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Nonthermal hard X-ray and TeV gamma-ray diagnostics of diffusion coefficient near supernova remnants shocks

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Naomi Tsuji, Yasunobu Uchiyama,
Dmitry Khangulyan, Ryota Higurashi (Rikkyo University),
David Berge (DESY), and Felix Aharonian (DIAS, MPI-K)

Introduction: CR propagation

✱ SNR paradigm

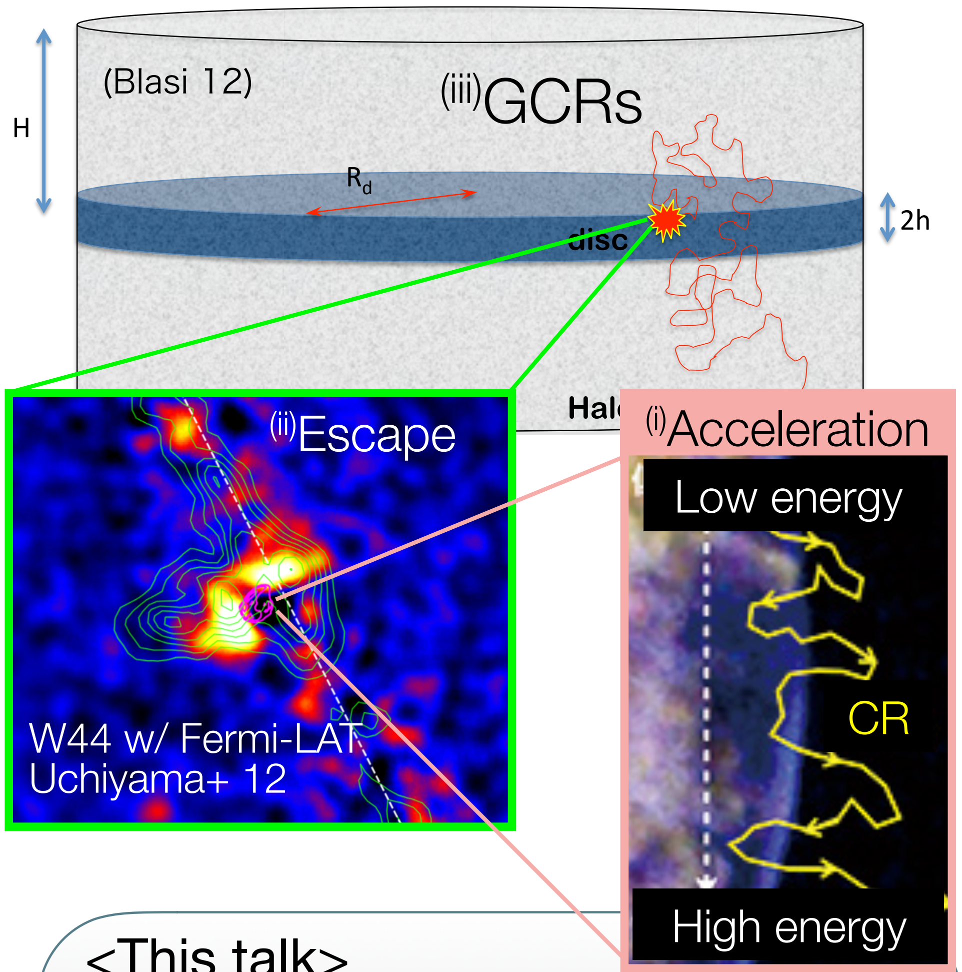
(i) Acceleration at SNR shocks
(ii) Escape from SNR
(iii) Propagation in Galaxy

✱ CR motion

Diffuse thru. scattering with B-field
→Characterized by diffusion coefficient (D)

$$D(p) = 10^{28} D_{28} \left(\frac{p}{10\ \mathrm{GeV}/c} \right)^{\alpha}\ \mathrm{cm^2/s}$$

	(i)SNR shock	(ii)SNR vicinity	(iii)Galaxy
	accelerated CRs	escaping CRs	GCRs
α	**~1?**	~0.3–0.6	~0.3–0.6
D_{28}	**$\sim 10^{-5}$?**	$\sim 10^{-2}$–1 ?	~1



W44 w/ Fermi-LAT
Uchiyama+ 12

<This talk>
Constrain the D(E)∝E$^{\alpha}$ from X/γ-ray observations

1. Bohm diffusion (α=1)
2. Arbitrary diffusion (α=0, 1/3, 1)

Bohm diffusion: SNR shocks

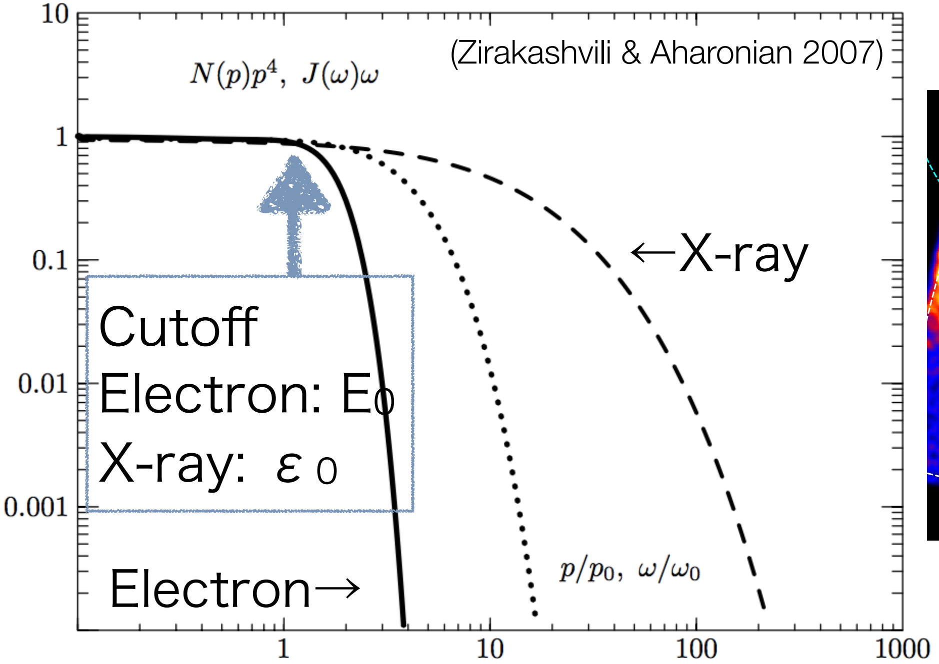
(Zirakashvili & Aharonian 2007; ZA07)

Bohm diffusion	Electron spectrum	X-ray spectrum
$D_{\rm Bohm}(E) = \frac{c}{3q}\eta B^{-1} E$	$\frac{dN_e}{dE} \propto E^{-3}\left[1+0.66\left(\frac{E}{E_0}\right)^{\frac{5}{2}}\right]^{\frac{9}{5}} \exp\left[-\left(\frac{E}{E_0}\right)^2\right]$	$\frac{dN^{\rm Syn}}{d\varepsilon} \propto \varepsilon^{-2}\left[1+0.46\left(\frac{\varepsilon}{\varepsilon_0}\right)^{0.6}\right]^{11/4.8} \exp\left[-\sqrt{\frac{\varepsilon}{\varepsilon_0}}\right]$
(η≧1: “Bohm factor”)	$E_0 \propto \eta^{-\frac{1}{2}} B^{-\frac{1}{2}} u_1$	$\varepsilon_0 \propto \eta^{-1} u_1^2$

Model

Electron: loss (=synch. cooling) limited

X-ray: synchrotron radiation



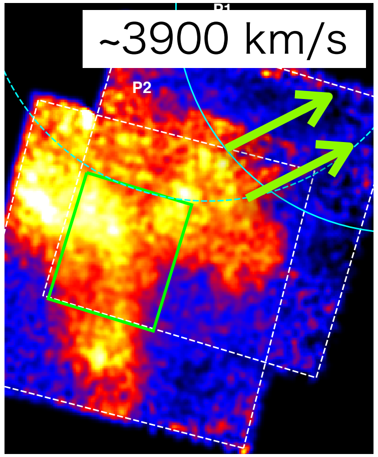
Observation

e.g.) RX J1713.7–3946 NW

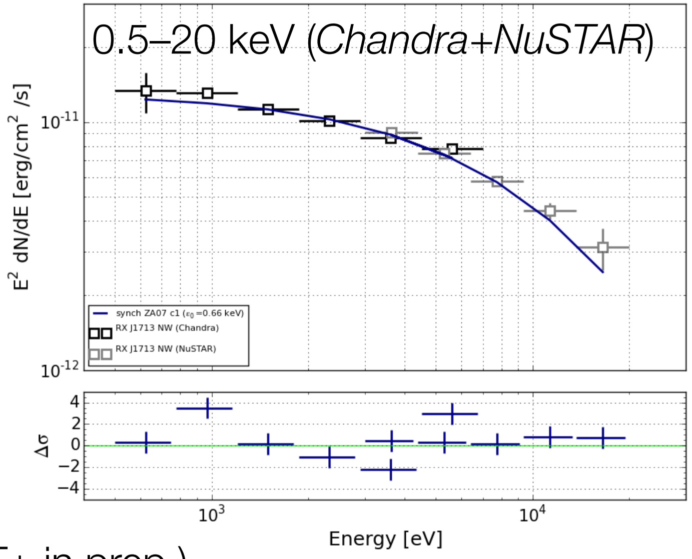
Cutoff energy: 1.1 keV

Shock speed: ~3900 km/s (NT & Uchiyama 16)

→Bohm factor: **η~1 (Bohm limit)**



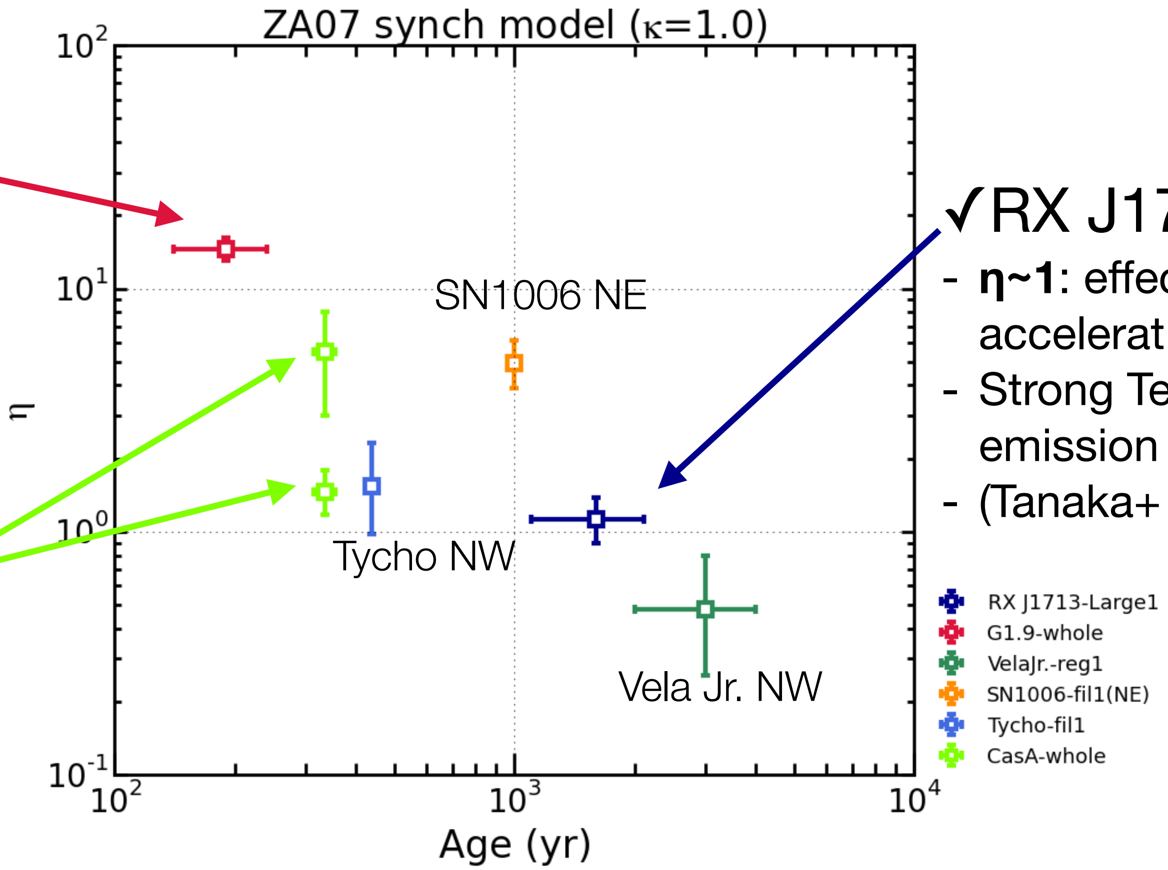
NuSTAR image in 3–20 keV



(NT+ in prep.)

Bohm diffusion: young SNR (X-ray)

SNR	Age (yr)	u1 (km/s)	SNR	Age (yr)	u1 (km/s)
RX J1713 -NW	1600	3900	SN1006 -NE	1000	4500
Vela Jr. -NW	2000–5000	1500–2500	Tycho -NW	440	4000
G1.9+0.3	190	14000	Cassiopea A	335	4700



✓G1.9+0.3

- Youngest in Galaxy
- **η~20**: one factor slower than Bohm limit
- (Aharonian+ 17)

✓Cassiopeia A

- **η~1** @forward shock
- **η>3** @reflection shock
- (Sato+ 18)

✓RX J1713

- **η~1**: effective acceleration
- Strong TeV gamma-ray emission
- (Tanaka+ 08; this work)

Bohm diffusion: X/γ-ray

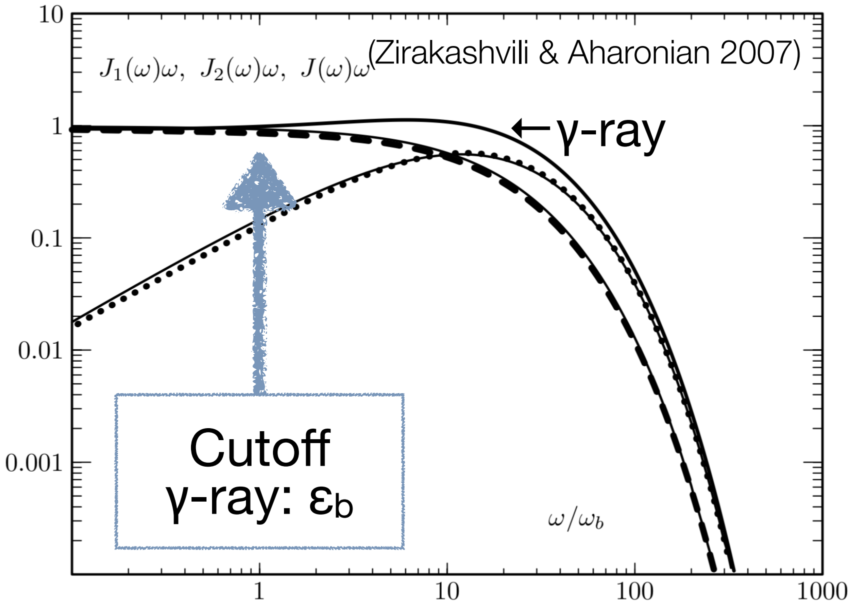
(Zirakashvili & Aharonian 2007)

※Assuming leptonic model, T=2.7 K (CMB)

Bohm diffusion	Electron	X-ray	γ-ray
$D_{\mathrm{Bohm}}(E) = \frac{c}{3q}\eta B^{-1} E$	$\frac{dN_e}{dE} \propto E^{-3}\left[1+0.66\left(\frac{E}{E_0}\right)^{\frac{5}{2}}\right]^{\frac{9}{5}} \exp\left[-\left(\frac{E}{E_0}\right)^2\right]$ $E_0 \propto \eta^{-\frac{1}{2}} B^{-\frac{1}{2}} u_1$	$\frac{dN^{\mathrm{Syn}}}{d\varepsilon} \propto \varepsilon^{-2}\left[1+0.46\left(\frac{\varepsilon}{\varepsilon_0}\right)^{0.6}\right]^{11/4.8} \exp\left[-\sqrt{\frac{\varepsilon}{\varepsilon_0}}\right.$ $\varepsilon_0 \propto \eta^{-1} u_1^2$	$\frac{dN^{\mathrm{IC}}}{d\varepsilon} \propto \left(\frac{\varepsilon}{\varepsilon_b}\right)^{-2}\left[1+0.36\left(\frac{\varepsilon}{\varepsilon_b}\right)^{0.7}\right]^{15/5.6} \exp\left[-\sqrt{\frac{\varepsilon}{\varepsilon_b}}\right.$ $\varepsilon_b \propto \eta^{-1} u_1^2 B^{-1} T$

Model

Electron: loss (synch. cooling) limited
Gamma-ray: Inverse Compton scattering

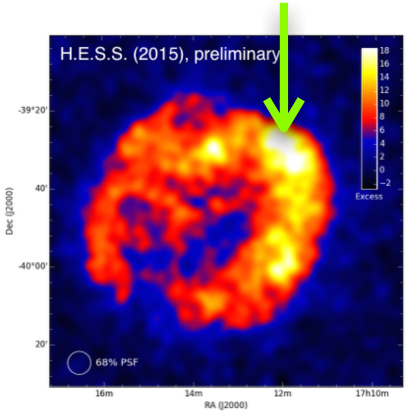


(Zirakashvili & Aharonian 2007)

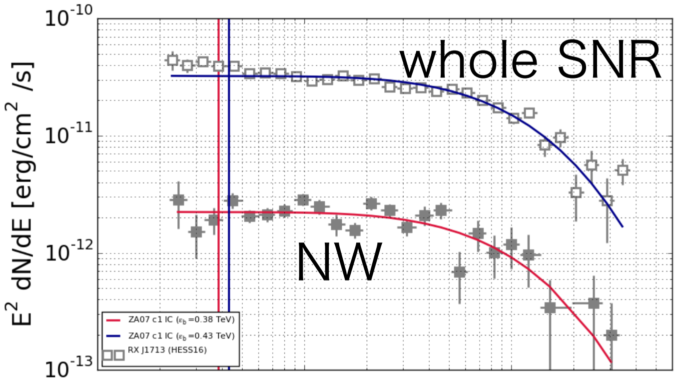
Observation

e.g.) RX J1713.7–3946 whole remnant
Cutoff energy: 0.43 TeV
Shock speed: ~3900 km/s (NT & Uchiyama 16)
→Bohm factor: **η~1(B/100 uG)$^{-1}$**

NW (Region09)



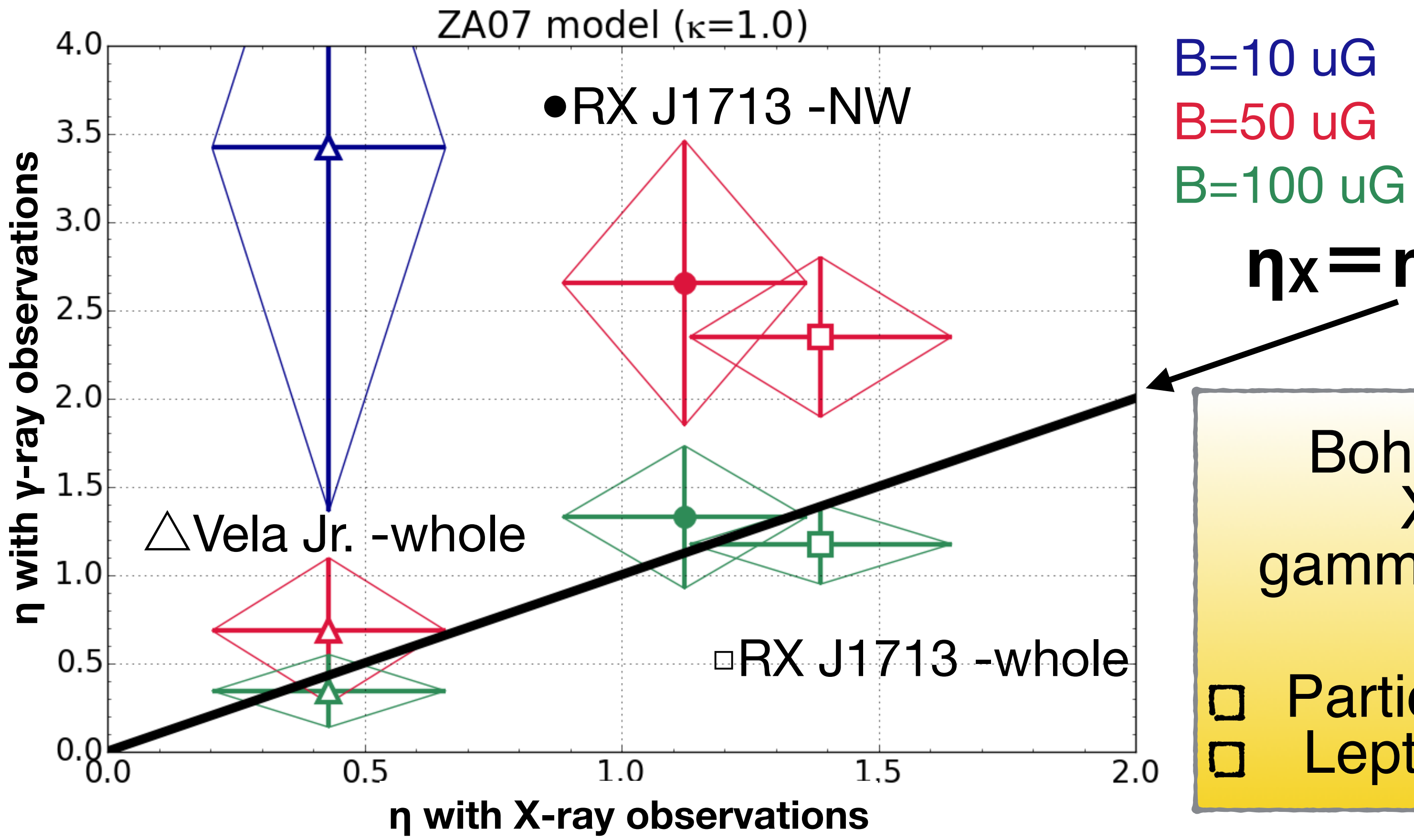
(HESS Coll. 2016)



Bohm diffusion: X/γ-ray

※Assuming leptonic model, T=2.7 K (CMB)

SNR	ε_0 (keV)	ε_b (TeV)	u_1 (km/s)
RX J1713 -whole	0.67 ± 0.02 (Tanaka+ 08)	0.43 ± 0.02	3600–4200
RX J1713 -NW	0.83 ± 0.05	0.38 ± 0.06	3600–4200
Vela Jr. -whole	0.57 ± 0.02 (Fukuyama+ in prep)	0.39 ± 0.04	1500–2500



$\eta_X = \eta_\gamma$ (B~100 uG)

Bohm factor with X-ray and gamma-ray spectrum

↓

☐ Particle acceleration

☐ Leptonic/hadronic?

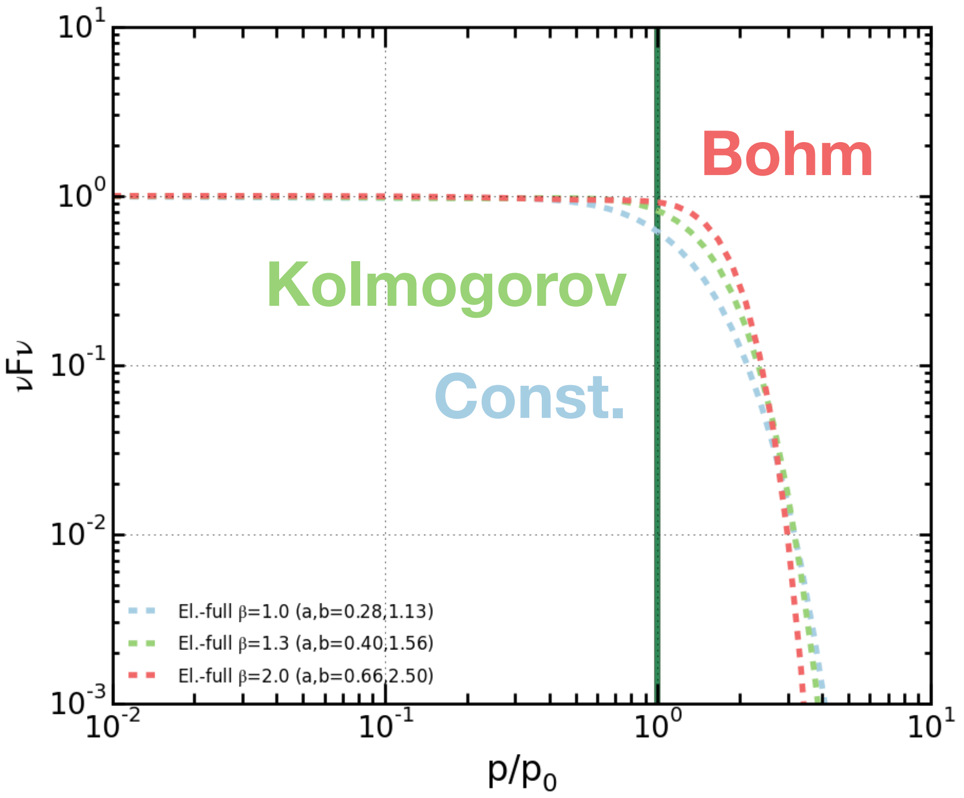
Arbitrary diffusion: Model (Electron)

Diffusion	Arbitrary diffusion	Bohm
Coefficient: D(E)	$D_{\mathrm{Bohm}}(E_c)\left(\frac{E}{E_c}\right)^{\alpha}$	$D_{\mathrm{Bohm}}(E) = \eta\frac{c}{3qB}E$
Electron: dN$_e$/dE	$E^{-3}\left[1+a\left(\frac{E}{E_0}\right)^{b}\right]^{c}\exp\left[-\left(\frac{E}{E_0}\right)^{\alpha+1}\right]$	$E^{-3}\left[1+0.66\left(\frac{E}{E_0}\right)^{5/2}\right]^{9/5}\exp\left[-\left(\frac{E}{E_0}\right)^{2}\right]$

※Loss-limited electrons around SNR shock in arbitrary diffusion regime.

		Electron	
α		a	b
0	Constant	0.28	1.1
1/3	Kolmogorov	0.40	1.6
1	Bohm	0.66	2.5

note: b*c = 4.5
α=1 from ZA07; α=0, 1/3 from Blasi10



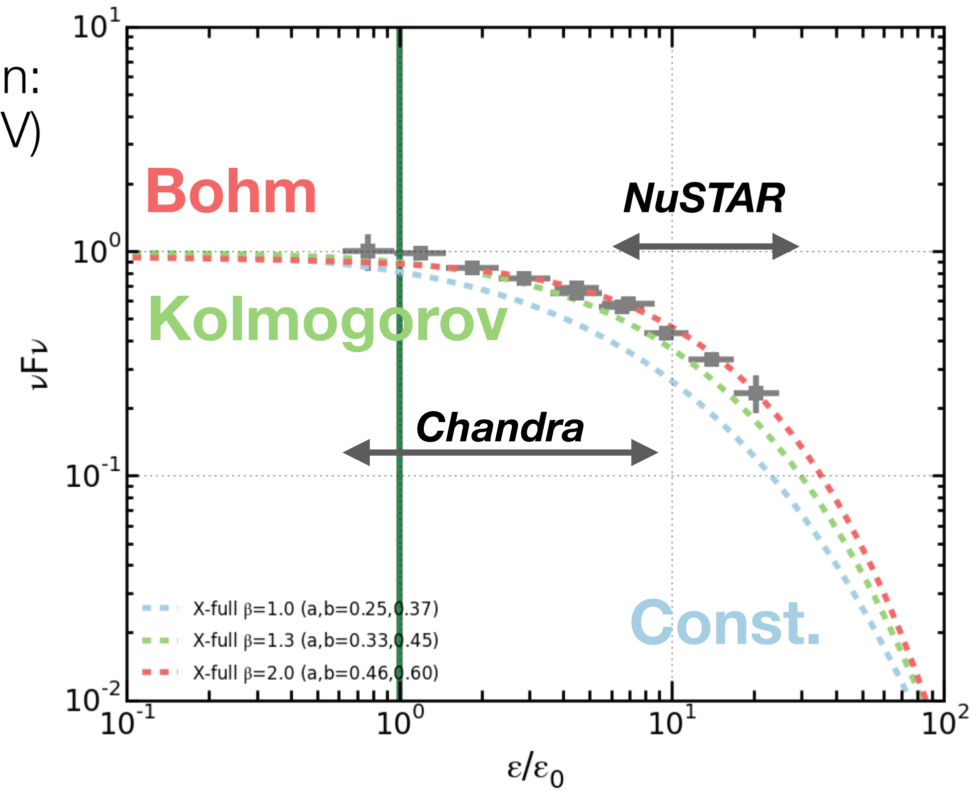
Arbitrary diffusion: Model (X-ray)

Diffusion	Arbitrary diffusion	Bohm
Coefficient: D(E)	$D_{\mathrm{Bohm}}(E_c)\left(\frac{E}{E_c}\right)^{\alpha}$	$D_{\mathrm{Bohm}}(E) = \eta\frac{c}{3qB}E$
Synchrotron X-ray: $dN_{\mathrm{synch}}/d\varepsilon$	$\varepsilon^{-2}\left[1+a\left(\frac{\varepsilon}{\varepsilon_0}\right)^{b}\right]^{c}\exp\left[-\left(\frac{\varepsilon}{\varepsilon_0}\right)^{\frac{\alpha+1}{\alpha+3}}\right]$	$\varepsilon^{-2}\left[1+0.46\left(\frac{\varepsilon}{\varepsilon_0}\right)^{0.6}\right]^{11/4.8}\exp\left[-\left(\frac{\varepsilon}{\varepsilon_0}\right)^{1/2}\right]$

Observation:
RX J1713.7–3946 NW (0.5–20 keV)

		Synch. X-ray	
α		a	b
0	Constant	0.25	0.37
1/3	Kolmogorov	0.33	0.45
1	Bohm	0.46	0.60

note: b*c = (α+10)/2(α+3)
α=1 from ZA07; α=0, 1/3 from Blasi10



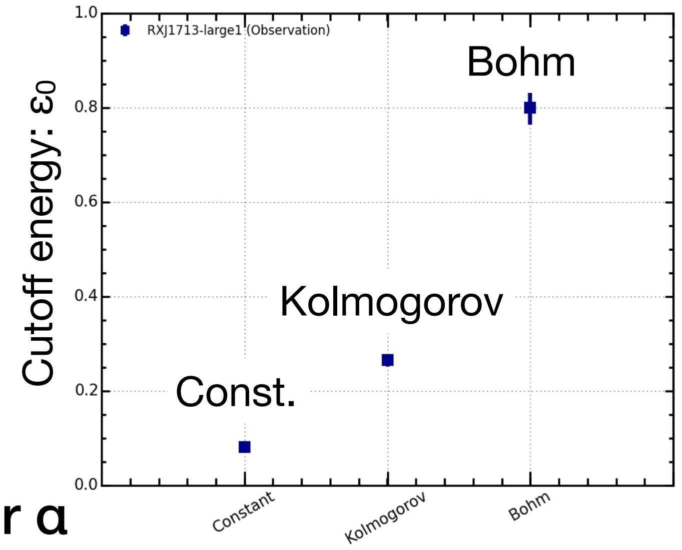
Arbitrary diffusion: Result

e.g.) RX J1713-NW

-Energy band: 0.5–7 keV (Chandra) + 3–20 keV (NuSTAR)

-Model : wabs * loss-limited synch.

Diffusion (α)	N_H (10^{22} cm^{-2})	ε_0 (keV)	$\chi^2_{\rm red}$ (dof)
Constant (0)	0.8±0.01	0.08±+0.01	1.556 (752)
Kolmogorov (1/3)	0.79±0.01	0.26±0.01	1.531 (752)
Bohm (1)	0.78±0.01	$0.8^{+0.04}_{-0.03}$	1.519 (752)



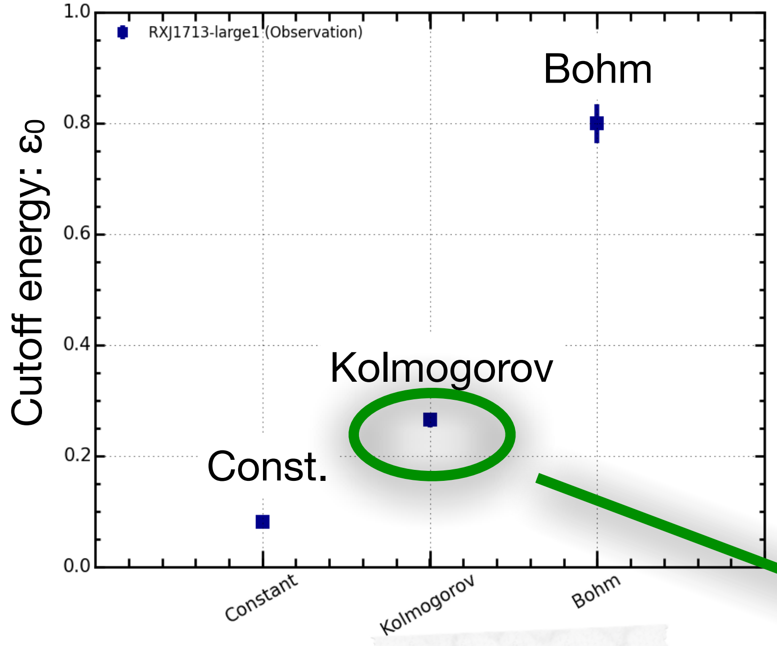
※ Hard X-ray (NuSTAR) observation is responsible for α

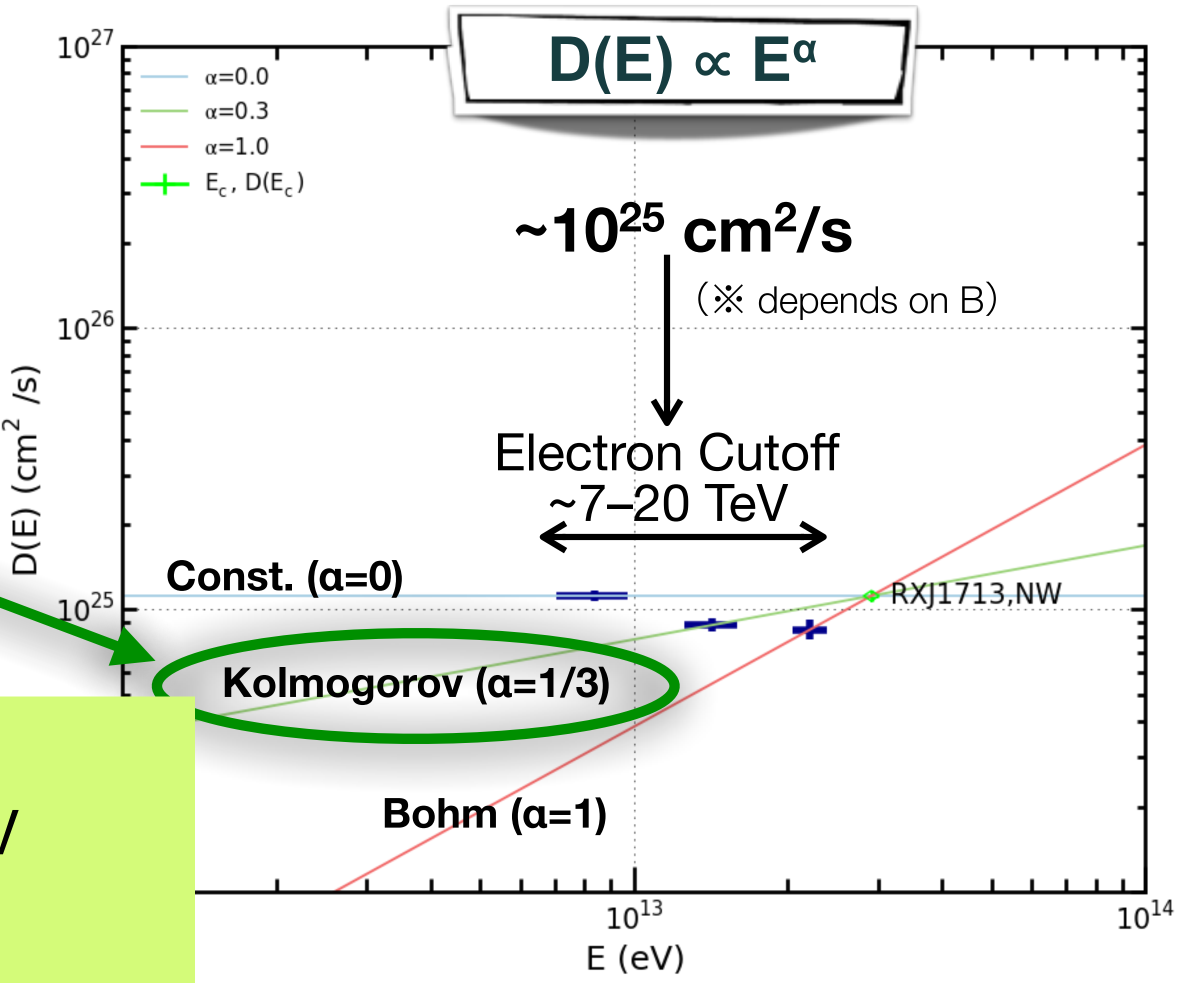
SNR	NuSTAR (ks)	Constant (α=0)	Kolmogorov (α=1/3)	Bohm (α=1)
RXJ1713-NW	50	×	✔	✔
G1.9-whole	350	×	×	✔
Vela Jr.-NW	170	×	✔	✔
SN1006-NE	200	×	✔	×

- ☐ Constant diffusion is excluded at 3σ for all SNRs
- ☐ Bohm diffusion is not valid for SN1006-NE?
- ☐ Deeper observation will determine α-parameter

Arbitrary diffusion: Result (RXJ1713-NW)

- Diffusion type (α-parameter) cannot be significantly constrained.
- How about the absolute value of diffusion coefficient at E_0?

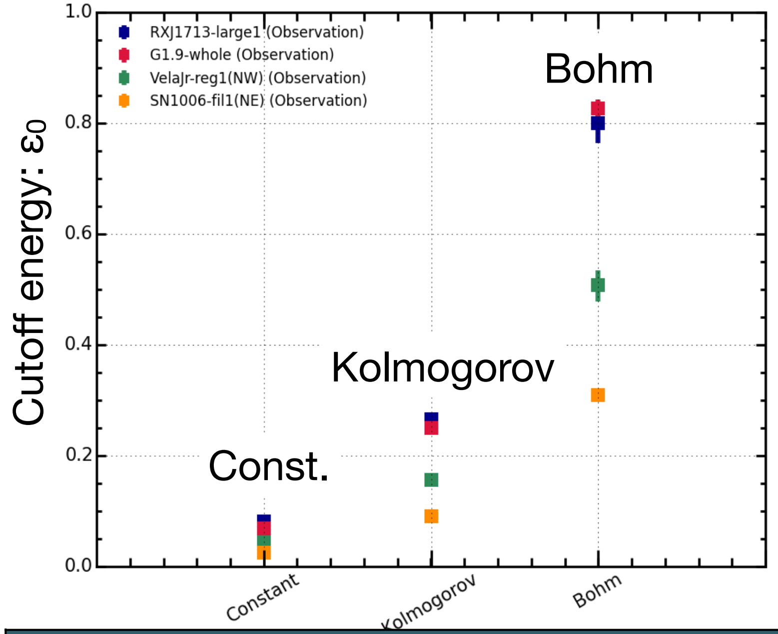


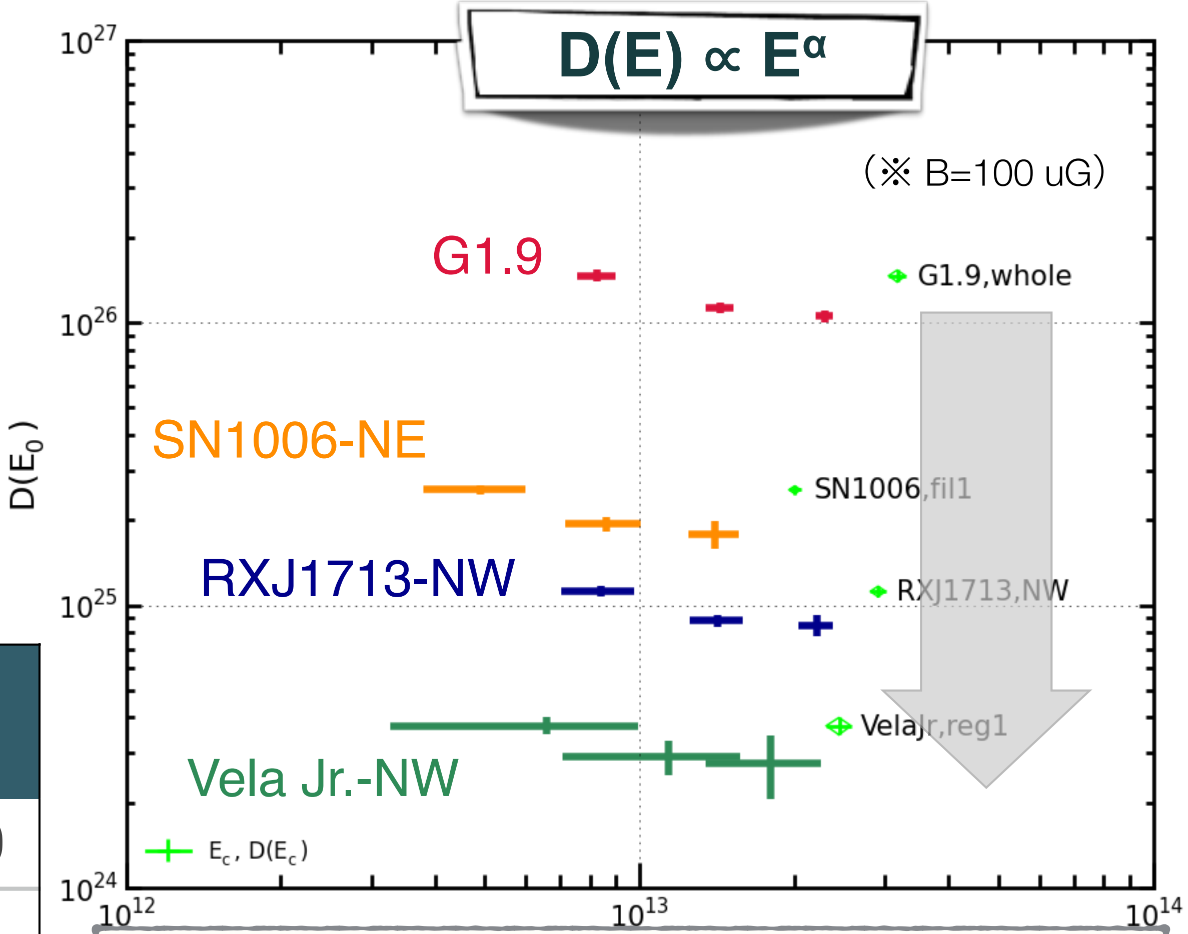


e.g.) Kolmogorov (α=1/3)
X-ray cutoff : ε_0~0.3 keV
↓ B=100 uG
Electron cutoff : E_0~10 TeV
Diffusion coeff : $D(E_0)$~10^{25} cm^2/s

Arbitrary diffusion: Result (RXJ1713-NW)

- Diffusion type (α-parameter) cannot be significantly constrained.
- How about the absolute value of diffusion coefficient at E_0?





	D(E_0) (cm^2/s)	E_0 (TeV)
G1.9-whole	**~10^{26}**	8–20
SN1006-NE	**~2×10^{25}**	4–15
RX J1713-NW	**~10^{25}**	7–20
Vela Jr.-NW	**~3×10^{24}**	3–20

☐ (ε_0, α) → (E_0, D(E_0))
☐ E_0 ~ 4–20 TeV for all (B=100 uG)
☐ D(E_0) is larger in younger SNR?

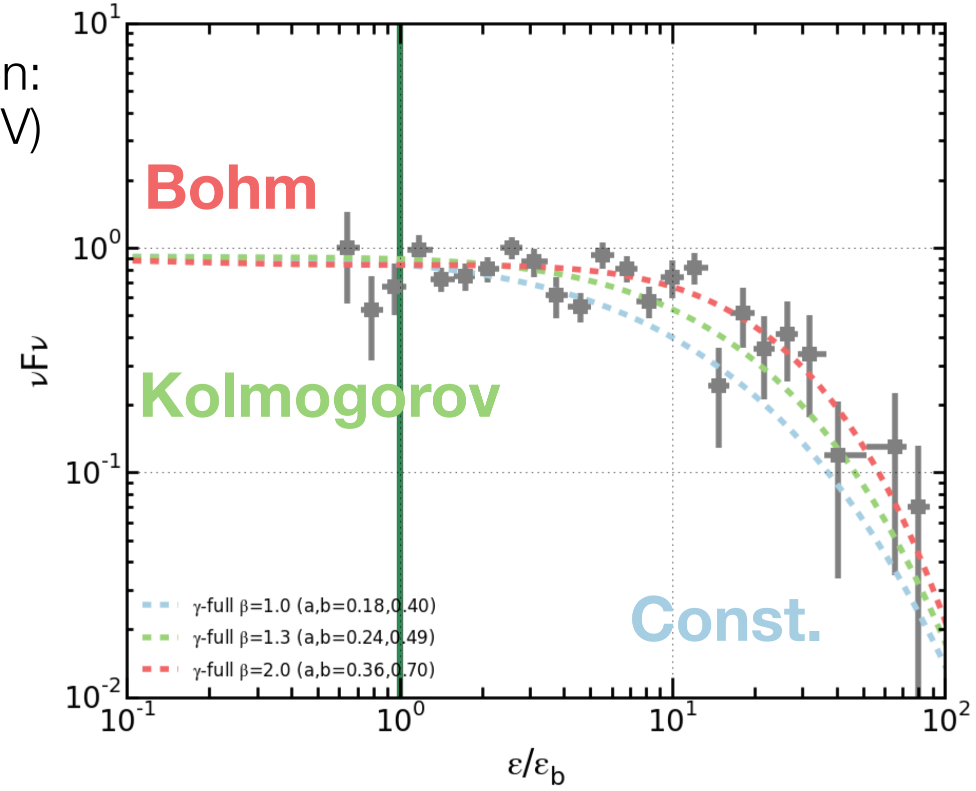
Arbitrary diffusion: Model (γ-ray)

Diffusion	Arbitrary diffusion	Bohm
Coefficient: D(E)	$D_{\mathrm{Bohm}}(E_c)\left(\frac{E}{E_c}\right)^{\alpha}$	$D_{\mathrm{Bohm}}(E) = \eta\frac{c}{3qB}E$
Inverse Compton γ-ray: $dN_{IC}/d\varepsilon$	$\varepsilon^{-2}\left[1+a\left(\frac{\varepsilon}{\varepsilon_b}\right)^{b}\right]^{c}\exp\left[-\left(\frac{\varepsilon}{\varepsilon_b}\right)^{\frac{\alpha+1}{\alpha+3}}\right]$	$\varepsilon^{-2}\left[1+0.36\left(\frac{\varepsilon}{\varepsilon_b}\right)^{0.7}\right]^{15/5.6}\exp\left[-\left(\frac{\varepsilon}{\varepsilon_b}\right)^{1/2}\right]$

Observation:
RX J1713.7–3946 NW (0.25–40 TeV)

		IC γ-ray	
α		a	b
0	Constant	0.18	0.40
1/3	Kolmogorov	0.24	0.49
1	Bohm	0.36	0.70

note: b*c = (2α+13)/2(α+3), **Thomson limit**
α=1 from ZA07; α=0, 1/3 from Blasi10



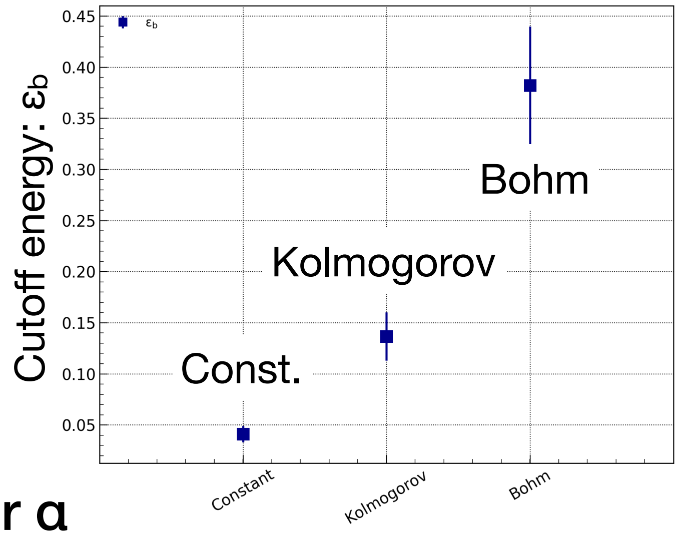
Arbitrary diffusion: Result

e.g.) RX J1713-NW

-Energy band: 0.25–40 TeV (HESS)

-Model : loss-limited IC

Model	Diffusion (α)	ε_b (TeV)	χ^2_{red} (dof)
Loss-limited IC	Constant (0)	0.04±+0.01	34.88 (23)
Loss-limited IC	Kolmogorov (1/3)	0.14±0.02	33.04 (23)
Loss-limited IC	Bohm (1)	0.38±0.06	32.502 (23)



※ Hard X-ray (NuSTAR) observation is responsible for α

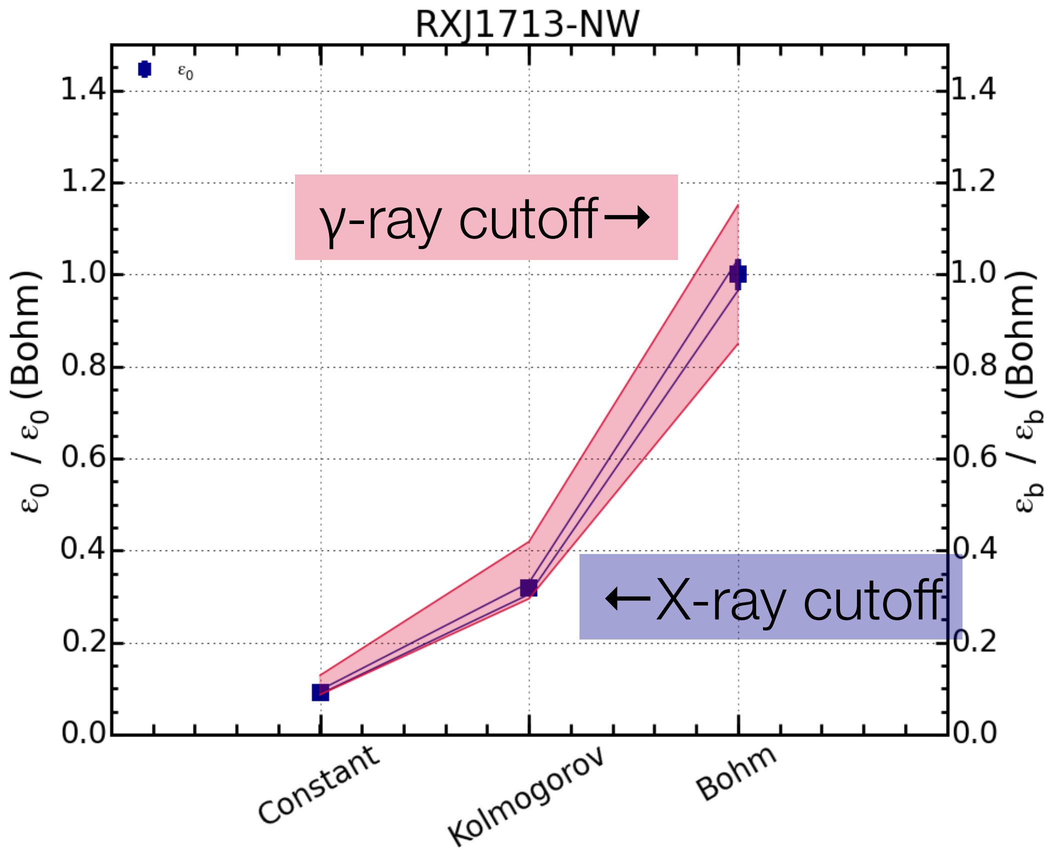
SNR	HESS (hr)	Constant (α=0)	Kolmogorov (α=1/3)	Bohm (α=1)
RXJ1713-NW	120	✔	✔	✔
RXJ1713-whole	120	×	✔	✔
Vela Jr.-whole	20	×	✔	✔

☐No constraint on α-parameter (α = 0 is excluded for entire remnants)
☐Deeper observation or CTA will determine α-parameter
☐Necessary to include Klein-Nishina effect

Arbitrary diffusion: X/γ

- Compare cutoff shape of synchrotron X-ray and IC gamma-ray.

e.g.) RXJ1713-NW



Cutoff energy
normalized by
Bohm-diffusion value
(B=110 uG)

☐ If B~100 uG, same degeneracy of cutoff shape parameters (ε_0, α) for X and γ → supportive for leptonic?
☐ X/γ flux ratio is not explained when B~100 uG (leptonic issue)
☐ New method to test leptonic/hadronic: using only cutoff shape

Summary

- Estimated the diffusion coefficient on SNR shock in RX J1713.7–3946 and Vela Jr. (using X/γ-ray observations) and in G1.9 and SN1006 (using X-ray observations only).

✤ Bohm diffusion

- Bohm factor (η) obtained by X-ray and gamma-ray are comparable for B~100 uG.

✤ Arbitrary diffusion

- Obtained the spectral model of synchrotron and IC radiation from loss (synch. cooling)-limited electrons in arbitrary diffusion regime (Zirakashvili & Aharonian 2007; Blasi 2010)
- Constrained on the diffusion coefficient for electrons with the maximum energy (4–30 TeV for B=100 uG), irrespective of diffusion regime (α-parameter).
- Revealed compatible cutoff shape for the nonthermal X-ray and TeV γ-ray spectra.

✤ Future work

- Deeper observations with NuSTAR and/or CTA can determine with higher accuracy the cutoff shape of X/γ-ray spectra and the diffusion regime.