I - 2

25th ITC: ‘Creating Future’
November 3, 2014

Non-Equilibrium and Extreme State of Plasmas

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In collaboration with:

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NIFS

Plasma Turbulence
Itoh Project

1. Plasma Physics and Fusion Science Stand at the Crossroads

It was routinely said that

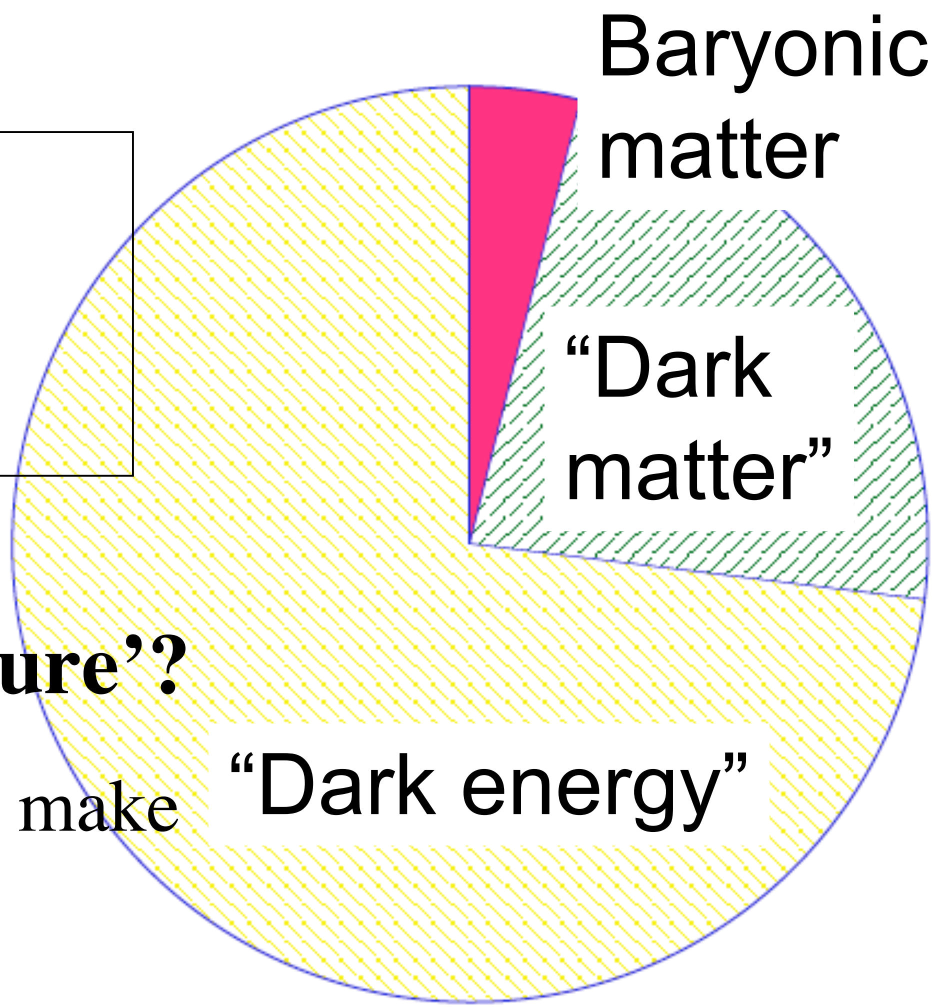
99.9 percent of the apparent universe exists in a plasma state ……

30 year for fusion energy ……

1. Plasma Physics and Fusion Science Stand at the Crossroads

Fusion research:
still some decades to go.

Plasmas:
small part in the universe.



Partition in the unit of "*Energy*"

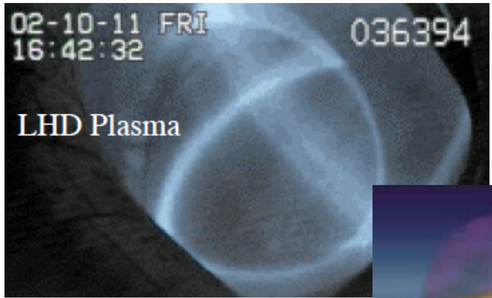
How can we ‘Create Future’?

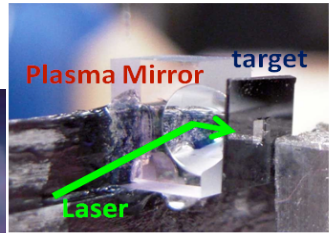
New endeavor is necessary to make more impacts on
understanding of nature,
industrial applications…

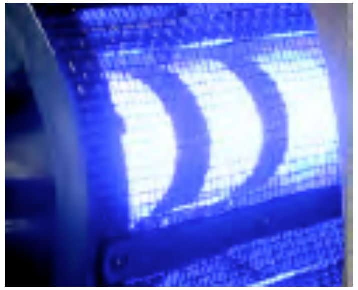
This is because a scientist grows up by *success*.

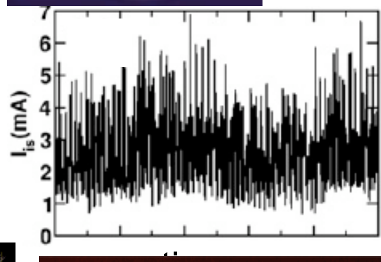
Frontier of Extremely non-Equilibrium Plasmas has rapidly expanded

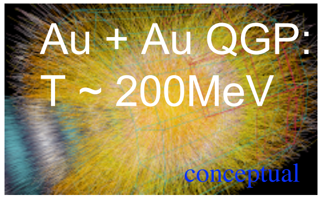
while the mass of plasmas in universe decreased

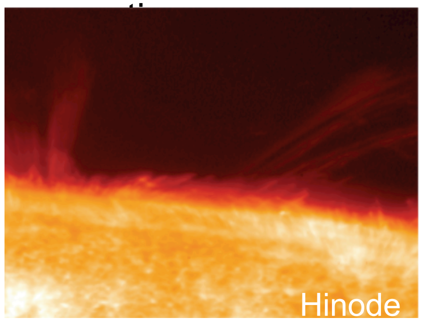


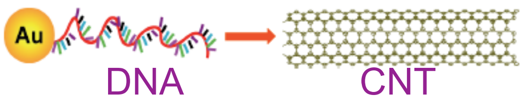












high temperature plasmas in MCF ,

high density plasmas in ICF,

intense energy density ,
intense charge beam (~10^8A/5μm ϕ),

strong turbulence in basic /fusion experiments,

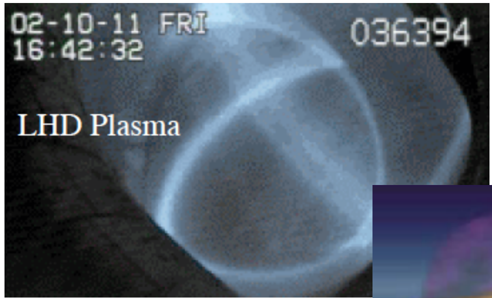
approach to solar plasma dynamics,

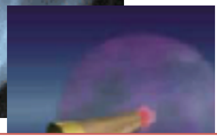
high energy density QG plasmas,

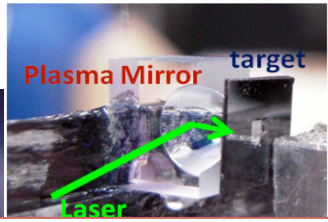
fine resolution in plasma processing,

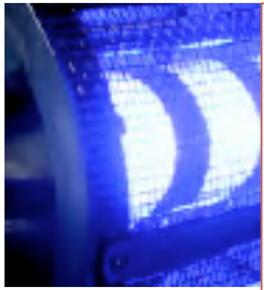
interaction with genes, cells and organs

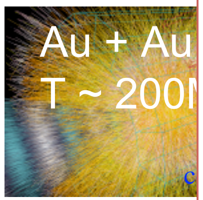
Frontier of Extremely non-Equilibrium Plasmas has rapidly expanded

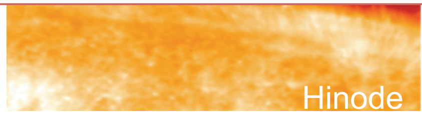


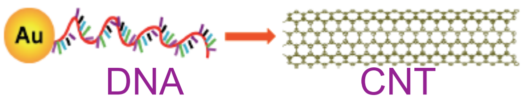












high temperature plasmas in MCF ,

high density plasmas in ICF,

intense energy density ,

intense charge beam (~10^8A/5μm ϕ),

Knowledge must be developed into Understanding.

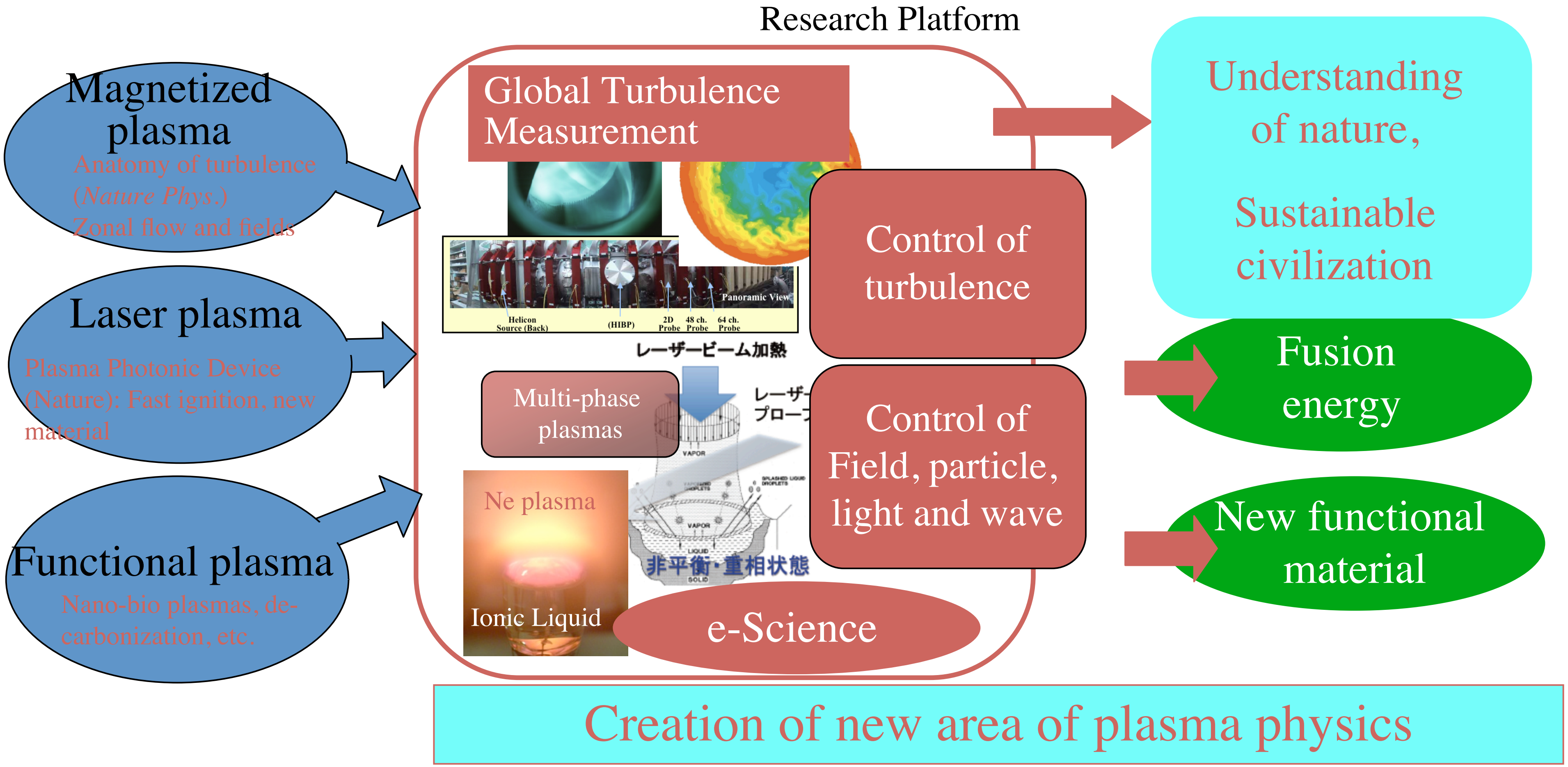
fine resolution in plasma processing,

interaction with genes, cells and organs

Master plan (2010, 2014) Science Council ; Road Map (2011, 2014) MEXT

Large-scale research project, which bridges individual research and large device.

"Circulation of knowledge" accelerates research, development and education.



Essentials of Extremely Non-equilibrium Plasmas

Near equilibrium	Far non-equilibrium
Uniform	Spatial inhomogeneity,
Equi-partition	Selective partition,
Thermal fluctuation	Selective excitation of fluctuation,
Onsager's ansatz	Cross-scale interaction,
Time-scale separation	Cross-interferences of time scales
Arrhenius law	Selection of path
Maximum entropy	Nonlinear dissipation
	Multi-ferroic turbulence
	Open system

Future……The way to go.

Essentials of Extremely Non-equilibrium Plasmas

Near equilibrium	Far non-equilibrium	
Uniform	Spatial inhomogeneity,	
Equi-partition	Selective partition,	
Thermal fluctuation	Selective excitation of fluctuation,	Axial vector field generation
Onsager's ansatz	Cross-scale interaction,	Axial vector field generation
Time-scale separation	Cross-interferences of time scales	Heating effect on transport
Arrhenius law	Selection of path	Heating effect on transport
Maximum entropy	Nonlinear dissipation	Heating effect on transport
	Multi-ferroic turbulence	Heating effect on transport
	Open system	Heating effect on transport

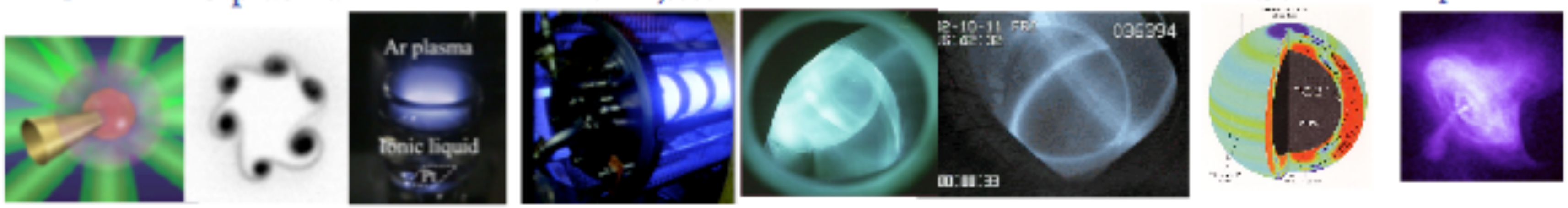
Shiratani, Kitano, Sato, ...

Future.....The way to go.

2.1 Law of ‘Παντα ρηει’

Drift Wave Turbulence & Meso/macro scale Electromagnetic Fields

ICF   e-plasma   PANTA,....   CHS   LHD   Sun   Super Nova



10^{-5}	10^{-2}	10^{-1}		1	10^{7}-10^{8}	>10^{16}	L (m)
10^{-10}		10^{-3}	10^{-1}	1	10^{8}	>10^{10}	t (s)

Weibel
Instability

Drift wave
Drift-Alfven wave

Rossby wave
Thermal Rossby wave
Magneto-rotational wave

Magnetic
field

Vortex

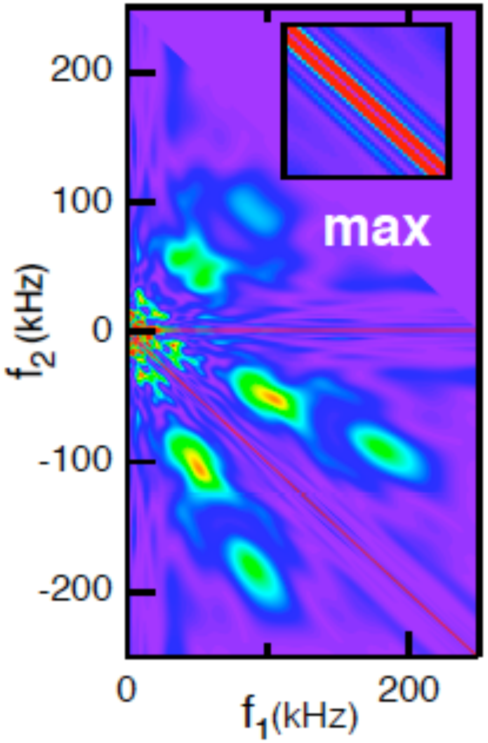
Zonal flow
Zonal field

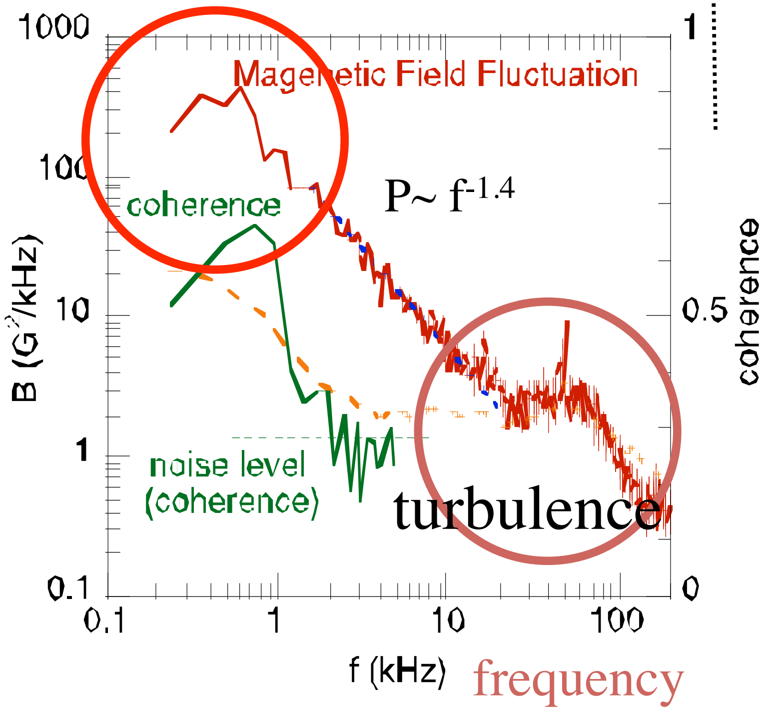
Zonal flow
Dynamo

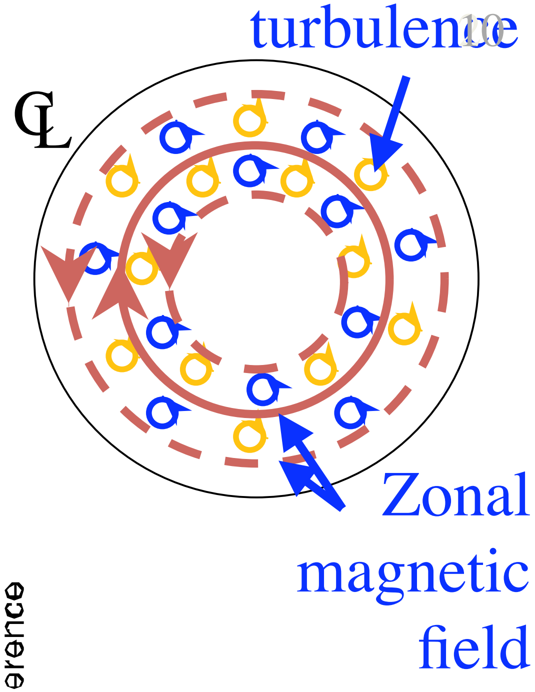
Discovery of Zonal Magnetic Field: meso-scale dynamo

CHS

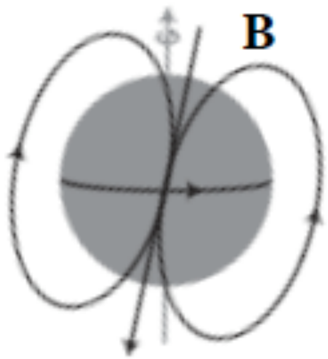
Zonal magnetic field







Geo-magnetic field



(Fujisawa, et al. Phys. Rev. Lett. **98** (2007) 165001)

In toroidal plasmas, turbulence generates large-scale magnetic field: The first historical evidence for meso-scale magnetic field generation by thermal convection.

Plasma Turbulence - Itoh Project -

Law of ‘Πανταρηει’ – Formation and Decay of Structures

Inhomogeneous plasmas

Homogenized

Evolution of turbuence

Cascade

Structure disappears

Generation of global axial vector field in limited domain

Disparate-scale interaction

Minimum principle

$$\frac{\partial}{\partial t}\tilde{f} + \mathcal{L}^{(0)}\tilde{f} = \mathcal{N}(\tilde{f}) + \tilde{S}_{th}$$

$$\frac{\partial}{\partial t}X + \Lambda X = g\, w(t)$$

最小原理

$$S(X) = \int^{X} 4\Lambda(X')\, g(X')^{-2} X' \, dX'$$

Nonlinear damping rate

Fluctuation force

Apparent edges

$$\frac{1}{lifetime}$$

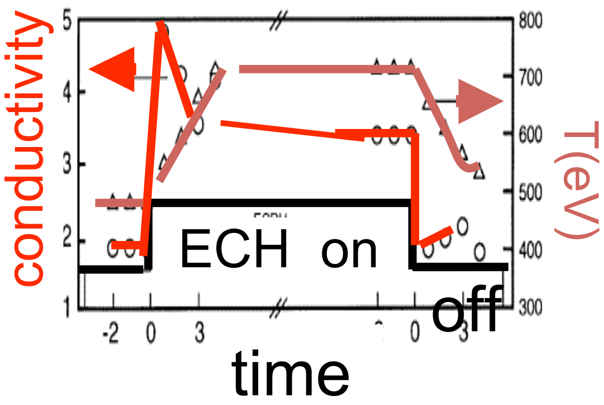
Structure appears

2.2 Acceleration of Fusion Science by Physics of Extremely non-Equilibrium Plasmas

It is usually believed that turbulence transport is driven by gradients:

$$q_r = -n\chi \text{ grad } T + \ldots. \qquad (\chi \text{ is given by gyro-Bohm……})$$

However, it has often been pointed out (and ignored) by experiments: **Heating directly influences transport**…..



W7-AS Stroth 1996

Heating may heat turbulence.

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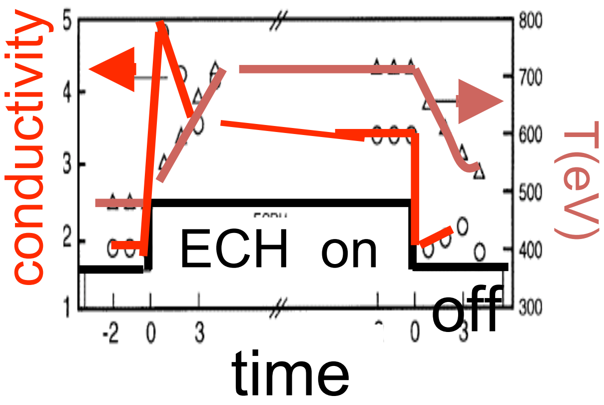
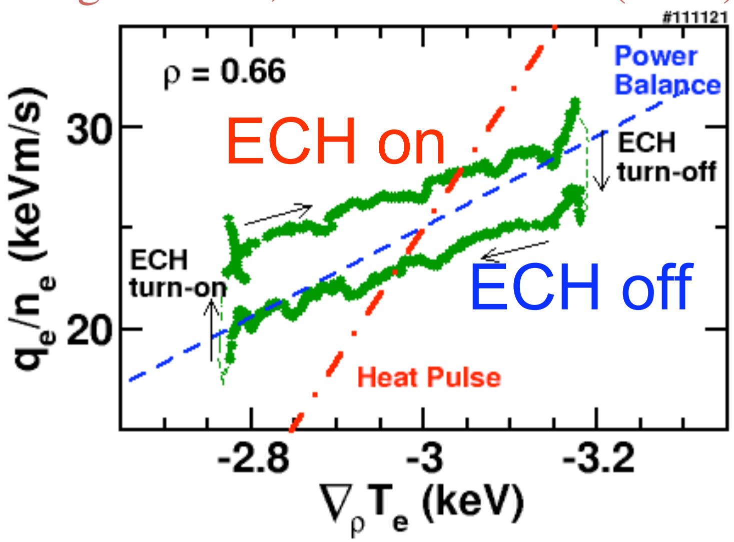


W7-AS Stroth 1996

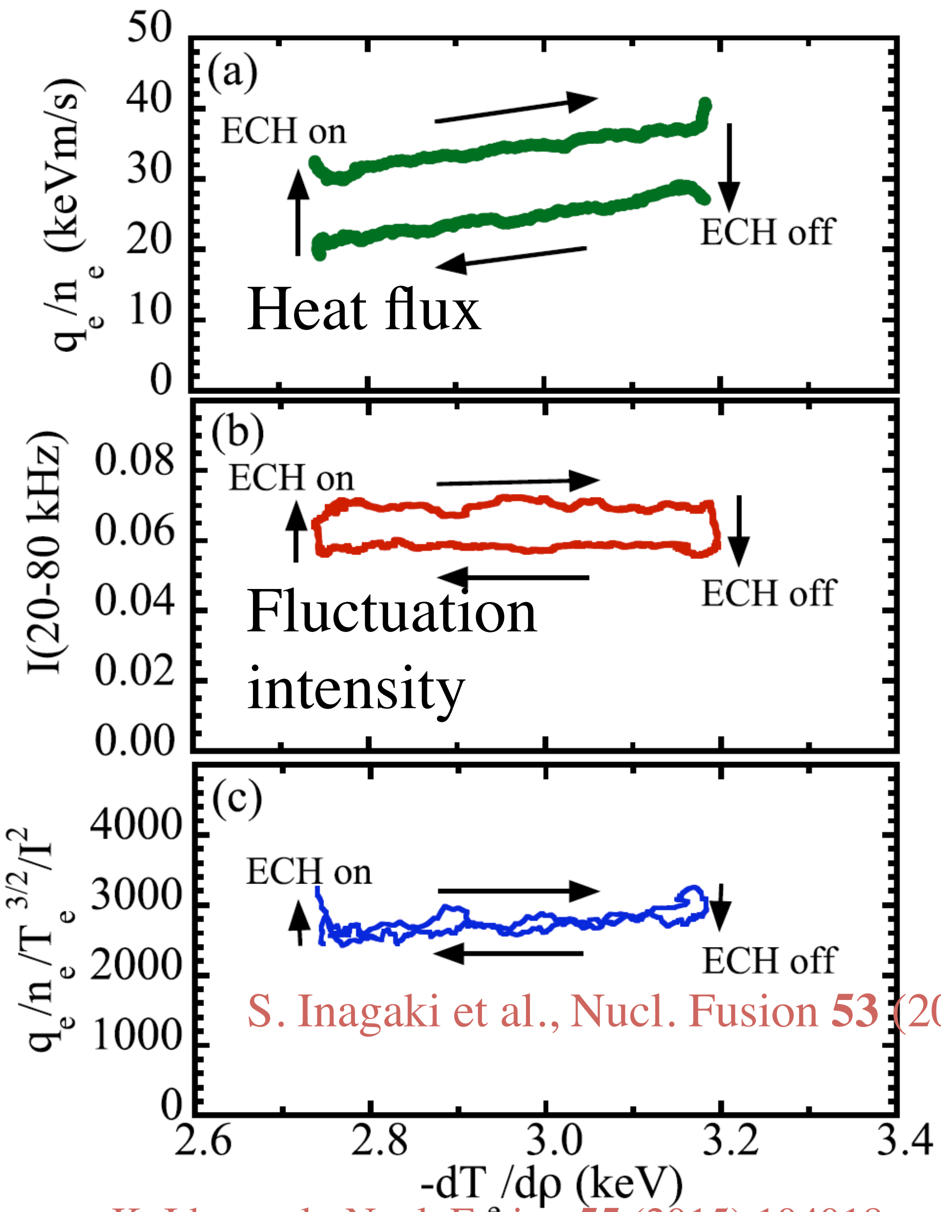
Decisive observation on LHD

S. Inagaki et al., Nucl. Fusion **53** (2013)



Heating may heat turbulence.

Gradient-flux-fluctuation relation



S. Inagaki et al., Nucl. Fusion **53** (2013)

K. Ida, et al.: Nucl. Fusion **55** (2015) 104018

The transport relation is directly influenced by heating power (without waiting the change of global parameter by the heating).

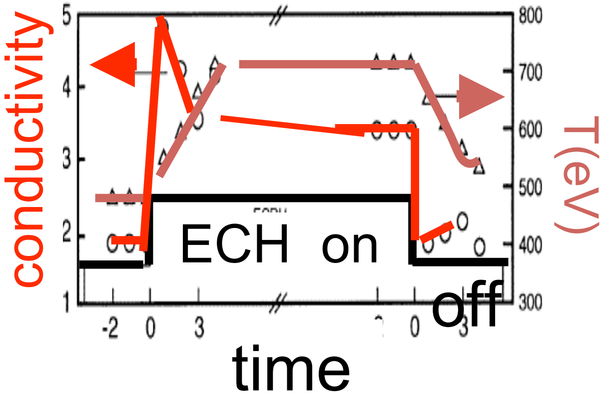
This is not an artifact (due to the error of evaluation of absorption power), because the fluctuations are found to change simultaneously.

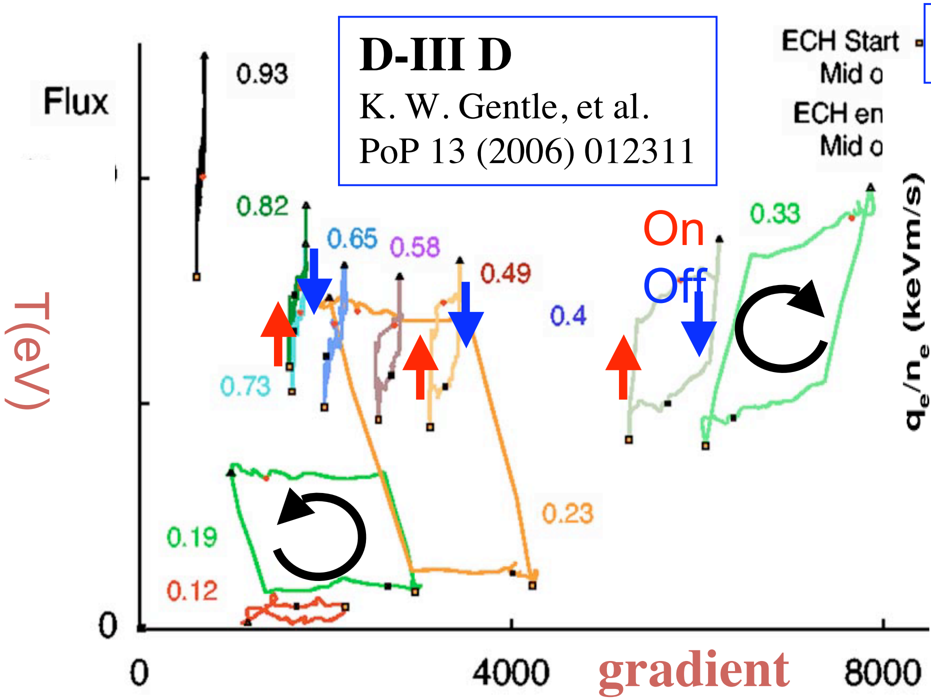
Decisive discovery on LHD

Observed Hysteresis

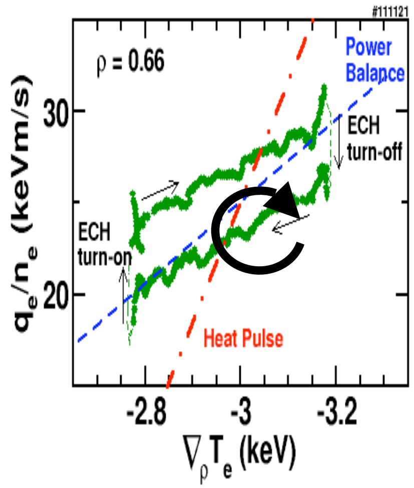
S.-I. Itoh, 15th H-mode WS (2015)

W7-AS Stroth 1996

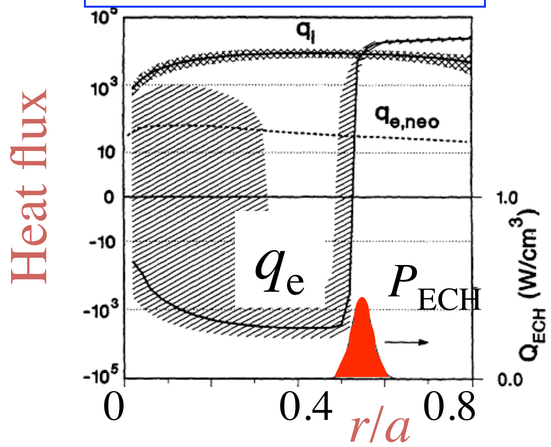




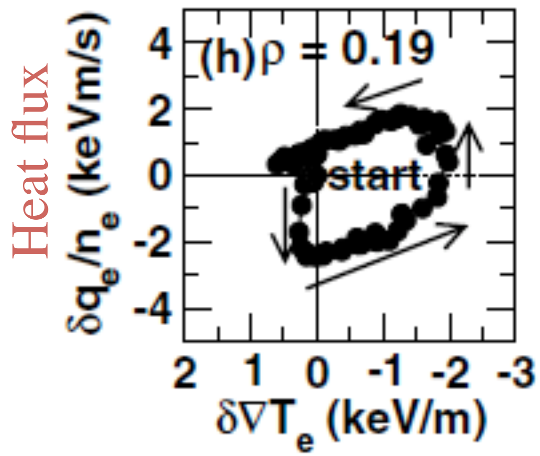
LHD Inagaki 2013



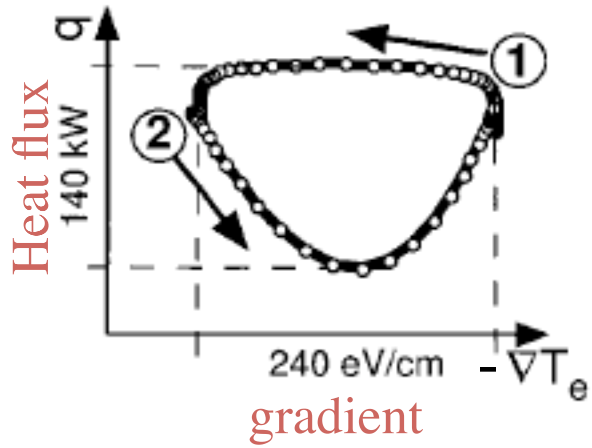
DIII-D Luce 1992



LHD Inagaki 2010



W7-AS Stroth 2001



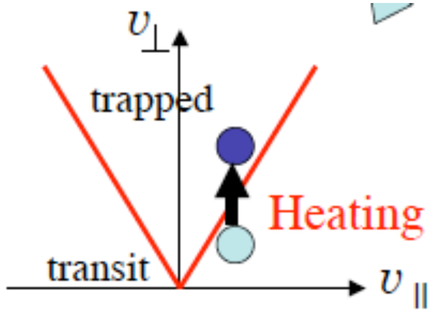
New Theoretical Approach

S.-I. Itoh, et al., Sci. Rep. **2** 860 (2012)

Kinetic Eq. with coupling of source $S[f; \boldsymbol{v}, x, t]$ with fluctuations

$$f = f_0 + \tilde{f},$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla + \frac{e_s}{m_s}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \nabla_{\boldsymbol{v}}\right) \tilde{f} = -\frac{e_s}{m_s}\tilde{\boldsymbol{E}} \cdot \nabla_{\boldsymbol{v}} f_0 + \frac{\delta S[f_0; \boldsymbol{v}, x, t]}{\delta f_0} \tilde{f} + \tilde{C}$$



Immediate influence by source (heating)

The 'force' that induces the change in velocity space influences gradient-driven turbulence.

Estimation of Fluctuation Level

$$\langle \varphi_1 \varphi_1 \rangle = \frac{1}{1 - \gamma_h \chi_0^{-1} k_\perp^{-2}} \langle \varphi_1 \varphi_1 \rangle_0$$

$$\gamma_h = \frac{\delta P_{heat}}{\delta p}$$

More effective for long-range modes

Heating heats turbulence.

Rapid Response in Turbulence/Transport

$$\frac{\delta S\left[f_0; \boldsymbol{v}, x, t\right]}{\delta f_0} \tilde{f} \Rightarrow \gamma_{\mathrm{heat}}(P)\, \tilde{f}$$

immediately responds
at on/off of heating

Fluctuation level

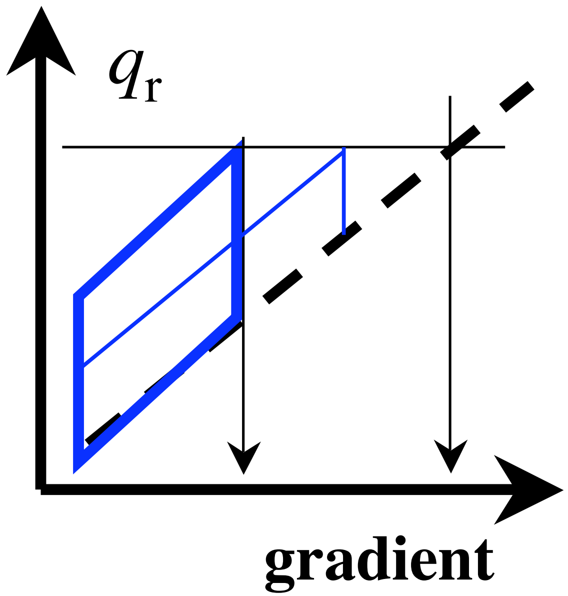
$$\langle \varphi_1 \varphi_1 \rangle = \frac{1}{1 - \gamma_h \chi_0^{-1} k_\perp^{-2}} \langle \varphi_1 \varphi_1 \rangle_0$$

More effective for
Long-range modes

Both gradients and heating power can enhance the turbulence transport.

This introduced new time scale in plasma response and control.

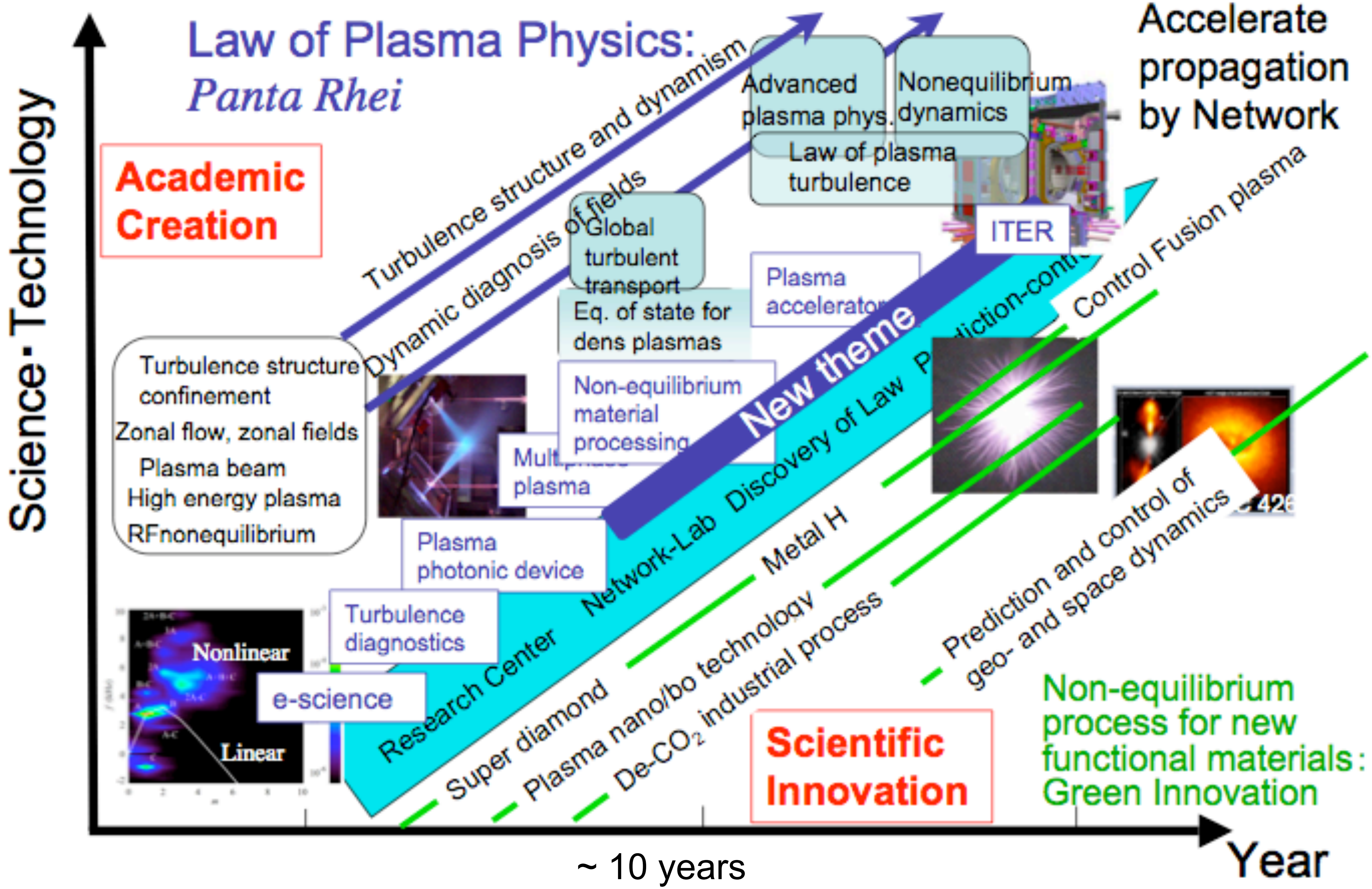
If the hysteresis height in gradient-flux relation is reduced, efficient confinement will be realized.



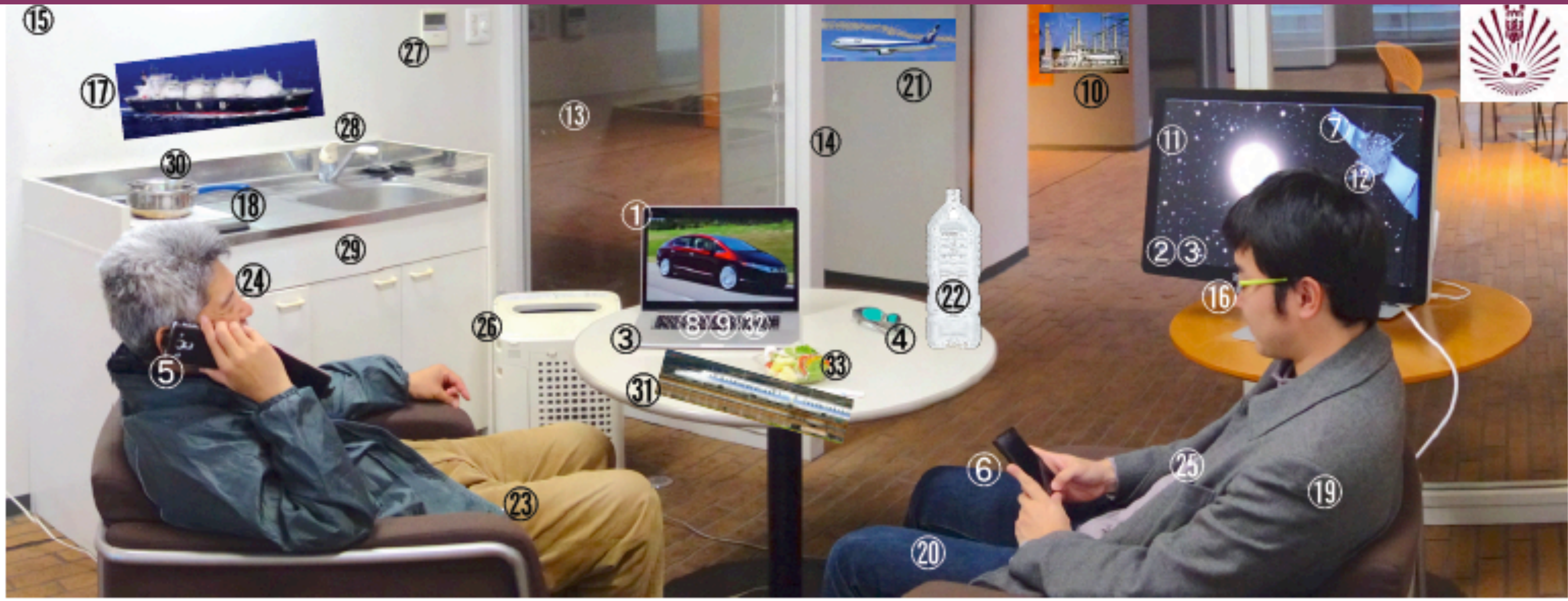
3. Futurology

Plasma physics drives breakthrough/innovation

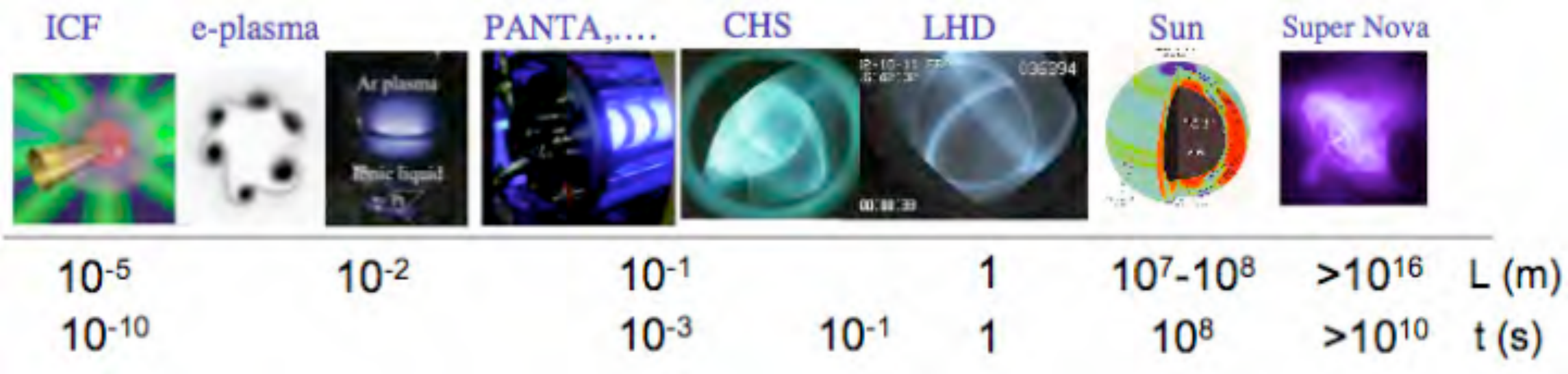
S.-I. Itoh et al.: J. Pl. Fus. Res. **87** (2011) 371



Civilization realized by Plasma Physics Science



Turbulence and generation of large-scale axial vector field



4. Message

1. Plasma physics and fusion science stand at the crossroads.
   Still some decades to go for fusion energy …..
   Discoveries in the universe…..

2. Knowledge of plasmas in extreme state is explosive, and must be developed into understanding.

3. This area of research leads the human understanding of the nature and accelerates fusion energy research.
   Heating directly influences plasma transport.

4. New programme 'Extremely non-Equilibrium Plasmas' will create the future, because scientists grow up by success.

Thanks to organizers for problem definition: '*creating future*'.