# Acceleration of Relativistic Outflows with Tangled Magnetic Field

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with

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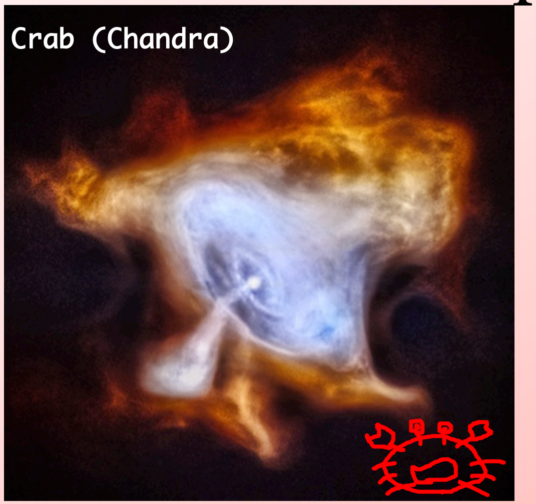
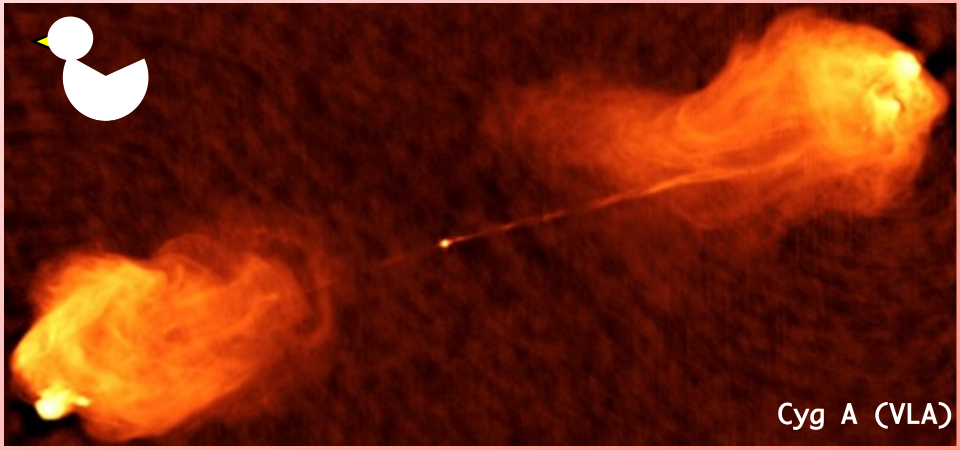


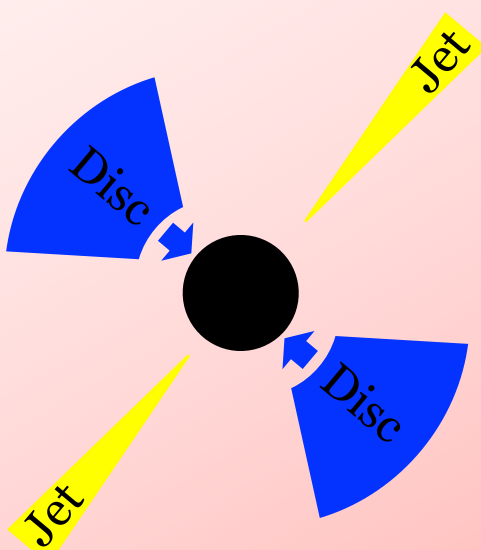



# Introduction

# Relativistic Jet

- Powered by NS or BH
- Relativistic plasma outflow
- High-energy (non-thermal) emission
- Bipolar jets from engine


Common astrophysical phenomena phenomena in AGN, microquasar & GRB



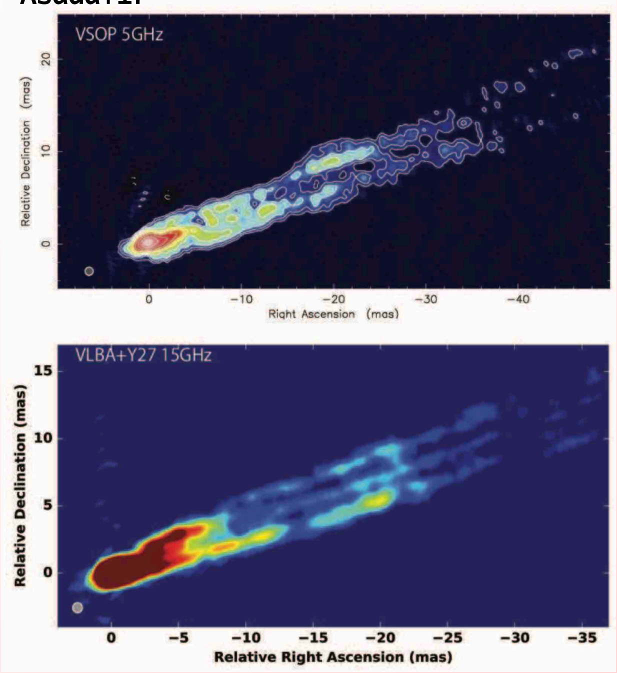

- Gravitational energy (inflow -> outflow)

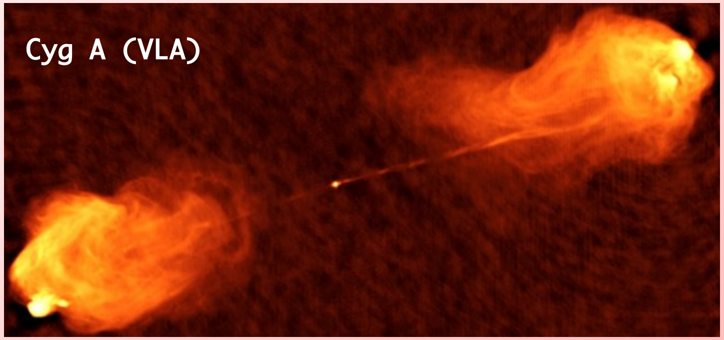
**Same as pulsar wind**

- Rotation powered?
- Role of magnetic field?
- How to accelerates to relativistic flow?
- How to collimate jets?

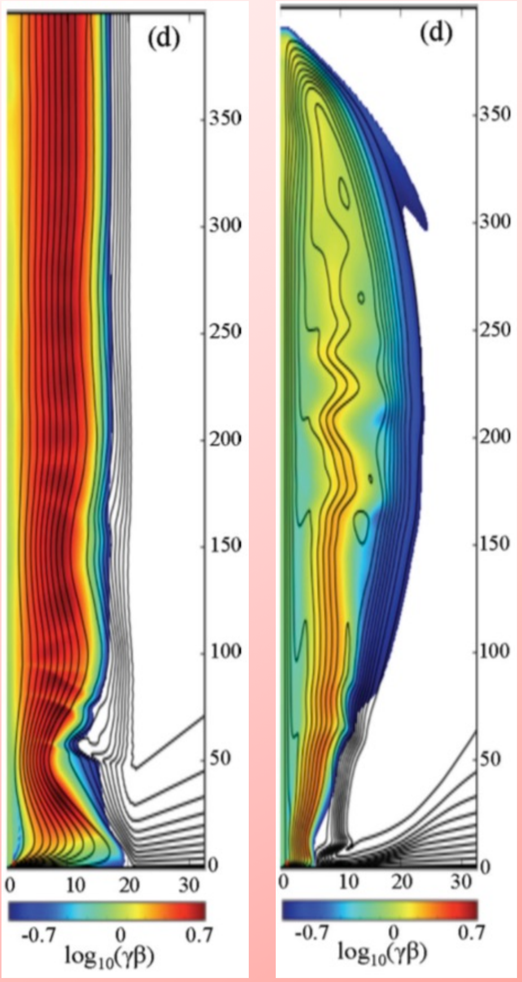
# Jet ~ Cylindrical Flows

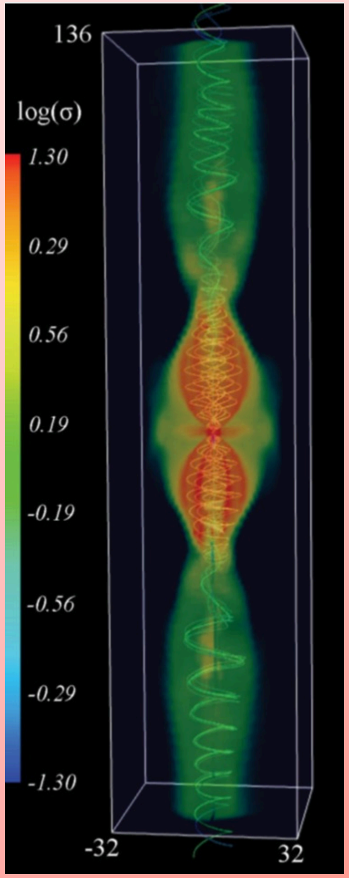
Asada+17



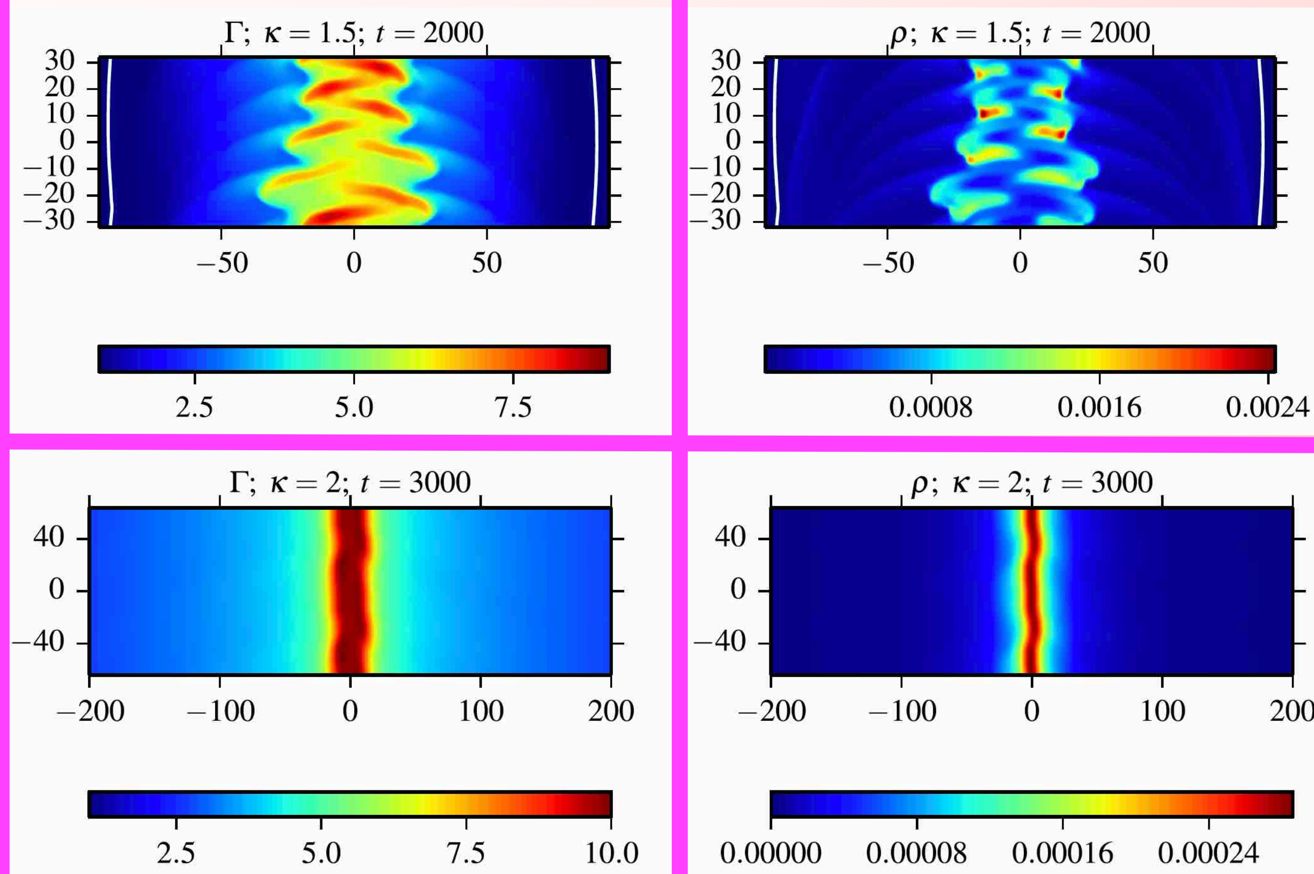

Bromberg&Tchekhovskoy16



# Inst. of Cylinder Jets

| | Lorentz factor of flow | Density |
|---|---|---|
| κ =1.5<br>t =2000 | | |
| κ =2.0<br>t =3000 | | |

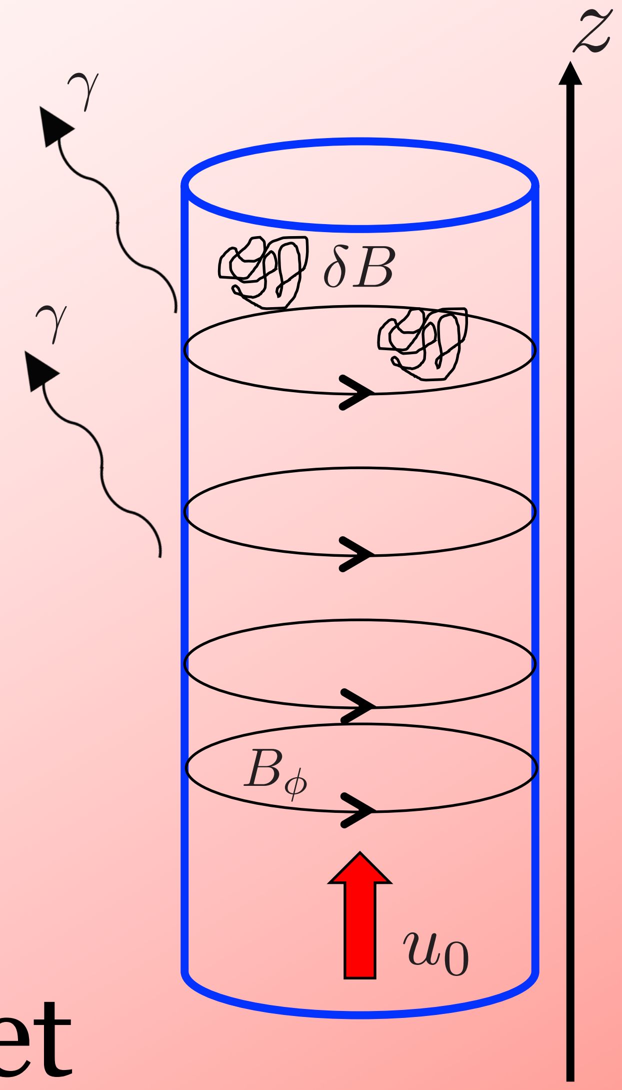



Porth&Komissarov15

$$P_{\rm ext} \propto z^{-\kappa}$$

κ = 2 is critical for ‘external’ kink instability.

**A lot of other intabilities... Focus on cylinder jet**




# A Model of Cylindrical Jet

# Basic Equations

Relativistic MHD model w/ tangled B-field Tanaka et al.18 MNRAS

**radiation** loss, **turbulent** magnetic field, & magnetic **dissipation**.

Eq. of continuity
$$\langle \nabla_\mu (n u^\mu) \rangle = 0,$$

Conservation of total energy
$$\langle \nabla_\mu T^{\mu t} \rangle = -\gamma \frac{\Lambda_{\rm rad}}{c},$$

Conservation of fluid internal energy
$$-\langle u_\nu \nabla_\mu T^{\mu\nu}_{\rm FL} \rangle = \frac{\delta b^2/2}{\tau_{\rm diss}} - \frac{\Lambda_{\rm rad}}{c},$$

Induction equation for (mean) toroidal field + turbulent field
$$\frac{1}{2}\langle \bar{b}_\mu e^{\mu\nu\alpha\beta} \nabla_\nu F_{\alpha\beta} \rangle = -\frac{\bar{b}^2/2}{\tau_{\rm conv}},$$
$$\frac{1}{2}\langle \delta b_\mu e^{\mu\nu\alpha\beta} \nabla_\nu F_{\alpha\beta} \rangle = \frac{\bar{b}^2/2}{\tau_{\rm conv}} - \frac{\delta b^2/2}{\tau_{\rm diss}}.$$

Applying to 'steady cylindrical' jets

# Mechanisms of Acceleration

1D steady flow in ideal MHD limit

no expansion ⇔ no acceleration

$$(\beta^2 - \beta_{\rm c}^2)\frac{du}{dr} = \frac{8u}{3r}\frac{p}{\epsilon}, \ \epsilon = w + \bar{b}^2$$

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Inclusion of non-ideal MHD terms adopted by Tanaka+18

$$(\beta^2 - \beta_{\rm c}^2)\frac{du}{dr} = \frac{8u}{3r}\frac{p}{\epsilon} + \frac{\Lambda_{\rm rad}}{3c} + \frac{\bar{b}^2}{3c\tau_{\rm conv}}$$

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$$(\beta^2 - \beta_{\rm c}^2)\frac{du}{dz} = \qquad \frac{\Lambda_{\rm rad}}{3c} + \frac{\bar{b}^2}{3c\tau_{\rm conv}}$$

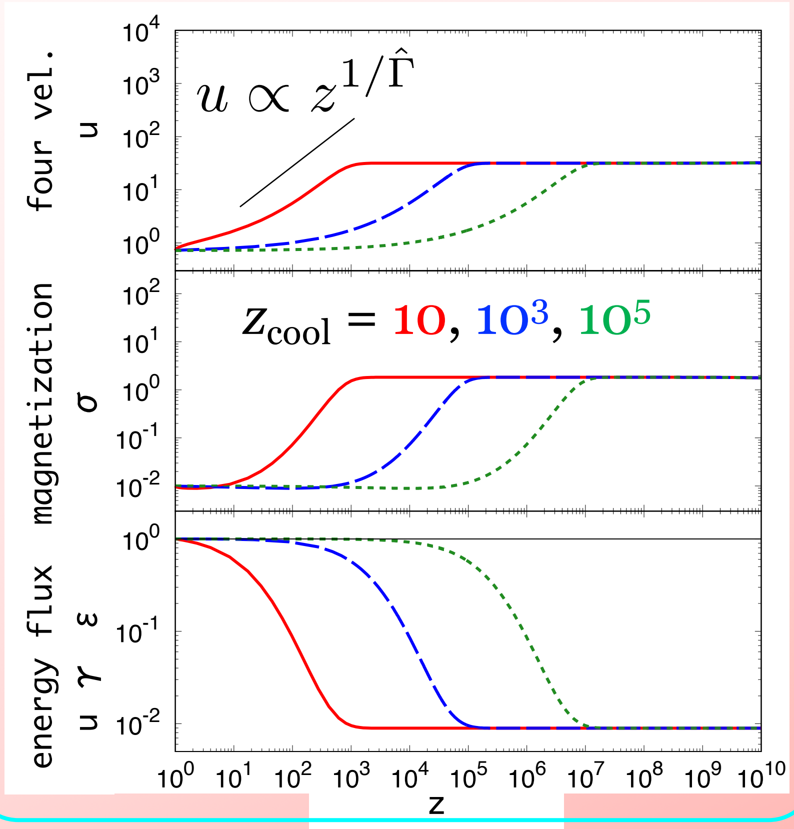
Different from the well-known rarefaction acceleration

# Results

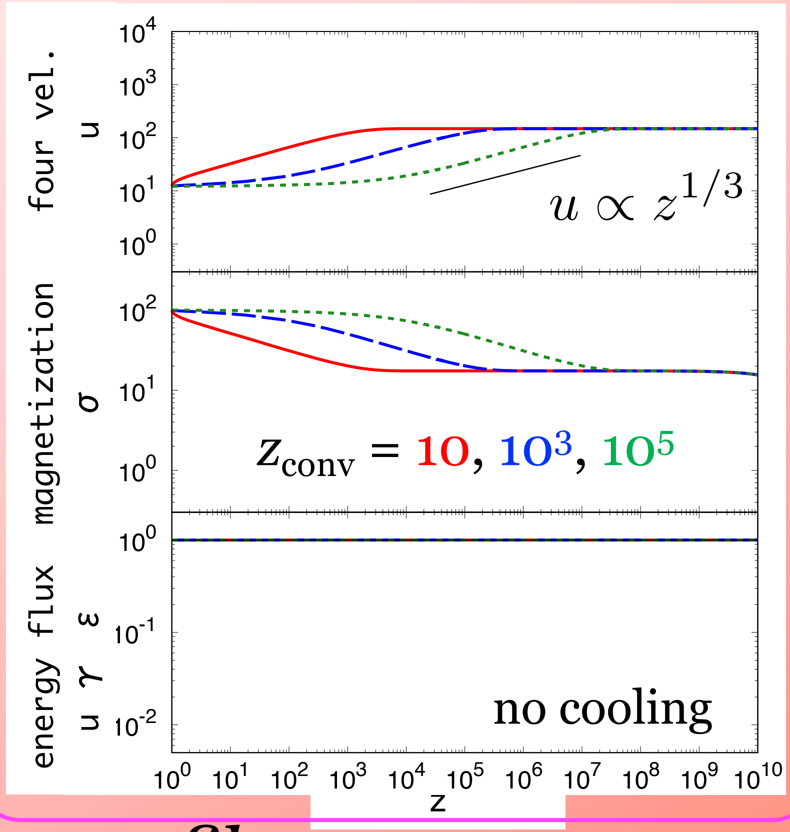
# Conversion vs. Cooling Accel.

$$(\beta^2 - \beta_c^2)\epsilon\frac{du}{dz} = (\hat{\Gamma}-1)\frac{e_{\rm int}}{z_{\rm cool}} + \frac{2}{3}\frac{\bar{b}^2/2}{z_{\rm conv}} + \left(\frac{4}{3}-\hat{\Gamma}\right)\frac{\delta b^2/2}{z_{\rm diss}\to\infty}$$

Low-$\sigma$ flow: $\sigma_0 = 10^{-2}$



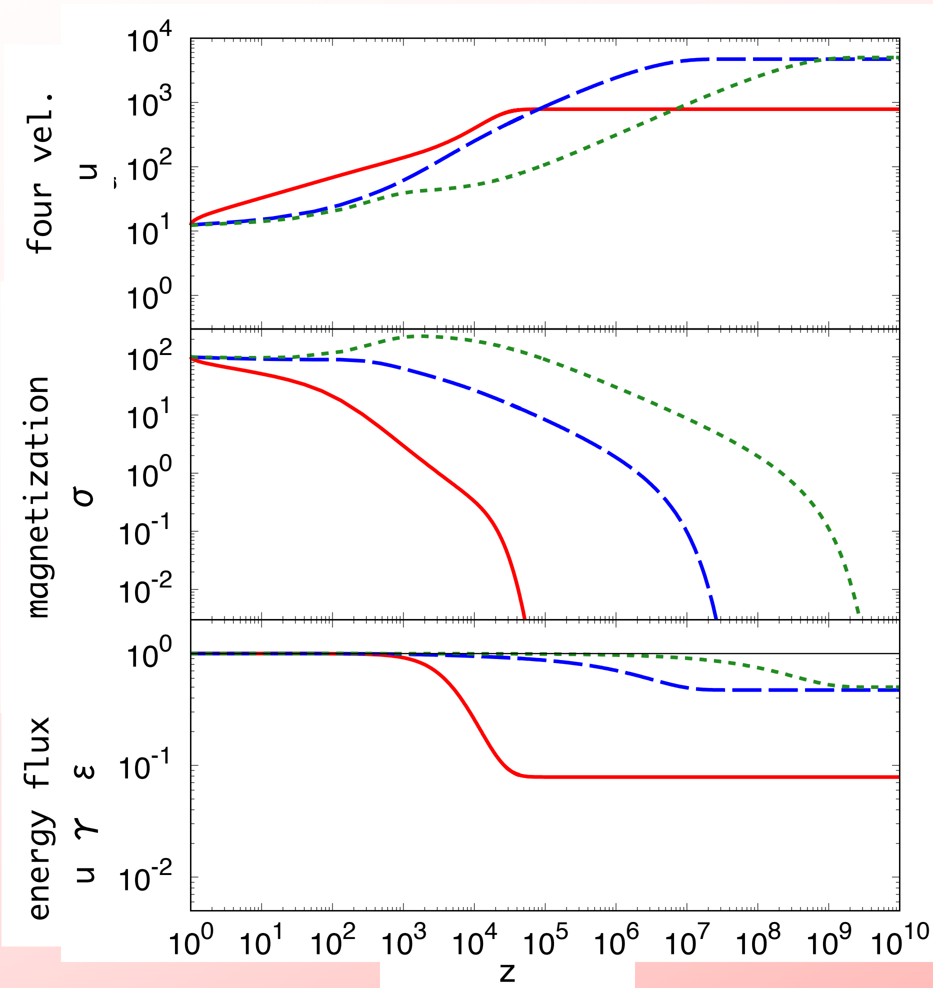

High-$\sigma$ flow: $\sigma_0 = 10^2$




$u_0 = u_c + \varepsilon$, $\gamma_{\rm max} = 10^4$, $\delta b_0 = 0$

# Conversion & Cooling Accel.

$\sigma_0 = 10^2, \gamma_{max} = 10^4$




For all lines, $z_{diss} = z_{cool} = 10$

$z_{conv} = 10, 10^3, 10^5$

- Slow conversion ⇔
  slow acceleration ⇔
  large maximum velocity ⇔
  large final luminosity
- Acceleration stops at σ ~ 1

Efficient accel. with small loss

# Summary

Acceleration of cylindrical flow beyond critical points

- Non-ideal MHD effects (cooling, conversion, dissipation) c.f., ST+18MNRAS
- Flow accelerates with cooling the flow by radiation or CR accel.
- Flow accelerates with converting toroidal B-field to turbulent one.
- Coupling of cooing & conversion effects efficiently accel. the flow
  - terminal vel. ~ maximum vel. / 2 for the most efficient case.
  - total energy flux ~ initial energy flux /2 for the most efficient case

Further studies

- Modeling other processes to understand their roles (mass loading etc.).
- Understanding complicated behaviors of 3D simulations.

$$(\beta^2 - \beta_c^2)\epsilon \frac{du}{dz} = (\hat{\Gamma} - 1)\frac{e_{\rm int}}{z_{\rm cool}} + \frac{2}{3}\frac{\bar{b}^2/2}{z_{\rm conv}} + \left(\frac{4}{3} - \hat{\Gamma}\right)\frac{\delta b^2/2}{z_{\rm diss}}$$