Magnetic field amplification by Cosmic Rays in SNR shocks

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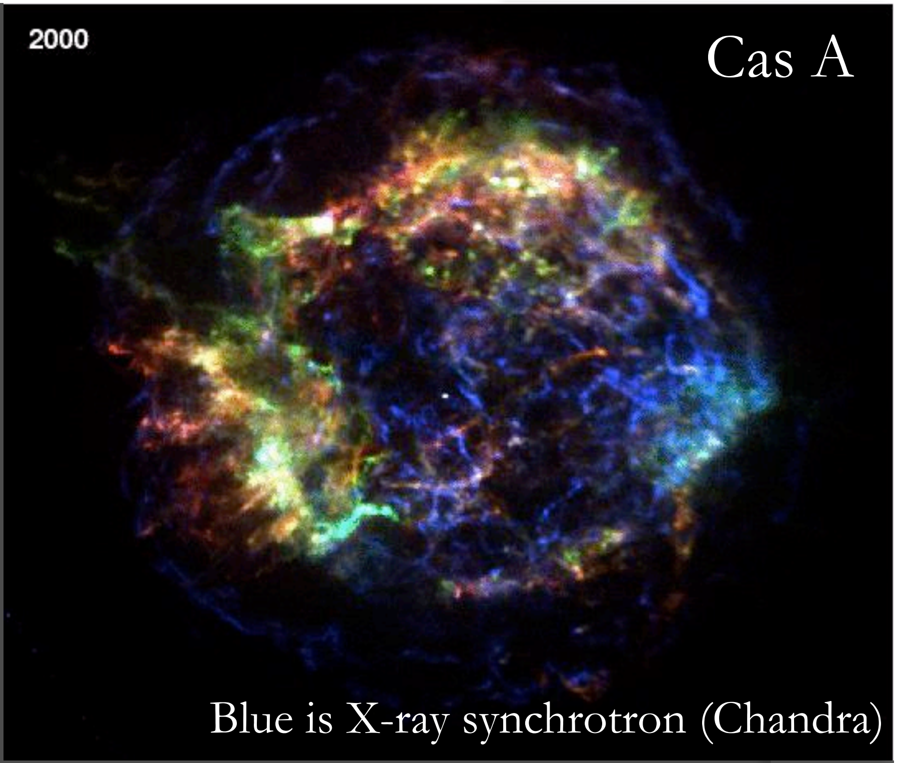
Motivation

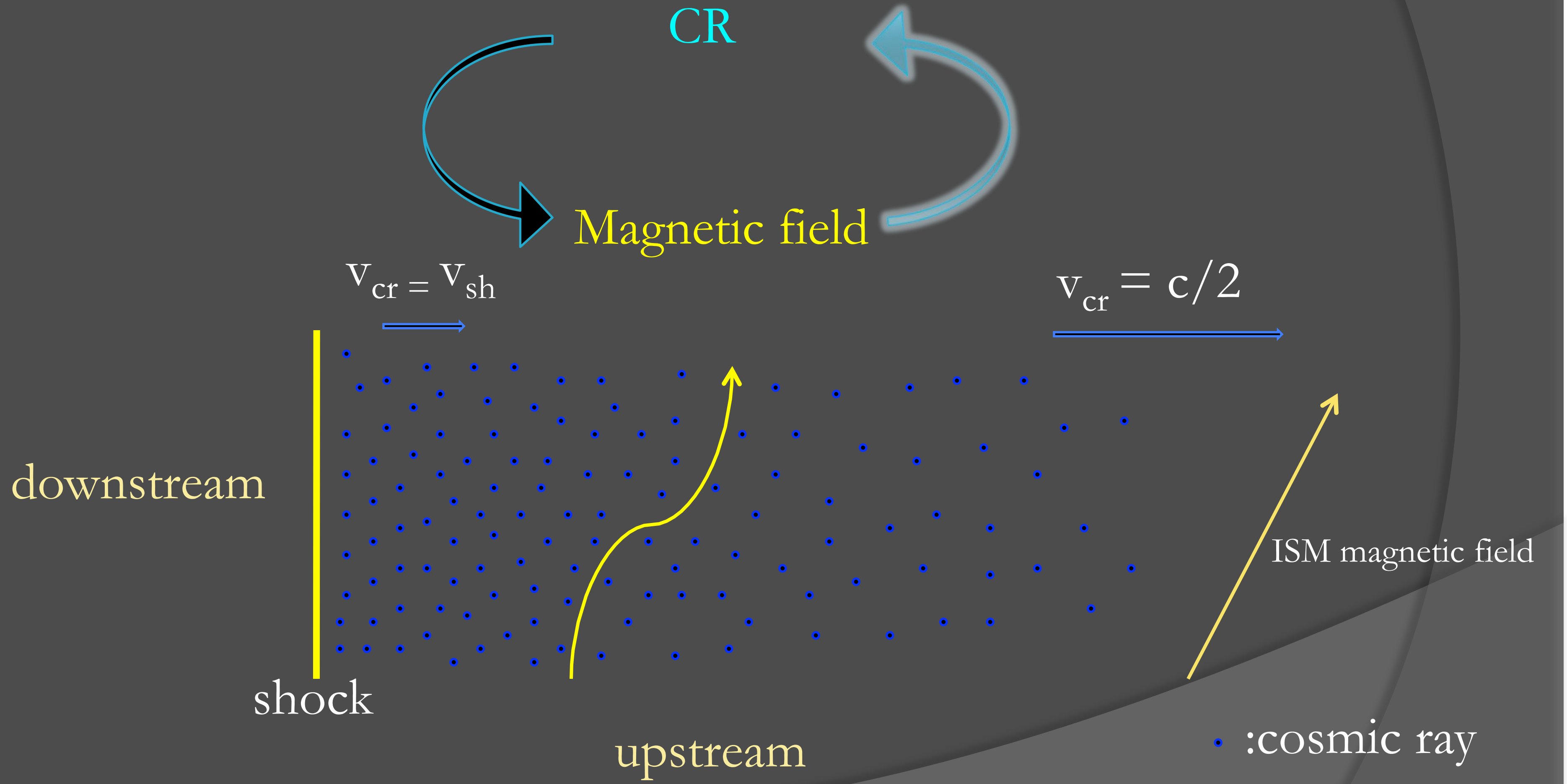


Blue is X-ray synchrotron (Chandra)

- The main observational evidence of such amplification comes from X-ray observation of thin rims in SNRs.
- This radiation has been interpreted as synchrotron emission from accelerated (TeV) electrons in presence of an amplified magnetic field.
- Time variability and width of the rims indicate the cooling time of the electrons, which gives a measure of the magnetic field intensity.
- Amplification factors of order 100.

Possible mechanism:

Idea: field is amplified by the CRs themselves.



CR

Magnetic field

$v_{cr} = v_{sh}$

$v_{cr} = c/2$

downstream

shock

upstream

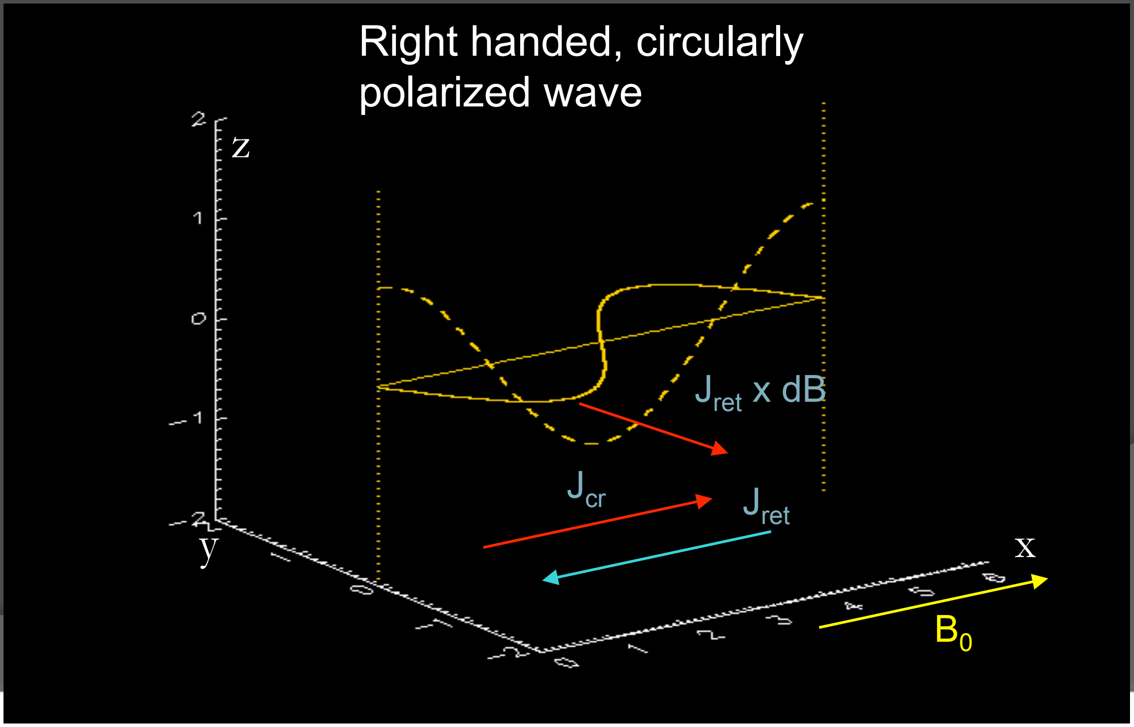
ISM magnetic field

• :cosmic ray

The non-resonant instability

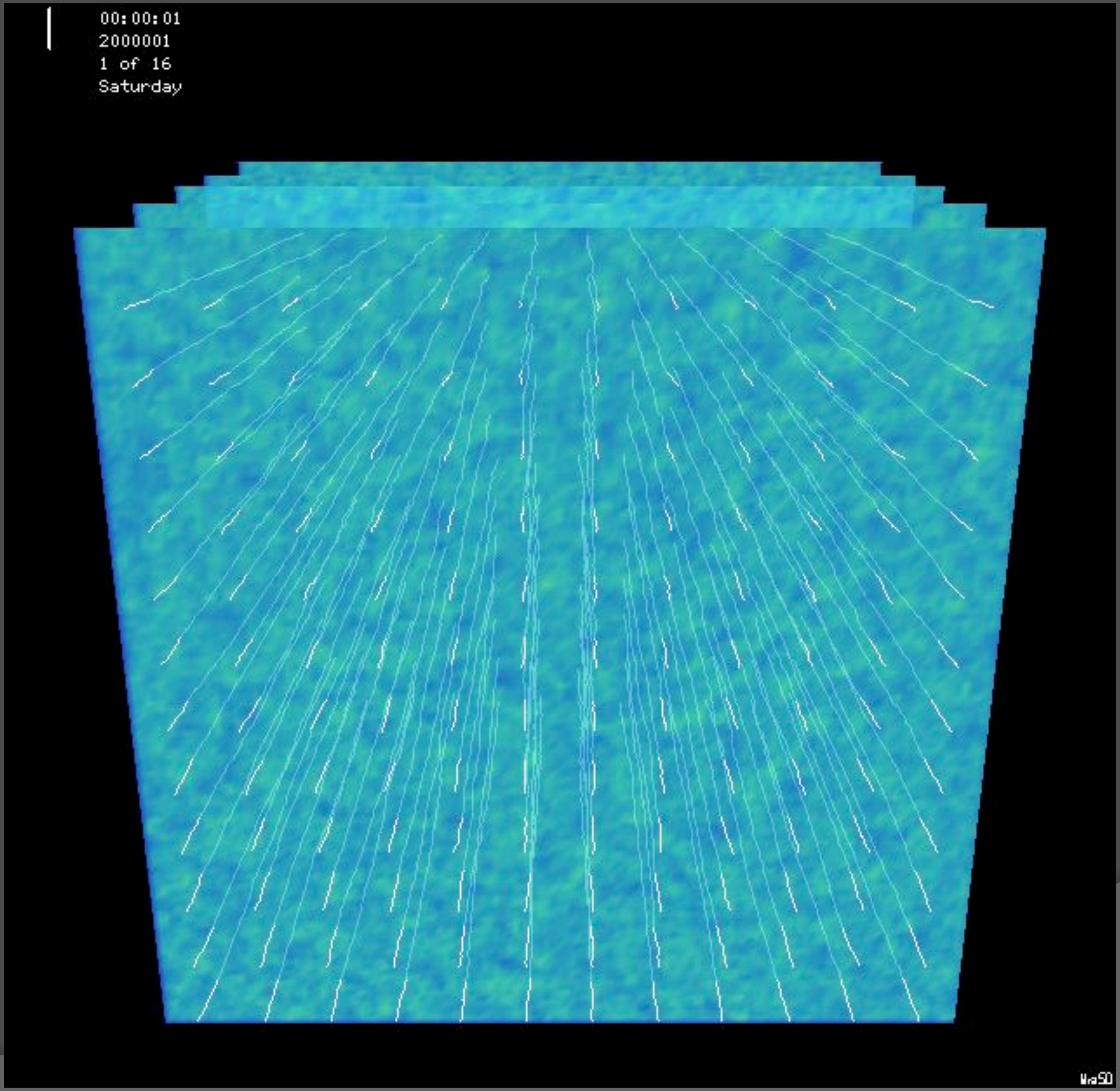
A serious candidate has been the non-resonant (NR) instability, proposed by Bell in 2004. It consists in plasma waves that grow due to the electric current, J_{CR}, provided by CR as they stream parallel to an ambient magnetic field, B_0. In the linear regime the growth is exponential and at:

$$\lambda_{NR} = cB_0 / J_{cr} \quad \text{and} \quad \gamma_{NR} = J_{cr}/(rc^2/p)^{1/2}$$



We use particle-in-cell simulations to study the CR back-reaction.

The non-resonant instability

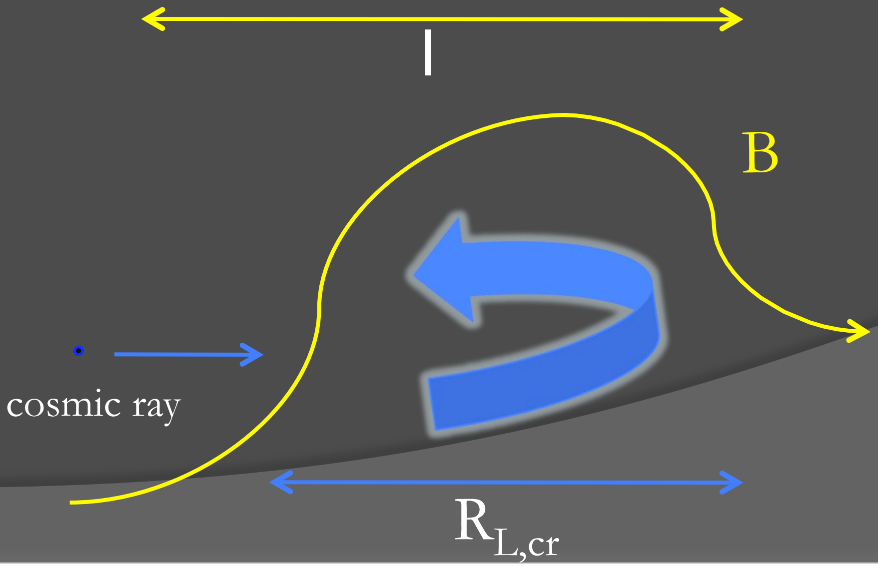


The non-resonant instability

Saturation mechanism:

⊙However, our simulations show that, when the back-reaction on the CRs is considered, the instability only grows if $R_{L,cr} >$ l.

⊙This trapping happens when the dominant wavelength, l, is about the size of the Larmor radius of the CRs, $R_{L,cr}$ (Riquelme & Spitkovsky, 2009a).



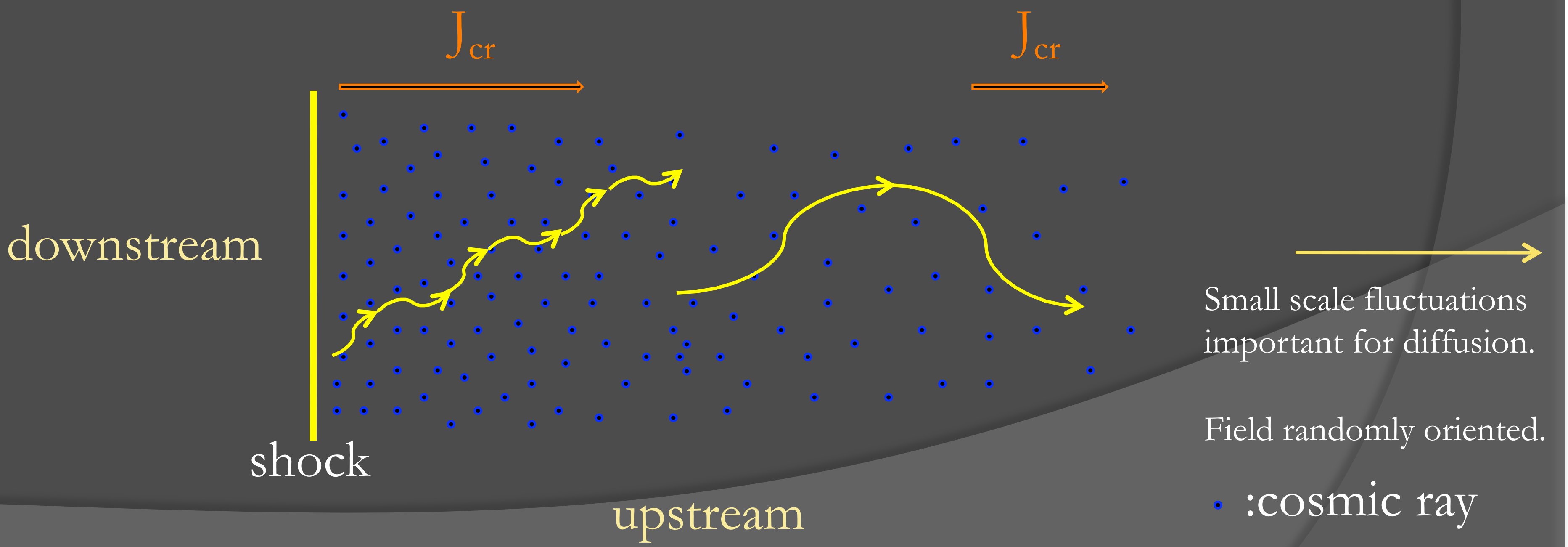
The non-resonant instability

The condition for saturation

$$R_{L,CR} \sim \lambda$$

implies an amplification factor, dB/B_0, that depends on the CR energy flux, $F_{E,cr}$, and the initial value of the field, B,

$$\boxed{\lambda = cB_0 / J_{cr}}$$



Small scale fluctuations important for diffusion.

Field randomly oriented.

• :cosmic ray

The non-resonant instability

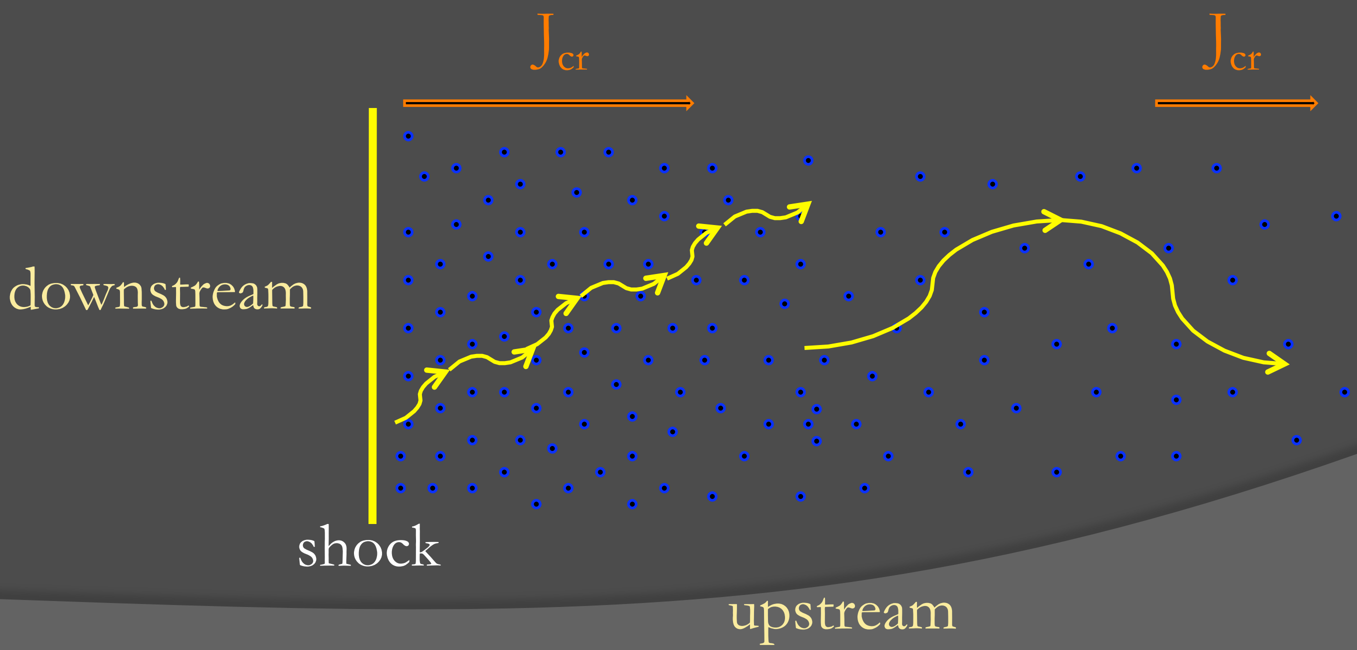
The condition for saturation

$$R_{L,CR} \sim \lambda$$

implies an amplification factor, dB/B_0, that depends on the CR energy flux, $F_{E,cr}$, and the initial value of the field, B,

$$dB/B_0 = (F_{E,cr}/cB_0^2)^{1/2} \text{ then } B_{sat}^2 \approx F_{E,cr}/c$$

$$\boxed{\lambda = cB_0 / J_{cr}}$$



Small scale fluctuations important for diffusion.

Field randomly oriented.

• :cosmic ray

The cosmic ray current-driven instability

Using this criterion we can obtain an estimate for the magnetic amplification in SNRs:

$$dB/B_0 \approx 15\ (V_{sh}/10^4 km/sec)^{3/2}(10 km/sec/V_{a,0})(h_{esc}/0.05)^{1/2},$$

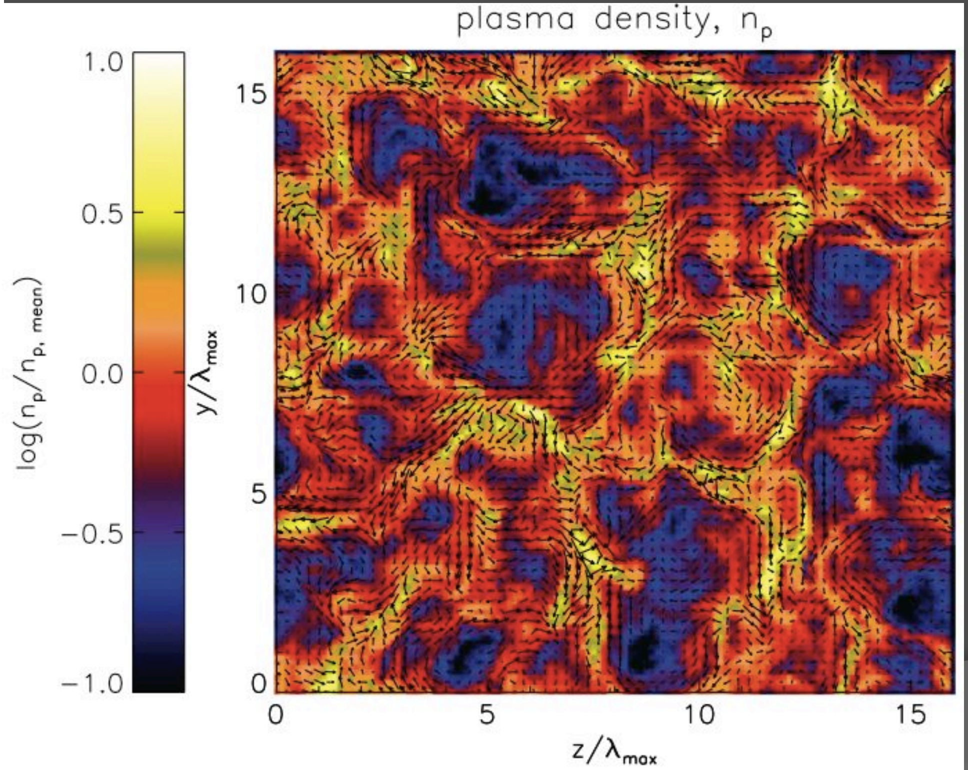
where $h_{esc} = F_{E,cr}/(n_i m_i V_{sh}{}^3/2)$.

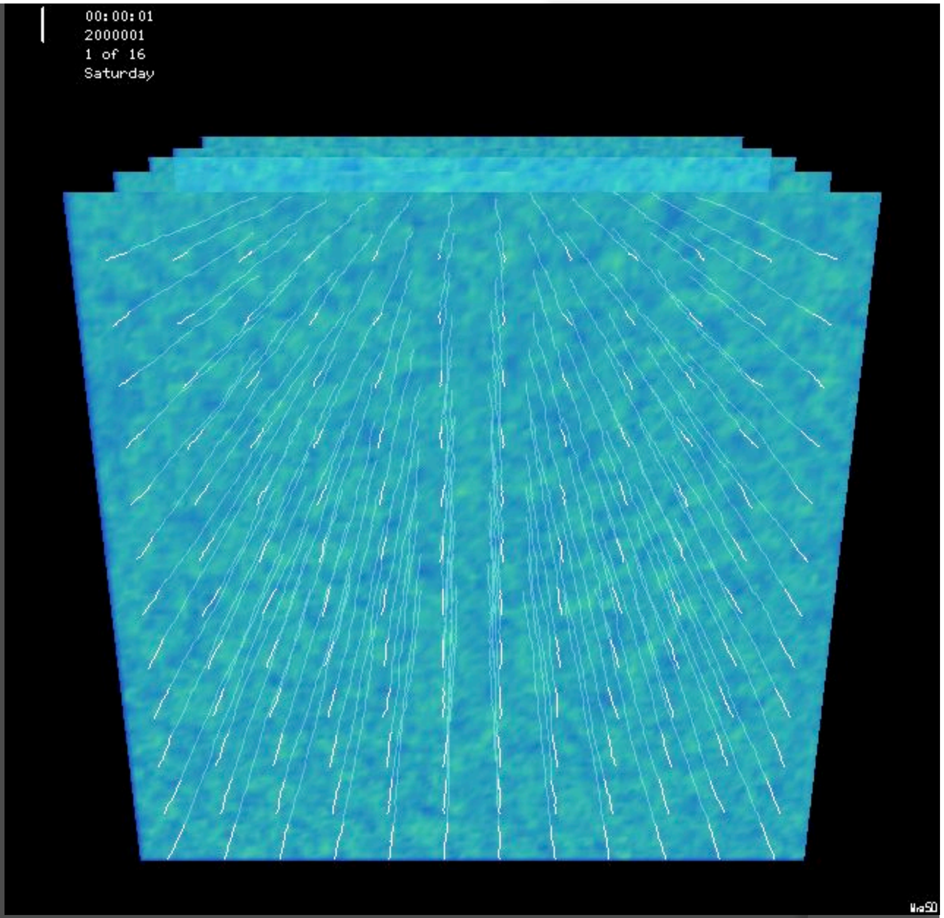
However, this value corresponds to an upper limit because it assumes that CR at each range of energy would carry *all* the CR energy.

An alternative mechanism

Non-resonant turbulence:

- ⊙ Formation of plasma cavities. Magnetic field correlated with plasma density.



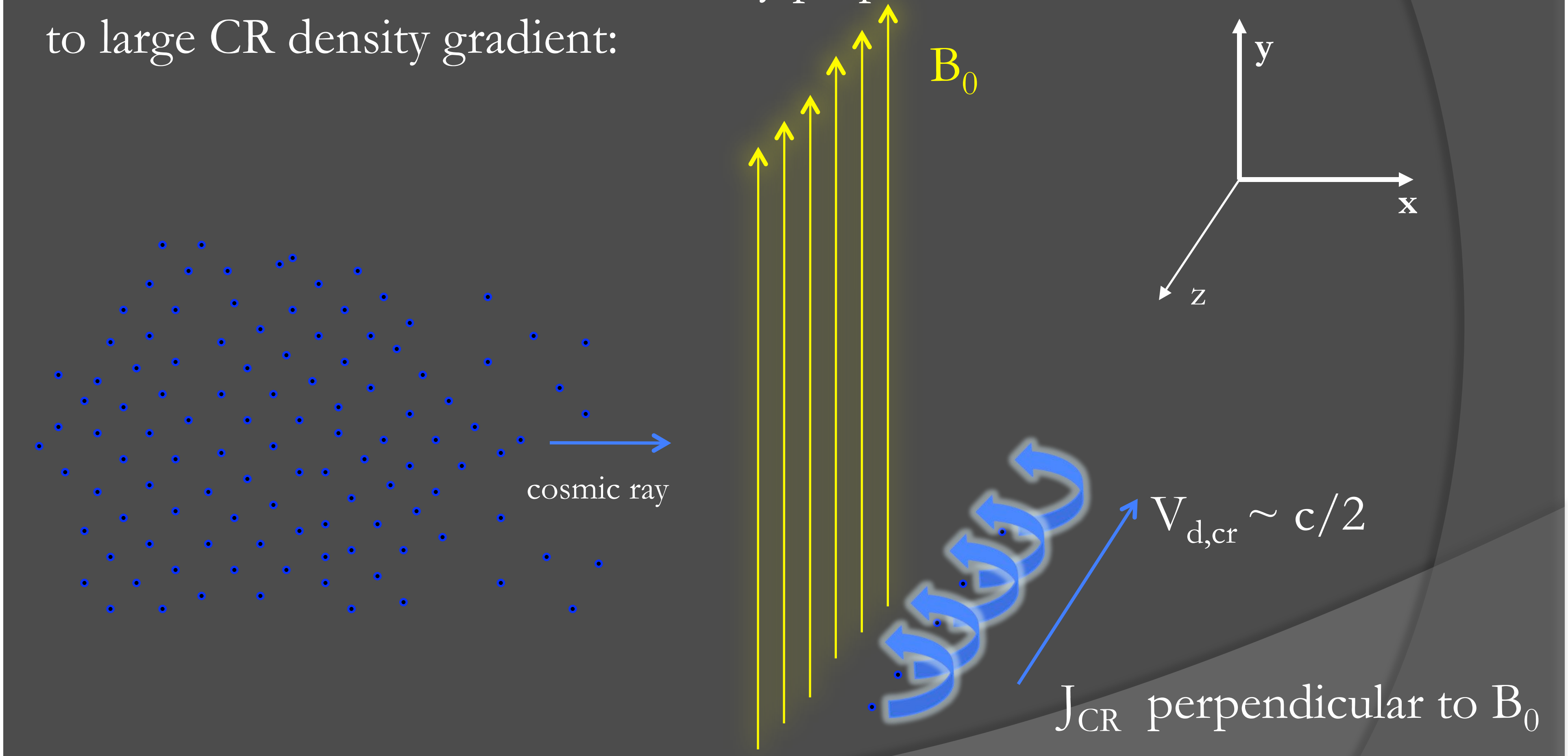


- ⊙ Magnetic field is no longer parallel to the CR mean velocity.

- ⊙ Typical Larmor radii of CRs will become smaller than the wavelength of the NR amplified field.

An alternative mechanism

Formation of a net CR drift velocity perpendicular to the field due to large CR density gradient:



An alternative mechanism

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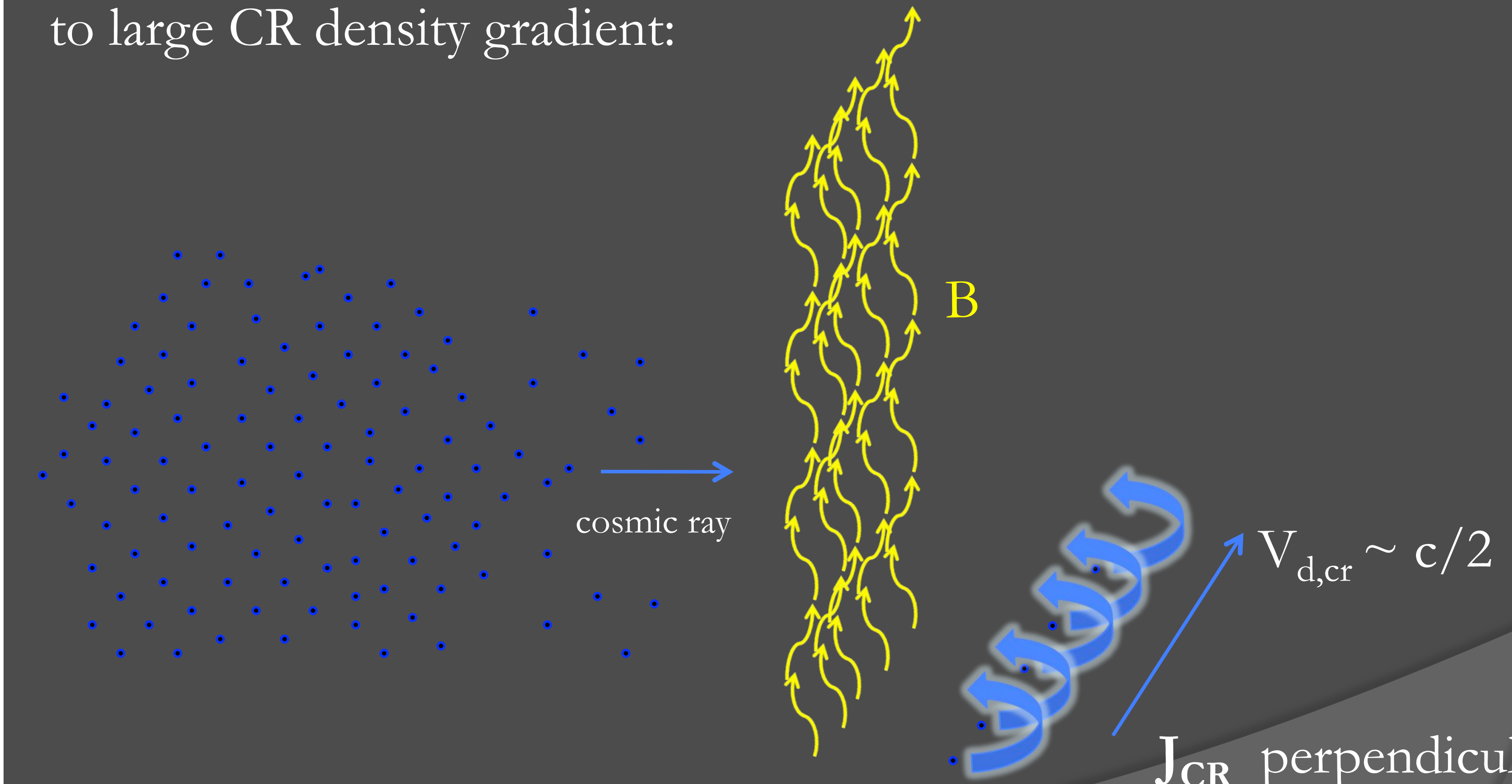


$\mathbf{J}_{CR}$ perpendicular to $\mathbf{B}_0$

$\mathbf{B}_0$ parallel to $\mathbf{k}$

An alternative mechanism

The dispersion relation is given by:

$$\gamma^2 \frac{c^2}{v_A^2} + c^2 k = \frac{4\pi J_{cr}^2 k^2}{\rho(\gamma^2 + k^2 c_{s,i}^2)}$$

(see also MHD calculation of Bell, 2005)

Thus a maximum growth rate and its corresponding wave number can be found:

$$\gamma_{max} = 2\gamma_{NR} \frac{v_A/c_{s,i}}{1 + v_A/c_{s,i}},$$

$$k_{max} c = \gamma_{max} \frac{c}{\sqrt{v_A c_{s,i}}}.$$

$k_{NR} c = 2p J_{cr} / B_0$

$\gamma_{NP} = k_{NR} v_A$

It is possible to show that, when d $B/B_0 \sim 1$, $c_{s,i} \sim v_A$. Thus

$$\gamma_{max} \approx \gamma_{NR}$$

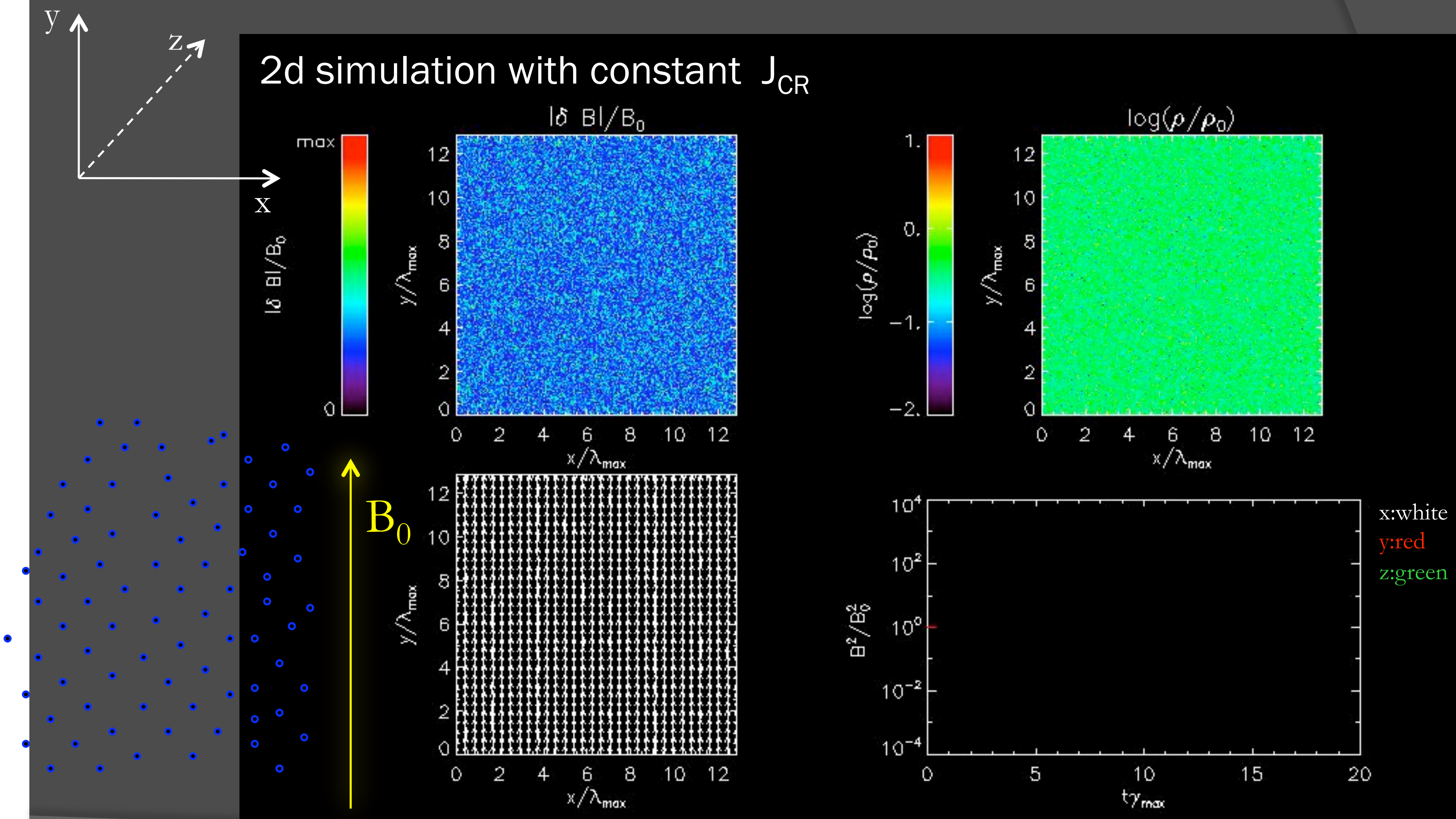
$$k_{max} \approx k_{NR}$$

This magnetic fluctuations should grow faster and in smaller scales than NR.

(Riquelme & Spitkovsky 2009b, in prep.)

An alternative mechanism

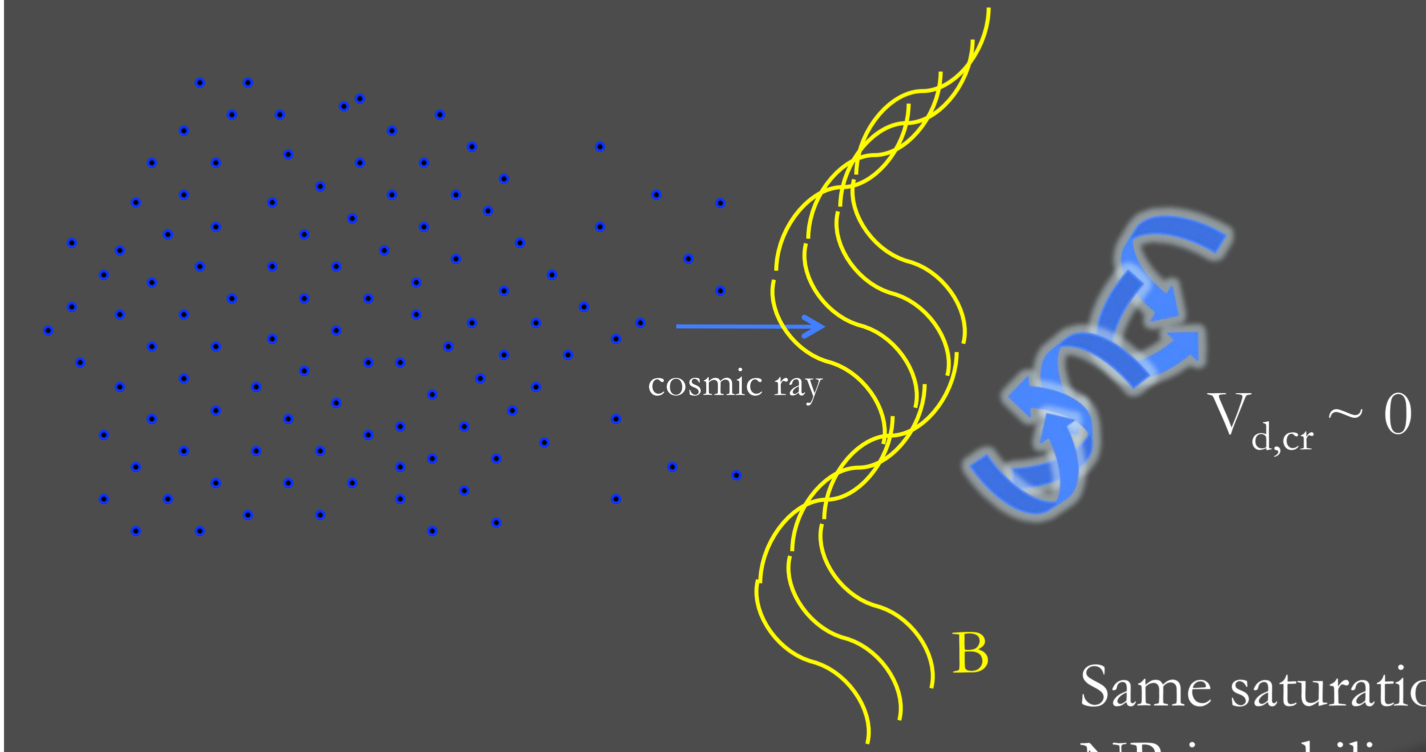
2d simulation with constant J_{CR}



J_{CR} comes out of the simulation plane

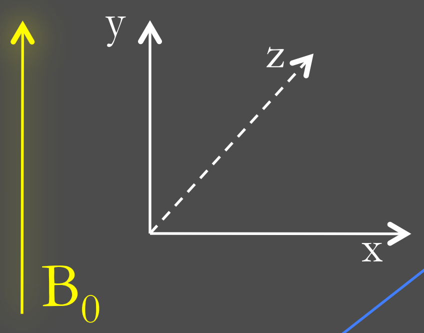
An alternative mechanism

Saturation will happen when the Larmor radii of the CRs become close to the wavelength of the fluctuations.



Same saturation mechanism than NR instability.

An alternative mechanism

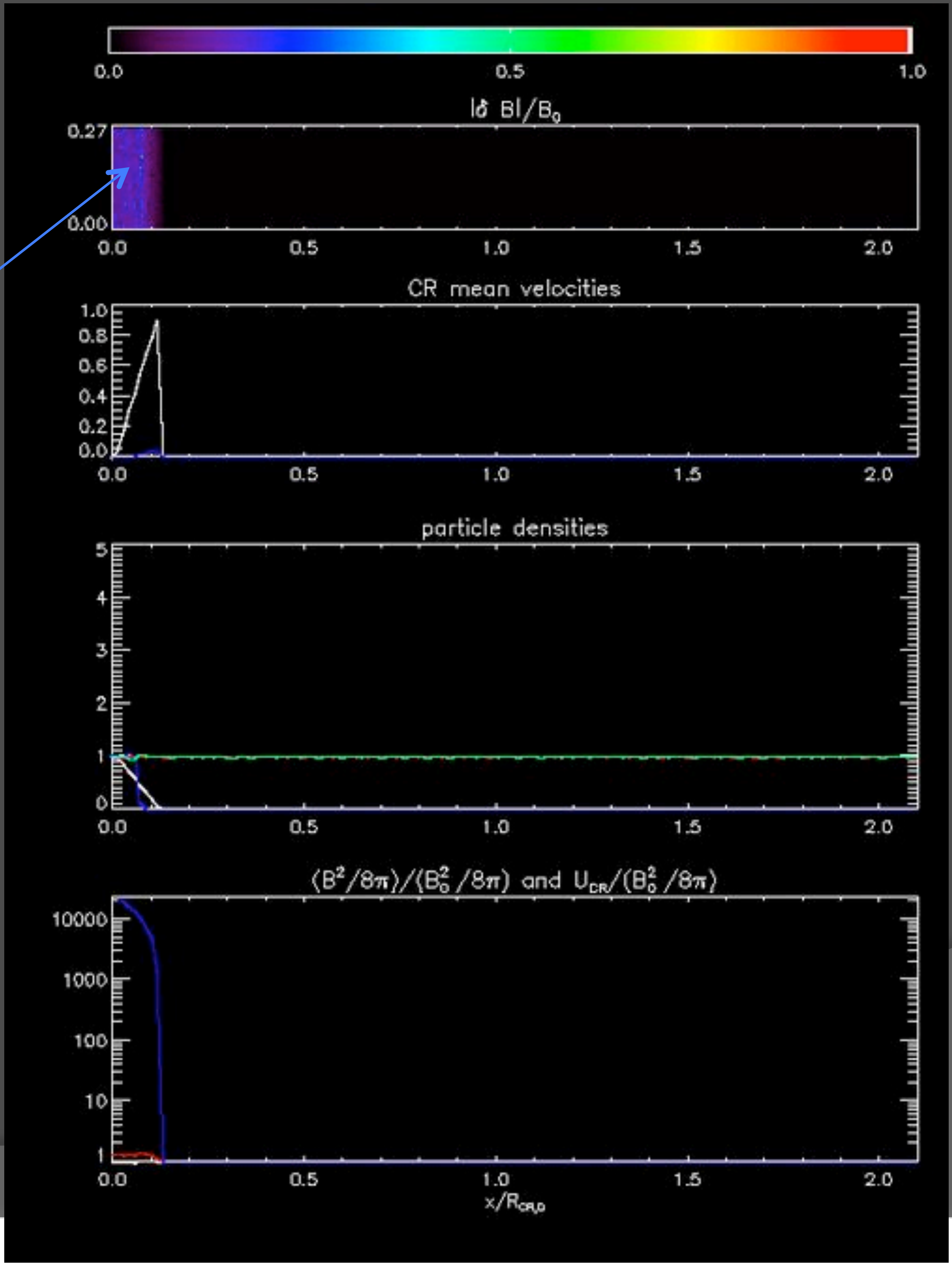


CRs are injected here

$V_A/c = 1/160$
$n_{cr}/n_i = 0.04$
$G_{cr} = 5$

2d simulation with no initial CR drift. CRs are injected in one end of the box. Magnetic field is initially uniform.

Saturation happens when $R_{L,cr} \sim l$



Blue: mean $V_{Z,CR}$
White: mean $V_{X,CR}$

Green:
background electrons
Red:
background ions
Blue:
injected electrons
White:
injected CRs

Red:
maximum magnetic energy
Blue:
magnetic energy, U_{CR}
White:
mean magnetic energy

Application to SNRs

Although these waves are essentially different from NR waves, they share the same saturation criterion.

$$B^2_{sat} = F_{E,cr}/c$$

However, since the CR drift velocity perpendicular to the field (~c/2) should be much larger than the parallel one (~V_{sh}), this mechanism should still be able to amplify the field beyond the NR saturation limit.

An estimate for dB/B_0 is:

$$dB/B_0 \approx 60\ (V_{sh}/10^4 km/sec)(10km/s/V_{a,0})(\eta/0.05)^{1/2},$$

where $\eta = F_{E,cr}/(n_i m_i V_{sh}{}^3/2)$.

In this case saturation limit is close to equipartition between CR and magnetic energies.

(Riquelme & Spitkovsky 2009b, in prep.)

Conclusions

- We study the possible mechanism for magnetic field amplification in SNR shocks.
- We show that the growth of NR waves seems insufficient to convincingly explain the magnetic amplification suggested by observations (a factor of ~100). But it would play a role far from the shock.
- We introduce a new candidate mechanism that is driven by the lowest energy CRs that are close to the shock.
- This mechanism can act on a field already amplified by the highest energy particles through the NR instability, and has an upper limit of upstream amplification of $dB/B_0 \sim 60$. Then in the downstream ~240 (upper limit).
- Since the saturation requires $R_{L,CR} \sim \lambda$, this magnetic amplification ensures efficient scattering mechanism for low energy CRs.
- Observational test: this mechanism implies $B^2 \sim V^2_{sh}$. Whereas for a scenario with only NR, $B^2 \sim V^3_{sh}$.