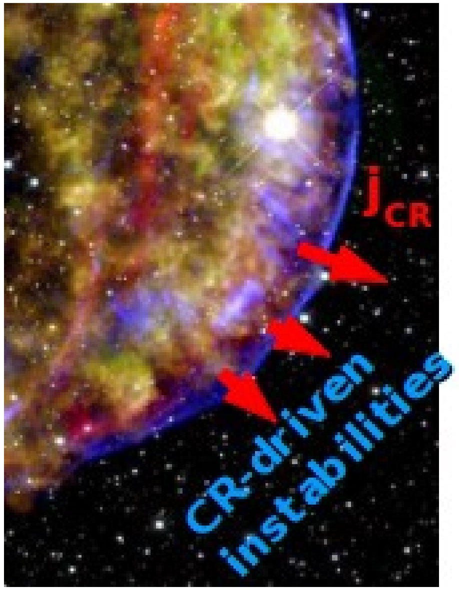
300 yrs, B ~ 3 µG, u_{shock} ~ 5000 km s^{-1}

=> E_{max} ~ 10 TeV !!!

= > Need for MF amplification

Sources, acceleration mechanism





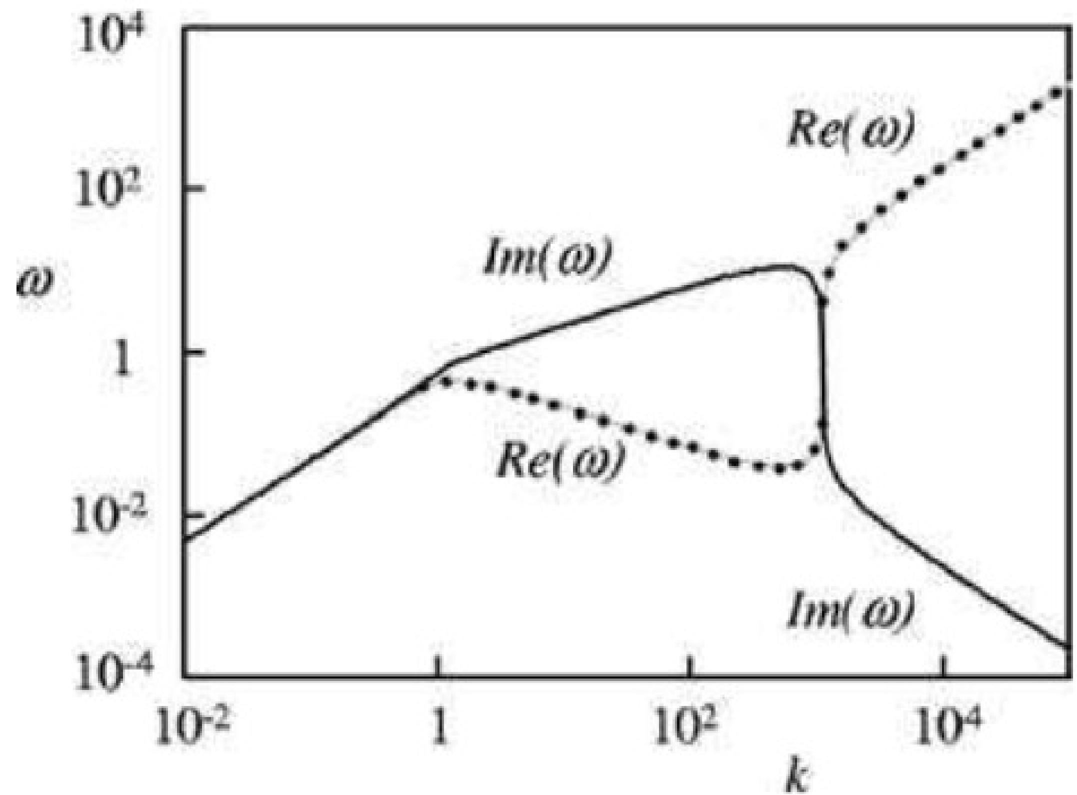
Bell's instability

Large CR current densities :
Bell's non-resonant hybrid instability

(Bell '04)

$$\text{if } B j_{\rm CR} r_{\rm L} / (\rho_{\rm ISM} v_{\rm A}^2) > 1$$

$$\Gamma_{\rm BNRH} = 0.5 j_{\rm CR} \sqrt{\mu_0 / \rho_{\rm ISM}}$$



Bell's instability

(Bell '04)

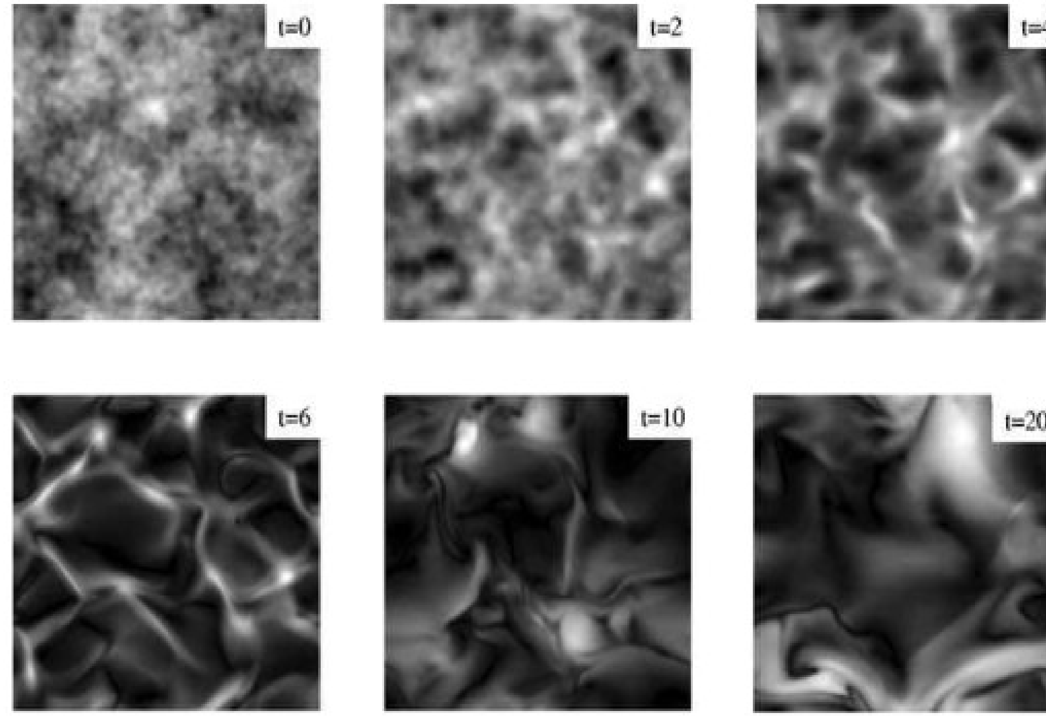
carries a charge density $-n_{\rm cr}e$. If the background plasma carries a current density $\boldsymbol{j}$ in its local rest frame, then $\nabla \wedge \boldsymbol{B} = \mu_0(\boldsymbol{j}_{\rm cr} + \boldsymbol{j} - n_{\rm cr}e\,\boldsymbol{u})$ where $\boldsymbol{u}$ is the local plasma fluid velocity. Consequently, in the upstream rest frame (moving at speed $v_{\rm s}$ relative to the shock), the momentum equation for the background plasma is

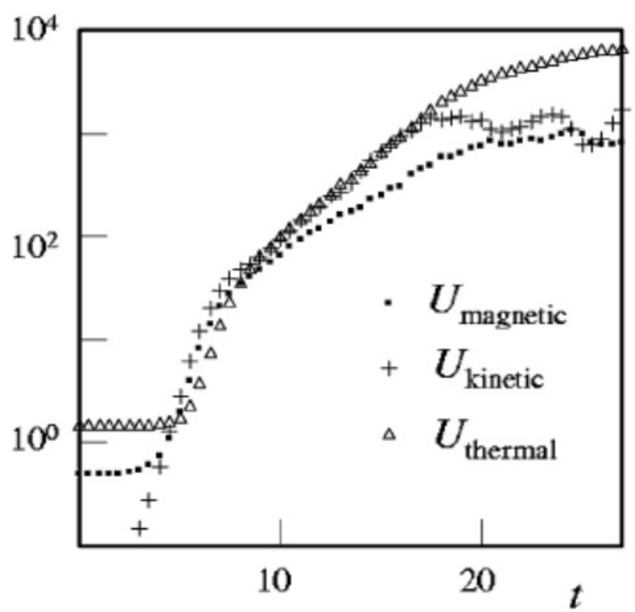
$$\rho \frac{{\rm d}\boldsymbol{u}}{{\rm d}t} = -\nabla P - \frac{1}{\mu_0}\boldsymbol{B} \wedge (\nabla \wedge \boldsymbol{B}) - \underline{\boldsymbol{j}_{\rm cr} \wedge \boldsymbol{B}} + n_{\rm cr}e\boldsymbol{u} \wedge \boldsymbol{B}, \qquad (1)$$

where P is the background plasma pressure. The plasma pressure plays no part in the linear calculation as the fluctuations are transverse in the cases we consider. The other MHD equations are unaffected by the presence of the CR:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \wedge (\boldsymbol{u} \wedge \boldsymbol{B}); \qquad \frac{{\rm d}\rho}{{\rm d}t} = -\nabla \cdot (\rho \boldsymbol{u}). \qquad (2)$$

These equations make it clear that the MHD turbulence is driven by the $-\boldsymbol{j}_{\rm cr} \wedge \boldsymbol{B}$ force exerted in reaction to the $\boldsymbol{j}_{\rm cr} \wedge \boldsymbol{B}$ force exerted on CR through the current they carry.





→ Instability grows & saturates ?
→ B field strength ?
→ Max. CR energy ?
→ CR escape upstream?

CR acceleration and escape

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Cosmic-ray acceleration and escape from supernova remnants

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a background plasma modelled magnetohydrodynamically. Standard MHD equations describe the background plasma except that a $-\mathbf{j}_{CR} \times \mathbf{B}$ force is added to the momentum equation:

Bkg plasma →

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla P - \frac{1}{\mu_0}\mathbf{B} \times (\nabla \times \mathbf{B}) - \underline{\mathbf{j}_{CR} \times \mathbf{B}} \quad (7)$$

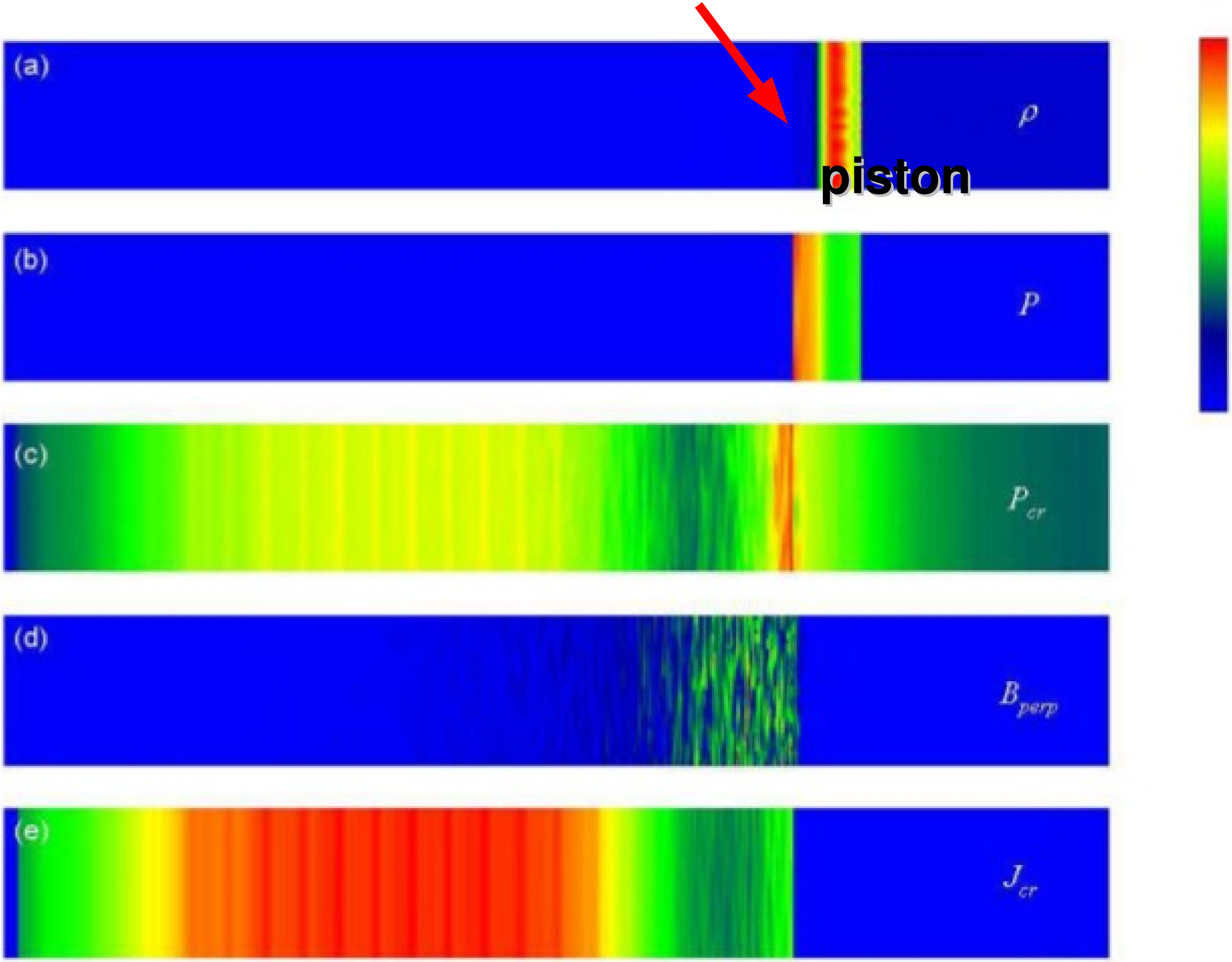
as described in Lucek & Bell (2000) and Bell (2004). The CR distribution function $f(\mathbf{r}, \mathbf{p}, t)$ at position $\mathbf{r}$ and momentum $\mathbf{p}$ is defined in the local fluid rest frame and evolves according to the Vlasov-Fokker-Planck (VFP) equation

CRs →

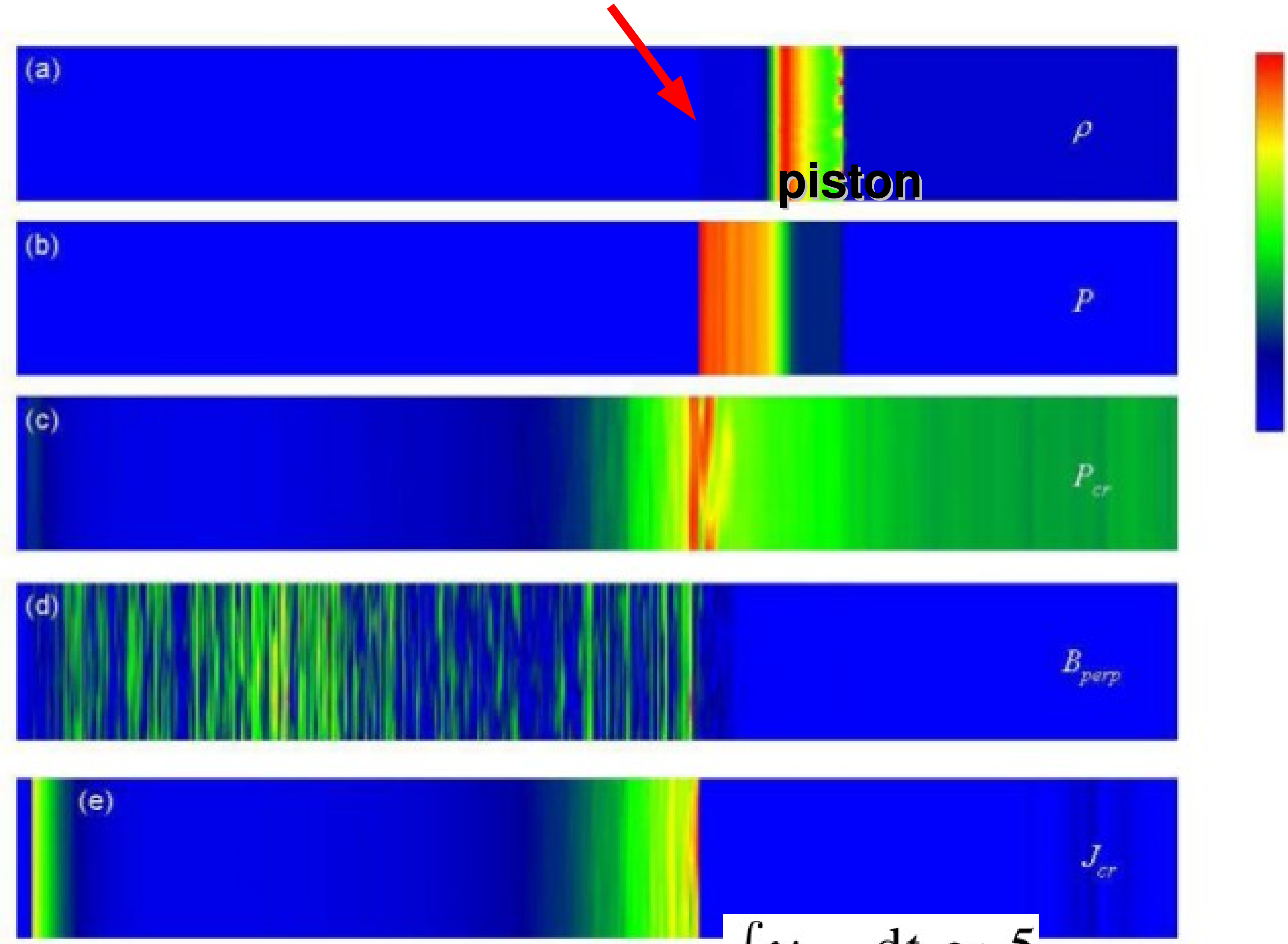
$$\frac{df}{dt} = -v_i \frac{\partial f}{\partial r_i} + p_i \frac{\partial u_j}{\partial r_i} \frac{\partial f}{\partial p_j} - \epsilon_{ijk} e v_i B_j \frac{\partial f}{\partial p_k} + C(f) \quad (8)$$

where $C(f)$ is an optional collision term included to represent scattering by magnetic fluctuations on a small scale. The electric field is zero in the local fluid rest frame.

CR acceleration and escape



CR acceleration and escape

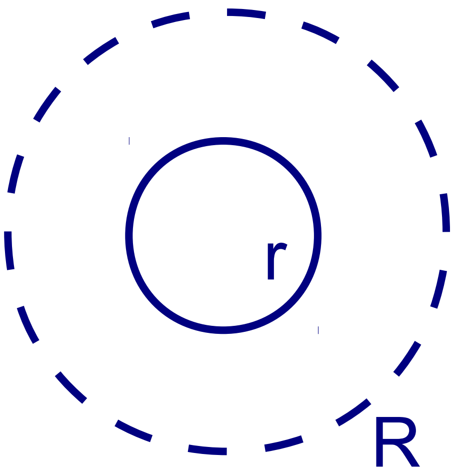


$$\int \gamma_{\rm max} {\rm d}t \sim 5$$

CR acceleration and escape

$$\int \gamma_{\max} \mathrm{d}t \sim 5 \qquad\qquad Q_{\mathrm{CR}} = \int j_{\mathrm{CR}} \mathrm{d}t = 10\sqrt{\rho/\mu_0}$$

CR charge through a unit surface, upstream



The CR current density at a radius R is $j_{\mathrm{CR}} = \eta\rho u_s^3 r^2/R^2 T$ (CRs accelerated to energy eT when the shock radius was r)

$$\int_0^R \frac{\eta\rho(r)u_s^2(r)}{T(r)}\, r^2 \mathrm{d}r = 10R^2\sqrt{\frac{\rho(R)}{\mu_0}}$$

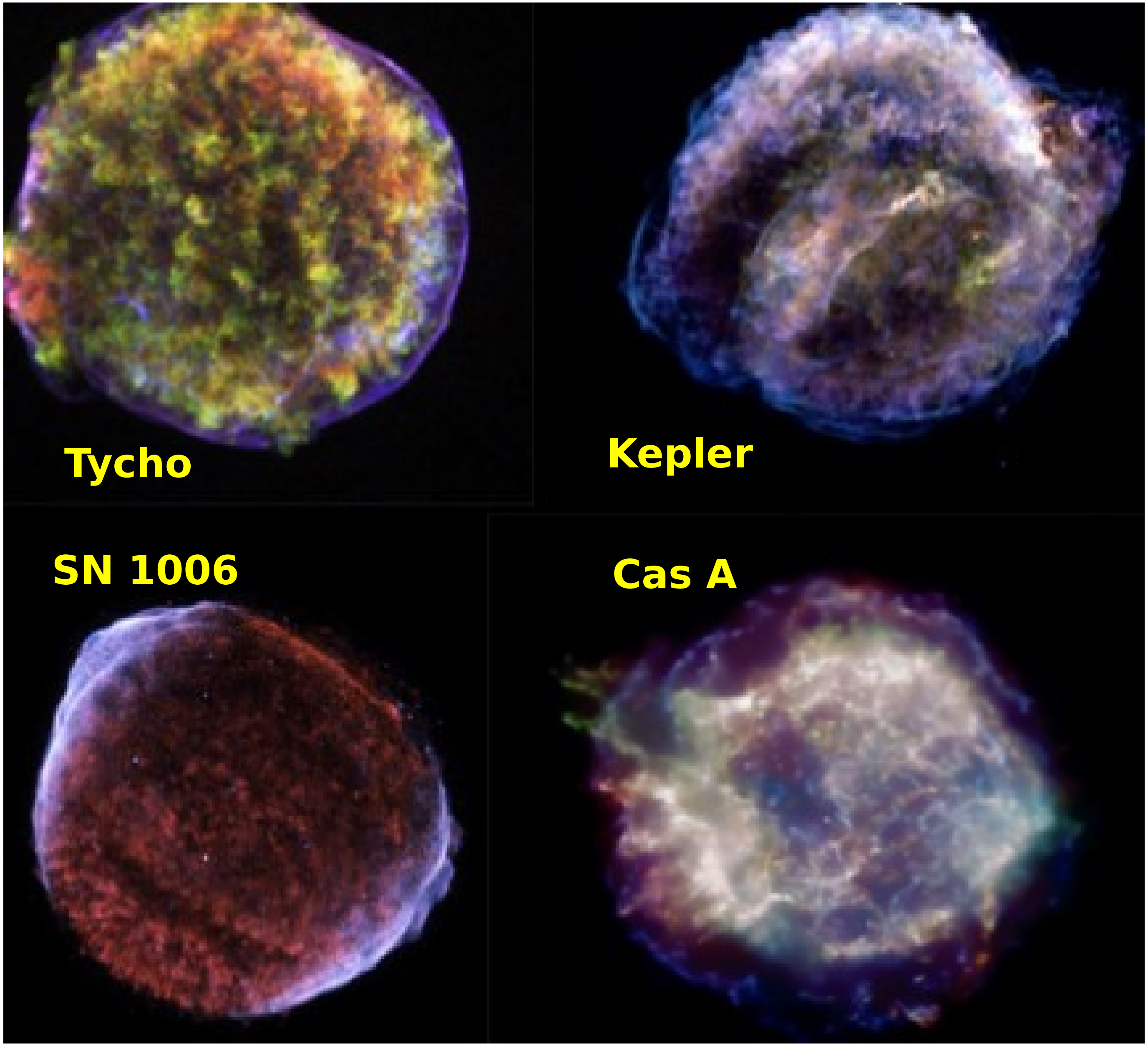
Diff. / R :

ρ = cst →

$$\boxed{T = 230\eta_{0.03} n_e^{1/2} u_7^2 R_{\mathrm{pc}}\ \mathrm{TeV}}$$

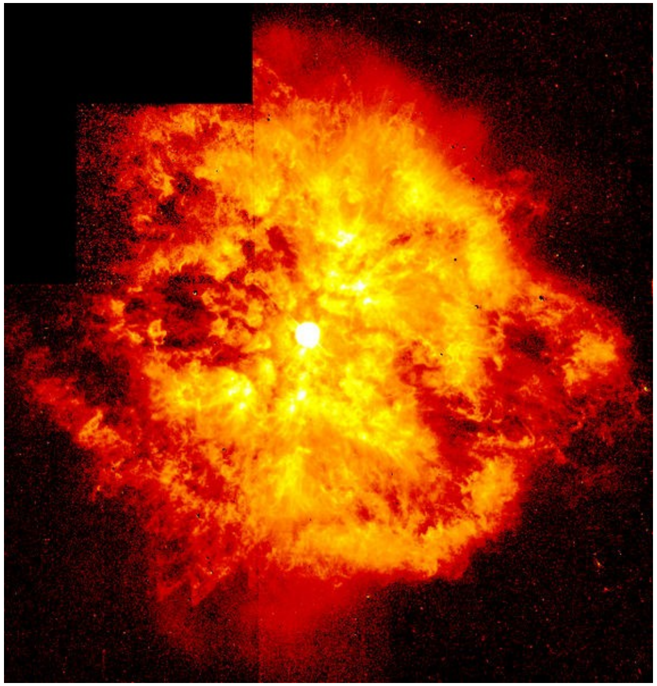
Cas A : T ≈ 400 TeV !!!

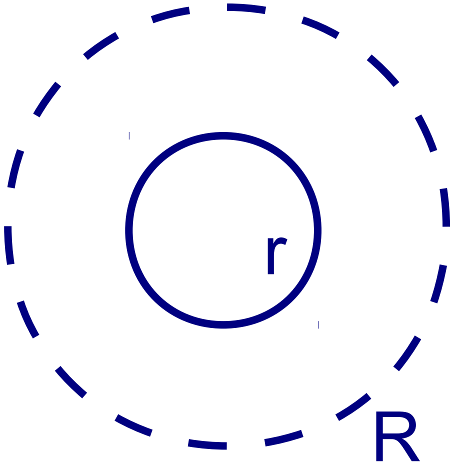
Nowadays, historical SNRs are <u>not</u> accelerating particles to the knee !



SNe in DENSE WINDS as PeVatrons

Bell et al. MNRAS 431, 415 (2013)





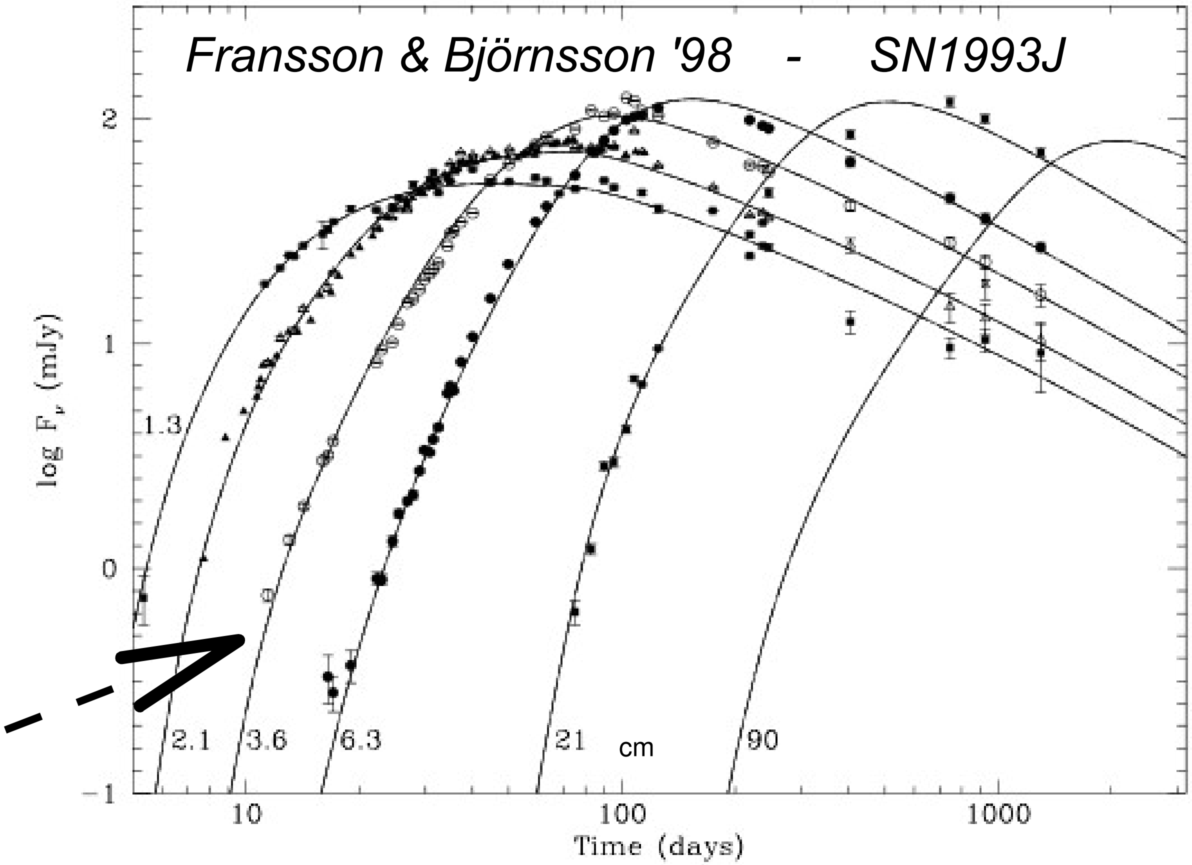
$$\int_0^R \frac{\eta \rho(r) u_s^2(r)}{T(r)} r^2 \mathrm{d}r = 10 R^2 \sqrt{\frac{\rho(R)}{\mu_0}}$$

Diff. / R :

$\rho \propto r^{-2} \rightarrow$

$$T = 760 \eta_{0.03} u_7^2 \sqrt{\frac{\dot{M}_5}{v_4}} \text{ TeV}$$

Radio SNe



Radio :

→ Due to **SSA**

→ A bit of free-free absorption at early times

$$F_\nu(\tau_{\rm ssa} \gg 1) \propto R^2 S_\nu e^{-\tau_{\rm ff}} \propto R^2 B^{-1/2} e^{-\tau_{\rm ff}} \propto t^{2.5} e^{-\tau_{\rm ff}}$$

Radio SNe

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RADIO EMISSION AND PARTICLE ACCELERATION IN SN 1993J

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ABSTRACT

The radio light curves of SN 1993J are discussed. We find that a fit to the individual spectra by a synchrotron spectrum, suppressed by external free-free absorption and synchrotron self-absorption, gives a superior fit to models based on pure free-free absorption. A standard r^{-2} circumstellar medium is assumed and is found to be adequate. From the flux and cutoff wavelength, the magnetic field in the synchrotron-emitting region behind the shock is determined to $B \approx 64(R_s/10^{15}\ \mathrm{cm})^{-1}$ G. The strength of the field argues strongly for turbulent amplification behind the shock. The ratio of the magnetic and thermal energy density behind the shock is ~ 0.14. Synchrotron losses dominate the cooling of the electrons, whereas inverse Compton losses due to photospheric photons are less important. For most of the time also Coulomb cooling affects the spectrum. A model where a constant fraction of the shocked, thermal electrons are injected and accelerated, and subsequently lose their energy due to synchrotron losses, reproduces the observed evolution of the flux and number of relativistic electrons well. The injected electron spectrum has $dn/d\gamma \propto \gamma^{-2.1}$, consistent with diffusive shock acceleration. The injected number density of relativistic electrons scales with the thermal electron energy density, ρV^2, rather than the density, ρ. The evolution of the flux is strongly connected to the deceleration of the shock wave. The total energy density of the relativistic electrons, if extrapolated to $\gamma \sim 1$, is $\sim 5 \times 10^{-4}$ of the thermal energy density. The free-free absorption required is consistent with previous calculations of the circum-

Radio SNe

The magnetic fields of the circumstellar media of late type supergiants are uncertain. Based on polarization observations of OH masers in supergiants, Cohen et al. (1987) and Nedoluha & Bowers (1992) estimate that at a radius of $\sim 10^{16}$ cm the magnetic field is $\sim$1–2 mG, although the uncertainty in this number is large. It is unlikely that the magnetic field in the wind is higher than that corresponding to equipartition between the magnetic field and the kinetic energy of the wind. This means that $B^2/8\pi \lesssim \rho u_w^2/2$, giving

$$B \lesssim \frac{(\dot{M} u_w)^{1/2}}{r} = 2.5\left(\frac{\dot{M}}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2} \times \left(\frac{u_w}{10\ \mathrm{km\ s}^{-1}}\right)^{1/2}\left(\frac{r}{10^{16}\ \mathrm{cm}}\right)^{-1} \mathrm{mG}\ . \quad (46)$$

Likely locations for the electron acceleration are at the position of the circumstellar shock or, alternatively, close to the contact discontinuity between the circumstellar swept-up gas and the shocked ejecta gas. The latter region is Rayleigh-Taylor unstable, and the associated turbulence may help in amplifying the magnetic field (Chevalier et al. 1992; Jun & Norman 1996).

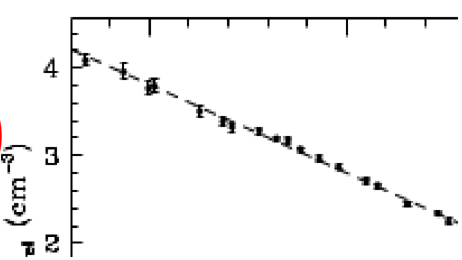
At 10 days, corresponding to a radius $\sim 1.9 \times 10^{15}$ cm, we find that the magnetic field in the emitting region is $\sim$34 G. Using the above estimate of the circumstellar magnetic field and a shock compression by a factor of 4, this post-shock magnetic field would be $B \approx (2.4\text{–}4.8) \times 10^{-2}$ G. This is a factor $\sim 10^3$ less than that inferred from the observations and therefore strongly argues for magnetic field amplification behind the shock. Although this conclusion rests on the very uncertain estimate of the circumstellar magnetic fields of the progenitor system, a simple shock

the discussion below. In Figure
the injected nonthermal electron
tion of shock radius. The value c
by the optically thin flux and, the
in § 5, can be shown to depe
$V^{3-2p_i} \propto V^{-1.2}$. A least-squares
for the first 100 days is given by

$$n_{\mathrm{rel}} = n_{\mathrm{rel\,15}}\, \gamma_{\min}^{-1.1}\left(\frac{R_s}{10^{15}\ \mathrm{cm}}\right)^{-\eta}\Big($$

where $n_{\mathrm{rel\,15}} = (6.1 \pm 0.7) \times 10^4$
After 100 days there is a promine
and one finds that $n_{\mathrm{rel\,15}} = (4.$
$\eta = 2.64 \pm 0.05$. A fit based on
days gives $n_{\mathrm{rel\,15}} = (6.4 \pm 0.8) \times$

Chevalier (1996) has discusse
density of relativistic particles b
fraction of the thermal particle d
or a constant fraction of the the
$\rho_{\mathrm{wind}}\ V^2 \propto R^{-2}V^2 \propto t^{-2}$. Here
These scalings have little physica



Radio SNe

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Radio emission and nonlinear diffusive shock acceleration of cosmic rays in the supernova SN 1993J

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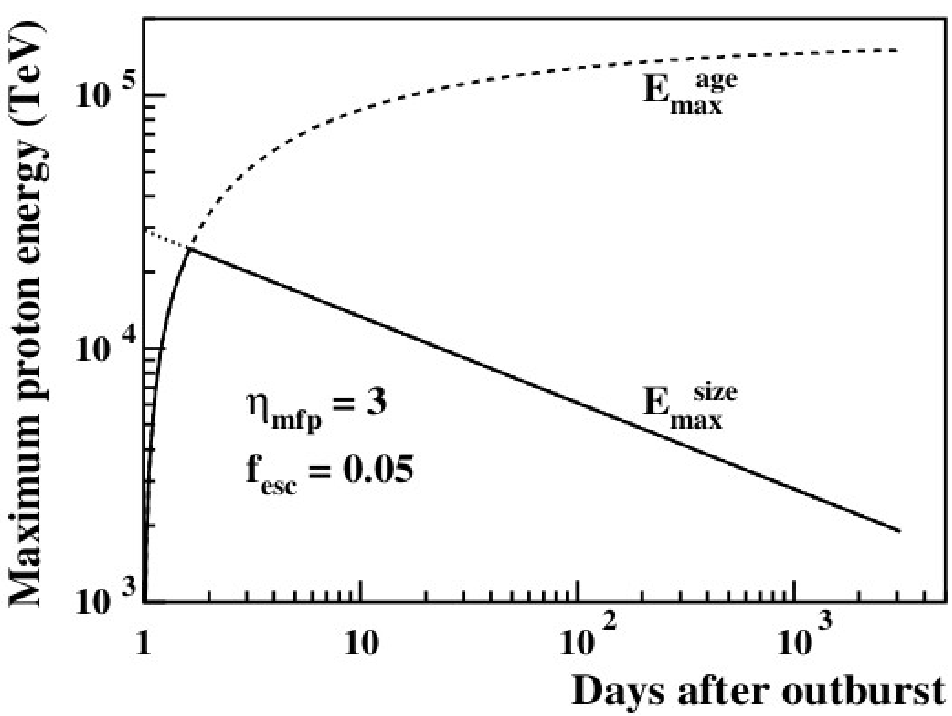
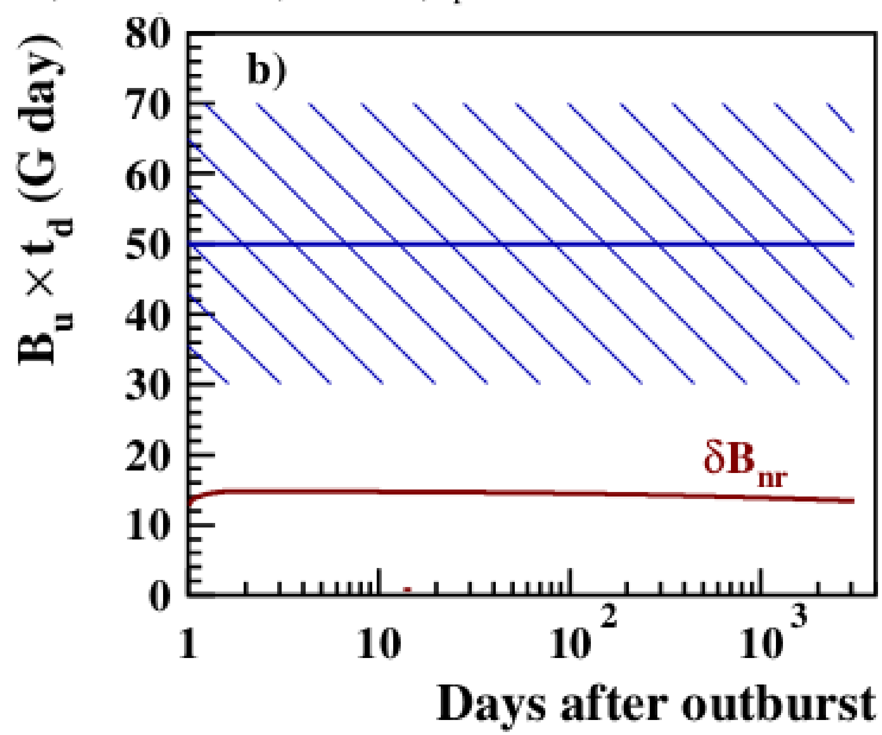
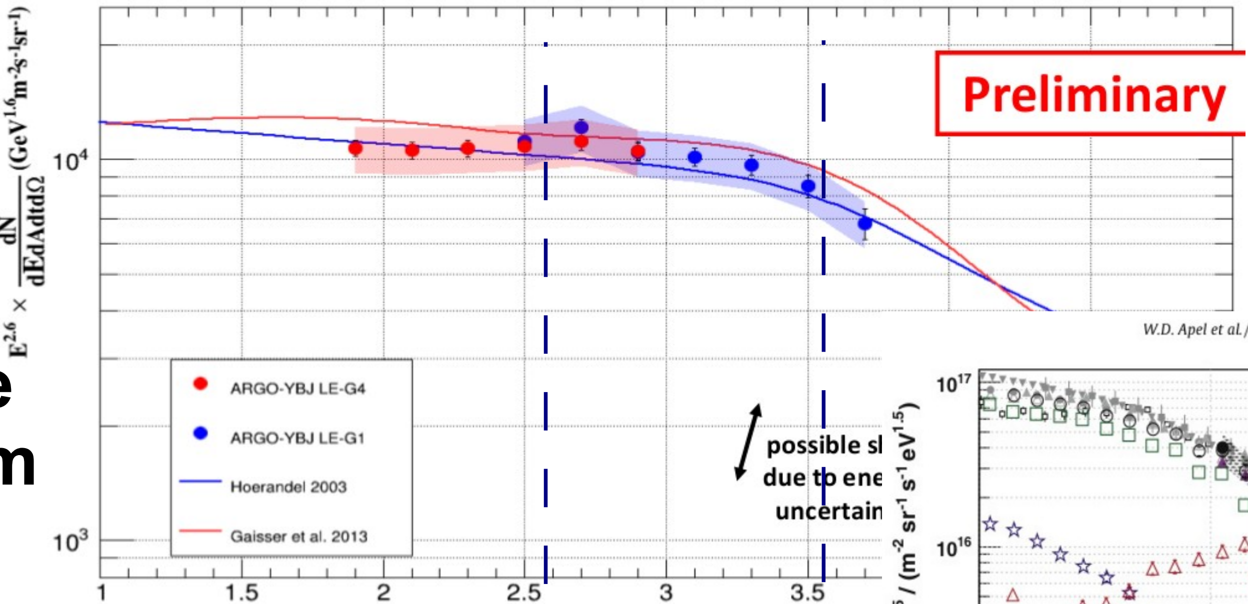
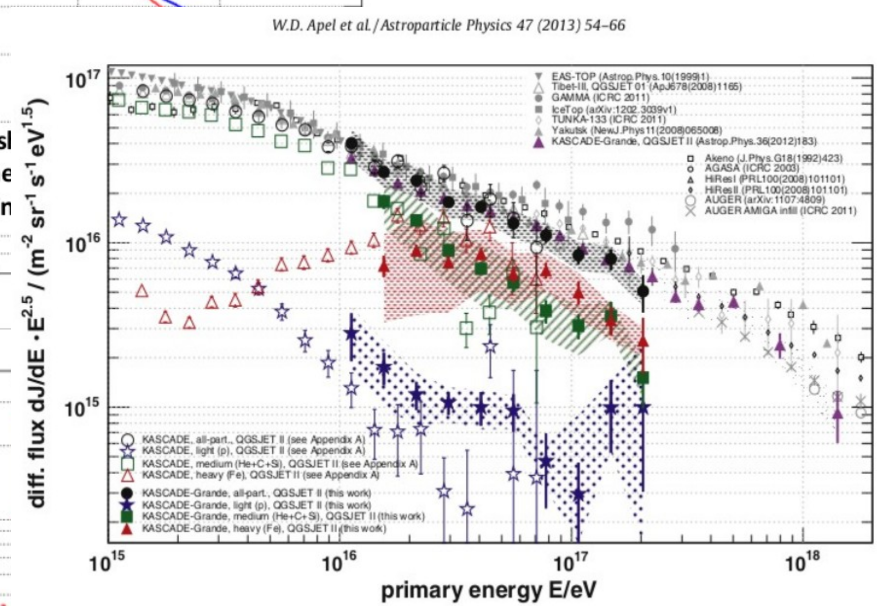


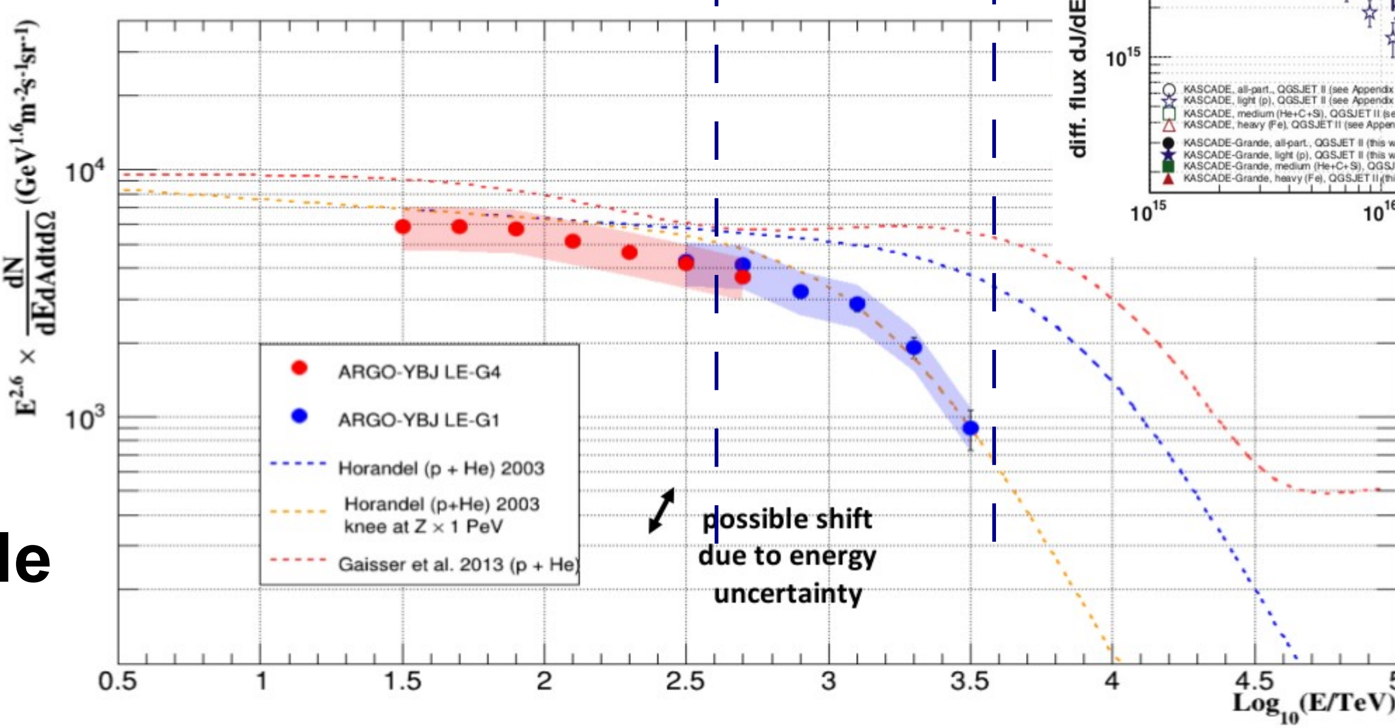


ARGO-YBJ : cutoff at ~ 700 TeV



All-particle spectrum

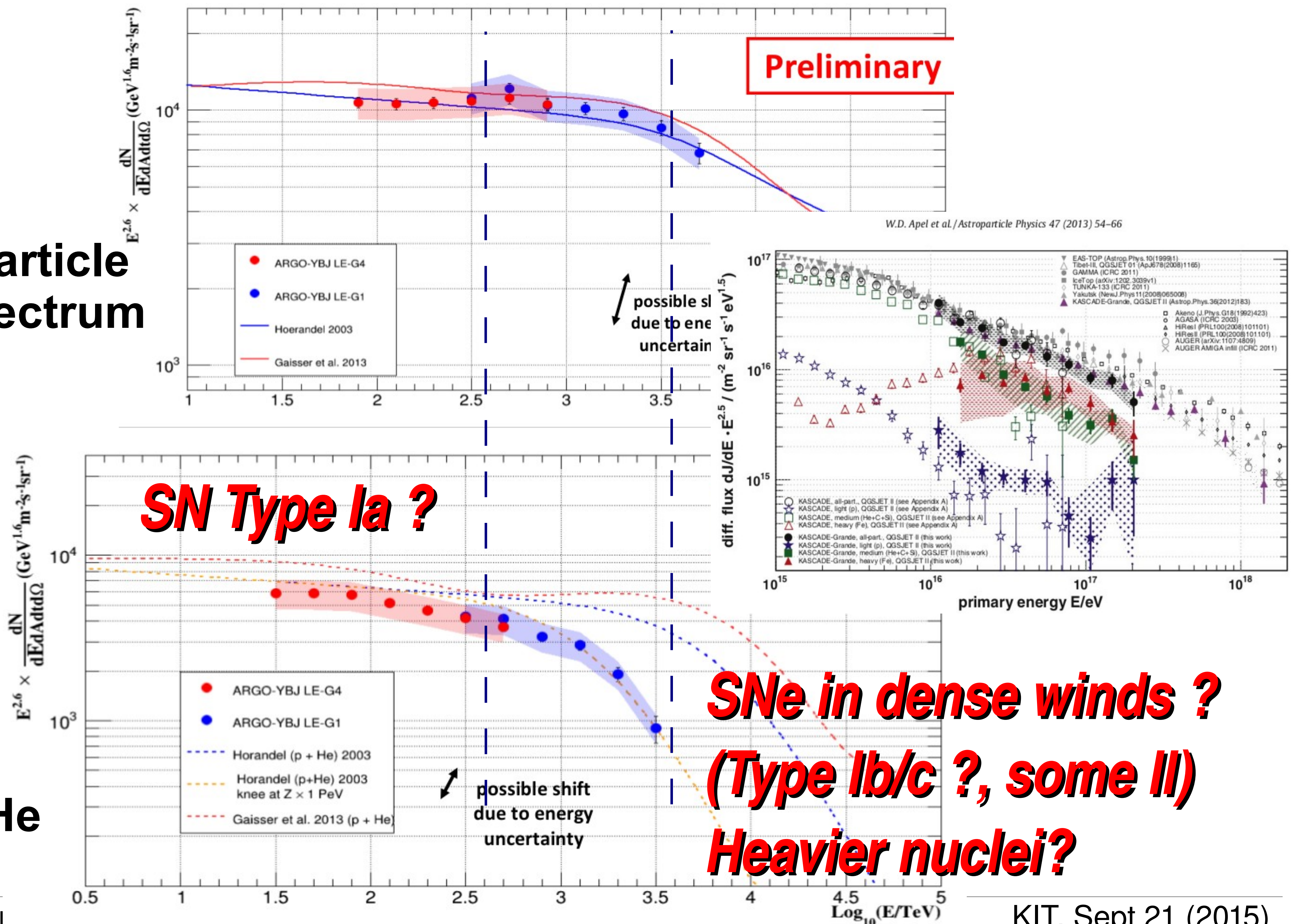




p+He

ARGO-YBJ : cutoff at ~ 700 TeV

All-particle spectrum



SN Type Ia ?

p+He

SNe in dense winds ?
(Type Ib/c ?, some II)
Heavier nuclei?

Conclusions and perspectives

- Summary of Bell's NR instability
- Instability growth / saturation => Limits CR E_{max}
- Tight link between CR Escape / E_{max} / MF amplification
- Type Ia fall short of reaching the knee
  => <u>COMPOSITION</u> ?
- First few decades of SNe in dense winds promising to reach knee and beyond