Magnetic Self-Organization in Multi-Scale Astrophysical Plasmas

or, How Macro-Scales Adapt to Accommodate Micro-Scale Constraints

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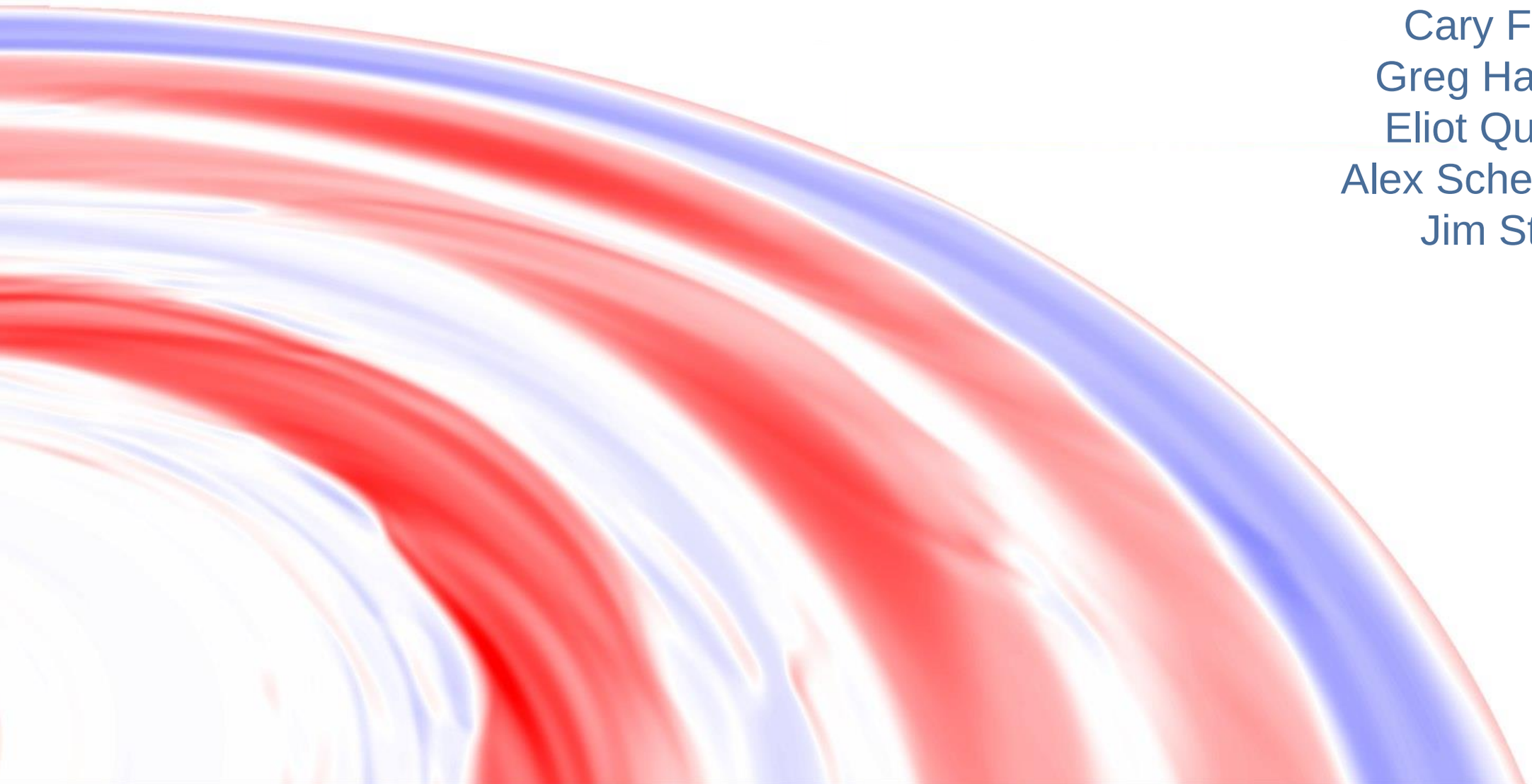


Outline

- I'll show some recent results concerning plasmas with which you may not be familiar that demonstrate two important points:
  (1) Micro-scale physics can play a fundamental role in dictating what macro-scale dynamics is allowed in a given system;
  (2) There are big gains to be had in the field of astrophysics by those who know plasma physics (and can appreciate gravity).

- Taking these examples as cues and, in so doing, moving beyond a single-fluid MHD description defines a frontier in the study of astrophysical fluid dynamics: how do we describe the evolution and properties of multi-scale high-beta plasmas?

- This requires concerted efforts in and sustained funding of:
  (1) Code development, particularly kinetic or reduced-kinetic;
  (2) National supercomputing support for availability of mid-level allocations;
  (3) Intermediate-scale laboratory experiments in basic plasma (astro)physics.

- The most immediate and ambitious application of this programme is *DYNAMO*.

Astrophysical plasmas are subject to a wide range of instabilities, which generically lead to sustained turbulence.

This is because gravity has a way of setting up and maintaining free-energy gradients in the face of diffusive transport, whether molecular or turbulent.

In some situations, however, the plasma find a way to limit or even shut off its access to the source of free energy, usually by re-organizing its magnetic field in some clever way.

Here I offer just two illustrative examples…

consider a protoplanetary accretion disk

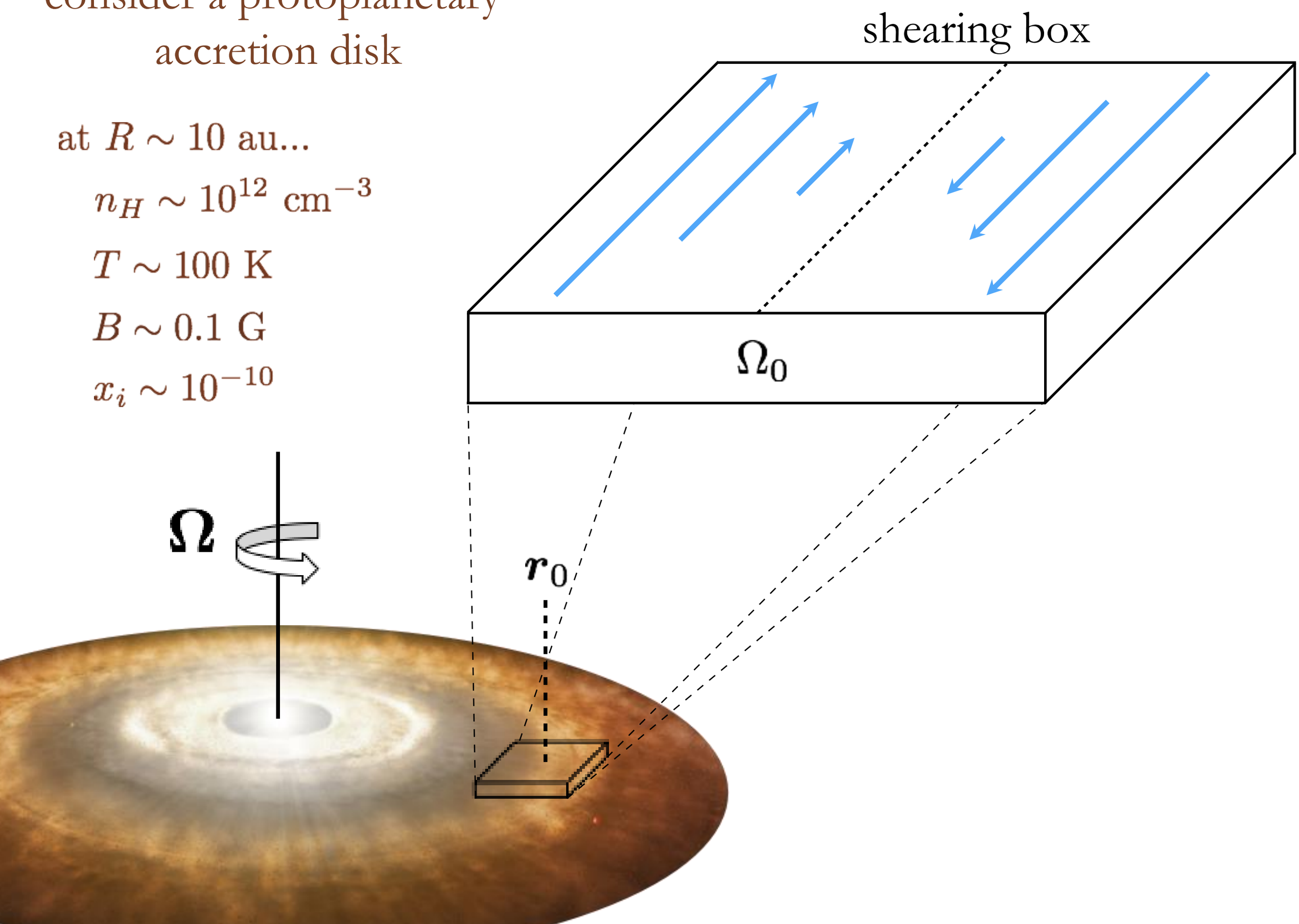
at $R \sim 10$ au...

$n_H \sim 10^{12}$ cm^{-3}

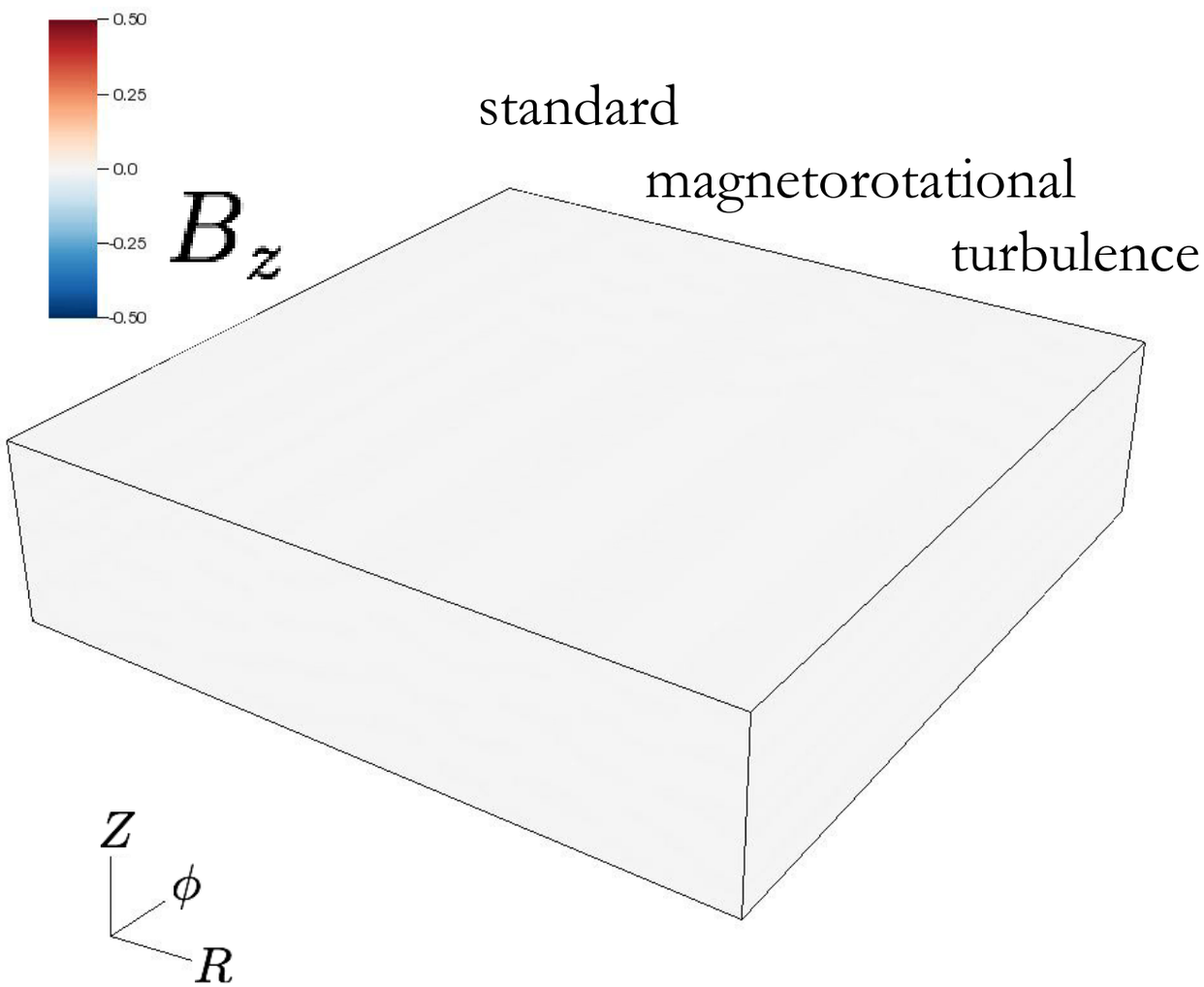
$T \sim 100$ K

$B \sim 0.1$ G

$x_i \sim 10^{-10}$



what happens if you
evolve this patch of the disk
using (inapplicable) standard MHD:



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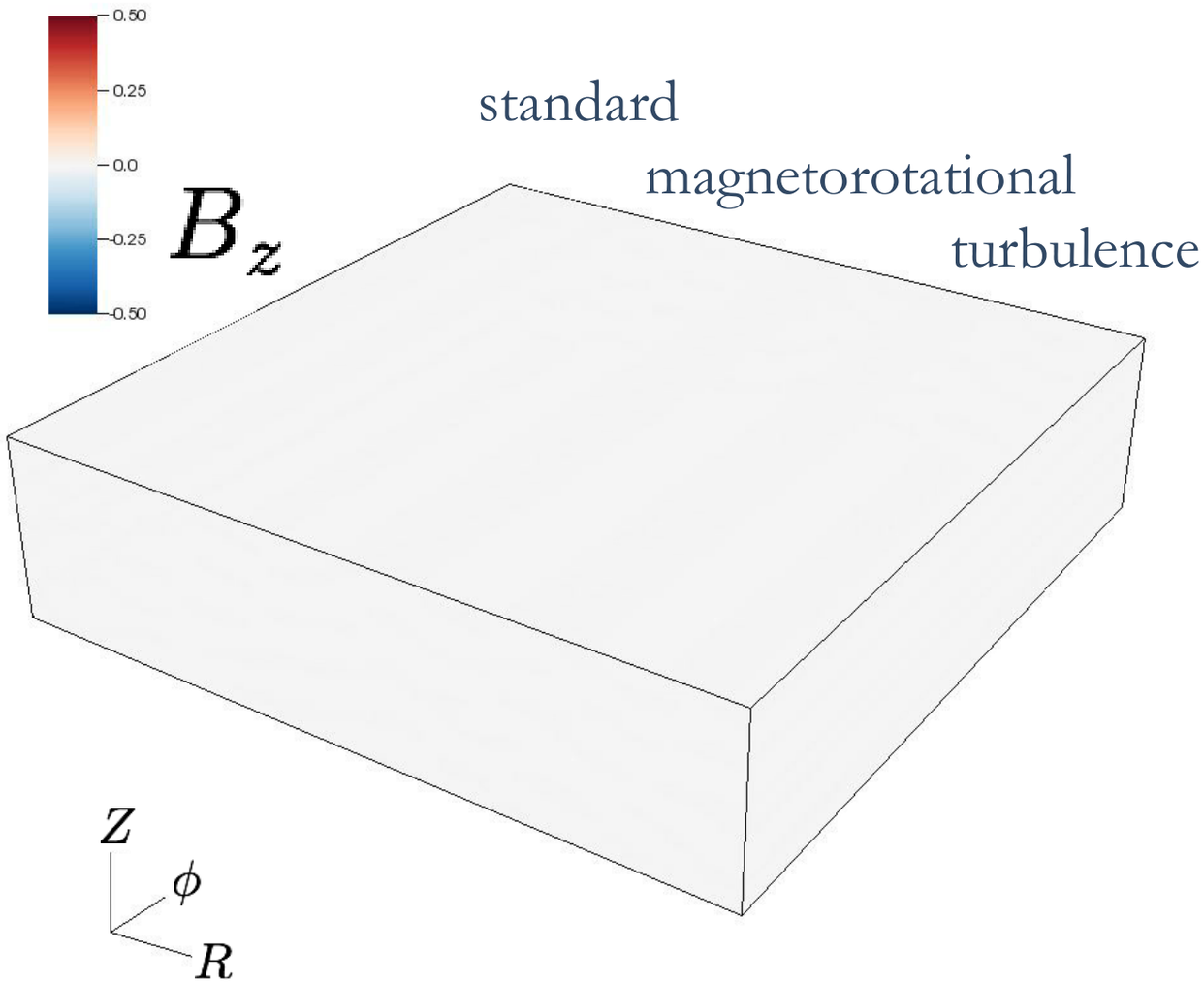
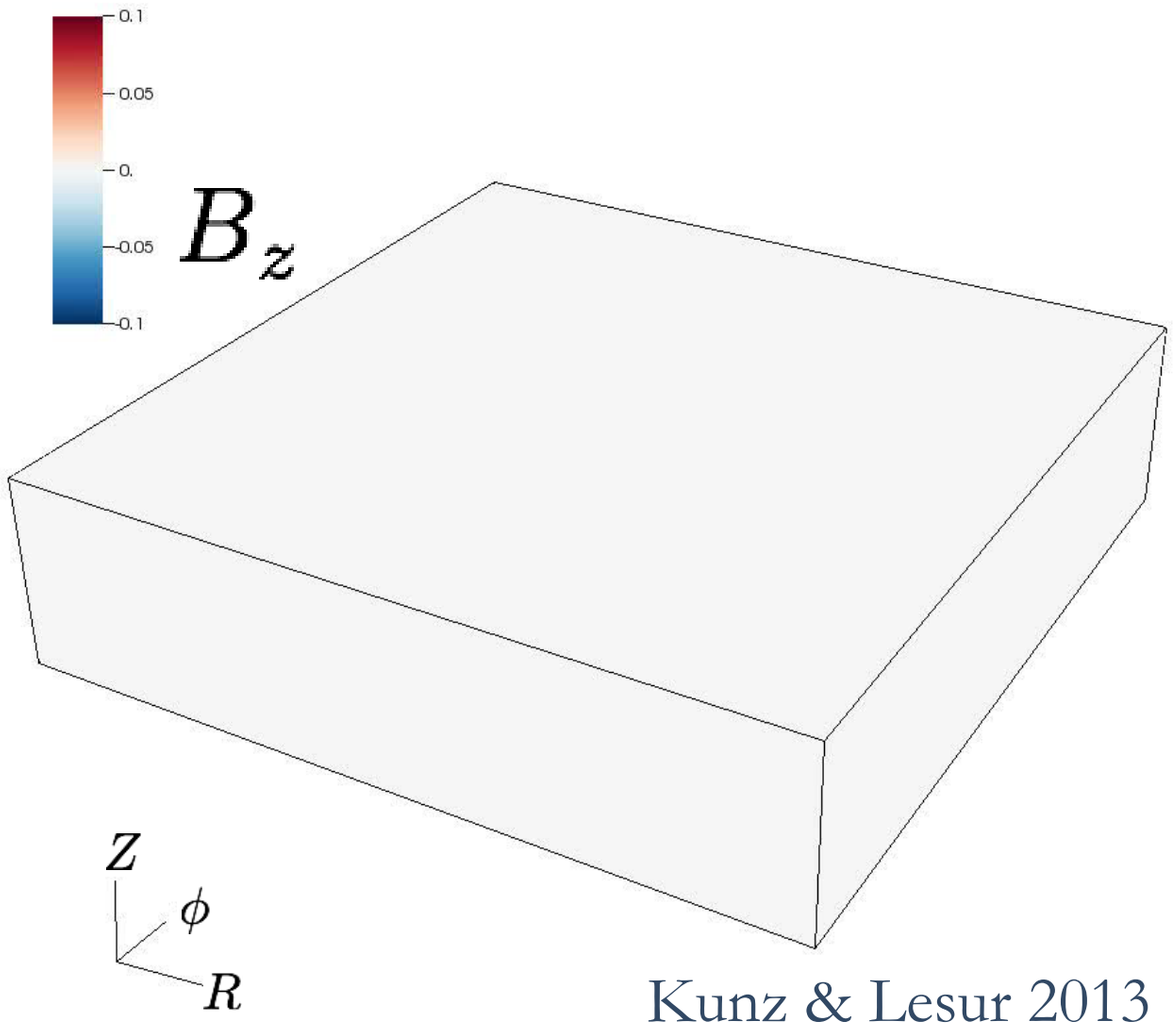


what happens if you
evolve this patch of the disk
using (applicable) Hall-MHD:



Kunz & Lesur 2013

Hall effect (a non-ideal MHD effect) leads to very different saturation:

magnetic self-organization

and greatly reduced angular-momentum transport

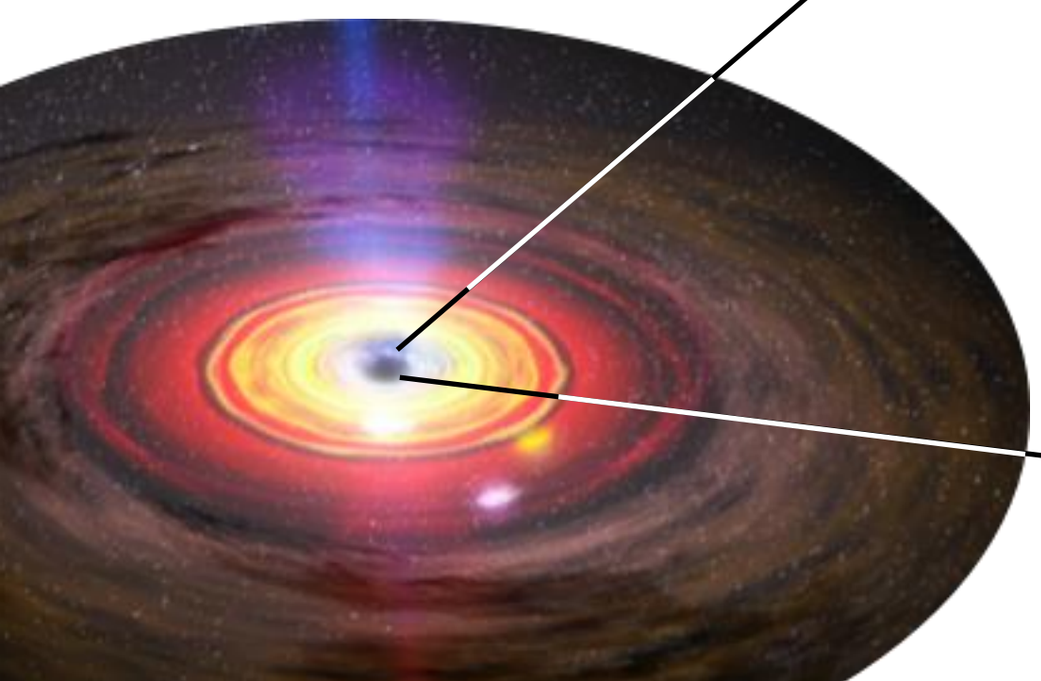
consider a black-hole accretion flow

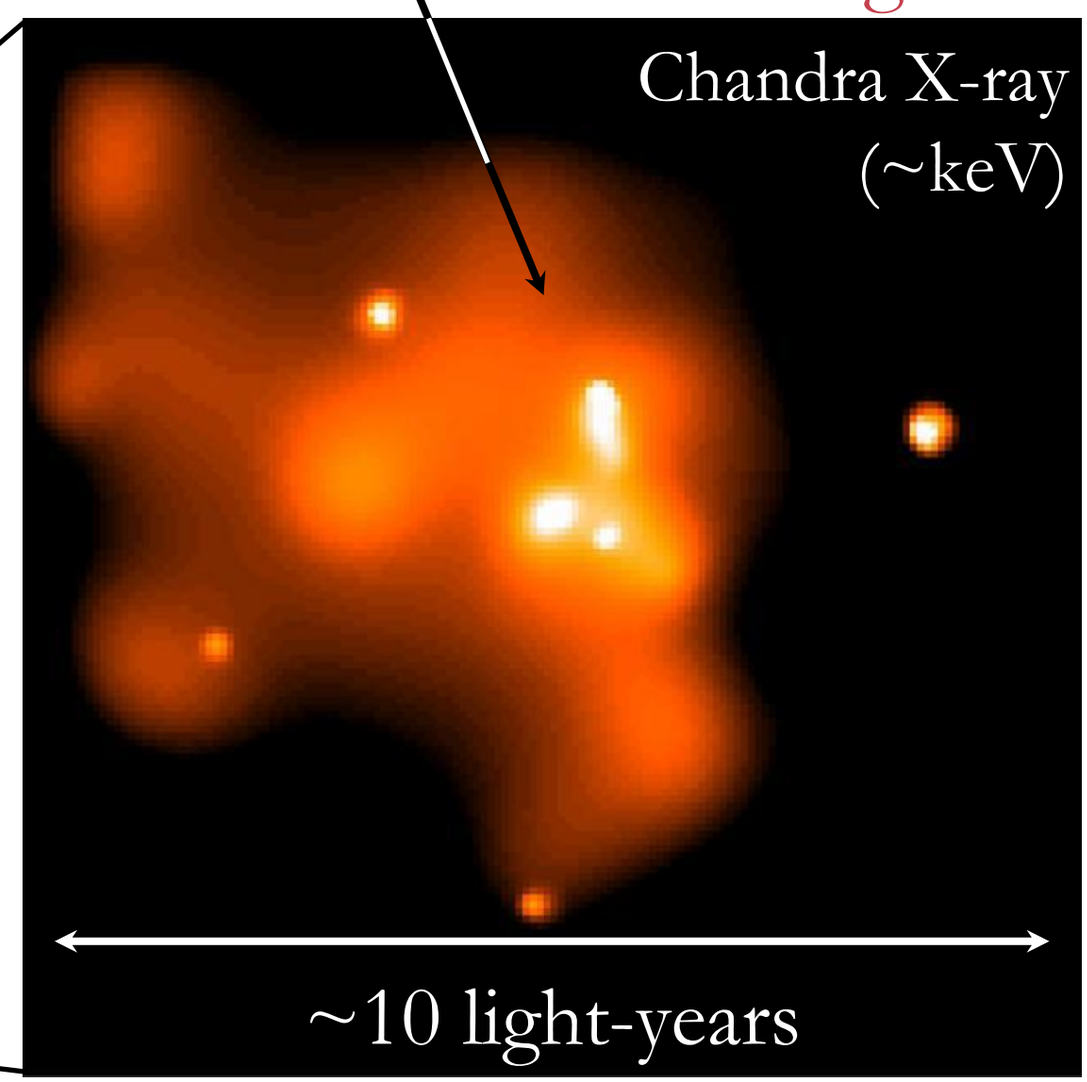
at $R \sim 0.1$ pc...

$n \sim 100\ \mathrm{cm}^{-3}$ $\lambda_{\mathrm{mfp}} \sim 0.01$ pc

$k_B T \sim 2$ keV $\rho_i \sim 1$ ppc

$B \sim 1$ mG $\Omega_i \sim 10\ \mathrm{s}^{-1}$





Baganoff *et al.* 2003

This is unstable to **kinetic** version of the **magnetorotational instability**
(Quataert, Dorland & Hammett 2002),
which generates **Maxwell stress** and **pressure anisotropy**.

stress responsible for requisite angular-momentum transport:
(Sharma *et al.* 2006, 2007)

$$T_{R\phi} \approx -\delta B_r \delta B_\phi \underbrace{\left(1 + \frac{p_\perp - p_\parallel}{B^2}\right)}_{\text{this factor is regulated by micro-scale plasma instabilities (between 0 and ~2)}}$$

Notable example of:

- direct connection between **plasma micro-physics** and **macro-scale dynamics**
- **magnetic self-organization** in weakly collisional plasma (e.g. Kunz *et al.* 2014a,b)
  (1) plasma produces magnetic fluctuations at gyro-scales, leading to wave-particle interactions that work to "scatter" the distribution function back to a stable configuration; and/or
  (2) magnetic field reorganizes itself so as to minimize the production of velocity-space anisotropy.

Despite their widely different characteristics, such astrophysical systems have one essential thing in common — they are *multi-scale plasmas, whose micro-scale properties dictate what kind of macro-scale dynamics is allowed.*

The frontier of plasma astrophysics is to treat them as such.

The problem the community faces…

It has historically been the case in the study of astrophysical fluid dynamics that, with a few notable exceptions, physical insight and analytical calculations precede numerical simulations.

This is understandable. Developing suitable, stable, and accurate numerical integration algorithms and finding large supercomputing facilities on which to run them tends to be more time-consuming and much more expensive than any pencil-and-paper calculation.

But this is no longer true when the only known set of equations guaranteed to accurately describe many astrophysical plasmas (and some processes, like plasma dynamo) is the Vlasov-Maxwell set.

Suitable reductions and/or closure models do not yet exist that simultaneously address the range of physical processes occurring below, at, and above kinetic scales. Analytical progress has been stifled…

Recommendations:

1. Code development

This physics must be explored from first principles using numerical techniques, in order to guide analytic reductions/closures. This is actually ongoing as we speak. What we're recommending to accelerate progress is:

- **Flexible code architecture**, enabling with ease:
  different physical treatments
  (e.g. kinetic ions and fluid, drift-kinetic, or gyrokinetic electrons; MHD fluid + kinetic energetic species; two-fluid MHD…)
  different geometries and boundary conditions
  (same code for Couette flow and spherical geometry as for slabs and shearing boxes)

- **Public availability** of codes: lots of duplication right now … very inefficient!

- **Optimization** of codes: national supercomputers have already made investments in co-processors to speed up computations intensive in floating-point operations (e.g. PIC codes) — should be leveraged!!!

Recommendations:

2. Supercomputing facilities

Current annual allocations on most national machines (e.g. those facilitated by NASA and NSF-funded XSEDE) are measured in millions of CPU-hours.

The exception is NASA's INCITE program, for which typical allocations are ~100M CPU-hours.

What is notably absent from the domestic program are **mid-level allocations** (~20-50M CPU-hours, like PRACE). Current ~1M CPU-hour allocations may be enough for routine fluid simulations, but not for kinetic plasma ones.

Recommendations:

3. Intermediate-Scale Laboratory Experiments

Experimental insight into basic plasma physics relevant to astrophysical systems is badly needed. There is no substitute for being able to create a plasma in a lab, subject it to stirring, differential rotation, magnetic fields, and measure its response.

Laboratory plasma experiments in poorly ionized plasmas or weakly collisional (i.e. ion Larmor radius < machine size) plasmas with ß > 1 would be particularly useful. (Think *flow*-dominated experiments.)

Universities are a natural venue for these sorts of experiments, which are larger than a typical single-PI experiment but do not require a major national facility. But this means that a program for continued funding operations of these facilities should be instituted, with accompanying university training of students borne in mind.

Recommendations:

3. Intermediate-Scale Laboratory Experiments

In my opinion, funding of laboratory (astro)plasmas is sorely lagging behind funding of plasma-relevant astronomy observatories (LOFAR, JVLA, SKA, ALMA, NuStar, Fermi, etc.), solar observatories (SDO, DKIST, GONG, SOHO, etc.), and solar-wind spacecraft (MMS, SPP, Orbiter, etc.), many of which are well-supported by NASA and NSF (often in **collaboration** with many international partners and/or universities).

Specific Application at the Frontier of Plasma Astrophysics:
PLASMA DYNAMO

(see white paper by Forest, Gregori, Kunz, Li, Miesch, Nornberg, Sarff, Schekochihin, Uzdenski, Zweibel)

Facilities are needed that can:

(1) Produce **quasi-stationary, flow-dominated** ($v/v_A >> 1$) plasmas with **large magnetic Reynolds number**. Techniques are required to confine and heat large unmagnetized plasma and then control large-scale flow and small-scale turbulence. Assessing **Pm dependence** would be ideal.

(2) Produce **magnetized weakly collisional** plasma ($\rho_i \ll L,\ \nu_{ii} \ll \Omega_i,\ \beta \geq 1$) and study the role on ion pressure anisotropy on magnetic-field generation.

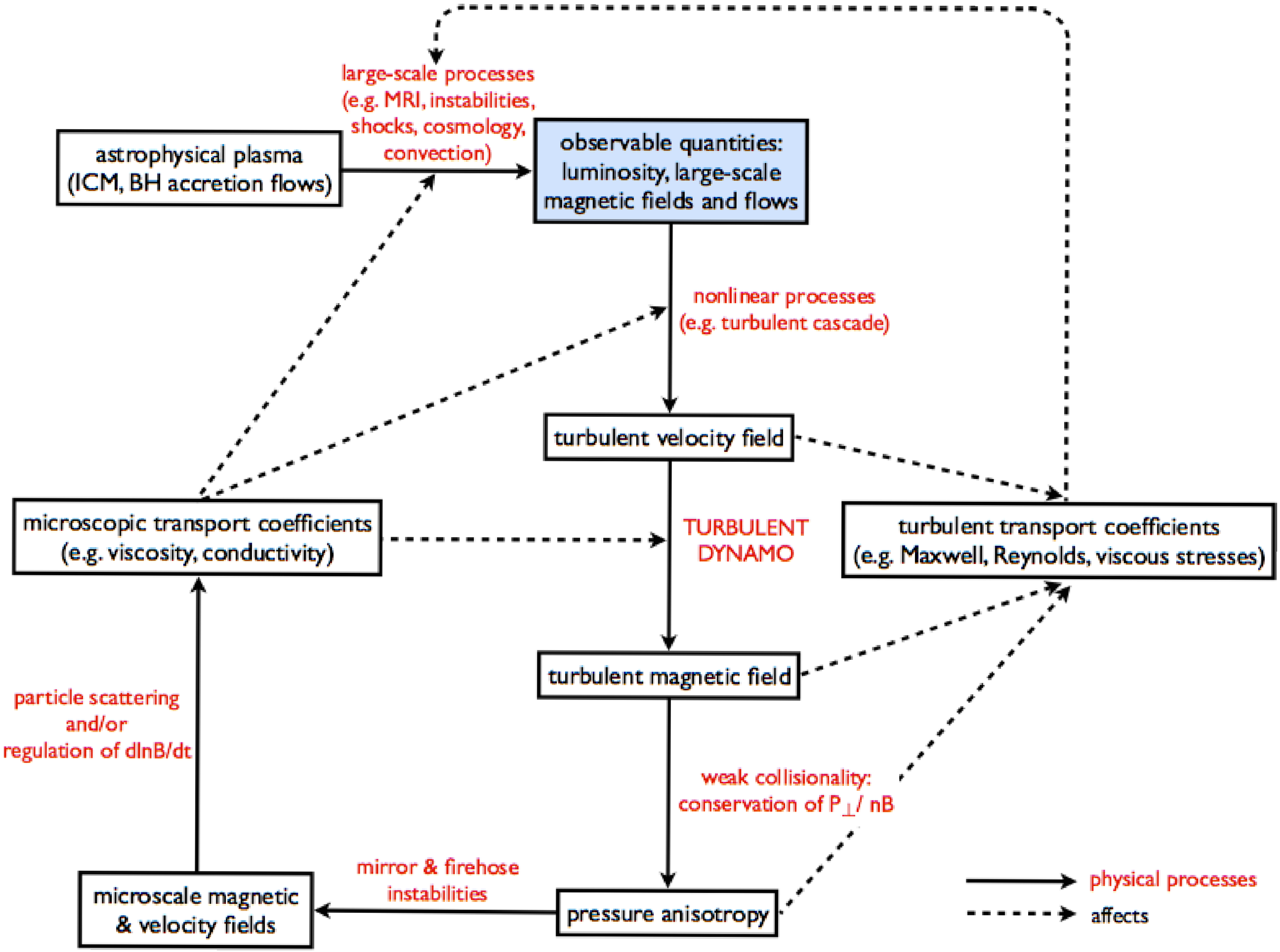
(3) Serve as a user facility, and thus be **flexible** and **accommodate diverse experiments**. The latter include:

(a) interface experiments between flow- and magnetically dominated plasmas (e.g. flux ejection into background plasmas, jet/wind launching and collimation)

(b) reconnection experiments in high-ß collisionless plasmas

(c) experiments exhibiting velocity-space instabilities (e.g. firehose, mirror)

(d) experiments with poorly ionized plasmas (e.g. Hall, ion-neutral drift)

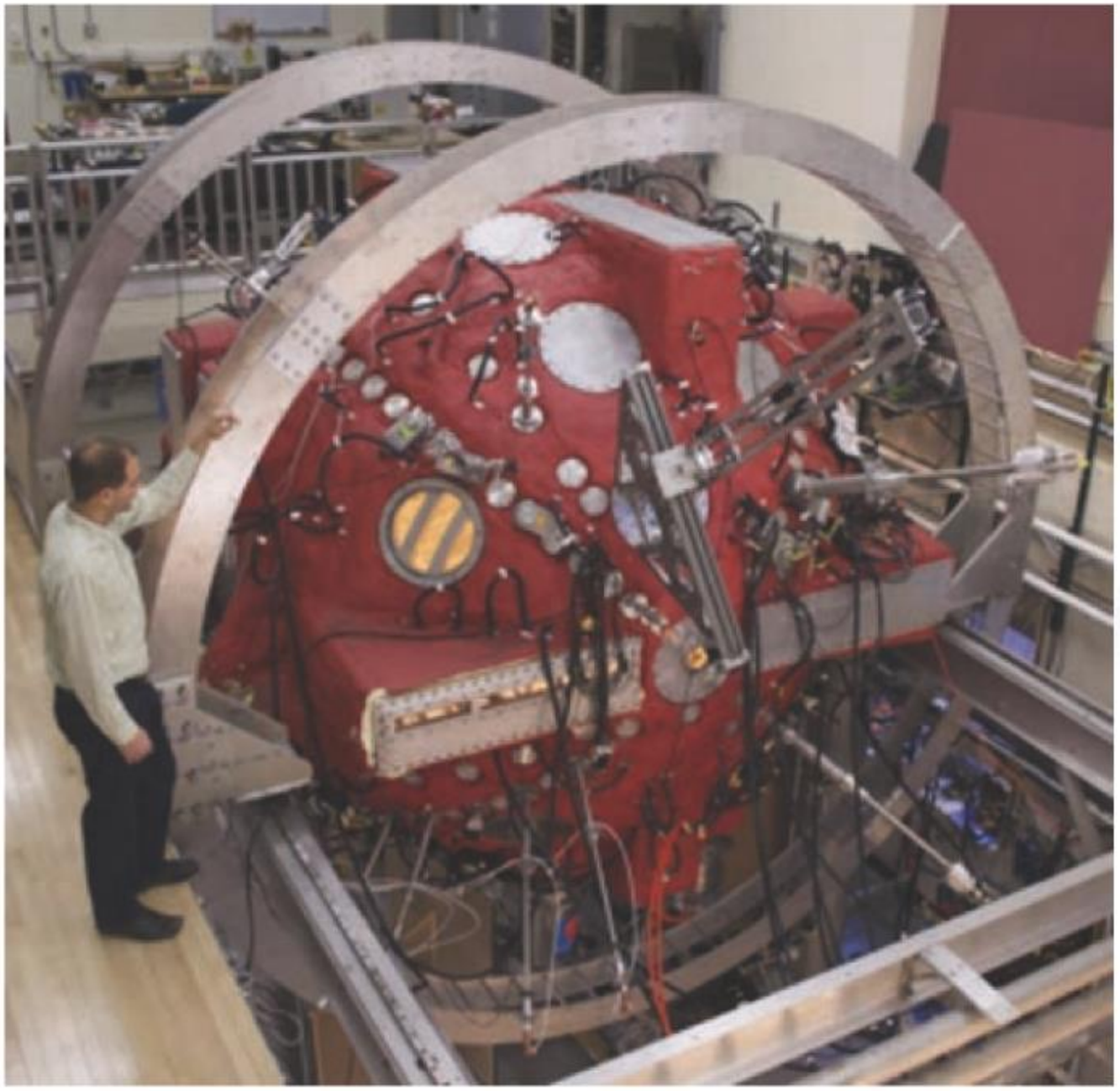

large-scale processes
(e.g. MRI, instabilities,
shocks, cosmology,
convection)
astrophysical plasma
(ICM, BH accretion flows)
observable quantities:
luminosity, large-scale
magnetic fields and flows
nonlinear processes
(e.g. turbulent cascade)
turbulent velocity field
microscopic transport coefficients
(e.g. viscosity, conductivity)
TURBULENT
DYNAMO
turbulent transport coefficients
(e.g. Maxwell, Reynolds, viscous stresses)
turbulent magnetic field
particle scattering
and/or
regulation of dlnB/dt
weak collisionality:
conservation of $P_\perp$ / nB
mirror & firehose
instabilities
microscale magnetic
& velocity fields
pressure anisotropy
physical processes
affects

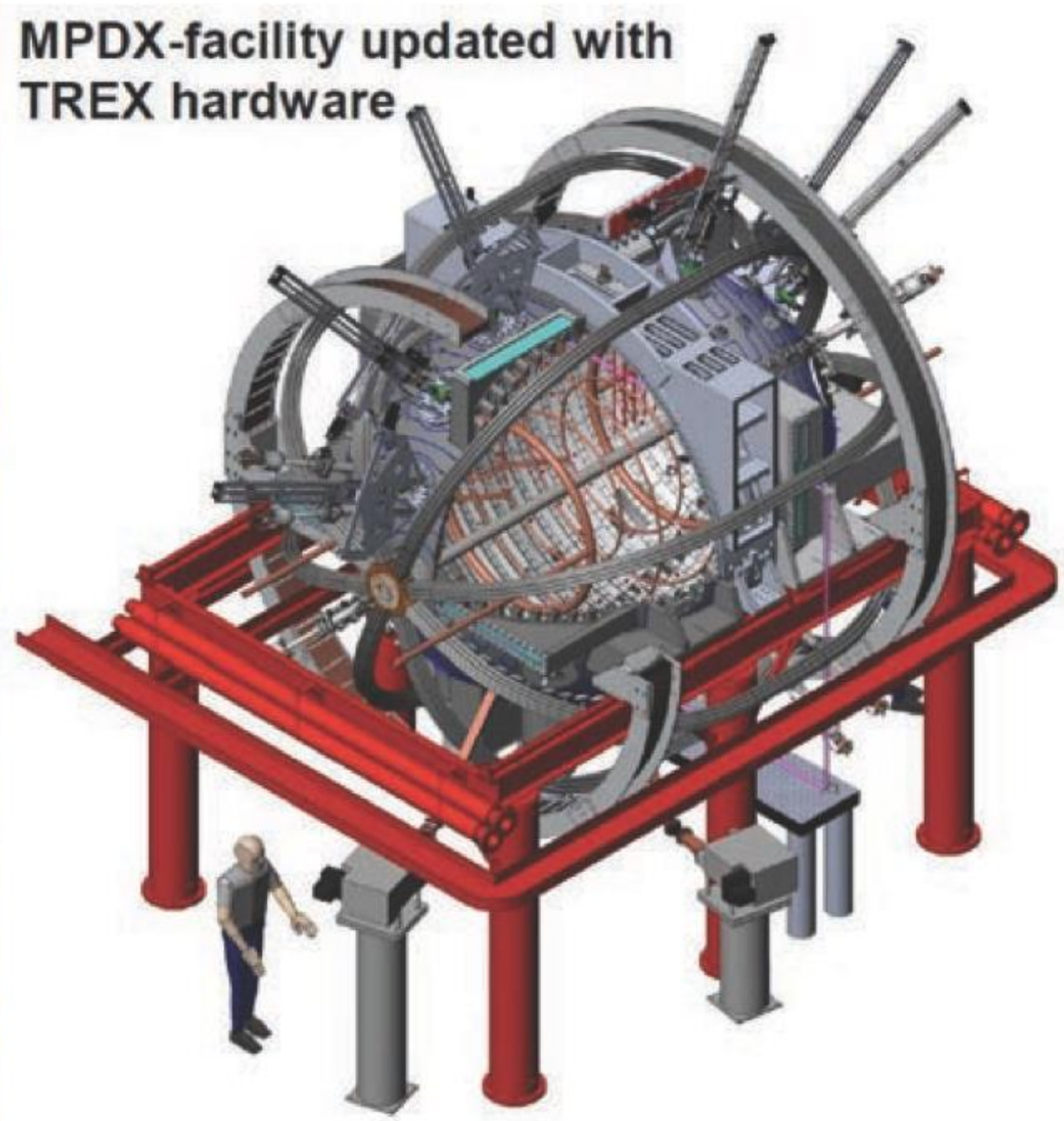
Summary

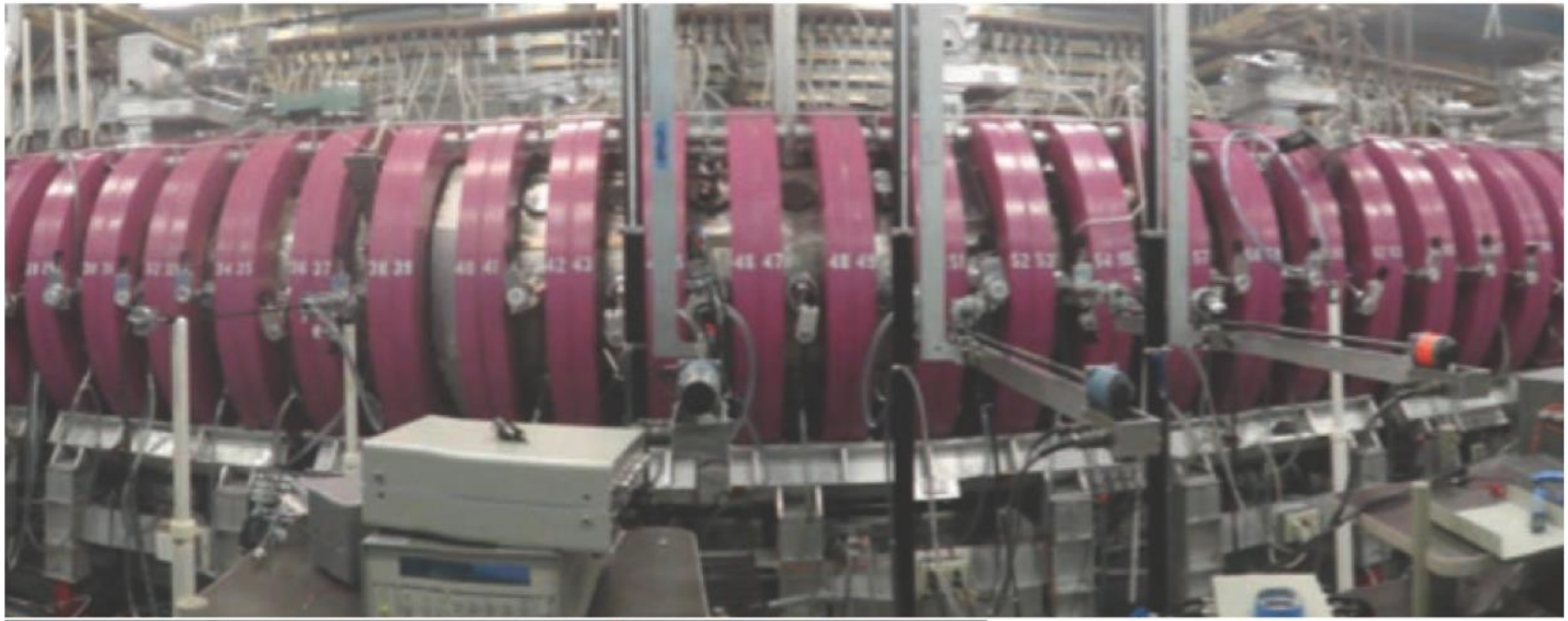
- Theoretical astrophysics needs plasma physics, both intellectually and financially. The same is true in reverse.

- Frontiers:
  (1) Effect of plasma micro-physics on macro-scale evolution.
  (2) Material properties of high-ß weakly collisional plasmas.
  (3) Plasma dynamo, *ab initio* on the computer and in the laboratory.

- This requires concerted efforts in and sustained funding of:
  (1) Code development, particularly kinetic or reduced-kinetic;
  (2) National supercomputing support for mid-level allocations;
  (3) Intermediate-scale experiments in basic plasma (astro)physics.

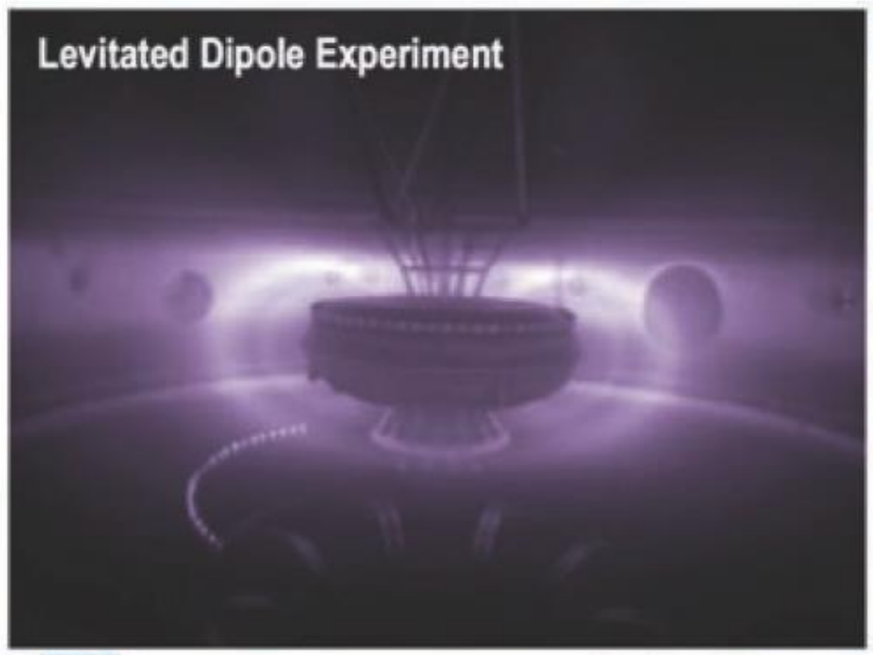



MPDX-facility updated with
TREX hardware



(top panel) Large Area Plasma Device (LAPD)

(left panel) Enormous Toroidal Plasma Device (ETPD)



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