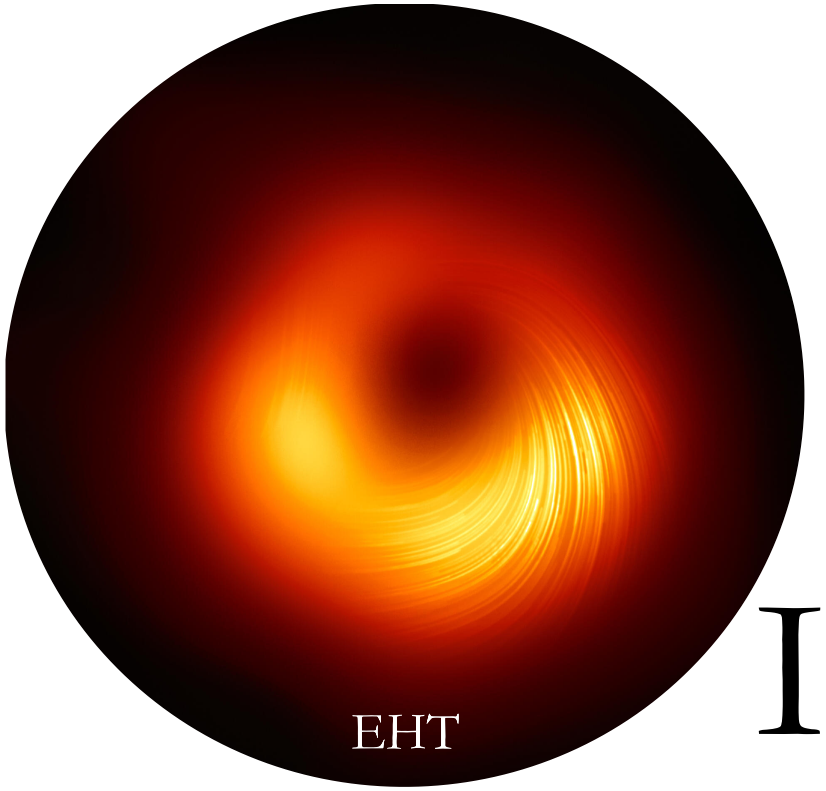
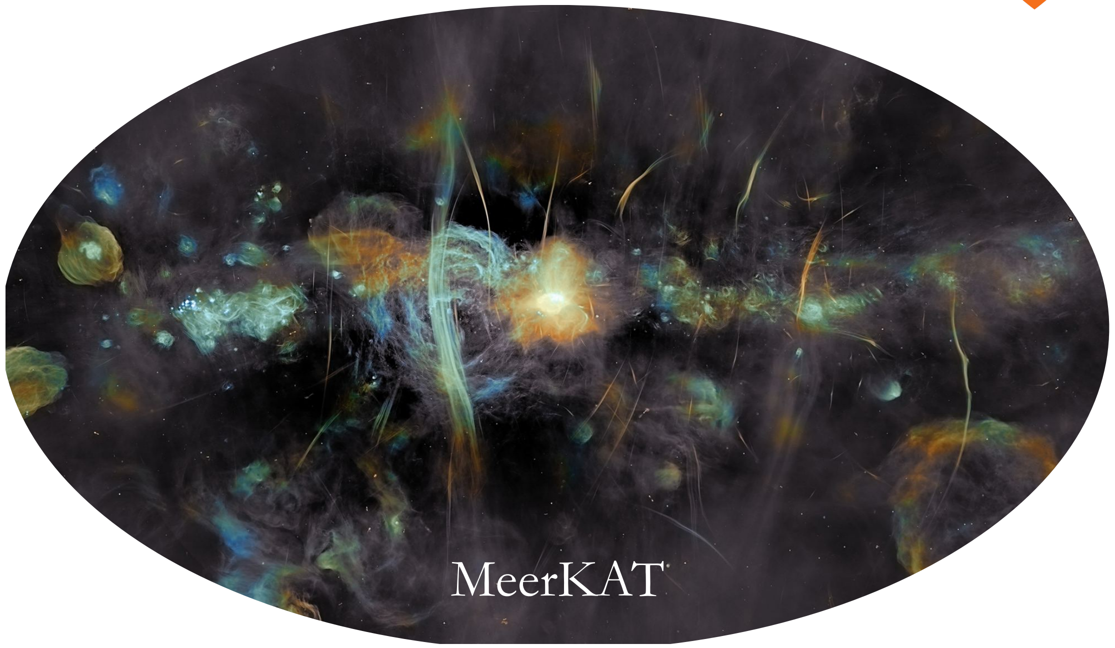
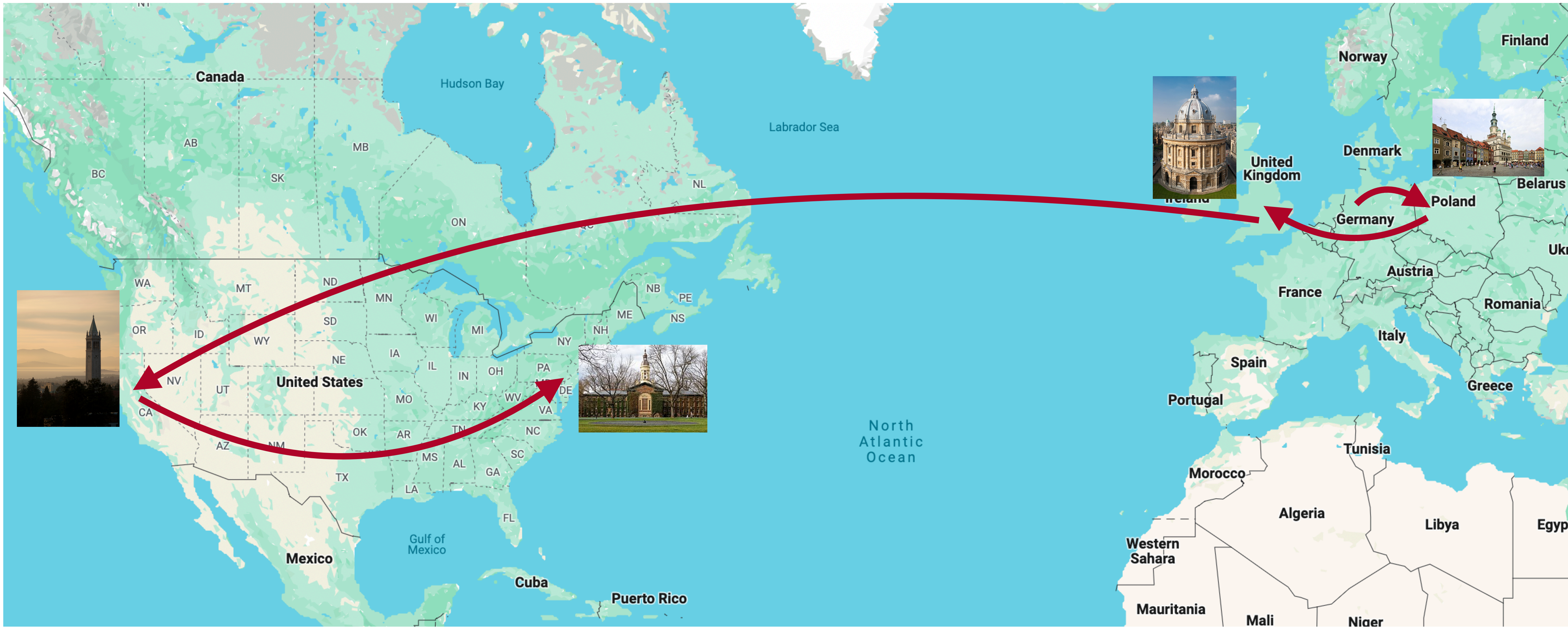


Introduction to Astrophysical Plasmas

Philipp Kempski
Princeton University



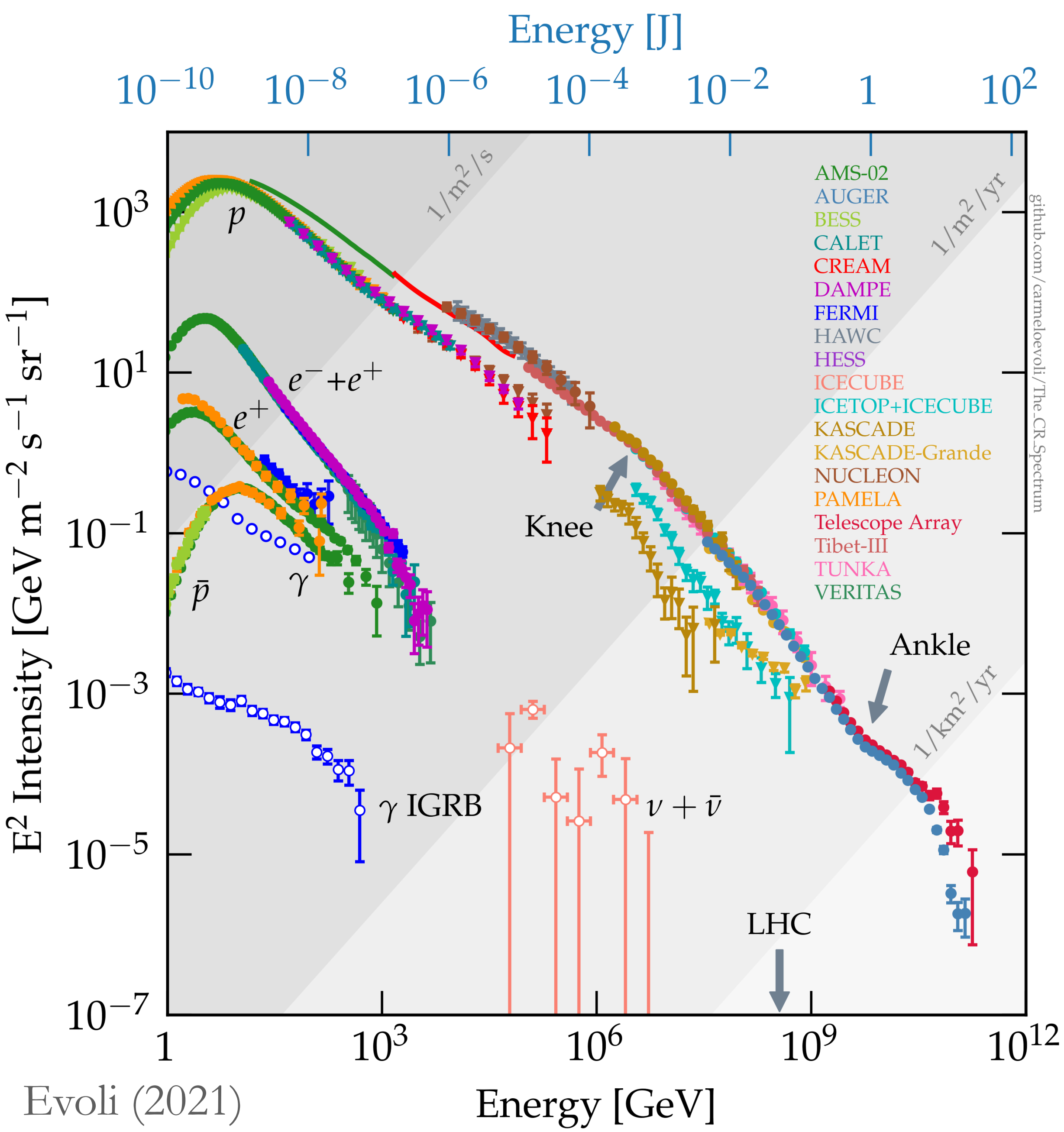
About me



Currently: Postdoctoral Fellow in the Department of Astrophysical Sciences at Princeton University

My research? You guessed it… plasma astrophysics

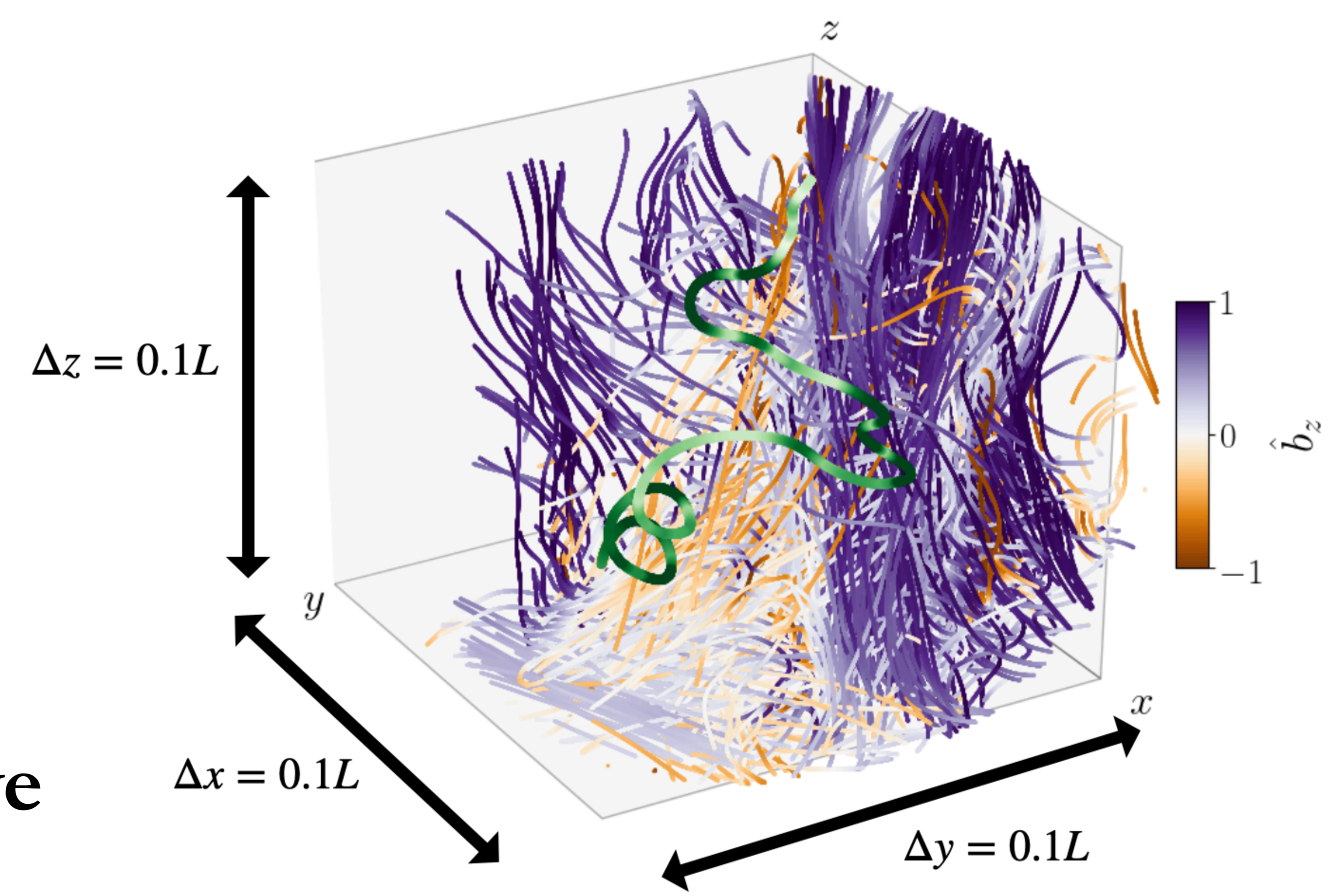
My Research: plasma physics of cosmic rays



Cosmic rays = relativistic charged particles that pervade galaxies

Cosmic rays arrive at Earth with an impressive power-law spectrum

The plasma physics of how the spectrum is formed remains elusive



Kempski et al. (2023)

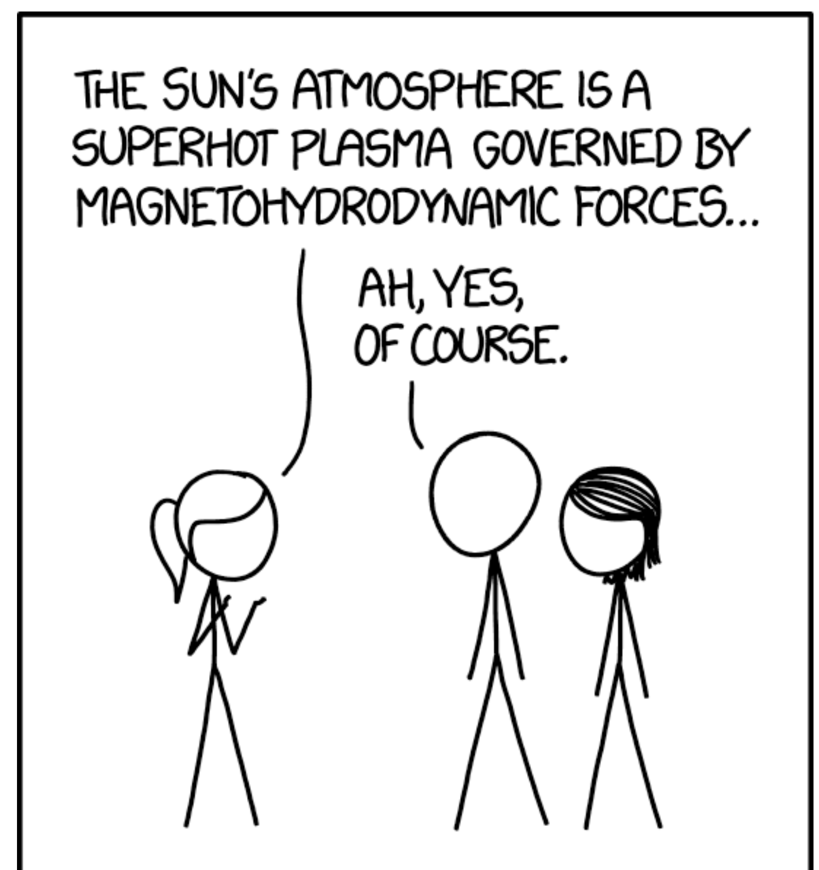
Why do astrophysicicists care about plasma physics?

The Universe is ionized!

Abell 1689,
adapted from NASA Chandra X-ray Obs.

The majority of baryonic matter in the Universe is ionized

Hydrodynamics not enough…



WHENEVER I HEAR THE WORD "MAGNETOHYDRODYNAMIC" MY BRAIN JUST REPLACES IT WITH "MAGIC."

From: XKCD

What are astrophysical plasmas like?

Plasma astrophysics includes gravity…

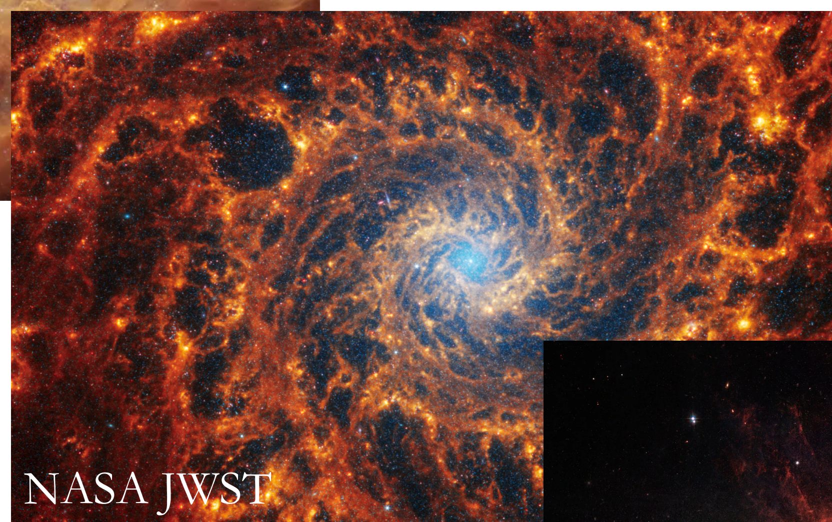
Whether you consider accretion onto compact objects, star formation or galactic winds… it's hard to escape gravity in astrophysics!

… and a lot of additional physics

Depending on what you do, you might have to simultaneously worry about plasma microphysics, general relativity, radiation transport and QFT…

… and in some environments chemistry plays a crucial role

Plasma astrophysics probes many environments



Multiphase Interstellar Medium

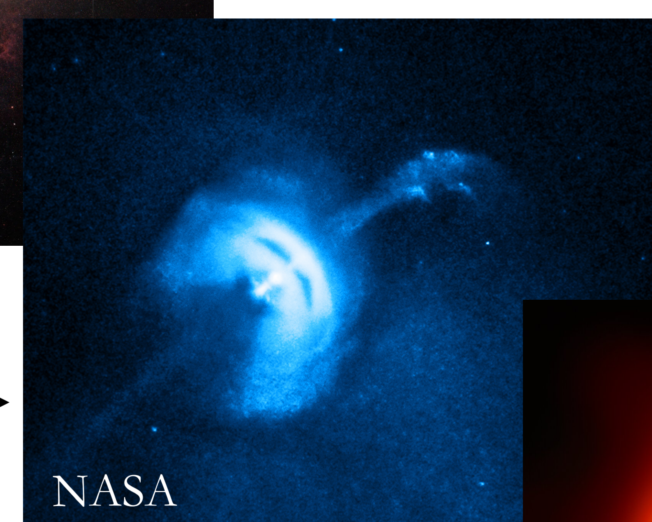
Cold phase: $n \gtrsim 10\ \mathrm{cm}^{-3}$, $T \lesssim 100$ K

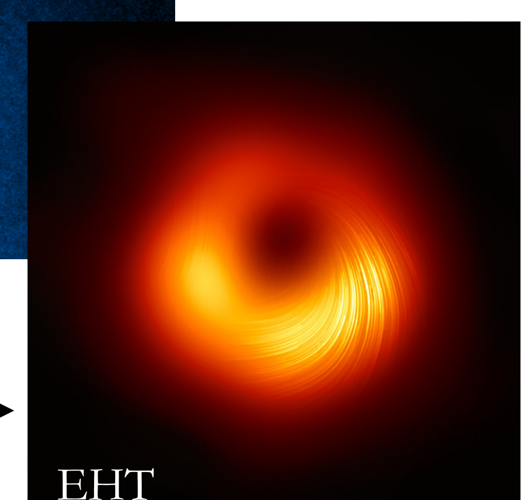
Warm phase: $n \sim 0.1\ \mathrm{cm}^{-3}$, $T \sim 10^4$ K

Hot phase: $n \lesssim 0.01\ \mathrm{cm}^{-3}$, $T \gtrsim 10^5$ K

$U_{\mathrm{th}} \sim U_{\mathrm{B}} \sim U_{\mathrm{CR}} \sim U_{\mathrm{rad}}$

Energy Equipartition

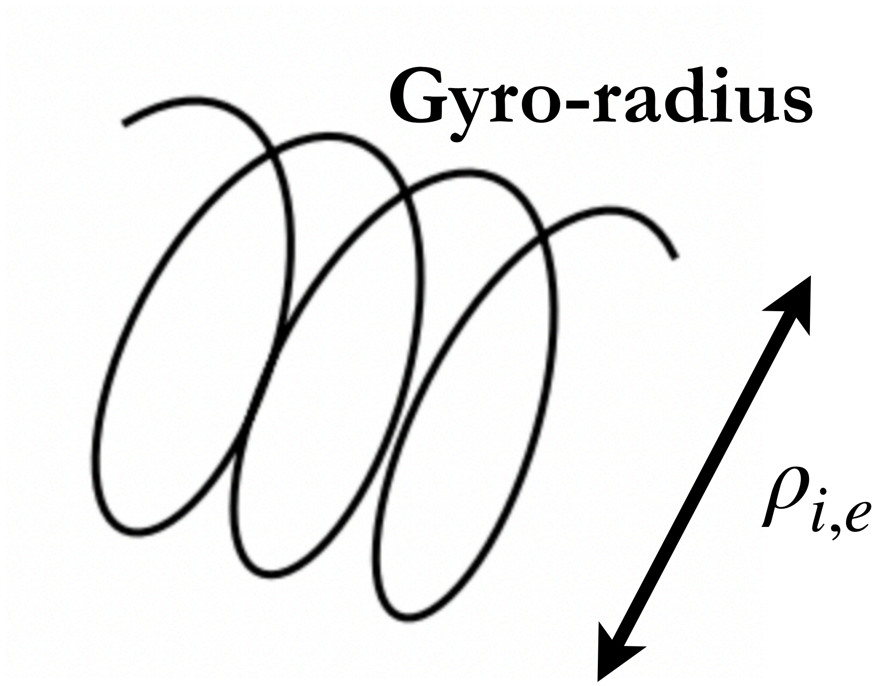


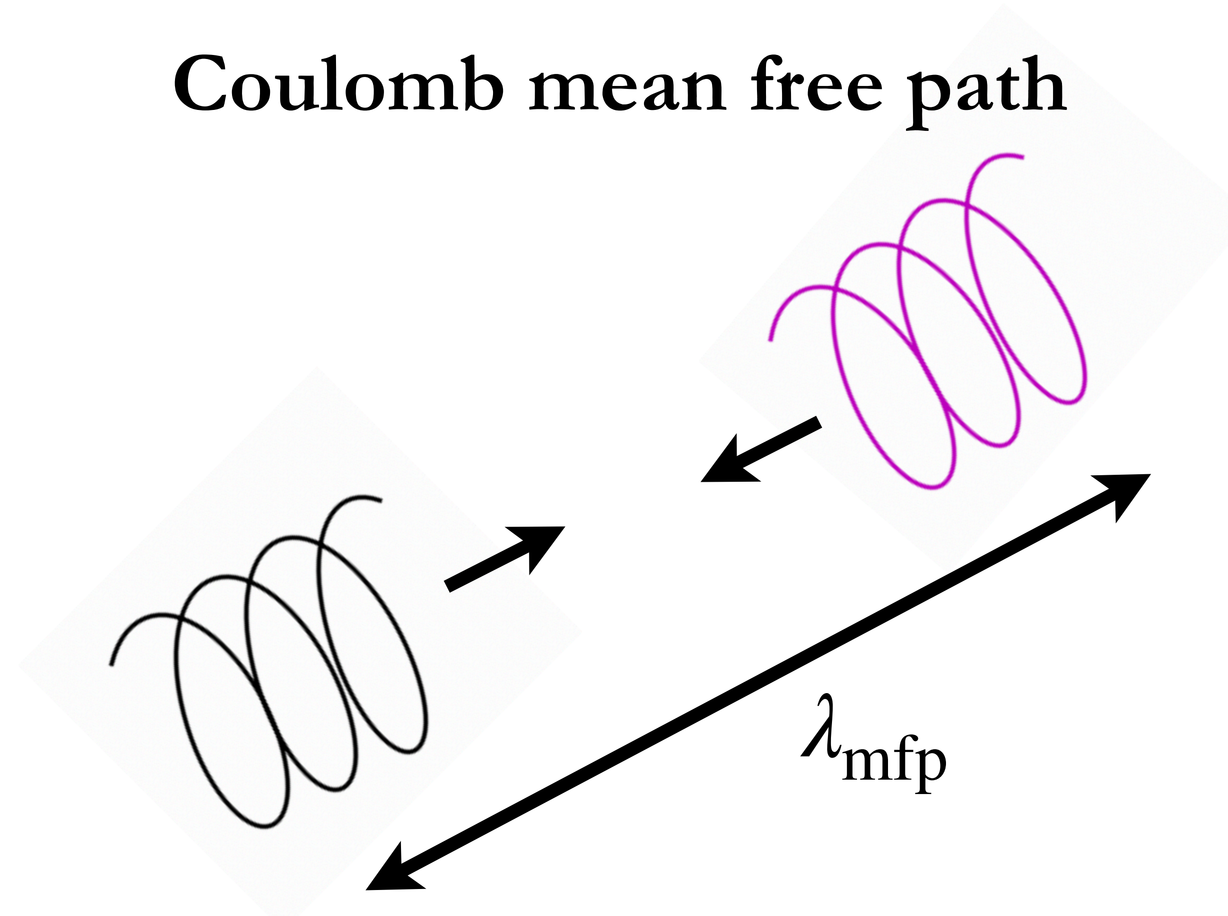


Plasmas around compact objects

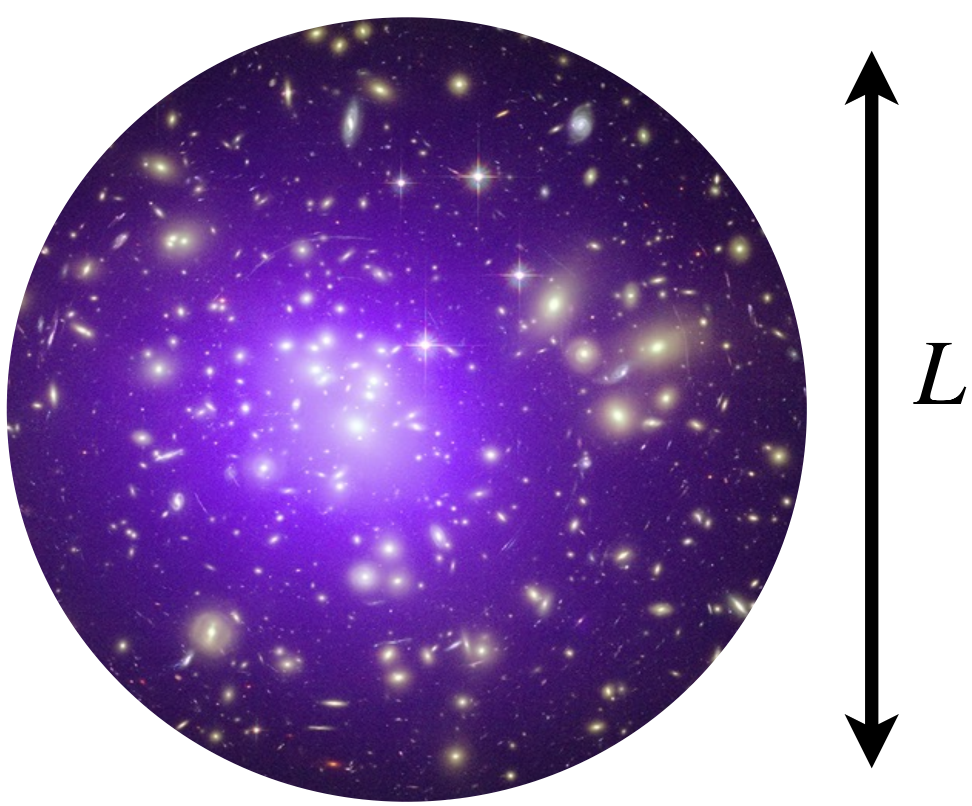
Strong magnetic fields, General Relativity & QFT effects

Plasma astrophysics probes many scales





System Scales



Abell 1689,
adapted from NASA Chandra X-ray Obs.

Most often in astrophysics we deal with

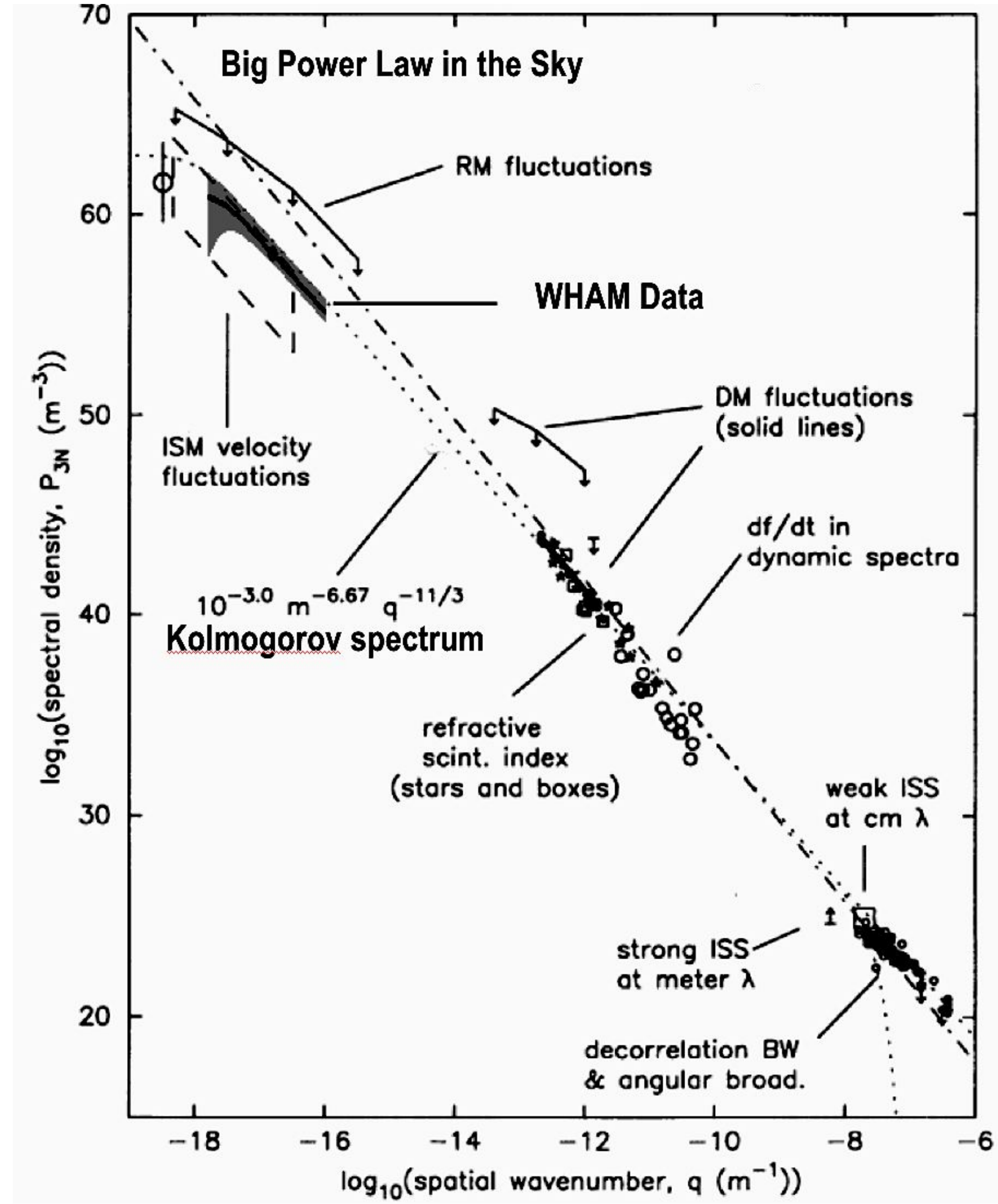
$$L \gg \lambda_{\mathrm{mfp}} \gg \rho_i$$

Many orders of magnitude

Astrophysical plasmas are generally turbulent

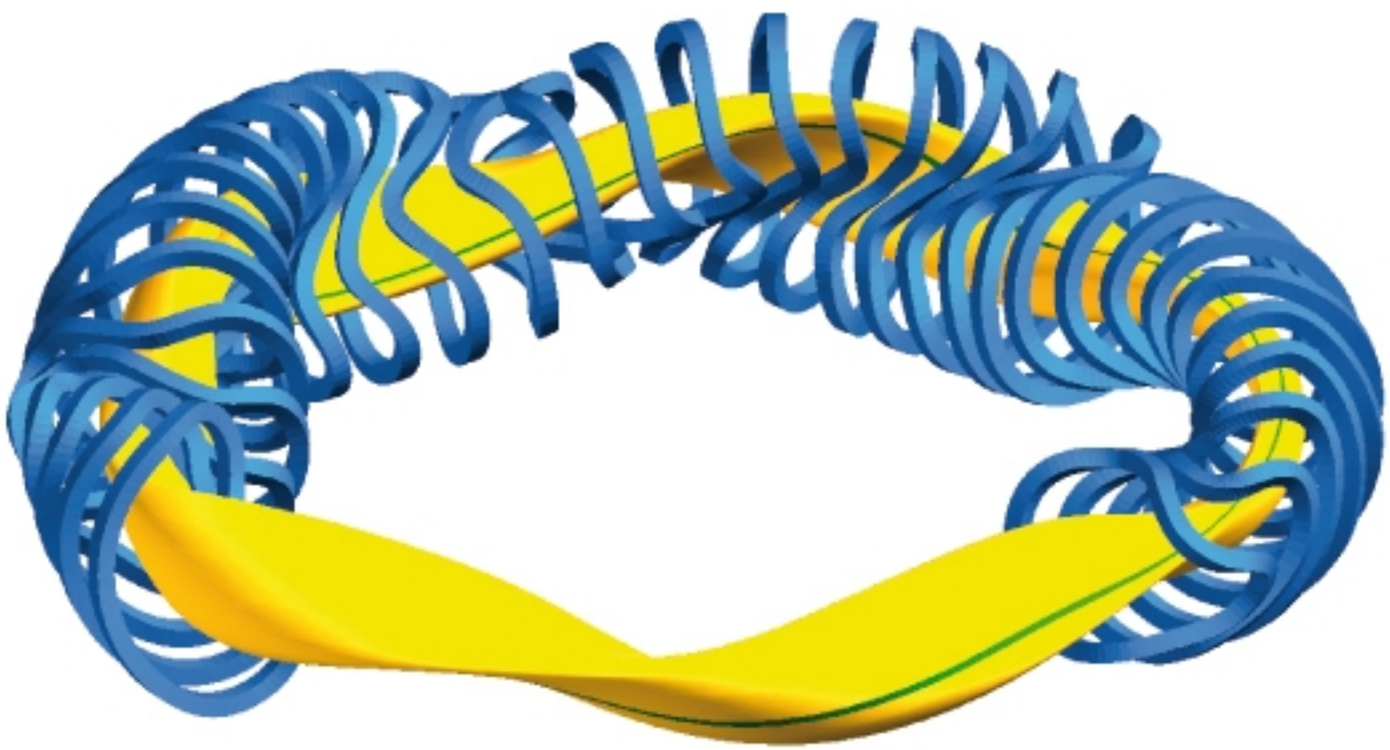
Large scale separations lead to large Reynolds numbers

Turbulent interstellar medium “Great Power Law in the Sky”



Armstrong, Cordes, Rickett 1981, Nature
Armstrong, Rickett, Spangler 1995, ApJ

But geometry often easier!



Wikipedia

This we usually don't have to deal with

Astrophysics uses different units!

Most astrophysicists abandoned SI and use CGS…

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{j}$$

$\longrightarrow$

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}$$

Mass in grams, distance in cm, energy in ergs…

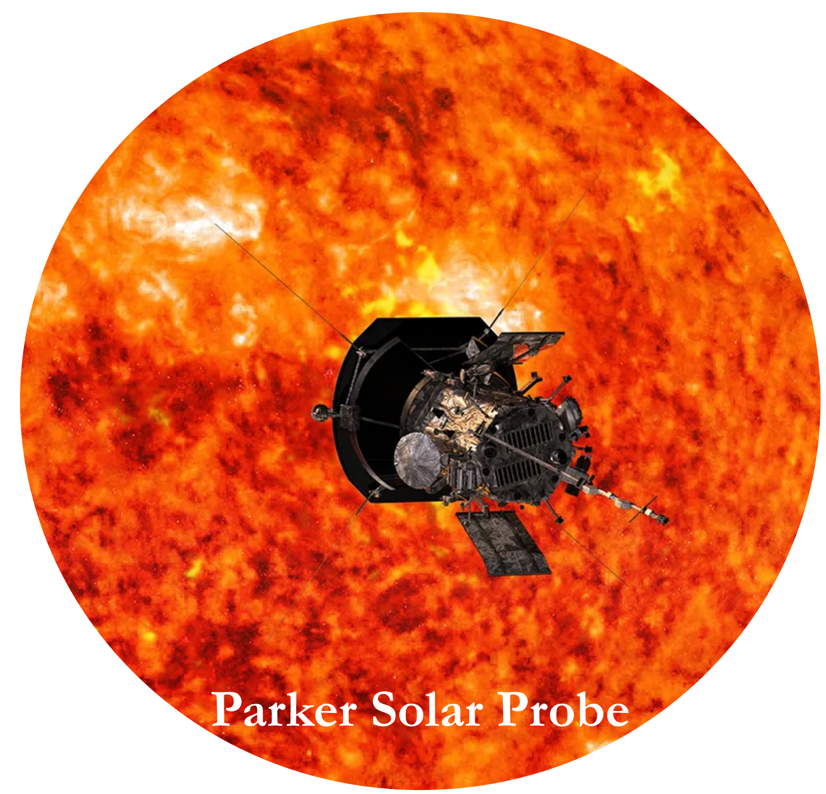
A unit that will come up a lot in this talk:

$$\text{parsec (pc)} \approx 3 \text{ light years}$$

Let’s look at some example systems

Galaxy Clusters

Galactic Center



Solar Wind

Galaxy Clusters

Abell 1689,
NASA Chandra

$10^{14-15} M_\odot$

$L \sim \text{Mpc}$

Most of the baryonic matter is in diffuse intra-cluster medium (ICM)

$T \sim 10^7 - 10^8$ K

$n \sim 10^{-4} - 10^{-2}$ cm^{-3}

$B \sim 1\ \mu$G

$$\beta = \frac{8\pi p_{\text{th}}}{B^2} \gg 1$$

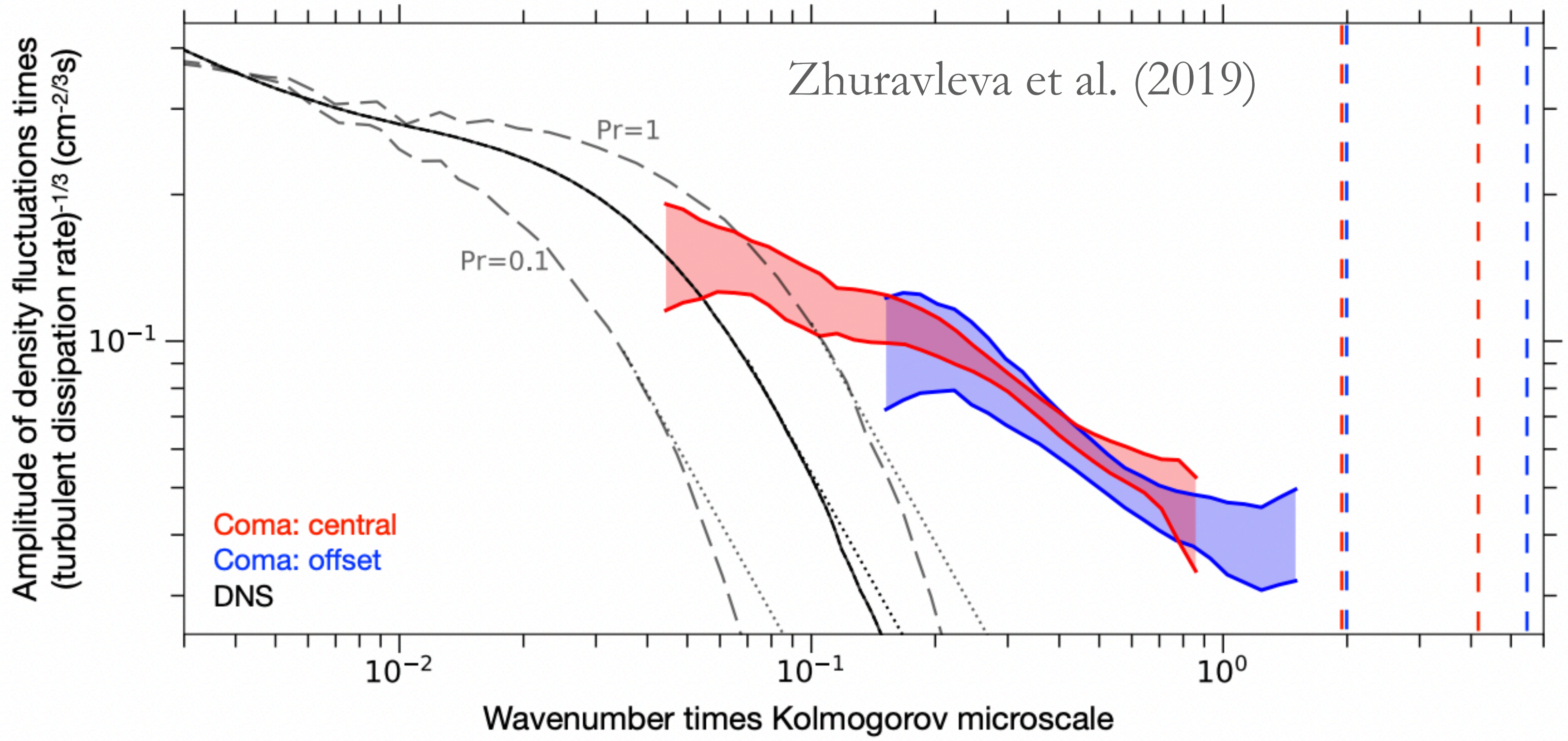
Enormous Coulomb mean free path

$\lambda_{\text{mfp}} \sim 0.1 - 10$ kpc

Great laboratory for plasma physics

Suppressed viscosity in clusters

In hydrodynamics, fluctuations are suppressed on scales smaller than the mean free path



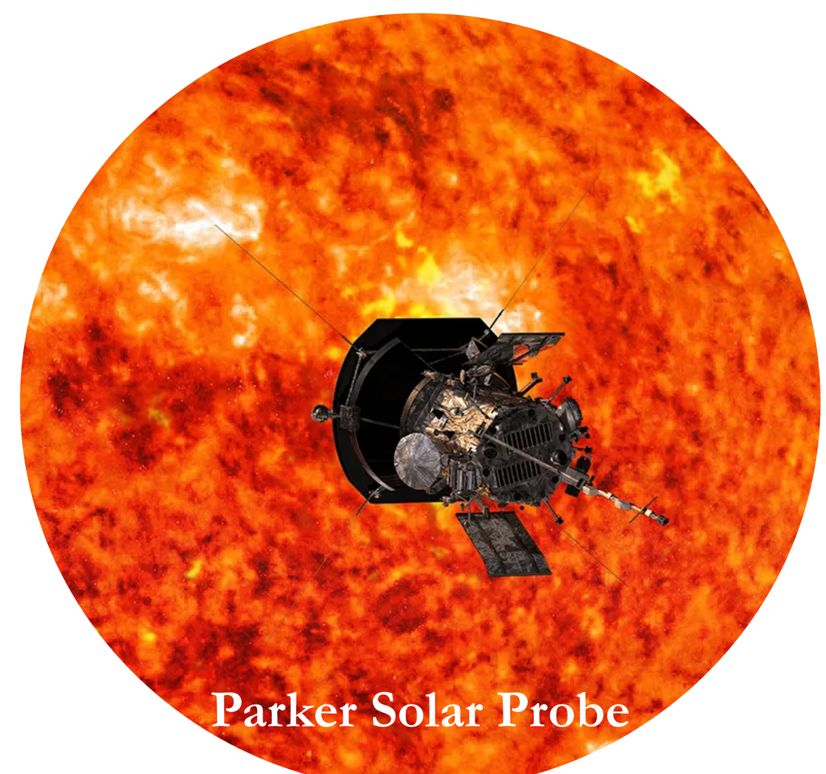
Turbulent cascade measured in Coma Cluster extends to scales smaller than the hydrodynamic Kolmogorov cutoff

How exactly viscosity is suppressed in these systems is an active area of plasma astrophysics research

Let's look at some example systems

Galaxy Clusters

Galactic Center



Solar Wind

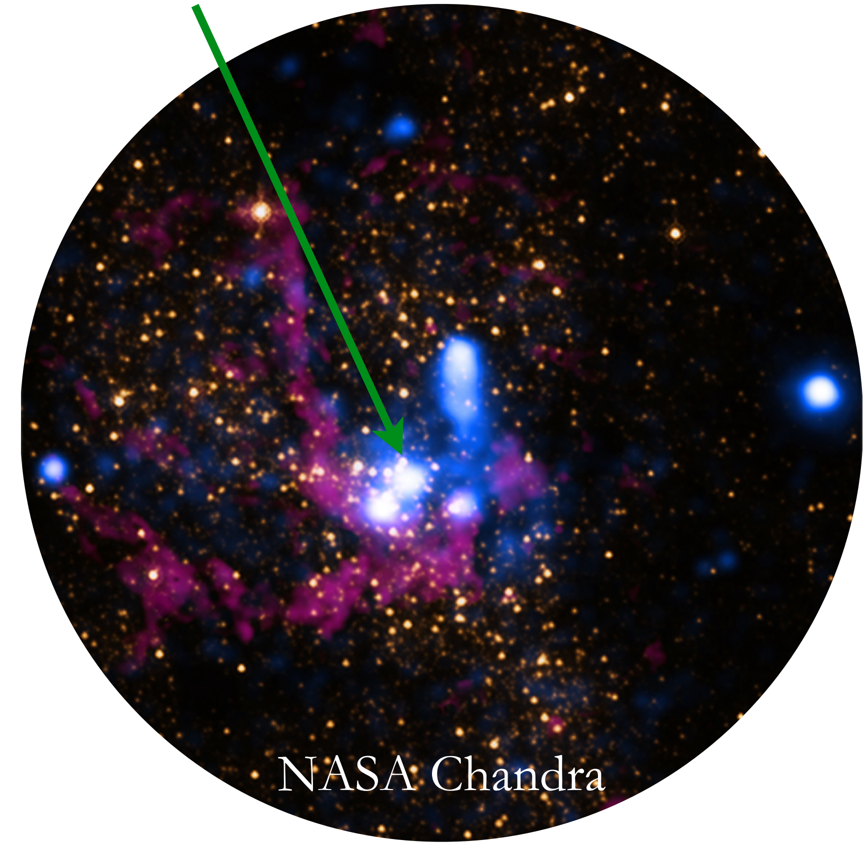
Galactic Center

$t_{\rm dyn} \lesssim 10$ minutes

$t_{\rm ii} \sim$ years

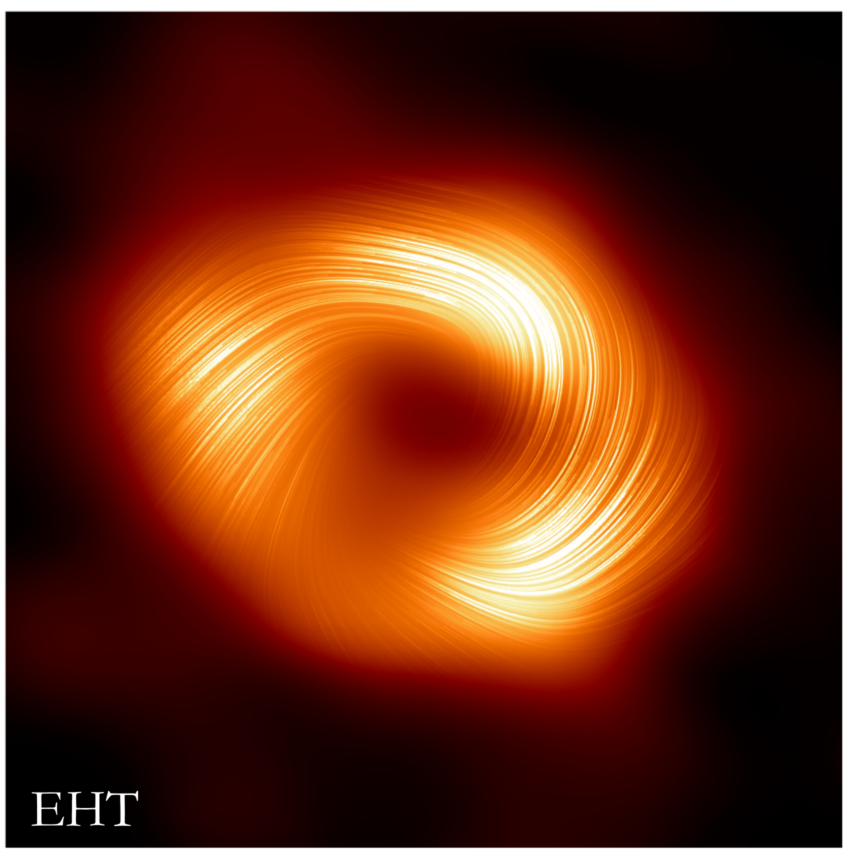
Accreting plasma is collisionless

$4 \times 10^{6}\ \mathrm{M}_{\odot}$ BH

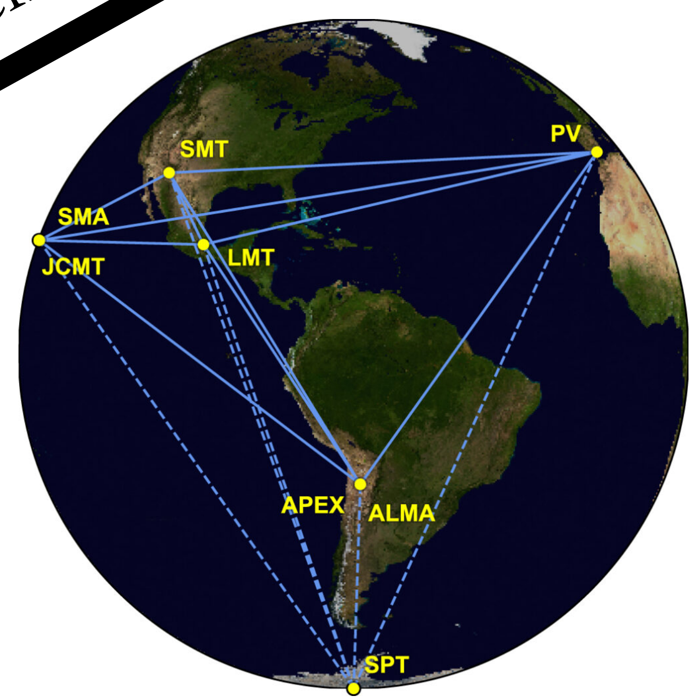


~ 10 light years

Event Horizon Telescope



$\sim$ AU

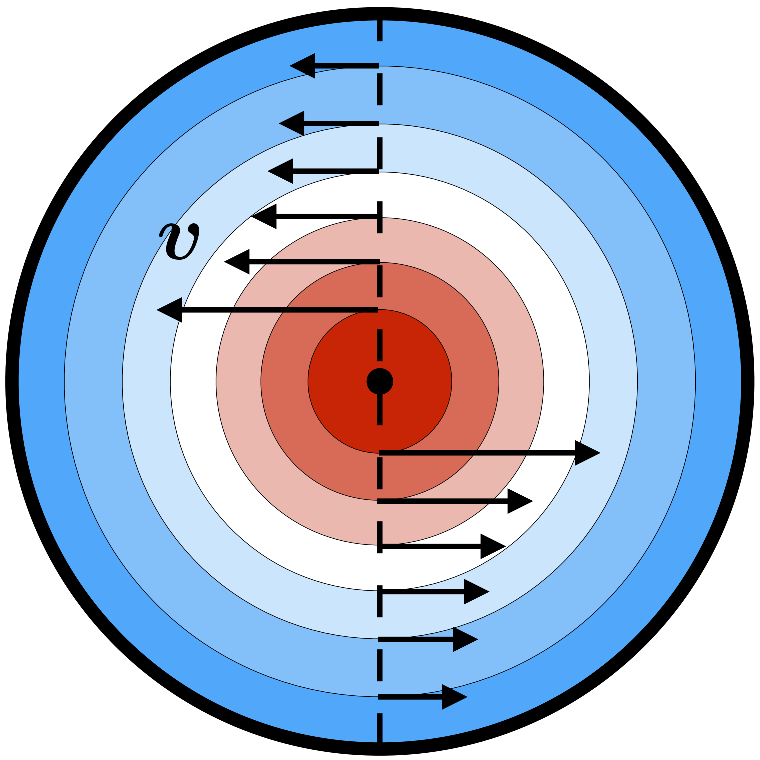


From MIT Haystack Observatory

$$\theta = \frac{\lambda}{D} \Rightarrow D = \frac{\lambda}{\theta} \sim \frac{1.3\mathrm{mm}}{1\mathrm{AU}/10\mathrm{kpc}} \sim R_{\oplus}$$

The accretion problem

Keplerian $\Omega \propto R^{-3/2}$



Credit: M. Kunz

Viscosities too small to explain inferred accretion rates in many systems

Possible solution: accretion via shear-driven turbulent mixing

But hydrodynamic disks are expected to be laminar flows by Rayleigh criterion

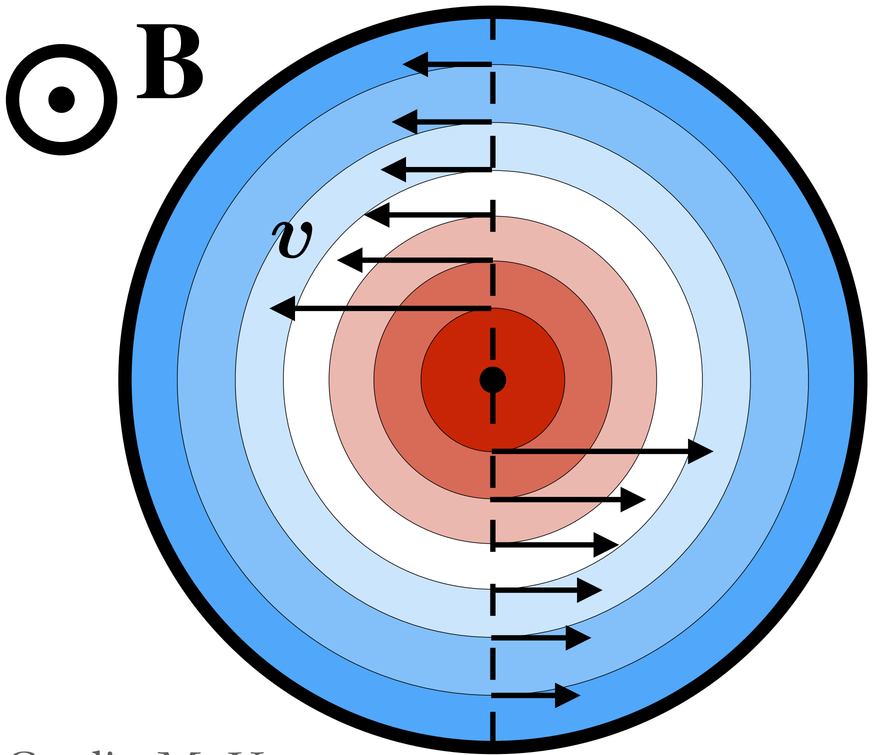
$\Updownarrow$

$$\frac{d\ell^2}{dR} \geq 0$$

Angular momentum $\ell = \Omega R^2 \propto R^{1/2}$

Magnetic fields allow accretion

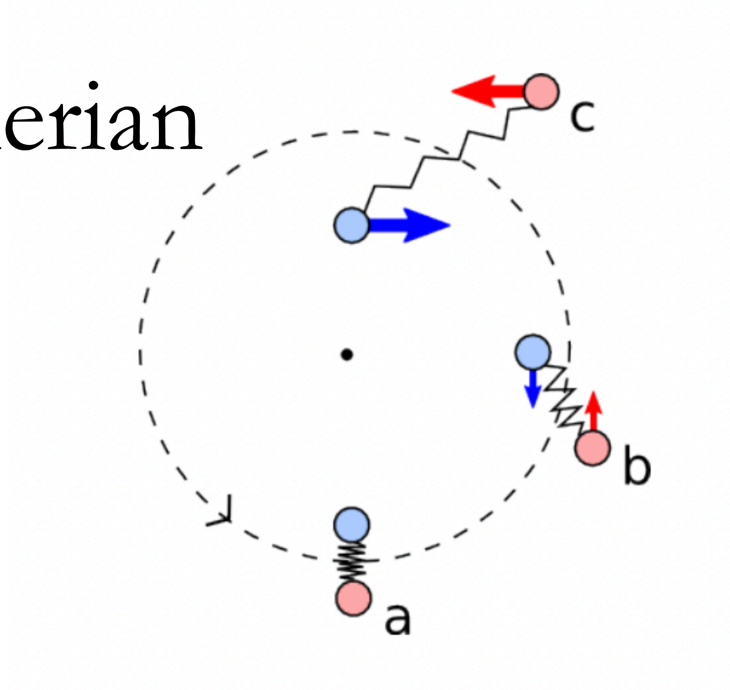
Keplerian $\Omega \propto R^{-3/2}$



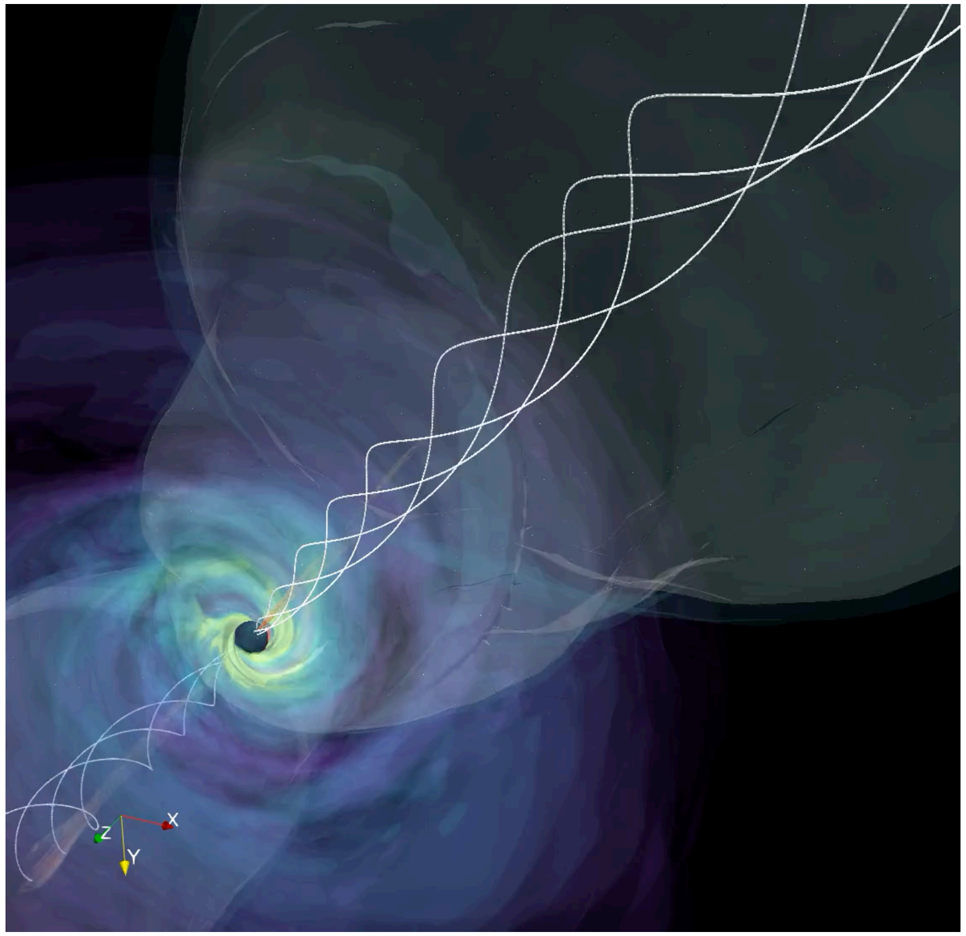
Credit: M. Kunz

With magnetic fields Keplerian flow becomes unstable

$$\frac{d\Omega^2}{dR} \leq 0$$



"Magneto-rotational instability (MRI)"

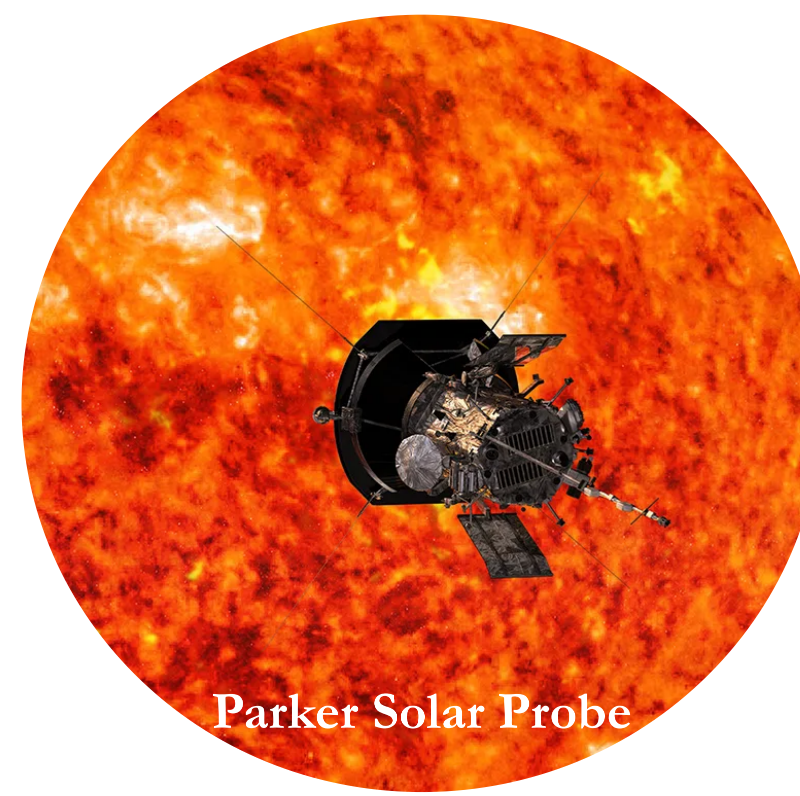


Movie by: Koushik Chatterjee
From NASA Chandra X-ray Obs.

Let's look at some example systems

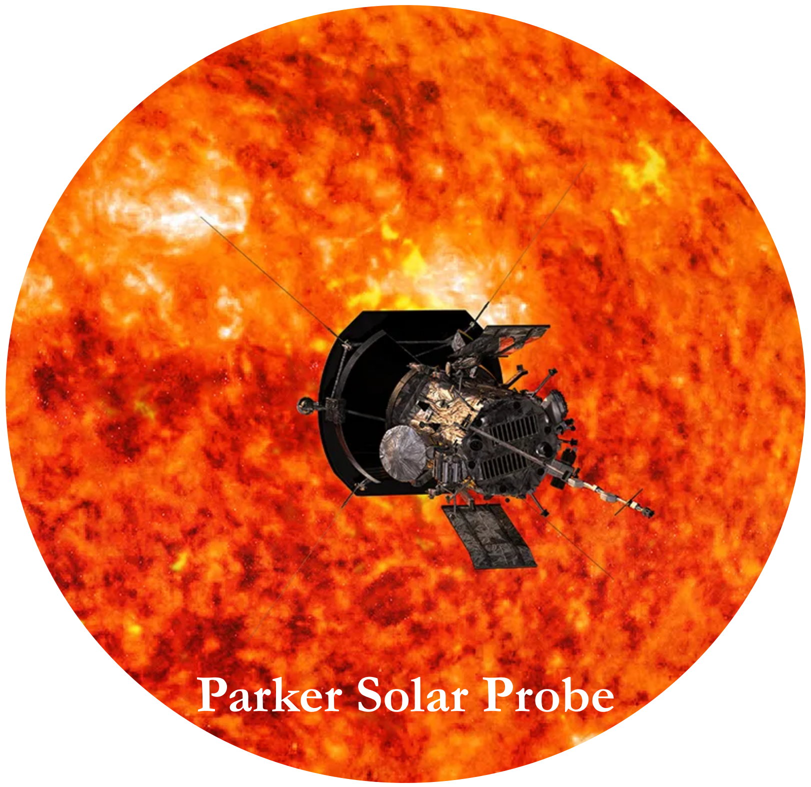
Galaxy Clusters

Galactic Center



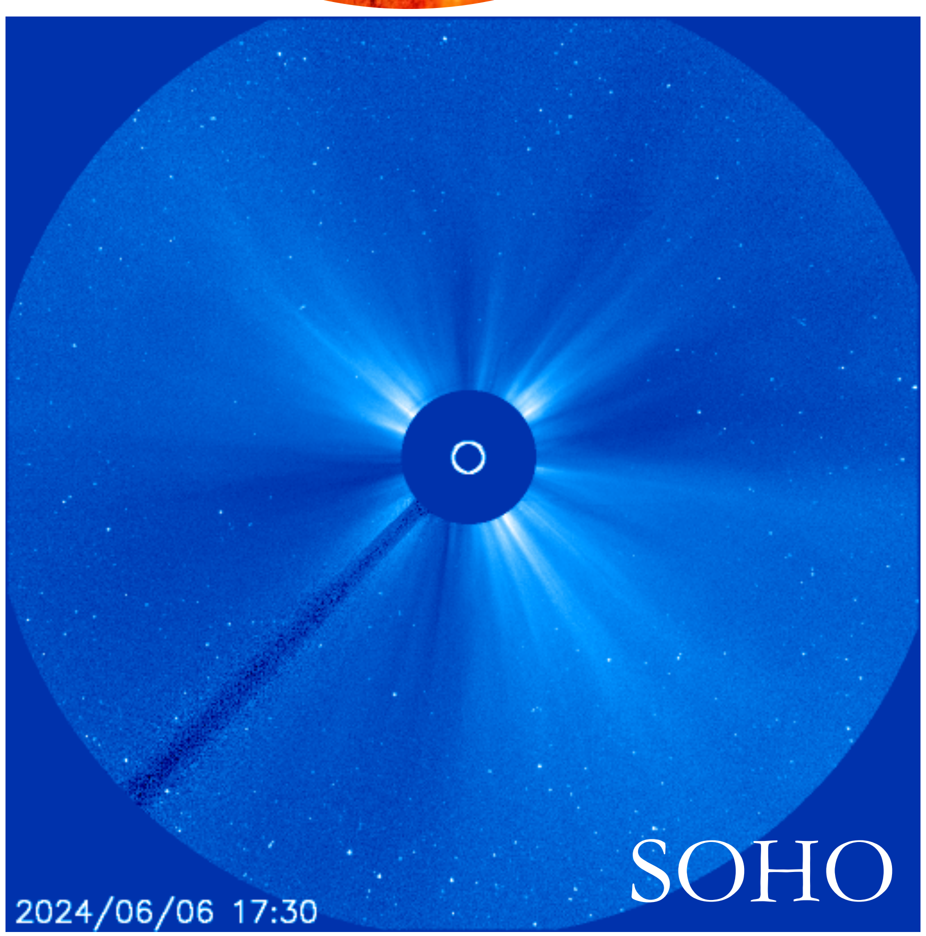
Solar Wind

Solar Wind



Well studied by many spacecraft missions

Helios 1 & 2: "inner" SW (Earth to Mercury)
Ulysses: polar and "outer" SW (Earth to Jupiter)
Voyager 1 & 2: recently passed boundary between SW & ISM
CLUSTER: "formation flying" spacecraft
STEREO A & B: focus on CMEs
Wind: near-Earth SW
Parker Solar Probe: launched Aug 2018, has by now made many passes of the Sun, will come within ~9 $R_\odot$ of solar surface (at 430,000 mph)



At R ~ 1AU:

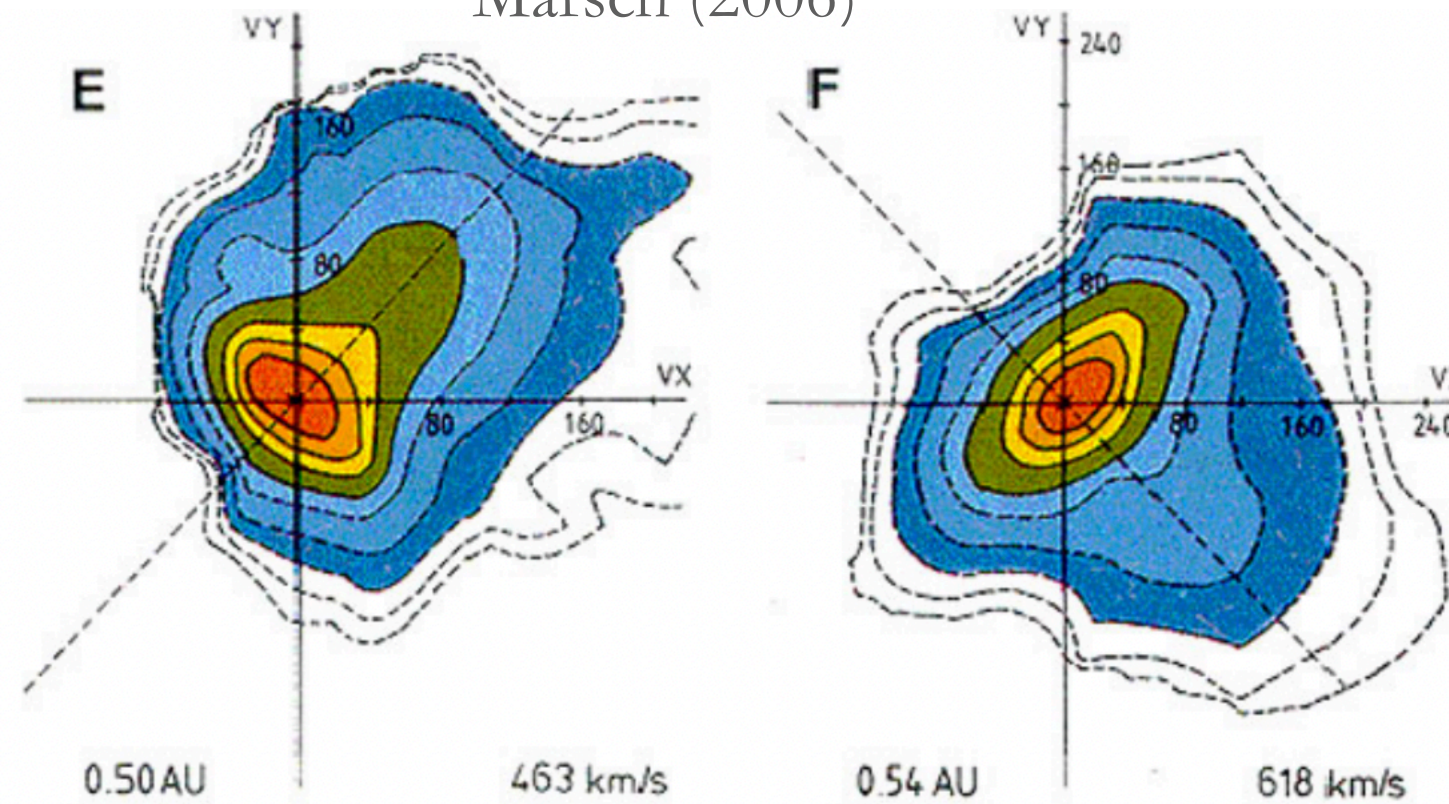
$$\lambda_{\rm mfp} \sim 1\ \text{AU}$$

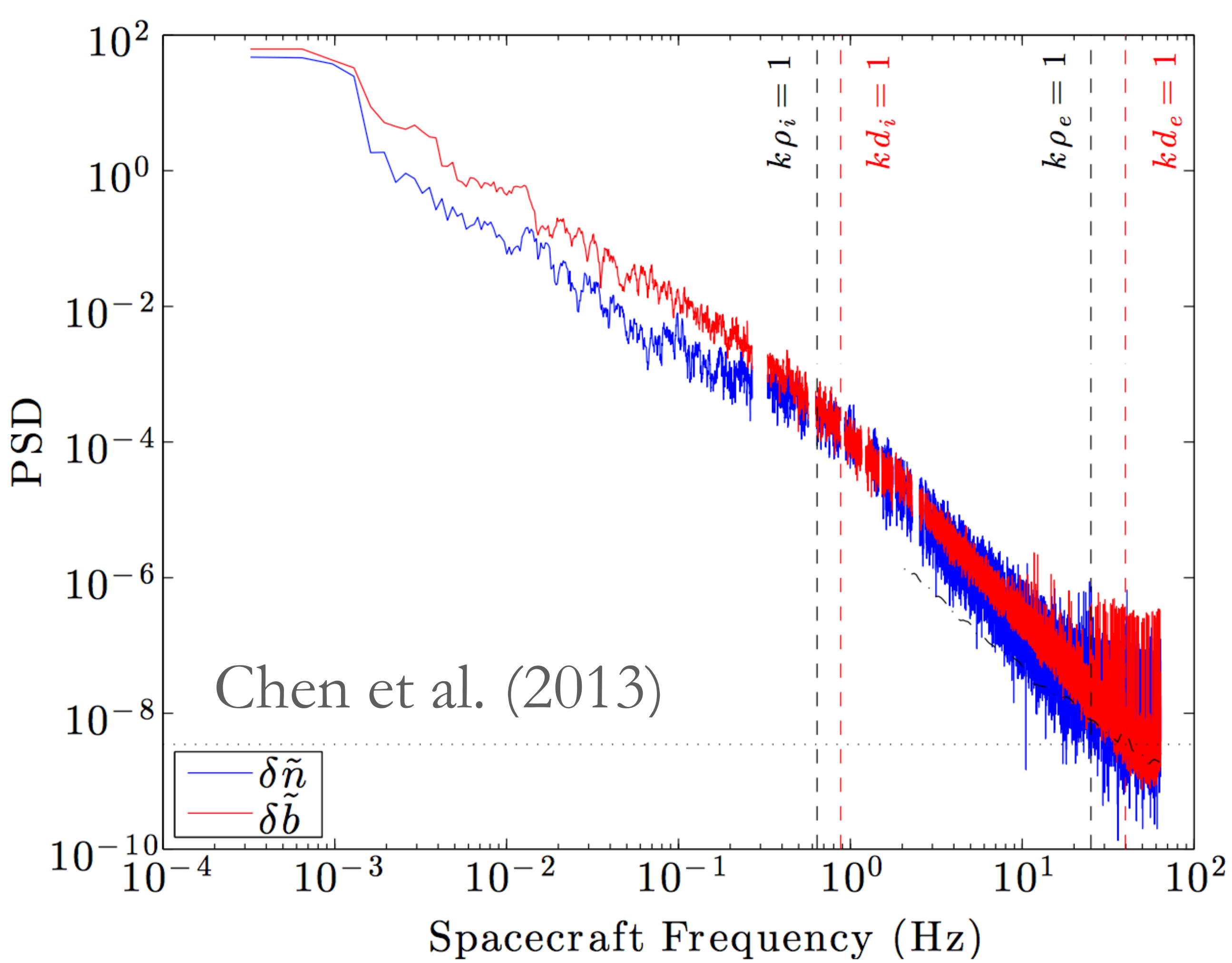
$$\rho_i \sim 10^{-6}\ \text{AU} \qquad \Omega_i \sim 1\ \text{s}^{-1}$$

Solar Wind

Many spacecraft measuring particle velocity distribution functions and electromagnetic fields in the solar wind…

Marsch (2006)





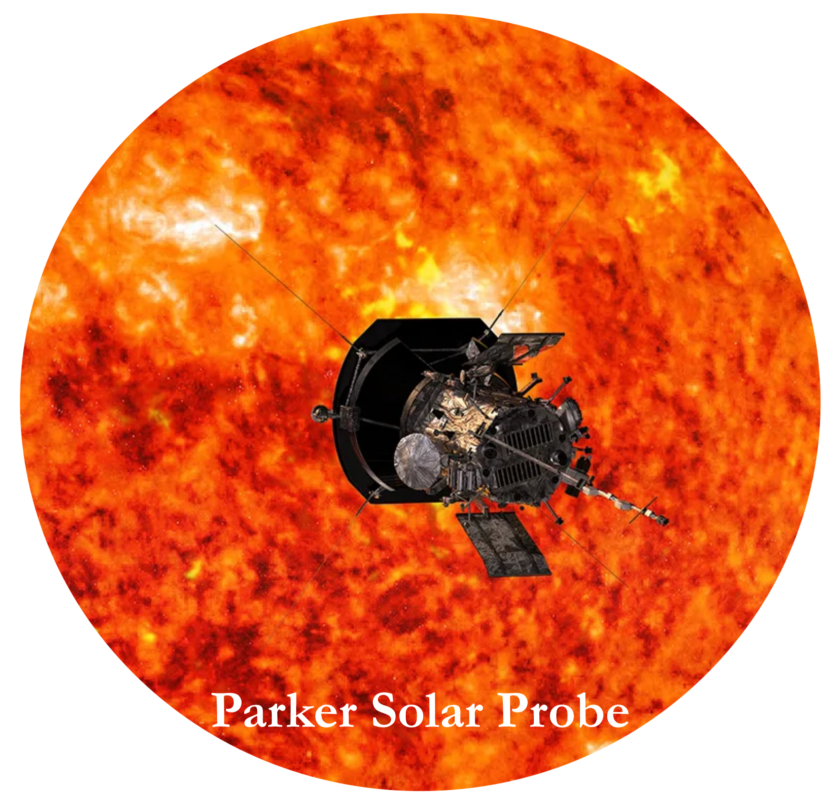
Particle distribution
in the collisionless solar wind
NOT an isotropic Maxwellian

Excellent laboratory for studying plasma kinetics and turbulence

Let's look at some example systems

Galaxy Clusters

Galactic Center



Solar Wind

Common theme

All these systems are characterized by large scale separations

$$L \gg \lambda_{\rm mfp} \gg \rho_i$$

$$(\text{or} \ldots \; \lambda_{\rm mfp} \gg L \gg \rho_i)$$

This makes theoretical modeling incredibly difficult

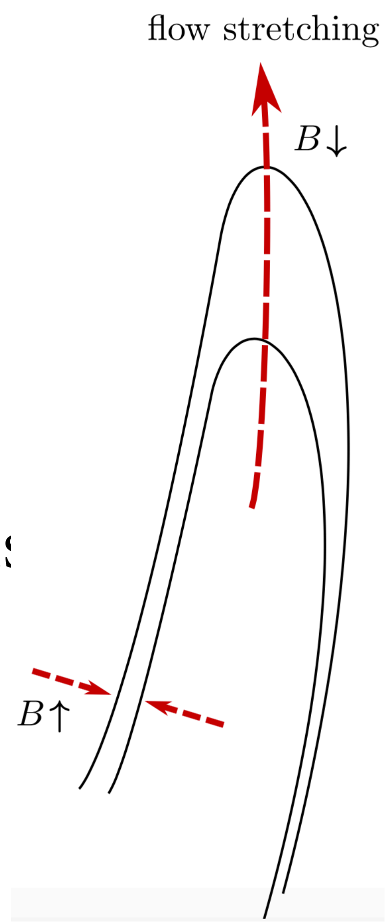
Many unsolved problem in plasma astrophysics are due to this challenge

An incomplete list of open problems (in no particular order)

1. **Origin of cosmic magnetic fields and dynamo**
2. **Cosmic ray transport and its role in regulating galaxy evolution**
3. **Turbulence in low-collisionality plasmas, accretion disks: particle heating, acceleration and its implications for EHT observed emission**
4. **Acceleration of high energy cosmic rays: where do the highest-energy CRs come from? What is the relative importance of shocks vs reconnection in energizing particles?**
5. Effective viscosity/conductivity of weakly-collisional plasmas
6. Heating of the solar corona and launching of the solar wind
7. Magnetic-flux and angular-momentum problems of star formation
8. Magnetospheres of compact objects (e.g., pulsars, black holes), emission of fast-radio bursts

1. Origin of magnetic fields and dynamo

Where do the ~micro-Gauss magnetic fields in environments like clusters come from?

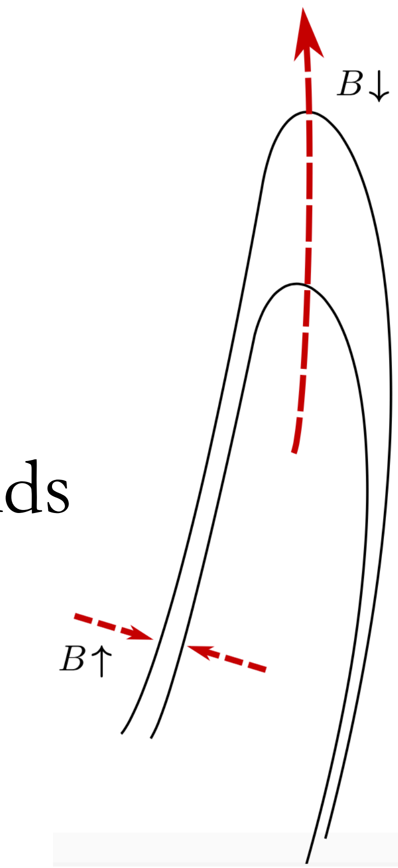


Fluctuation ("turbulent") dynamo (Batchelor 1950; Zel'dovich et al. 1984): succession of random velocity shears stretches and folds the field and leads to its growth

Where do the seed fields come from?
Can the seed fields be effectively amplified by the fluctuation dynamo in a self-consistent manner?

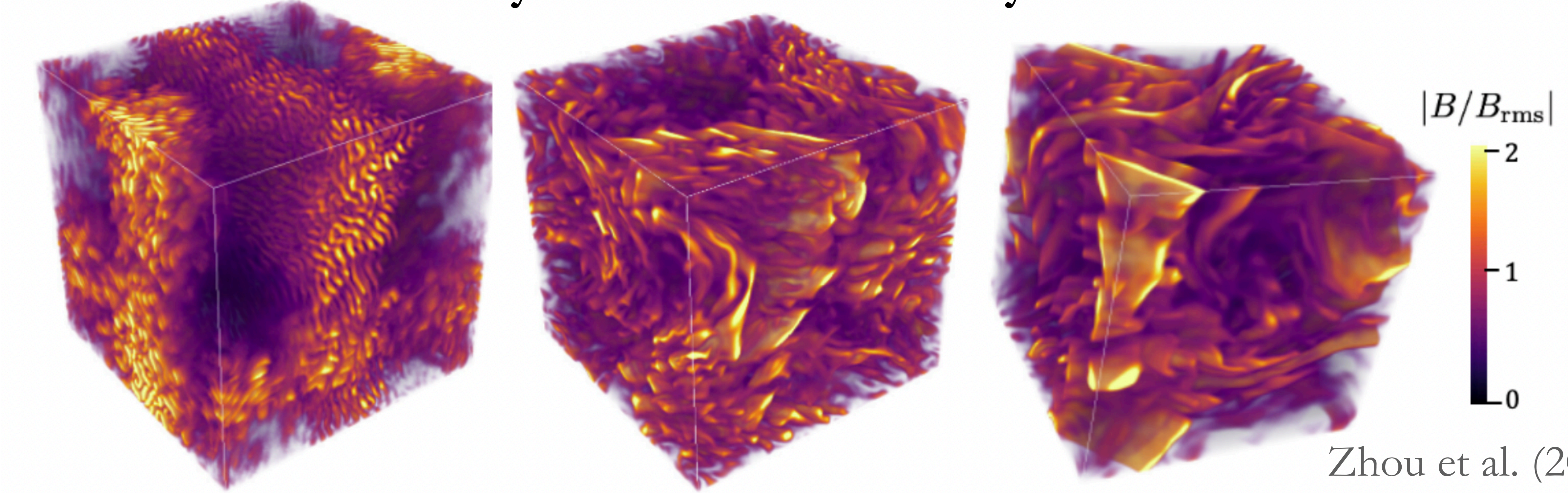
1. Origin of magnetic fields and dynamo

Where do the ~micro-Gauss magnetic fields in environments like clusters come from?



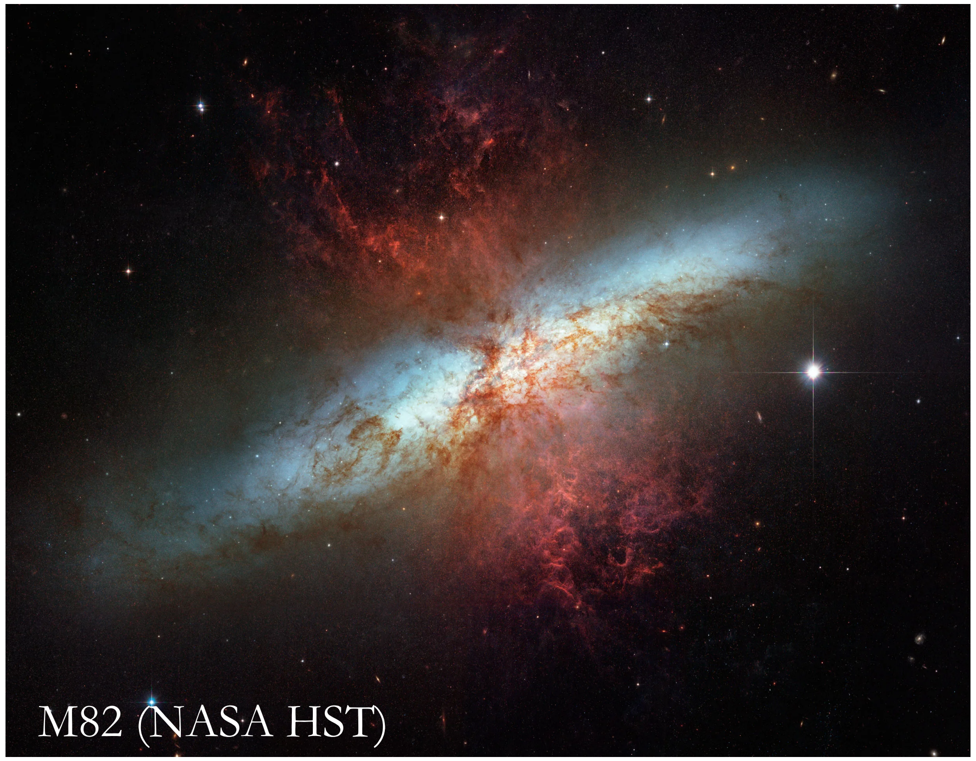
Fluctuation ("turbulent") dynamo (Batchelor 1950; Zel'dovich et al. 1984): succession of random velocity shears stretches and folds the field and leads to its growth

Seeds from Weibel Instability → **Dynamo saturation**



Zhou et al. (2024)

2. Cosmic ray transport and its role in regulating galaxy evolution


M82 (NASA HST)

Key question in galactic astrophysics:
How do galaxies grow and what regulates their star formation?

Galactic star formation (SF) is a self-regulating process

High SF → High Supernova Rate → **Blows out gas (galactic wind)**

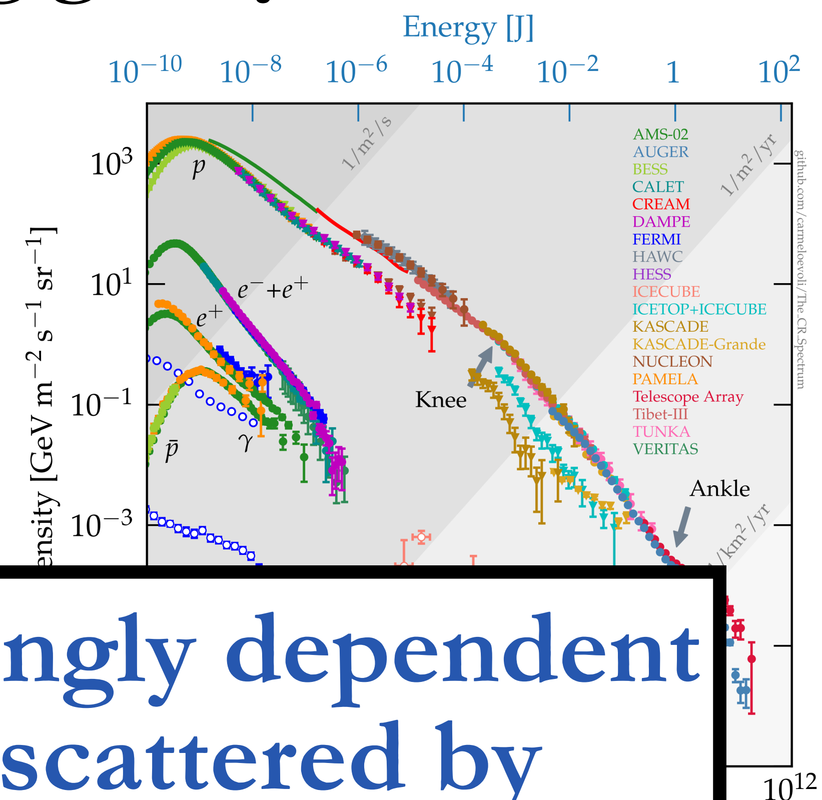
↓

Low SF → Low Supernova Rate → Gas cools and accretes → High SF

This feedback process is essential to how galaxies grow and form their stars

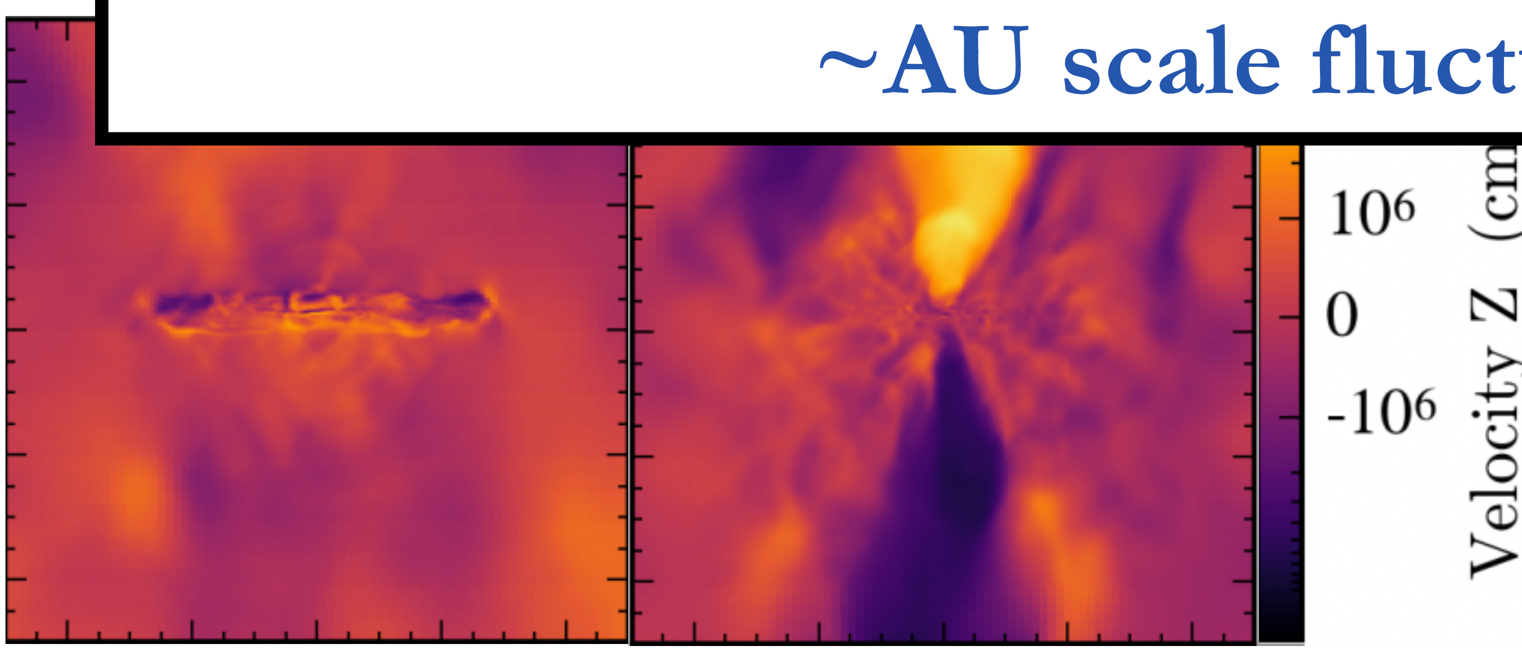
2. Cosmic ray transport and its role in regulating galaxy evolution

Turns out that it is surprisingly hard to drive a galactic wind without SNe injecting ~10% of their energy in cosmic rays

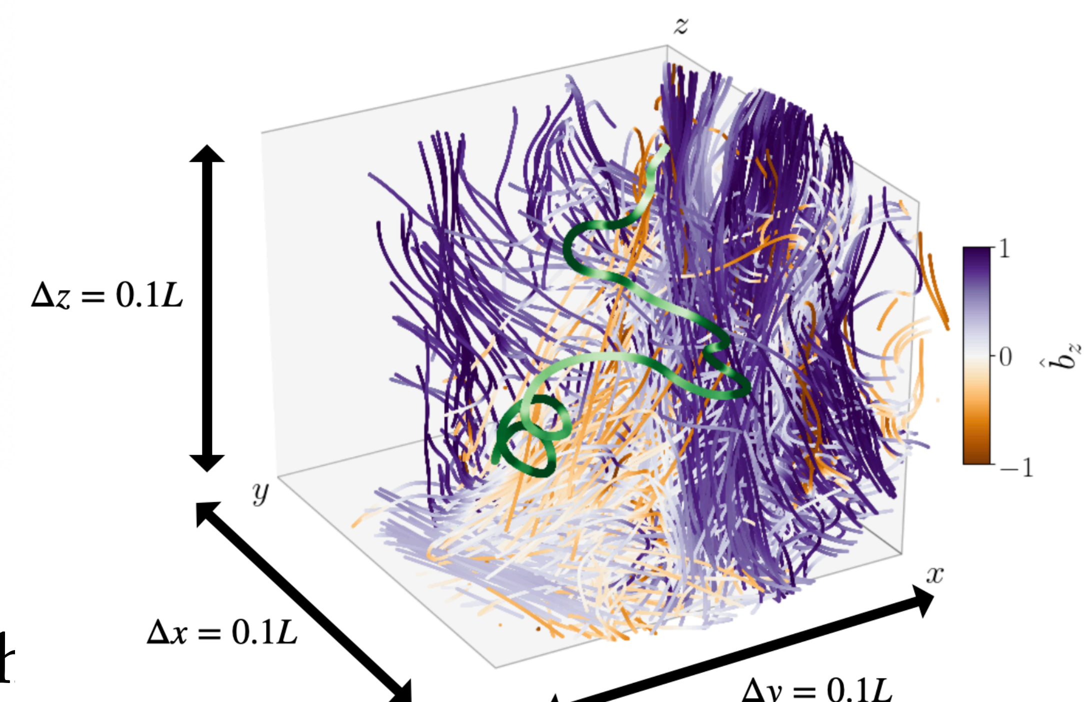


Evoli (2021)

How many stars a galaxy forms is strongly dependent on details of how cosmic rays are scattered by ~AU scale fluctuations



Butsky & Quinn (2018)

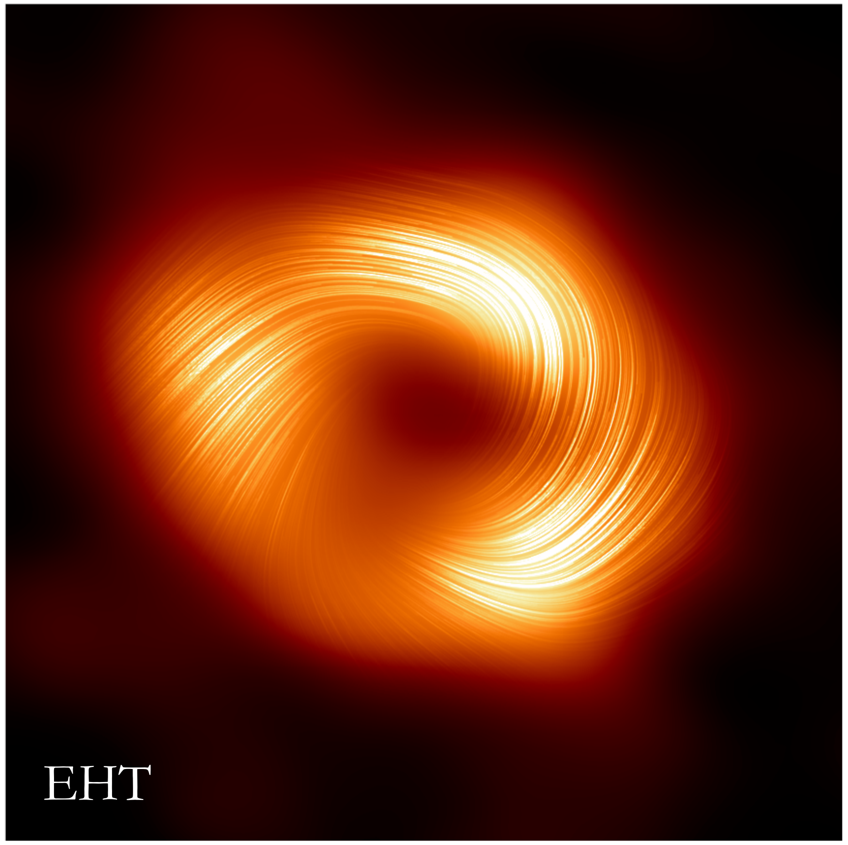


The efficiency depends sensitively on how th

couple to the ambient plasma by scattering o

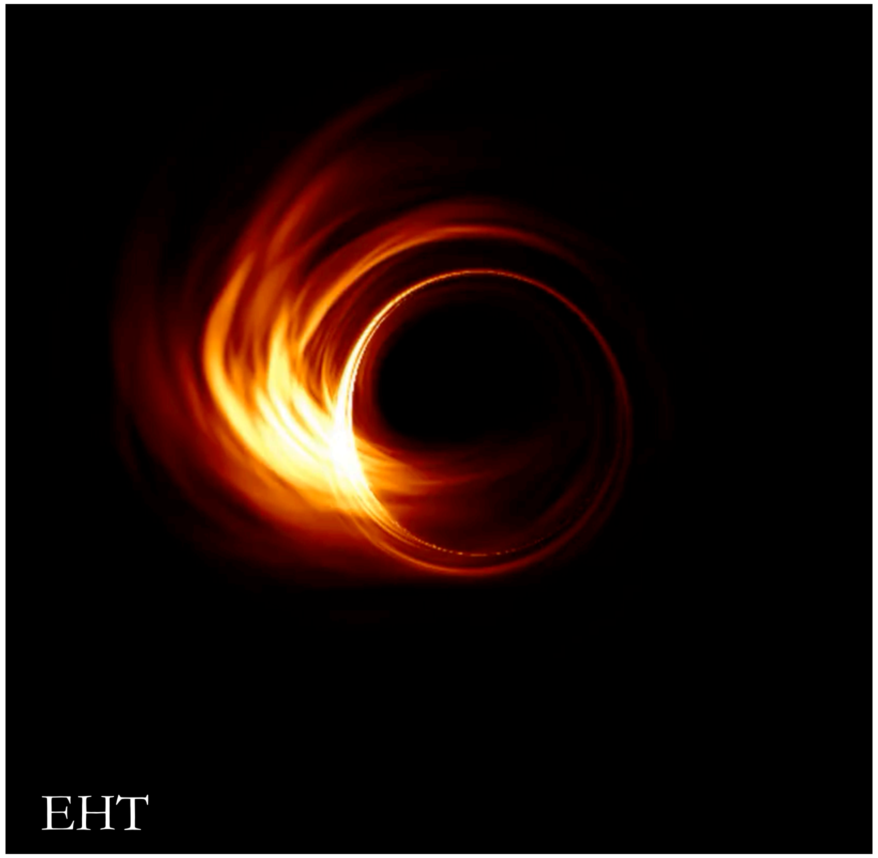
3. Kinetic turbulence, particle acceleration, accretion disks

Collisionless Plasma



$t_{ii} \sim$ years $\quad t_{dyn} \lesssim 10$ minutes

Modeled using GR MHD

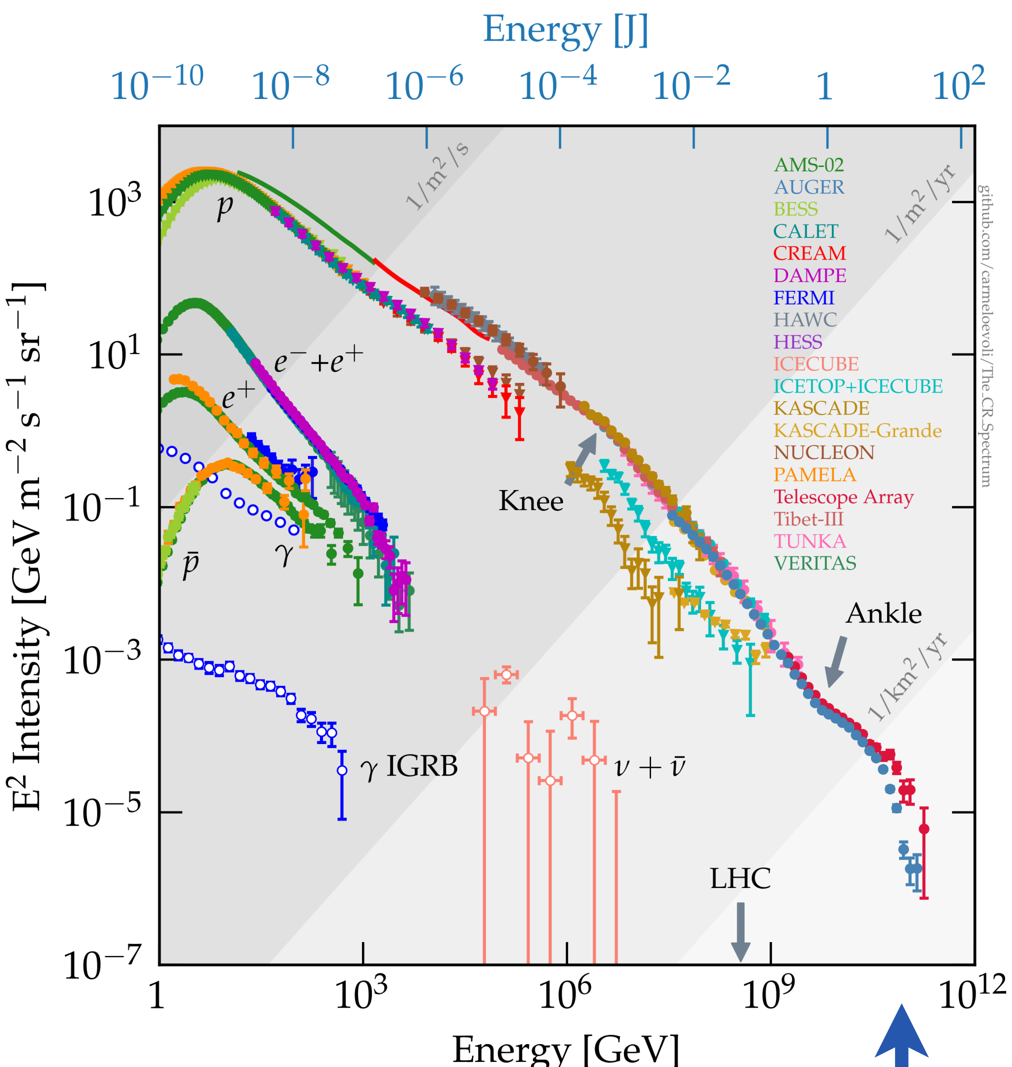


Fluid model!

These models fail to reproduce the variability of the sources (e.g. flares)

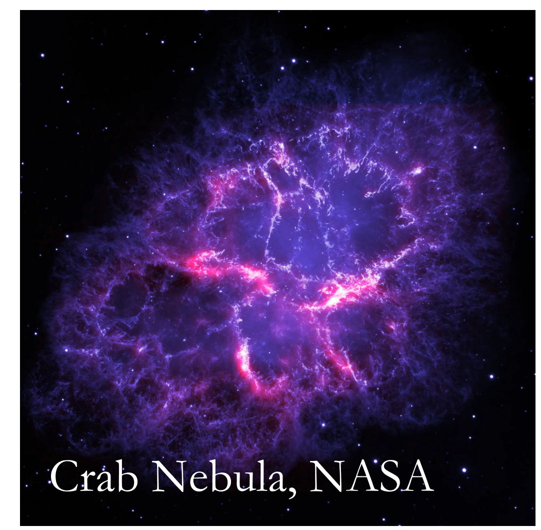
Simulations incorporating kinetic effects and non-thermal particle acceleration are the frontier

4. Where do the highest-energy CRs come from?



Evoli (2021)

Hillas Criterion: hard to confine and continue accelerating a particle once its gyro-radius becomes comparable to the accelerator size



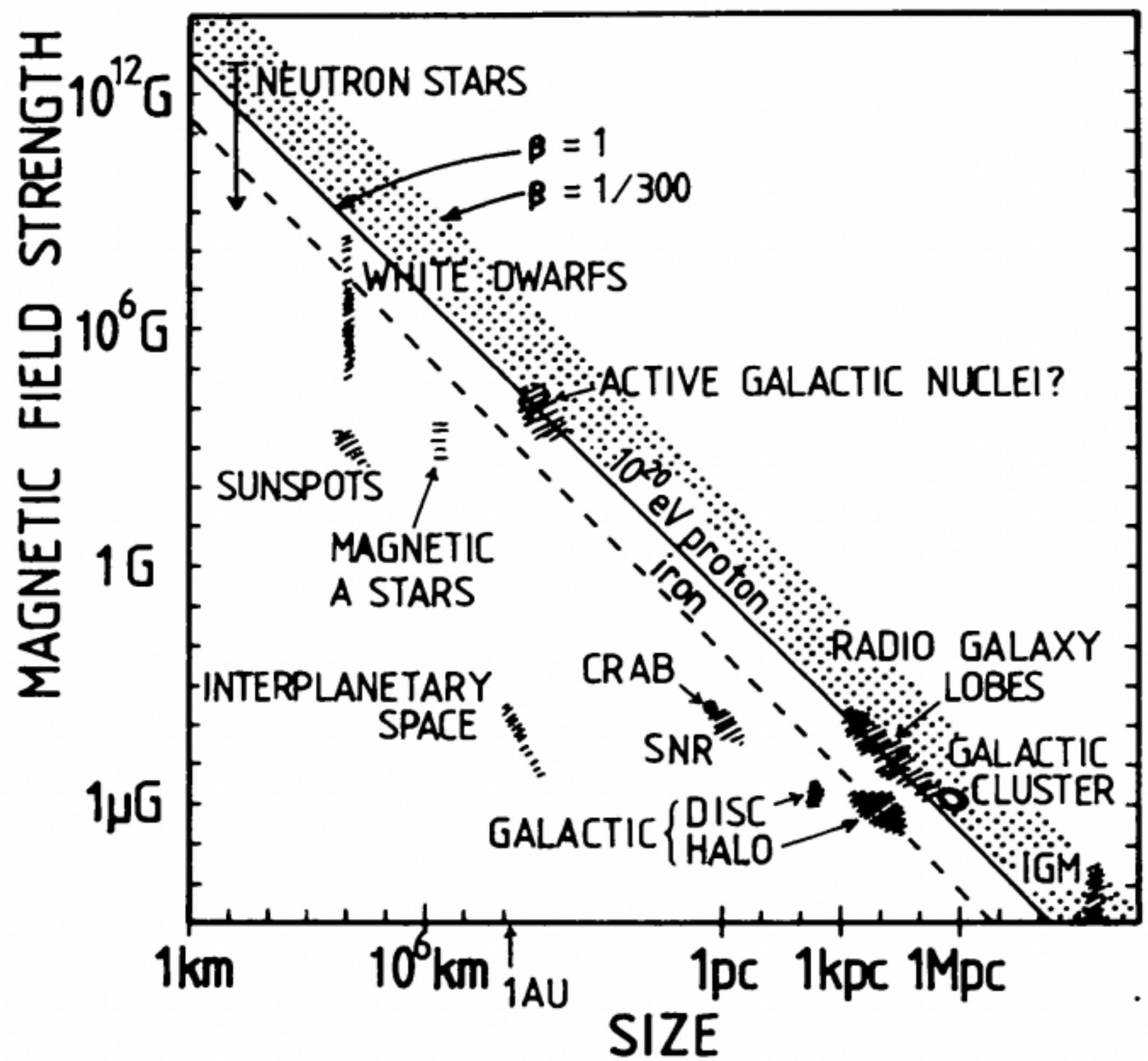
For typical ISM B-field:

$\rho_{10^{11}\ \mathrm{GeV}} \sim 100$ kpc

Below a PeV, Supernova shocks likely responsible for acceleration. At higher energies, things become less and less clear…

Size of Galaxy Clusters!

Hillas Plot



Hillas (1984)

Figure 1 Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV.

Thank you!!