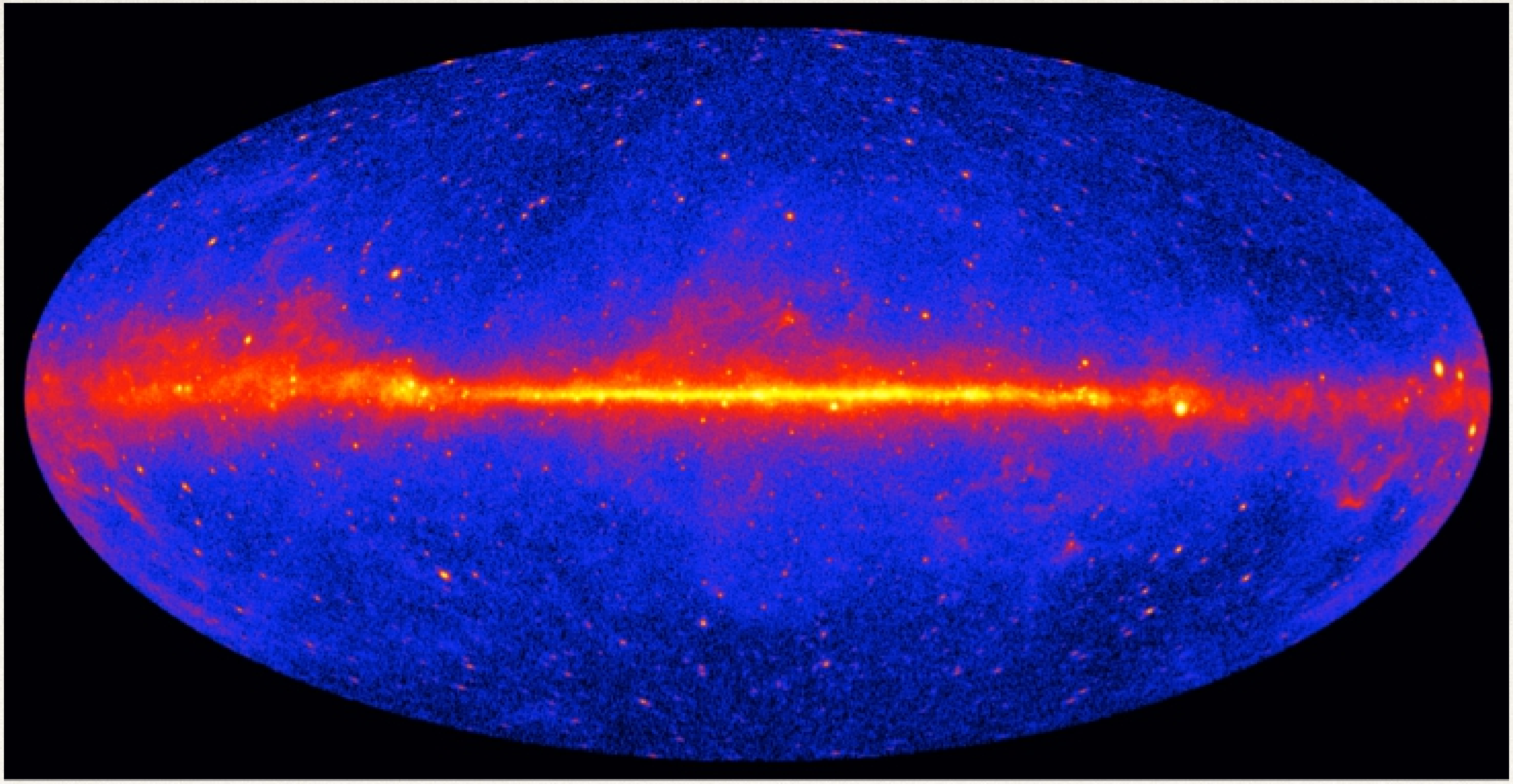


SNR-CR connection: a modern view

Giovanni Morlino,

Gran Sasso Science Institute, L'Aquila, ITALY

IAU Symposium 331:*"SN 1987A, 30 years later"* — February 23, 2017 — La Réunion Island, FRANCE

The path to became a cosmic ray

Acceleration inside sources

- Accelerated spectrum at the shocks
- Magnetic field amplification
- Maximum energy

Escape from sources

- When do particles escape?
- Self confinement around the sources
- Interaction with molecular clouds

Propagation accross the Galaxy

- Standard halo model
- What produces the turbulence?
- CR-driven Galactic wind

Diffusive shock acceleration

Acceleration inside sources

Diffusive Shock Acceleration (DSA) predicts:

$$f(p) \propto p^{-4} \rightarrow f(E) \propto E^{-2}$$

Equating the acceleration time with the end of the ejecta dominated phase $t_{acc} = t_{ST}$:

$$E_{max} = 5 \times 10^{13} Z \mathscr{F}(k_{min}) \left(\frac{B_0}{\mu G}\right) \left(\frac{M_{ej}}{M_\odot}\right)^{-\frac{1}{6}} \left(\frac{E_{SN}}{10^{51} erg}\right)^{\frac{1}{2}} \left(\frac{n_{ISM}}{cm^{-3}}\right)^{-\frac{1}{3}} eV$$

Strong dependence on magnetic field

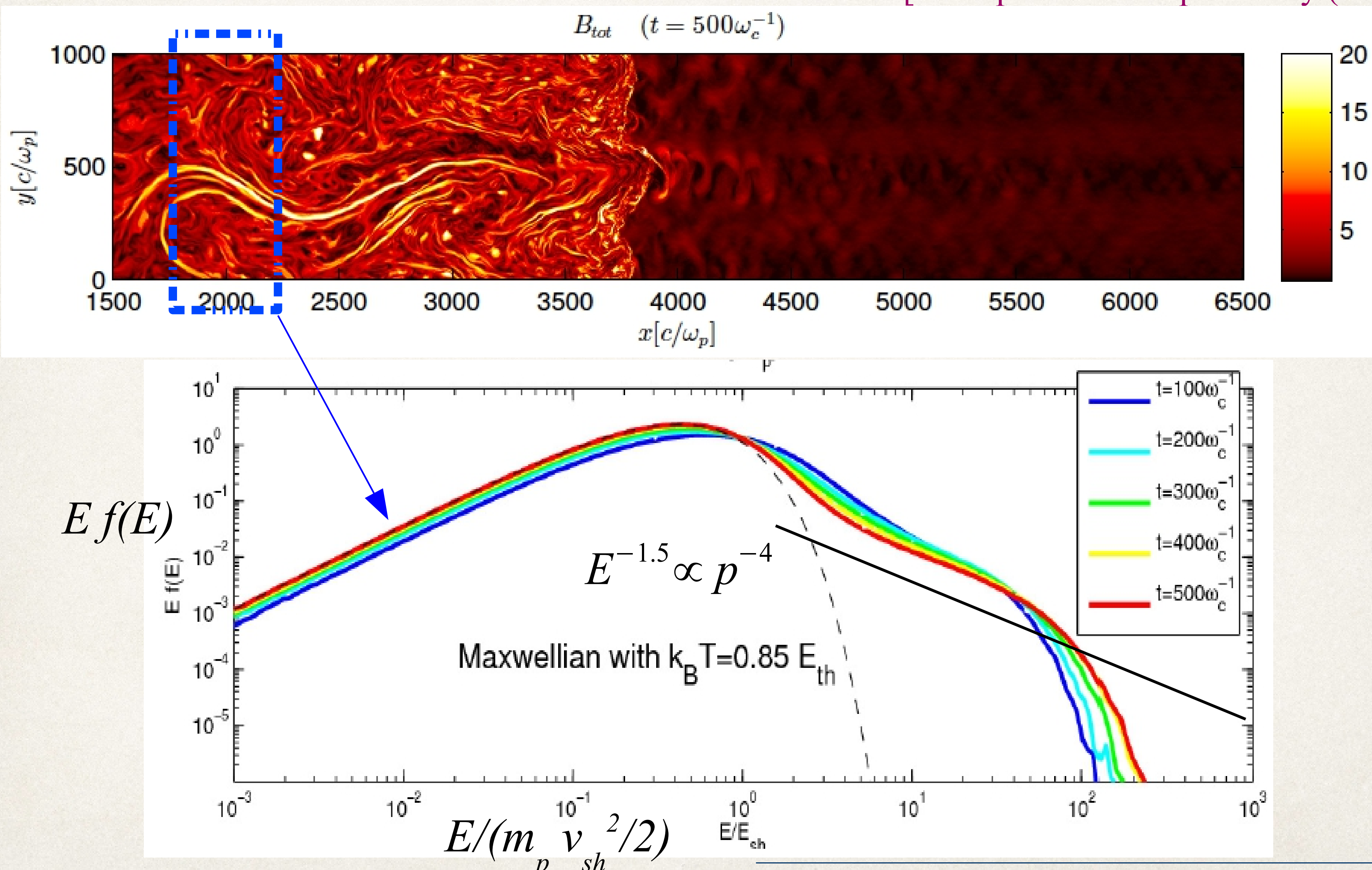
Weak dependence on the ejecta mass and ISM density

High energies, up to PeV, can be achieved only if $\mathcal{F}(k) = (\delta B/B_0)^2 >> 1$.

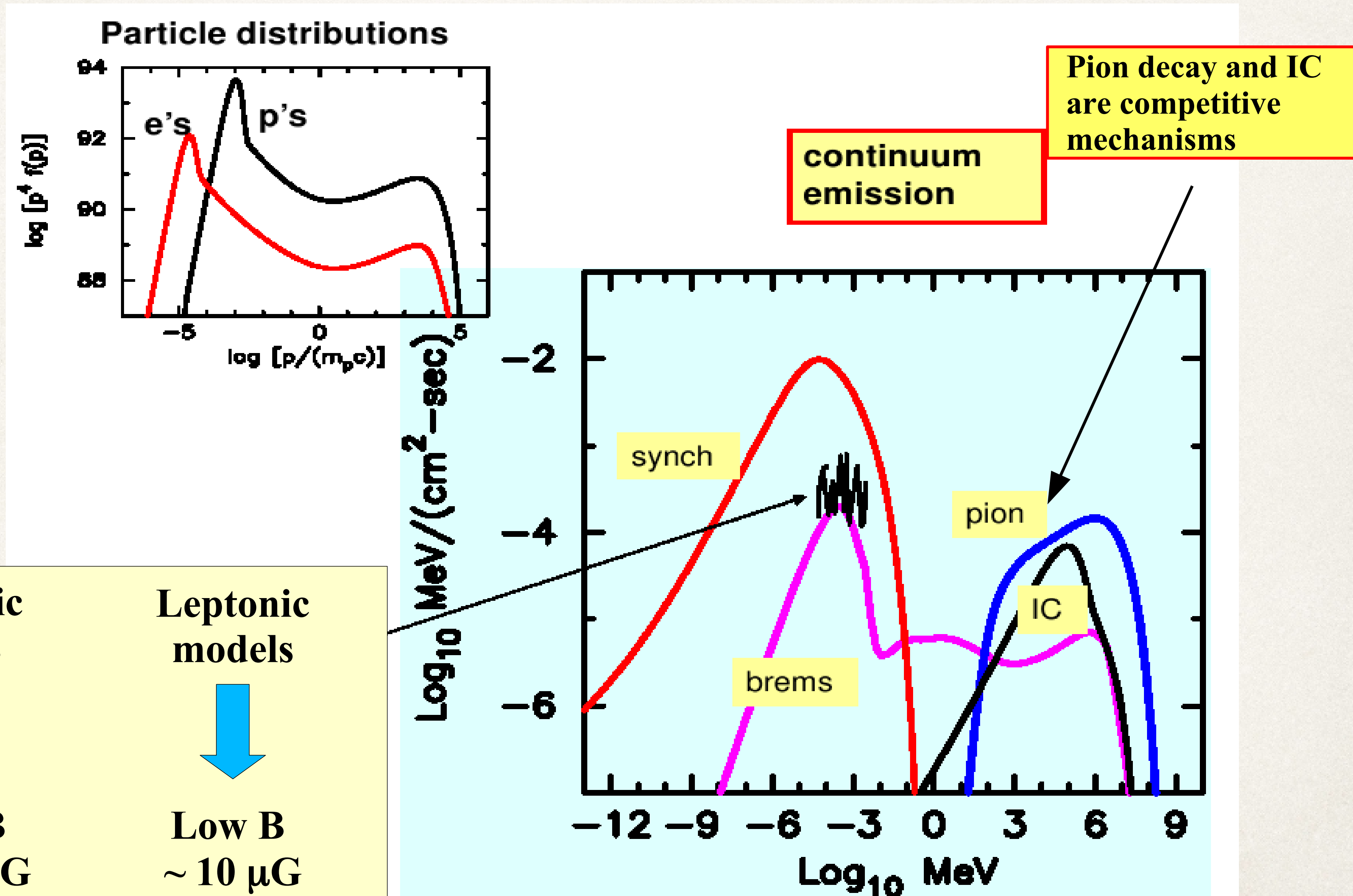
This condition requires amplification of the magnetic field

PIC simulation of particle acceleration

[D. Caprioli & A. Spitkovsky (2013)]

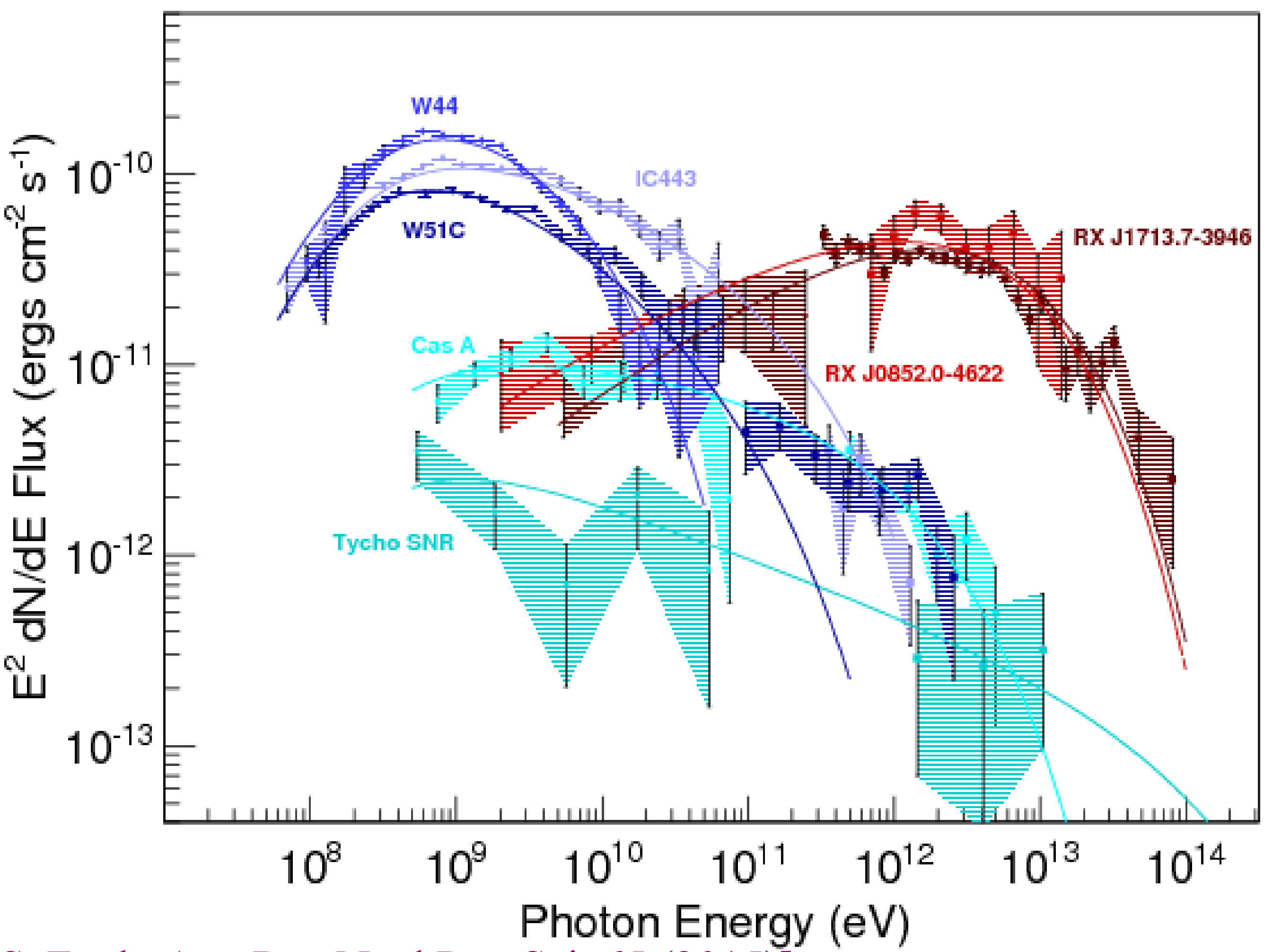


Non-thermal spectrum from SNRs



Hadronic models	**Leptonic models**
↓	↓
Large B	**Low B**
>~ 100 μG	**~ 10 μG**

Gamma-rays from SNRs



[S. Funk, Ann.Rev.Nucl.Part.Sci. 65 (2015)]

- Middle-aged SNRs (~20.000 yrs)
  - hadronic emission
  - steep spectra
  - E_{max} < 1 TeV

Young SNRs (~2000 yr)
  - Hadronic/leptonic?
  - Hard spectra
  - E_{max} ~ 10-100 TeV

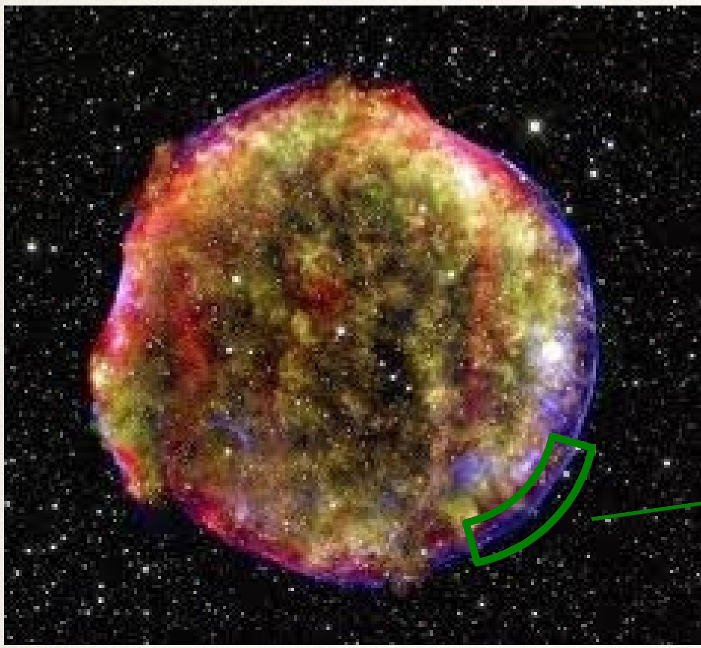
Very young SNRs (~300 yr)
  - hadronic
  - steep spectra ~$E^{-2.3}$
  - E_{max} ~ 10-100 TeV

Not enough to explain the Knee at ~ PeV

See also talk by Francesco de Palma

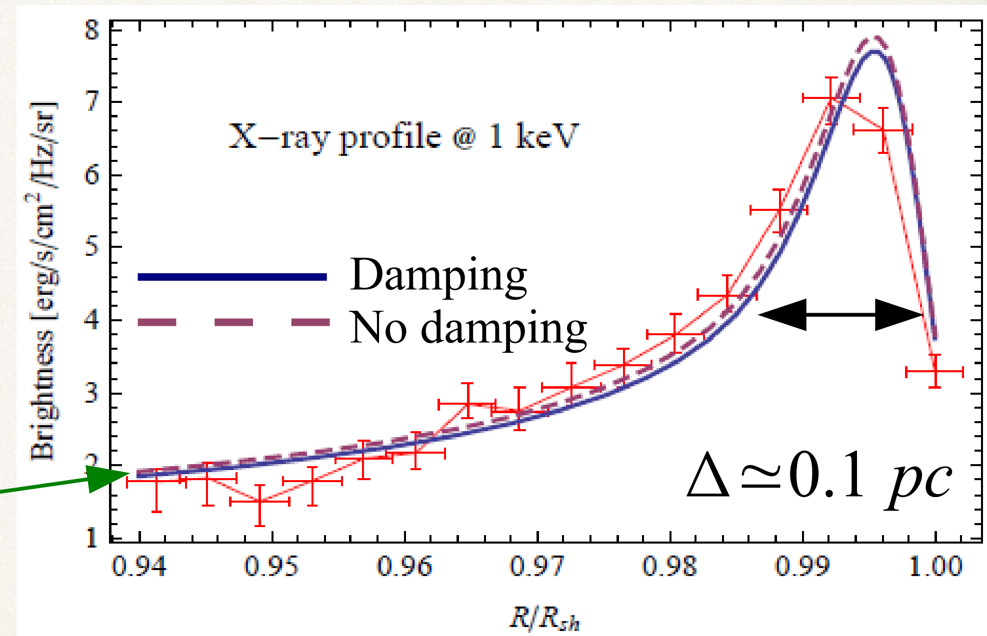
Magnetic field amplification: observations

Chandra X-ray map.
Data for the green sector are from Cassam-Chenaï et al (2007)



Thin non-thermal X-ray filaments provide evidence for magnetic field amplification

[Hwang el al(2002); Bamba et al (2005)]



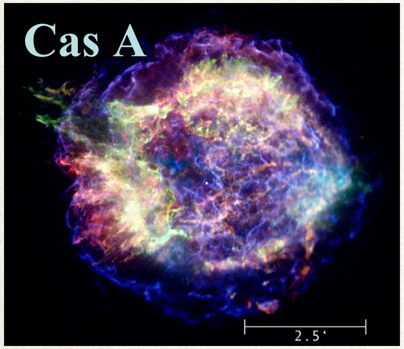
$$\begin{cases} D = r_L c/3 \propto E B^{-1} \\ \tau_{syn} = \dfrac{3 m_e c^2}{4 \sigma_T c \gamma \beta^2 U_B} \propto E B^{-2} \end{cases}$$

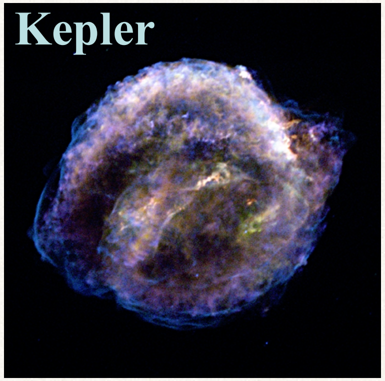
$$\Delta \simeq \sqrt{D \tau_{syn}} \propto B^{-3/2}$$

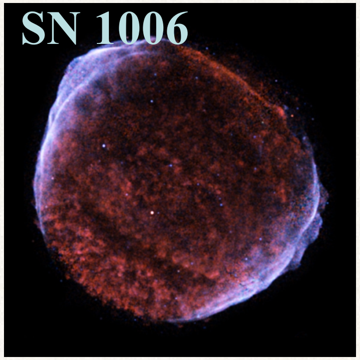
⇒ ***B*~200-300 μG >> *B*$_{\text{ISM}}$**

Magnetic field amplification: observations

Thin X-ray rims (~0.1 pc) are observed in almost all young SNRs







Magnetic pressure downstream can reach ~few% of total pressure

SNR	B_{down} (μG)	$B^2_{down}/(8\pi p)$ [%]
Cas A	250-390	3.2-3.6
Kepler	210-340	2.3-2.5
Tycho	240-530	1.8-3.1
SN1006	90-110	4.0-4.2
RCW 86	75-145	1.5-3.8

Magnetic field amplification: observations

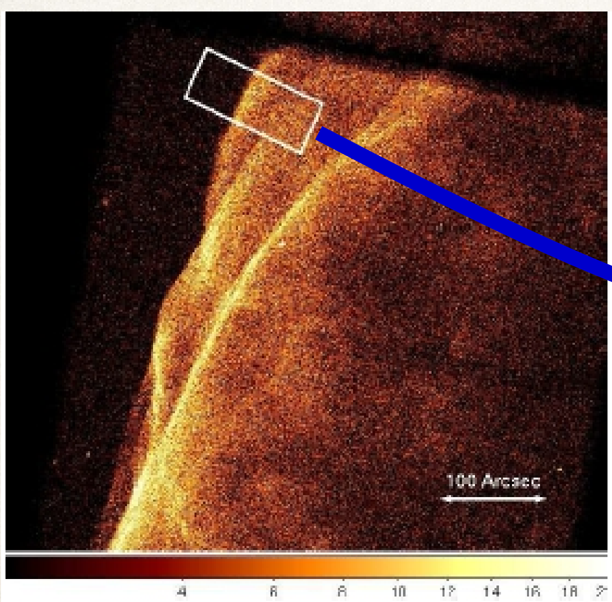
Where is the magnetic field amplified?

DOWNSTREAM: MHD instabilities (shear-like)

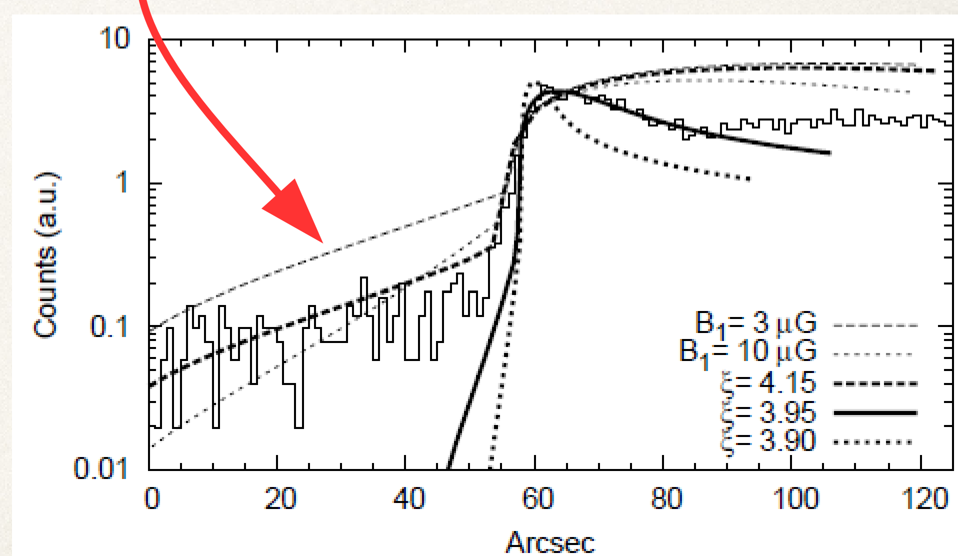
UPSTREAM: only through instabilities driven by CRs (Streaming, Bell)

BUT we need amplification upstream of the shock to reach high energies

Low magnetic field upstream produces a more extended emission NOT OBSERVED!



SN1006 in X-rays (*Chandra*)



[from G.M., Amato, Blasi, 2009, MNRAS]

Magnetic field amplification: Theory

How is the magnetic field amplified?

Resonant Straming instability

[e.g. Skilling (1975), Bell & Lucek (2001), Amato & Blasi (2006), Blasi (2014)]

Particles amplify Alfvèn waves with wave-number
$k = 1/r_L(p)$

Fast growth rate but

$(\delta B/B_0)^2 \simeq few$

$E_{max} \approx 10^5\, GeV$

A factor 10 below the knee

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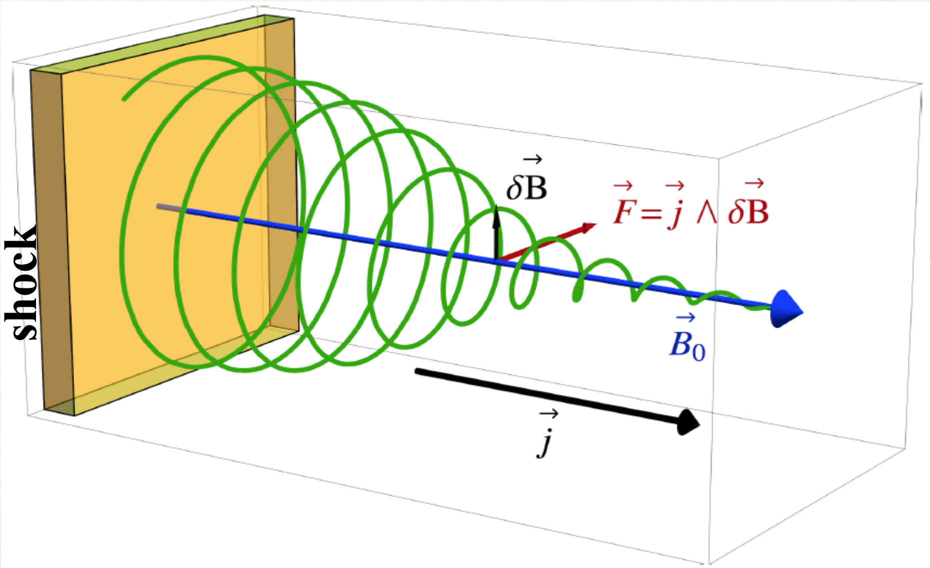
Non-resonant
***Bell* instability**

[Bell (2004)]

$E_{max} \propto \sqrt{\rho_{CSM}}$

Amplification due to $\vec{j} \wedge \vec{B}$ force



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Non-resonant
***Bell* instability**

[Bell (2004)]

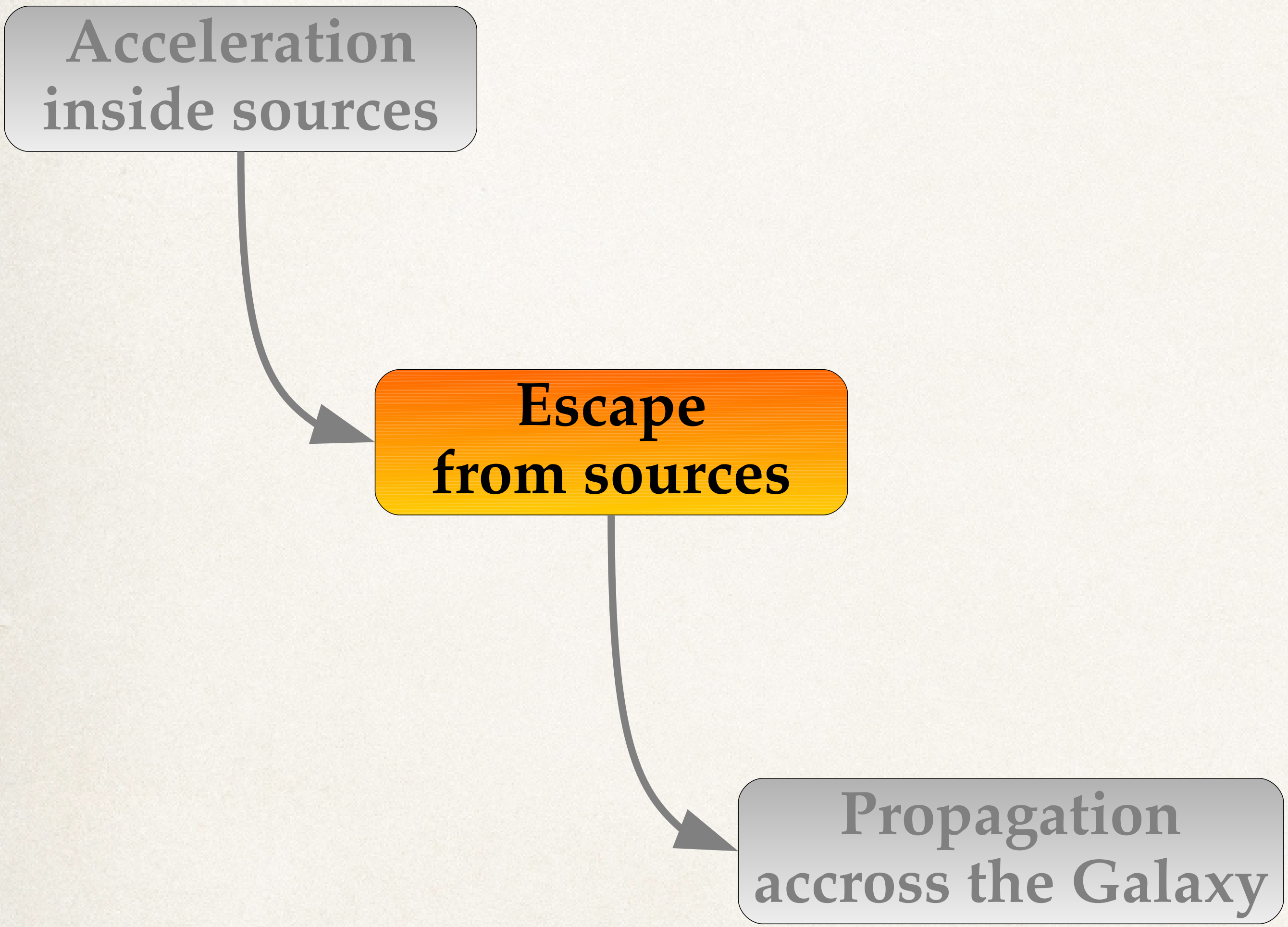
$E_{max} \propto \sqrt{\rho_{CSM}}$

Type Ia SNR expanding into a uniform medium → $E_{max} \approx 10^5\,GeV$

Type II SNR expanding into a red supergiant wind → $E_{max} \approx 2 \times 10^6\,GeV$

Right number, but this last only ~50 yr!

The path to became a cosmic ray



Particle escape from SNRs

If particles are not released all at the same time, in general:

Spectrum injected into the Galaxy $f_{esc}(p) \neq f_{SNR}(p)$ Spectrum inside SNRs

Assume that at time t only particles at maximum momentum $p_{\max}(t)$ can escape

$$4\pi f_{esc}(p)\, c\, p\, p^2\, dp = \xi_{esc}(t) \frac{1}{2}\rho V_{sh}^3 4\pi R_{sh}^2\, dt$$

Released energy — Converted fraction — Incoming energy flux

$$f_{esc}(p) \propto p^{-4} V_{sh}(t)^{5\alpha-2} \xi_{esc}(t)$$

$$f_{esc}(p) \propto p^{-4}$$

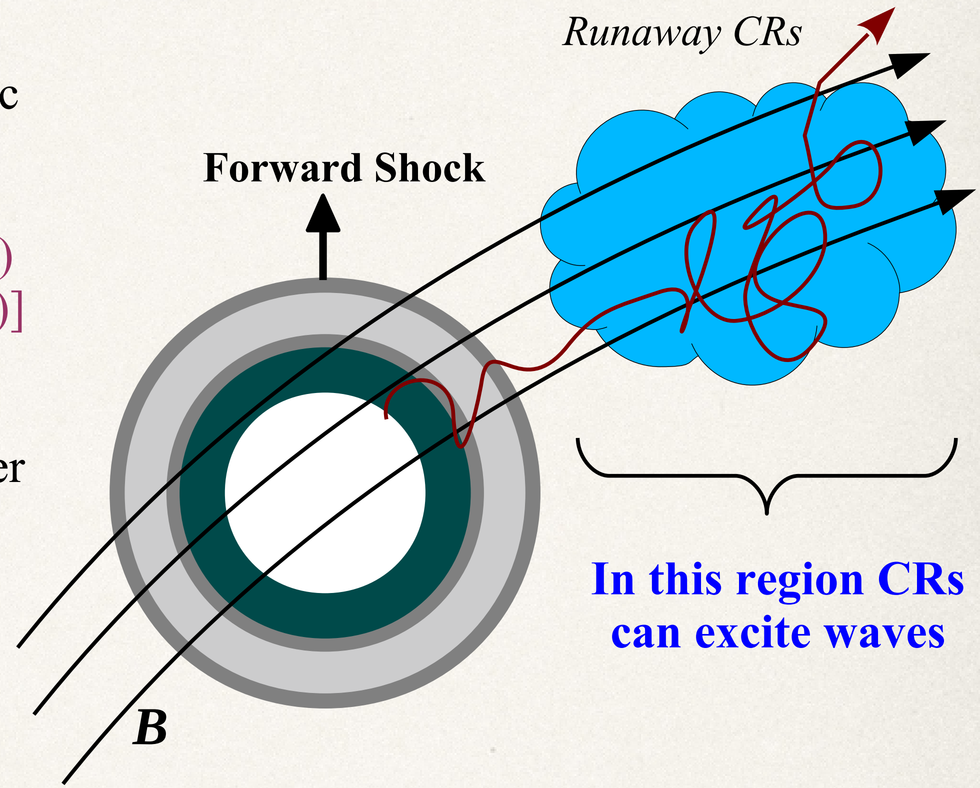
- Expantion in omogeneous medium with $R_{sh}(t) \propto t^{\alpha}$
- Escaping during the Sedov-Tayor phase (^ α=2/5)
- ξ_{esc}(t) ≈const

Spectrum NOT related to Fermi acceleration process!

Effect of self-amplification near the CR sources

During the process of escaping, CR can excite magnetic turbulence (via streaming instability) that keep the CR close to the SNR for a long time, up to ~10^5 yr

[Malkom et al. (2013)
Nava et al. (2015)]

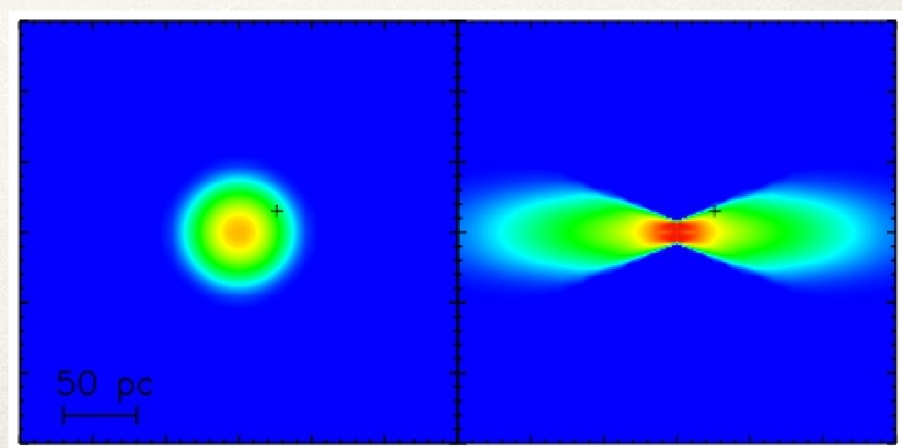


The region where this can happen is at most of the order of the coherence-length of the magnetic field (after this distance the diffusion becomes 3D and the CR dendity drops rapidly below the average Galactic value)

During the time CR spend in the vicinity of sources they can produce diffuse emission via $\pi^0 \rightarrow \gamma\ \gamma$

If a molecular cloud is close enough the enhanced γ-ray emission will be seen for long time

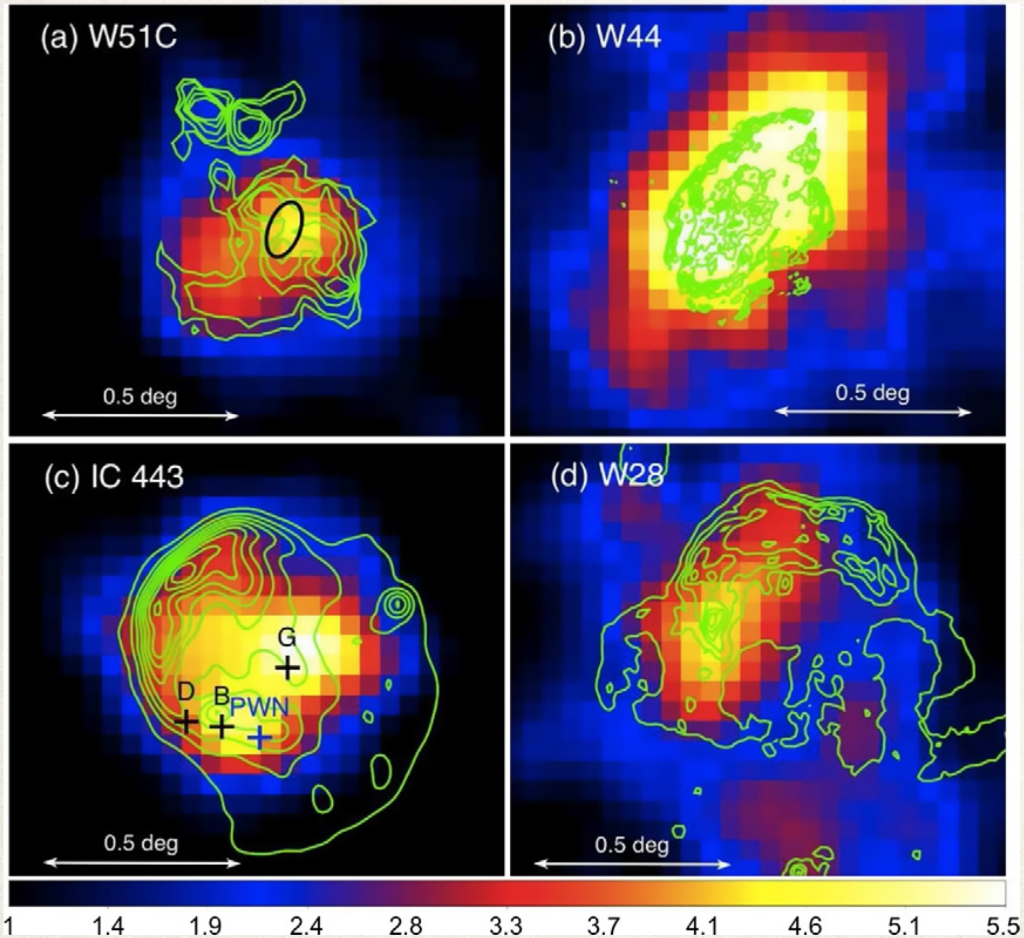
CTA will probably discover tens of SNR-MC associations



Simulation from Nava & Gabici (2012)

Using molecular clouds as CR barometer

Examples of γ-ray emission from clouds close or interacting with SNRs - [*Fermi*-LAT]



<u>OBSERVATIONS of MCs in γ-RAYS:</u>

- CRs interact inside MCs
  $$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$
- strong emission in GeV range
- γ-emission sensible to CR energy $E > 280$ MeV

<u>DETECTION OF IONIZATION</u>

- The ionization rate of several molecules depends on the CR flux (H_2, H_3^+, CH, OH, C_2, DCO^+, HCO^+,......)

- Ionization sensible to CR energy $E > 0.1$ MeV

Is it possible to use combined information from ionization and γ-ray emission to infer the CR spectrum from ~MeV up to ~TeV

Using molecular clouds as CR barometer

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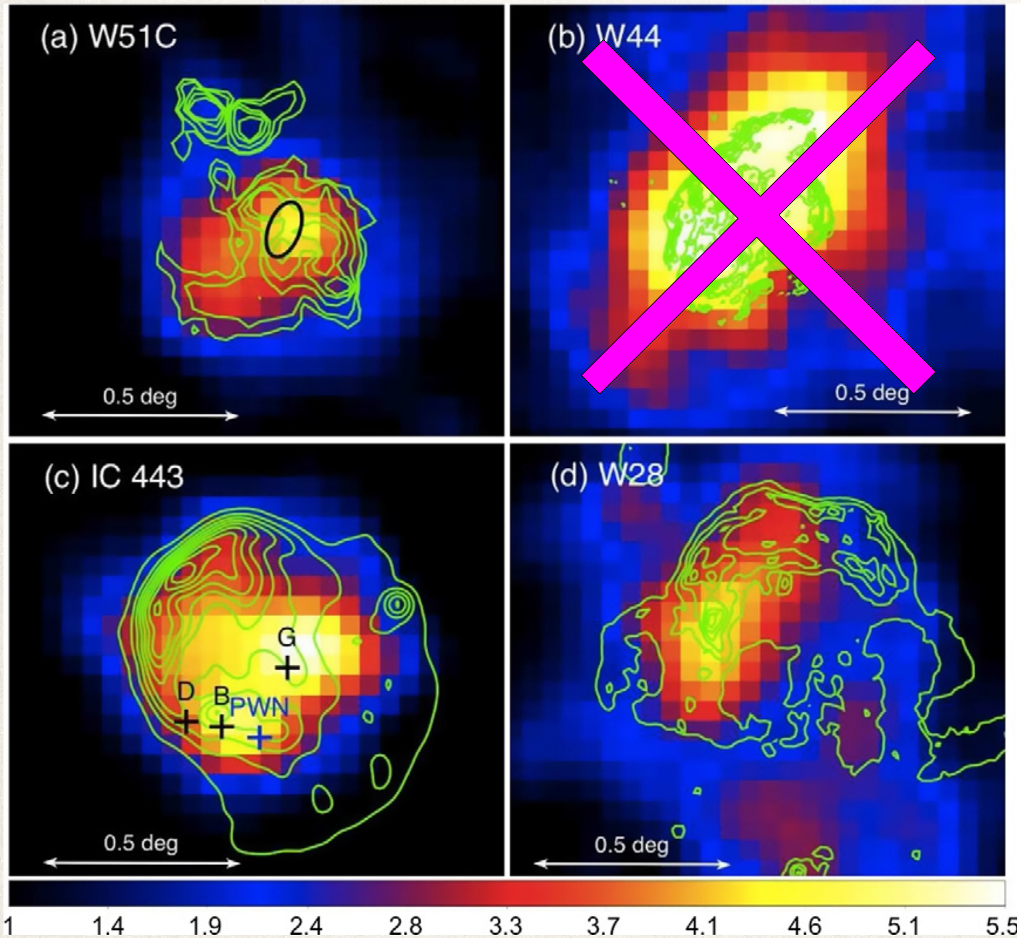
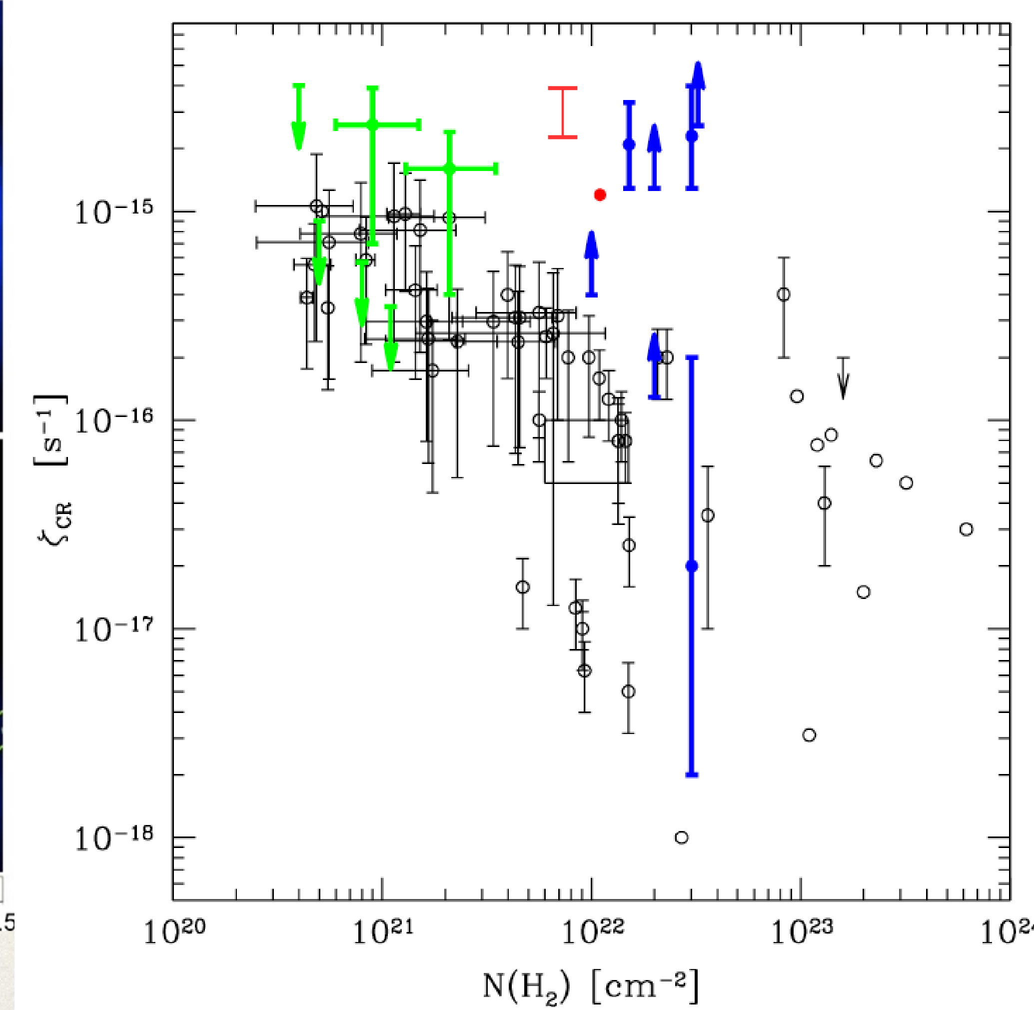
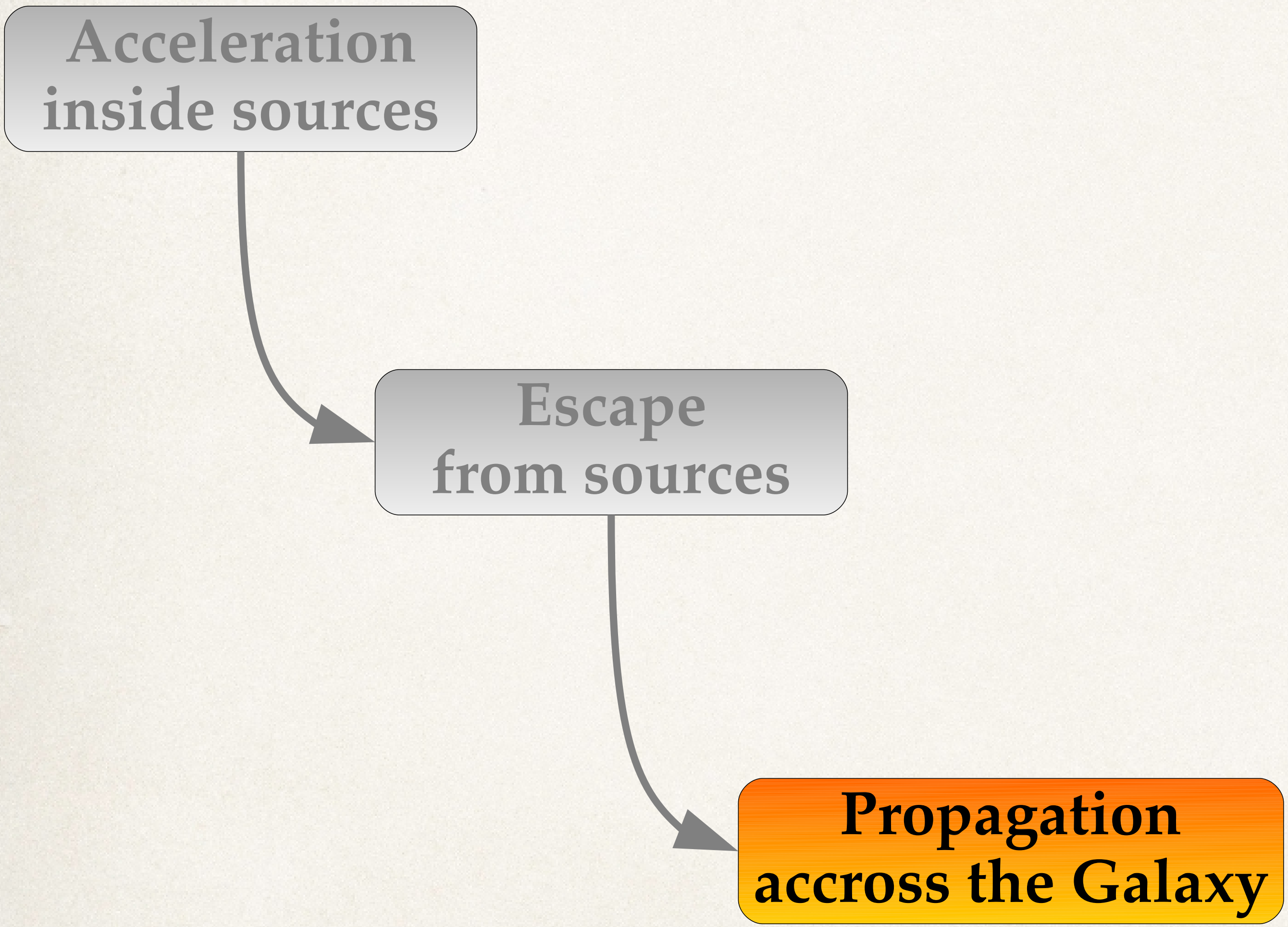


Average level of ionization is lager for MCs close to SNRs

IC 443 W 51C W28



Diffusion in the Galactic Halo



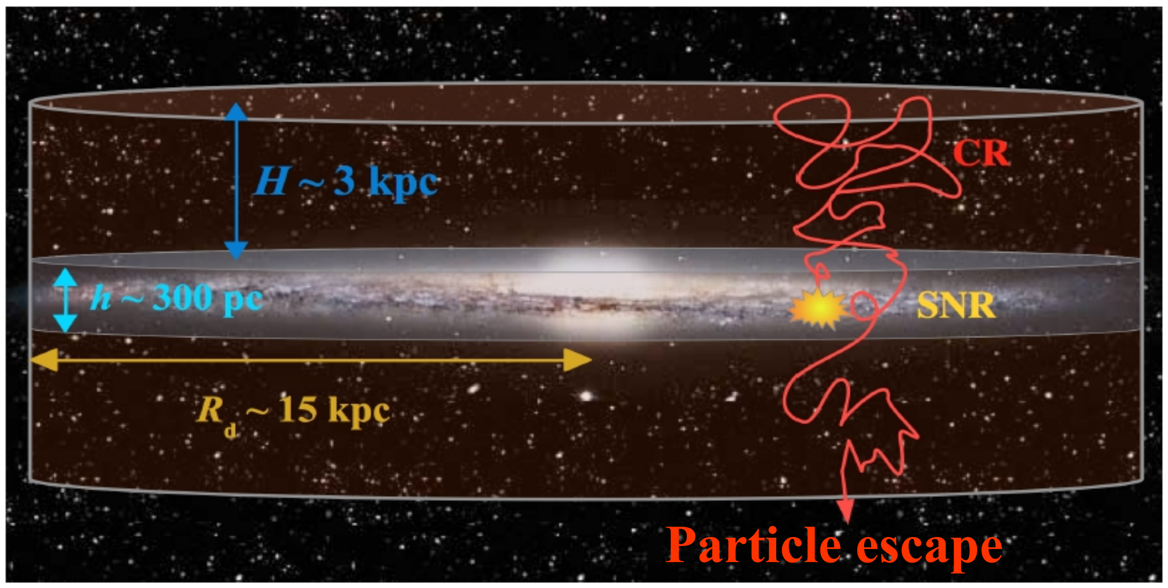
Basic Halo model

The most widely used model is the leaky-box with the following properties

- CRs diffuse in a magnetic halo larger than the Galactic disc
- The CR distribution vanish at $z = H$ (H~3-4 kpc from diffuse synchrotron emission)
- The diffusion coefficient $D(E)$ is assumed constant everywhere in the halo

This picture is unsatisfactory for at least two reasons:

- Which is the physical meaning of H?
- What generates the diffusion?



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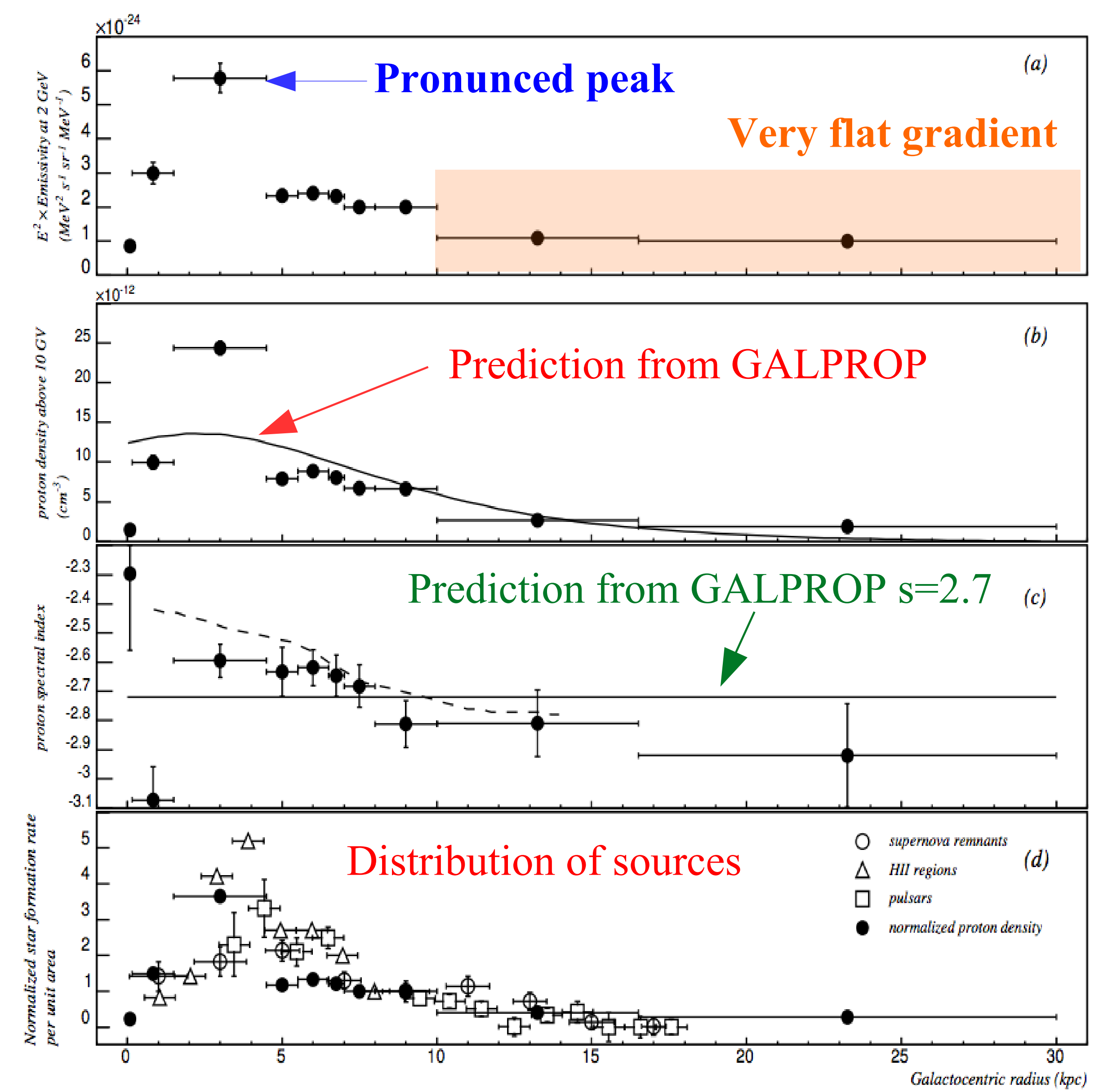
- Which is the physical meaning of H?
- What generates the diffusion?

Several anomalies suggest a more complex propagation model

- Excess in $e^+/(e^++e^-)$
- Hint of an excess in antiproton flux
- Break in the p and He spectrum @ ~200 GeV
- Diffuse Galactic γ-ray spectrum
  - a progressive hardening of the proton spectrum towards the Galactic center
  - the flat gradient of the CR density in the Galactic plane

The problem of the cosmic ray gradient in the Galactic plane seen by Fermi-LAT



Recent results from FermiLAT collaboration on the CR distribution in the Galactic plane
[Acero et al. arXiv:1602.07246]

- In the outer region (R > 8kpc) the CR density at ~20 GeV is flat (i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

- The slope @ 20 GeV is not constant

This scenario is difficult to accommodate in a standard diffusion model

Possible solutions

In the context of leaky-box model several solution have been proposed:

- Extended halo, $H > 4$ kpc
  (Dogiel, Uryson, 1988; Strong et al.,1988; Bloemen, 1993, Ackerman et al., 2011)
  - ^ predices a flat spectrum (but not flat enough)
  - ^ cannot explain the denity bump in the inner Galaxy
- Flatter distribution of SNR in the outer Galaxy
  (Ackerman et al., 2011)
- Enhancement of CO/H_2 density ratio (X_{CO}) in the outer Galaxy (Strong et al., 2004)
- Injection dependence on the ISM temperature
  (Erlykin et al., 2015)
- Advection effects due to the Galactic wind
  (Bloemen, 1993; Breitschwerdt, Dogiel, Voelk, 2002)

None of these ideas can simoultaneously account for all signatures

- flatness $R > 8$ kpc,
- peak at R~3-4 kpc,
- variation in the slope

CAN SELF-GENERATED DIFFUSION EXPLAIN THE OBSERVATIONS?

1-D slab model with self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

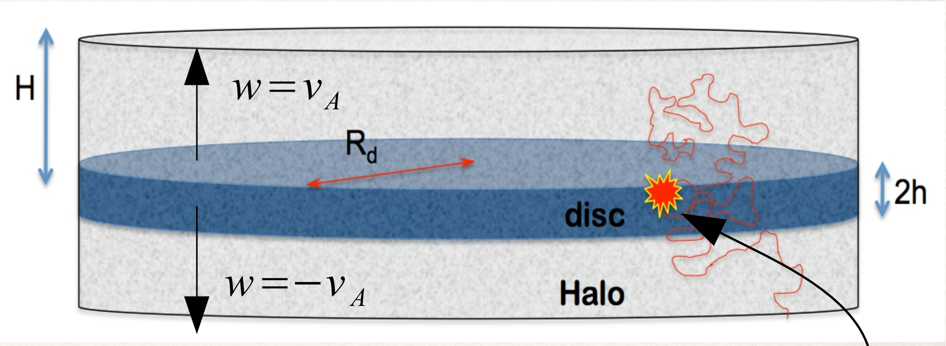
- CR escaping from the Galactic plane produce magnetic turbulence through resonant streaming instability

$$\Gamma_{cr} = \frac{16\pi^2}{3} \frac{v_A}{\mathcal{F}(k) B_0^2} \left[p^4 v(p) \frac{\partial f}{\partial z} \right]_{p = eB_0/kc}$$

- Turbulence scatter CRs (mainly) along large scale mag. field lines with Bohm-like diffusion coeffcent

$$D(z,p) = \frac{r_L(p) v(p)}{3} \left[\frac{1}{\mathcal{F}(k)} \right]_{k=1/r_L}$$

- CRs are also advected by the global motion of the waves at the Alfvén speed



Spectrum injected at the disk

$$Q_0(p,R) \propto N_{SNR}(R) p^{-\gamma}$$

Propagated spectrum in the disk

$$f_{disk}(p) \propto p^7 \left(\frac{Q_0(p,R)}{B_0(R)} \right)^s ; \qquad s = 1 \div 3$$

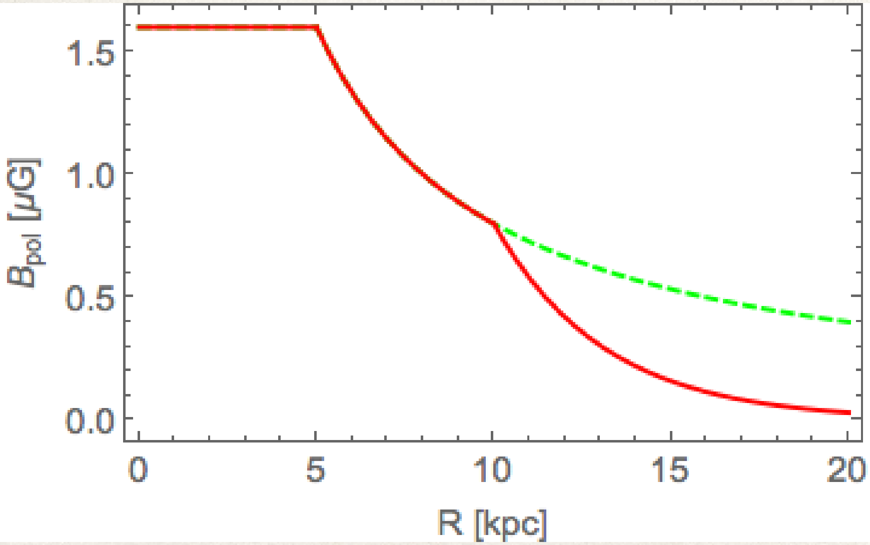
1-D slab model with self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

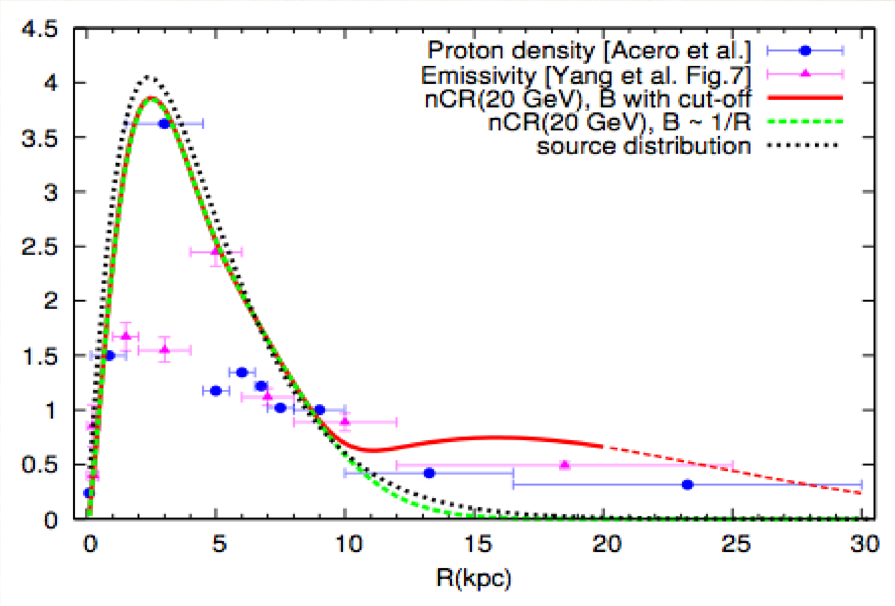
Large scale magentic field in the Galaxy:

$$B_0(R < 5\,\mathrm{kpc}) = B_\odot R_\odot / 5\,\mathrm{kpc}$$
$$B_0(R > 5\,\mathrm{kpc}) = B_\odot R_\odot / R,$$

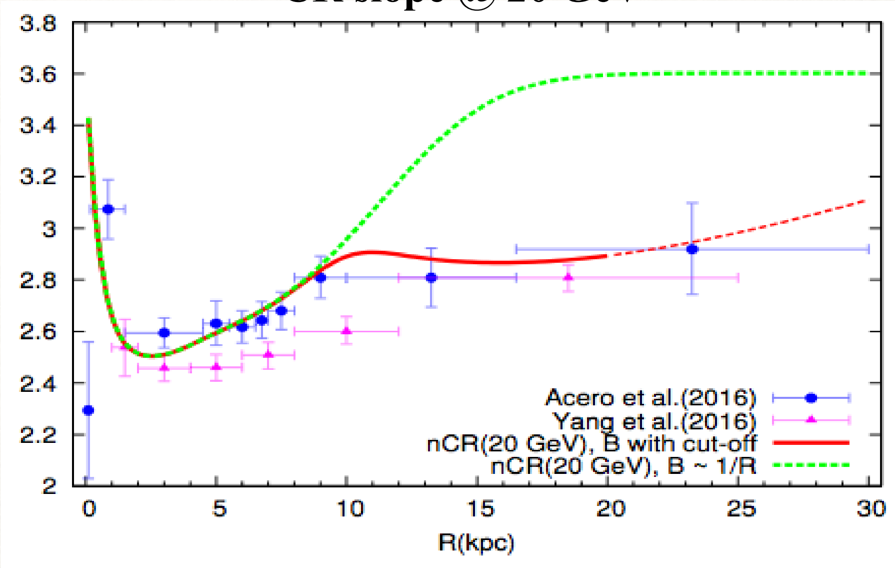
$$B_0(R > 10\,\mathrm{kpc}) = \frac{B_\odot R_\odot}{R} \exp\left[-\frac{R - 10\,\mathrm{kpc}}{d}\right]$$



CR spectrum density @ 20 GeV



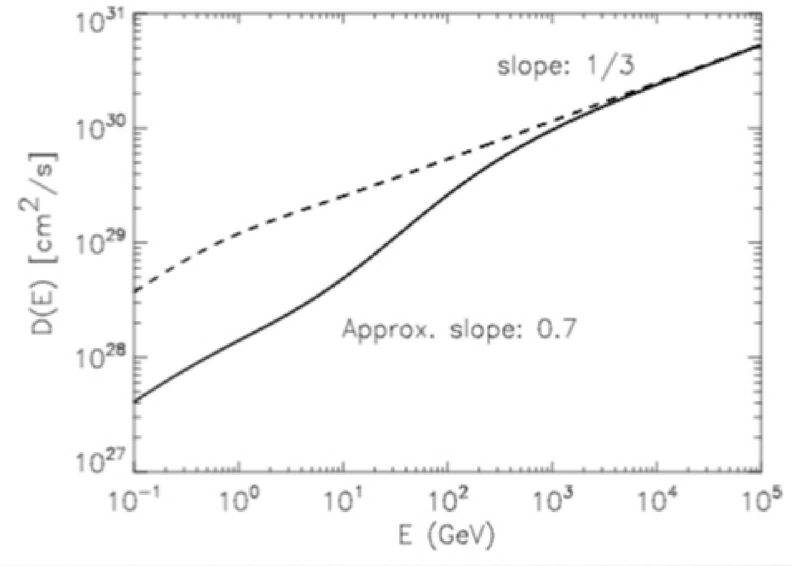
CR slope @ 20 GeV

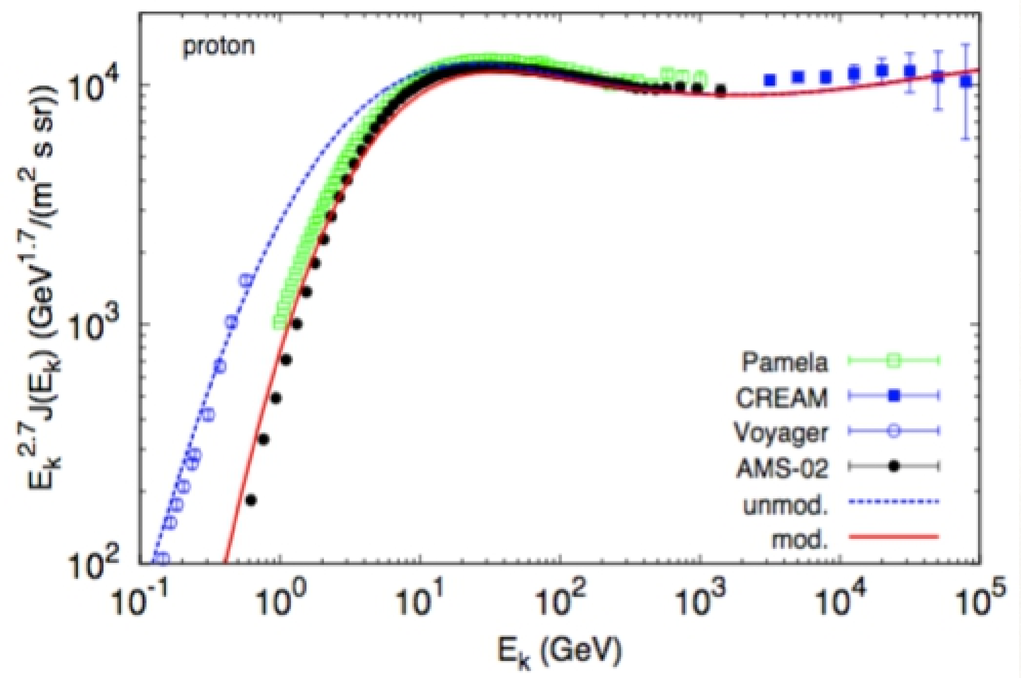


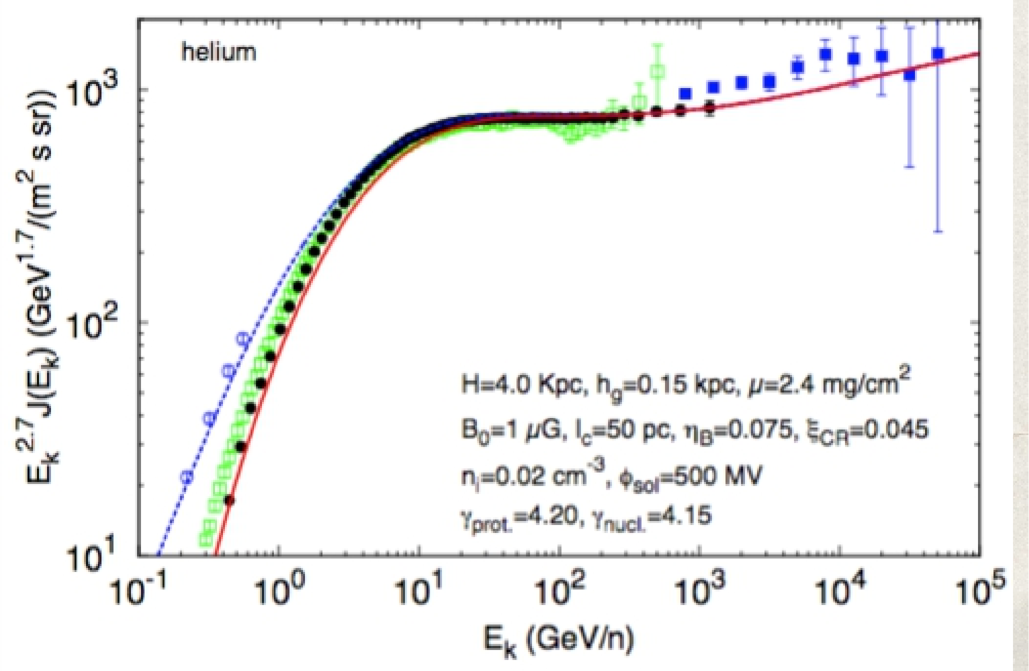
Spectral breaks as signatures of CR-induced turbulence

The presence of breaks in the PAMELA and AMS-02 data can be explained by a different diffusion regime
[Blasi, Amato Serpico (2012)
Aloisio, Blasi, Serpico (2015)]

- $E < 200$ GeV ^ self generated diffusion
- $E > 200$ GeV ^ external preexisting turbulence







Why a Galactic magnetic Halo?

Evidences for the Galactic magnetic halo:

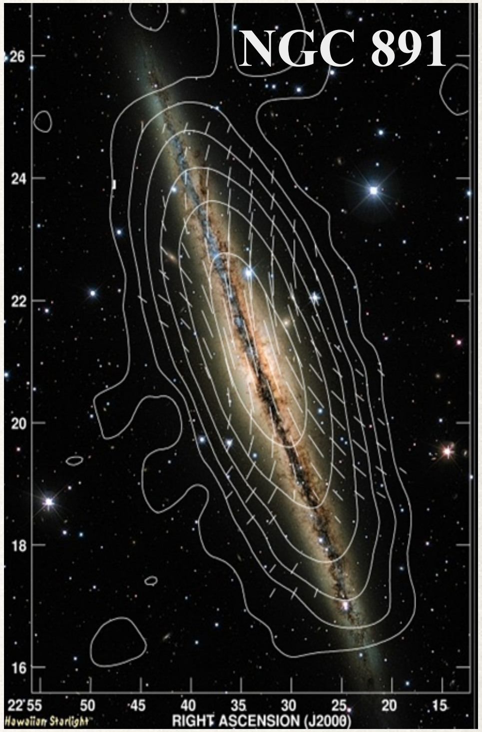
1) Detection of magnetic field around other galaxies
2) Detection of synchrotron emission around the Milky Way

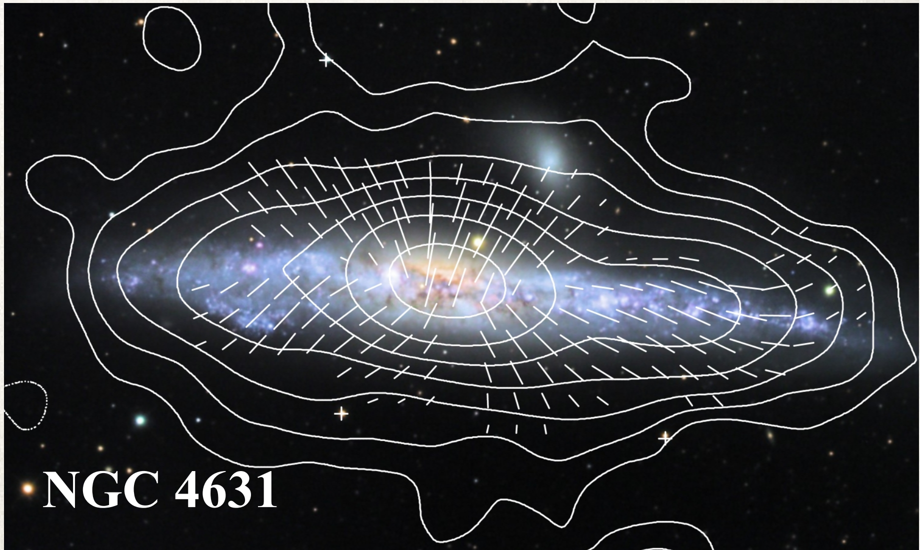
What is the origin of the magnetic Halo?

Sometimes the X-shaped magnetic field structure in the halo is accompanied by strong vertical fields above and below the central region of the disk.

These observations support the idea of a "**galactic wind**" which is driven by the energy of star formation processes in the disk and transports gas, magnetic fields and cosmic-ray particles into the halo.

The speed of the outflow can be measured from radio observations and is of the order of 300 km/s.





Evidence from X-ray emission and absorption lines

Thermal X-ray emission has been observed from the region around sturbust galaxies.

- In some "normal" galaxies the presence of a hot temperature gax (T~10^6 K) has been inferred from absorption lines in X-rays (especially lines OVI , OVII and OVIII)

- Also the Milky Way presents the same absorption lines [e.g. Kalberla & Dedes (2008), Miller & Bregman (2013)]

- From those lines the total mass of the halo can be estimated

$$M_{halo} \sim 10^{10}\, M_{sol}$$

(comparable with the total barionic mass in the disk!!)

- And also the matallicity: $Z \sim$ **0.2-0.3**

→ The halo has been probably polluted by a Galactic wind

BUT In the Milky Way thermal pressure alone is unable to drive a Galactic wind.

Galactic wind observed in X-rays from starburst galaxy M82

Can CRs drive a Galactic wind?

[Breitschwerdt, McKenzie & Vòlk (1993), Everett J. E., Zweibel (2011), Recchia, Blasi, GM (2016) Pakmor, Pfrommer, Simpson et al. (2016)]

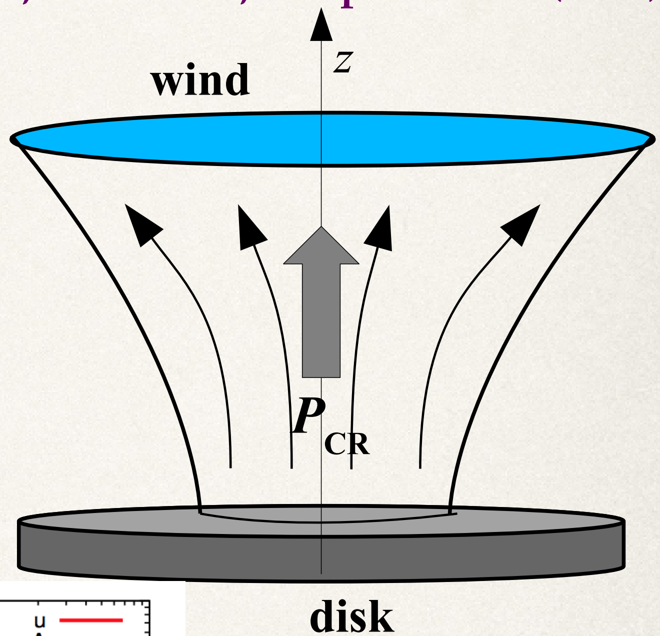
- CRs behave as a relativisic gas ⇒ pressure drops less than thermal pressure ⇒ **can drive a wind**

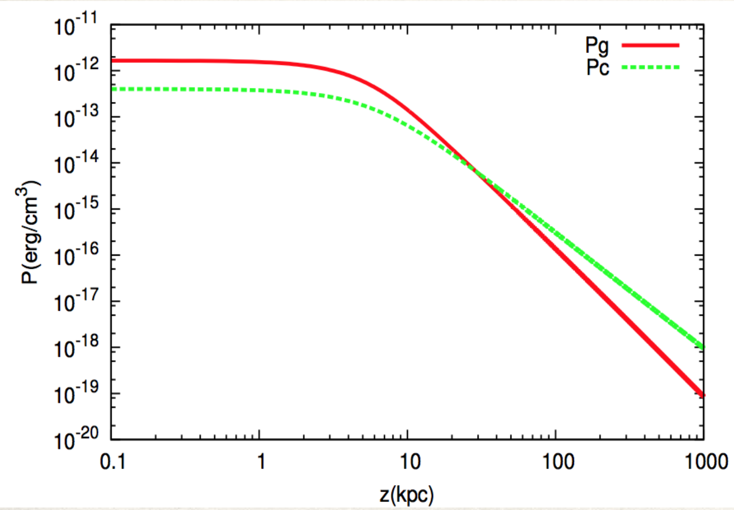
- Properties of the wind can explain the hot barionic halo around Milky Way
  - Wind speed increases up to ~ few 100 km/s
  - T wind up to 10^6 K

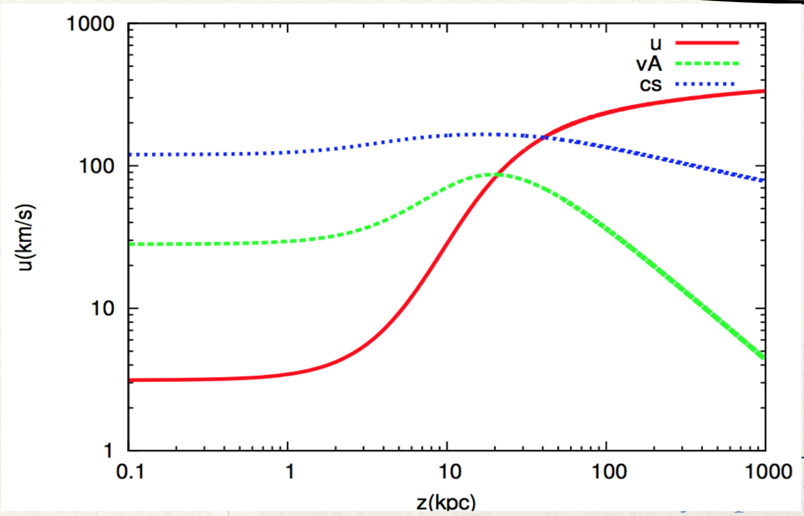
- Wind can produce a mass loss rate ~0.5 $M_\odot$/yr

  ⇒ in agreement with star formation models

- The CR halo ends where advection dominated over diffusion ⇒ **energy dependent halo size**







Conclusions

ACCELERATION

- DSA is a well developed theory but we need to account for different ambient media where SNRs expand
- Strong evidence for magnetic field amplification induced by CRs

ESCAPING

- Escaping process is a key issue and is not undestood yet.
- Possible way to study it
    - Emission from molecular cloud close to SNR
    - Contribution of escaping particles to diffuse γ-ray emission

PROPAGATION IN THE GALAXY

- We still lack of a realstic description of Galactic propagation
- Going beyond the simple view of the leaky-box model is required by data
    - Self-generated turblence produced via streaming instability could play a major role for the propagation of CRs with $E \lesssim 100$ GeV
    - CR pressure could drive a Galactic wind