Cosmic ray escape from supernova remnants and related radiative signatures

Stefano Gabici
APC, Paris

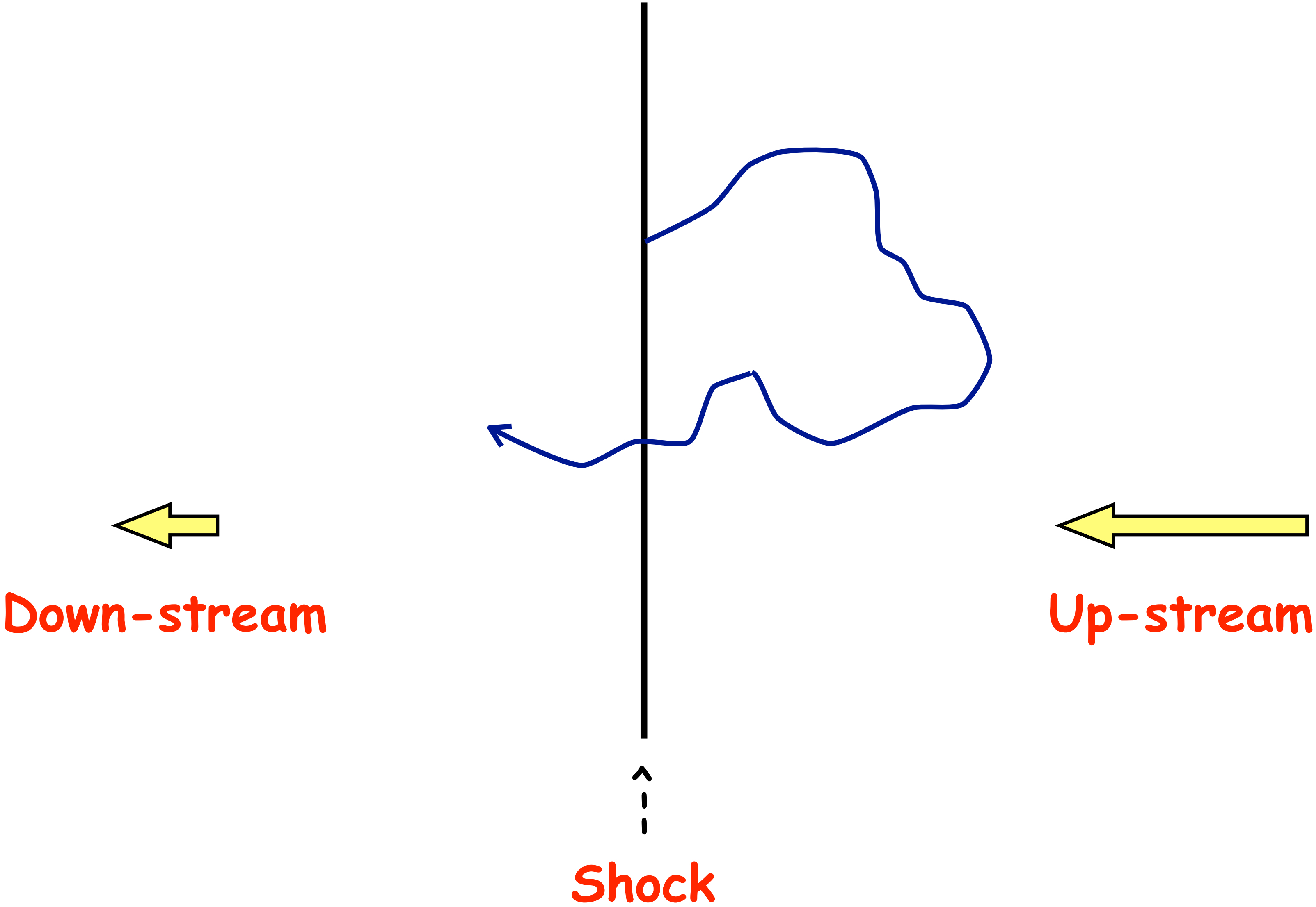
www.cnrs.fr

Overview of the talk

- Escape
- Propagation
- Radiation

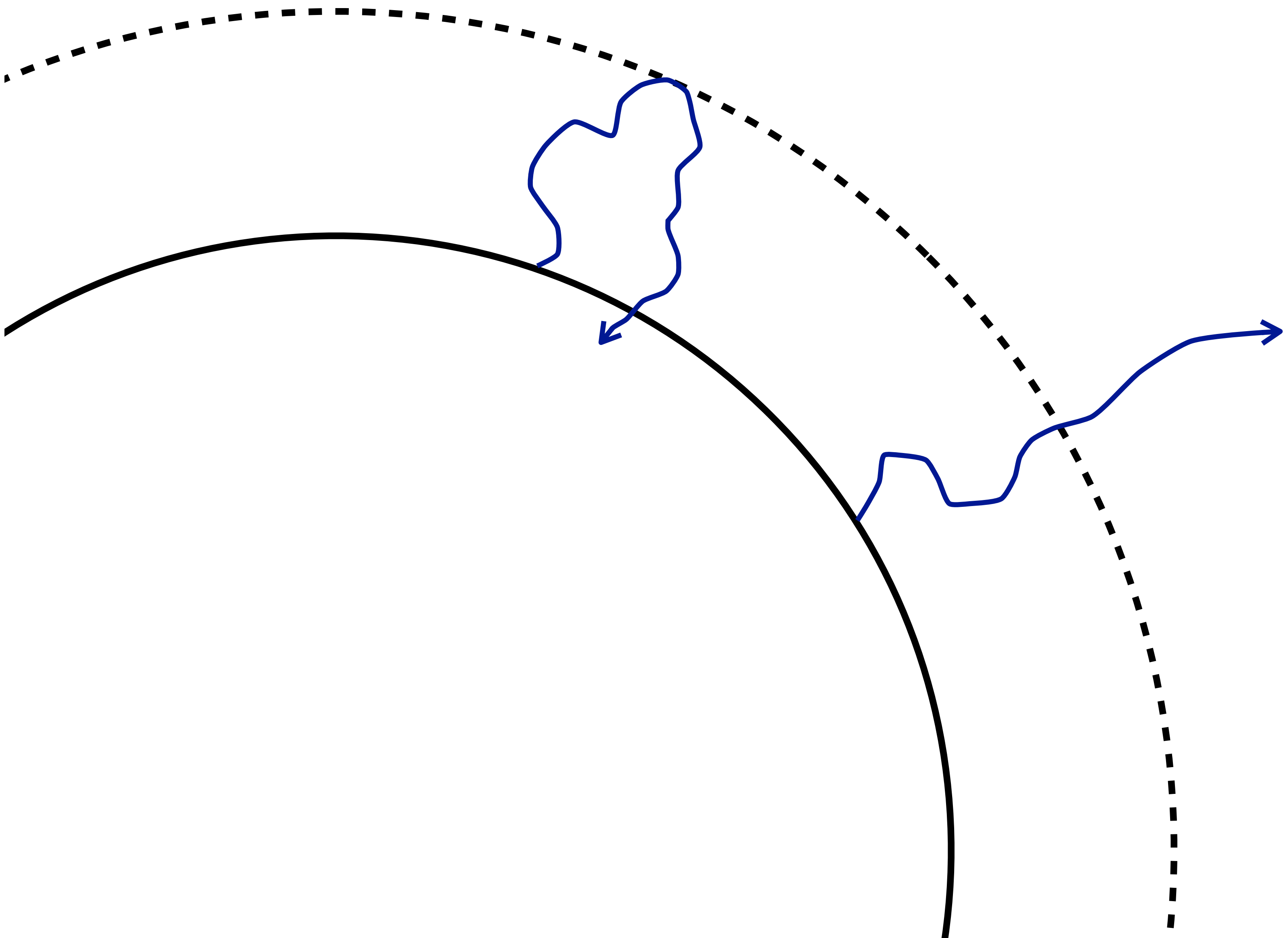
Overview of the talk (cartoon)

CRs are accelerated at SNR shocks



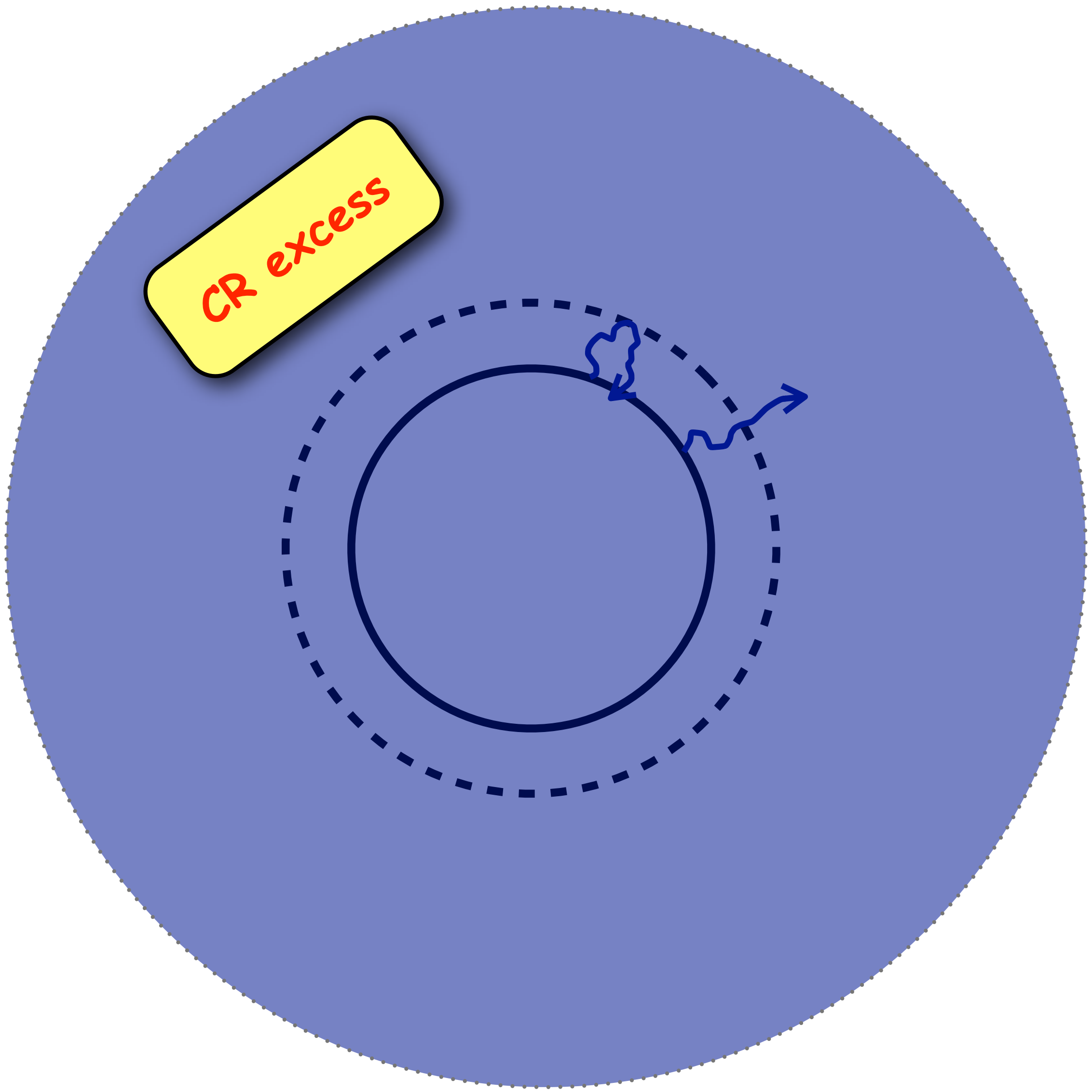
Overview of the talk (cartoon)

They form a CR precursor, some of them may escape



Overview of the talk (cartoon)

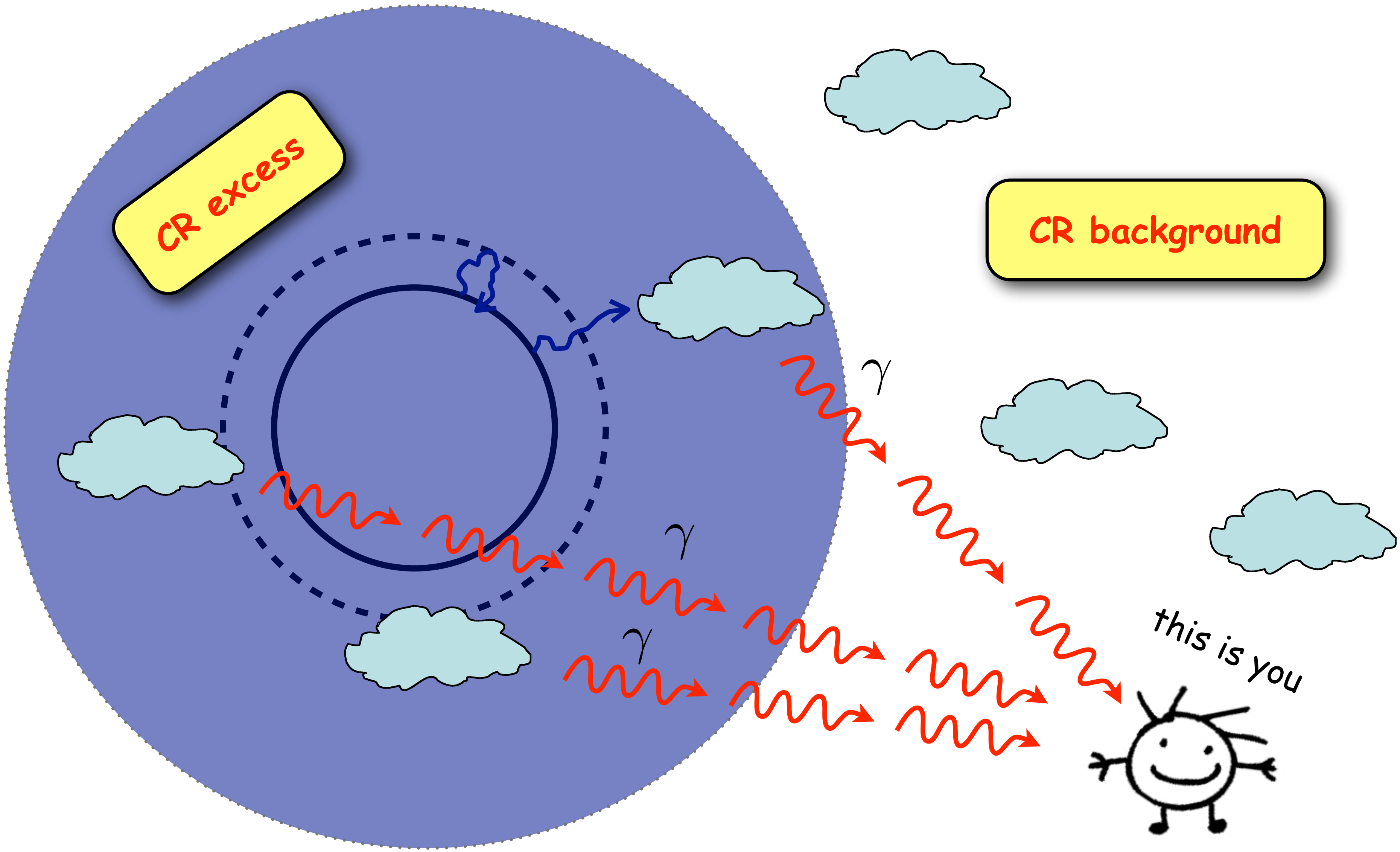
They diffuse away from the SNR, and create a CR excess around the SNR



CR background

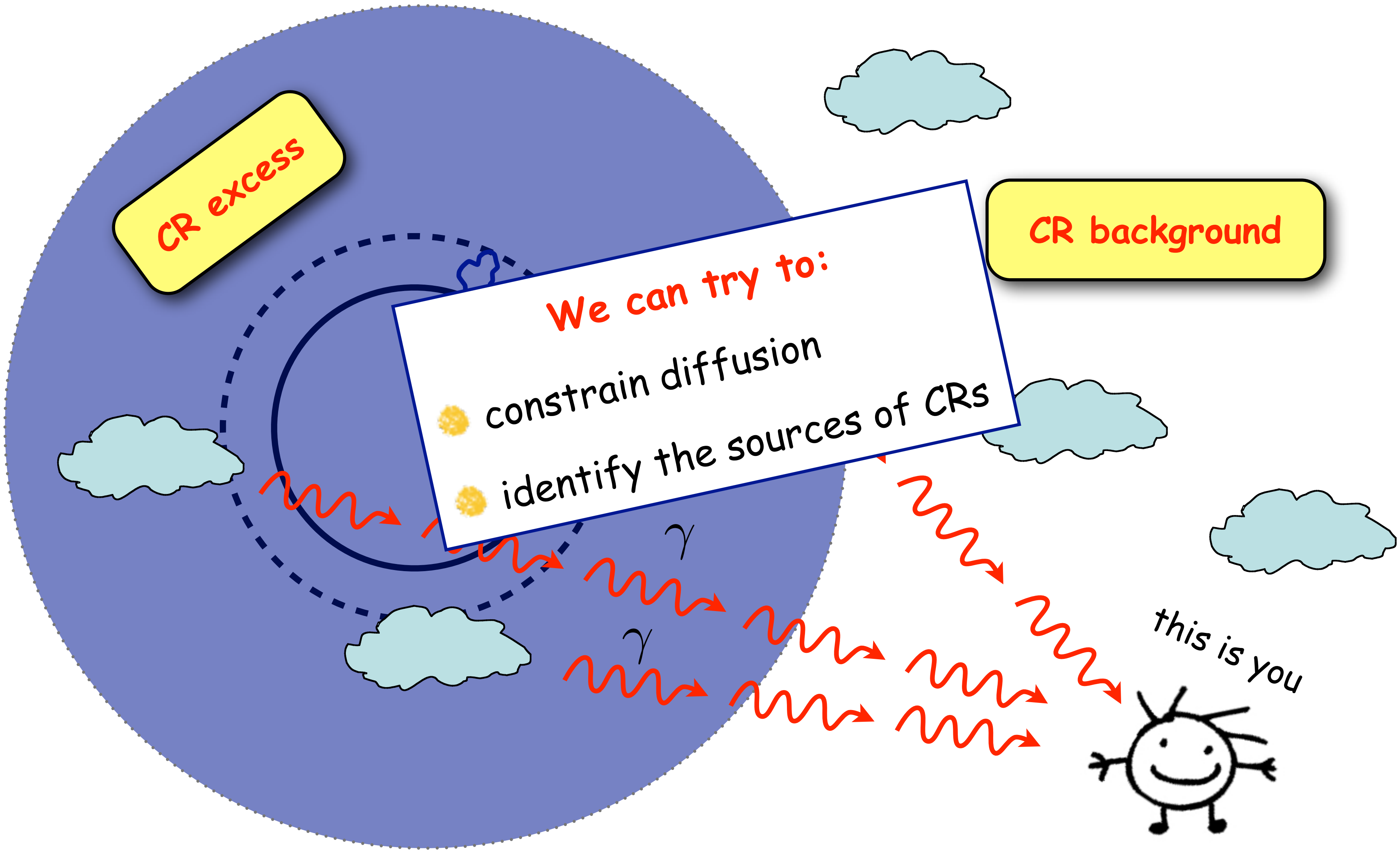
Overview of the talk (cartoon)

CRs can produce gamma rays if dense gas is present



Overview of the talk (cartoon)

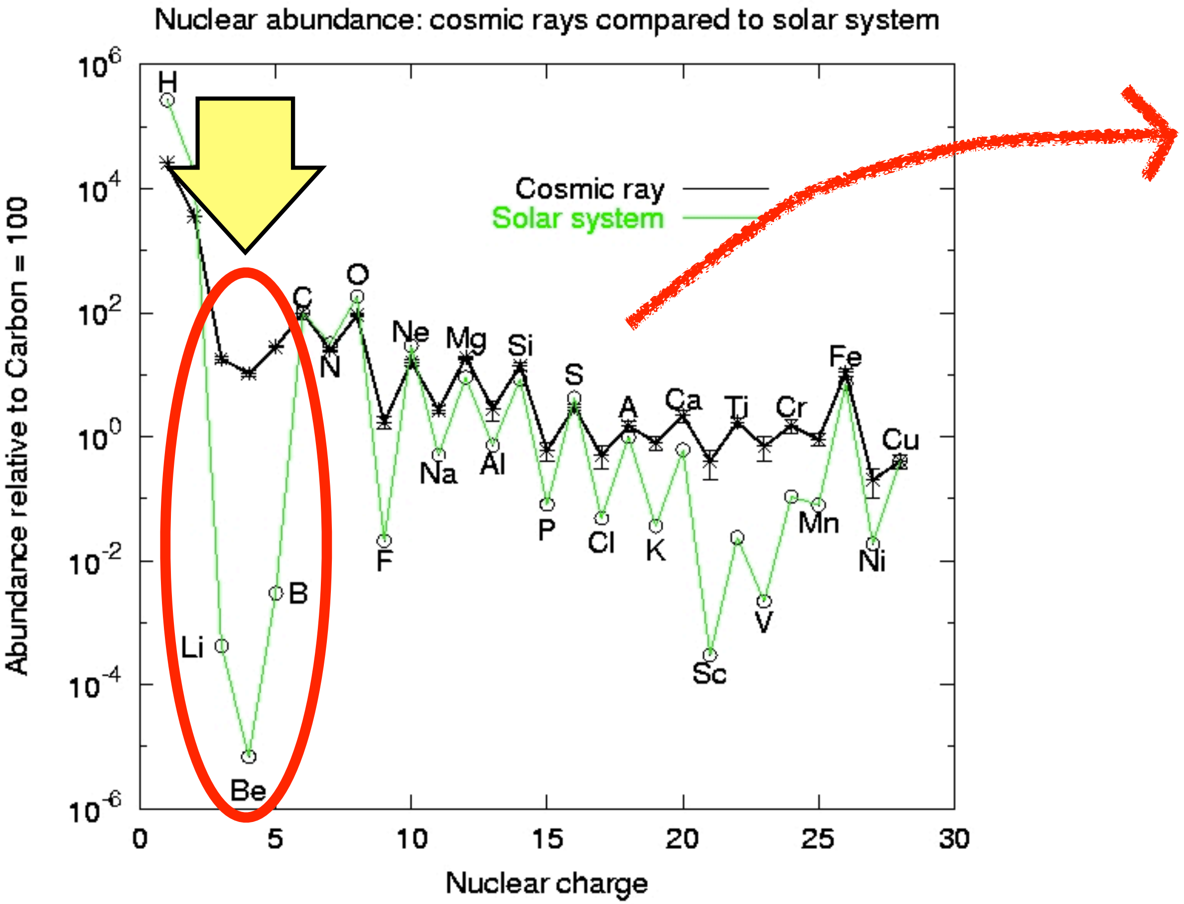
CRs can produce gamma rays if dense gas is present



(1) Escape

A remarkable "coincidence"

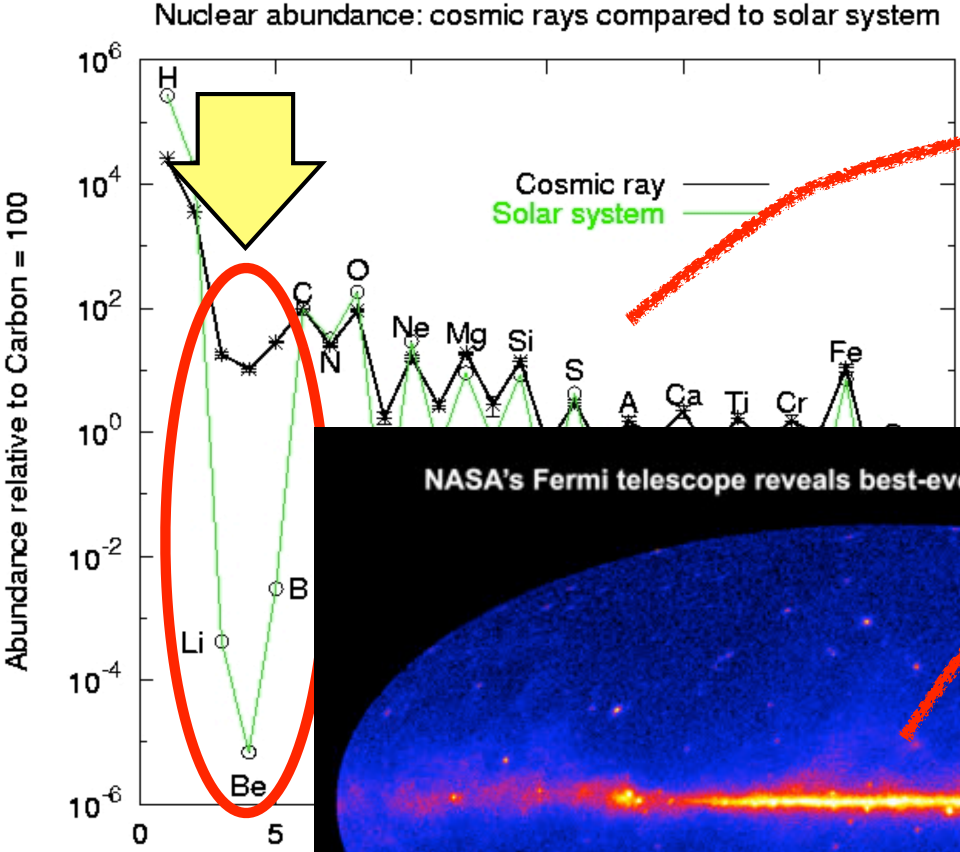
~ Baade & Zwicky, 1934

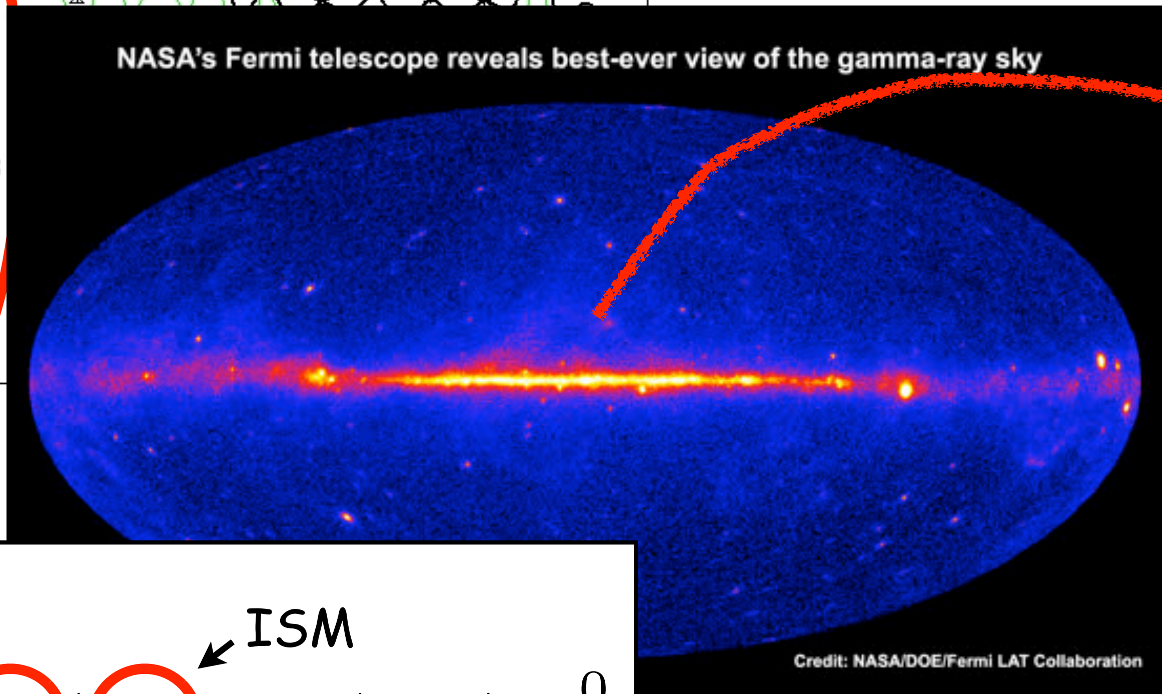


CR escape time

A remarkable "coincidence"

~ Baade & Zwicky, 1934





CR escape time

-> power of CR sources 3 x 10^{40} erg/s

CR total energy

CR

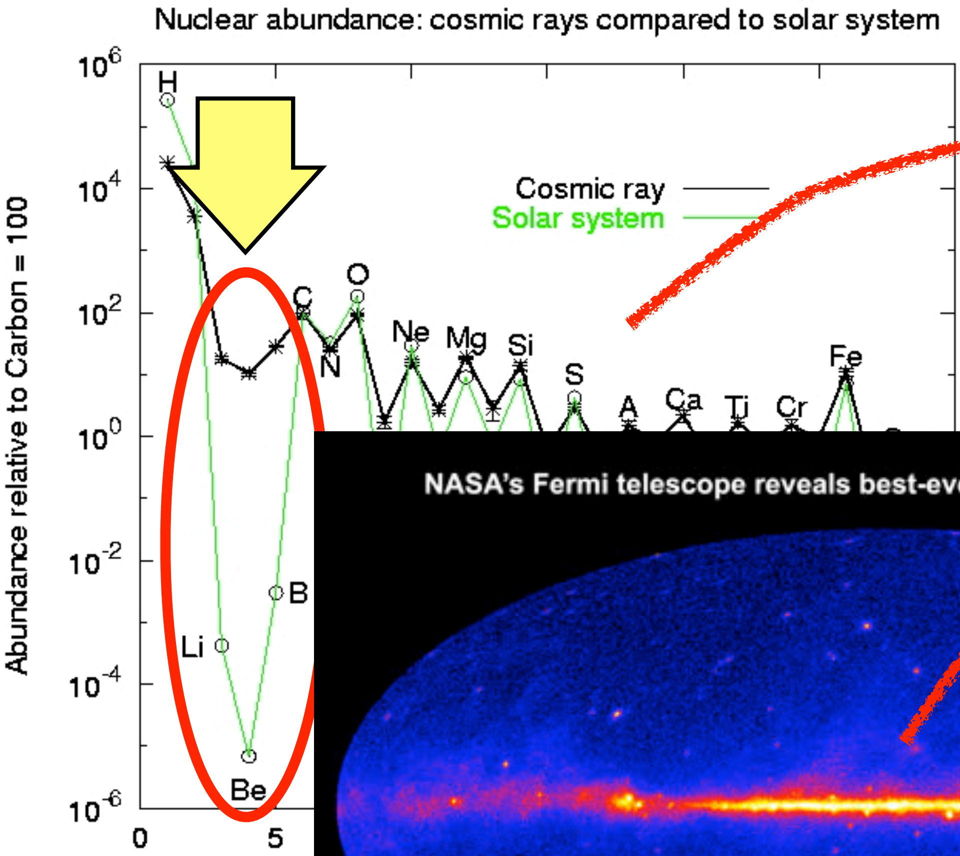
ISM

$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

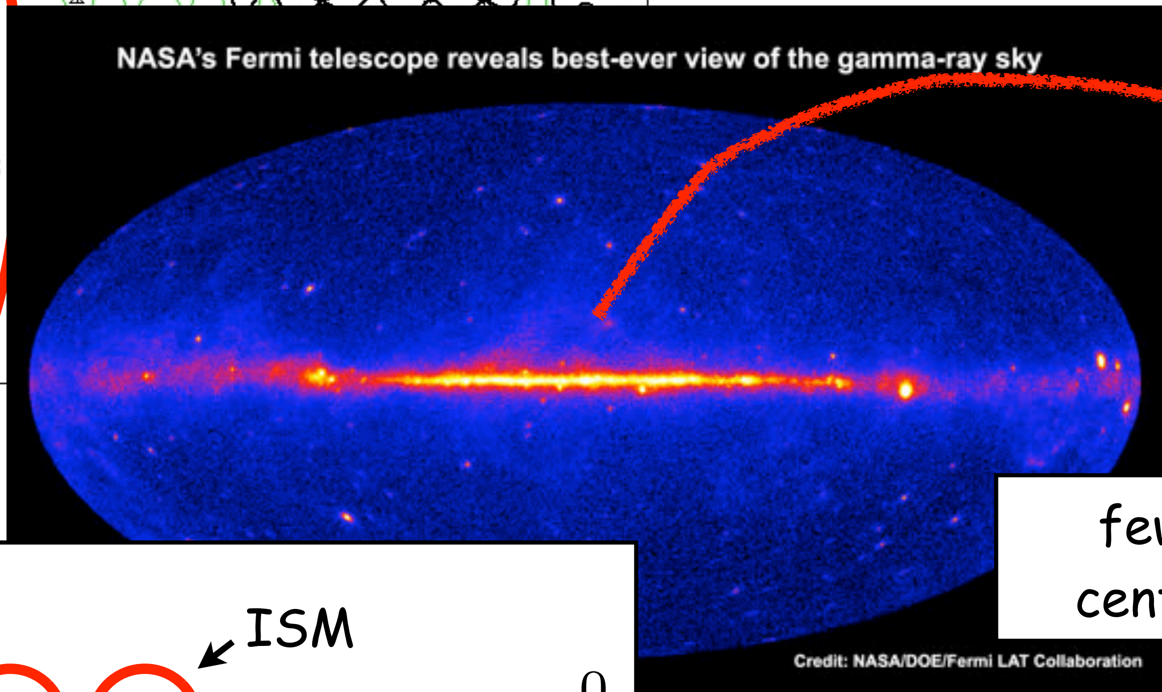
A remarkable “coincidence”

~ Baade & Zwicky, 1934



CR escape time

-> power of CR sources 3 x 10^{40} erg/s



CR total energy

few supernovae per century in the Galaxy

-> power of SuperNovae 3 x 10^{41} erg/s

CR

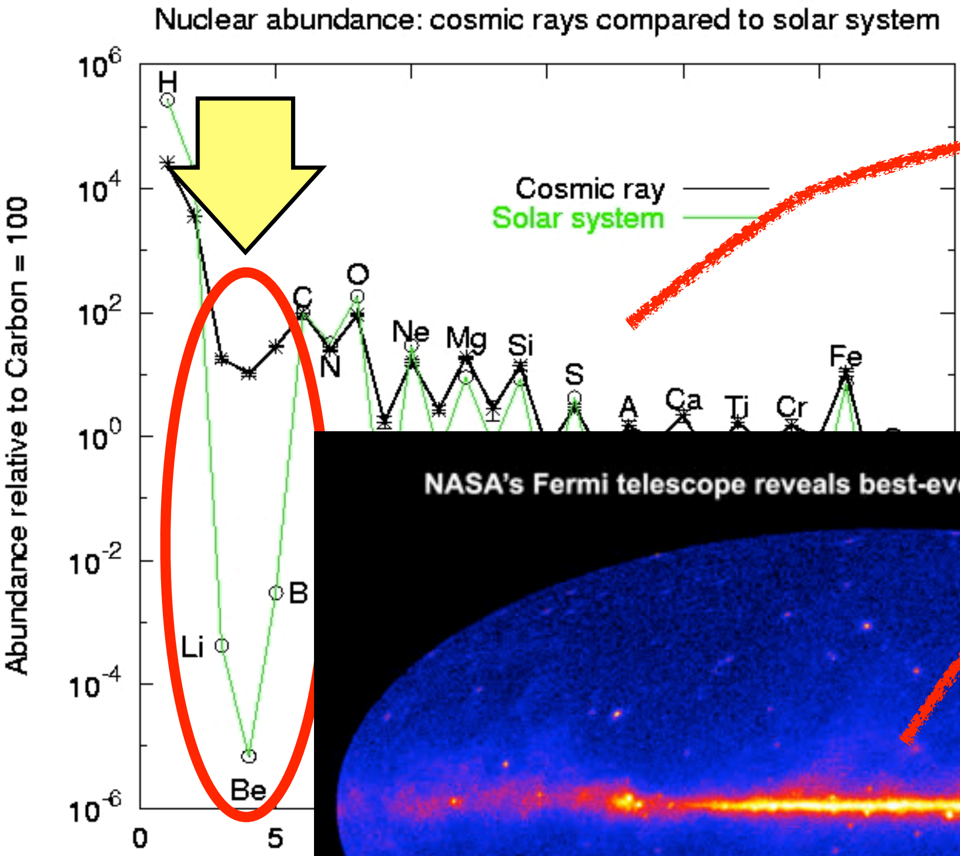
ISM

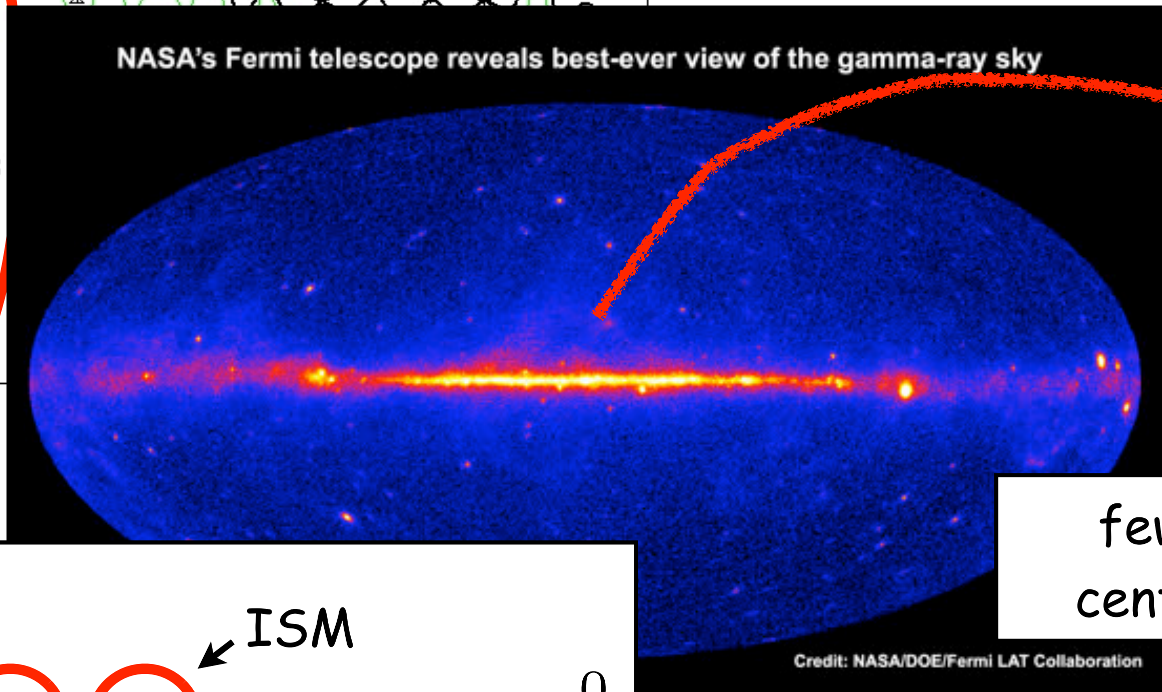
$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

A remarkable "coincidence"

~ Baade & Zwicky, 1934





CR escape time

-> power of CR sources 3 x 10^{40} erg/s

CR total energy

few supernovae per century in the Galaxy

-> power of SuperNovae 3 x 10^{41} erg/s

CR

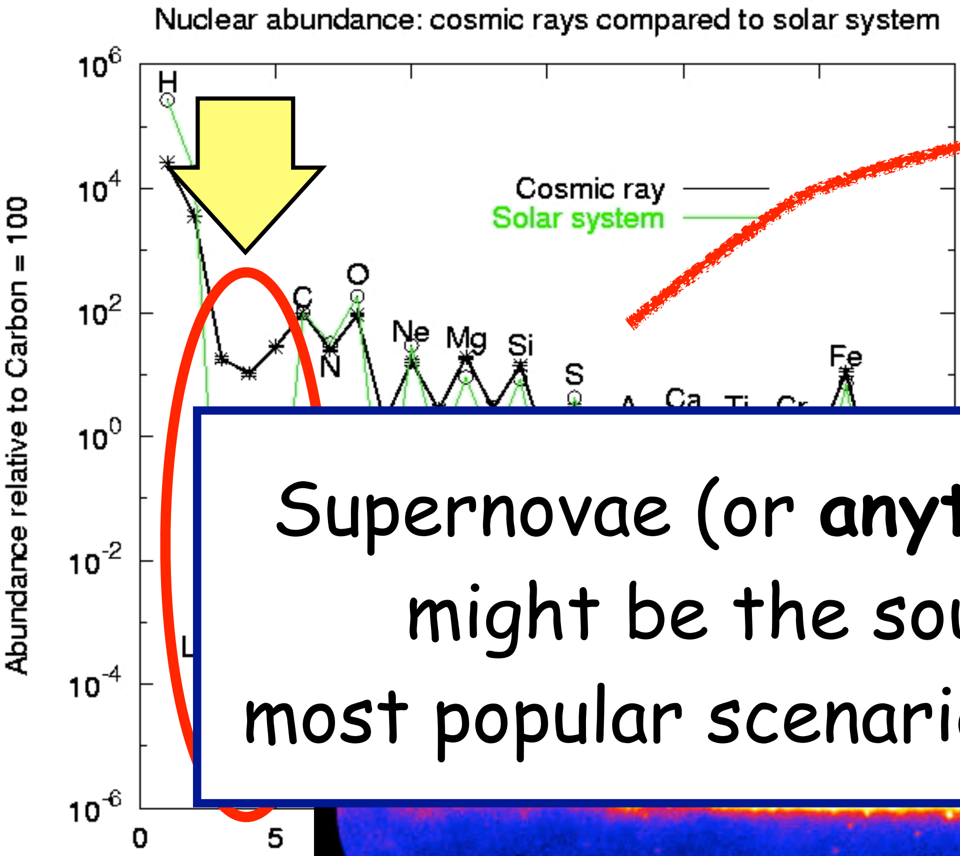
ISM

$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

A remarkable "coincidence"

~ Baade & Zwicky, 1934

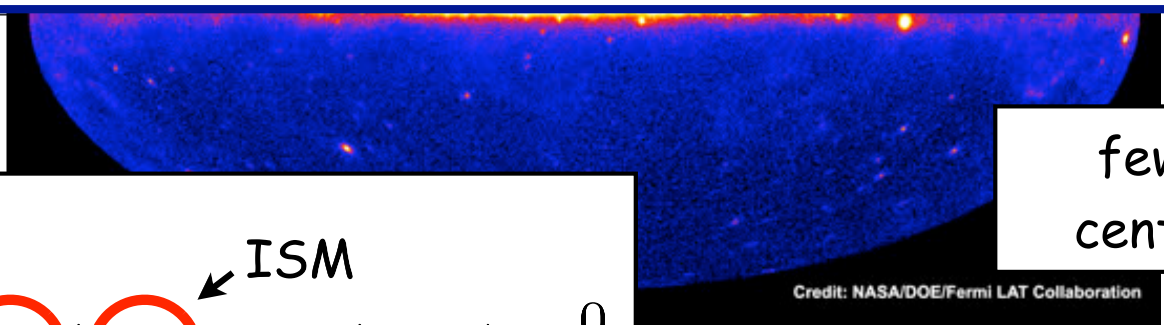


CR escape time

-> power of CR sources 3 x 10^{40} erg/s

Supernovae (or **anything** connected to them) might be the sources of cosmic rays:
most popular scenario -> supernova remnants

nergy



CR ISM

$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

few supernovae per century in the Galaxy

-> power of SuperNovae 3 x 10^{41} erg/s

Diffusive Shock Acceleration at SuperNova Remnants and the origin of Galactic Cosmic Rays

(1) Spallation measurements of Cosmic Rays suggest that CR sources have to inject in the Galaxy a spectrum close to E^{-2}.

(2) Strong shocks at SNRs can indeed accelerate E^{-2} spectra.

-> Thus SNRs are good candidates as sources of Galactic CRs.

Diffusive Shock Acceleration at SuperNova Remnants and the origin of Galactic Cosmic Rays

(1) Spallation measu[illegible]ents of [illegible]ic Rays suggest that CR sources h[illegible] in the Galaxy a spectru[illegible]o E^{-2}.

(2) Strong shocks at [illegible]an indeed accelerate [illegible]

-> Thus SNRs a[illegible]d c[illegible]es as sources of [illegible]actic CRs.

Diffusive Shock Acceleration at SuperNova Remnants and the origin of Galactic Cosmic Rays

(1) Spallation measu[illegible]ents of [illegible]ic Rays suggest that CR sources h[illegible]o i[illegible] in the Galaxy a spectru[illegible]o E^{-2}.

(2) Strong shocks at [illegible]an indeed accelerate [illegible]

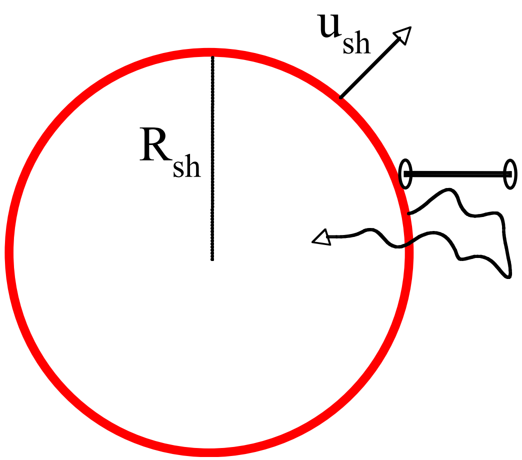
-> Thus SNRs a[illegible]d c[illegible]es as sources of [illegible]actic C[illegible]s.

E^{-2} is the spectrum at the shock, not the one released in the ISM!

When do CRs escape SNRs?

We need to know a bit of shock acceleration theory...

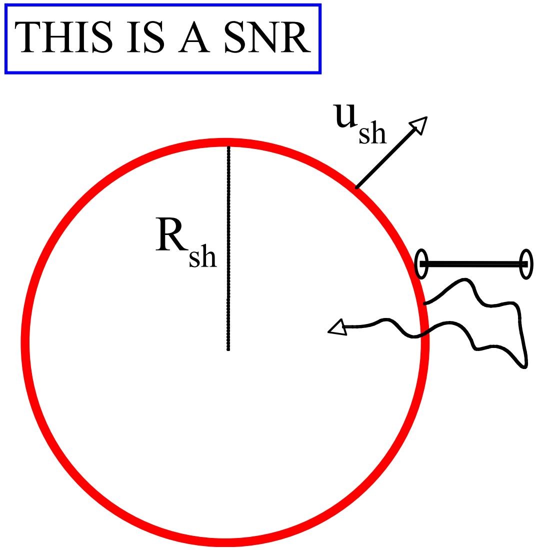
THIS IS A SNR



Diffusion length: $l_{diff} \sim \frac{D(E)}{u_{sh}} \propto \frac{E}{B_{sh} u_{sh}}$

When do CRs escape SNRs?

We need to know a bit of shock acceleration theory...



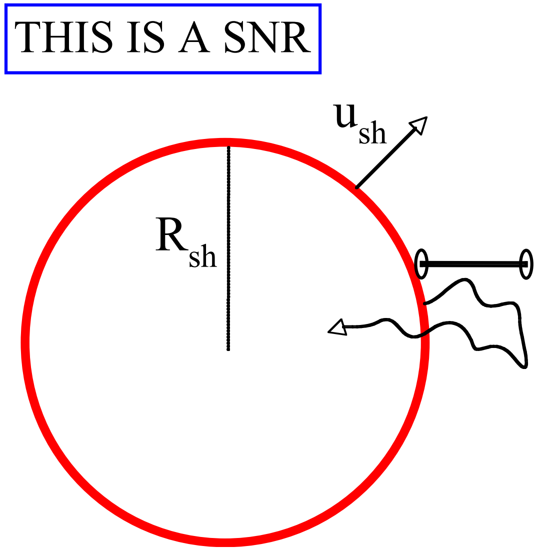
Diffusion length: $l_{diff} \sim \frac{D(E)}{u_{sh}} \propto \frac{E}{B_{sh} u_{sh}}$

Confinement condition:

$$\frac{D(E)}{u_{sh}(t)} < R_{sh}(t) \;\rightarrow\; E_{max} \sim B_{sh}\, u_{sh}(t)\, R_{sh}(t)$$

When do CRs escape SNRs?

We need to know a bit of shock acceleration theory...



Diffusion length: $l_{diff} \sim \frac{D(E)}{u_{sh}} \propto \frac{E}{B_{sh} u_{sh}}$

Confinement condition:

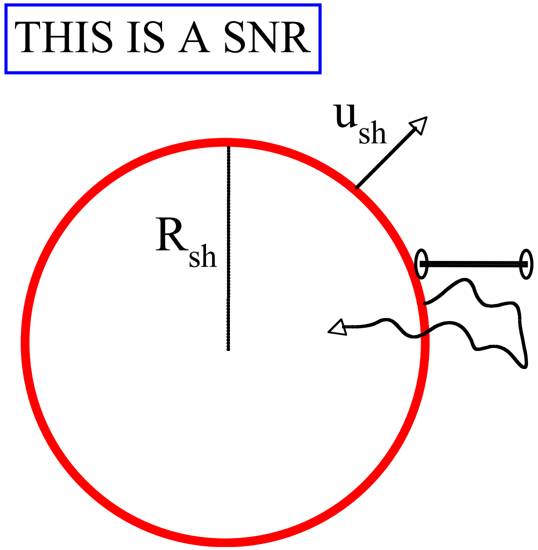
$$\frac{D(E)}{u_{sh}(t)} < R_{sh}(t) \rightarrow E_{max} \sim B_{sh}\, u_{sh}(t)\, R_{sh}(t)$$

Sedov phase:

$$R_{sh}(t) \propto t^{2/5}$$
$$u_{sh}(t) \propto t^{-3/5}$$

When do CRs escape SNRs?

We need to know a bit of shock acceleration theory...



Diffusion length: $$l_{diff} \sim \frac{D(E)}{u_{sh}} \propto \frac{E}{B_{sh} u_{sh}}$$

Confinement condition:

$$\frac{D(E)}{u_{sh}(t)} < R_{sh}(t) \;\rightarrow\; E_{max} \sim B_{sh}\, u_{sh}(t)\, R_{sh}(t)$$

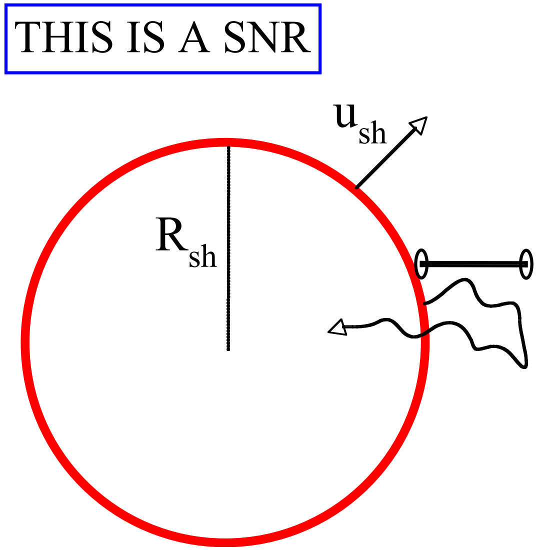
Sedov phase:

$$R_{sh}(t) \propto t^{2/5}$$
$$u_{sh}(t) \propto t^{-3/5}$$

$$\boxed{E_{max} \propto B_{sh} t^{-1/5}}$$

When do CRs escape SNRs?

We need to know a bit of shock acceleration theory...



Diffusion length: $l_{diff} \sim \frac{D(E)}{u_{sh}} \propto \frac{E}{B_{sh} u_{sh}}$

Confinement condition:

$$\frac{D(E)}{u_{sh}(t)} < R_{sh}(t) \;\rightarrow\; E_{max} \sim B_{sh}\, u_{sh}(t)\, R_{sh}(t)$$

$$\boxed{E_{max} \propto B_{sh} t^{-1/5}}$$

B_{sh} also depends on time

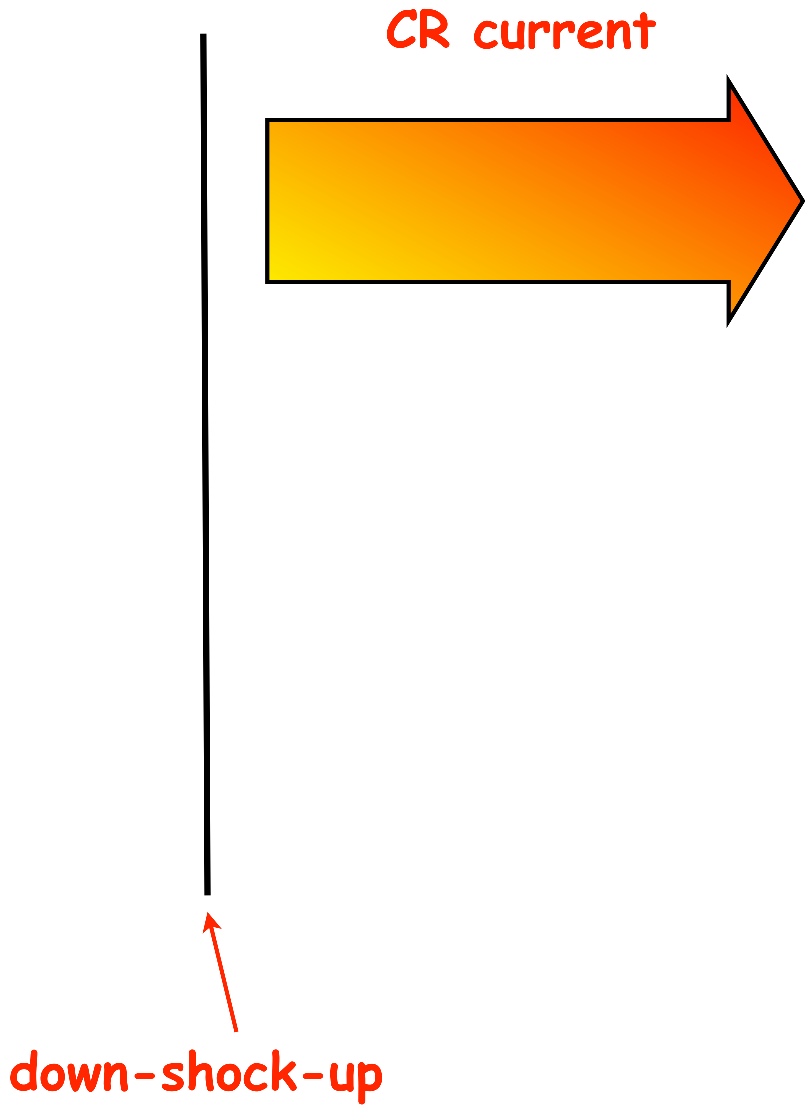
Sedov phase:

$$R_{sh}(t) \propto t^{2/5}$$
$$u_{sh}(t) \propto t^{-3/5}$$

E_{max} decreases with time
Particles with E > E_{max} escape the SNR

(Non resonant) current driven instability

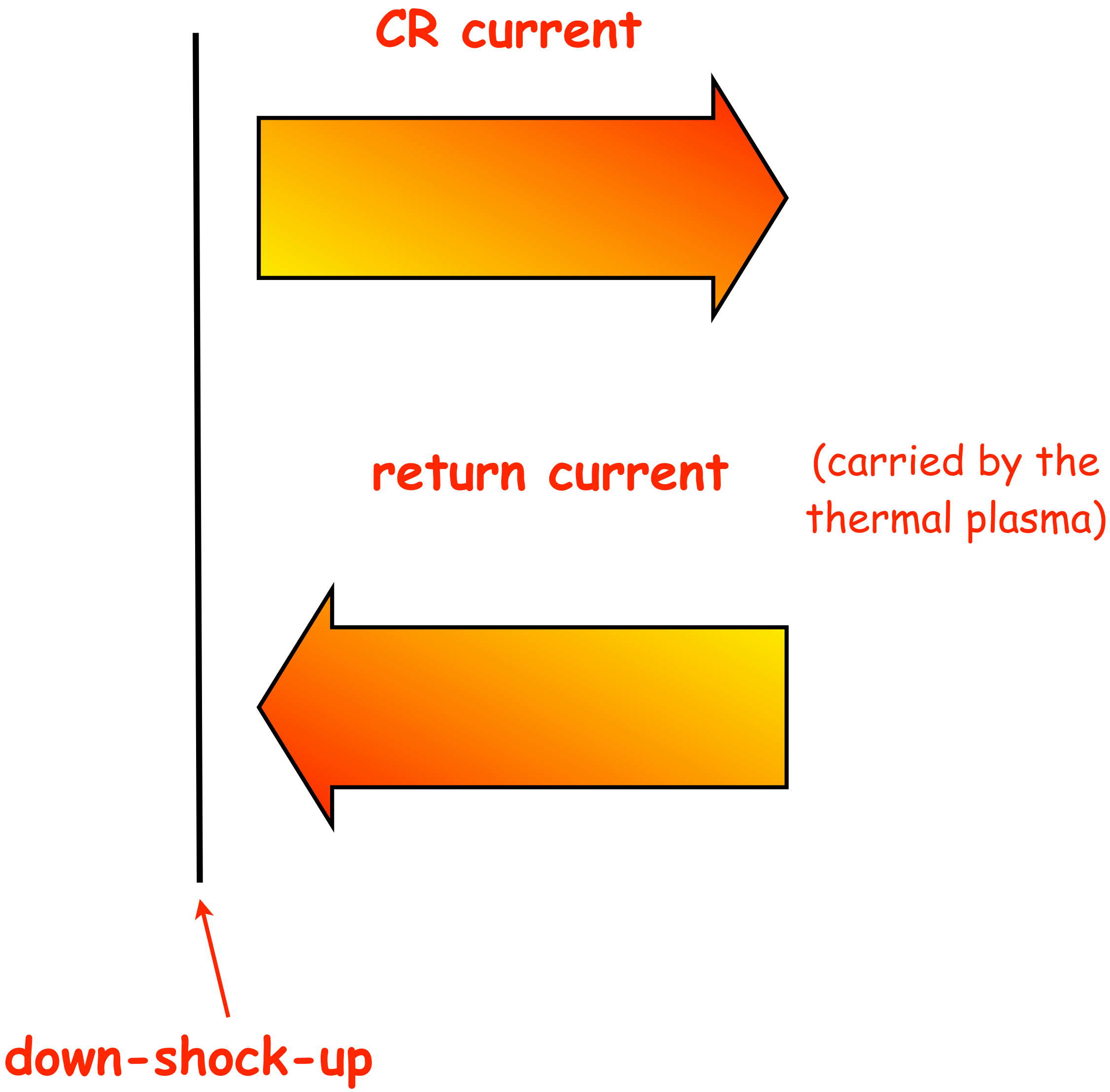
CRs stream at the shock velocity relative to the background plasma



Bell 2004

(Non resonant) current driven instability

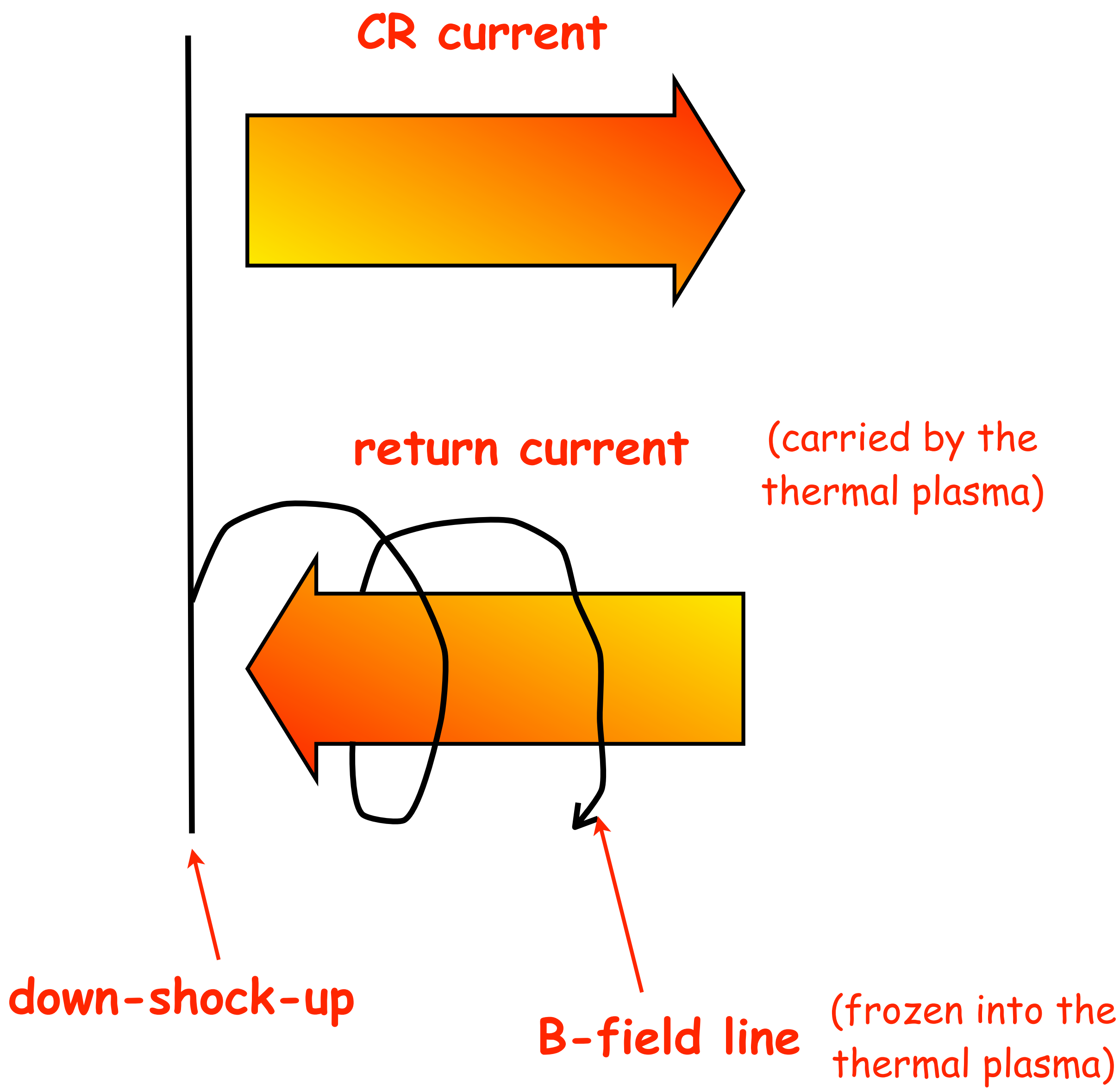
CRs stream at the shock velocity relative to the background plasma



Bell 2004

(Non resonant) current driven instability

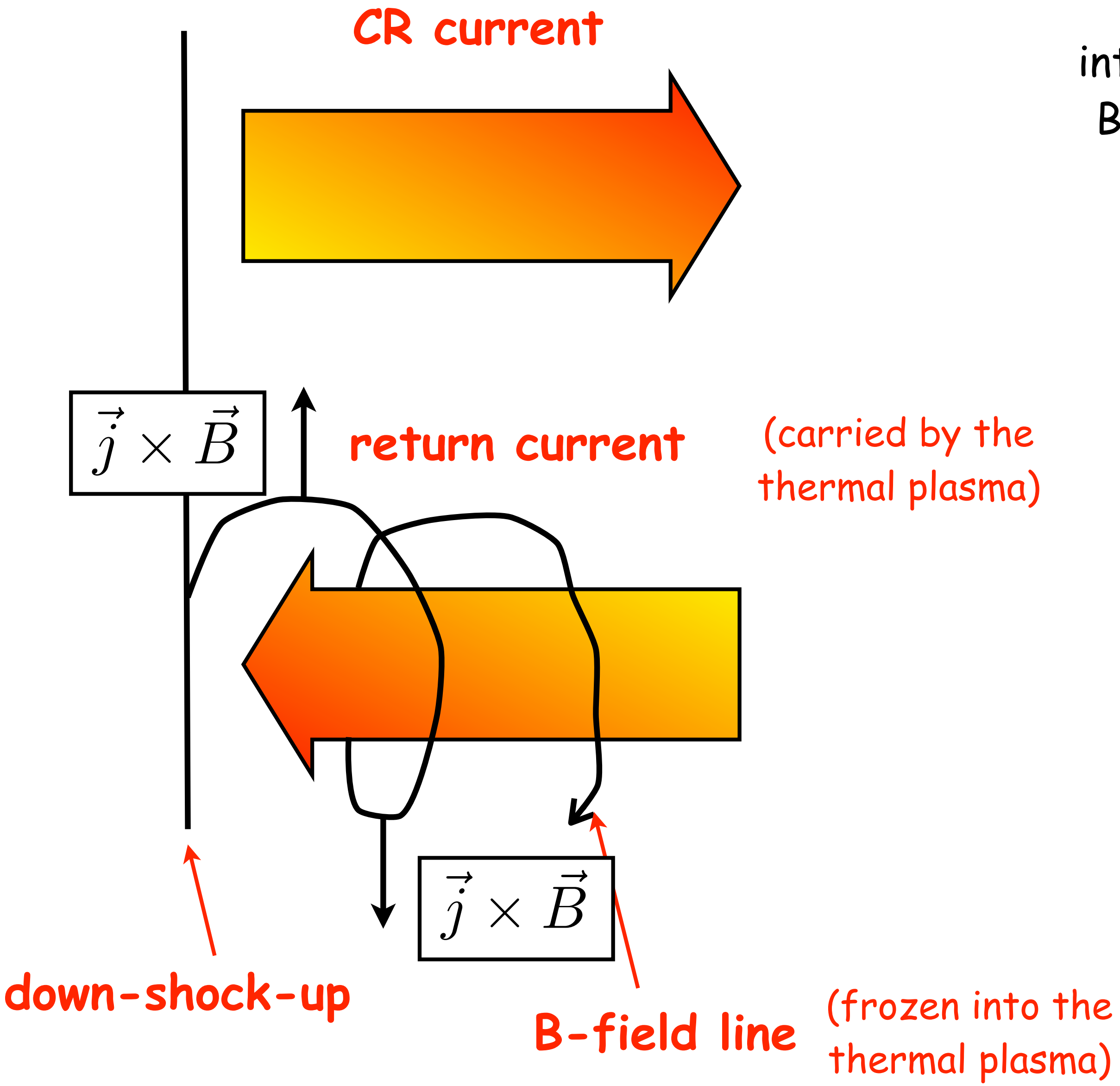
CRs stream at the shock velocity relative to the background plasma



Bell 2004

(Non resonant) current driven instability

CRs stream at the shock velocity relative to the background plasma

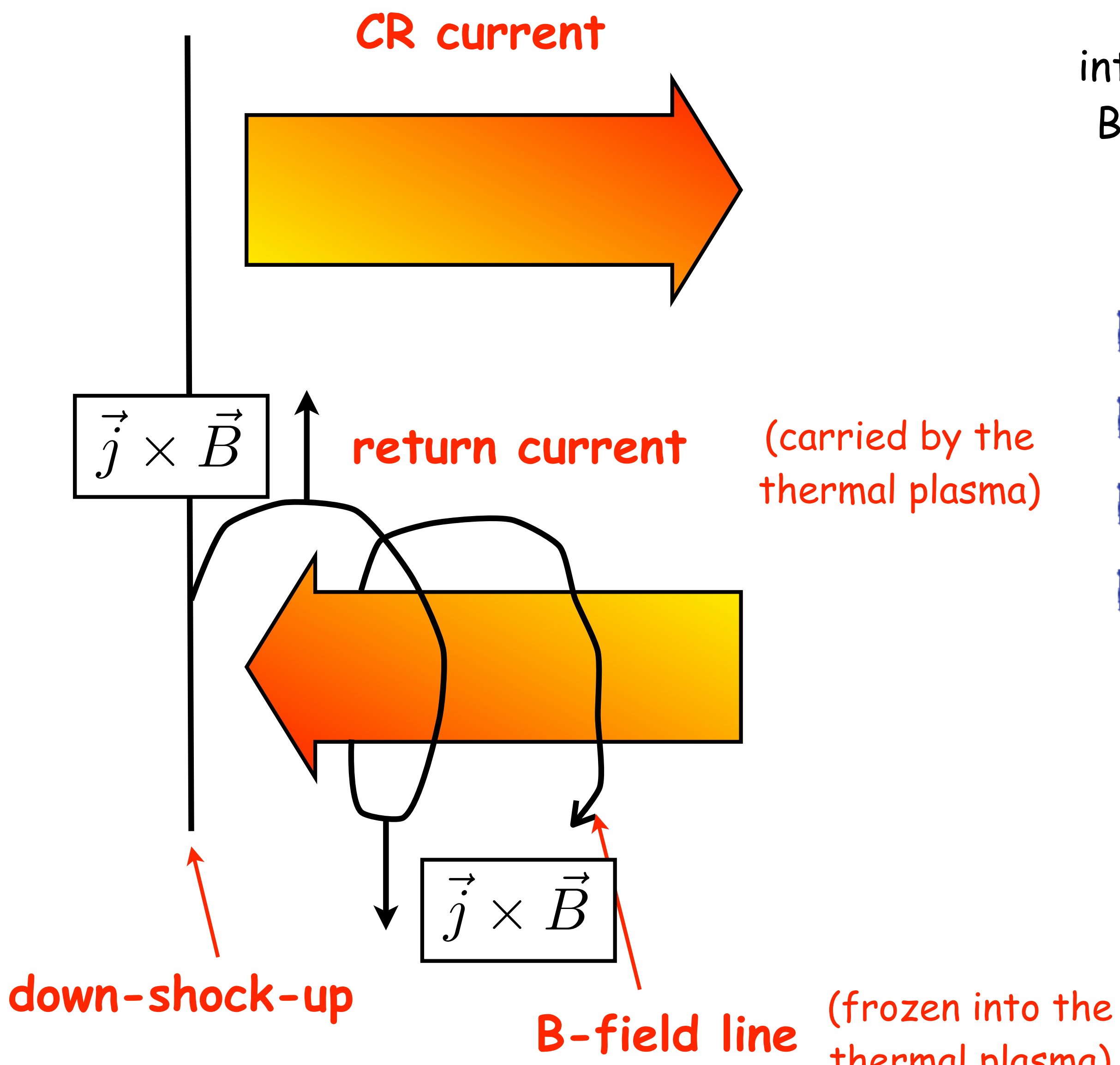


interaction between return current and B-field sets the background plasma in motion and drives the instability

Bell 2004

(Non resonant) current driven instability

CRs stream at the shock velocity relative to the background plasma



interaction between return current and B-field sets the background plasma in motion and drives the instability

- ☑ j x B force expands the spiral
- ☑ lengthens B-field lines
- ☑ increases B-field
- ☑ increase j x B force!

instability!

Bell 2004

Amplified B-field and particle escape...

brutal (and naive) estimate...

saturation field: $$\frac{B_{sat}^2}{8\pi} \approx \frac{1}{2} \frac{u_{sh}}{c} U_{cr} \propto \varrho \, u_{sh}^3$$

Bell 2004

$$\boxed{E_{max} \propto B \; R_{sh} \; u_{sh} \;\; \propto \;\; t^{-11/10}}$$

Guess:

at the beginning (end) of the Sedov phase [100 - 10^5 yrs] CRs with the energy of the knee (proton mass) are released in the ISM

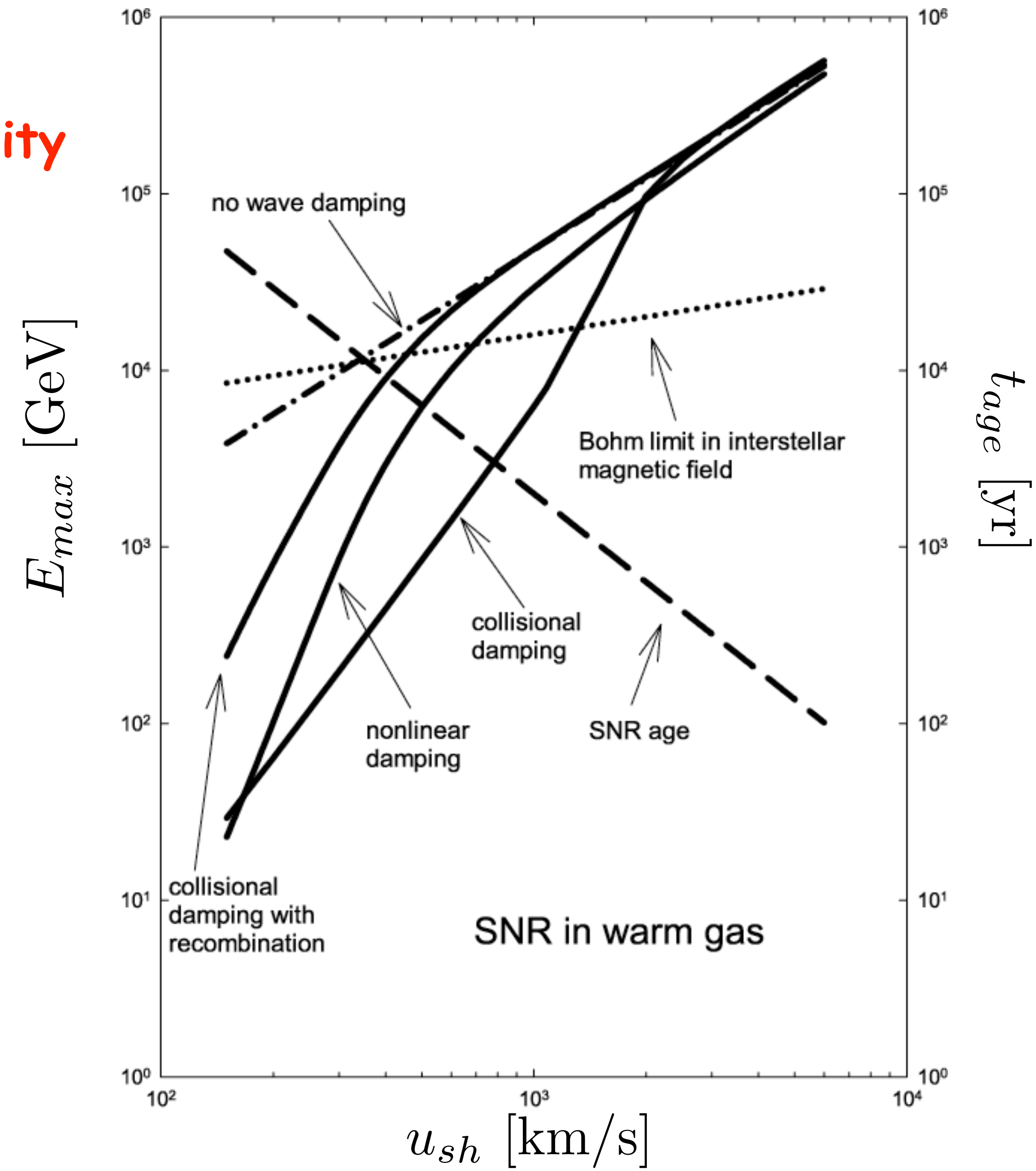
$$\boxed{E_{max} \propto \; t^{-2.16}}$$

adopted for phenomenological studies by Gabici& Aharonian 2007, Gabici et al 2009 and by Fujita et al 2010, Li & Chen 2010, Ohira et al 2010, 2011

Many papers on E_{max} versus t - (1)

Ptuskin&Zirakashvili 2003, 2005

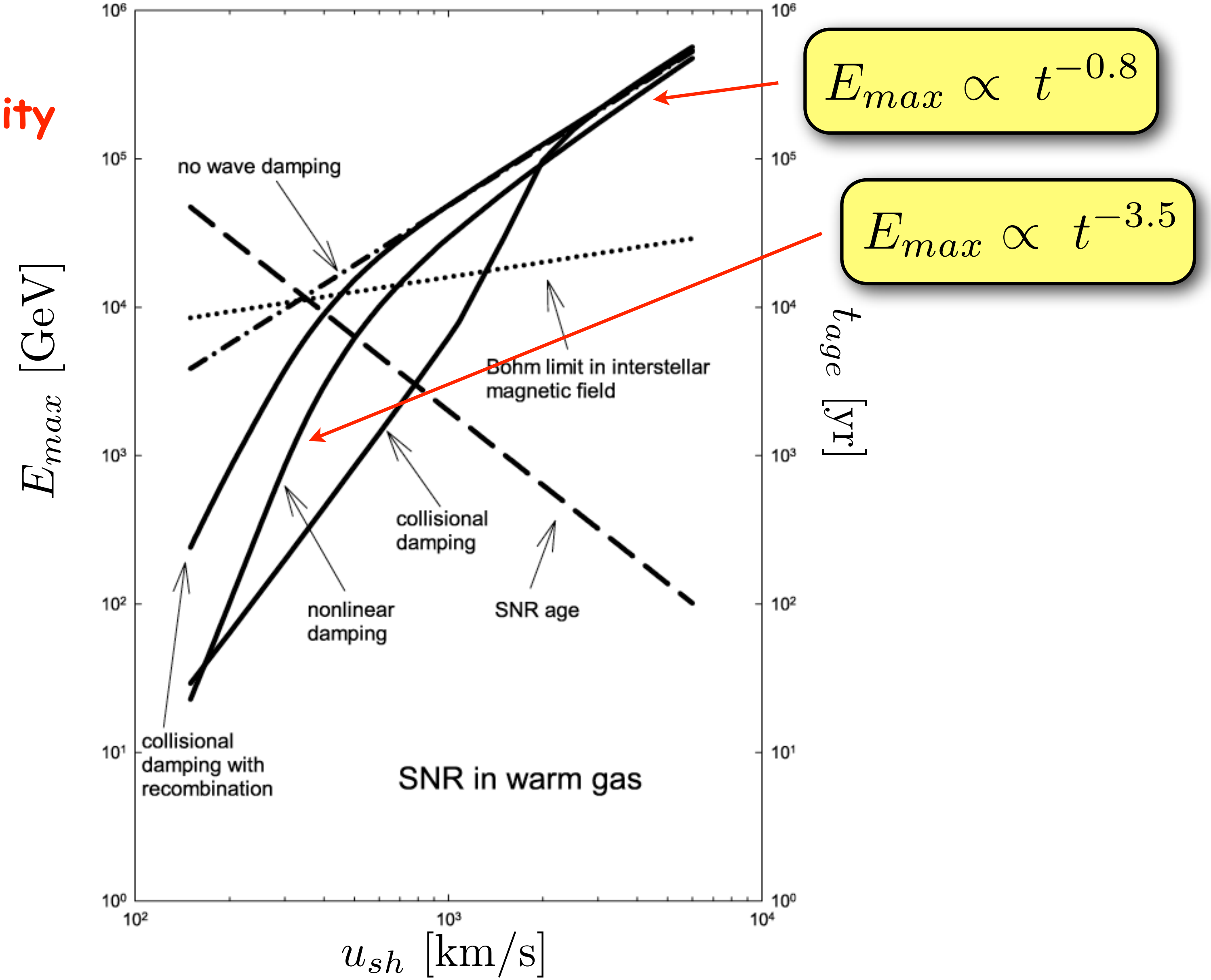
growth rate:
streaming instability



Many papers on E_{max} versus t - (1)

Ptuskin&Zirakashvili 2003, 2005

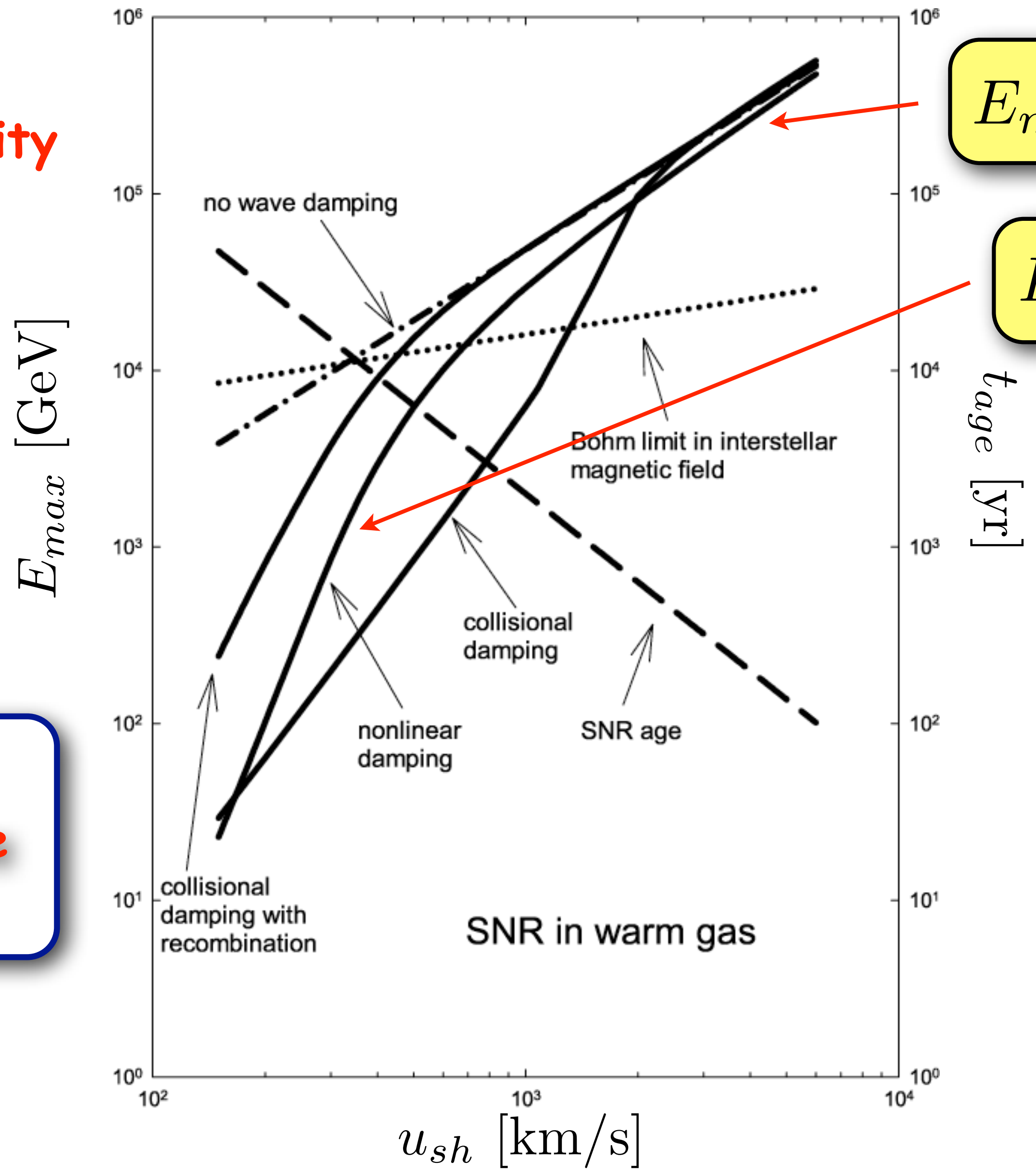
growth rate:
streaming instability



Many papers on E_{max} versus t - (1)

Ptuskin&Zirakashvili 2003, 2005

growth rate: streaming instability



$E_{max} \propto t^{-0.8}$

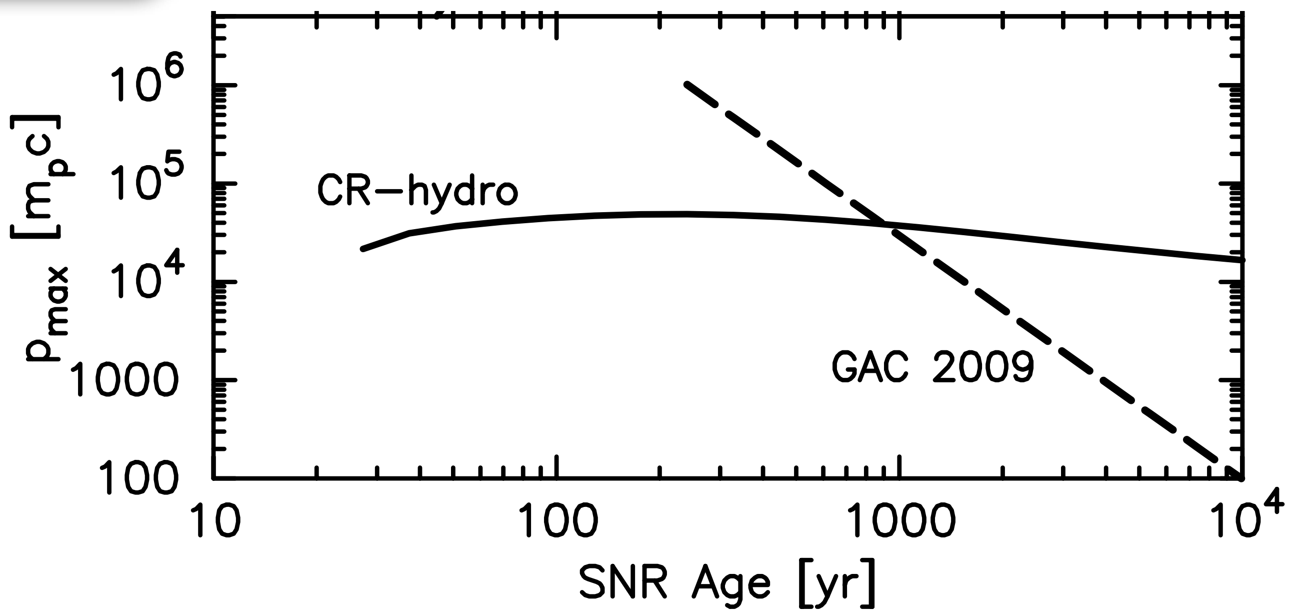
$E_{max} \propto t^{-3.5}$

damping is important at late times!

Many papers on E_{max} versus t - (2)

Ellison & Bykov 2011

no B-field amplification

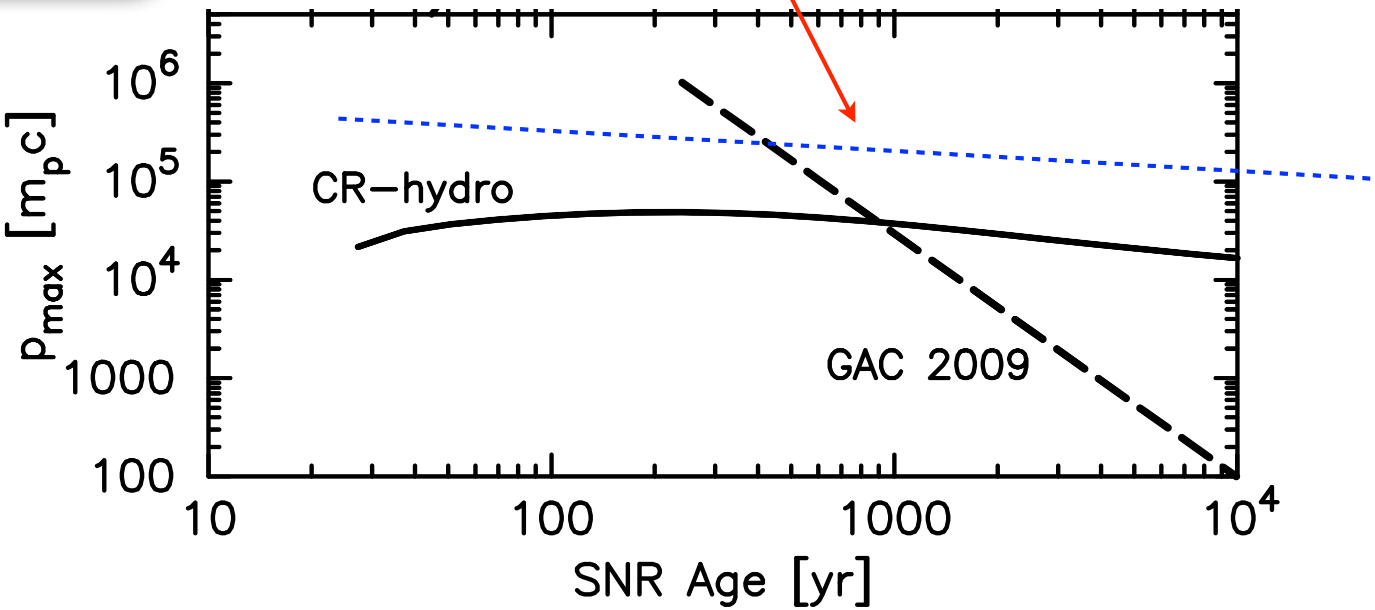


Many papers on E_{max} versus t - (2)

Ellison & Bykov 2011

no B-field amplification

$$E_{max} \propto B_{sh} t^{-1/5}$$

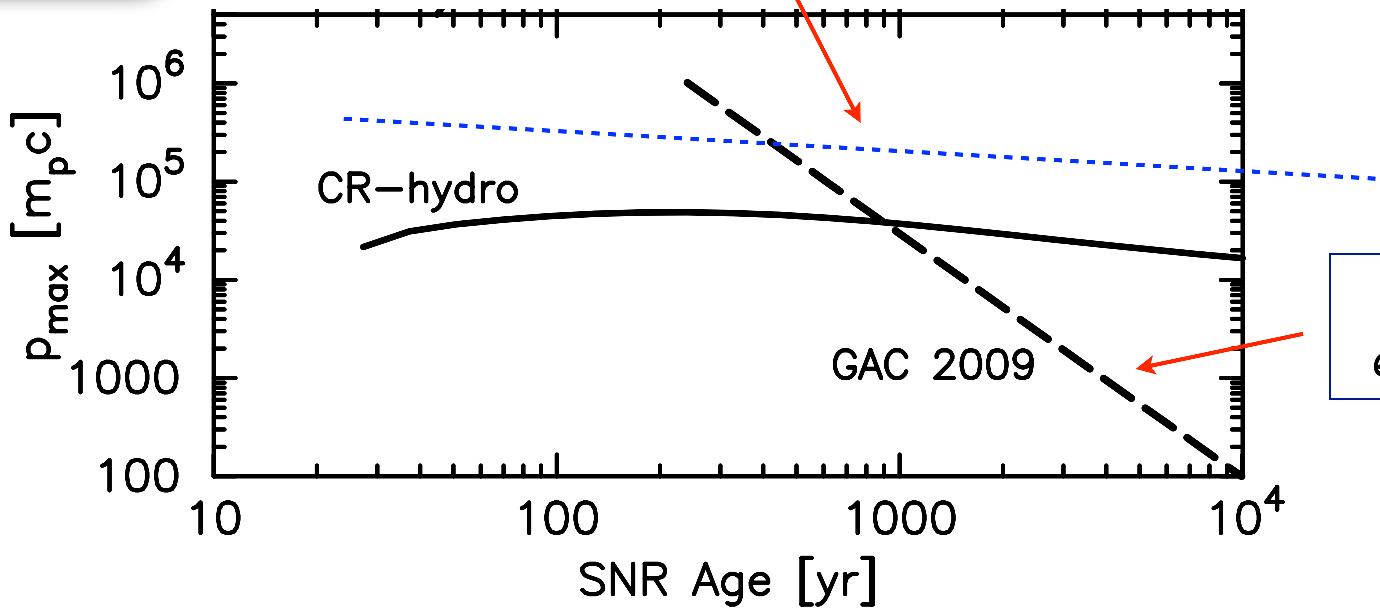


Many papers on E_{max} versus t - (2)

Ellison & Bykov 2011

no B-field amplification

$$E_{max} \propto B_{sh} t^{-1/5}$$



Gabici et al 2009

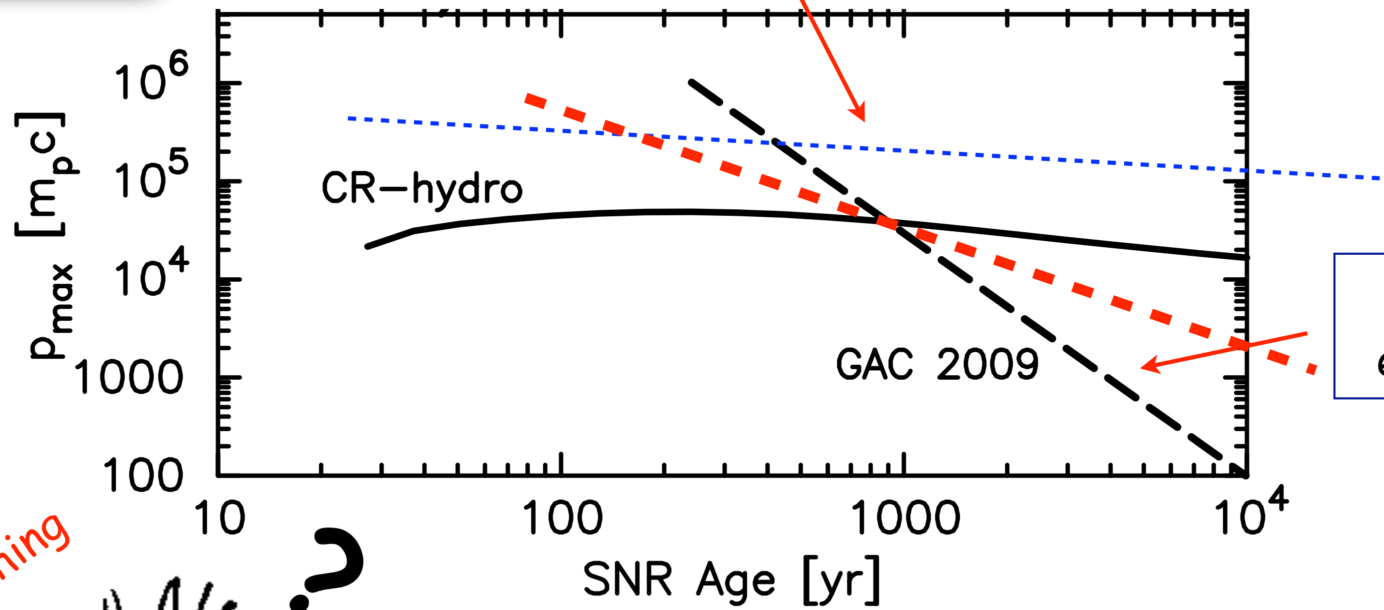
"Non linear feedback may reduce the full effects of magnetic field amplification and we feel it is unlikely that a time dependence as strong as assumed by Gabici et al will be obtained."

Many papers on E_{max} versus t - (2)

Ellison & Bykov 2011

no B-field amplification

$$E_{max} \propto B_{sh} t^{-1/5}$$



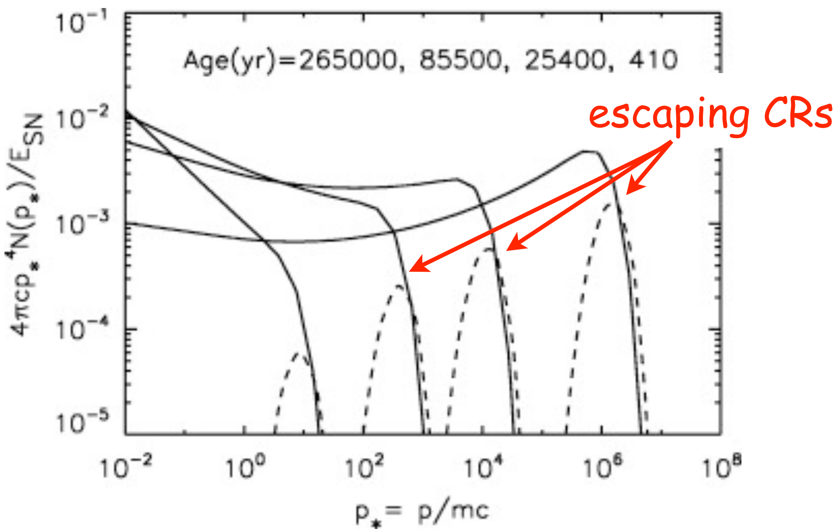
Gabici et al 2009

I feel it is "something in between" ...

"Non linear feedback may reduce the full effects of magnetic field amplification and we feel it is unlikely that a time dependence as strong as assumed by Gabici et al will be obtained."

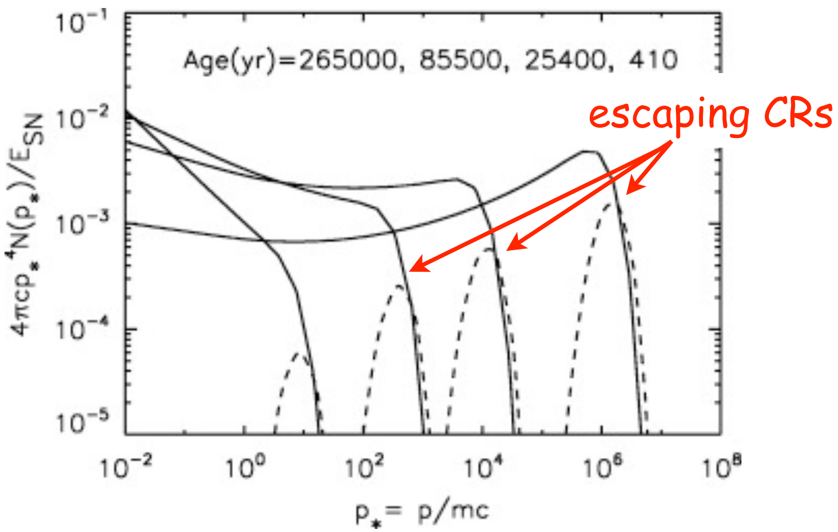
Many papers on E_{max} versus t - (3)

Caprioli et al 2009, 2010

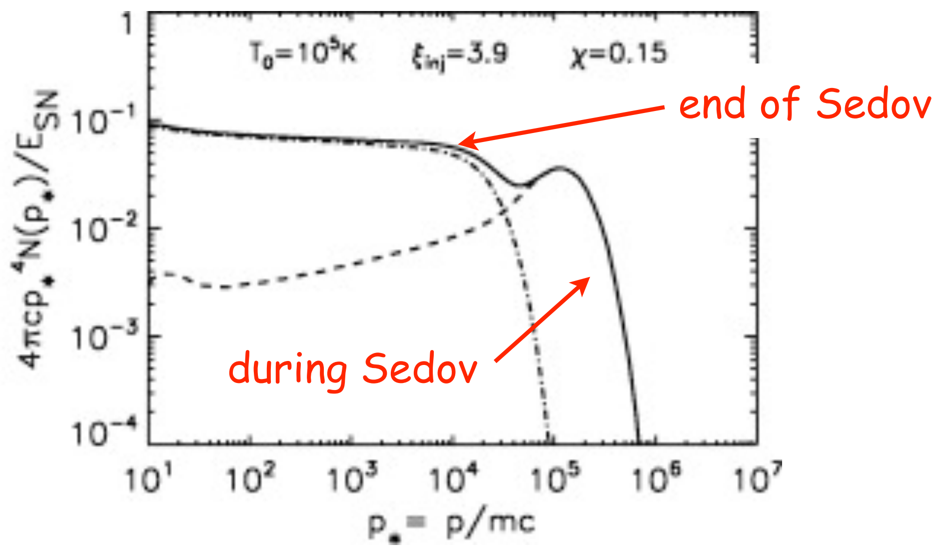


Many papers on E_{max} versus t - (3)

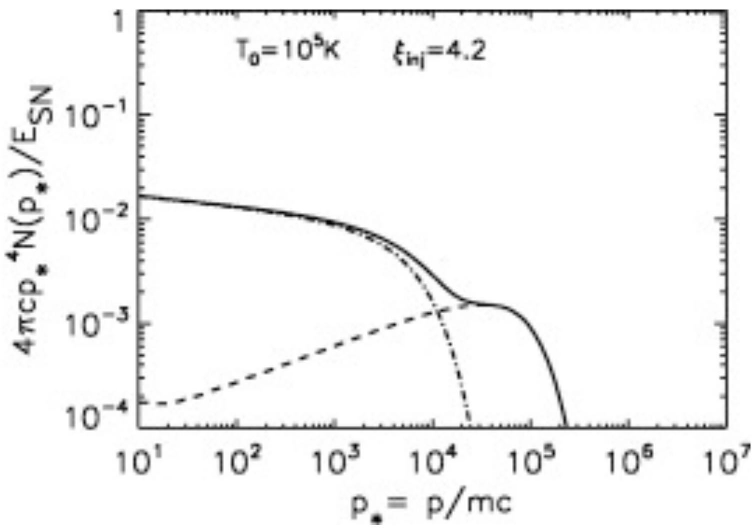
Caprioli et al 2009, 2010



high CR acceleration efficiency

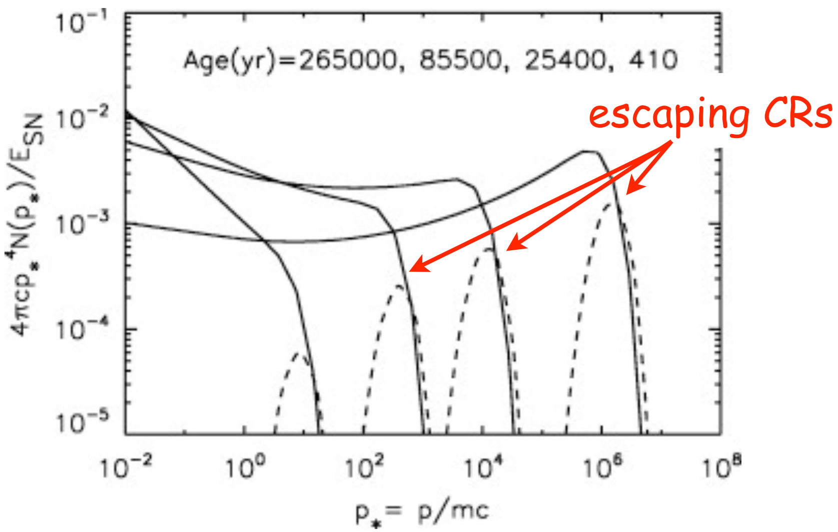


low CR acceleration efficiency

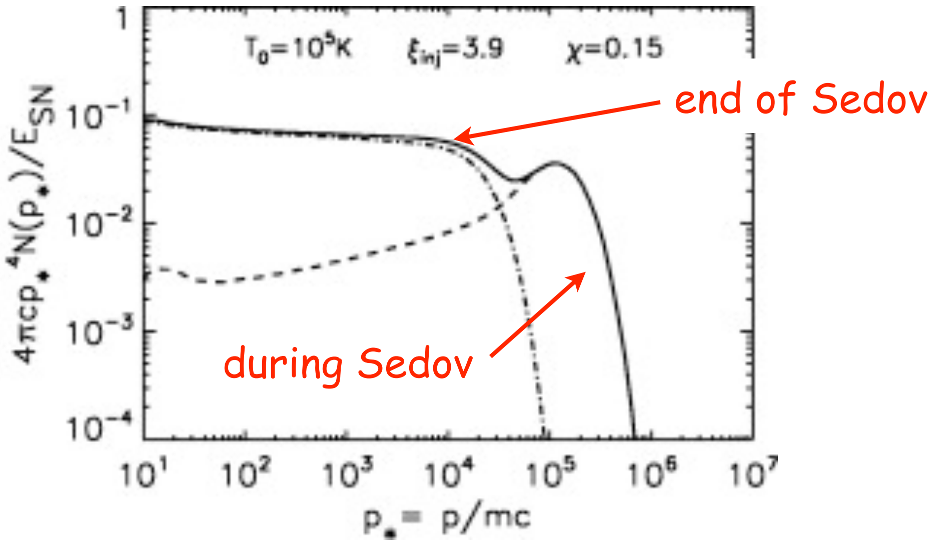


Many papers on E_{max} versus t - (3)

Caprioli et al 2009, 2010

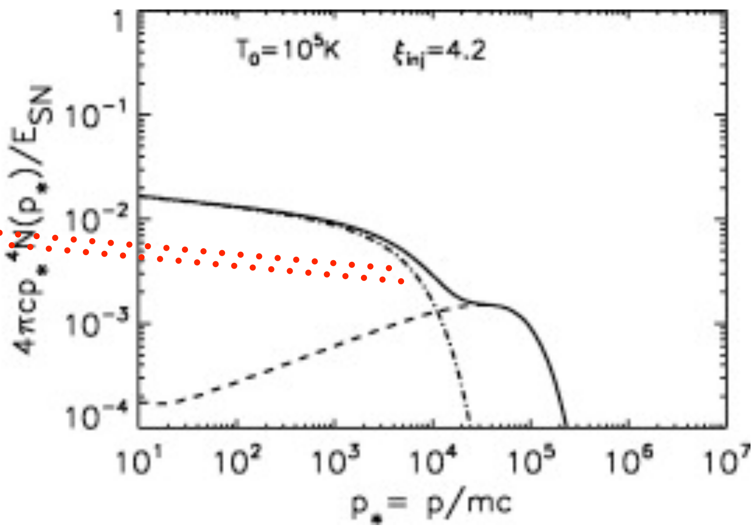


high CR acceleration efficiency



Check: TeV emission from old SNRs?

low CR acceleration efficiency



CR spectrum released in the ISM

<u>very naive</u> summary of: Ptuskin & Zirakashvili 2003, 2005

Assumption 1: particles of energy E are released at a time defined by -> $\boxed{E \propto t^{-\delta}}$

SNR in Sedov phase: $R_s \propto t^{\frac{2}{5}}$ $u_s \propto t^{-\frac{3}{5}}$

Shock kinetic luminosity: $L_k \propto \varrho \, u_s^3 \, (4\pi R_s^2) \propto t^{-1}$

CR spectrum released in the ISM

very naive summary of: Ptuskin & Zirakashvili 2003, 2005

Assumption 1: particles of energy E are released at a time defined by -> $\boxed{E \propto t^{-\delta}}$

SNR in Sedov phase: $R_s \propto t^{\frac{2}{5}}$ $\quad u_s \propto t^{-\frac{3}{5}}$

Shock kinetic luminosity: $L_k \propto \varrho\, u_s^3\, (4\pi R_s^2) \propto t^{-1}$

Assumption 2: a fixed fraction of L_k is released in form of CRs

$$\frac{dN_{CR}}{dE} = \frac{dN_{CR}}{dt}\frac{dt}{dE} \propto \frac{L_k}{E} \times \frac{t}{E}\left(\frac{E}{t}\frac{dt}{dE}\right) \propto E^{-2}$$

CR spectrum released in the ISM

very naive summary of: Ptuskin & Zirakashvili 2003, 2005

Assumption 1: particles of energy E are released at a time defined by -> $\boxed{E \propto t^{-\delta}}$

SNR in Sedov phase: $R_s \propto t^{\frac{2}{5}}$ $\qquad u_s \propto t^{-\frac{3}{5}}$

Shock kinetic luminosity: $L_k \propto \varrho\, u_s^3\, (4\pi R_s^2) \propto t^{-1}$

Assumption 2: a fixed fraction of L_k is released in form of CRs

$$\frac{dN_{CR}}{dE} = \frac{dN_{CR}}{dt}\frac{dt}{dE} \propto \frac{L_k}{E} \times \frac{t}{E}\left(\frac{E}{t}\frac{dt}{dE}\right) \propto E^{-2}$$

CR spectrum released in the ISM

<u>very naive</u> summary of: Ptuskin & Zirakashvili 2003, 2005

Assumption 1: particles of energy E are released at a time defined by -> $\boxed{E \propto t^{-\delta}}$

SNR in Sedov phase: $R_s \propto t^{\frac{2}{5}}$ $\quad u_s \propto t^{-\frac{3}{5}}$

Shock kinetic luminosity: $L_k \propto \varrho \, u_s^3 \, (4\pi R_s^2) \propto t^{-1}$

Assumption 2: a fixed fraction of L_k is released in form of CRs

$$\frac{dN_{CR}}{dE} = \frac{dN_{CR}}{dt}\frac{dt}{dE} \propto \overbrace{\frac{L_k}{E}}^{1/t} \times \frac{t}{E}\Big(\overbrace{\frac{E}{t}\frac{dt}{dE}}^{\text{const}}\Big) \propto E^{-2}$$

CR spectrum released in the ISM

very naive summary of: Ptuskin & Zirakashvili 2003, 2005

Assumption 1: particles of energy E are released at a time defined by -> $\boxed{E \propto t^{-\delta}}$

SNR in Sedov phase: $R_s \propto t^{\frac{2}{5}}$ $u_s \propto t^{-\frac{3}{5}}$

Shock kinetic luminosity: $L_k \propto \varrho\, u_s^3\, (4\pi R_s^2) \propto t^{-1}$

Assumption 2: a fixed fraction of L_k is released in form of CRs

again!

$$\frac{dN_{CR}}{dE} = \frac{dN_{CR}}{dt}\frac{dt}{dE} \propto \overset{1/t}{L_k} \over E \times \frac{t}{E}\underbrace{\left(\frac{E}{t}\frac{dt}{dE}\right)}_{\text{const}} \propto E^{-2}$$

A bit more general solution...

very naive summary of: Ohira et al 2010

a fraction $\boxed{\eta_{cr}}$ of the shock kin. energy $\boxed{L_k}$ -> CRs with spectrum: $\boxed{Q_{CR} \propto E^{-s}}$

A bit more general solution...

very naive summary of: Ohira et al 2010

a fraction $\boxed{\eta_{cr}}$ of the shock kin. energy $\boxed{L_k}$ -> CRs with spectrum: $\boxed{Q_{CR} \propto E^{-s}}$

if only recent acceleration relevant -> $\boxed{Q_{esc} \propto Q_{CR}\ \delta(E - E_{max}(t))}$

A bit more general solution...

very naive summary of: Ohira et al 2010

a fraction $\boxed{\eta_{cr}}$ of the shock kin. energy $\boxed{L_k}$ -> CRs with spectrum: $\boxed{Q_{CR} \propto E^{-s}}$

if only recent acceleration relevant -> $\boxed{Q_{esc} \propto Q_{CR}\, \delta(E - E_{max}(t))}$

(a) Hard spectrum -> s < 2

$$\eta_{cr}\ L_k\ \approx\ Q_{cr}(E_{max})E_{max}^2\ \propto \boxed{Q_{esc}(E_{max})E_{max}^2} \longrightarrow \boxed{N_{esc} \propto E^{-2}}$$

escaping energy flux

A bit more general solution...

<u>very naive</u> summary of: Ohira et al 2010

a fraction η_{cr} of the shock kin. energy L_k -> CRs with spectrum: $Q_{CR} \propto E^{-s}$

if only recent acceleration relevant -> $\boxed{Q_{esc} \propto Q_{CR}\ \delta(E - E_{max}(t))}$

(a) Hard spectrum -> s < 2

$$\eta_{cr}\ L_k \ \approx\ Q_{cr}(E_{max})E^2_{max} \ \propto \boxed{Q_{esc}(E_{max})E^2_{max}} \rightarrow \boxed{N_{esc} \propto E^{-2}}$$

escaping energy flux

(b) Soft spectrum -> s > 2

$$\eta_{cr}\ L_k \ \approx\ Q_{cr}(E_0)E^2_0 \ \propto \boxed{Q_{esc}(E_{max})E^2_{max}} \left(\frac{E_0}{E_{max}}\right)^{2-s}$$

$$\boxed{N_{esc} \propto E^{-s}}$$

A bit more general solution...

very naive summary of: Ohira et al 2010

a fraction η_{cr} of the shock kin. energy L_k -> CRs with spectrum: $Q_{CR} \propto E^{-s}$

if only r... $_{ax}(t))$

$\eta_{cr}\ L_k\ \approx$ ... $_c \propto E^{-2}$

CAVEATS....

- CR acceleration efficiency is likely to change with time
- Alfven drift may change (steepen) the spectrum of accelerated particles (Zirakashvili & Ptuskin 2008)
- the scaling Emax versus time may well be different than a single power law

$$\eta_{cr}\ L_k\ \approx\ Q_{cr}(E_0)E_0^2\ \propto \boxed{Q_{esc}(E_{max})E_{max}^2} \left(\frac{E_0}{E_{max}}\right)^{2-s}$$

$$N_{esc} \propto E^{-s}$$

Conclusions on escape

- ☑ qualitative agreement on one fact: **higher energy CRs are released first, lower energy ones later**...
- ☑ relation Emax versus time still quite unknown...
- ☑ most of the approaches do not include the non resonant (Bell) instability
- ☑ the spectrum released in the ISM may fit with the standard SNR/CR scenario (i.e. a spectrum a bit steeper than E^{-2})
- ☑ for electrons see Ohira et al 2011

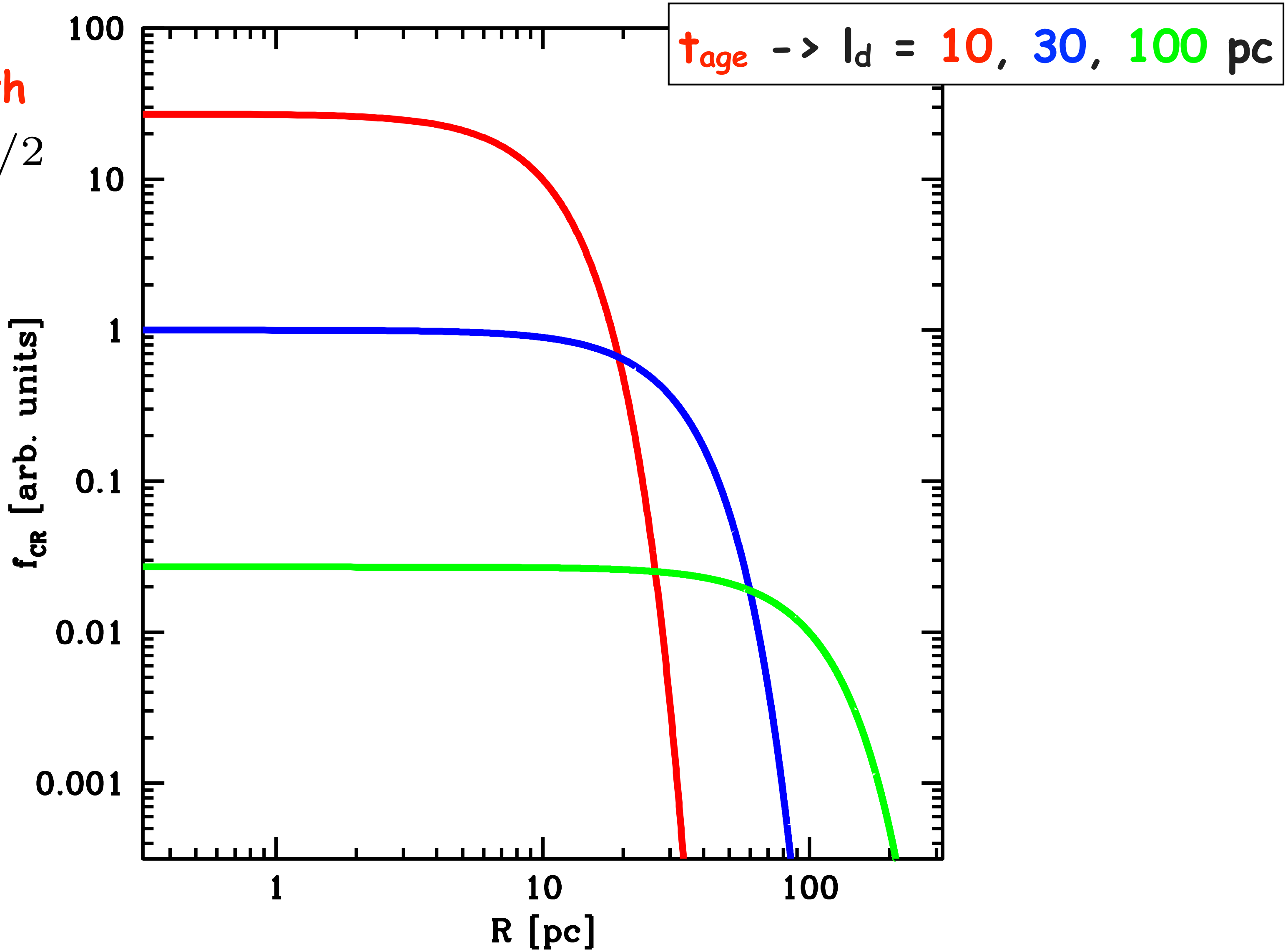
(2) Propagation

Isotropic diffusion

Main motivation: it's simple...

diffusion length

$$l_d \approx (D\ t)^{1/2}$$



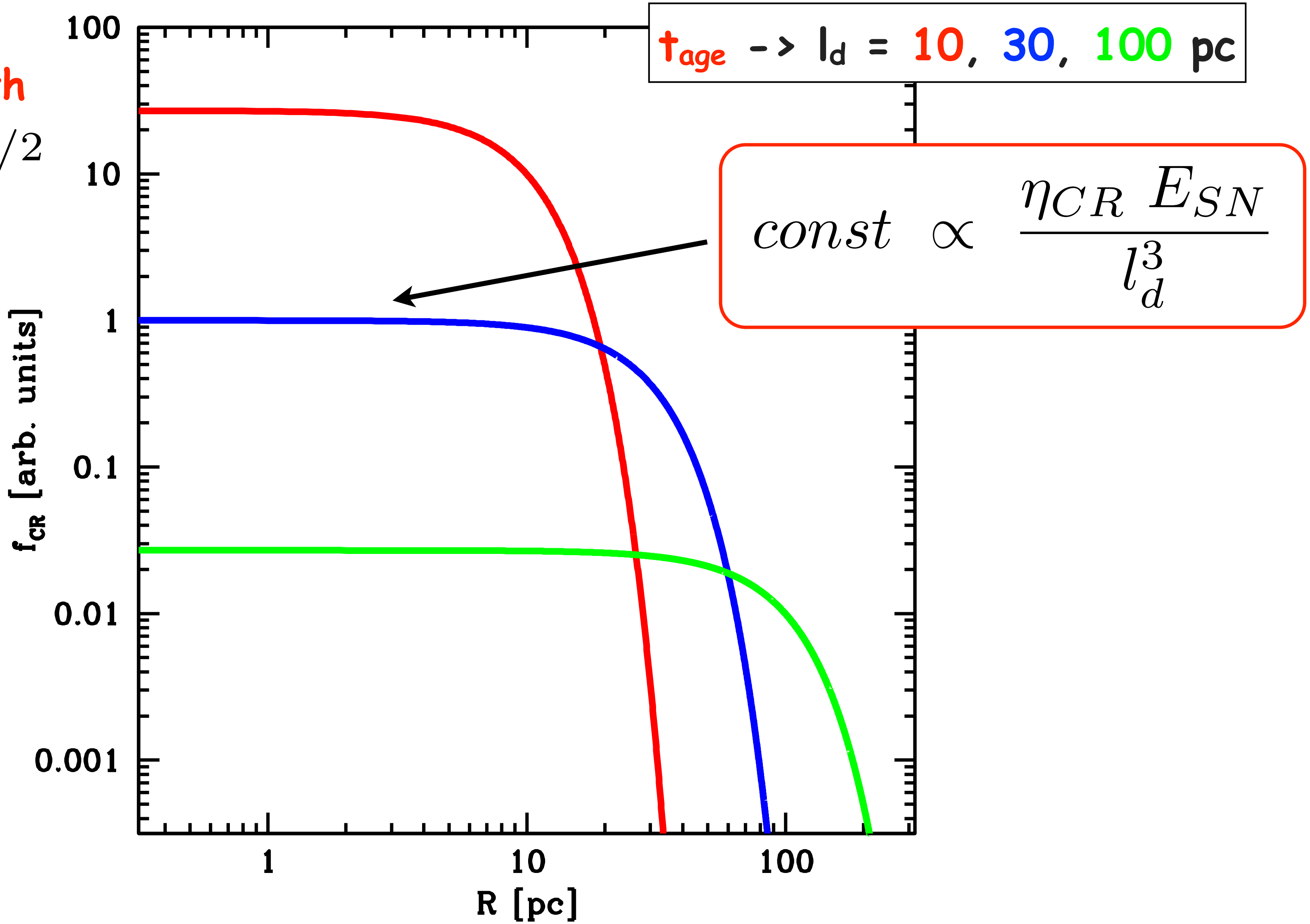
Aharonian&Atoyan 1996;Gabici et al 2007,2009,2010;Torres et al 2008,2010;Rodriguez Marrero et al 2008;Lee et al 2008;Fujita et al 2009;Casanova et al 2010;Li&Chen 2010;Ohira et al 2011;Ellison&Bikov 2011 ...

Isotropic diffusion

Main motivation:it's simple...

diffusion length

$$l_d \approx (D\ t)^{1/2}$$



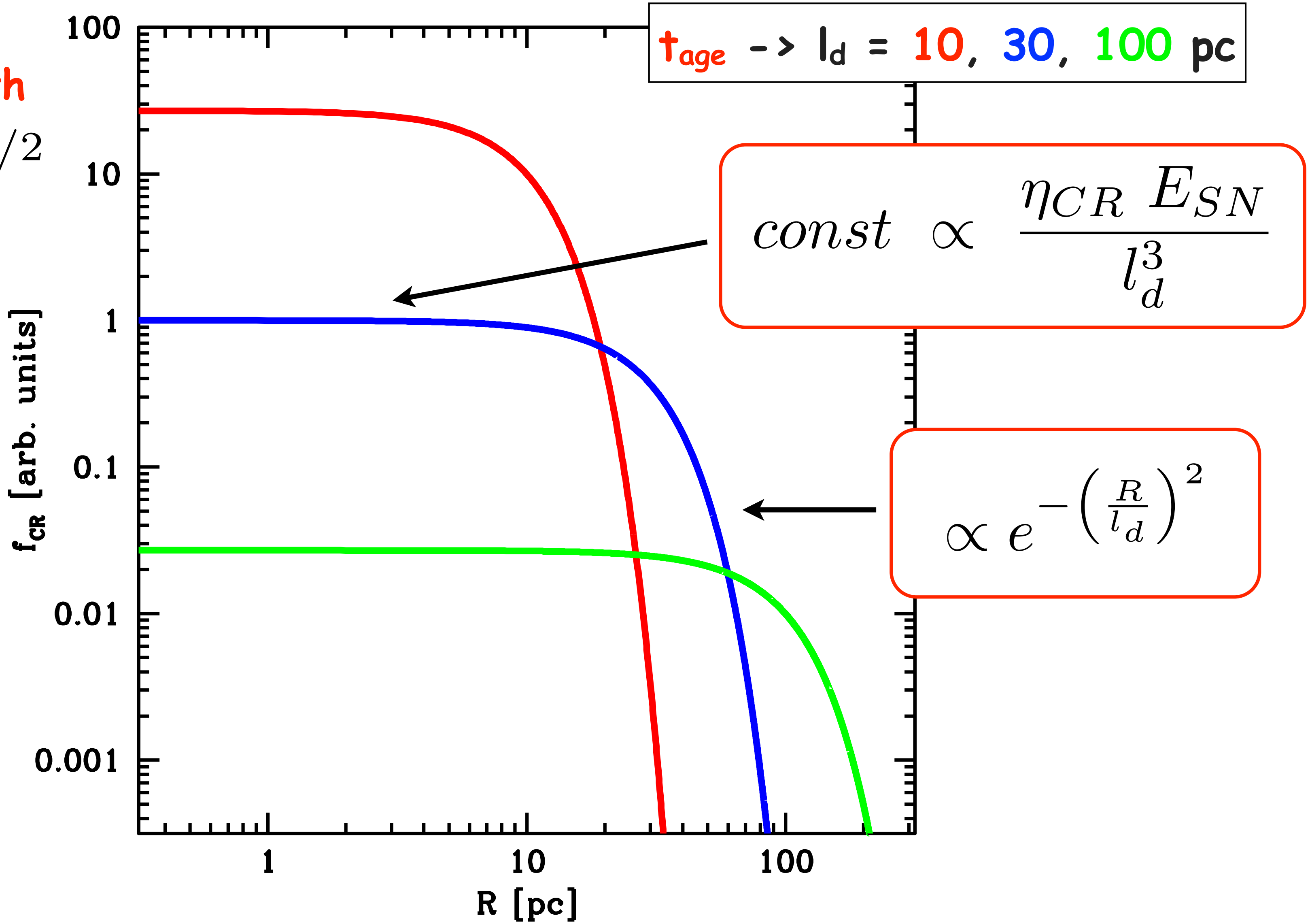
Aharonian&Atoyan 1996;Gabici et al 2007,2009,2010;Torres et al 2008,2010;Rodriguez Marrero et al 2008;Lee et al 2008;Fujita et al 2009;Casanova et al 2010;Li&Chen 2010;Ohira et al 2011;Ellison&Bikov 2011 ...

Isotropic diffusion

Main motivation: it's simple...

diffusion length

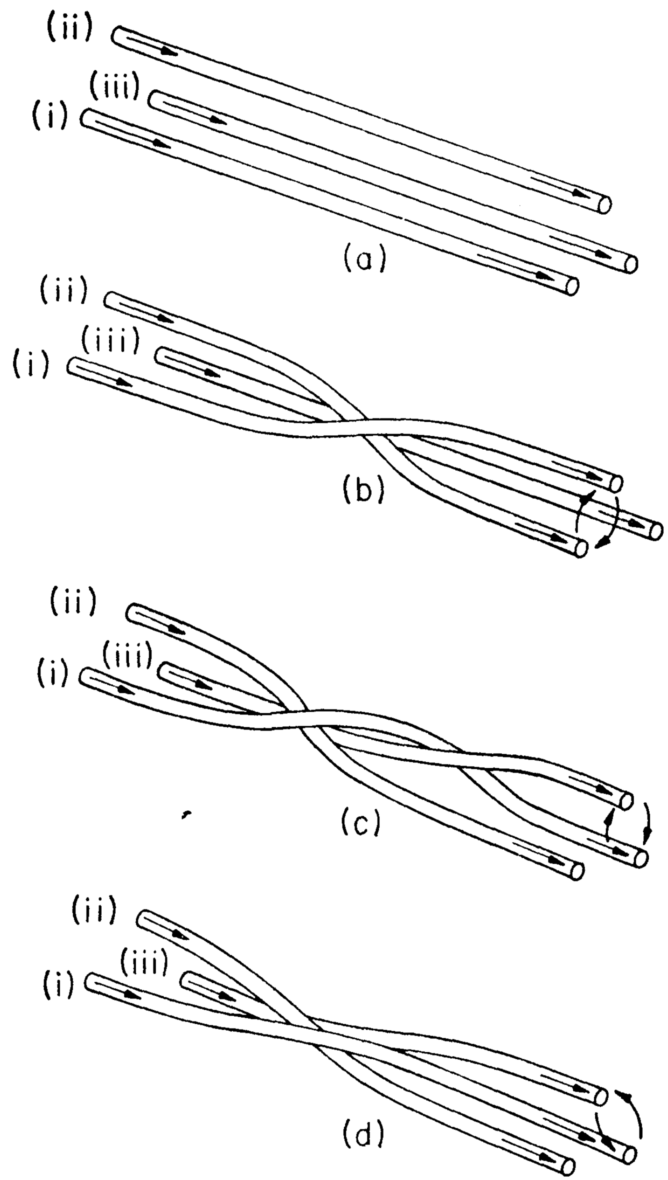
$$l_d \approx (D\ t)^{1/2}$$



Aharonian&Atoyan 1996;Gabici et al 2007,2009,2010;Torres et al 2008,2010;Rodriguez Marrero et al 2008;Lee et al 2008;Fujita et al 2009;Casanova et al 2010;Li&Chen 2010;Ohira et al 2011;Ellison&Bikov 2011 ...

More realistic scenario...

Magnetic field line wandering
induced by fluid motions

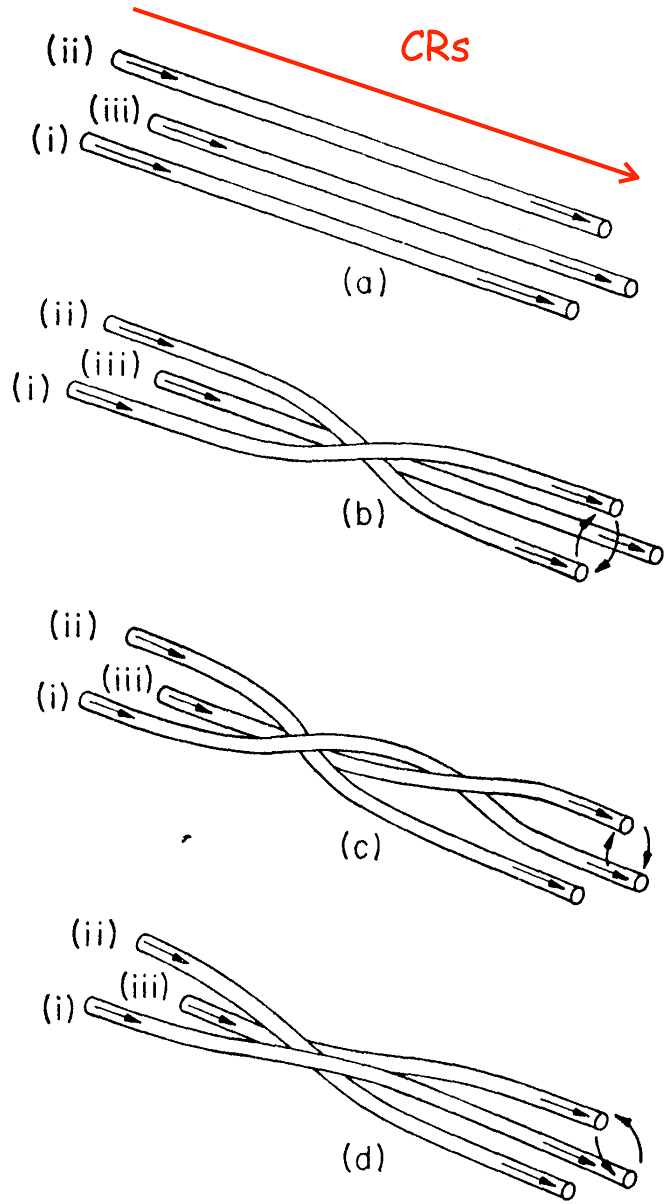


Jokipii & Parker 1969

More realistic scenario...

Magnetic field line wandering induced by fluid motions

CRs propagate mainly along field lines...



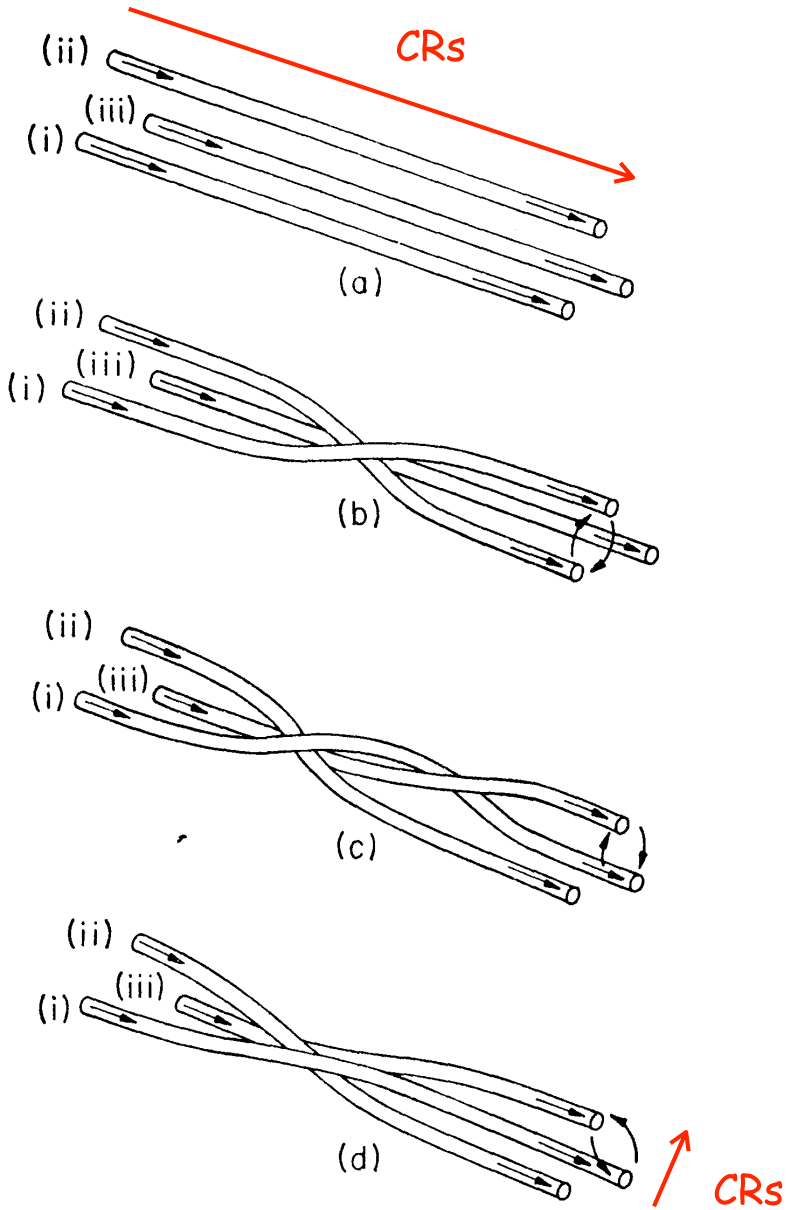
Jokipii & Parker 1969

More realistic scenario...

Magnetic field line wandering induced by fluid motions

CRs propagate mainly along field lines...

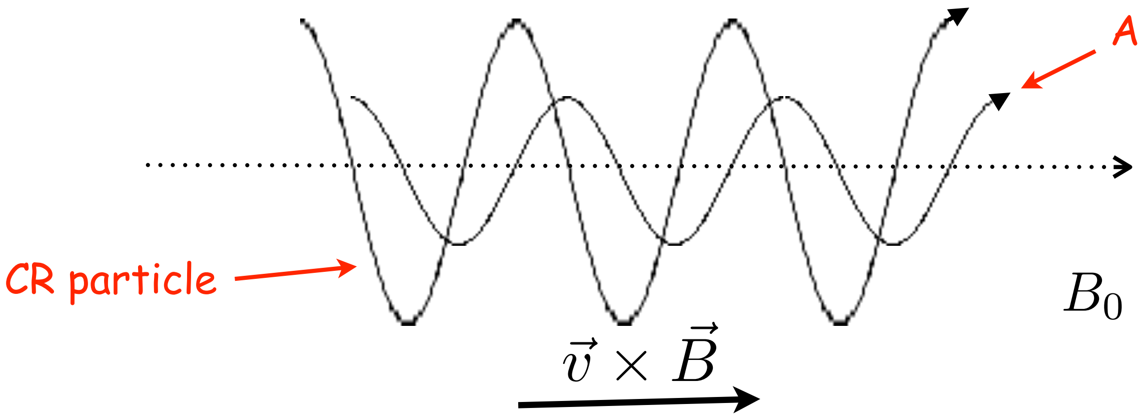
The transport perpendicular to the magnetic field direction mainly due to the wandering of the magnetic field lines (cross-field diffusion can be often neglected [see Elena's talk])



Jokipii & Parker 1969

Streaming instability*

e.g. Wentzel 1972, 1974



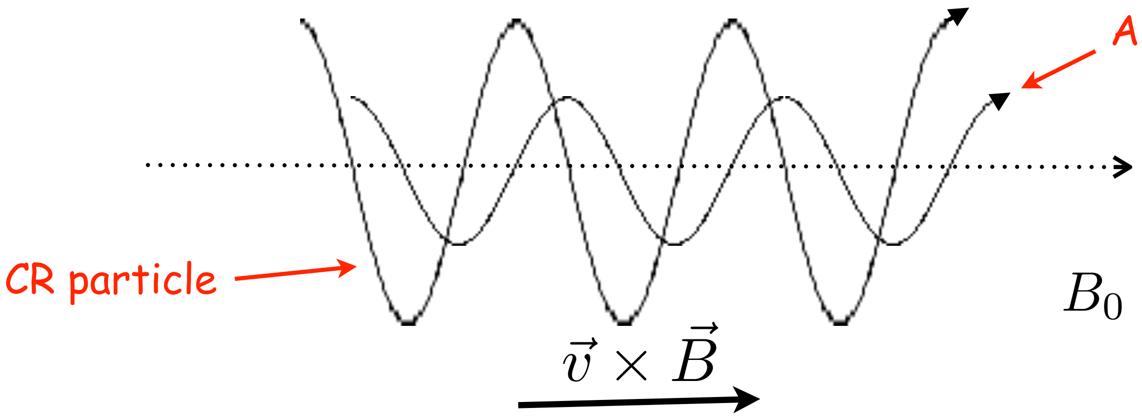
resonant interaction between CRs and Alfven waves

$$\boxed{R_L \sim \frac{1}{k}}$$

*see Elena's talk

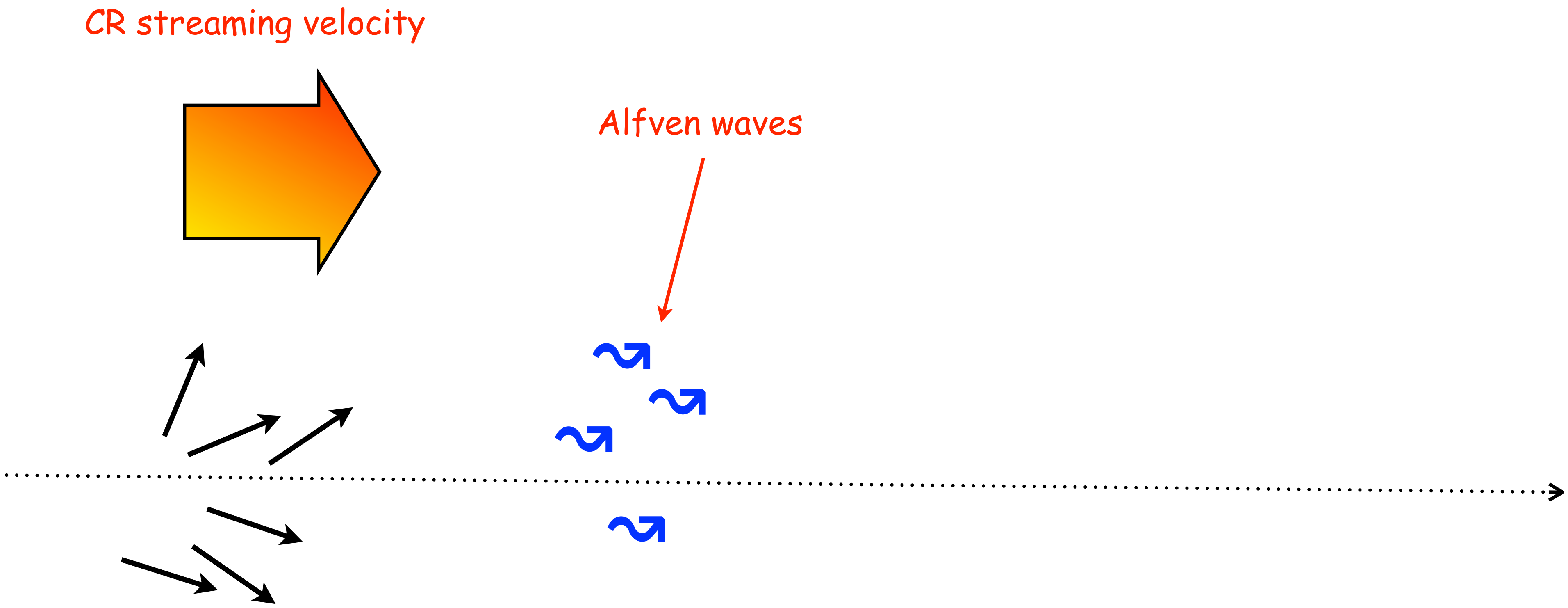
Streaming instability*

e.g. Wentzel 1972, 1974



resonant interaction between CRs and Alfven waves

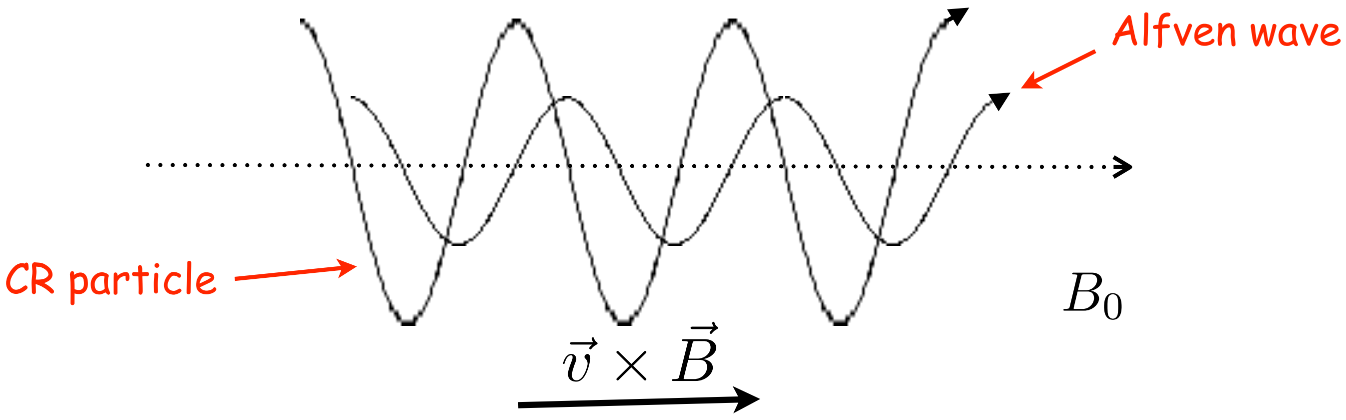
$$\boxed{R_L \sim \frac{1}{k}}$$



*see Elena's talk

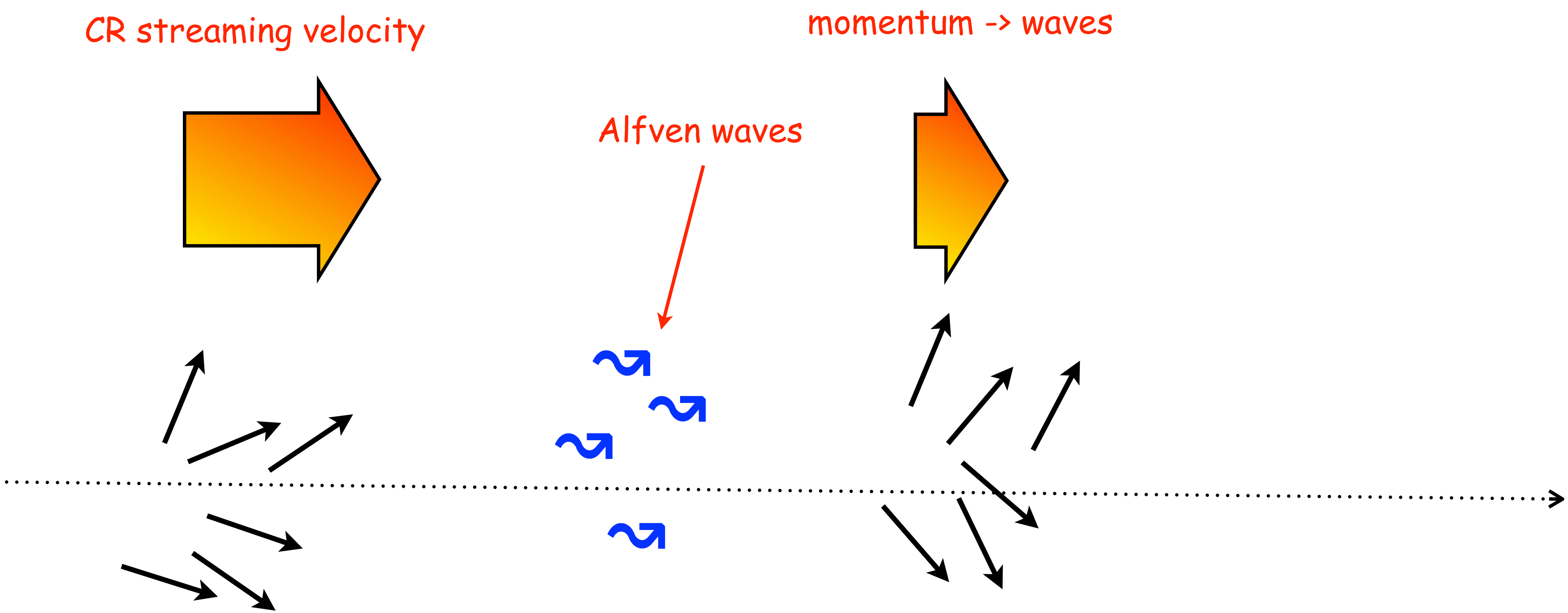
Streaming instability*

e.g. Wentzel 1972, 1974



resonant interaction
between CRs and
Alfven waves

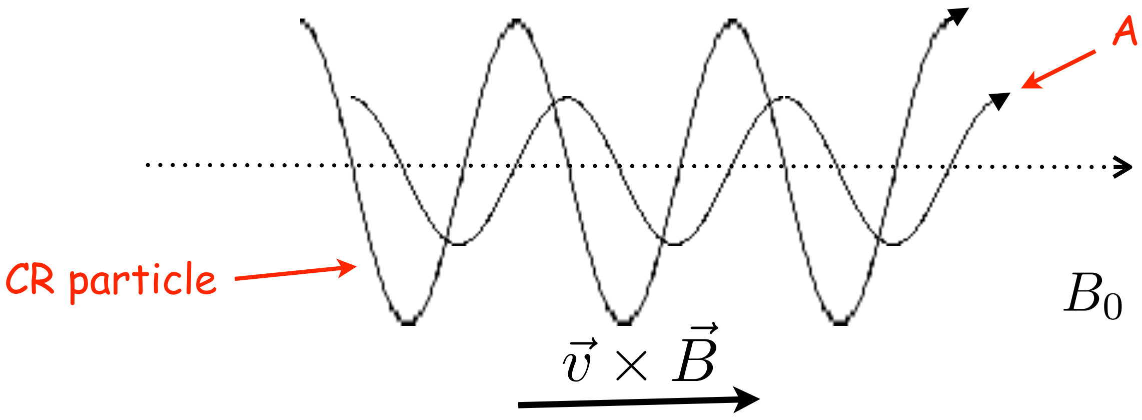
$$\boxed{R_L \sim \frac{1}{k}}$$



*see Elena's talk

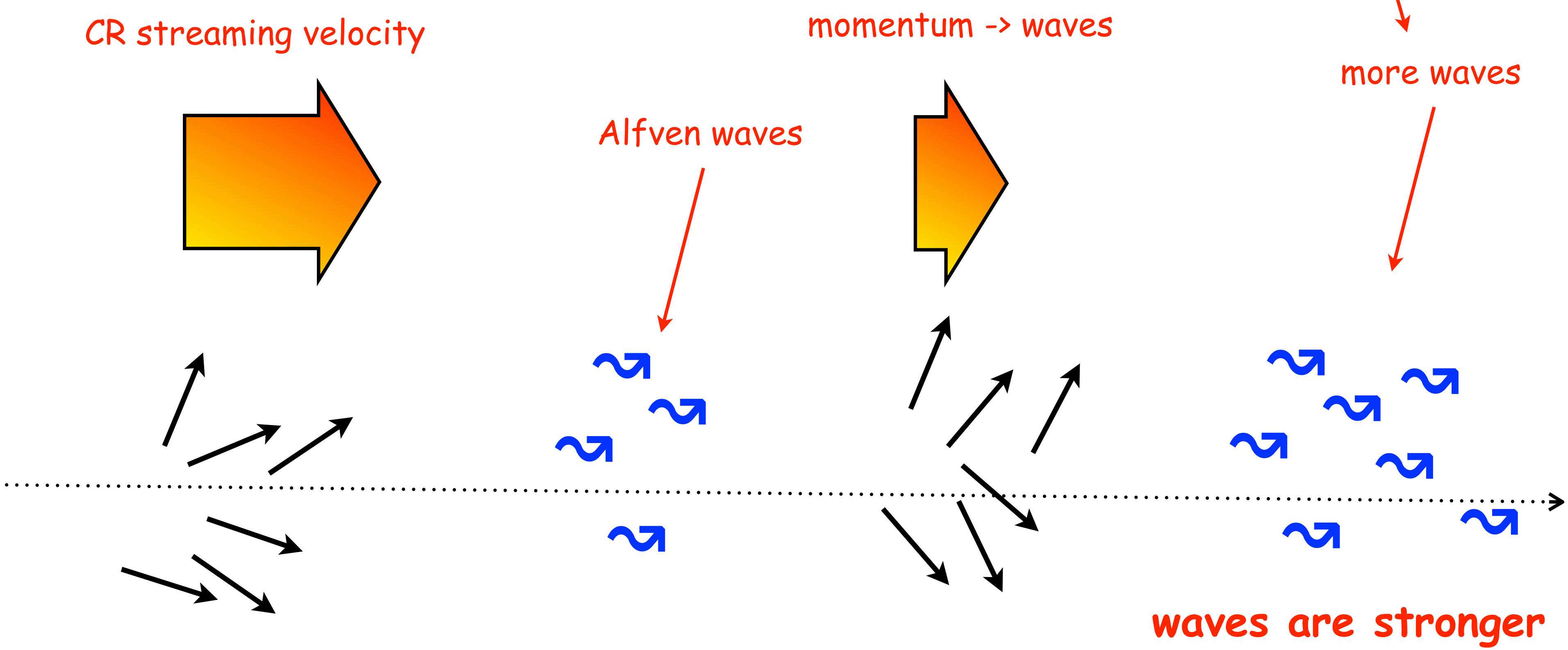
Streaming instability*

e.g. Wentzel 1972, 1974



resonant interaction
between CRs and
Alfven waves

$$R_L \sim \frac{1}{k}$$



*see Elena's talk

Non linear CR diffusion along B

Ptuskin, Zirakashvili, & Plesser 2007

$$\frac{\partial f}{\partial t} - \nabla D \nabla f = 0$$

along the field lines

$$D = \frac{4\ c\ R_L}{3\ \pi\ U(k_r)}$$

$$\Gamma_g = \Gamma_d$$

Non linear CR diffusion along B

Ptuskin, Zirakashvili, & Plesser 2007

$$\frac{\partial f}{\partial t} - \nabla D \nabla f = 0$$

along the field lines

$$D = \frac{4\ c\ R_L}{3\ \pi\ U(k_r)}$$

more waves -> less diffusion

energy density of Alfven waves per unit log bandwidth which are resonant with CRs with momentum p

$$\Gamma_g = \Gamma_d$$

Non linear CR diffusion along B

Ptuskin, Zirakashvili, & Plesser 2007

$$\frac{\partial f}{\partial t} - \nabla D \nabla f = 0$$

along the
field lines

$$D = \frac{4\ c\ R_L}{3\ \pi\ U(k_r)}$$

more waves -> less diffusion

energy density of Alfven waves per
unit log bandwidth which are resonant
with CRs with momentum p

$$\Gamma_g = \Gamma_d$$

growth rate
(streaming instability)

damping rate
(Kolmogorov)

$$\boxed{x_* \approx 150 \left(\frac{W_{CR}}{10^{50}\mathrm{erg}}\right)^{-1} \left(\frac{p}{\mathrm{GeV}}\right)^{0.4} \left(\frac{t_*}{\mathrm{Myr}}\right)^{3/2} \mathrm{pc}}$$

Non linear CR diffusion along B

Ptuskin, Zirakashvili, & Plesser 2007

$$\frac{\partial f}{\partial t} - \nabla D \nabla f = 0$$

along the field lines

Very small diffusion!
-> more damping? (ion neutral)
-> B-field line wandering?

$$D = \frac{4\ c\ R_L}{3\ \pi\ U(k_r)}$$

more waves -> less diffusion

energy density of Alfven waves per unit log bandwidth which are resonant with CRs with momentum p

$$\Gamma_g = \Gamma_d$$

growth rate (streaming instability)

damping rate (Kolmogorov)

$$x_* \approx 150 \left(\frac{W_{CR}}{10^{50}\mathrm{erg}}\right)^{-1} \left(\frac{p}{\mathrm{GeV}}\right)^{0.4} \left(\frac{t_*}{\mathrm{Myr}}\right)^{3/2} \mathrm{pc}$$

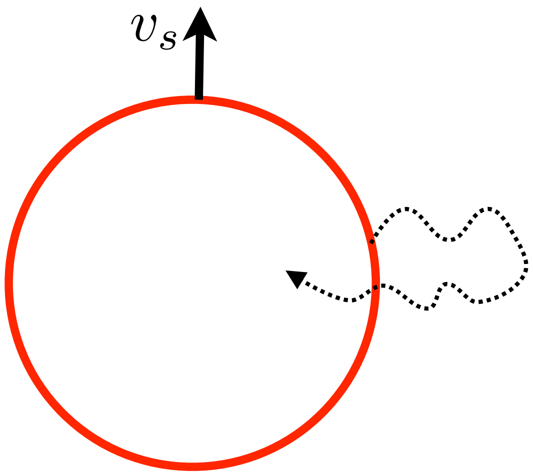
Conclusions on propagation

- ☑ in my view the aspect that still needs more work
- ☑ difficult because non-linear + B-field wandering (this needs to be considered in calculations...)
- ☑ probably the isotropic diffusion (though an obvious step-zero for calculations) is not appropriate to describe diffusion close to CR sources (might be OK in the Galaxy...)

(3) Radiation*

* see Sabrina's talk

How to use Molecular Clouds...

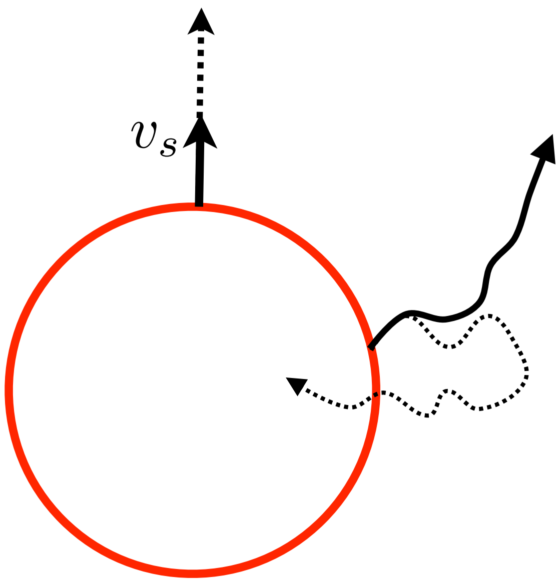


SNRs accelerate CRs

Aharonian&Atoyan, 1996; SG&Aharonian, 2007

How to use Molecular Clouds...

CRs "somehow" escape the SNR



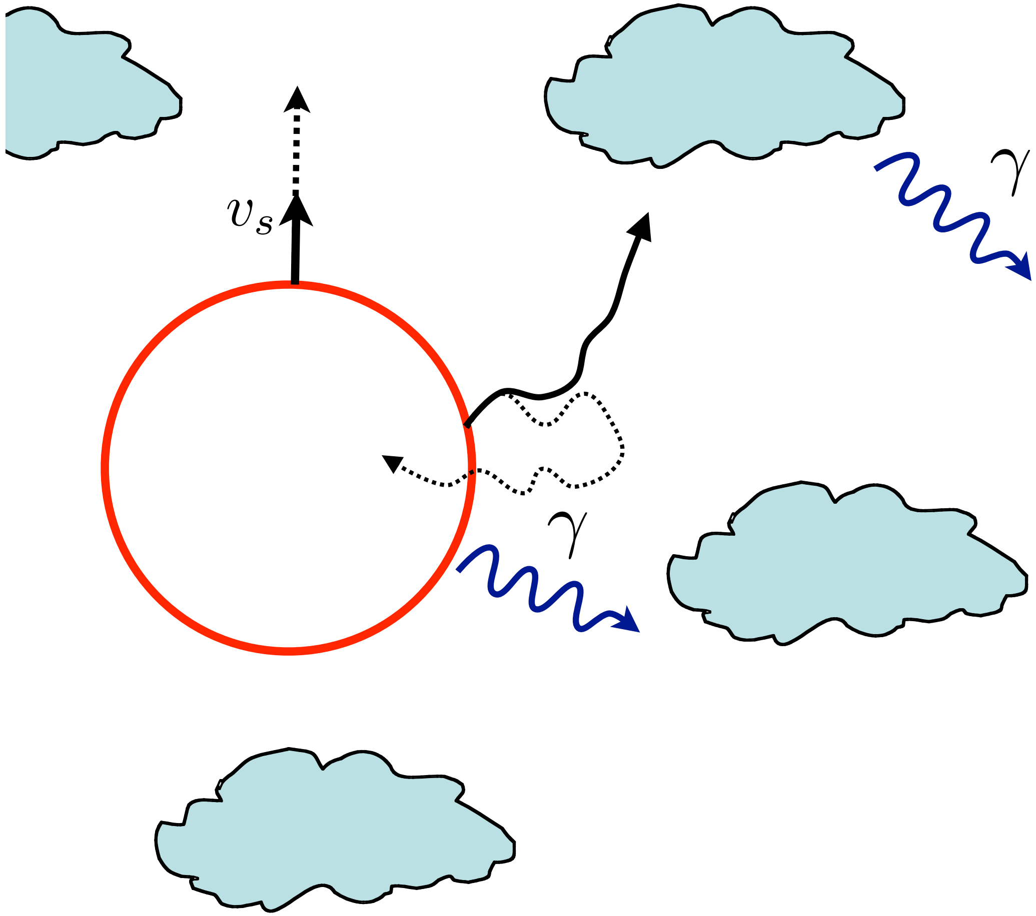
SNRs accelerate CRs

Aharonian&Atoyan, 1996; SG&Aharonian, 2007

How to use Molecular Clouds...

CRs "somehow" escape the SNR

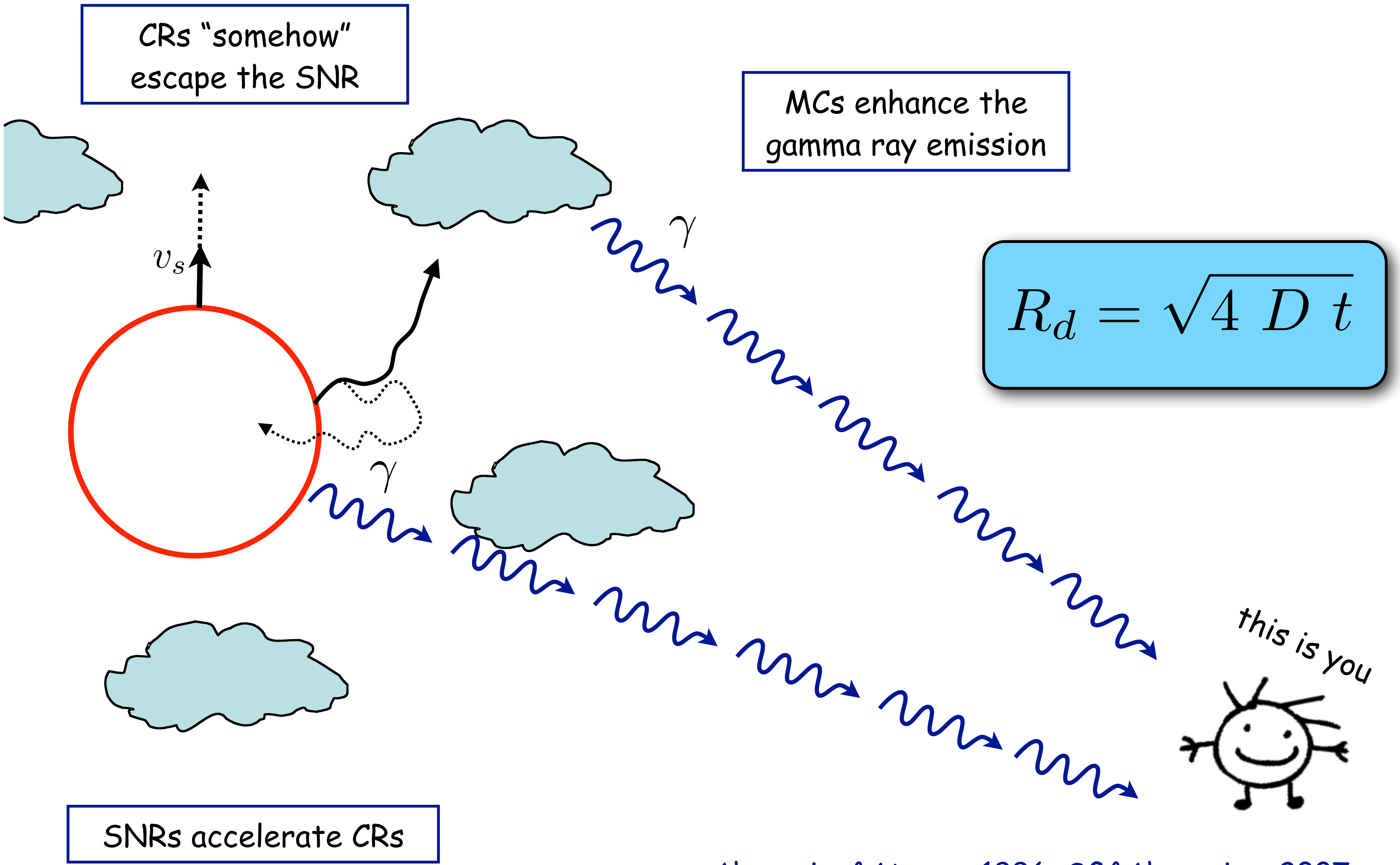
MCs enhance the gamma ray emission



SNRs accelerate CRs

Aharonian&Atoyan, 1996; SG&Aharonian, 2007

How to use Molecular Clouds...



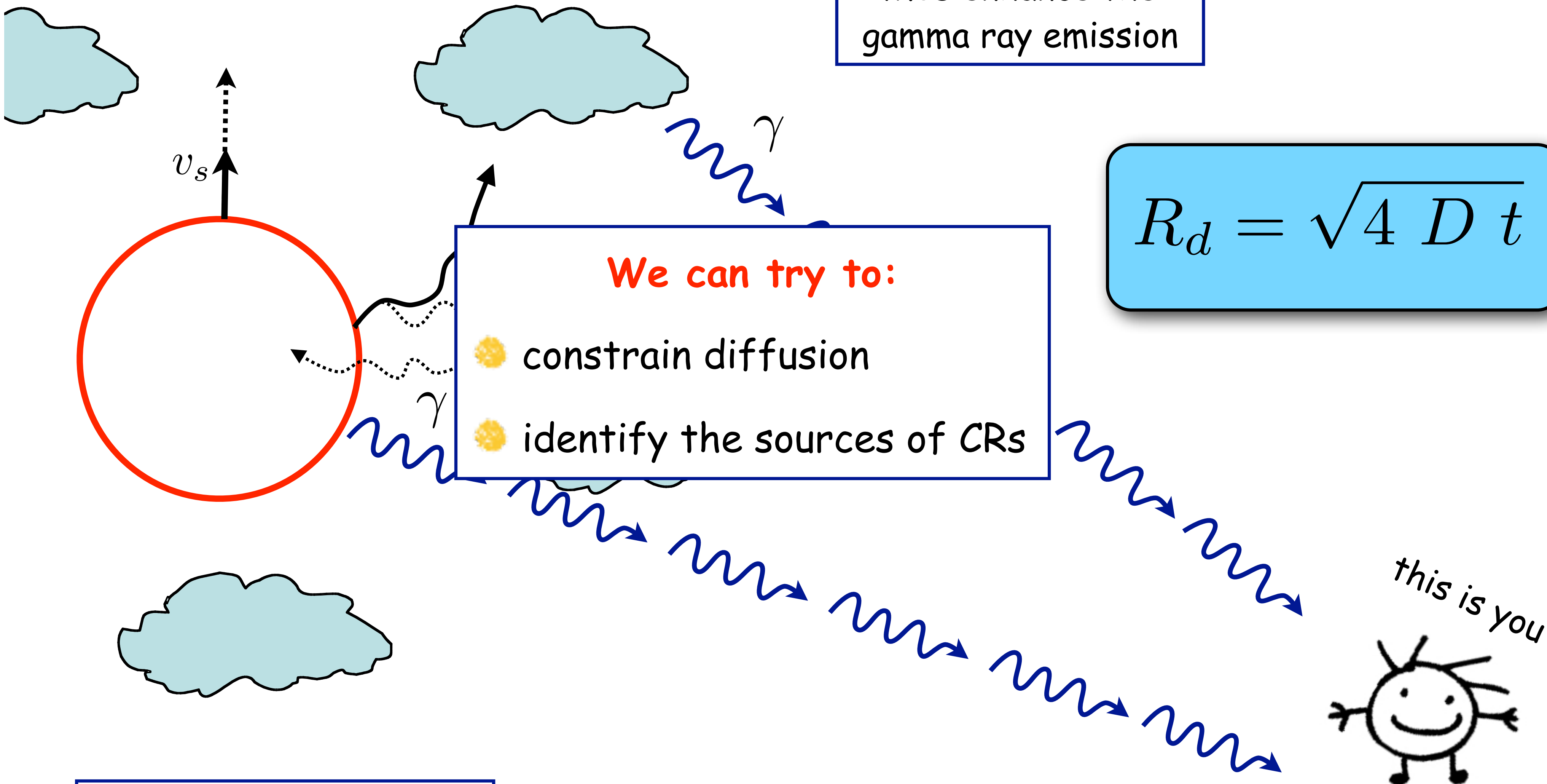
Aharonian&Atoyan, 1996; SG&Aharonian, 2007

How to use Molecular Clouds...

CRs "somehow" escape the SNR

MCs enhance the gamma ray emission

$$R_d = \sqrt{4\ D\ t}$$



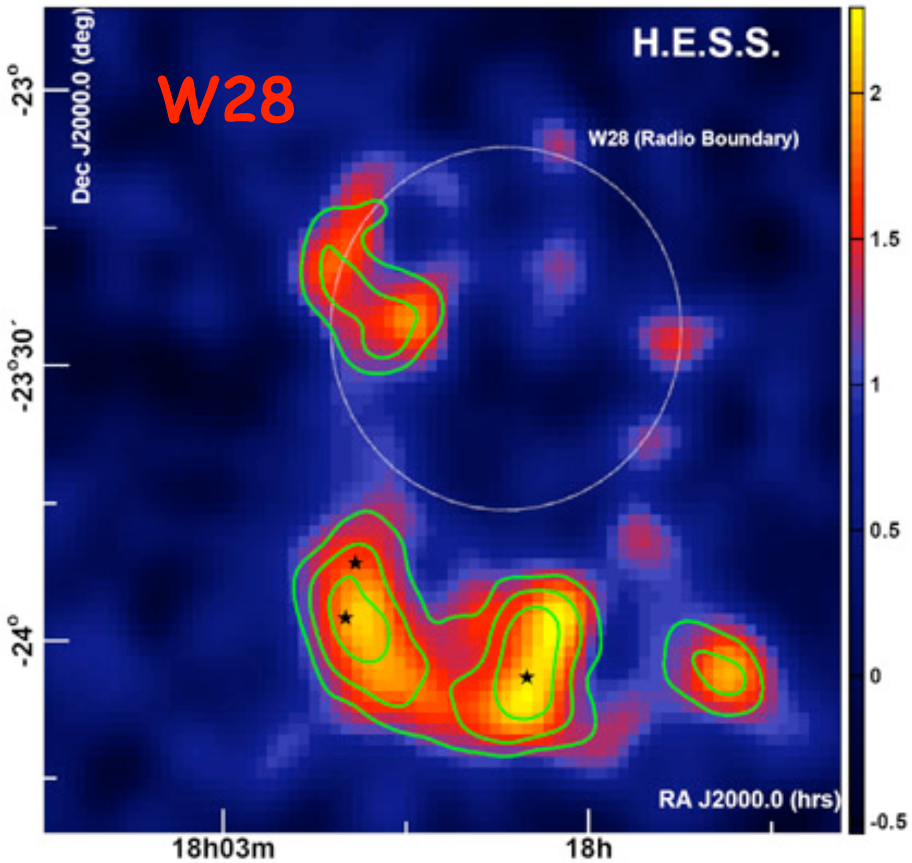
We can try to:

- constrain diffusion
- identify the sources of CRs

SNRs accelerate CRs

Aharonian&Atoyan, 1996; SG&Aharonian, 2007

The W28 region in gammas, CO, & radio

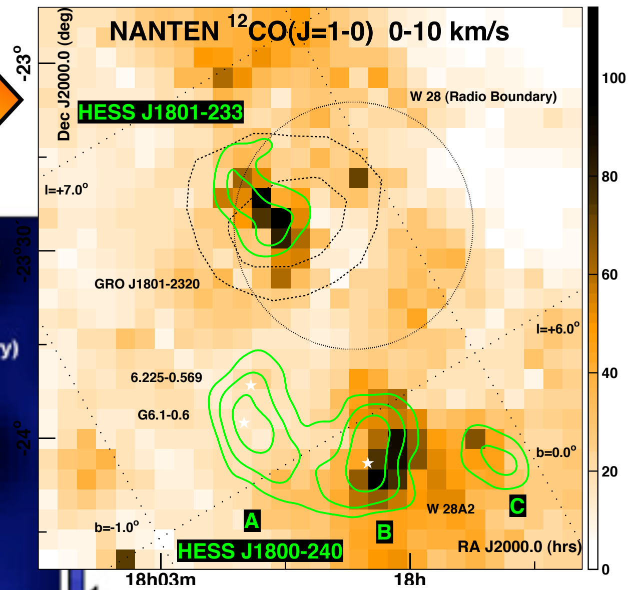


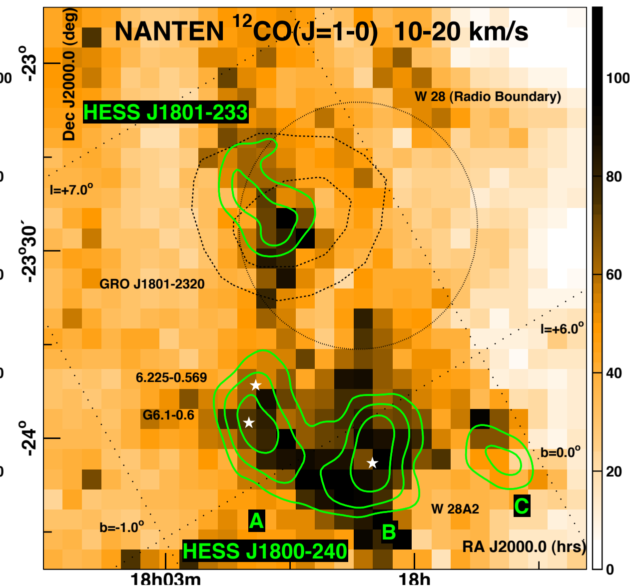
HESS - TeV emission

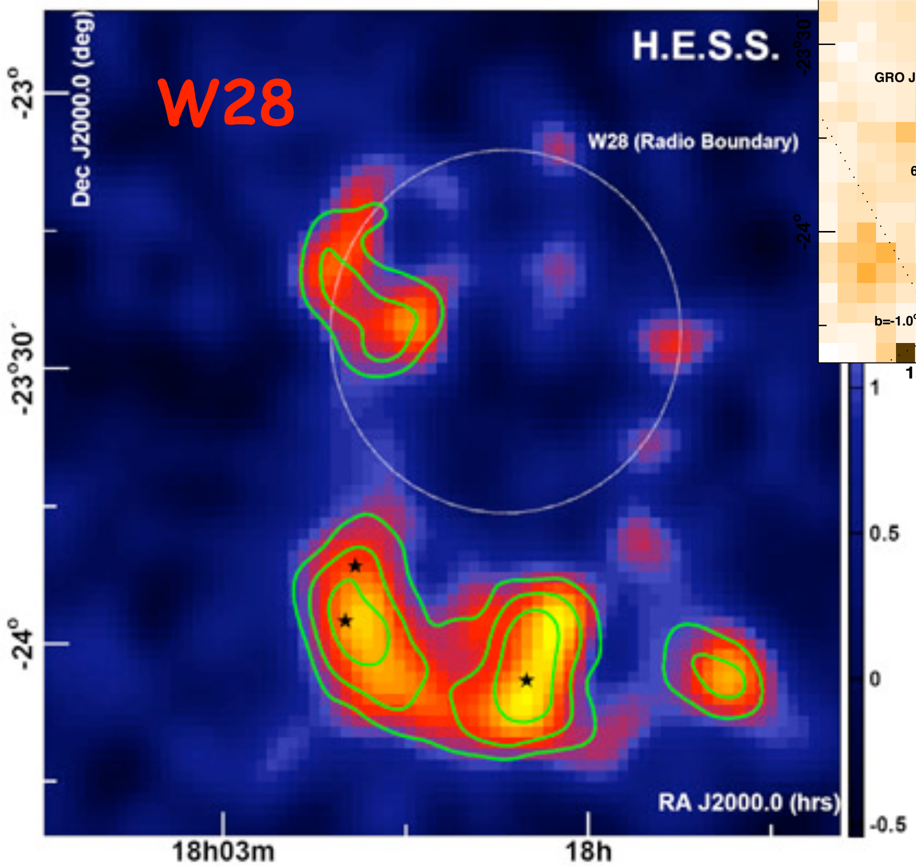
Aharonian et al, 2008

The W28 region in gammas, CO, & radio

NANTEN data - CO line





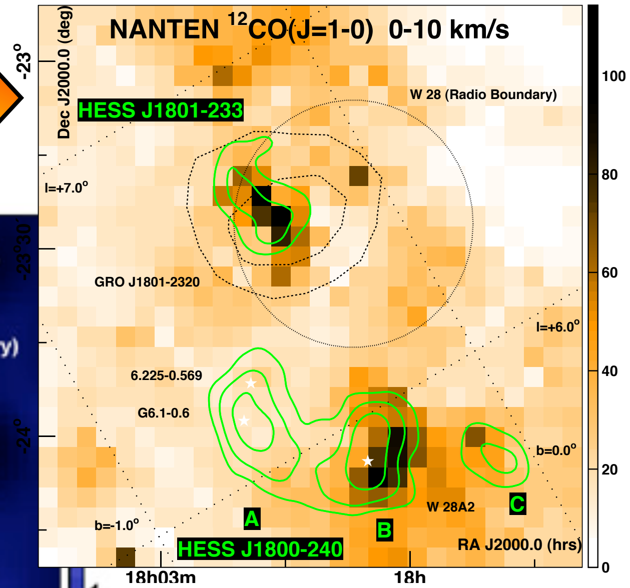


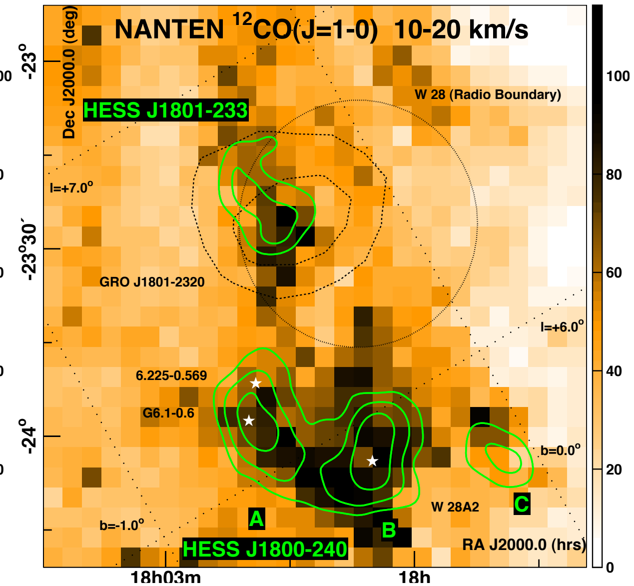
HESS - TeV emission

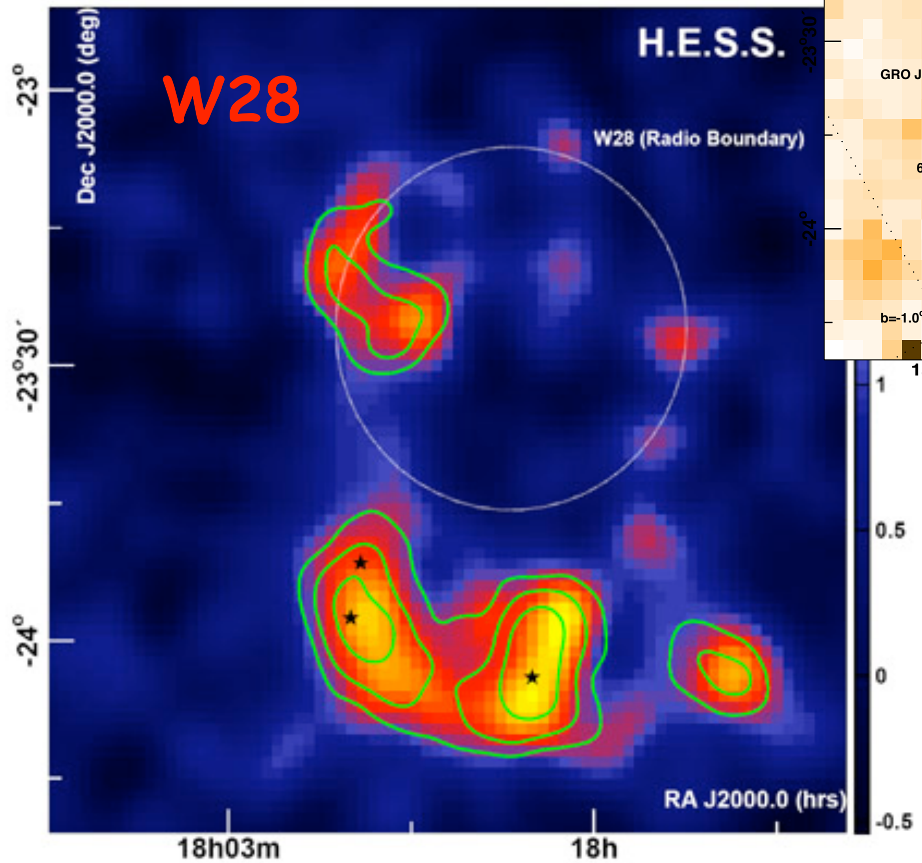
Aharonian et al, 2008

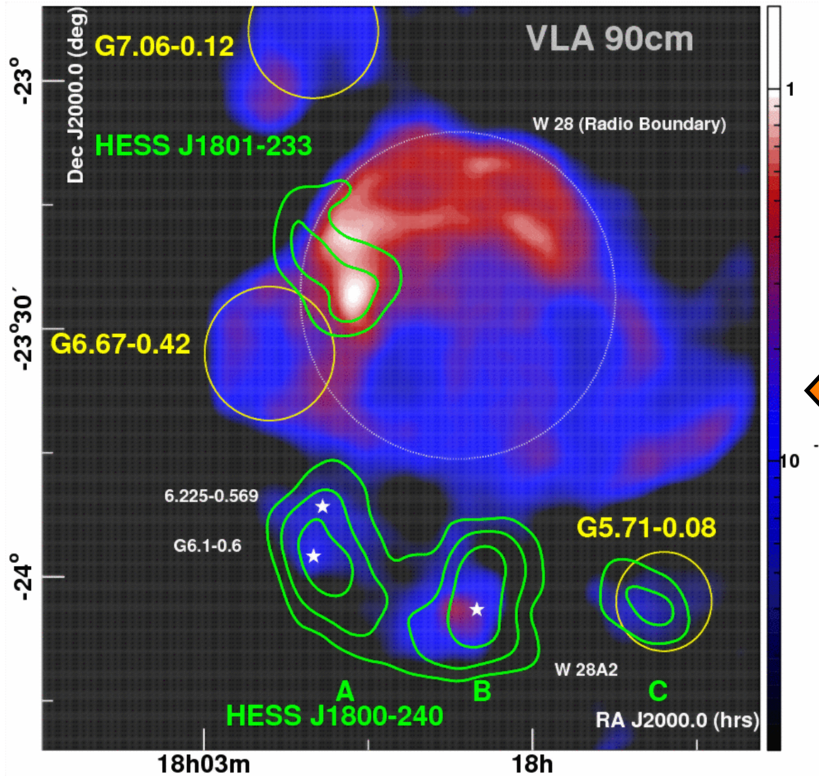
The W28 region in gammas, CO, & radio

NANTEN data - CO line









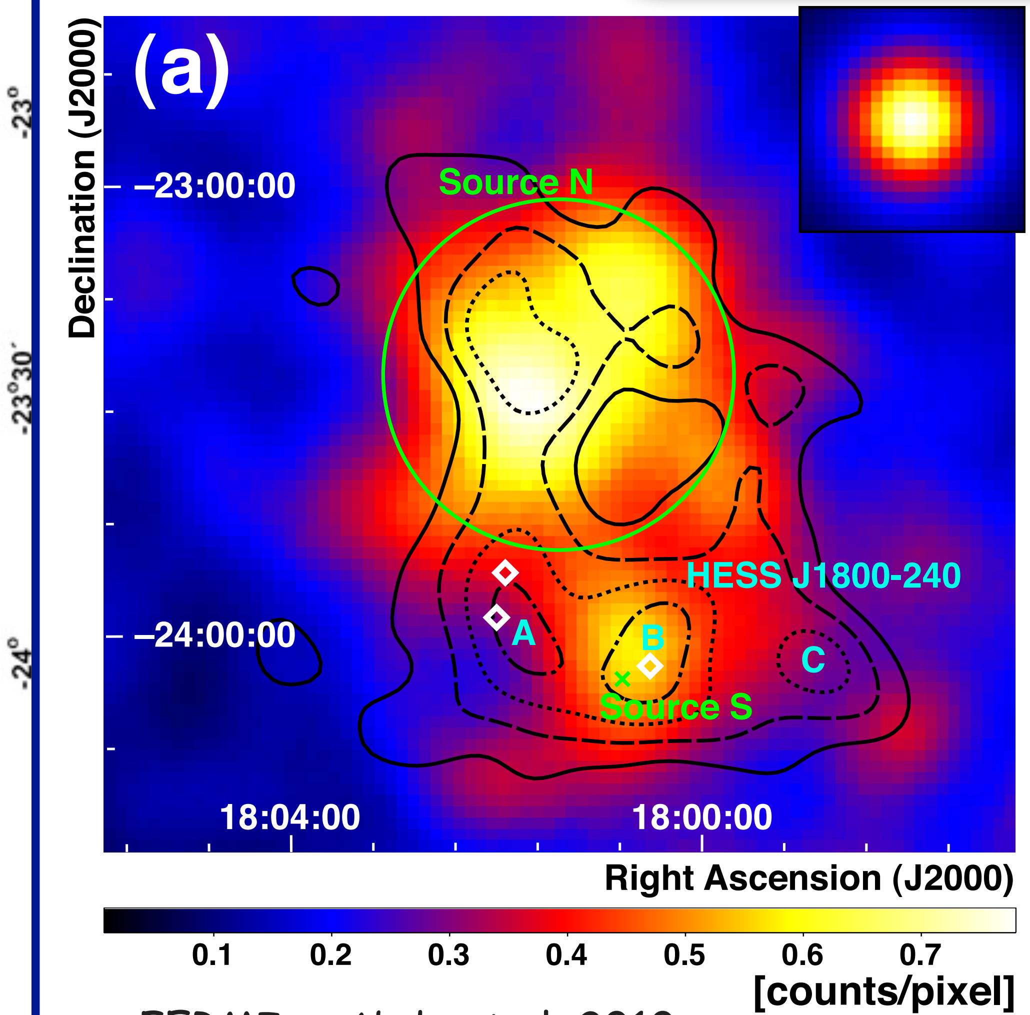
Radio (Dubner et al 2000)

HESS - TeV emission

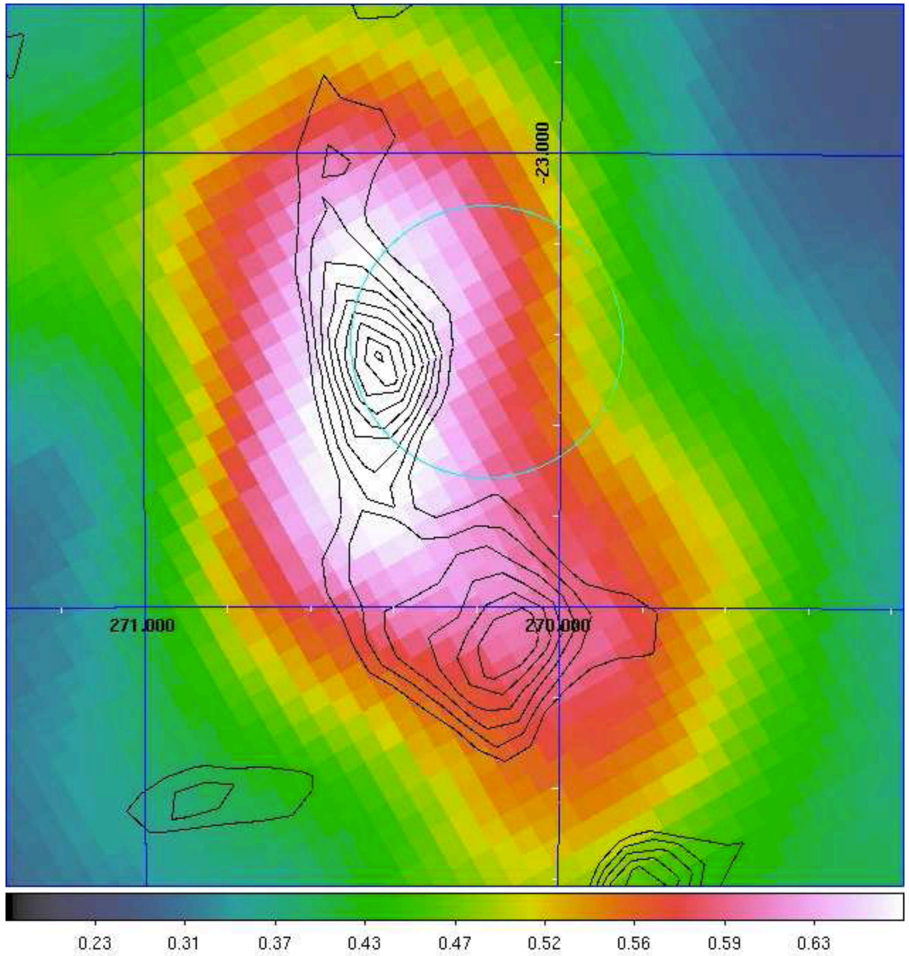
Aharonian et al, 2008

The W28 region in gammas, CO, & radio

FERMI and AGILE - GeV emission



FERMI -> Abdo et al, 2010



AGILE -> Giuliani et al, 2010

Aharonian et al, 2008

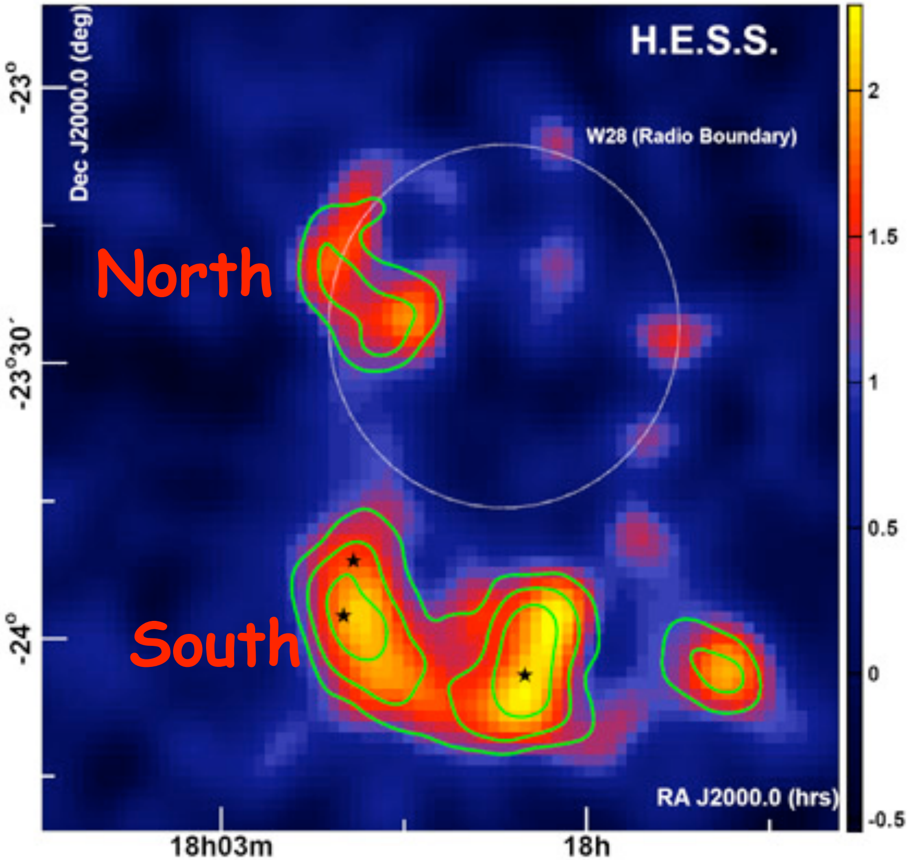
HESS J1800-240

RA J2000.0 (hrs)

18h03m

18h

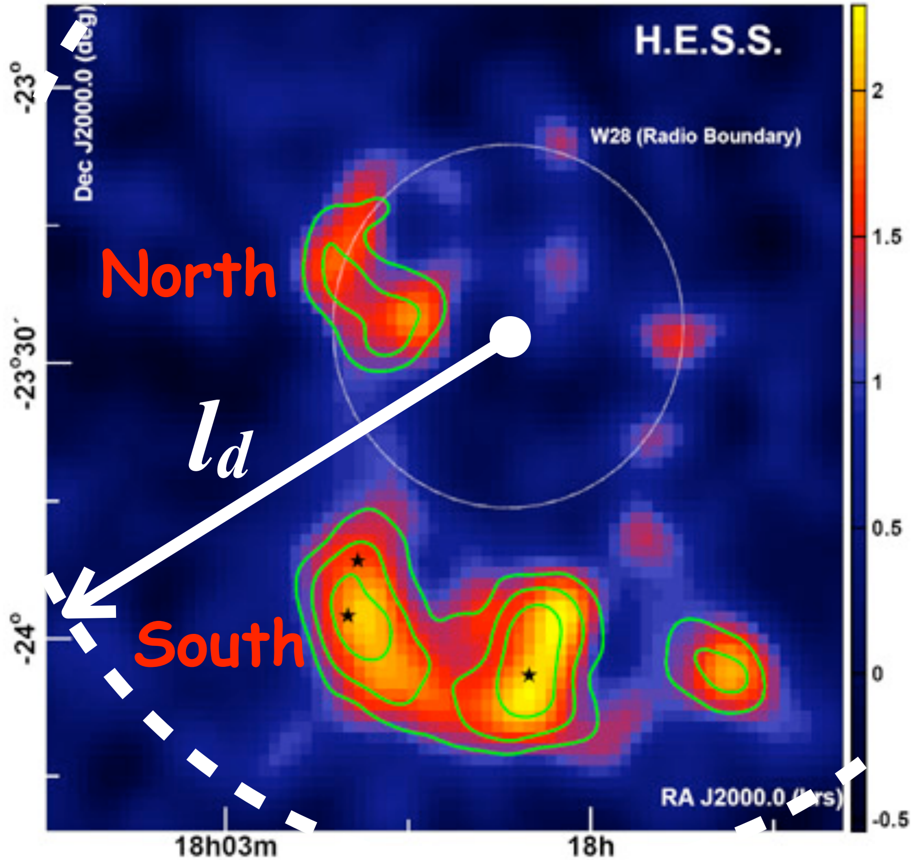
Escaping particles: W28



$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

isotropic diffusion!

Escaping particles: W28



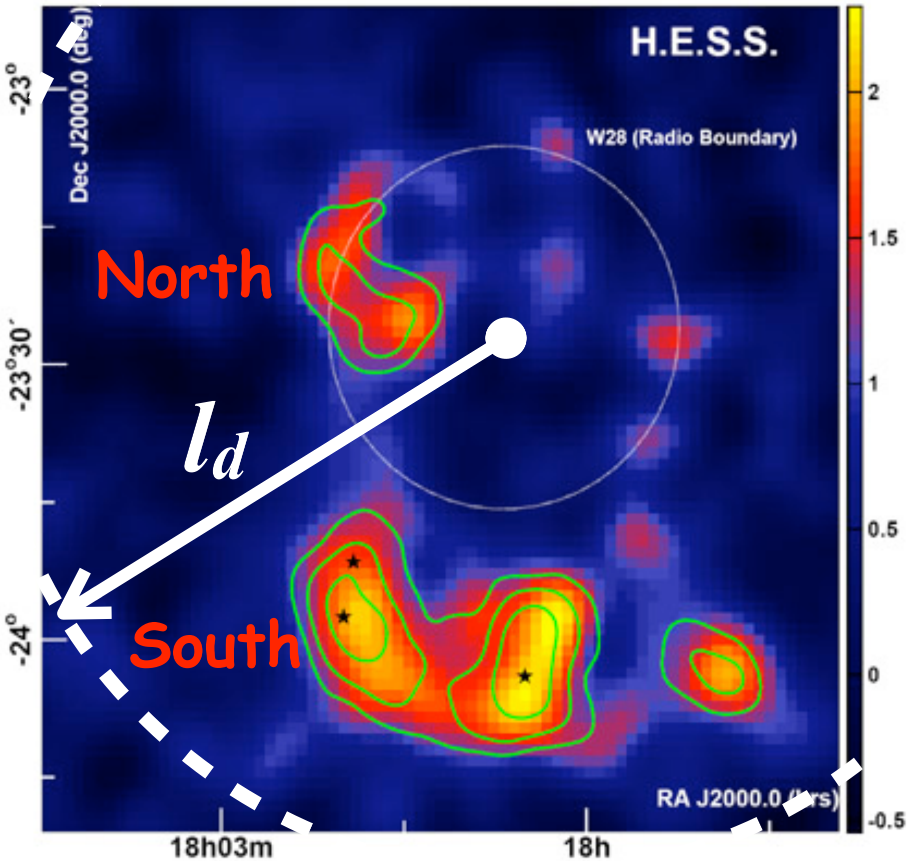
isotropic diffusion!

$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

Escaping particles: W28

isotropic diffusion!



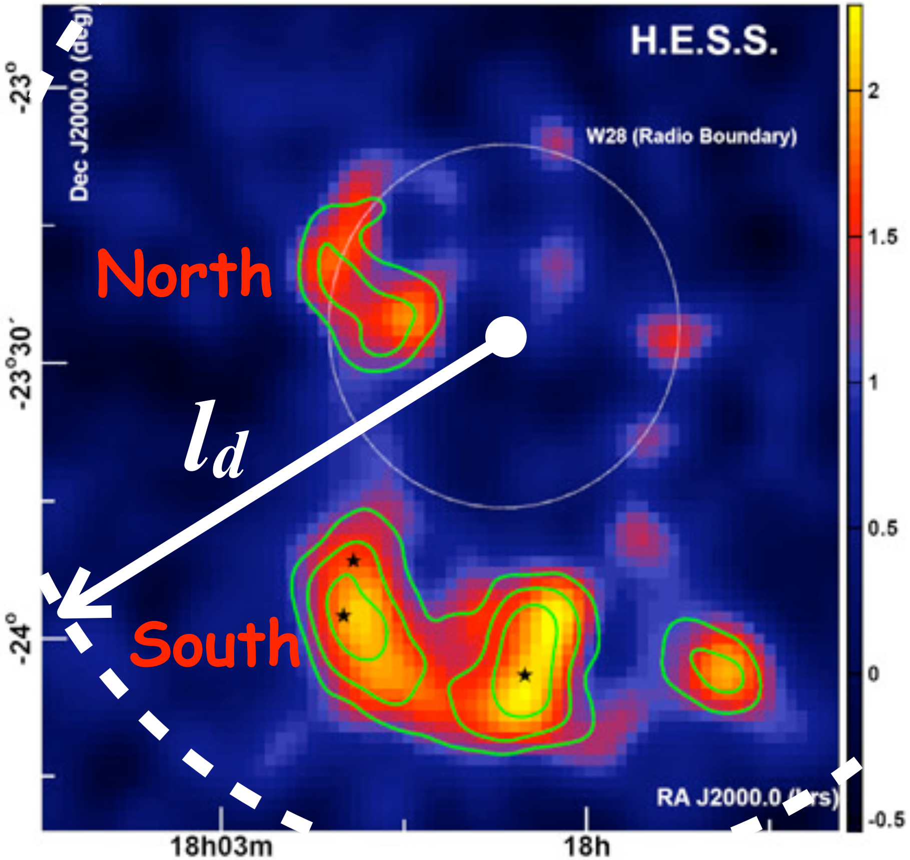
$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2}$$

Escaping particles: W28

isotropic diffusion!



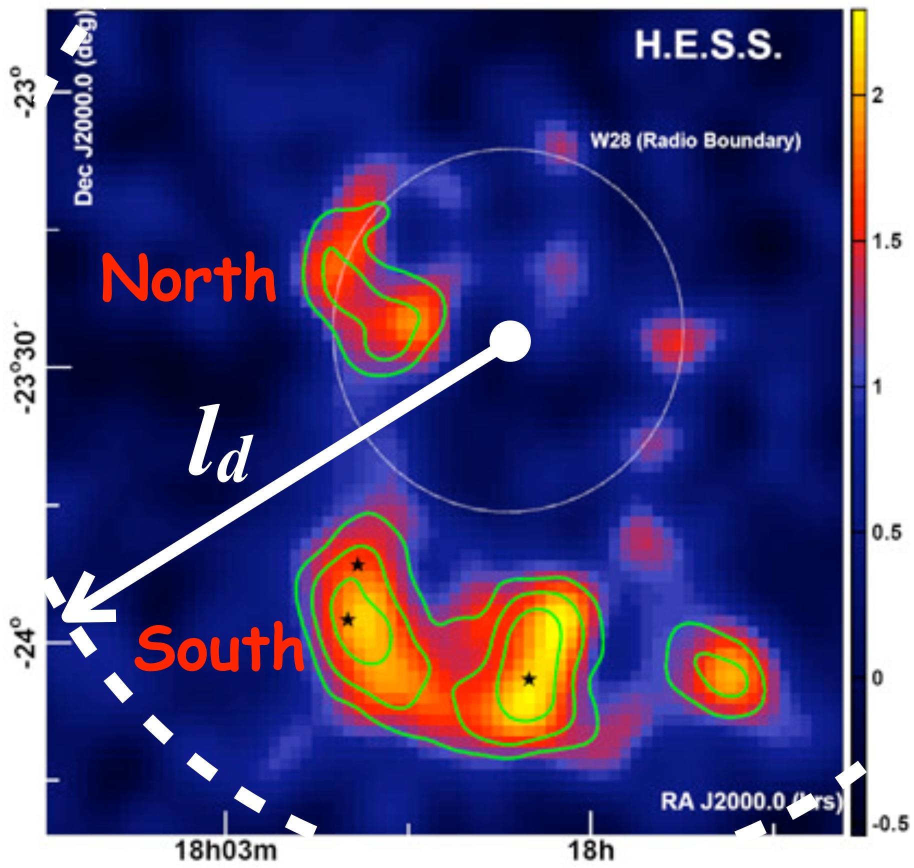
$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

$$F_\gamma \propto \frac{f_{CR}\, M_{cl}}{d^2} \propto \frac{\eta_{CR}\, E_{SN}}{(D\ t_{age})^{3/2}} \left(\frac{M_{cl}}{d^2}\right)$$

Escaping particles: W28

isotropic diffusion!



$$\left(\frac{F_\gamma}{M_{cl}}\right)_{North} \approx \left(\frac{F_\gamma}{M_{cl}}\right)_{South}$$

both clouds within a distance l_d

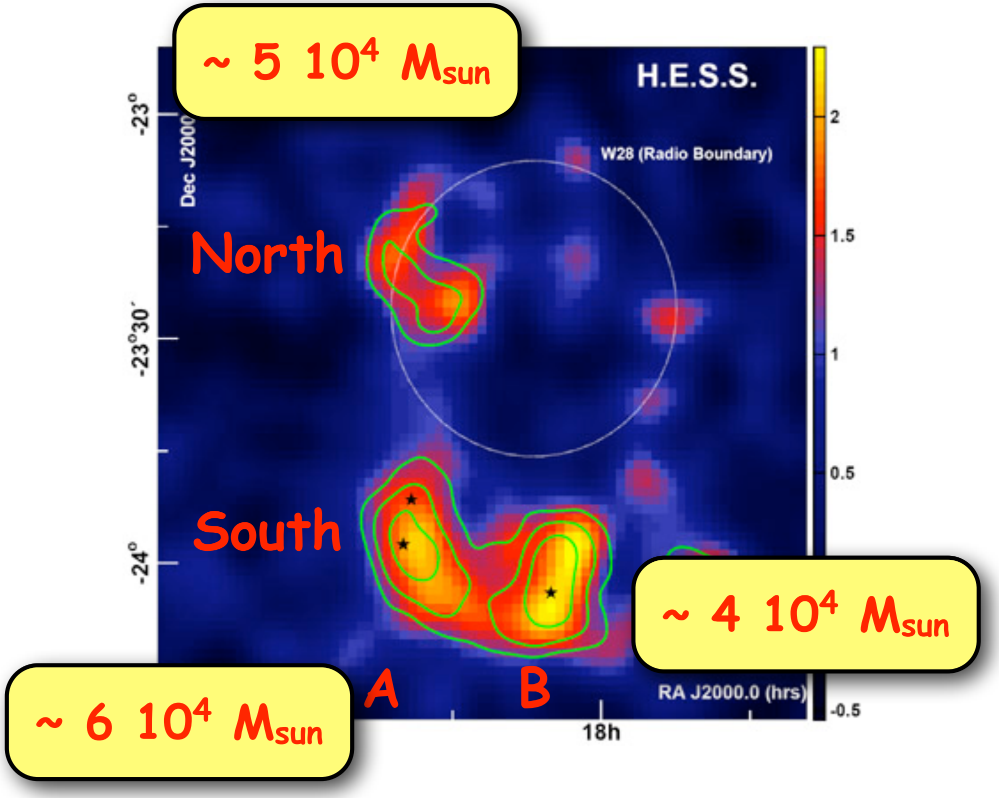
$$F_\gamma \propto \frac{f_{CR}\,M_{cl}}{d^2} \propto \frac{\eta_{CR}\,E_{SN}}{(D\ t_{age})^{3/2}}\left(\frac{M_{cl}}{d^2}\right)$$

and we get... ->

$$D \propto \left(\frac{\eta_{CR} E_{SN}\ M_{cl}}{F_\gamma d^2}\right)^{2/3} t_{age}^{-1}$$

W28: TeV emission

isotropic diffusion!



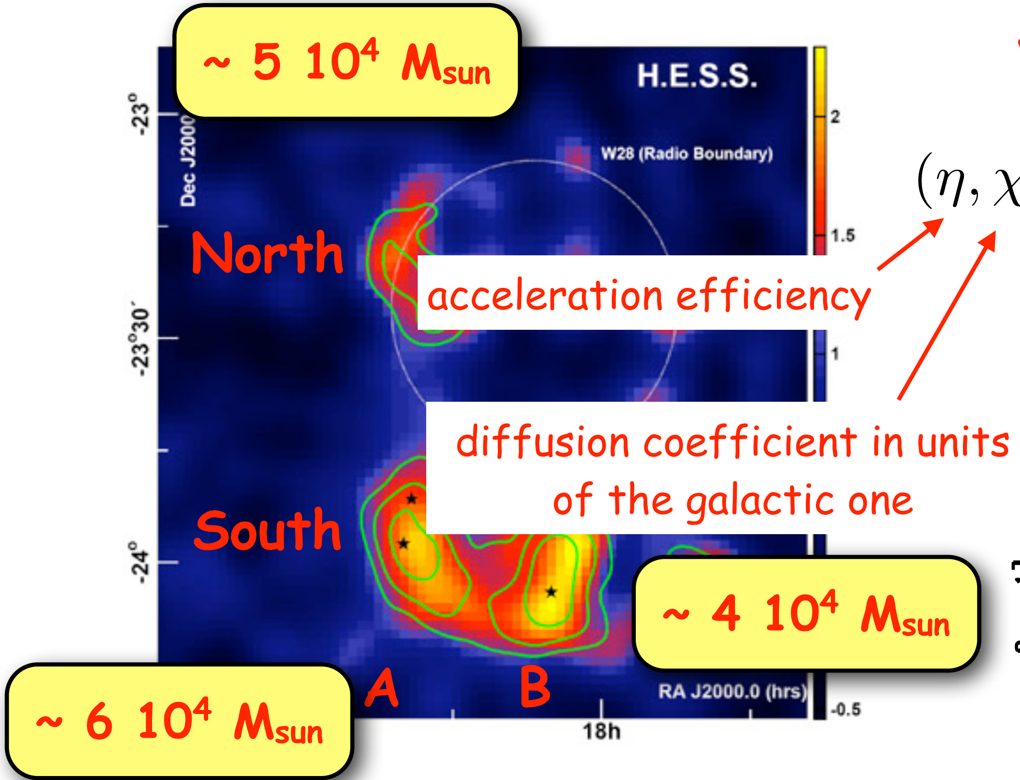
Gabici et al 2010

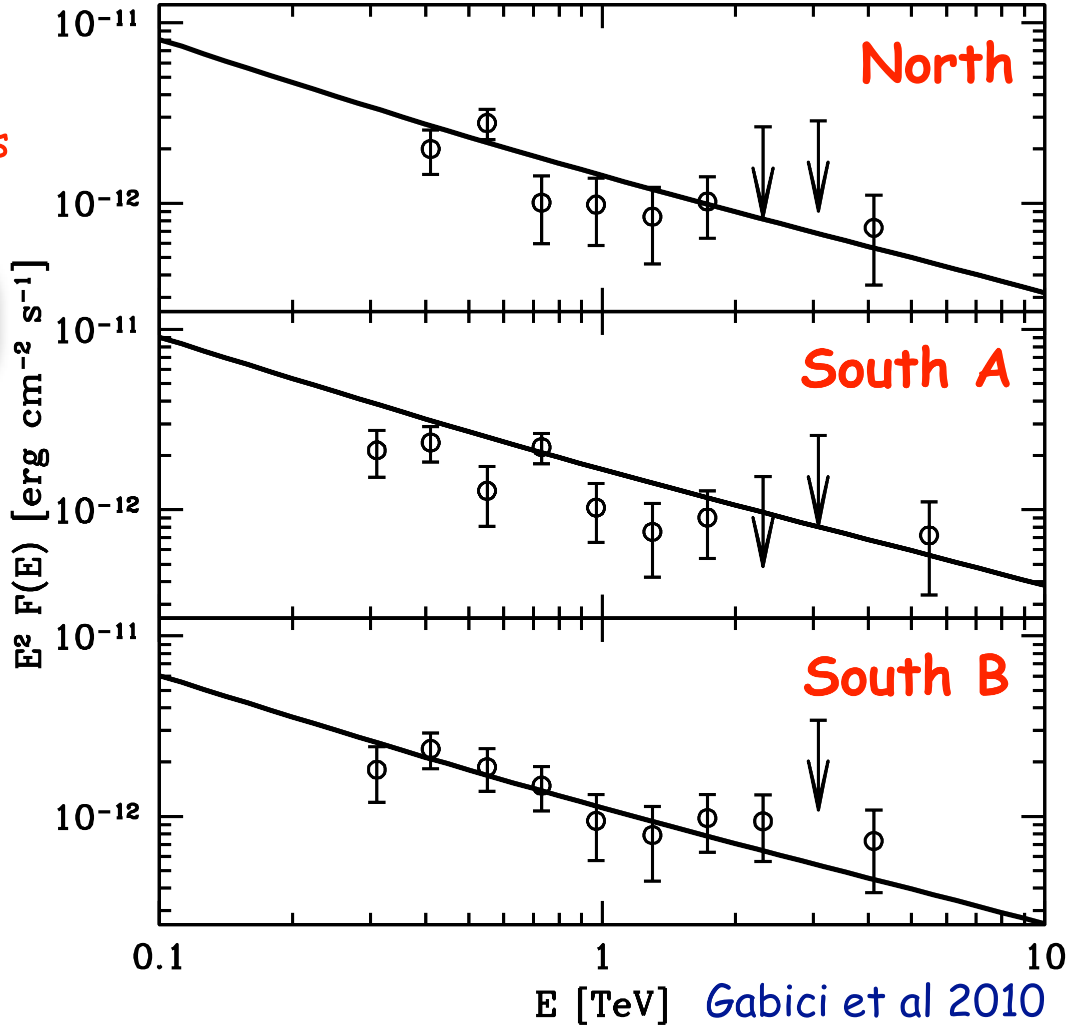
W28: TeV emission

isotropic diffusion!

virtually the same curves for:

$$(\eta, \chi) = (10\%, 0.028); (30\%, 0.06); (50\%, 0.085)$$





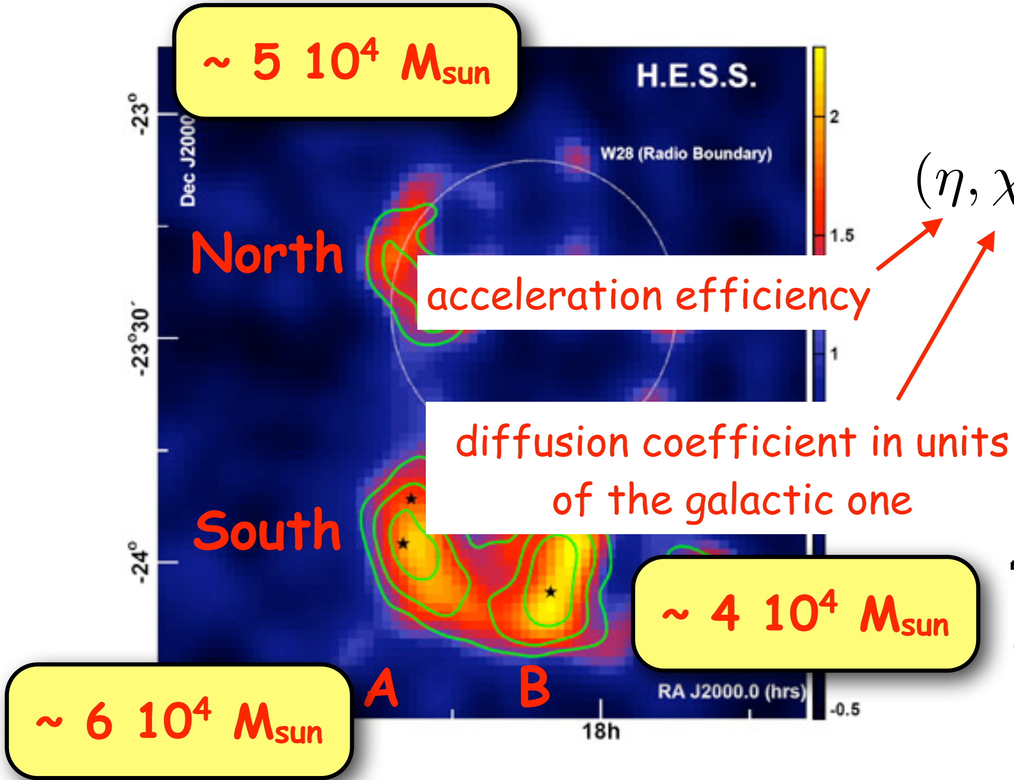
Gabici et al 2010

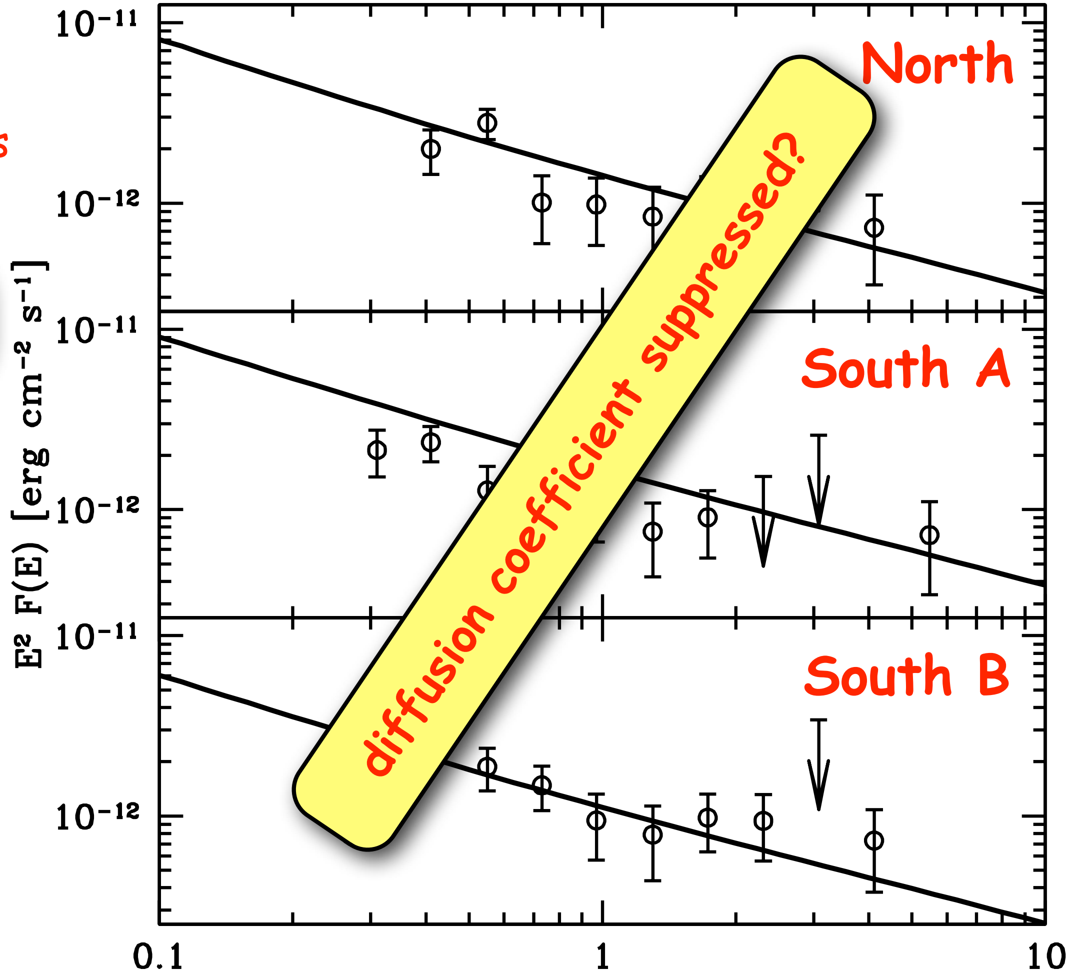
W28: TeV emission

isotropic diffusion!

virtually the same curves for:

$$(\eta, \chi) = (10\%, 0.028); (30\%, 0.06); (50\%, 0.085)$$





Gabici et al 2010

W28: TeV emission

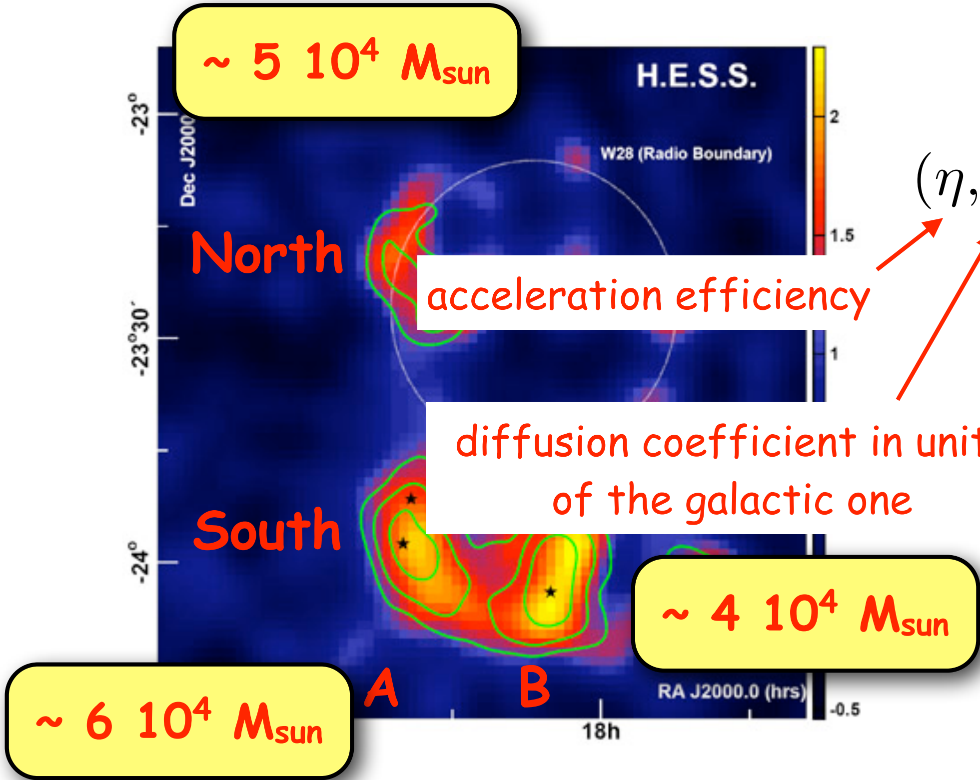
isotropic diffusion!

virtually the same curves for:

$$(\eta, \chi) = (10\%, 0.028); (30\%, 0.06); (50\%, 0.085)$$

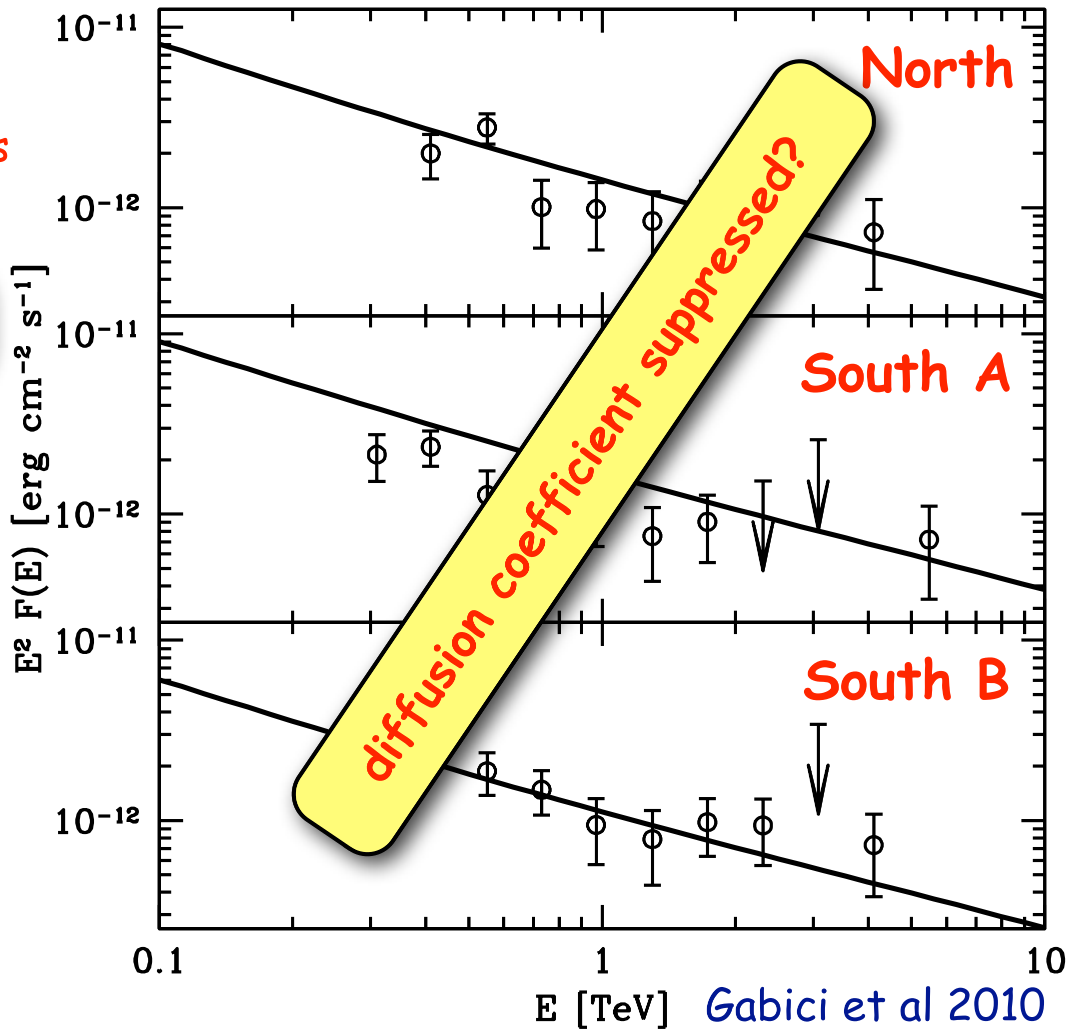
acceleration efficiency

diffusion coefficient in units of the galactic one



size of "CR bubble" @3 TeV

$$l_d \approx 70 \text{ pc} \rightarrow \chi = 0.028$$
$$\approx 95 \text{ pc} \rightarrow \chi = 0.06$$
$$\approx 115 \text{ pc} \rightarrow \chi = 0.085$$



Gabici et al 2010

Conclusions on radiation

☑ detection of **gamma rays** from the surroundings of SNRs (or any CR source) may serve as probes to **identify CR sources** and **constrain the diffusion coefficient**

☑ isotropic diffusion probably not the best: **anisotropic effects + self generation of waves**

☑ more details in Sabrina's talk!