Fun With Plasma Turbulence, From Fusion Energy to Black Holes

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Miller Institute Lunch 10/19/2004

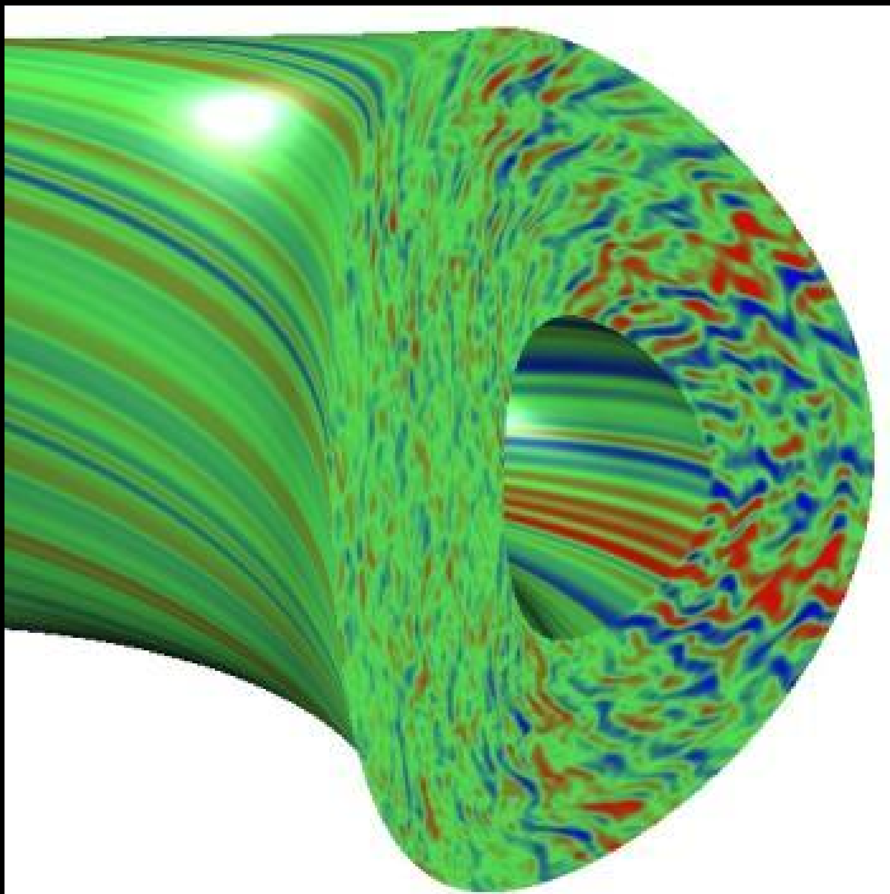
Collab.: Prof. Eliot Quataert, Berkeley Astro. Dept.
Prateek Sharma, Prof. J. Stone, Princeton

Thanks to Prof. Jon Arons and the Miller Institute for a wonderful time at Berkeley!

Fun With Plasma Turbulence, From Fusion Energy to Black Holes

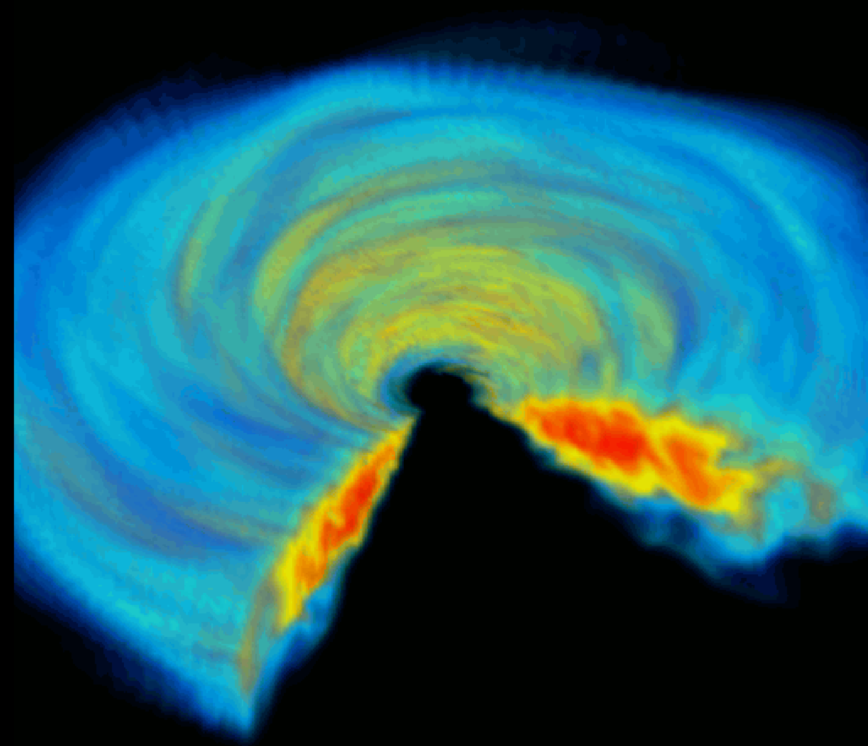
- If there is a unifying theme: beauty & fascination of complex turbulent processes in plasmas on earth (for fusion energy research) & in astrophysics
- Summarize status of fusion energy research
- Cross-validation: statistical techniques useful in all sciences
- Plasma instability plays a key role in accretion disks near black holes (Balbus & Hawley 1991).
- Some tools developed in fusion energy research are useful for astrophysics & v.v.

Plasma Turbulence Occurs in Many Contexts



5-D gyrokinetic simulation of tokamak fusion device

(Candy & Waltz, 2003)

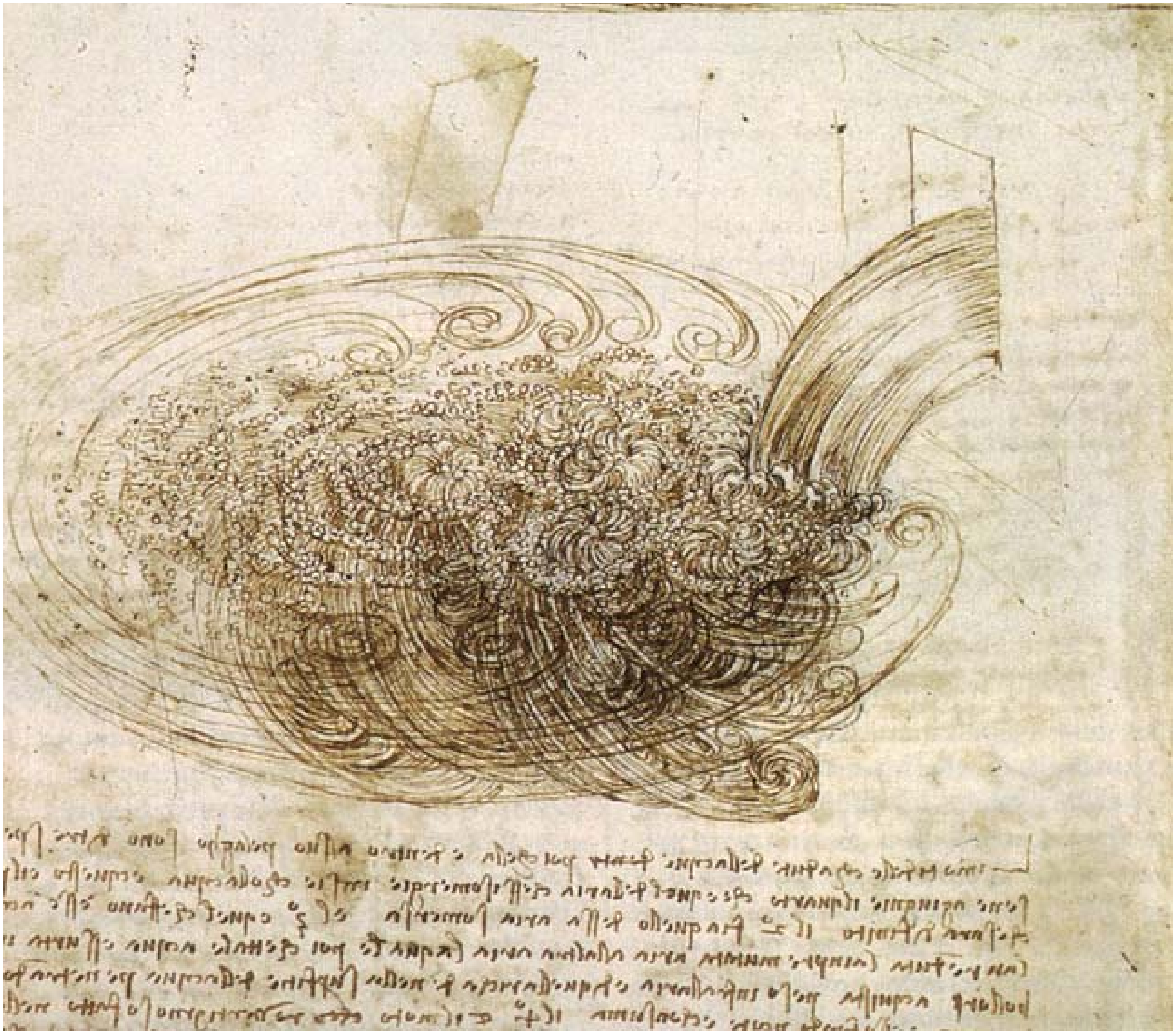


MHD simulation of accretion disk around a black hole

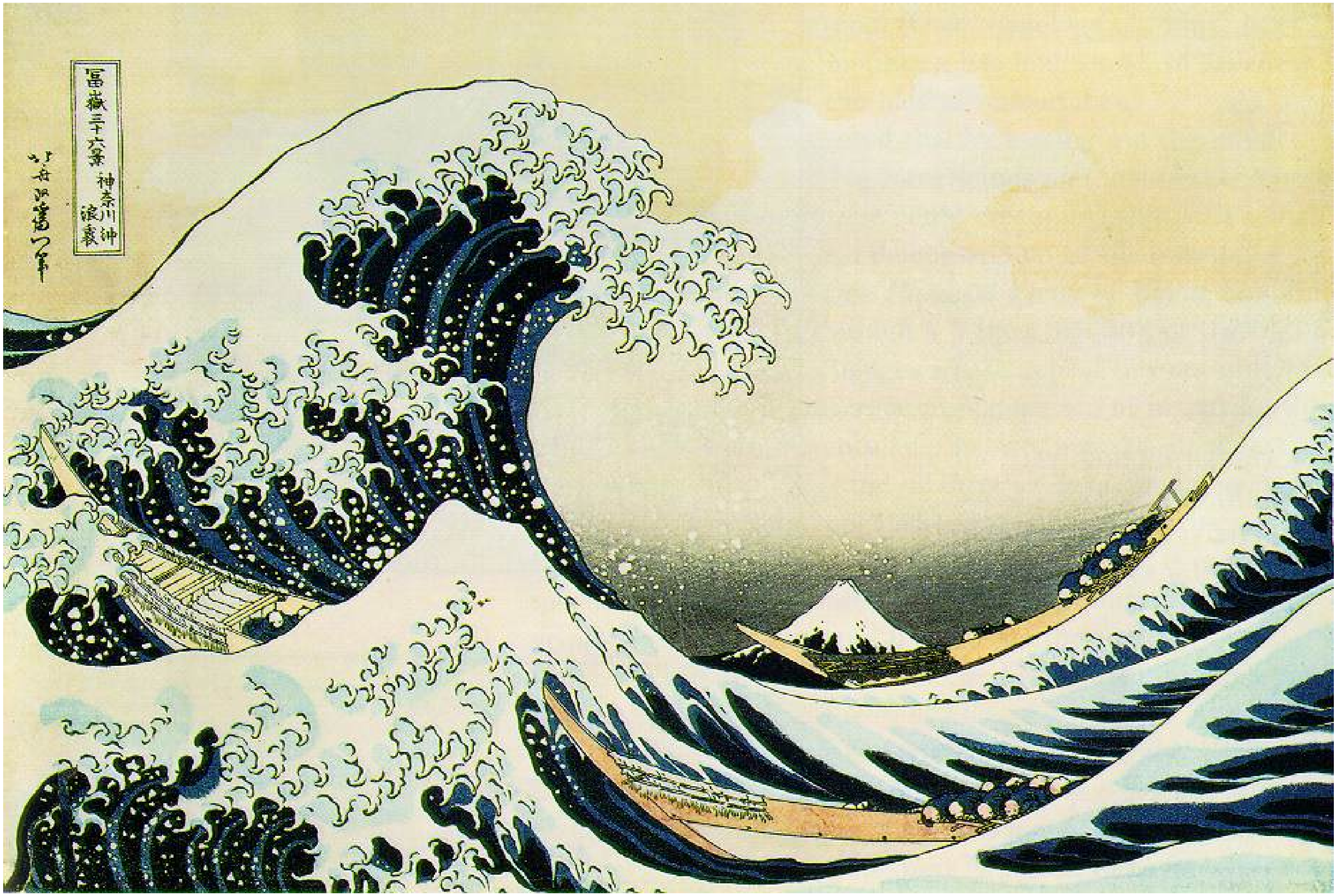
(Hawley, Balbus, & Stone 2001)

Artists & Scientists Study Nature

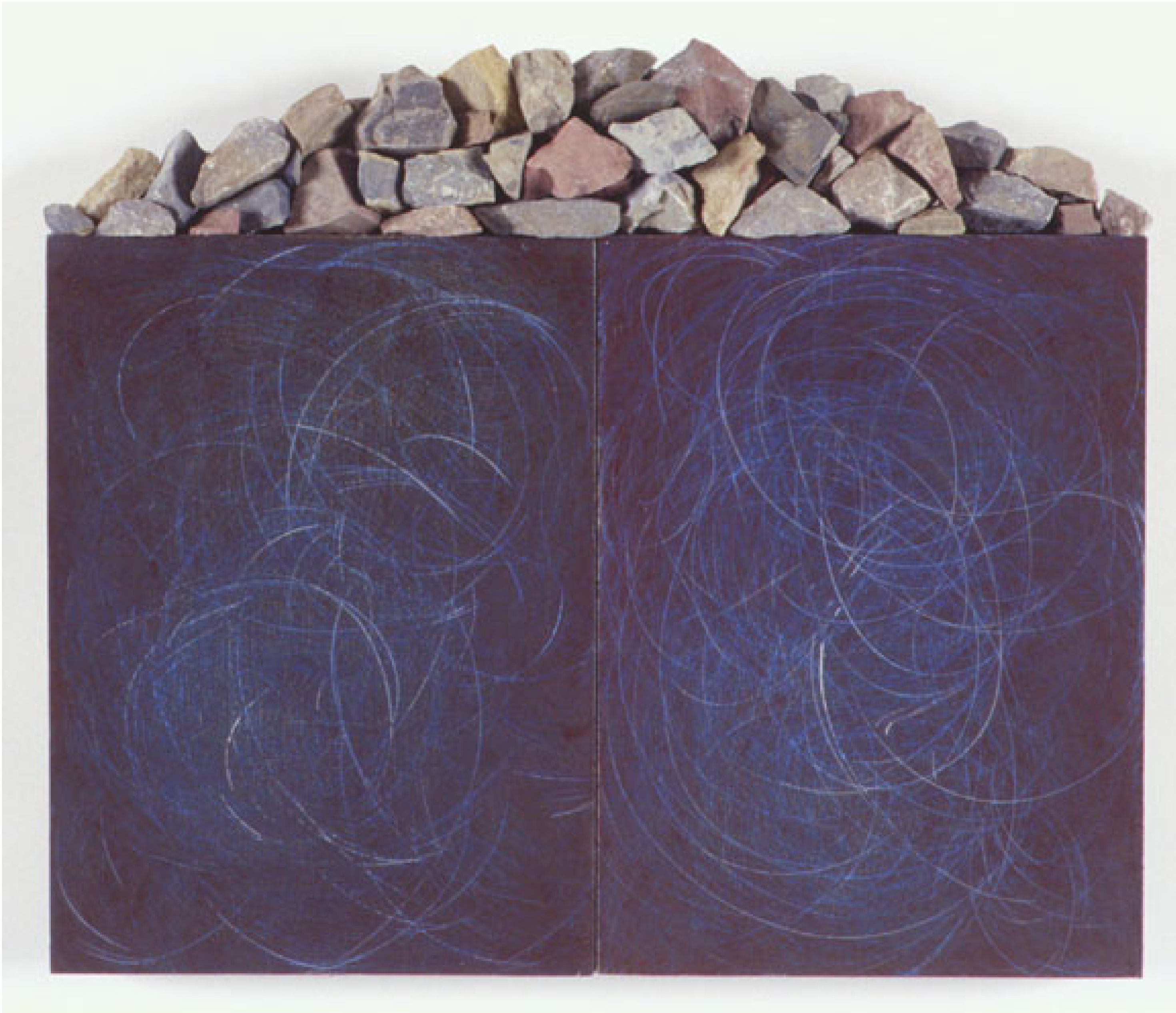
Leonardo da Vinci’s keen insights into turbulent water flow



Eddies of different scales in Leonardo da Vinci drawing



“The Great Wave” or “Mount Fuji Between the Waves”, Hokusai, 1830’s

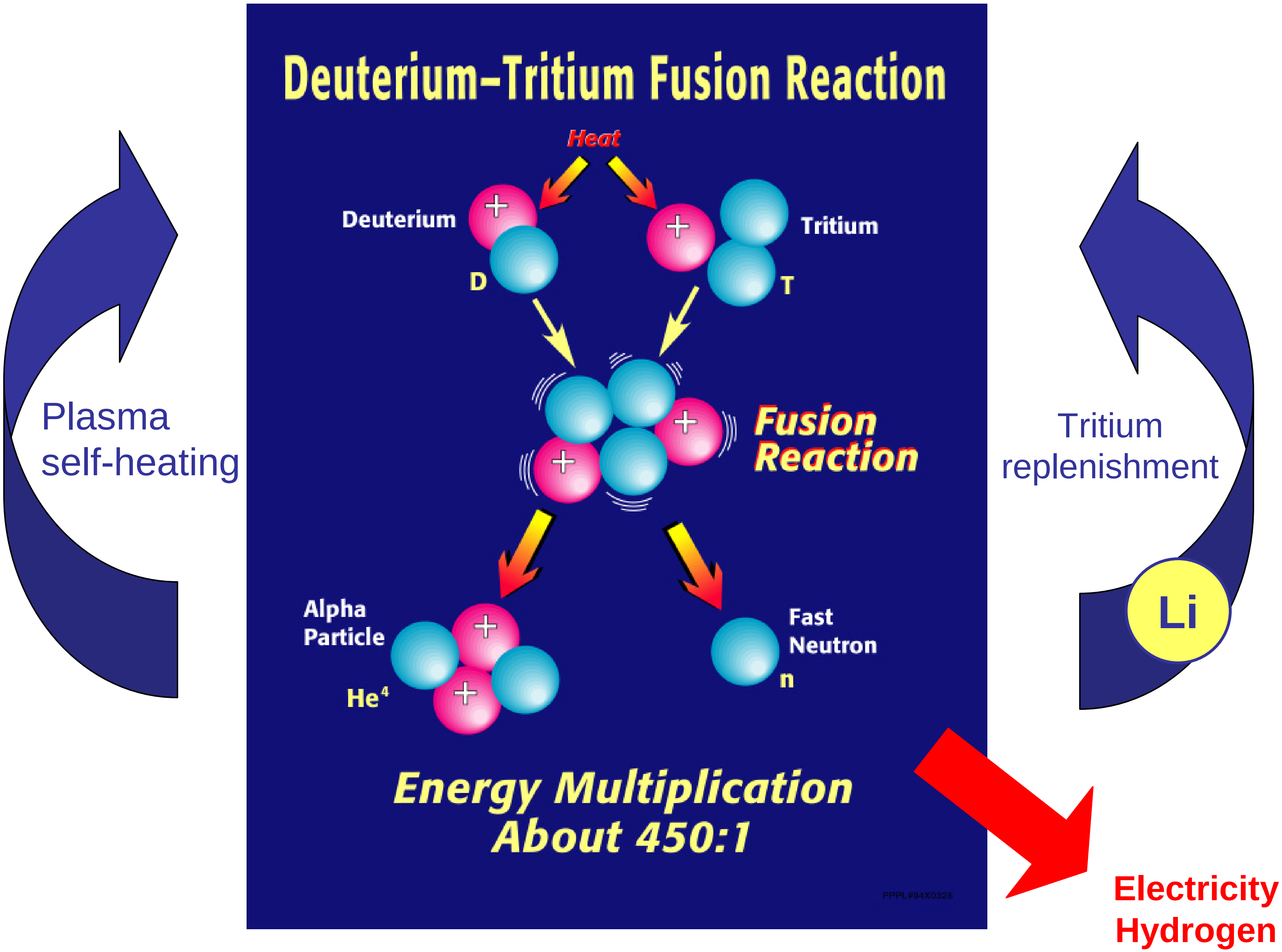


Nature inspires abstract art too. “Drilling it out” Kate Hammett (2003), www.khammett.com

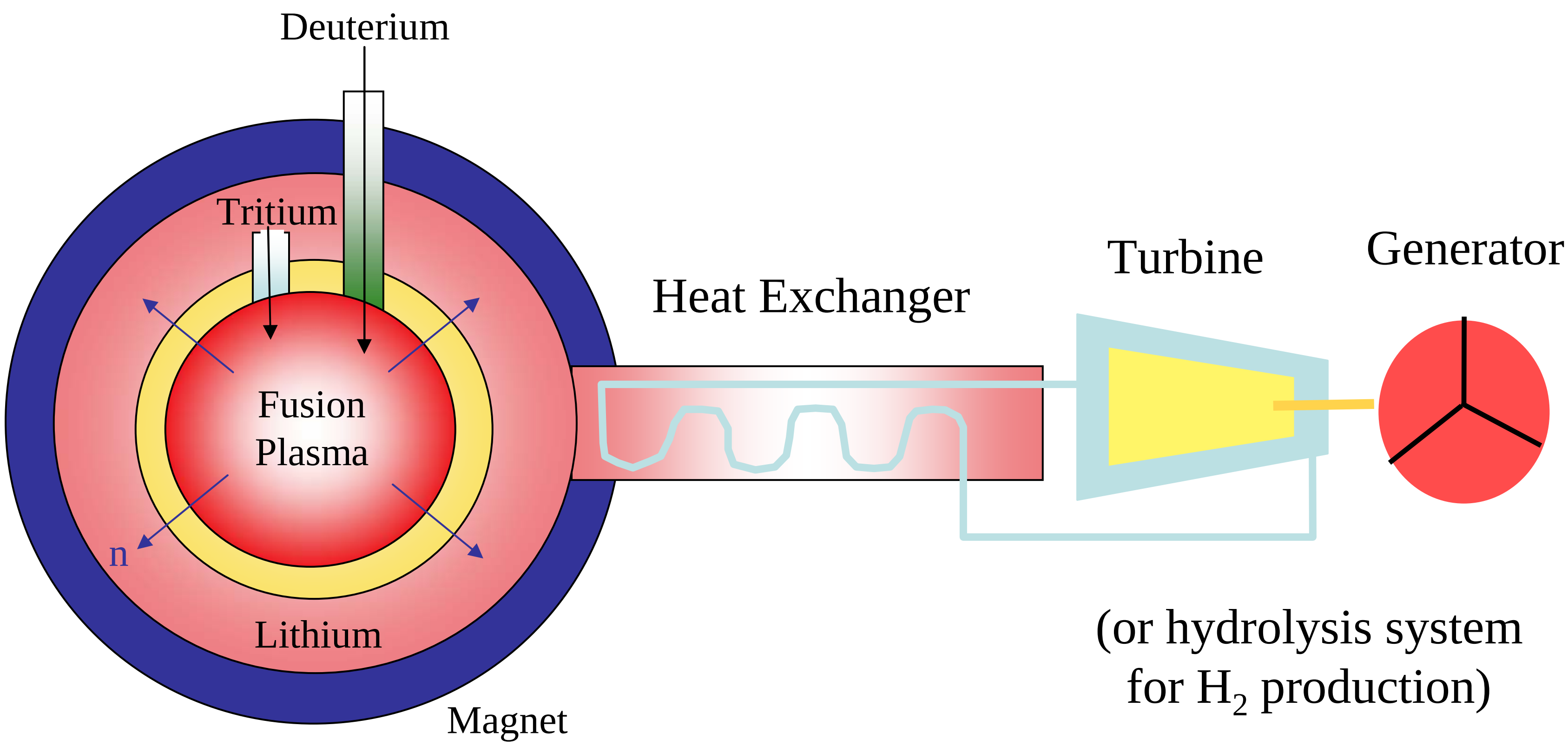
Turbulence

Big whorls have little whorls,
Which feed on their velocity;
And little whorls have lesser whorls,
And so on to viscosity.

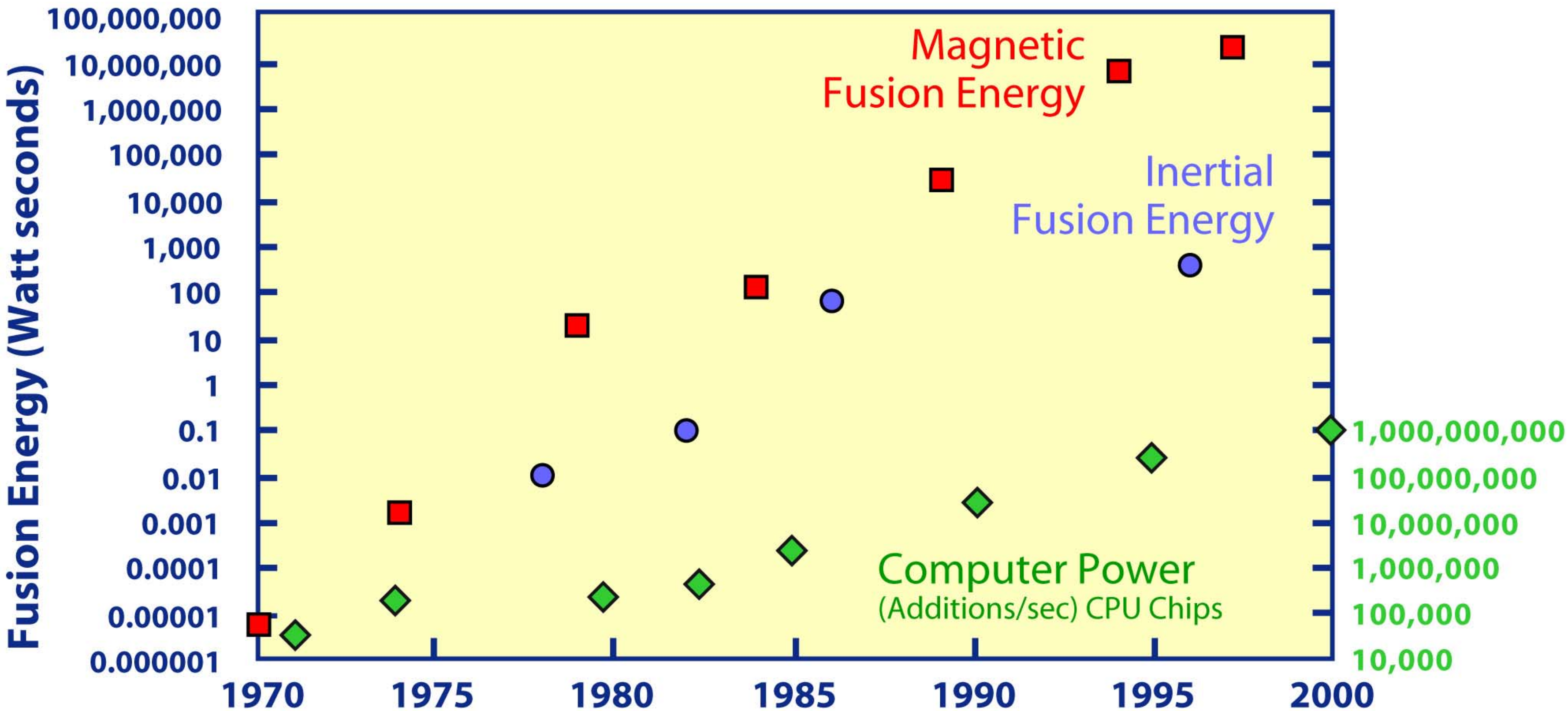
L. F. Richardson (1881-1953)


Deuterium–Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Alpha Particle
He4
Fast Neutron
n
Energy Multiplication About 450:1
Plasma self-heating
Tritium replenishment
Li
Electricity
Hydrogen

Magnetic Fusion Power System

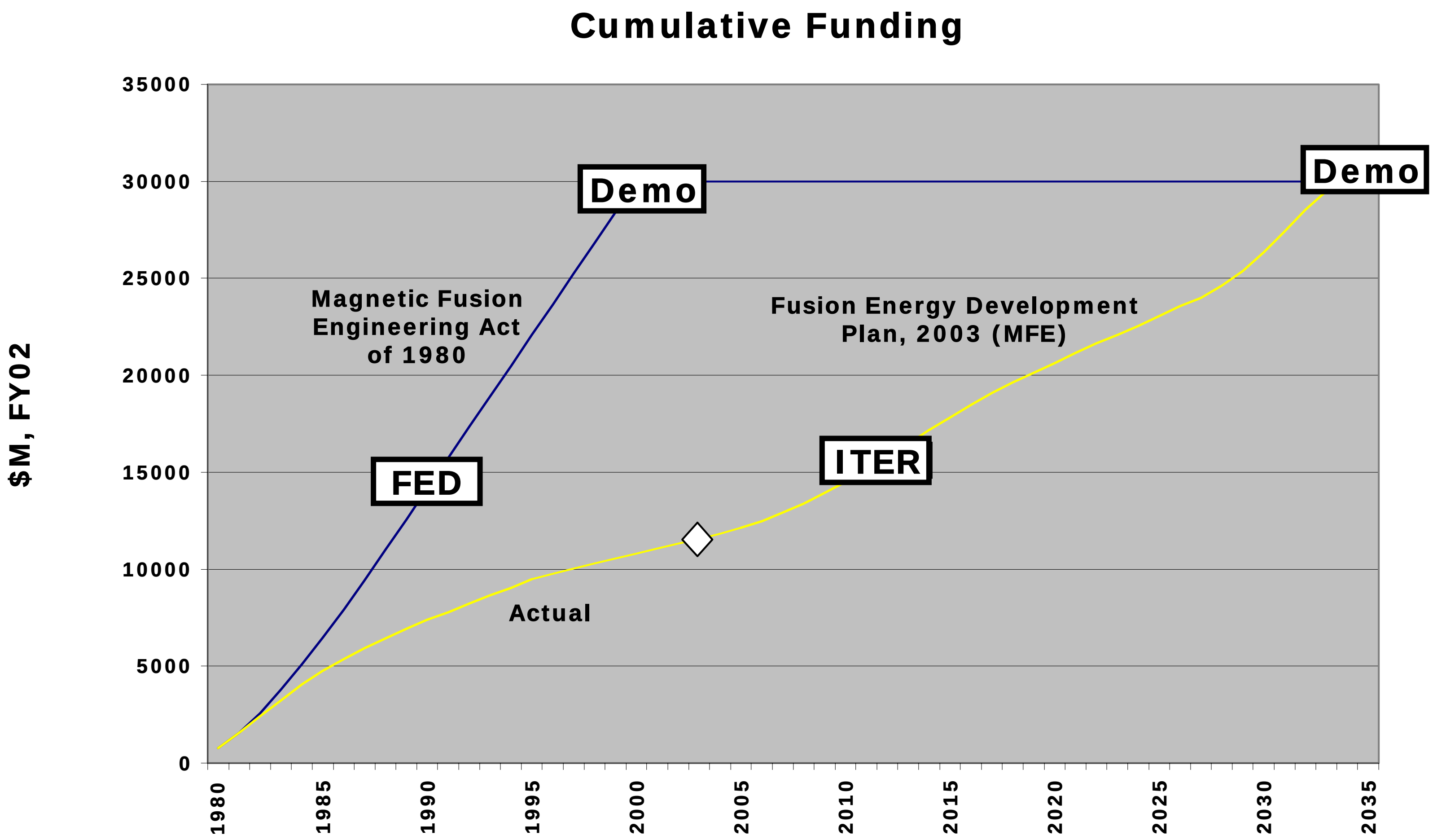


Progress in Fusion has Outpaced Computer Speed



Progress is paced by the construction of new facilities.

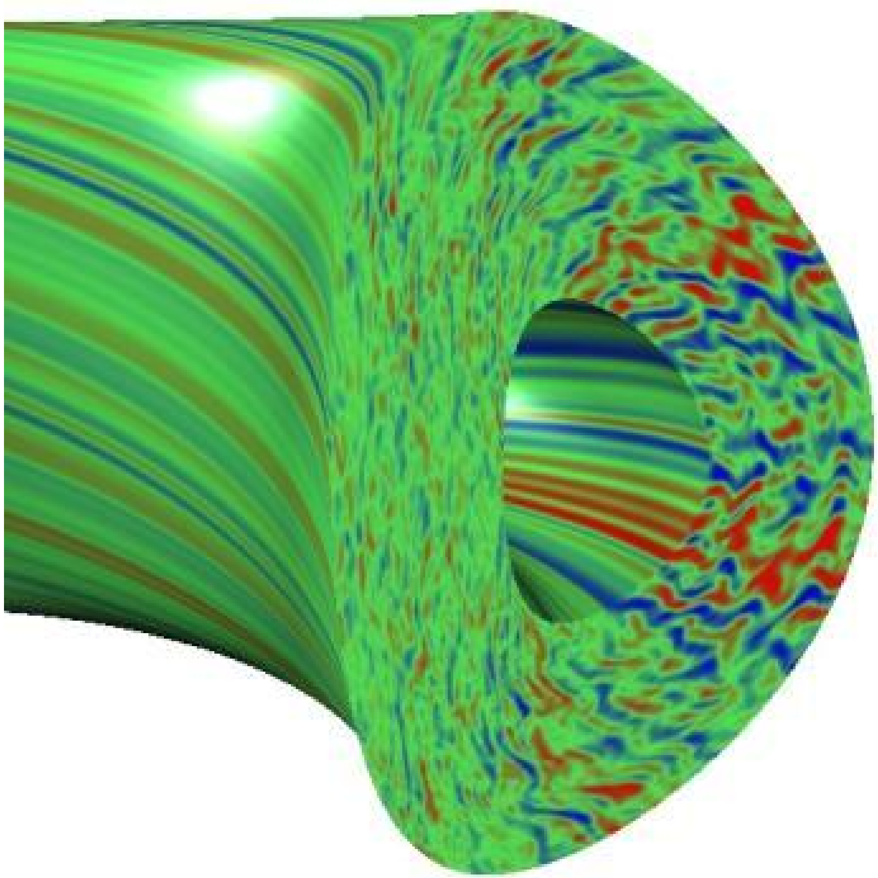
The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



On budget,
if not on time.

$30B development cost tiny compared to >$100 Trillion energy needs of 21st century and potential costs of global warming. Still 40:1 payoff after discounting 50+ years.

Understanding Turbulence That Affects the Performance of Fusion Device



(Candy & Waltz, GA 2003)

Central temp ~ 10 keV ~ 10^8 K

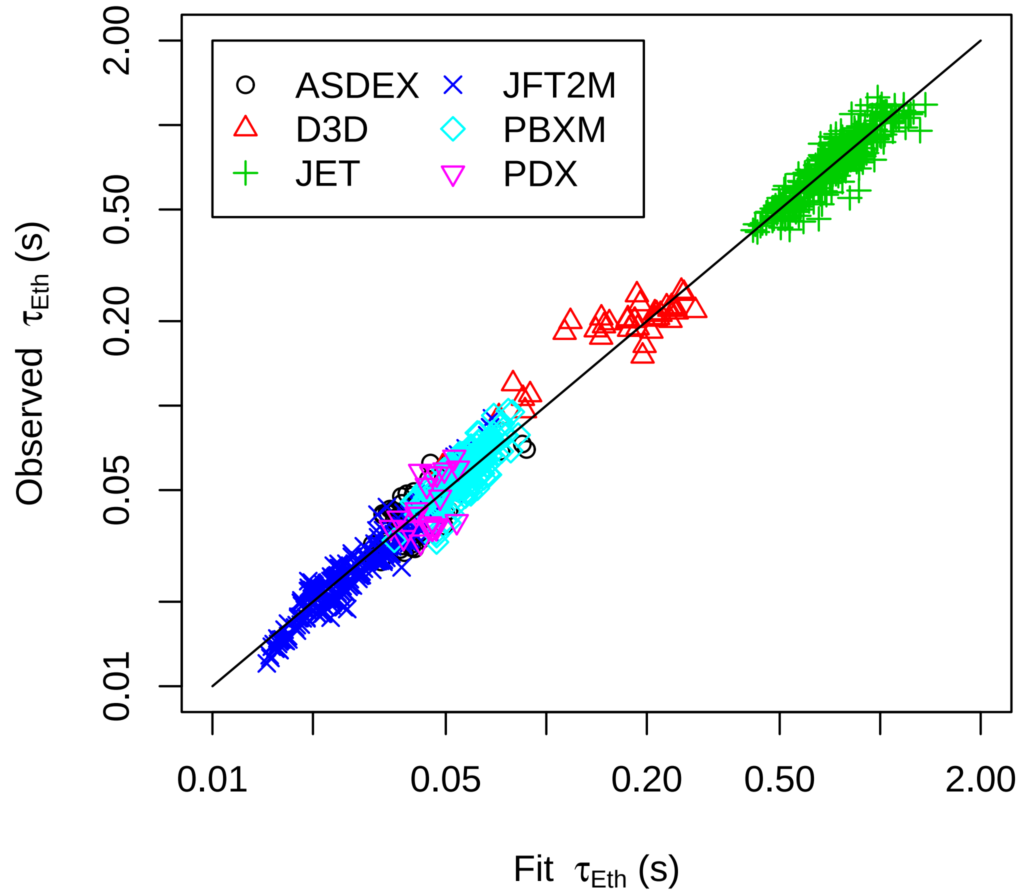
Large temperature gradient
$\rightarrow$ turbulent eddies
$\rightarrow$ cools plasmas
$\rightarrow$ determines plasma size needed for fusion ignition

Major progress in last decade:
detailed nonlinear simulations
(first 3-D fluid approximations,
then 5-D $f(\vec{x}, v_{||}, v_{\perp}, t)$)
& detailed understanding

Empirical Confinement Time Scaling Looks Good at First

If all measurements are independent (i.e. random uncorrelated errors), (and if model has correct functional form)

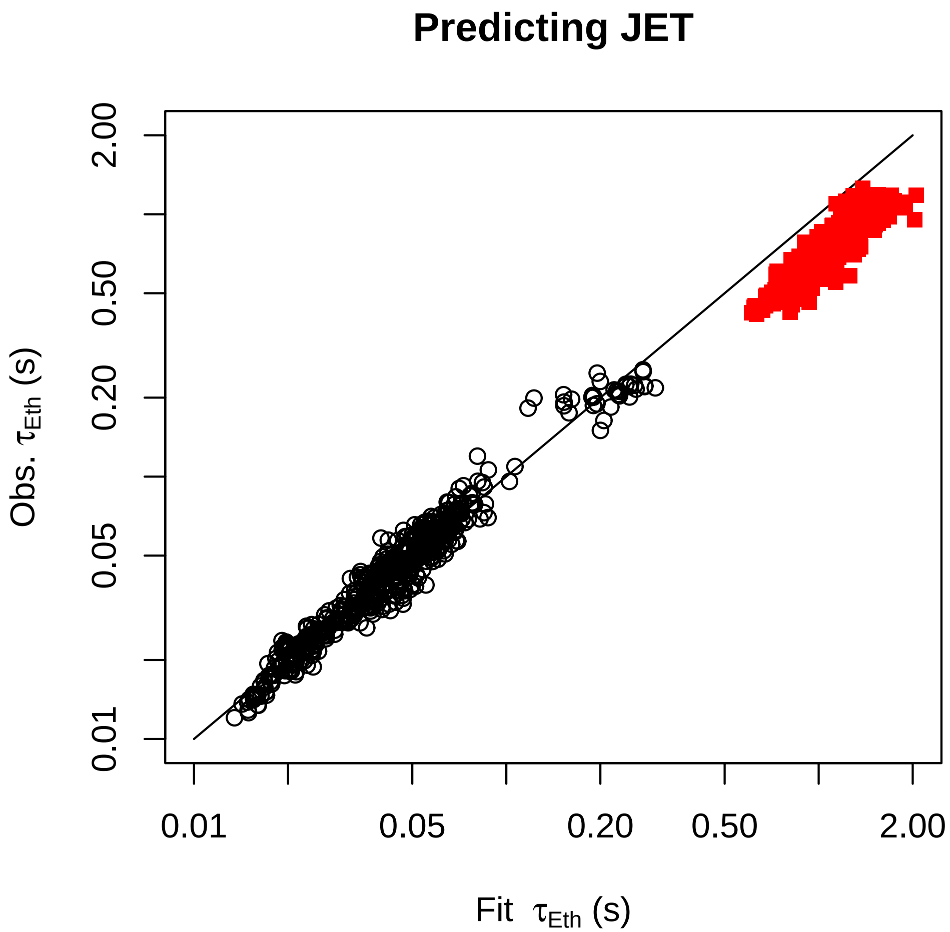
then error in fit ~ 1/sqrt(N) and there is a very small error in predicting performance of new machine



$$\tau_{E,93H} = e^{-3.35\pm0.071}\, I_p^{1.06\pm0.028}\, B_T^{0.33\pm0.038}\, P_{Lth}^{-0.68\pm0.014}$$
$$n_e^{0.17\pm0.022}\, R^{\pm1.80\pm0.062}\, (a/R)^{-0.11\pm0.041}\, \kappa^{0.65\pm0.051}\, M^{0.40\pm0.027}$$

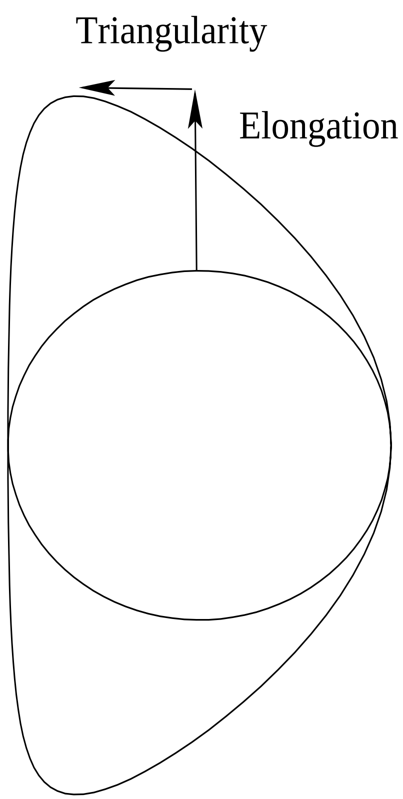
Cross-validation (fit to a subset of data, test by predicting rest of data) shows significant uncertainties

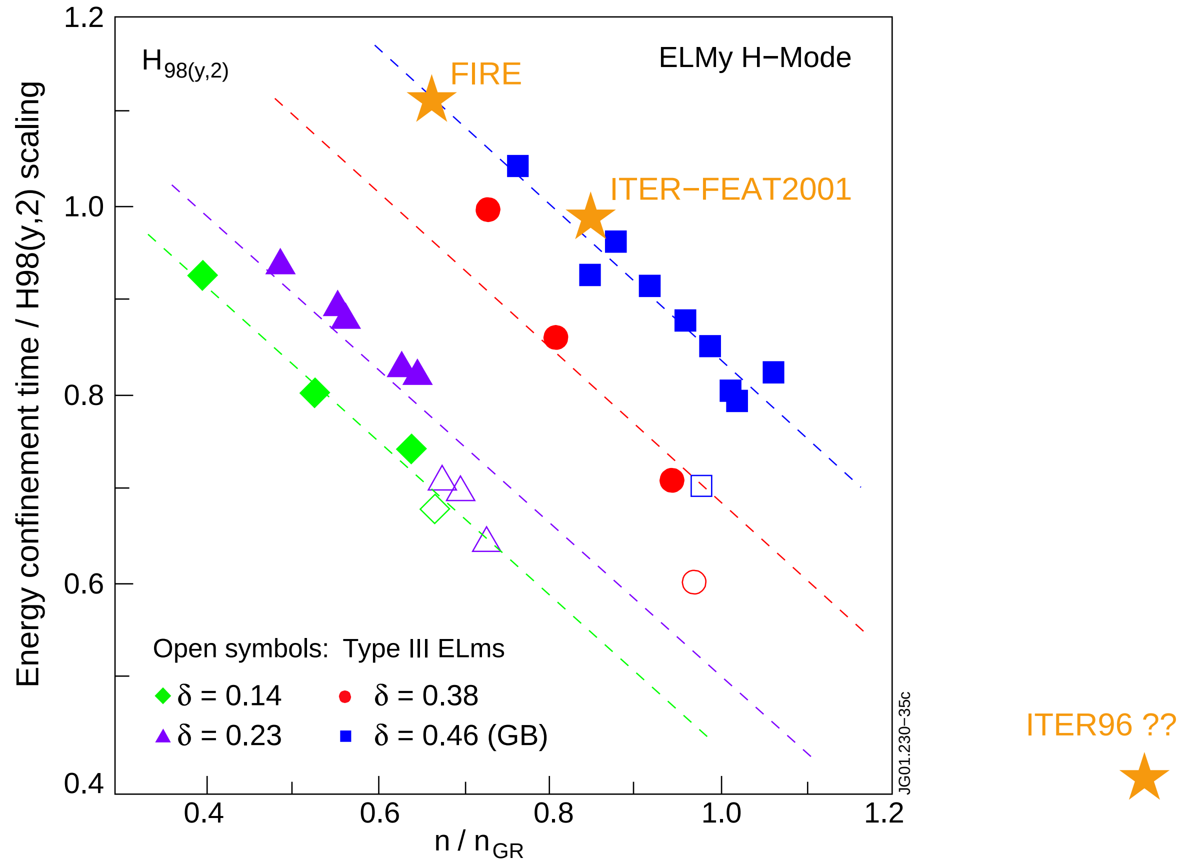
- Prediction of JET data (red) using fit to other 5 tokamaks excluding JET. RMS error of fit to data excluding JET is 0.125. RMSE of predicting JET is 0.408, significantly larger than expected error 0.138 if all errors statistically independent.
- JET data systematically low, mean prediction error -0.393, significantly larger than expected ideal error in the mean of ±0.060.
- Repeat for all other tokamaks.
- Conclusion: significant correlations among errors (i.e., systematic errors between different tokamaks, or between different regimes). Uncertainties in predicting ITER much larger than previously acknowledged.



Related to jackknife and bootstrap methods, or looking at residuals. Choose subsets from different regimes or instruments to look for correlated systematic errors.

New Reactor Designs Much Better than 1996 ITER





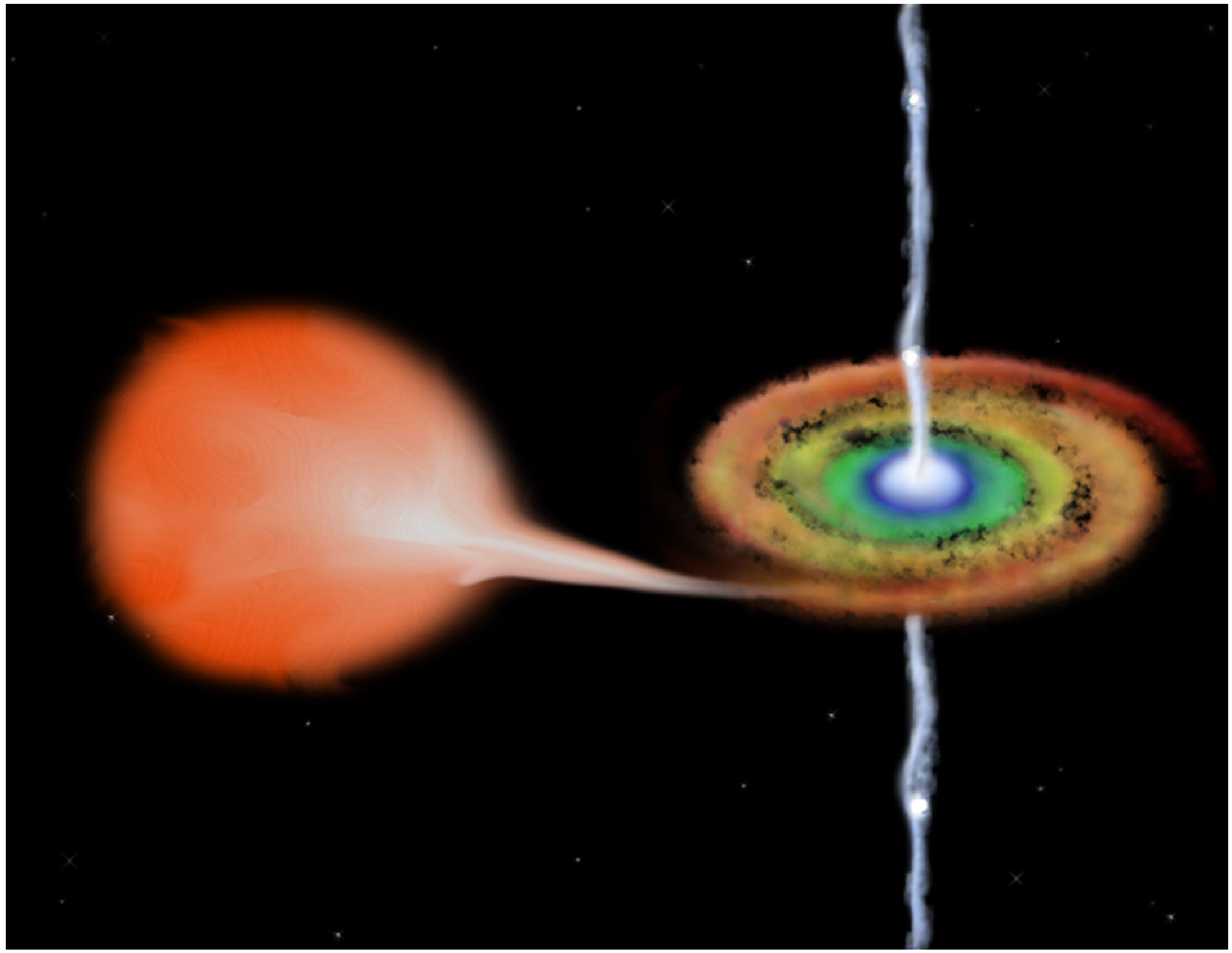
Confinement degrades if density too large relative to empirical Greenwald density limit $n_{Gr} = I_p / (\pi a^2)$, but improves with higher triangularity.

Compared to original 1996 ITER design, new ITER-FEAT 2001 and FIRE designs can operate at significantly lower density relative to Greenwald limit, in part because of stronger plasma shaping (higher triangularity and elongation).

JET data from G. Saibene, EPS 2001, J. Ongena, PPCF 2001. Seen in other tokamaks also.

Plasma Turbulence Near Black Holes

But first:
evidence for
the existence
of black holes

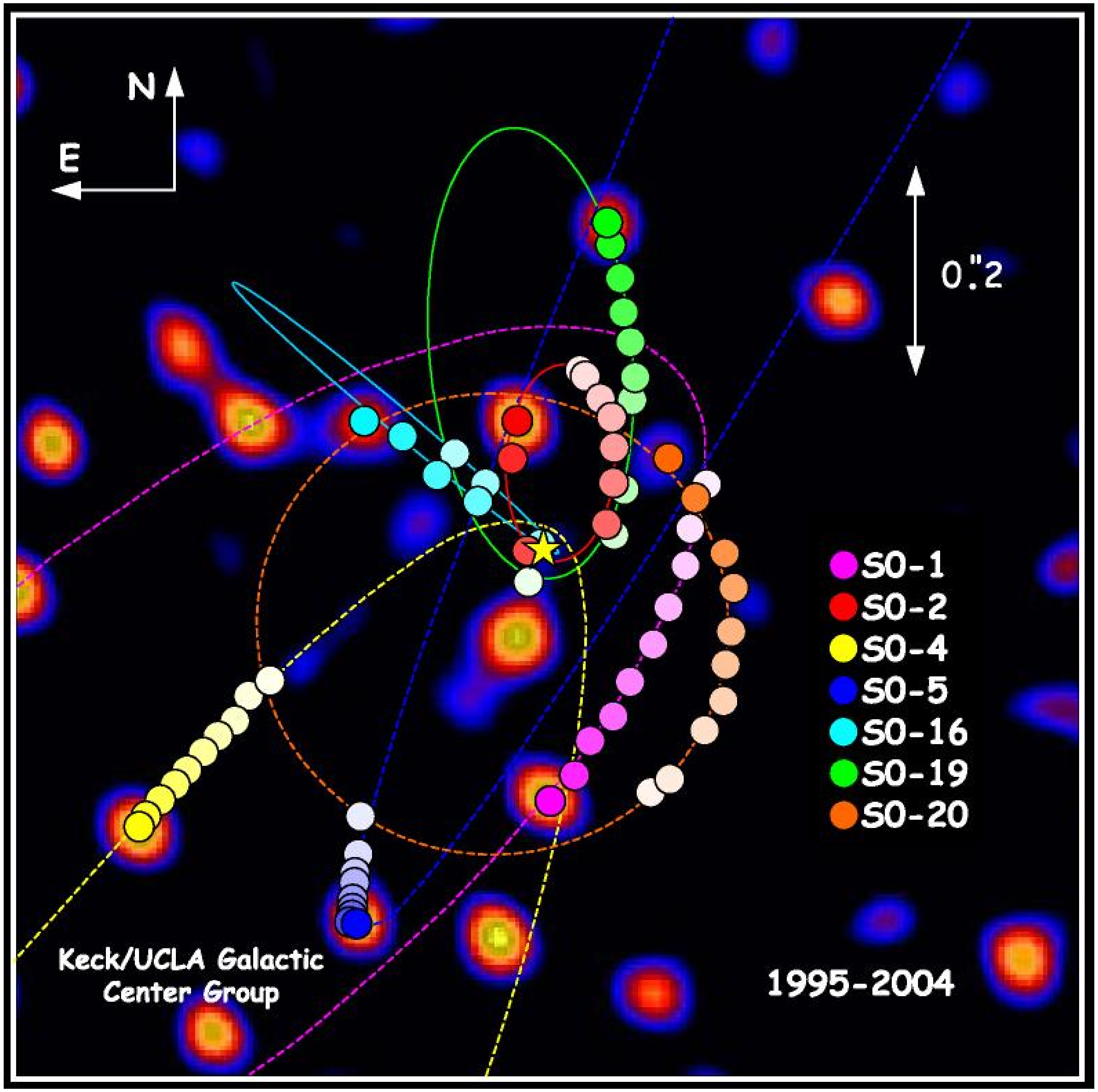


Artist's conception

NASA/CXC/SAO A.Hobart http://chandra.harvard.edu/resources/illustrations.html

Stars near center of our Milky Way Galaxy seen orbiting "Something" 4 Million times as Massive as our Sun

- Closest star came within 90 AU (90 times the earth-sun distance, comparable to pluto-sun distance)
- Fastest: 15 year period
- Adaptive optics critical: equivalent to seeing hand waving in New York from LA



A.M. Ghez et al. 2003
http://www.astro.ucla.edu/~jlu/gc/

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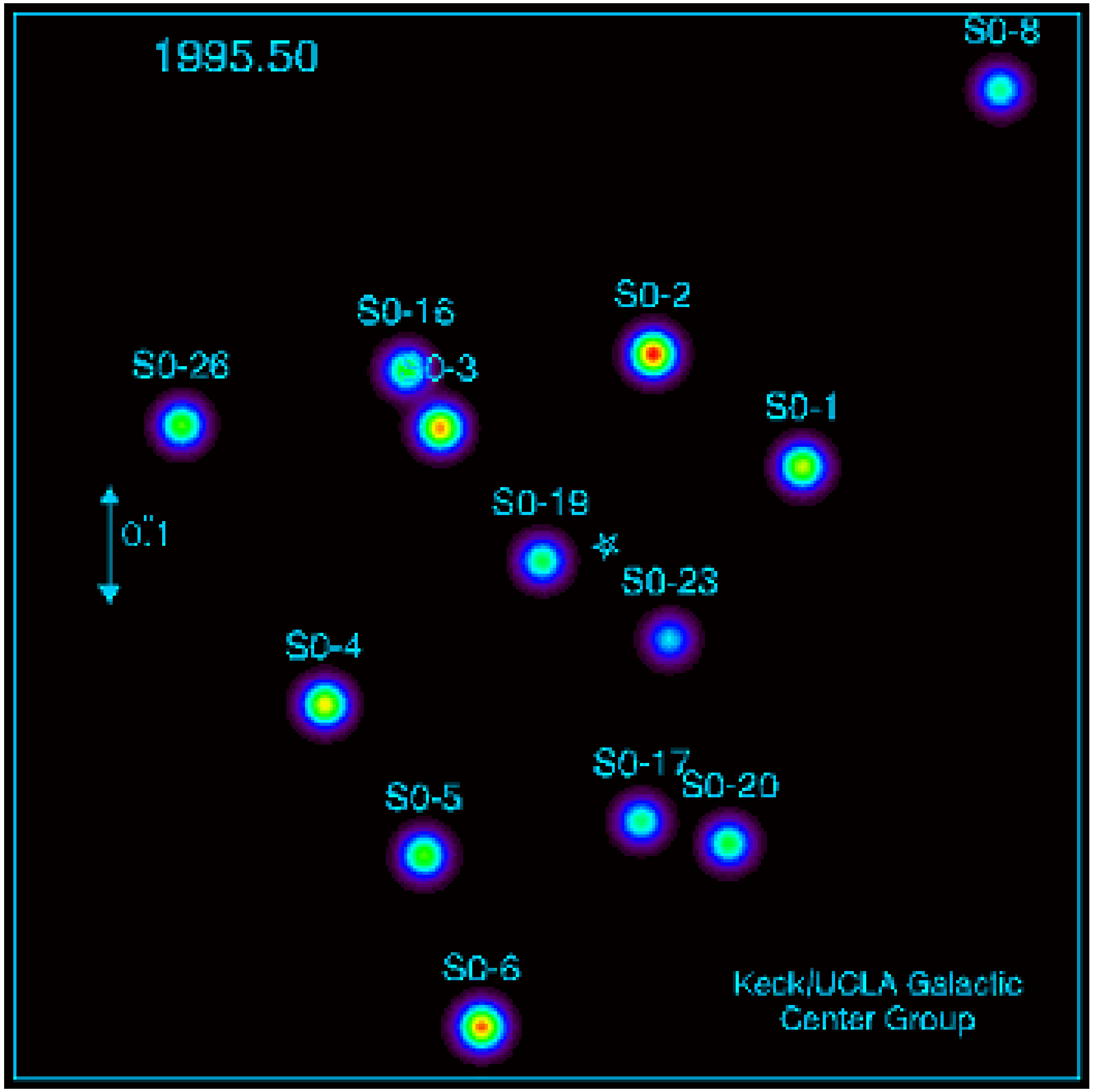

A.M. Ghez et al. 2003
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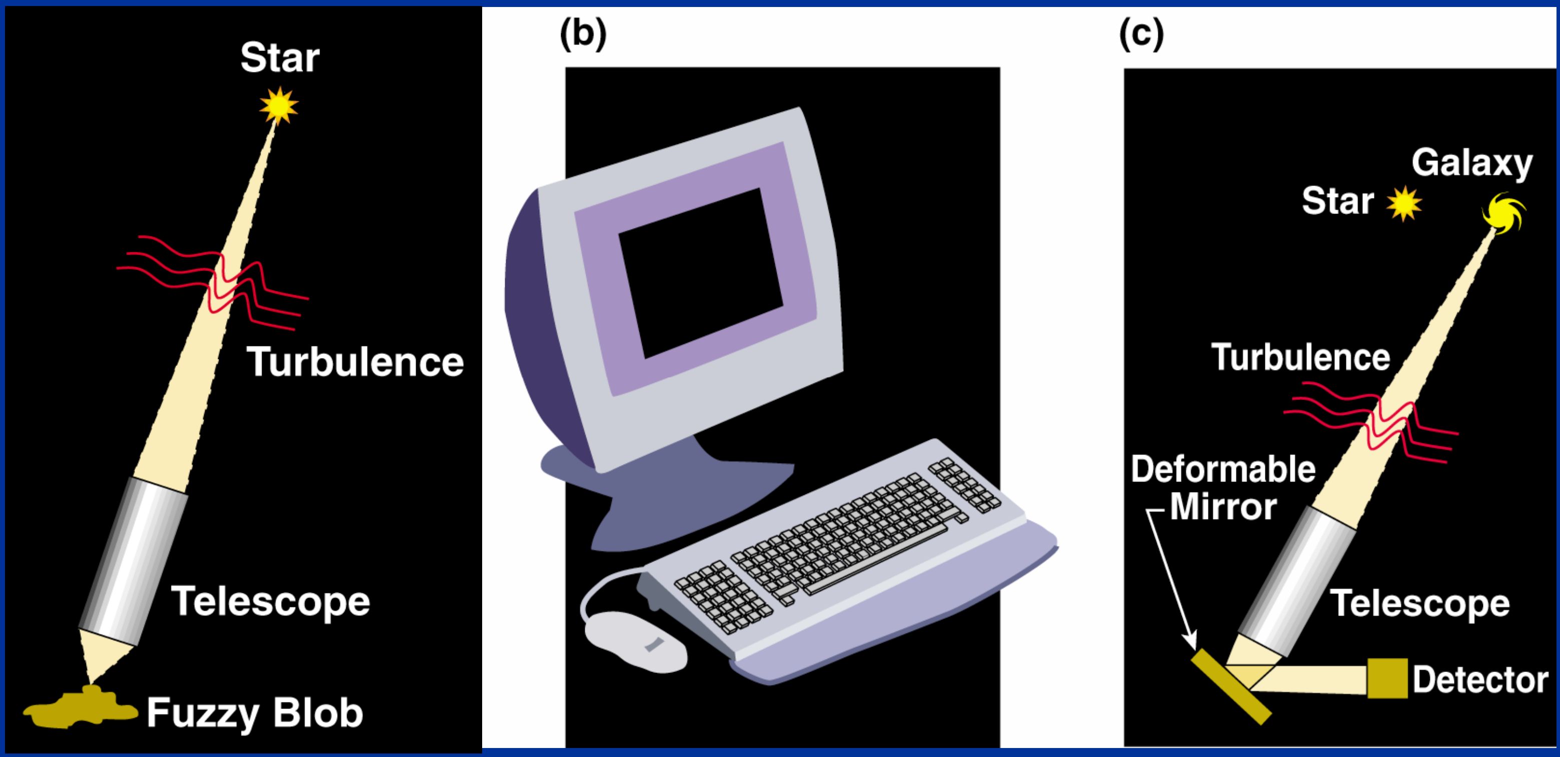
How does adaptive optics help? (cartoon approximation)

Measure details of blurring from "guide star" near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



From Prof. Claire Max, http://www.ucolick.org/~max/289C/

Images of a bright star, Arcturus

Lick Observatory, 1 m telescope

Speckles (each is at diffraction limit of telescope)

From Prof. Claire Max, http://www.ucolick.org/~max/289C/

Laser is operating at Lick Observatory, being commissioned at Keck

Lick Observatory

Keck Observatory

From Prof. Claire Max, http://www.ucolick.org/~max/289C/

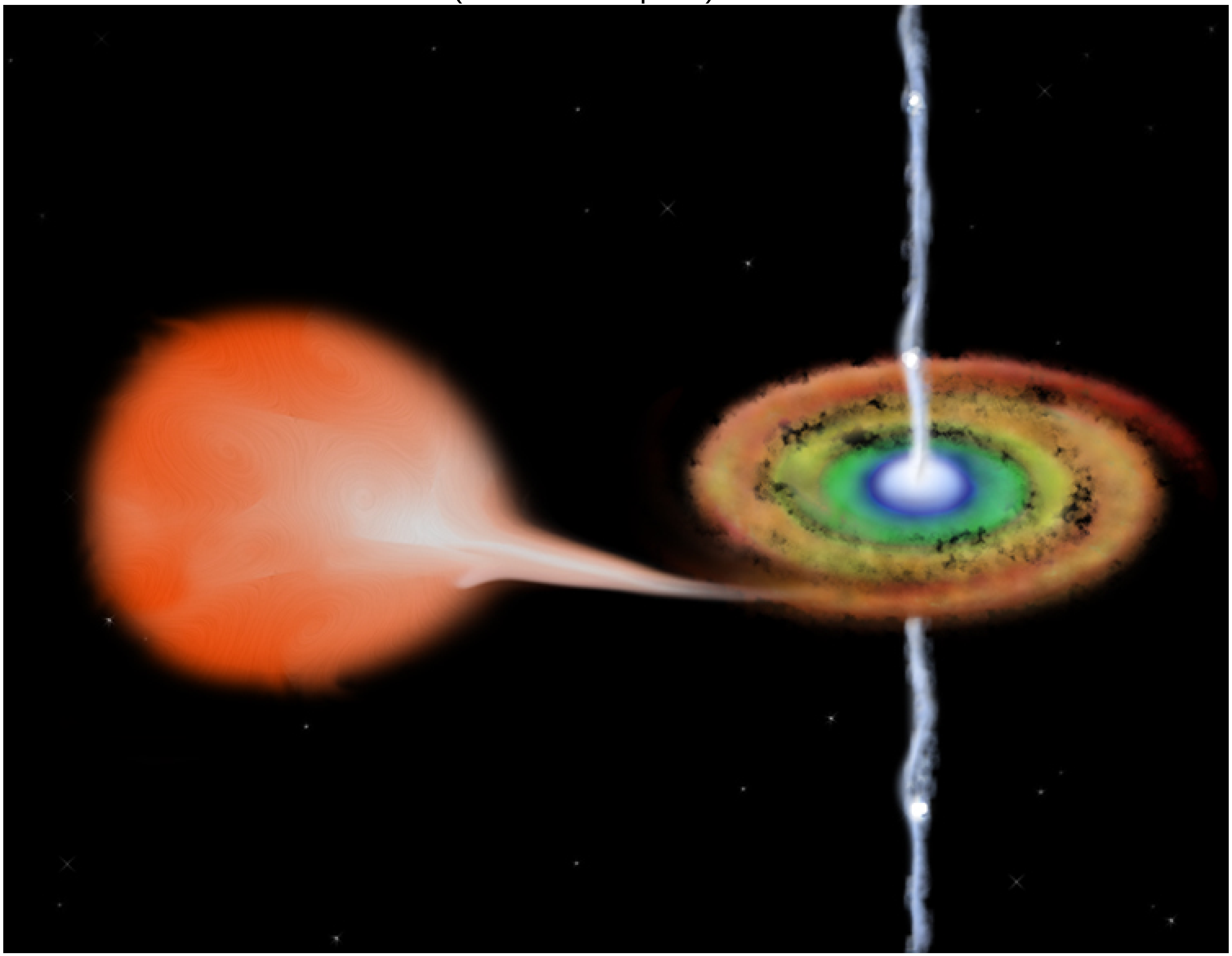
Prof. Claire Max, an astrophysicist at UC Santa Cruz and LLNL (and spouse of Prof. Jon Arons), will receive a 2004 E.O. Lawrence award from the Dept. of Energy,

"for her contributions to the theory of laser guide star adaptive optics and its application in ground-based astronomy to correct telescopic images for the blurring caused by light passing through the atmosphere."

http://www.sc.doe.gov/sc-5/lawrence/

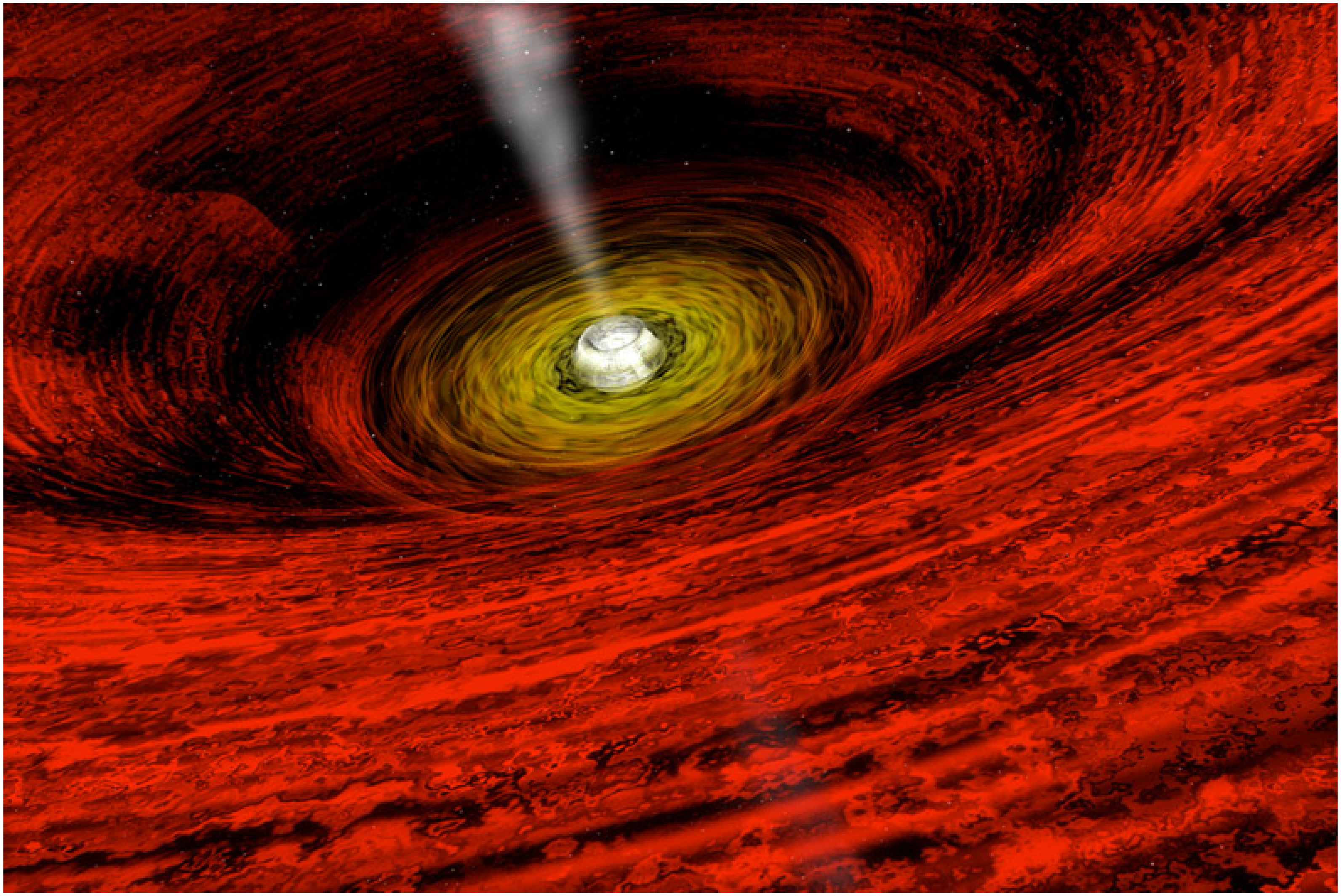
Star orbiting black hole & feeding accretion disk

(artist's conception)



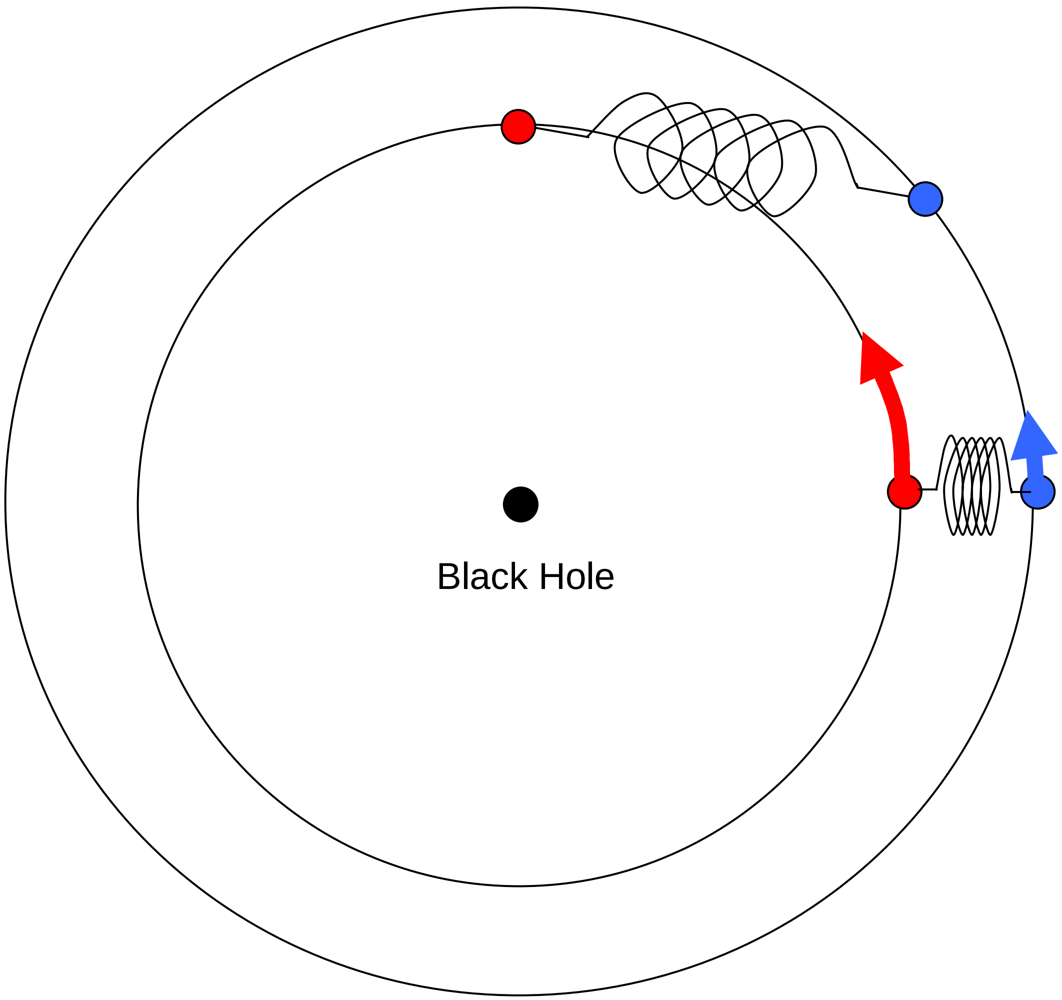
NASA/CXC/SAO A.Hobart   http://chandra.harvard.edu/resources/illustrations.html

Black Hole Neighborhood. (artist's conception)



NASA/CXC/SAO A.Hobart   http://chandra.harvard.edu/resources/illustrations.html

Plasma instability explains how accretion disks accrete (Balbus & Hawley, 1991)

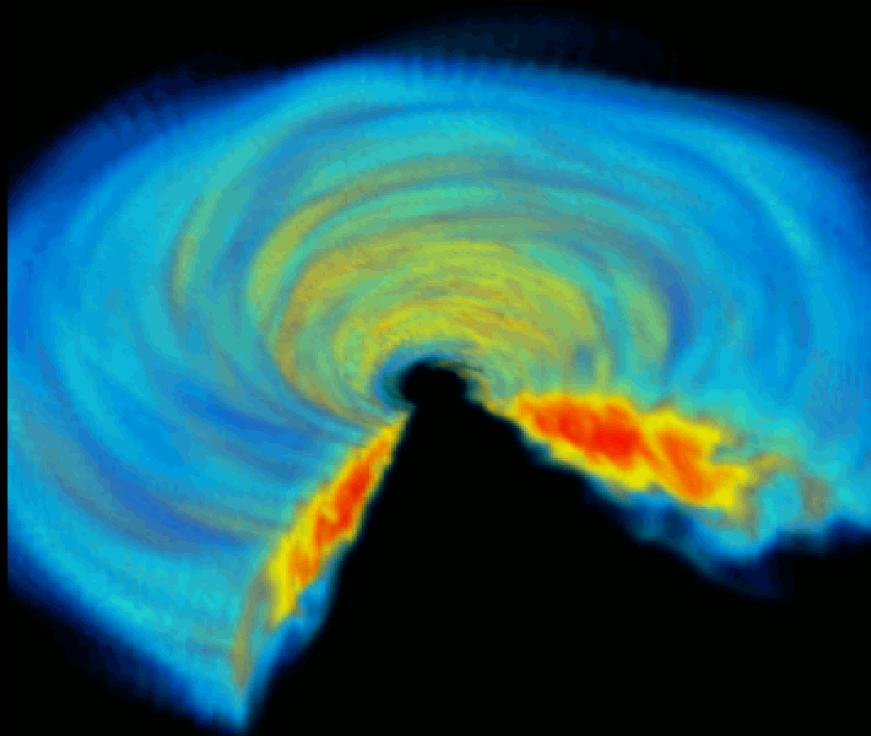


Inner particle orbits faster,
Spring stretches out
Spring force causes
Inner particle to move further in
Outer particle to move further out
Exponentially amplified.

Magnetic fields
Are like springs

Fully 3-D MHD simulations are possible.

Repeat of “Run F” from Stone & Pringle (2001):



MHD turbulence is more vigorous and is sustained in 3D

But time-averaged flow not much different than 2D

(Hawley, Balbus, & Stone 2001)

My main study: Why are some black hole accretion disks ~million times less luminous than expected?

Quasars among the brightest objects in the universe:

Quasar Luminosity ~ 10^{12}–10^{14} L_{sun}

Quasars now understood to be massive black holes at center of galaxies, accreting large quantities of matter

As matter is accelerated down huge gravitational well, it is heated to high energies and produces a lot of radiation observed by radio telescopes to X-ray telescopes

The *Chandra* X-ray telescope has observed thermal bremsstrahlung from accreting plasma in the galactic center

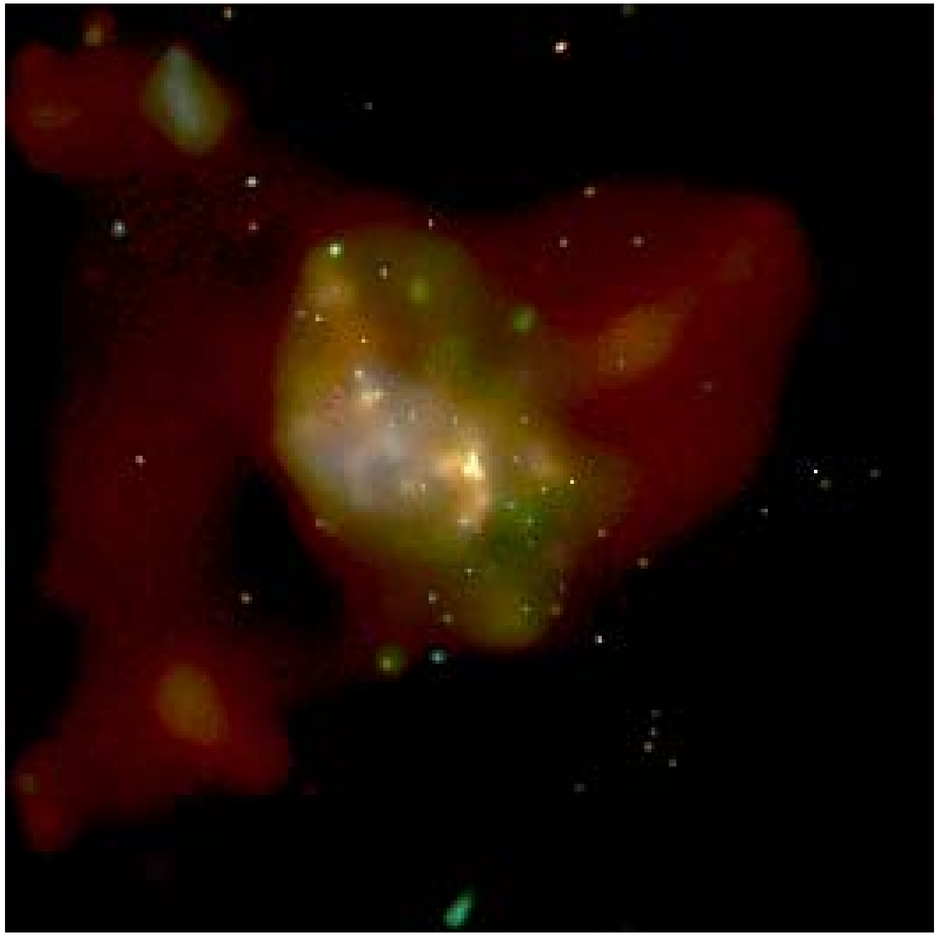
From measured density and temperature of surrounding plasma, simple expectation is

$$L_{expected} \sim 10^{40} \text{ ergs/s}$$

$$\sim 10^{6} L_{sun}$$

But the observed luminosity in quiescence is only
2×10^{33} ergs/s $\sim L_{sun}$

Much dimmer than typical Quasar $\sim 10^{12} L_{sun}$

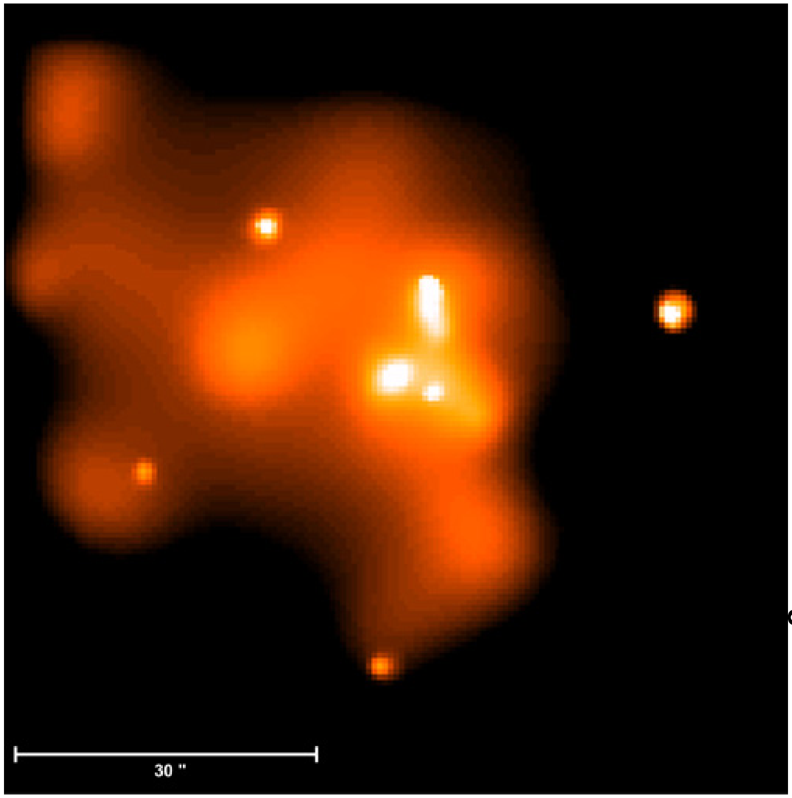


8’ x 8’

Baganoff et al. 2001

(From J. Stone)

***Chandra* image of central ~ 3 pc**



Baganoff et al.

Hot x-ray emitting gas
(T = 1-2 keV; n = 100 cm^{-3})
produced via shocked
stellar winds

Kinetic effects on Accretion Turbulence?

Traditional MHD (Magneto-Hydro-Dynamics) works well in many cases. But in low-luminosity, low-density hot plasmas, the mean-free path between collisions becomes very large, Can't treat as simple fluid in local thermodynamic equilibrium. "Kinetic" effects such as Landau damping become important

Two main modifications to model kinetic effects:

- Pressure becomes a tensor, pressure can be different

a long magnetic field lines or perpendicular to field lines

- Long mean-free path: heat conduction becomes non-local

$$q(z) = -Cn\mathrm{v}_t \int_0^\infty dz' \frac{T(z+z') - T(z-z')}{z'} \exp(-z'/\lambda_{mfp})$$

Interesting mathematical properties: provides multipole Pade approximation to exact linear response, fast evalution with FFT's, For now using a local approximation to this, focussing on pressure anisotropy

Why is the black hole at the galactic center so dim?

1. $\dot{M} = \dot{M}_{Bondi}$ but plasma is "non-radiative"
   - Accretion energy stored as ion thermal energy, $T_i >> T_e$
   - Requires poor coupling between ions and electrons
   - Thermal energy is advected into hole → ADAF

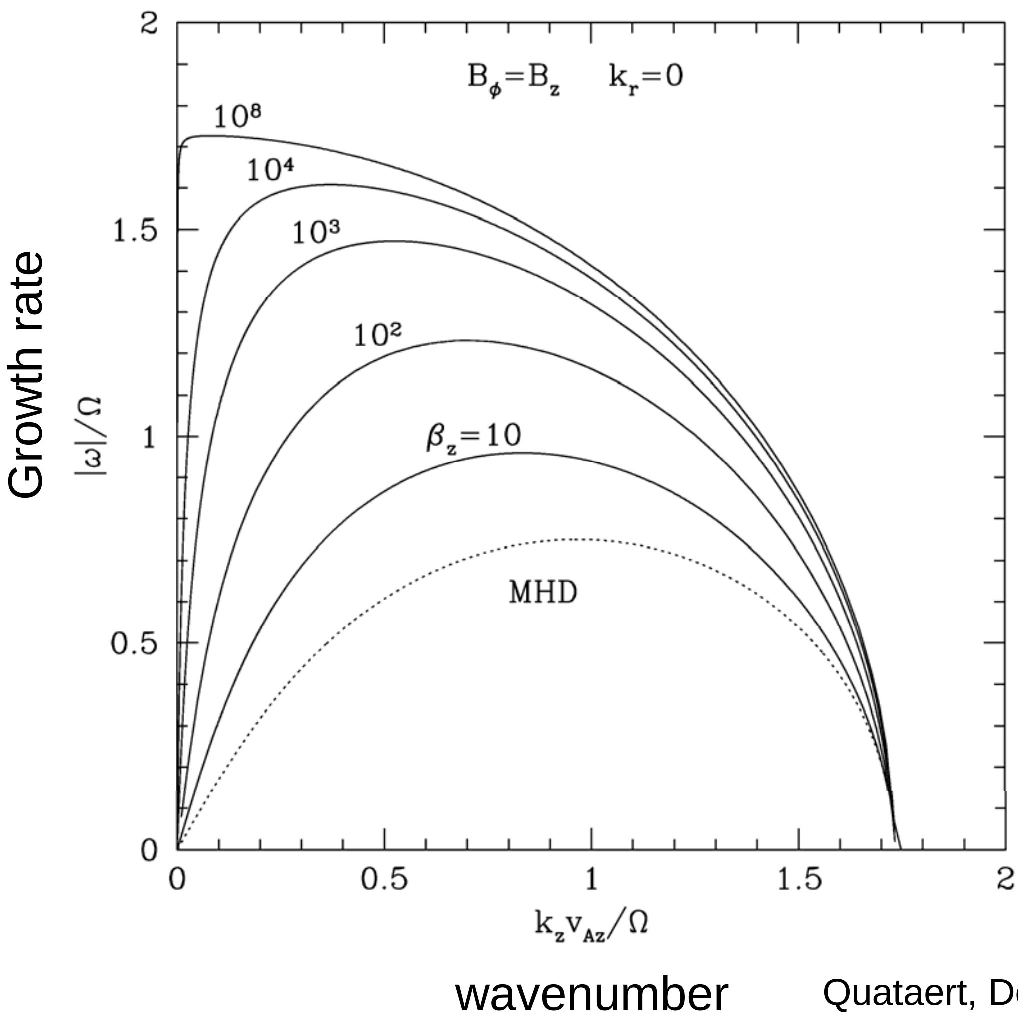
     (e.g., Narayan & Yi 1994; 1995)

2. $\dot{M} << \dot{M}_{Bondi}$ most of the accreting plasma is lost in outflows.
   - Outflows carry away mass, energy, and angular momentum
   - ADIOS (Blandford & Begelman 1999)

Understanding which is correct requires detailed study of the dynamics of the accreting plasma.

(From J. Stone)

Collisionless kinetic effects can significantly enhance the growth rate of the Magnetorotational Instability over usual MHD, particularly at large scales.



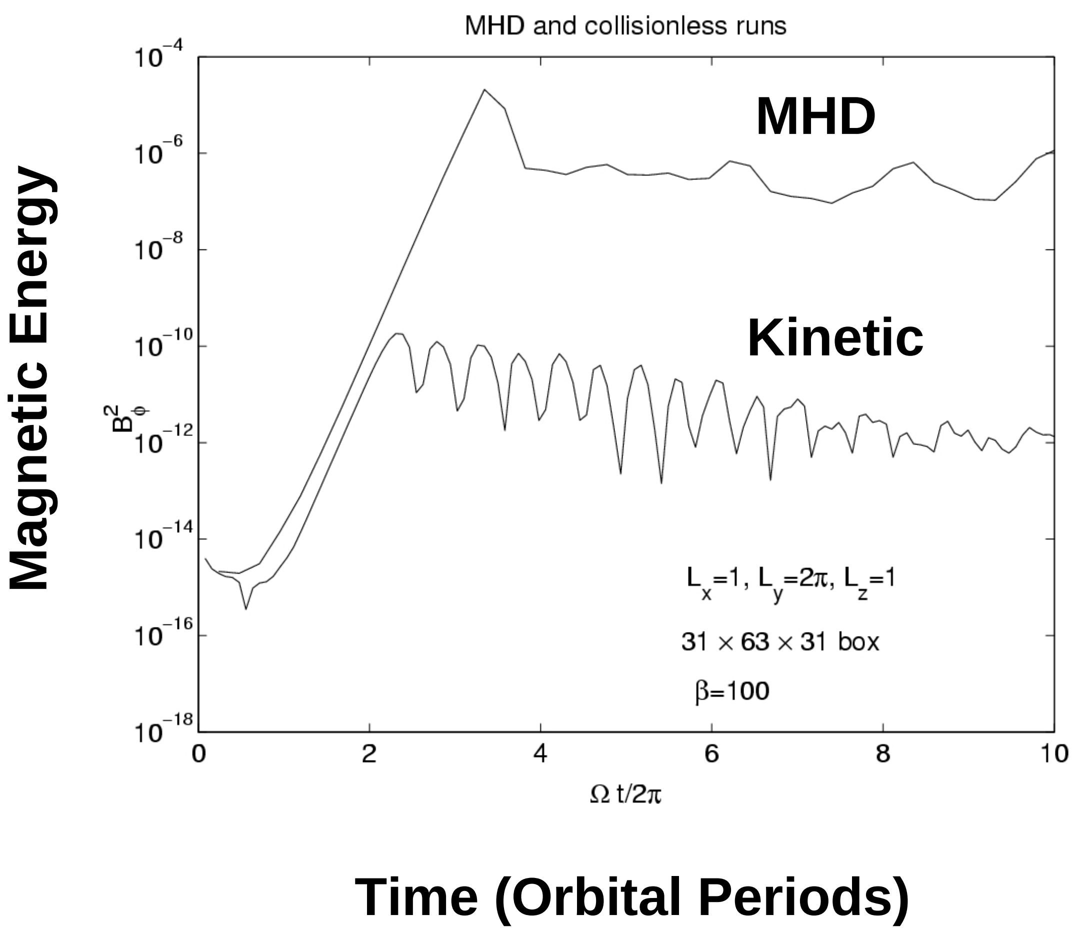
But what happens nonlinearly?

Modifying ZEUS MHD code, widely used to study MRI, to include models of collisionless effects.

Preliminary nonlinear results suggest turbulence initially saturates at much lower level than in MHD, due to μ conservation constraints.

Quataert, Dorland, Hammett, Astro-ph/0205492 (Ap.J. 2002)
Sharma, Hammett, Quataert, Astro-ph/0305486 (Ap. J. 2003)

Preliminary Nonlinear Kinetic Sims



Kinetic sims initially saturate at much lower field strength (due to anisotropic pressure tensor)

Further nonlinear evolution unclear, Mirror instability may Isotropize pressure (work in progress …)

Sharma, Hammett, Quataert, & Stone

Summary

- Turbulence in nature inspires artists and scientists.
- Status of Fusion Energy Research: significant progress made, futher work worth the investment
- Tools common to all sciences: cross-validation is useful statistical technique
- Tools developed in fusion research can help astrophysics & v.v.
- Astrophysics has a fascinating variety of turbulent plasmas in extreme regimes: rethink various phenomena from new perspectives