TeV Particle Astrophysics 2019
@University of Sydney

Particle Acceleration in Young Supernova Remnants with Nonthermal X-ray and TeV Gamma-ray Observations

December 2nd, 2019

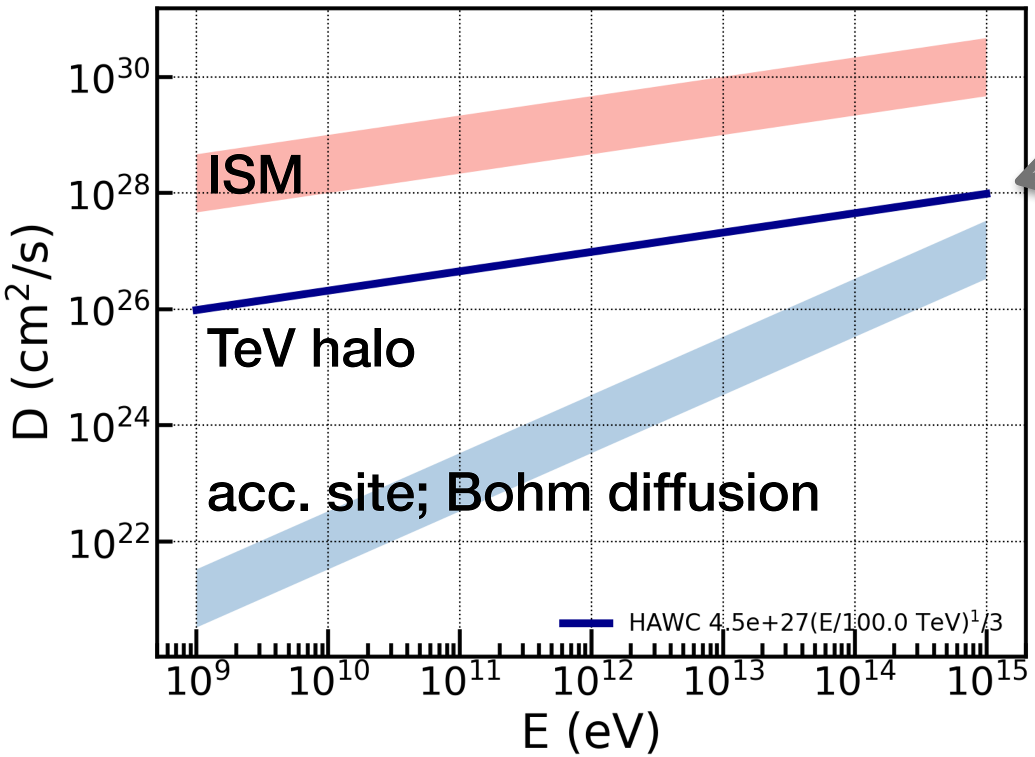
Naomi Tsuji, Yasunobu Uchiyama, Dmitry Khangulyan (Rikkyo U), and Felix Aharonian (MPIK)

CR diffusion

Diffusion coefficient

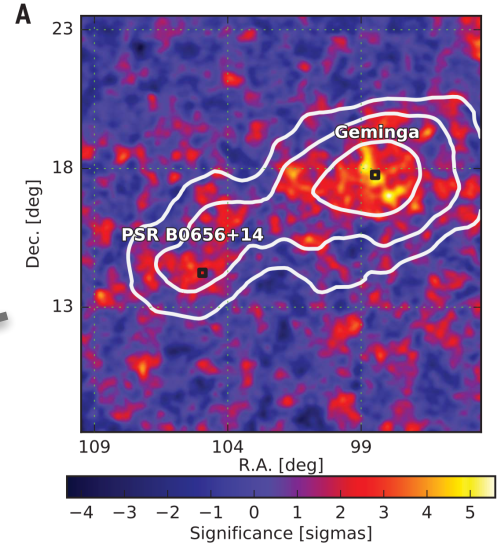
$$D(E) = D_* \left(\frac{E}{E_c}\right)^{\alpha} \ \mathrm{cm}^2/\mathrm{s}$$

- 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

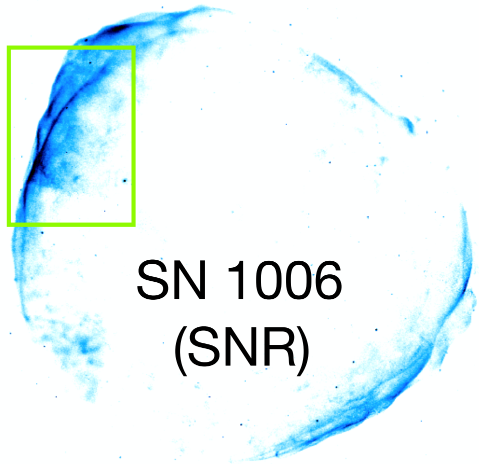


<This talk>

- Acceleration site: SNR shock
- Bohm diffusion (α=1)

1. X-ray observations
2. Gamma-ray observations

Particle acceleration



Diffusive shock acceleration (DSA)

Standard theory for particle acceleration in astrophysics.

Accelerated by diffusing back and forth across shock.

One-round energy gain:

$\Delta E/E \sim V_{shock}/c$

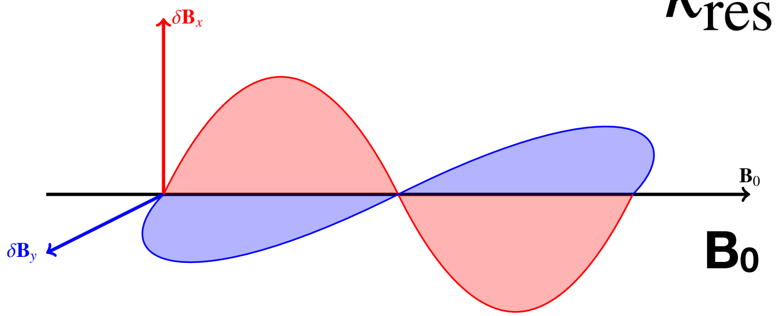
Energy spectrum:

$dN/dE = E^{-2}$

Diffusion:

(Resonance) scattering with B-field

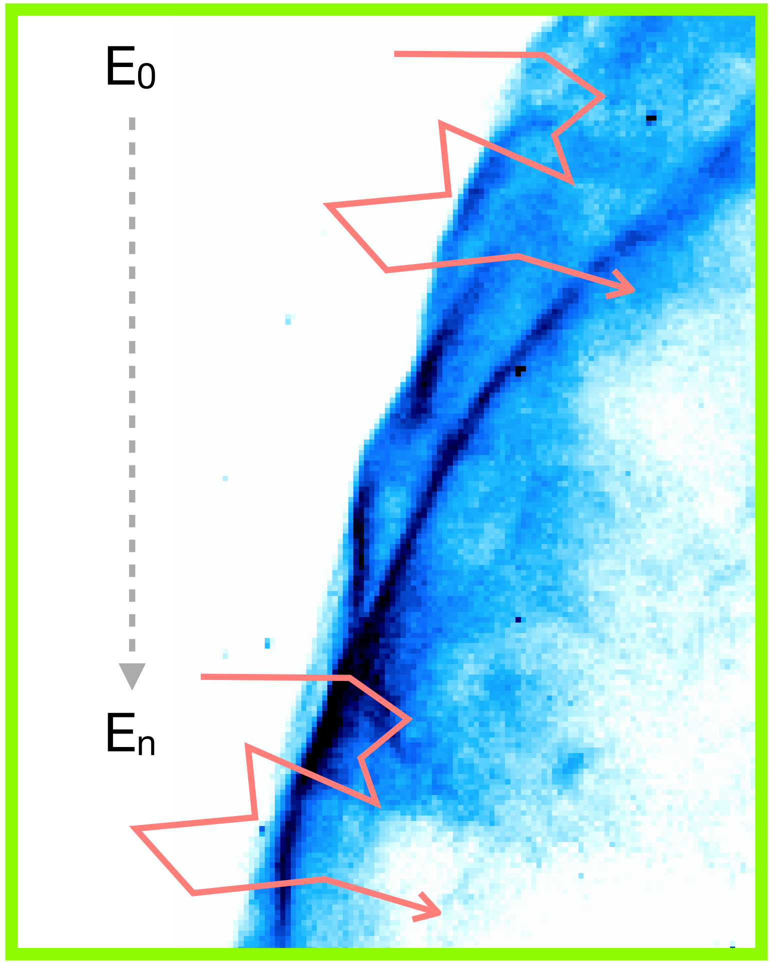
$\delta B \perp B_0$



δB wavenumber

$$k_{res} \approx \frac{1}{R_L}$$

Lamor radius



Acceleration efficiency

Acceleration timescale: $t_{\rm acc} \propto \frac{E\eta}{v_{\rm sh}^2 B}$

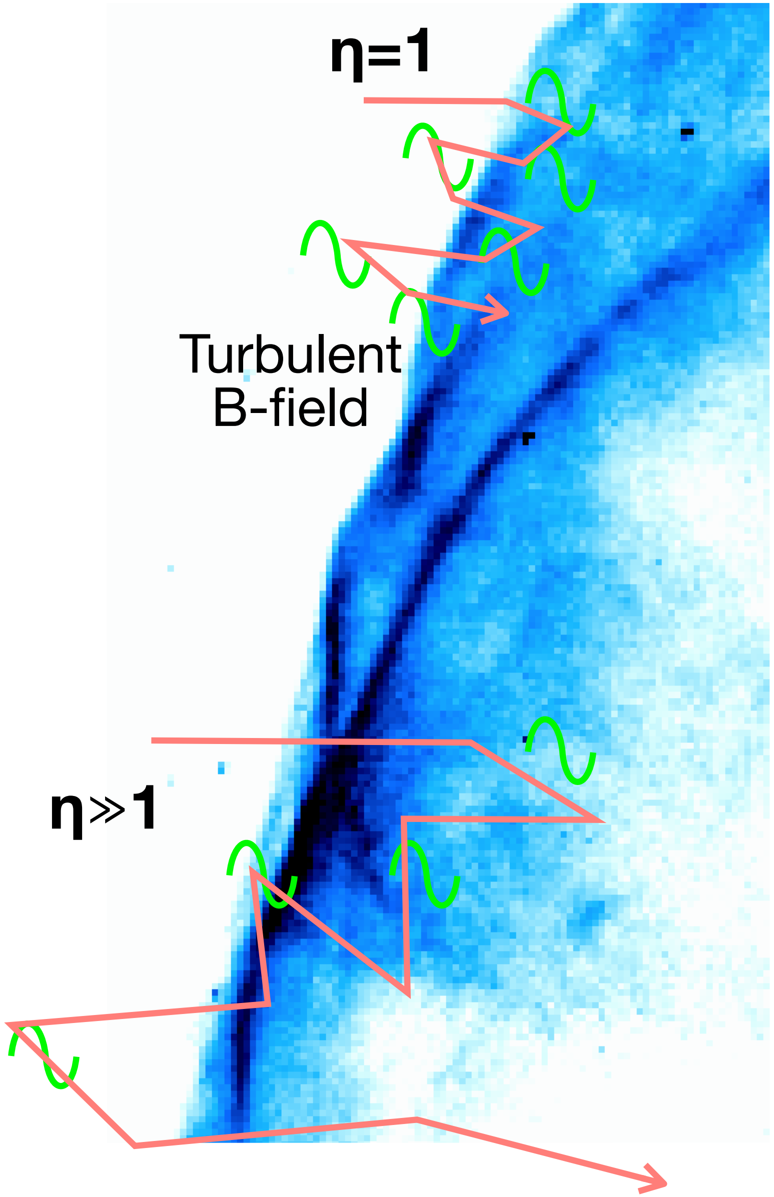
"Bohm factor" η

Acceleration efficiency

η = (particle m.f.p.) / (gyroradius)

$\eta \sim (B_0 / \delta B)^2$

	η=1 (Bohm limit)	η ≫1
m.f.p.	smallest	large
$t_{\rm acc}$	shortest	long
B-field	turbulent	less turbulent
Acceleration	efficient!	inefficient



How to derive η from observations?

Acceleration timescale: $t_{\mathrm{acc}} \propto \frac{E\eta}{v_{\mathrm{sh}}^2 B}$

Cooling (synchrotron) timescale: $t_{\mathrm{synch}} \propto \frac{1}{EB^2}$

Cooling-limited acceleration:

$t_{\mathrm{acc}} \approx t_{\mathrm{synch}}$ gives cutoff energy

Electron cutoff: $E_c \propto v_{\mathrm{sh}} B^{-1/2} \eta^{-1/2}$

Synchrotron X-ray cutoff: $\varepsilon_c \propto E_c^2 B \propto v_{\mathrm{sh}}^2 \eta^{-1}$

<u>If we measure cutoff and shock speed, we can obtain η!</u>

※ More detailed analytical calculations are done by Zirakashvili & Aharonian 2007

X-ray observations

Application to Observation

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:

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

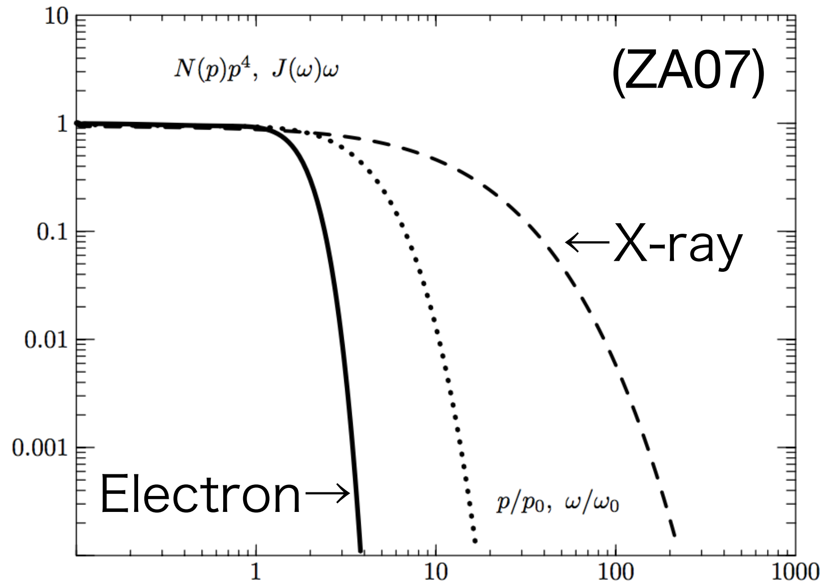
Observation

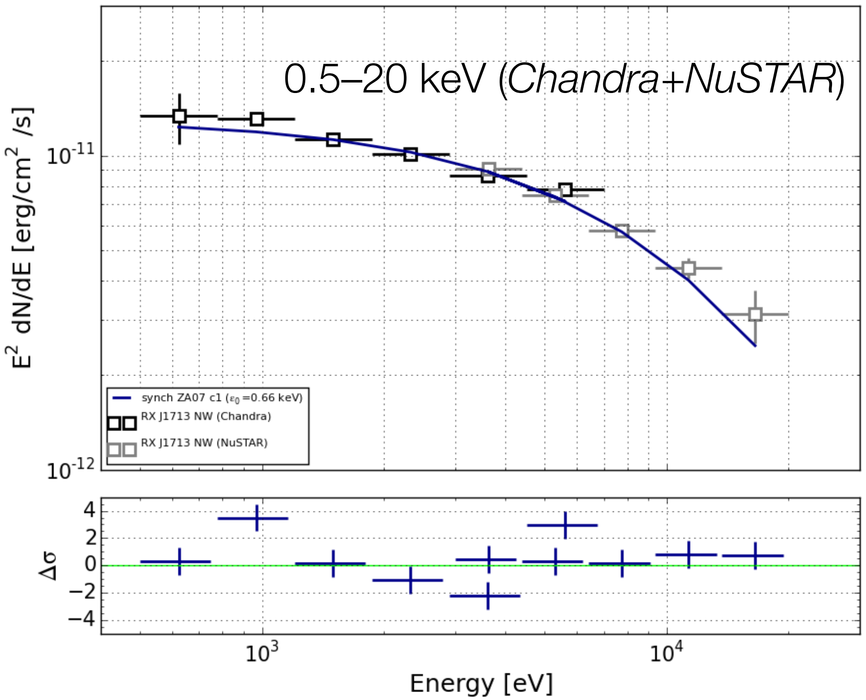
e.g.) RX J1713.7–3946 NW

Cutoff energy: 1.1 keV

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

→Bohm factor: **η~1 (Bohm limit)**





Young SNRs in X-ray

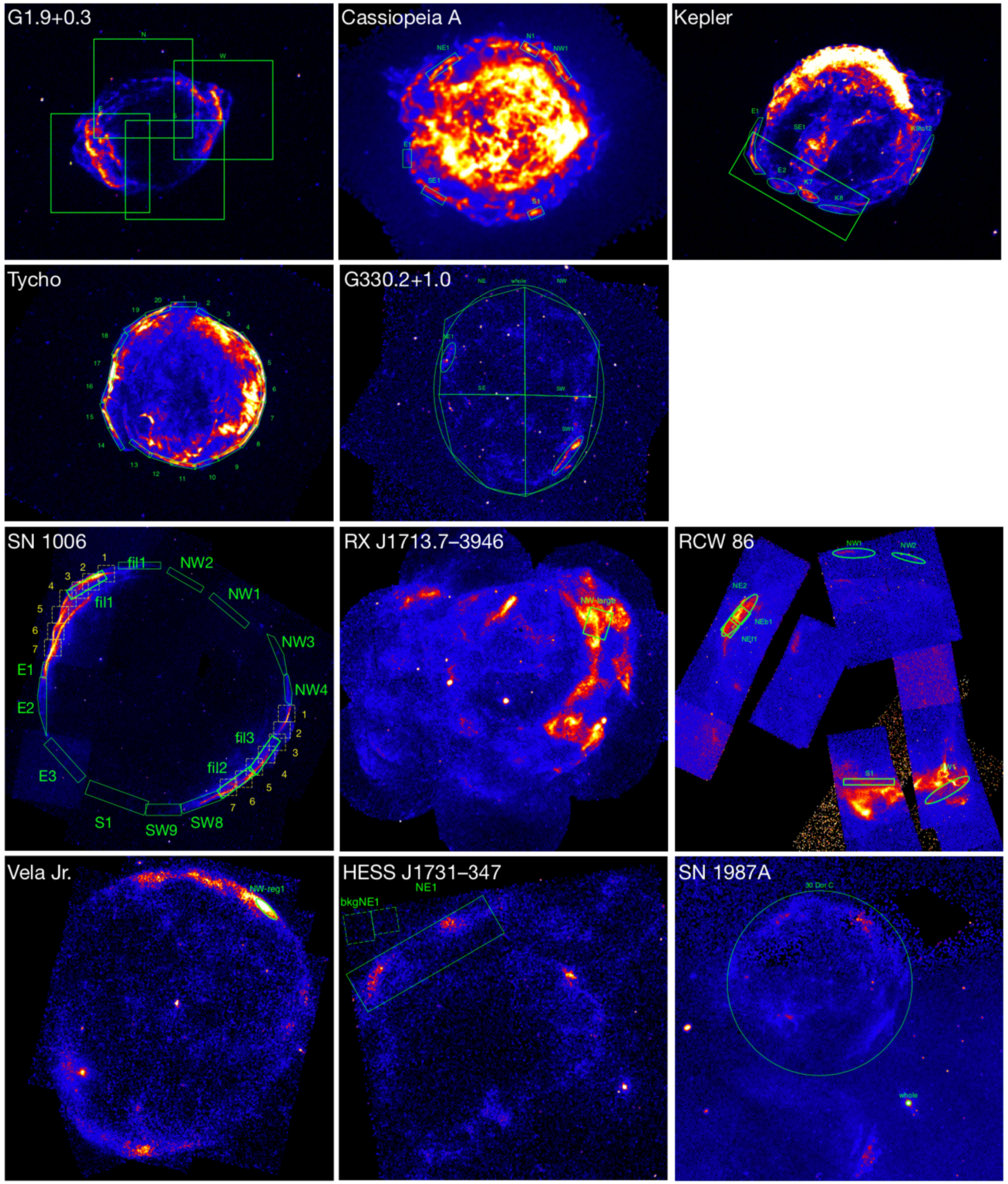
(NT+ in prep.)

- Systematical analysis of young Galactic SNRs:
  - G1.9+0.3, Cassiopeia A, Kepler, Tycho, G330.2+1.0, SN1006, RX J1713.7–3946, RCW 86, Vela Jr., HESSJ 1731-347 (, SN 1987A)

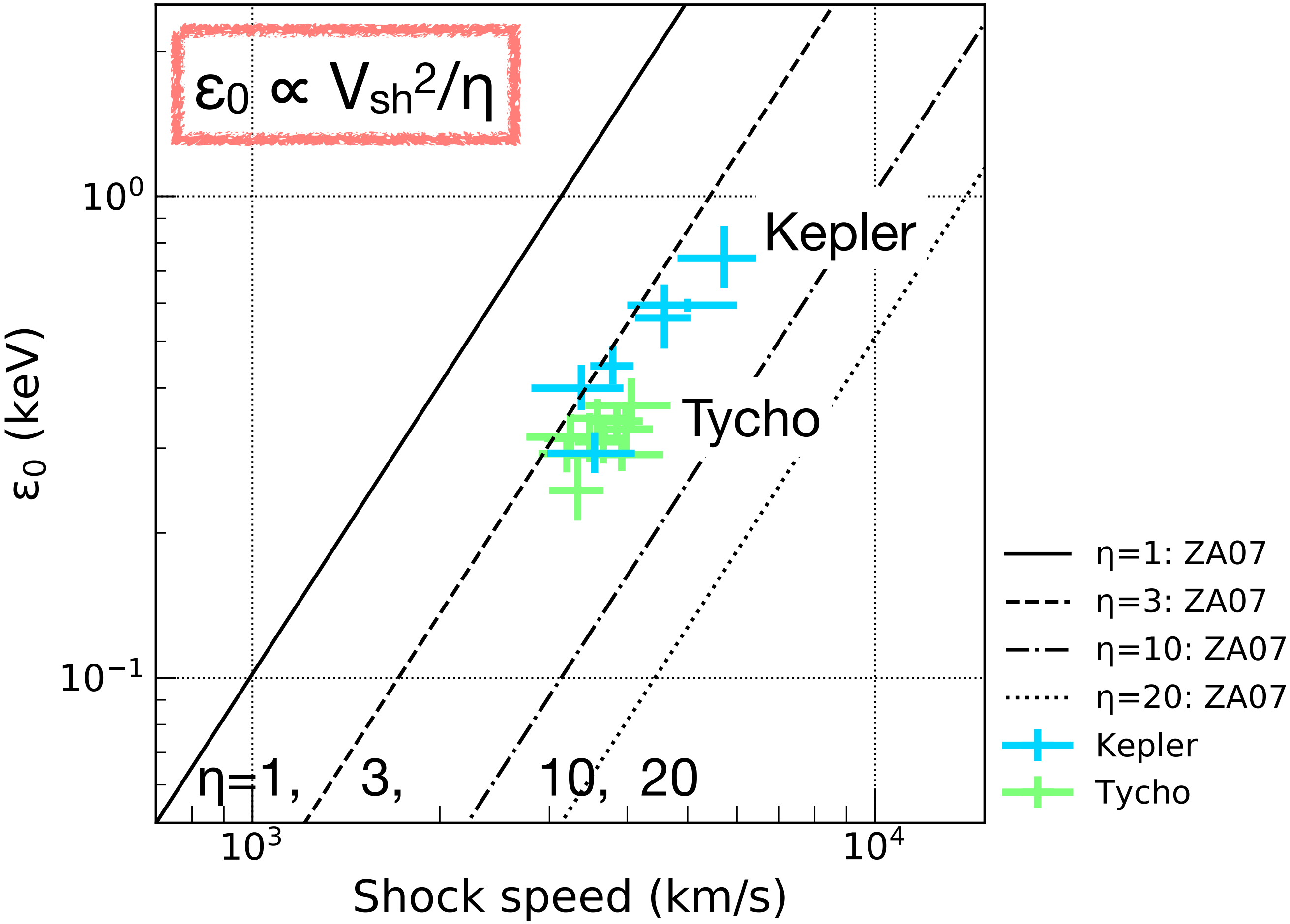
Assume the hard continuum is synchrotron for SN1987A

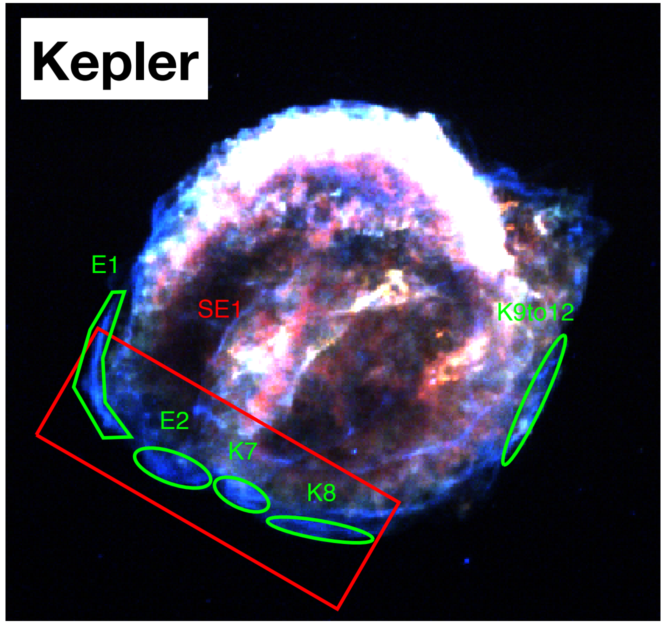
- Spectral fitting:
  - soft X-ray: Chandra/Suzaku
  - hard X-ray: NuSTAR
  - Model: ZA07

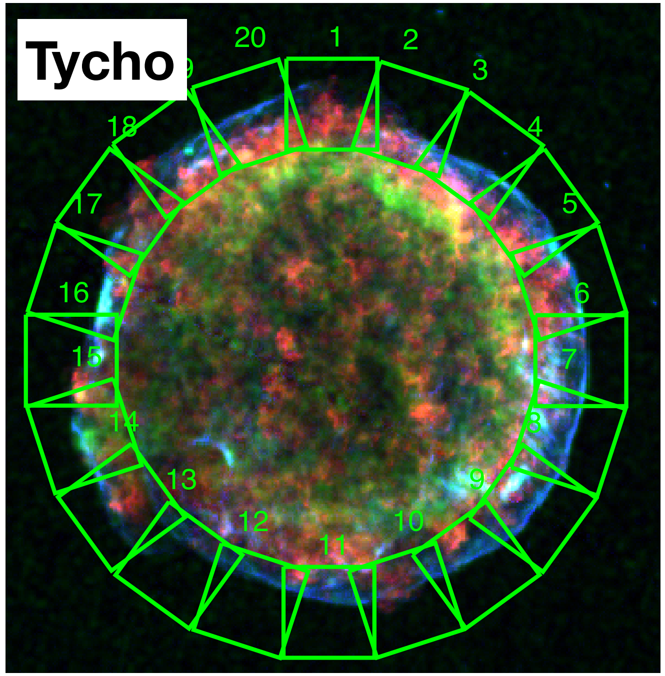
- Derived cutoff energy
  + known shock speed
  → acceleration efficiency (η)



Kepler & Tycho



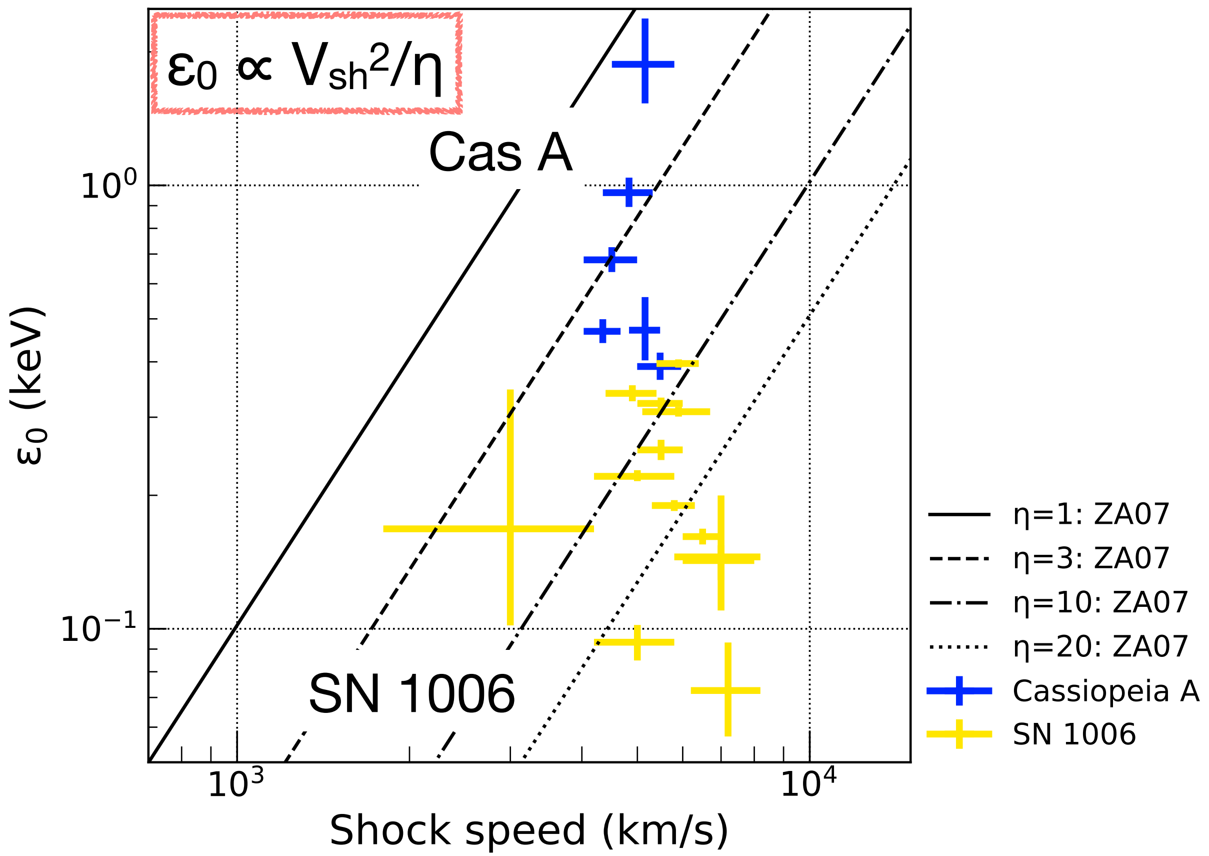


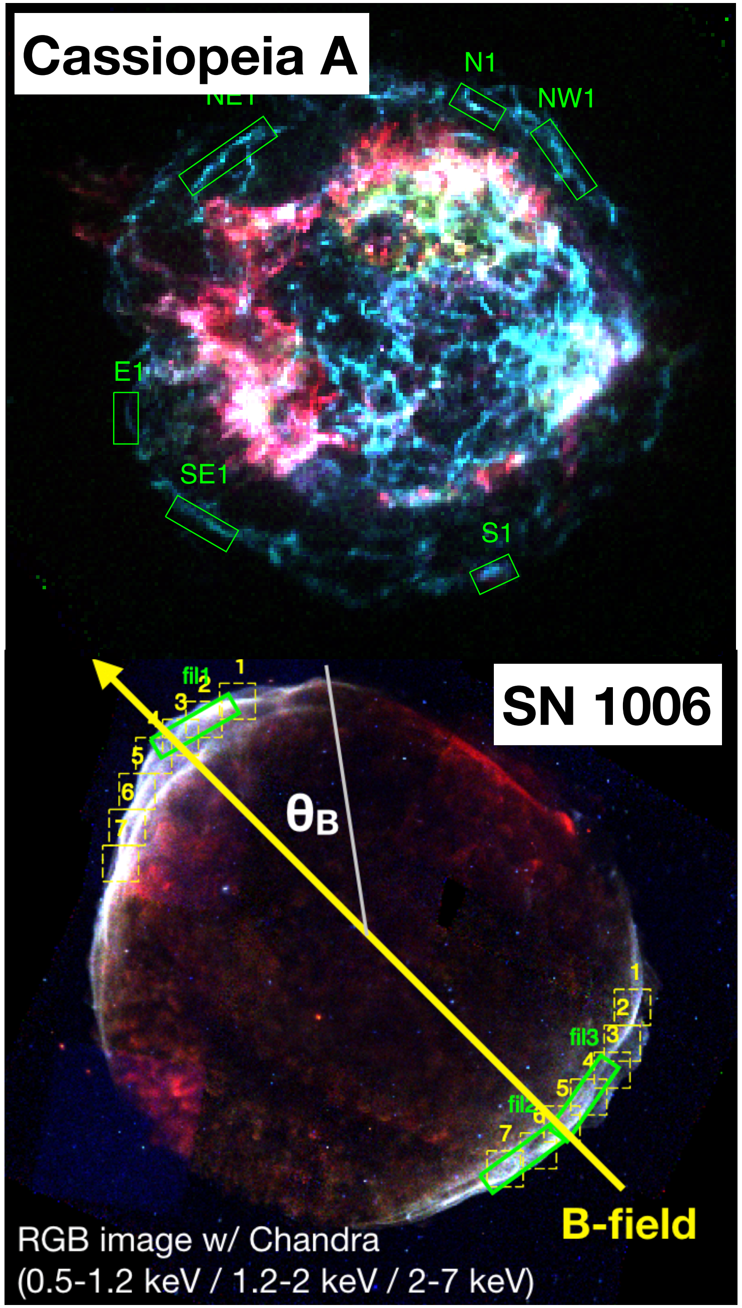


'Standard' acceleration

- Observed ε_0-v_{sh} diagram is well-reproduced by the theoretical prediction
- Constant η = 3–5

Cassiopeia A & SN 1006

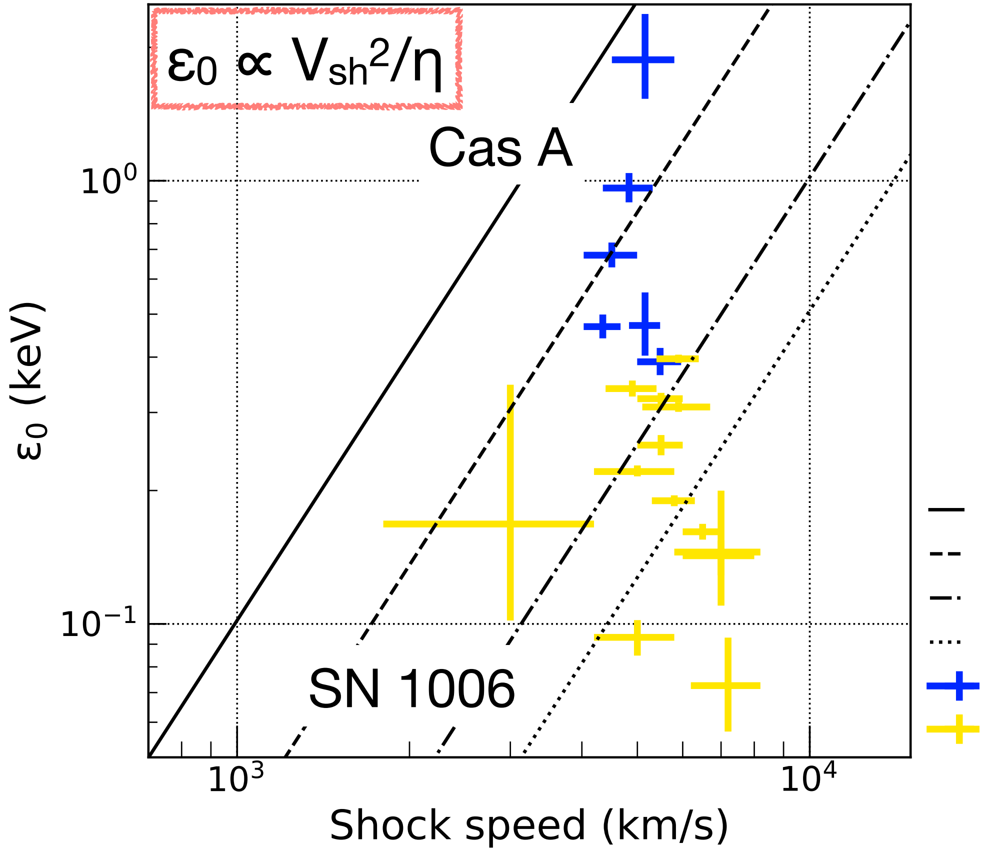


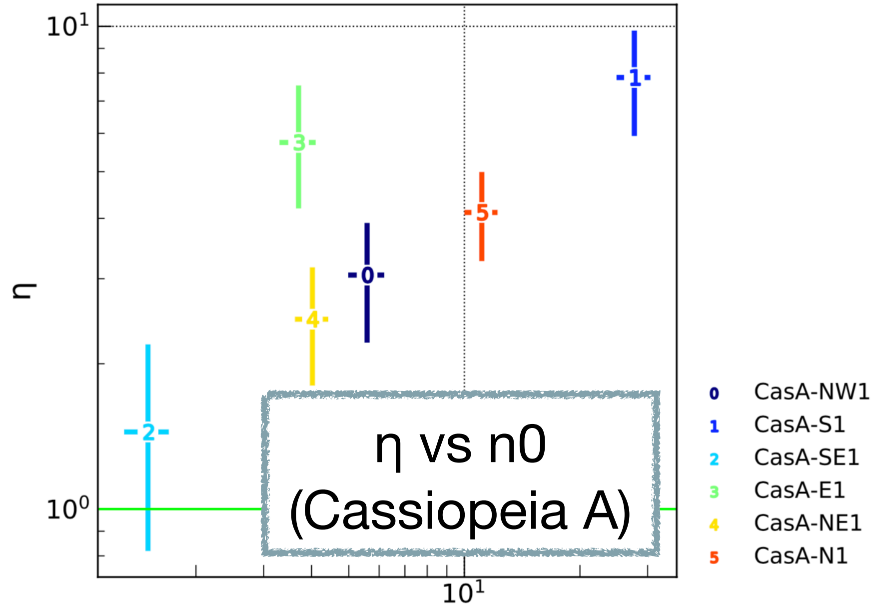


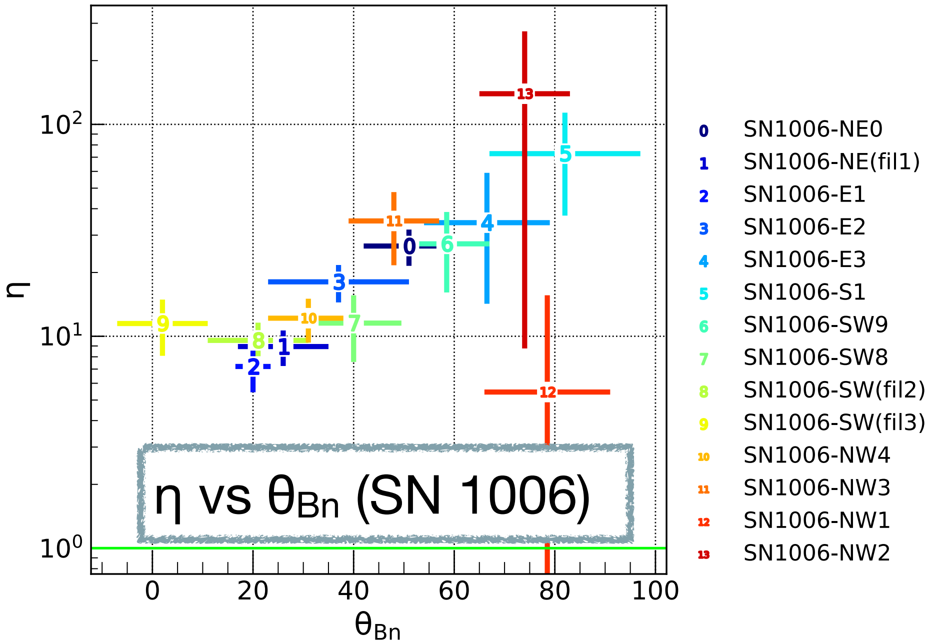
Observed ε_0-v_{sh} diagram is NOT well-reproduced by the theoretical prediction

- Cassiopeia A
  - constant v_{sh}; variable ε_0
- SN 1006
  - inverse trend of the theoretical curve

Cassiopeia A & SN 1006



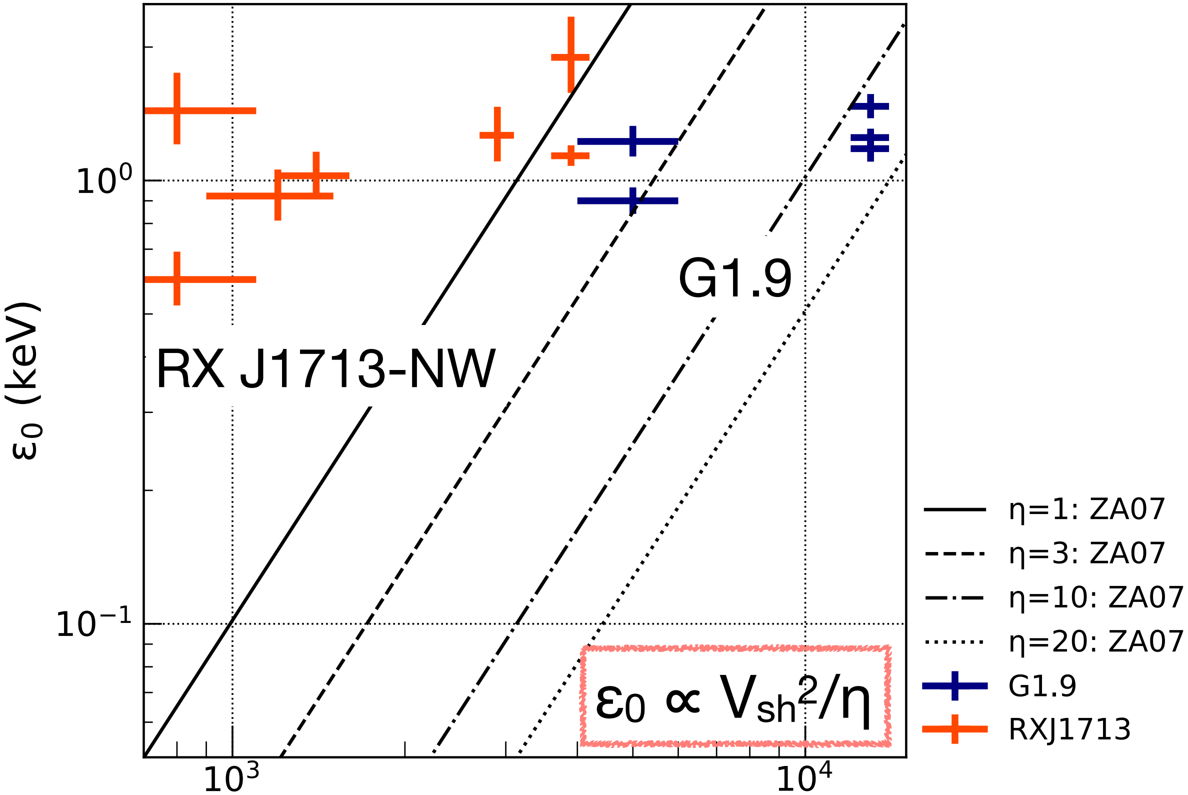


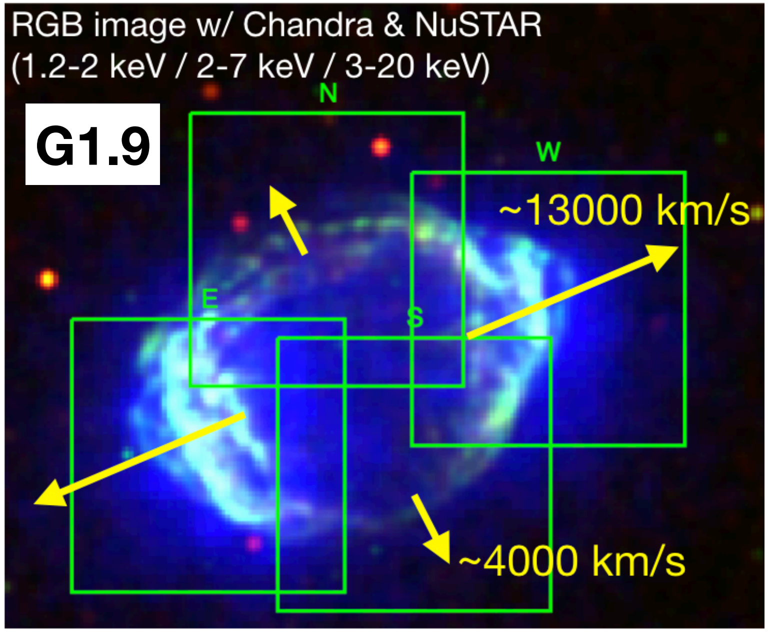


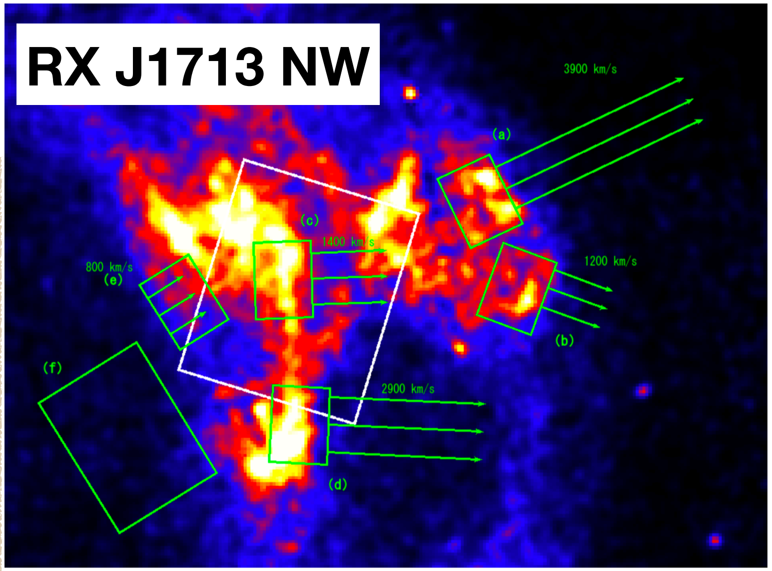
Acceleration affected by surroundings

- Cassiopeia A
  - Ambient density
- SN 1006
  - B-field; shock obliquity (Miceli+ 09)

G1.9+0.3 & RXJ 1713.7–3946



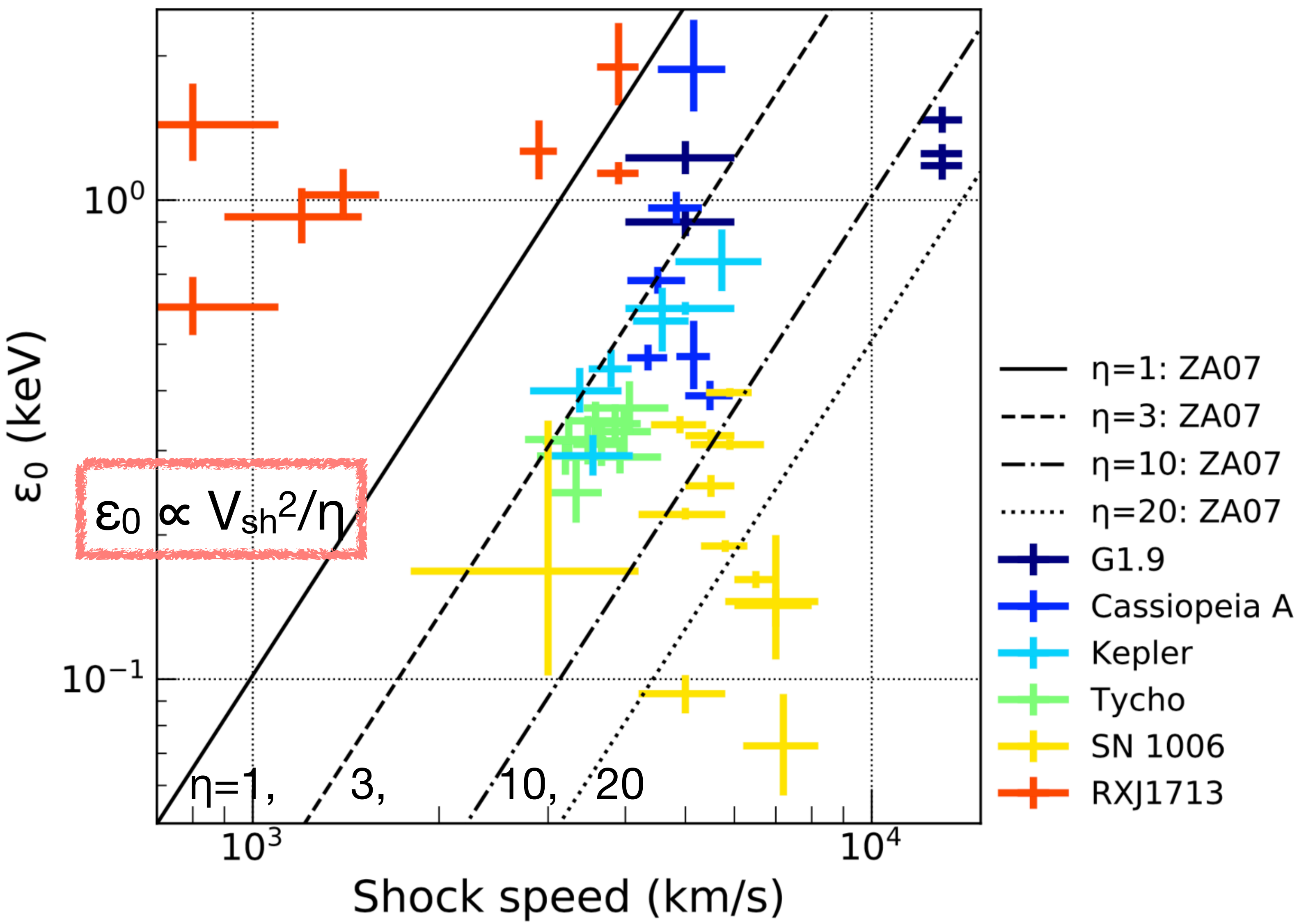




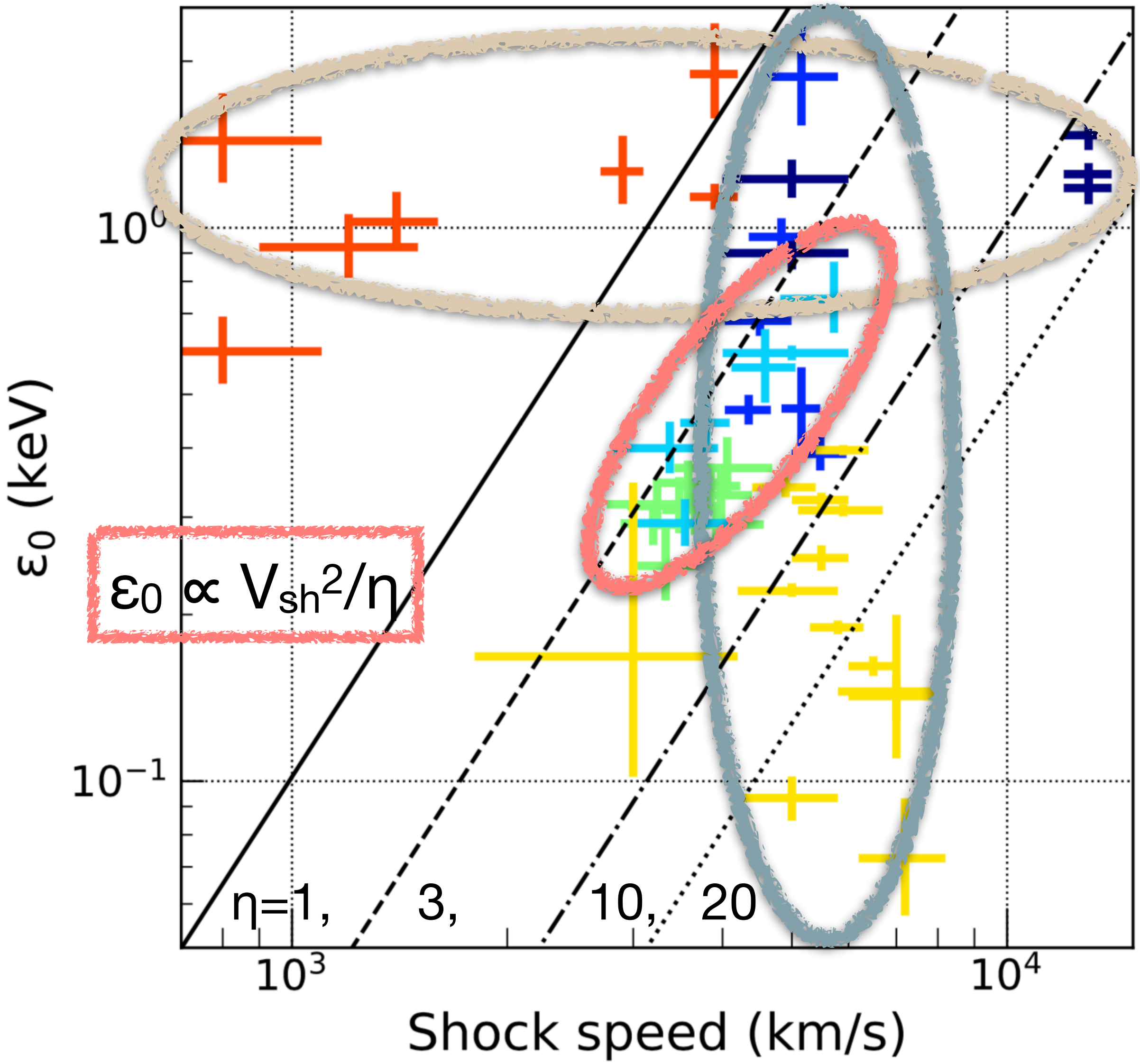
Observed ε_0-v_{sh} diagram is NOT well-reproduced by the theoretical prediction

- G1.9
  - (too) young accelerator
- RX J1713-NW (Tsuji+ 2019)
  - Bohm limit @forward shock
  - η<1 (invalid) @inner region →not acc. site

E_0 v.s. V_{sh} (summary)



E_0 v.s. V_{sh} (summary)



'Standard' acceleration

- ε_0-v_{sh} is well-reproduced by the theoretical prediction
- Constant η
- Kepler and Tycho

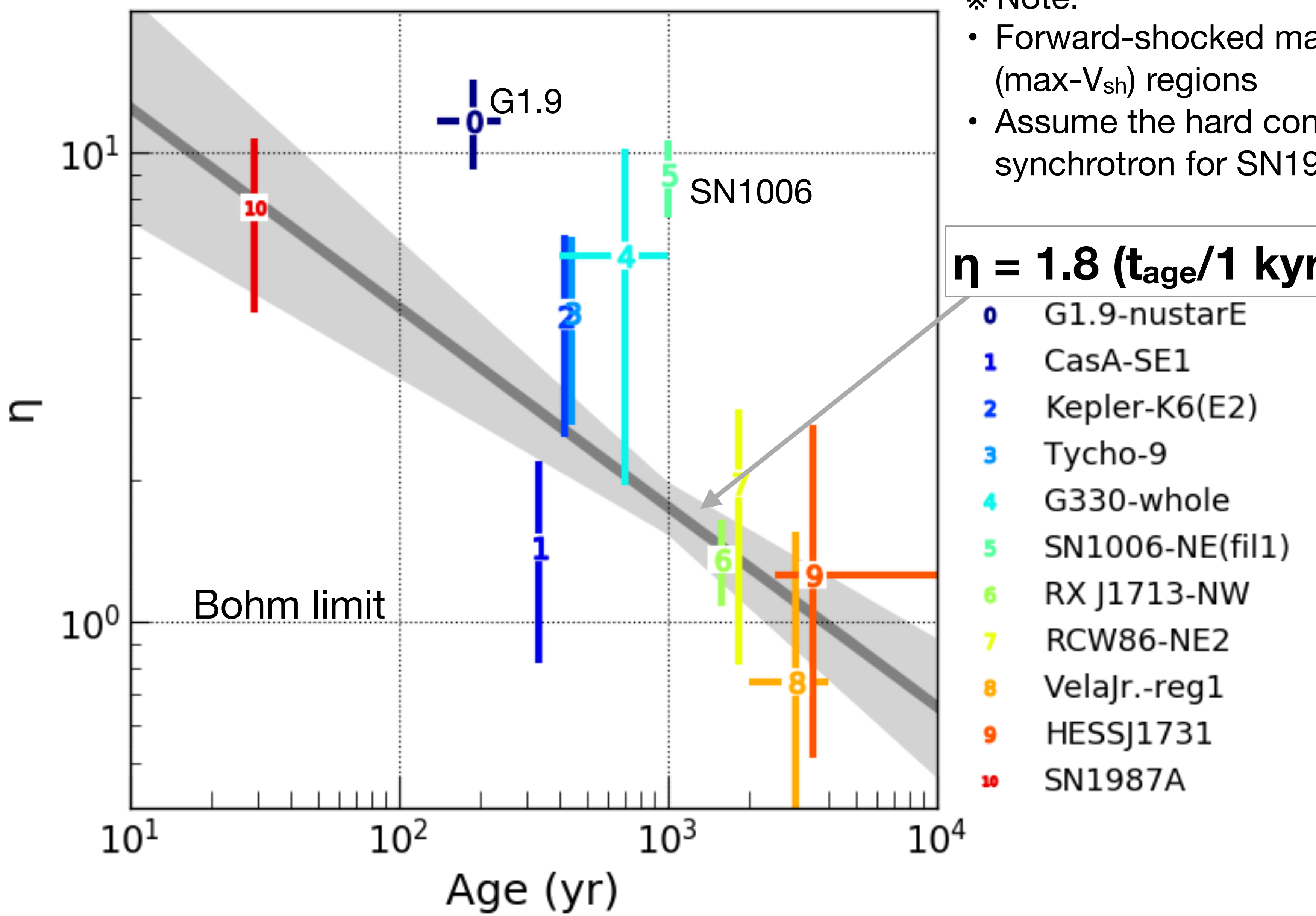
Affected by surroundings

- B-field; shock obliquity
  - SN 1006
- Density
  - Cassiopeia A

Not cooling-limited?

- (too) young accelerator
  - G1.9
- Not acc. site?
  - inner regions of RXJ1713-NW

Acceleration efficiency: young SNRs

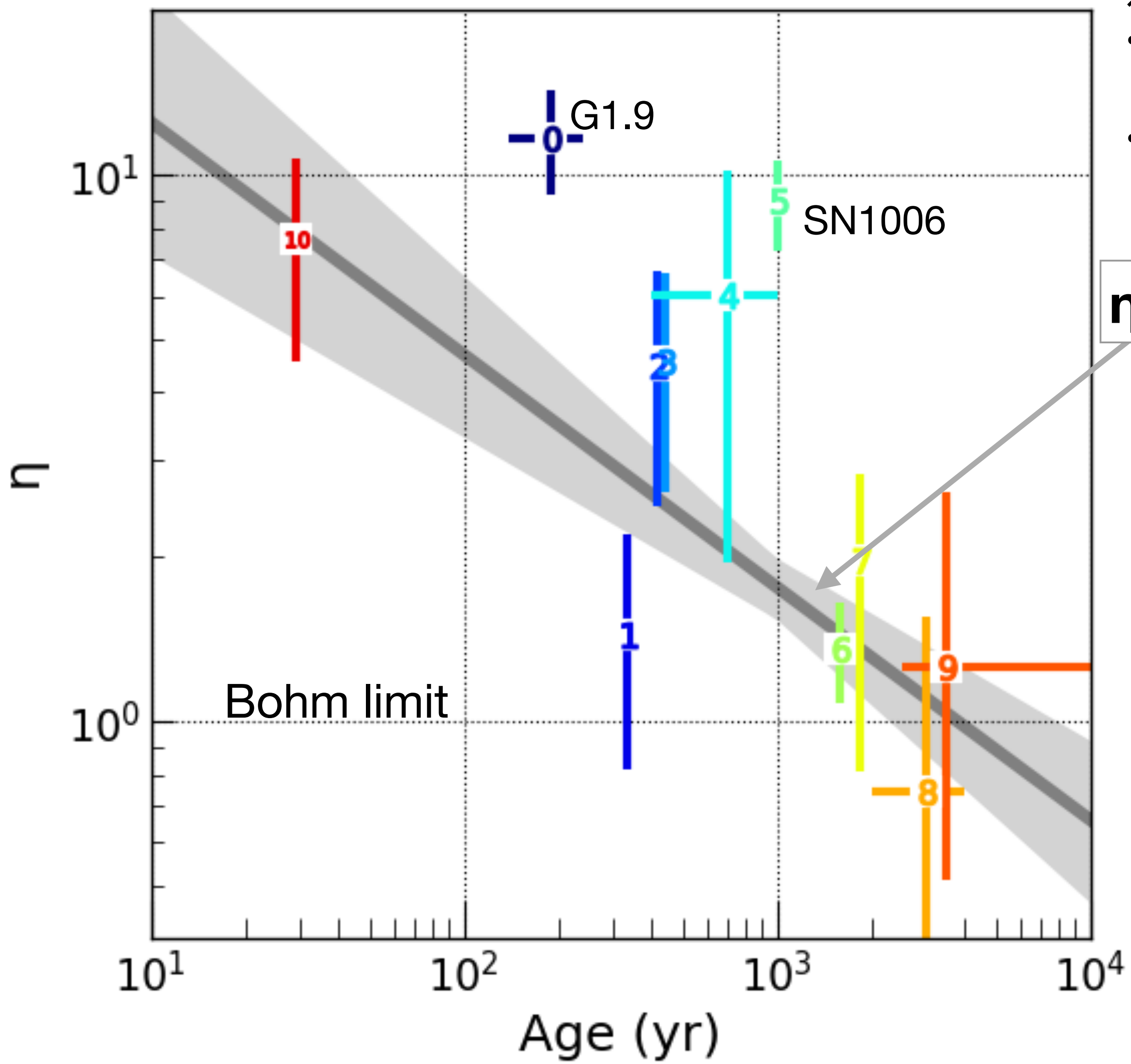


※ Note:

- Forward-shocked max-ε_0 (max-V_{sh}) regions
- Assume the hard continuum is synchrotron for SN1987A

$$\eta = 1.8\ (t_{age}/1\ \mathrm{kyr})^{-0.43}$$

Acceleration efficiency: young SNRs



※ Note:

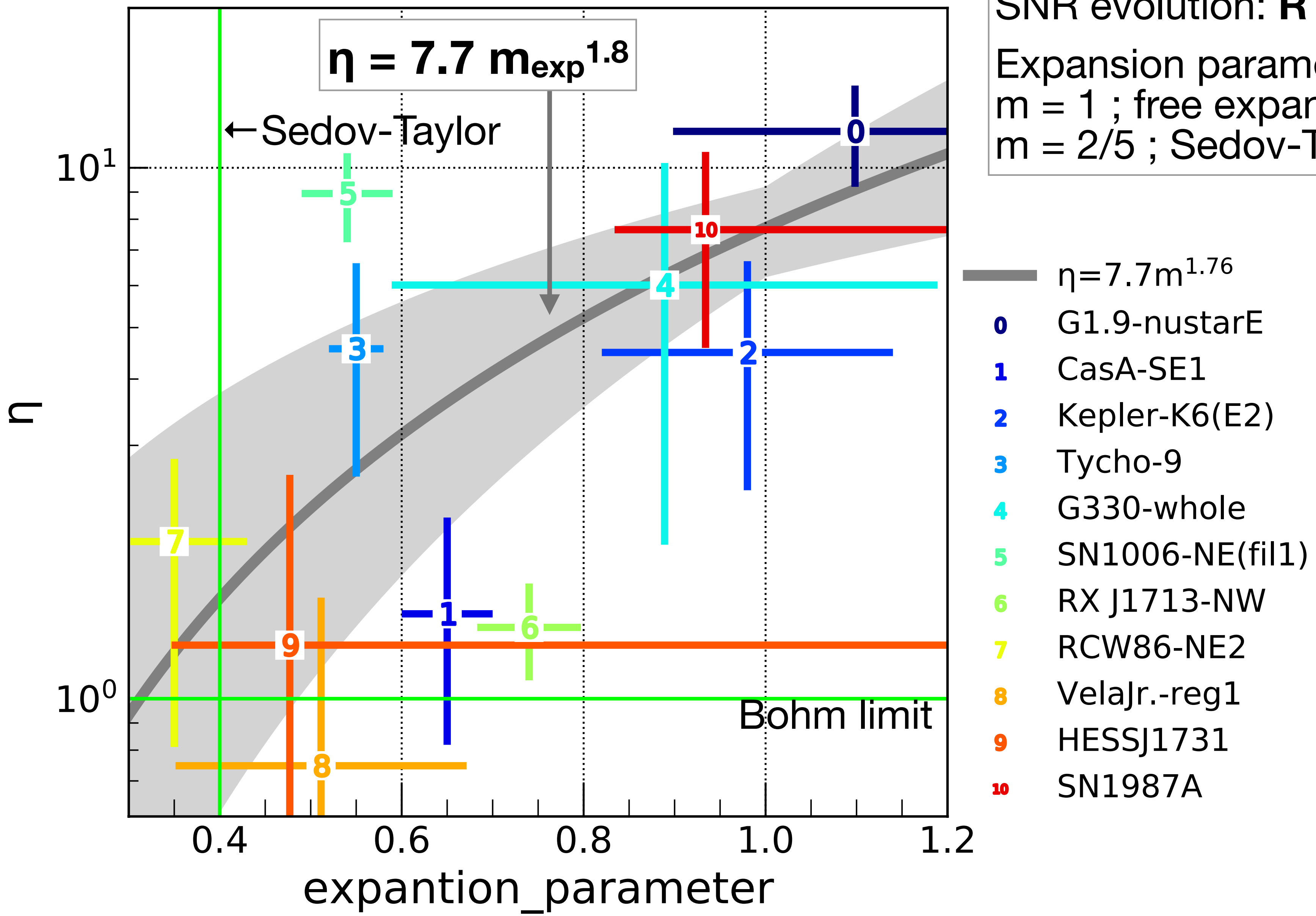
- Forward-shocked max-ε_0 (max-V_{sh}) regions
- Assume the hard continuum is synchrotron for SN1987A

$$\eta = 1.8\ (t_{age}/1\ \mathrm{kyr})^{-0.43}$$

- 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 ~0.4

η v.s. expansion parameter



SNR evolution: $\mathbf{R \propto t^m}$

Expansion parameter (m)
m = 1 ; free expansion
m = 2/5 ; Sedov-Taylor

Maximum energy

Age-limited maximum energy: $E_{\mathrm{max,age}} = \frac{Zq}{c} t v_{\mathrm{sh}}^2 B \eta^{-1}$

Shock speed: $v_{\mathrm{sh}} \propto \begin{cases} t^0 & \text{(Free-expansion phase)} \\ t^{-3/5} & \text{(Sedov-Taylor phase)} \end{cases}$

Bohm factor: $\eta \propto t^{-\delta}$ (δ~0.4; this work)

$E_{\mathrm{max,age}} \propto \begin{cases} t^{1+\delta} & \text{(Free-expansion)} \\ t^{-1/5+\delta} & \text{(Sedov-Taylor)} \end{cases}$

e.g.) Tycho (free-expansion)

Age (yr)	E (PeV)	η
440 (now)	0.044	3.3
4800	1.5	1
4800	0.47	3.3

- Assume that η evolves as $\eta \propto t^{-\delta}$ at free-expansion/ST stages until η=1
- Max energy can be higher than expected before (δ=0)

Gamma-ray observations

Application to gamma-ray observation

Model (electron)

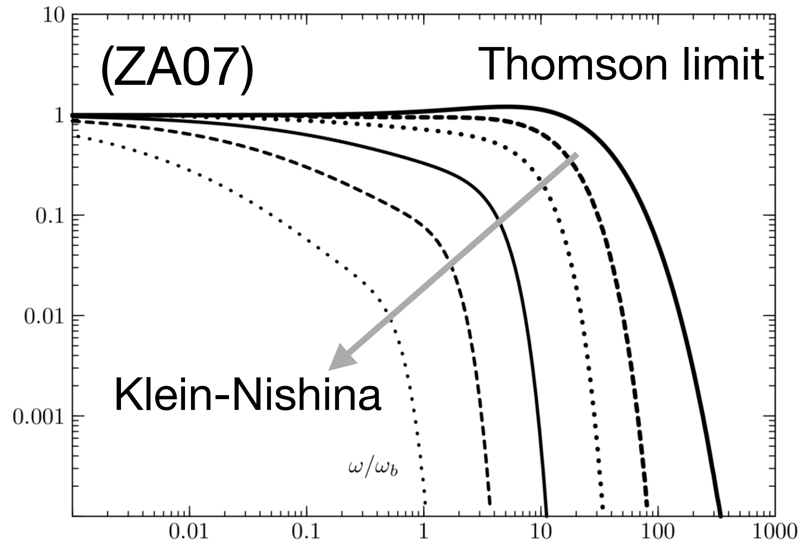
- SNR shock
- Zirakashvili & Aharonian 2007 (ZA07)
- Energy loss: synchrotron cooling
- Diffusion: Bohm type

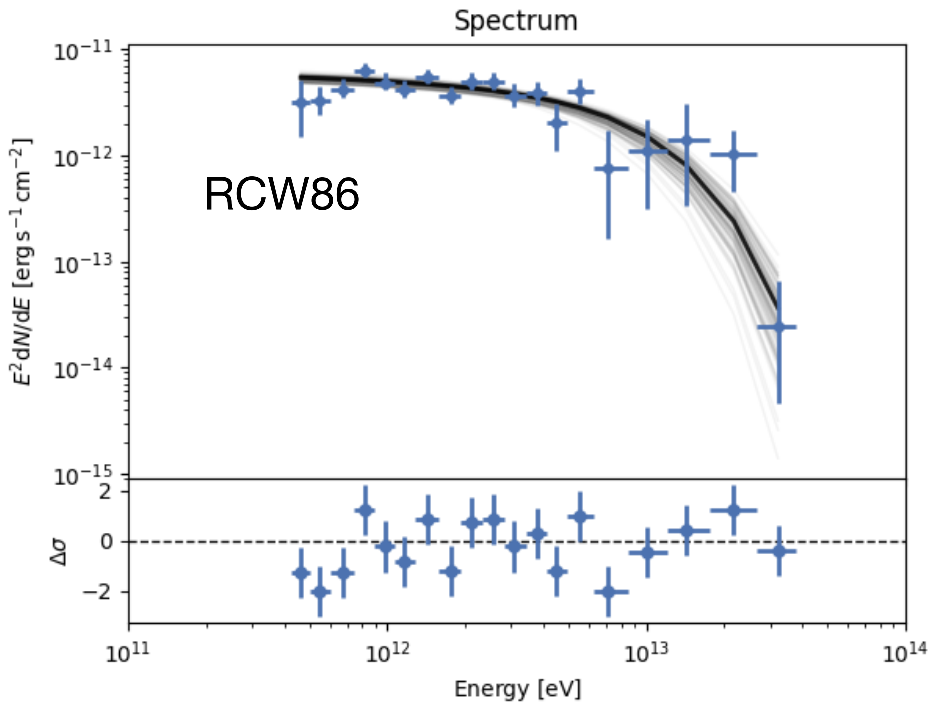
Model (gamma-ray)

Inverse Compton scattering
(in KN regime using Naima)

Observation

e.g.) RCW 86-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



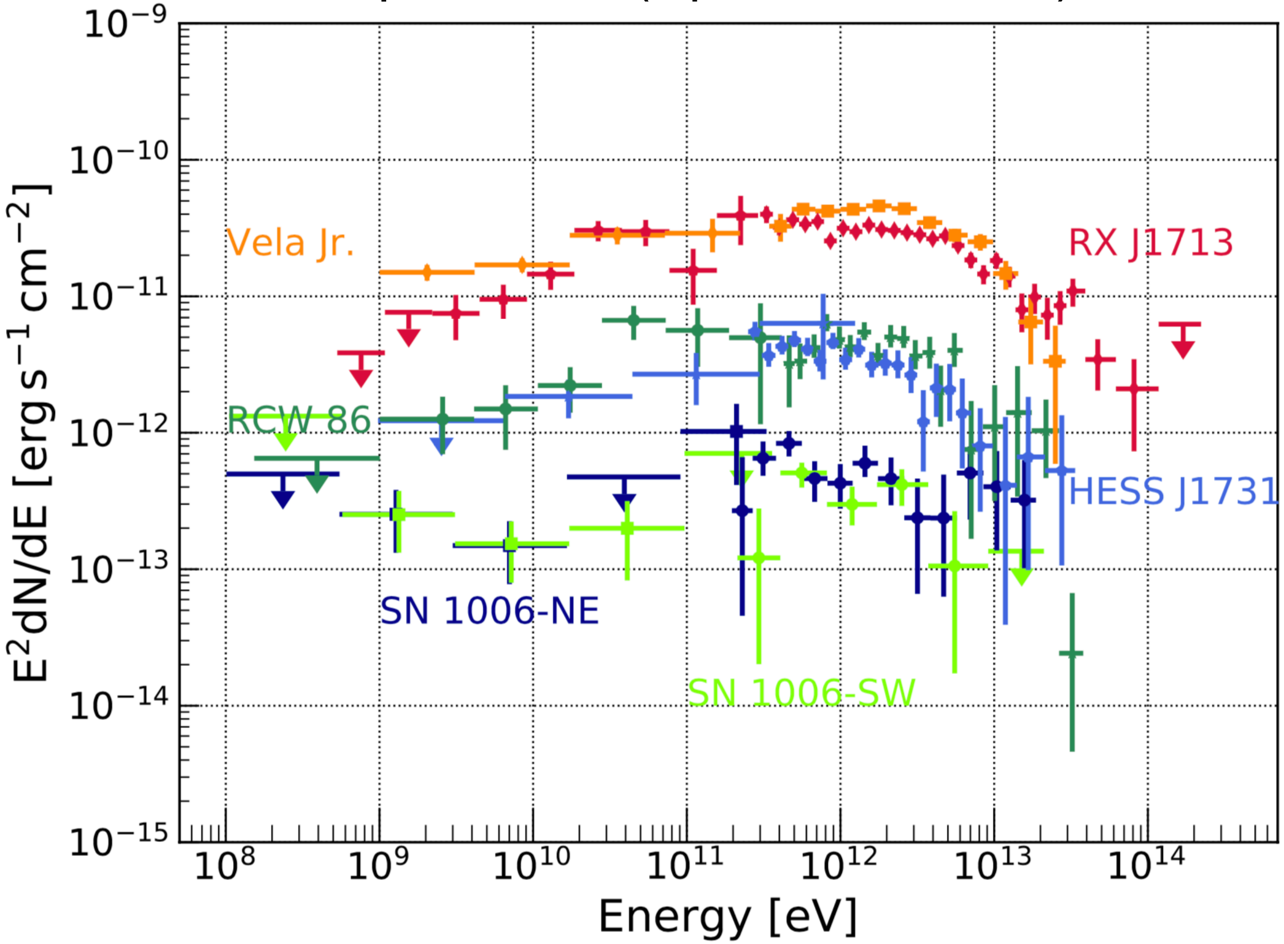


Young SNRs in gamma-ray

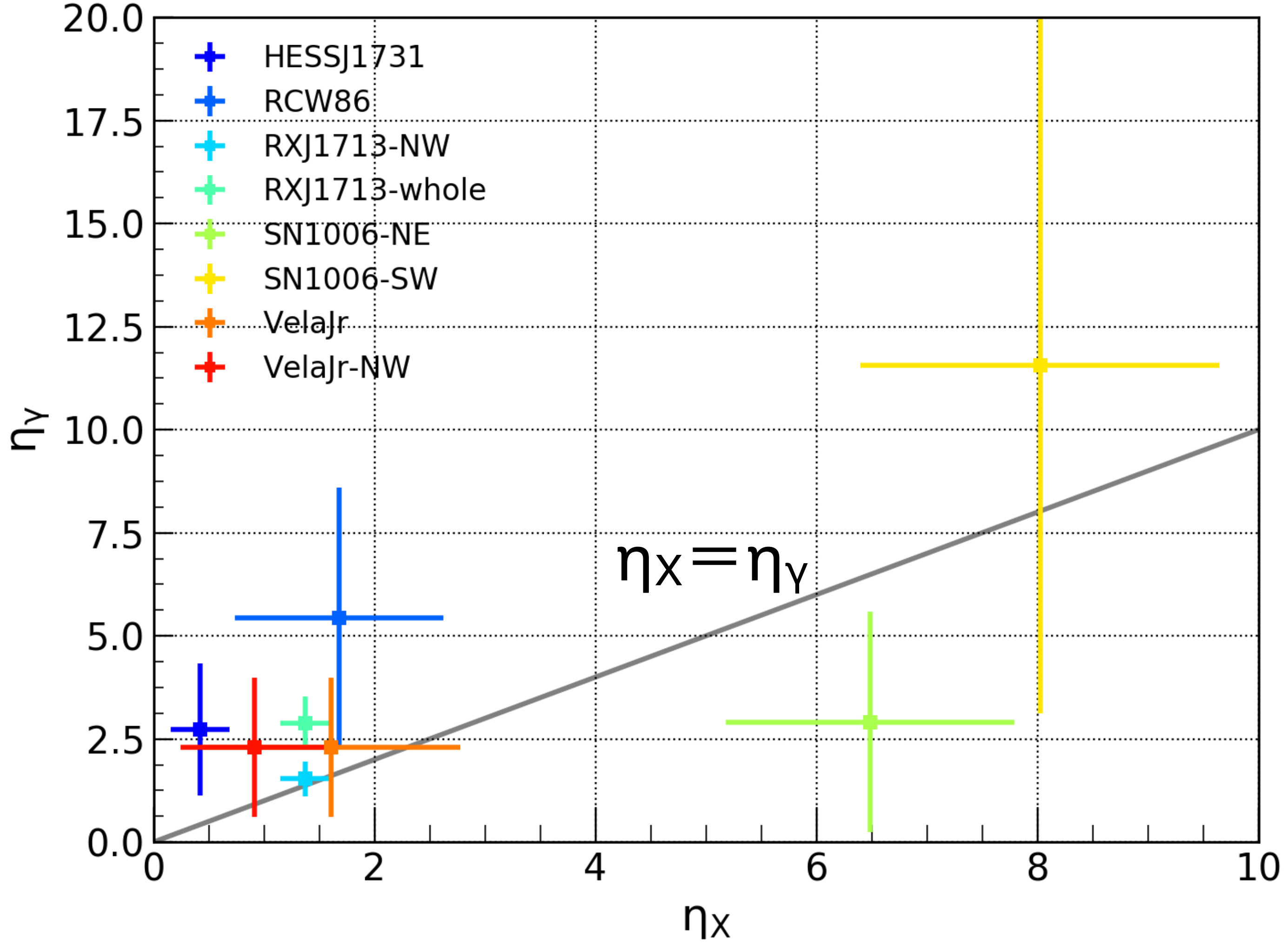
Shell-type TeV emitting SNRs (taken with H.E.S.S. +Fermi)

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

- Leptonic / Hadronic?
- B-field is estimated from X/γ flux ratio (leptonic scenario)



Bohm factor: X/γ-ray



- $\eta_\gamma > \eta_X$; 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)

Summary

- Estimated the diffusion coefficient (Bohm factor; η) 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

✤ X-ray observations

- Different types of acceleration:
  - standard and not standard (affected by ambient environment or age)
- Revealed the more efficient acceleration for the older SNR

✤ Gamma-ray observations

- TeV gamma-ray spectrum also provides a useful tool to estimate acceleration efficiency (assuming leptonic scenario)
- $\eta_\gamma > \eta_X$ arises from different regions, B-field, or hadronic contribution

✤ 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 coefficient