大阪大学
THE UNIVERSITY OF OSAKA

Institute of Laser Engineering
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Collisionless Shocks and Particle Acceleration in Black Hole Coronae: Results from Particle-In-Cell (PIC) Simulations

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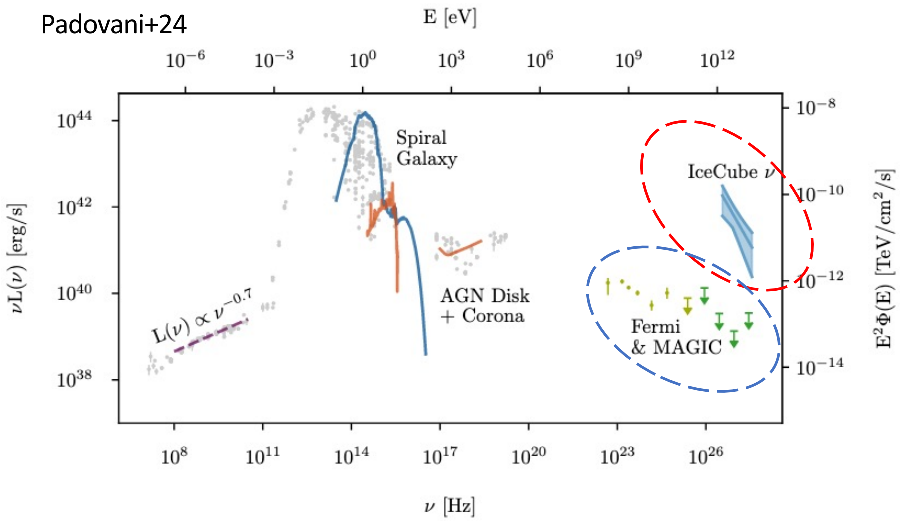
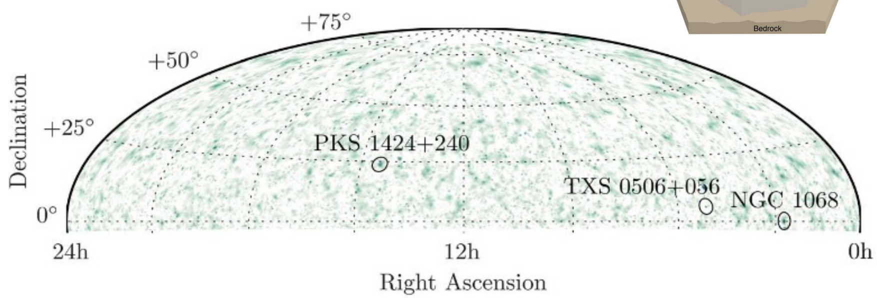
High-energy neutrinos from Black Hole (BH) Coronae

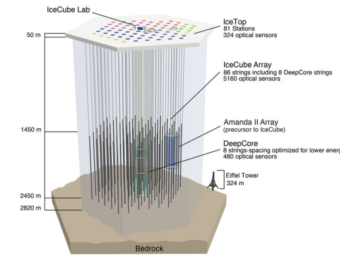
Neutrino: IceCube 10 years survey

Padovani+24



I.C +2022

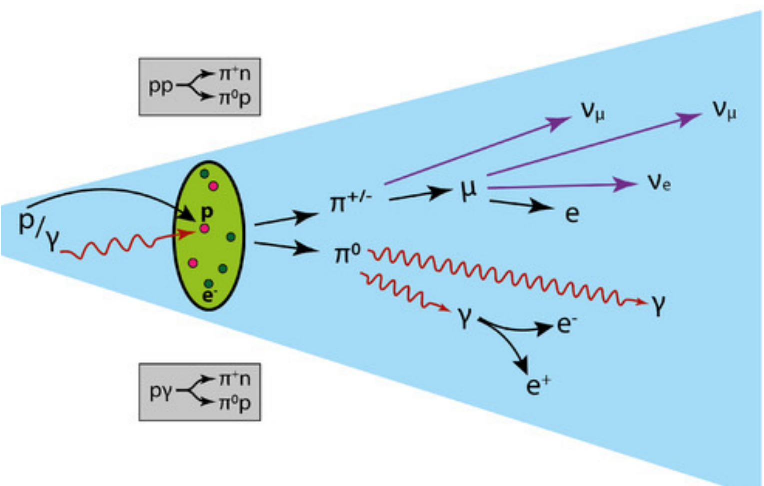




- IceCube survey reveal **high-energy ν excess (1.5 – 15 TeV) from NGC1068** – a AGN and Seyfert Galaxy
- **Required $\sim 30 - 300$ TeV ions (proton)** to produce the ν signal through hadronic processes (pp and pγ)
- Insufficient high-energy γ-rays suggest **high-energy ν produced in the Black hole (BH) Corona**

Hadronic interactions

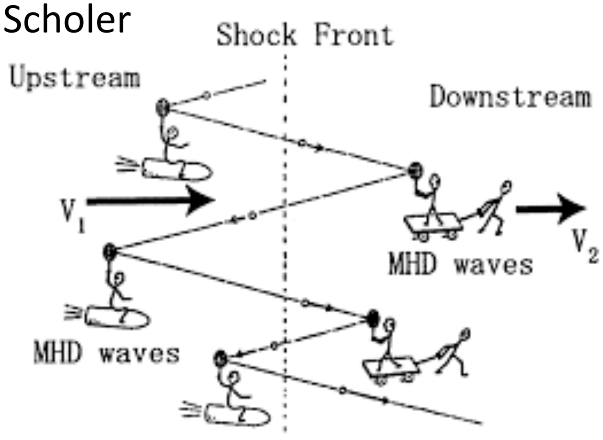
- Hadronuclear pp: π^0, π^+, π^- equal ratio
- Photopion pγ: π^0 (1/2), π^+ and π^- (1/2)



Acceleration of particles in BH Coronae

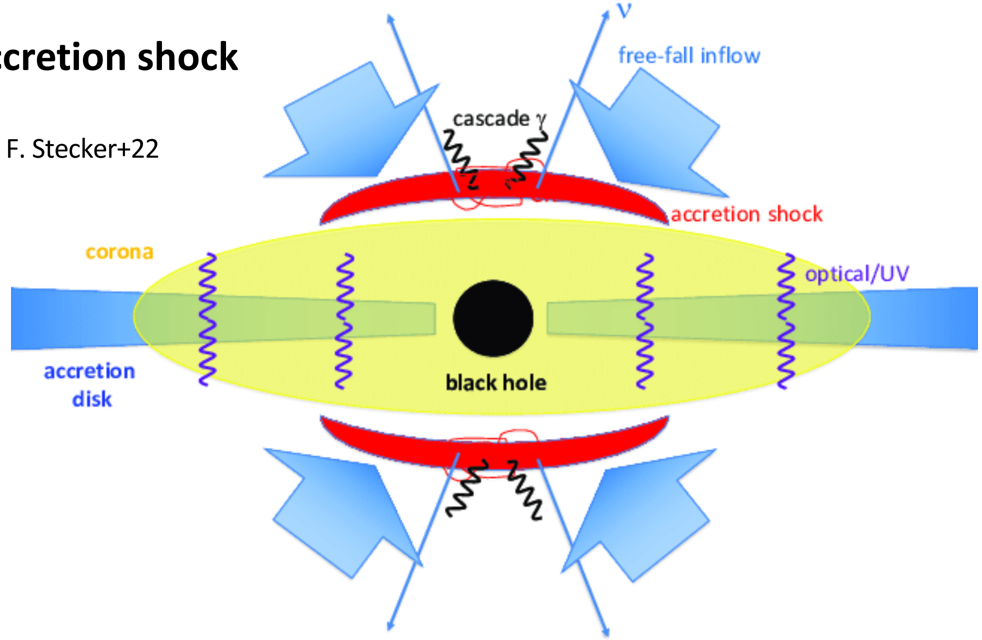
Diffusive shock acceleration (DSA) (Y. Inoue+19,20) is a prominent candidate

Scholer



Accretion shock

F. Stecker+22



Shock conditions in BH Coronae

- **Shock velocity v_{sh}** order-estimate from free-fall velocity $v_{sh} \approx 0.1 - 0.3$ c
- BH Corona is a **hot plasmas with large temperature ratio** $T_i/T_e \gg 1$. $T_e = 100$ keV, $T_i = 1 - 10$ MeV. **Sonic Mach number $M_s \approx 3 - 8$**
- **Alfven Mach number $M_A \approx 26$**, with $B \approx 100$ G from synchrotron emission (Y. Inoue+20, Michiyama+23)

Why first-principle study is needed?

Summary of “likely” shock paramters

v_{sh}/c	M_s	M_A	T_i/T_e
$0.1-0.3$	$\sim 3-8$	~ 26	$\gtrsim 10$

Astrophysical motivation

1. **Can strong shocks really form in such extremely hot plasmas?**
   (Fundamental plasma physics challenge)
2. **How efficient is ion acceleration in the early phase?**
   Can protons reach energies up to ~100 TeV under coronal conditions?
3. **Do these shocks inject enough energy into cosmic rays to explain the observed neutrino luminosity from AGN like NGC 1068?**

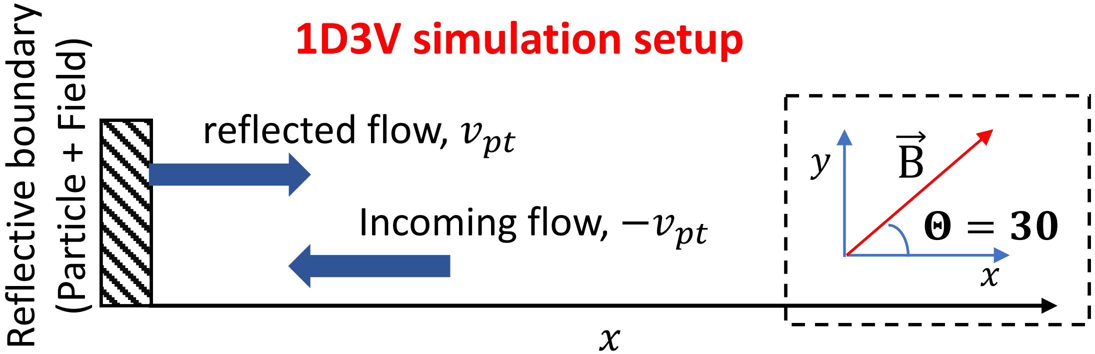
Numerical perspective

Lack of systematic survey for

1. Effect of temperature ratio T_i/T_e
2. Trans-relativistic shock velocity $\mathrm{v_{sh}} \approx 0.33\ \mathrm{c}$

Simulation setup
& summary of survey parameters

Particle-in-cell (PIC) simulation setup



Resolution: 10 cells per c/ω_{pe}, $\Delta t = 0.4\times\Delta x$, 150 particles/cell/species

$$v_{sh} = \frac{r}{r-1} v_{pt} = \frac{4}{3} v_{pt}$$

Long-term 1D3V PIC simulations of quasi-parallel collisionless shocks (SMILEI code, J. Derouillat et al. 2018).

Shock driven by "piston" set up: **lab frame ≡ downstream rest frame**

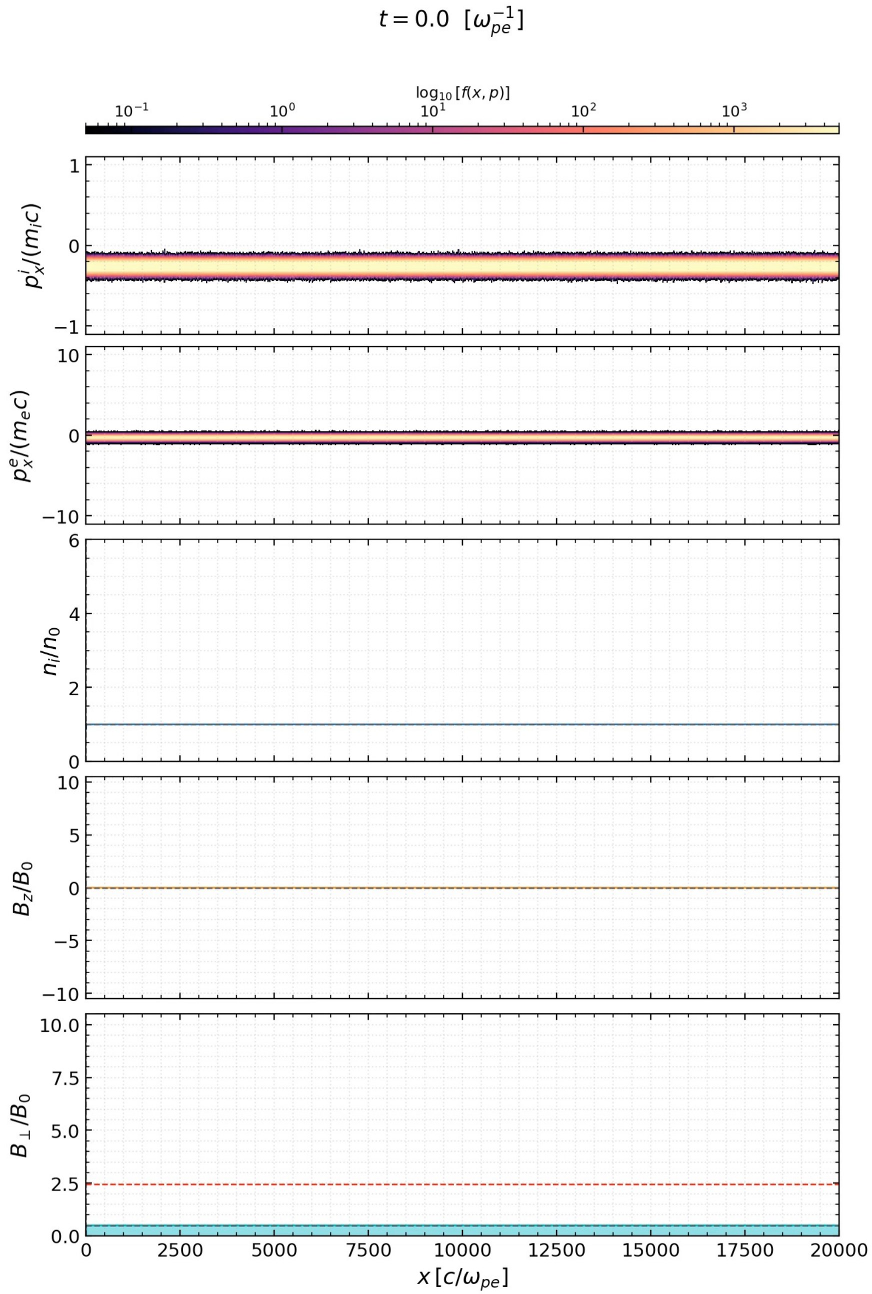
- Use reduced mass ratio $m_i/m_e = 100$, scale $B_0, T_{e,i}$→ preserve $M_A, M_s^*, T_i/T_e$.

Study parameters

- **Typical parameters:** $M_A = 26,\ M_s = 8,\ T_i/T_e = 10,\ v_{sh} = 0.33$ c
- Survey shock conditions by changing temperature ratios, Mach number and shock speed
- 15 simulations in total

*in other words, we did keep v_A, c_s value as expected value

Shock formation & structure

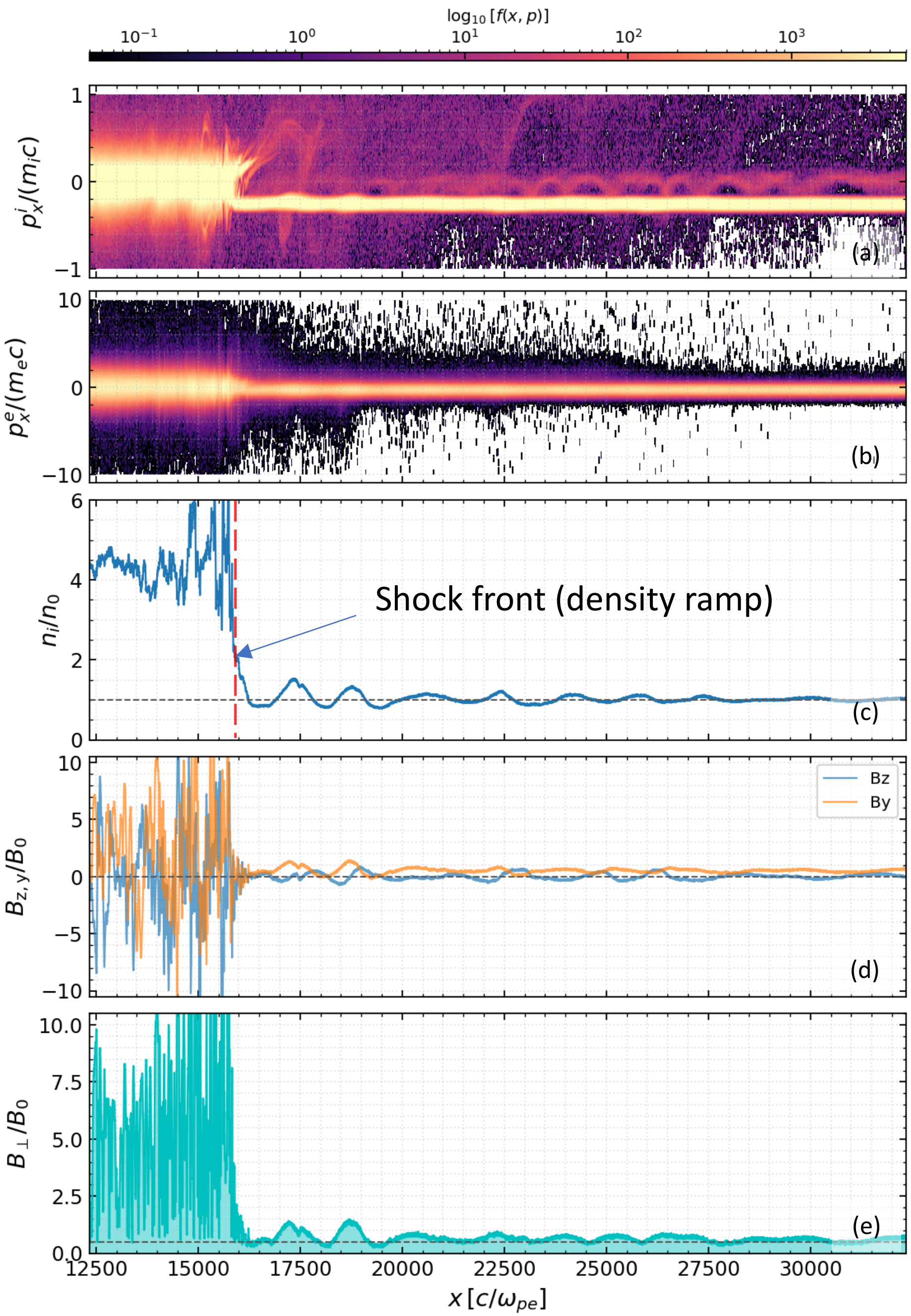


Reference case T010

ID	v_{sh}	M_s	M_A	T_i/T_e
T10	0.33c	8	26	10

- Ions reflected at the shock moving upstream – **Shock precusor**
- Shock reformation cycle
- **Magnetic field fluctuation** and amplification by streaming instability from reflected ions

Shock formation & structure



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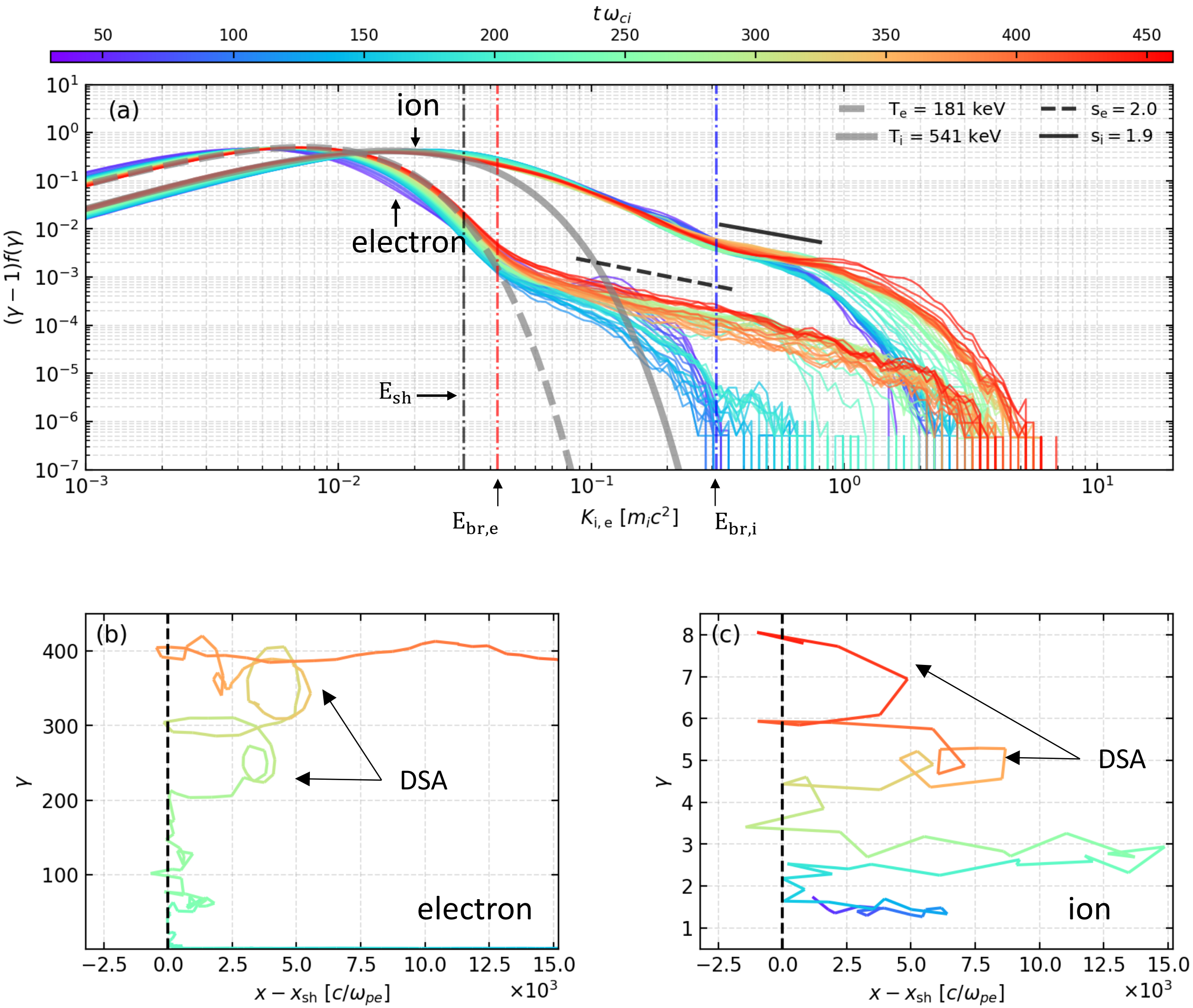
Downstream particle spectrum

Hard-spectrum ~2, typical DSA case.

Non-thermal energy fraction: electron 0.8%, Ion 9% total energy in particles



Non-thermal energy break

$$E_{br,e} = 12 \langle T_e \rangle$$

$$E_{br,i} = 10\, E_{inj} = 5 m_i v_{pt}^2$$

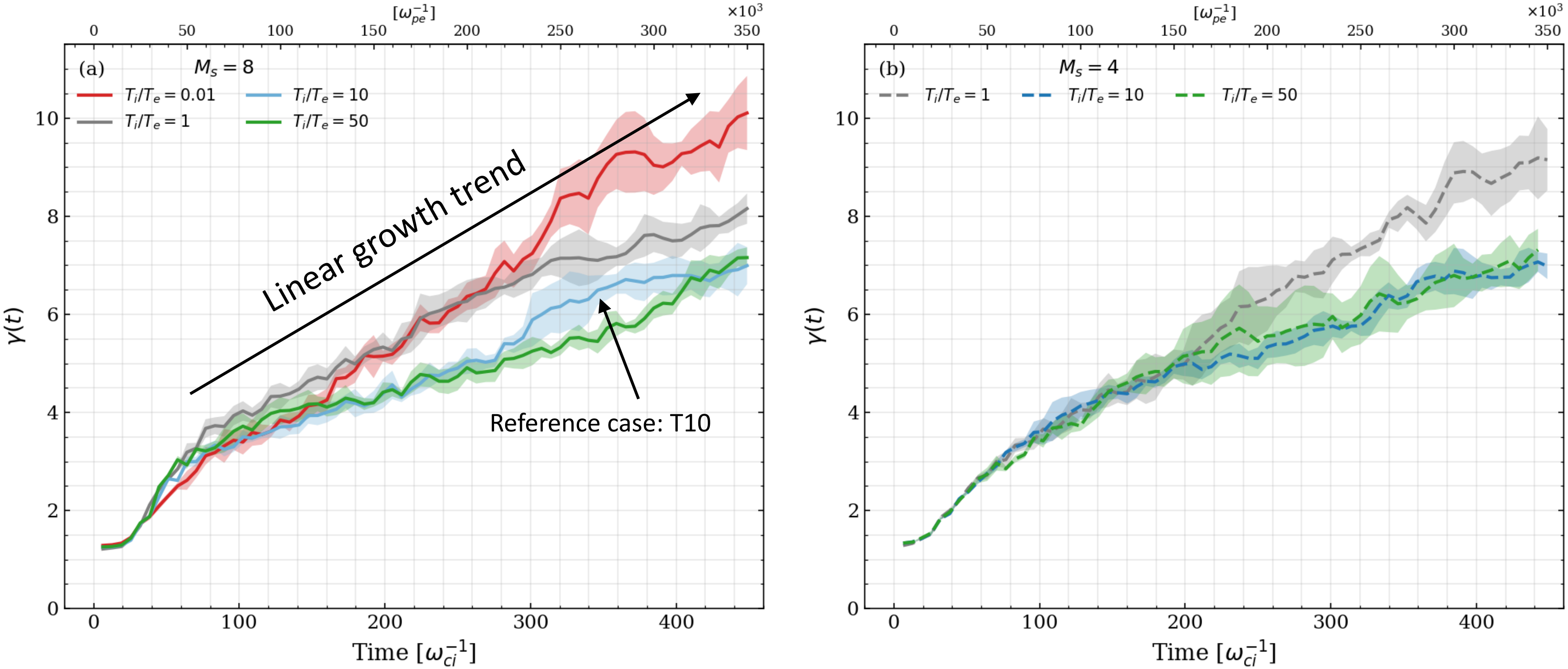
- Pre-acceleration near shock surface before going through DSA cycles
- Particles mostly resided between excited wave upstream and shock front

How efficient is proton acceleration in the early phase?

Can protons reach energies up to 100 TeV under BH corona conditions?

Growth of ion energy with time

Fixed Ms = 8, vary $T_i/T_e = 0.01 - 50$ | Fixed Ms = 4, vary $T_i/T_e = 1 - 50$



We track **average energy of top 10 protons energy → max energy evolution.**

- After $t \gtrsim 100\,\omega_{ci}^{-1}$: linear growth → DSA-like
- Fit slope → acceleration efficiency.

Compare with DSA prediction

In standard DSA theory: acceleration rate depend on diffusive (and scattering) of particle near the shock

$$t_{acc}(\gamma) \approx \frac{D_u}{v_{sh}^2}$$ With Bohm-like diffusive coefficient $$D_u = \eta_g \frac{c r_L}{3}$$

This leading to predicted energy gain:

$$\gamma = (t\omega_{ci}) \times \frac{3}{\eta_g} \times {\beta_{sh}}^2$$

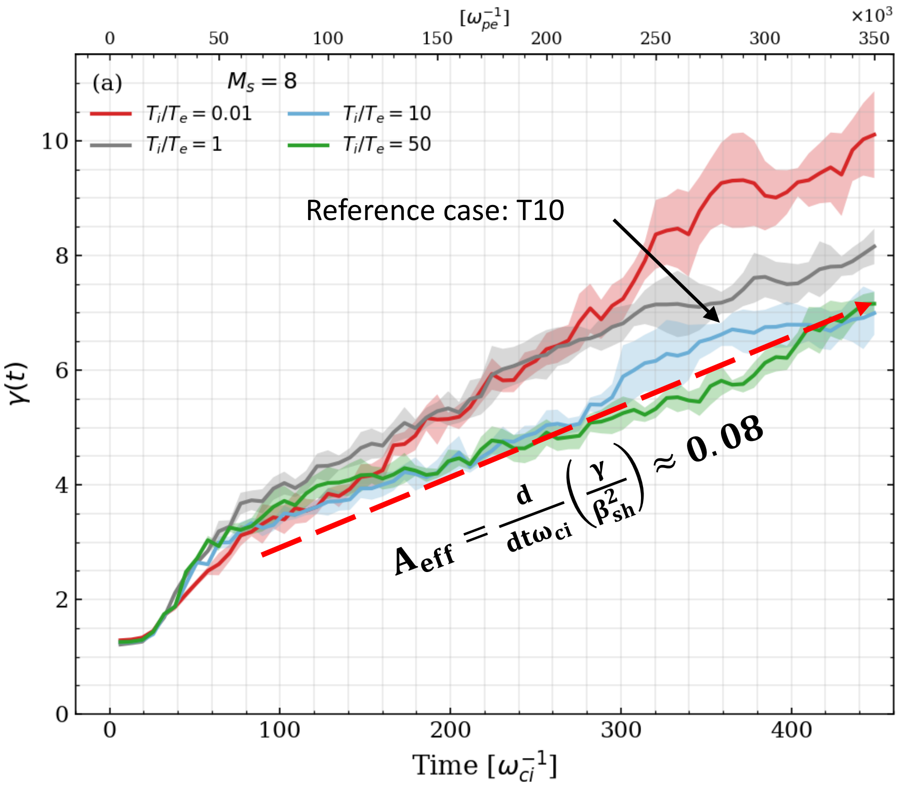
Where $\beta_{sh} = v_{sh}/c$

The normalized acceleration rate = fitting slope

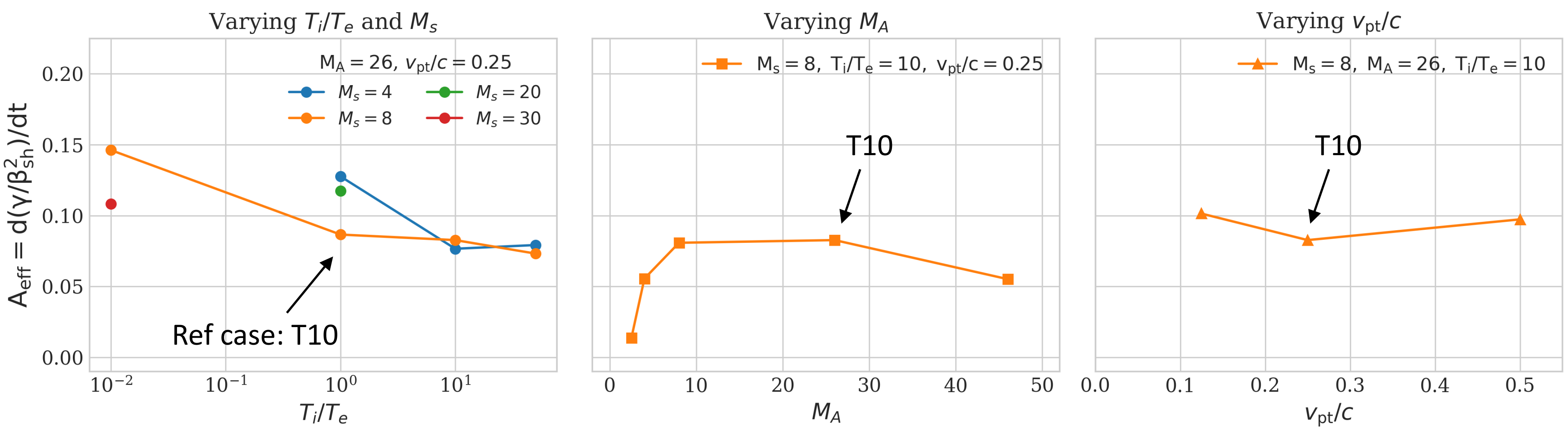
$$\mathrm{A_{eff}} = \frac{d}{d(t\omega_{ci})}\left(\frac{\gamma}{\beta_{sh}^2}\right)$$

Also $\frac{3}{\eta_g} = \mathrm{A_{eff}}$

Fixed Ms = 8, vary $T_i/T_e = 0.01 - 50$



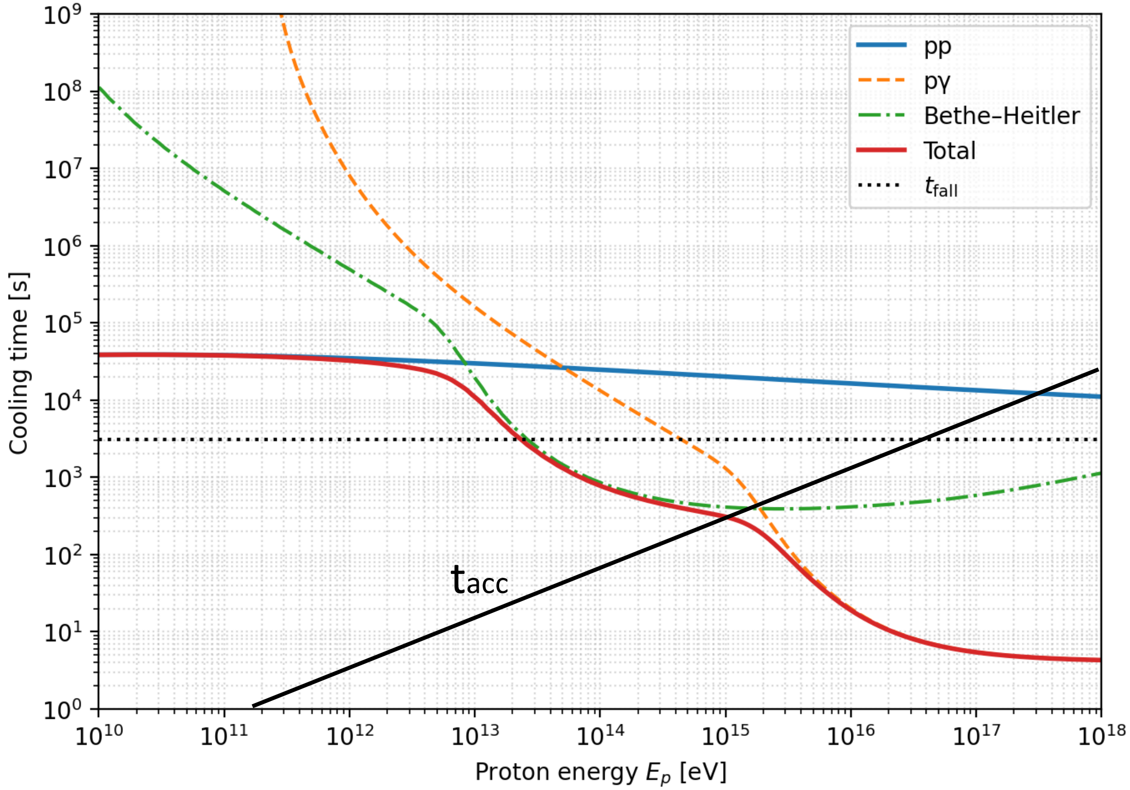
Scaling $A_{eff} = d\left(\gamma/\beta_{sh}^2\right)/dt$



- Overall, $\mathbf{A_{eff}} = \frac{\mathbf{d}}{\mathbf{dt\omega_{ci}}}\left(\frac{\boldsymbol{\gamma}}{\boldsymbol{\beta_{sh}^2}}\right) \approx \mathbf{0.1}$
- Efficiency **sharply declines** as the Alfvén Mach number approaches unity (MA→1), where the shock is weakest
- Efficiency shows **weak dependence** on other parameters like the sonic Mach number (Ms) and temperature ratio (Ti/Te).

Neutrino emission: cooling and acceleration time

Acceleration timescale to 100 TeV <= cooling time



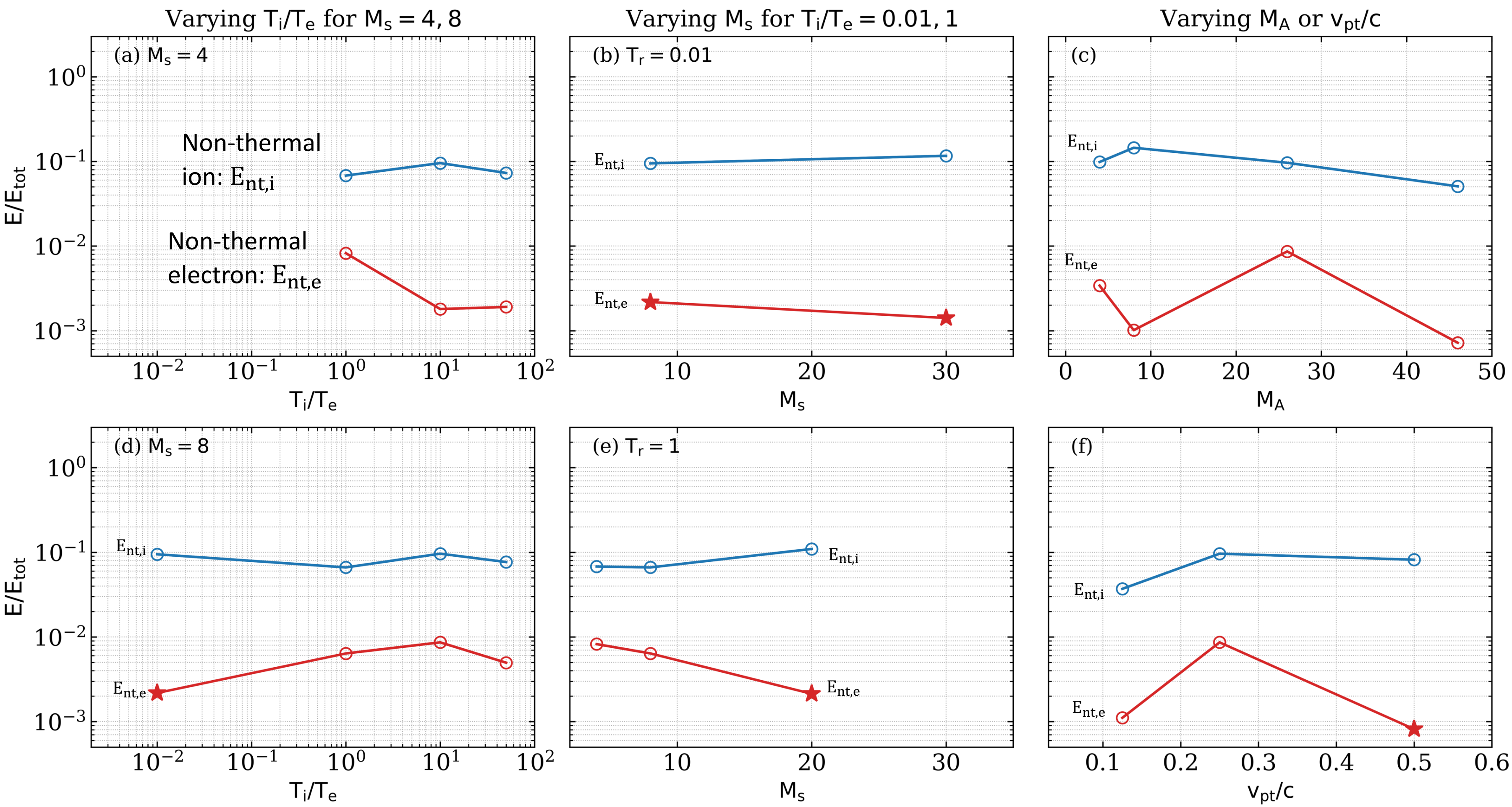
- t_{acc} of reference case T010
- Most of our simulations naturally **sastified cooling timescale condition** unless:

$$v_{sh}/c < 0.1 \text{ and } B_0 \leq 10\ G$$

Energy injected into protons luminosity required by neutrino spectrum

Can the shock inject sufficient energy to **explain observed neutrinos luminosity?**

Energy partition: non-thermal (NT) ion & electron



- **NT ion universally 10% of injected energy from shock**
- **NT electron >1% of injected energy,** however, it is much more complicated…

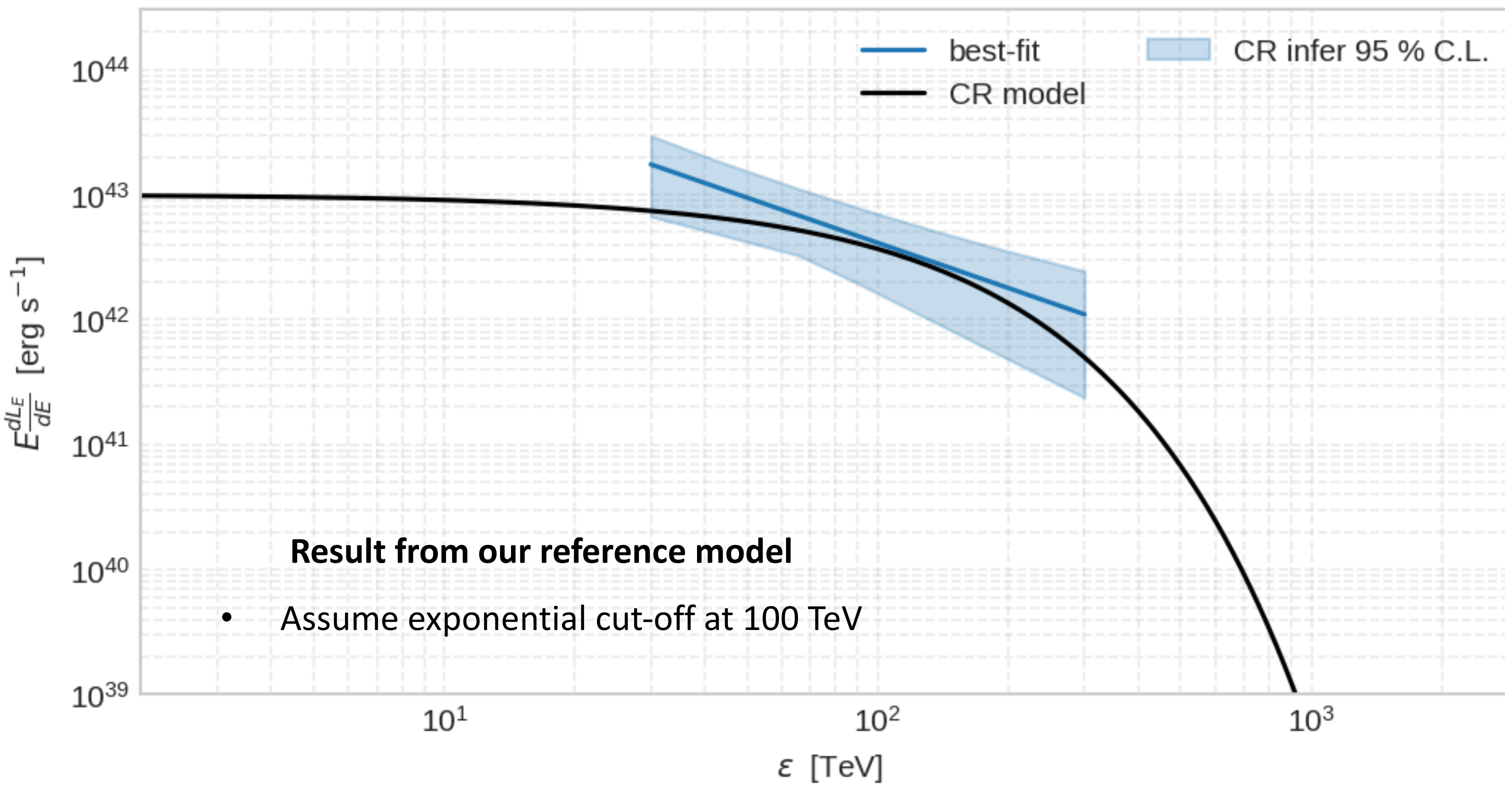
Neutrino emission: observed neutrino luminosity

Estimation of shock injected energy:

$$P_{sh} = 4\pi R_{sh}^2 n_p m_p v_{sh}^3 \qquad \text{with } R_{sh} \leq R_c$$

$$\approx 5\times10^{44} \left(\frac{R_{sh}}{10R_s}\right)\left(\frac{M_{BH}}{1\times10^7 M_\odot}\right)\left(\frac{v_{sh}}{0.33c}\right)^3 \quad \text{erg/s}$$

$$L_{CR} \approx 5\times10^{43} \left(\frac{\epsilon_{NT}}{0.1}\right)\left(\frac{R_{sh}}{10R_s}\right)\left(\frac{M_{BH}}{1\times10^7 M_\odot}\right)\left(\frac{v_{sh}}{0.33c}\right)^3 \quad \text{erg/s}$$



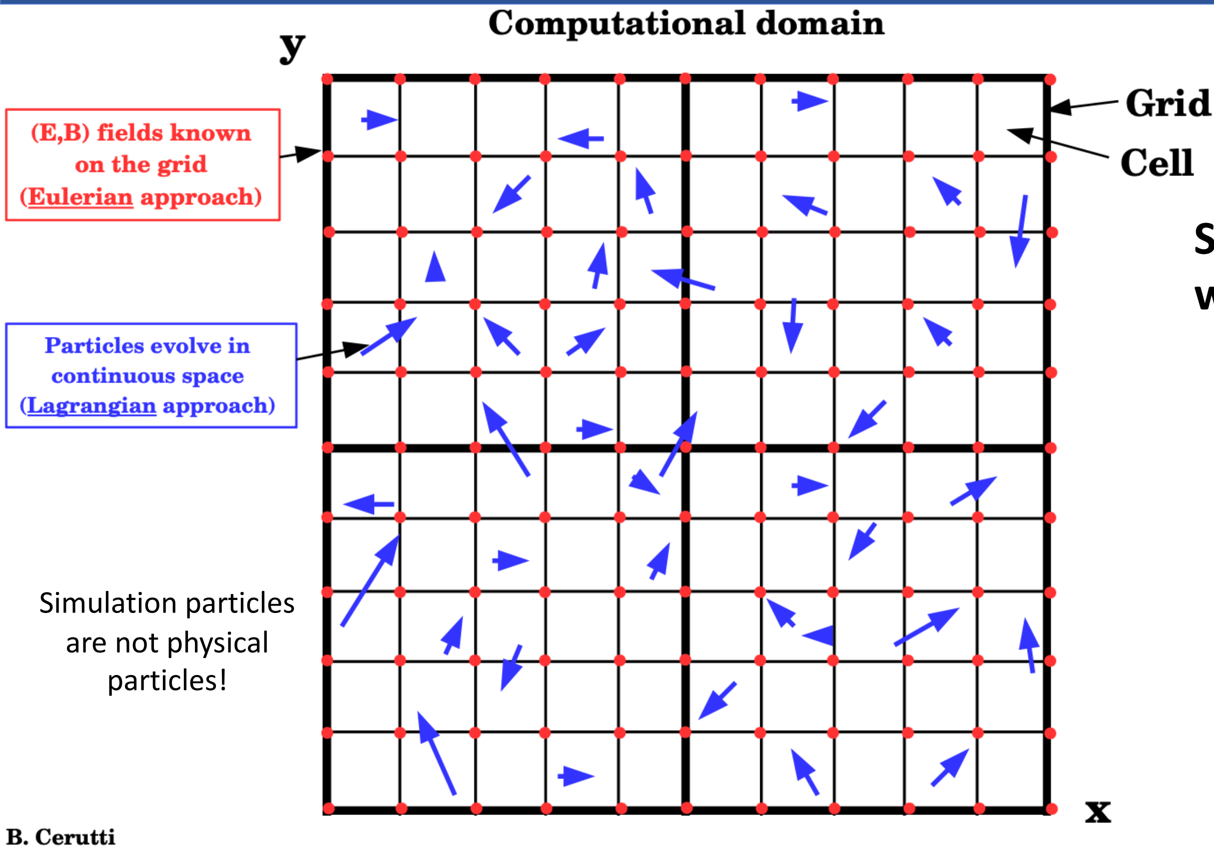
D =10.8 Mpc

Conclusion

- **Strong collisionless shocks can formed** even under extreme hot coronal plasmas and can efficiently accelerate protons by DSA
- **DSA can accelerate proton to energy > 100 TeV** in a wide conditions of plasma corona region
- Non-thermal proton universally receive ~10% of total shock injected energy. Based on our estimation, it is **sufficient to produce the neutrino luminosity** observed by IceCube

Thank you for your attention

Particle-in-cell (PIC) method



Simulation particles are not physical particles!

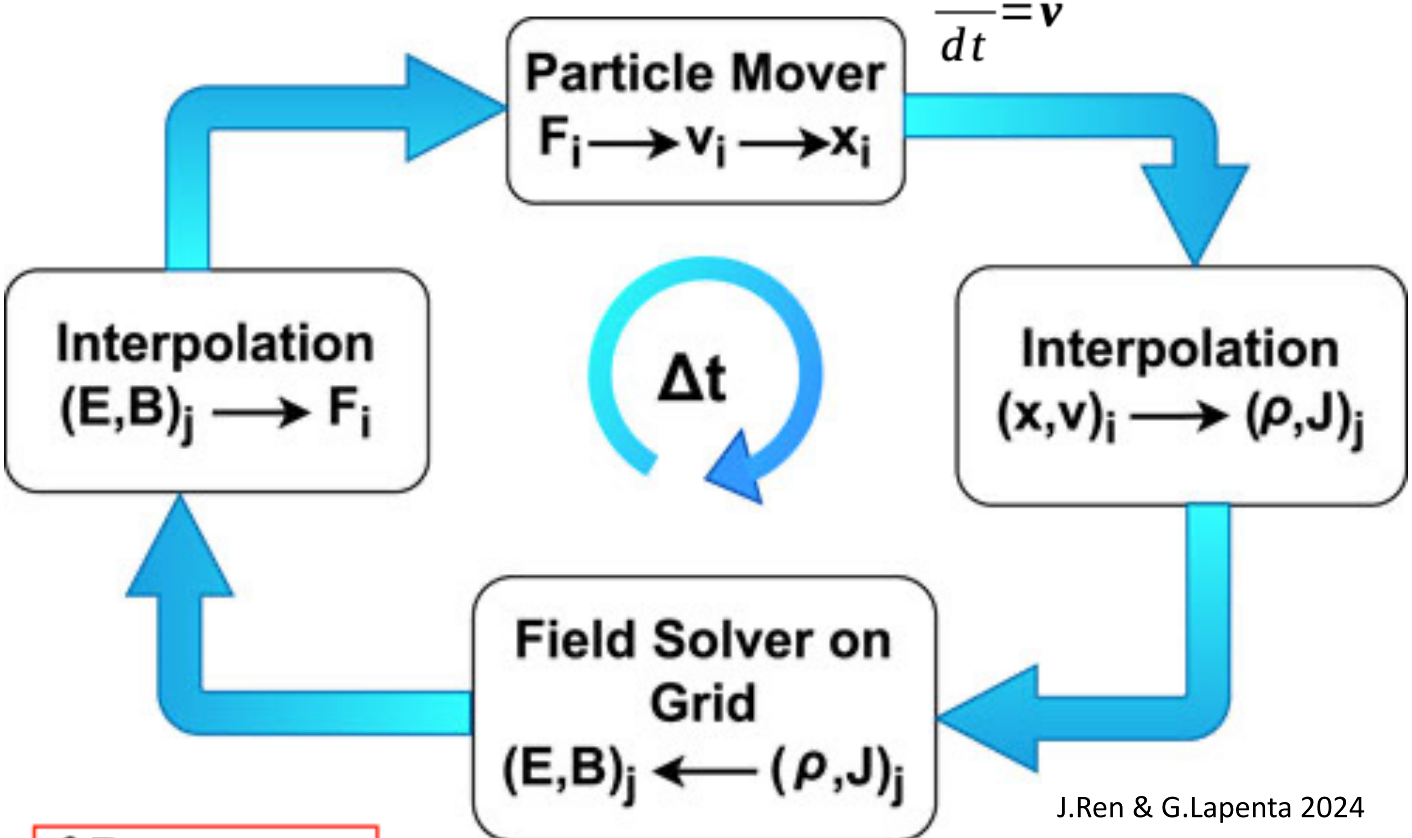
Simulation particles interacting with each other through the grid

Binary interactions are rare

Particle-in-cell (PIC) method

$$\frac{d\boldsymbol{p}}{dt} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}\times\boldsymbol{B}}{c}\right)$$ Lorentz-Newton equation

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}$$



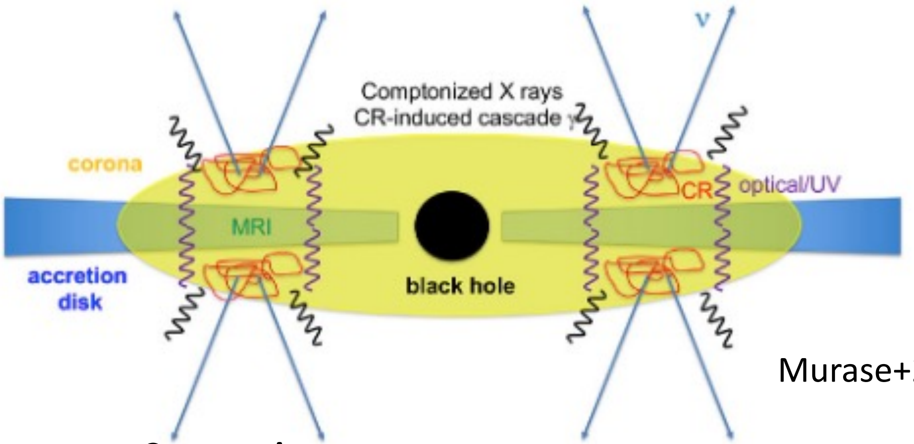
J.Ren & G.Lapenta 2024

$$\frac{\partial\boldsymbol{B}}{\partial t} = -c\nabla\times\boldsymbol{E}$$

$$\frac{\partial\boldsymbol{E}}{\partial t} = c\nabla\times\boldsymbol{B} - 4\pi\boldsymbol{J}$$

Solve time-dependent Maxwell equations

Conditions of BH corona



Murase+22

BH Coronae refer to the hot collisionless plasma in the inner accretion disk.

X-rays emissions from Comptonization

Corona size $R_c = 10 - 100\ r_S$

Shock velocity Order estimate from Free-fall velocity

$$v_{sh} = \sqrt{\frac{2GM_{BH}}{R_c}} \cong 0.1 - 0.3\ [c]$$

Plasma temperature

- $T_e \approx 100$ keV estimate directly from X-rays cut-off
- $T_i \geq 10\ T_e$, order estimate from virial/ADAF model

Sonic Mach number

$$\mathrm{M_s} \approx 3, 8$$

$$T_i = \frac{GM_{BH}m_p}{6k_BR_c} = \frac{m_pc^2}{12k_Br_c}$$

Coronal magnetic field

- Inoue+20: estimate magnetic field order $B \approx 100$ G by analyzing Synchrotron emission
- Michiyama+23: $B \approx 20$ G
- Stochastic acceleration assumed $B \geq 10^4$ G

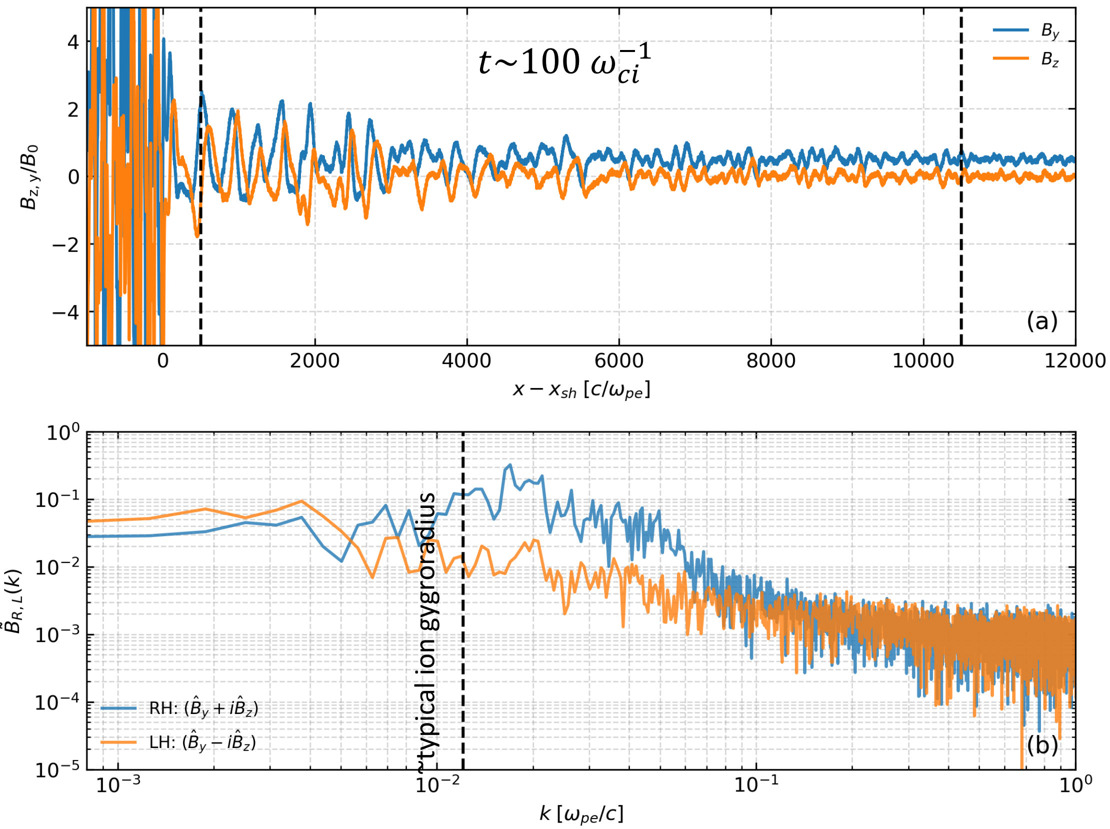
Alfven Mach number

$$\mathrm{M_A} = 26\times\left(\frac{R_c}{20\ r_S}\right)^{-1}\left(\frac{B}{100\ G}\right)^{-1}\left(\frac{M_{BH}}{5\times10^7 M_\odot}\right)^{-0.5}$$

Origin of magnetic field fluctuation

Non-resonant streaming instability (Bell's instability) : **right-handed circular polarization**

Resonant streaming instability: **left-handed circular polarization**

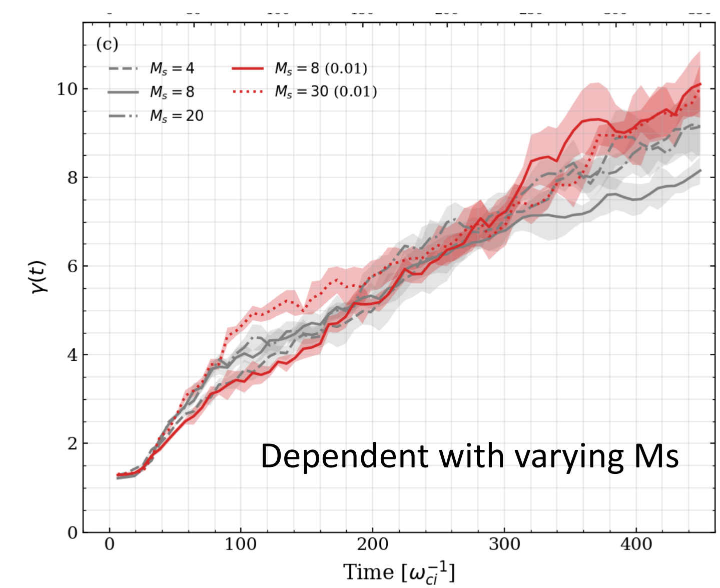


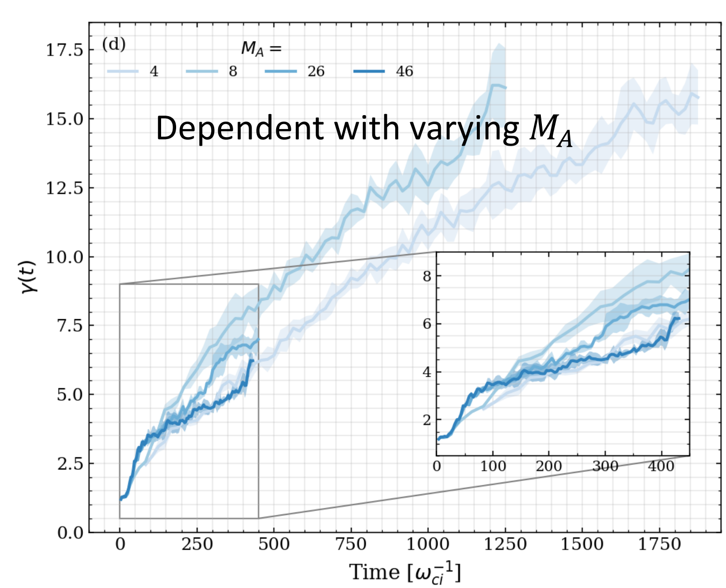
Magnetic field amplified by **non-resonant streaming instability**

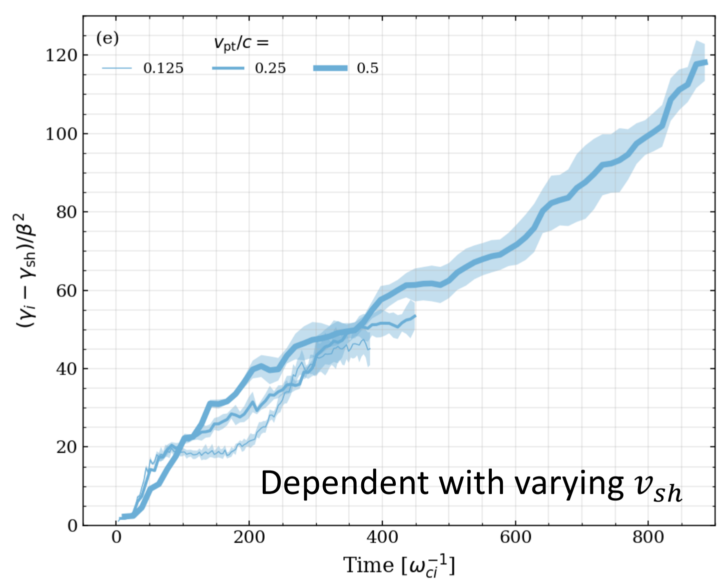
RH: $\bar{B}_R = \left|\overline{B_y} + i\overline{B_z}\right|$

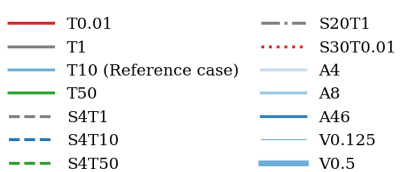
LH: $\bar{B}_L = \left|\overline{B_y} - i\overline{B_z}\right|$

Time evolution of maximum ions energy

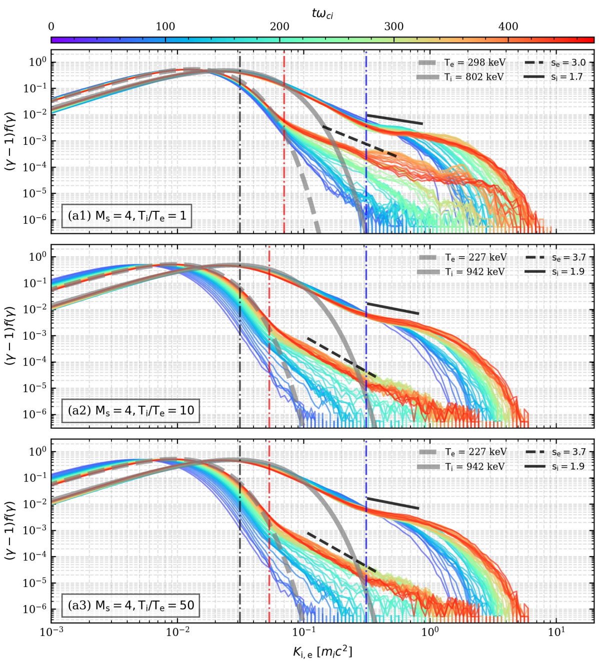




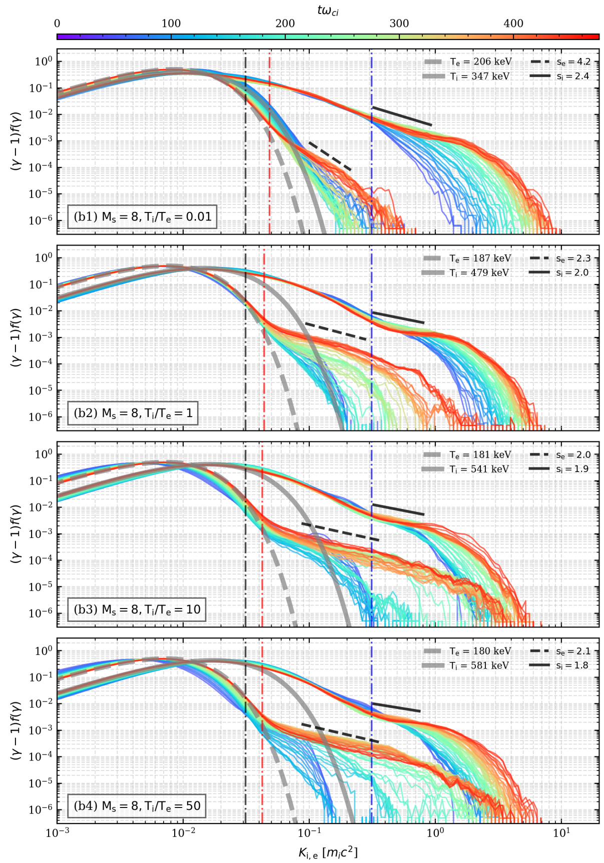




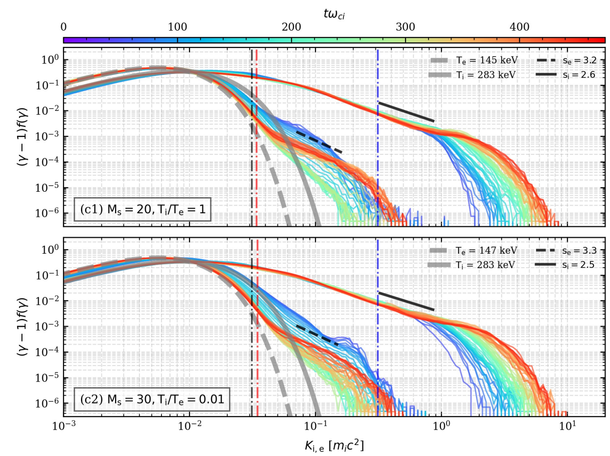
Ms=4 varying Ti/Te



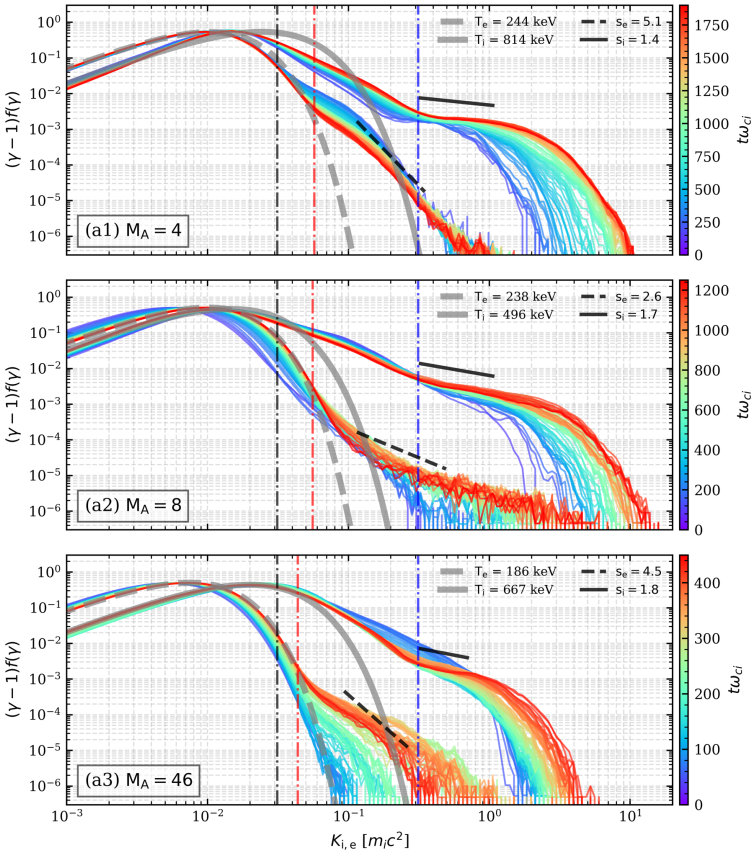
Ms=8 varying Ti/Te



Ms=20 and Ms=30



Varying M_A



Varying v_{sh}