

慣性型フュージョンエネルギー システムの概要と課題

高部英明

大阪大学

バーチャルラボラトリとAI×データ戦略～ムーンショット目標10デジタルシステムプロ
ジェクト連続ワークショップ (1)

アットビジネスセンター東京駅八重洲通り501号室

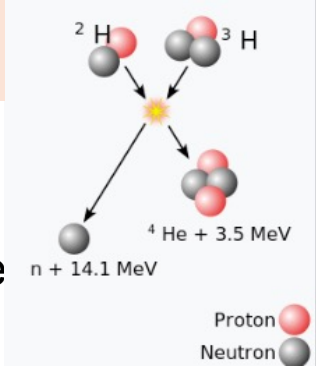
2025年3月3日

太陽とレーザー核融合

$$\rho \frac{du}{dt} = \rho g - \nabla P$$



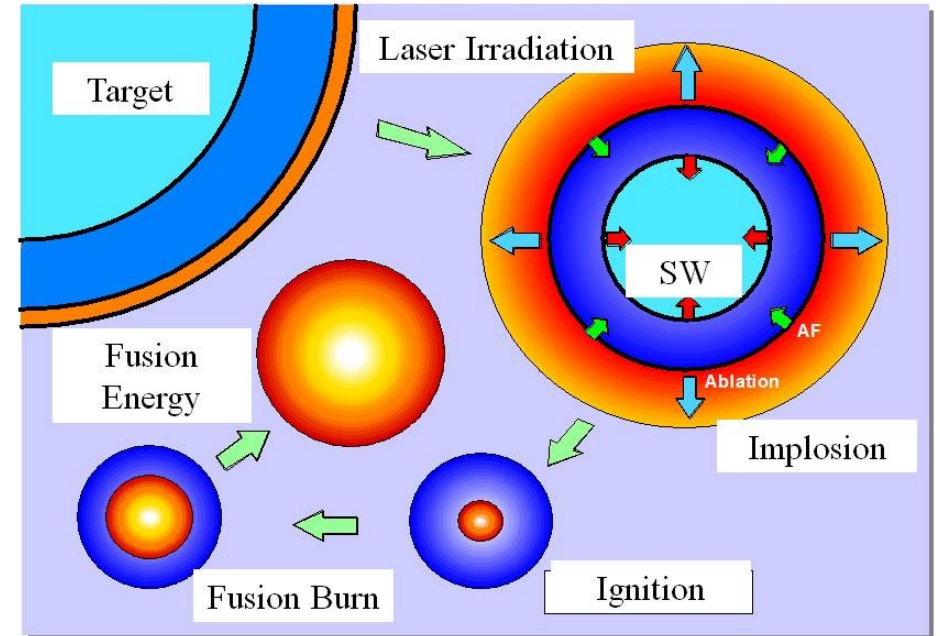
$$\rho \frac{du}{dt} = -\nabla P$$



Evolution of LF

Dynamical (~ns)
because of pressure
from outside and
inside

Principle of Laser Fusion

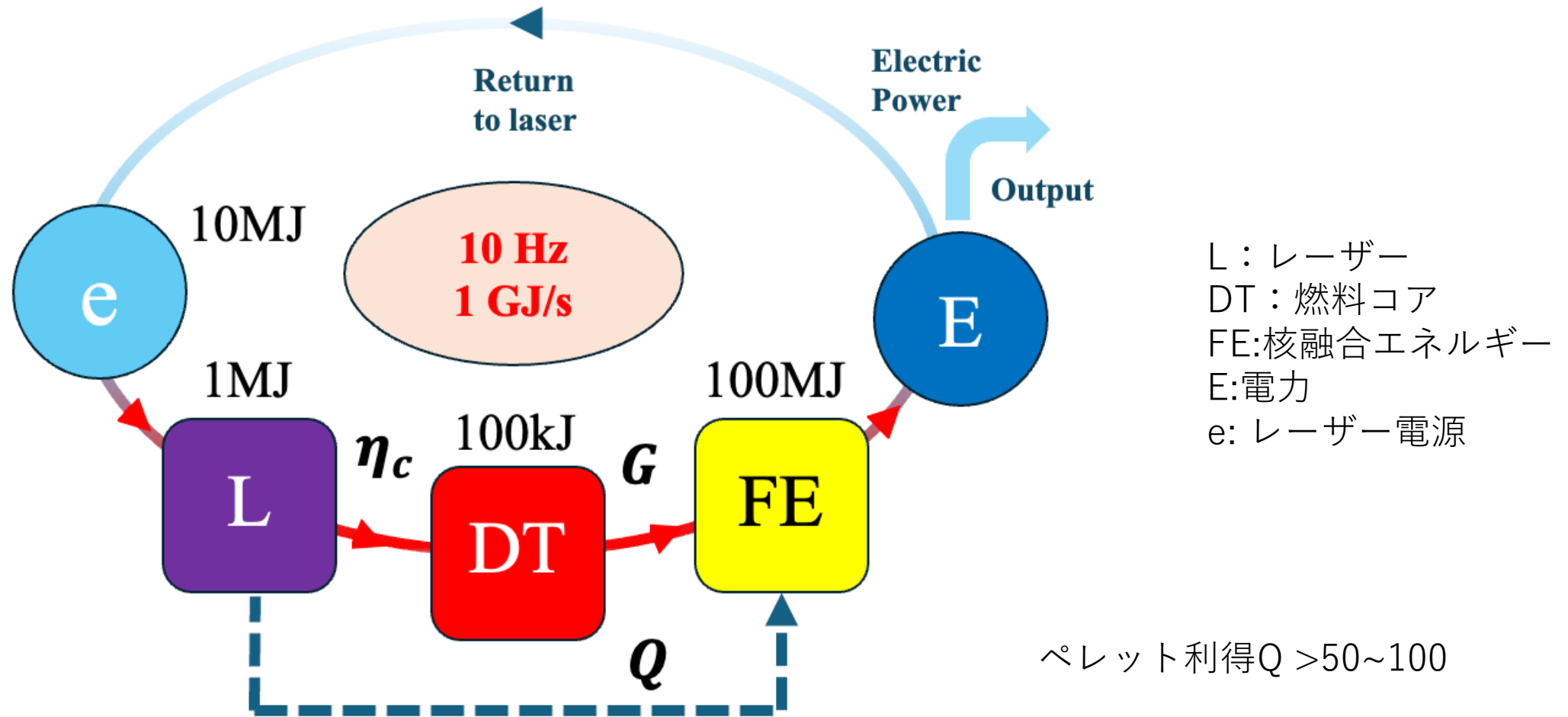


Inside of the Sun

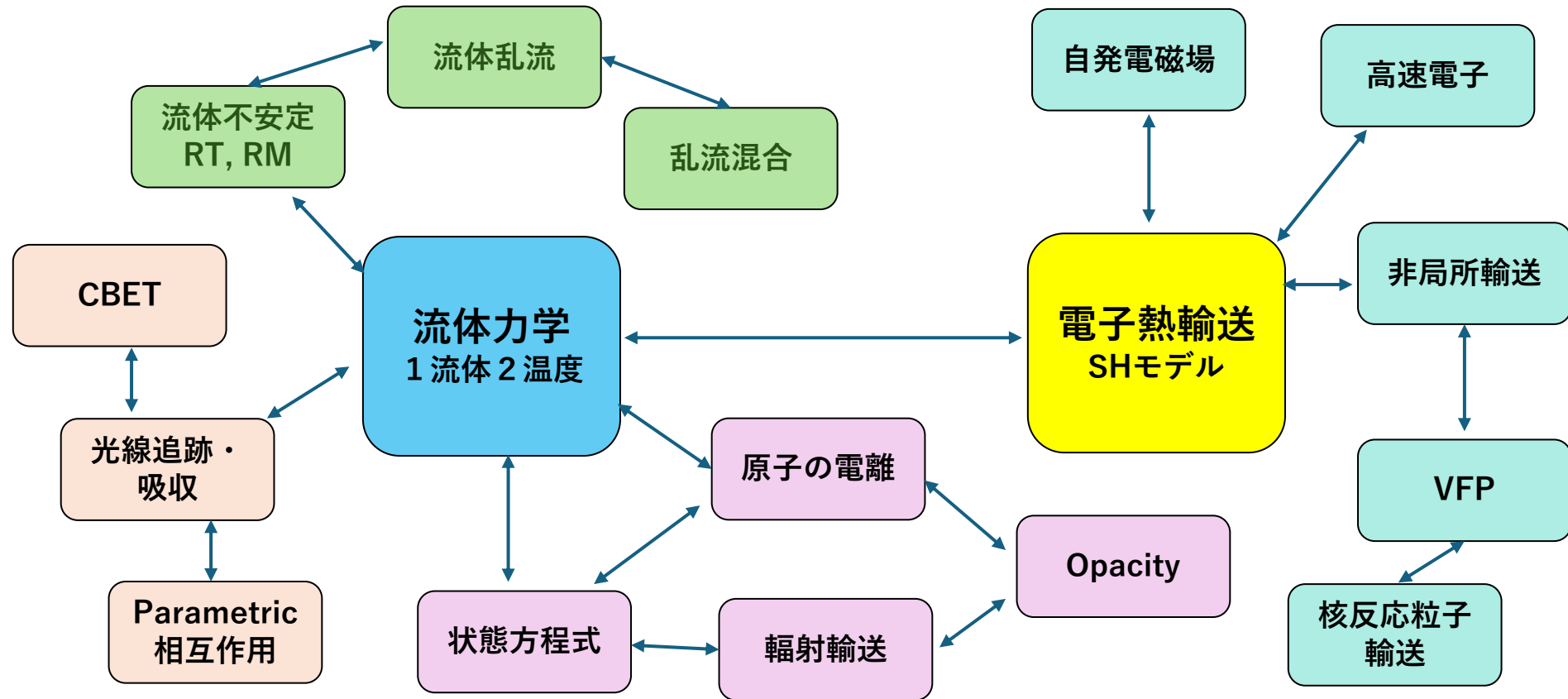


Steady state (B-years)
due to balance of
pressure and gravity

フュージョン・エネルギーの流れ



レーザー核融合物理の要素と統合



Elements of physics included in laser fusion energy production. The cores are 3D hydrodynamics and electron transport. The elements consist of roughly four parts, laser-plasma interaction (orange), atomic physics of plasma (pink), hydrodynamic instability (green), and electron energy transport (blue-green).

流体力学 = 1 流体 2 温度モデル =

$$\frac{d}{dt} \rho = -\rho \nabla \mathbf{u}$$

$$\rho \frac{d}{dt} \mathbf{u} = -\nabla P$$

$$\rho \frac{d\varepsilon_i}{dt} = -P_i \nabla \mathbf{u} - \nabla \mathbf{q}_i + Q_{ei} + S_i$$

$$\rho \frac{d\varepsilon_e}{dt} = -P_e \nabla \mathbf{u} - \nabla \mathbf{q}_e - Q_{ei} + S_e$$

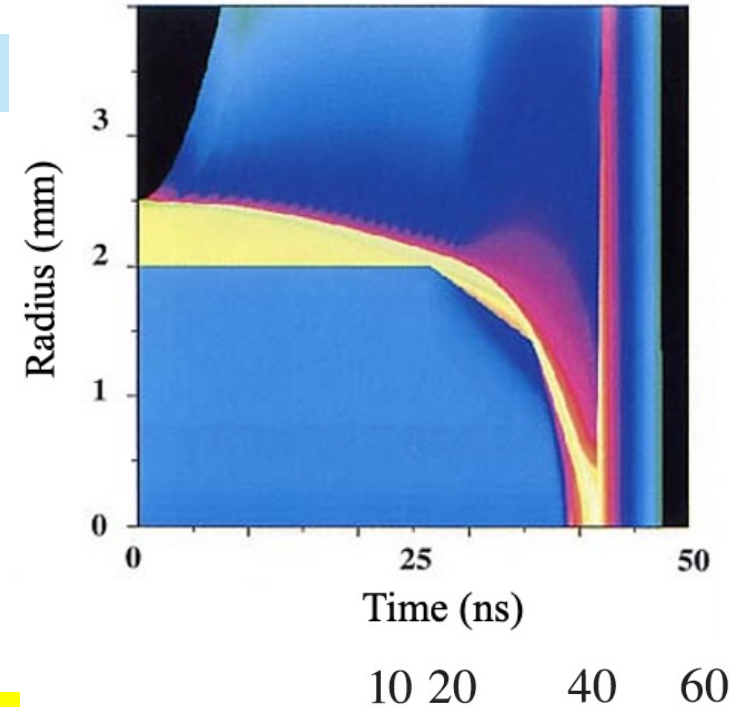
3次元球座標

$$\nabla \cdot \mathbf{A} = \frac{1}{R^2} \frac{\partial(R^2 A_r)}{\partial R} + \frac{1}{R \sin \theta} \frac{\partial(A_\theta \sin \theta)}{\partial \theta} + \frac{1}{R \sin \theta} \frac{\partial A_\phi}{\partial \phi},$$

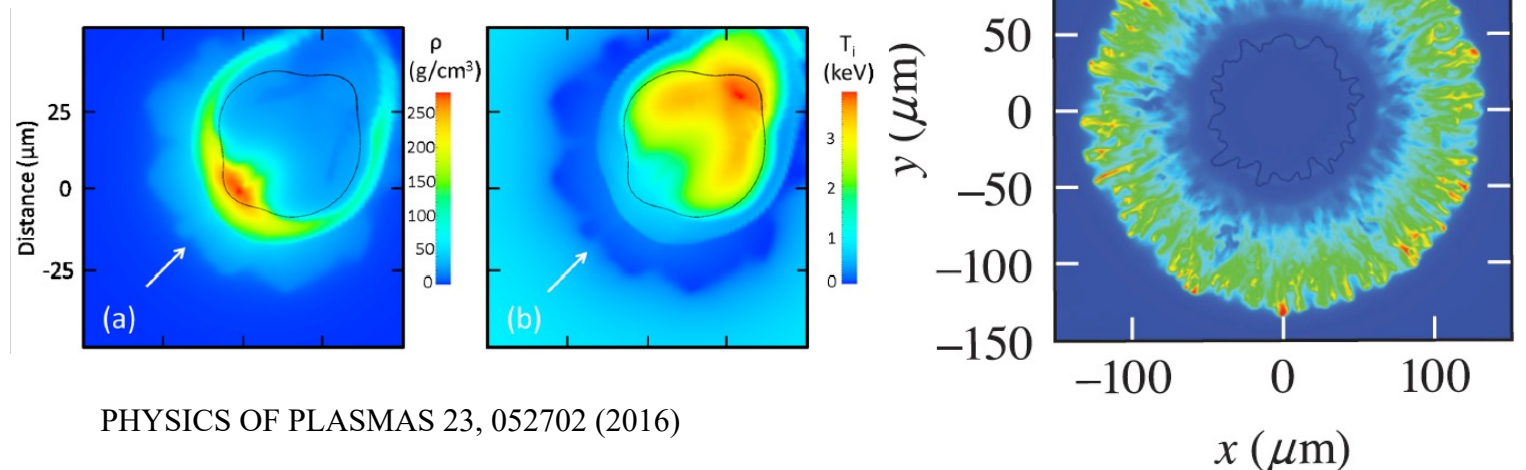
$$\nabla A = \left(\frac{\partial A}{\partial R}, \frac{1}{R} \frac{\partial A}{\partial \theta}, \frac{1}{R \sin \theta} \frac{\partial A}{\partial \phi} \right).$$

Grid : 648X120X240

1次元



3次元



3次元プラズマ流体モデル

$$\frac{\partial}{\partial t} \boldsymbol{\omega} + \mathbf{u} \cdot \nabla \boldsymbol{\omega} = (\boldsymbol{\omega} \cdot \nabla) \mathbf{u} - \boldsymbol{\omega} (\nabla \cdot \mathbf{u}) + \frac{1}{\rho^2} \nabla \rho \times \nabla P + \frac{4}{3} \nu \nabla^2 \boldsymbol{\omega}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times \left(\frac{1}{\mu_0 \sigma_{ei}} \nabla \times \mathbf{B} \right) - \nabla \times \left(\frac{\mathbf{j} \times \mathbf{B}}{en} \right) - \frac{1}{en} \nabla n \times \nabla T_e$$

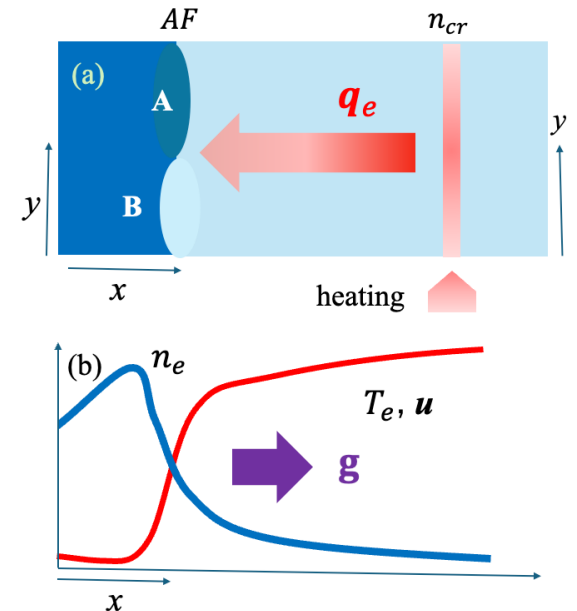
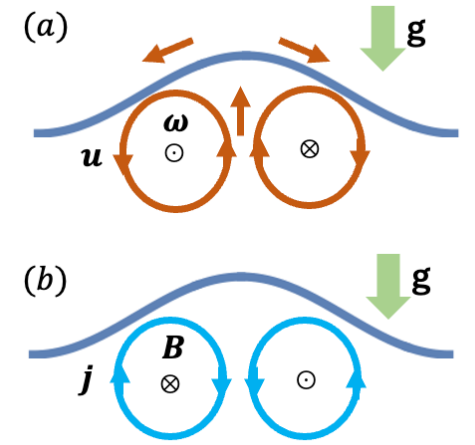
$$\frac{\partial}{\partial t} \left(\boldsymbol{\omega} + \frac{Ze}{m_i} \mathbf{B} \right) = 0$$

熱輸送は磁場も輸送する

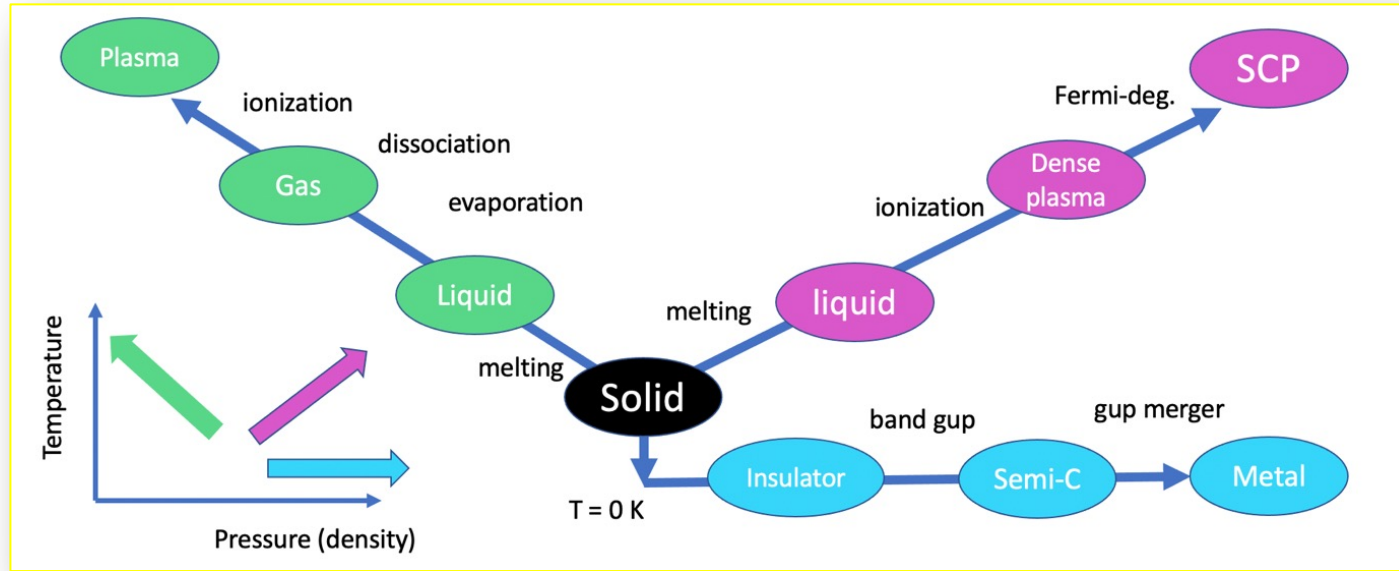
$$\frac{\partial}{\partial t} \mathbf{B} = \nabla \times [(\mathbf{u}_e + \mathbf{u}_c + \mathbf{u}_{N\perp} + \mathbf{u}_{N\parallel}) \times \mathbf{B}] + \frac{\mathbf{Z}}{em_i n_e} \nabla T_e \times \nabla n_e - \nabla \times (D_{\parallel} \nabla \times \mathbf{B}) - \nabla \times \left(\frac{\beta_{\parallel}}{e} \nabla T_e \right)$$

電磁場中での非局所熱輸送が流体を支配 (Fokker-Planck方程式)

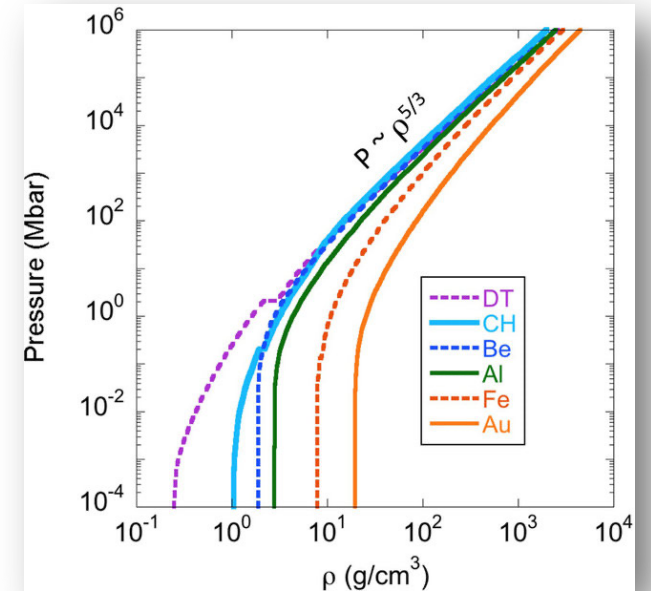
$$\frac{\partial}{\partial t} f(t, \mathbf{r}, \mathbf{v}) + \mathbf{v} \cdot \nabla f(t, \mathbf{r}, \mathbf{v}) - \frac{e}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial}{\partial \mathbf{v}} f(t, \mathbf{r}, \mathbf{v}) = \left(\frac{d}{dt} f \right)_{coll}$$



状態方程式



Thomas-Fermi model
Molecular bonding
.....



Density Functional Theory (DFT)

$$i \frac{\partial}{\partial t} \varphi_i(\mathbf{r}, t) = H_{KS}(\mathbf{r}, t) \varphi_i(\mathbf{r}, t)$$

$$H_{KS}(\mathbf{r}) = -\frac{\hbar^2}{2m} \nabla^2 + V_{KS}(\mathbf{r})$$

$$V_{KS}(\mathbf{r}) = f[n(\mathbf{r})]$$

$$n(\mathbf{r}) = \sum_{i=1}^N |\varphi_i(\mathbf{r})|^2$$

$$V_{KS}(\mathbf{r}) = V_{ne}(\mathbf{r}) + V_H(\mathbf{r}) + V_{xc}(\mathbf{r})$$

$$V_{KS}(\mathbf{r}) \Rightarrow V_{KS}(\mathbf{r}, t) + V_L(\mathbf{r}, t)$$

放射輸送

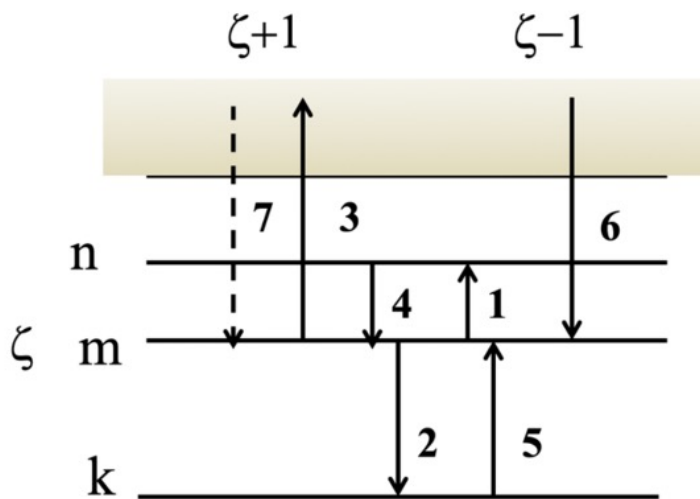
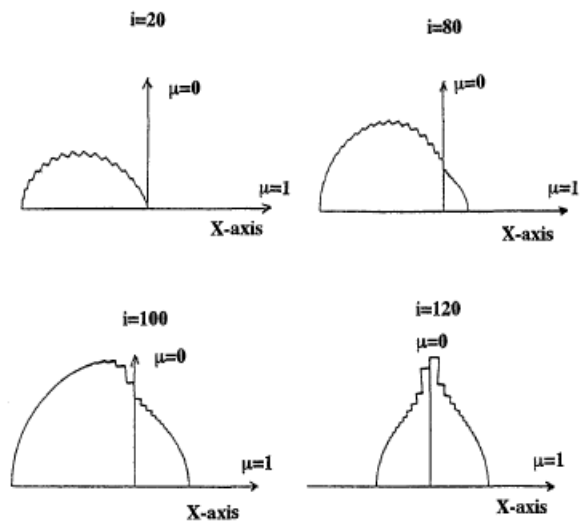
$$\frac{1}{c} \frac{\partial}{\partial t} I^\nu(t, \mathbf{r}, \boldsymbol{\Omega}) + \boldsymbol{\Omega} \cdot \nabla I^\nu(t, \mathbf{r}, \boldsymbol{\Omega}) = \eta^\nu(t, \mathbf{r}) - \chi^\nu(t, \mathbf{r}) I^\nu(t, \mathbf{r}, \boldsymbol{\Omega})$$

原子状態

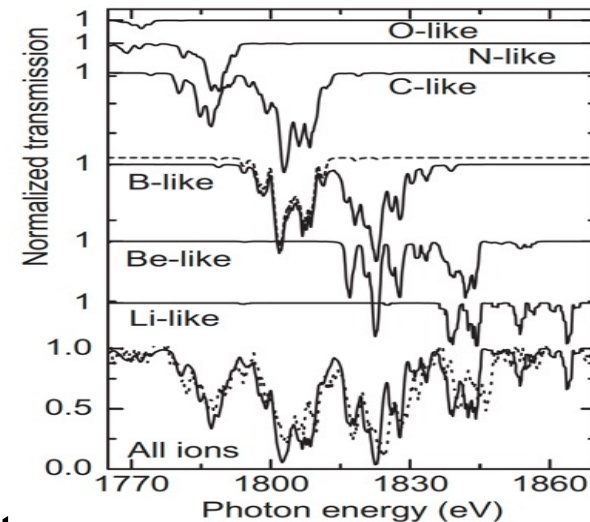
$$\frac{dN_m^\zeta}{dt} = -A_1 + A_2$$

$$A_1 = \left(\sum_{n>m} v_{m,n}^{bb} + \sum_{k<m} v_{m,k}^{bb} + \sum_j v_{m,j}^{bf} \right) N_m^\zeta$$

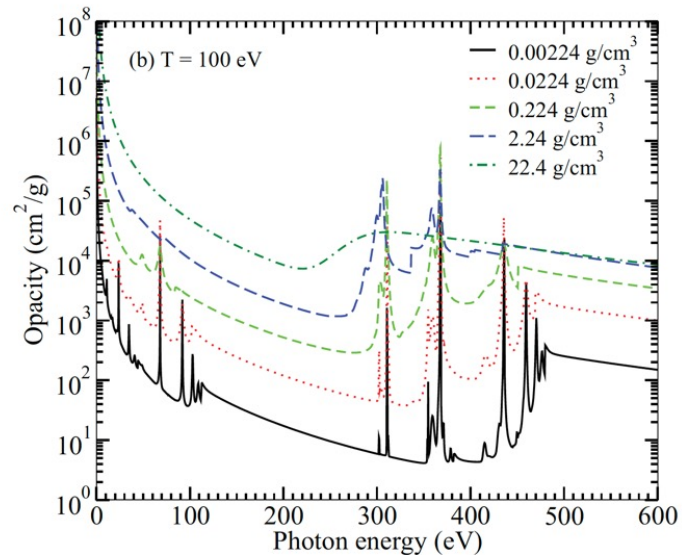
$$A_2 = \sum_{n>m} v_{n,m}^{bb} N_n^\zeta + \sum_{k<m} v_{k,m}^{bb} N_k^\zeta + \sum_j v_{j,m}^{fb} N_j^{\zeta+1} + \sum_j v_{j,m}^{bf} N_j^{\zeta-1}$$



Theory VS exp



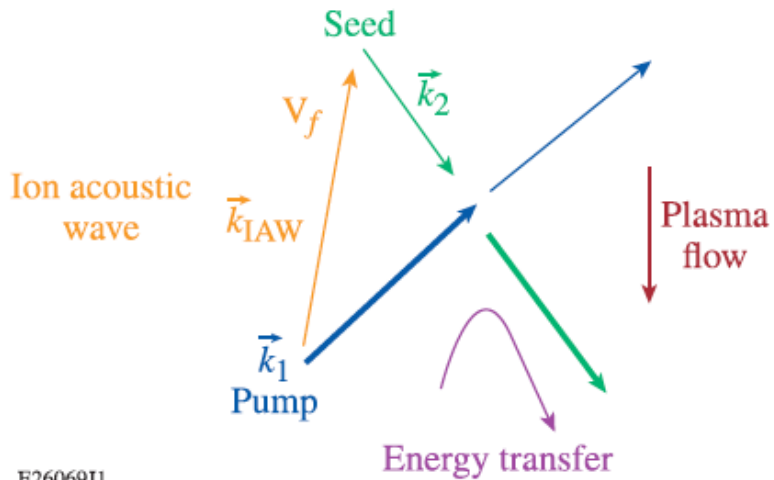
Opacity



レーザープラズマ相互作用

パラメトリック相互作用

CBET(Cross beam energy transfer)



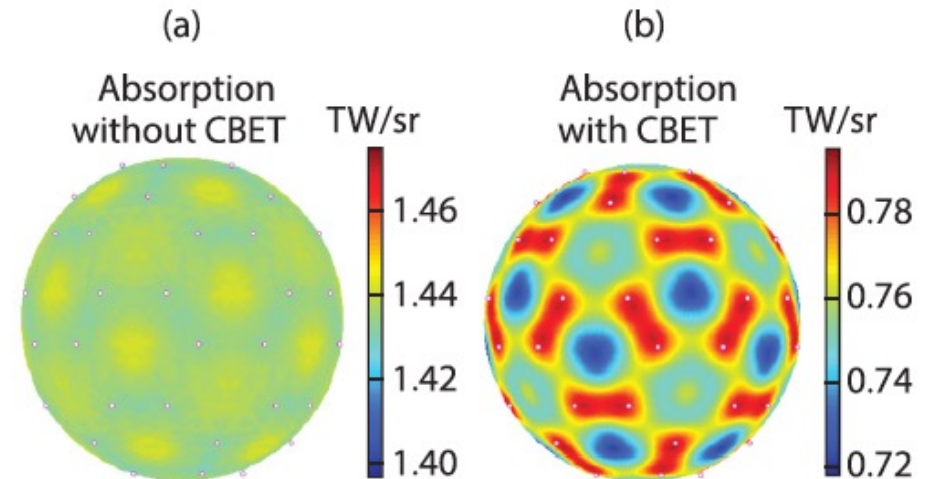
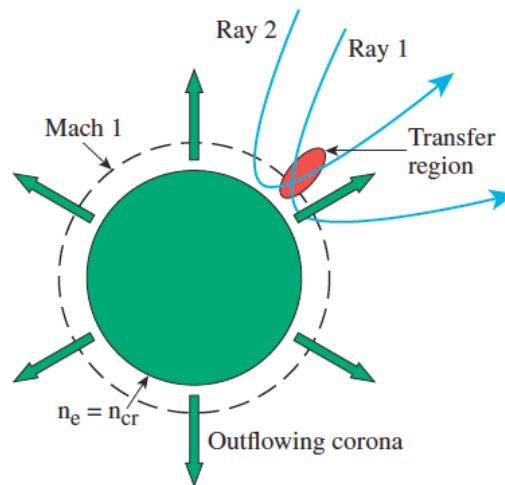
E26069J1

$$\frac{\partial}{\partial t^2} \mathbf{E} - c^2 \nabla^2 \mathbf{E} - \omega_{pe}^2 \mathbf{E} = -\frac{1}{\epsilon_0} \frac{\partial}{\partial t} \mathbf{j}_{NL}$$

$$\mathbf{j}_{NL} = -en_e v_{os}$$

Stimulated Brillouin Scattering (SBS)

$$\begin{aligned} \omega_{IAW} - \vec{u}_f \cdot \vec{k}_{IAW} &= \pm c_s |k_{IAW}|, \\ \omega_{IAW} &= \omega_1 - \omega_2, \\ \vec{k}_{IAW} &= \vec{k}_1 - \vec{k}_2, \end{aligned}$$

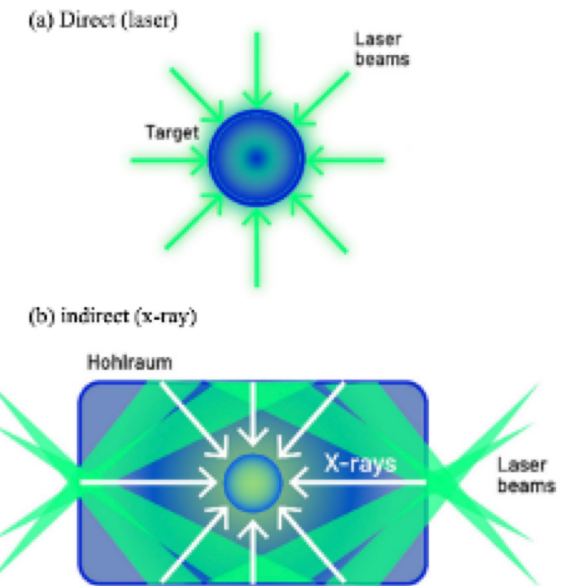
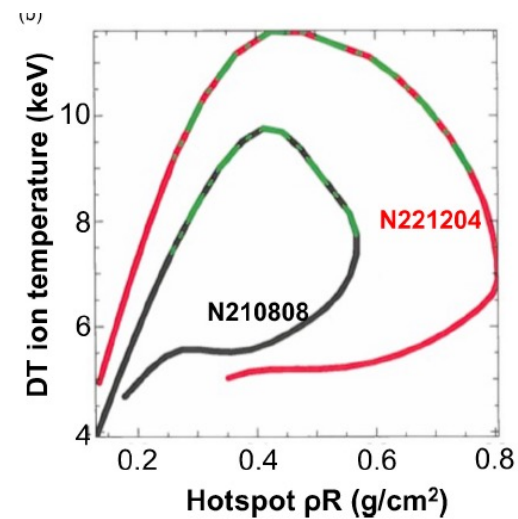
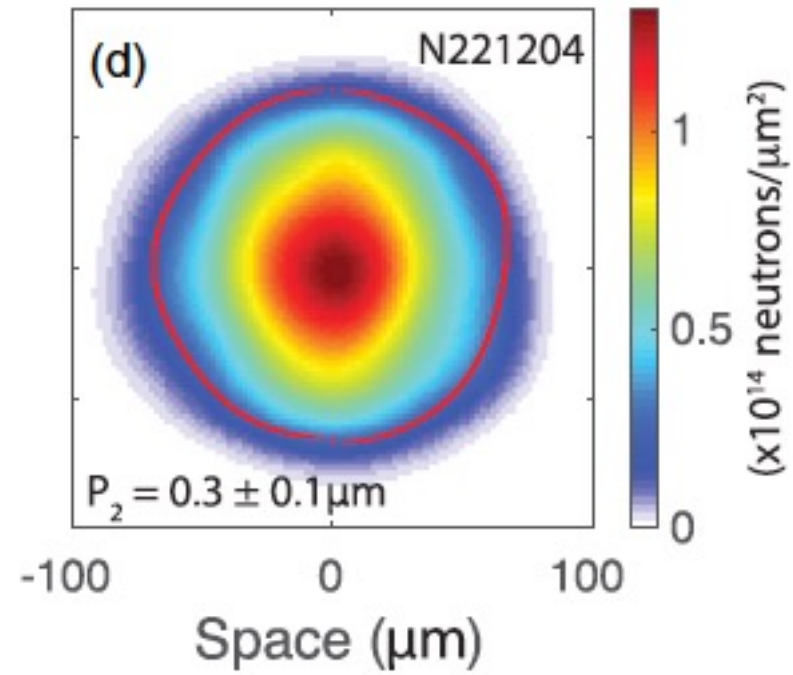
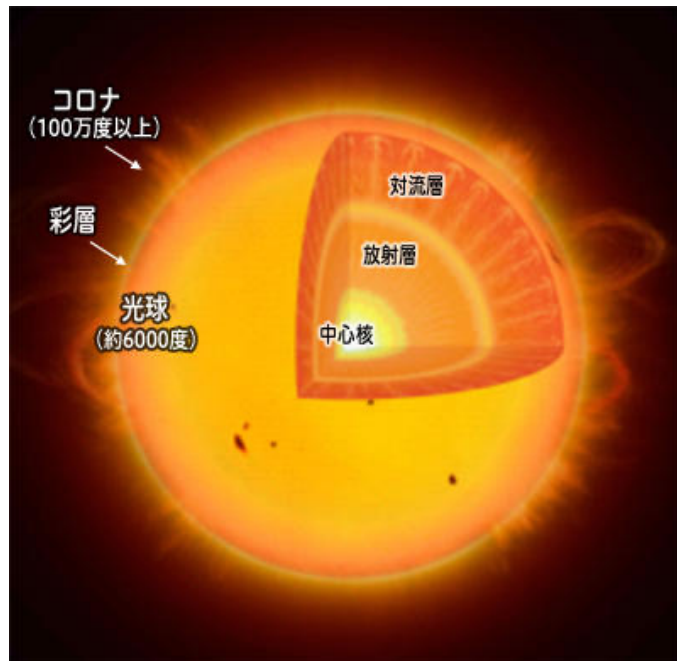


E25957J1

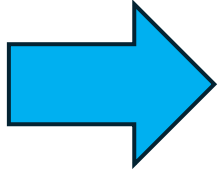
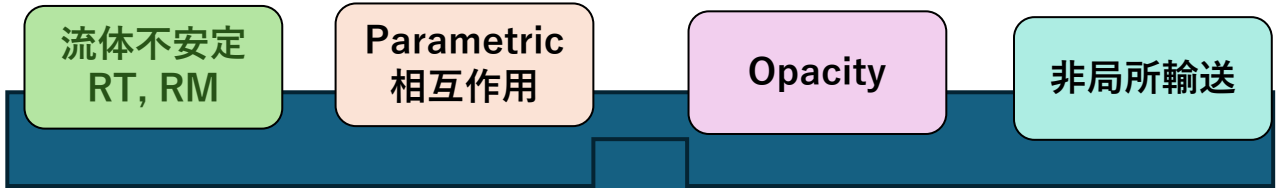
爆縮コア

X線駆動では点火・燃焼が実現している。
直接照射で点火・燃焼が実現し、高利得になる条件を明らかにする。

太陽



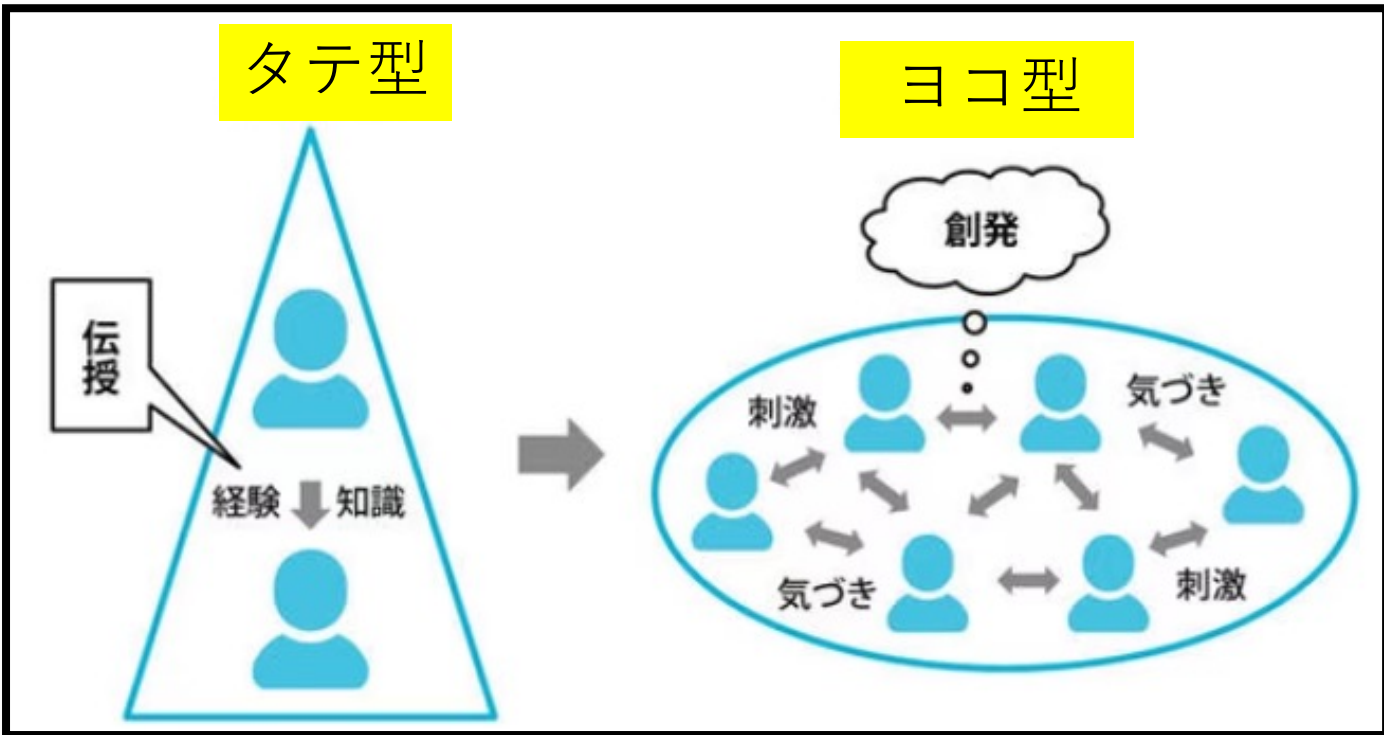
連携でしか達成できない課題に挑戦



学術の統合化の試み

物理統合型のコード開発

(学位の資格)
深く洞察し成果
を上げる研究力



物理統合コードは学術におけるオーケストラ



The Philharmonic Orchestra, the concert orchestra of the Saxon state capital, substantially shapes the cultural life of Dresden with over 80 concerts every year, Dresden, Germany

