The Importance of Upstream Inhomogeneity in Cosmic-ray Acceleration at Supernova Remnants

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(With T. Inoue, Y. Ohira, S. Inutsuka, Y. Fukui)

Similarities between us and "SN" people

Our claim:
Multi-dimensional model is necessary to fully understand cosmic ray acceleration.

Importance of inhomogeneity of circumstellar material and multi-dimensionality effects.

However, quantitative discussion is difficult, because it's hard to solve kinetic equation describing CR transport in multi-D models.

$\Rightarrow$ In this talk, I present qualitative arguments.
Quantitative arguments coming soon?

Open Questions in CR community

Is the supernova remnant (SNR) really "proton" accelerators ?

(We have already known from synchrotron radio-X-ray emissions that "electrons" are accelerated at SNR.)

If the answer is "yes", then

a) How large is the maximum CR proton energy?

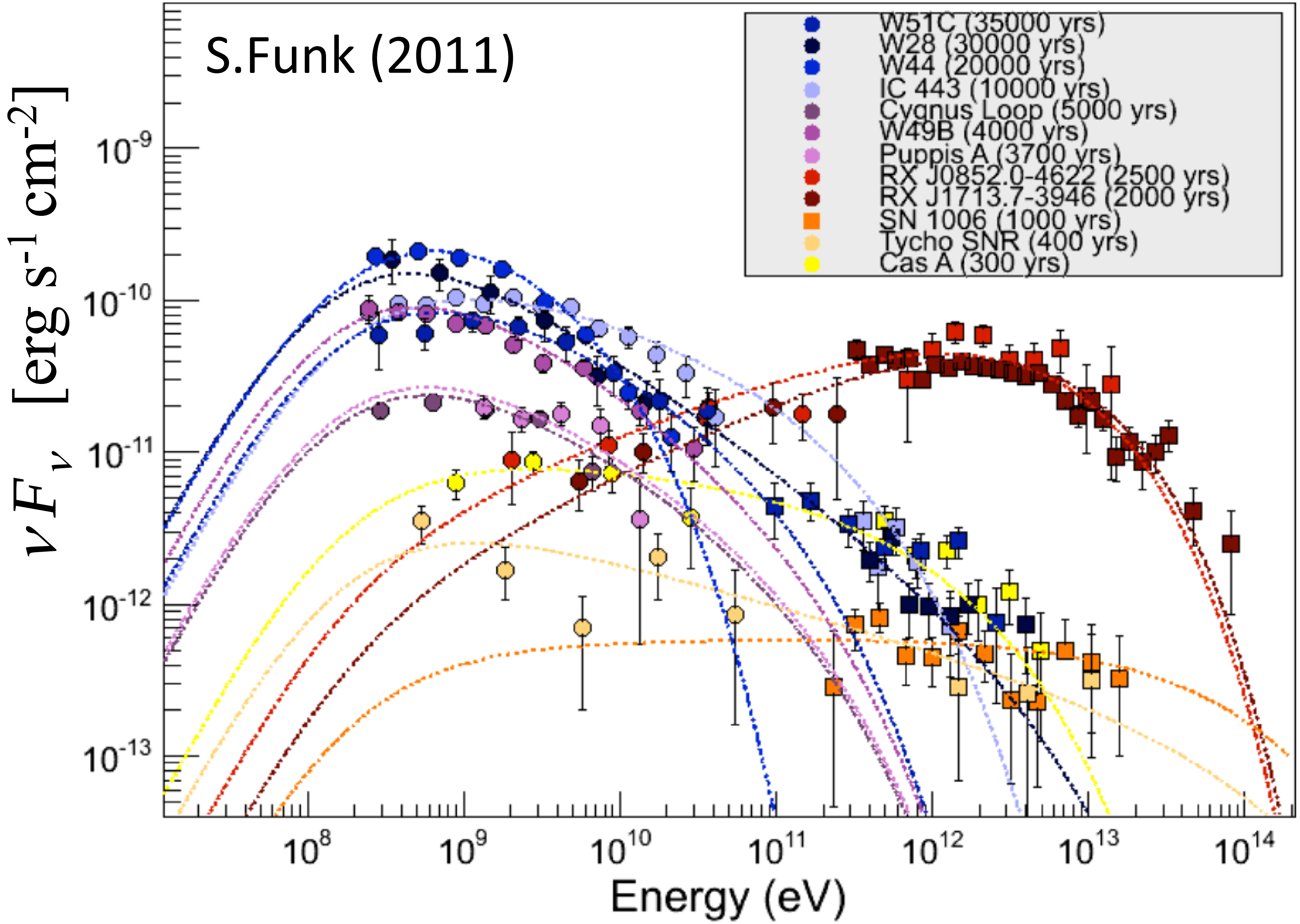
Measured CR spectrum implies $E_{max} \sim 10^{15.5}$ eV.

b) How much energy of SN explosion goes into CR protons?

Measured CR flux implies 1~10%.

=> Gamma-ray and X-ray observations play important roles.

Wide-band γ-ray spectra of SNRs



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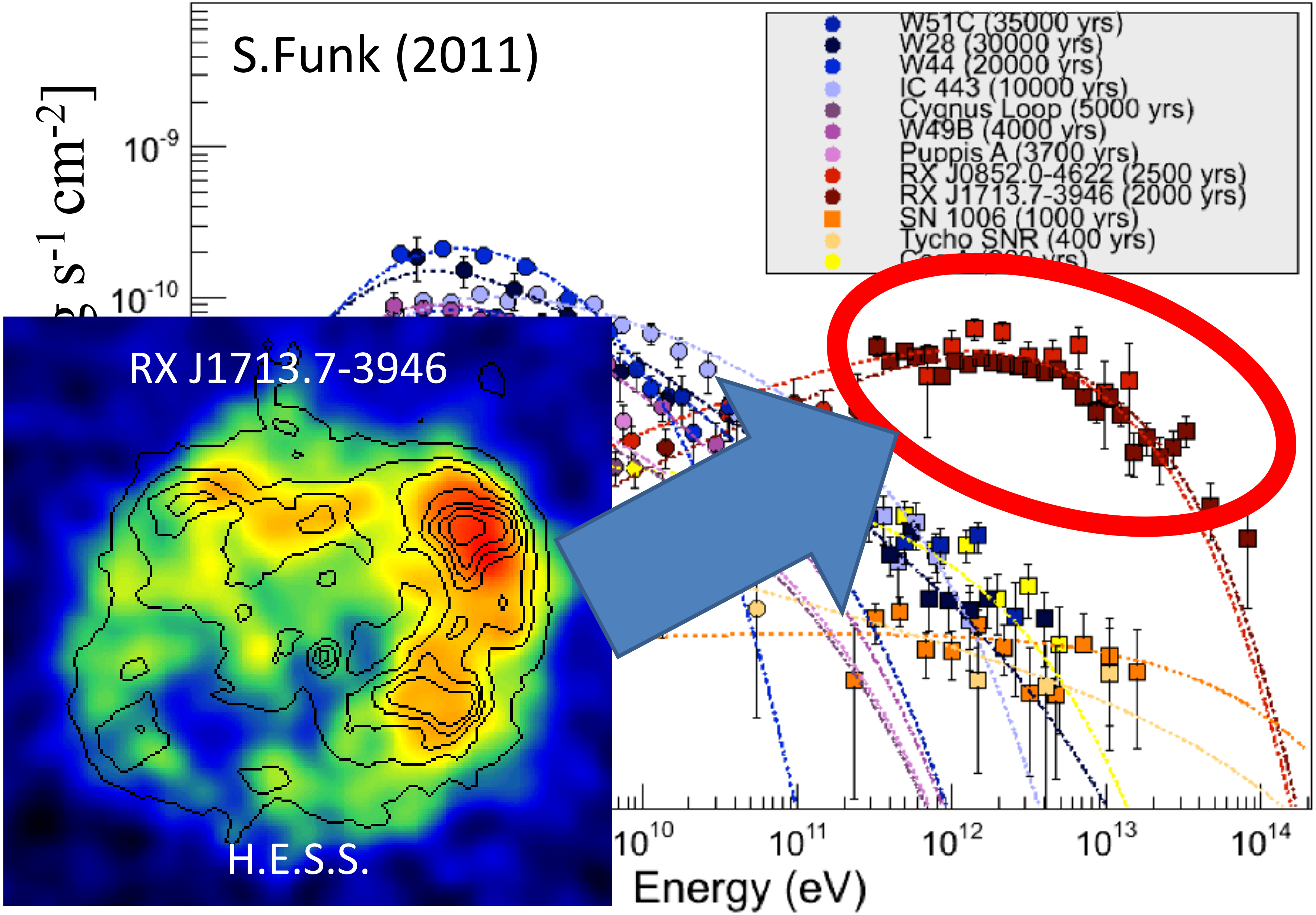


Spectrum of RX J1713.7-3946

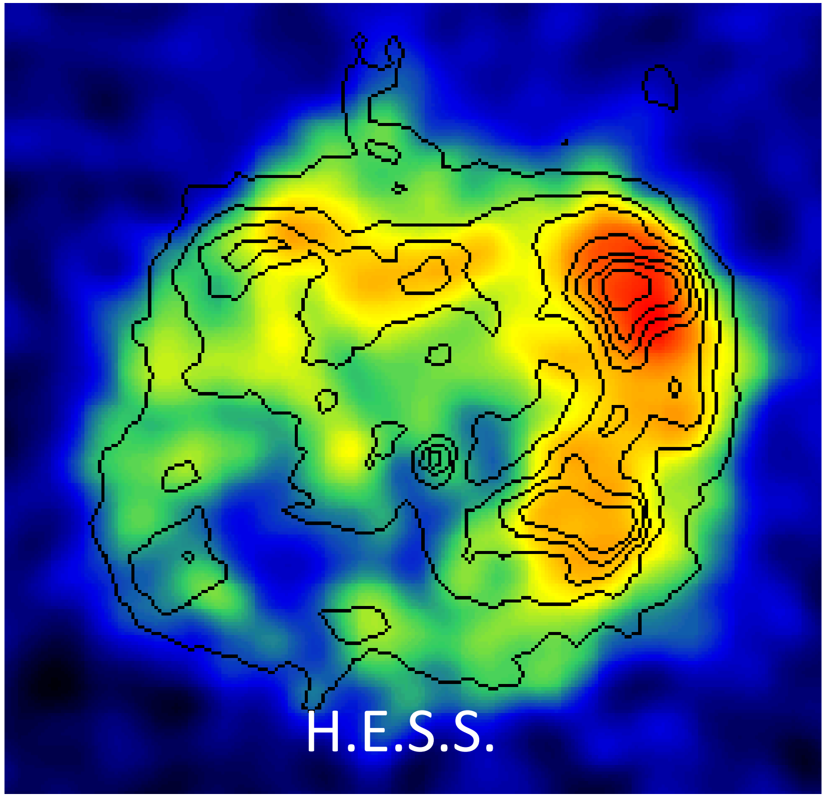
Observed spectrum (Fermi LAT) : $\nu F_\nu \propto \nu^{0.5}$

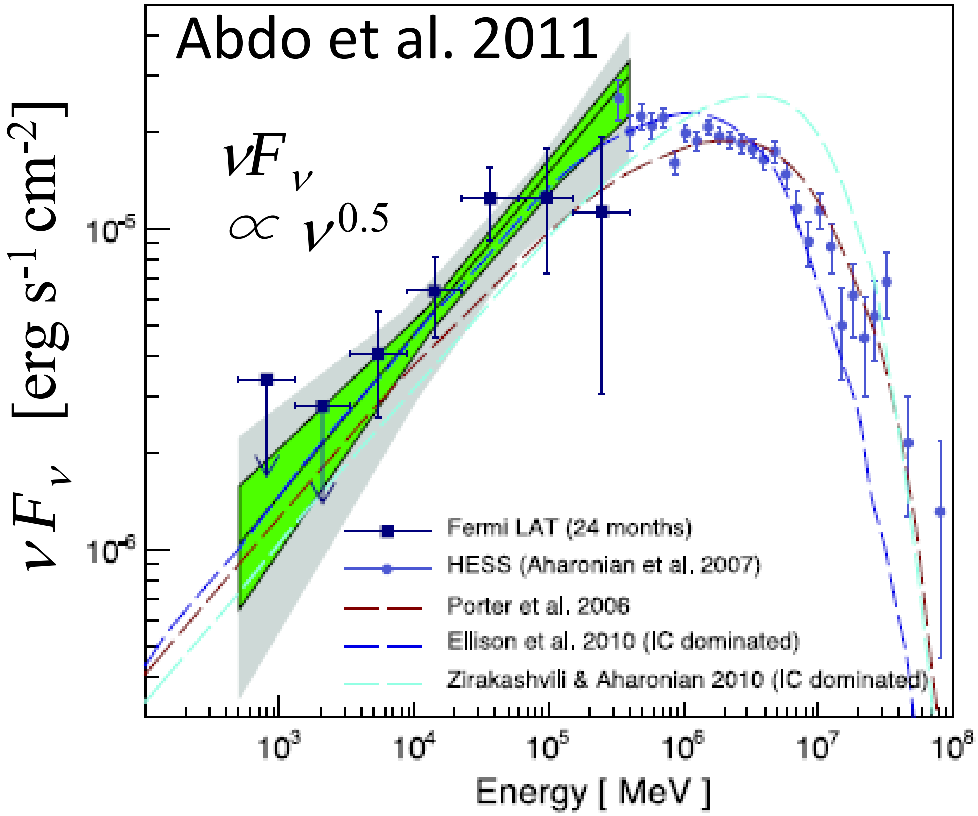
If γ-rays are "electron" origin (IC),

$$\nu F_\nu \propto \nu^{(3-p)/2} \propto \nu^{0.5} \quad \Rightarrow \quad p = 2.0$$

If γ-rays are "proton" origin (decay of π^0),

$$\nu F_\nu \propto \nu^{2-p} \propto \nu^{0.5} \quad \Rightarrow \quad p = 1.5$$





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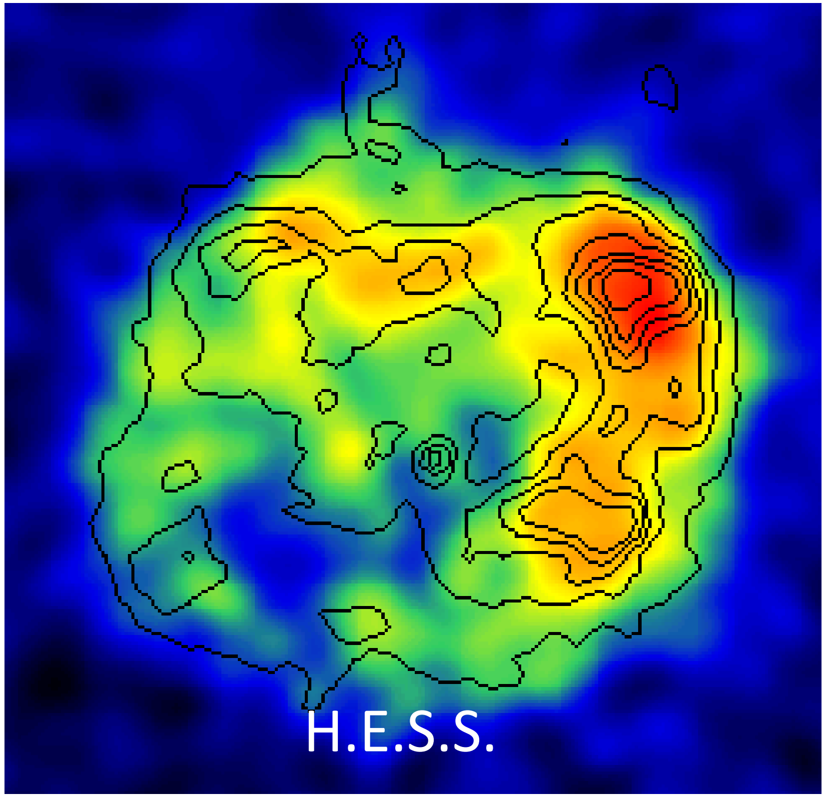
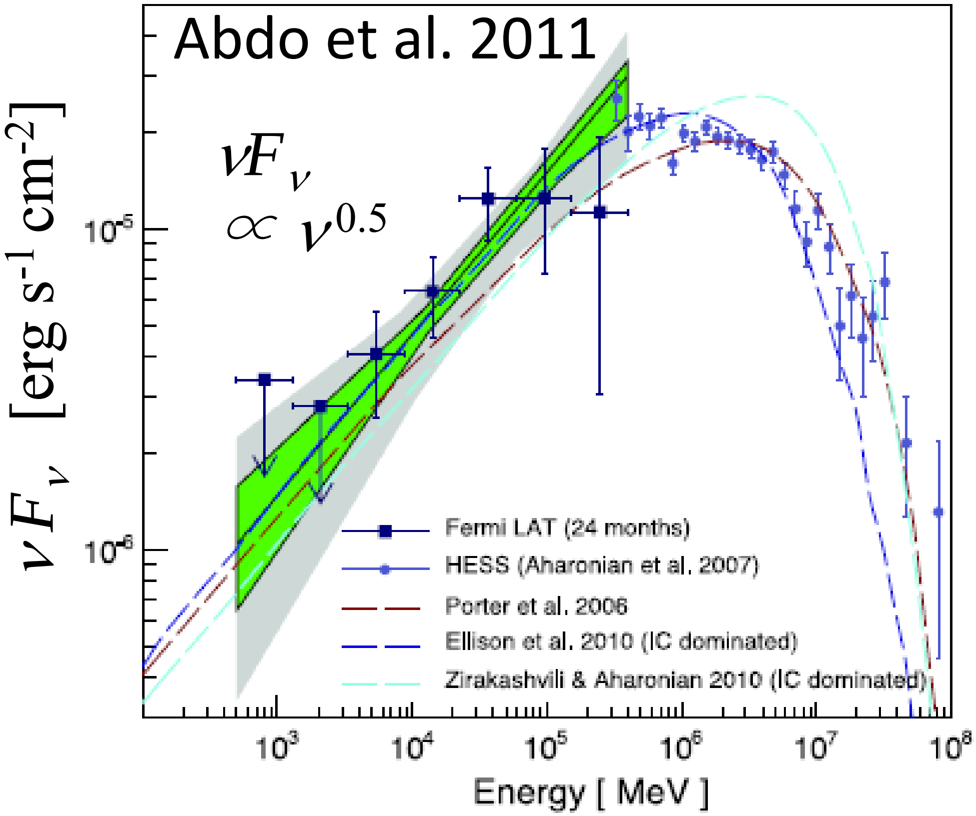
Just right a prediction of Fermi acceleration theory.





Non-detection of X-ray lines

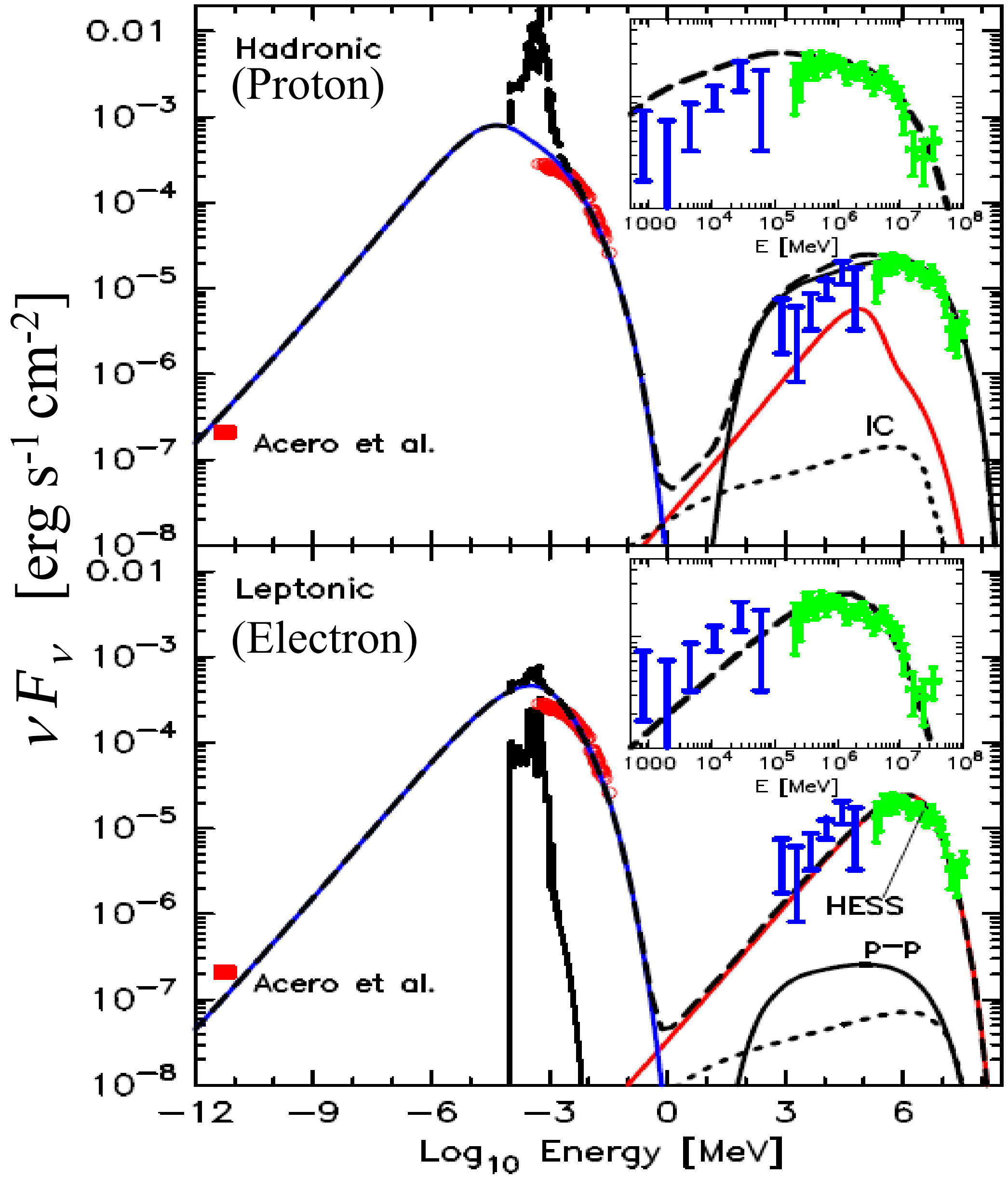
X-rays from RX J1713

purely non-thermal
(that is synchrotron radiation
From ~ 1-10 TeV electrons):

Dim (non-detected) thermal
X-ray lines.

Ellison + 10:

"Proton" model overpredicts
thermal X-ray lines in order
to fit the gamma-ray flux
with pi^0 decay process.
→ prefers "electron" model.



If γ-rays are electron-IC, then B~10 μG

Power of synch. radiation

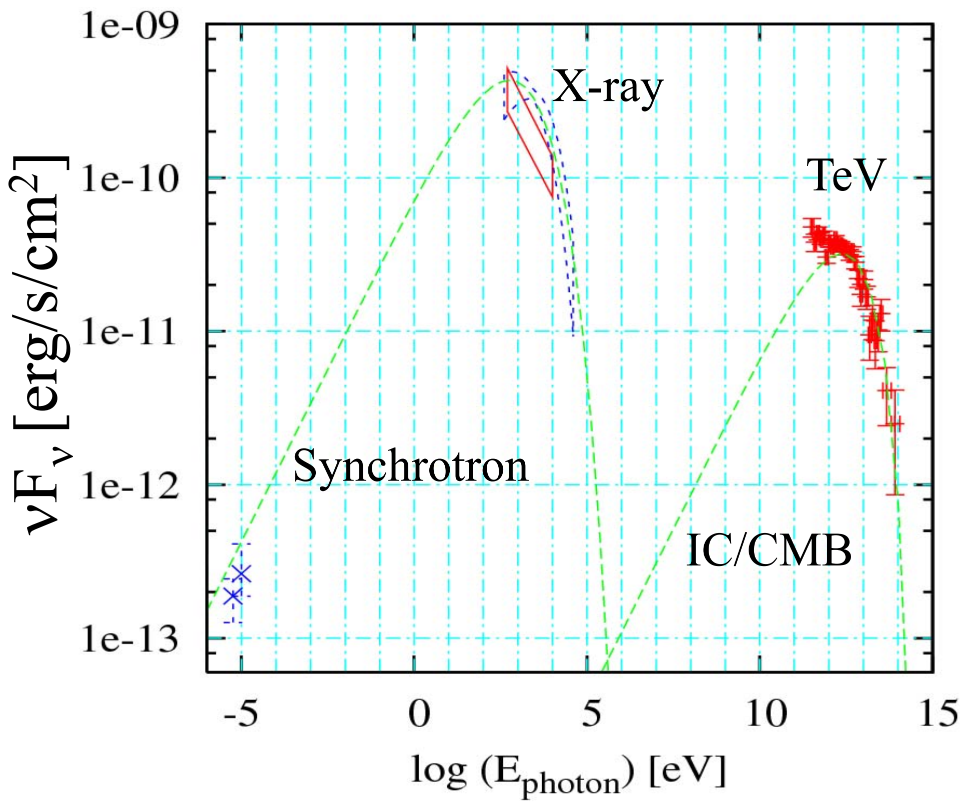
$$P_{syn} = \frac{4}{3}\sigma_T C\beta^2\frac{B^2}{8\pi}\left(\frac{E_e}{m_e c^2}\right)^2$$

Power of IC emission

$$P_{IC} = \frac{4}{3}\sigma_T C\beta^2 U_{ph}\left(\frac{E_e}{m_e c^2}\right)^2$$

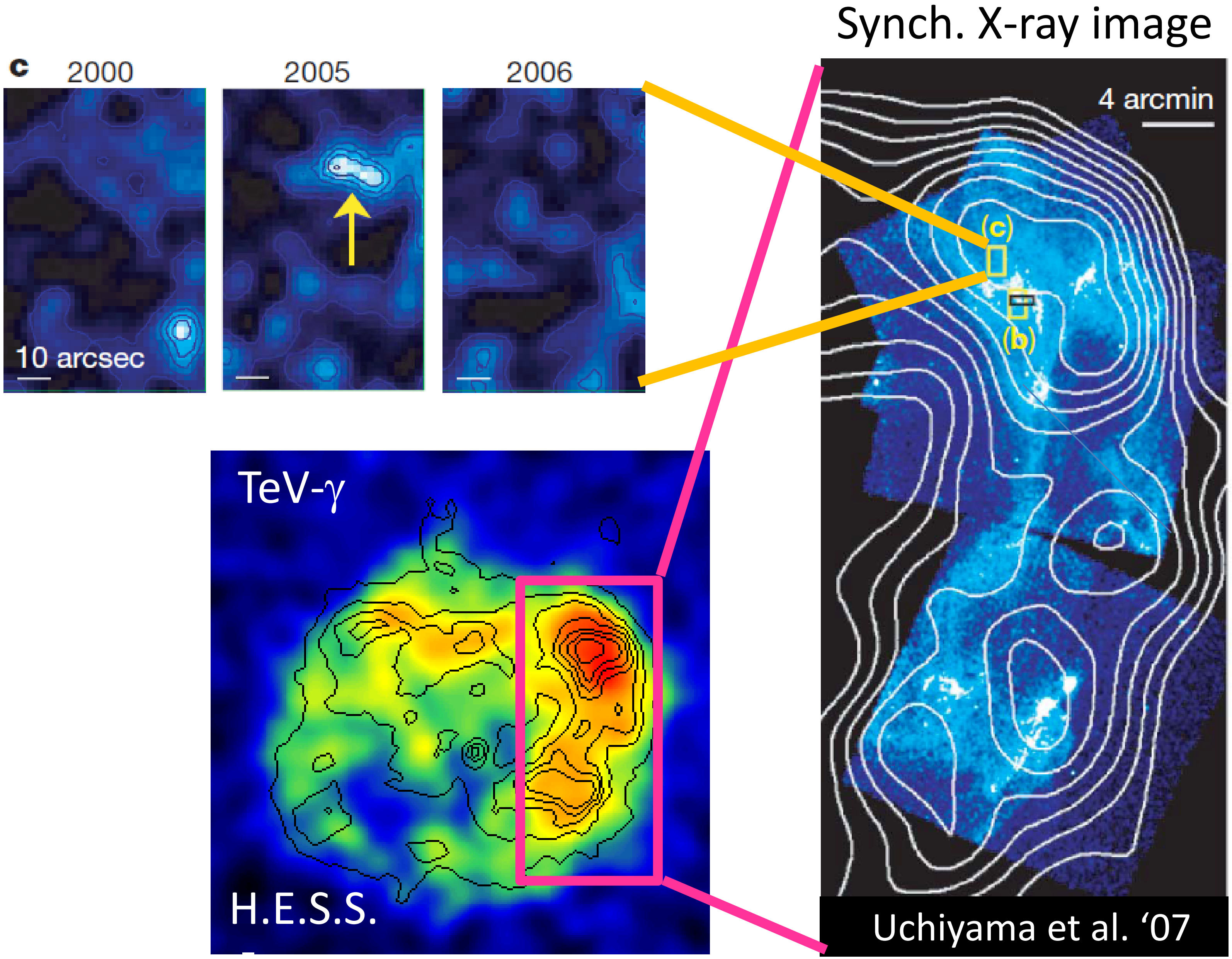
$$\frac{P_{syn}}{P_{IC}} = \left(\frac{B}{3.27\ \mu\mathrm{G}}\right)^2$$

for CMB background

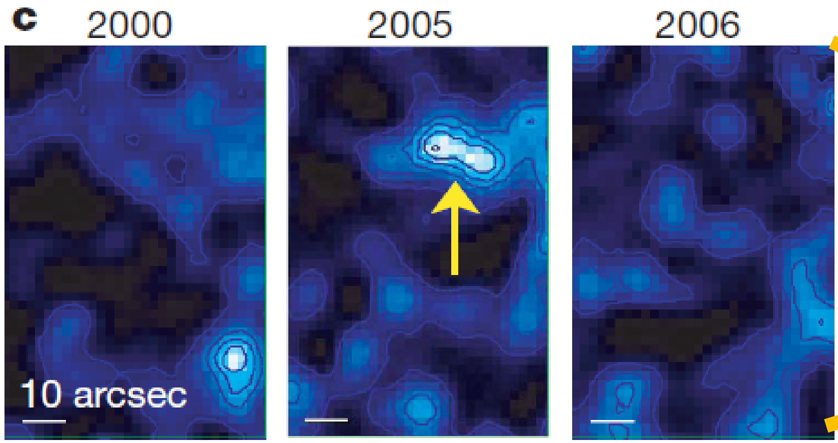


B ~10μG from observed ratio, "P_{syn}/ P_{IC} ~ 10".

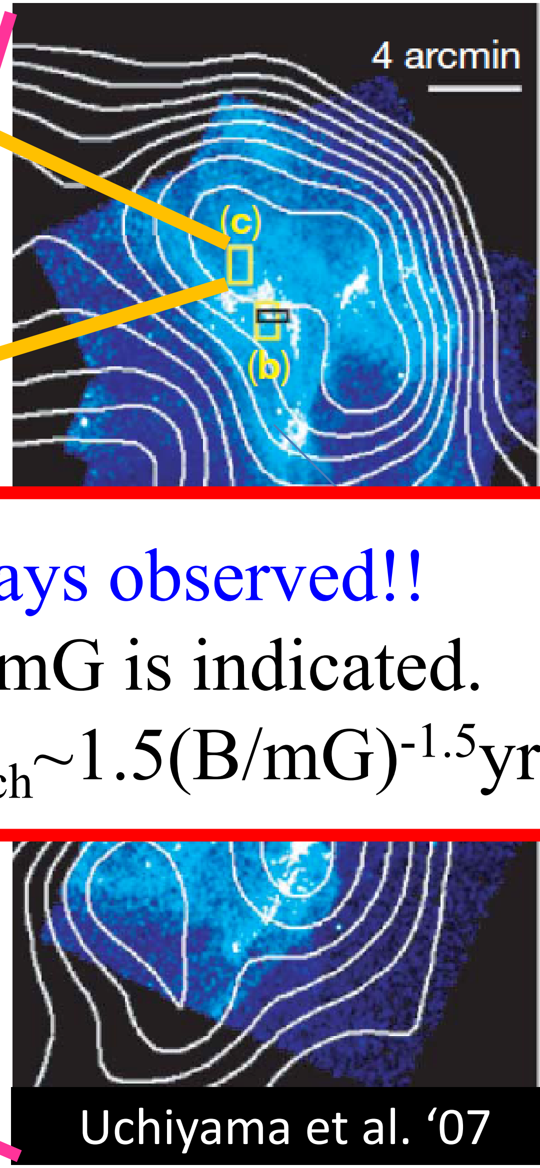
B~mG at RX J1713.7-3946 ?



B~mG at RX J1713.7-3946 ?



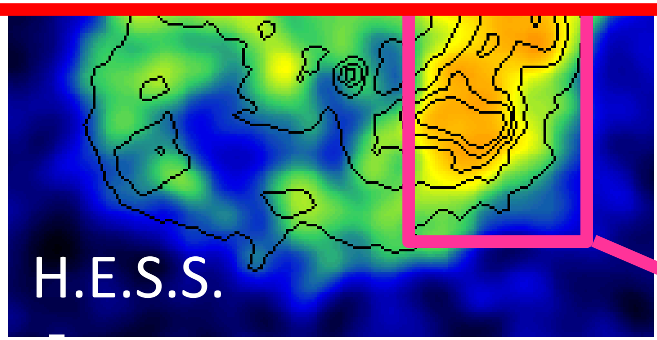
Synch. X-ray image



Time-variable synchrotron X-rays observed!!

If synch. cooling time ~1yr, B~mG is indicated.

(for X-ray emitting electrons, $t_{synch} \sim 1.5(B/mG)^{-1.5}$yr)



Problems on RXJ1713

If gamma-rays are leptonic (“electron” origin)…

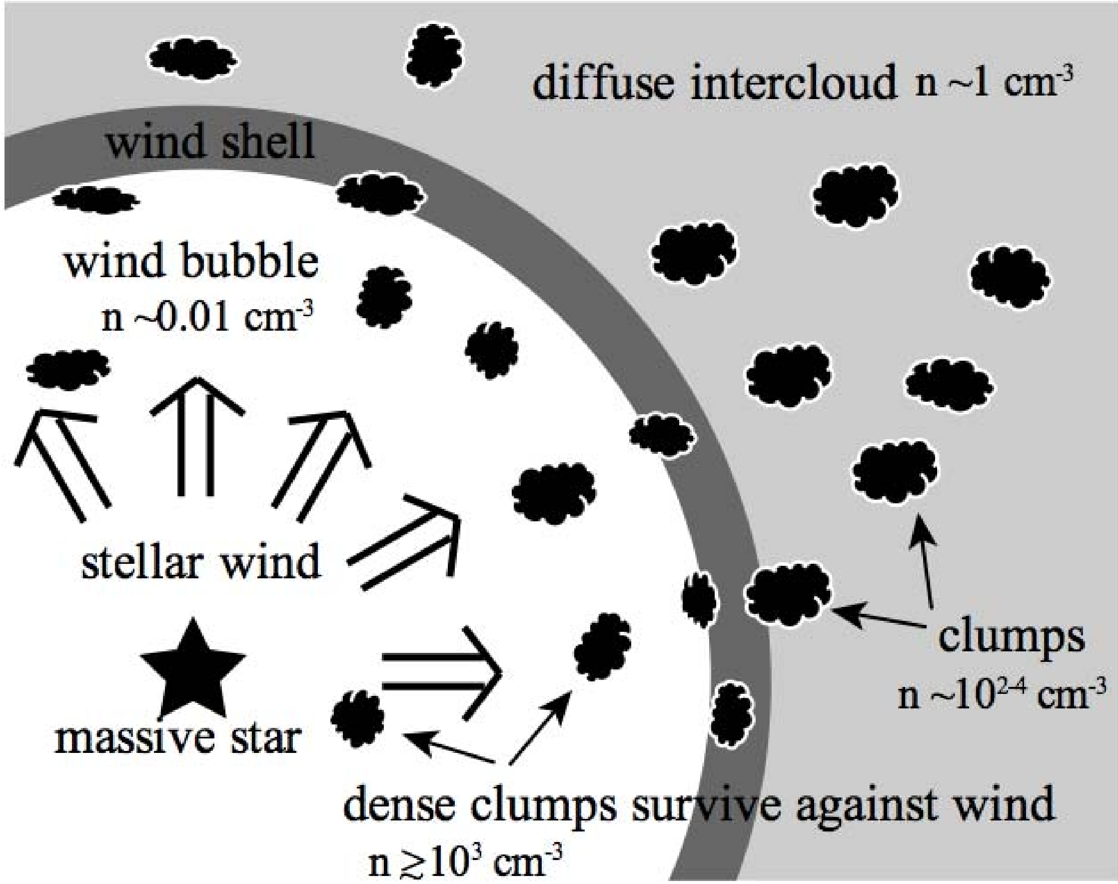
* Magnetic field ~ 10μG is much smaller than expected?
  => We need different interpretation of thin X-ray filament
  and X-ray time variability?

If gamma-rays are hadronic (“proton” origin)…

* too hard GeV-TeV spectral slope ($\nu F_\nu \propto \nu^{0.5}$ => p ~1.5 ?)
* predicted X-ray lines too bright.
* e/p ratio ~10^{-5} , much smaller than measured at Earth.

A possible solution (Inoue, RY+2012)

If SN explosion occurs in the inhomogeneous environment, "proton" model may explain all observational results.

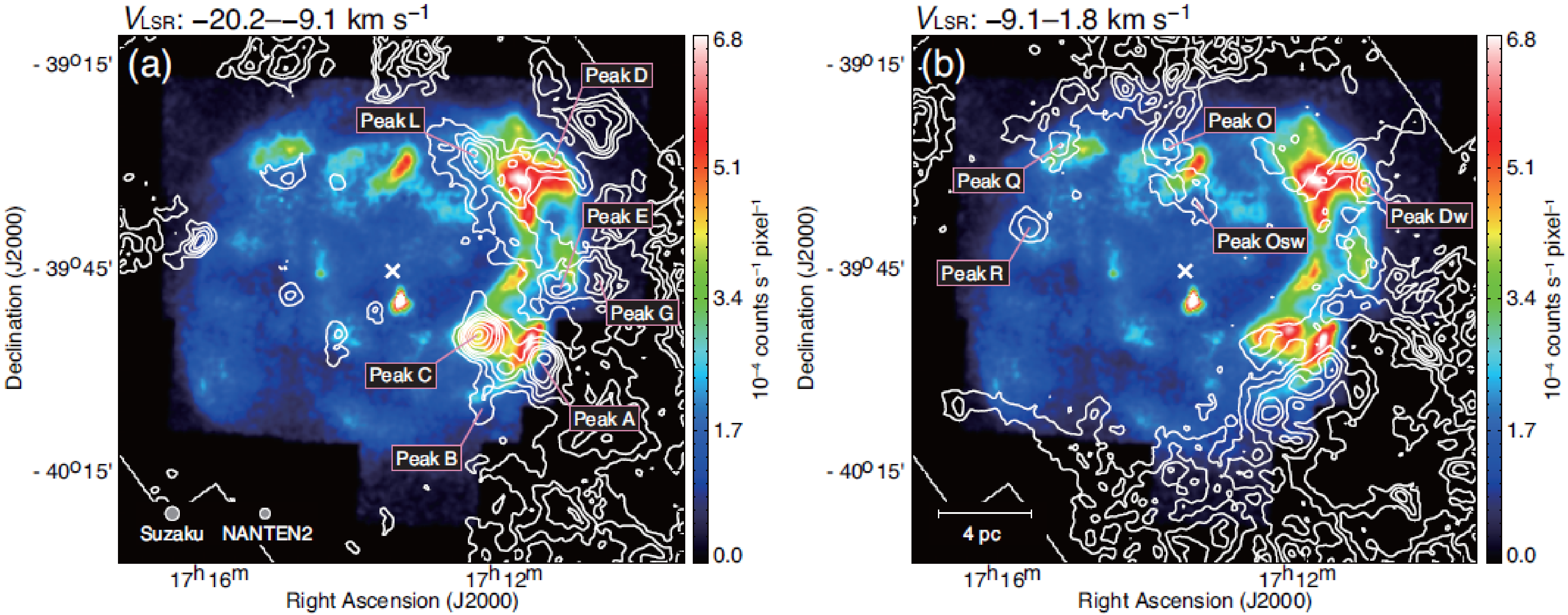


← environment just before SN explosion: wind cavity (bubble), & dense clouds.

Inoue, RY+2012

A possible solution (Inoue, RY+2012)

Indeed, RX J1713.7-3946 is embedded in highly inhomogeneous medium.



Color: 1-5 keV (Suzaku) = Synchrotron X-rays

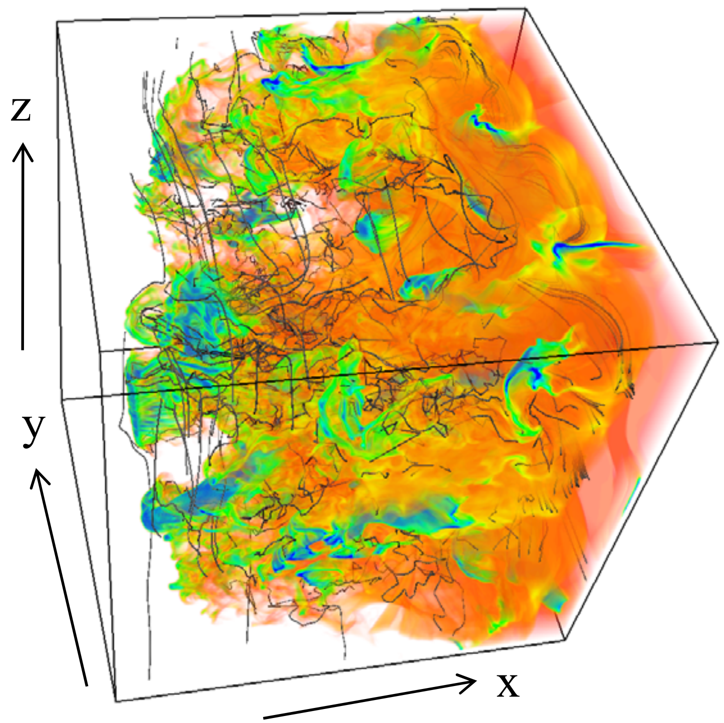
Contour: $^{12}CO(J=2\text{-}1)$ (NANTEN) = Molecular clouds

Sano, RY et al. (2013)

A possible solution (Inoue, RY+2012)

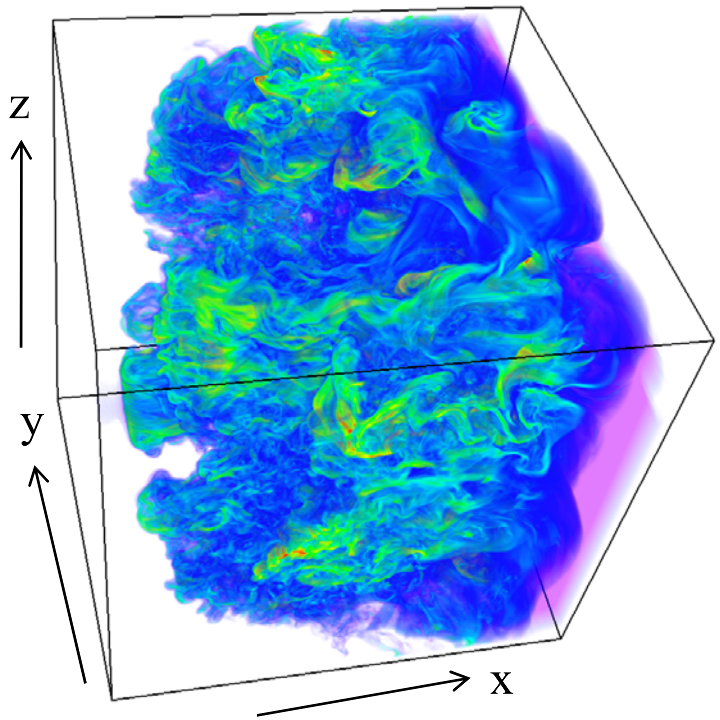
3D MHD simulation shows that the shock-cloud interaction generates vorticity around which magnetic field is amplified.

Structure of n



Blue : shocked cloud
Orange : shocked diffuse gas

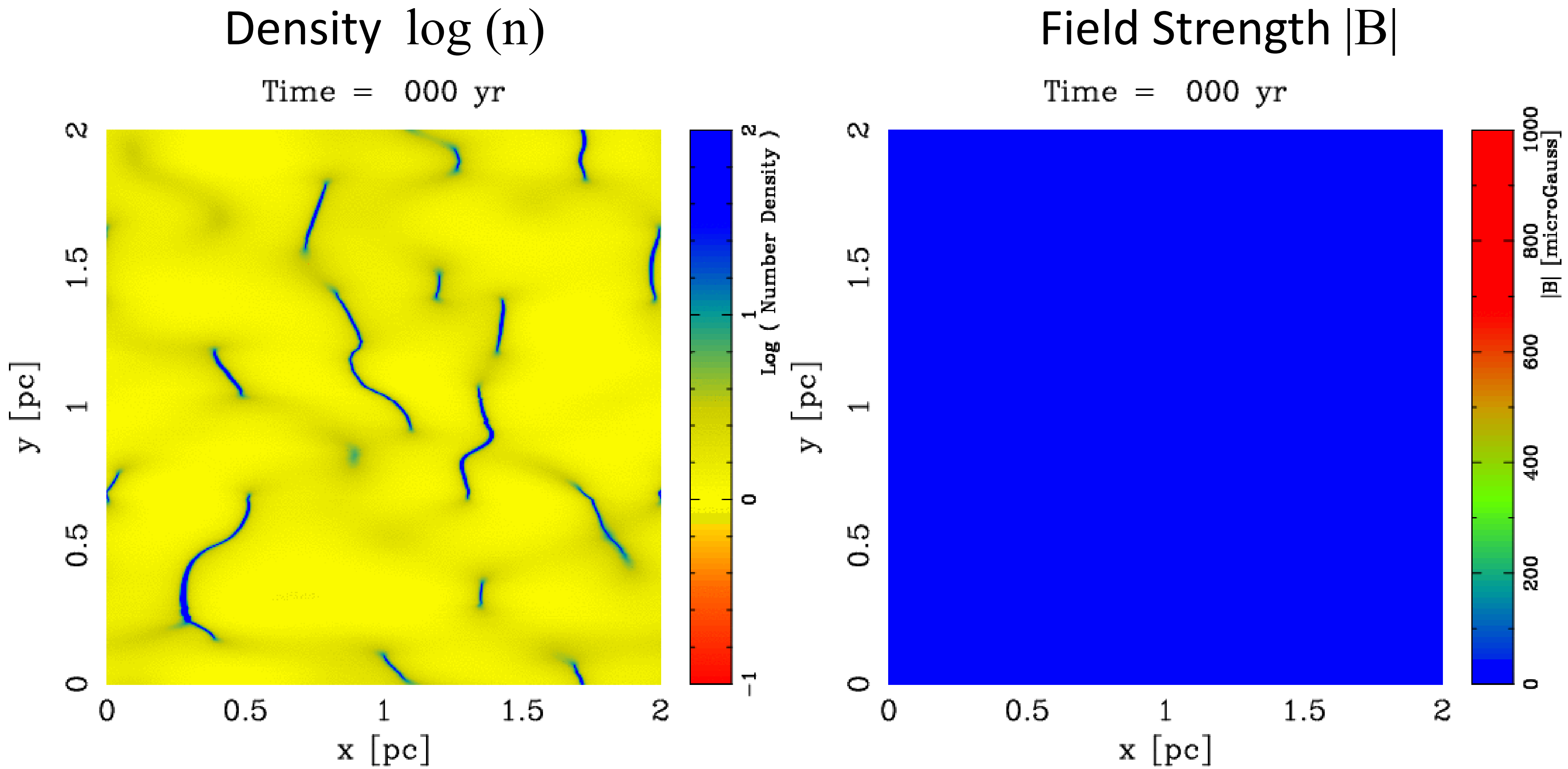
Structure of $|B|$



Blue : $10\ \mu G < |B| < 100\ \mu G$
Green : $100\ \mu G < |B| < 500\ \mu G$
Red : $500\ \mu G < |B|$

Result of MHD simulation

Magnetic Field is amplified via turbulent dynamo.



Inoue, RY, Inutsuka 09

A possible solution (Inoue, RY+2012)

* Dim thermal X-ray lines:

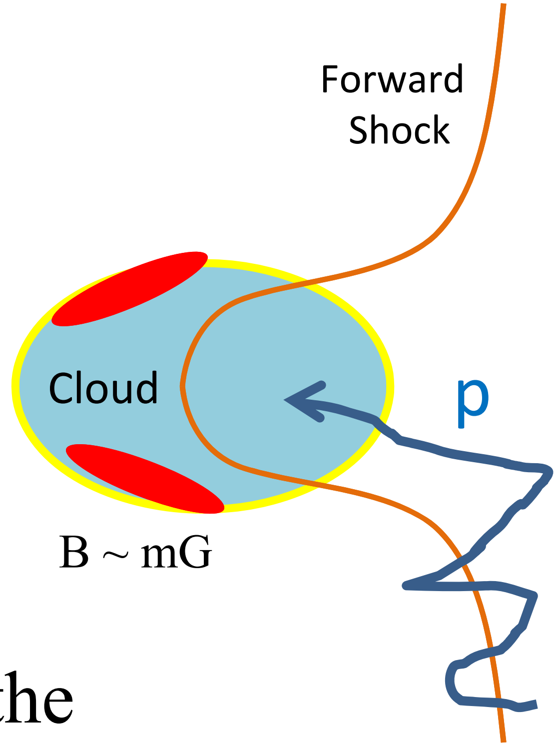
- shocked wind (n~0.01)

  => low density.

- shocked cloud (n~10^3)

  => low shock velocity

  => low temperature.



* Gamma-ray spectrum:

high-energy protons (produced in the diffuse gas region) hit clouds.

penetration length: $L \propto (Dt)^{1/2} \propto E^{0.5} \propto \nu^{0.5}$

=> $\nu F_\nu \propto \nu^{p-2} \times L \propto \nu^{0.5}$ (for $p = 2.0$)

(observed "*electron*-IC-like" spectral slope!!)

Summary

If SN explosion occurs in the inhomogeneous environment, hadronic model (in which gamma-rays are *proton* origin) may not contradict observational results.
More quantitative arguments are under investigation.

Reference:
Inoue et al. ApJ, 744, 71 (2012)

Others:
Inoue et al. ApJL, 723, L108 (2010), ApJ, 695, 825 (2009)
Yamazaki et al. A&A, 495, 9 (2009)

Neutrino observation will answer the problem?