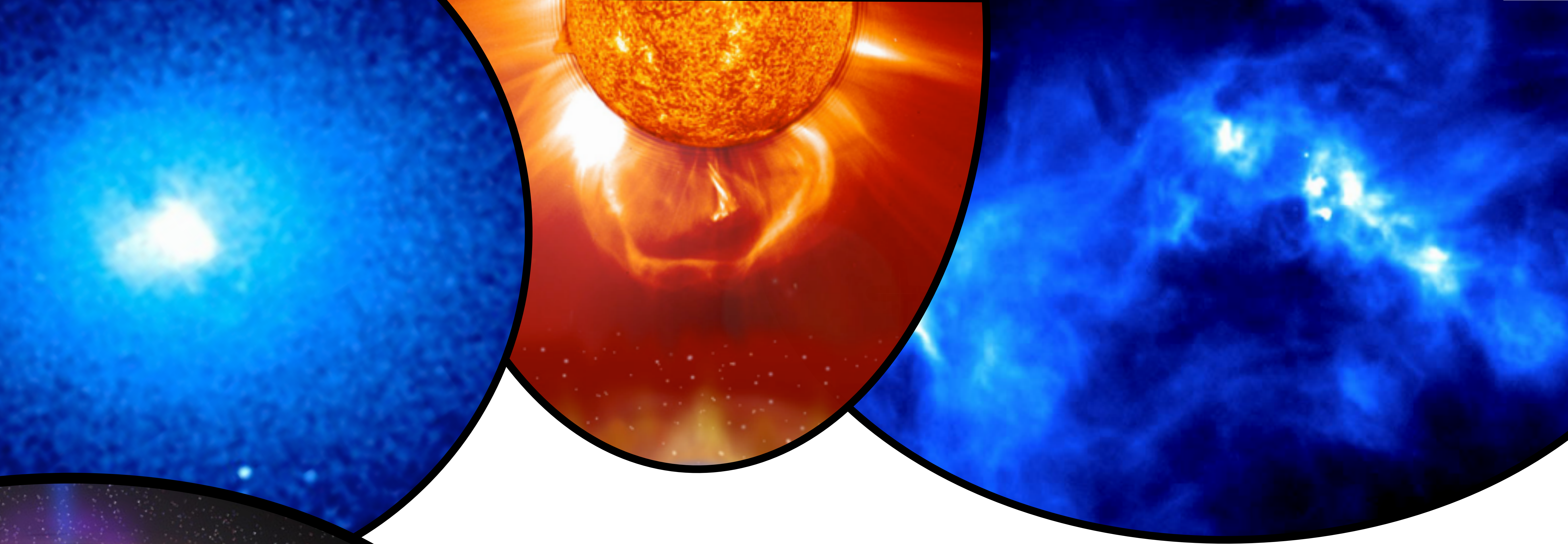
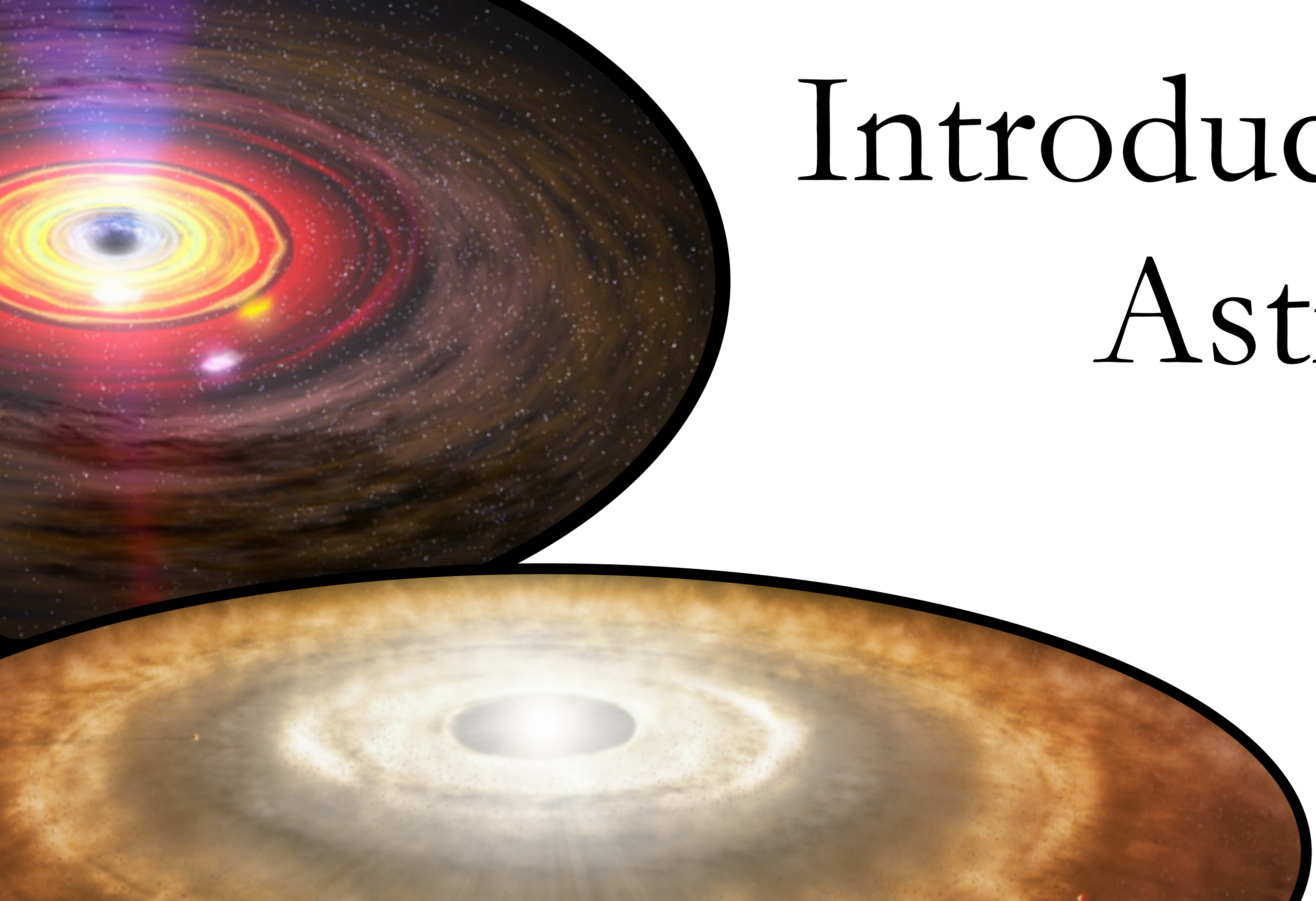


Introduction to Astrophysical Plasmas



Matthew Kunz
Princeton University

How are astrophysical plasmas different?

1. **Gravity!**
   There are lots of free-energy sources, almost all of which are set up by gravity. Just as astronomers often underestimate the importance of plasma physics, plasma physicists who make forays into astronomy often underestimate gravity.
   Do either at your own peril.

How are astrophysical plasmas different?

2. **Size**
   Lengthscales and timescale are *looooooooooong*. Again, this is often under-appreciated. Degree of ionization only 10^{-7}? Don't worry, you have million of years for those "trace" charges to communicate the presence of a magnetic field to the bulk fluid through collisions.

How are astrophysical plasmas different?

3. **Cosmic magnetism**
   This is tricky. With some notable exceptions, plasma ß's are often ≥100. Weak magnetic field? Not so fast. A magnetic field of just ~10^{-18} G can magnetize the plasma in galaxy clusters, so be very careful what you call "weak"!

$$\left(\beta = \frac{8\pi P}{B^2}\right)$$

How are astrophysical plasmas different?

4. **Lots of additional physics**
   Want to do plasma astrophysics? Well, be prepared to also do chemistry, relativity, radiation, dynamics… In some environments, general relativity, radiative transport, fluid dynamics, magnetic fields, and plasma microphysics are all important.

How are astrophysical plasmas different?

5. **(No) Geometry**
   Most of the time, you need not worry about complicated geometries or boundary conditions, as there are few solid boundaries.

   Make your fusion friends jealous with periodic slabs!

How are astrophysical plasmas different?

6. **Units**
   I haven't used meters, Joules, Newtons, Teslas, etc. for at least 14 years, and I'm not about to start. Astrophysicists like the speed of light in their equations, and for good reason…
   Maxwell happened 156 years ago and, besides, $1/\sqrt{\varepsilon_0\mu_0}$ is just plain ugly.

What are astrophysical plasmas?

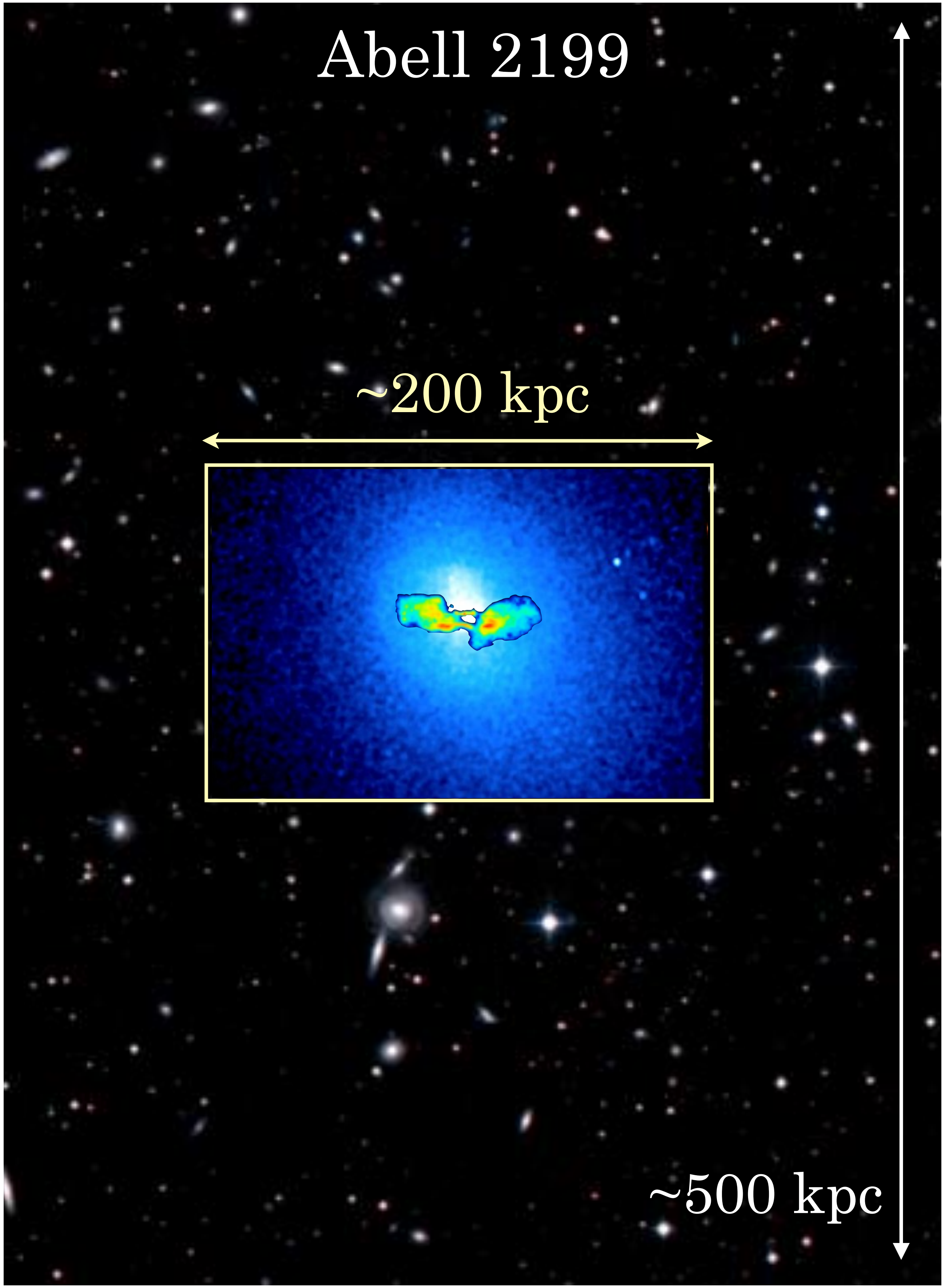
Usually consist of several interacting parts:

- thermal gas (neutral and ionized)
- non-thermal particles / cosmic rays
- magnetic fields
- large-scale gradients and/or flows
- small-scale turbulence / waves
- radiation
- dust grains (neutral and charged)

often, these are in **energy equipartition**

time for some examples,
with a focus on the plasma properties

start big and work our way down
(things generally get colder)



Clusters of Galaxies

$M \sim 10^{14-15}\ \mathrm{M}_\odot$

in ~1 Mpc

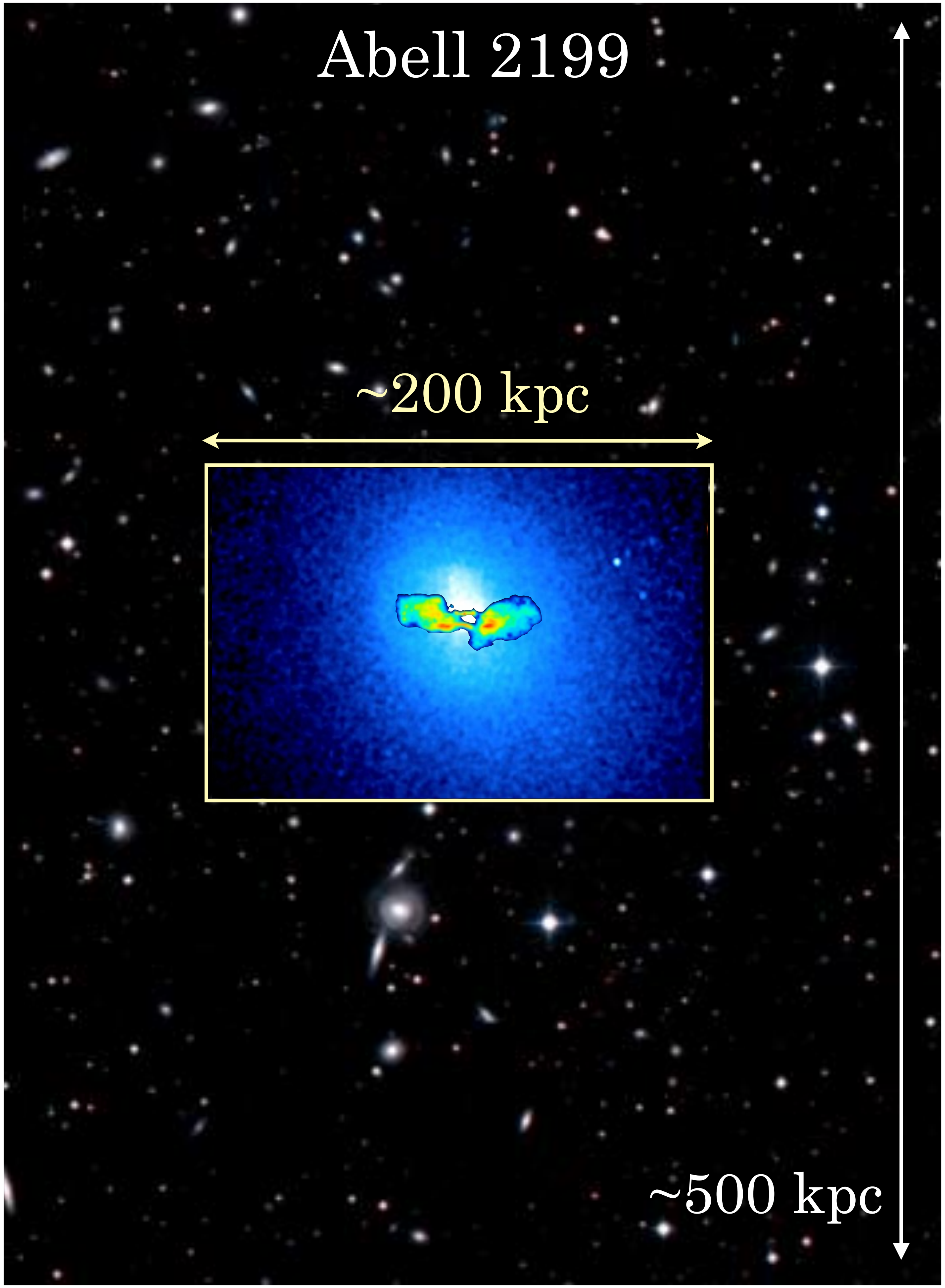
14% thermal plasma

$T \sim 1\text{–}10$ keV

$n \sim 10^{-4}\text{–}10^{-1}\ \mathrm{cm}^{-3}$

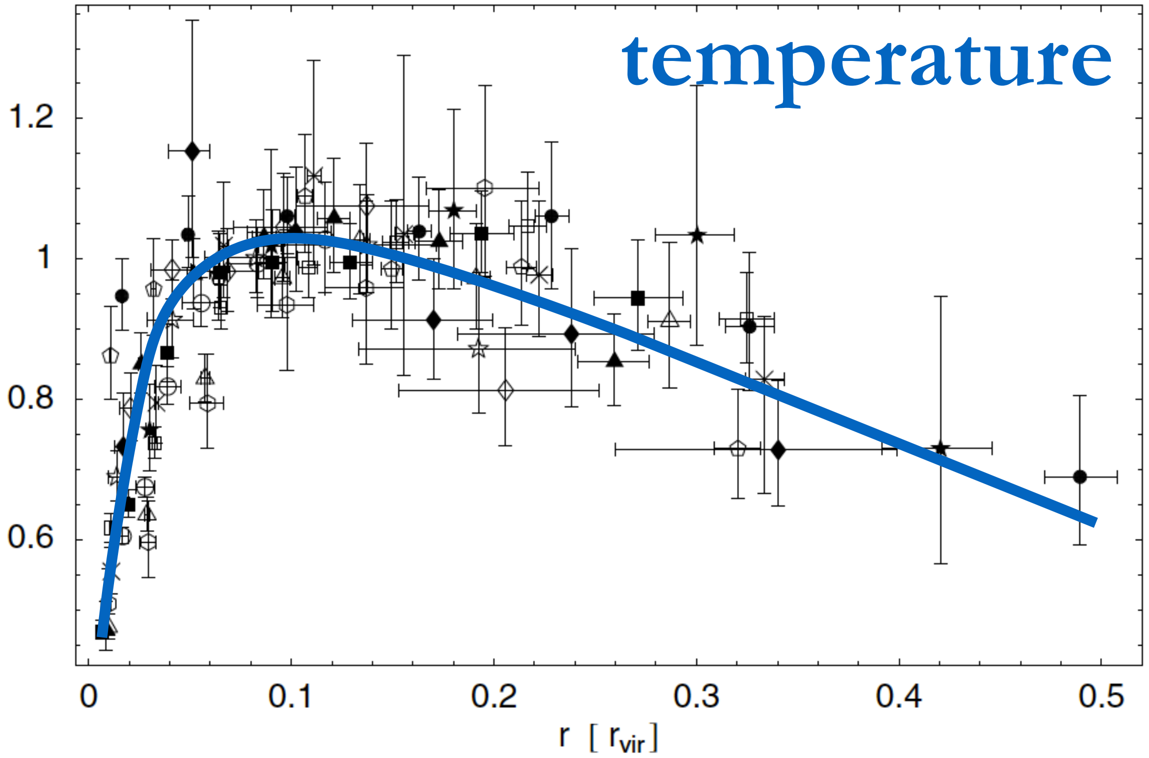
$B \sim 1\ \mu\mathrm{G}$

radio (BH &
relativistic plasma)



Intracluster Medium

$$\beta \sim 10^{2-4}$$



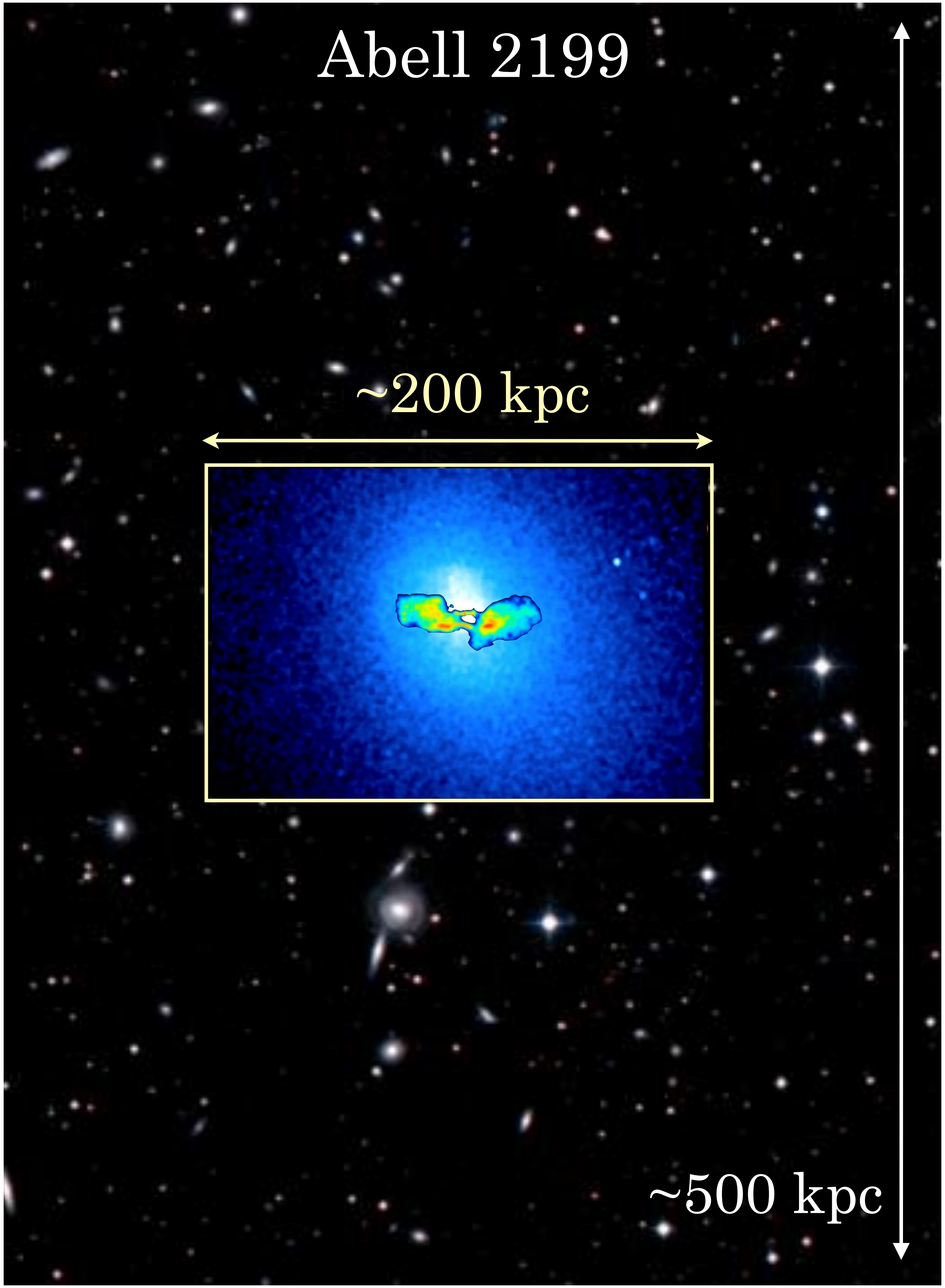
$$t_{\rm dyn} \gtrsim 100 \text{ Myr}$$

$$t_{\rm ii,coll} \sim 1 - 10 \text{ Myr}$$

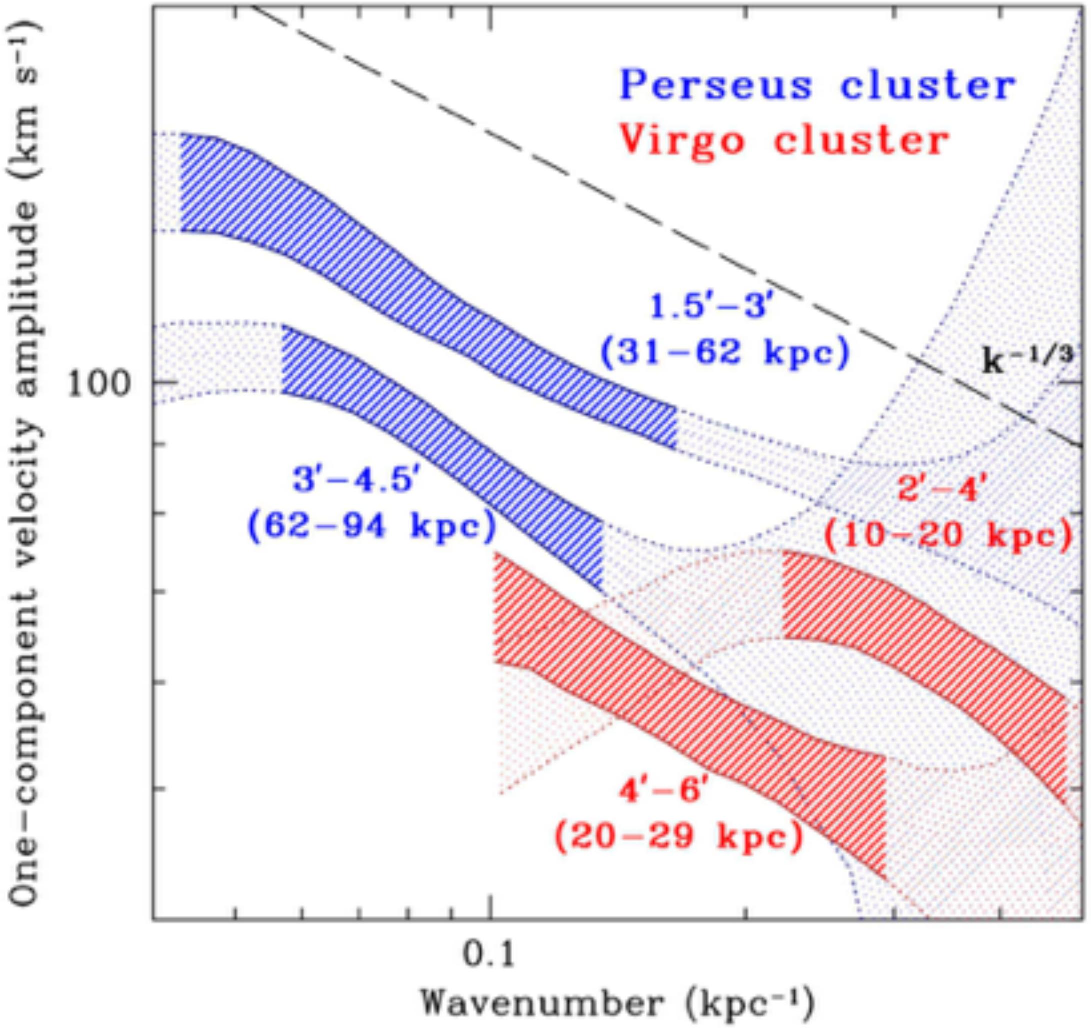
$$t_{\rm gyr,i} \sim 10 \text{ min}$$

(ion Larmor orbit ~ size of Jupiter)

Intracluster Medium



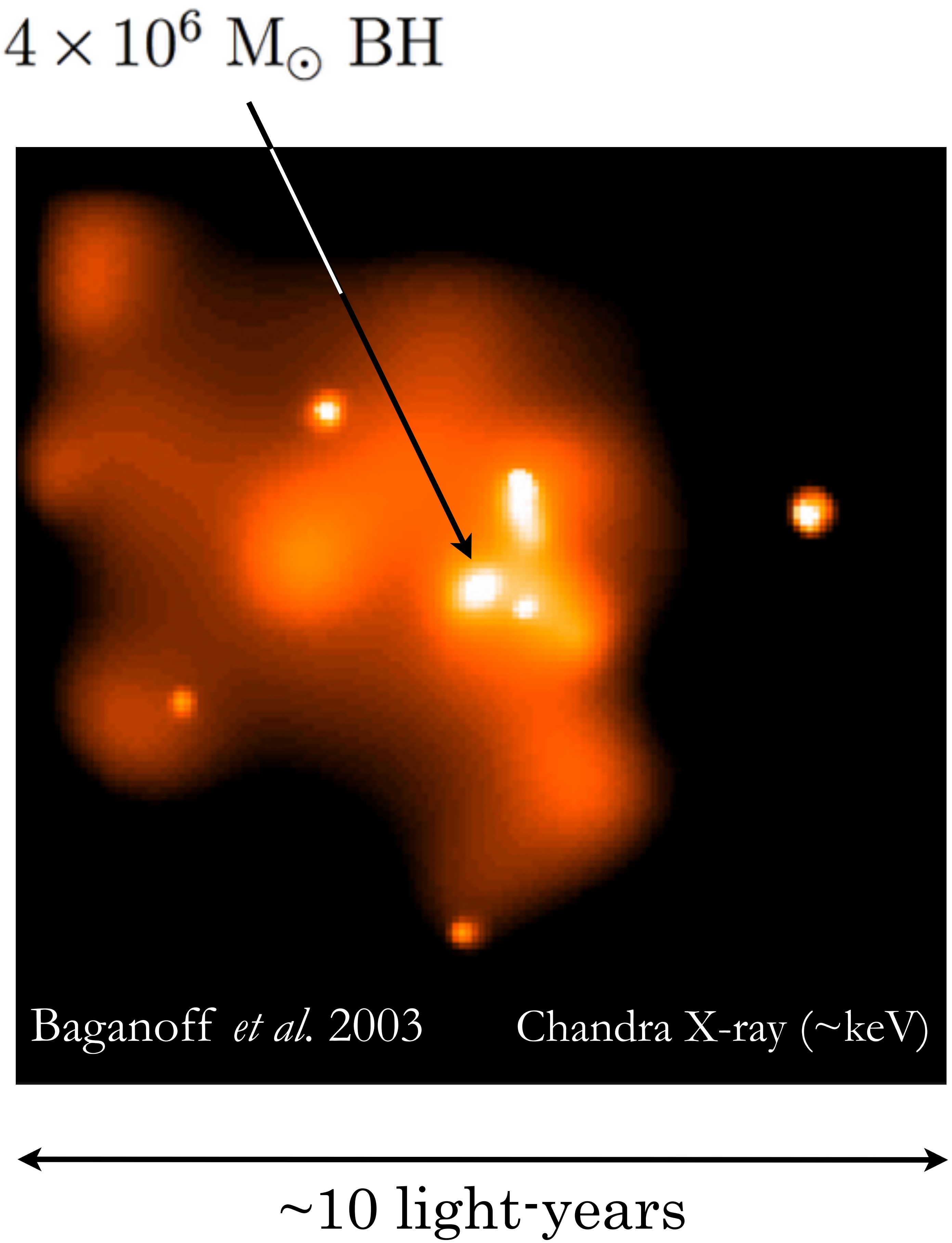
subsonic, trans-Alfvénic turbulence!



Zhuravleva *et al.* 2014, Nature

Hitomi, before its death:

$u \sim 160$ km/s



Galactic Center

$$r_{\mathrm{Bondi}} \sim 0.1\ \mathrm{pc}$$

$$T \sim 2\ \mathrm{keV}$$

$$n \sim 100\ \mathrm{cm}^{-3}$$

$$B \sim 1\ \mathrm{mG}$$

$$\beta \sim 10^{1-2}$$

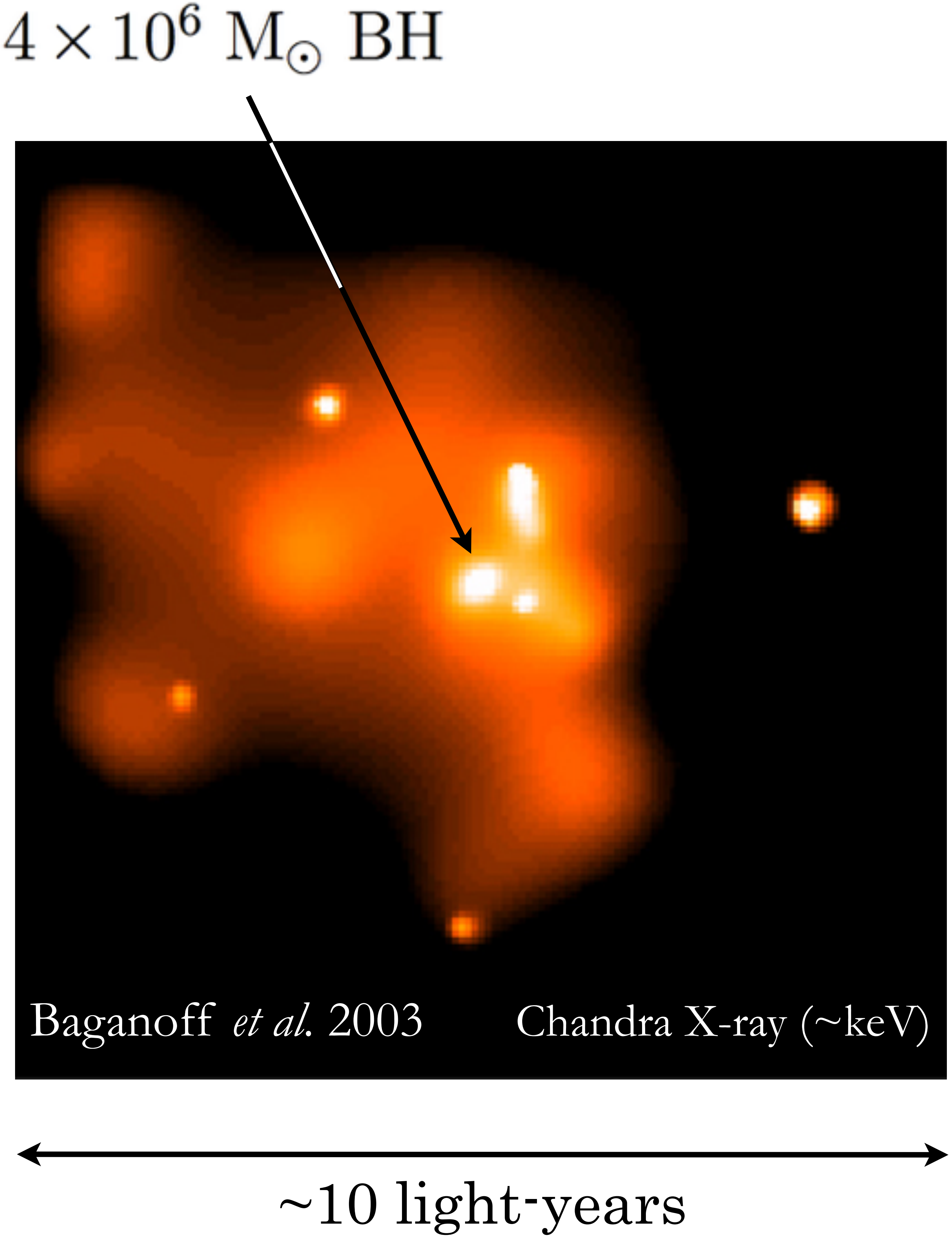
$$t_{\mathrm{dyn}} \lesssim 200\ \mathrm{yr}$$

$$t_{\mathrm{ii,coll}} \sim 20\ \mathrm{yr}$$

$$t_{\mathrm{gyr,i}} \sim 1\ \mathrm{s}$$

(can drive ion Larmor orbit in ~2 hrs)

Galactic Center



get within 10 Schwarzschild radii:

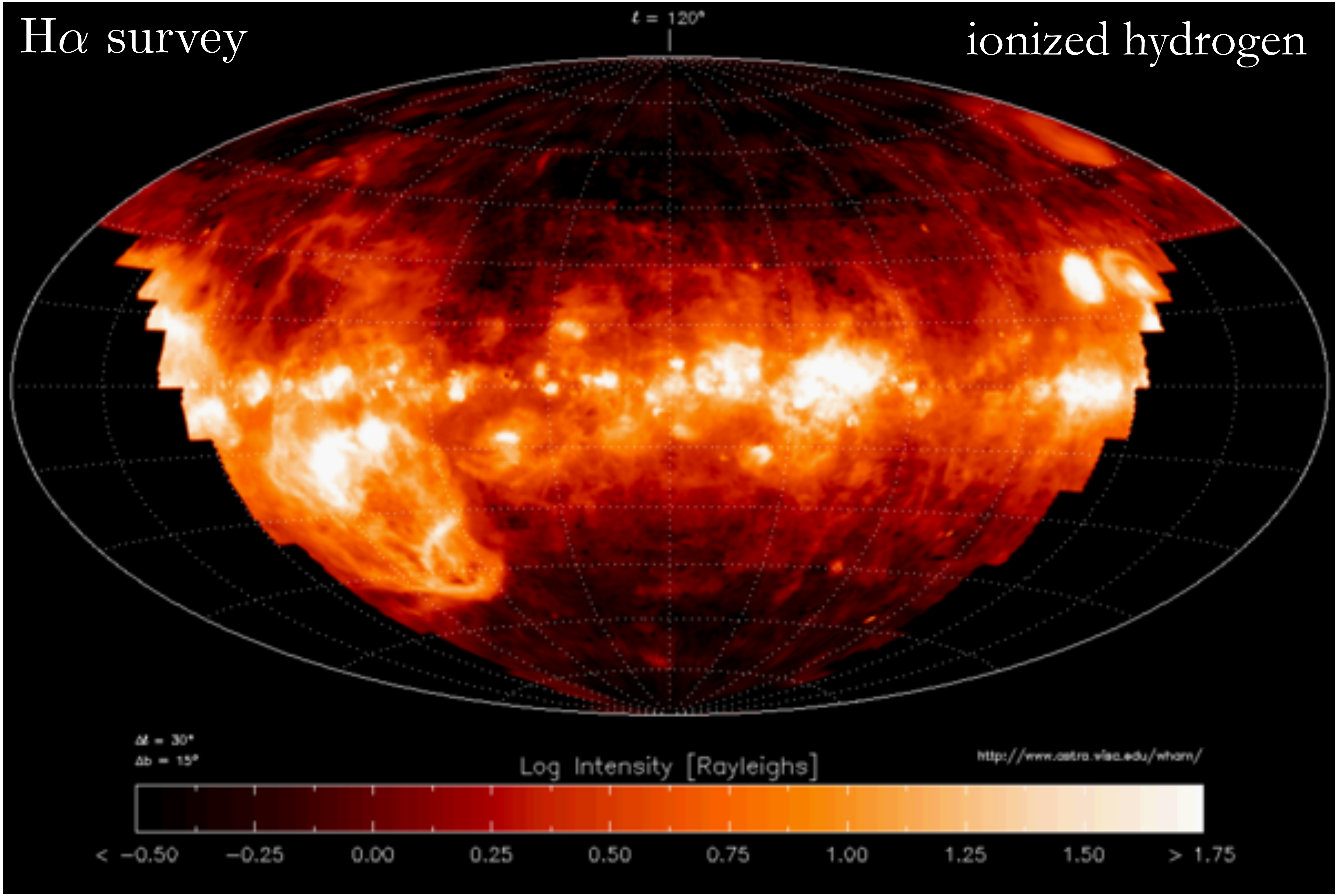
$$r \sim 20\ GM_\bullet/c^2$$

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

$$t_{\rm ii,coll} \sim 200\ {\rm yr}$$

$$t_{\rm gyr,i} \sim 100\ \mu{\rm s}$$

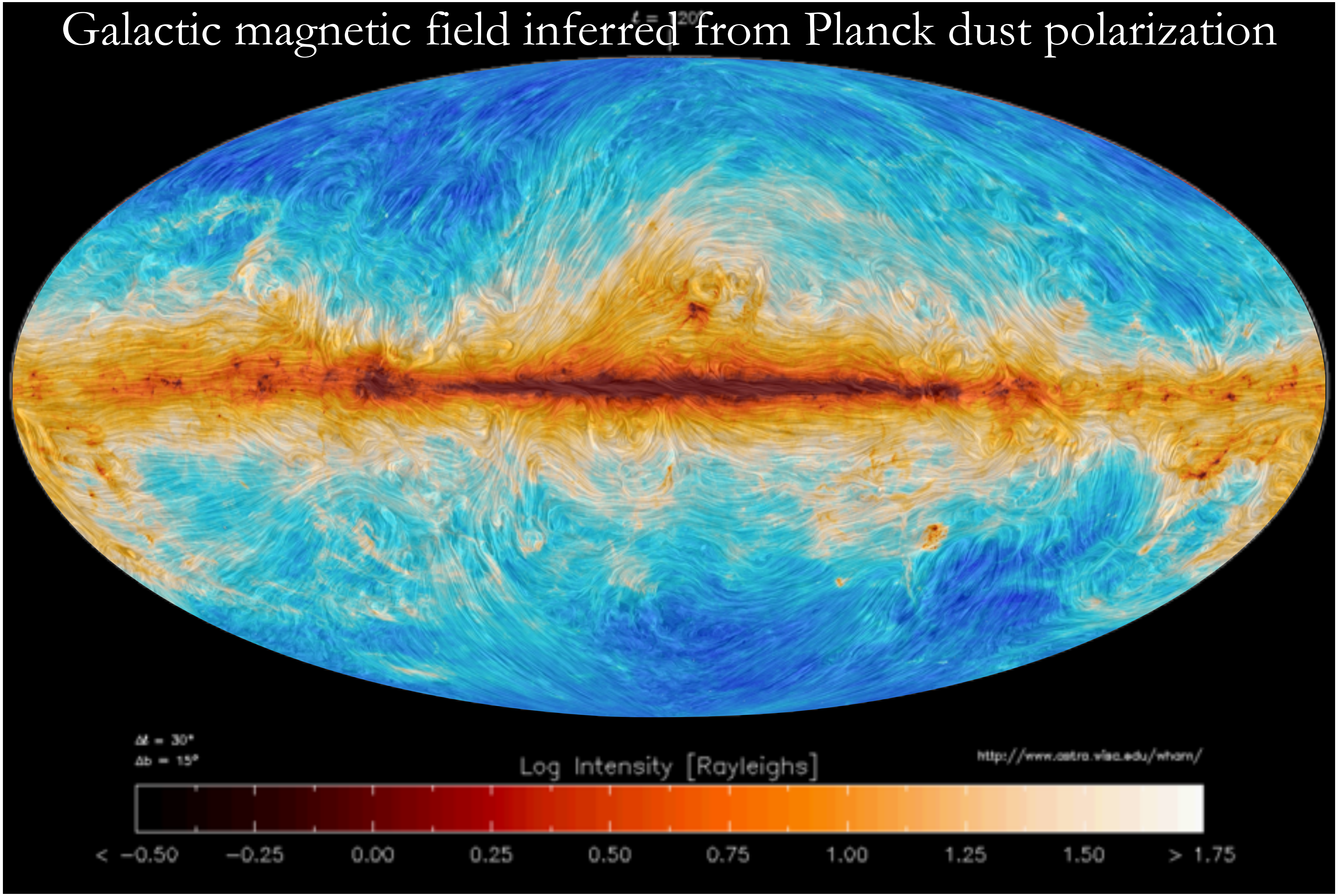
Interstellar Medium



Hα survey

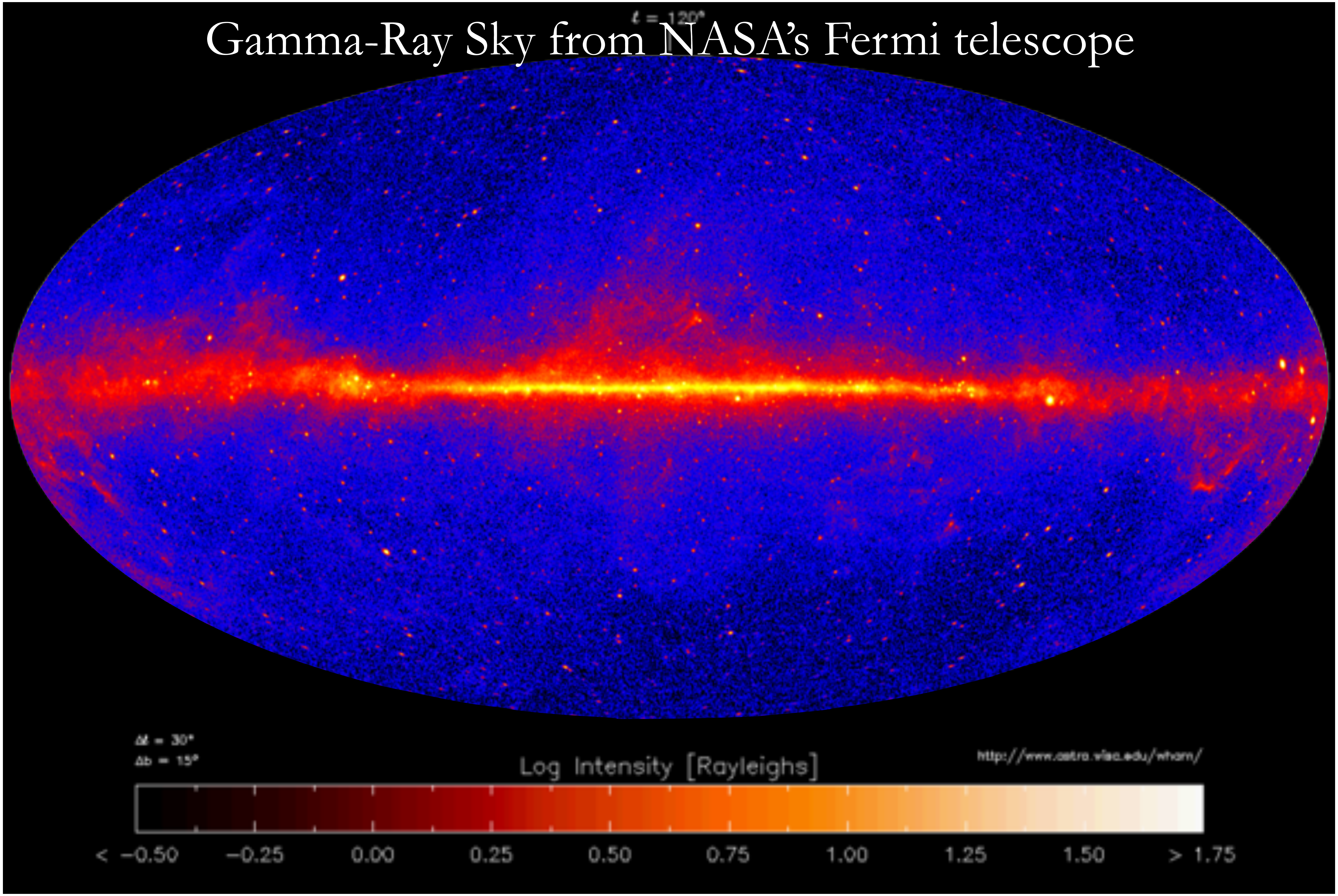
ionized hydrogen

Interstellar Medium



Galactic magnetic field inferred from Planck dust polarization

Interstellar Medium



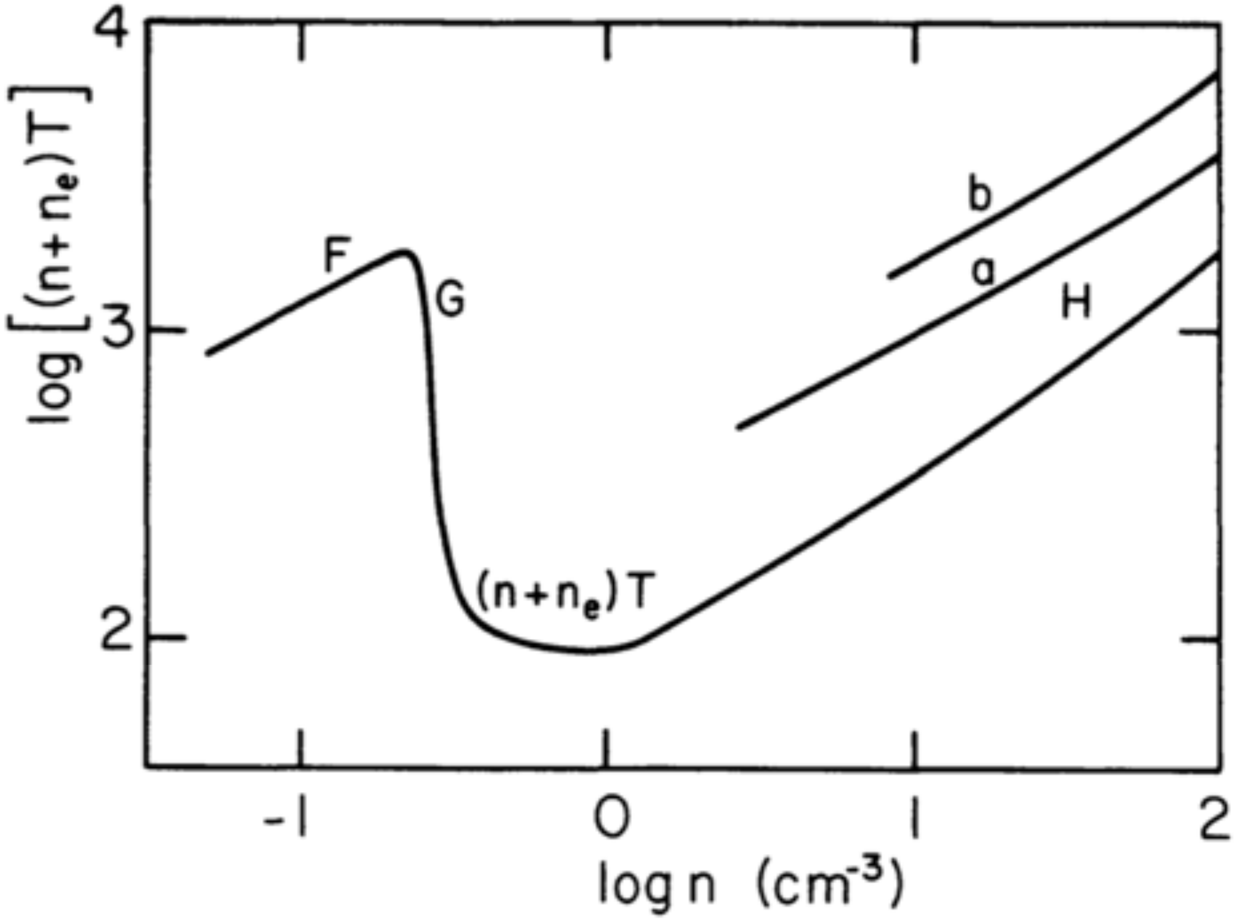
Gamma-Ray Sky from NASA's Fermi telescope

Interstellar Medium

99% gas (mostly H & He, some molecules: H_20, CO_2, CO, CH_4, NH_3)
1% dust (metals, graphites, silicates) ⟵ important plasma component

Multi-phase (Pikel'ner 1968; Field, Goldsmith & Habing 1969; McKee & Ostriker 1977)

warm component $n \sim 0.1 - 1\ \mathrm{cm}^{-3}$ $T \gtrsim 10^3$ K
cold component $n \gtrsim 10\ \mathrm{cm}^{-3}$ $T \lesssim 100$ K
hot (coronal) component $n \lesssim 0.01\ \mathrm{cm}^{-3}$ $T \gtrsim 10^5$ K

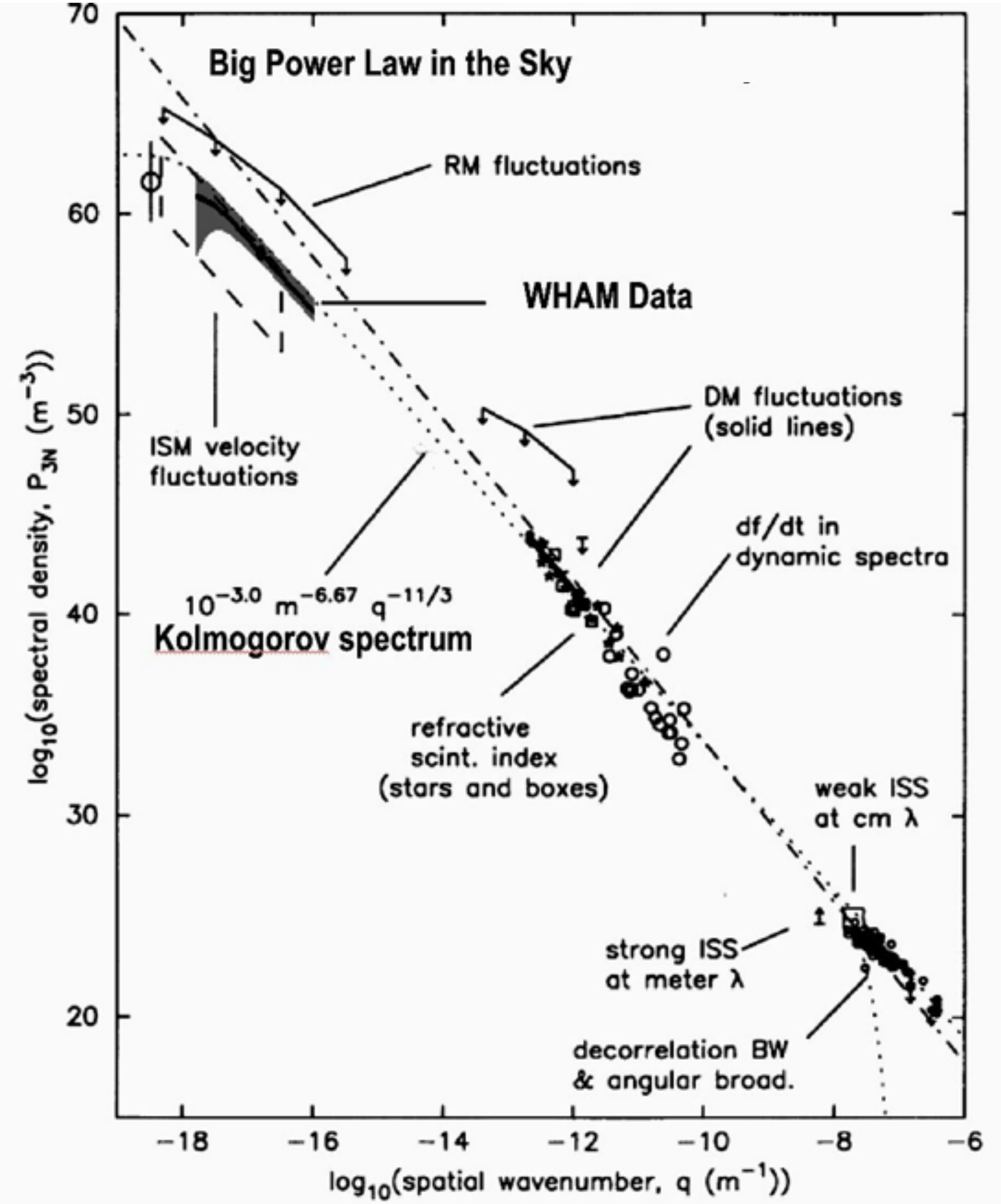


Crab nebula, young SNR

Interstellar Medium

Turbulence

"Great Power Law in the Sky"



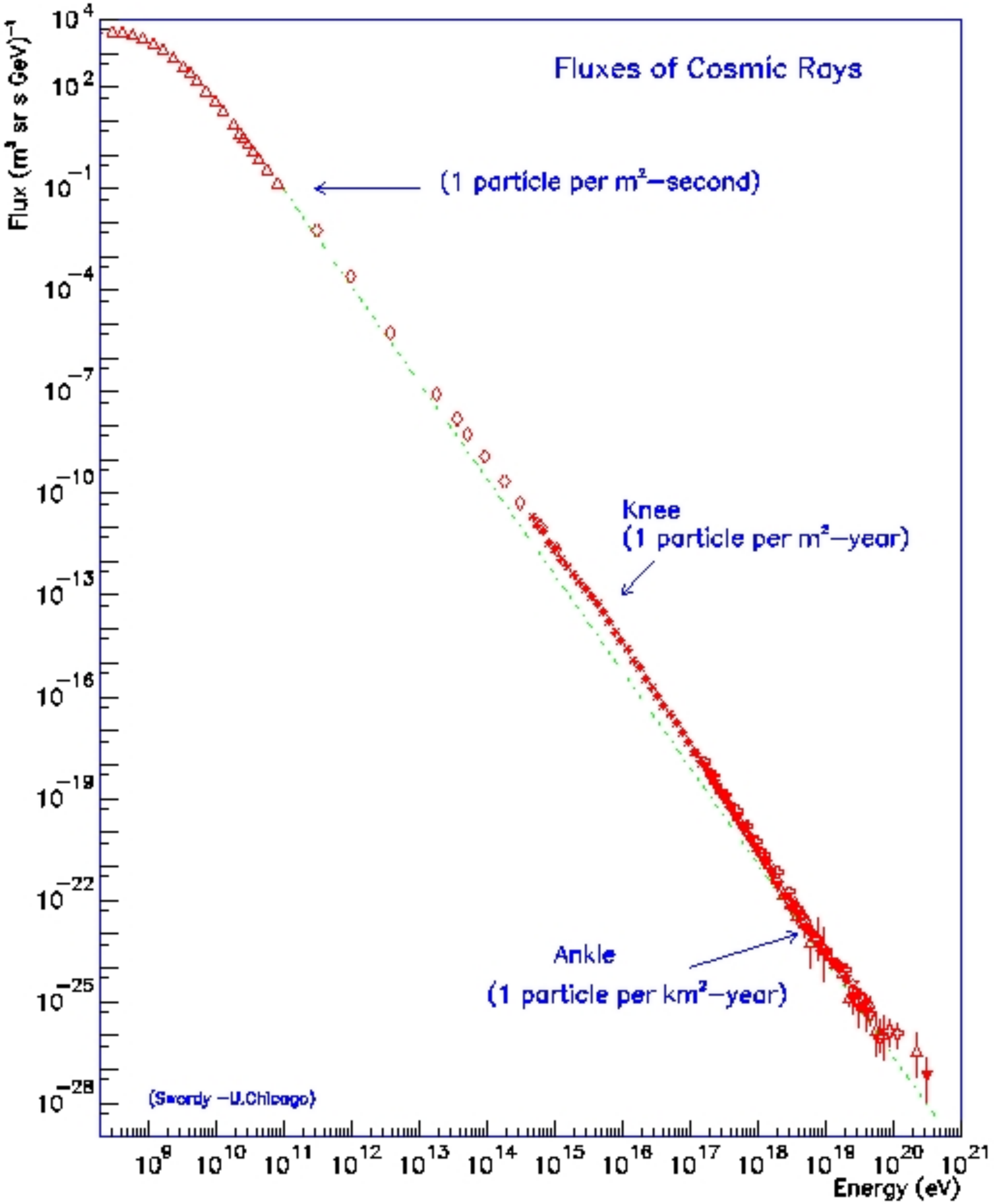
Armstrong, Cordes, Rickett 1981, Nature

Armstrong, Rickett, Spangler 1995, ApJ

Interstellar Medium

Cosmic Rays

2nd great power law in the sky

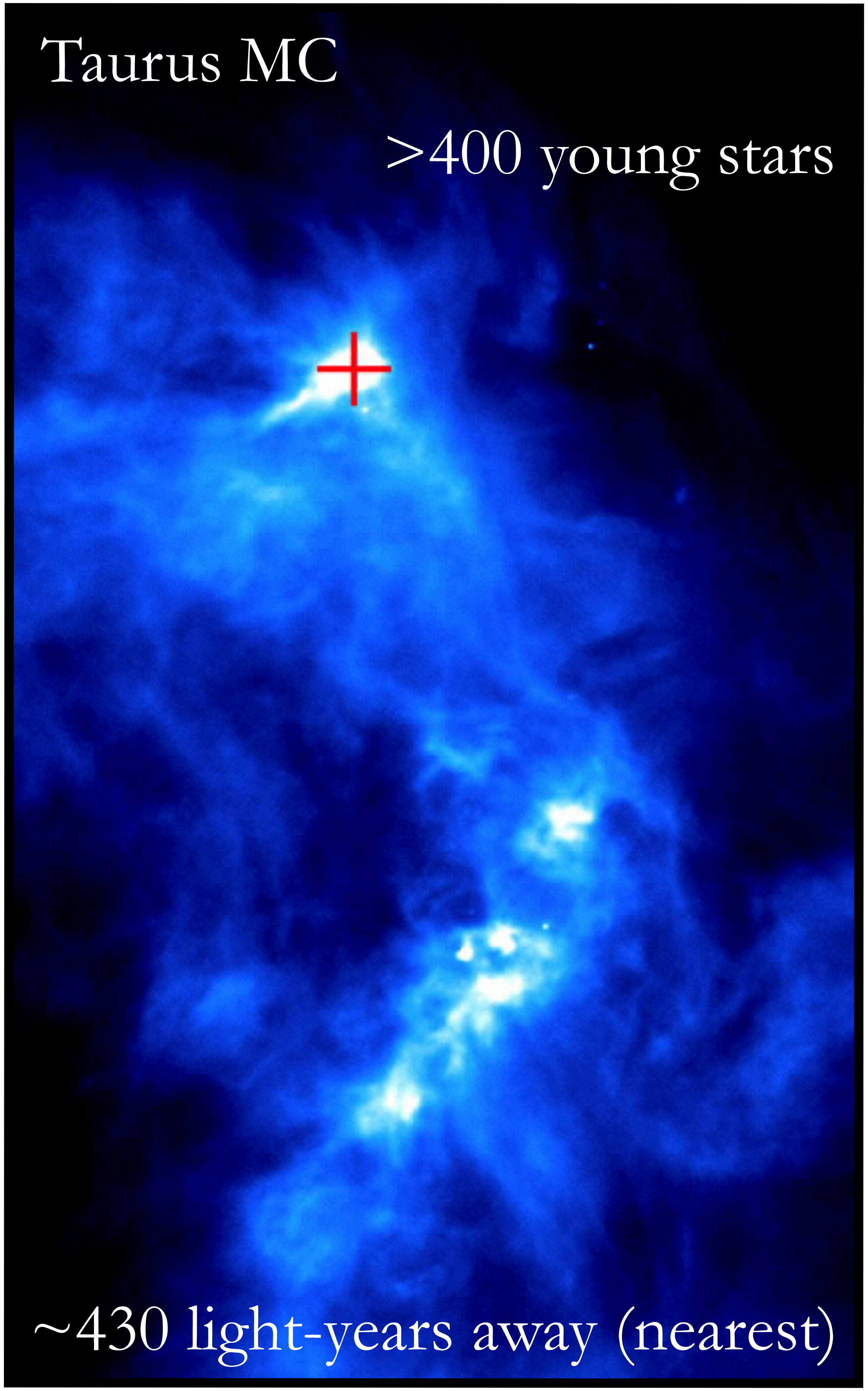


Interstellar Medium

what makes studying the ISM both fascinating and difficult:

$$u_{\rm thermal} \sim u_{\rm turb} \sim u_{\rm B} \sim u_{\rm CR} \sim u_{\rm stars} \sim 0.5 \text{ eV cm}^{-3}$$

Molecular Clouds



Taurus MC

>400 young stars

~430 light-years away (nearest)

part of the "cold phase" of the ISM

$$n_n \sim 10^{2-3}\ \mathrm{cm}^{-3}$$

$$T \sim 10^{1-2}\ \mathrm{K}$$

$$B \sim 10 - 100\ \mu\mathrm{G}$$

low degree of ionization!

$$x_i \doteq \frac{n_i}{n_n} \sim 10^{-8} - 10^{-4}$$

$$t_{\mathrm{gyr},i} \sim 10\ \mathrm{min}$$

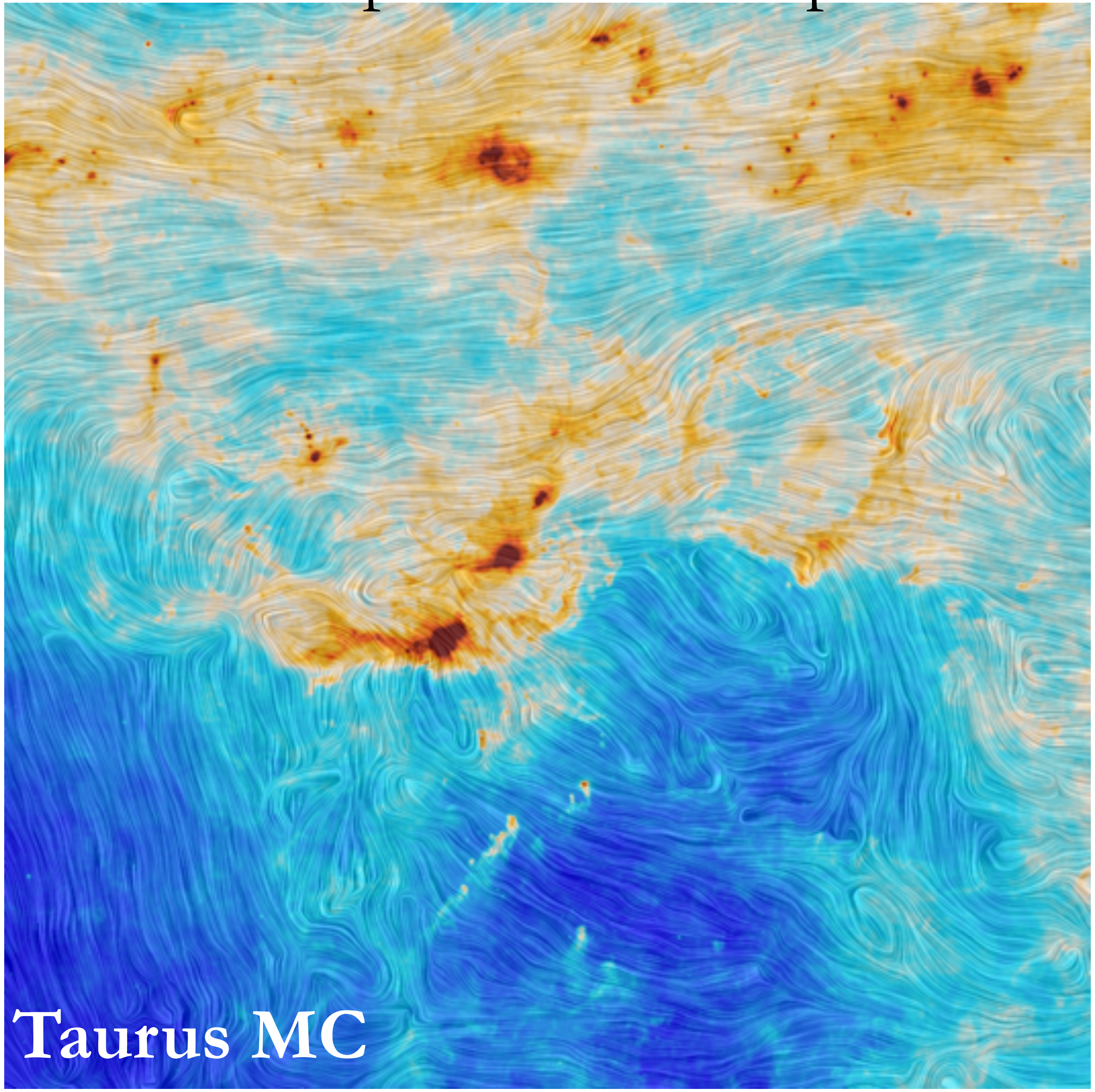
$$t_{\mathrm{coll},in} \sim 1\ \mathrm{mth}$$

$$t_{\mathrm{coll},ni} \sim 0.1\ \mathrm{Myr}$$

$$t_{\mathrm{dyn}} \sim 0.1 - 1\ \mathrm{Myr}$$

Molecular Clouds

Planck dust polarization map



fairly ordered magnetic fields, in the presence of supersonic (but trans-Alfvénic) turbulence

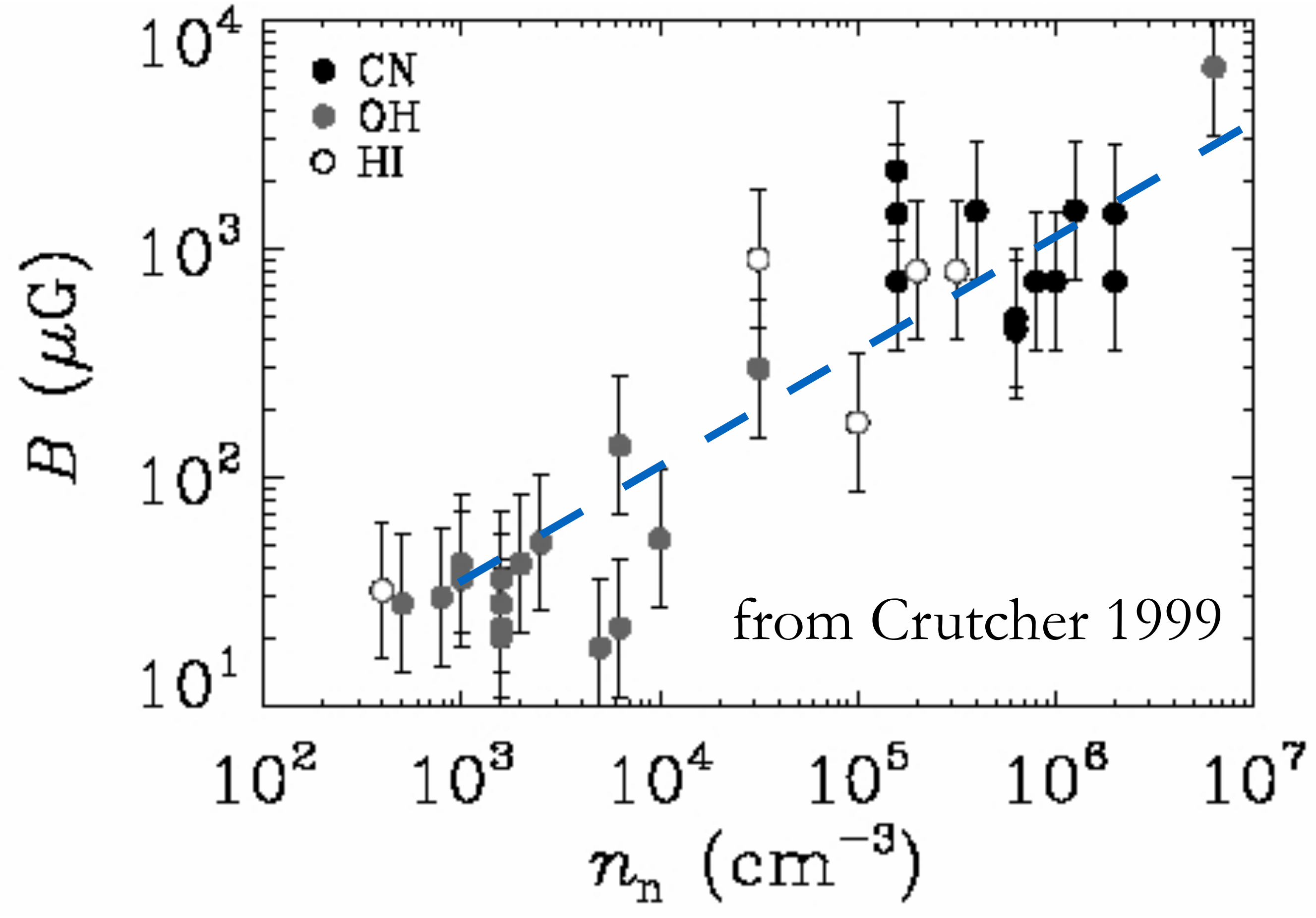
$$\beta \sim 0.01 - 0.1$$

$$M_A \sim 1$$

turbulence, magnetic fields, and gravity in rough energy equipartition

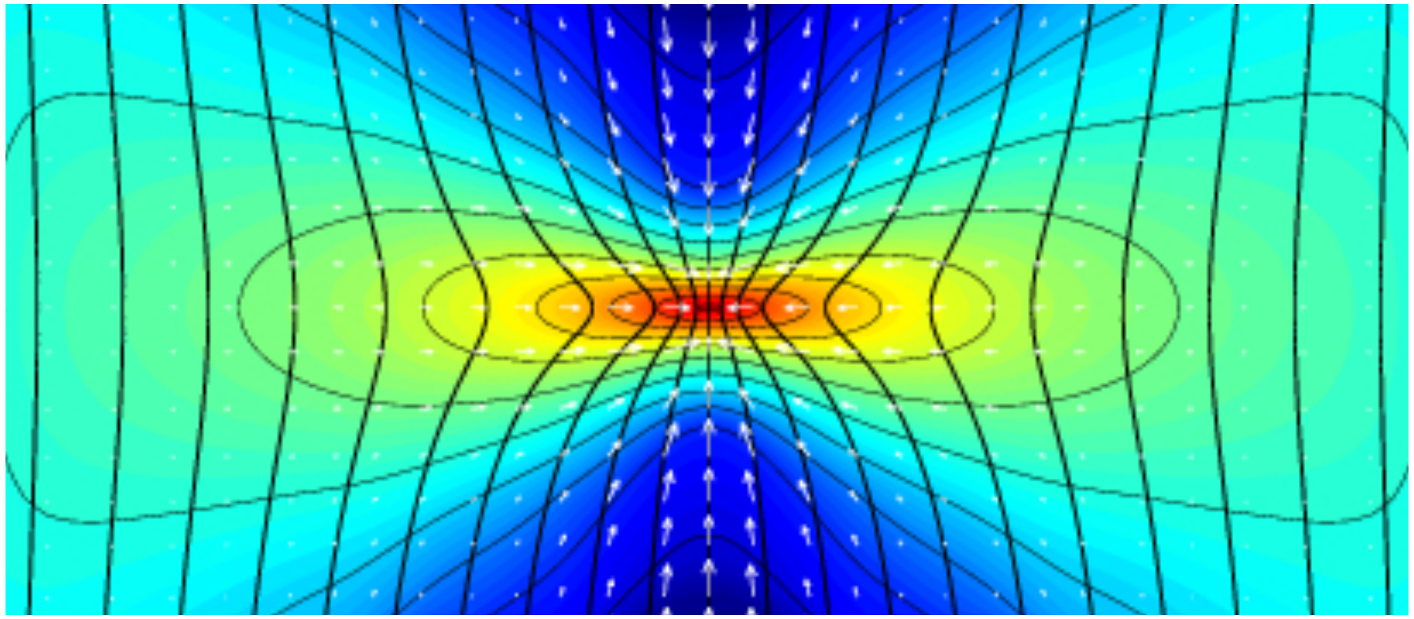
Protostellar Cores

Zeeman observations



from Crutcher 1999

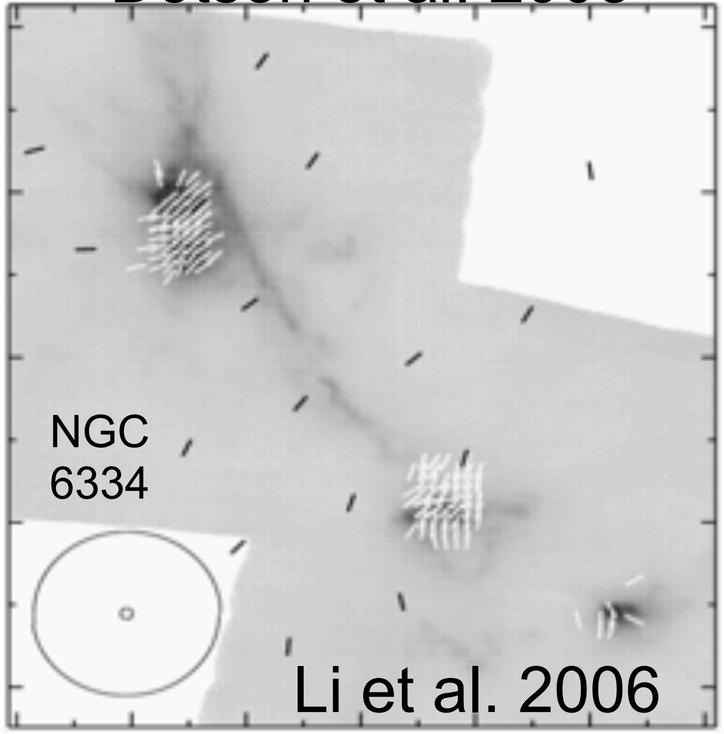
magnetic-field strength increases during gravitational contraction of protostellar core, $B \sim n^{1/2}$, which is near-flux-freezing for a flattened geometry



Kunz & Mouschovias 2010

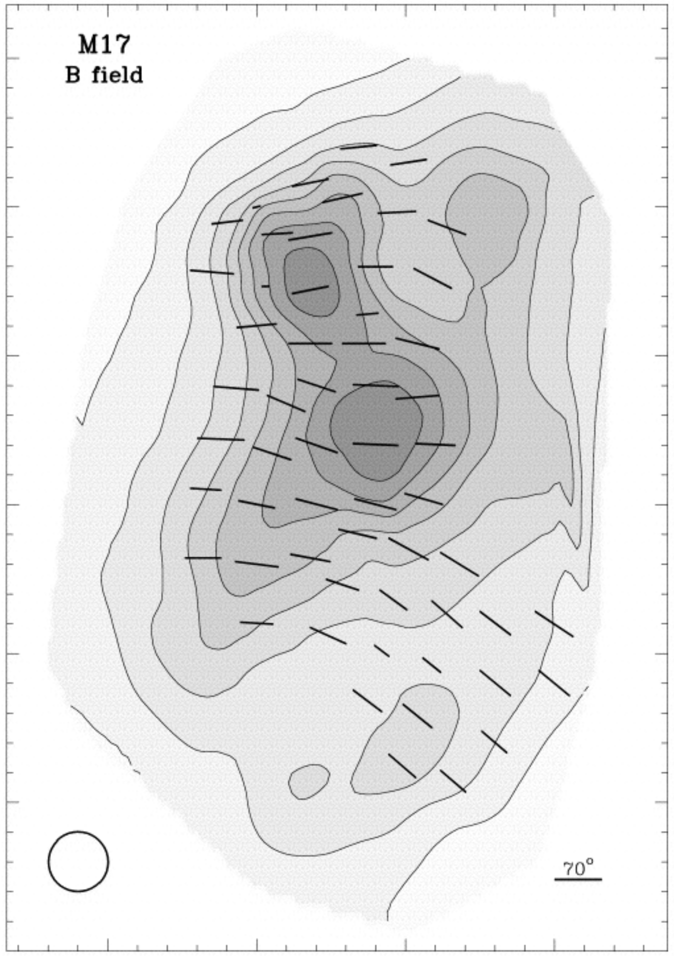
Protostellar Cores

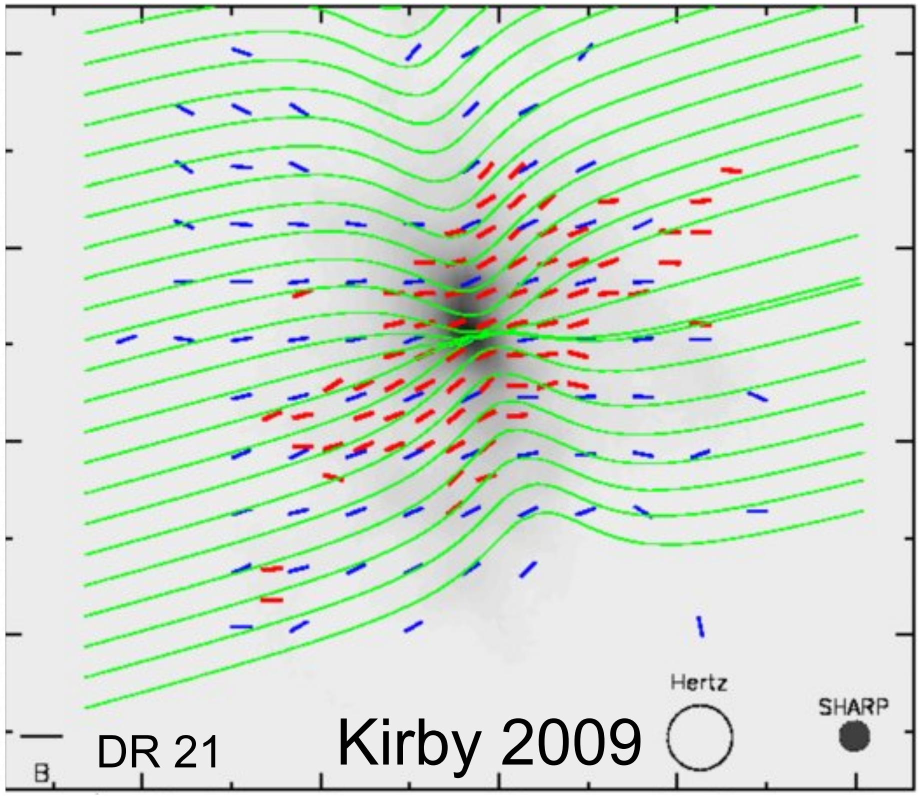
Dotson et al. 2008



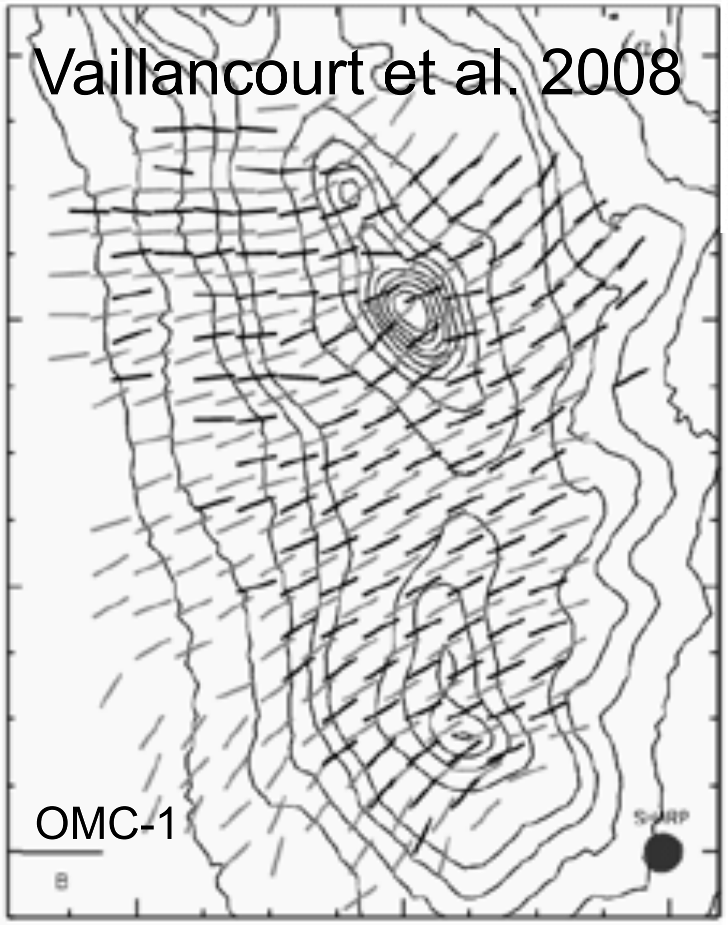
Li et al. 2006

Houde et al 2002

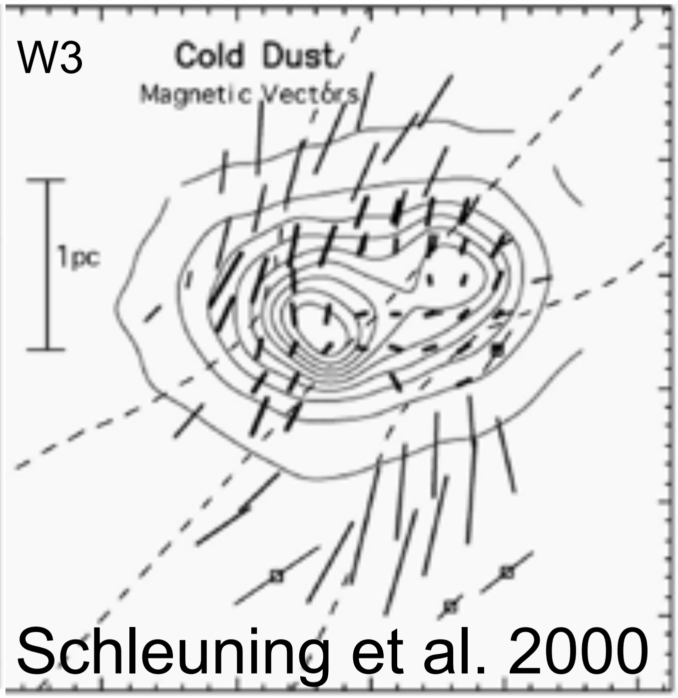




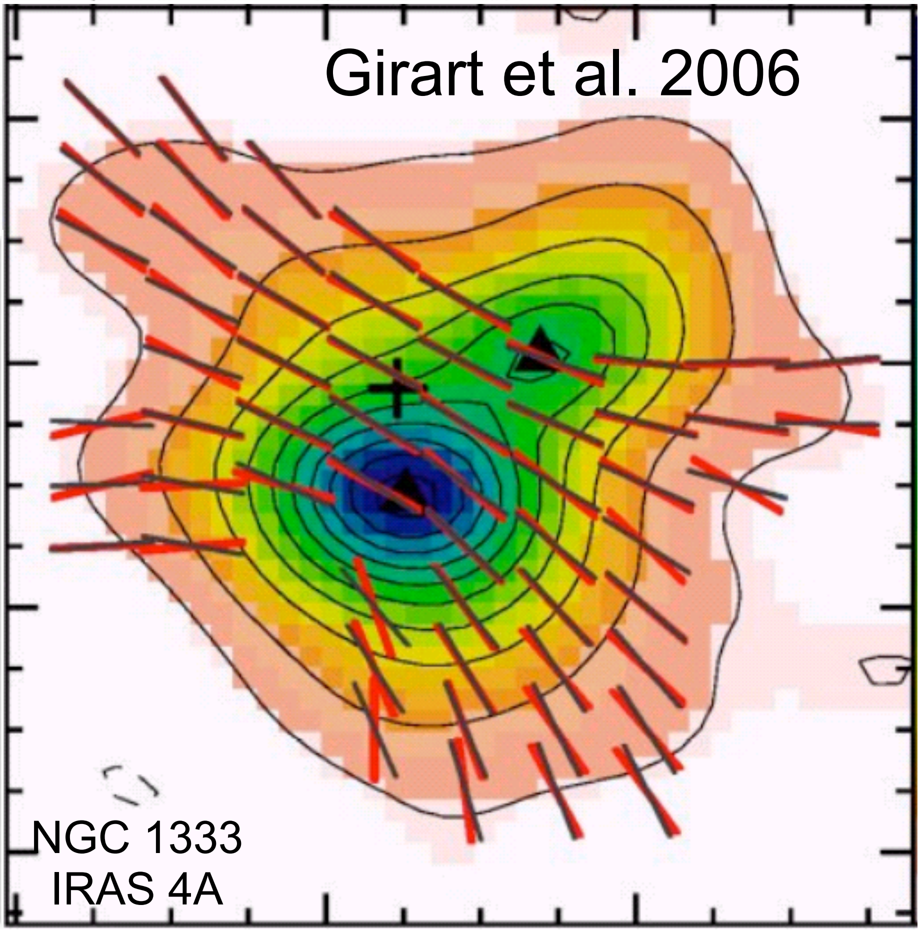
Kirby 2009



Vaillancourt et al. 2008



Schleuning et al. 2000



Girart et al. 2006

Protoplanetary Disks

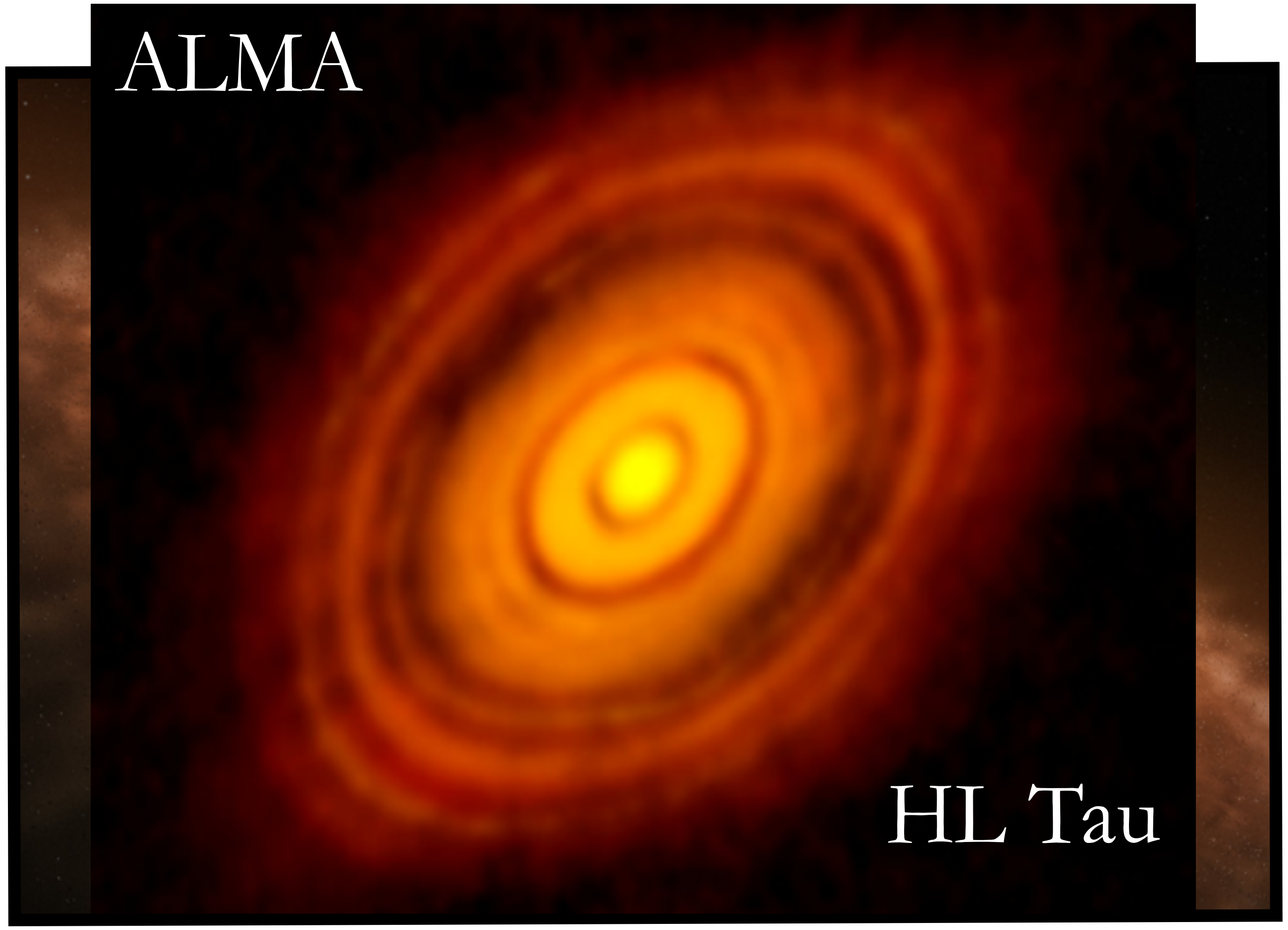
Keplerian disks of gas and dust, evolving on ~yr to ~Myr timescales

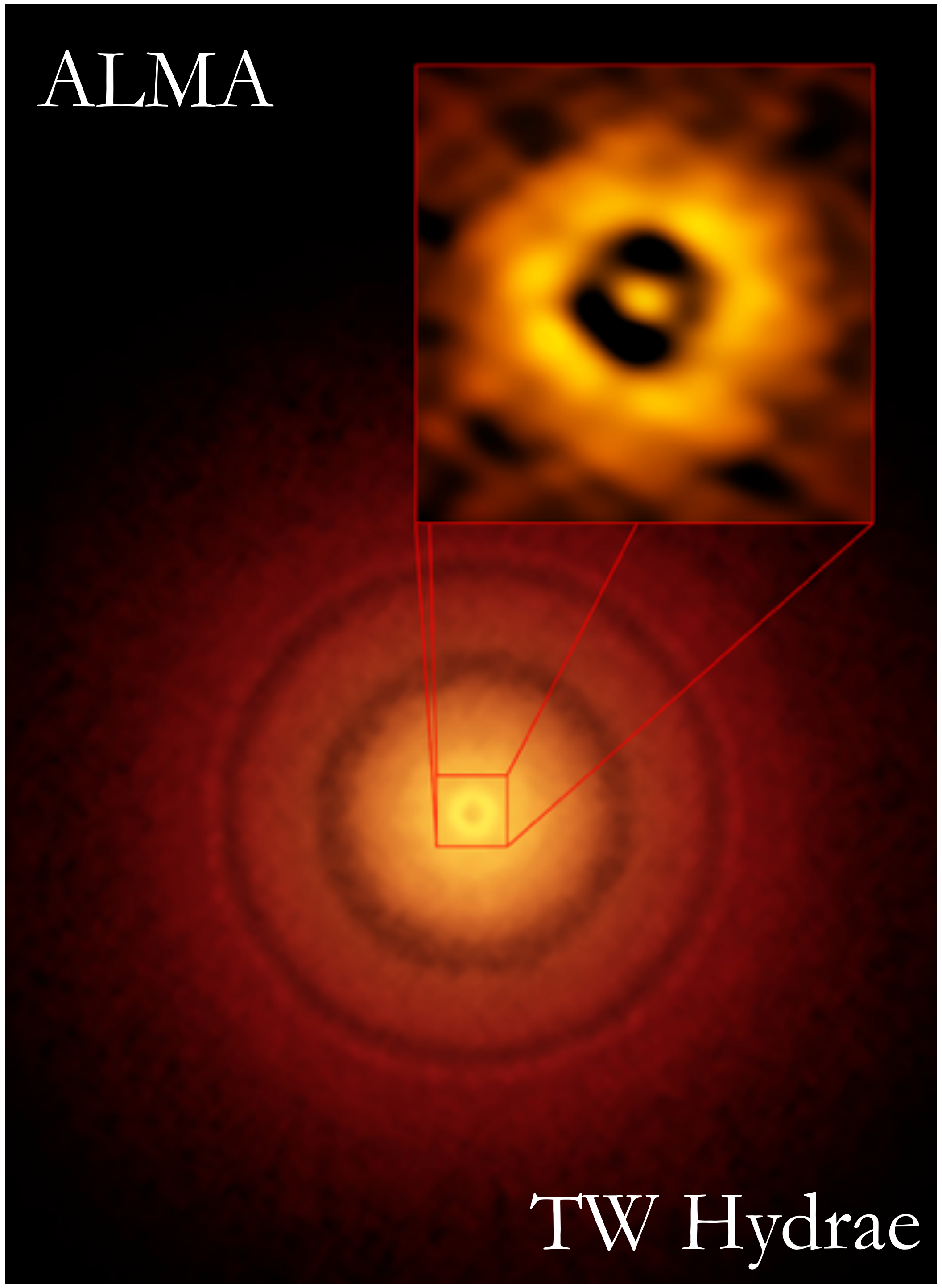
$$n_n \sim 10^{9-15}\ \mathrm{cm}^{-3}$$

$$T \sim 10^{1-3}\ \mathrm{K}$$

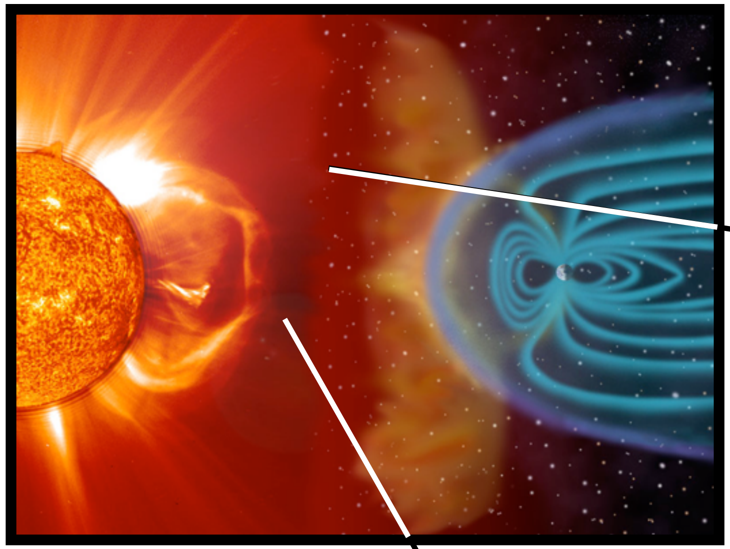
$$x_i \sim 10^{-10} - 10^{-15\ldots}$$

$$B \sim 0.01 - 1\ \mathrm{G}\ ??$$





Solar Wind



at $r \sim 1$ au...

$n \sim 10\ \mathrm{cm}^{-3}$

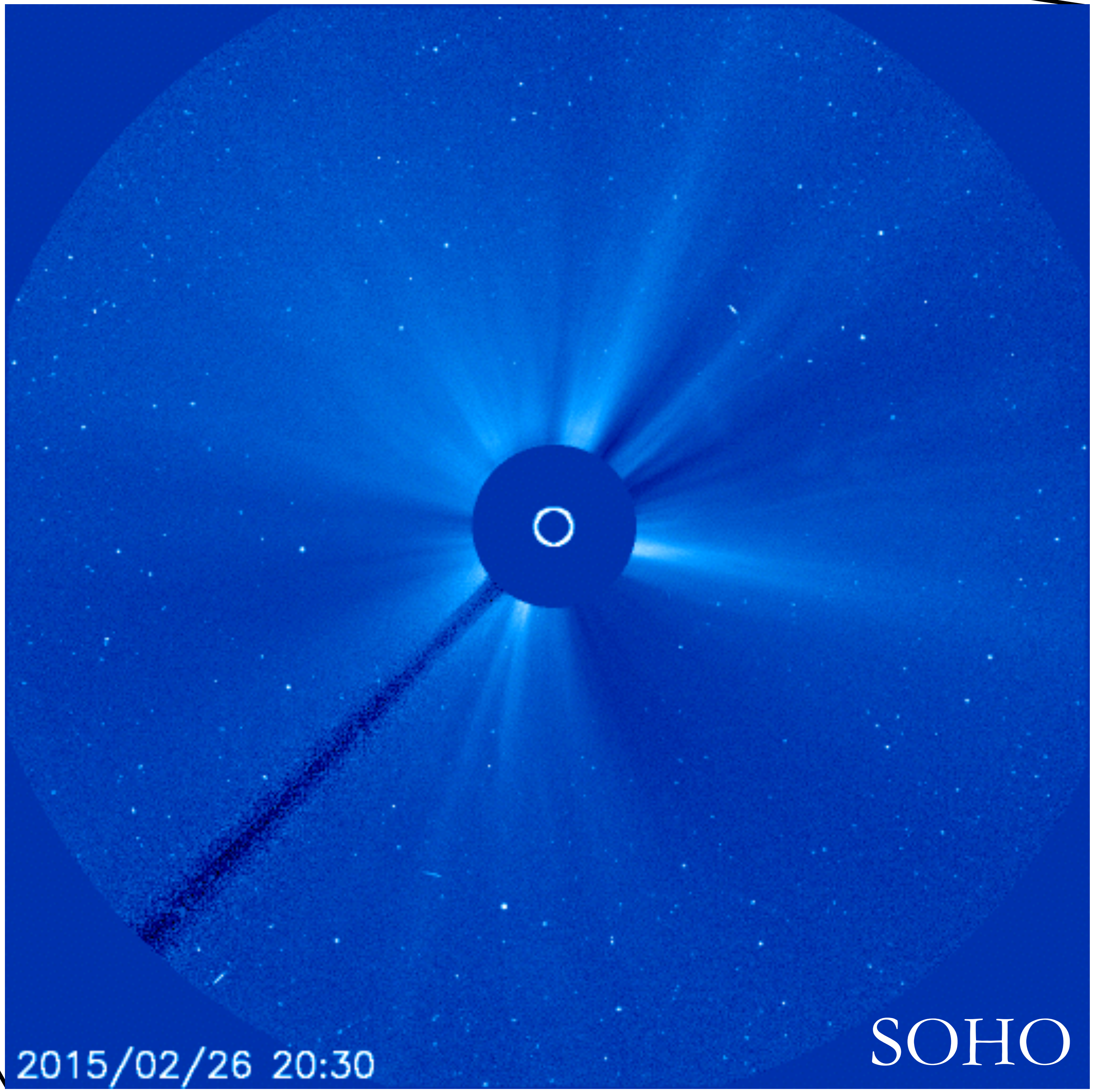
$k_B T \sim 10\ \mathrm{eV}$

$B \sim 100\ \mu\mathrm{G}$

$\lambda_{\mathrm{mfp}} \sim 1$ au

$\rho_i \sim 10^{-6}$ au

$\Omega_i \sim 1\ \mathrm{s}^{-1}$



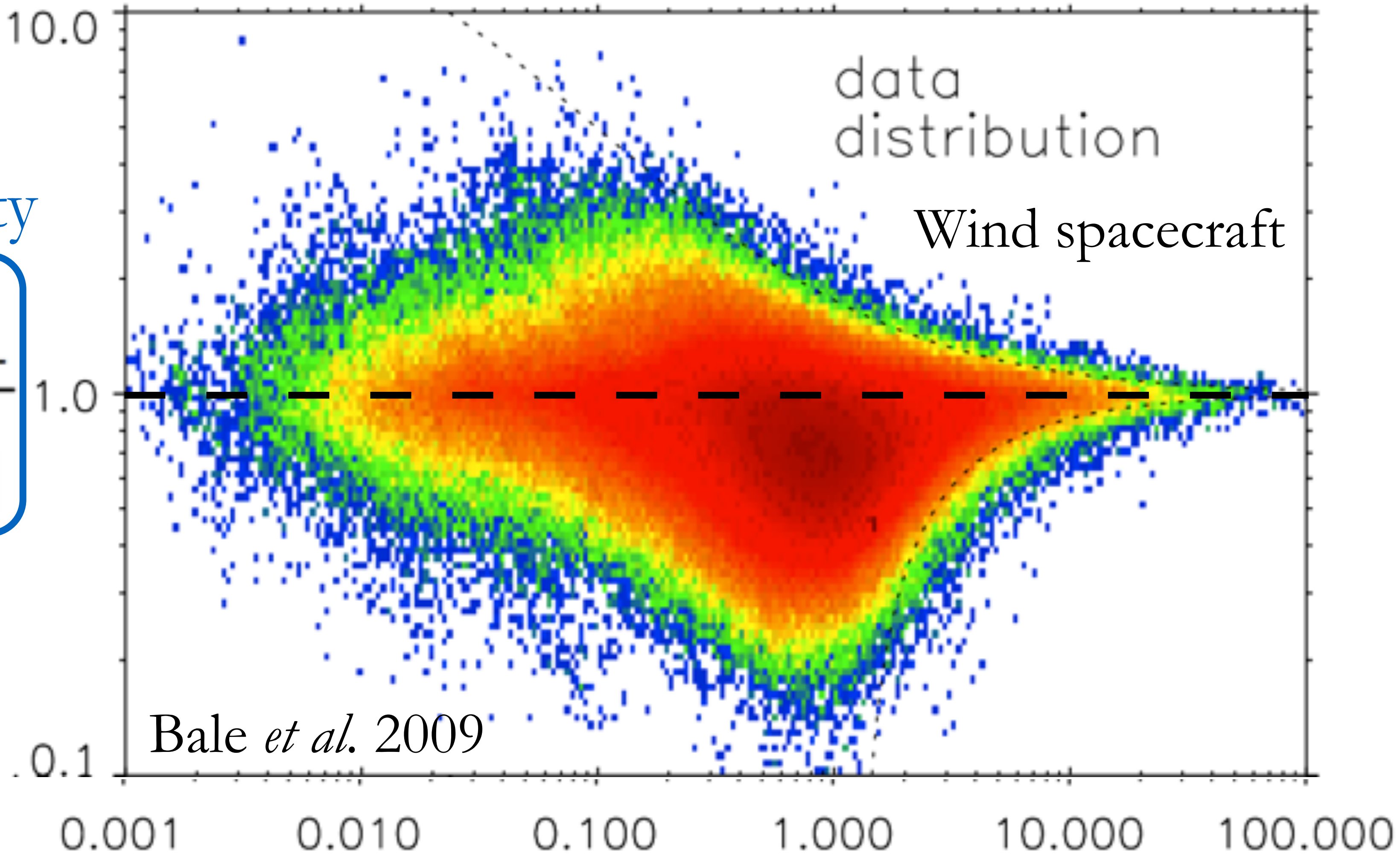
SOHO

Solar Wind

observed departures from isotropy of particle distribution

measure of
non-Maxwellian-ity

$$\boxed{\frac{T_\perp}{T_{||}}}$$



Wind spacecraft

Bale *et al.* 2009

$$\beta_{||} = \frac{8\pi n T_{||}}{B^2}$$

“temperature anisotropy”
$\perp$ and $\|$ to local B

What were the common themes?

(other than plasma and magnetic fields)

huge scale separations!

one consequence is that ideal MHD
is generally not valid in these systems…

good thing you just learned it

(Some) Outstanding Questions in Plasma Astrophysics

1. Cosmic magnetogenesis
2. Material properties of high-β, weakly collisional plasmas (e.g., ICM) (viscosity, conductivity, interplay of macro- and microscales, (in)stability)
3. Magnetic-flux and angular-momentum problems of star formation

let's make the Sun…

Take 1 $\mathrm{M}_\odot$ blob of interstellar medium ($n \sim 1$ cm^{-3}, $B \sim 1$ μG).

Density of the Sun is $\sim 10^{24}$ cm^{-3}.

Conserve magnetic flux ($\Phi_B \propto Br^2 = \text{const}$) and mass ($M \propto nr^3 = \text{const}$) during spherical contraction $\quad \Longrightarrow \quad B \propto n^{2/3}$

$\Longrightarrow \quad B_\odot \sim 10^{10}$ G!!! (actual field is $\sim$1 G)

Having a phase of cylindrical contraction ($nR^2 = \text{const}$) helps, but isn't enough. Substantial flux redistribution *must* take place.

recognized early on (Babcock & Cowling 1953)

let’s make the Sun…

Take 1 $\mathrm{M}_\odot$ blob of interstellar medium ($\Omega \sim 10^{-15}\ \mathrm{s}^{-1}$).

Conserve angular momentum during contraction:

$$\Omega_{\rm final} = \Omega_{\rm init}\left(\frac{R_{\rm init}}{R_{\rm final}}\right)^2 = \Omega_{\rm init}\left(\frac{n_{\rm final}}{n_{\rm init}}\right)^{2/3} \sim 10\ \mathrm{s}^{-1} \ldots \text{yikes}$$

Larger problem: $\dfrac{|W_{\rm grav}|}{2W_{\rm rot}} = 2\pi\dfrac{G\rho}{\Omega^2} \sim 1$ for spherical blob of ISM

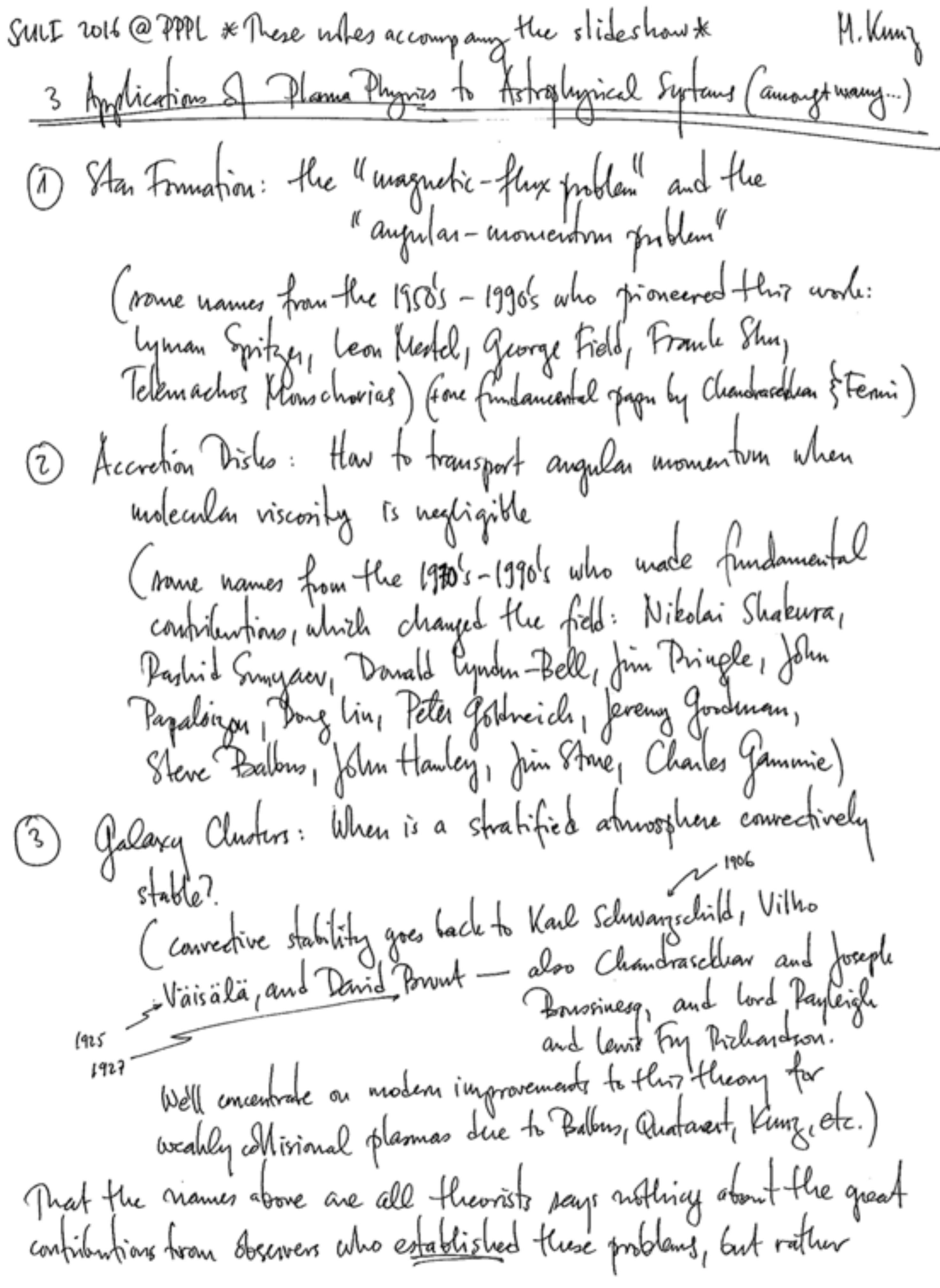
(Mouschovias 1991)

(Some) Outstanding Questions in Plasma Astrophysics

1. Cosmic magnetogenesis
2. Material properties of high-β, weakly collisional plasmas (e.g., ICM)
   (viscosity, conductivity, interplay of macro- and microscales, (in)stability)
3. Magnetic-flux and angular-momentum problems of star formation
4. Angular-momentum transport in realistic accretion disks
   (what powers most luminous sources in the Universe?)
5. Heating of the solar corona and launching of the solar wind
6. Kinetic turbulence and particle heating (T_e vs T_i)
7. 11-year solar cycle and the Maunder minimum (1645-1715)
8. Supernovae and gamma-ray bursts
9. Cosmic-ray spectrum and non-thermal particle acceleration (up to $\sim 10^{20}$ eV!)
10. Magnetospheres of compact objects
11. Jet/outflow launching and collimation
12. Magnetic reconnection in realistic environments
    (rate, onset, particle acceleration, cross-scale coupling, relativistic effects…)

sample of some plasma astrophysics, related to the systems I presented

(Prof. Loureiro will cover reconnection)



SULI 2016 @ PPPL *These notes accompany the slideshow* M. Kunz

3 Applications of Plasma Physics to Astrophysical Systems (amongst many...)

① Star Formation: the "magnetic-flux problem" and the "angular-momentum problem"

(some names from the 1950's – 1990's who pioneered this work: Lyman Spitzer, Leon Mestel, George Field, Frank Shu, Telemachos Mouschovias) (some fundamental paper by Chandrasekhar & Fermi)

② Accretion Disks: How to transport angular momentum when molecular viscosity is negligible

(some names from the 1970's – 1990's who made fundamental contributions, which changed the field: Nikolai Shakura, Rashid Sunyaev, Donald Lynden-Bell, Jim Pringle, John Papaloizou, Doug Lin, Peter Goldreich, Jeremy Goodman, Steve Balbus, John Hawley, Jim Stone, Charles Gammie)

③ Galaxy Clusters: When is a stratified atmosphere convectively stable?

(convective stability goes back to Karl Schwarzschild (1906), Vilho Väisälä (1925), and David Brunt (1927) — also Chandrasekhar and Joseph Boussinesq, and Lord Rayleigh and Lewis Fry Richardson.

We'll concentrate on modern improvements to this theory for weakly collisional plasmas due to Balbus, Quataert, Kunz, etc.)

That the names above are all theorists says nothing about the great contributions from observers who established these problems, but rather