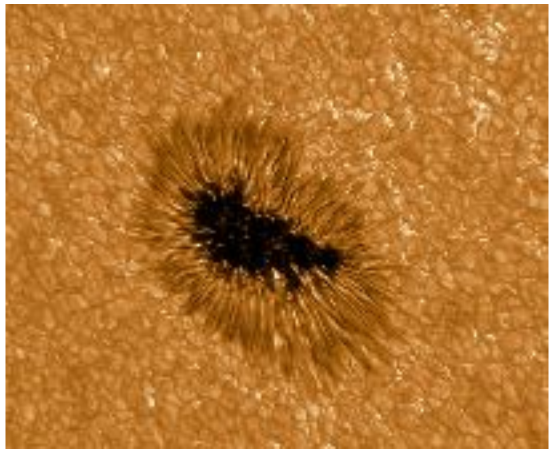
Lecture course: Computational Fluid Dynamics

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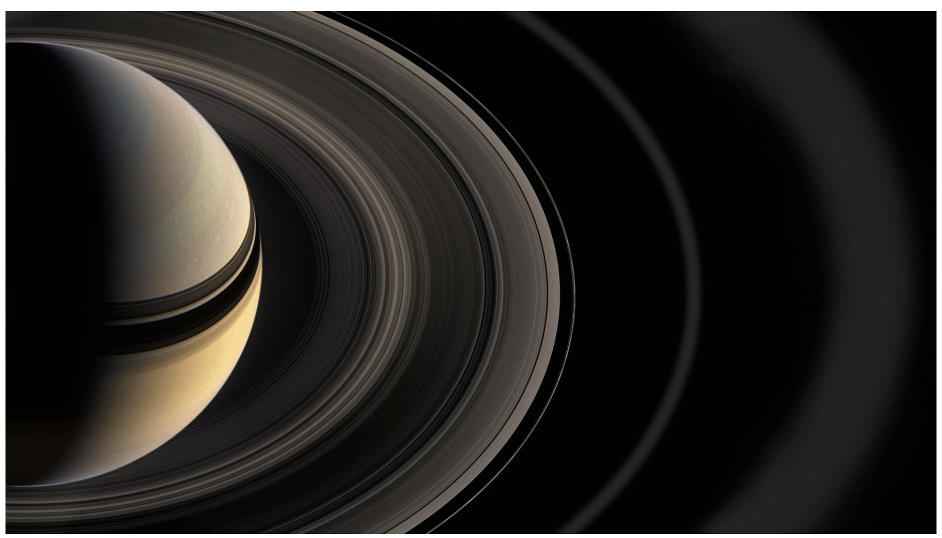
Lecture 1: Preliminaries

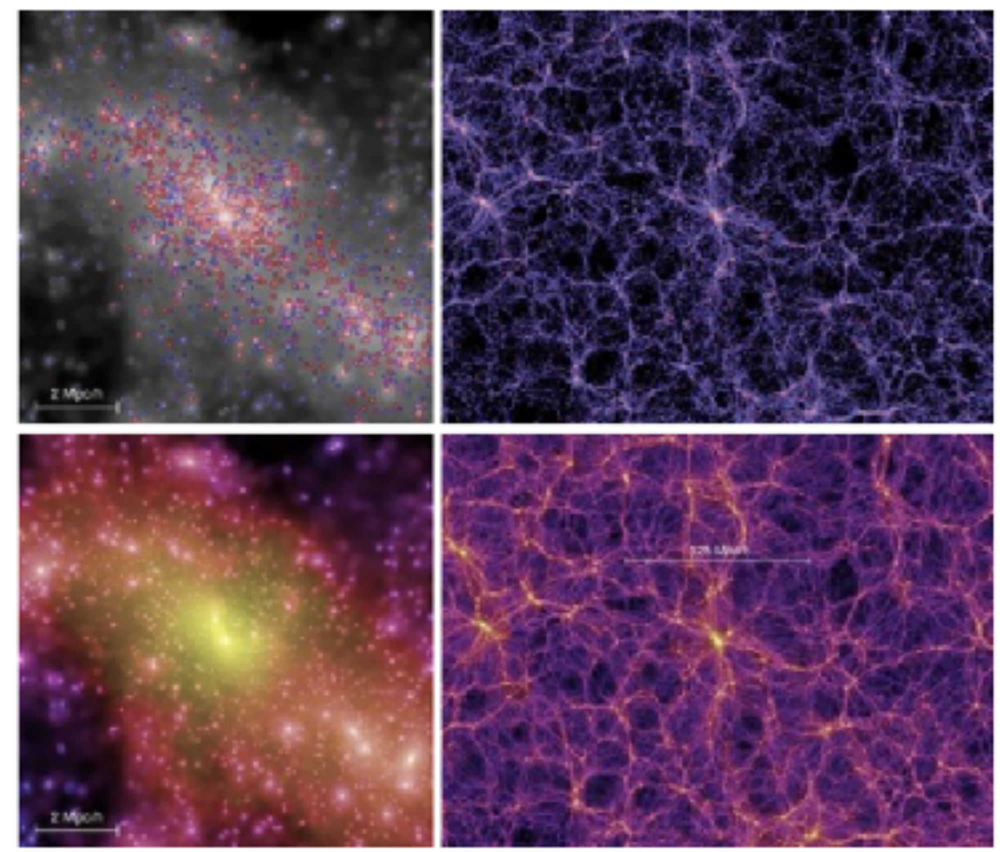
Astrophysical ‘fluids’: ubiquitous in the Universe on all scales

Dust rings of Saturn



Credit: NASA/JPL-Caltech/Space Science Institute

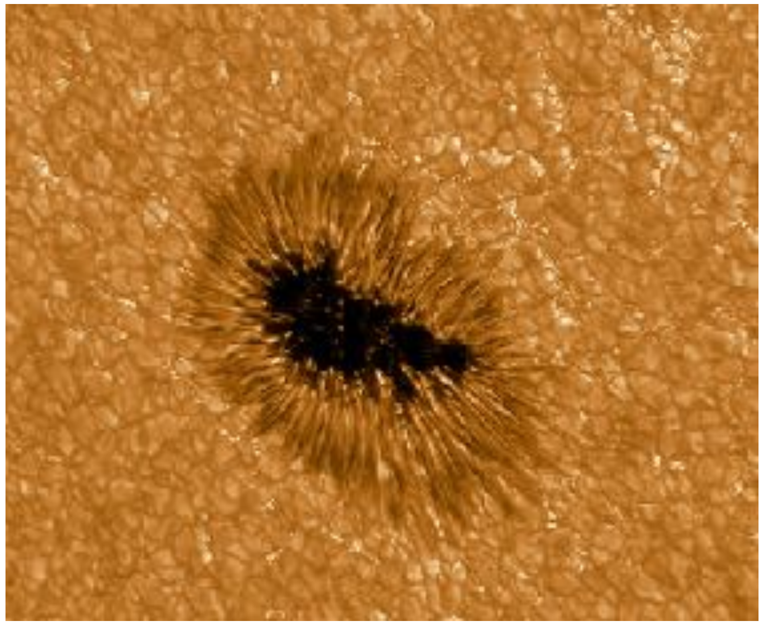
Matter distribution of the Universe



Credit: Springel et al. 2005, Nature, 435, 629

Astrophysical ‘fluids’: a few more examples…

Solar & stellar astrophysics



Credit: Leibniz Institute for Solar Physics (KIS)

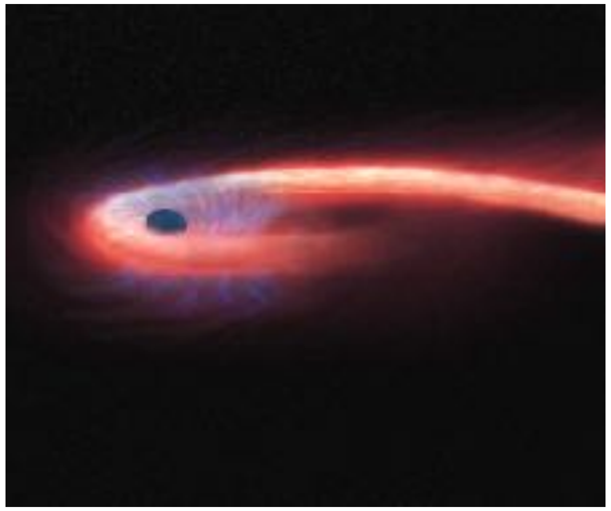
Supernova remnants

Credit: NASA, STScI, ESA

Interstellar medium

Credit: NASA

Tidal disruption events



Credit: NASA / CXC / M. Weiss

Neutron-star mergers

Credit: Robin Dienel, Carnegie Institution for Science

Astrophysical fluid dynamics

- Astrophysical fluid flows central to understanding our universe

  → equations of gas/plasma dynamics (hydrodynamics)
  (+ gravity and microphysics: chemistry, nuclear & atomic physics, EM fields, etc.)

- Receive information about the universe based on EM radiation that is reprocessed as it travels toward us

  → equations of radiation transport

- We now also receive information via gravitational waves and high-energy particles

  → multi-messenger astrophysics

Interpretation of observational data

Theoretical interpretation of observational data (stages of refinement):

Analytical estimates

("back of the envelope" calculations)

(Semi-)analytic calculations

(using simplifications/approximations)

Full-scale numerical simulations

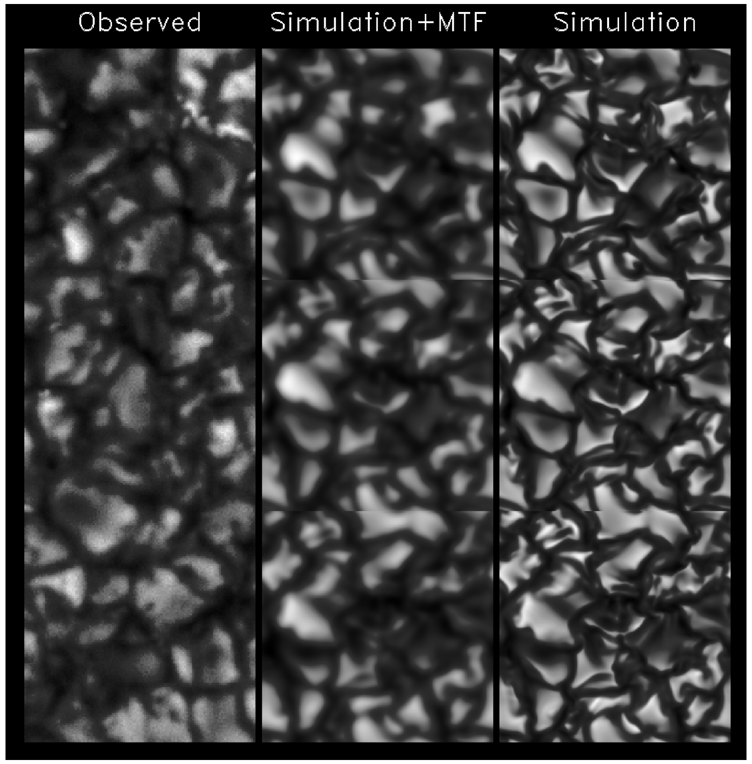
Credit: NASA

experiment
'substitute'

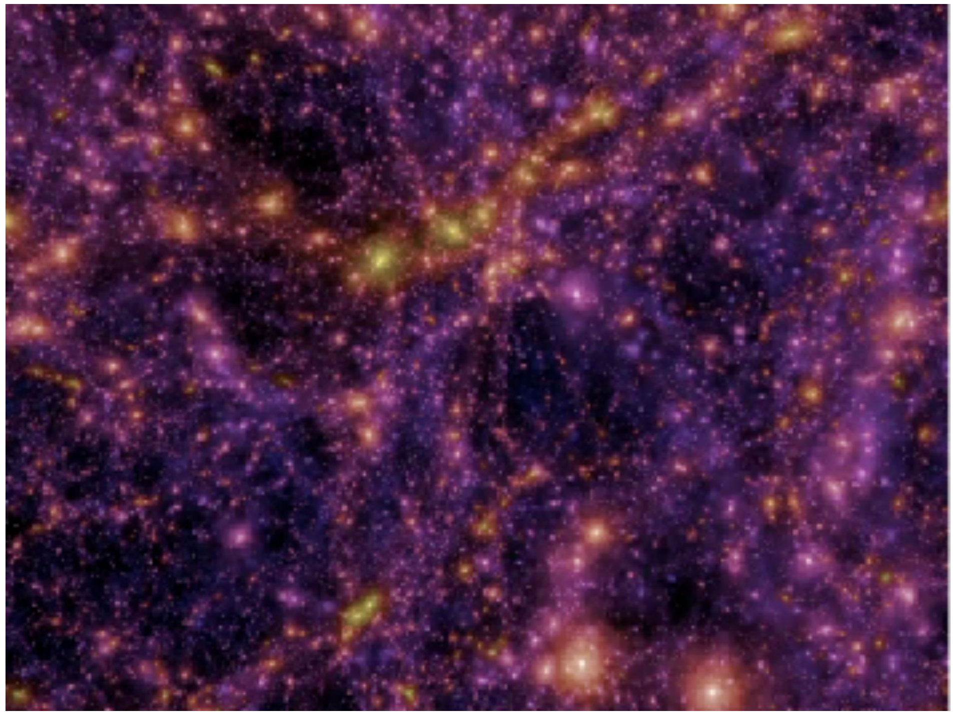
Simulations can achieve amazing things…

Movie credit: Ciolfi+, Siegel 2017, PRD 95, 063016

Solar granulation
(radiation hydrodynamics)



Credit: Stein+ 1998, ApJ 499, 914



Credit: Springel et al. 2005, Nature, 435, 629

Interpretation of observational data

Theoretical interpretation of observational data (stages of refinement):

Analytical estimates

("back of the envelope" calculations)

(Semi-)analytic calculations

(using simplifications/approximations)

Full-scale numerical simulations

'healthy skepticism'

(still approximate, numerical effects)

Credit: NASA

experiment 'substitute'

Expectations of expectations

reduce complexity and provide stability to social systems (Luhmann)

…so let's talk about expectations:

Course contents and 'mechanics'

- For course outline and policies, please see:

  https://www.physics.uoguelph.ca/course-outlines/special-topics-astrophysics-numerical-hydrodynamics-phys7900

- Course website (repository with course material):

  https://github.com/dmsiegel/computational-fluid-dynamics-course.git

- 'Interpolation' between applied mathematics, physics, astrophysics

  'blackboard' lectures, *hand-written* lecture notes

- Homework (30% final grade):

  Problem sets with analytical problems

  Project component with hands-on problems to implement

  - finite difference schemes and explore their properties
  - an 'exact' Riemann solver for the Euler Equation
  - a Godunov-type scheme for Newtonian hydrodynamics

- Exam (70% final grade): date & time TBD

Course contents and 'mechanics'

- Contents

1. Basic Notions of Partial Differential Equations
2. Basic Equations of Computational Fluid Dynamics
3. Finite Difference Methods for PDEs
4. Properties of conservation laws (theoretical background)
5. Riemann problem for the Euler Equations
6. Numerical schemes for conservation laws
7. Approximate Riemann solvers
8. Source terms and higher dimensions
9. Outlook: a primer on discontinuous Galerkin methods

Very general, directly relevant for Einstein's equations as well!

Course contents and ‘mechanics’

- References

Numerical Methods:

- E. Toro: *Riemann Solvers and Numerical Methods for Fluid Dynamics* (Springer, 3rd edition, 2009)
- R. Leveque: *Finite Volume Methods for Hyperbolic Problems* (Cambridge Univ. Press, Cambridge Texts in Applied Mathematics, 2002)

More mathematically inclined literature:

- D. Kröner: *Numerical Schemes for Conservation Laws* (Wiley, 1997)
- L. Evans: *Partial Differential Equations* (Graduate Studies in Mathematics, American Mathematical Society, 2nd edition, 2010)

Other useful literature:

- A. Anile: *Relativistic fluids and magneto-fluids* (Cambridge Univ. Press, 1990)
- P. Bodenheimer, G. Laughlin, M. Rozyczka, H. Yorke: *Numerical Methods in Astrophysics* (Taylor & Francis, 2007)
- R. Leveque: *Finite Difference Methods for Ordinary and Partial Differential Equations* (SIAM, 2007)

Course contents and ‘mechanics’

- First ‘Homework’:

  1) please install *python* on your laptop/computer

  2) please familiarize yourself with GitHub and create a first git repository.
     This will be useful for working on the hands-on assignments.

- Office hours: virtually, on demand