PARTICLE ACCELERATION IN SUPERNOVA REMNANTS

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LECTURE II

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OUTLINE

- **Maximum energy in Diffusive Shock Acceleration (DSA)**

- **Self-generation of magnetic waves**
    - ***Resonant (streaming) instability***
    - ***Non-resonant (Bell) instability***

- **Non-linear Diffusive Shock Acceleration (NLDSA)**
    - ***Problems for the test-particle approach***
    - ***Back reaction of accelerated particles***

- **Application to SNR shocks**
    - ***Radiative processes***
    - ***The role of scattering centers***

MAXIMUM ENERGY

Is it possible to accelerate protons up to the *knee* ?

The maximum energy is obtained comparing the acceleration time with the age of the accelerator and the energy losses

$$\boxed{t_{acc} = min\left[t_{loss}, T_{age}\right]} \Rightarrow E_{max}$$

Energy losses are usually negligible for protons but are important for electrons

Acceleration time: $t_{\rm acc} = \dfrac{t_{\rm cycle}}{\Delta E/E}$

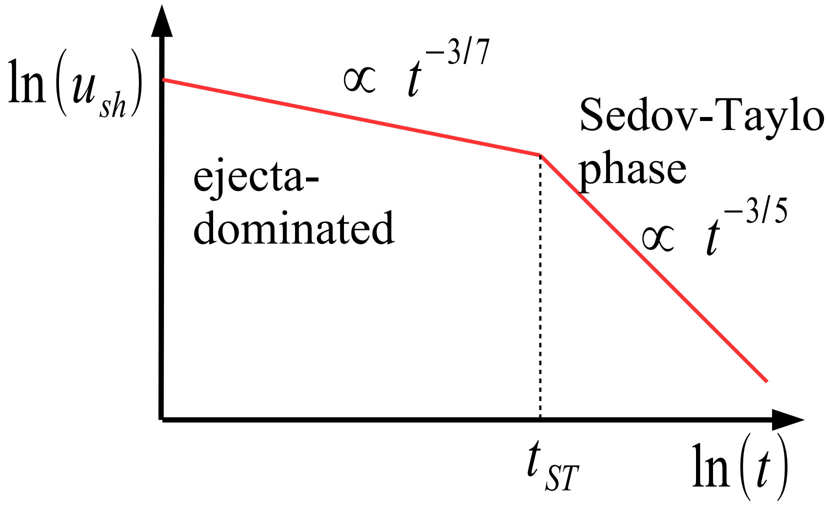
Time for one cicle upstream → downstream → upstream: $t_{cycle} = \tau_{diff,1} + \tau_{diff,2}$

Equating the particle injected from downstream with the particles upstream: $\dfrac{nc}{4}\Sigma\tau_{\rm diff,1} = n\Sigma\dfrac{D_1}{u_1} \Rightarrow \tau_{diff,1} = \dfrac{4D_1}{c\,u_1} \wedge \tau_{diff,2} = \dfrac{4D_2}{c\,u_2}$

$$\frac{\Delta E}{E} = \frac{4}{3}\frac{u_1 - u_2}{c} \Rightarrow \boxed{t_{\rm acc} = \frac{t_{\rm cycle}}{\Delta E/E} = \frac{3}{u_1 - u_2}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right) \approx 8\,\frac{D_1}{u_{\rm sh}^2}}$$

MAXIMUM ENERGY

Maximum energy can increase only during the ejecta dominated phase of the SNRs because $u_{sh} \sim const$



Shock radius:
$$\begin{cases} R_{sh}(t) \propto t^{5/7} & \text{Ejecta-dominated} \\ R_{sh}(t) \propto t^{2/5} & \text{Sedov-Taylor} \end{cases}$$

But particles diffuse ahead of the shock: $d \propto \sqrt{D\,t}$

→ **during the ST phase the highest energy particles cannot be catched by the shock and escape towards upsteam**

Estimate of the beginning of the Sedov-Taylor phase:

$$\begin{cases} t_{ST} = R_{ST}/u_{sh} \\ \frac{1}{2} M_{ej} u_{sh}^2 = E_{SN} \\ \frac{4\pi}{3} \rho_{ISM} R_{ST}^3 = M_{ej} \end{cases} \Longrightarrow t_{\rm ST} \approx 50 \left(\frac{M_{\rm ej}}{M_\odot}\right)^{\frac{5}{6}} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-\frac{1}{2}} \left(\frac{n_{\rm ISM}}{{\rm cm}^{-3}}\right)^{-\frac{1}{3}} {\rm yr},$$

MAXIMUM ENERGY

We use the diffusion coefficient from quasi-linear theory:

$$D = \frac{1}{3}\frac{r_L v}{F(k_{res})}; \qquad F(k) = \frac{\delta B_k^2}{B_0^2}$$

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

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

Emax is weakly dependent on
the ejecta mass and ISM density

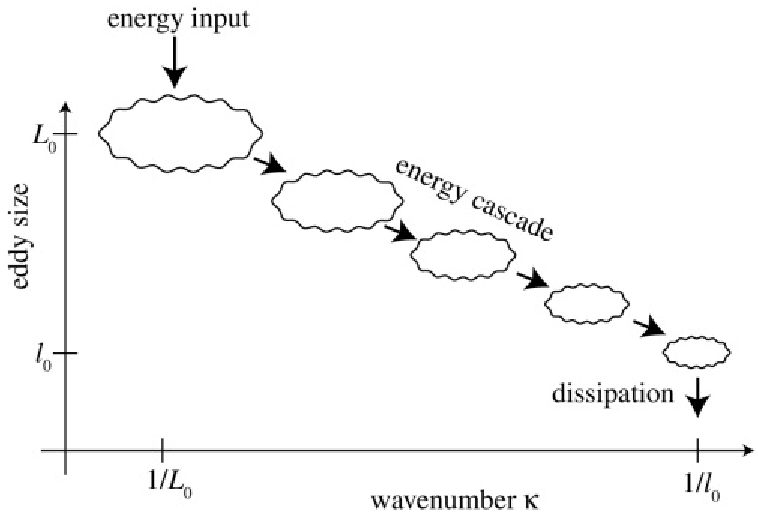
High energies, up to PeV, can be achieved only if $\mathcal{F}(k) >> 1$.
This condition requires amplification of the magnetic field

BUT WHAT PRODUCES THE TURBULENCE?

TURBULENCE IN THE GALAXY

The main origin of turbulence are thought to be SN explotion.

Turbulence is injected at a scale comparable with the size of SNR (or super-bubbles)and than cascades at smaller scales



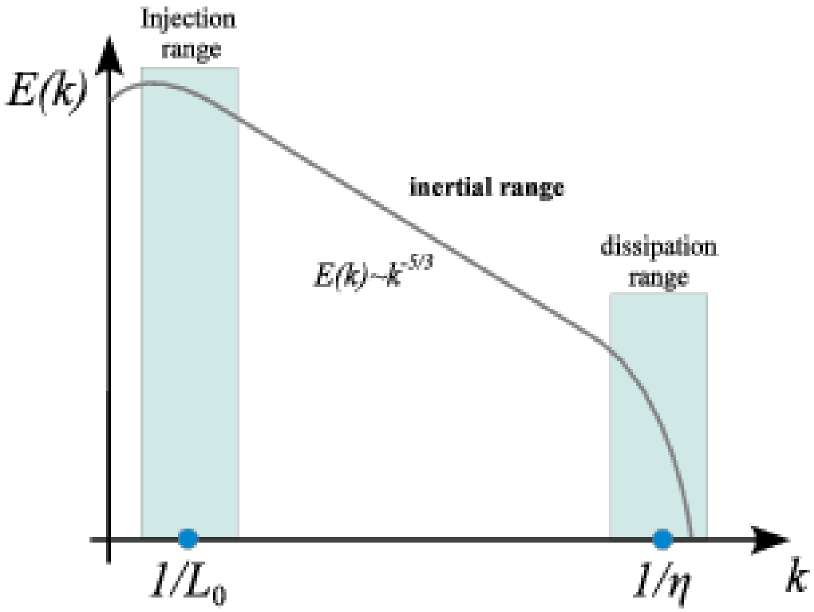
Power injected at: $k_{min} = 1/L_0 \approx 50\ pc$

Kolmogorov cascade: $P(k) = \frac{\delta B(k)^2}{B_0^2} \propto k^{-5/3}$

$$k_{res}(E_{max}) = \frac{1}{r_L(E_{max})} = 1\times\left(\frac{E}{10^{15}eV}\right)^{-1}\left(\frac{B_0}{1\mu G}\right)pc^{-1}$$

➡ $$\frac{P(k_{res})}{P(k_{min})} = \left(\frac{k_{res}}{k_{min}}\right)^{-5/3} \approx 10^{-3}\left(\frac{E}{10^{15}eV}\right)^{5/3}$$

➡ $$E_{max} < 10\,GeV$$

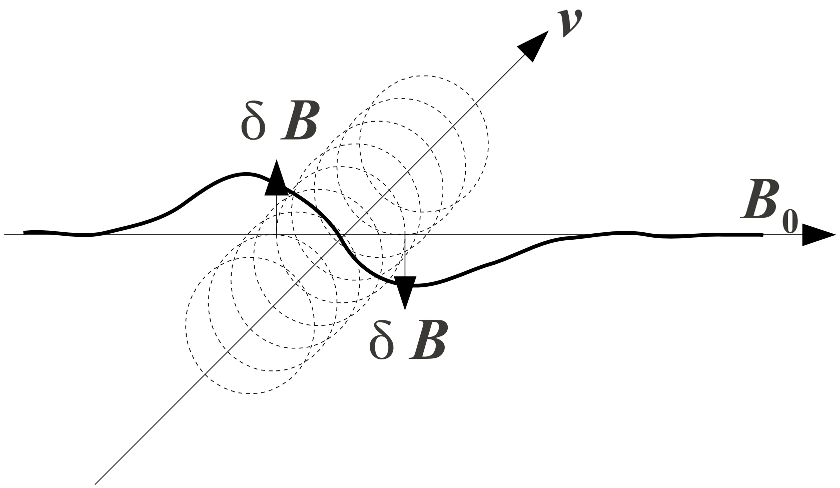


The Kolmogorow turbulence is not enough!

SELF-GENERATION OF WAVES

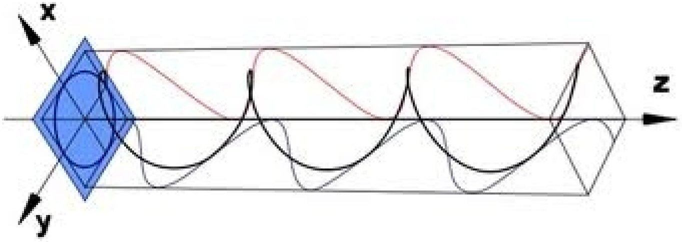
WHO GENERATES WAVES?

WAVES MAY BE GENERATED BY DIFFERENT SOURCES (e. g. SN EXPLOSION) BUT THERE IS A MORE INTERESTING AND PHYSICALLY IMPORTANT PHENOMENON: SELF GENERATION



Charged particles moving transverse to the magnetic field line produce a variable magnetic field $\delta \boldsymbol{B}$ which perturb $\boldsymbol{B}_0$ producing an Alfvén wave.
→ Alfvén wave in turn scatter particles

The effect of scatter is to isotropize CRs.



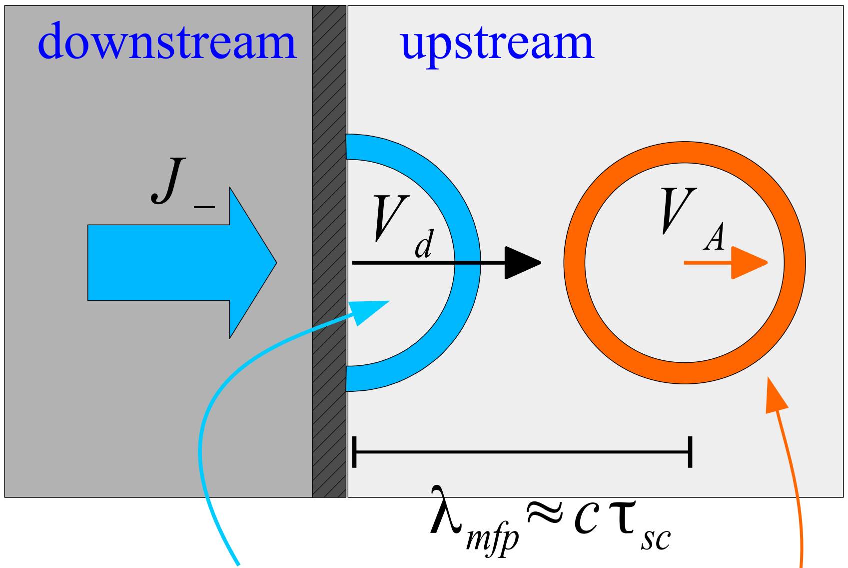
Generated Alfvén waves are circularly polarized

SELF GENERATION OF WAVES: RESONANT INSTABILITY

WAVES MAY BE GENERATED BY DIFFERENT SOURCES (e. g. SN EXPLOSION) BUT THERE IS A MORE INTERESTING AND PHYSICALLY IMPORTANT PHENOMENON:

SELF - GENERATION VIA RESONAT INSTABILITY

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



After the shock the distribution is anisotropic

The distribution becomes isotropic after one mean free path and moves at the same speed of the waves

Assume particles are drifting with $v_d > v_A$ and are isotropyzed on a time-scale τ_{sc}:

$$\tau_{sc} \approx \frac{1}{\nu_{sc}} = \frac{\pi}{4} F(k) \Omega$$

Initial momentum **final momentum**

$$n_{CR}\, m\, \gamma_{CR}\, v_d \longrightarrow n_{CR}\, m\, \gamma_{CR}\, v_A$$

The momentum lost by particles is:

$$\frac{dP_{CR}}{dt} = \frac{P_2 - P_1}{\tau_{sc}} = \frac{n_{CR}\, m\, \gamma_{CR} (v_d - v_A)}{\tau_{sc}}$$

SELF GENERATION OF WAVES: RESONANT INSTABILITY

The momentum lost is transferred to waves

$$\frac{dP_{CR}}{dt} = \frac{n_{CR}\, m\, \gamma_{CR} \left(v_d - v_A\right)}{\tau_{sc}}$$

Transport equation for waves:

$$v_A \frac{dP_W}{dt} = \Gamma_W \frac{\delta B^2}{8\pi}$$

Growth rate

Equating momentum lost by CR
and momentum gain by waves

$$\frac{dP_W}{dt} = \frac{dP_{CR}}{dt} \longrightarrow \Gamma_W = \frac{n_{CR}}{n_{gas}} \Omega_{cyc} \left(\frac{v_D - v_A}{v_A}\right)$$

For $n_{CR}=10^{-10}$ cm$^{-3,}$ $n_{gas}=10^{-1}$ cm^{-3} and $B_0=1\mu$G, and assuming $v_d=2\ v_A$, one finds:

$v_A = 7\ 10^5$ cm/s
$\Omega_{cyc} = 10^{-2}$ s^{-1}

$$\longrightarrow \Gamma_W = \frac{n_{CR}}{n_{gas}} \Omega_{cyc} \left(\frac{v_D - v_A}{v_A}\right) \approx 10^{-3}\ \ yr^{-1}$$

VERY RAPID GROWTH

HOW MUCH THE SELF-GENERATED TURBULENCE CAN GROW?

Turbulence can grow for at most one advection time

$$t_{adv} = D_1 / u_{sh}^2$$

Equating the grow time with the advection time we get the maximum level of turbulence at the shock:

$$t_{adv} = t_{grow} = 1/\Gamma_W$$

$$\Rightarrow \quad F_0(k) = \frac{\pi}{2} \frac{\xi_{CR}}{\ln\left(p_{max}/m_p c\right)} \frac{u_{sh}}{v_A} \approx 10$$

$$\left\{ \begin{array}{l} \xi_{CR} = P_{CR}/(\rho\, u_{sh}^2) \sim 0.1 \\ u_{sh} \sim 5000\, km/s \\ v_A \sim 10\, km/s \\ p_{max} \sim 10^5\, GeV \end{array} \right.$$

The condition *F*(*k*) >> 1 violates the quasi-linear theory used to derive the growth time.

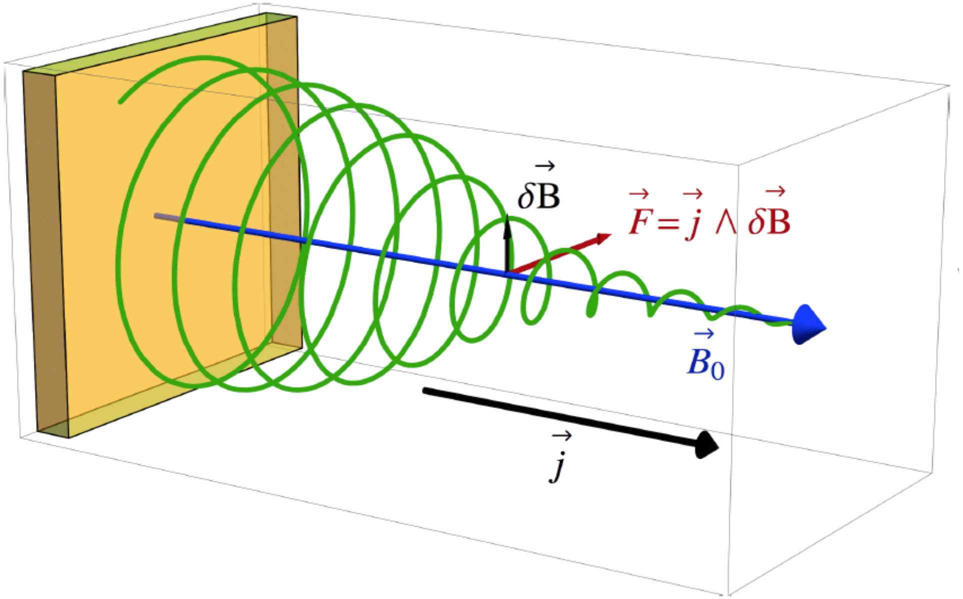
A more realistic estimate including the modification to the dispertion relation induced by CRs gives:

$$F_0(k) = \left(\frac{\pi}{6} \frac{\xi_{CR}}{\ln\left(p_{max}/m_p c\right)} \frac{c}{u_{sh}} \right)^{1/2} \leq 1$$

Self-amplification can produce $\delta B \sim B_0$

$$\Rightarrow \quad \boxed{E_{max} \approx 10^{13} - 10^{14}\, eV}$$

NON-RESONANT AMPLIFICATION



There are other possibilty to amplify the magnetic field.

The most invoked one is the non-resonant Bell instability **[Bell, A.R. (2004)]**

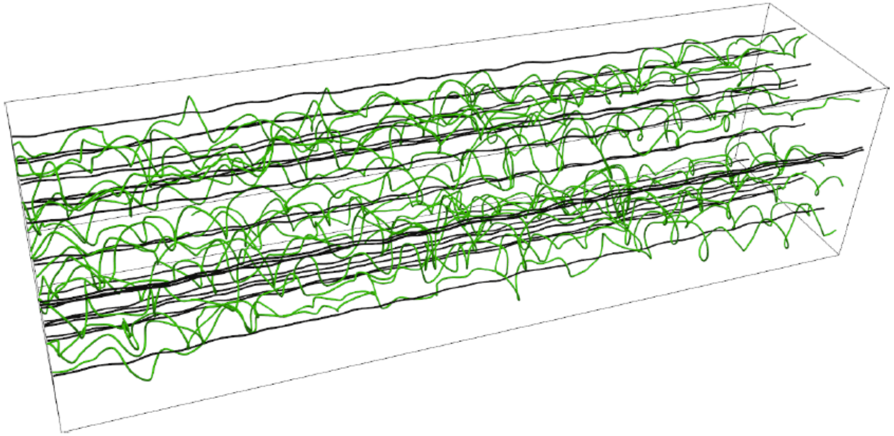
This instability is excited by the force

$$\vec{j}_{CR} \times \delta \vec{B}$$

where the current is due to escaping particles upstream.
It amplifies almost purely growing waves with wavenumbers much greater than the inverse particle gyroradius.

➔ **works for very high shock velocity (initial phase of SNR expansion)**

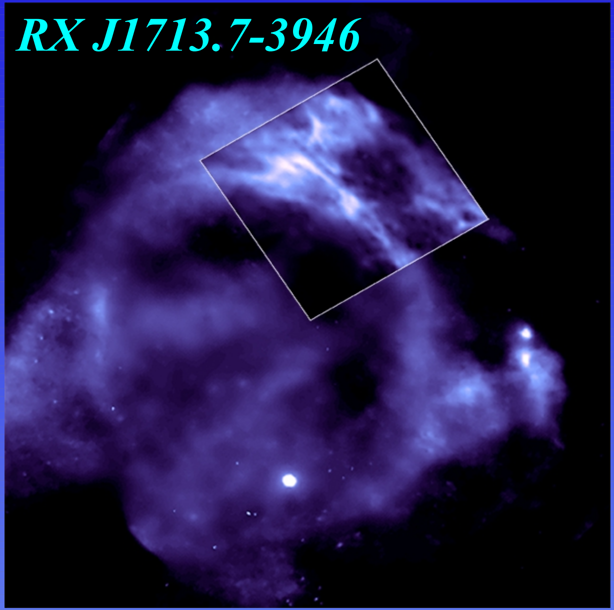
We can have $\frac{\delta B}{B_0} > 10$ if $\xi_{CR} = \frac{P_{CR}}{\rho u_{sh}^2} > 0.1$

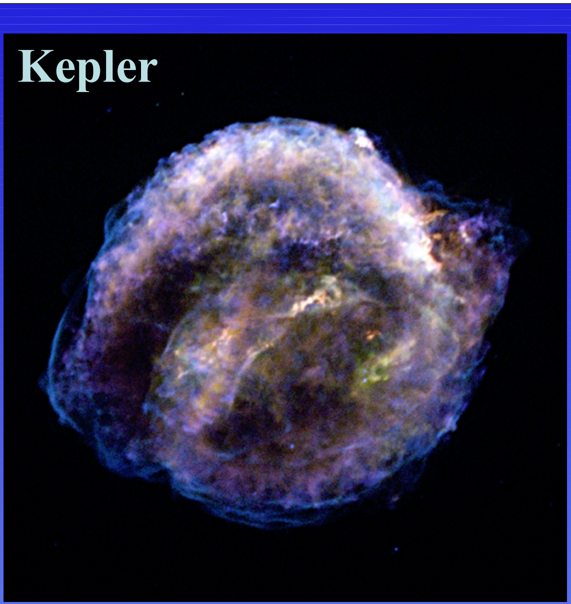


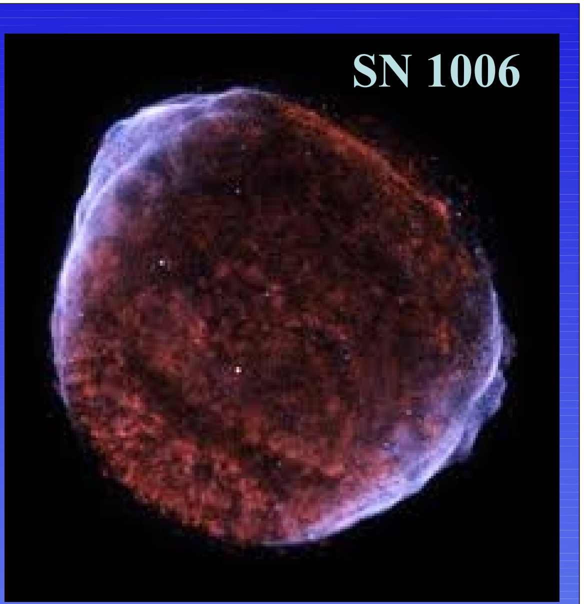
Simulation from Revill & Bell (2013)

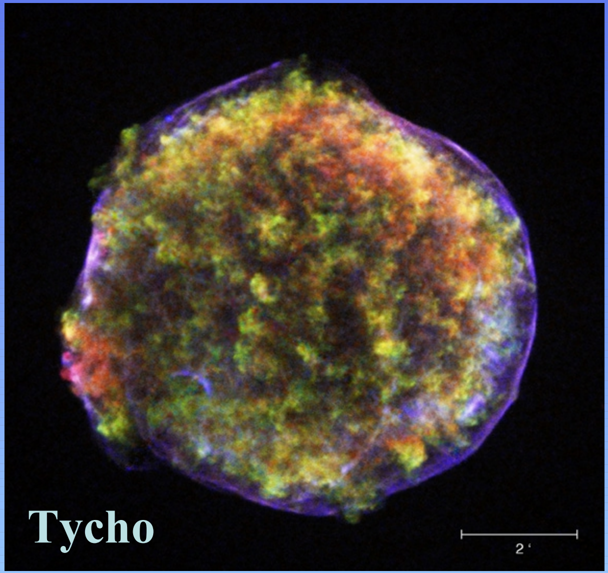
DO WE SEE MAGNETIC FIELD AMPLIFICATION?

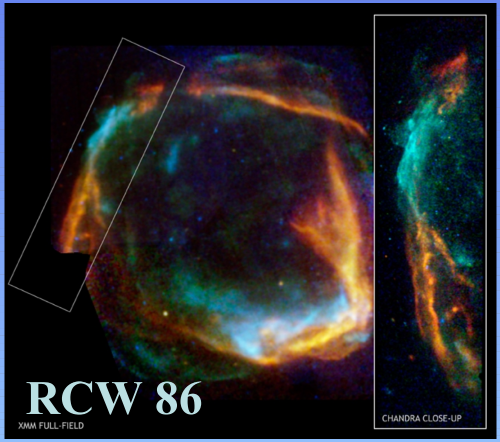
Galactic SNRs in X-rays

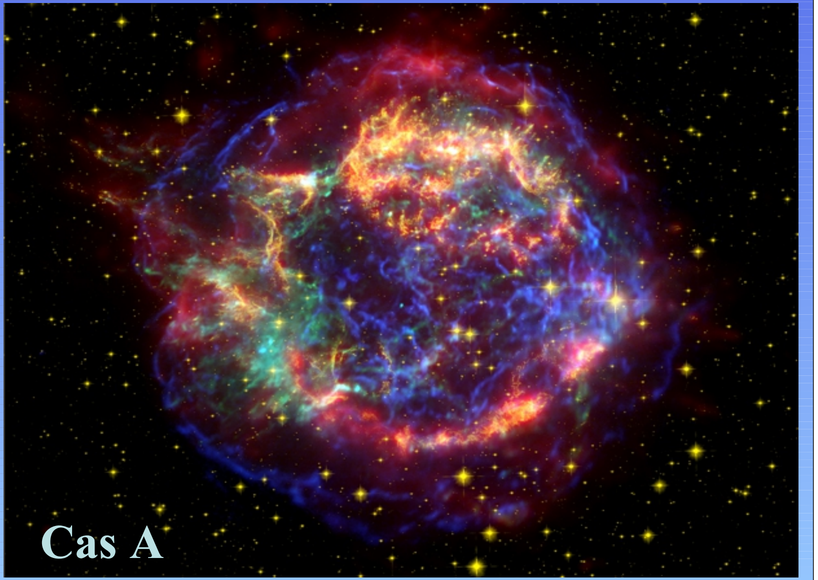

RX J1713.7-3946


Kepler


SN 1006


Tycho


RCW 86

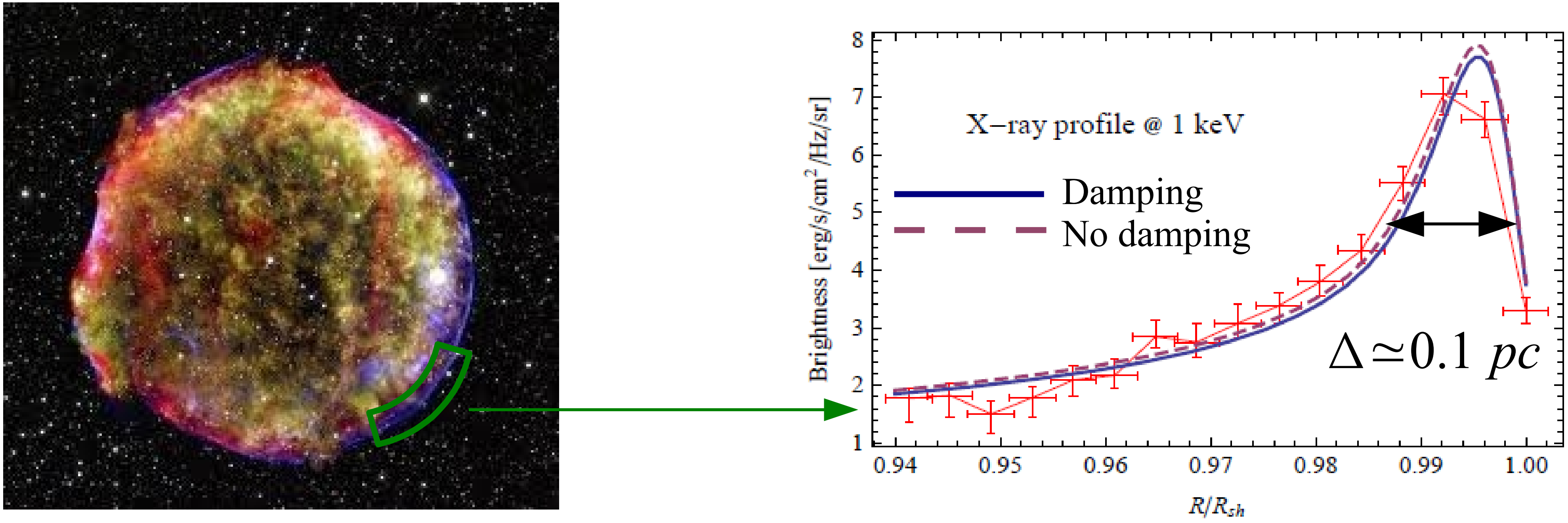

Cas A

Evidences for magnetic field amplification

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)]



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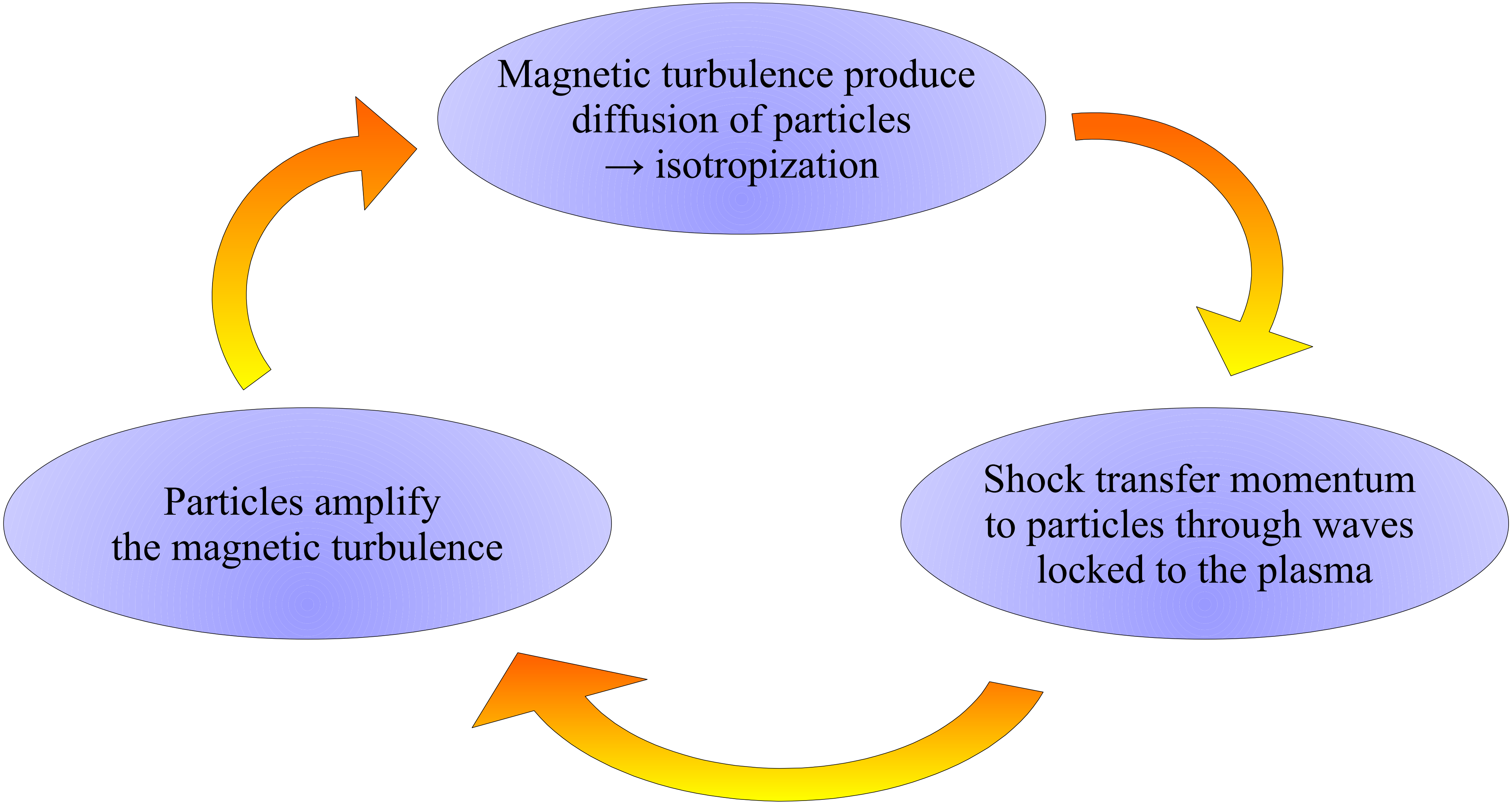
$$\Delta \simeq \sqrt{D \tau_{syn}} \propto B^{-3/2}$$

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

B~200-300 μG

THE ESSENCE OF NON-LINEARITY



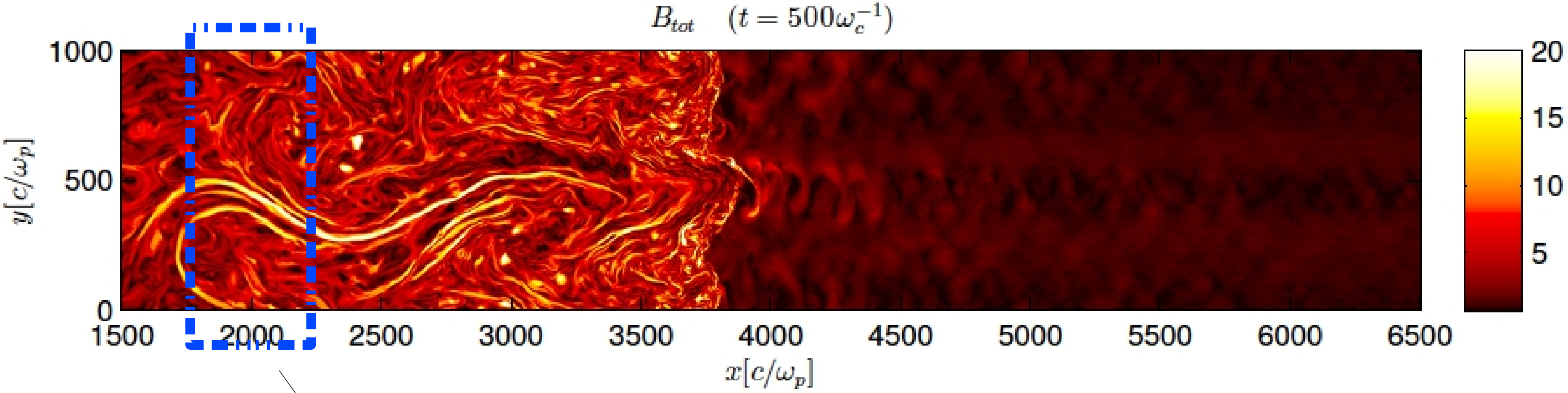
Magnetic turbulence produce
diffusion of particles
→ isotropization

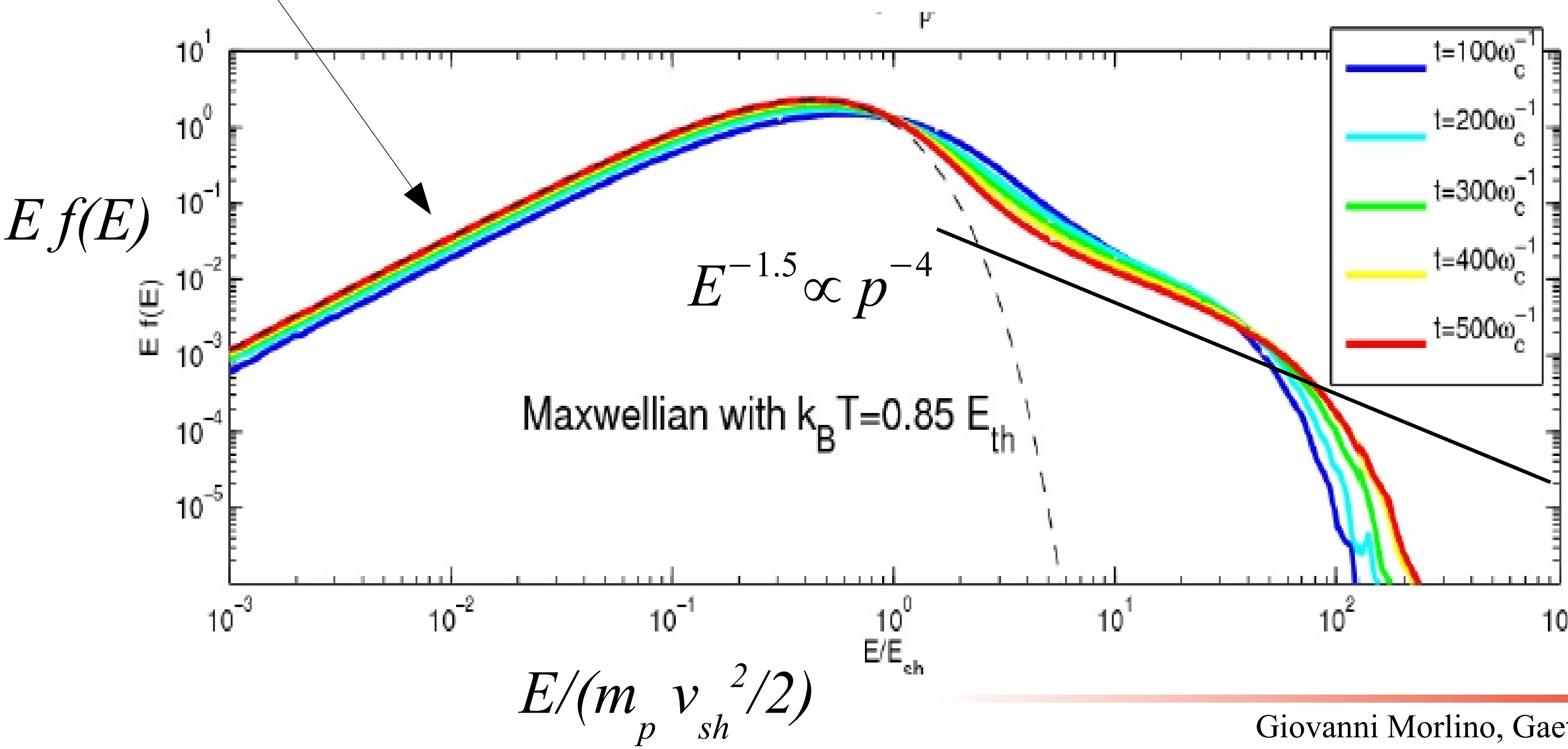
Shock transfer momentum
to particles through waves
locked to the plasma

Particles amplify
the magnetic turbulence

SIMULATIONS: results for the spectrum

D. Caprioli & A. Spitkovsky, 2013





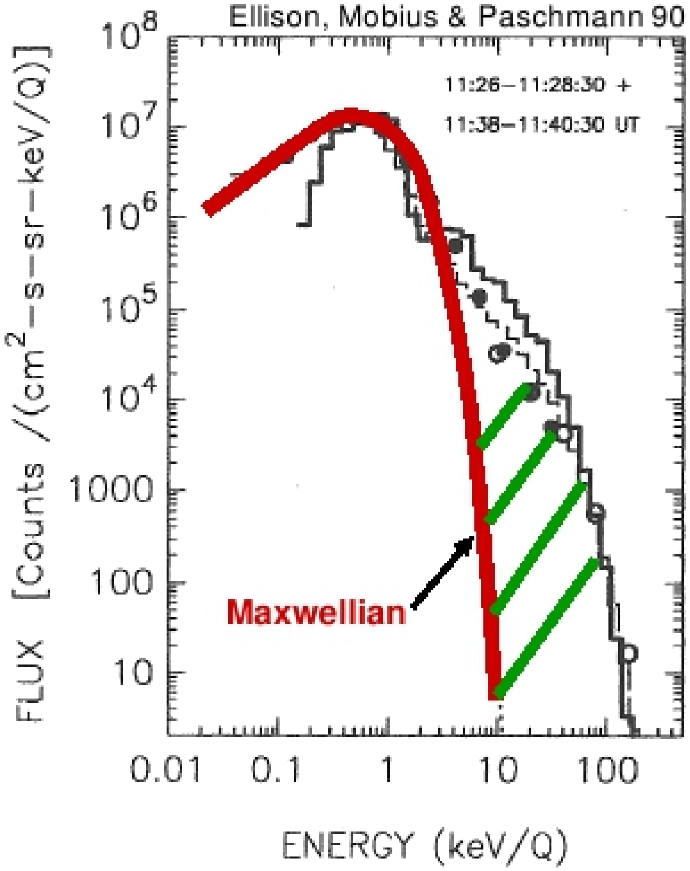
E f(E)

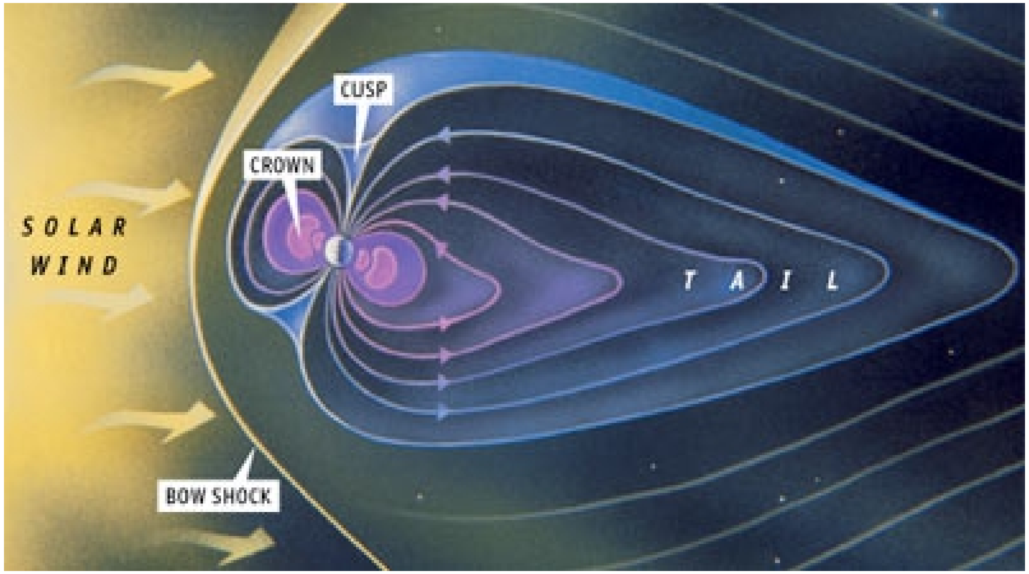
$E^{-1.5} \propto p^{-4}$

$E/(m_p\, v_{sh}^2/2)$

Evidence for efficient shock acceleration in Earth bow shock

Earth Bow Shock (direct evidence)





>25% of energy flux in superthermal ions

Problems with linear theory

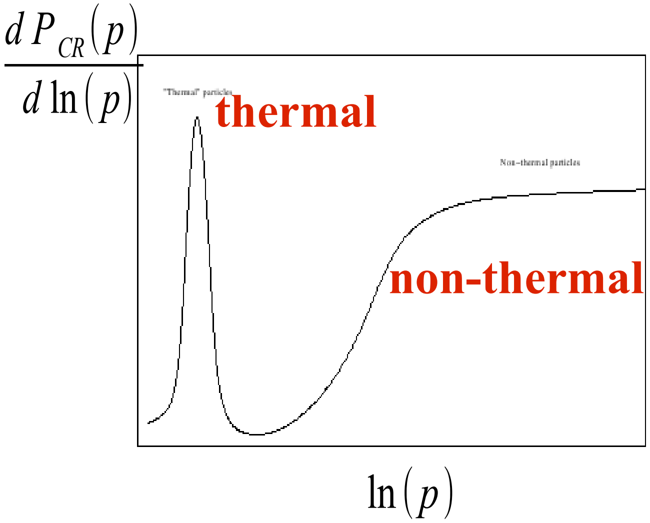
1 - Observation: CRs power

$$\begin{aligned} &W_{CR} \sim U_{CR}\, Vol_{CR}/\tau_{res} \approx 10^{40}\, erg/sec \\ &W_{SN} \sim R_{SN}\ \ E_{SN} \approx 3\,10^{41}\, erg/sec \ \ with\ \ R_{SN}=0.03 \end{aligned} \quad \Rightarrow \quad \frac{W_{CR}}{W_{SN}} \approx 0.03 \div 0.3$$

Lower Limit!! (Average value) Instantaneous power can be greater

2 – Theory: CRs pressure

$$P_{CR} \propto \int d\ln(p)\ v(p)\, p^4 f_{CR}(p) \quad \Rightarrow \quad \frac{P_{CR}}{P_{gas}} \approx 2.3\ \xi \left(\frac{\eta}{10^{-5}}\right) \ln\left(\frac{p_{max}}{10^5\, GeV/c}\right) \left(\frac{T}{10^5\, K}\right)^{-1/2}$$



3 – Theory: Maximum CR energy

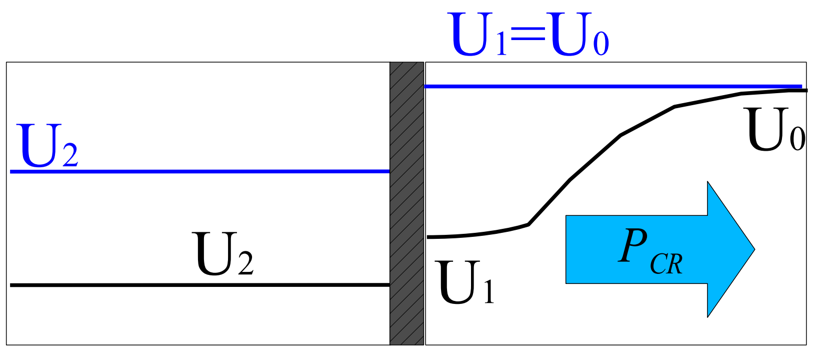
Linear theory (with self generated magnetic turbulence) predict for protons

$$\delta B < B_{Gal} \quad \Rightarrow \quad E_{max} \leq 10^4\, GeV$$

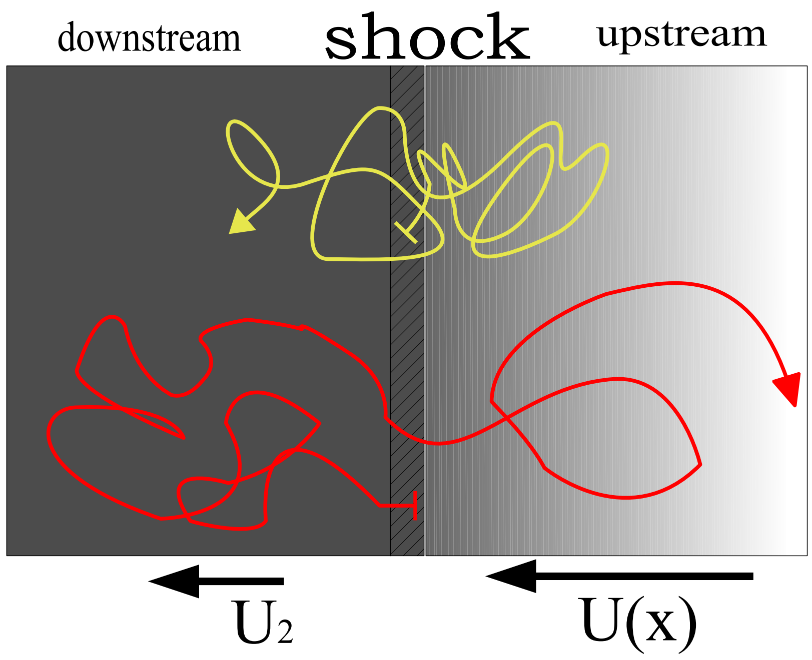
BUT

$$E_{knee} \simeq 3 \cdot 10^5\, GeV$$

Including the CR Back-Reaction



velocity profile u(x)



What happen when non-thermal particles exert non negligible pressure?

1 – CRs pressure compresses the gas upstream
➔ The subshock compression factor decreases

$$r_{sub} = \frac{U_1}{U_2} < 4$$

2 – CRs subtract energy from the downstream plasma which becomes more compressible
➔ The total compression factor increases

$$r_{tot} = \frac{U_0}{U_2} > 4$$

Particles feel a different compression factor depending on their momentum

$$r(p) = \frac{\bar{U}(p)}{U_2}$$

We expect a momentum dependent slope

$$n(E) = E^{-s(p)}$$

Basic equations

Transport equation for CRs

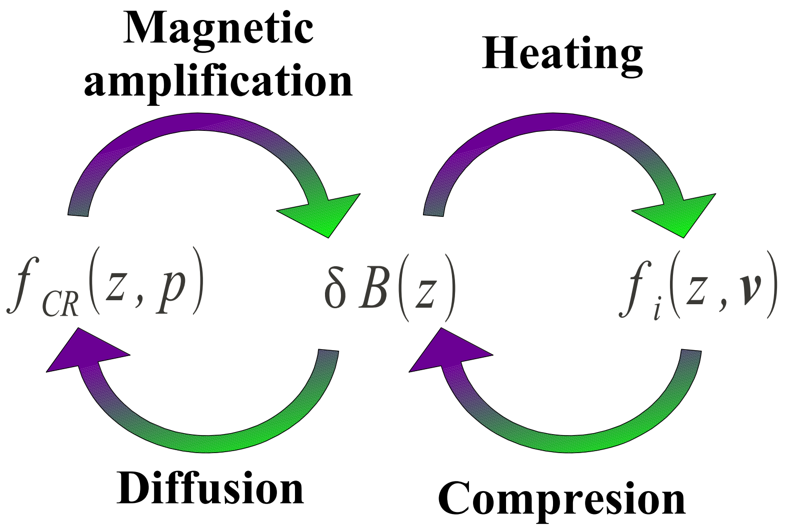
$$\frac{\partial}{\partial z}\left[D(z,p)\frac{\partial f_{CR}}{\partial z}\right]-u\frac{\partial f_{CR}}{\partial z}+\frac{1}{3}\frac{du}{dz}p\frac{\partial f_{CR}}{\partial p}=0$$

Fluid equations couple CRs + ions + waves

$$\frac{\partial}{\partial z}\left[\rho_i u_i\right]=0$$

$$\frac{\partial}{\partial z}\left[\rho_i u_i^2+P_i+P_{CR}+P_W\right]=0$$

$$\frac{\partial}{\partial z}\left[\frac{1}{2}\rho_i u_i^3+\frac{\gamma}{\gamma-1}P_i u_i+F_W\right]=-u\frac{\partial P_{CR}}{\partial z}+\Gamma_W$$



Magnetic amplification

Heating

$f_{CR}(z,p)$

$\delta B(z)$

$f_i(z,v)$

Diffusion

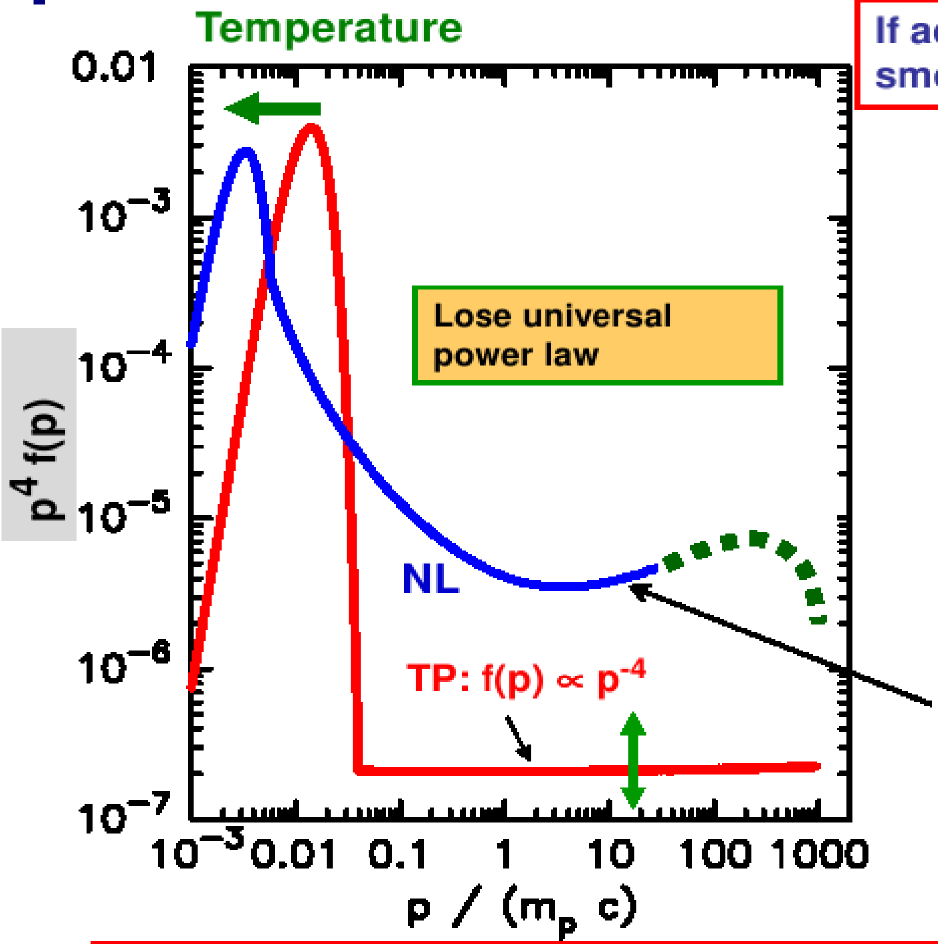
Compresion

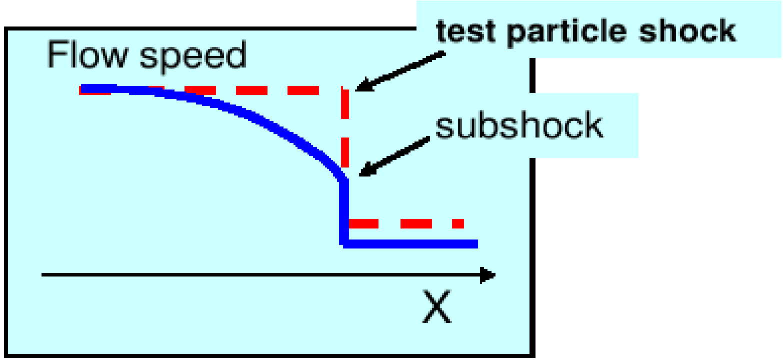
Transport equation for magnetic field

$$\frac{\partial F_w}{\partial z}=u\frac{\partial P_w}{\partial z}+P_w\left[\sigma_{CR}(k,z)-\Gamma(k,z)\right]$$

Including the CR Back-Reaction

If acceleration is **efficient**, shock becomes smooth from backpressure of CRs



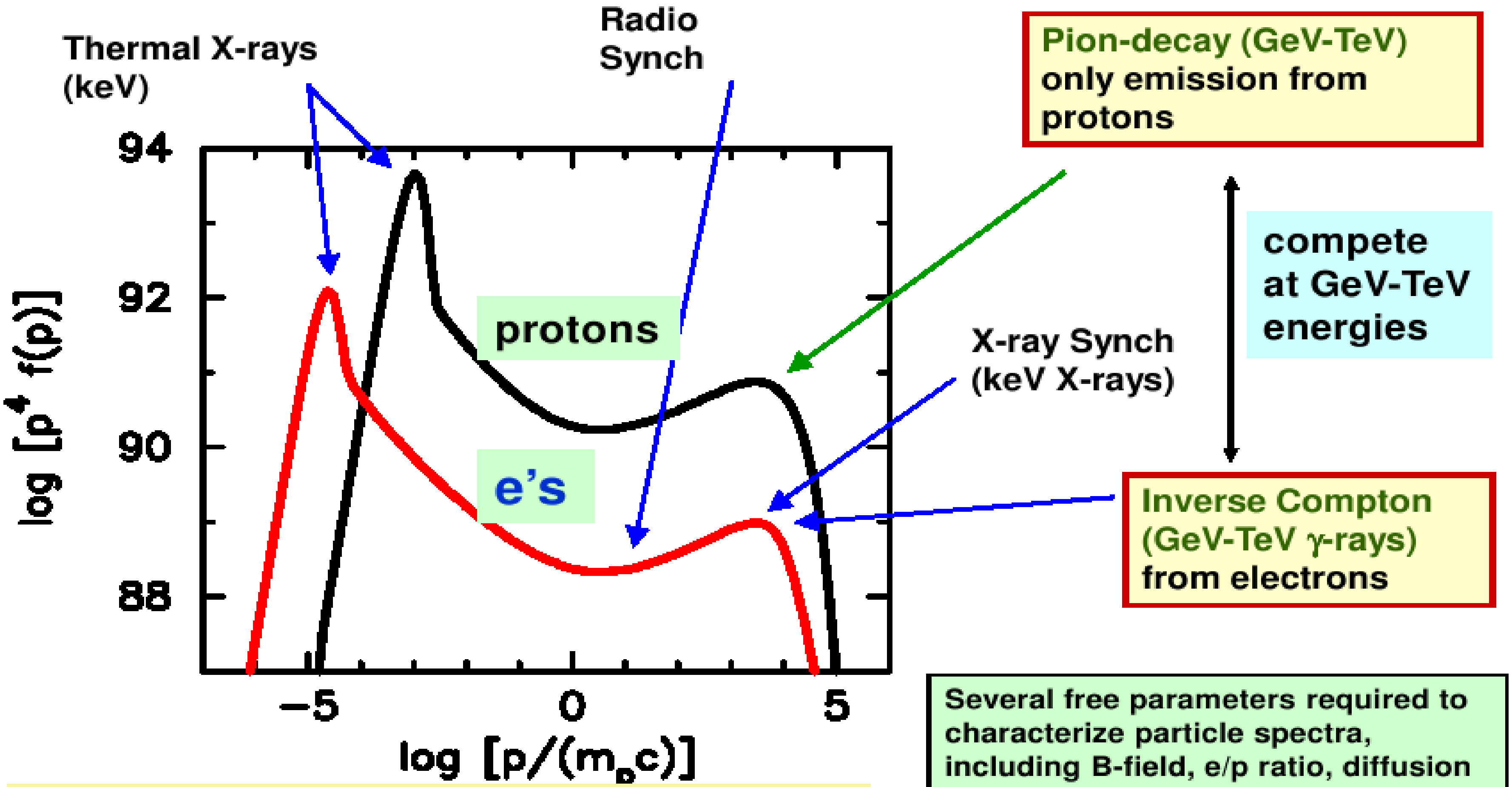


- **Concave spectrum**
- **Compression ratio, $r_{tot} > 4$**
- **Low shocked temp. $r_{sub} < 4$**

In efficient acceleration, entire spectrum must be described consistently, including escaping particles
➔ much harder mathematically
BUT, connects photon emission across spectrum from radio to γ-rays

EM radiation from accelerated particles

Electron and Proton distributions from efficient (nonlinear) diffusive shock acceleration



Thermal X-rays (keV)

Radio Synch

Pion-decay (GeV-TeV) only emission from protons

compete at GeV-TeV energies

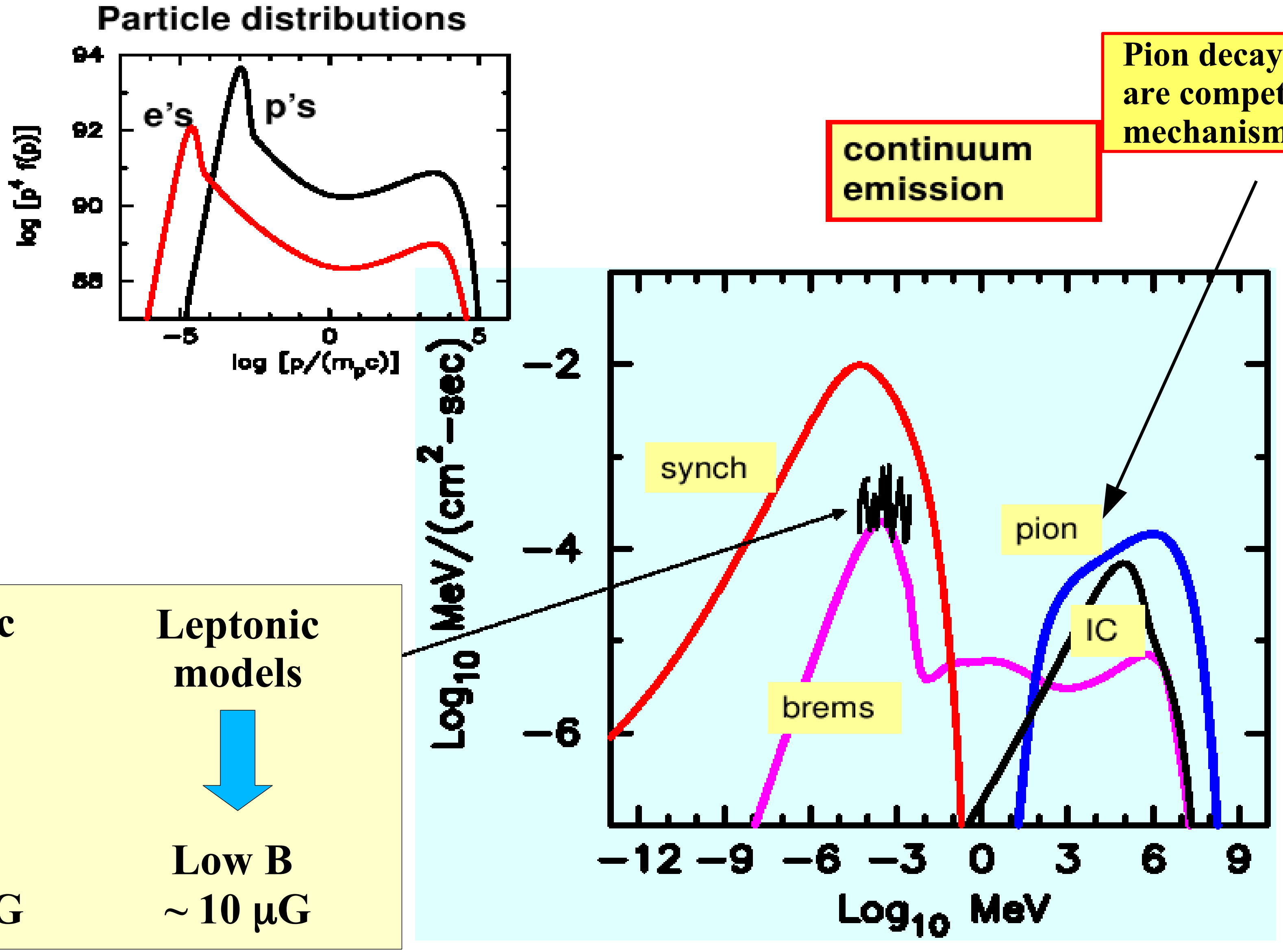
X-ray Synch (keV X-rays)

Inverse Compton (GeV-TeV γ-rays) from electrons

Spectra calculated with semi-analytic model of Blasi, Gabici & Vannoni 2005

Several free parameters required to characterize particle spectra, including B-field, e/p ratio, diffusion coefficient

EM radiation from accelerated particles



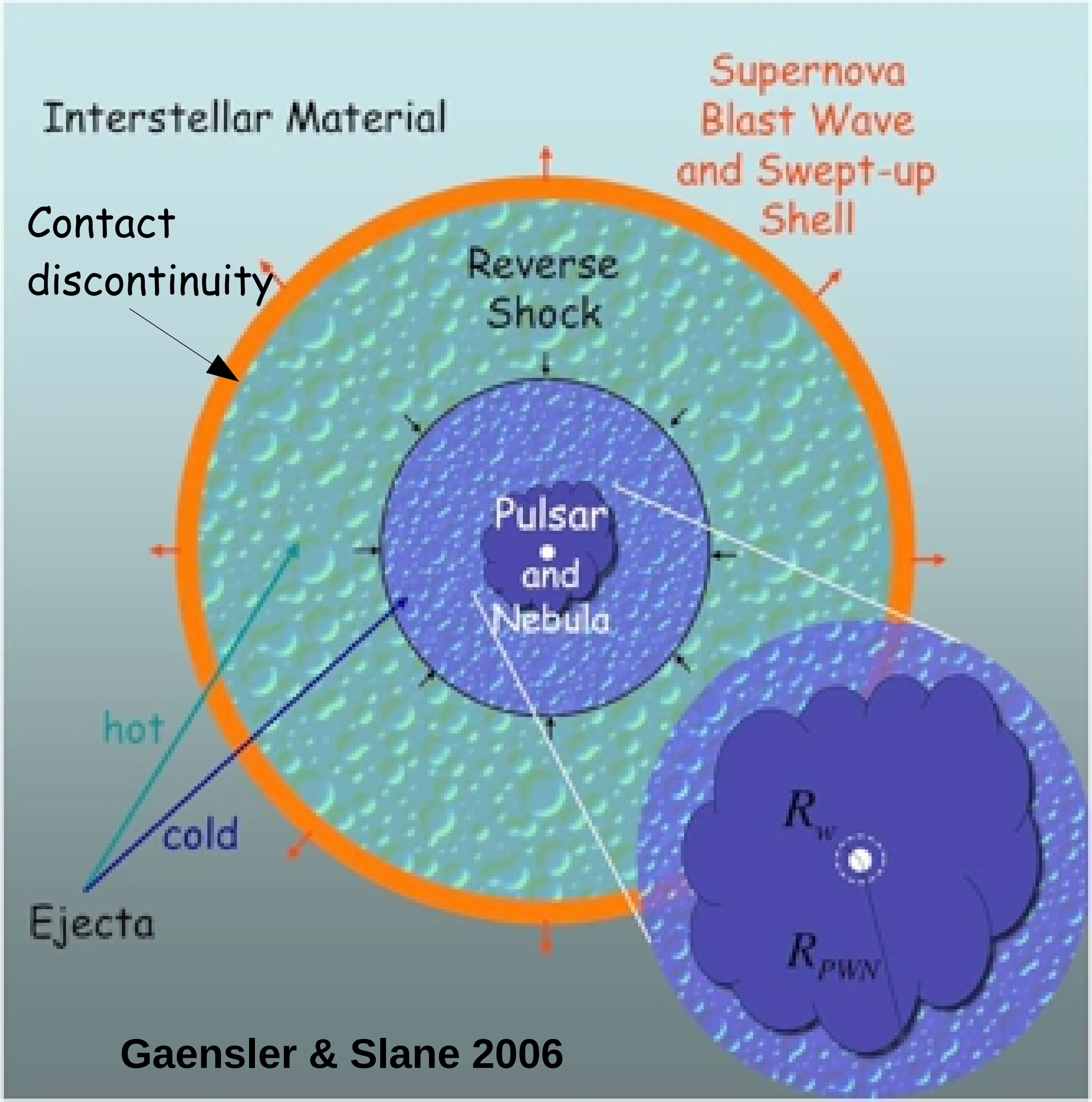
continuum emission

Pion decay and IC are competitive mechanisms

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

APPLICATION TO ISOLATED SNRs

SNR structure



Gaensler & Slane 2006

SNR structure

- ISM
- Forward shock
- Shocked ISM
- Contact discontinuity
- Shocked ejecta
- Reverse shock
- Unshocked ejecta

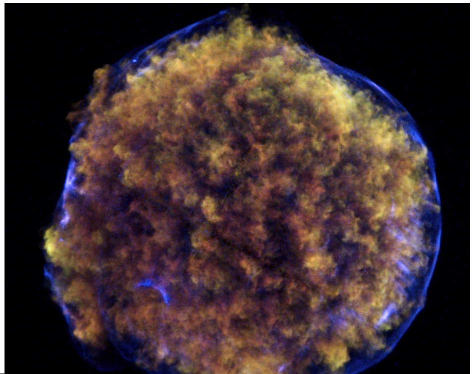
For core-collapse SNR

- PWN
- Termination shock
- Pulsar wind
- Pulsar

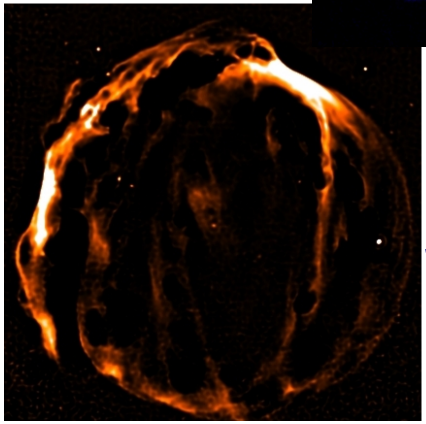
WHERE NON-THERMAL PARTICLE ARE PRODUCED?

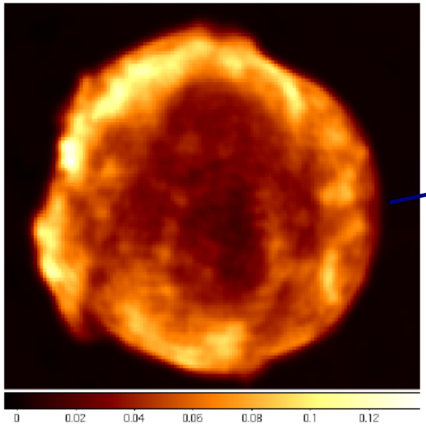
Tycho's SNR (Type Ia SNR)

X-rays (Chandra)



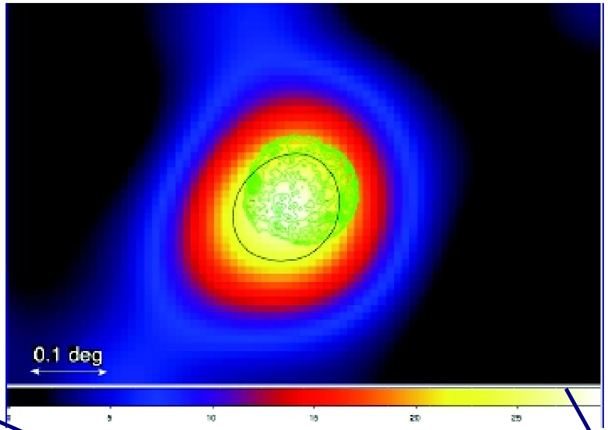
Spitzer image at 24 μm



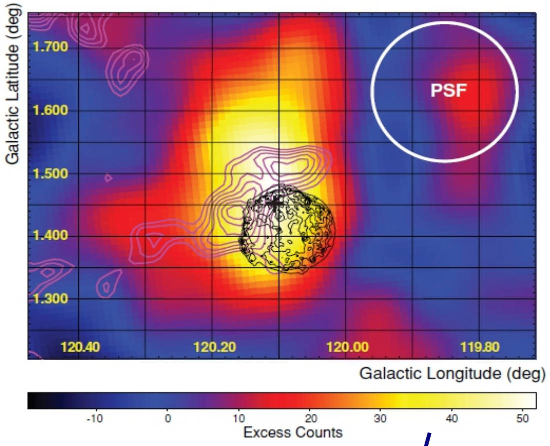


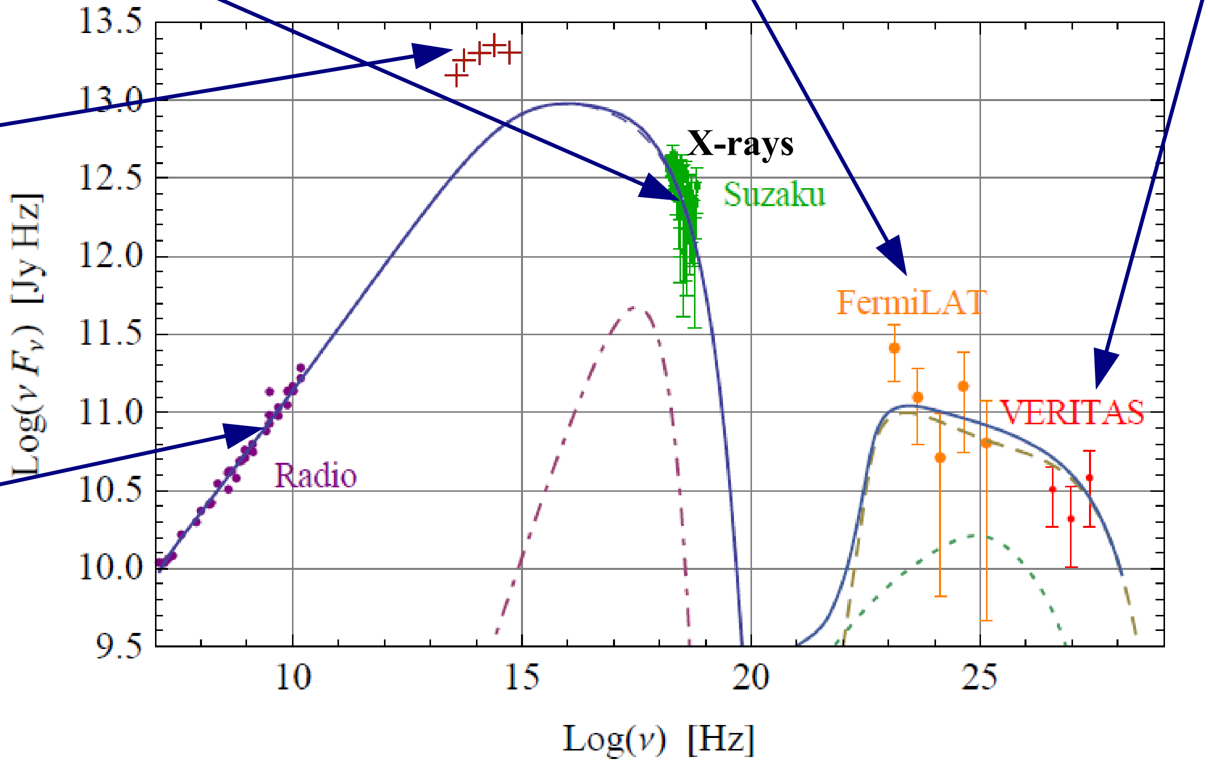
Radio map at 1.5 GHz

1-100 GeV from FermiLAT [Giordano et al. 2011]



VERITAS map $E > 1$ TeV [Acciari et al. 2011]





Look for PeVatrons in known SNRs

Summary of shell SNRs emitting TeV gamma rays

NAME	Age [yr]	Distance [kpc]	Flux(>1TeV) [10^{-12} cm^{-2} s^{-1}]	Γ_{TeV} Spectral index	Evidence of cutoff	$E_{\gamma,max}$ [TeV]
Cas A North. em.	330	3.4	0.77±0.11	2.61±0.24	(?)	5
Tycho	440	3.3	0.19±0.05	1.95±0.6 $\Gamma_{GeV-TeV}$=2.2	(?)	10
SN 1006 (NE)	1000	2.2	0.23±0.05	2.36±0.2	(?)	20
SN 1006 (SW)	"	"	0.15±0.05	2.43±0.2	(?)	6
RX J1713.7-3946	~1600	1	15.9±0.6	2.32±0.01	YES @10TeV	80
RX J0852 (Vela Jr.)	420-1400 (best ~700)	200 pc - 1 kpc	15.2±3.2	2.24±0.15	YES	10
RCW 86	1600	~2.5	2.34	2.54	(?)	20
G353.6-0.7	~14000(?)	3.2(?)	6.91±0.75	2.32±0.06	NO	30

Maximum detected energy in γ-rays.
In case of hadronic model $E_{p,max} \sim 10E_{\gamma,max}$

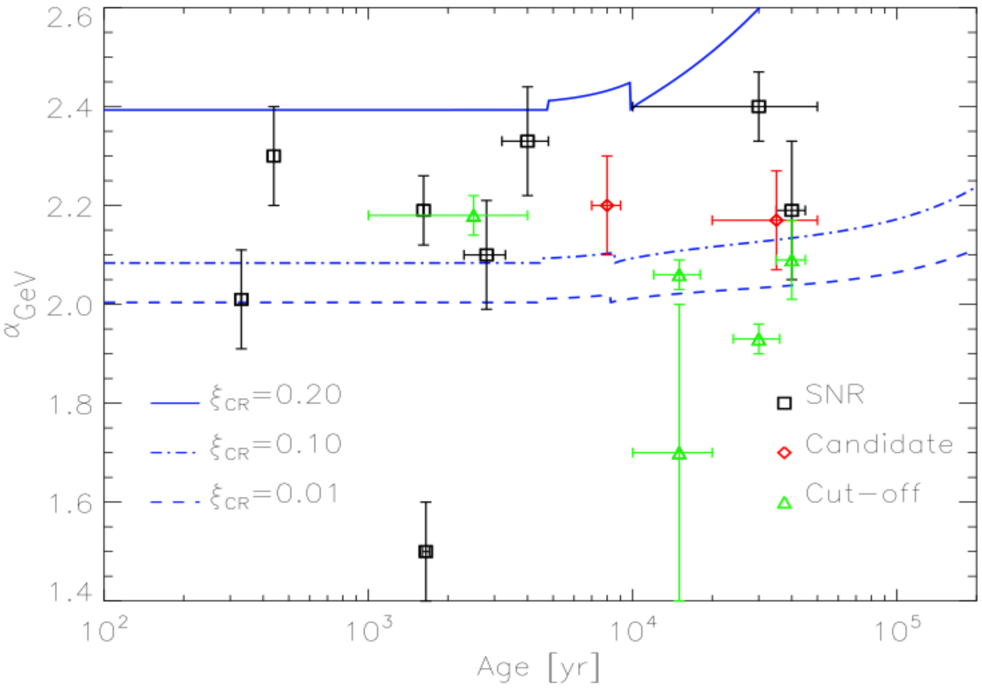
Slope of gamma-ray emission of SNRs

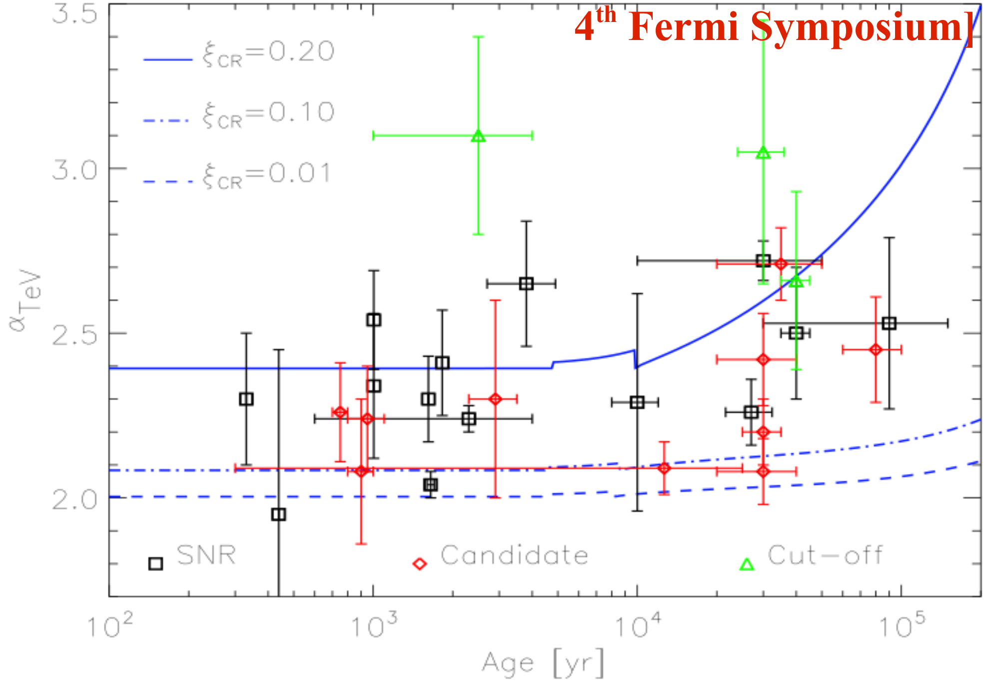
In many observed SNRs the slope is steeper than E^{-2}
** difficult to explain theoretically**

If the γ-ray spectrum is hadronic ($\pi^0 \rightarrow \gamma\gamma$) the slope is the same as the proton spectrum

If the γ-ray spectrum is leptonic (IC) the spectrum is harder

$$f_e(E) \propto E^{-s} \rightarrow \phi_\gamma \propto E^{-(s-1)/2}$$

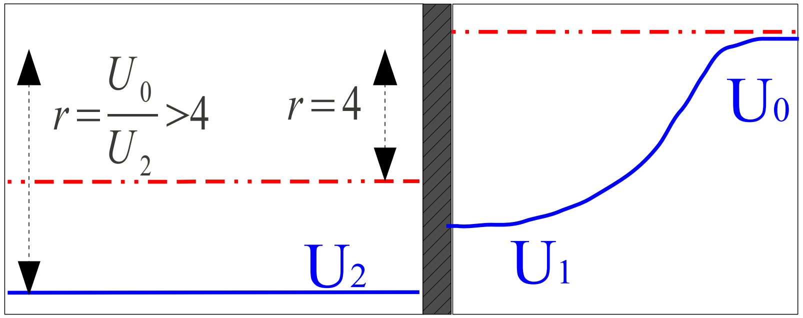




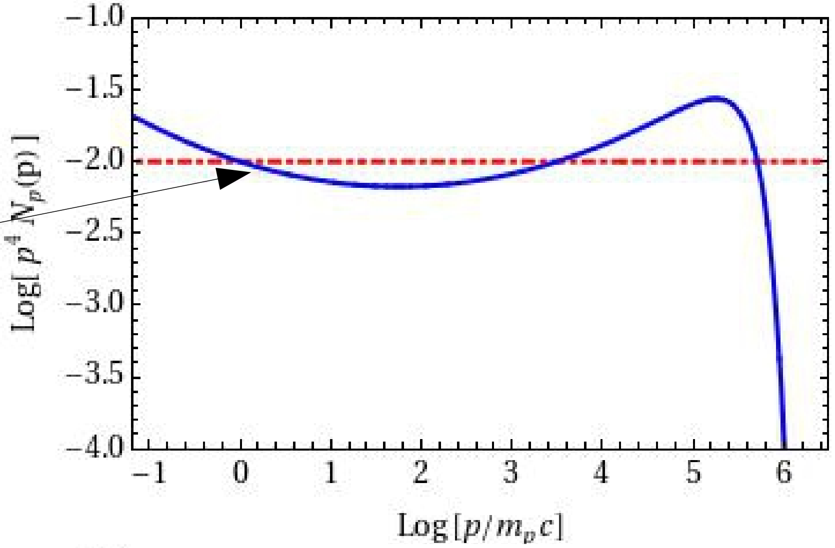
[plot from D. Caprioli (2012) 4th Fermi Symposium]

The role of scattering centers in presence of strong magnetic amplification

In the standard NLDSA the CR pressure modifies the shock structure in such a way to produce concave particle spectra with spectral slope < 2 at higher energies



Shock modified by CRs

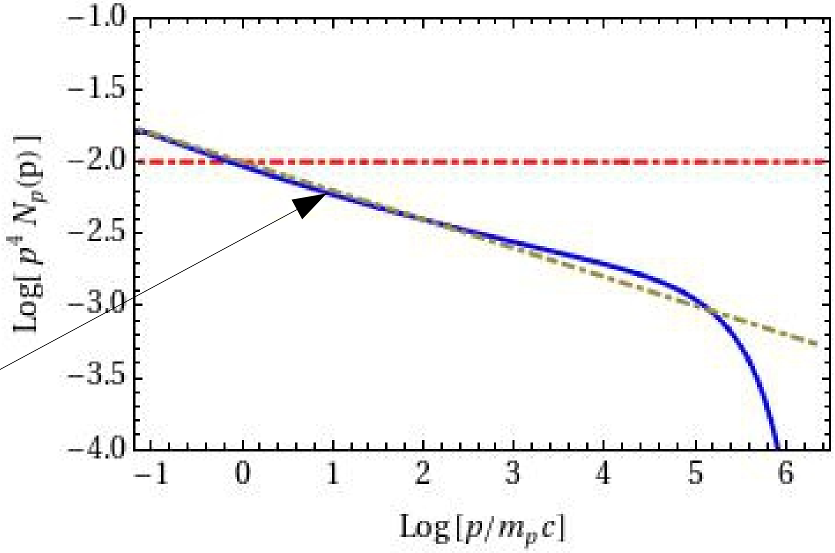


When the magnetic field is strongly amplified the Alfvén speed upstream can become a non negligible fraction of the shock speed. In this case the effective compression ratio is:

$$\boxed{r = \frac{u_1 - v_{A,1}}{u_2 \pm v_{A,2}} \simeq \frac{u_1 - v_{A,1}}{u_2}}$$

Downstream $v_{A,2} \approx 0$ because of helicity mixing.
In the case of Tycho:

$$v_{A,1} = \frac{B_1}{\sqrt{4\pi\rho_1}} \approx 0.15\,V_{sh} \rightarrow s = \frac{r+2}{r-1} \simeq 4.2$$ (2.2 in energy)



Modelling the multi-wavelength spectrum of Tycho

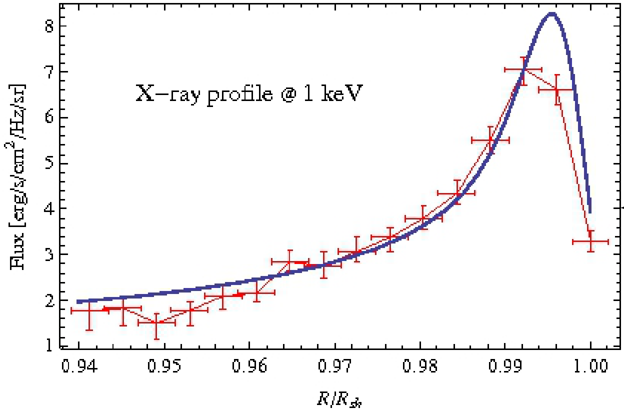
[G.M. & D. Caprioli, 2012]

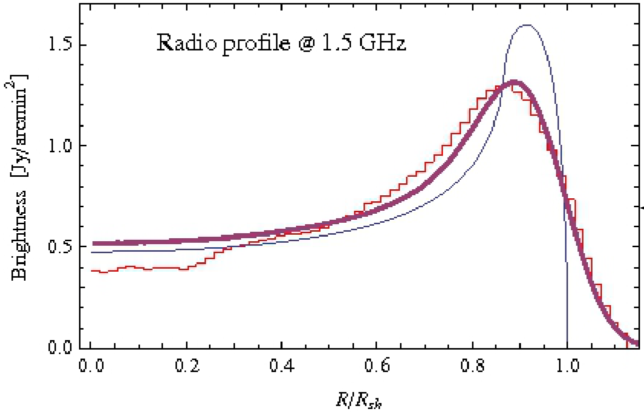
Simultaneous fit of multi-wavelength spectrum with non-linear DSA model

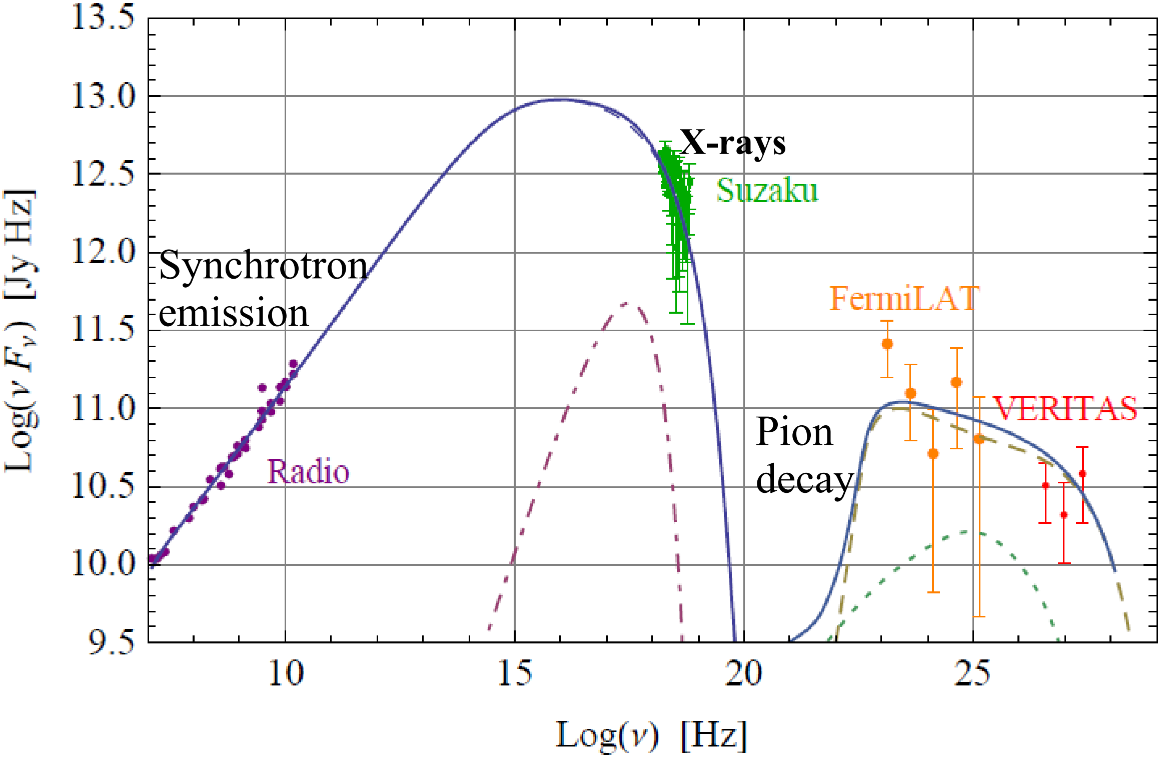
1) **Maximum energy of ions** $E_{max} = 470\,TeV$
2) **Non-thermal spectrum** $N(E) \propto E^{-2.3}$
3) **Amplified magnetic field** $\delta B_2 \approx 300\,\mu G$

4) TOTAL CRs ENERGY $\epsilon_{CR} = 12\%\ E_{SN}$

Results for the Tycho's remnant





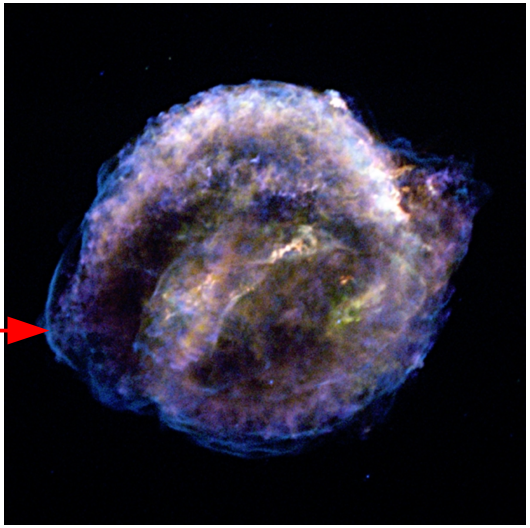


Application to the Kepler's SNR

[D. Caprioli & G.M., preliminary results]

The Kepler's Remnant shows remarkable similarities with Tycho:

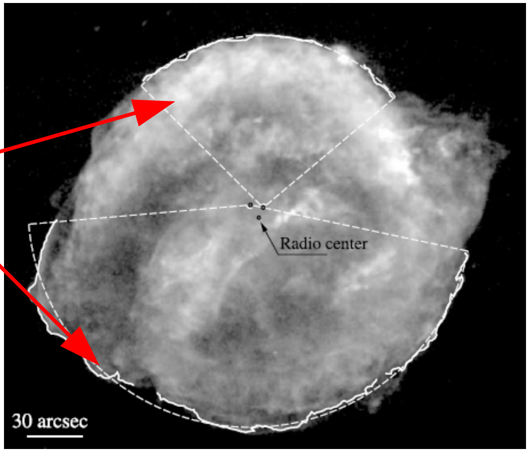
→ both originate from Type Ia SN
→ similar age (408 vs 440 yrs)
→ similar radio spectral index (0.64 vs 0.65)
→ presence of non-thermal X-ray emission in thin filaments



But also differences:

→ Kepler is not detected in gamma rays (larger distance?)
→ Several north-south asymmetry has been detected
  - Radio and X-ray emission more pronounced in the North
  - different shock speed
  - different expansion rate

Due to expansion in a non-uniform CSM
(probably progenitor's wind?)



Chandra X-ray map.
From Katsuda et al (2008)

We apply a model similar to the one used for Tycho:
results must be taken with care because <u>we use uniform CSM density</u>

Multi-wavelength spectrum of Kepler

[D. Caprioli & G.M., preliminary results]

Assumed

$$E_{SN} = 10^{51}\,erg$$
$$M_{eje} = 1\,M_{sol}$$
$$T_{SNR} = 400\,yr$$
$$f(v) \propto (v/v_{eje})^{-7}$$

Fitted

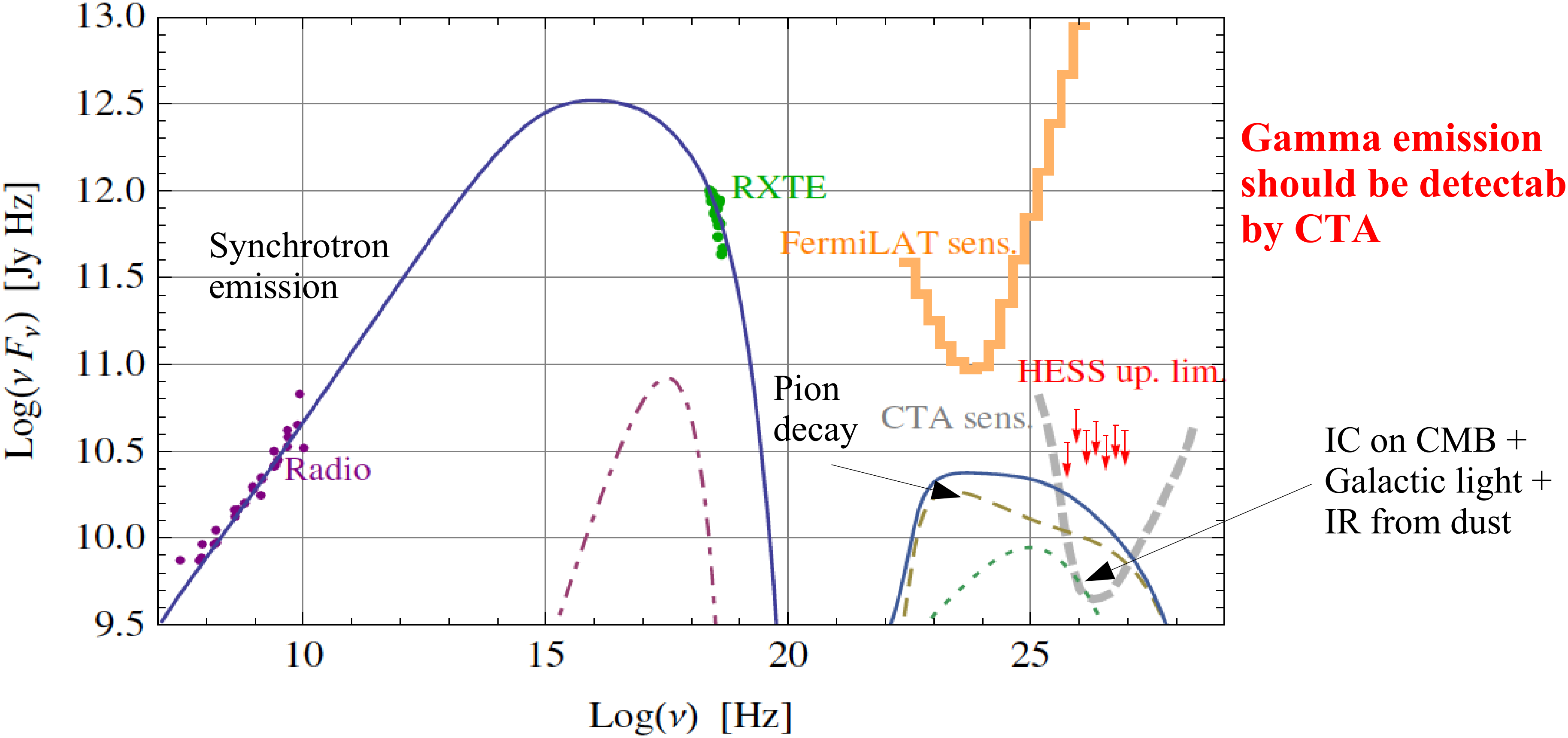
$$n_0 = 0.3\,p/cm^3$$
$$\xi_{inj} = 3.7$$
$$\chi_{esc} = 0.1\,R_{sh}$$
$$K_{ep} = 2.8\times10^{-3}$$

Inferred

$$d = 7.1\,pc$$
$$V_{sh} = 5200\,km/s$$
$$R_{sh} = 3.7\,pc$$

CR efficiency

$$\epsilon_{\pm\hat{}} \simeq 12\%$$

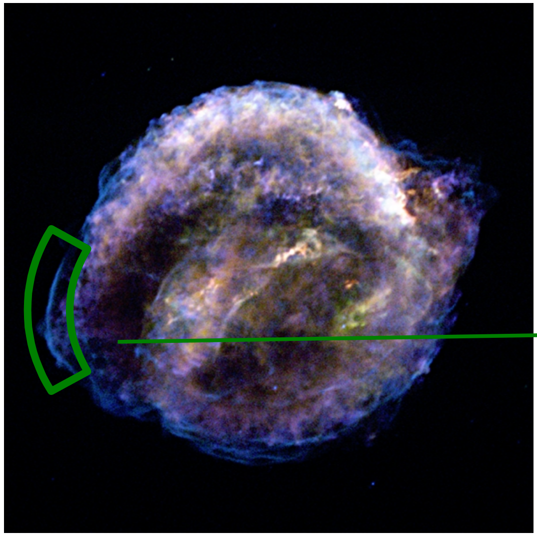


Gamma emission should be detectable by CTA

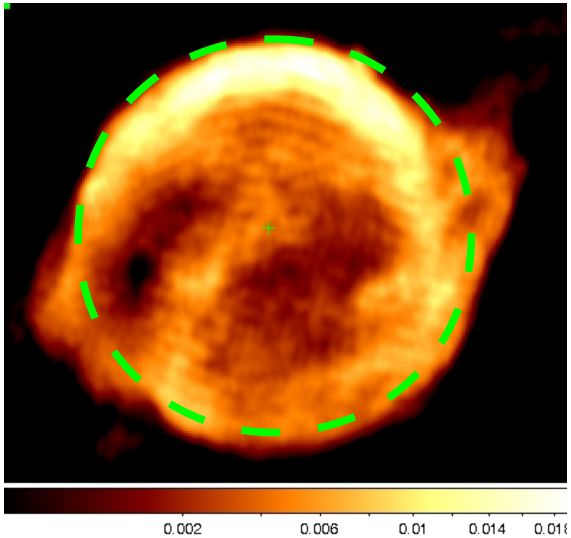
Radial profile of X and radio emission for Kepler

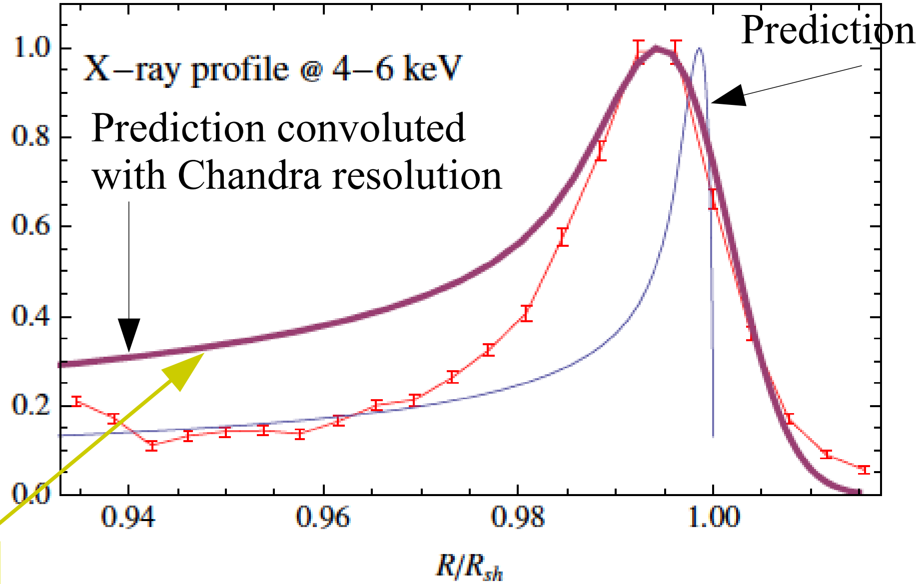
[D. Caprioli & G.M., preliminary results]

Chandra X-ray map.
Data for the green sector are from Vink (2008)

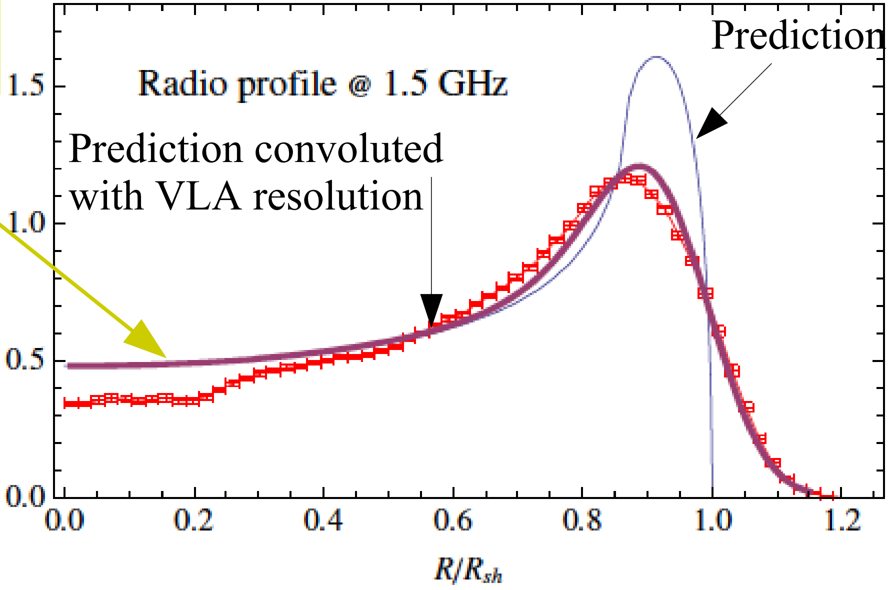


Radio map at 5 GHz from
NRAO/VLA archive Survey



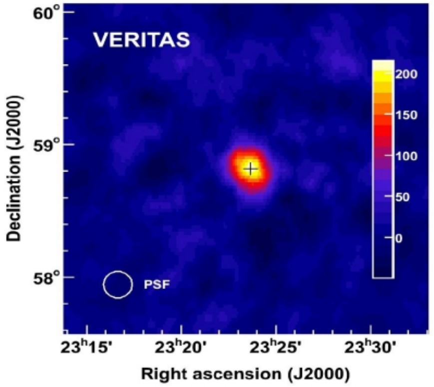


These excesses could be due to deviation from spherical symmetry

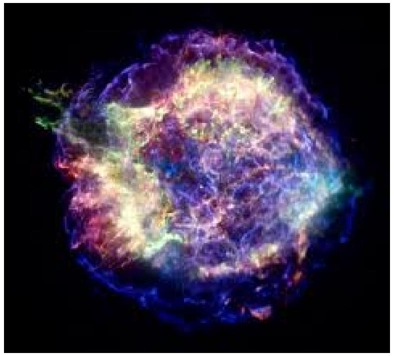


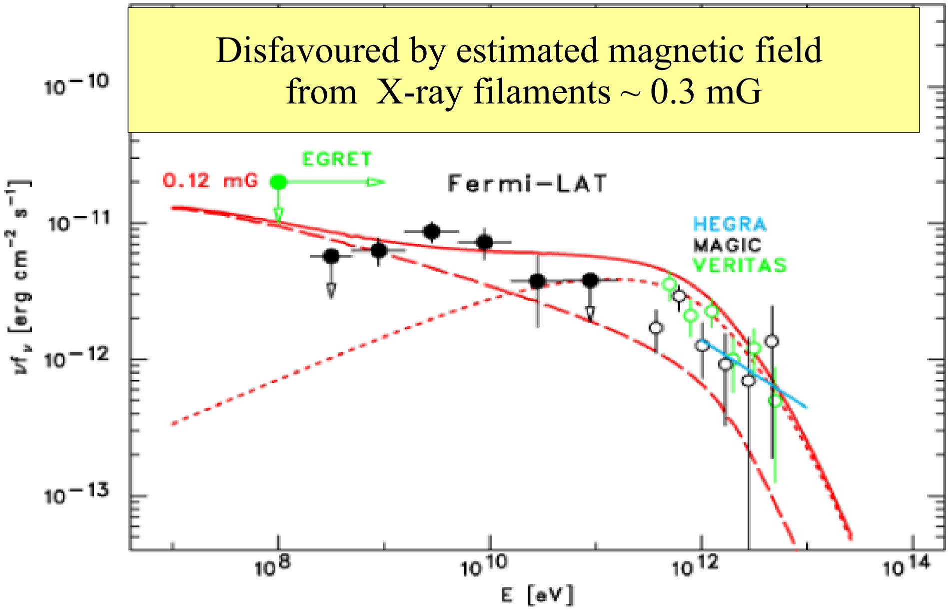
SNR Cassiopea A

Cas A in TeV
(*VERITAS*)

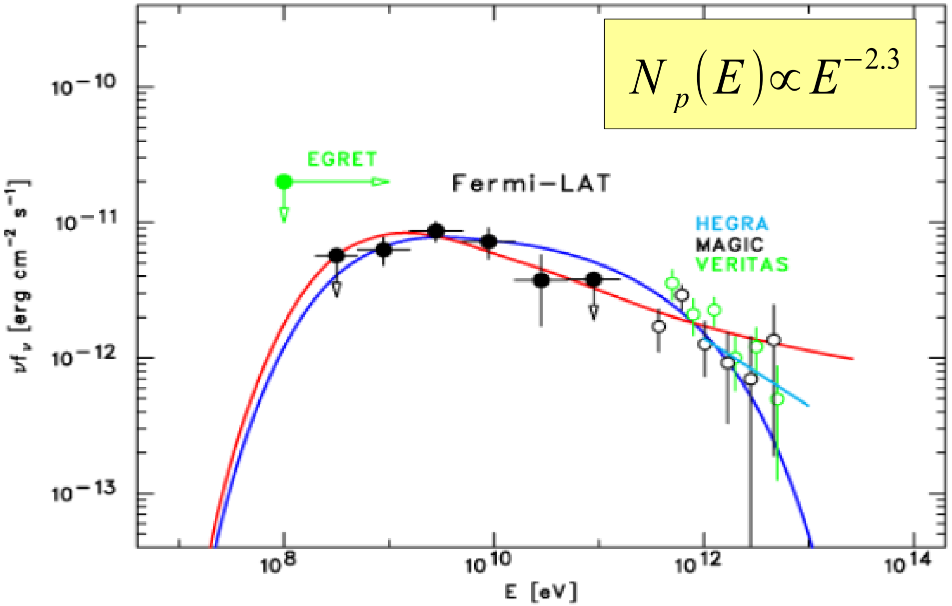


Cas A in X-rays
(*Chandra*)





Disfavoured by estimated magnetic field
from X-ray filaments ~ 0.3 mG



$$N_p(E) \propto E^{-2.3}$$

Leptonic Model
B=120μG, PL (-2.34) + cutoff @ 40 TeV
Dashed Line – Bremsstrahlung
Dotted Line – IC (dominated by FIR)

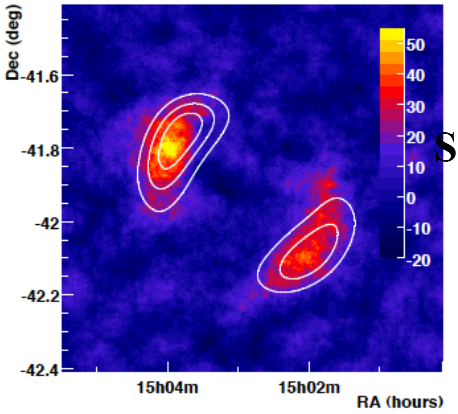
Hadronic Models
Blue: PL (-2.1) + cutoff @ 10 TeV
Red: PL (-2.3)

Hadronic model is favored, but leptons not ruled out

Abdo et al. ApJL 710 (2010)

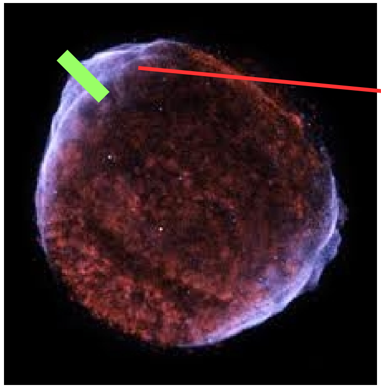
SN 1006

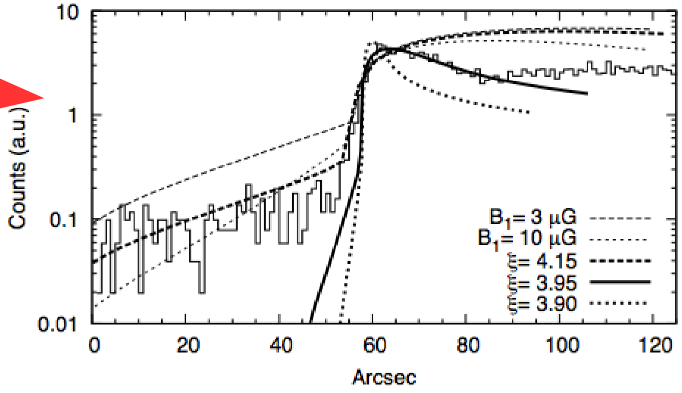
SN 1006 in TeV
(HESS)



Size 30 arcmin

SN 1006 in X-rays
(*Chandra*)

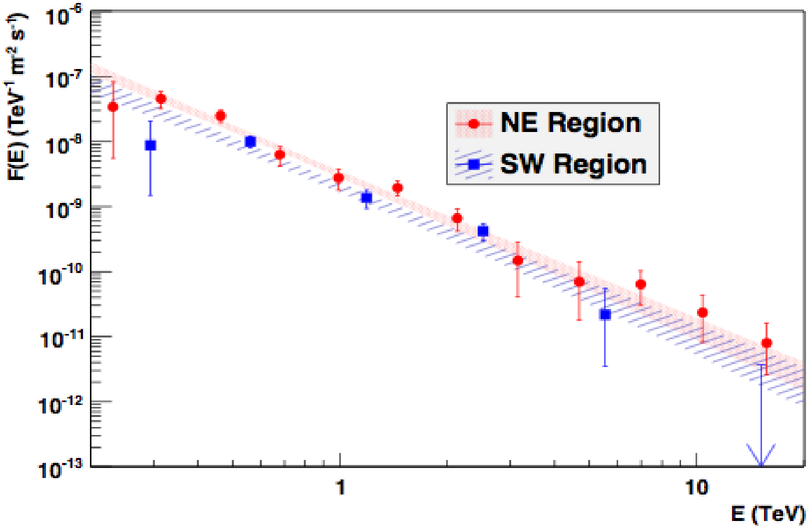




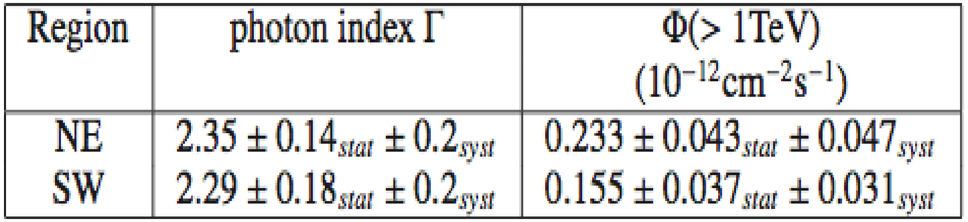
$B_{\text{down}} \sim 80\text{-}120\ \mu\text{G}$

The magnetic field amplification is occurring upstream!!

HESS data (130 hrs of observation)

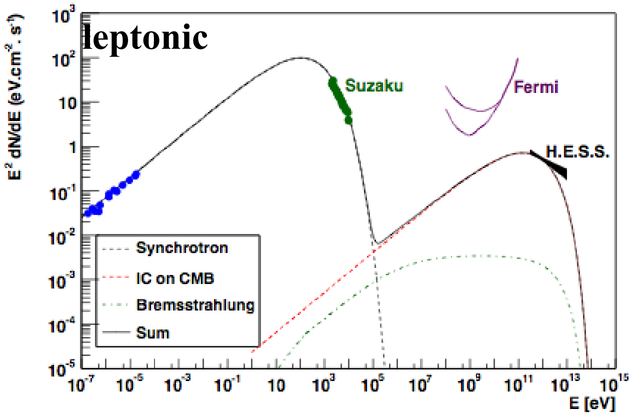


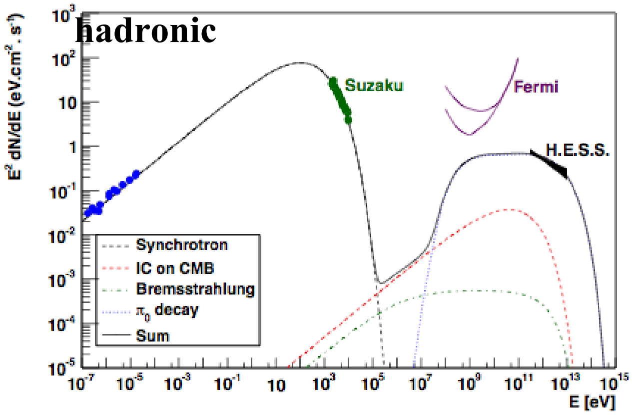
Total gamma-ray flux <~ 1% Crab

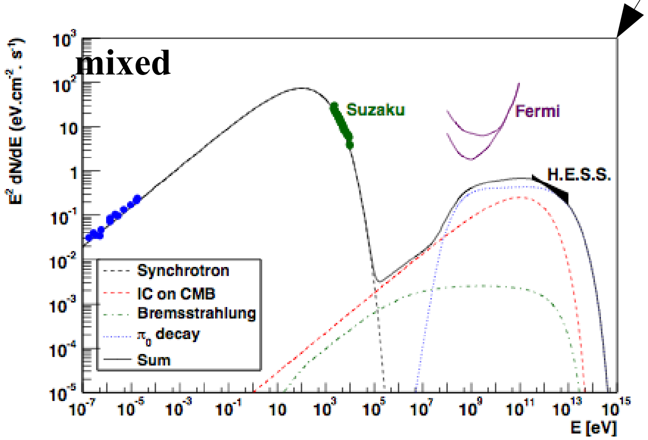


Region	photon index Γ	Φ(> 1TeV) (10^{-12}cm^{-2}s^{-1})
NE	$2.35 \pm 0.14_{stat} \pm 0.2_{syst}$	$0.233 \pm 0.043_{stat} \pm 0.047_{syst}$
SW	$2.29 \pm 0.18_{stat} \pm 0.2_{syst}$	$0.155 \pm 0.037_{stat} \pm 0.031_{syst}$

SN 1006







Model fit parameters from Aharonian et al.(2014), arXiv:1004.2124

Model	$E_{cut,e}$ [TeV]	$E_{cut,p}$ [TeV]	W_e [10^{47}erg]	W_p [10^{50}erg]	B [μG]
Leptonic	10	-	3.3	-	30
Hadronic	5	80	0.3	3.0	120
Mixed	8	100	1.4	2.0	45

Leptonic model (1 zone):

- Explain the integrated gamma-ray flux
- Fails to explain the steep spectrum
- Requires low B, contrary to what inferred from observed thin X-ray rim (B~120 μG)

Hadronic model (1 zone):

- Requires efficiency ~ 30%
- 1) Steep spectrum $E^{-2.3}$ with E_{cut}>>100 TeV
- 2) hard spectrum E^{-2} with E_{cut}~80 TeV

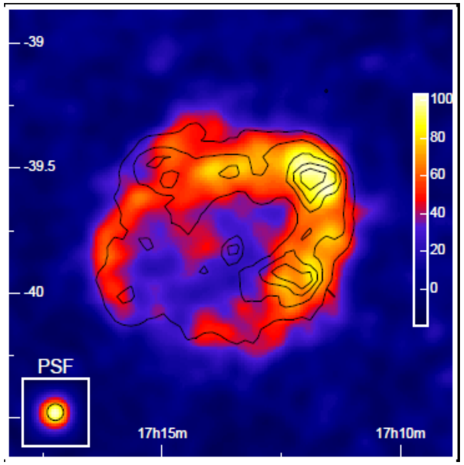
How to distinguish between the two scenarios?

- At high energies X-rays come from downstream while IC photons come from upstream → 1' resolution will be able to detect a displacement between X-rays and γ-rays
- Extending the detection to E>10 TeV will reveal the presence of a cutoff

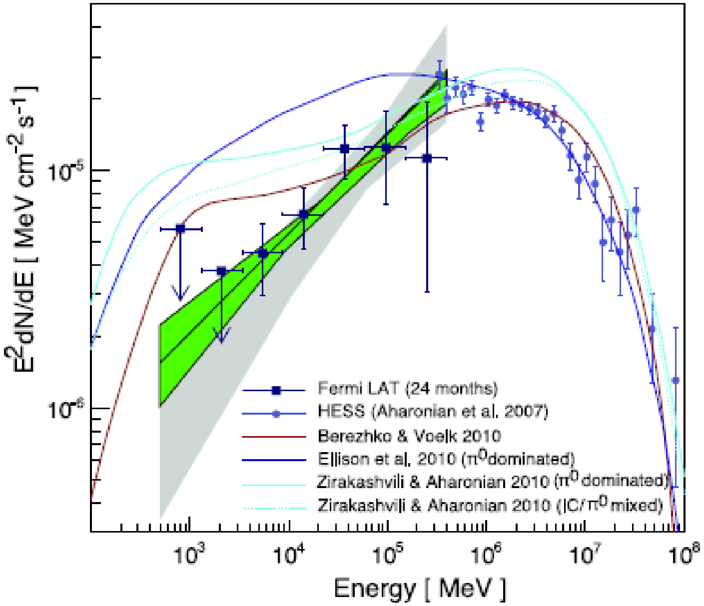
HESS J1713.7-3946

The remnant **RX J1713.7-3946** has been considered the most promising candidate to prove the existence of accelerated hadrons
FermiLAT data seem to favor a probable leptonic origin

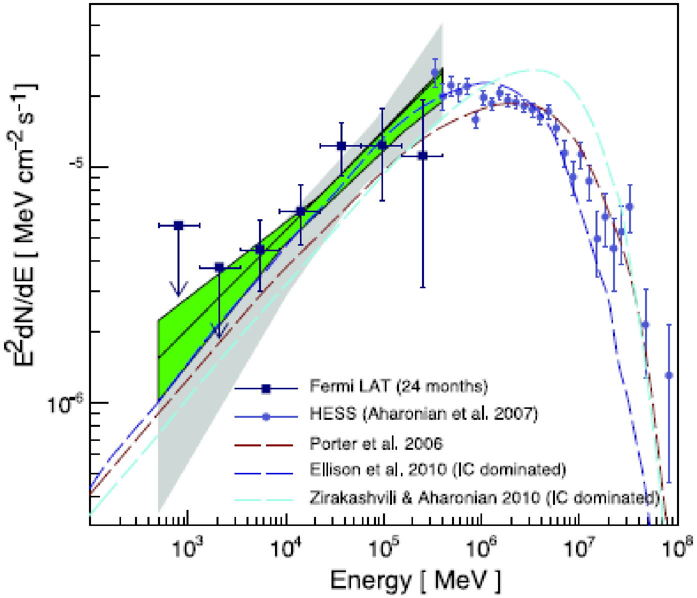
BUT…



Hadronic model(s): $\pi^0 \to \gamma\gamma$

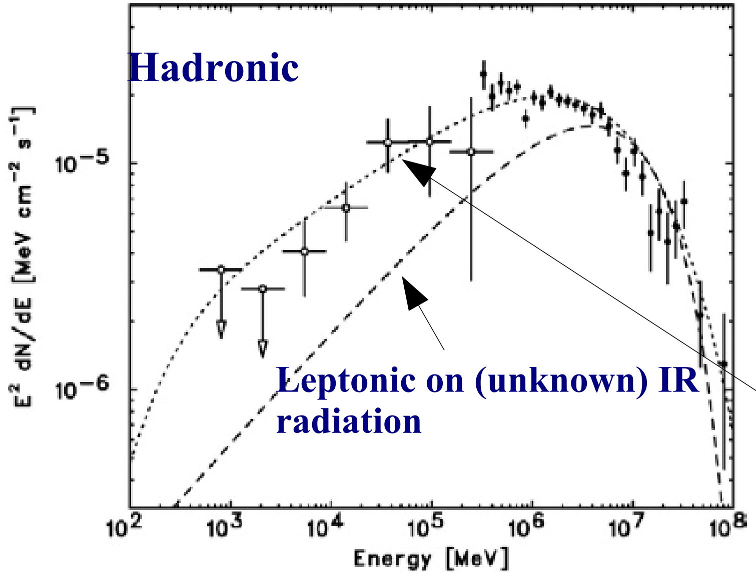


Leptonic model(s):
inverse Compton scattering



HESS J1713.7-3946

Curves from
T. Tanaka et al., ApJ 685 (2008)



Both leptonic and hadronic models have problems in fitting Ge-TeV emission.

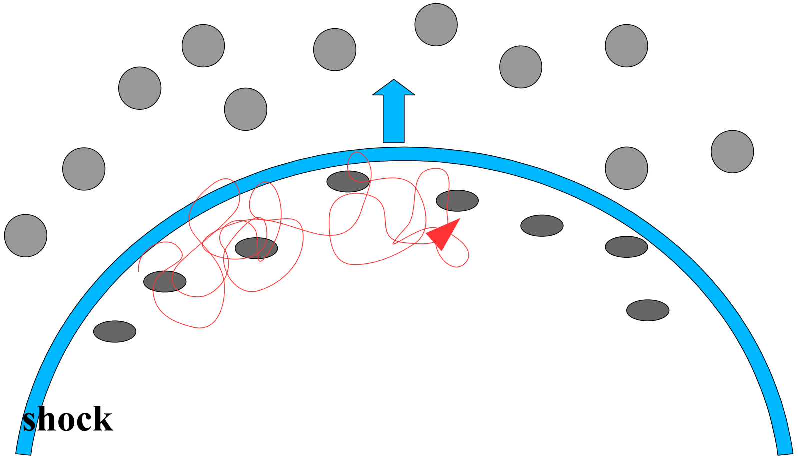
Leptonic model (1 zone):

- Problems in fitting the highest energy points
- Need a IR background 30 > Gal. average

Hadronic model in clumpy medium:

- Reasonable fit with hard spectrum $E^{-1.72}$ and with $E_{p,cut}$~250 TeV

Clumpy CSM



How to produce hard spectrum?

Expansion in circumstellar medium with low average density but with high density clumps:

Nj High en. particles penetrate inside the clumps

Nj Low en. particles do not penetrate

Nj **we get a hard spectrum**

HESS J0852-4622 (Vela Jr.)

- γ-ray emission well correlate with Radio and X-ray emission
- Main uncertainty due to distance
  200pc < d < 1kpc

- Both hadronic and leptonic model can fit the data
- Lept. model favored for spectral shape but need B ~ 6 μG
  - X-ray filaments require B~100 μG
  - Issue in fitting the shell in γ-rays

→ A better morphological study in γ-rays will help in distinguish between L. and H.

Remnant size ~ 120'