TURBULENCE AND DYNAMO IN WEAKLY COLLISIONAL PLASMAS

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Along with: *E. Quataert, A. Schekochihin, M. Kunz*

Key projects [edit]

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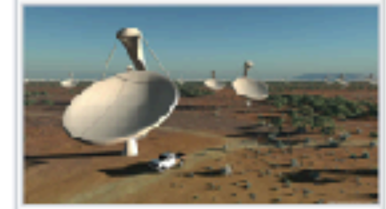
Find sources: "Square Kilometre Array" – news · newspapers · books · scholar · JSTOR (May 2012) (Learn how and when to remove this template message)


Artist's impression of a SKA Dense Aperture Array Station

The capabilities of the SKA will be designed to address a wide range of questions in astrophysics, fundamental physics, cosmology and particle astrophysics as well as extending the range of the observable universe. A number of key science projects that have been selected for implementation via the SKA are listed below.


Artistic impression of the Offset Gregorian Antennas

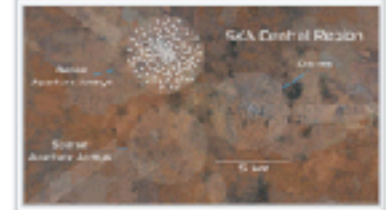
Extreme tests of general relativity [edit]

Main article: Tests of general relativity

For almost one hundred years, Einstein's general theory of relativity has precisely predicted the outcome of every experiment made to test it. Most of these tests, including the most stringent ones, have been carried out using radio astronomical measurements. By using pulsars as cosmic gravitational wave detectors, or timing pulsars found orbiting black holes, astronomers will be able to examine the limits of general relativity such as the behaviour of spacetime in regions of extremely curved space. The goal is to reveal whether Einstein was correct in his description of space, time and gravity, or whether alternatives to general relativity are needed to account for these phenomena.

Galaxies, cosmology, dark matter and dark energy [edit]

Main articles: Galaxy formation and evolution and Dark matter



Schematic of the SKA Central Region

The sensitivity of the SKA in the 21 cm hydrogen line will map a billion galaxies out to the edge of the observable Universe. The large-scale structure of the cosmos revealed will give constraints to determine the processes resulting in galaxy formation and evolution. Imaging hydrogen through the Universe will provide a three-dimensional picture of the first ripples of structure that formed individual galaxies and clusters. This may also allow the measurement of effects hypothetically caused by dark energy and causing the increasing rate of expansion of the universe.[28]

The cosmological measurements enabled by SKA galaxy surveys include testing models of dark energy,[29] gravity,[30] the primordial universe,[31] fundamental cosmology tests,[32] and they are summarized in a series of papers available online.[33][34][35][36]

Epoch of re-ionization [edit]

The SKA is intended to provide observational data from the so-called Dark Ages (between 300,000 years after the Big Bang when the universe became cool enough for hydrogen to become neutral and decouple from radiation) and the time of First Light (a billion years later when young galaxies are seen to form for the first time and hydrogen becomes again ionized). By observing the primordial distribution of gas, the SKA should be able to see how the Universe gradually lit up as its stars and galaxies formed and then evolved. This period between the Dark Ages and First Light is considered the first chapter in the cosmic story of creation and the distance to see this event is the reason for the Square Kilometre Array's design. To see back to First Light requires a telescope 100 ... taking up 1 million square metres of collecting area, or one square kilometre.[37]

Cosmic magnetism [edit]

It is still not possible to answer basic questions about the origin and evolution of cosmic magnetic fields, but it is clear that they are an important component of interstellar and intergalactic space. By mapping the effects of magnetism on the radiation from very distant galaxies, the SKA will investigate the form of cosmic magnetism and the role it has played in the evolving Universe.

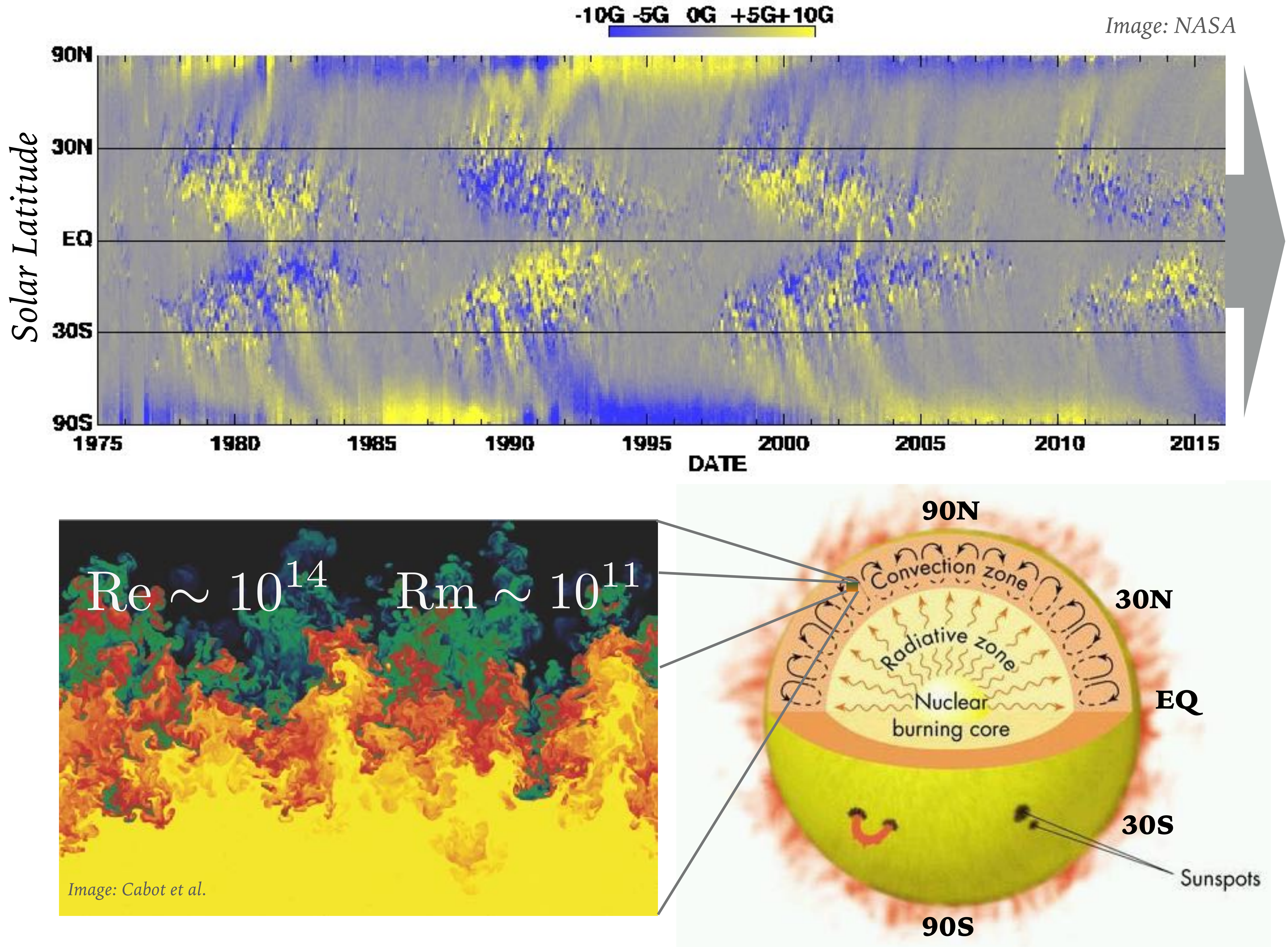
Search for ...

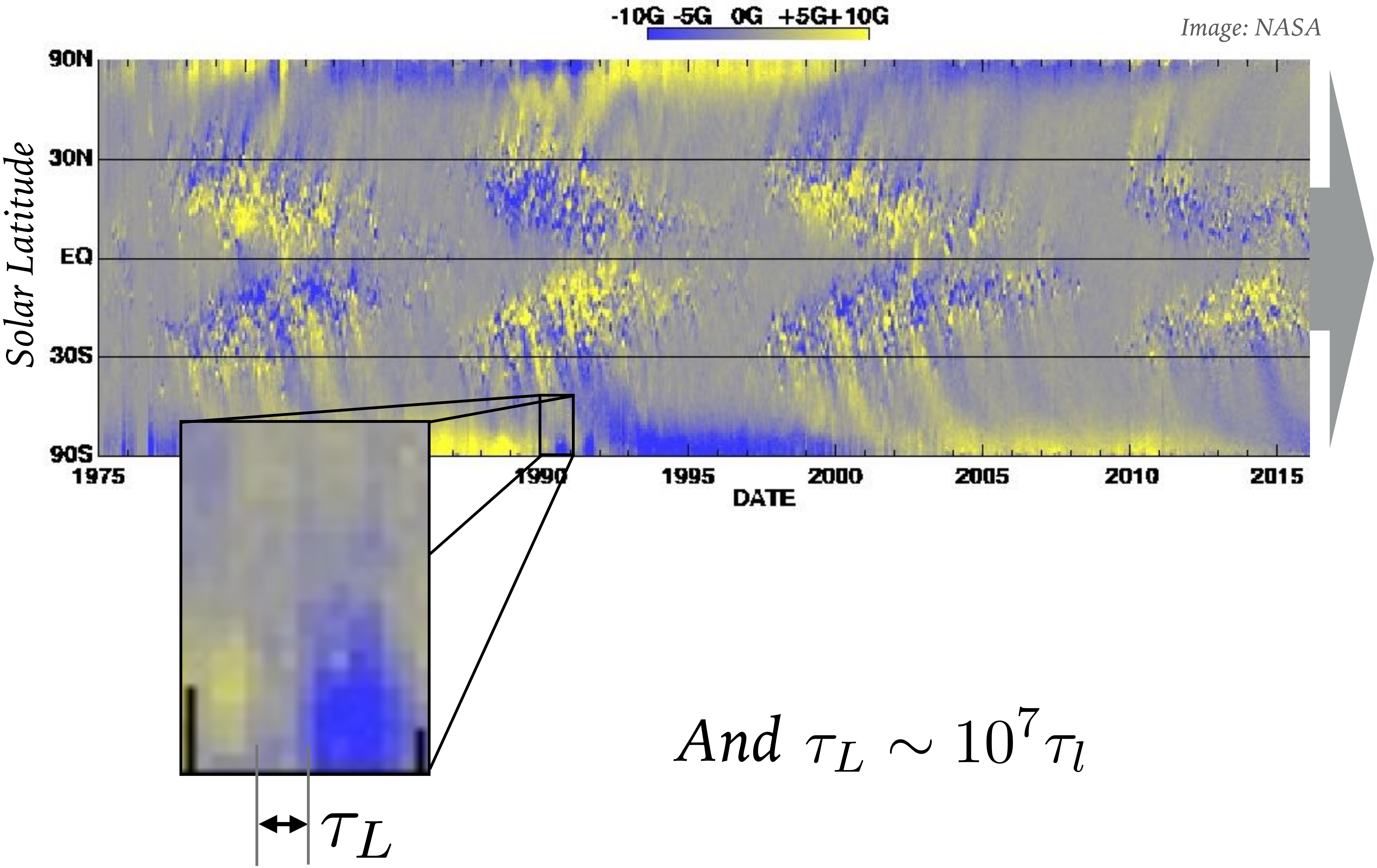
This key science program, called "Cradle of Life", will focus on three objectives: protoplanetary discs in habitable zones, search for prebiotic chemistry, and the search for extraterrestrial intelligence (SETI).[38]

- The SKA will be able to probe the habitable zone of Sun-like protostars, where Earth-like planets or moons are most likely to have environments favourable for the development of life.[39] The signatures of forming Earth-like planets imprinted on circumstellar dust may be the most conspicuous evidence of their presence and evolution,[39] and may even detect planets capable of supporting life.[39][40]
- Astrobiologists will also use the SKA to search for complex organic compounds (carbon-containing chemicals) in outer space, including amino acids, by identifying spectral lines at specific frequencies.[39]
- The SKA will be capable of detecting extremely weak radio emissions "leakage" from nearby extraterrestrial civilizations, if they exist.[39]

COSMIC MAGNETISM IS (MOSTLY) A STORY OF PLASMA PHYSICS

- How are magnetic fields created? *Magnetogenesis*
- How are magnetic fields amplified to what we see? *Dynamo*
- How do magnetic fields influence matter?


-10G -5G 0G +5G +10G
Image: NASA
Solar Latitude
90N
30N
EQ
30S
90S
1975
1980
1985
1990
1995
2000
2005
2010
2015
DATE
$\mathrm{Re} \sim 10^{14}$
$\mathrm{Rm} \sim 10^{11}$
Image: Cabot et al.
90N
Convection zone
30N
Radiative zone
EQ
Nuclear
burning core
30S
Sunspots
90S

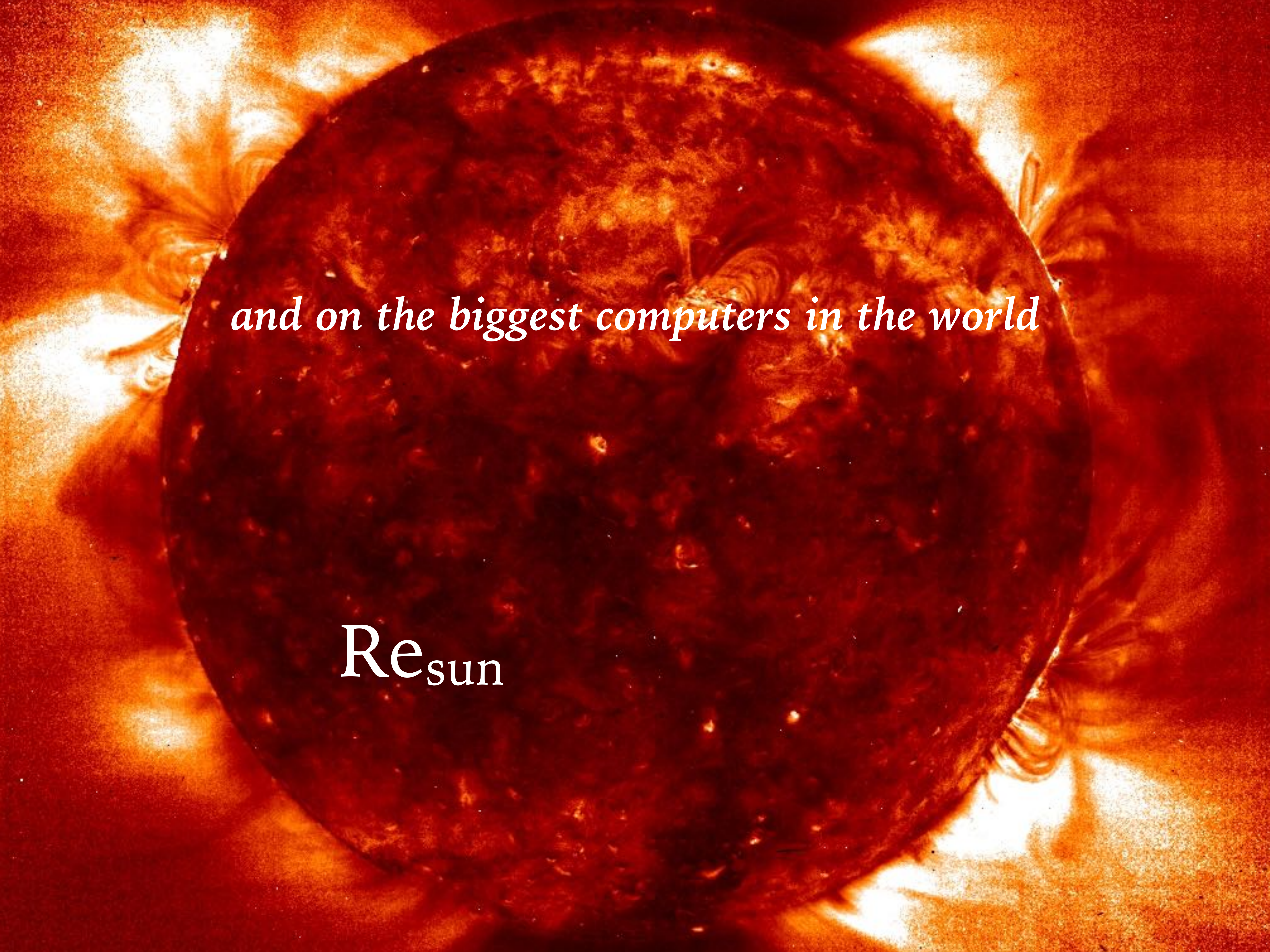


And $\tau_L \sim 10^7 \tau_l$

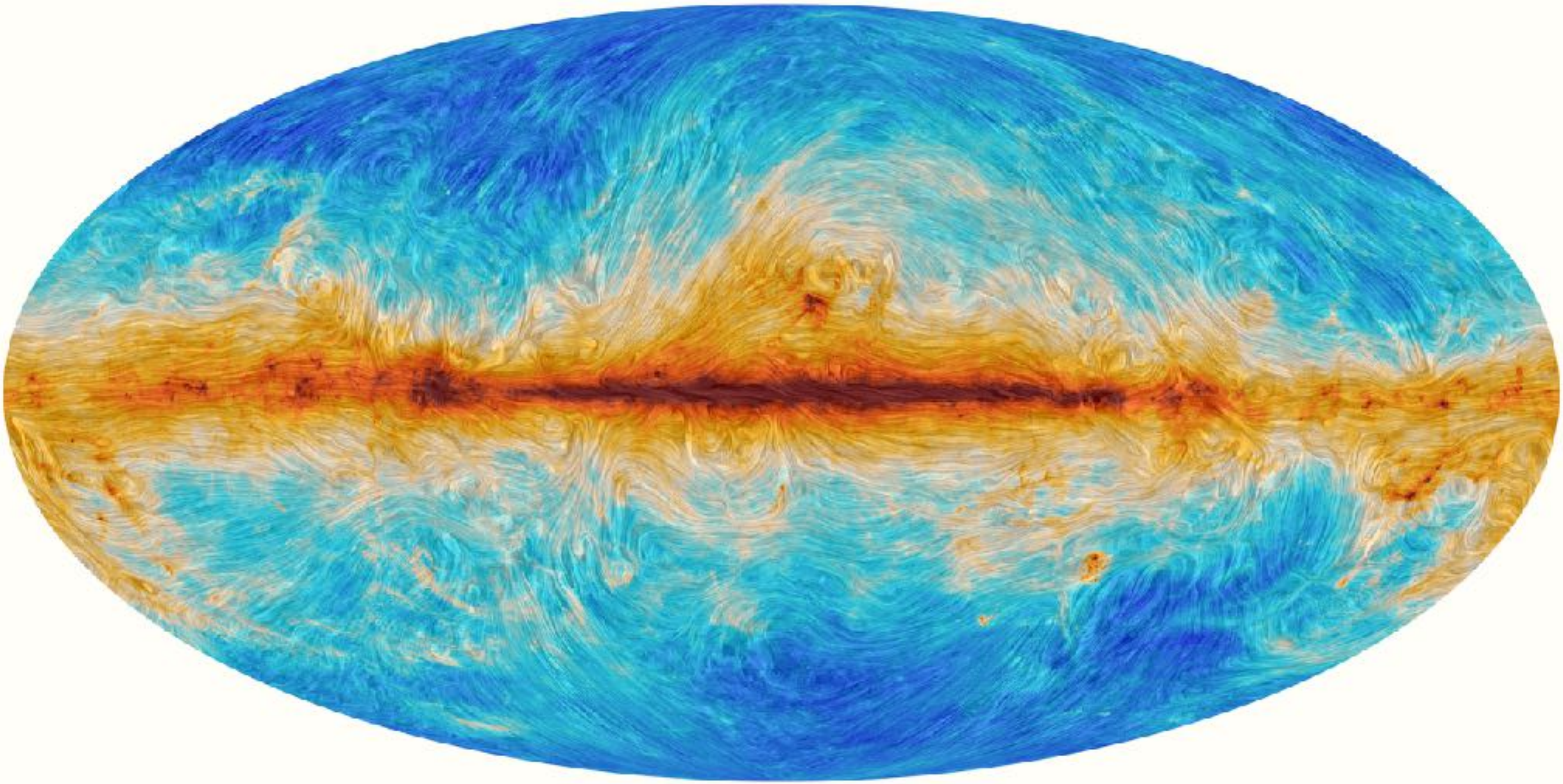
The slowest fluid motions (rotation similar)

WHY DOES THIS HAPPEN?

WHAT CAN BE EXPECTED IN DIFFERENT REGIMES?


and on the biggest computers in the world
Re_{sun}

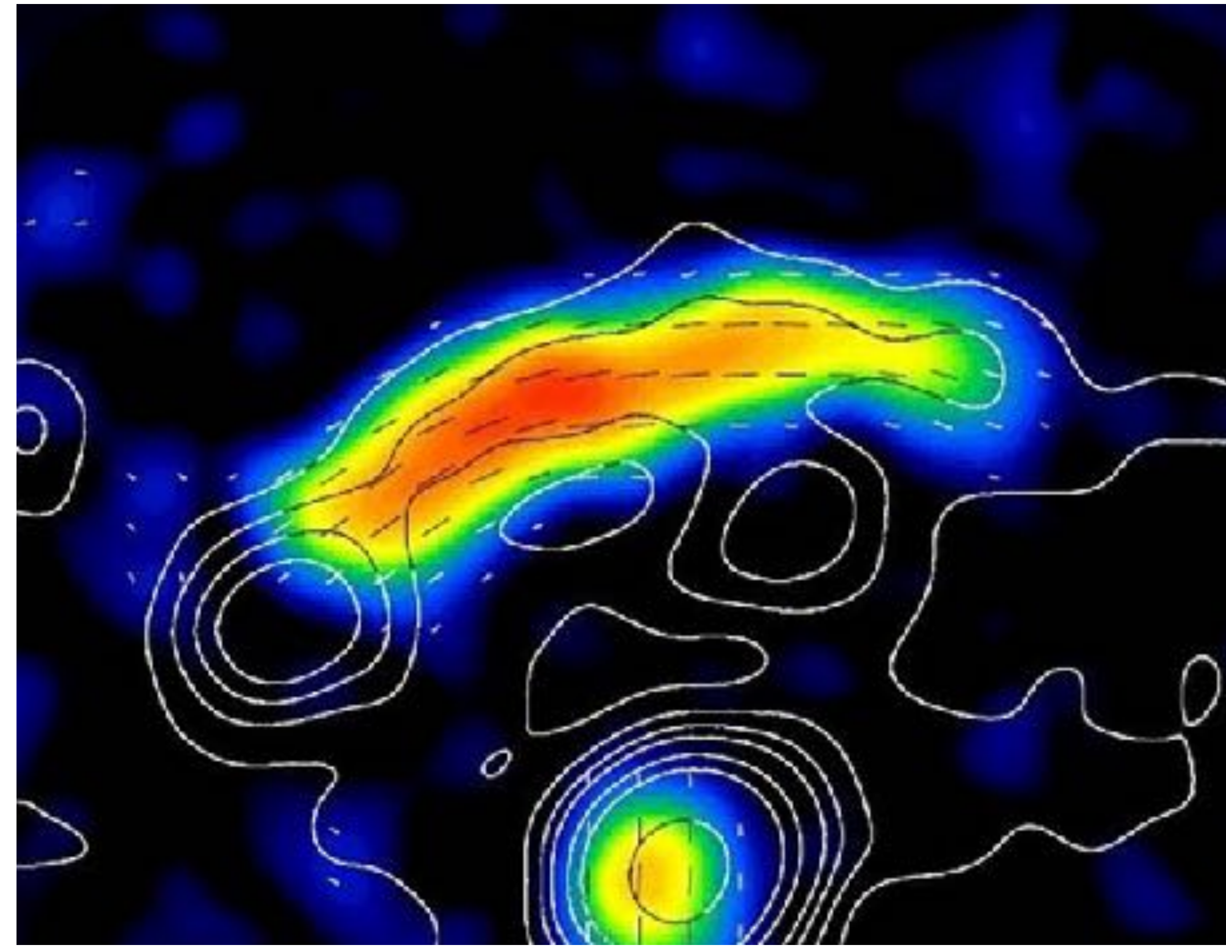
WE SEE SIMILAR SELF-ORGANIZATION IN GALAXIES AND CLUSTERS



Milky way field structure, Planck

Credit ESA/Planck collaboration

Correlated fields in the "Sausage relic" in cluster CIZA J2242+53, Kierdorf+ (2017)



IC 342, combined Optical/Radio

Credit: R. Beck, MPIfR; NRAO/AUI/NSF

I want to talk about a regime where we don't even know what equations to solve…

HIGH β

$$\beta \equiv \frac{P_{\mathrm{thermal}}}{P_{\mathrm{magnetic}}} = \frac{8\pi P_0}{B^2}$$

High β plasma
= weak magnetic fields
= dominated by thermal energy

WEAKLY COLLISIONAL

λ_{mfp} > *other scales*

System scales
Ion gyroradius
Plasma motions

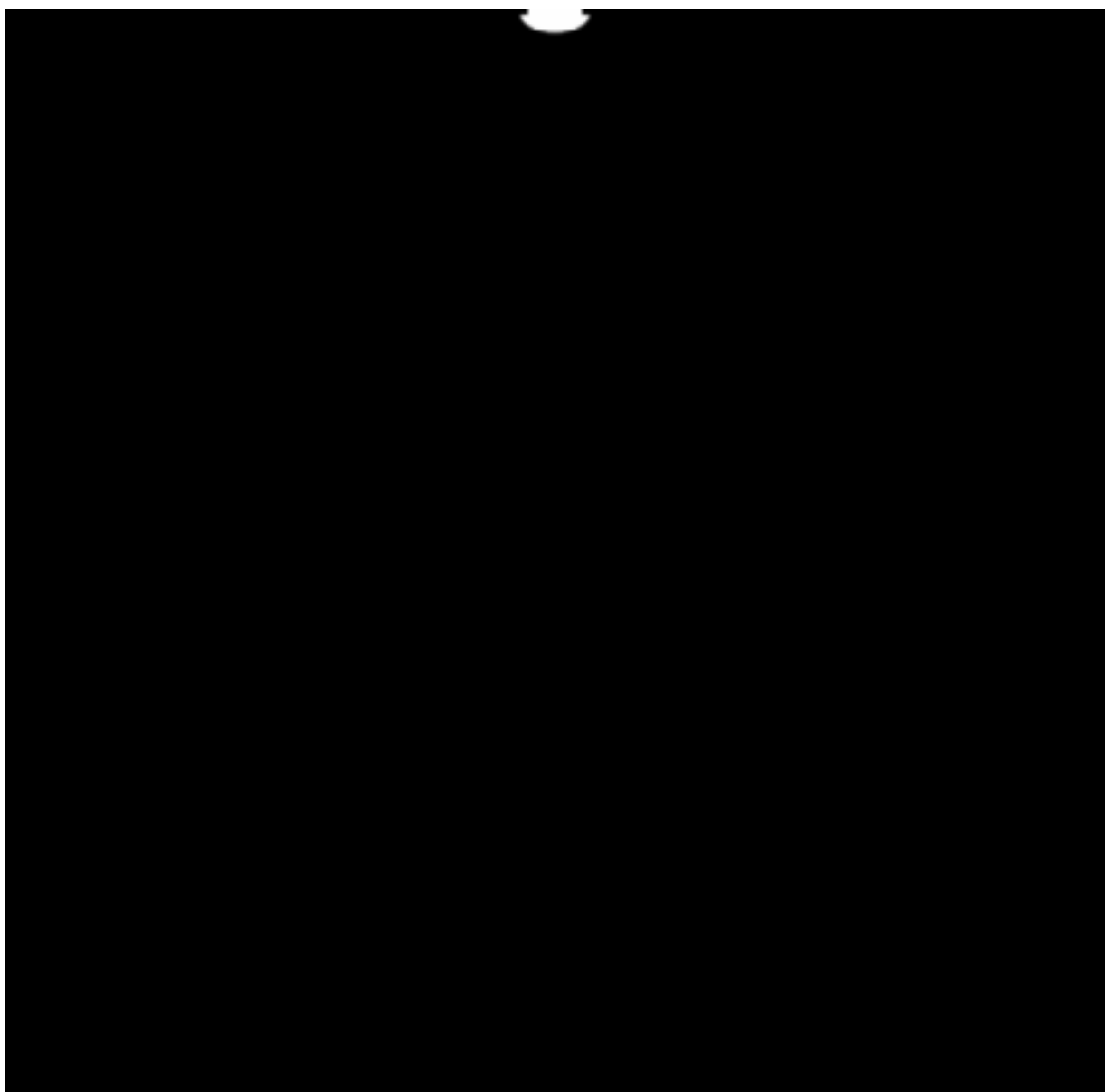
Fluid theory (e.g., MHD) applies?

A theory of "fluid dynamics"

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\rho^{-1} \nabla P + \ldots ?$$

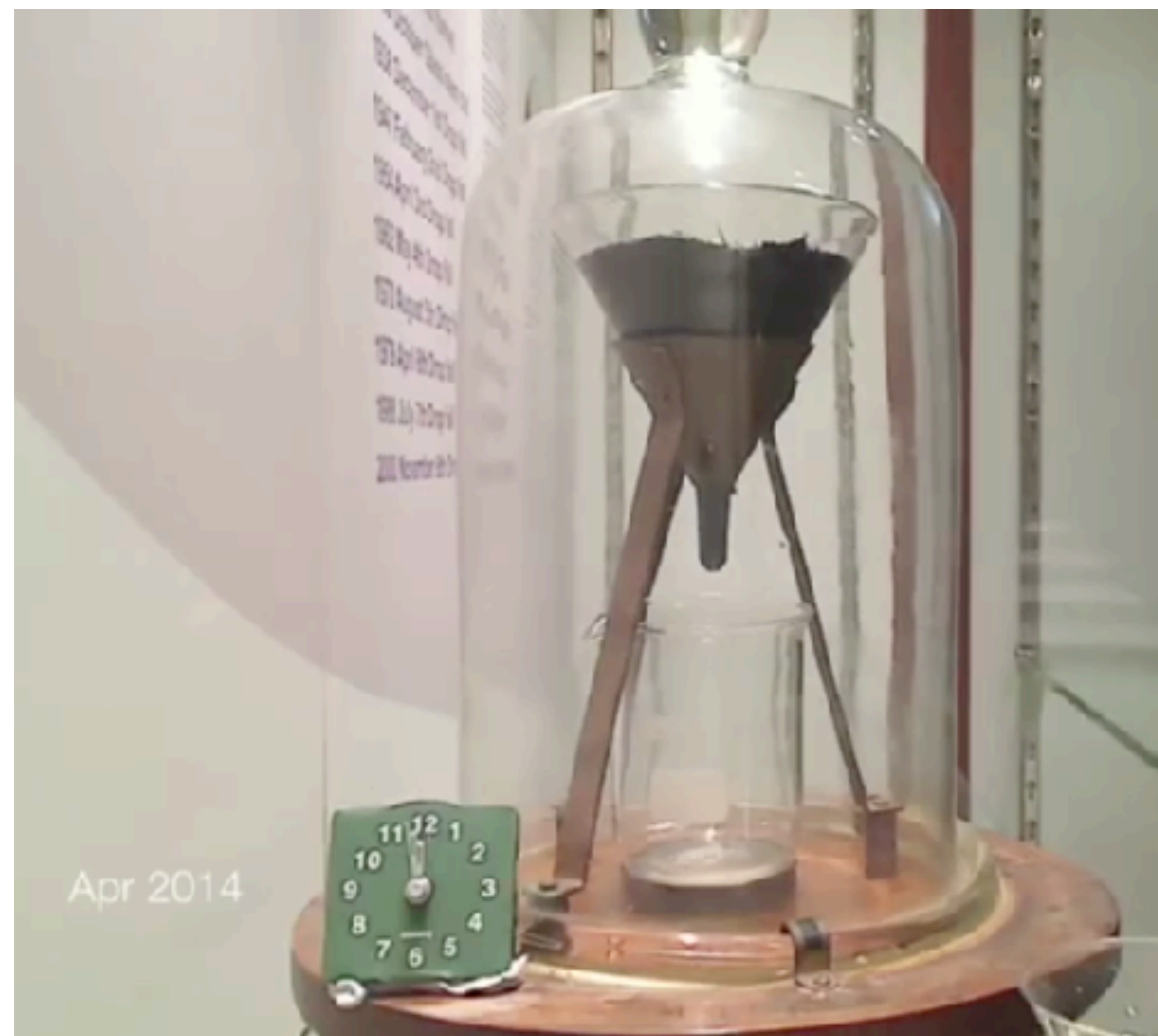
Well described by normal (magneto)hydrodynamics?

e.g., viscosity, conductivity, energy dissipation, …



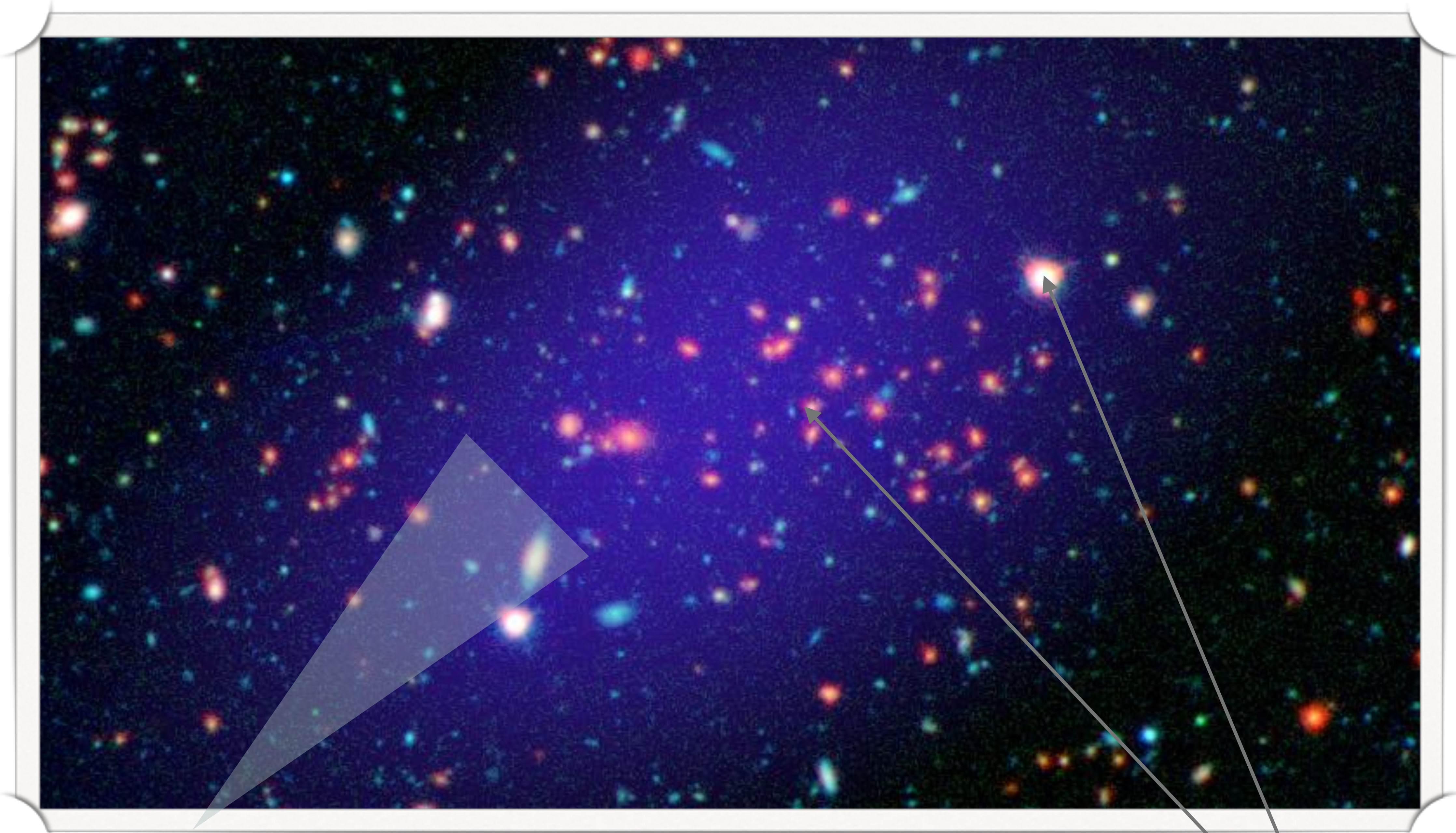
Credit: Universität Duisburg-Essen

vs.



Credit: University of Queensland

Intracluster Medium (ICM)

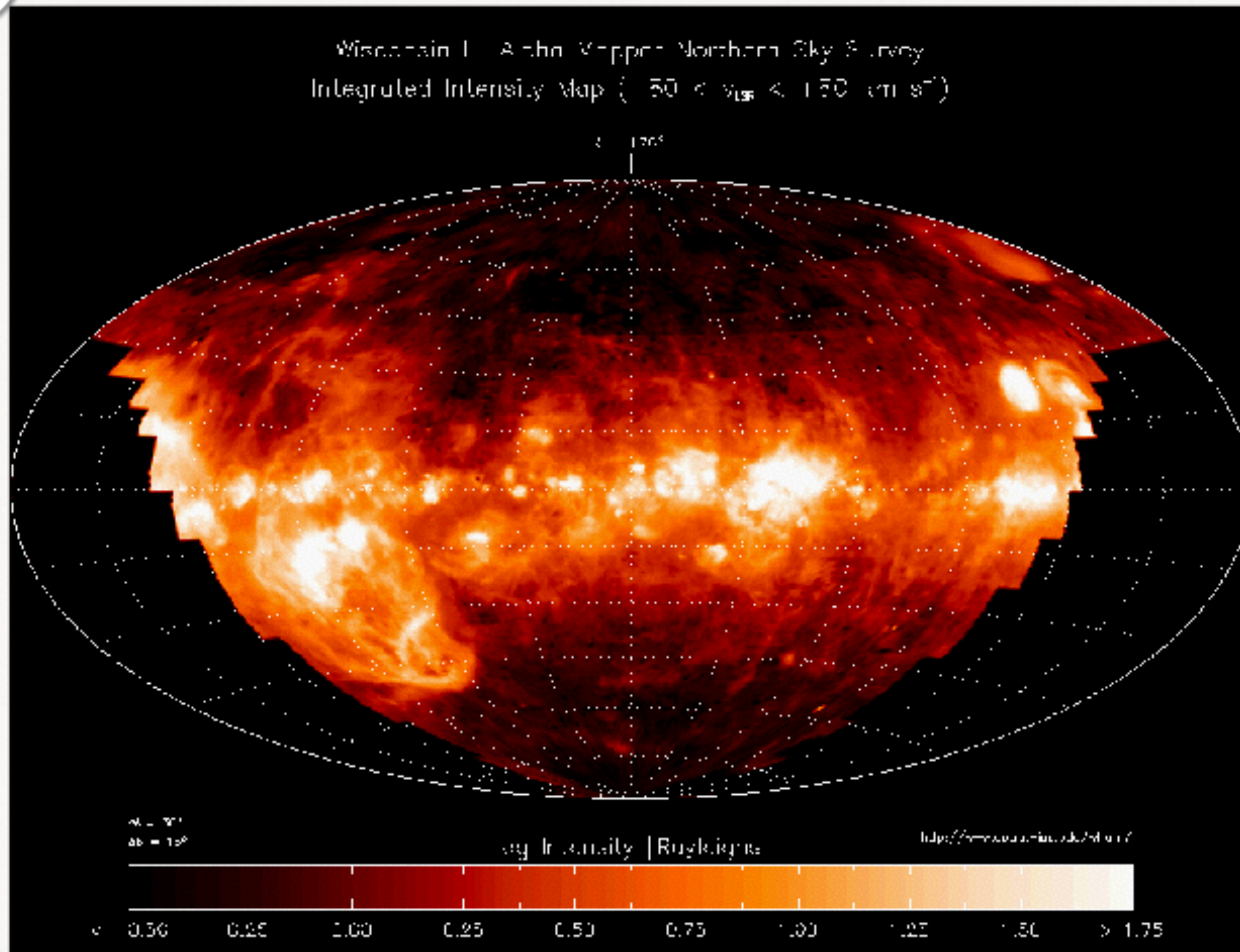


$$\lambda_{\mathrm{mfp}} \sim 10^{11} \rho_i$$

$$P_{\mathrm{mag}} \ll p_0 \;\Rightarrow\; \beta \gg 1$$

Image: NASA

The Warm/Hot Ionized Mediums

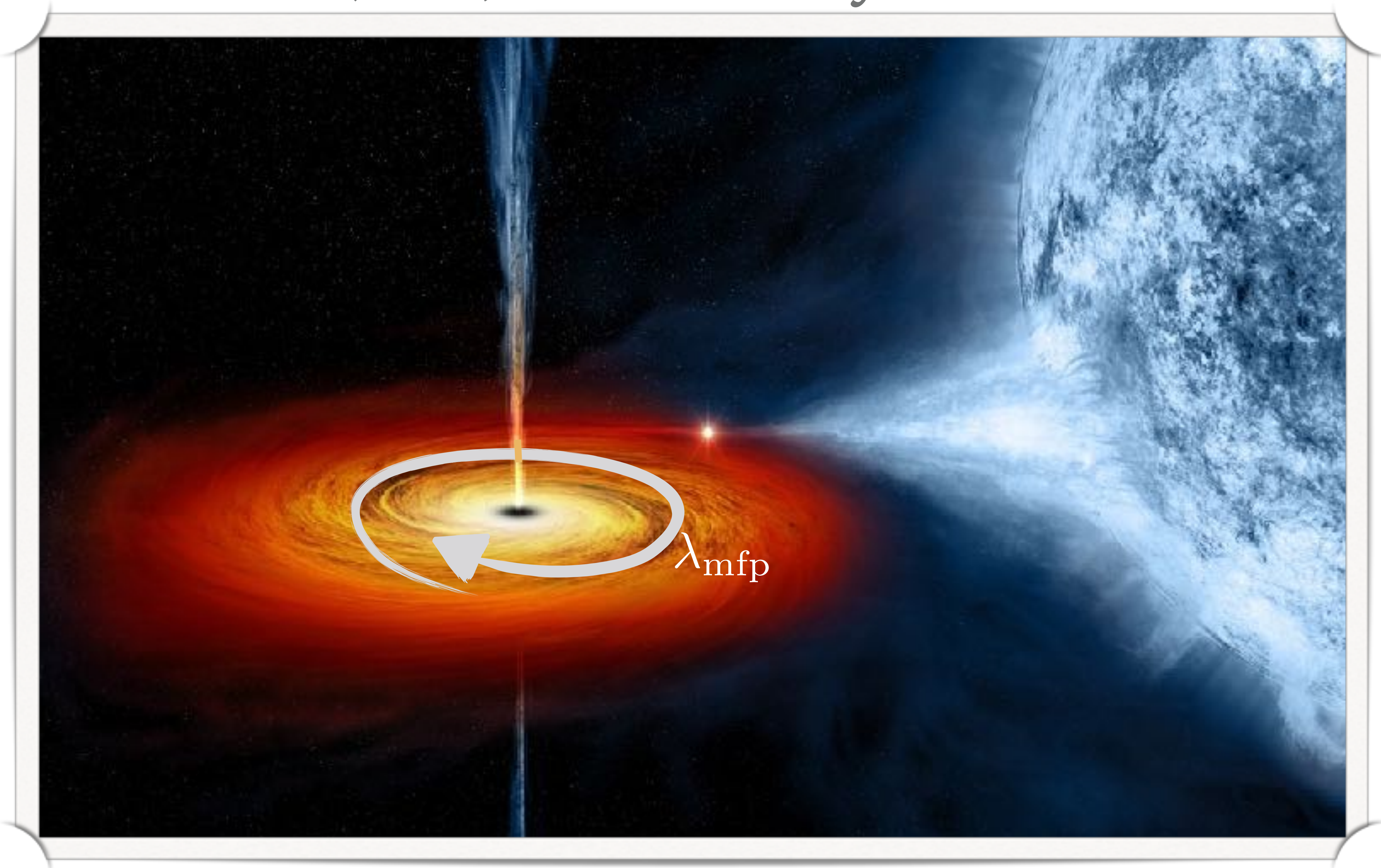


Haffner et al, 2003, ApJS

$$\lambda_{\rm mfp} \sim 10^5 \rho_i$$

$$P_{\rm mag} \lesssim p_0 \quad \Rightarrow \quad \beta \gtrsim 1$$

(Hot) Accretion flows

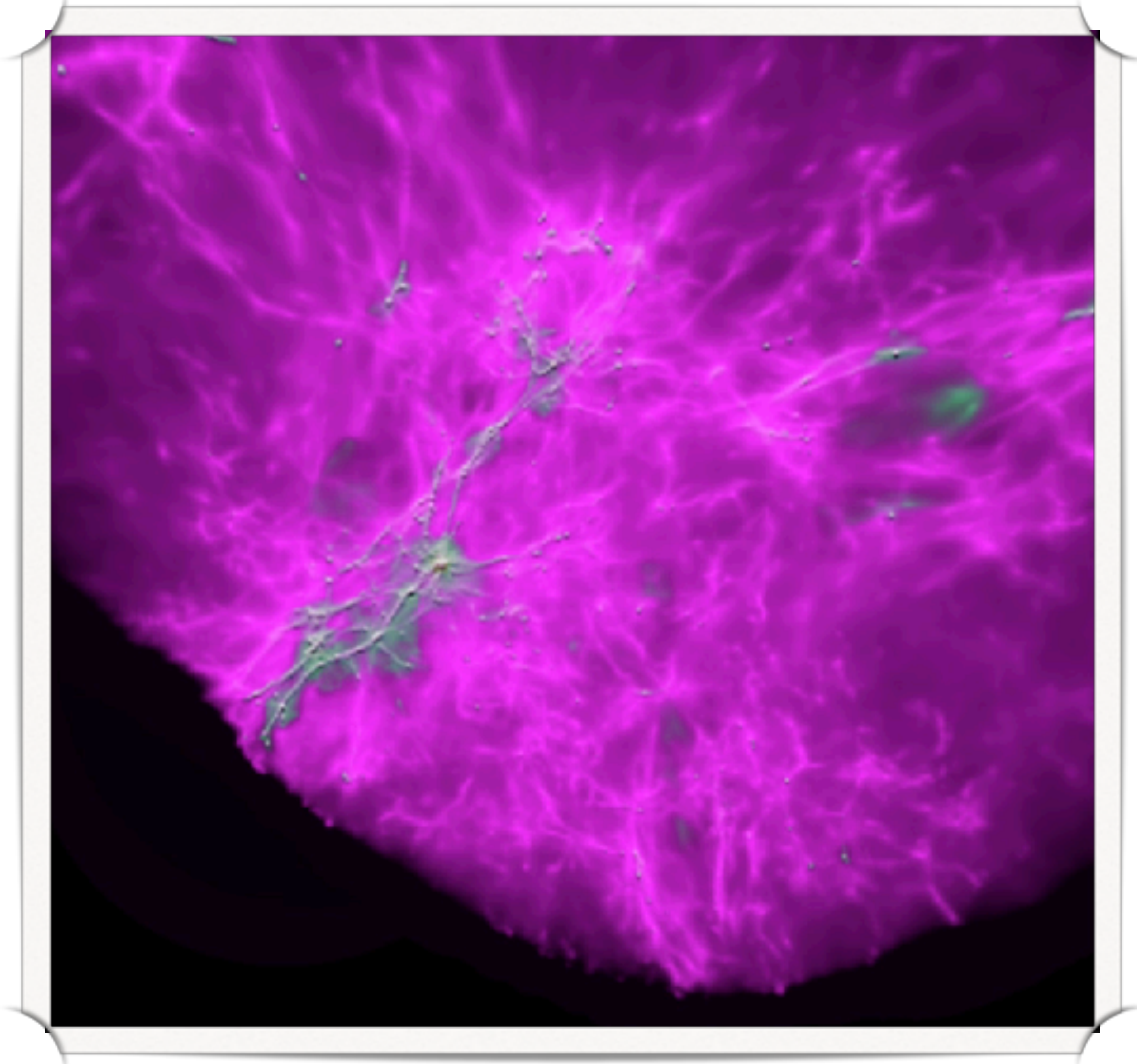


$$\lambda_{\rm mfp} \gg R \gg \rho_i$$

$$\beta > 1$$

Image: MPIFR

High-z halos



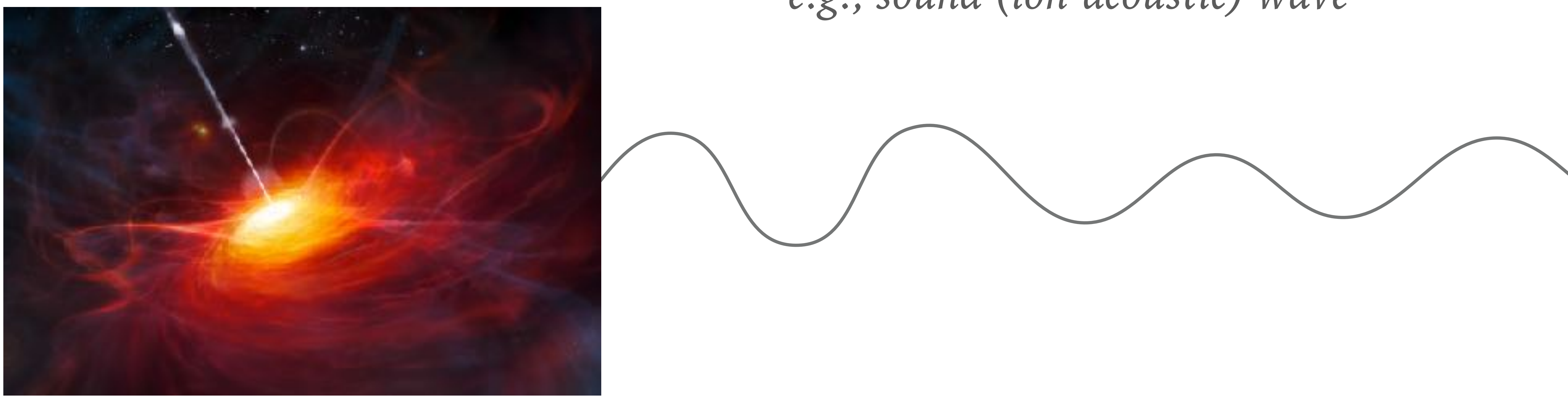
$\beta \gtrsim 10^{10}$? *Unmagnetized?? Magnetogenesis?*

$\lambda_{\rm mfp} = ?$

Image: FIRE collaboration

PERTURB MAGNETIC FIELD?

e.g., sound (ion-acoustic) wave



$\omega \gtrsim \nu_{ii}$

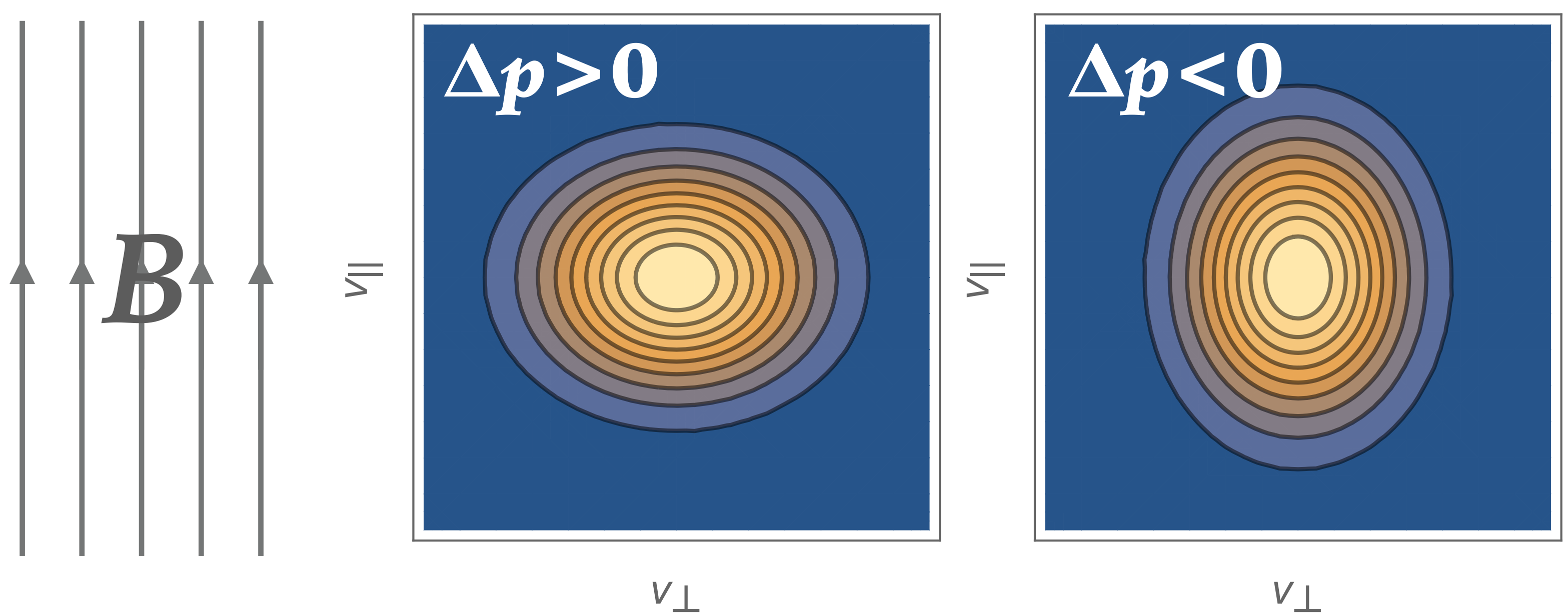
$\omega \lll \Omega_i$

wavelength ~ galaxy size

see also Verscharen et al. (2016)

PRESSURE PERTURBATION

- Can have a different pressure parallel and perpendicular to the field, $p_\perp$ and $p_{||}$



$$\Delta p = p_\perp - p_{||}$$

$$\hat{\boldsymbol{b}} = \frac{\boldsymbol{B}}{|\boldsymbol{B}|}$$

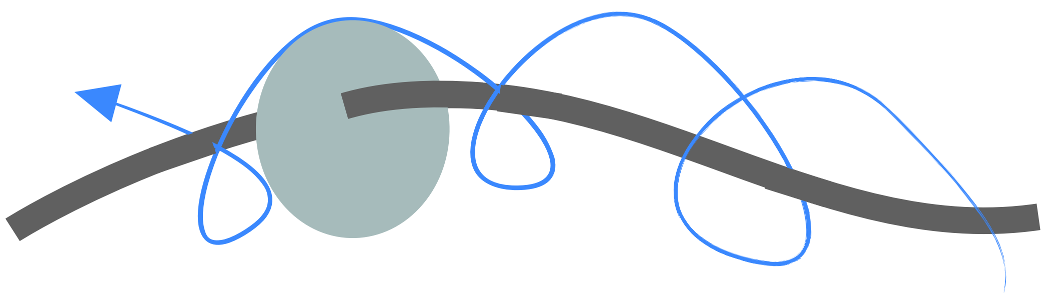
$$\partial_t \boldsymbol{u}_{MHD} = \partial_t \boldsymbol{u} + \nabla \cdot [\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}(B^2 - \Delta p)]$$

Magnetic tension

PERTURB MAGNETIC FIELD?

$\omega \gtrsim \nu_{ii}$ (wavelength < 0.01*galaxy)

$$\mu = \frac{mv_\perp^2}{2B}$$
conserved



$|B|$ ↑ ➡ $p_\perp$ ↑ ➡ Δp ↑

$|B|$ ↓ ➡ Δp ↓

PERTURB MAGNETIC FIELD?

$$\frac{\delta B^2}{B_0^2} \sim \frac{\delta \Delta p}{p_0}$$

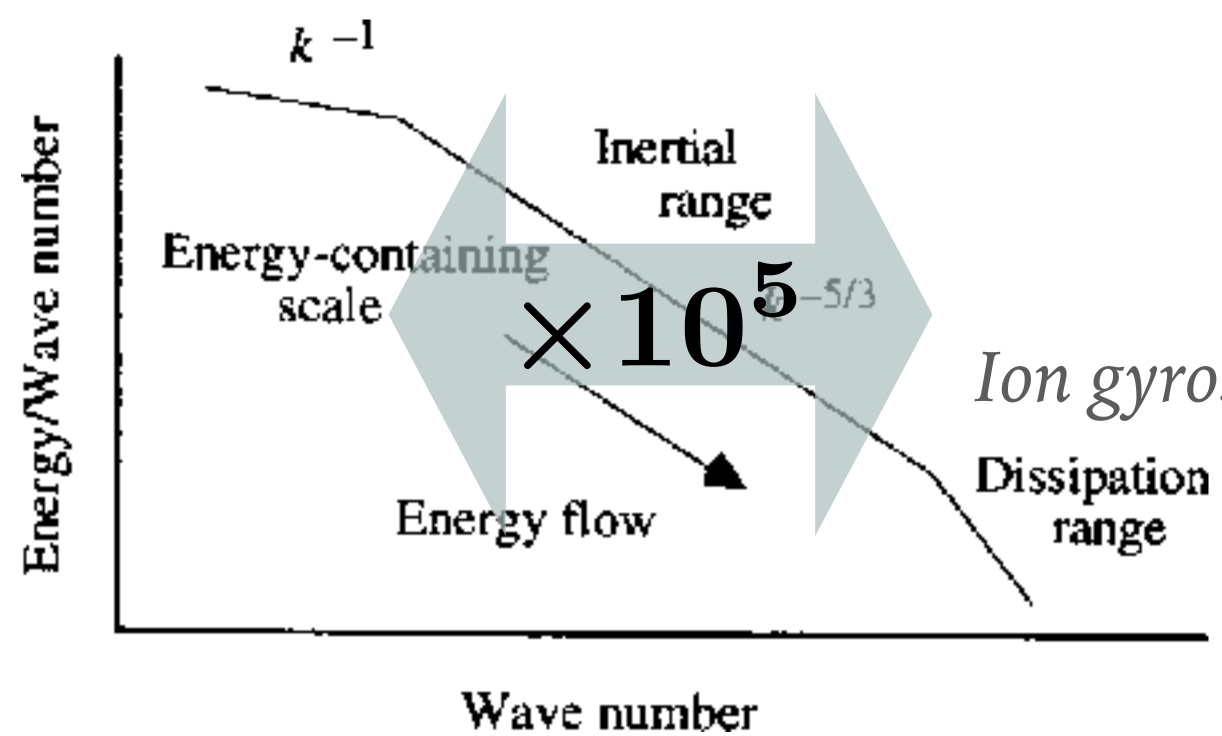
$$\partial_t \boldsymbol{u} = \cdots + \nabla \cdot [\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}(B^2 + \Delta p)]$$

$$\delta B^2 \sim \beta^{-1} \delta \Delta p$$

*Momentum stress due to Δp ~ β*magnetic pressure*

Fluid theory (MHD) completely wrong?

Even though
$L \ggg \rho_i$

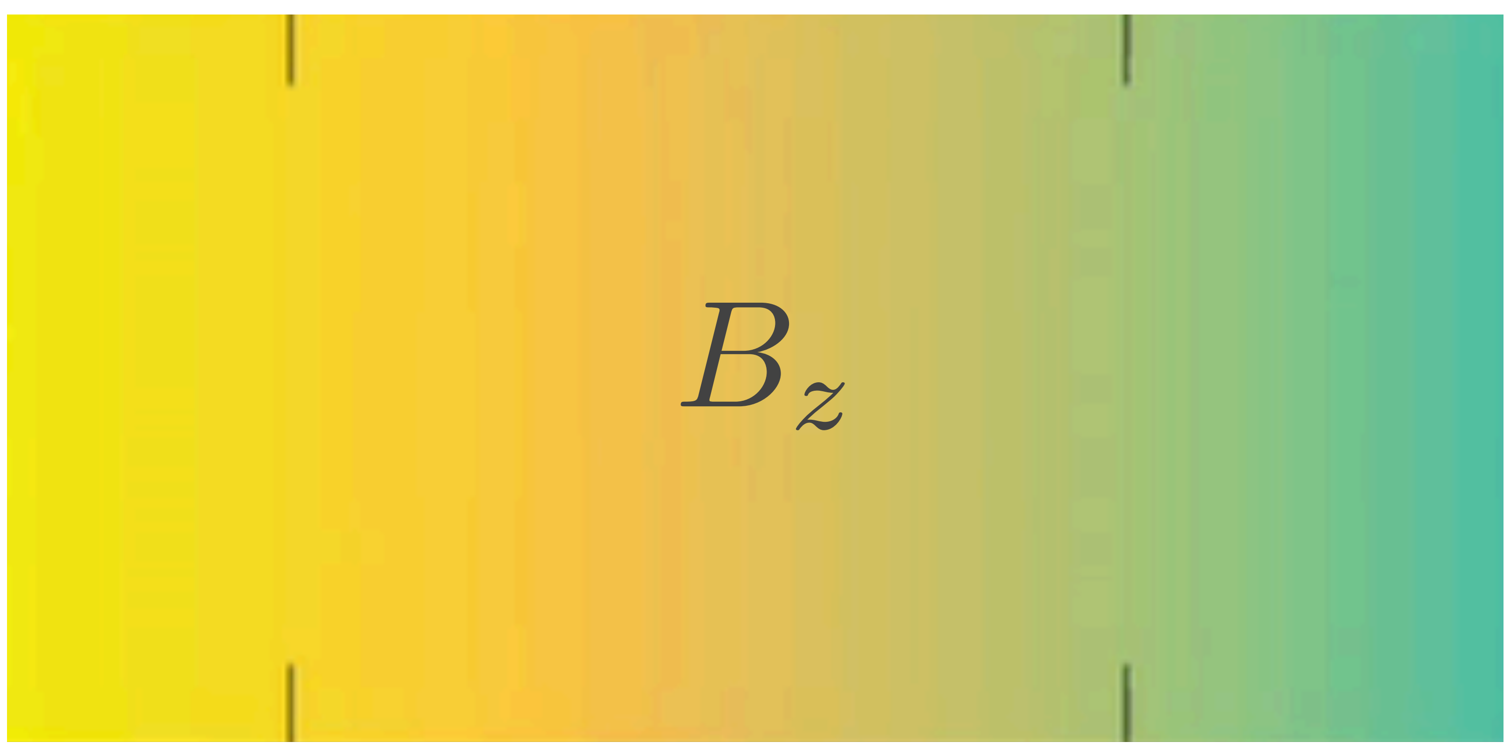


Ion gyroscale

PRESSURE ANISOTROPY MICRO-INSTABILITIES

$$\frac{\Delta p}{p} \gtrsim \frac{1}{\beta} \quad \text{OR} \quad \frac{\Delta p}{p} \lesssim -\frac{2}{\beta}$$

Too far from LTE!

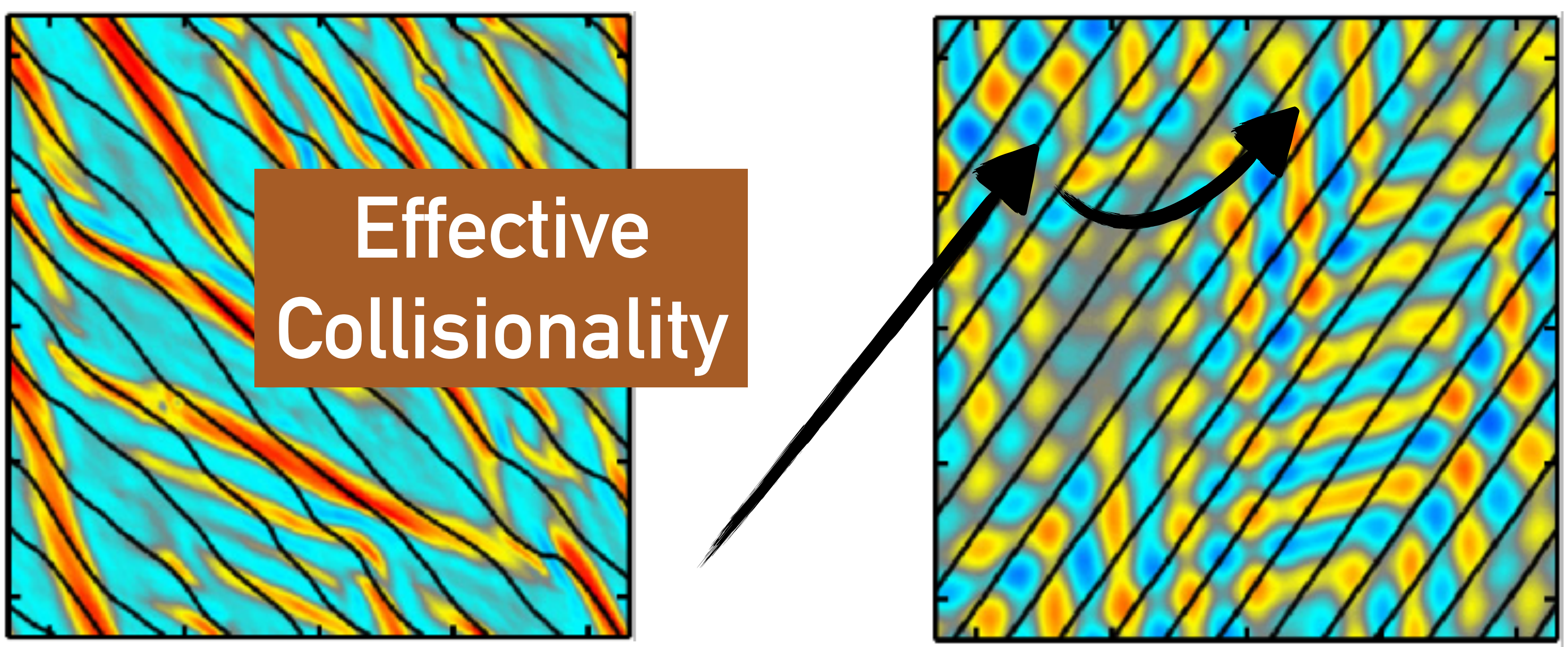


PRESSURE ANISOTROPY INSTABILITIES

$$\frac{\Delta p}{p} \gtrsim \frac{1}{\beta} \quad \textbf{OR} \quad \frac{\Delta p}{p} \lesssim -\frac{2}{\beta}$$

$$\nabla \cdot [\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}(B^2 + \Delta p)] \lesssim 0$$

Mirror Instability *Firehose Instability*



Kunz et al. 2014

ICM WAVE

$\frac{\delta n}{n} > 0.01$??

Key points:

- Firehose/mirror excited *very* easily.
- Act to limit Δp

$\Omega_i/|\nabla \boldsymbol{u}| \sim (k\rho_i)^{-1} \sim 10^{11}$ → they act instantaneously

- Saturation controls large-scale dynamics

LARGE SCALES

$\lambda \gg \rho_i$

- Maybe not like a fluid?

Drive microinstabilities

Effective collisionality

MICROSCALES

$\lambda \sim \rho_i$

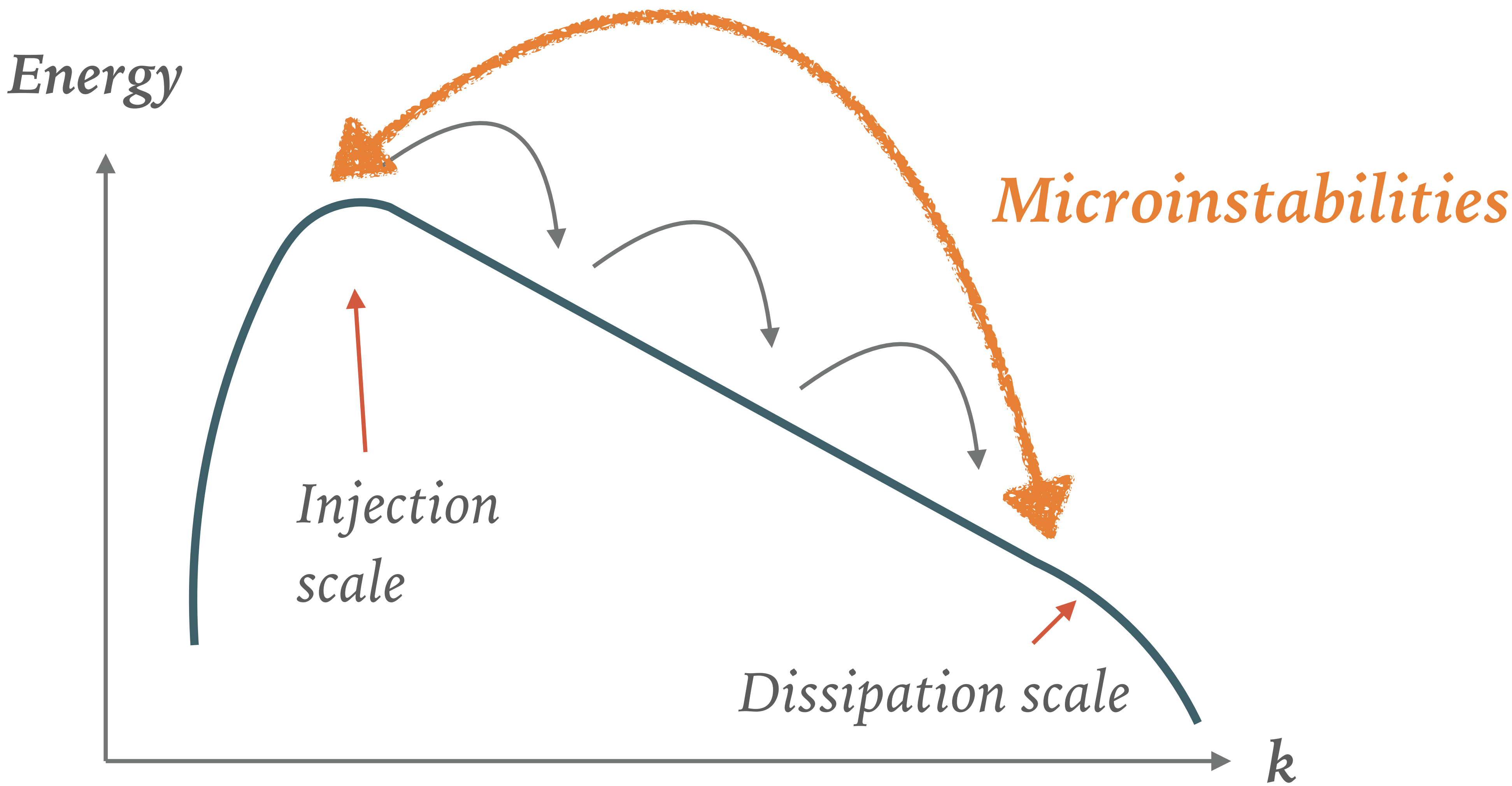
- Plasma unstable if $|\Delta p| \gtrsim B^2$

IN A COLLISIONAL GAS/PLASMA

LARGE SCALES

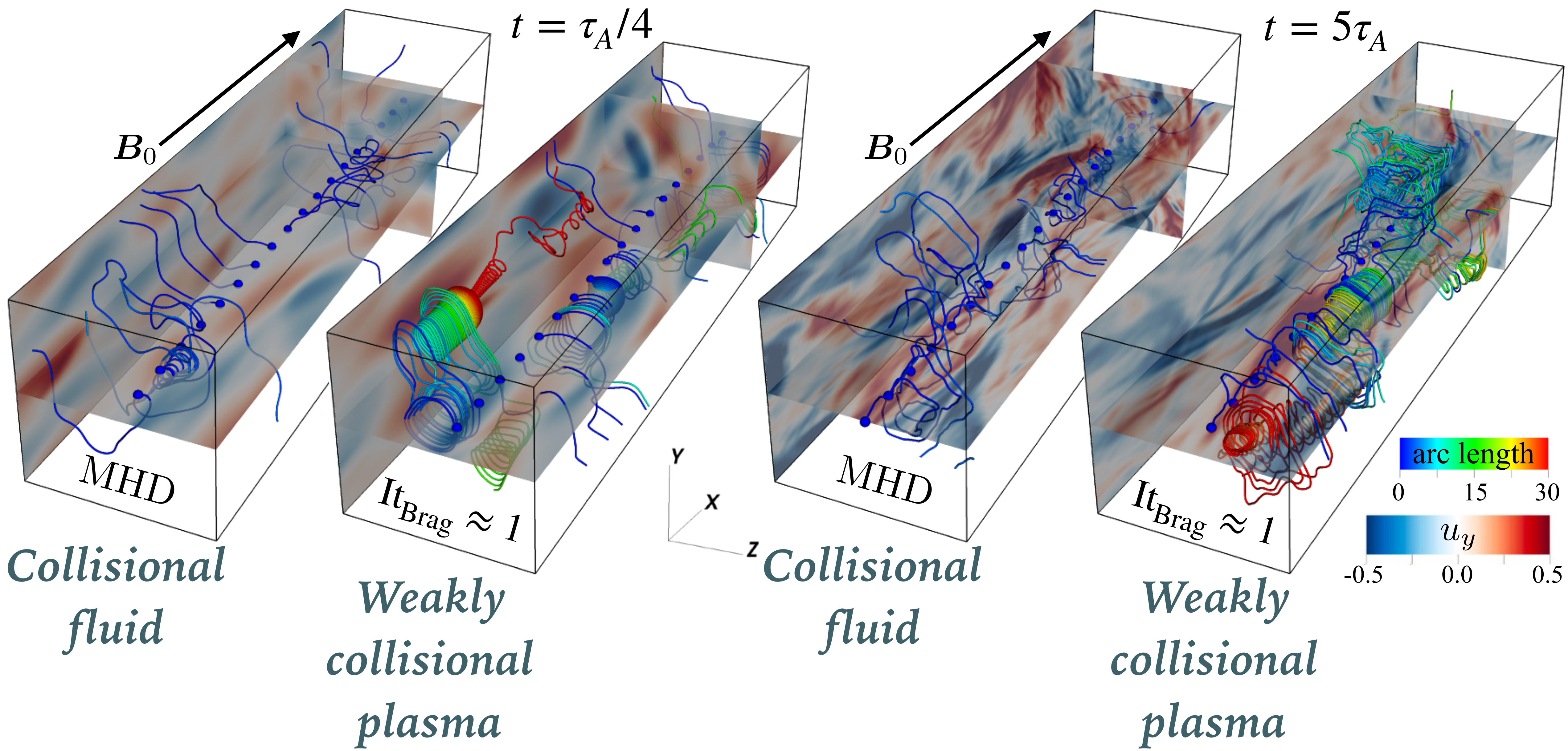
MICROSCALES


IN THE ICM


Energy
Microinstabilities
Injection
scale
Dissipation scale
k

WE'VE BEEN WORKING TO UNDERSTAND TURBULENCE AND ENERGY FLOW

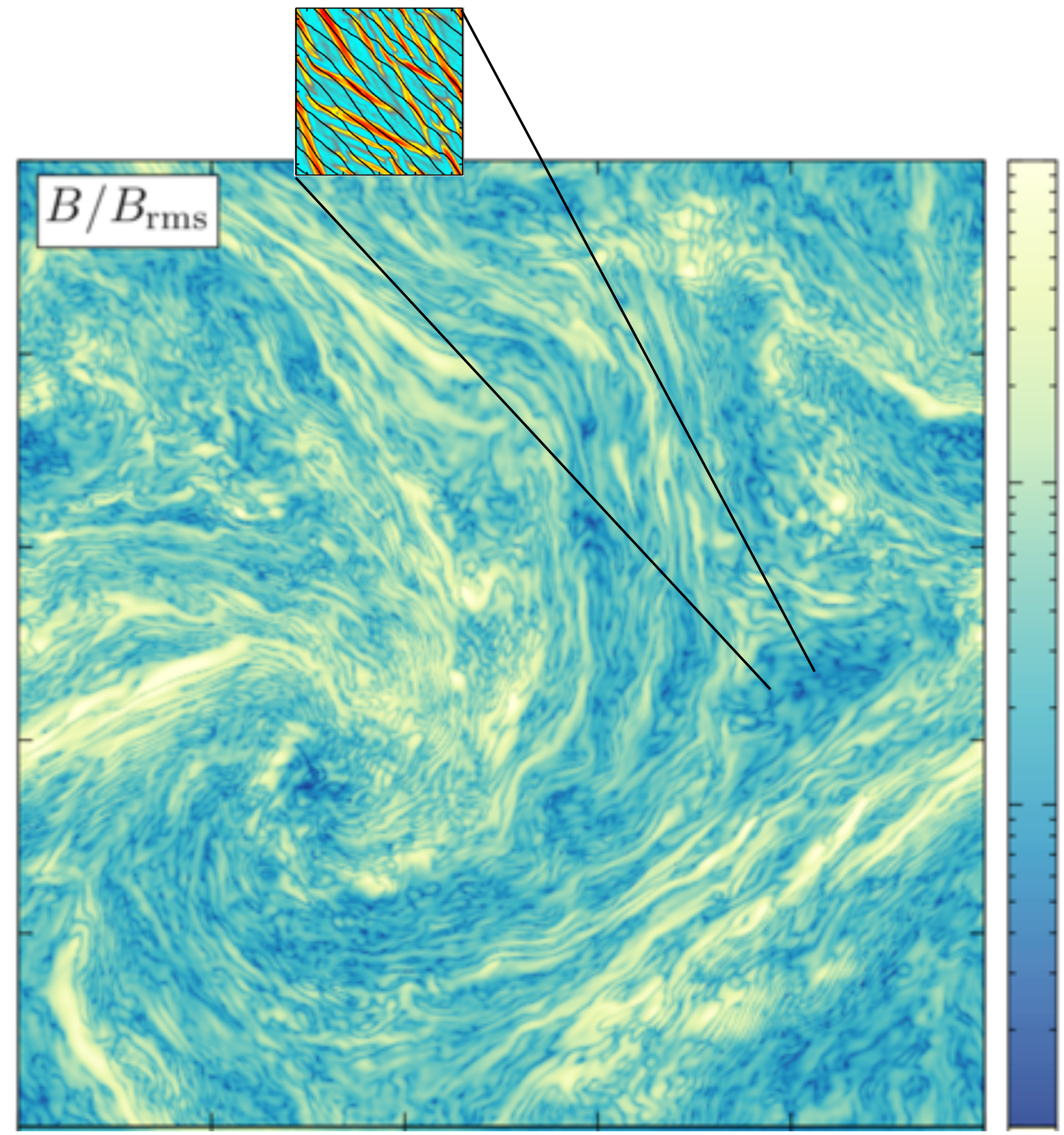
Squire et al. JPP (2019)



Some interesting differences…

AND DYNAMO — WHERE DO THE FIELDS COME FROM?

- Most dynamo theory assumes "flow not influenced by magnetic field"
- This cannot be true in weakly collisional plasmas
- Even with very small fields $\beta \gg 1$ the plasma becomes unstable because of their presence.
- Do the fields grow more or less easily?



St Onge & Kunz (2018)

CONCLUSIONS

- There remains much to learn about the behavior of hot, weakly magnetized plasmas.
- Did primordial fields exist before stars and galaxies? Was a field left over from the big bang? What is the structure of the universe's field today?
- The SKA will increase field measurements ~1000's fold:
  - RMs for local sources ➡ detailed 3D maps
  - High-z synchrotron measurements ➡ the origin of present day fields
  - Faraday rotation of the CMB ➡ big-bang fields?