Predicting and utilizing turbulence in compressing plasma

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Thank you

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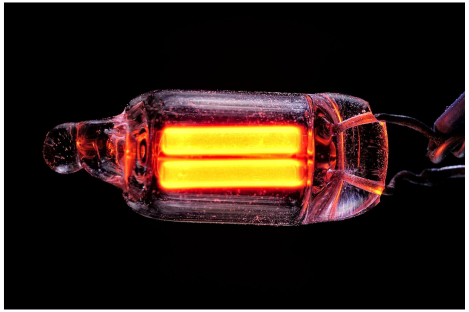
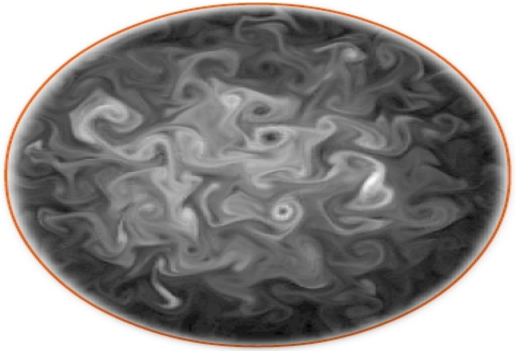
- DOE CSGF and Krell Institute
- The Howes committee
- Thesis adviser: Professor Nathaniel Fisch (Princeton University)
- Collaborators at the Weizmann Institute of Science Plasma Laboratory (Prof. Yizhak Maron et al.); Prof. Amnon Fruchtman
- Thesis funders: NSF, DOE/NNSA, DTRA

Introduction

Today: Turbulence in compressing plasma

Three ingredients: 1. Plasma 2. Compression 3. Turbulence





Coexist in a variety of laboratory and natural systems. E.g.

- Inertial confinement fusion (laser compression)
- Astrophysical molecular clouds (gravitational compression)

Plasma

- A gas that is at least partially ionized
- Gas-like behavior, but with additional effects

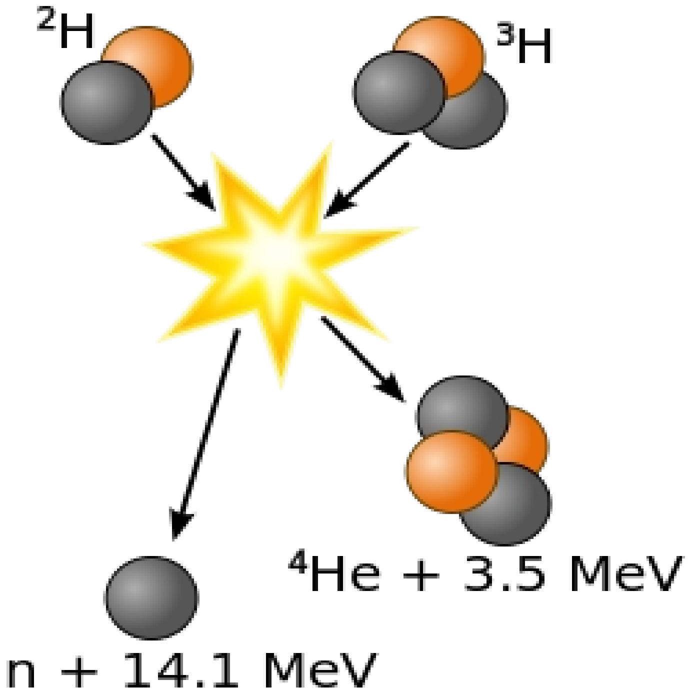
Natural:

Lightning, aurora, stars, …

Laboratory:

Fusion energy experiments, neutron sources, …

High temperature → Ionization to plasma



Plasma viscosity unusual & important

- Plasma viscosity: stronger temperature (T) dependence; ionization state dependent (Z)

$$\boxed{\mu_{\text{plasma}} \sim T^{5/2}/Z^4}$$

$$\mu_{\text{gas}} \sim T^{3/4}$$

Heating →

← Ionization

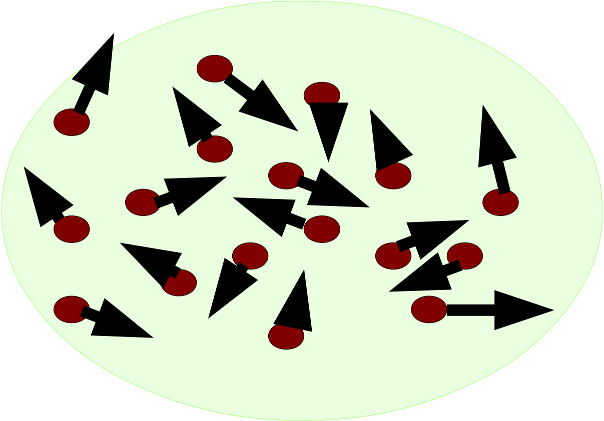
Turbulence

For the purpose of this talk:

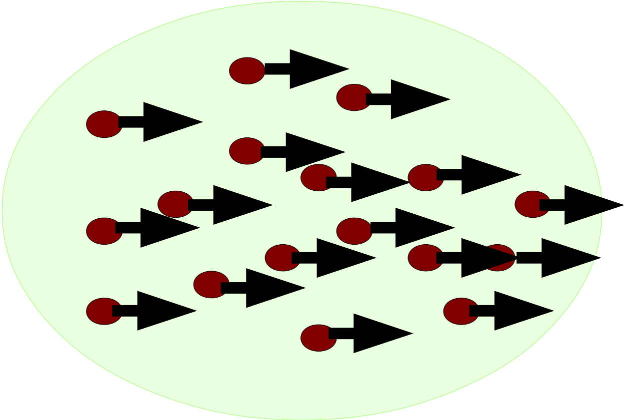
- Turbulence = ("disorganized") flow in the plasma/gas

- Will focus primarily on the *energy* in this turbulent flow, **TKE** (one property)

- Total energy is thermal/temperature (locally uncorrelated) plus flow (locally correlated)



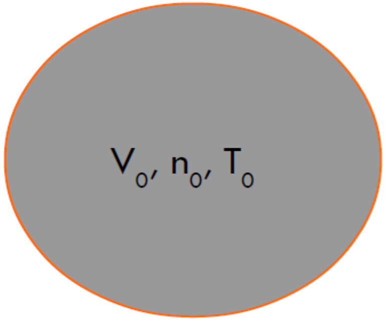
Temperature (thermal energy)



Flow energy

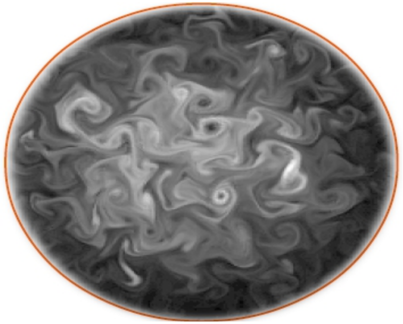
The problem conceptually

All thermal energy



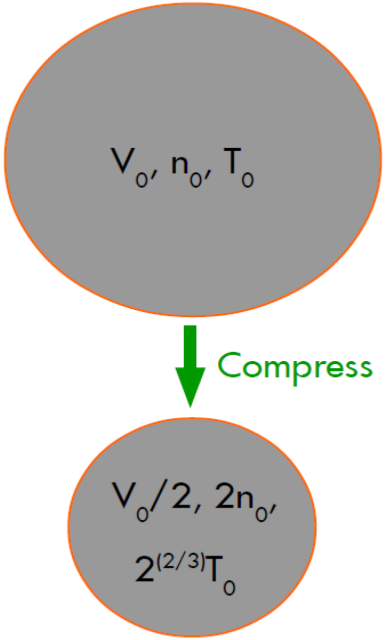
Two plasmas,
same initial energy

¾ thermal, ¼ turbulent



The problem conceptually

All thermal energy



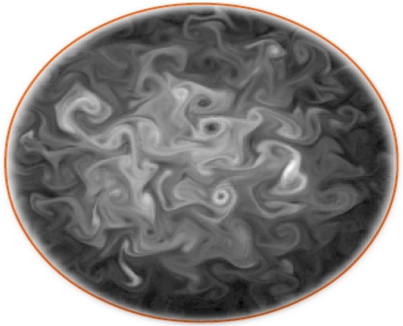
V_0, n_0, T_0

Compress

$V_0/2, 2n_0,$

$2^{(2/3)}T_0$

¾ thermal, ¼ turbulent



Compress adiabatically

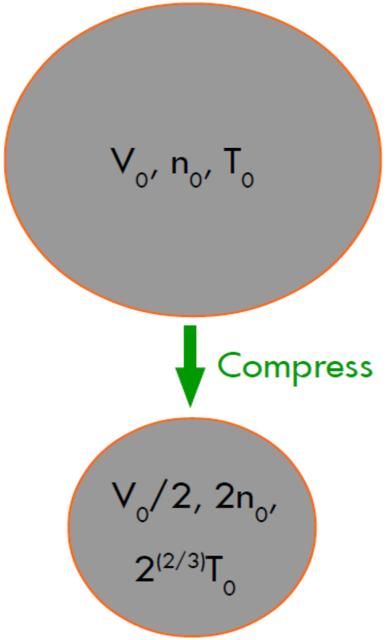
(Ideal gas)

$PV = nRT$

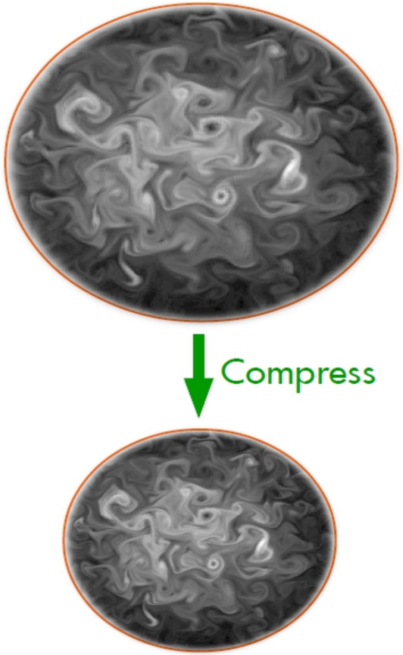
Final state - known

The problem conceptually

All thermal energy



¾ thermal, ¼ turbulent



Compress adiabatically

(Ideal gas)

PV = nRT

???

Final partition - Known

Energy injected - Known

Final partition?

Energy injected?

Flow vs. temperature partition: many impacts

Understanding this partition important in applications:

- Affects thermal and particle transport, mixing
- Affects fusion and X-ray production
- Can confound diagnostics
- Could affect compressibility / energy injected by compression
- Density distribution impacts

Will discuss some of these impacts in context.

What was already known?

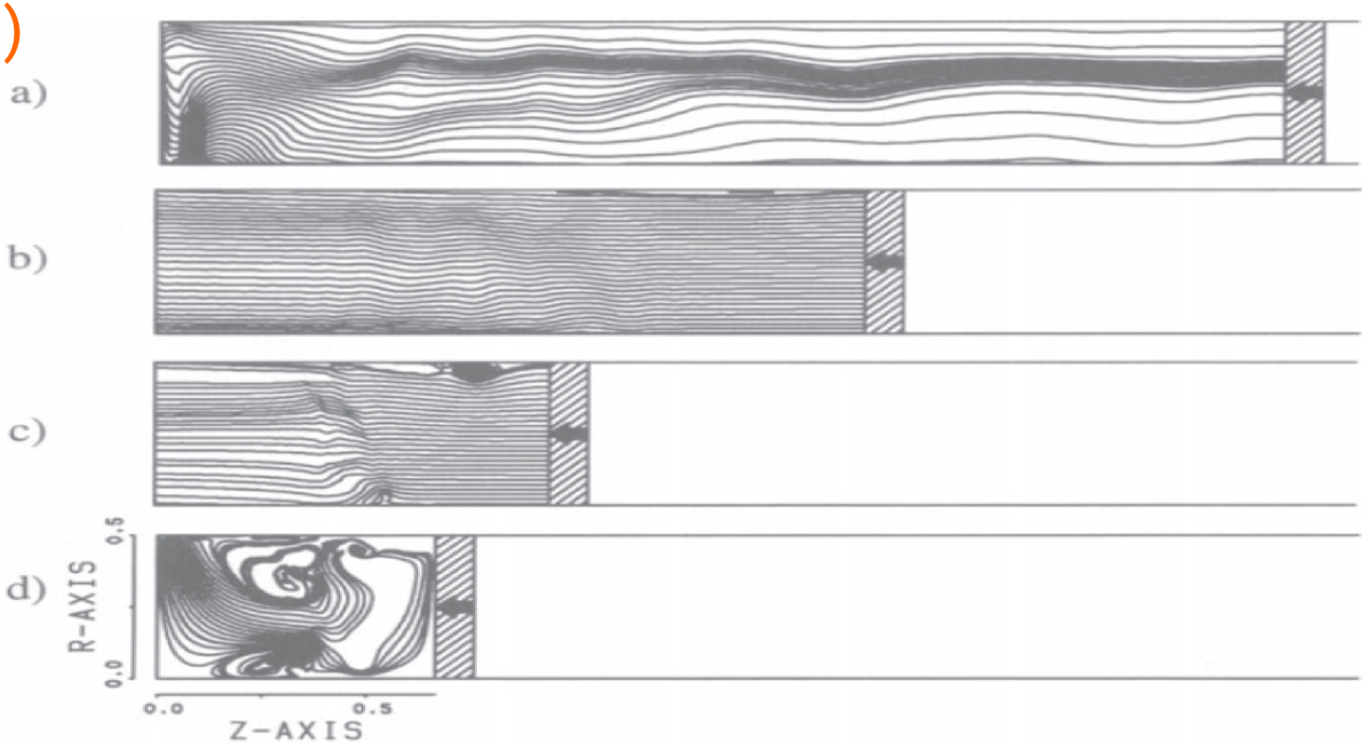
In fluid/gas literature – substantial: Aerodynamics/Combustion

Turbulent energy (TKE) can grow under compression (acts as a forcing)

Timescales important

In astro – a little

In plasma – ??



Guntsch & Friedrich in *Flow Simulation with high-performance computers II* (1996)

What's new for plasma cases?

Size of compression:

- Combustion engine (V → V/10)
- NIF (V → V/10000)

Dominance of turbulent energy (TKE)

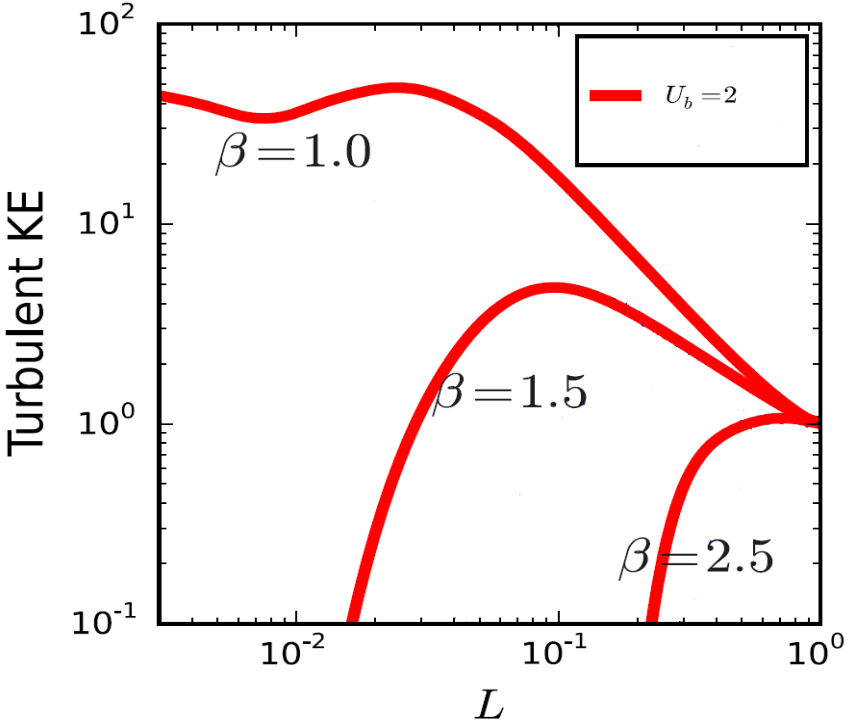
- Z-Pinch stagnation – TKE:Thermal ~ 2:1
- Molecular clouds – TKE:Thermal ~ 10:1

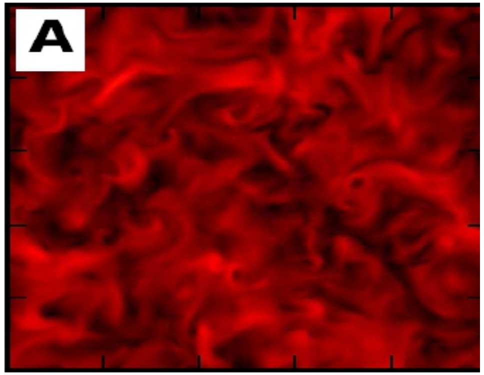
Properties & Processes:

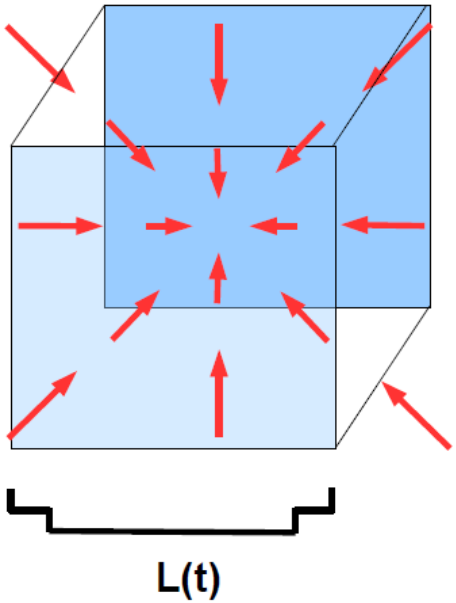
- Viscosity (This alone causes existing fluid/gas models to fail)
- B fields, radiation

Filling in the gap

- Simulations (~1000s cpu hours each) paired with analytic calculations
- Will be showing plots like:

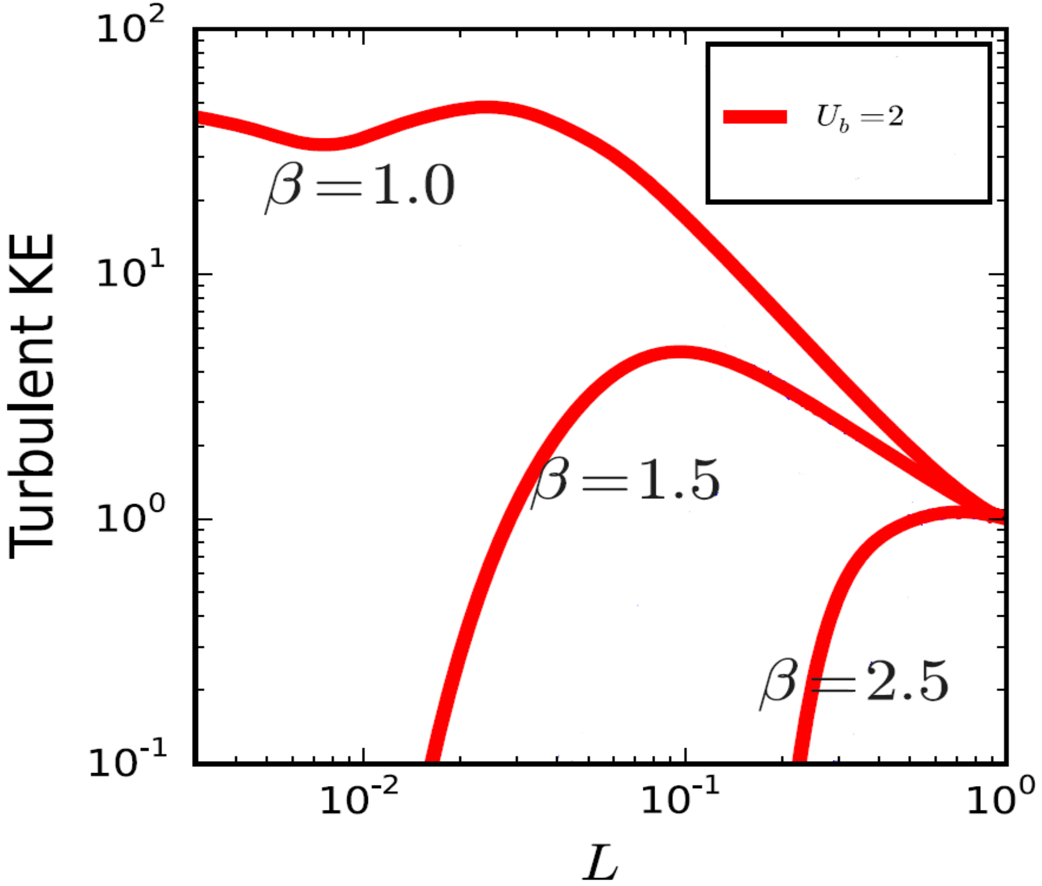






Davidovits & Fisch, PRE **94** 053206 (2016)

Viscous behavior important & many possible



Davidovits & Fisch, PRE **94** 053206 (2016)

- T & Z can both be functions of L

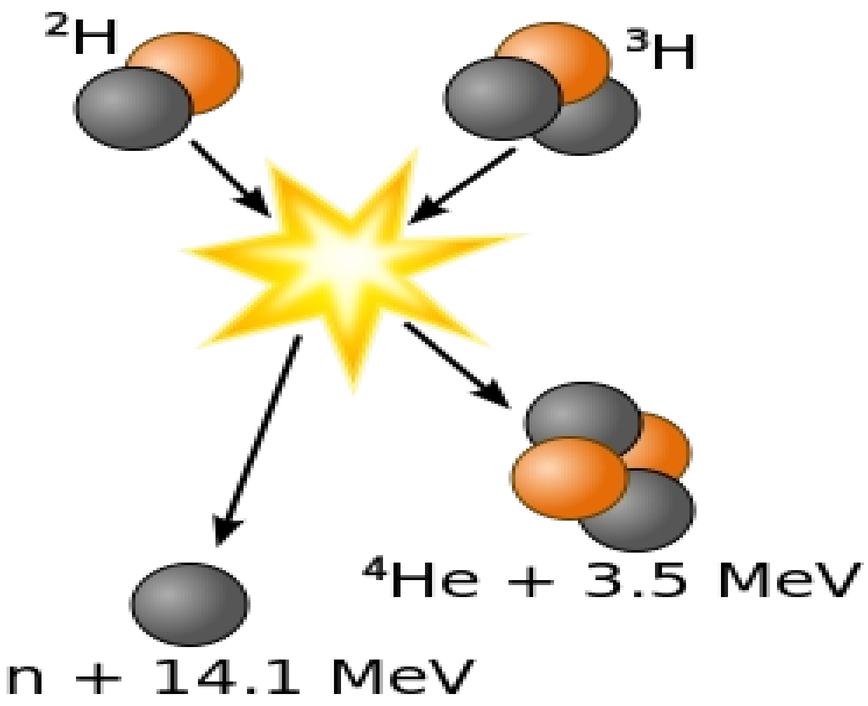
  (Balance of heating and cooling processes)

Different viscosity behavior during compression
→ different results!

Quick intro to inertial fusion

Laboratory fusion?

- Basic science
- Energy
- Stockpile stewardship

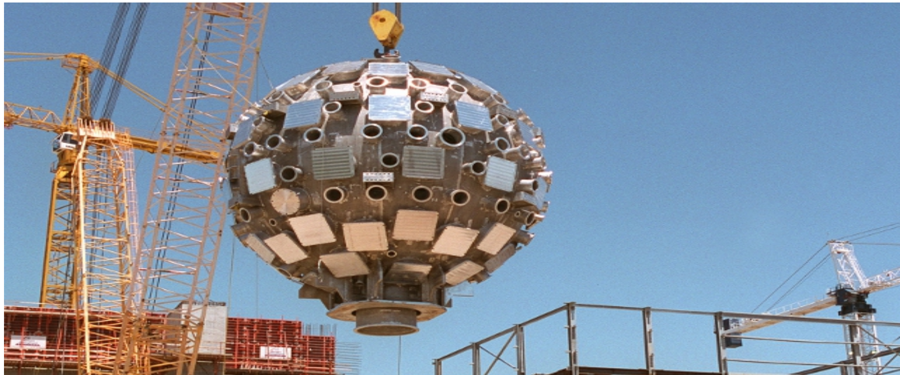


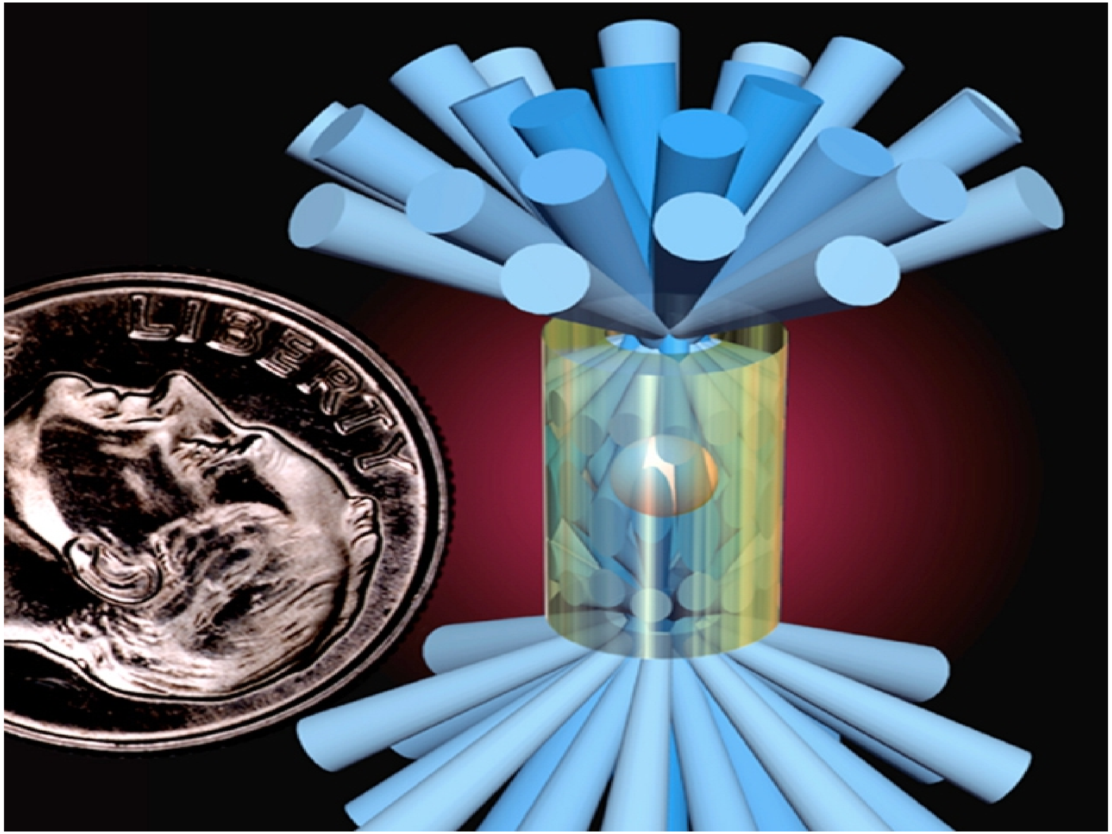
Needed for inertial fusion

- High temperature (gas will be a plasma)
- Self heating (capture He → high-density)

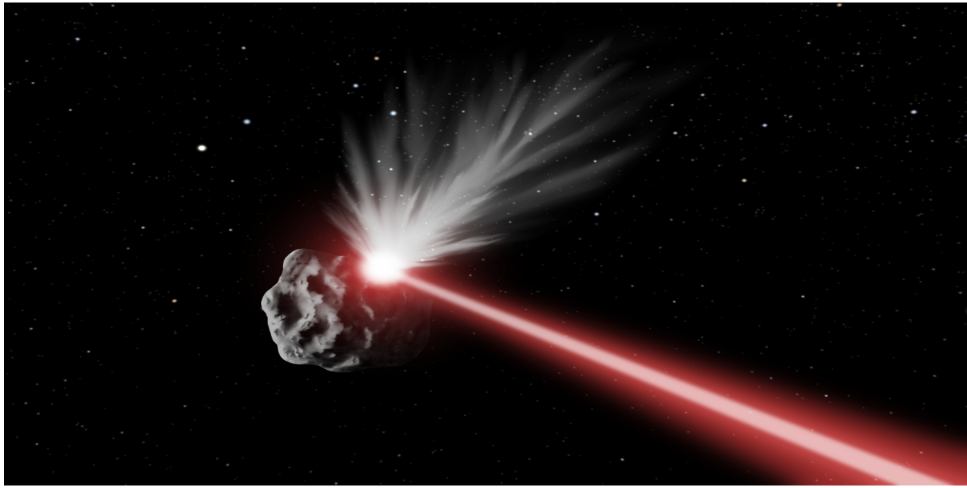
NIF/LLNL

NIF/LLNL

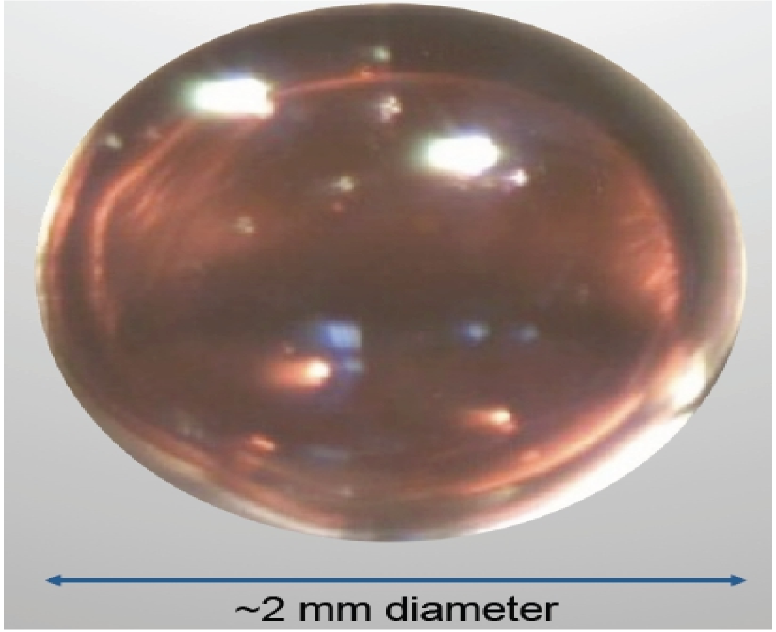




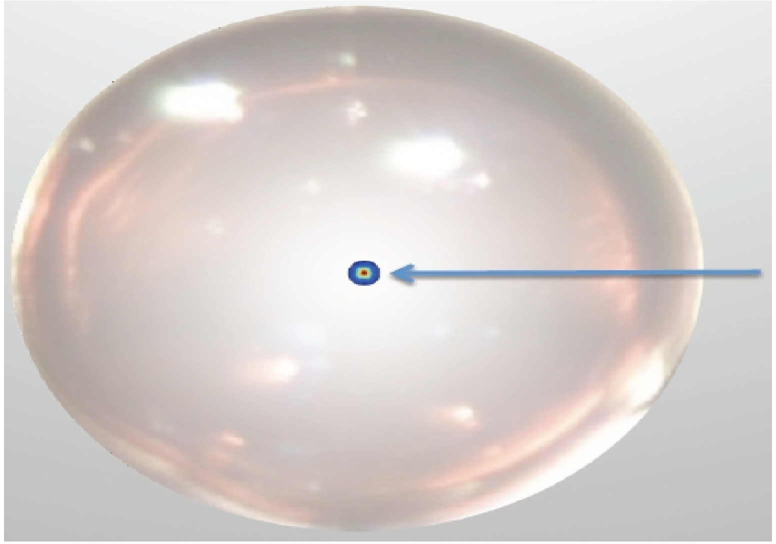
NIF/LLNL



Q. Zhang, UCSB, DE-STAR

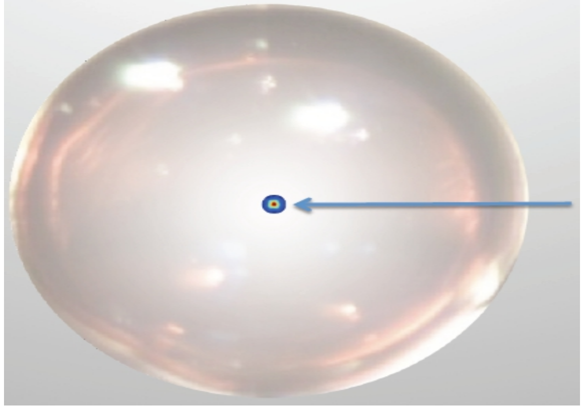


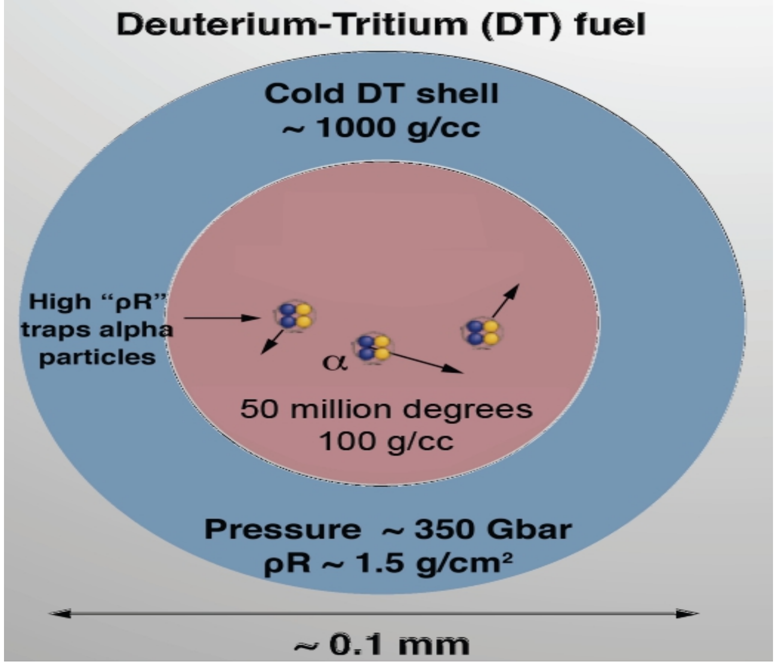
John Edwards, PPPL Colloquium



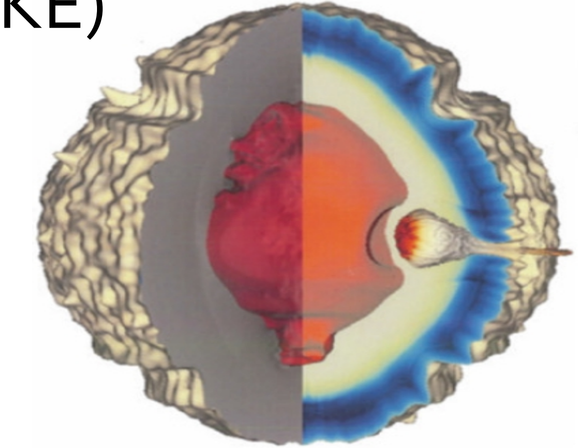
John Edwards, PPPL Colloquium

Want: All thermal (T)

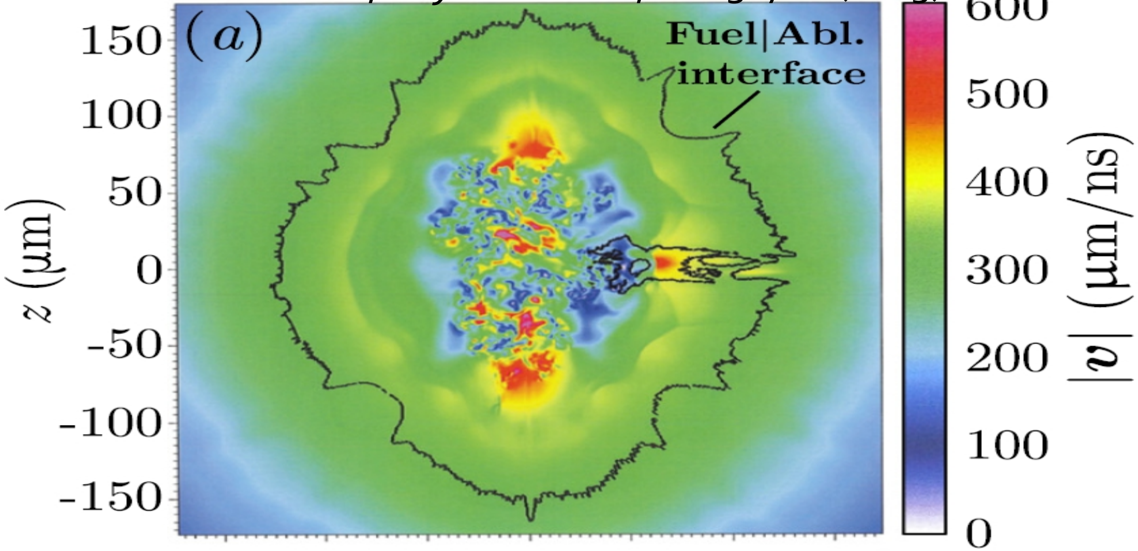


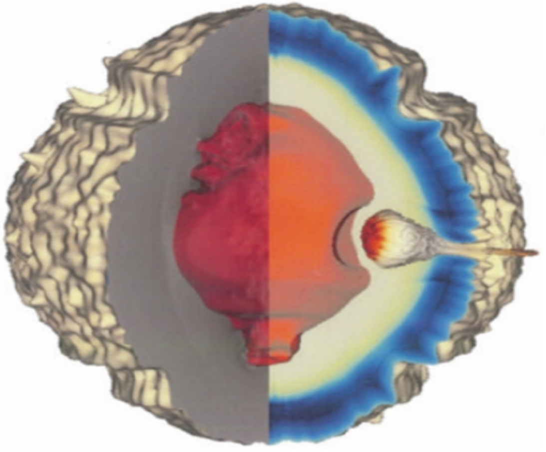


Have?: Mix of thermal (T) and turbulence (TKE)

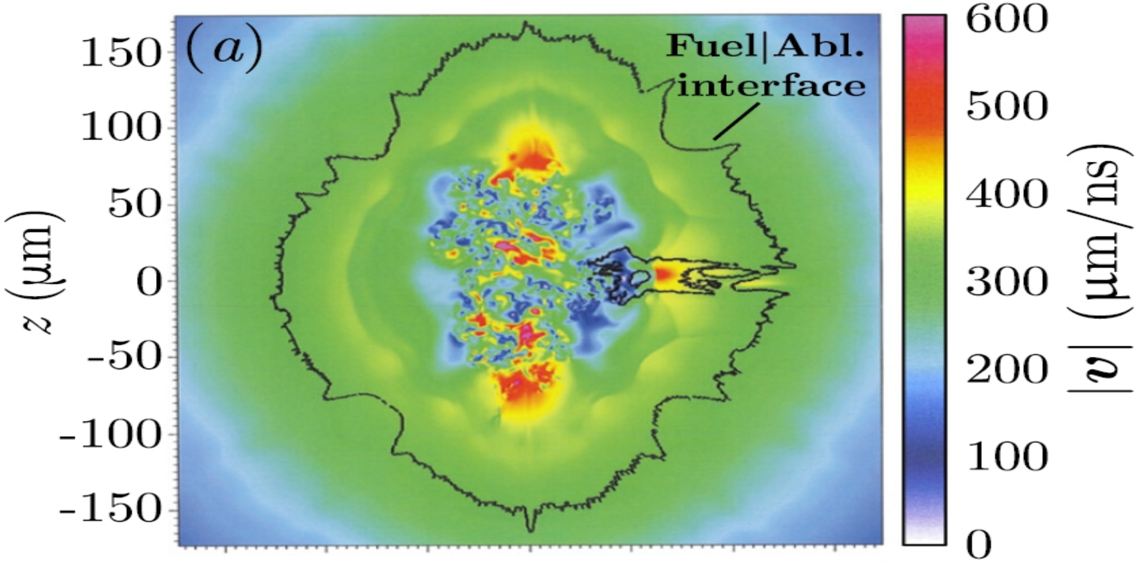


Weber et al., *Phys. Plasmas*, **22** 032702 (2015)





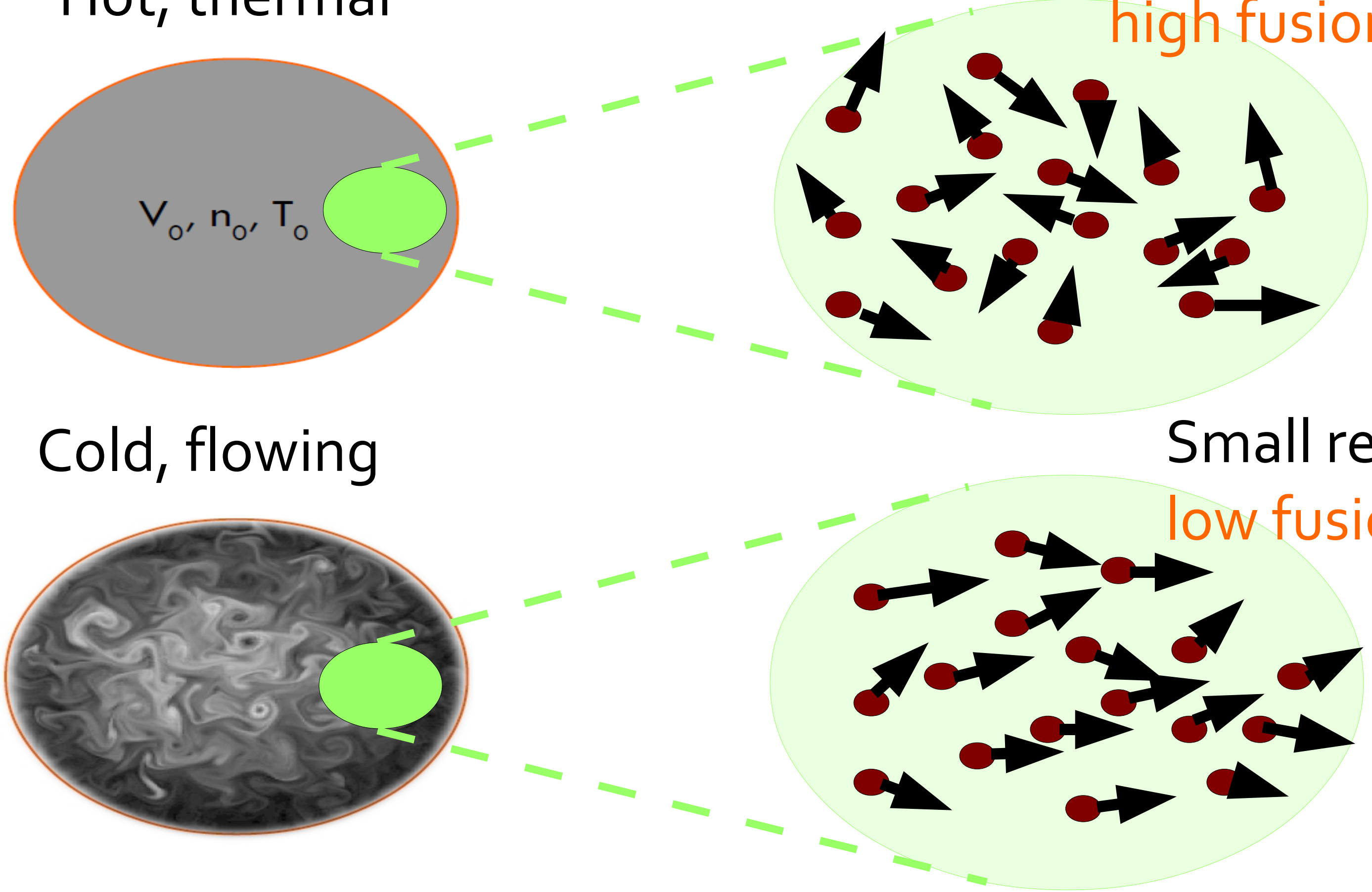
Weber et al., *Phys. Plasmas*, **22** 032702 (2015)



Possible issues (non-exhaustive):

- “Mix” - cooling & introduction of high Z
- Hard to differentiate T vs Turb in experimental measurements
- Hydromotion not (directly) useful for fusion (or X-rays); "wasted" input energy if left in hydromotion.

Flow/turbulence vs. temperature



Hot, thermal

Large relative motion →
high fusion, lots of X-rays

Same
total
energy

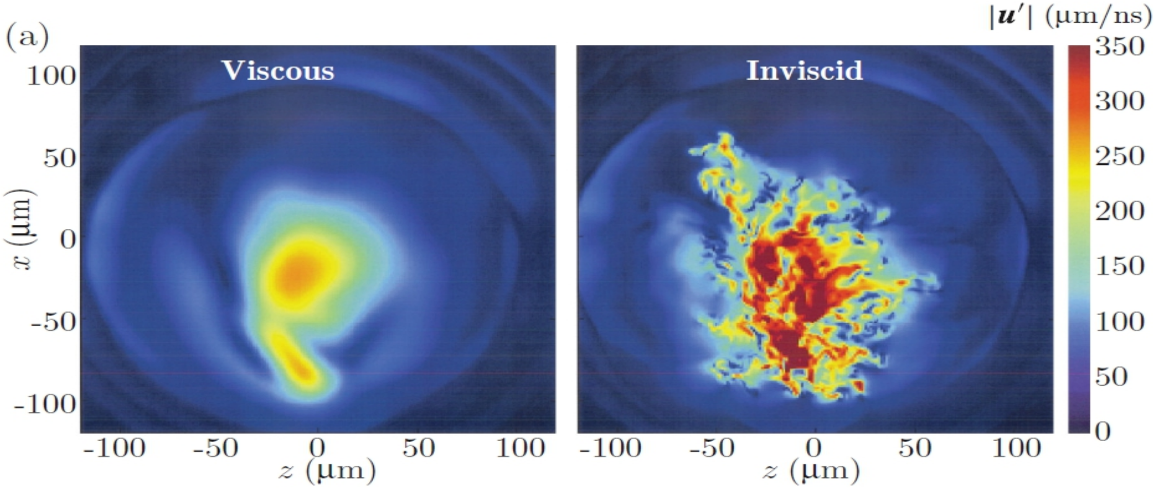
Cold, flowing

Small relative motion →
low fusion, few X-rays

In NIF: Turbulence may be an issue, may not be, but:

- Checking a single case: high resource investment (ex. 5 million cpu-hours)

→ Lack of overarching understanding



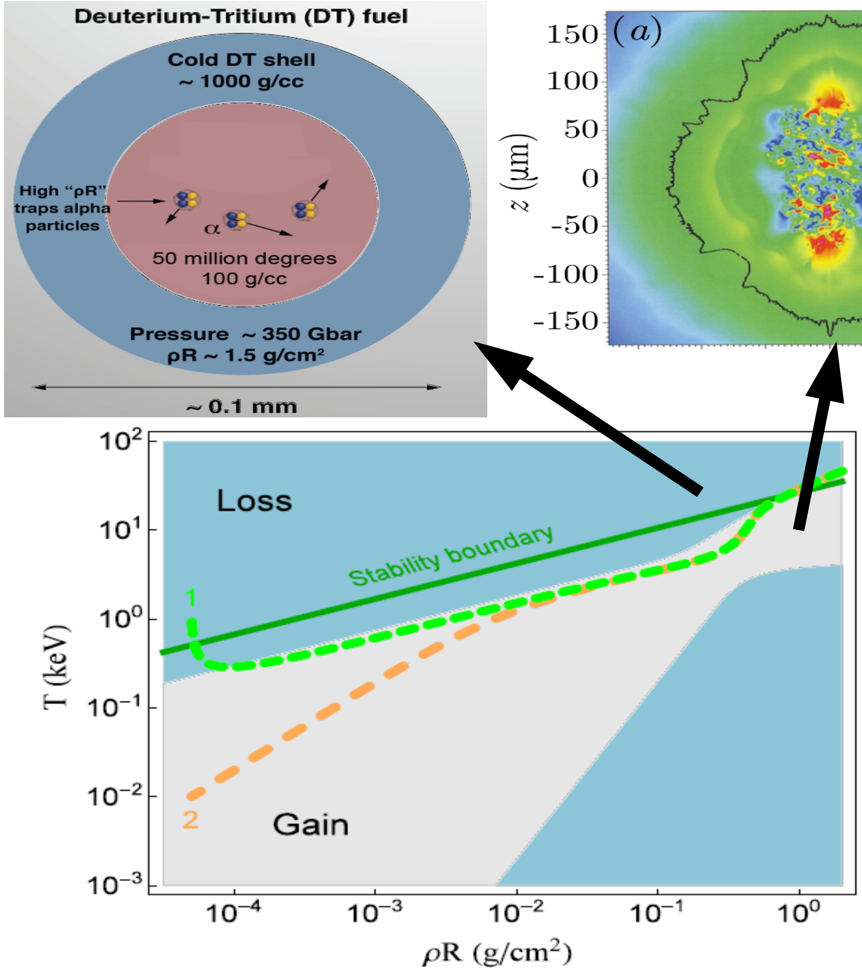
Weber et al., Phys. Rev. E, **89** 053106 (2014)

- Can we get a gross sense of the TKE dynamics?

(Most detailed simulations will always have a place)

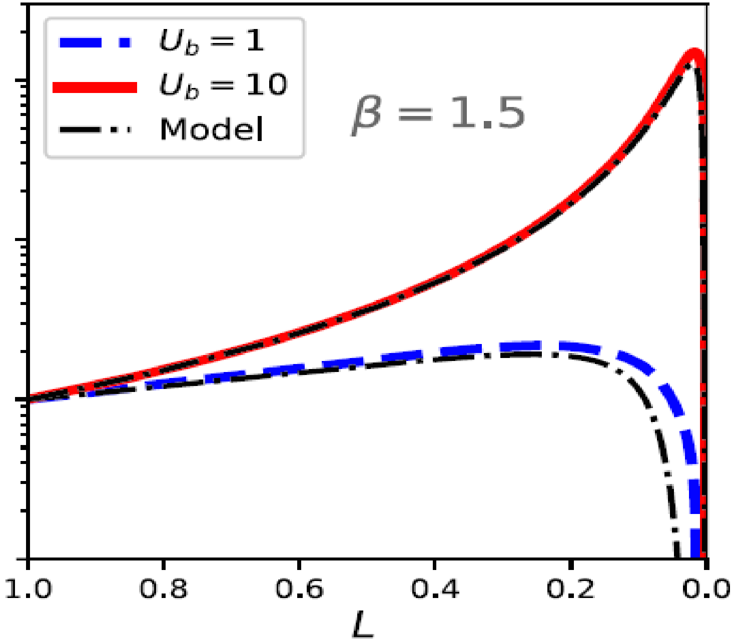
Bird's-eye view of NIF TKE behavior

- Stability, gives map
- Saturation, "how bad can it possibly get"



Davidovits & Fisch, Phys. Plasmas **25** 042703(2018)

- Modeling, ideally to be paired with 1D, 2D, simulations



Davidovits & Fisch, Phys. Plasmas **24** 122311 (2017)

Turbulence/hydromotion can be an issue

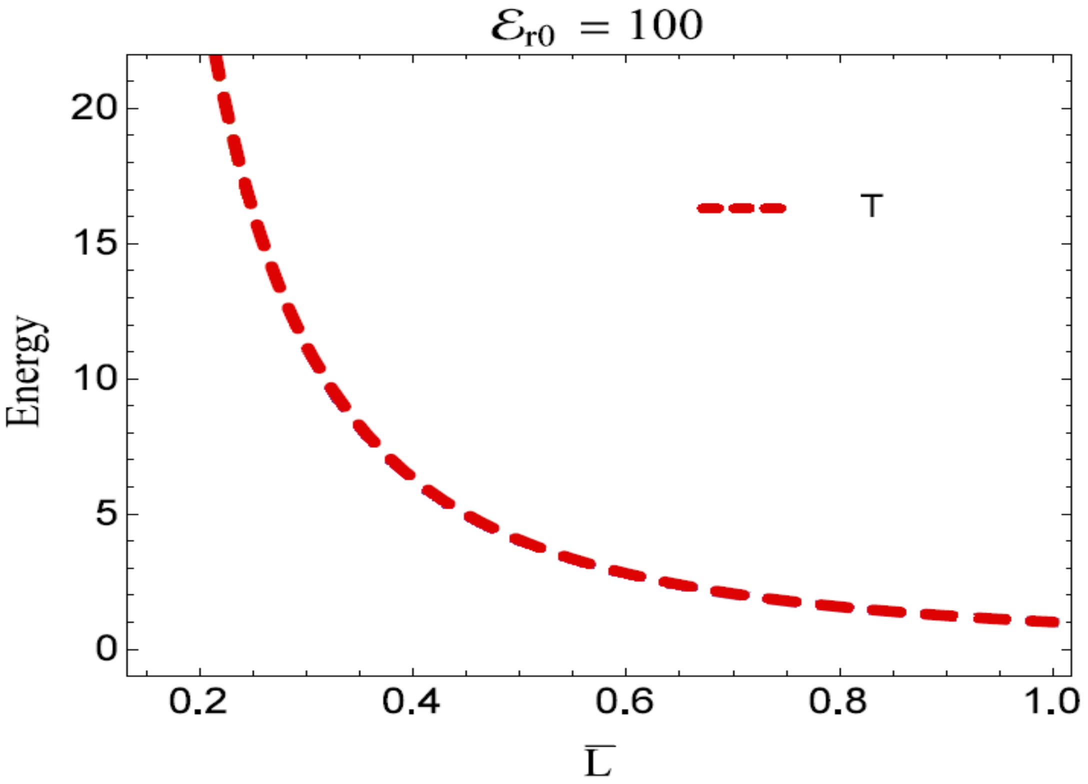
but

Can we also possibly utilize it?

New ignition paradigm

Usually:

1. Start with all T
2. Compress, steadily increasing T



New ignition paradigm

Usually:

1. Start with all T

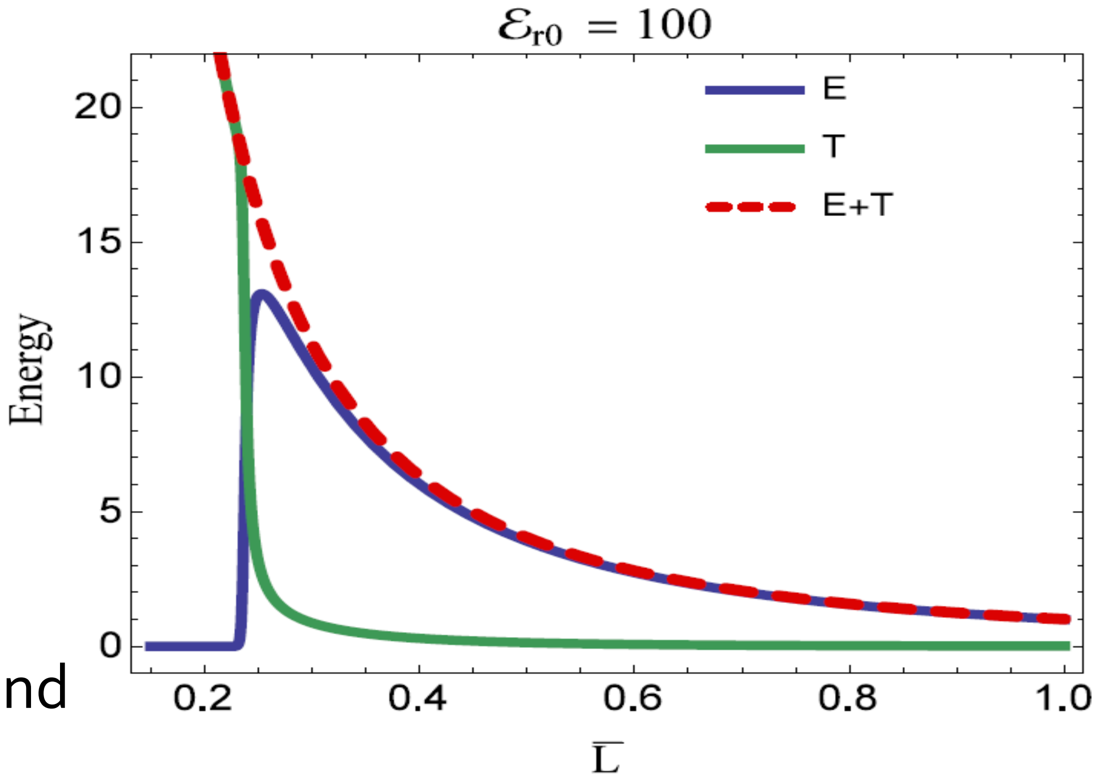
2. Compress, steadily increasing T

Instead:

1. Start with mostly TKE (E)

2. Compress, increasing both TKE and T (but, *colder → smaller losses?*)

3. Convert TKE → T at late stage



Need a conversion mechanism!

Plasma has a conversion mechanism!

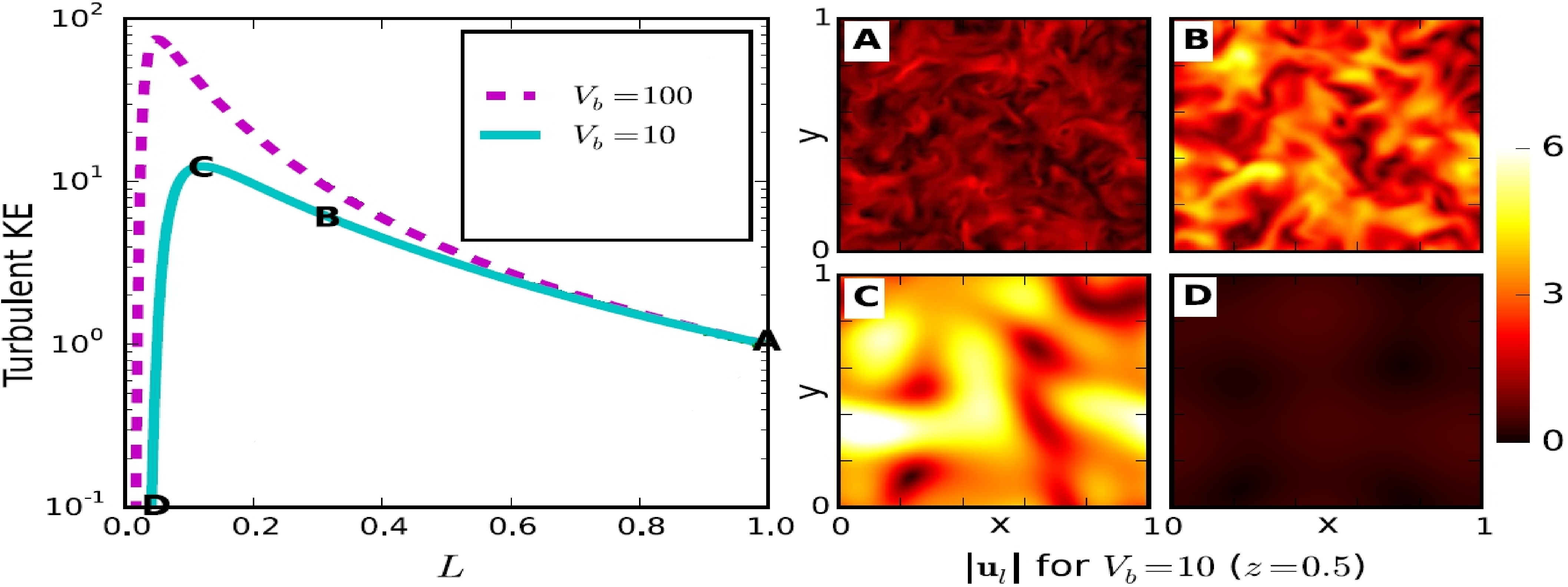
- Exists in plasma because of unique viscosity

$$\boxed{\mu_{\text{plasma}} \sim T^{5/2}/Z^4}$$

Heating →

Sudden viscous dissipation

- Compression: Amplifies TKE, T, … and the viscosity.



Davidovits & Fisch, *Phys. Rev. Lett.*, **116** 105004 (2016)

Sudden viscous dissipation animation

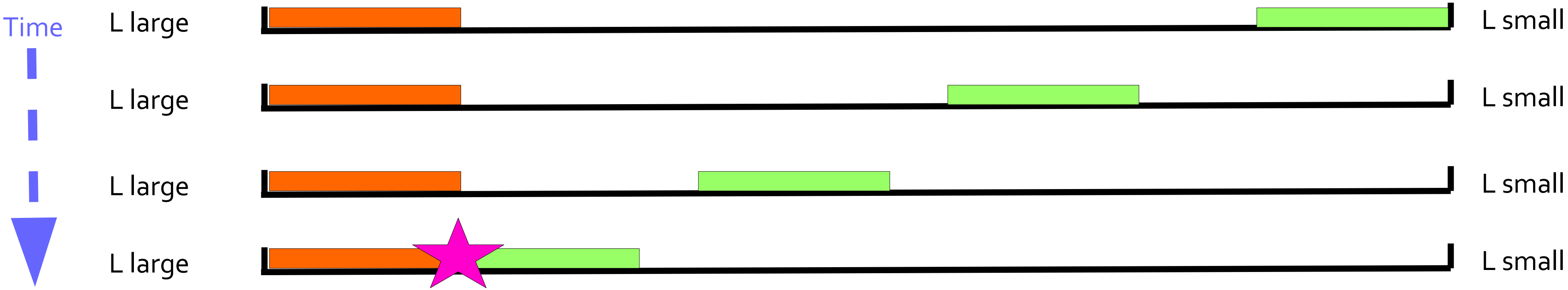
Sudden viscous dissipation

- Initial scale separation between energy injection (and containing) and energy removal

$$\frac{\partial \mathbf{v}}{\partial t} + \boxed{\frac{1}{\bar{L}}\mathbf{v}\cdot\nabla\mathbf{v}} - \frac{2U_b}{L}\mathbf{v} + \frac{\bar{L}^2}{\rho_0}\nabla P = \boxed{\frac{\bar{L}}{\rho_0}\mu(T,Z)\,\nabla^2\mathbf{v}}$$

Injection primarily at largest scales, where most energy resides

Cascade to removal at smallest scales

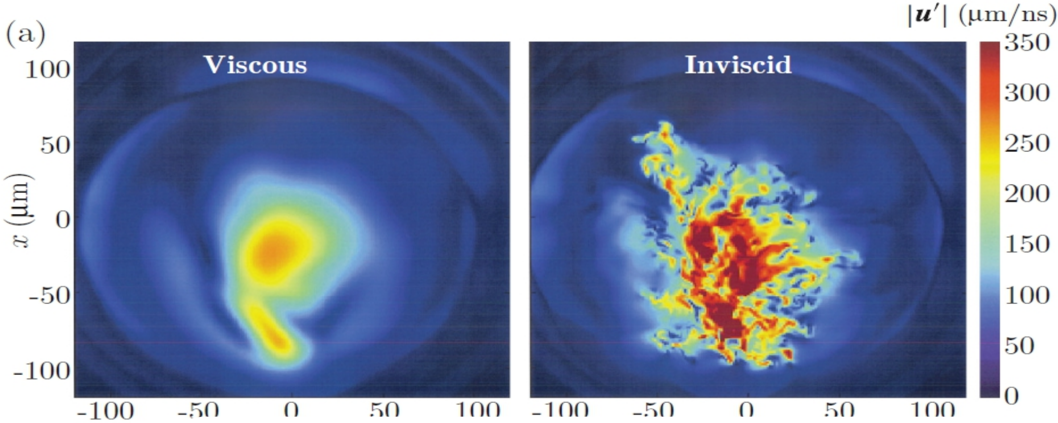


Viscous and inviscid regimes

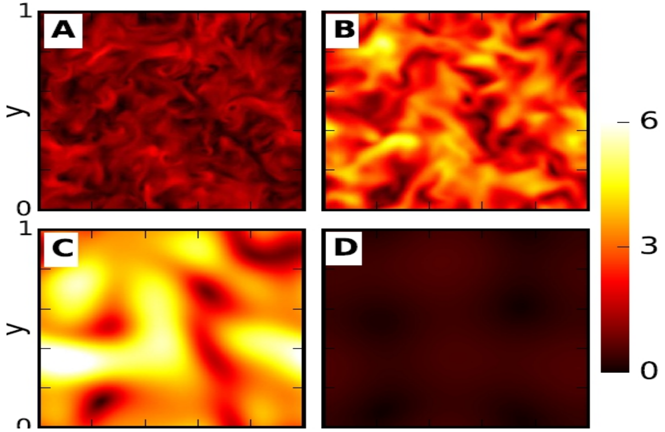
- Been discussing: strongly heated compressions, crossing between inviscid and viscous regimes

- Understanding of viscous impacts useful even in highly inviscid compressing turbulence:

  → molecular clouds



Weber et al., Phys. Rev. E, **89** 053106 (2014)



Davidovits & Fisch, *Phys. Rev. Lett.*, **116** 105004 (2016)

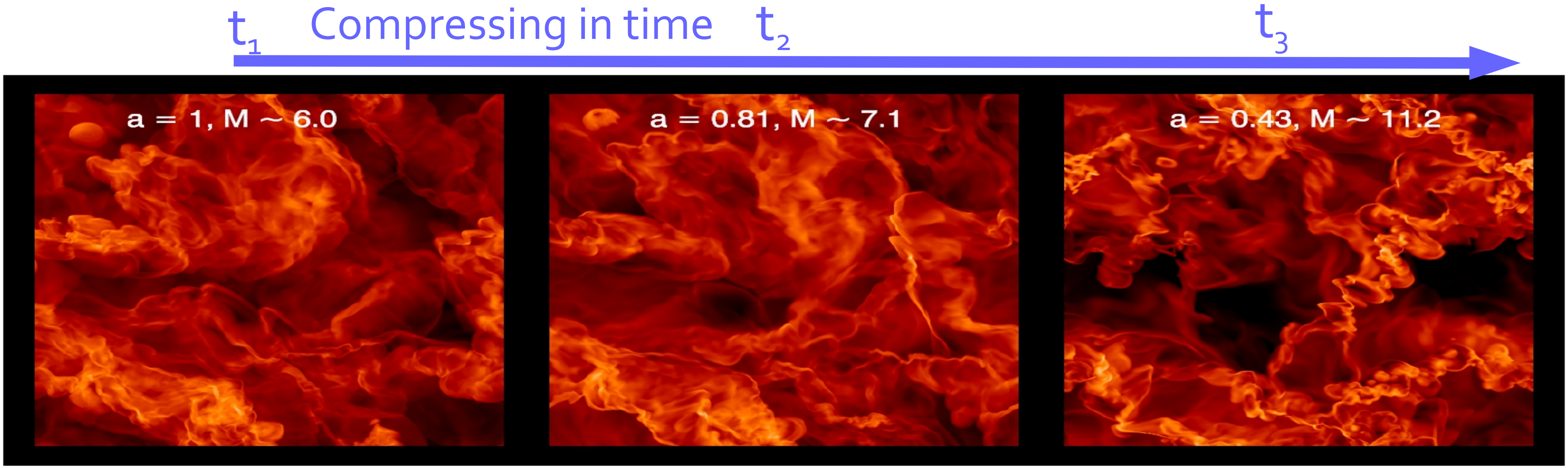
Molecular clouds

- Cloud of partially ionized gas
- Highly turbulent (supersonic, M_t~10), inviscid (Re huge)
- Compressing under self-gravity
- Star forming regions

  Turbulence → density distrubtion → star formation rate

European Space Agency/Herschel/PACS/SPIRE/HOBYS

TKE level → density distribution

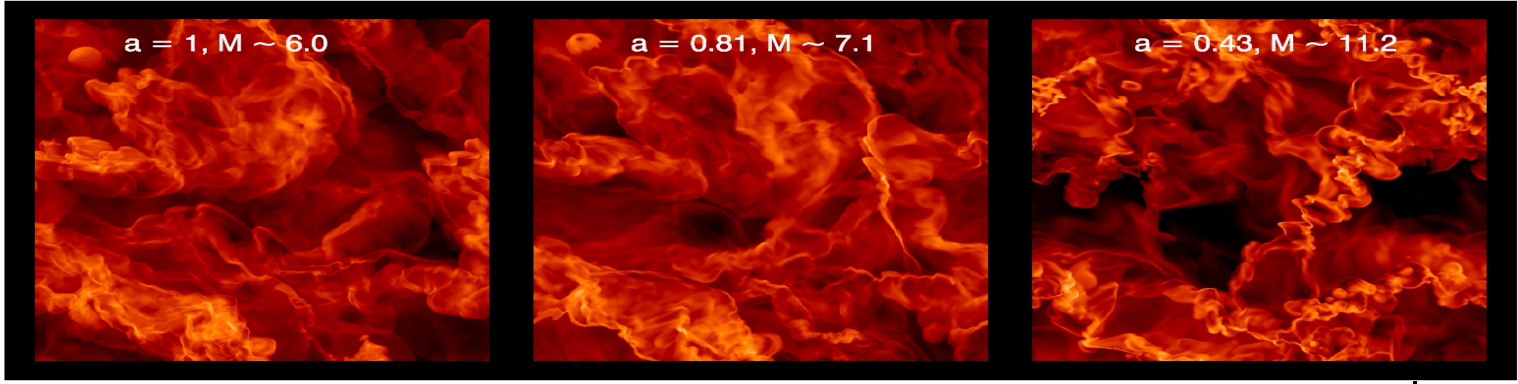


Robertson & Goldreich, *ApJL* **750** L31 (2012)

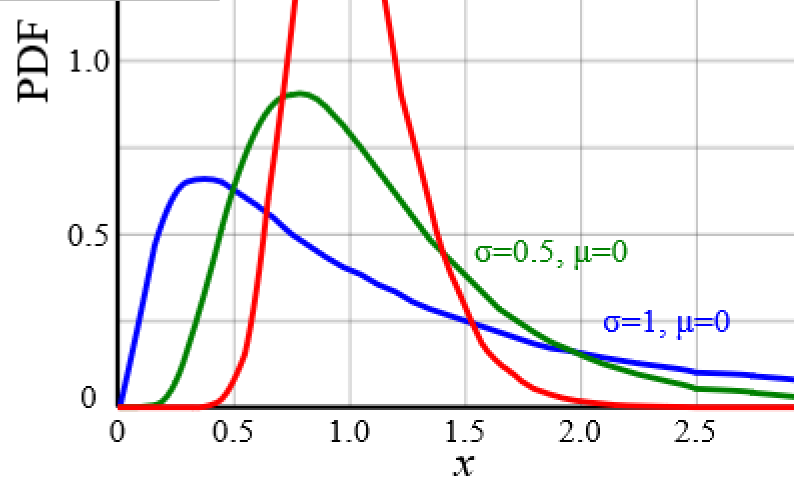
- Plotting plasma density (light → high, dark → low)
- M = turbulent mach number (~flow velocity)

TKE level → density distribution

t_1 t_2 t_3



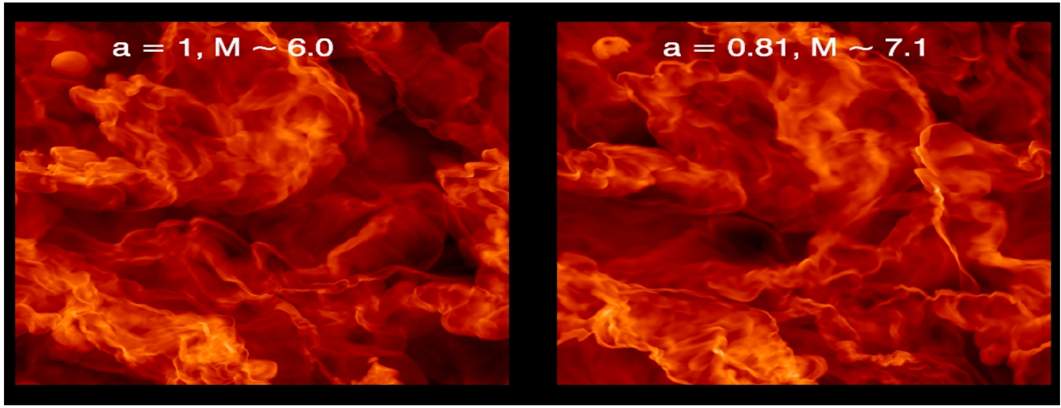
Red Green Blue

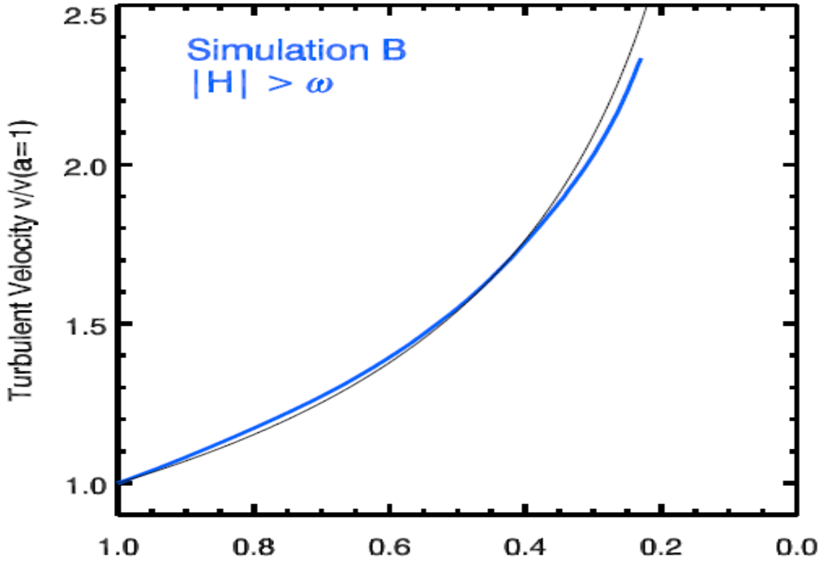


- Compression → increased TKE/M_t → changing density PDF → more extreme density region, more "holes" → impacts star formation activity

Existing modeling efforts

- Analytic model with coefficient determined by numerical simulation
- Correct?

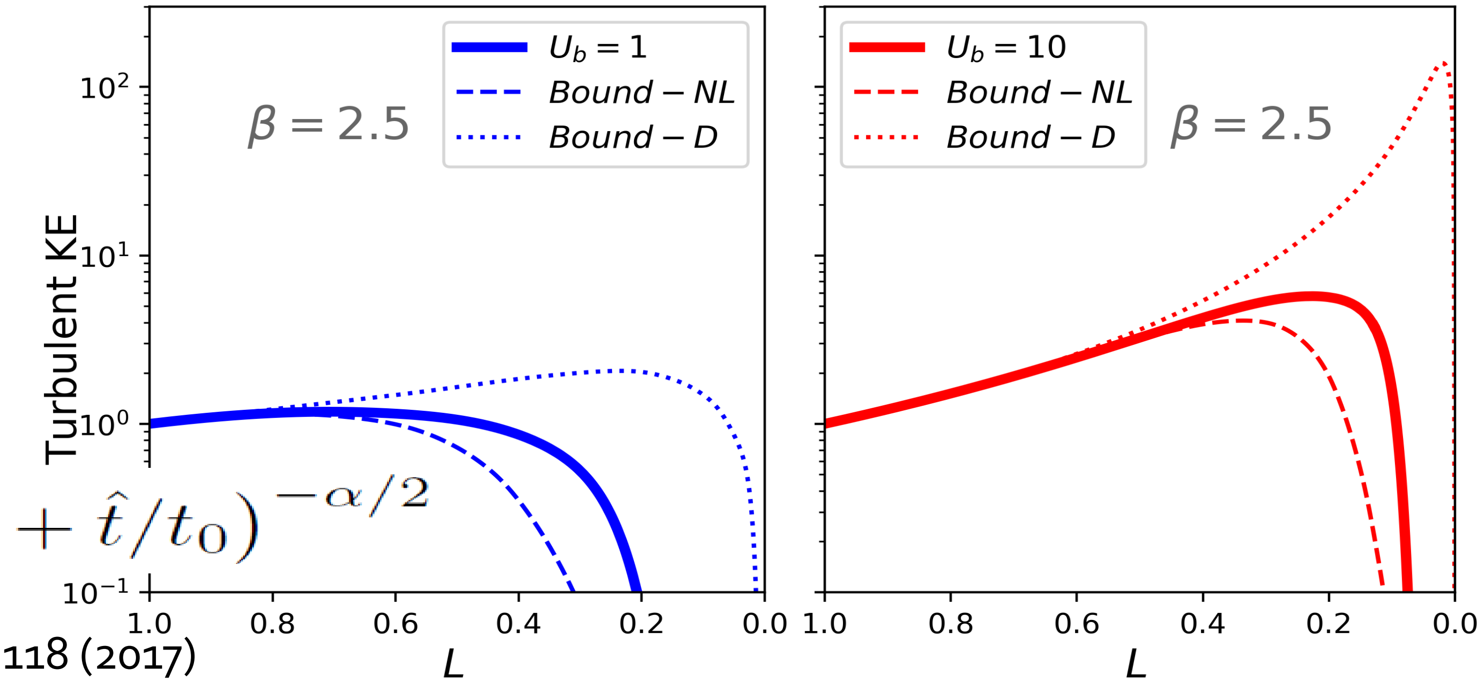




Robertson & Goldreich, *ApJL* **750** L31 (2012)

Created class of semi-analytic bounds on TKE

- Created by understanding the impact of viscosity variation
- Applied as a validation tool to existing molecular cloud TKE model
- Indicates simulation/model overestimate the amount of dissipation



$$\hat{v}_{\mathrm{rms}} \geq \hat{v}_{\mathrm{rms},0}\left(1+\hat{t}/t_0\right)^{-\alpha/2}$$

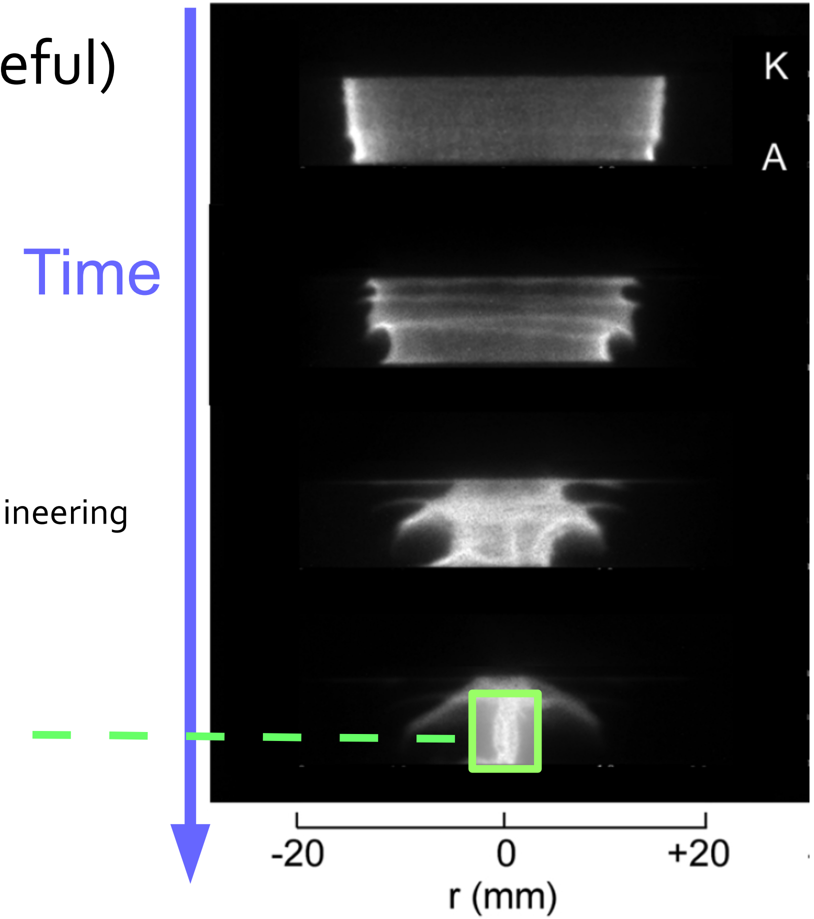
Davidovits & Fisch, *ApJ* **838** 118 (2017)

Supersonic plasma turbulence in the lab?

- Z-pinch compressions to generate X-rays (useful)
- Plasma compressed by magnetic field. Cylindrical geometry:

Bert Hickman/Stoneridge Engineering

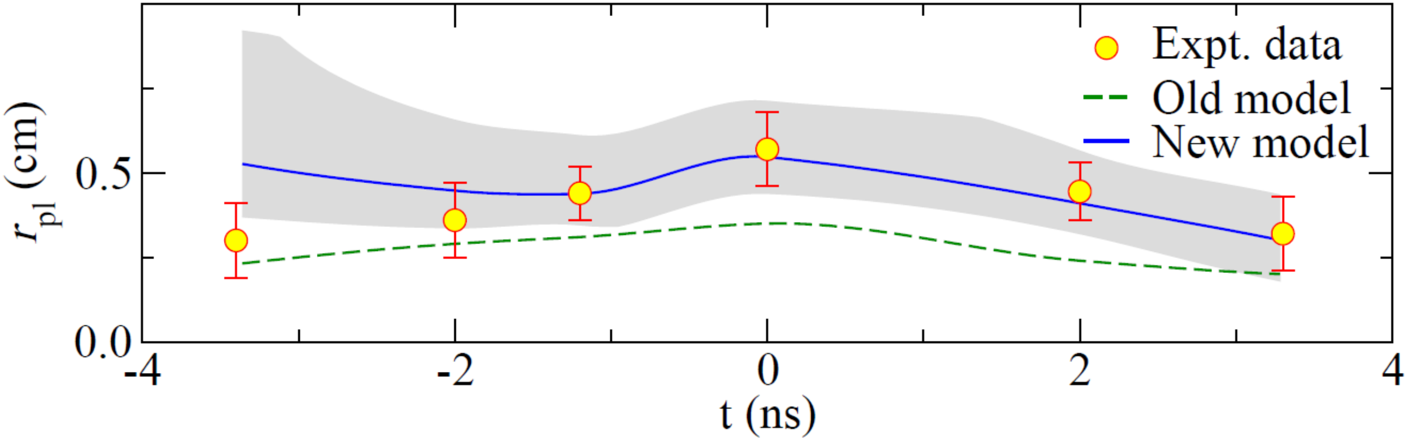
- Detailed measurements find large non-radial flow (Kroupp et al., PRL **107** 105001 (2011))



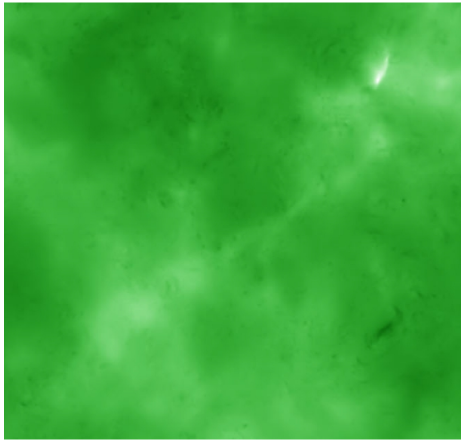
Osin et al., IEEE Transactions on Plasma Science **39** 2392 (2011)
Giuliani et al., Physics of Plasmas **21** 031209 (2014)

Supersonic plasma turbulence in the lab

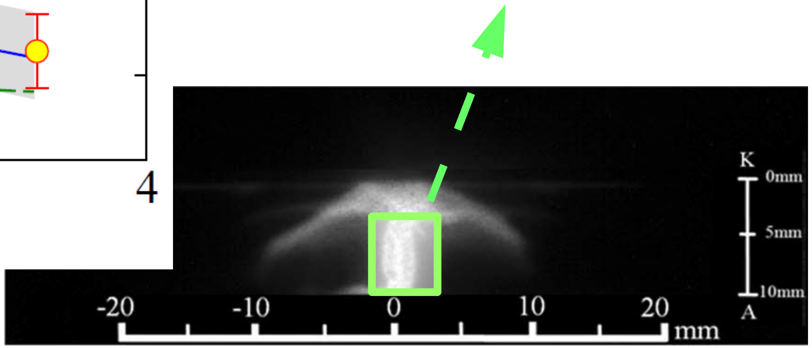
- New picture: Supersonic turbulence in Z-pinch stagnation
  - Better measurement agreement, physical consistency
- New spectroscopic analysis: account for density PDF



Kroupp et al. (incl. Davidovits),
Phys. Rev. E **97** 013202 (2018)



Adapted from:
Konstandin et al.
MNRAS **460** 4483 (2016)



Osin et al., IEEE Transactions on Plasma Science **39** 2392 (2011)

Viscosity context

- What makes these pinches so turbulent?
    - Active area
- Plasma viscosity is enabling:
  X-ray generating pinches compressing high Z (NIF hydrogen)

$$\boxed{\mu_{\text{plasma}} \sim T^{5/2}/Z^4}$$

Ionization

Summary

Turbulence undergoes compression in a variety of scenarios

-Important impacts in lab experiments (inertial fusion, Z-pinch) and natural world (molecular clouds)

-Need for understanding of plasma impacts [this talk: viscosity]

Conducting simulations, building predictive models, bounds

Highlighted today:

- Sudden viscous dissipation & new inertial fusion design concept
- Bound on turbulent velocity in molecular clouds
- New Z-pinch picture: turbulent stagnation

Thank you!

For further information on this topic

- Davidovits & Fisch, *Phys. Rev. E* **94** 053206 (2016)
- Davidovits & Fisch, *Phys. Rev. Lett.*, **116** 105004 (2016)
- Davidovits & Fisch, *ApJ* **838** 118 (2017)
- Davidovits & Fisch, *Phys. Plasmas* **24** 122311 (2017)
- Kroupp et al., *Phys. Rev. E* **97** 013202 (2018)
- Davidovits & Fisch, Phys. Plasmas **25** 042703(2018)