Supernova remnants II —an odyssey in space after stellar death— @Chania, Crete
Session 4: Shock Physics and Particle Acceleration in SNRs
June, 4th, 2019

Constraint on Diffusion Coefficient at SNR Shock Using Nonthermal X-ray and Gamma-ray Observations

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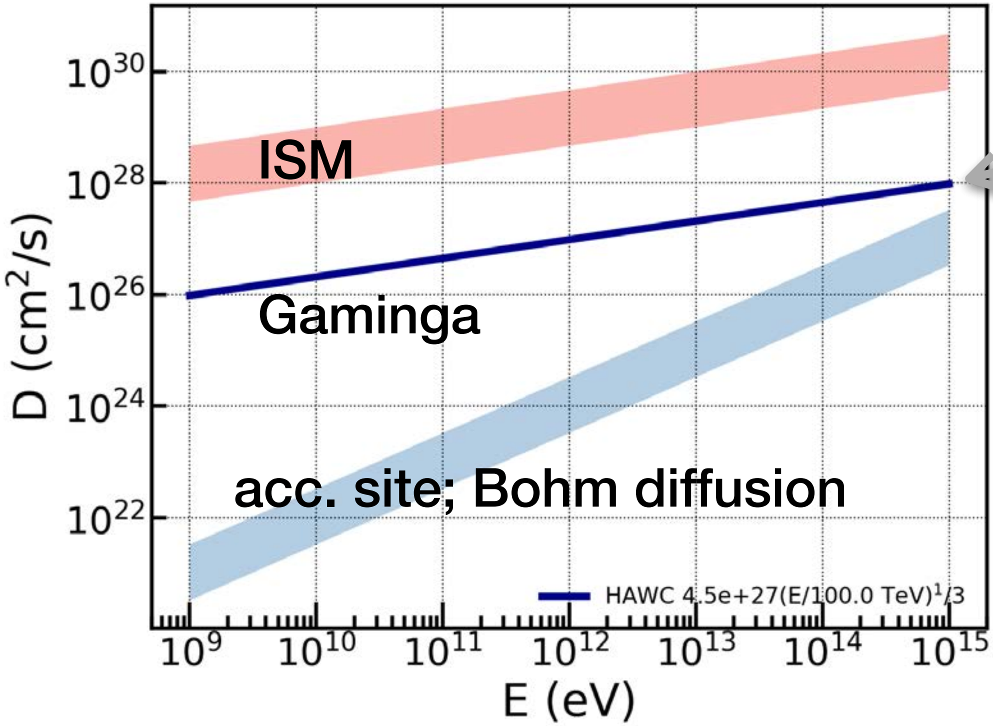
CR diffusion

Diffusion coefficient

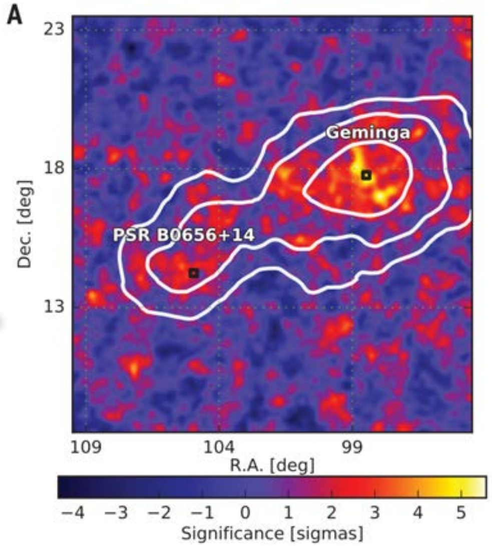
$$D(E) = D_* \left(\frac{E}{E_c} \right)^{\alpha} \ \mathrm{cm^2/s}$$

- α: energy dependence; diffusion type
- D_*: diffusion coefficient at $E=E_c$



"TeV halo" around Geminga (PSR)
(HAWC Coll. 2017)

- size ~ radius of 20 pc
- Electron diffusion
  - α=1/3
  - D^*~4.5x10^{27}
  - E_c=100 TeV



<This talk>
Acceleration site: SNR shock

1. Bohm diffusion (α=1)
2. Arbitrary diffusion (α=0, 1/3, 1)
3. Gamma-ray observations

Bohm diffusion

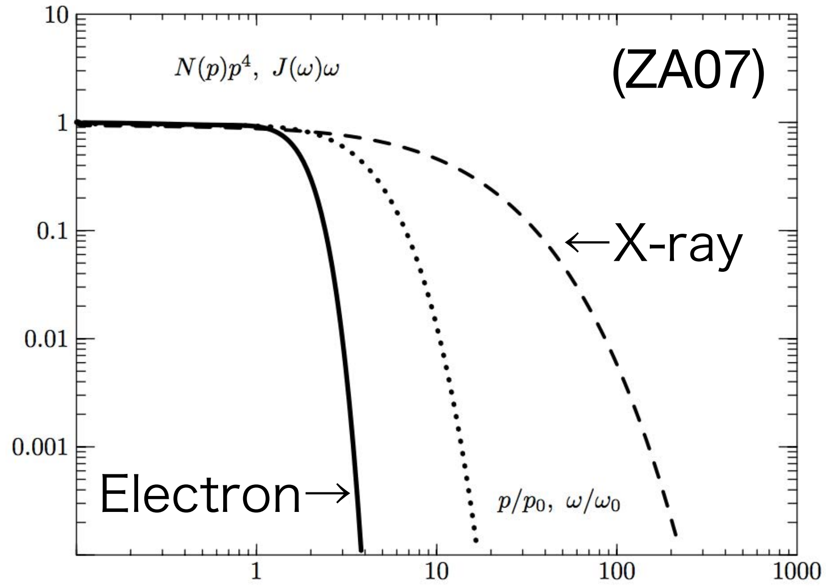
Diffusion around SNR shock

Bohm diffusion

diffusion coefficient: D = η *(gyro radius)*c

η=1 (Bohm limit) “efficient acc.”

η≫1 “inefficient acc.”



Model

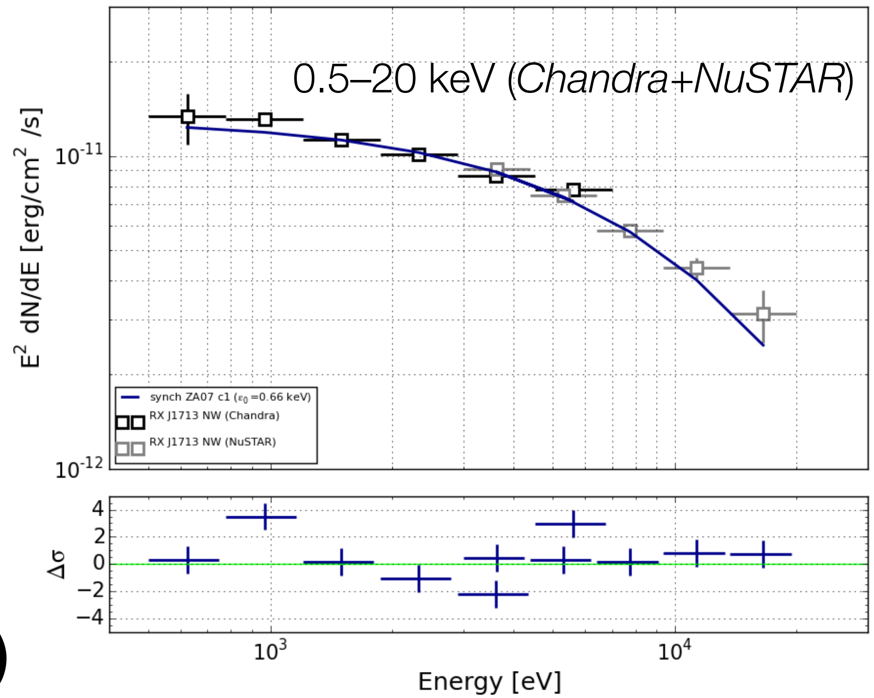
Zirakashvili & Aharonian 2007 (ZA07)

Electron: synch. cooling + Bohm diffusion

X-ray: synchrotron

ε_0-v_{sh} relation:

$$\varepsilon_0 = 0.93 \left(\frac{v_{\rm sh}}{3900\ {\rm km/s}} \right)^2 \eta^{-1}\ {\rm keV}$$



Observation

e.g.) RX J1713.7–3946 NW

Cutoff energy: 1.1 keV

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

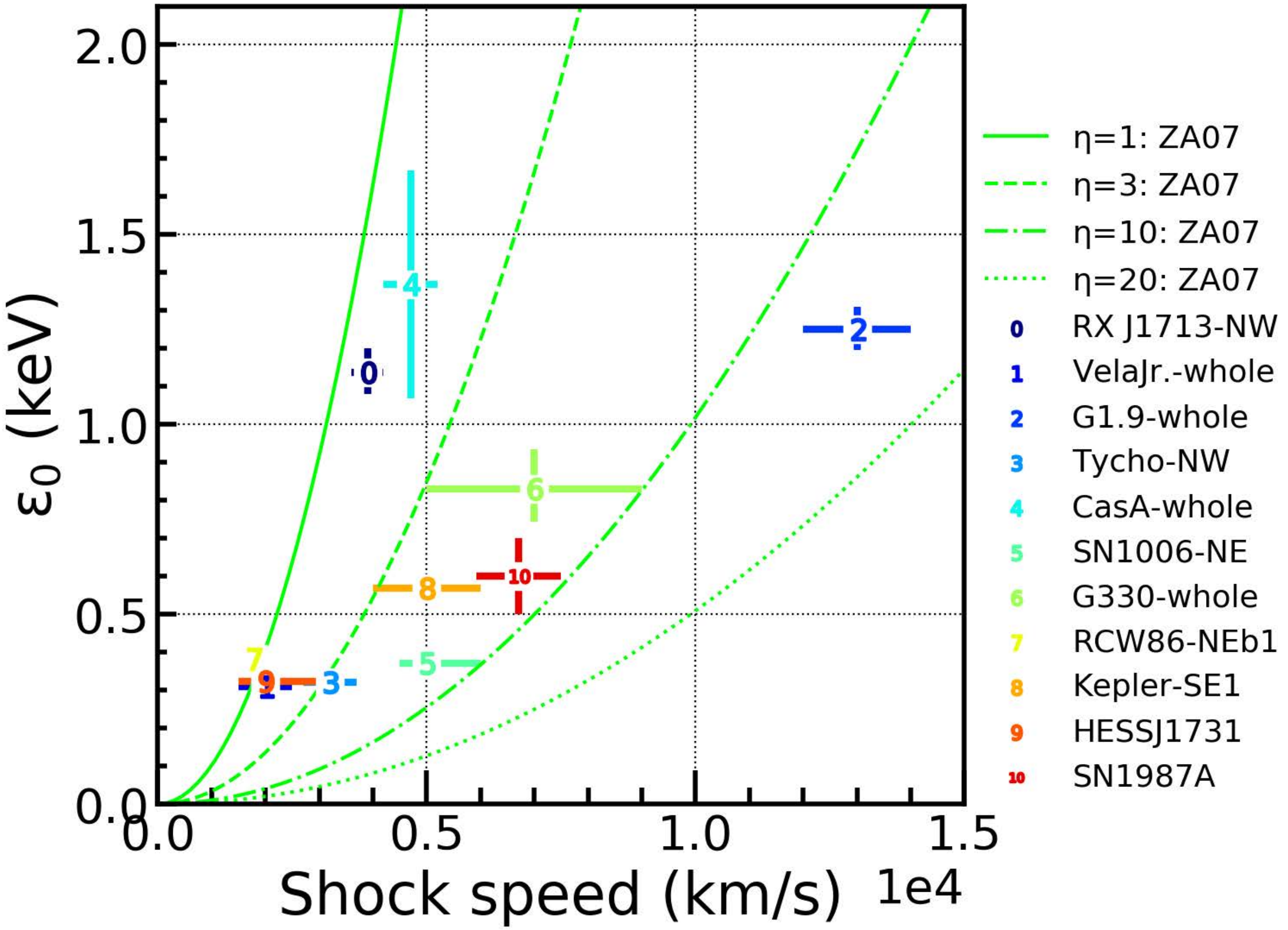
→Bohm factor: **η~1 (Bohm limit)**

Bohm diffusion: young SNR

- Systematical analysis of young Galactic SNRs:
  - **G1.9+0.3**, Cassiopeia A, **Kepler's SNR**, Tycho's SNR, G330.+1.0, SN1006, **RX J1713.7–3946**, RCW 86, Vela Jr., HESSJ 1731 (, SN 1987A)

$$\varepsilon_0 = 0.93\left(\frac{v_{sh}}{3900\ \mathrm{km/s}}\right)^2 \eta^{-1}\ \mathrm{keV}$$

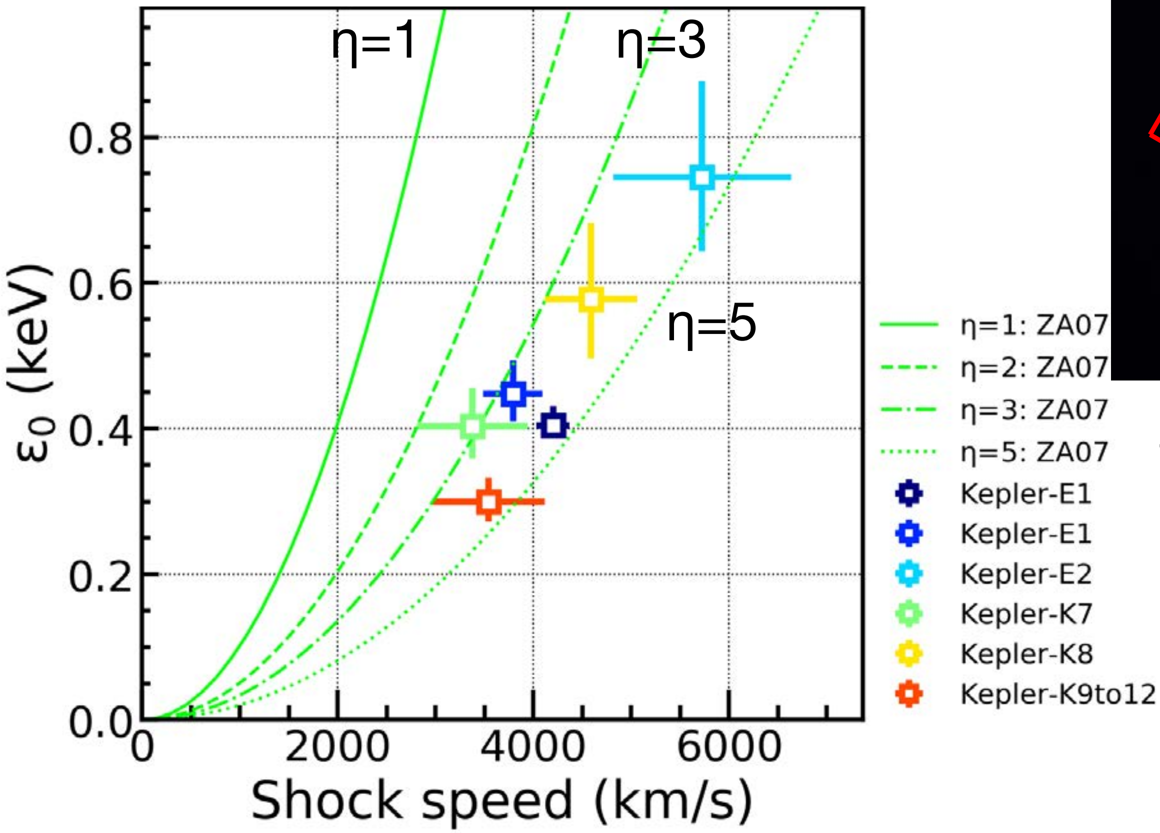
- Assume the hard continuum is synchrotron for SN1987A

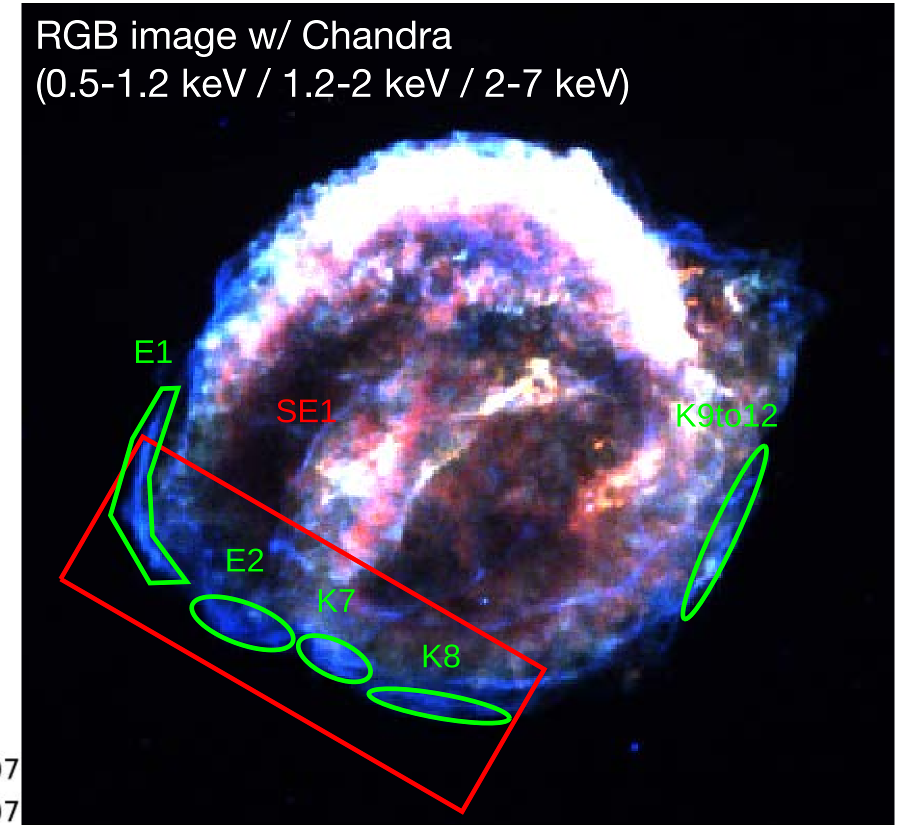


- Spectral fitting:
  - soft X-ray: Chandra/ XMM-Newton/Suzaku
  - hard X-ray: NuSTAR
  - Model: ZA07 (Bohm diffusion+synchrotron cooling)
- Derived cutoff energy + known shock speed → acceleration efficiency (η)

Acceleration efficiency: Kepler's SNR

- Kepler's SNR (SN 1604)
- Type Ia; shell
- Spectral fitting:
    - Energy: 0.5–7 keV w/ Chandra
    - Model: wabs*(vnei + ZA07)
- Shock speed: Katsuda+ 08, Vink 08





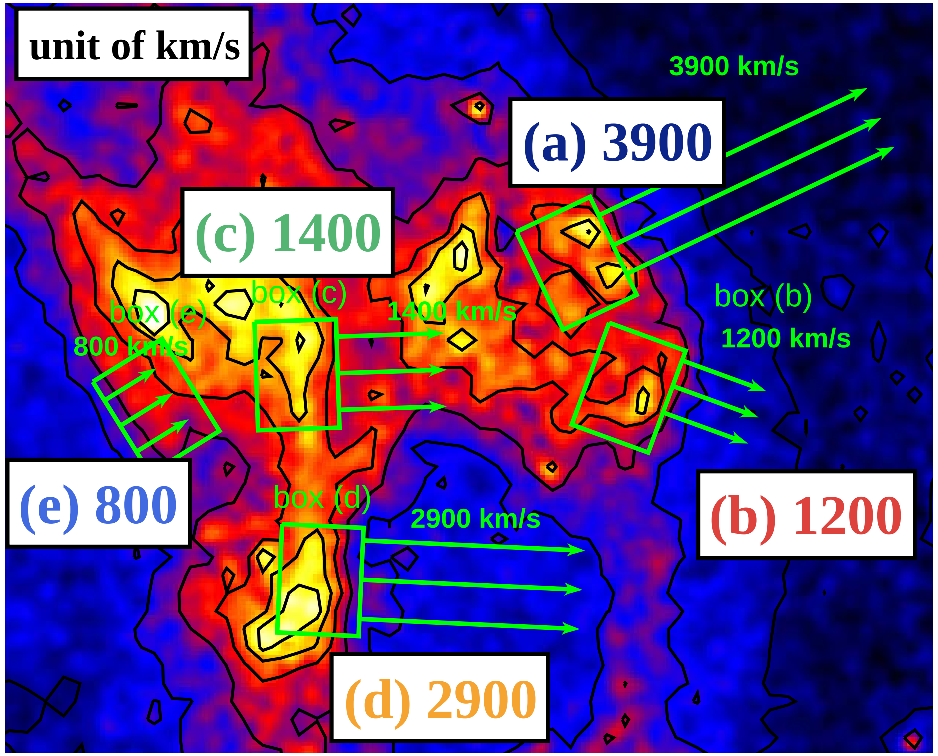
(The sub-regions roughly correspond to those in Katsuda+08)

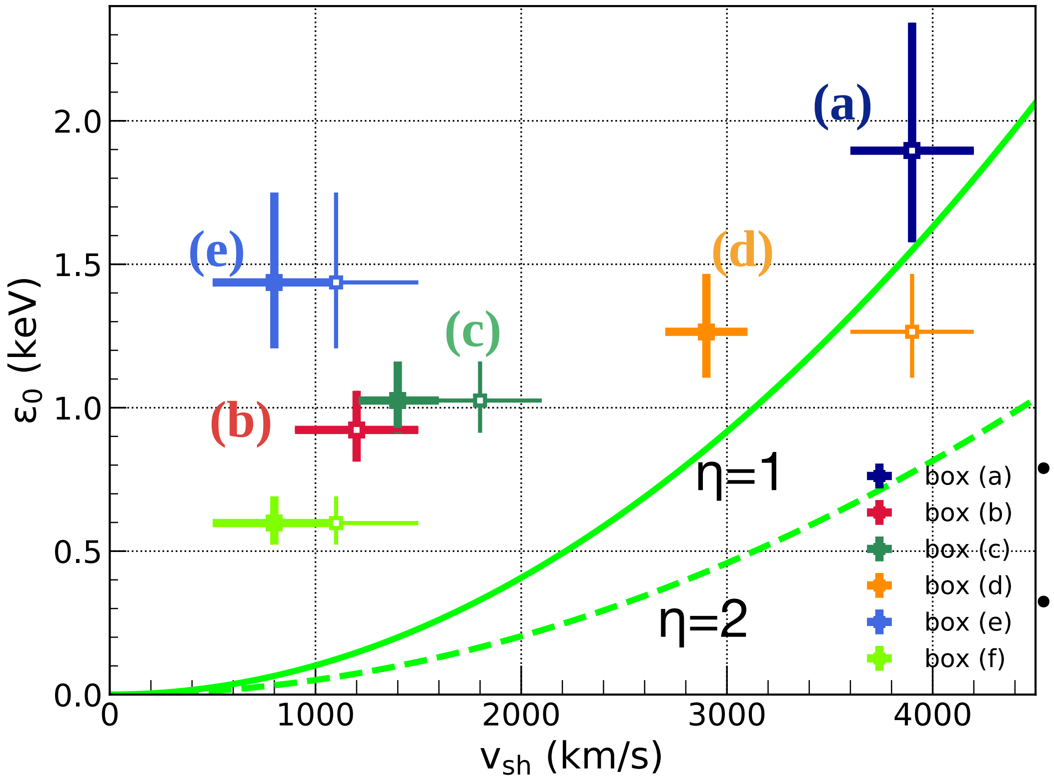
$$\varepsilon_0 = 0.93 \left(\frac{v_{sh}}{3900 \text{ km/s}} \right)^2 \eta^{-1} \text{ keV}$$

Observed ε_0-v_{sh} diagram
→η=3–5

Acceleration efficiency: RX J1713-NW (NT+ 2019)

- RX J1713.7-3946 (~SN 393)
- Type II; shell
- Spectral fitting:
  - Energy: 0.5–7 keV w/ Chandra+NuSTAR
  - Model: wabs* ZA07
- Shock speed: NT & Uchiyama 16



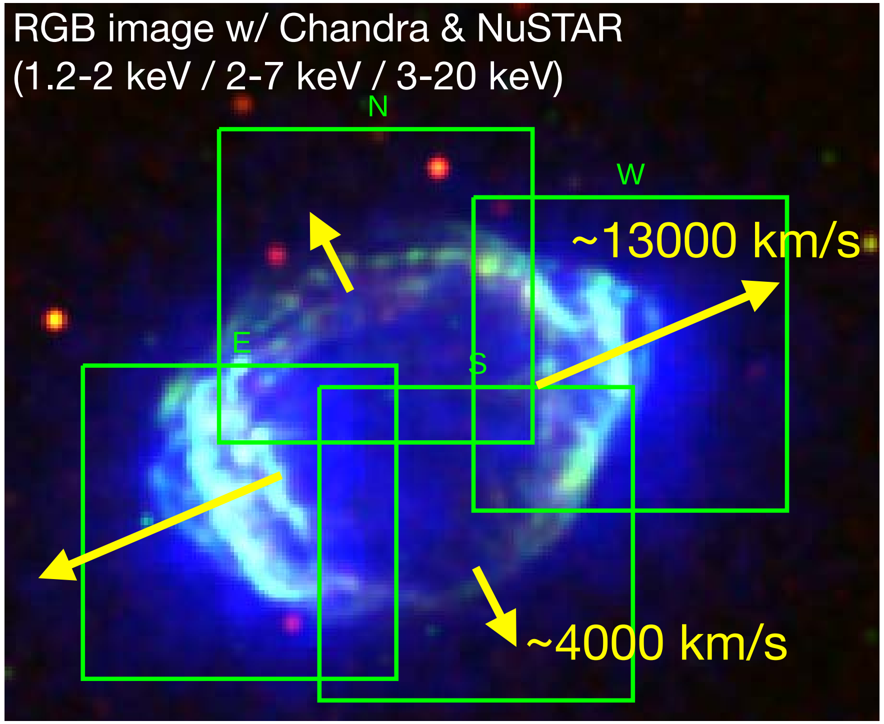


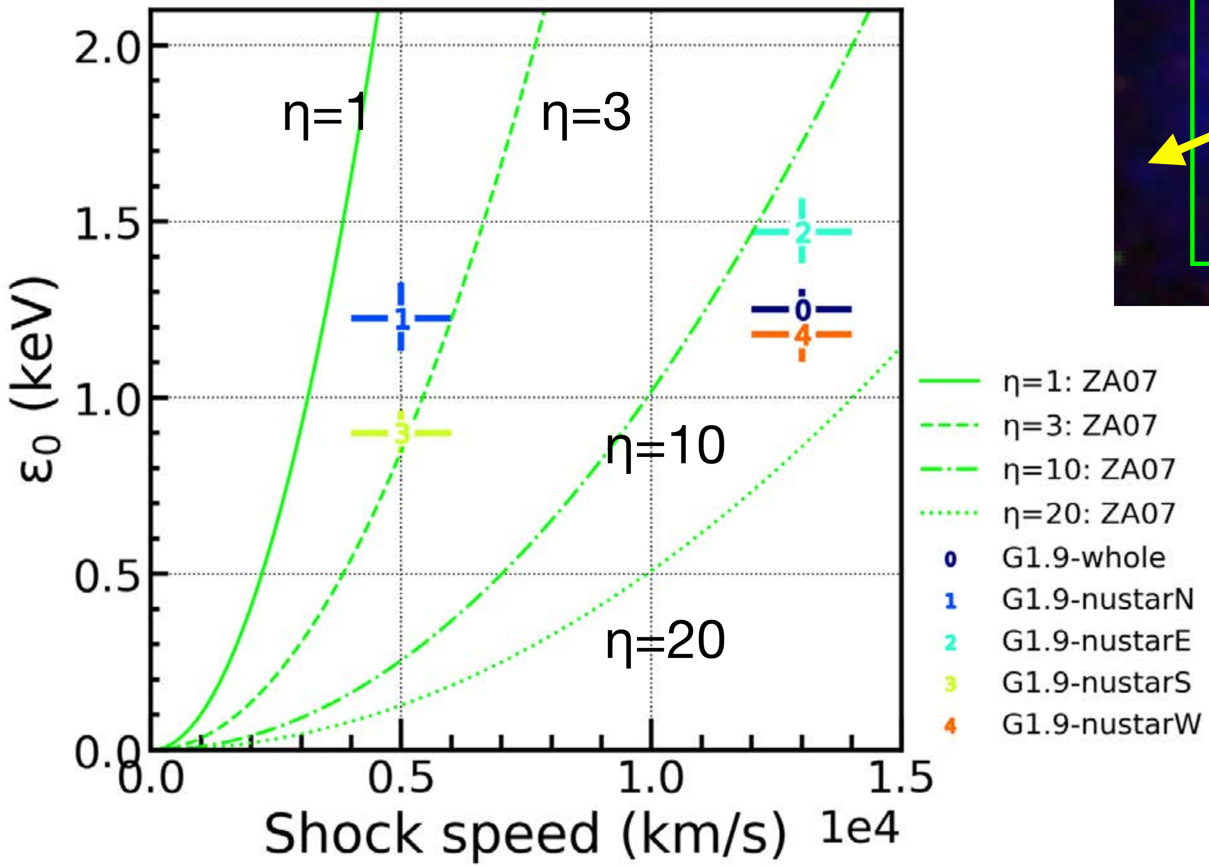
$$\varepsilon_0 = 0.93 \left(\frac{v_{\rm sh}}{3900\ {\rm km/s}} \right)^2 \eta^{-1}\ {\rm keV}$$

- Fast-speed regions: (a) and (d)
  - η~1 → acc. site
- Slow-speed regions: (b), (c) and (e)
  - NOT described with theoretical curve
  - → NOT acc. site; enhanced B-field?

Acceleration efficiency: G1.9

- G1.9+0.3
- The youngest SNR in our Galaxy
- Spectral fitting:
  - Energy: 0.5–50 keV w/ Chandra+NuSTAR
  - Model: wabs* ZA07
- Shock speed: Borkowski+ 17

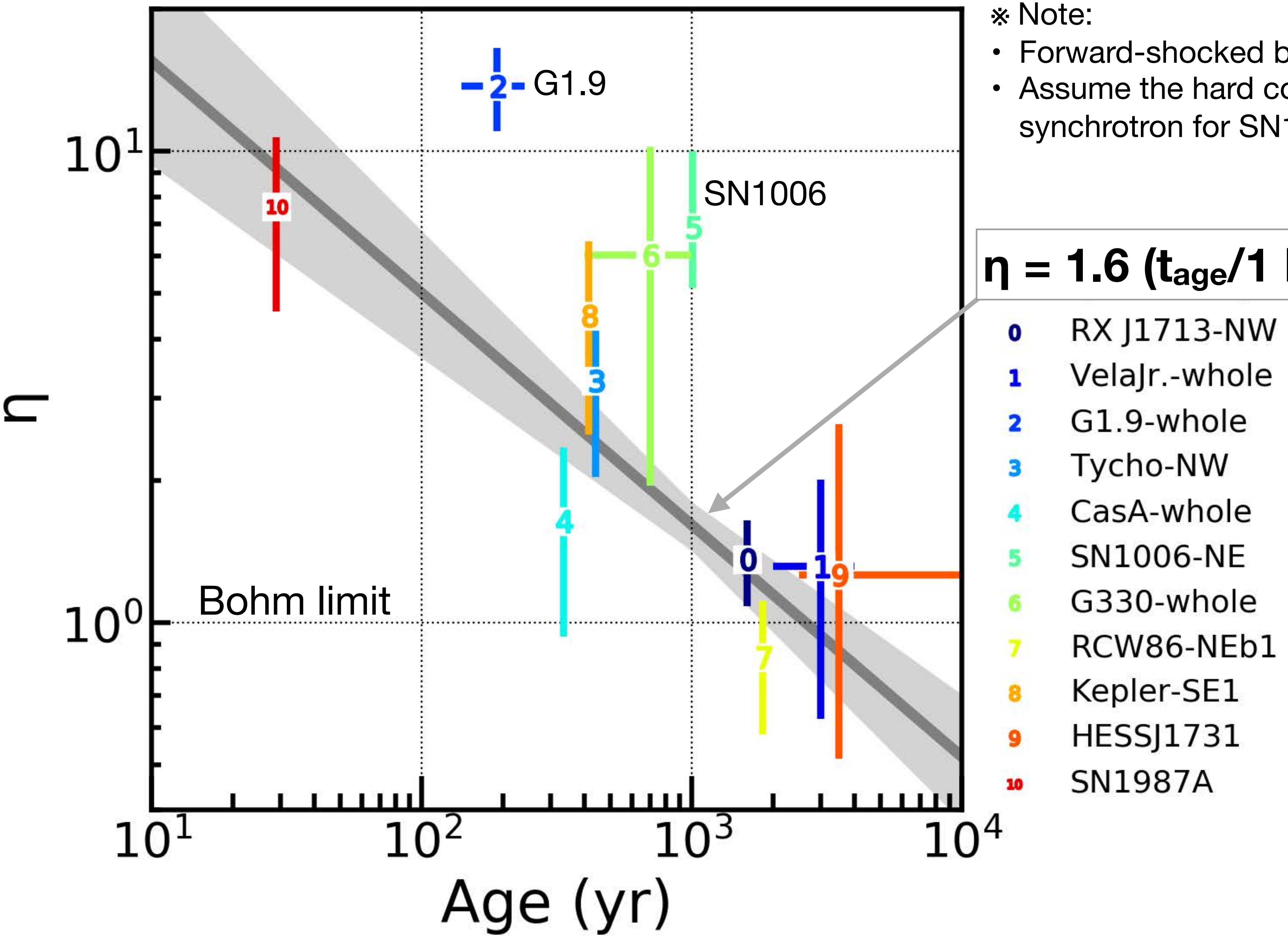




- E and W:
  - η~10–20 (forward shock)
- N and S:
  - η~1–2 (forward shock)
  - η~2–3 (reverse shock)

Cas A (Sato+ 18)
η~1 at forward shock
η~3–8 at reflection shock

Acceleration efficiency: young SNRs (NT+ in prep.)

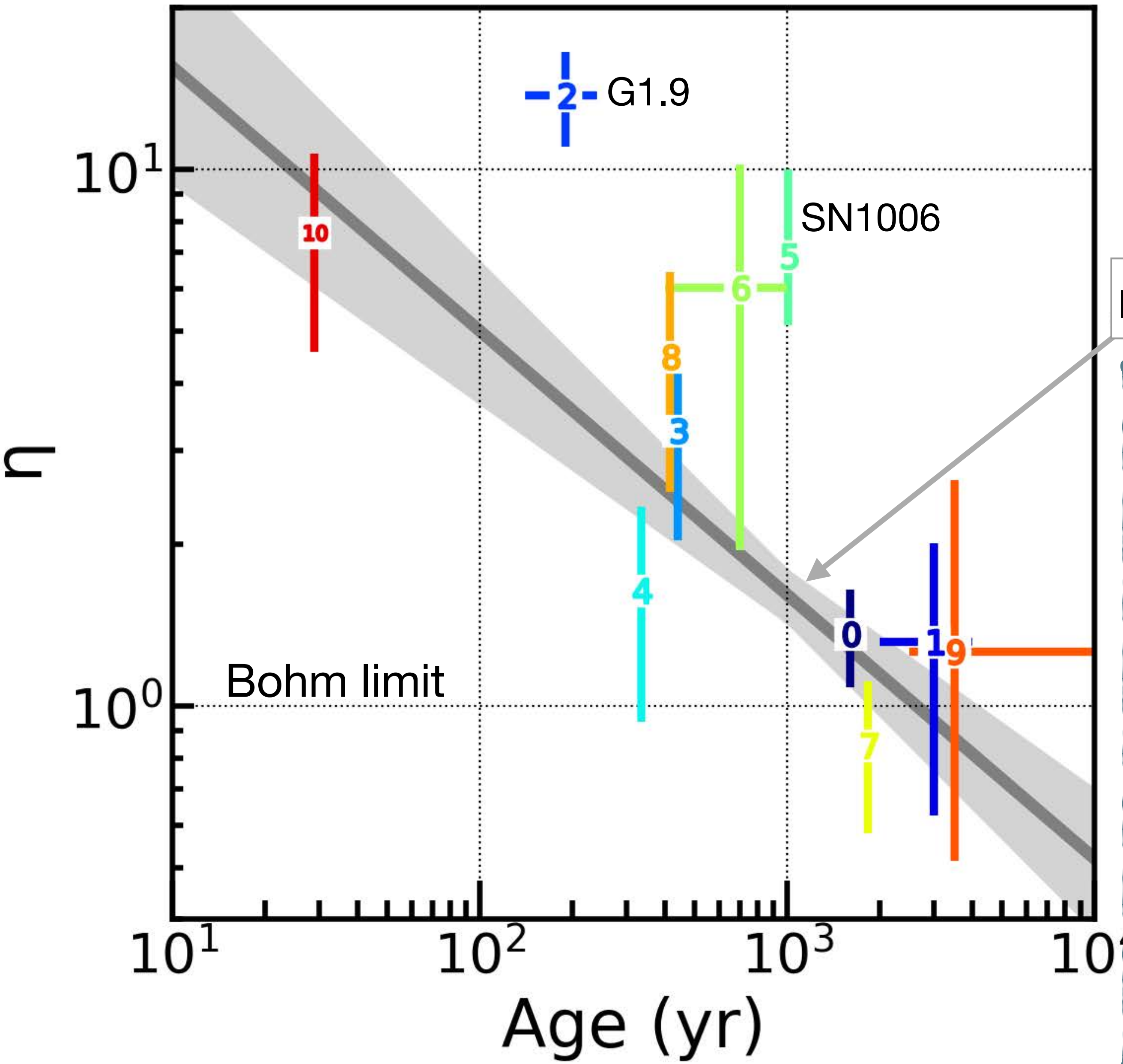


※ Note:

- Forward-shocked bright regions
- Assume the hard continuum is synchrotron for SN1987A

$\eta = 1.6 \, (t_{age}/1 \text{ kyr})^{-0.5}$

Acceleration efficiency: young SNRs (NT+ in prep.)



※ Note:

- Forward-shocked bright regions
- Assume the hard continuum is synchrotron for SN1987A

$\eta = 1.6\ (t_{age}/1\ \mathrm{kyr})^{-0.5}$

- Evolution of η:
- ~100s yr
- not fully turbulent
- inefficient acc. (large η)
- >1 kyr
- turbulent
- efficient acc. (small η)

- Open questions:
  - quantitative interpretation
  - slope of ~0.5

Arbitrary diffusion

Arbitrary diffusion

Diffusion coefficient

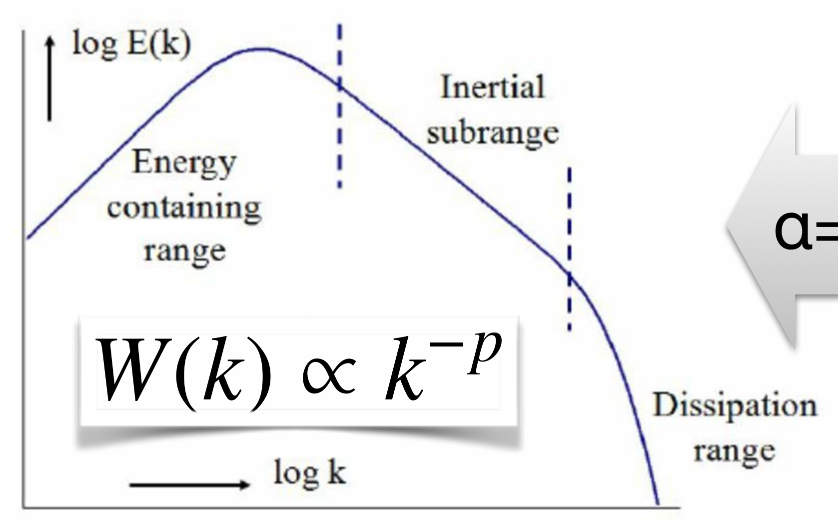
$$D(E) = D_* \left(\frac{E}{E_c}\right)^{\alpha} \ \mathrm{cm^2/s}$$

Bohm diffusion (α=1)

$$D_{\mathrm{Bohm}}(E) = \frac{c}{3q}\eta B^{-1} E$$

- Validity of Bohm diffusion is not confirmed
- CR itself produces B-field turbulence, which determines CR diffusion
- Open issue: what kind of turbulence (p-parameter)?

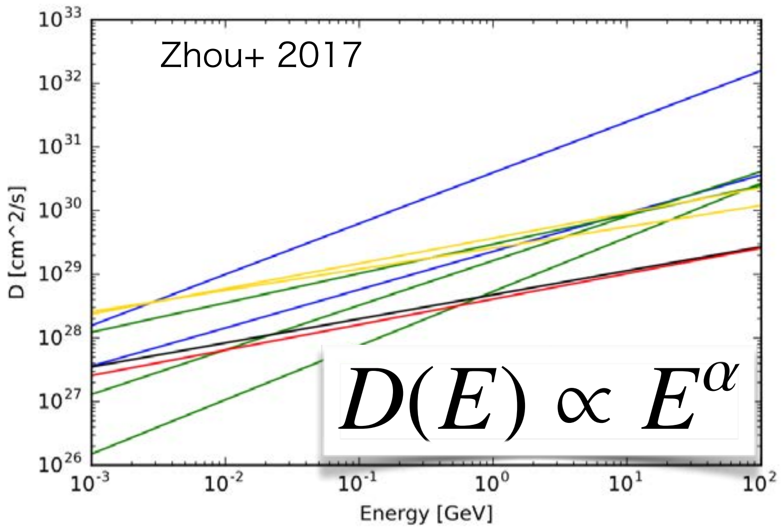
B-field turbulence



$$W(k) \propto k^{-p}$$

α=2-p

CR diffusion



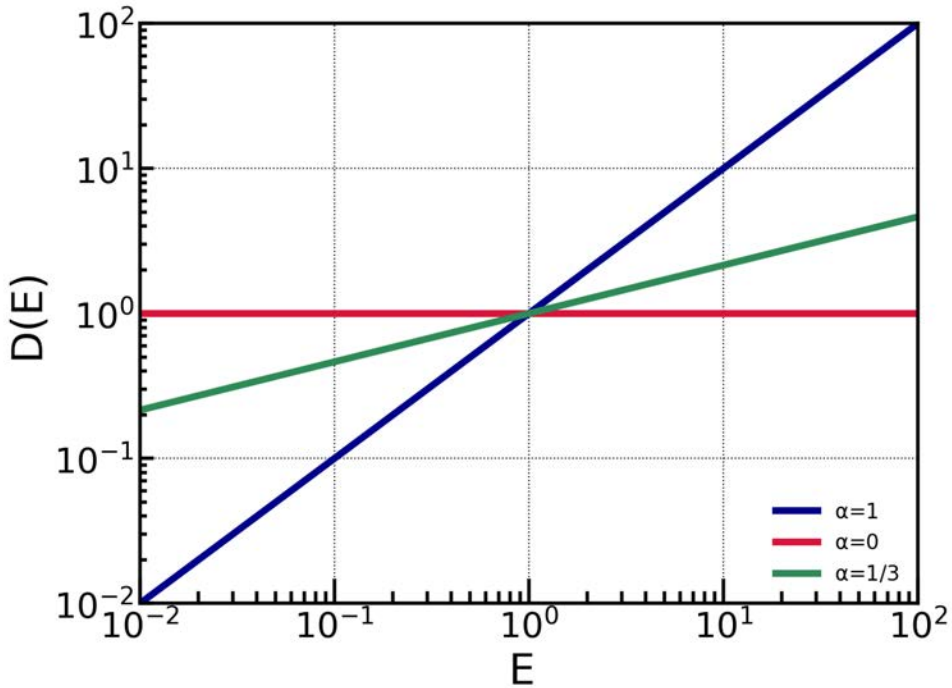
$$D(E) \propto E^{\alpha}$$

Arbitrary diffusion: Model (electron)

Diffusion coefficient

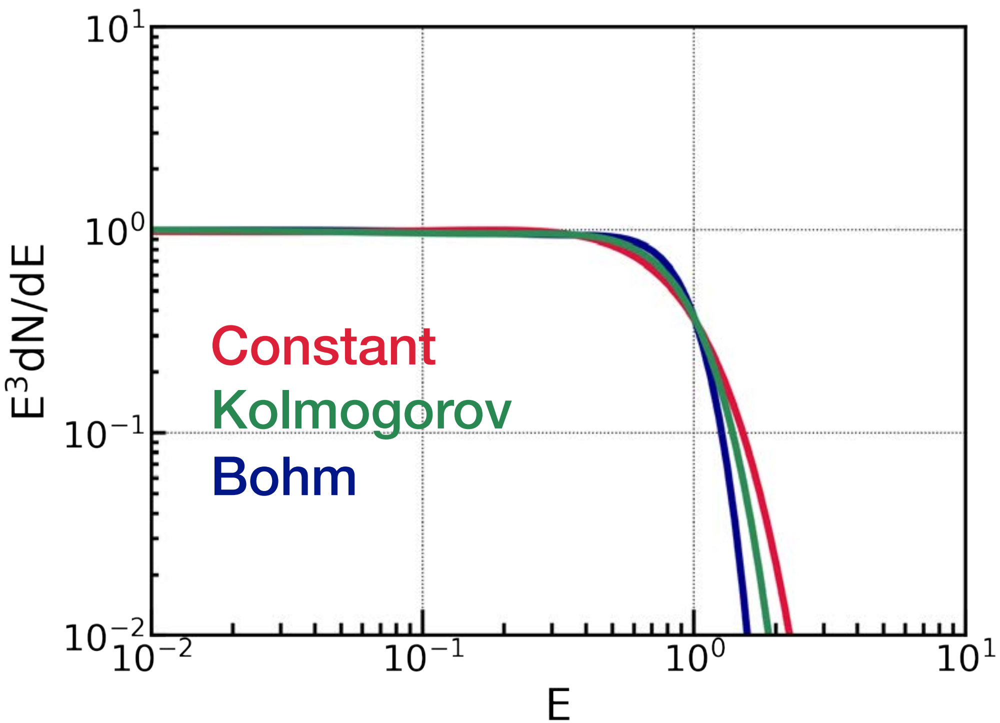
$$D(E) = D_* \left(\frac{E}{E_c}\right)^\alpha \ \mathrm{cm^2/s}$$

α=0	Constant
α=1/3	Kolmogorov
α=1	Bohm



Model (electron)

- SNR shock
- Arbitrary diffusion type (α=0, 1/3, 1)
- Synchrotron cooling
- α=0, 1/3 → Blasi 2010
- α=1 → Zirakashvili & Aharonian 2007



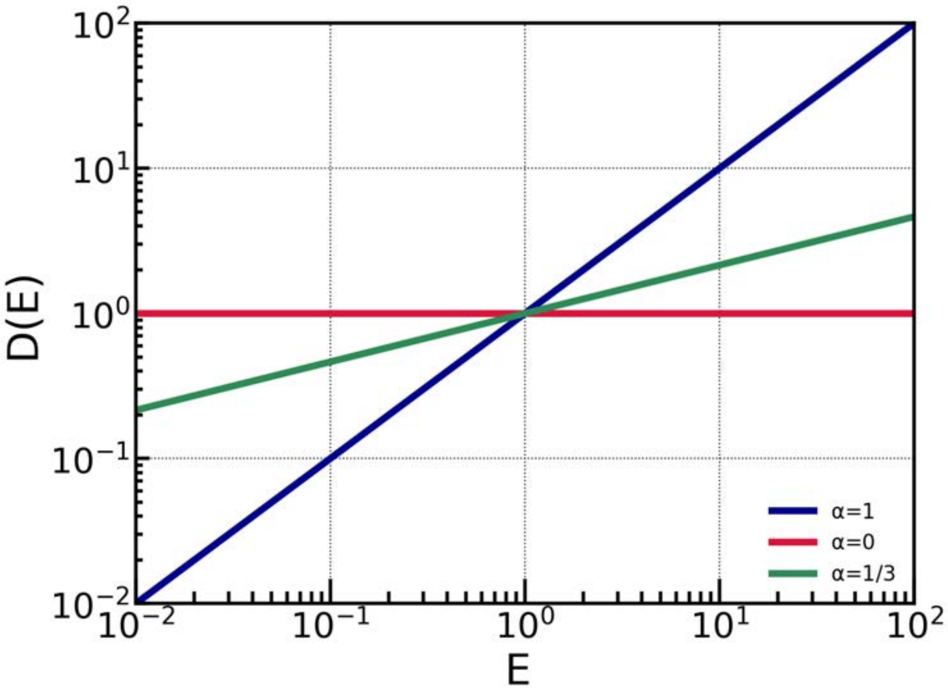
※Cutoff shape depends on α!

Arbitrary diffusion: Model (X-ray)

Diffusion coefficient

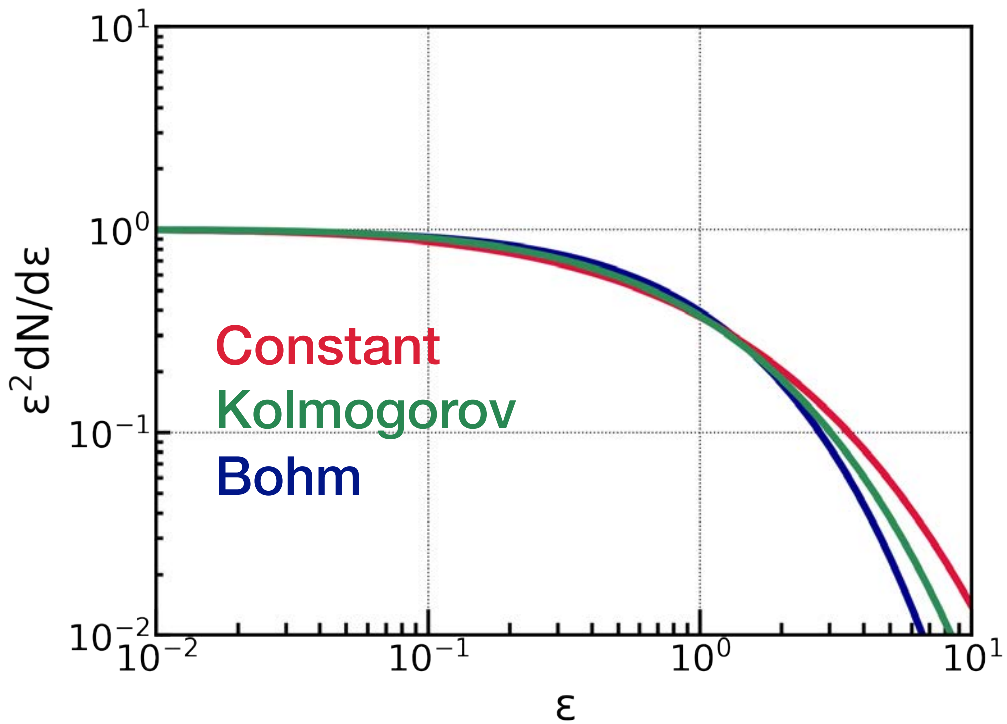
$$D(E) = D_* \left(\frac{E}{E_c}\right)^{\alpha} \ \mathrm{cm^2/s}$$

α=0	Constant
α=1/3	Kolmogorov
α=1	Bohm



Model (X-ray)

- Synchrotron radiation from electron
    - SNR shock
    - arbitrary diffusion (α=0, 1/3, 1)
    - synchrotron cooling
- α=0, 1/3 → Blasi 2010
- α=1 → Zirakashvili & Aharonian 2007

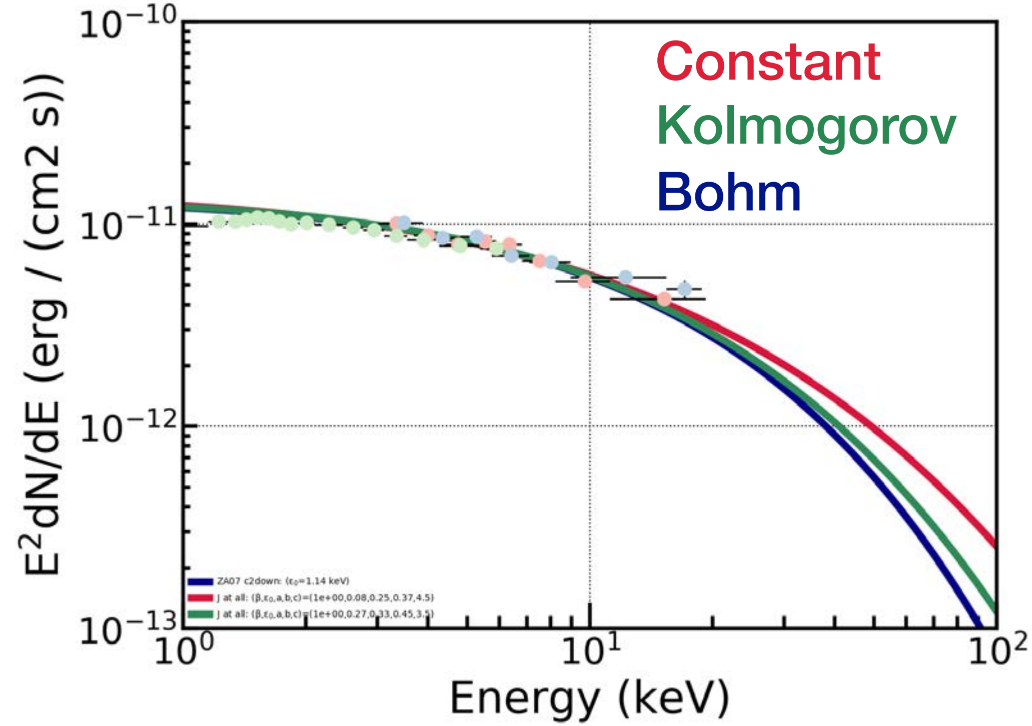


※Cutoff shape depends on α!

Arbitrary diffusion: Observation (RX J1713)

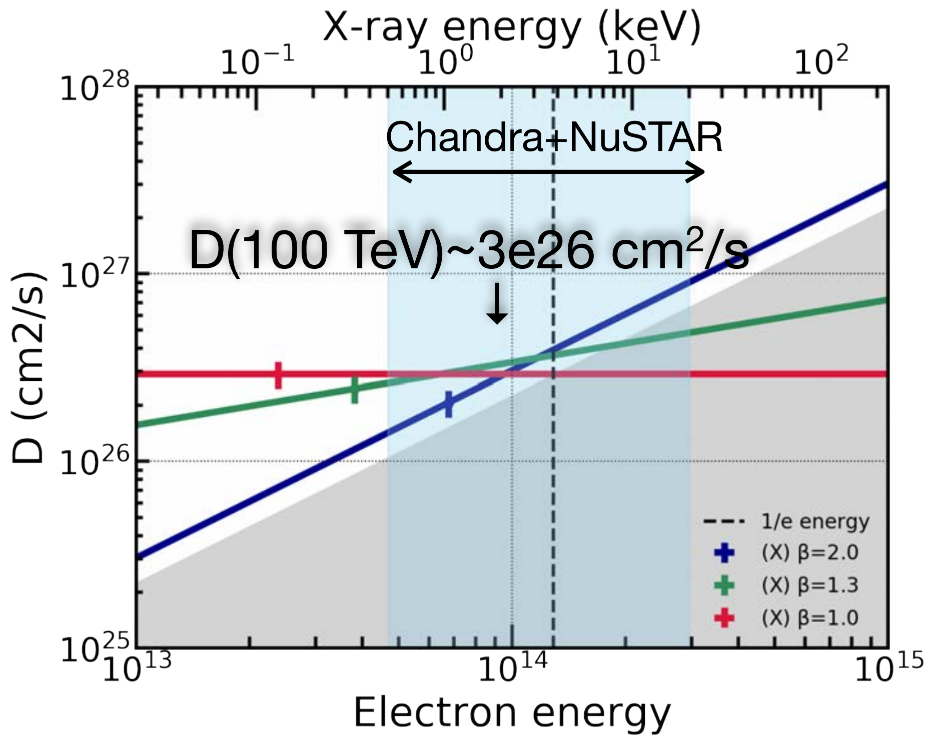
Observation (X-ray)

- RX J1713-NW
- 0.5–20 keV (Chandra+NuSTAR)
- Shock speed: ~3900 km/s (NT & Uchiyama 16)
- B ~ 15μG (HESS Coll. 2018)



Constrained diffusion coefficient

$$D(E) = D_* \left(\frac{E}{E_c}\right)^{\alpha} \ \mathrm{cm^2/s}$$

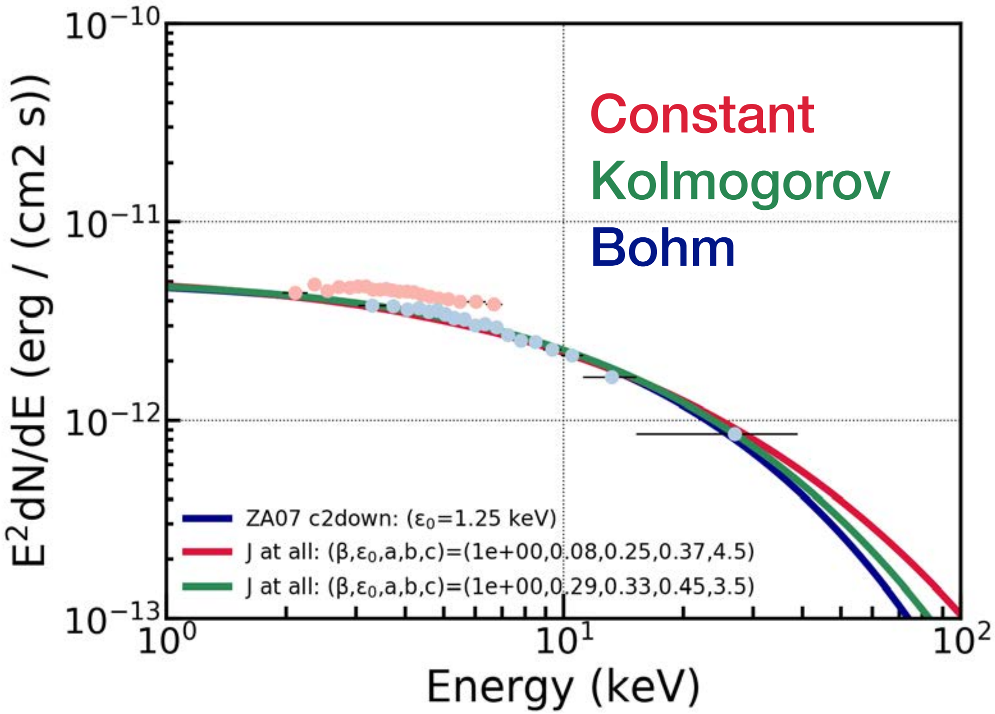


- Deeper observations in hard X-ray would determine α-parameter
- Characteristic value: D(100 TeV)~3e26 cm^2/s
- Only Bohm diffusion is consistent with “D(E) > Bohm limit”

Arbitrary diffusion: Observation (G1.9)

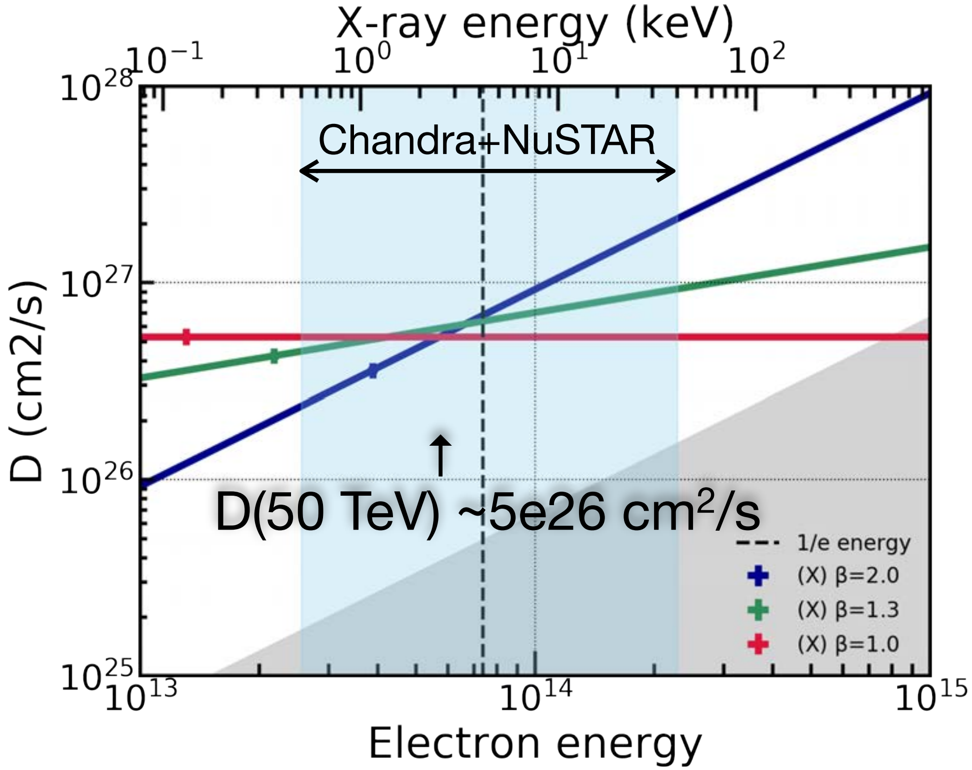
Observation (X-ray)

- G1.9-whole
- 0.5–40 keV (Chandra+NuSTAR)
- Shock speed: ~13000 km/s (Borkowski+ 17)
- Assume B =50 μG



Constrained diffusion coefficient

$$D(E) = D_* \left(\frac{E}{E_c}\right)^{\alpha} \ \mathrm{cm^2/s}$$



- Characteristic value: D(50 TeV)~5e26 cm^2/s
- All diffusion types are consistent with “D(E) > Bohm limit”

Gamma-ray

Arbitrary diffusion: γ-ray spectrum

Model (electron)

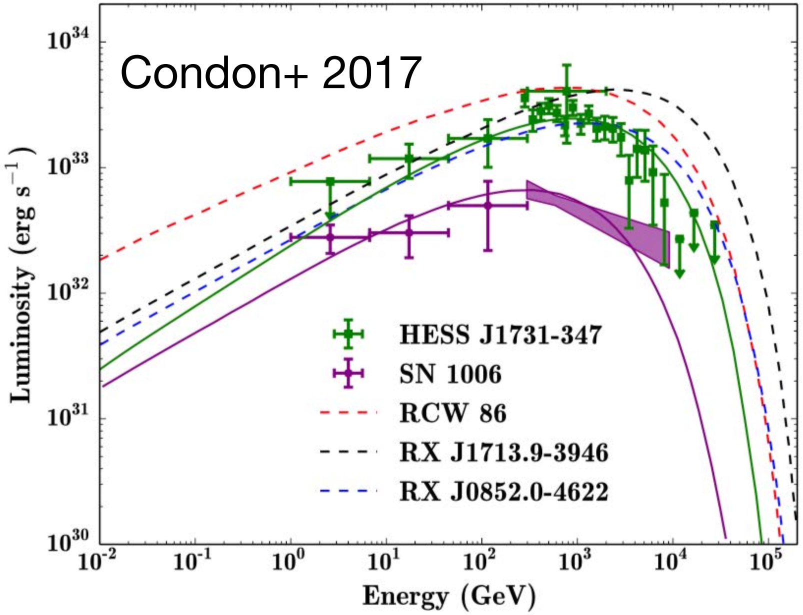
- SNR shock
- Arbitrary diffusion type (α=0, 1/3, 1)
- Synchrotron cooling
- α=0, 1/3 → Blasi 2010
- α=1 → Zirakashvili & Aharonian 2007

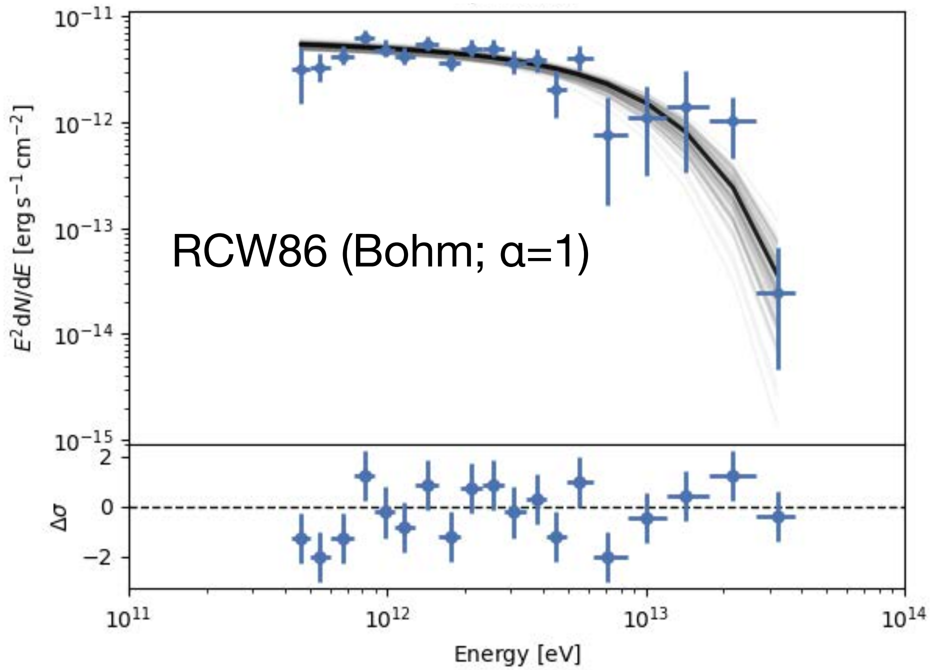
Model (gamma-ray)

Inverse Compton scattering
(in KN regime using naima)

Observation

e.g.) RCW86-whole (w/ H.E.S.S.)
Cutoff energy (electron): 26 TeV
Shock speed: ~3000 km/s (Yamaguchi+ 16)
B-field: ~10 uG (Ajello+ 16)
→Bohm factor: η~8





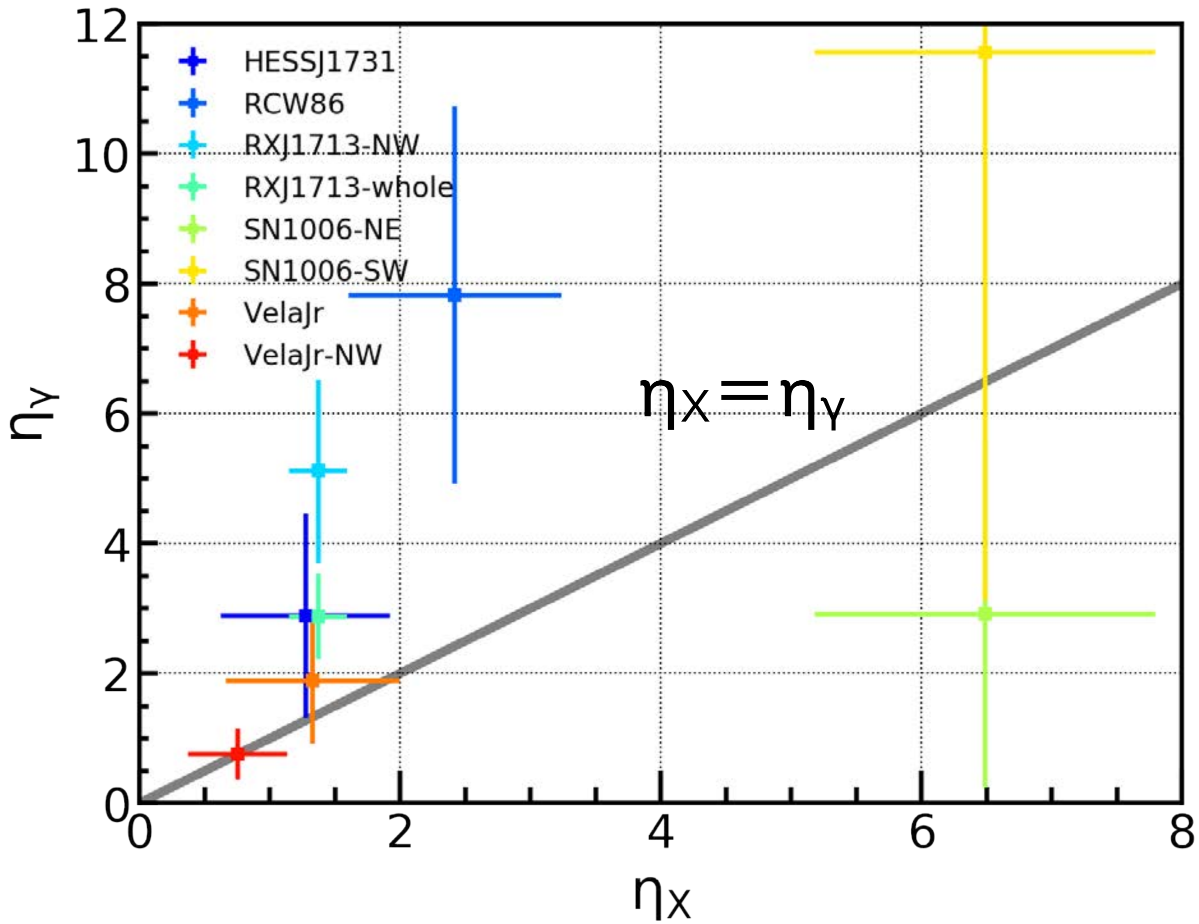
Bohm diffusion: X/γ-ray

Shell-type SNRs:

✓hard GeV gamma-ray

✓strong TeV gamma-ray emission (w/ H.E.S.S.)

- SN 1006 (B~24 μG)
- RXJ1713 (B~15 μG)
- RCW86 (B~10 μG)
- VelaJr (B~12 μG)
- HESS J1731 (B~25 μG)



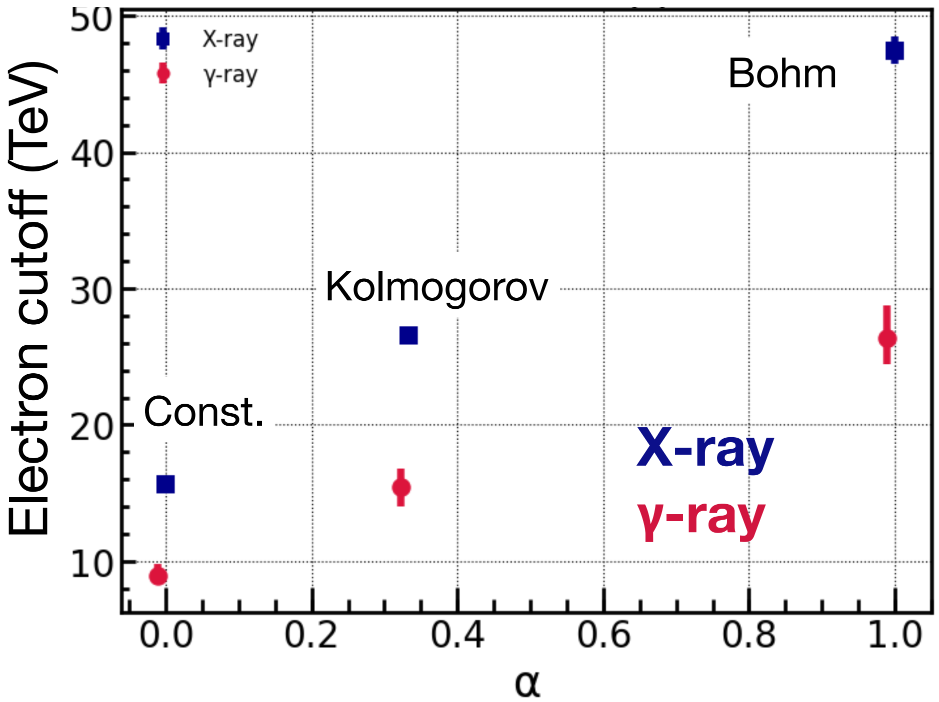
- Leptonic / Hadronic?
- B-field: by X/γ flux ratio (leptonic scenario)

- Gamma-ray spectrum can be used to estimate η (if leptonic)
- $\eta_\gamma > \eta_X$; different regions, B-field, hadronic contribution… (gamma-ray from the entire remnant and X-ray from the rim)
- constrained with spatially resolved gamma-ray observations (CTA)

Arbitrary diffusion: X/γ-ray

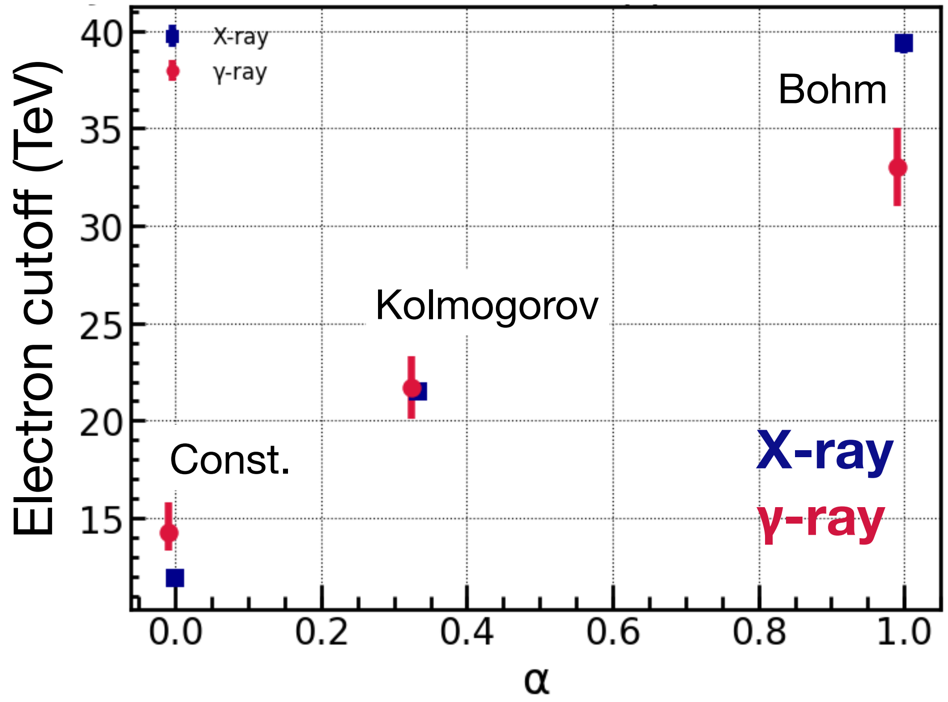
e.g.) RCW86-whole/NE

- TeV gamma-ray spectrum: whole, HESS 18
- X-ray spectrum: NE
- B = 10 μG



e.g.) VelaJr-whole

- TeV gamma-ray spectrum: HESS 18
- X-ray spectrum: Suzaku-XIS (Fukuyama in prep.)
- B = 12 μG



- RCW 86: cutoff with X-ray > cutoff with γ-ray
- Vela Jr.: Kolmogorov diffusion? (B=12 uG; Tanaka+ 11)
- Spatially resolved gamma-ray observations (CTA) would determine α

Summary

- Estimated the diffusion coefficient of SNR shock in SN 1006, RX J1713.7–3946, RCW86, Vela Jr., and HESSJ 1731 (using X/γ-ray observations) and in G1.9, Cassiopeia A, Kepler, Tycho, G330, and SN 1987A (using X-ray observations only).

✤ <u>Bohm diffusion</u>

- Revealed the more efficient acceleration for the older SNR.
- Bohm factor (η) obtained with gamma-ray spectrum is larger than that with X-ray.

✤ <u>Arbitrary diffusion</u>

- 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 around the maximum energy (sub 100 TeV), irrespective of diffusion regime (α-parameter).

✤ <u>Future work</u>

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