Cosmic-ray Escape from Supernova Remnants in the Circumstellar Medium

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□Cosmic Ray(CR) Acceleration in Perpendicular Shocks

Rapid acceleration at perpendicular shocks (e.g. Jokipii 1987, Giacalone 2005, Guo & Giacalone 2010)

Gyration is important for rapid perp. shock acceleration. (e.g. Takamoto & Kirk 2015, Kamijima+2020)

$$\rightarrow E_{\mathrm{max,age,perp}} \sim 1\mathrm{PeV}\left(\frac{u_{\mathrm{sh}}}{0.02c}\right)\left(\frac{B_{\mathrm{up}}}{3\mu\mathrm{G}}\right)\left(\frac{t_{\mathrm{age}}}{200\ \mathrm{yr}}\right)$$ (Kamijima+2020)

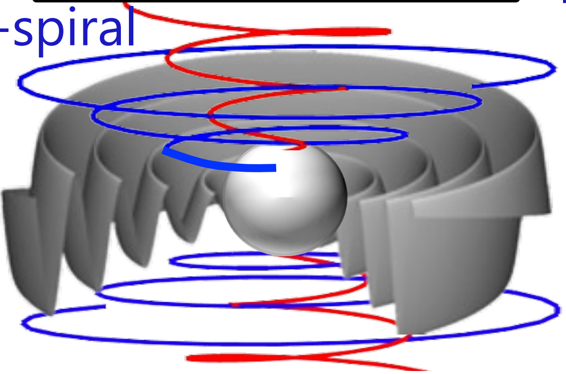
□CR Escape from Perpendicular Shocks

We consider

- **Solve gyration → Rapid acceleration**
- **Magnetic field geometry**
- **Shape of the shock surface**
- **Surrounding environment**

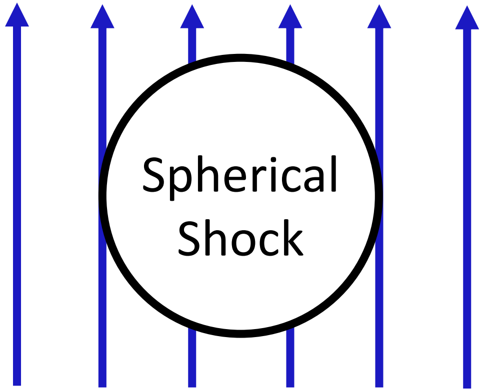
We investigate CR escape from perp. shocks of supernova remnants(SNRs) in the circumstellar medium with the Parker-spiral magnetic field.

Core Collapse SNRs (This Work)



Kamijima & Ohira in preparation

Type Ia SNRs



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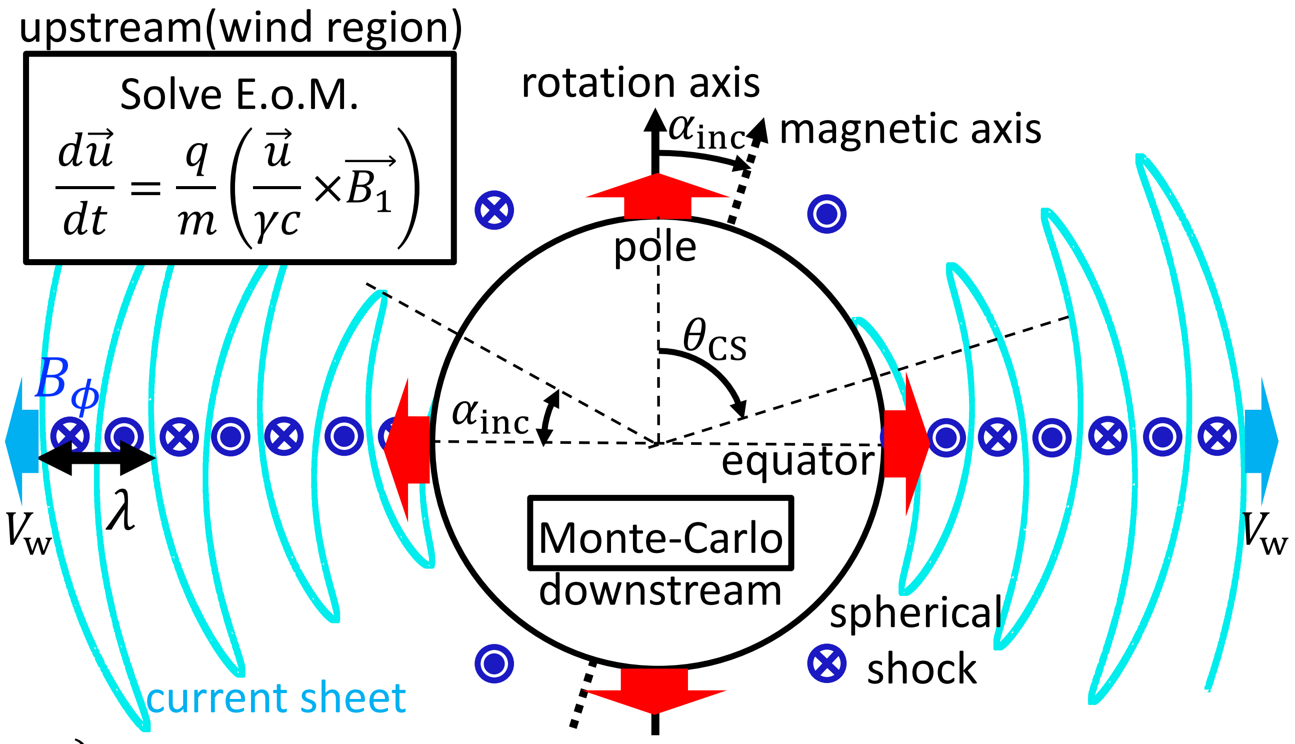
Simulation Setup

- test particle simulation (upstream) + Monte-Carlo (downstream)
- RSG: $B_* = 1\ \mathrm{G}, R_* = 1000R_{\mathrm{sun}}, V_{\mathrm{w}} = 10^6\ \mathrm{cm/s}, P_* = 40\ \mathrm{yr}$ (Betelgeuse)(Kervella+2018)
- WR stars: $B_* = 1\ \mathrm{kG}, R_* = 5\ R_{\mathrm{sun}}, V_{\mathrm{w}} = 10^8\ \mathrm{cm/s}, P_* = 10\ \mathrm{days}$ (Chene & St-Louis 2008, 2010)
- shock velocity (e.g. Chevalier 1987, Moriya+2013): $E_{\mathrm{SN}} = 10^{51}\ \mathrm{erg}, M_{\mathrm{ej}} = 5M_{\mathrm{sun}}, \dot{M} = 10^{-5}M_{\mathrm{sun}}/\mathrm{yr}$
- density profile in the wind region: $\rho_{\mathrm{w}} = \dot{M}/(4\pi V_{\mathrm{w}} r^2)$
- down. flow velocity (only radial component): $u_{\mathrm{d}}(r) = (3/4)u_{\mathrm{sh}}(r/R_{\mathrm{sh}})$ for $0 \le r \le R_{\mathrm{sh}}$
- Isotropic scattering in the local down. fluid rest frame.
- downstream B-field: $B_{\mathrm{d}} = 100B_{\mathrm{w}}$
- unperturbed B-field in the wind region:

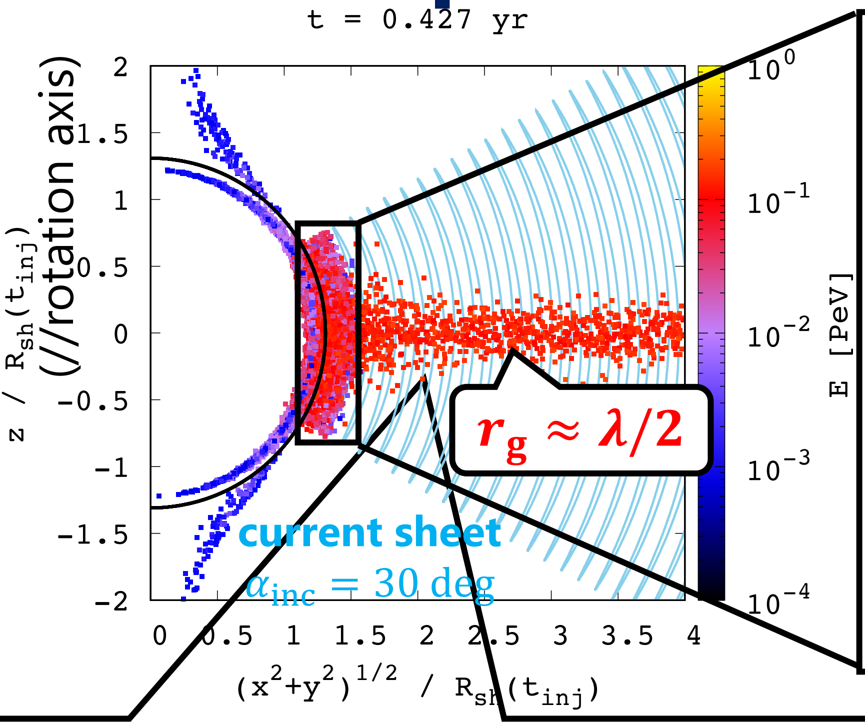
$$\begin{cases} B_{\mathrm{w},r} = B_A\left(\frac{R_A}{r}\right)^2\{1-2H(\theta-\theta_{\mathrm{CS}})\} \quad B_{\mathrm{w},\theta} = 0 \\ B_{\mathrm{w},\phi} = -B_A\frac{R_A}{r}\frac{R_A\Omega_*}{V_{\mathrm{w}}}\sin\theta\{1-2H(\theta-\theta_{\mathrm{CS}})\} \end{cases}$$

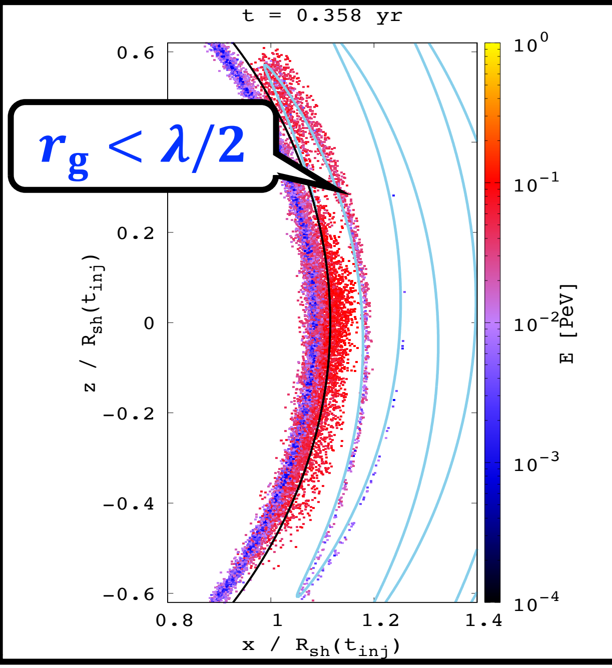
$$\theta_{\mathrm{CS}} = \frac{\pi}{2} - \sin^{-1}\left[\sin\alpha_{\mathrm{inc}}\sin\left[\phi+\Omega_*\left(t-\frac{r-R_*}{V_{\mathrm{w}}}\right)\right]\right]$$

- polarity: pole → equator ($\alpha_{\mathrm{inc}} = 0, 30, 60, 90\ \mathrm{deg}$)
- impulsive injection at t_{inj}, $E_{\mathrm{inj}} = 1\ \mathrm{TeV}$, isotropic
- $t_{\mathrm{inj}} = 0.3, 10, 100, 1000\ \mathrm{yr}$ (RSGs), $0.1, 10, 1000\ \mathrm{yr}$ (WR stars)



Oblique Rotator: Early Phase Injection



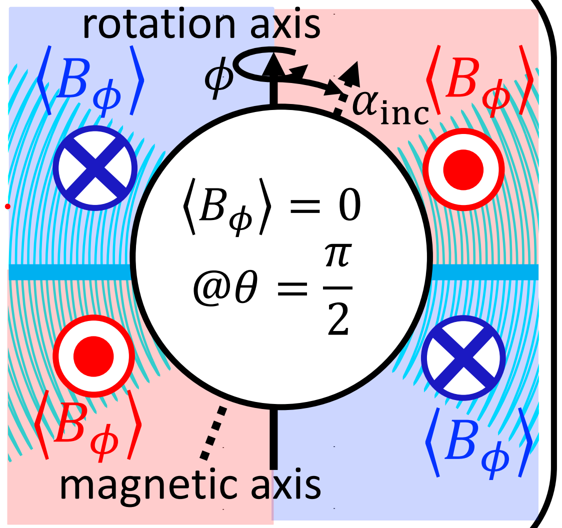


1. Particles interact with the current sheet.
   → meandering motion
2. The shock catches up with particles. (∵The radial particle velocity decreases as particles are distant from the shock.)
   → Acceleration

Particles pass more than two current sheets during one gyromotion.

→Particles feels the mean B-field, $\langle B_\phi \rangle$.
and escape along the equator($\langle B_\phi \rangle = 0$).

$$\langle B_\phi \rangle = \frac{1}{\lambda}\int_0^\lambda dr B_\phi \approx \frac{1}{2\pi}\int_0^{2\pi} d\phi B_\phi$$
$$= -B_A \frac{R_A}{R_{sh}} \frac{R_A \Omega_*}{V_w} \sin\theta \left\{1 - 2H\left(\theta - \frac{\pi}{2}\right)\right\}$$
$$\times \left\{1 - \frac{2}{\pi}\cos^{-1}\left(\frac{\cos\theta}{\sin\alpha_{inc}}\right)\right\}$$



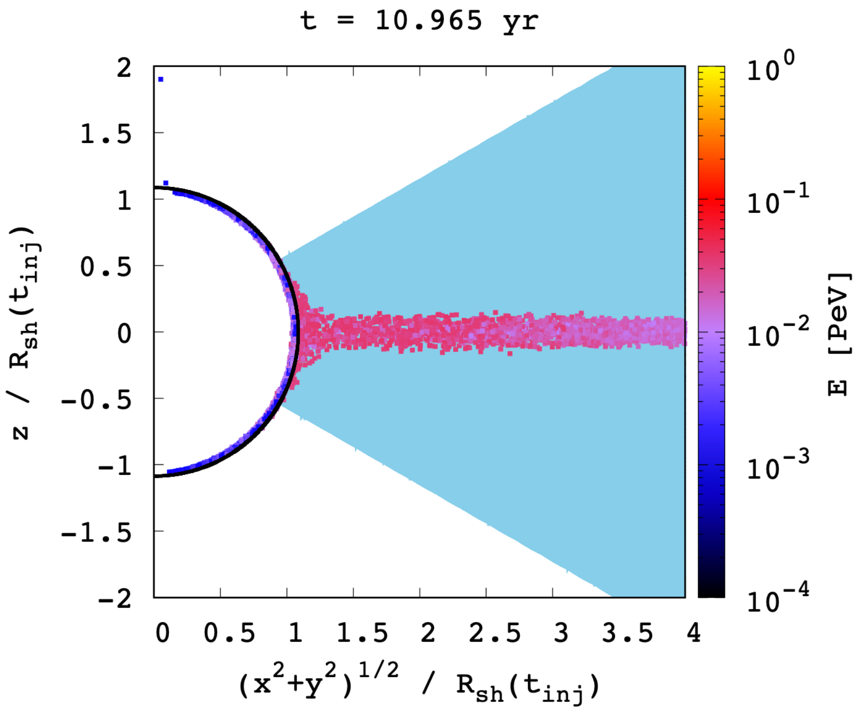
□ E_{max} is limited by $r_g = \lambda/2$

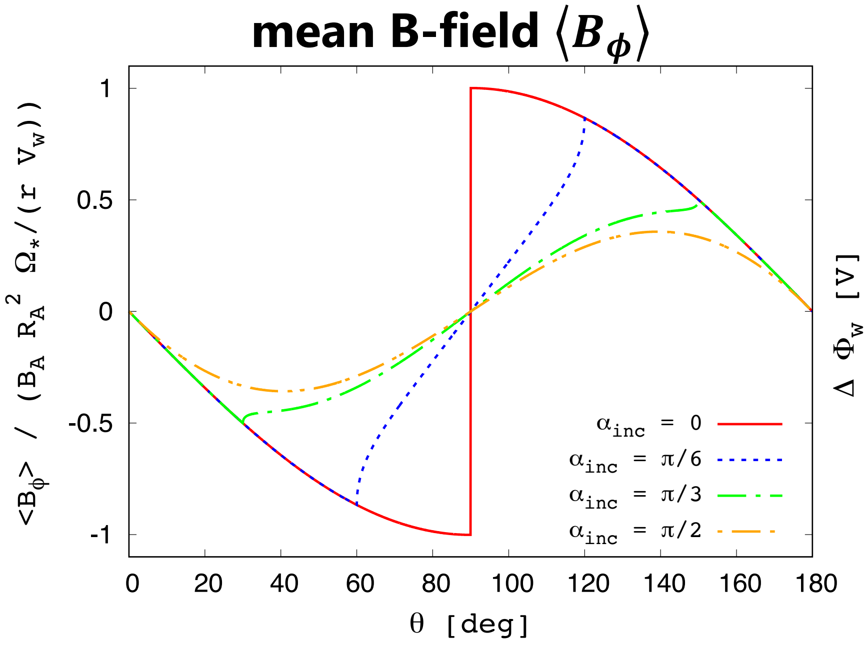
$$E_{max,\lambda/2} = eB_\phi \frac{\lambda}{2} = \pi\left(\frac{R_A}{R_{sh}}\right) eB_A R_A$$

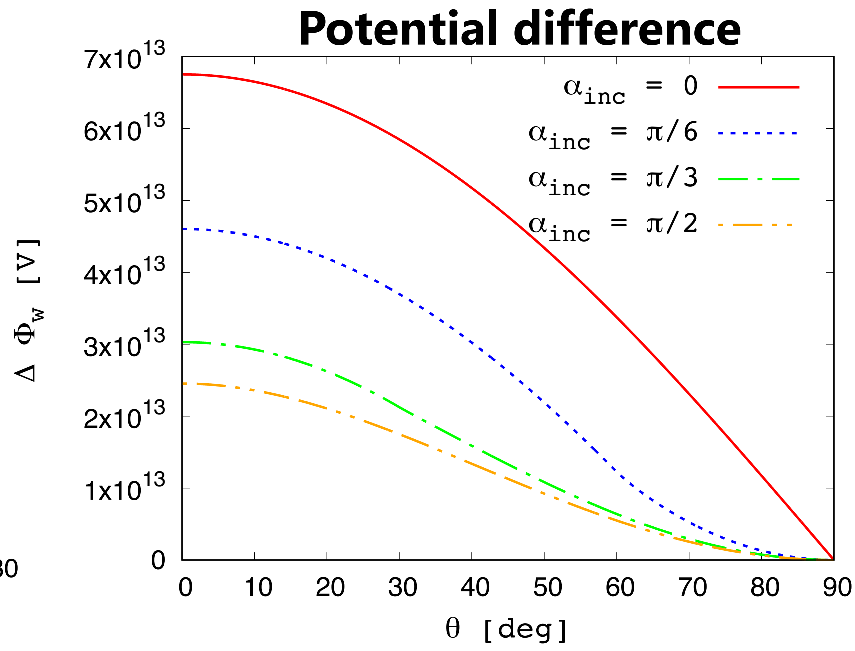
$$\left(B_A = B_*\left(\frac{R_*}{R_A}\right)^3 \approx \eta_*^{-\frac{3}{4}} B_*, R_A \approx \eta_*^{\frac{1}{4}} R_*, \eta_* = \frac{B_*^2 R_*^2}{\dot{M} V_w}\right)$$

$$E_{max,\lambda/2} \approx 1\ \mathrm{PeV}\left(\frac{B_*}{1\ \mathrm{G}}\right)^{1/2}\left(\frac{R_*}{10^3 R_\odot}\right)^{3/2}$$
$$\times\left(\frac{\dot{M}}{10^{-5} M_\odot/\mathrm{yr}}\right)^{1/4}\left(\frac{V_w}{10^6\mathrm{cm/s}}\right)^{1/4}\left(\frac{R_{sh}}{10^{-3}\ \mathrm{pc}}\right)^{-1}$$

Oblique Rotator: Late Phase Injection







If $r_g > \lambda$, particles feel $\langle B_\phi \rangle$ **inside the current sheet structure.**

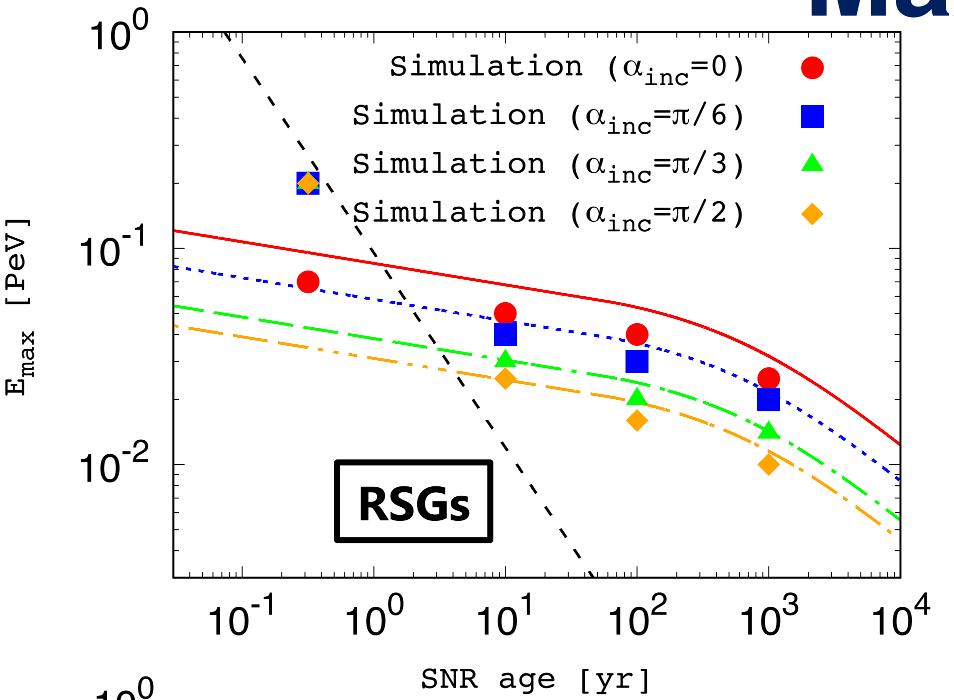
$$\langle B_\phi \rangle = \frac{1}{\lambda}\int_0^{\lambda} dr B_\phi \approx \frac{1}{2\pi}\int_0^{2\pi} d\phi B_\phi = -B_A \frac{R_A}{R_{\rm sh}} \frac{R_A \Omega_*}{V_{\rm w}} \sin\theta \left\{1 - 2H\left(\theta - \frac{\pi}{2}\right)\right\}\left\{1 - \frac{2}{\pi}\cos^{-1}\left(\frac{\cos\theta}{\sin\alpha_{\rm inc}}\right)\right\}$$

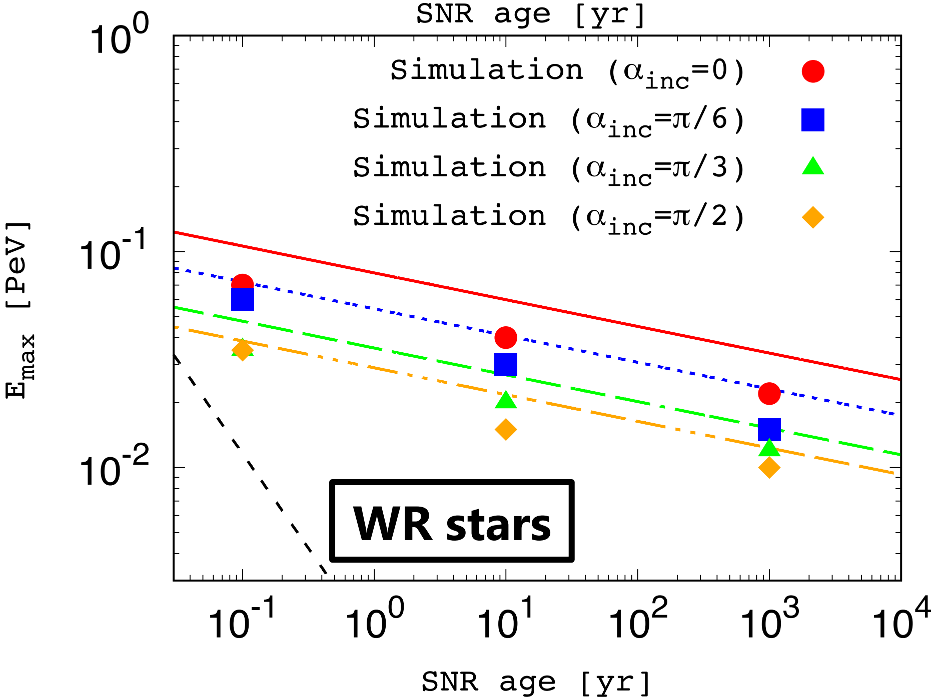
□ E_{max} is limited by the potential difference between the pole and the equator.

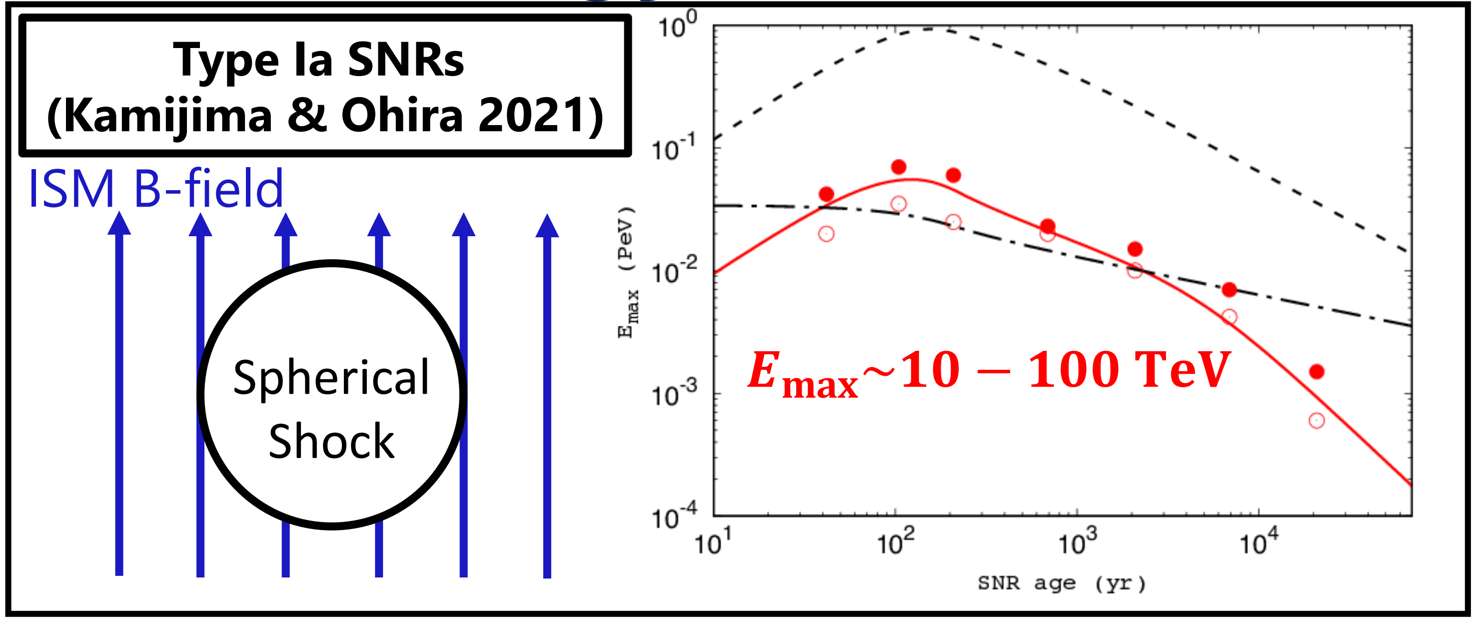
$$E_{\rm max,PD} = \int_0^{\pi/2} eE_{\rm w}^{\rm sh} R_{\rm sh} d\theta \approx \int_0^{\pi/2} e\left(-\frac{u_{\rm sh}}{c}\langle B_\phi \rangle\right) R_{\rm sh} d\theta = \left(1 - \frac{2}{\pi}\sin\alpha_{\rm inc}\right)\frac{u_{\rm sh}}{c}\frac{R_A \Omega_*}{V_w} eB_A R_A$$ @shock rest frame

$$\approx 44\ {\rm TeV}\left(1 - \frac{2}{\pi}\sin\alpha_{\rm inc}\right)\left(\frac{u_{\rm sh}}{0.01c}\right)\left(\frac{B_*}{1\ {\rm G}}\right)^{1/2}\left(\frac{R_*}{10^3 R_\odot}\right)^{3/2}\left(\frac{\dot{M}}{10^{-5} M_\odot/{\rm yr}}\right)^{1/4}\left(\frac{V_{\rm w}}{10^6 {\rm cm/s}}\right)^{-3/4}\left(\frac{P_*}{40\ {\rm yr}}\right)^{-1}$$

Maximum Energy







- In the early phase (t<1yr for RSGs, t<10^{-2}yr for WR stars), the maximum energy is limited by the half wavelength of the wavy current sheet, $E_{\max,\lambda/2} = \pi\left(\frac{R_A}{R_{\rm sh}}\right) eB_A R_A$.
- In the late phase, the maximum energy is limited by the potential difference between the equator and pole, $E_{\max,\rm PD} = \left(1-\frac{2}{\pi}\sin\alpha_{\rm inc}\right)\frac{u_{\rm sh}}{c}\frac{R_A\Omega_*}{V_w}eB_A R_A$.

→ SNRs that the upstream B-field amplification is insufficient could be the origin of 10 TeV break reported by CREAM, NUCLEON, DAMPE, and HAWC.