Physical Mechanisms Driving Gyrokinetic Turbulence

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(based on APS talk
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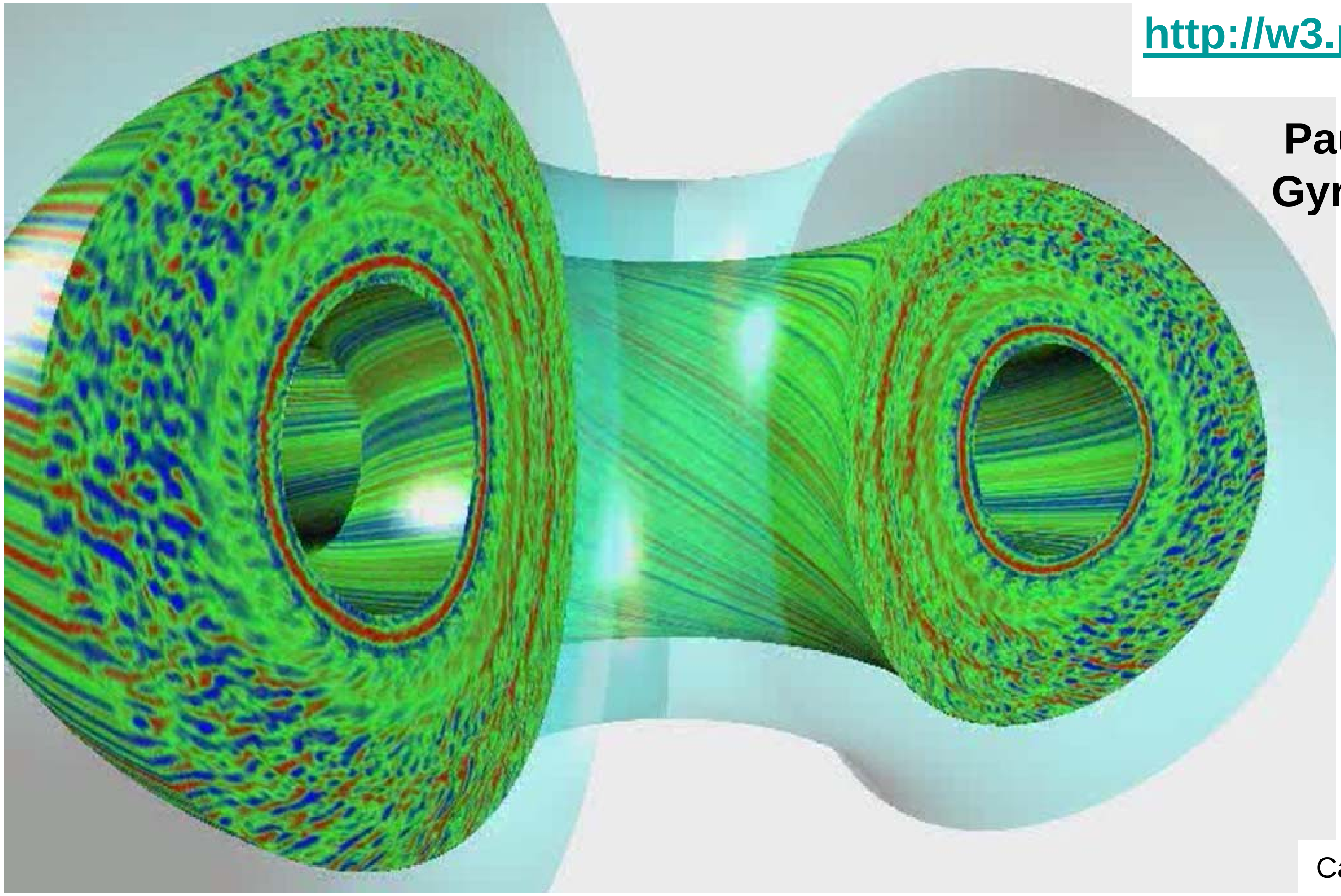


Candy, Waltz (General Atomics)

Physical Mechanisms Driving Gyrokinetic Turbulence

Intuitive pictures of gyrokinetic turbulence, & how to reduce it:

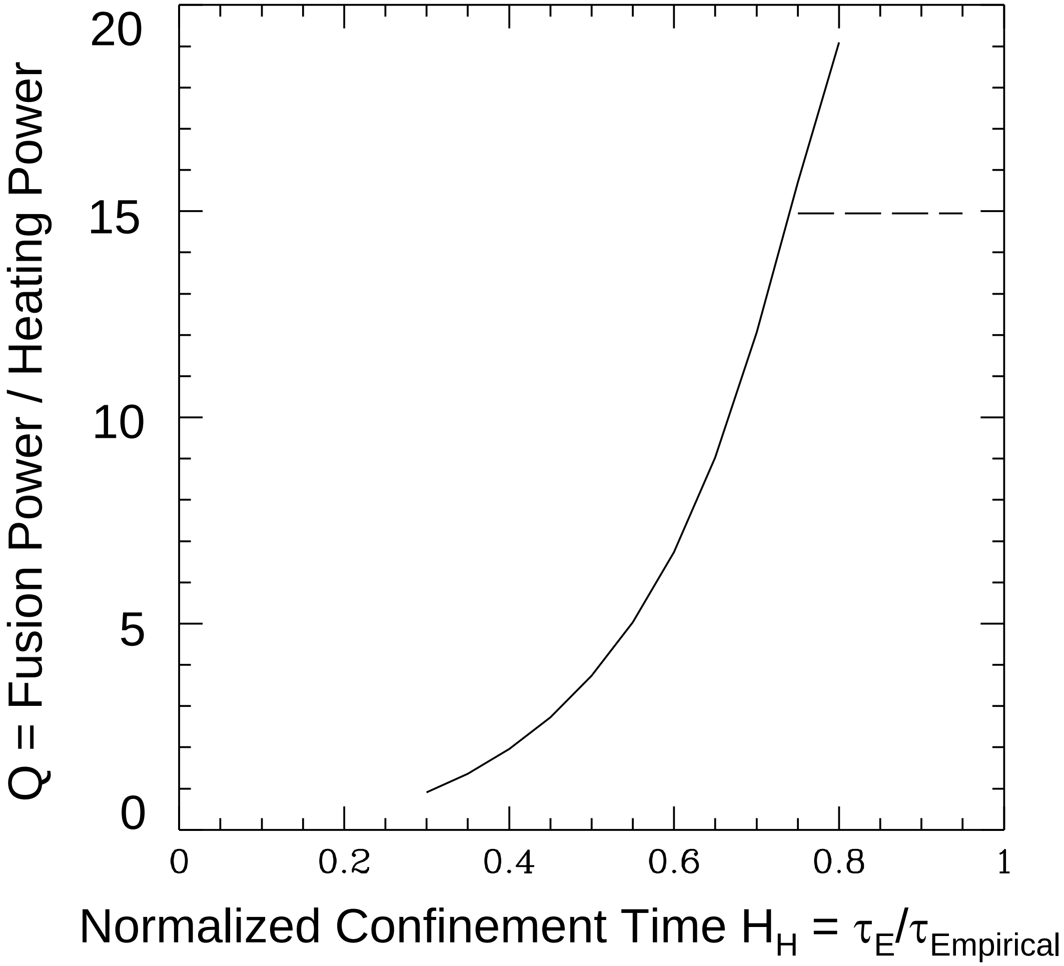
- analogy with inverted pendulum / Rayleigh-Taylor instability
- reducing turbulence with sheared flows, magnetic shear, plasma shaping → advanced tokamak & advanced stellarator designs

Motivation & Summary

Fusion performance depends sensitively on confinement

Sensitive dependence on turbulent confinement causes some uncertainties, but also gives opportunities for significant improvements, if methods of reducing turbulence extrapolate to larger reactor scales.

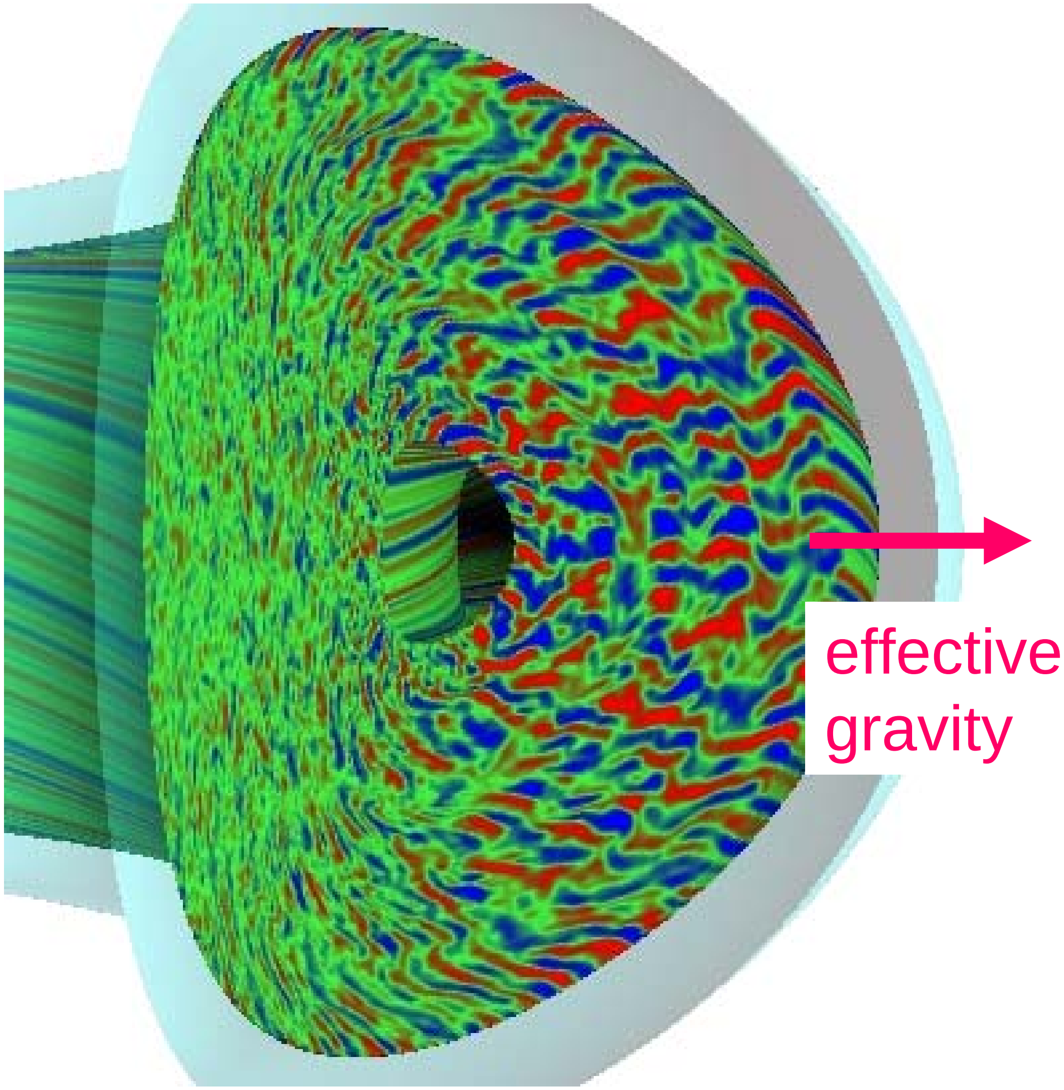
$$\frac{dE}{dt} = P_{ext} + P_{fusion} - \frac{E}{\tau_E}$$



Caveats: best if MHD pressure limits also improve with improved confinement.
Other limits also: power load on divertor & wall, …

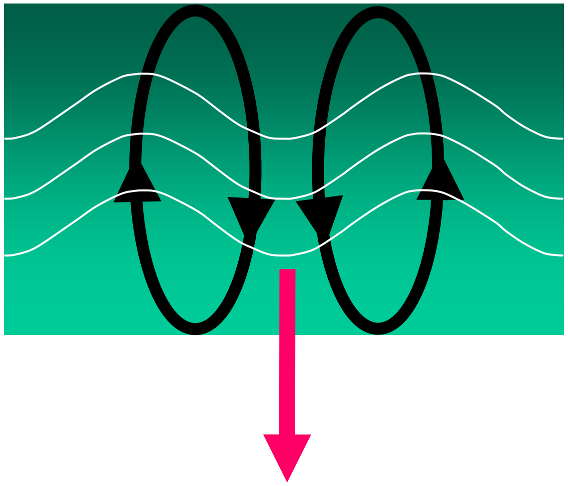
1. Intuitive pictures of gyrokinetic turbulence, & how to reduce it

- analogy w/ inverted pendulum / Rayleigh-Taylor instability
- reduce turbulence with sheared flows, magnetic shear, …



Inverted-density fluid

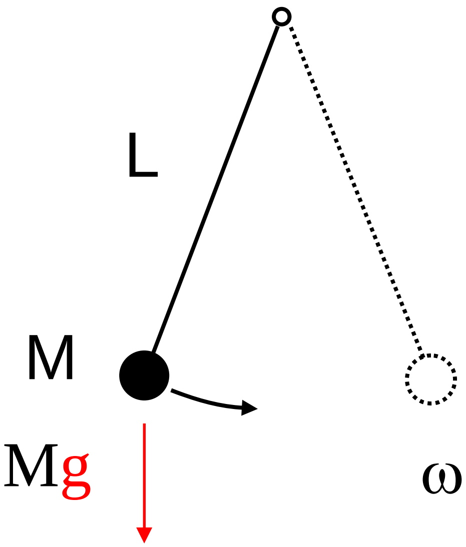
⇒Rayleigh-Taylor Instability



1. Intuitive pictures of gyrokinetic turbulence, & how to reduce it

(many of these insights developed with gyrofluid simulations in 1990's, but gyrokinetics provides higher accuracy.)

Stable Pendulum

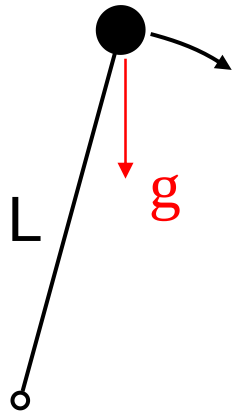


$F=Mg$

$\omega=(g/L)^{1/2}$

Unstable Inverted Pendulum

(rigid rod)

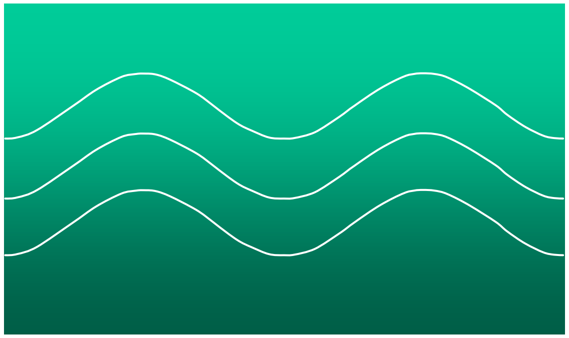


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

$\rho=\exp(-y/L)$

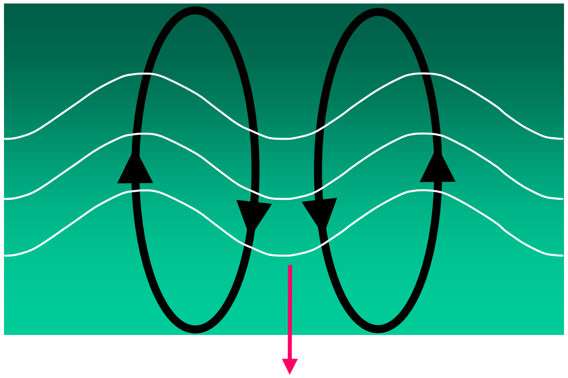


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

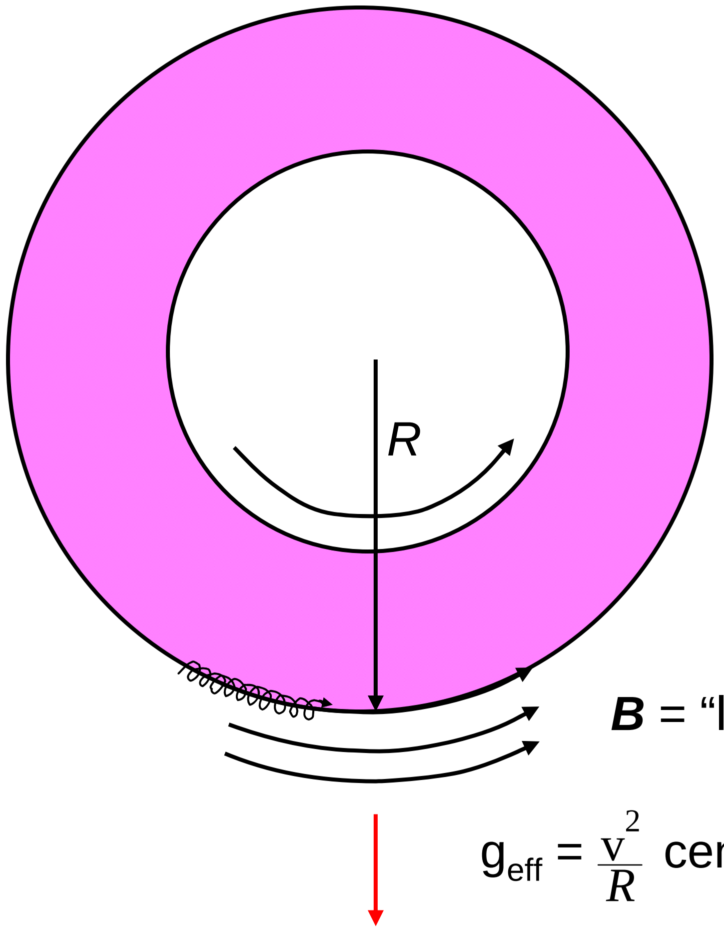
$\rho=\exp(y/L)$



Max growth rate $\gamma=(g/L)^{1/2}$

“Bad Curvature” instability in plasmas
≈ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



plasma = heavy fluid

B = “light fluid”

$g_{eff} = \frac{v^2}{R}$ centrifugal force

Growth rate:

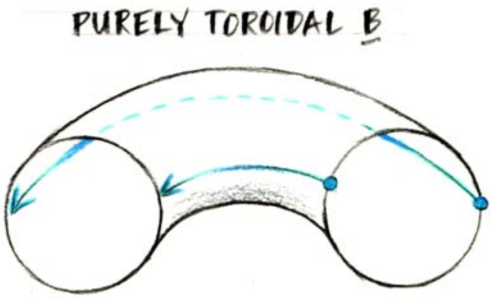
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{V_t^2}{RL}} = \frac{V_t}{\sqrt{RL}}$$

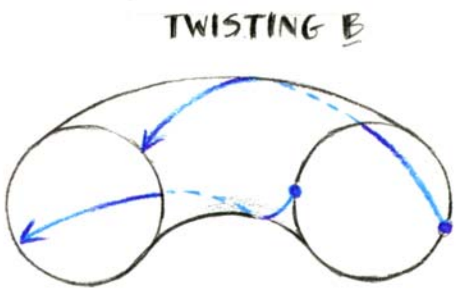
Similar instability mechanism
in MHD & drift/microinstabilities

1/L = ∇p/p in MHD,
∝ combination of ∇n & ∇T
in microinstabilities.

The Secret for Stabilizing Bad-Curvature Instabilities

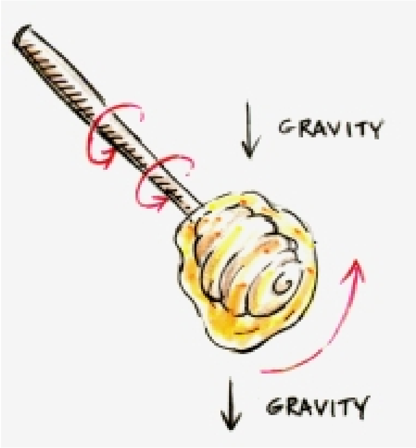
Twist in ***B*** carries plasma from bad curvature region to good curvature region:





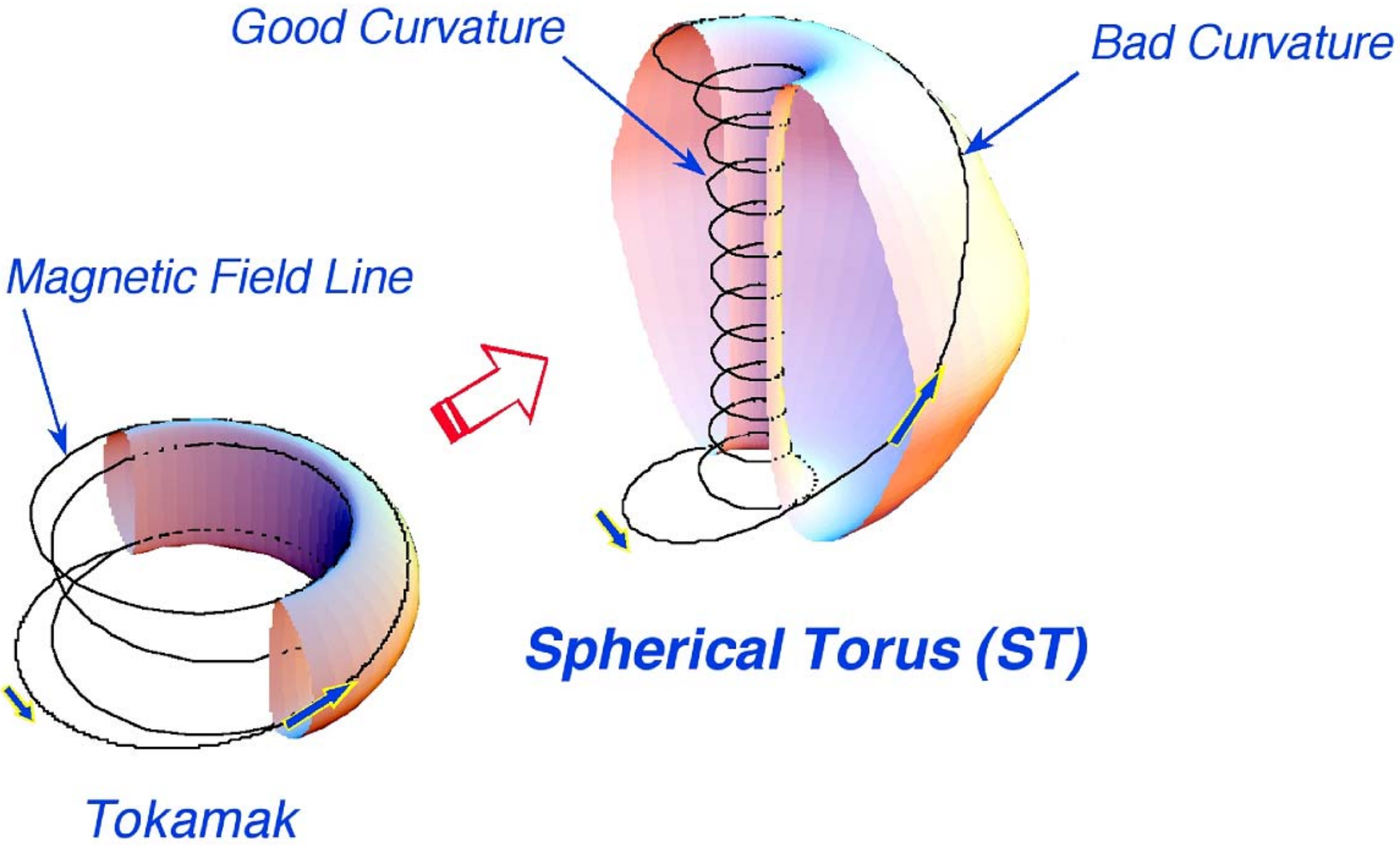
Unstable

Stable

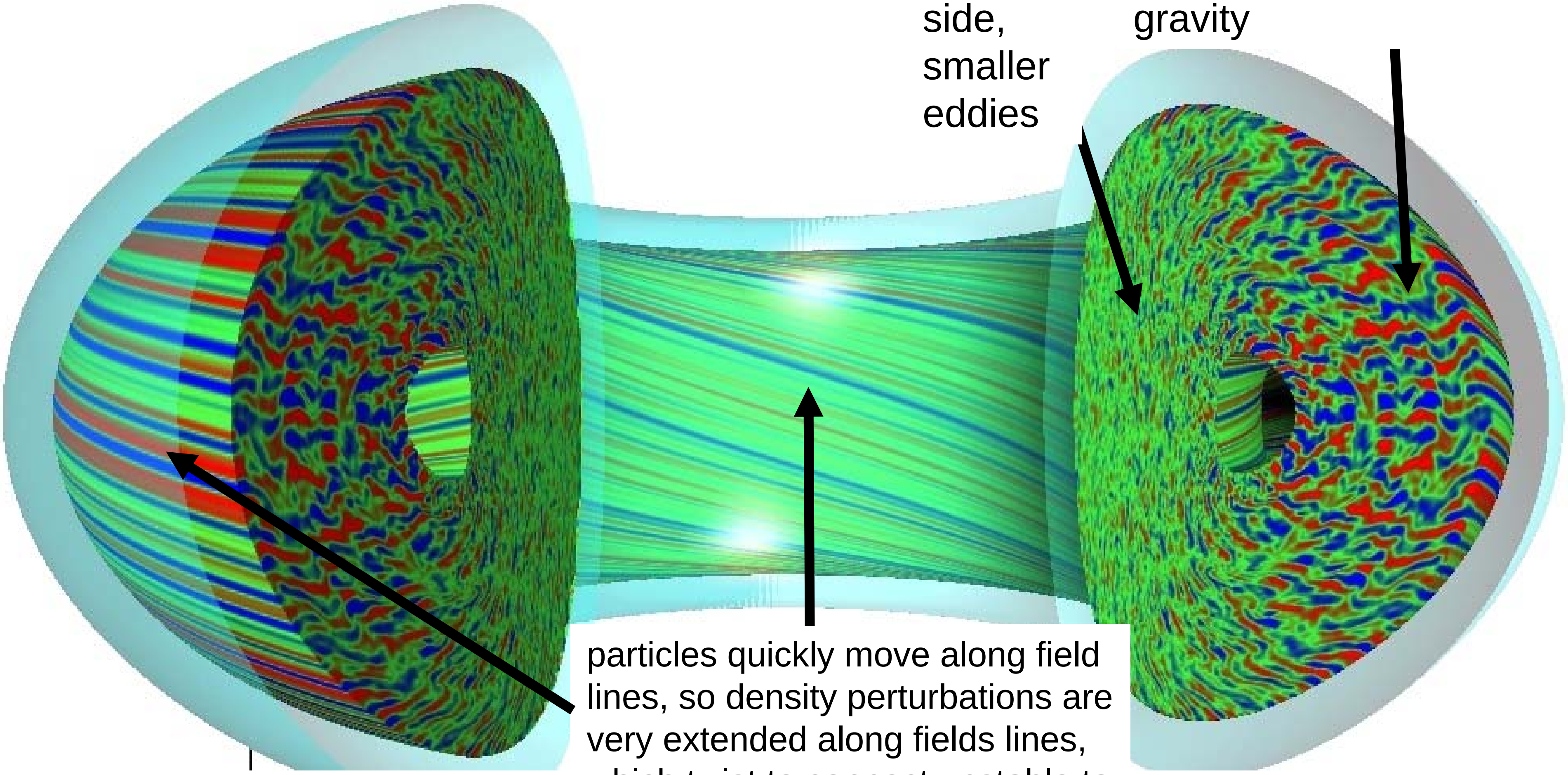


Similar to how twirling a honey dipper can prevent honey from dripping.

Spherical Torus has improved confinement and pressure limits (but less room in center for coils)



These physical mechanisms can be seen in gyrokinetic simulations and movies

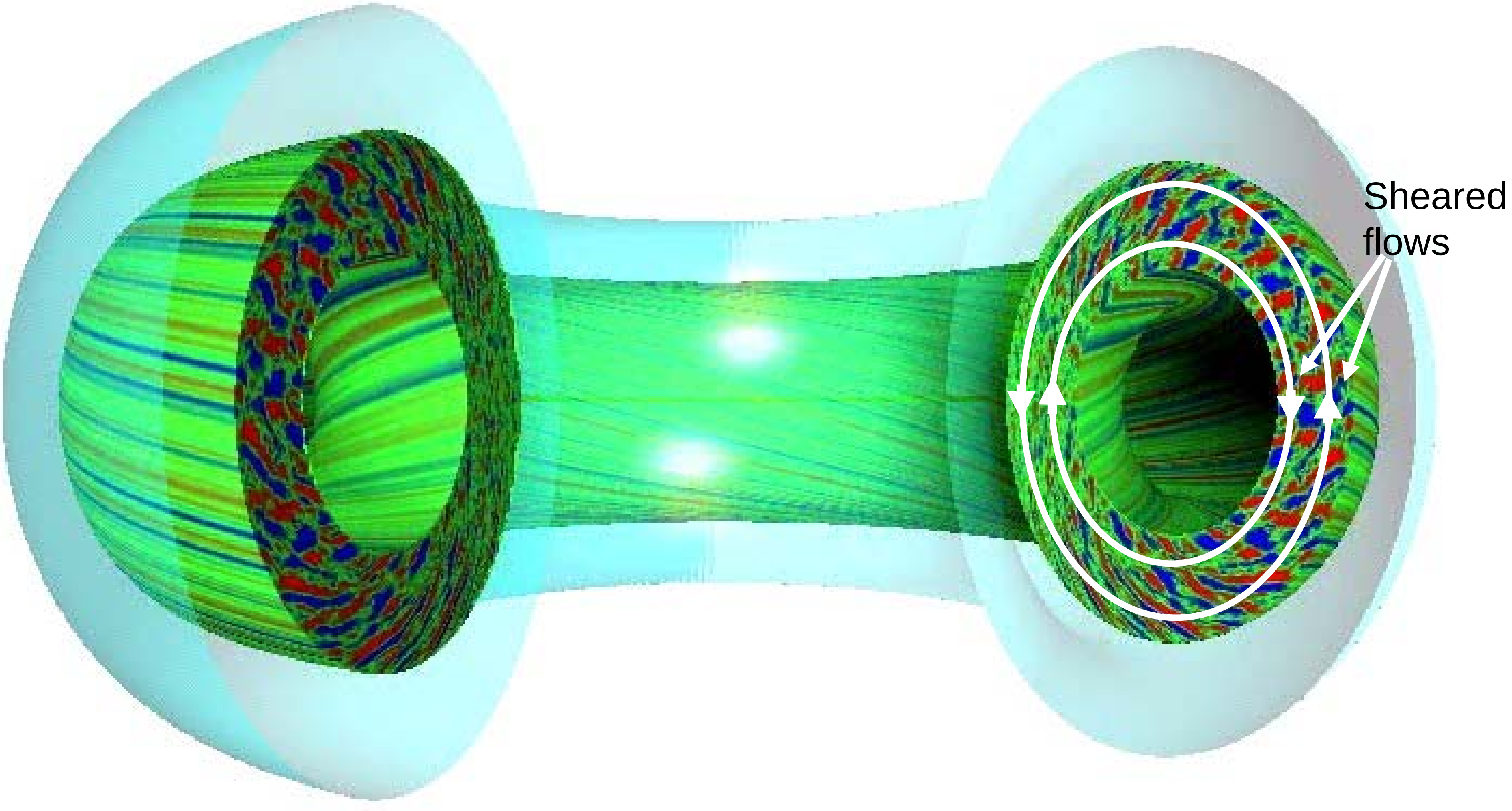


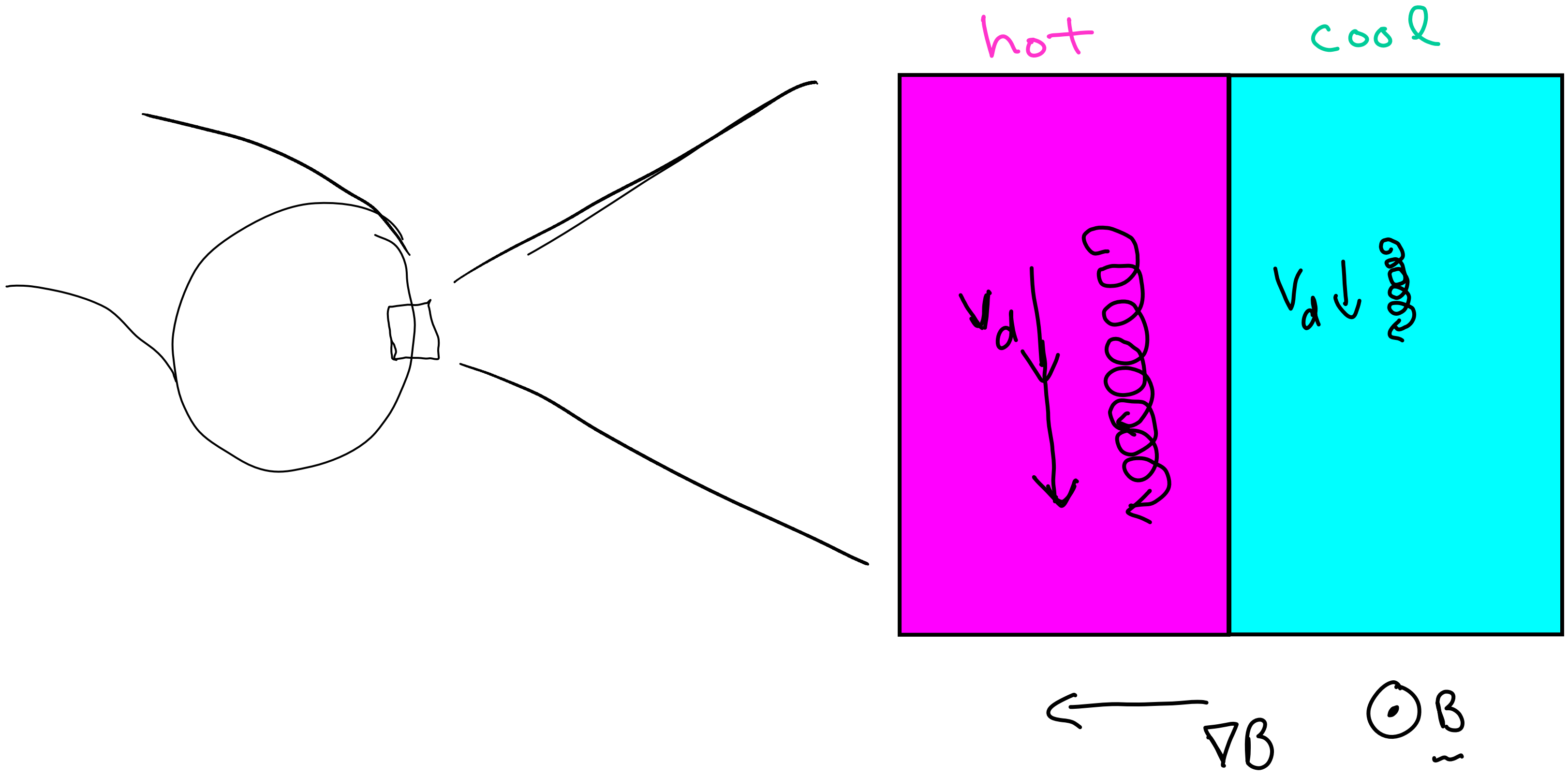
Stable side, smaller eddies

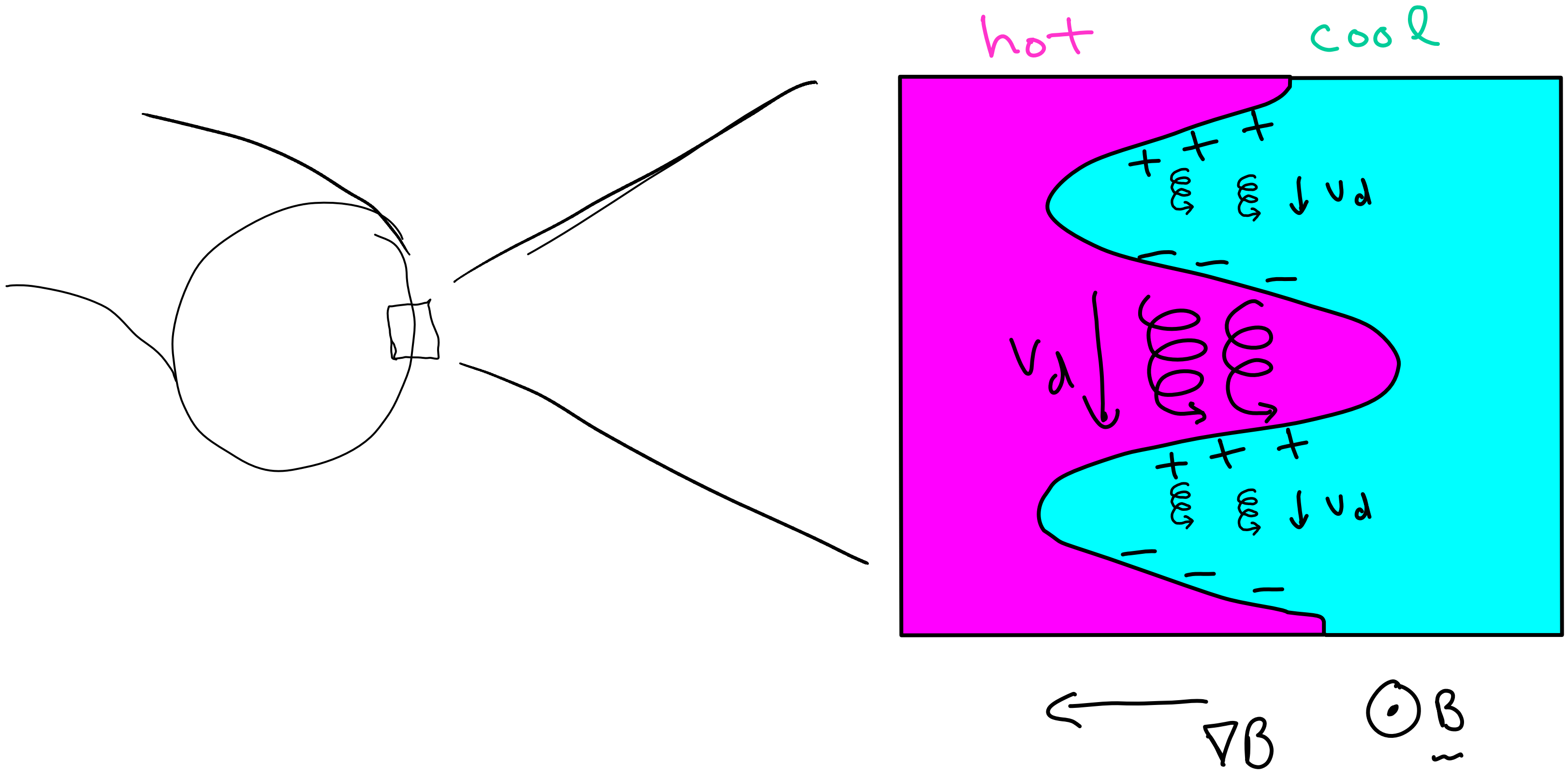
Unstable bad-curvature side, eddies point out, direction of effective gravity

particles quickly move along field lines, so density perturbations are very extended along fields lines, which twist to connect unstable to stable side

Movie http://fusion.gat.com/THEORY/images/3/35/D3d.n16.2x_0.6_fly.mpg from http://fusion.gat.com/theory/Gyromovies shows contour plots of density fluctuations in a cut-away view of a GYRO simulation (Candy & Waltz, GA). This movie illustrates the physical mechanisms described in the last few slides. It also illustrates the important effect of sheared flows in breaking up and limiting the turbulent eddies. Long-wavelength equilibrium sheared flows in this case are driven primarily by external toroidal beam injection. (The movie is made in the frame of reference rotating with the plasma in the middle of the simulation. Barber pole effect makes the dominantly-toroidal rotation appear poloidal..) Short-wavelength, turbulent-driven flows also play important role in nonlinear saturation.




hot
cool
V_d
V_d
∇B
$\odot \underset{\sim}{B}$


hot
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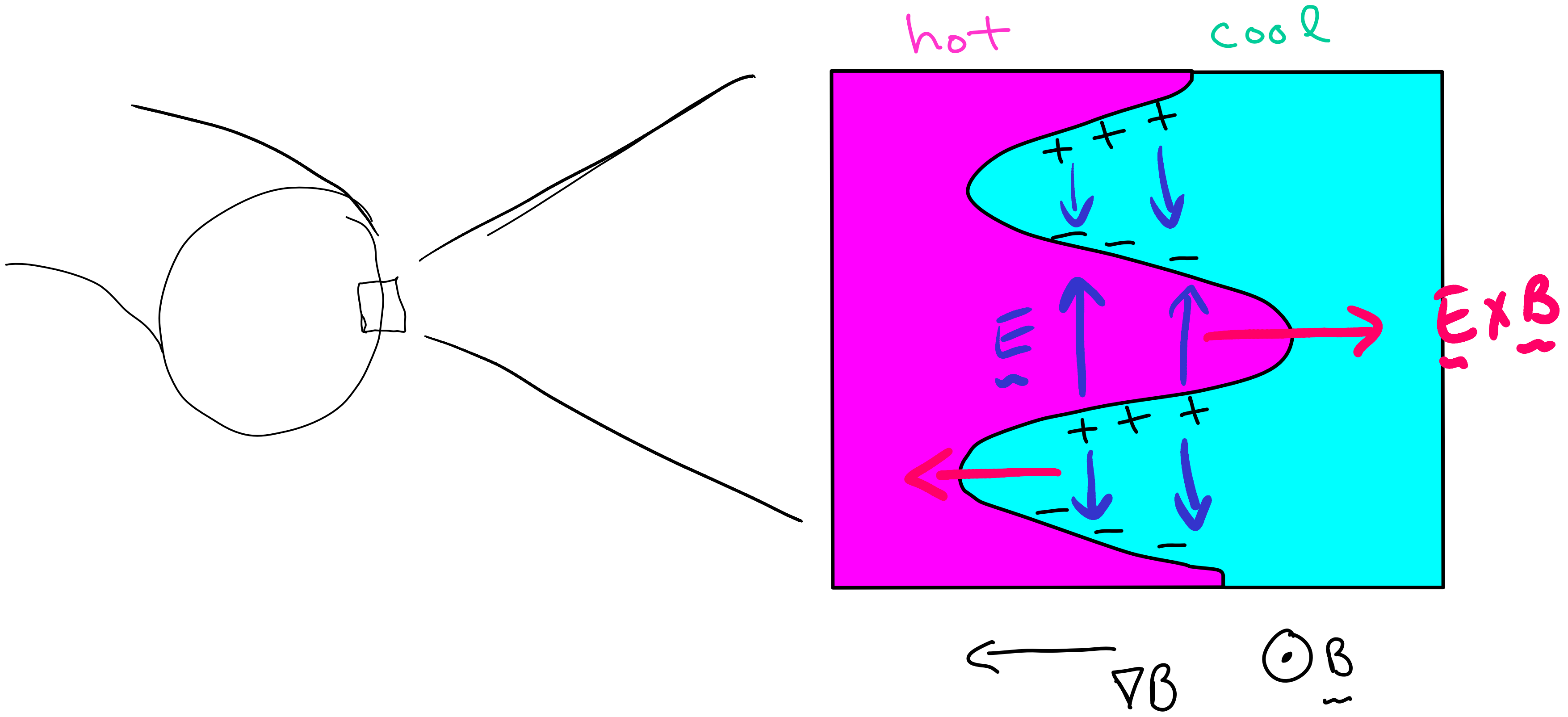
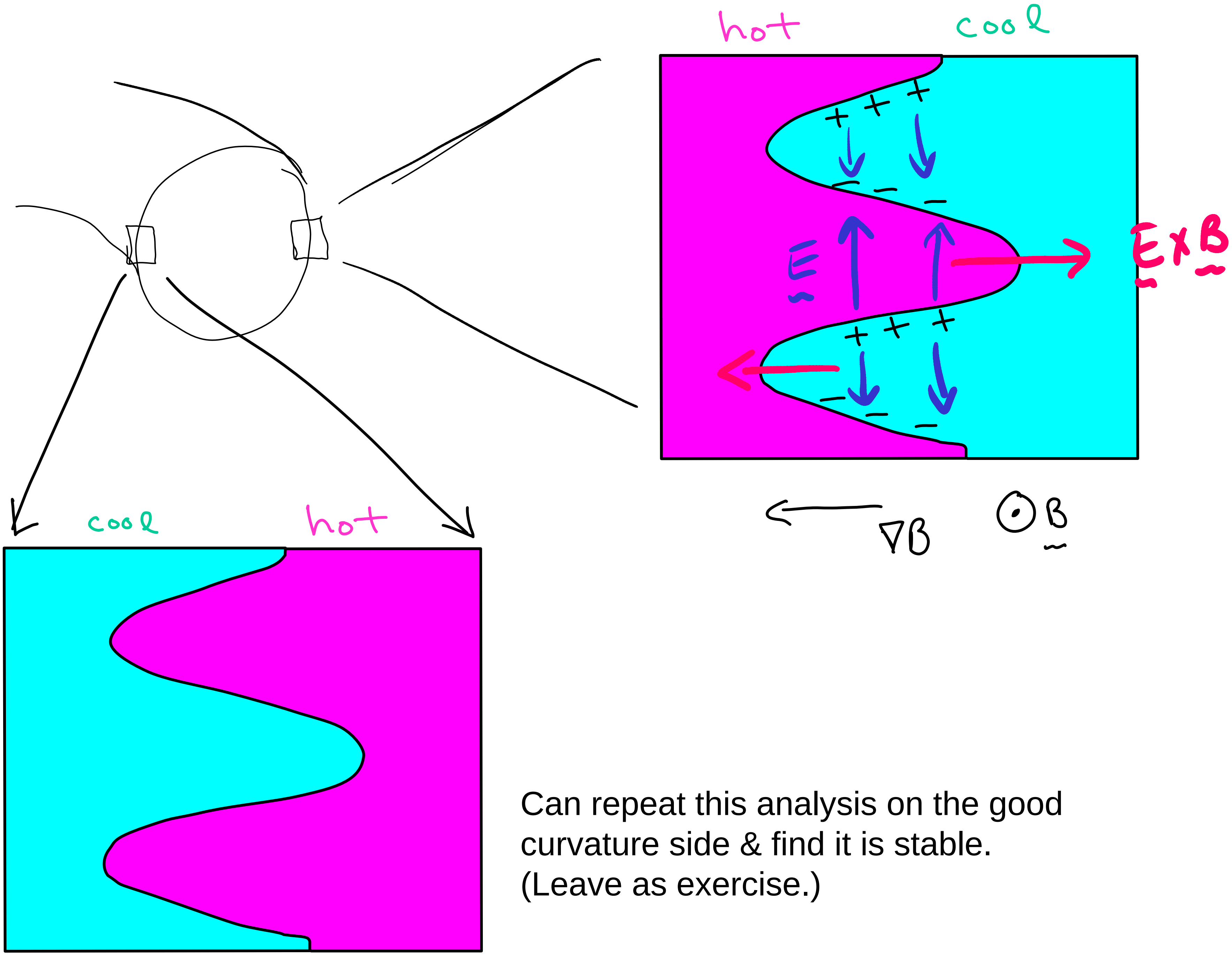
+ + +
v_d
- - -
∇B
B



Higher energy particles ∇B drift faster, creates charge separation & thus $\underset{\sim}{E}$ field, causes $E \times B$ flow that further accentuates perturbation. Positive feedback ⇒ instability.

Rosenbluth-Longmire picture



Can repeat this analysis on the good curvature side & find it is stable. (Leave as exercise.)

Rosenbluth-Longmire picture

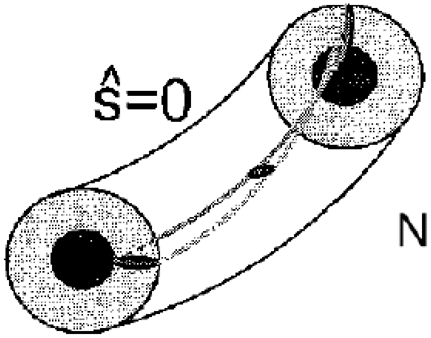
Simple picture of reducing turbulence by negative magnetic shear

Particles that produce an eddy tend to follow field lines.

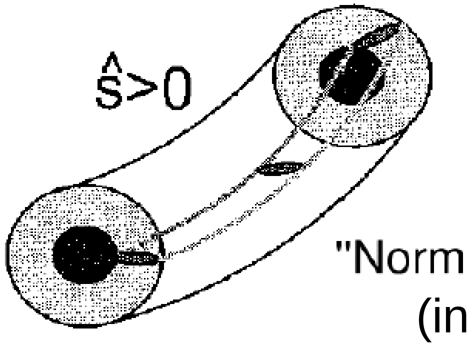
Reversed magnetic shear twists eddy in a short distance to point in the ``good curvature direction".

Locally reversed magnetic shear naturally produced by squeezing magnetic fields at high plasma pressure: ``Second stability" Advanced Tokamak or Spherical Torus.

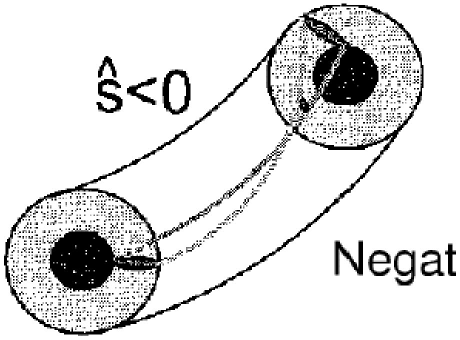
Shaping the plasma (elongation and triangularity) can also change local shear



No Magnetic Shear



"Normal" Magnetic Shear
(in std tokamaks)



Advanced Tokamaks

Negative Magnetic Shear
“Normal” in stellarators

Fig. from Antonsen, Drake, Guzdar et al. Phys. Plasmas 96
Kessel, Manickam, Rewoldt, Tang Phys. Rev. Lett. 94

Selected Gyrokinetic References

- This talk available at w3.pppl.gov/~hammett/talks
- 3 GYRO movies shown (d3d.n16.2x_06_fly, n32o6d0.8, & ETG-ki) from http://fusion.gat.com/theory/Gyromovies
- Web sites for 4 main gyrokinetic codes discussed here (incl. refs., documentation):
  - GYRO (Waltz & Candy, GA): fusion.gat.com/theory/Gyro
  - GS2 (Dorland & Kotschenreuther, U. Maryland/Texas): gs2.sourceforge.net
  - GENE (Jenko, Garching): www.ipp.mpg.de/~fsj
  - GEM (Parker & Chen, U. Colorado): cips.colorado.edu/simulation/gem.htm

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- T.S. Hahm, A. Brizard, W.W. Lee, W. Tang, J. Krommes, T. Stoltzfus-Dueck
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- DOE Scientific Discovery Through Advanced Computing (SciDAC)
  - Center for the Study of Plasma Microturbulence
  - Edge Simulation Laboratory
  - Earlier DOE SciDAC & Computational Grand Challenge projects, including Plasma Microturbulence Project & Numerical Tokamak Project
- DOE National Energy Research Supercomputing Center (NERSC)
- Many others…