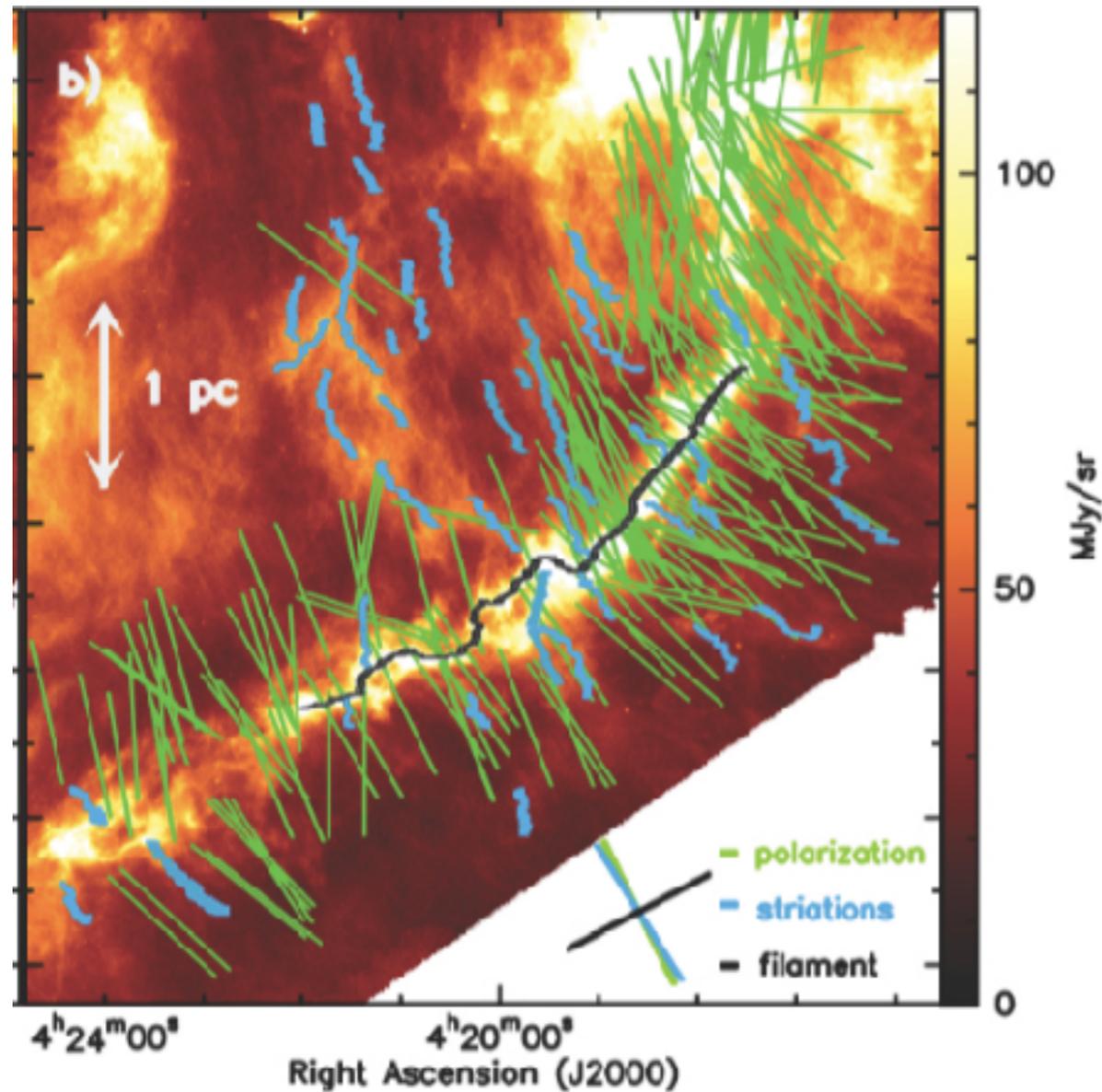


軸に垂直な磁場に貫かれたフィラメント状分子雲 の不安定性



磁場の向きが重要

花輪 知幸 (千葉大)

工藤 哲洋 (長崎大)

富阪 幸治 (国立天文台)

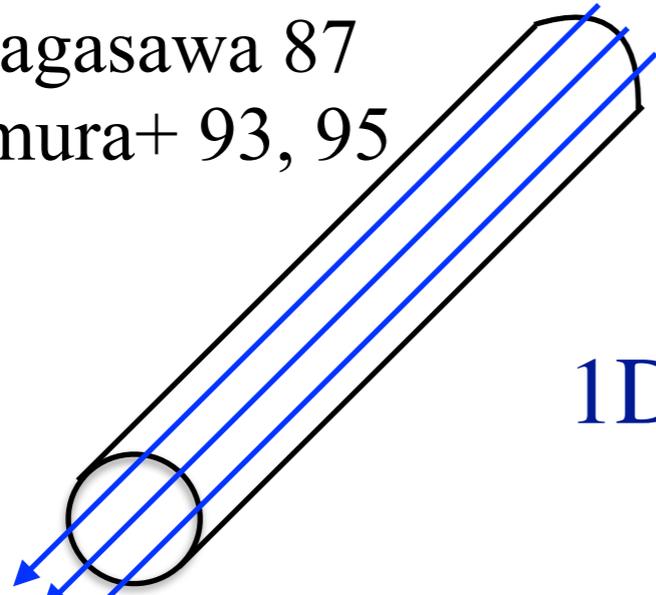
Taurus Palmeirim+ 13

250 cont. + Magnetic Field (Polarization)

フィラメント状分子雲の分裂

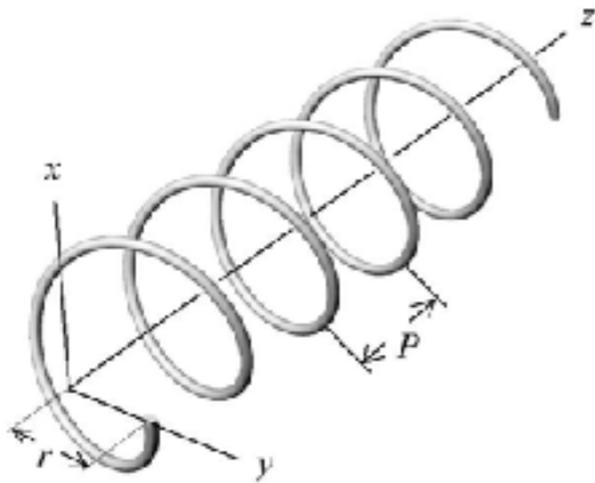
Stodolkiewicz 63

cf. Nagasawa 87
Nakamura+ 93, 95



1D

B_ϕ : hoop stress
cf. Fiege & Pudritz 00

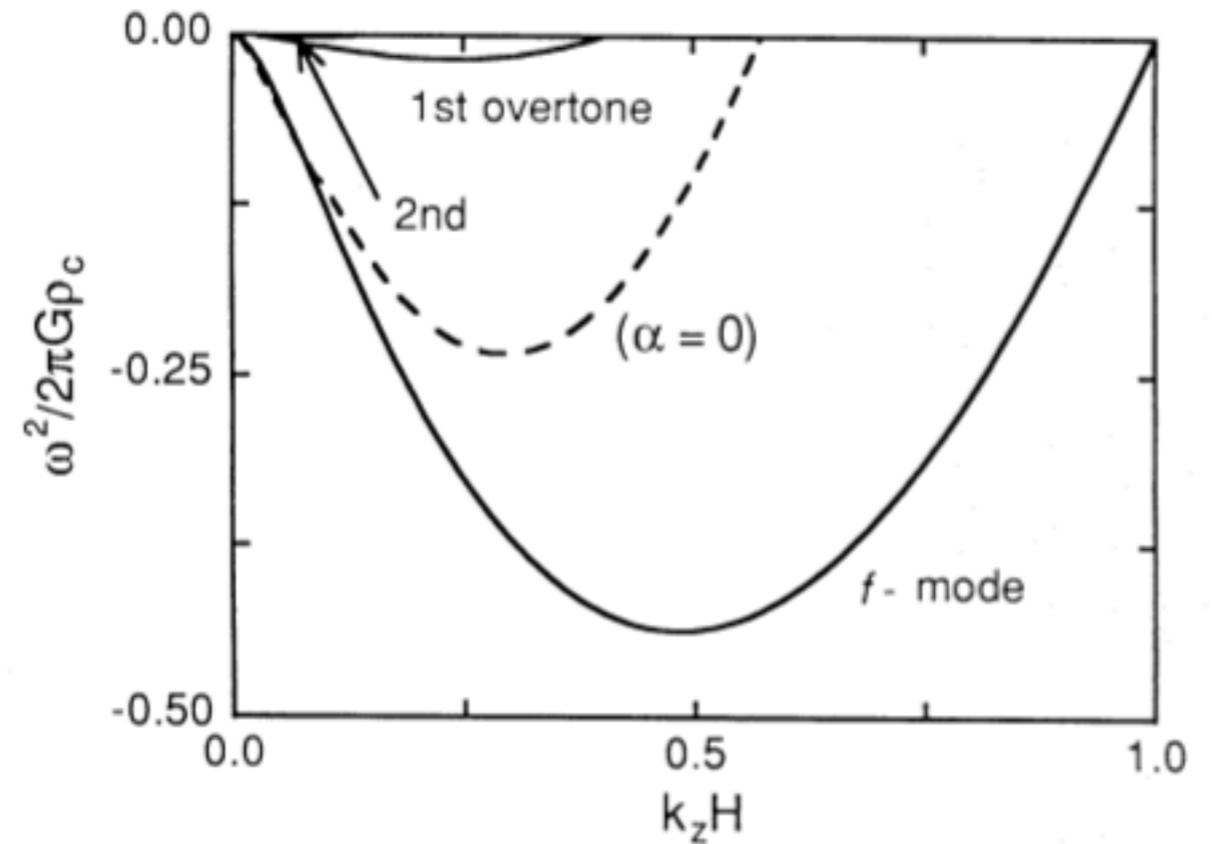


軸対称分布

$$\rho(r) = \rho_0 \left(1 + \frac{r^2}{8H^2} \right)^{-2}$$

$$B_z(r) = B_0 \left(1 + \frac{r^2}{8H^2} \right)^{-1}$$

$$4\pi G \rho_0 H^2 = c_s^2 + \frac{B_0^2}{8\pi \rho_0}$$

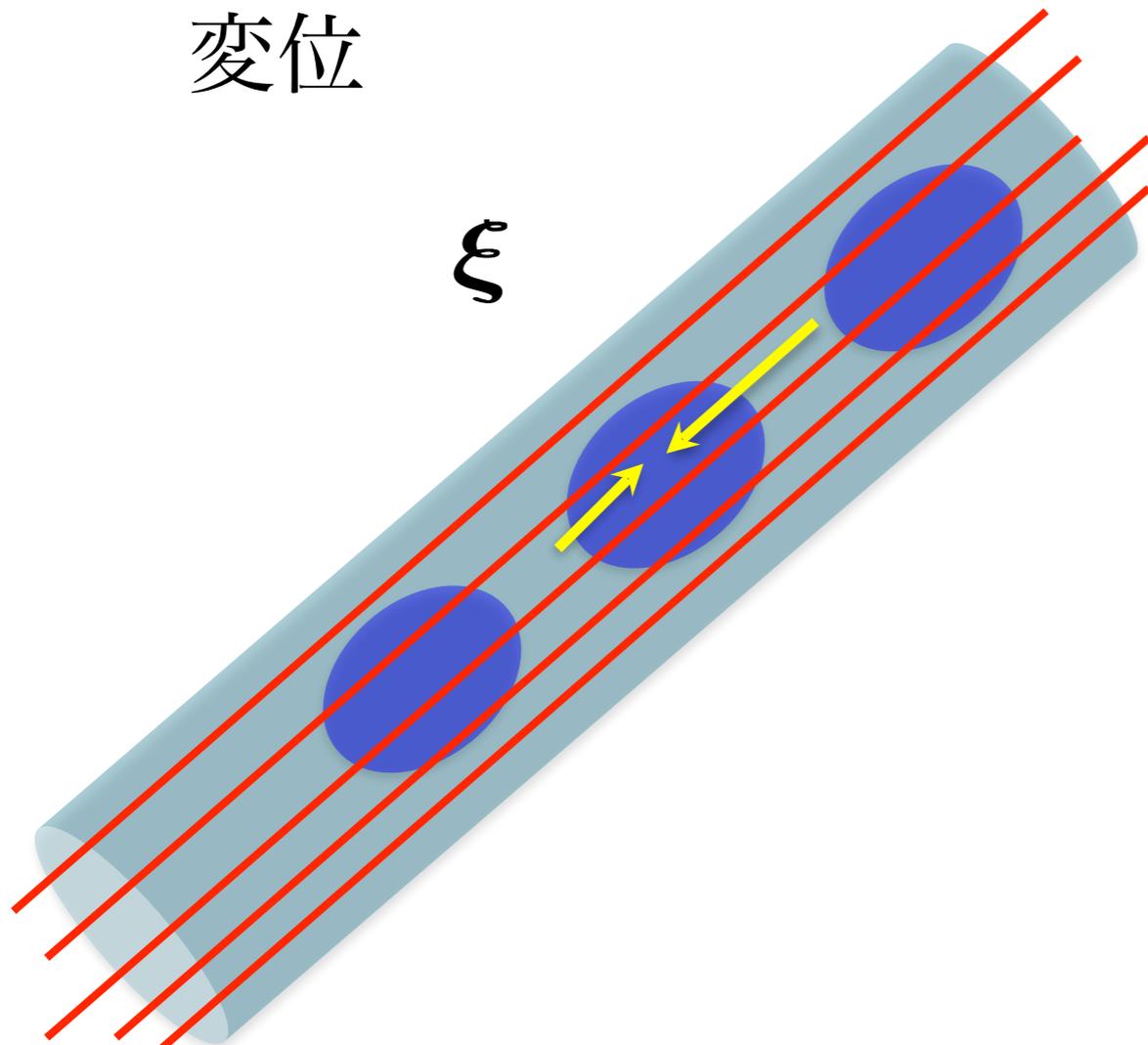


Nakamura+93

磁場の向きは重要.

1. 磁気力は磁場に垂直 B .
2. 臨界質量磁束比, $B_{cr} = 2\pi v G \Sigma$

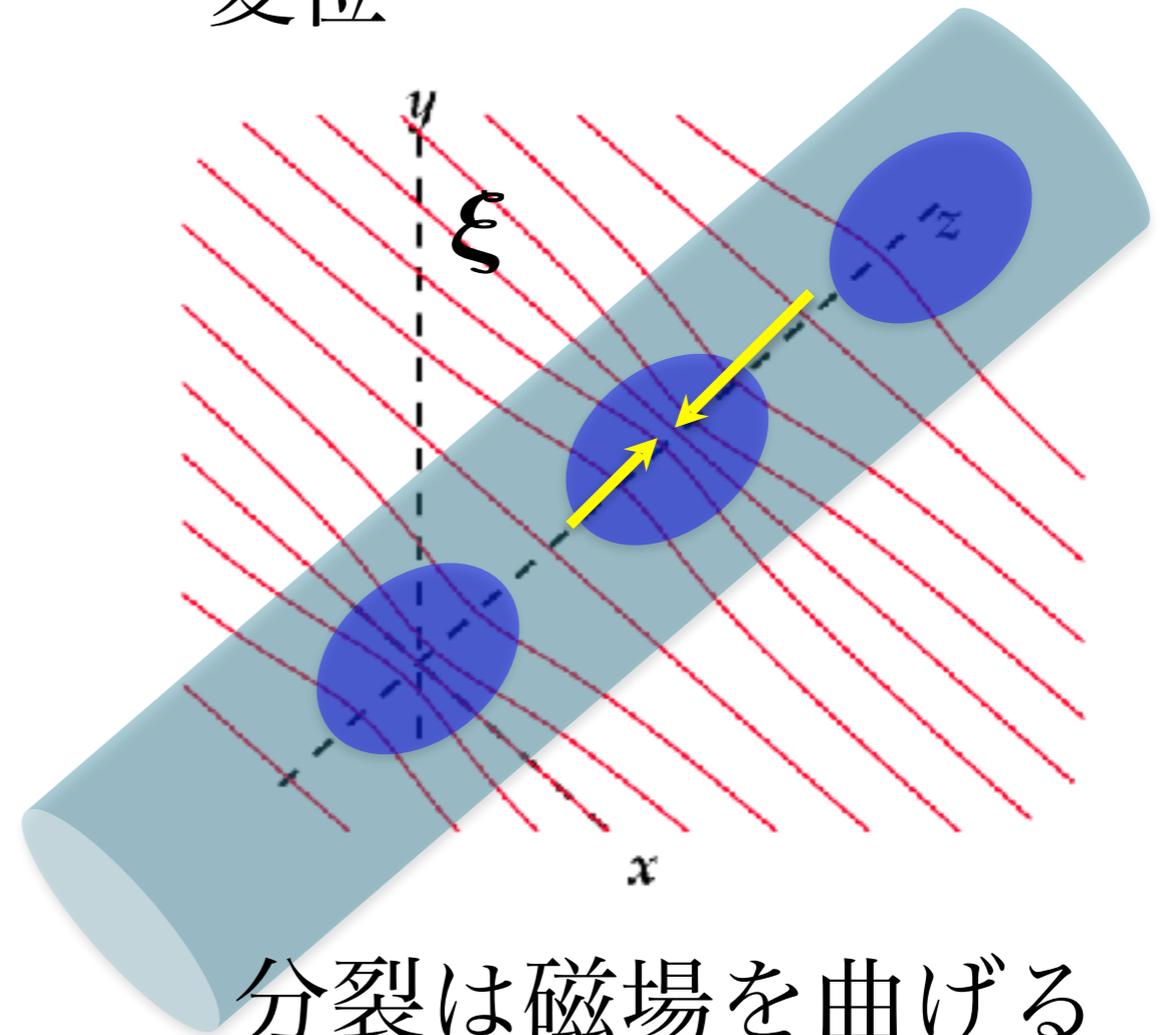
変位



磁場に沿って分裂可

常に超臨界状態

変位



分裂は磁場を曲げる

亜臨界かもしれない

理想化した平衡モデル

$$\rho_0 = \rho_c \left(1 + \frac{r^2}{4pH^2} \right)^{-p}$$

1D 軸対称
+ 一様磁場

$$\mathbf{B}_0 = B_0 \mathbf{e}_x$$

$$\frac{dP_0}{dr} = -\frac{4\pi G}{r^2} \int_0^r \rho_0(r') r' dr'$$

平衡条件を満たす状態方程式

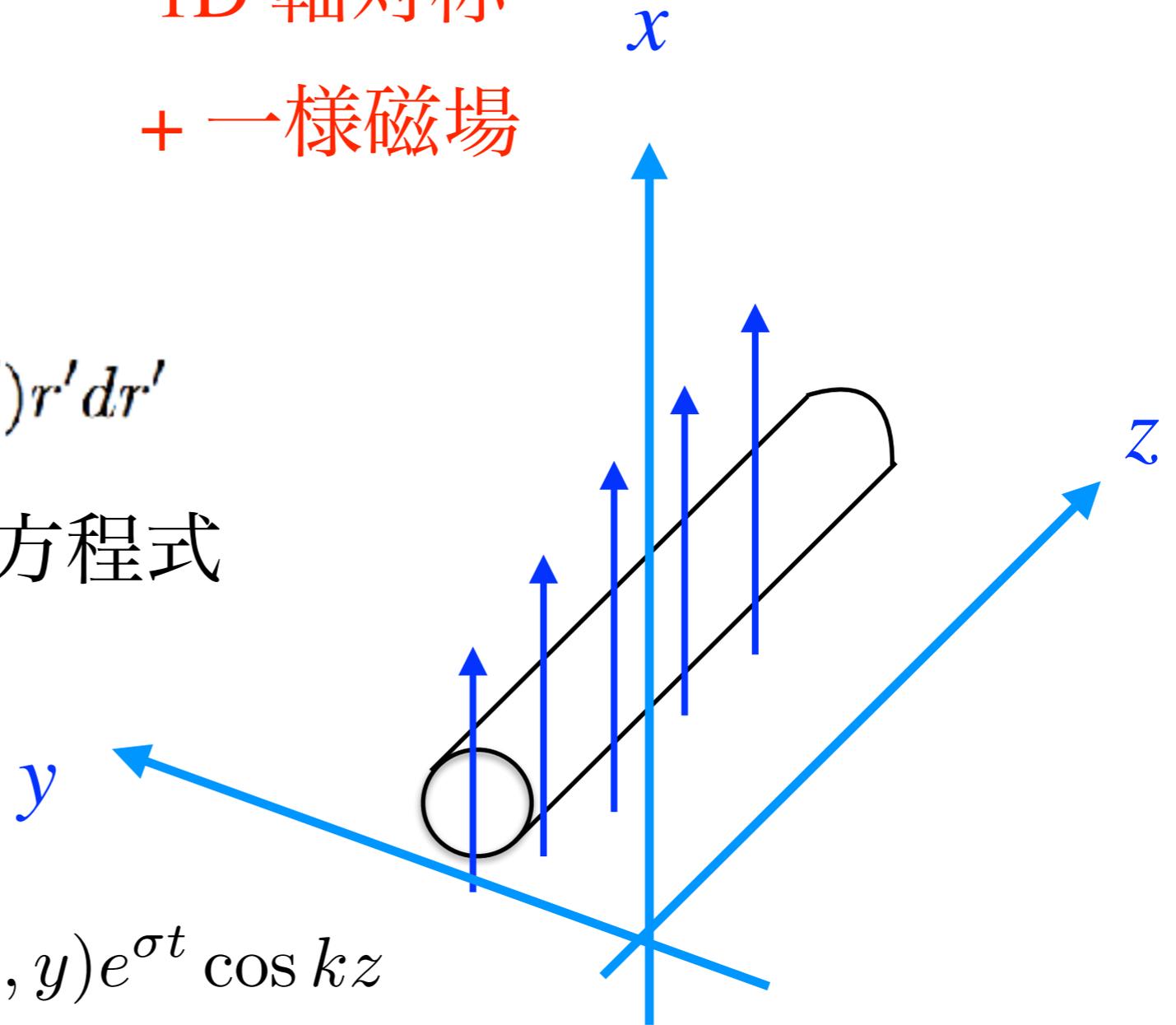
$p = 2$: 等温

3D 次元ゆらぎ

$$\rho(x, y, z, t) = \rho_0(x, y) + \varrho(x, y) e^{\sigma t} \cos kz$$

$$c_s^2 = (dP/d\rho)_c = 1$$

$$\beta = \frac{8\pi \rho_c c_s^2}{B_0^2}$$

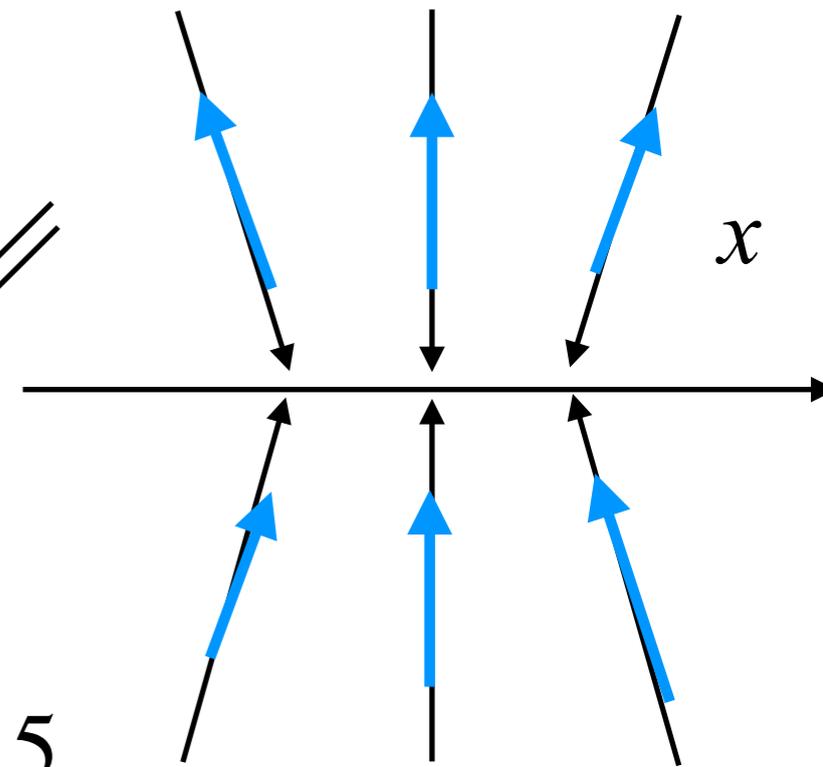
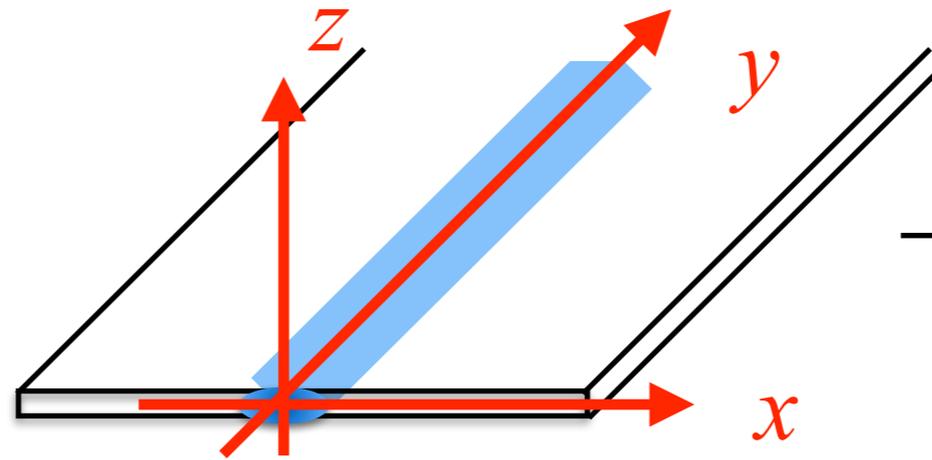
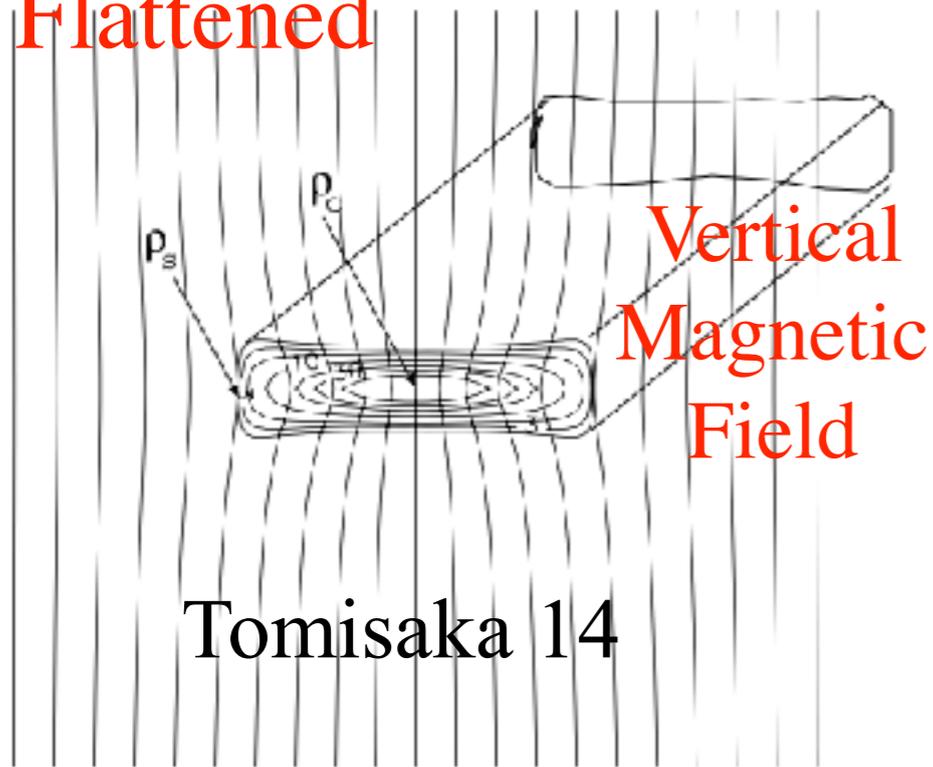


フィラメント状分子雲は扁平かもしれない

2D

magneto-hydrostatic configuration

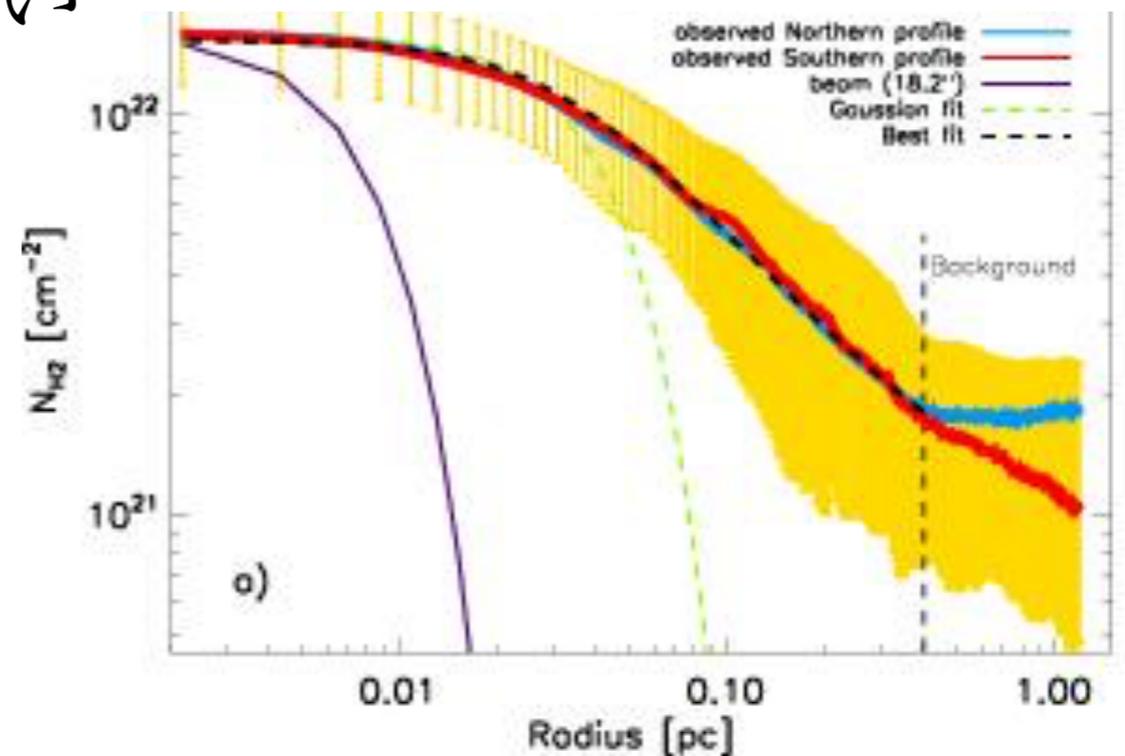
Flattened



等温分布でないかもしれない

Arzoumanina+11

$$\rho \simeq \rho_0 \left(1 + \frac{r^2}{R^2} \right)^{-1}$$



平衡状態

$$\rho_0 = \rho_c \left(1 + \frac{r^2}{4pH^2} \right)^{-p}$$

$$\mathbf{B}_0 = B_0 \mathbf{e}_x$$

$$\frac{dP_0}{dr} = -\frac{4\pi G}{r^2} \int_0^r \rho_0(r') r' dr'$$

x : 磁場, z : フイラメント

理想MHD

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}),$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \psi + \mathbf{j} \times \mathbf{B},$$

$$\frac{d\mathbf{B}}{dt} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

$$\mathbf{j} = \frac{\nabla \times \mathbf{B}}{4\pi},$$

$$\nabla^2 \psi = 4\pi G \rho.$$

$$\rho = \rho_0 + \delta \rho(x, y) e^{\sigma t} \cos kz,$$

$$\boldsymbol{\xi} = e^{\sigma t} [\xi_x(x, y) \cos kz \mathbf{e}_x + \xi_y(x, y) \cos kz \mathbf{e}_y + \xi_z(x, y) \sin kz \mathbf{e}_z],$$

$$\mathbf{B} = B_0 \mathbf{e}_x + e^{\sigma t} [b_x(x, y) \cos kz \mathbf{e}_x + b_y(x, y) \cos kz \mathbf{e}_y + b_z(x, y) \sin kz \mathbf{e}_z],$$

$$\mathbf{j} = e^{\sigma t} [j_x(x, y) \sin kz \mathbf{e}_x + j_y(x, y) \sin kz \mathbf{e}_y + j_z(x, y) \cos kz \mathbf{e}_z],$$

$$\psi = \psi_0 + e^{\sigma t} \delta \psi(x, y) \cos kz,$$

数値解法

変位ベクトル ξ :

$$\xi = \int v dt$$

$$\delta \rho = -\frac{\partial}{\partial x} (\rho_0 \xi_x) - \frac{\partial}{\partial y} (\rho_0 \xi_y) - k \rho_0 \xi_z,$$

$$b_x = -B_0 \left[\frac{\partial}{\partial y} \xi_y(x, y) + k \xi_z \right],$$

$$b_y = B_0 \frac{\partial \xi_y}{\partial x},$$

$$b_z = -B_0 \frac{\partial \xi_z}{\partial x},$$

$$j_x = \frac{1}{4\pi} \left(\frac{\partial b_z}{\partial y} + k b_y \right),$$

$$j_y = -\frac{1}{4\pi} \left(k \delta b_x + \frac{\partial b_z}{\partial x} \right),$$

$$j_z = \frac{1}{4\pi} \left(\frac{\partial b_y}{\partial x} - \frac{\partial b_x}{\partial y} \right).$$

$$\delta \psi(\mathbf{r}) = \int \mathbf{G}(\mathbf{r}, \mathbf{r}') \rho(\mathbf{r}') d\mathbf{r}'$$

$$\rho_0 \frac{d^2 \xi}{dt^2} = \mathbf{F}(\xi),$$

$$\rho_0 \sigma^2 \xi = \left(\mathbf{A} + \frac{B_0^2}{4\pi} \mathbf{C} \right) \xi.$$

力は変位 ξ に比例

generalized eigenvalue problem

$$\left| \mathbf{A} + \frac{B_0^2}{4\pi} \mathbf{C} - \rho_0 \mathbf{I} \right| = 0$$

LAPACK

Numerical Library

微小変化は変位(ξ)の関数

平衡解を満たす状態方程式

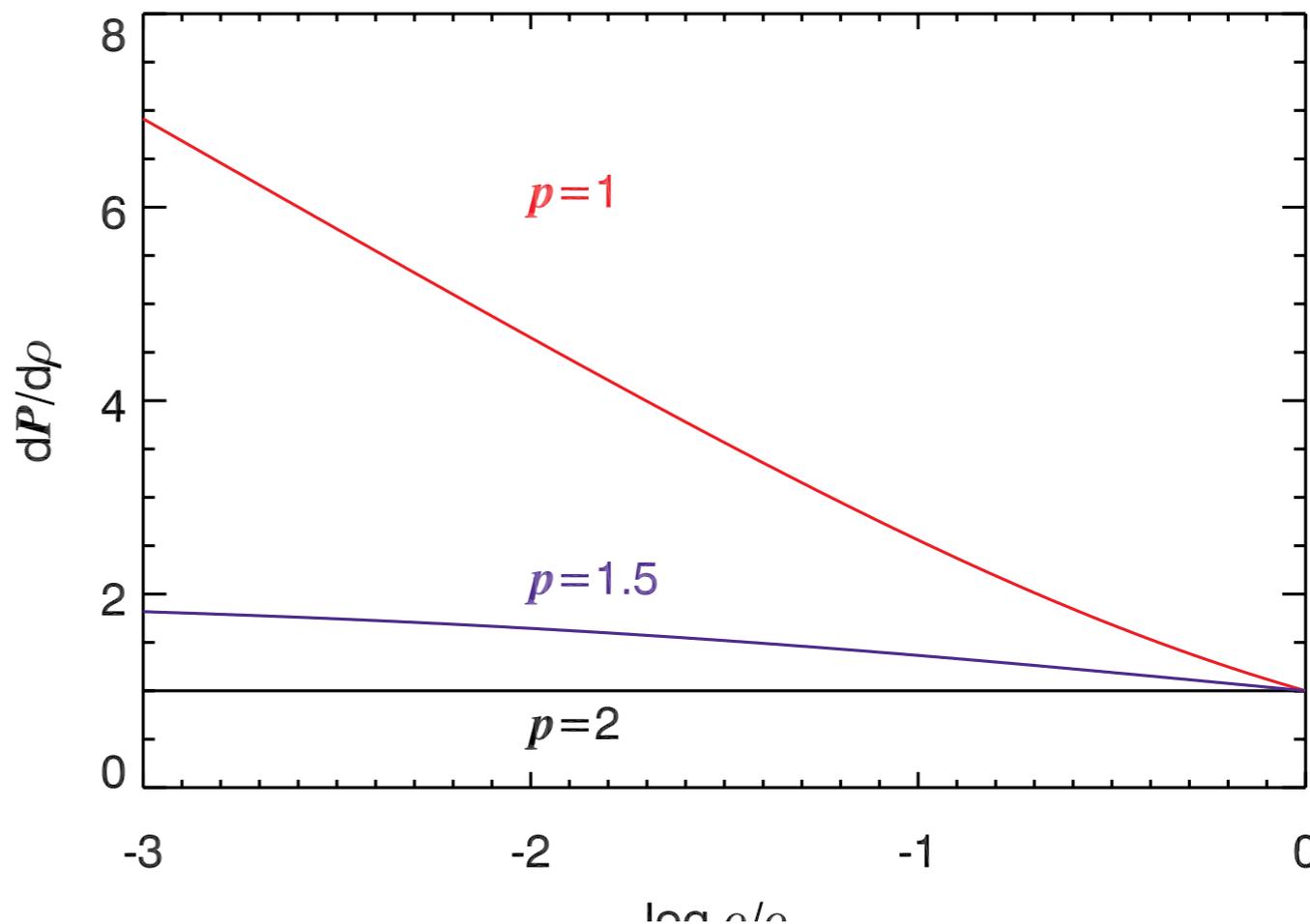
$$\rho_0 = \rho_c \left(1 + \frac{r^2}{4pH^2} \right)^{-p},$$

$$\lambda_r = \int_0^r 2\pi r' \rho(r') dr'$$

$$g_r = -\frac{2G\lambda_r}{r},$$

$$\frac{dP}{dr} = \rho g_r,$$

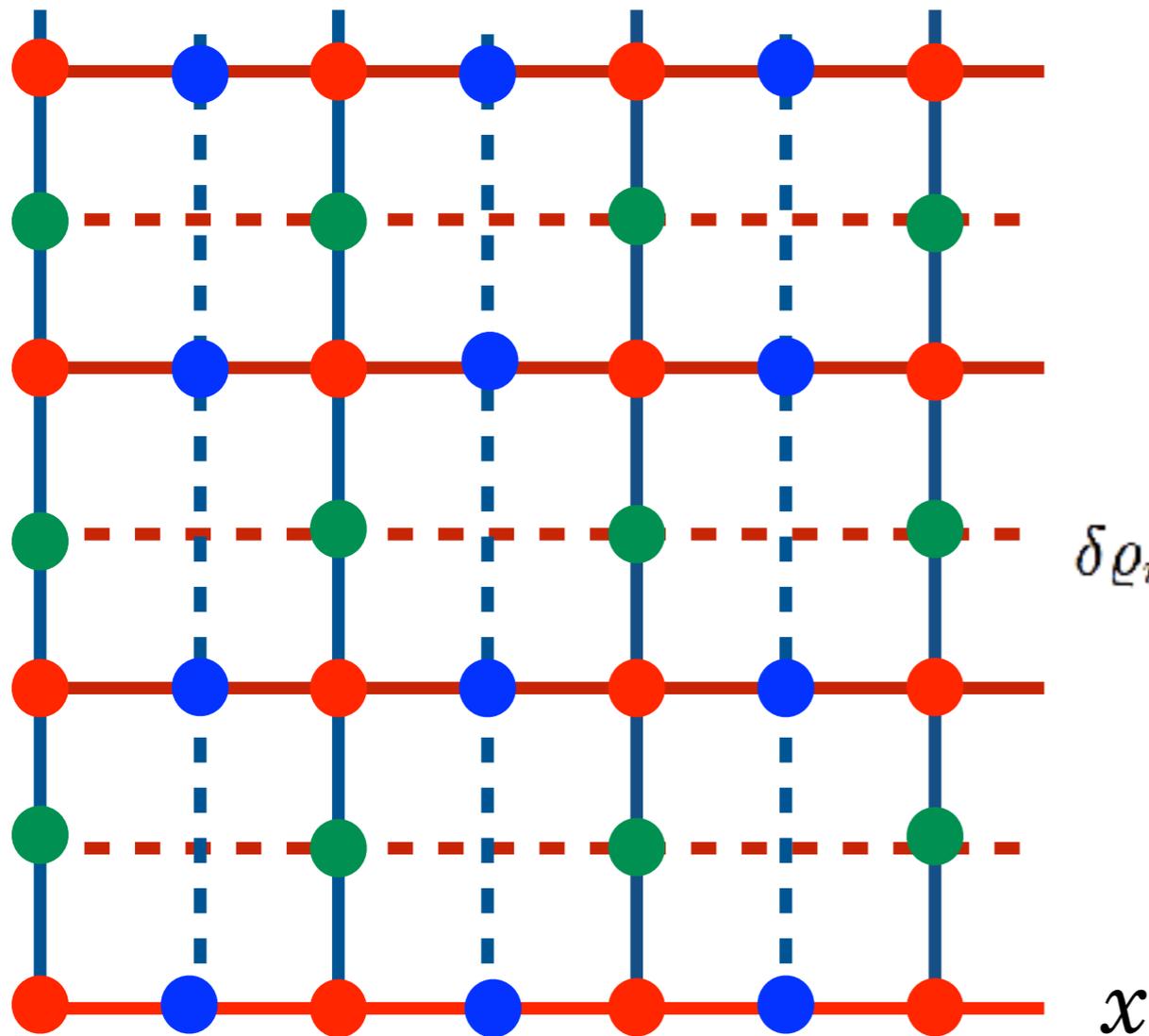
$$\frac{dP}{d\rho} = \begin{cases} \frac{4\pi G\rho_c}{p-1} \left[\left(\frac{\rho_c}{\rho} \right)^{-1/p} - 1 \right]^{-1} \left(\frac{\rho_c}{\rho} \right)^{1/p} \left[1 - \left(\frac{\rho_c}{\rho} \right)^{1/p-1} \right] & (p \neq 1) \\ 4\pi G\rho_c \left(1 - \frac{\rho}{\rho_c} \right) \ln \left(\frac{\rho_c}{\rho} \right) & (p = 1) \end{cases}$$



乱流による実効音速の増加

差分化

y staggered mesh



● $\xi_z, \rho, \delta\psi, b_x, j_y$ x, y sym

● ξ_x, b_z x anti, y sym

● ξ_y, j_z x sym, y anti

$$\delta\rho_{i,j} = \frac{\rho_{0,i+1/2,j}\xi_{x,i+1/2,j} - \rho_{0,i-1/2,j}\xi_{x,i-1/2,j}}{\Delta x} - \frac{\rho_{0,i,j+1/2}\xi_{x,i,j+1/2} - \rho_{0,i,j-1/2}\xi_{x,i,j-1/2}}{\Delta y} - k\rho_{0,i,j}\xi_{z,i,j}$$

2次精度

境界条件 (1) 固定

$$\xi_x, \xi_y, \xi_z = 0$$

$$\text{for } x > n_x \Delta x \text{ or } y > n_y \Delta y$$

(2) 自由

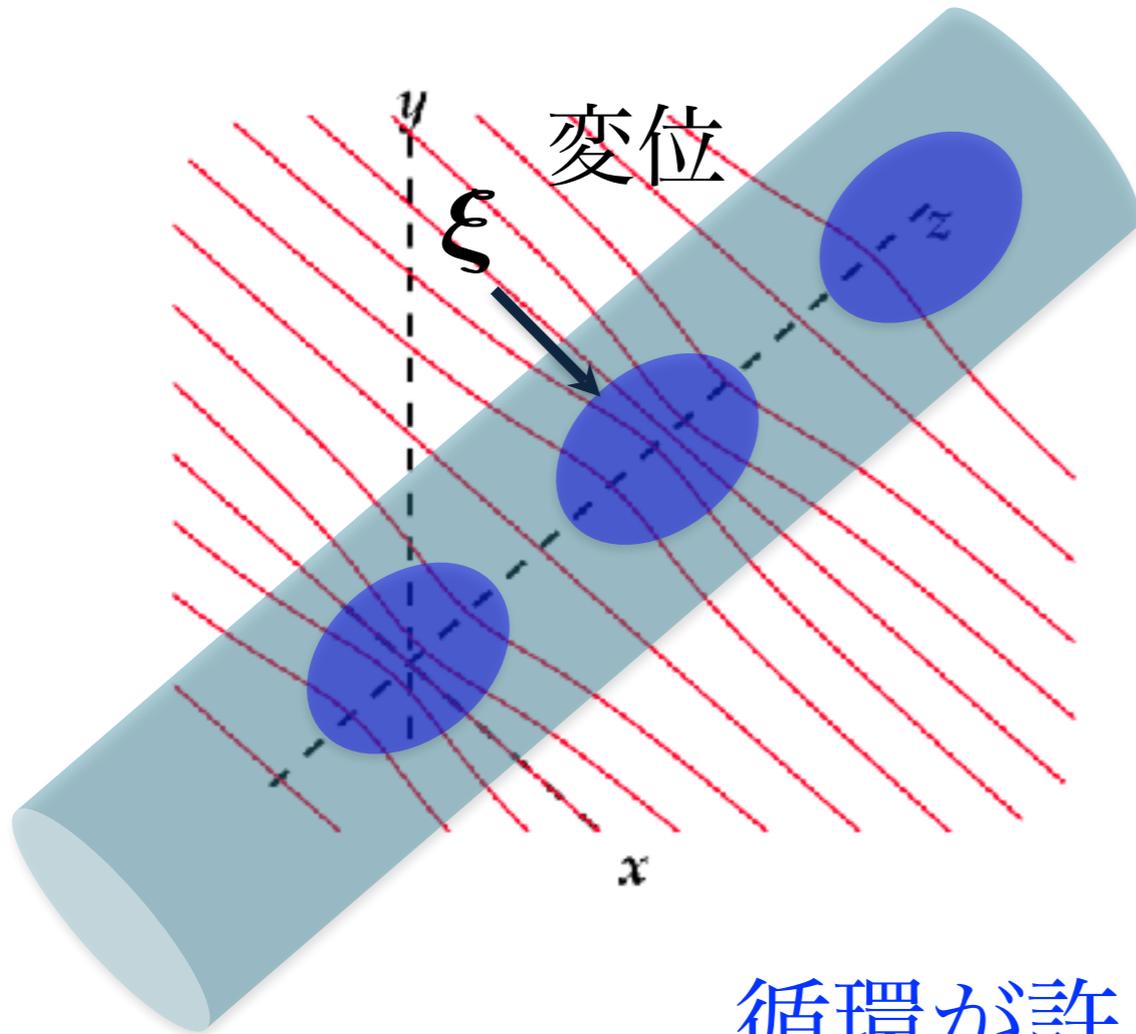
$$\frac{\partial \xi}{\partial x} = 0$$

$$\text{for } x > n_x \Delta x$$

$$\frac{\partial \xi}{\partial y} = 0$$

$$\text{for } y > n_y \Delta y$$

境界条件



循環が許される

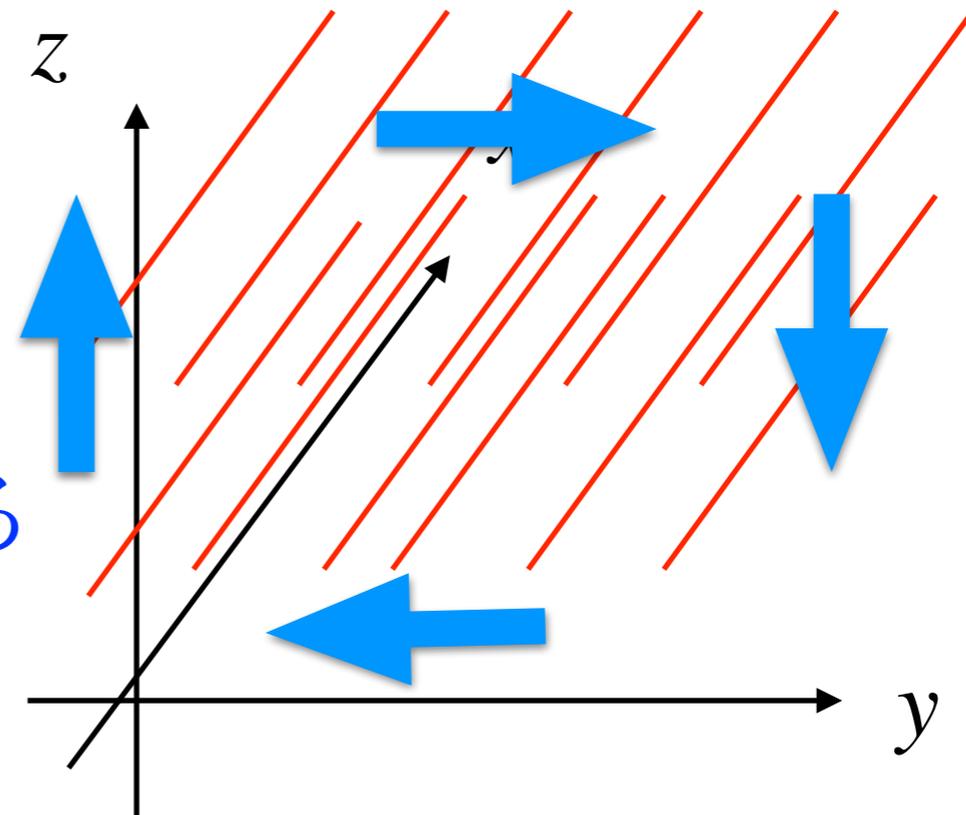
1) 固定

$$\xi = 0$$

2) 自由

$$\partial\xi/\partial x = 0$$

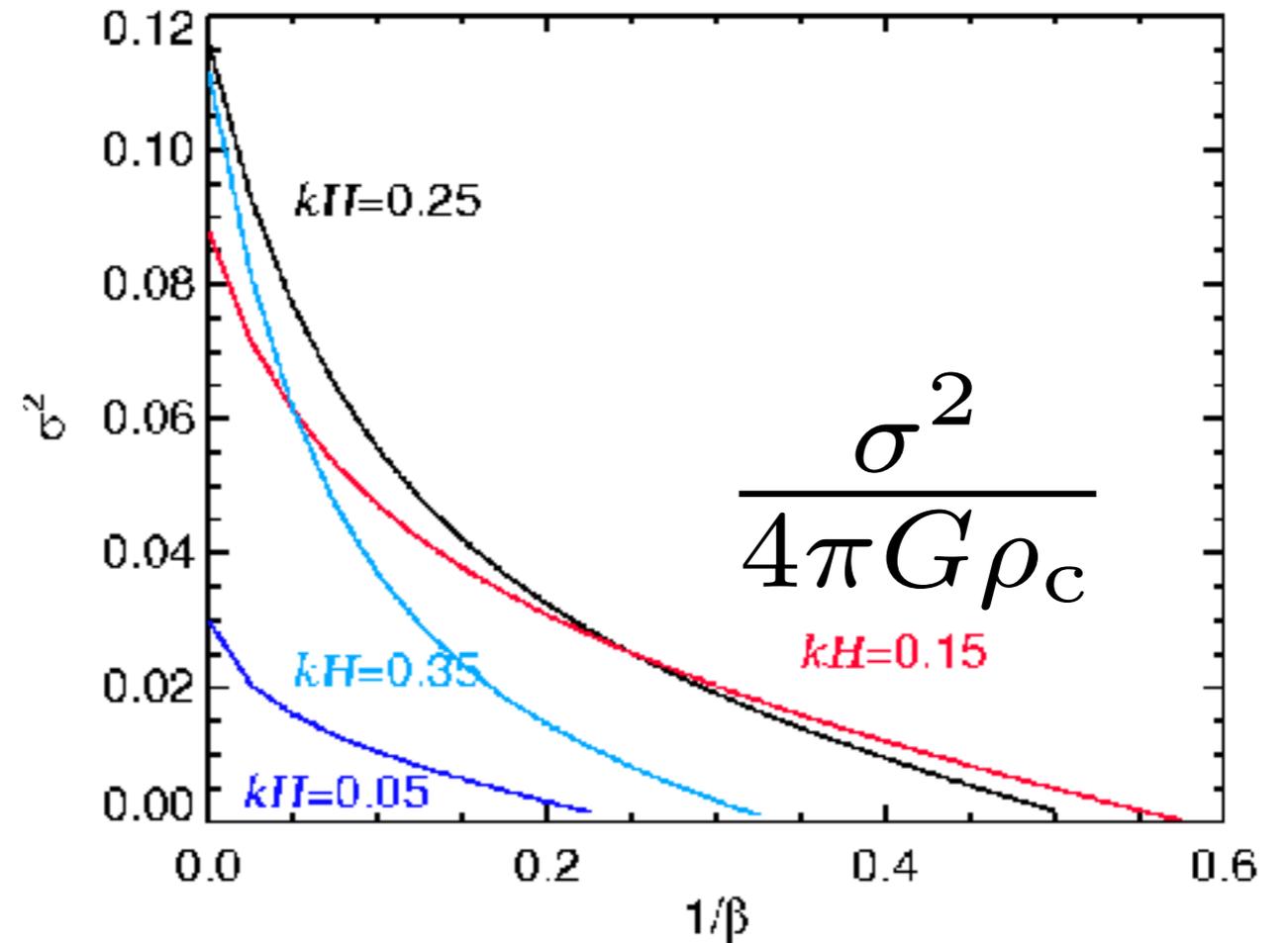
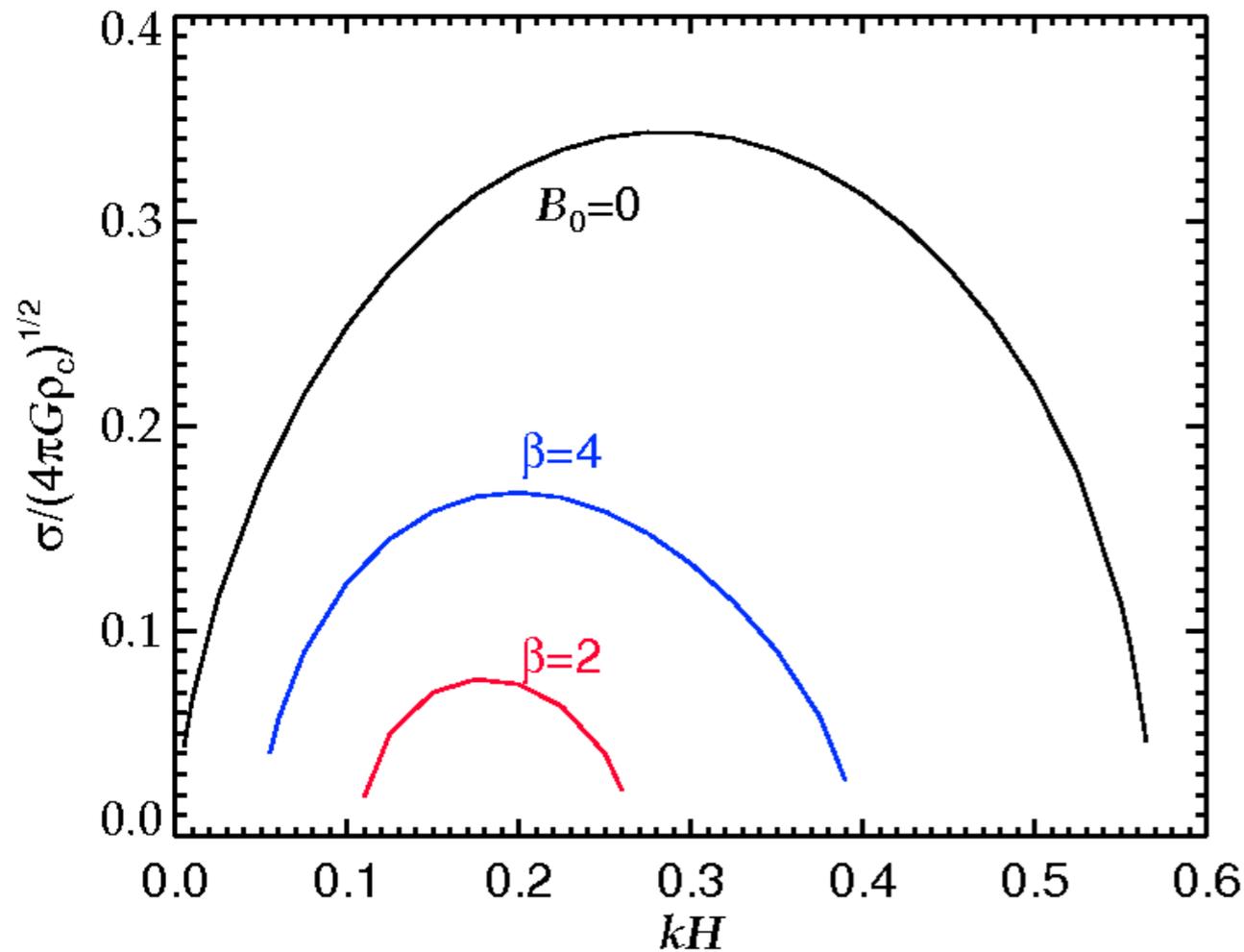
真っ直ぐのままなら移動可



固定境界 ($p = 2$)

成長率

$$\Delta x = \Delta y = 0.6 H, \quad n_x = n_y = 40$$

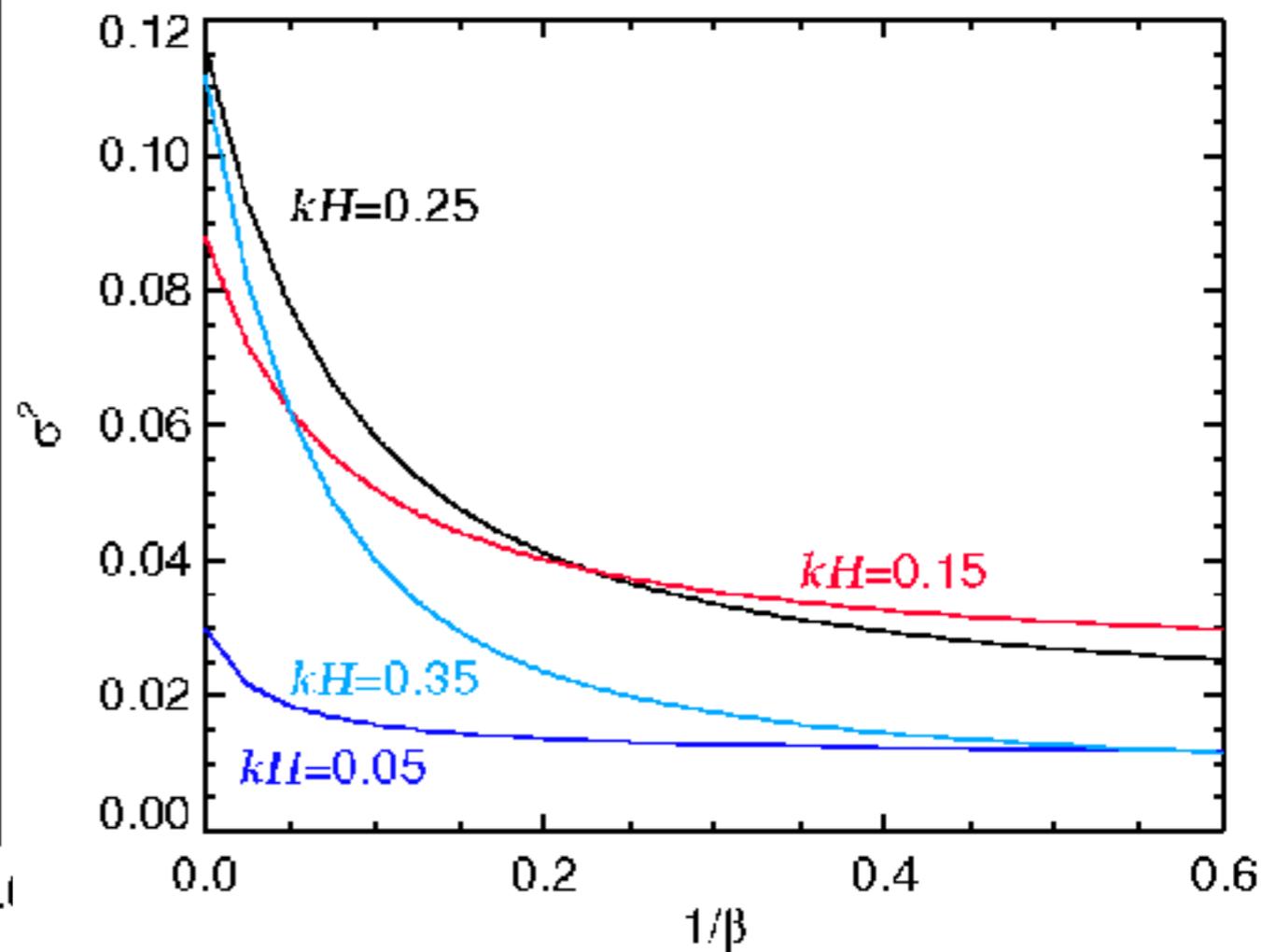
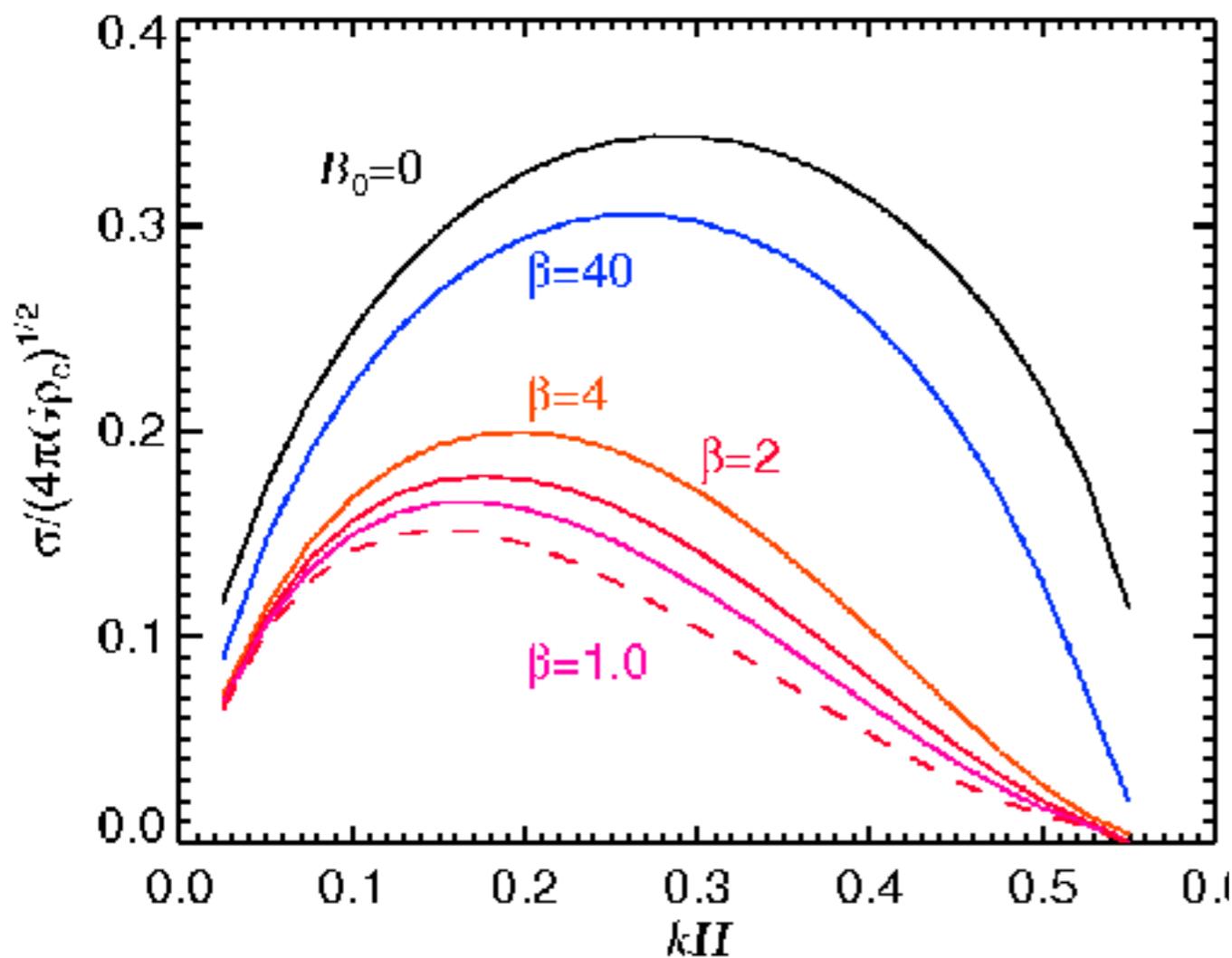


臨界磁束質量比

$$\frac{2\pi\sqrt{G}\Sigma_c}{B_0} = \sqrt{\frac{\beta}{0.405}}$$

$$kH = 0.3 \rightarrow \lambda = 5.8 d_{\text{FWHM}}$$

自由境界 ($p = 2$)

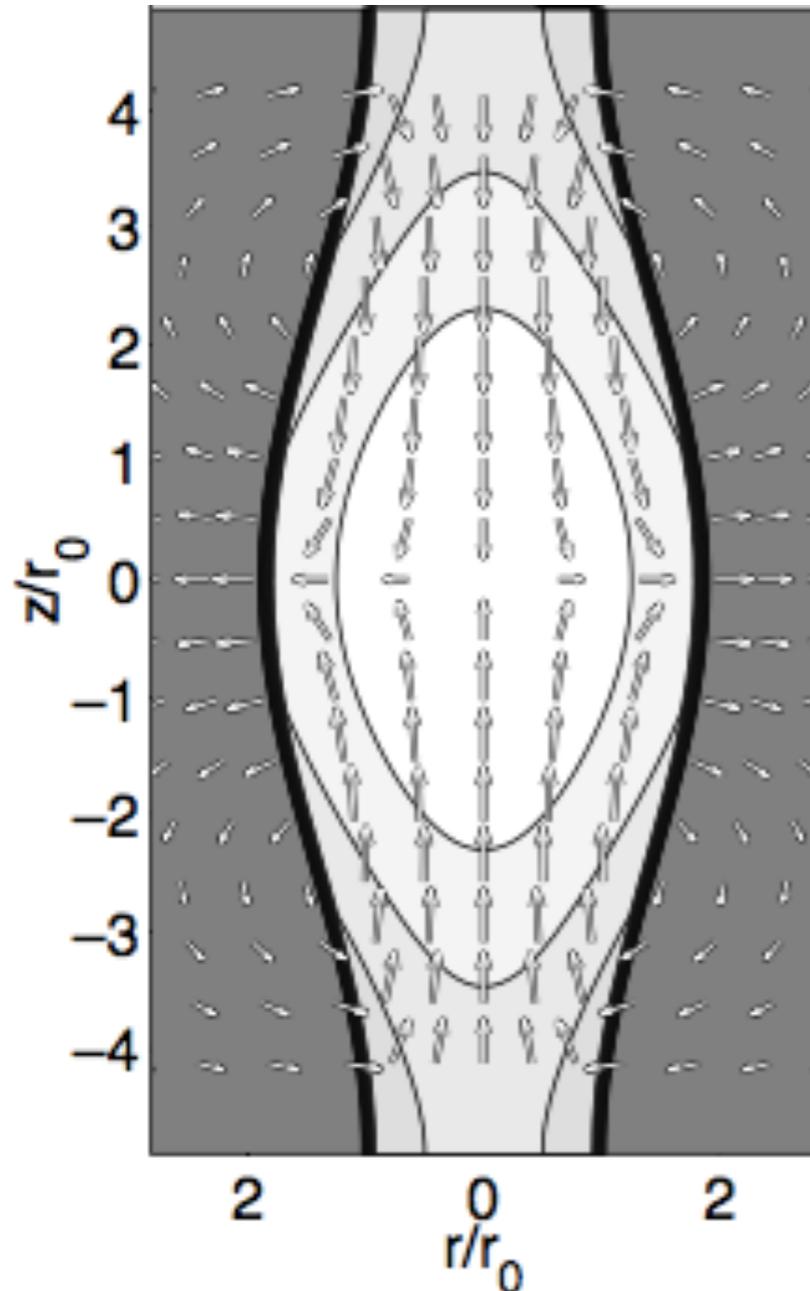


incompressible mode
(cf. Nagai+98, Fiege & Pudritz 00)

Similarity to truncated filament model.

Fiege & Pudritz 00

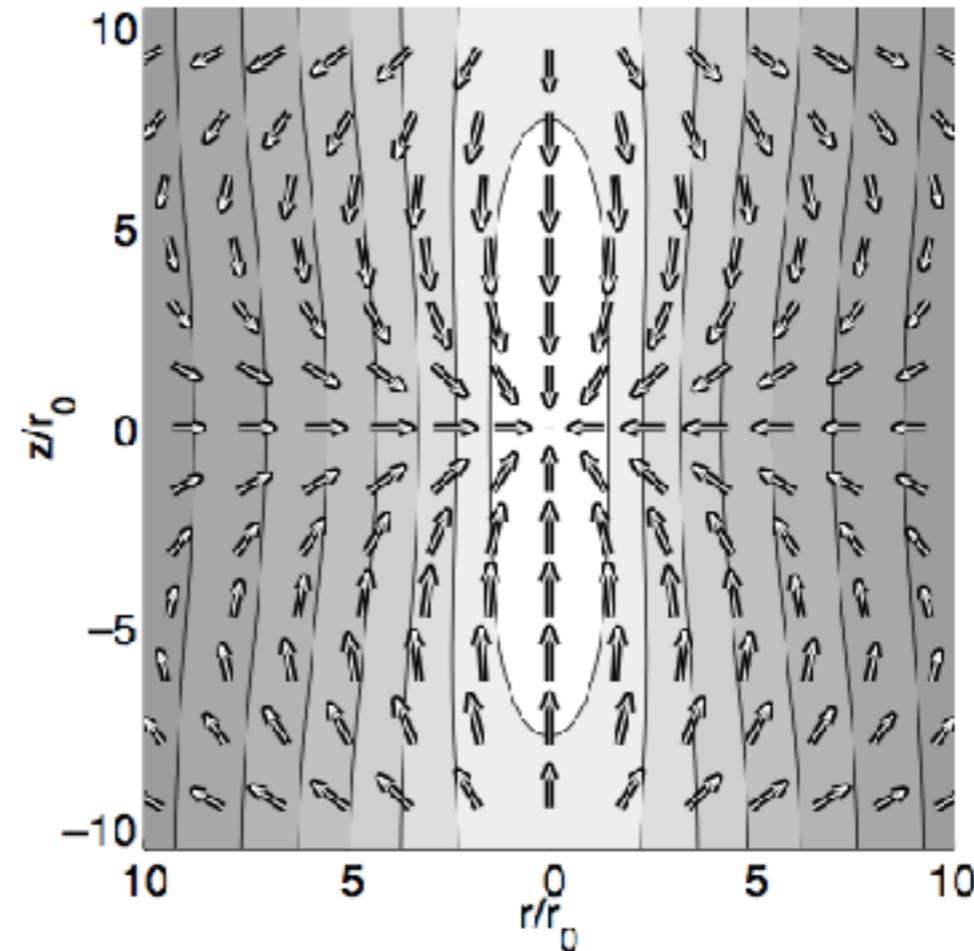
truncated filament



circulation

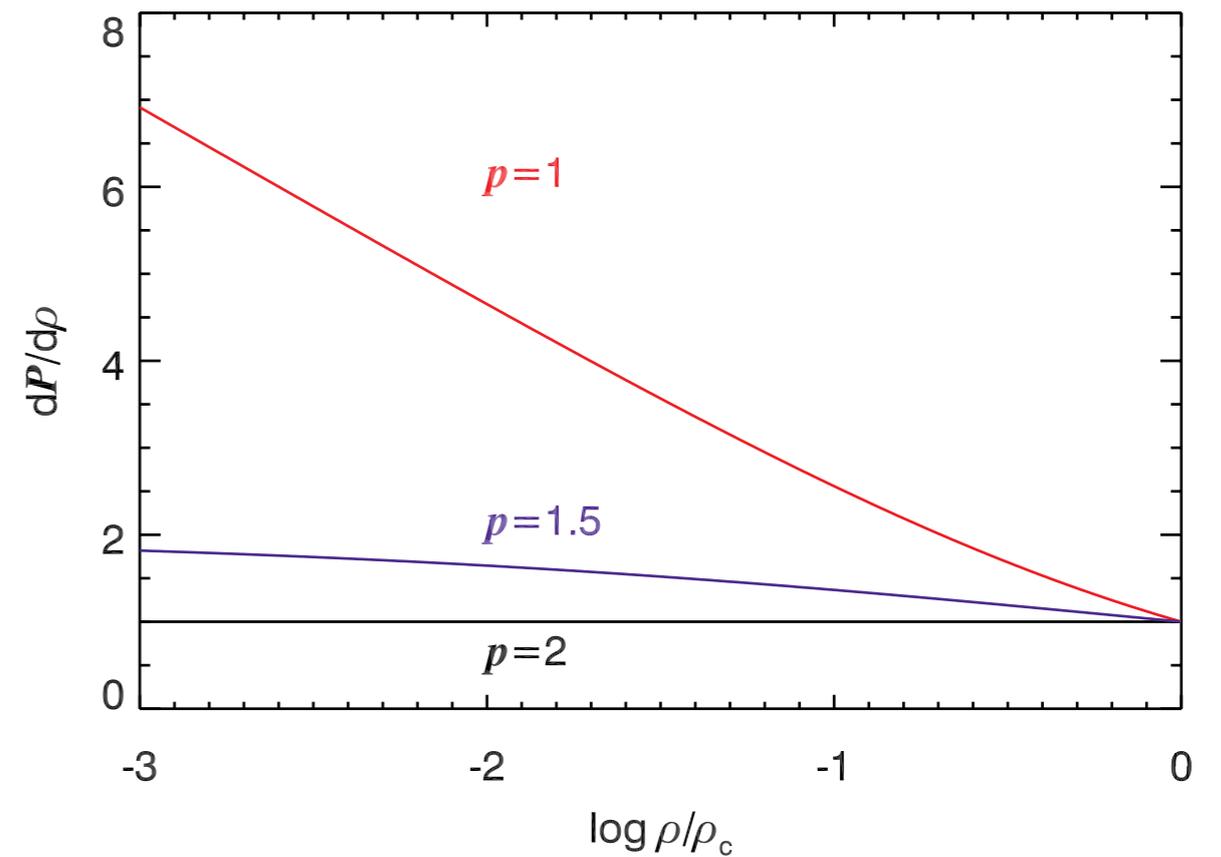
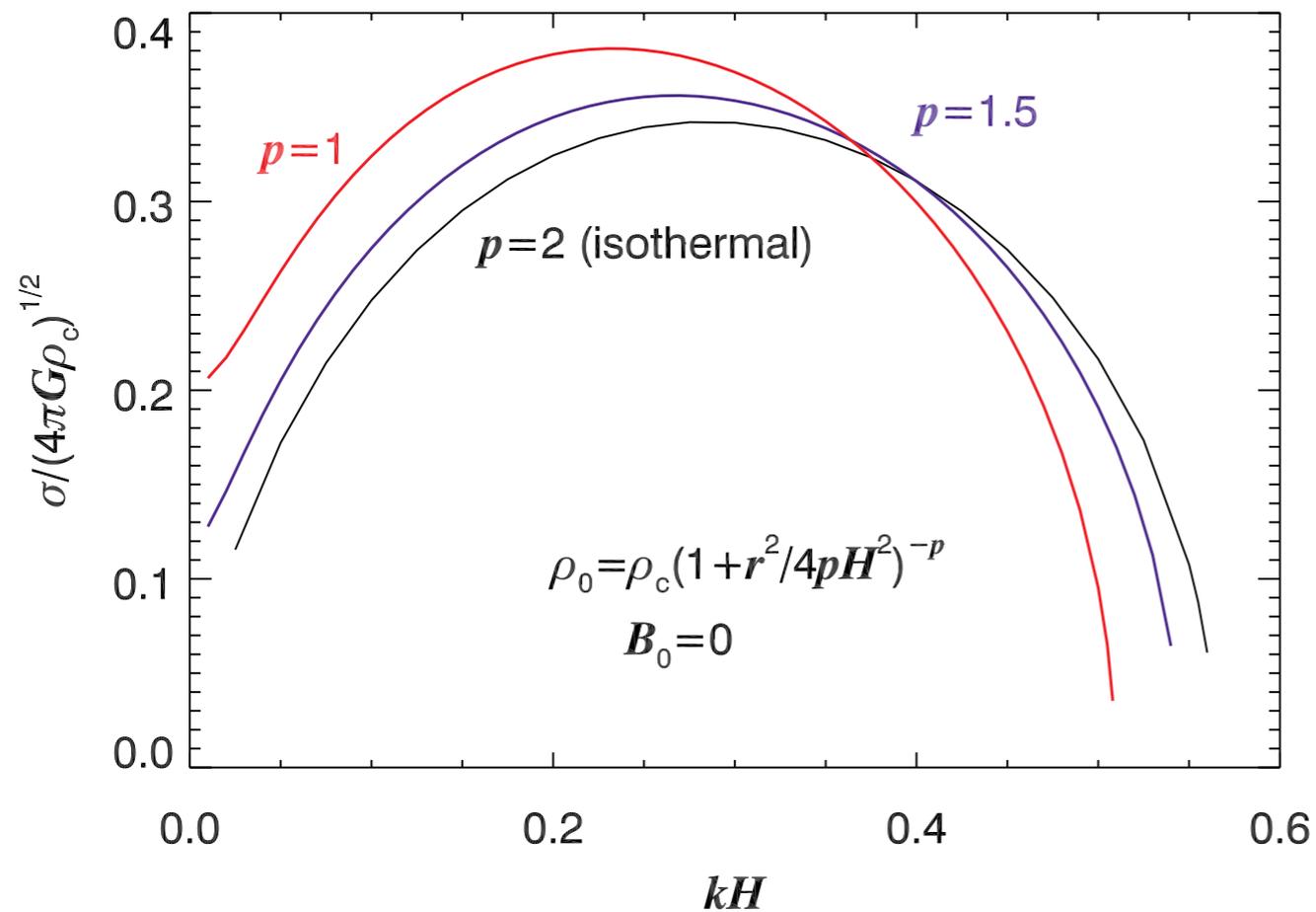
cf. Nagai+98 (truncated sheet)

compression

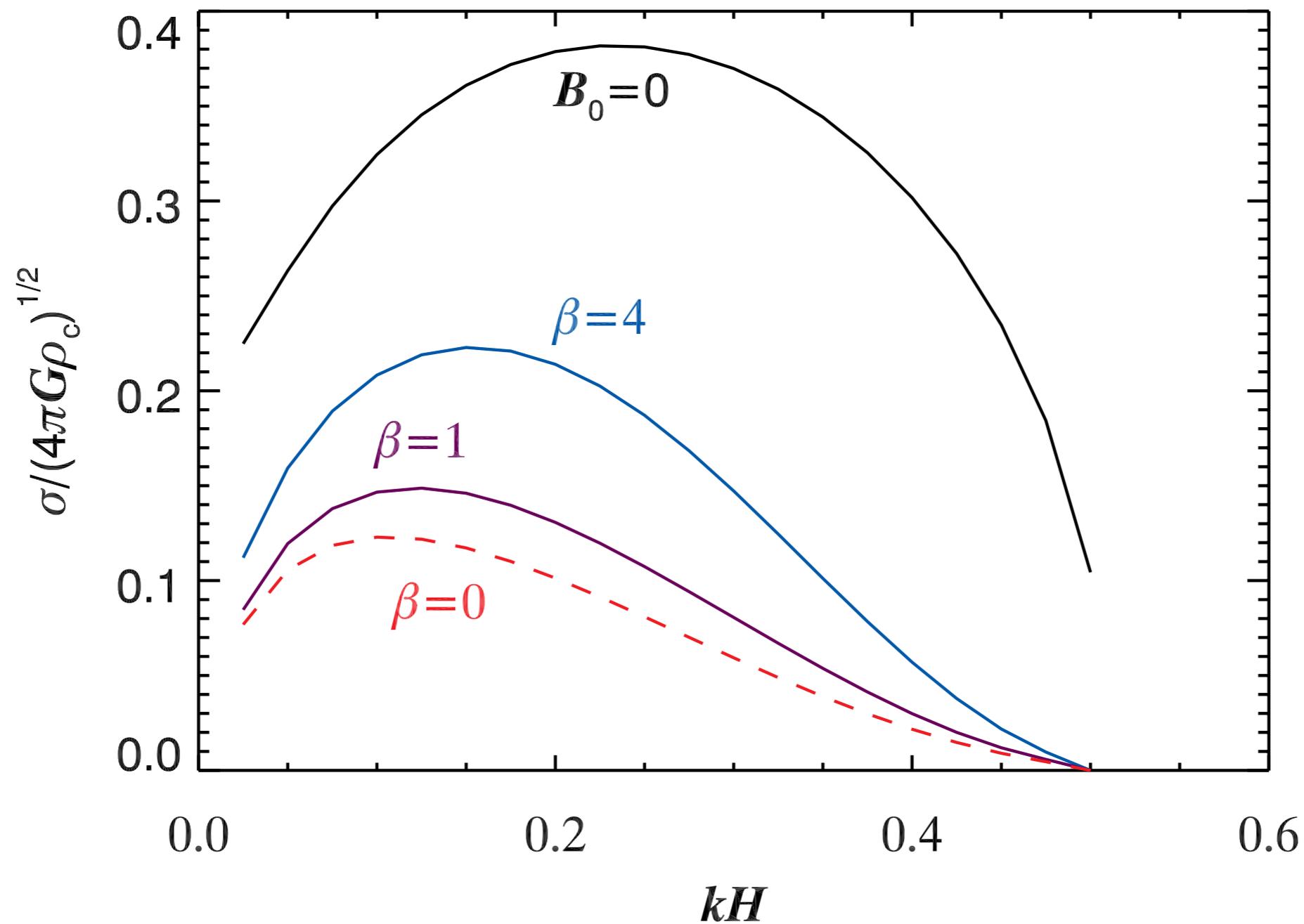


low β plasma \equiv high T

等温より柔らかいEOSでは 動径収縮 ($k=0$) も不安定



磁場あり ($p=1$) 自由境界



動径収縮は起きにくくなる

まとめ

- (当然) 軸に垂直な磁場は分裂を抑制する
- 圧縮モードは比較的弱い磁場でも抑制される
- どれほど強い磁場でも、変形不安定は抑えられない
- (意外!) 低密度領域での磁場が不安定性に影響を与える。