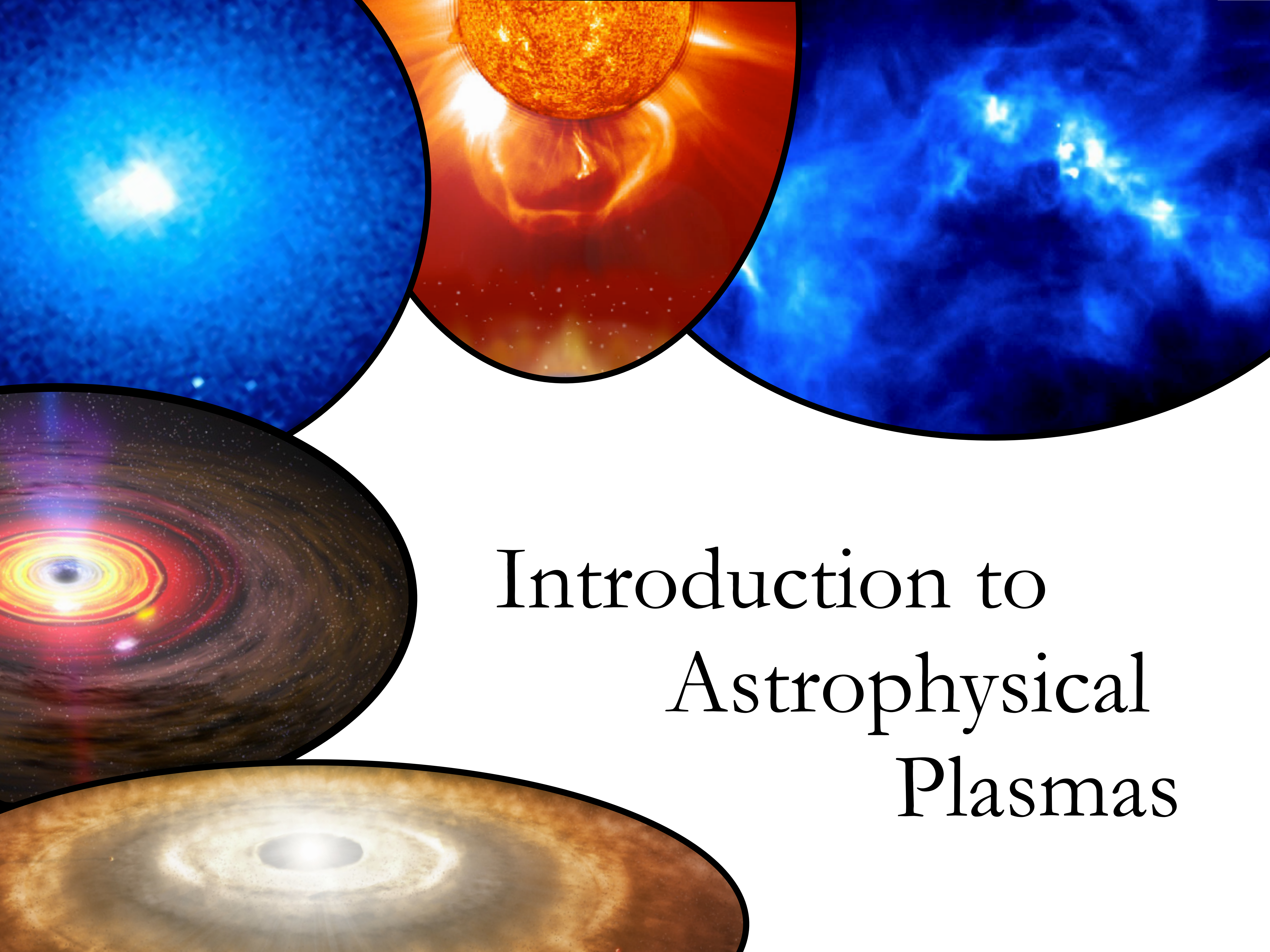


Introduction to Astrophysical Plasmas

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)

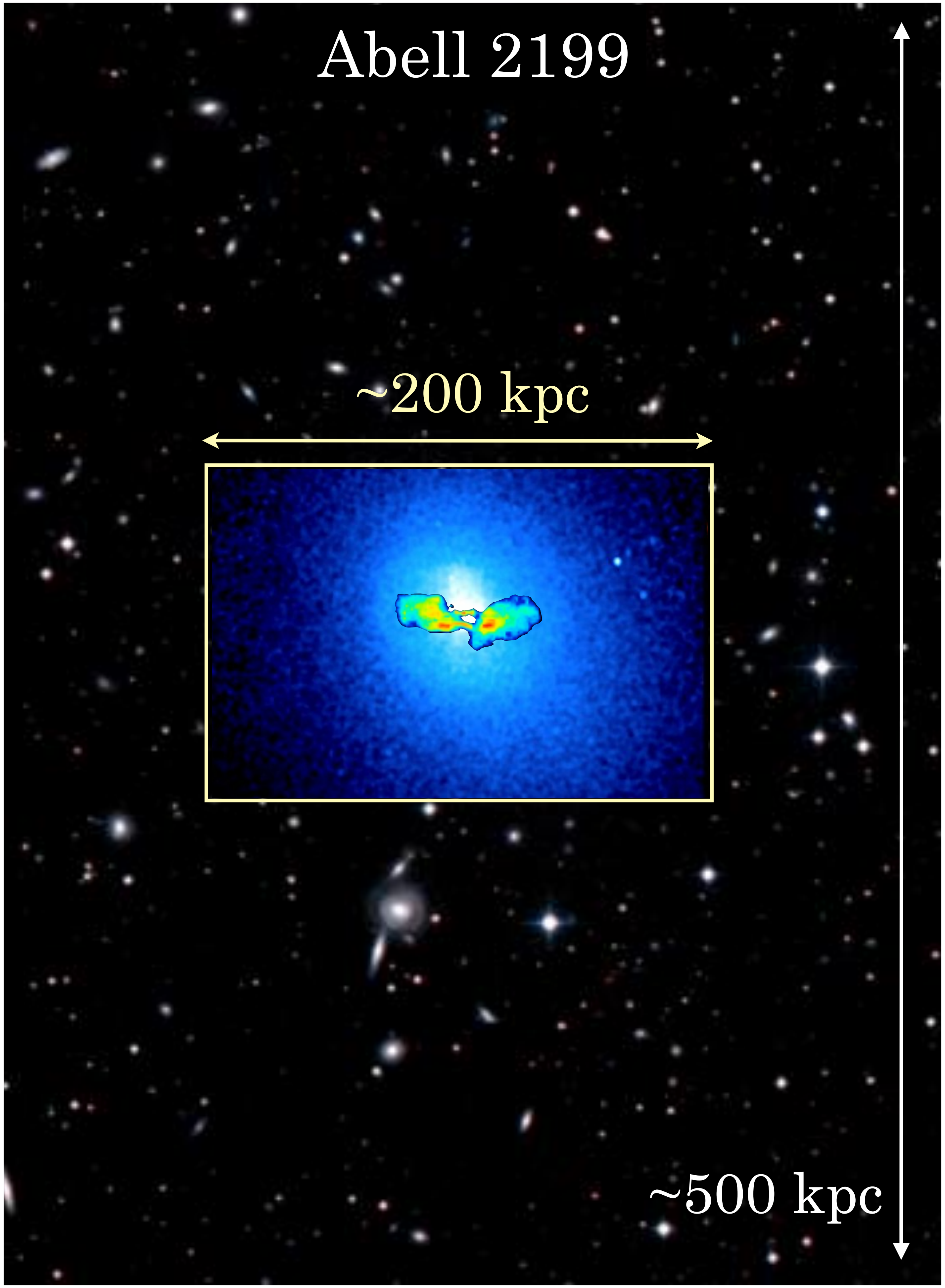
often, these are in **energy equipartition**

definition of a plasma and
characteristics time/length scales
done at the board

now for some astrophysical examples,
with a focus on the plasma properties

start big and work our way down

(things generally get colder, until we get to a star)



Clusters of Galaxies

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

in ~1 Mpc

~84% dark matter

14% thermal plasma

$T \sim 1\text{–}10\ \mathrm{keV}$

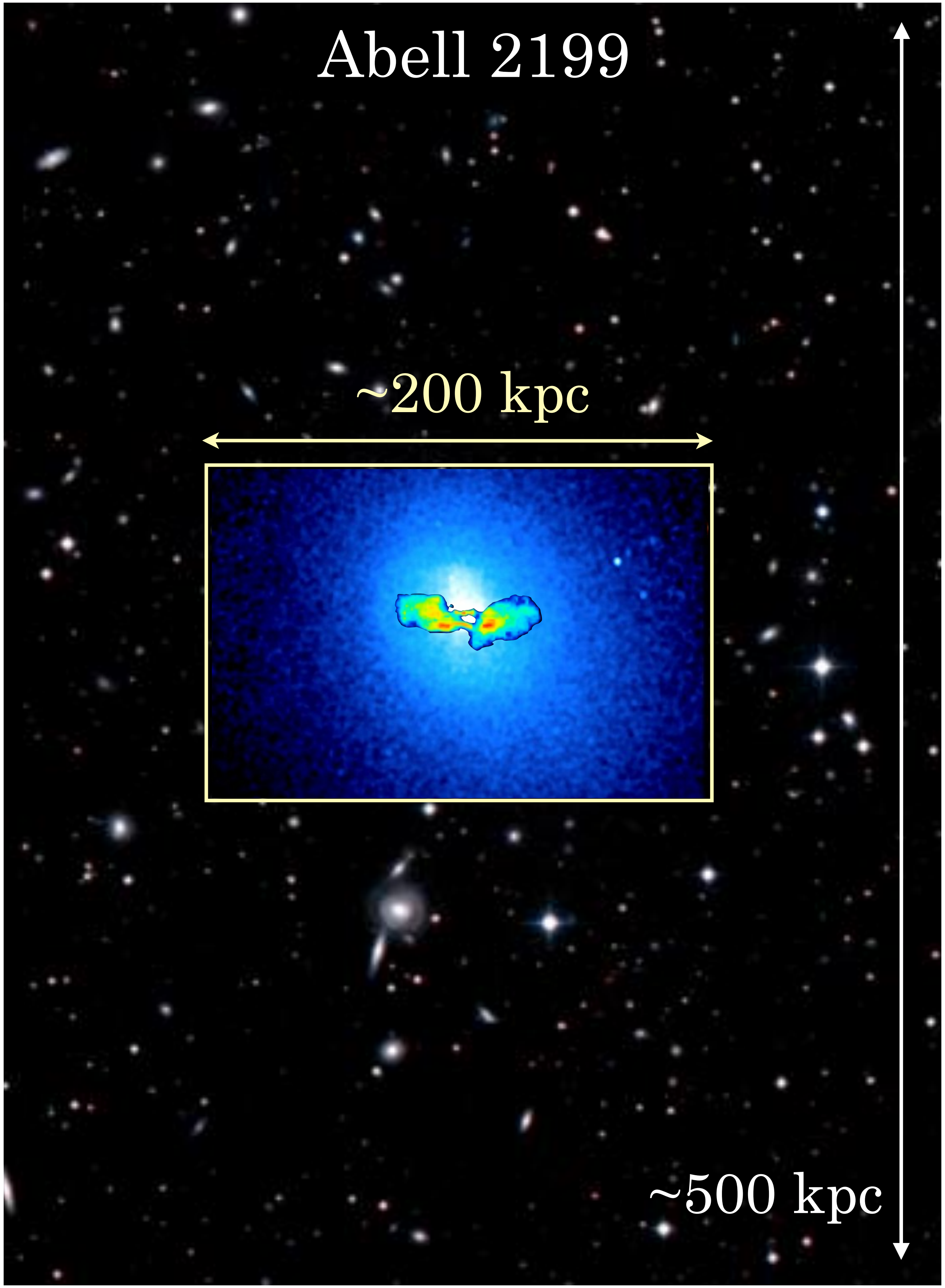
$(v_{\mathrm{th,i}} \sim 1000\ \mathrm{km\ s^{-1}})$

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

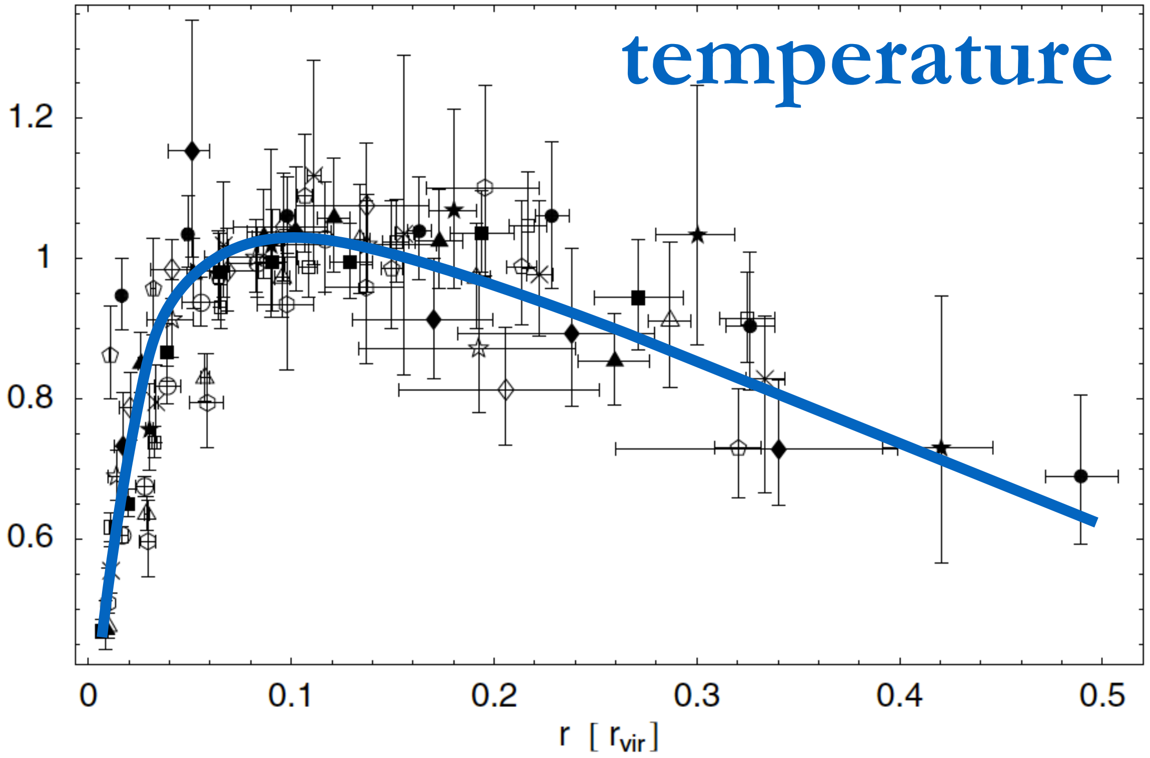
$B \sim 1\ \mu\mathrm{G}$

radio (BH & relativistic plasma)

Intracluster Medium



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



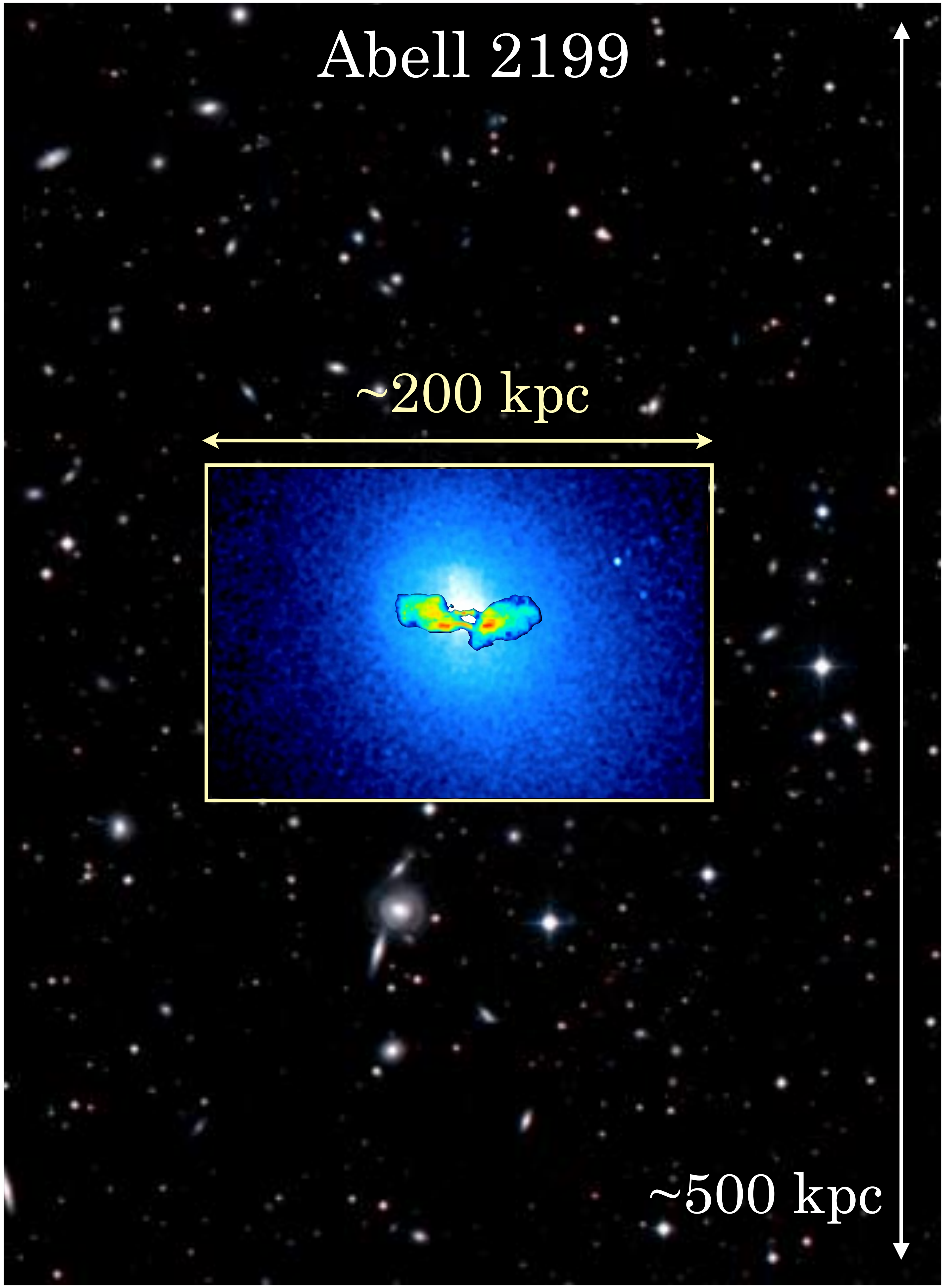
$$t_{\rm dyn} \gtrsim 100\ {\rm Myr}$$

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

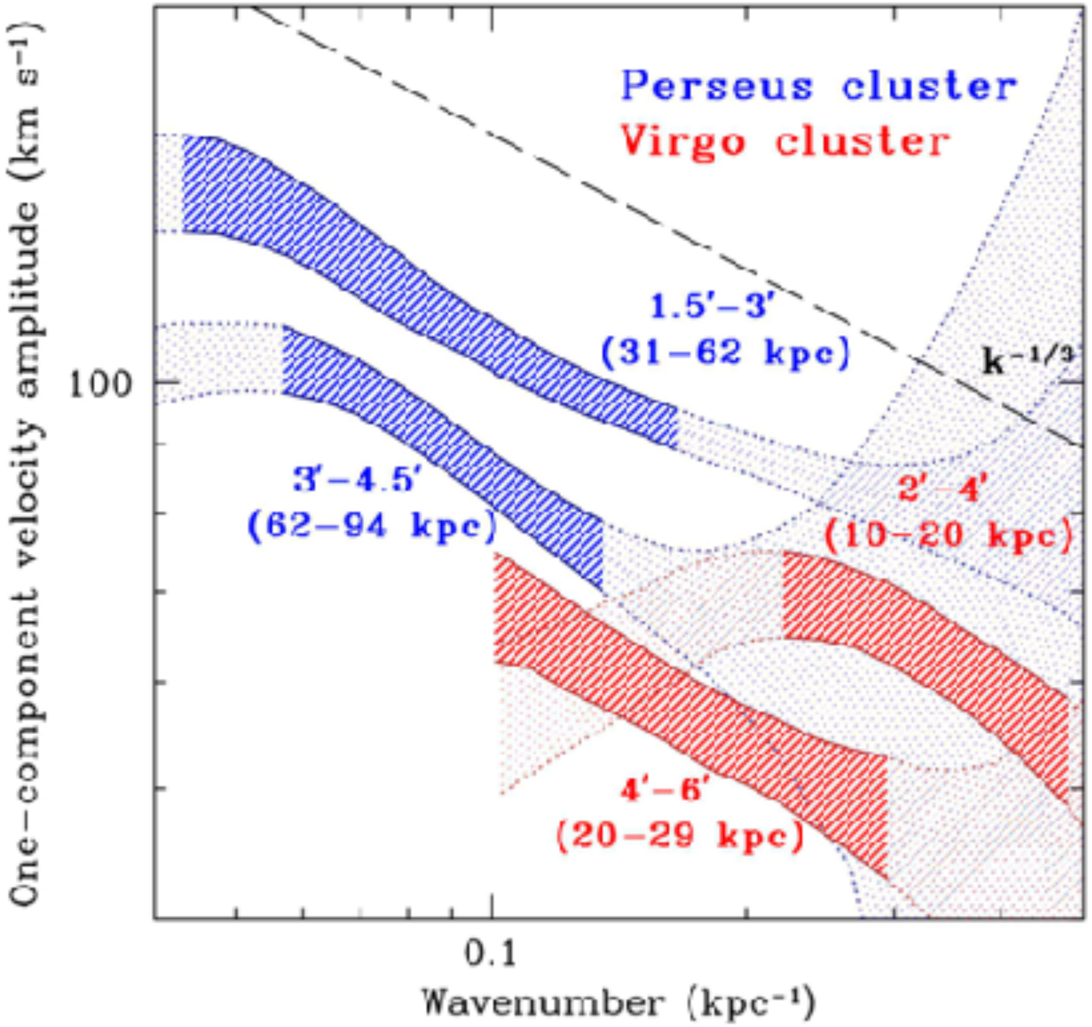
$$t_{\rm gyr,i} \sim 10\ {\rm min}$$

(ion Larmor orbit ~ size of Jupiter)

Intracluster Medium



subsonic, trans-Alfvénic turbulence!

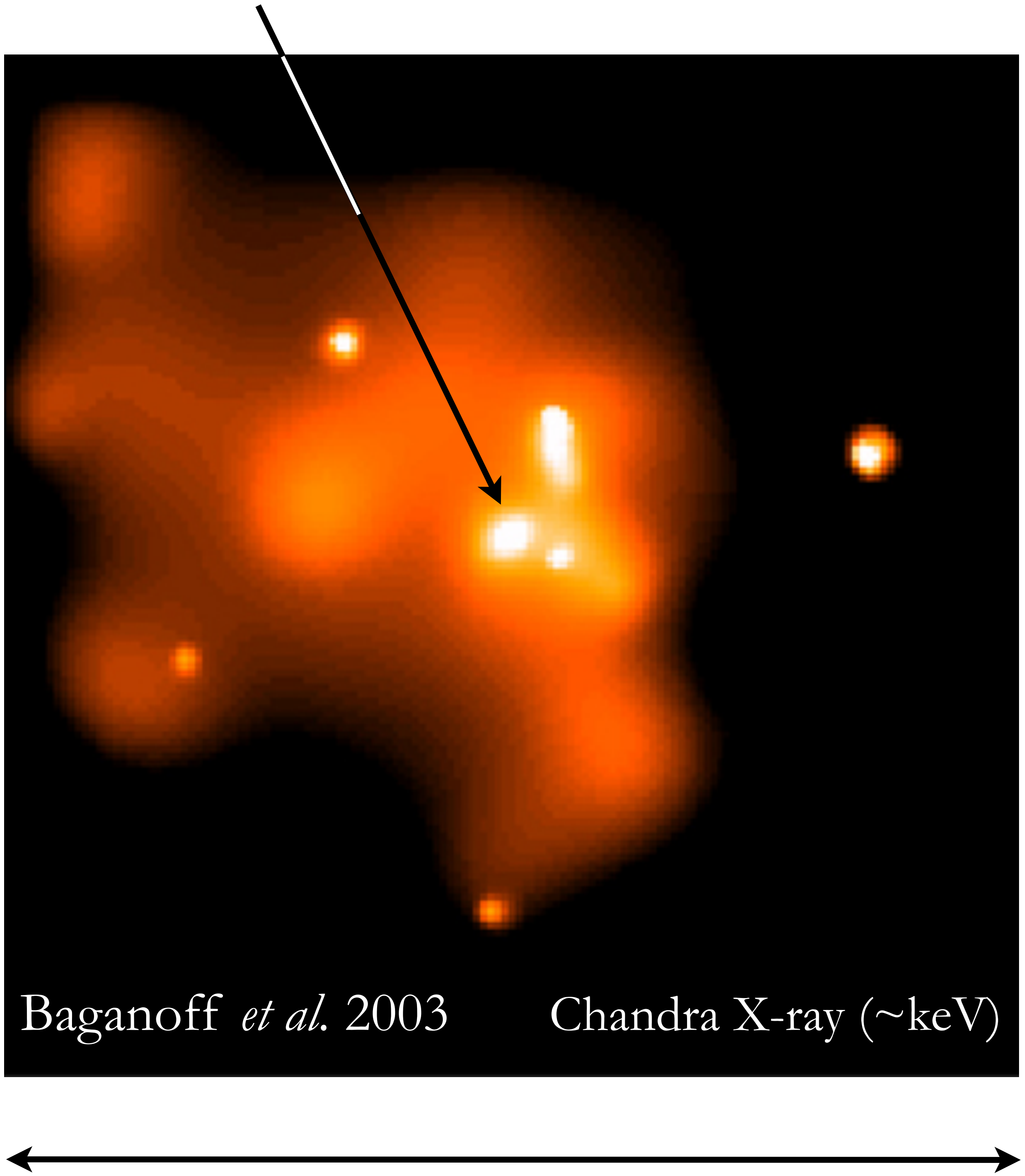


Zhuravleva *et al.* 2014, Nature

Hitomi, before its death:

$u \sim 160$ km/s

Galactic Center



4×10^6 M$_\odot$ BH

Baganoff *et al.* 2003

Chandra X-ray (~keV)

~10 light-years

$$r_{\rm Bondi} \sim 0.1 \text{ pc}$$

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

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

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

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

$$t_{\rm dyn} \lesssim 200 \text{ yr}$$

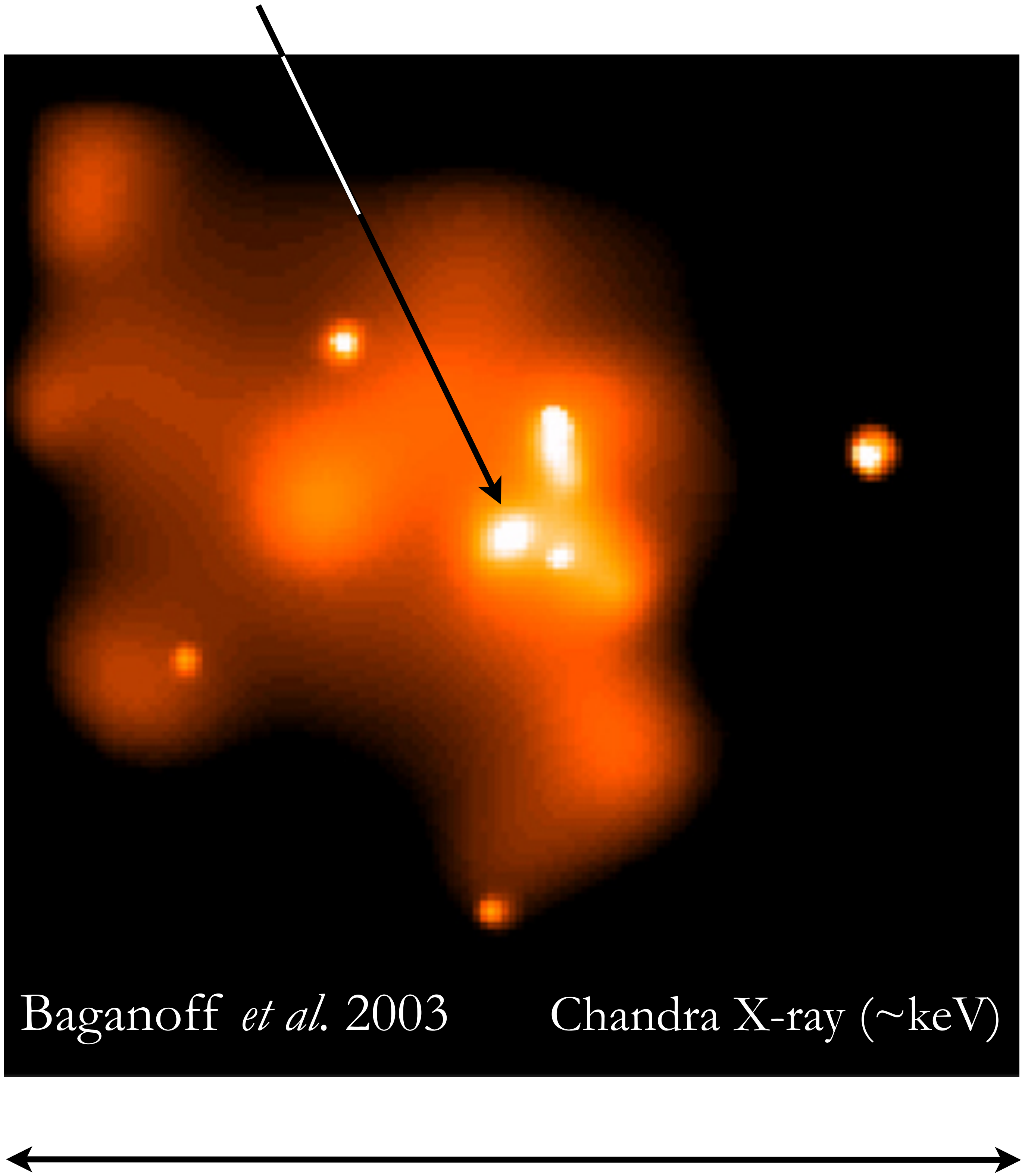
$$t_{\rm ii,coll} \sim 20 \text{ yr}$$

$$t_{\rm gyr,i} \sim 1 \text{ s}$$

(can drive ion Larmor orbit in ~2 hrs)

Galactic Center

4×10^6 M$_\odot$ BH

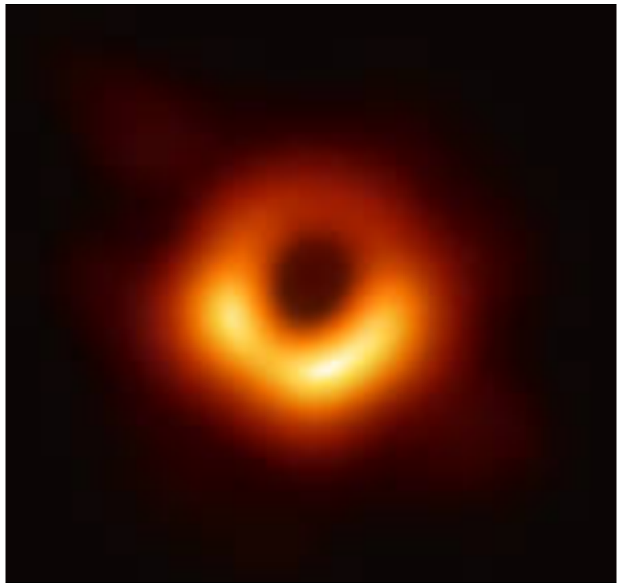

Baganoff *et al.* 2003

Chandra X-ray (~keV)

~10 light-years

get within 10 Schwarzschild radii:

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


EHT collaboration

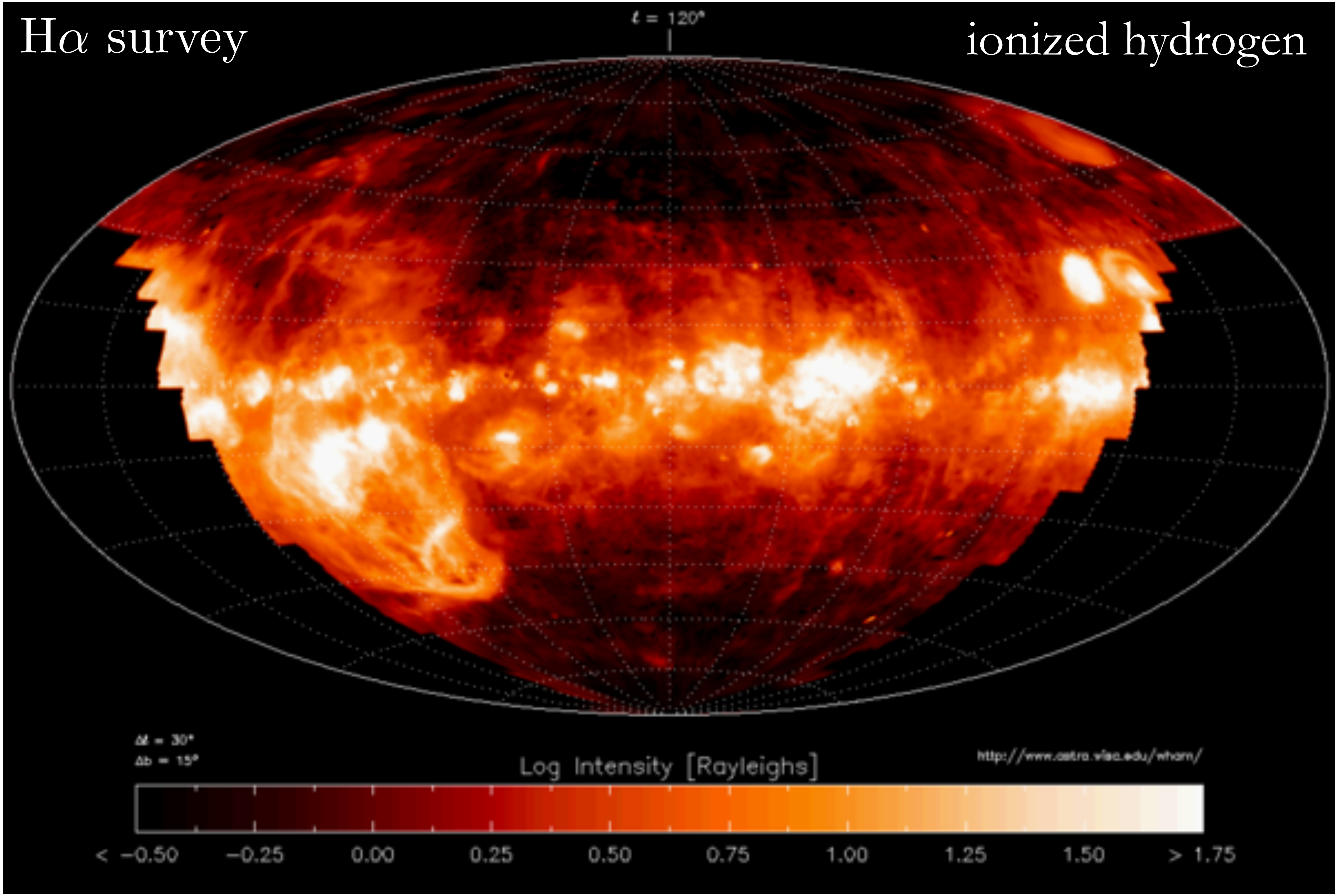
$$t_{\rm dyn} \lesssim 10\ {\rm min}$$

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

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

fun fact: Schwz. radius of Sun ~3 km

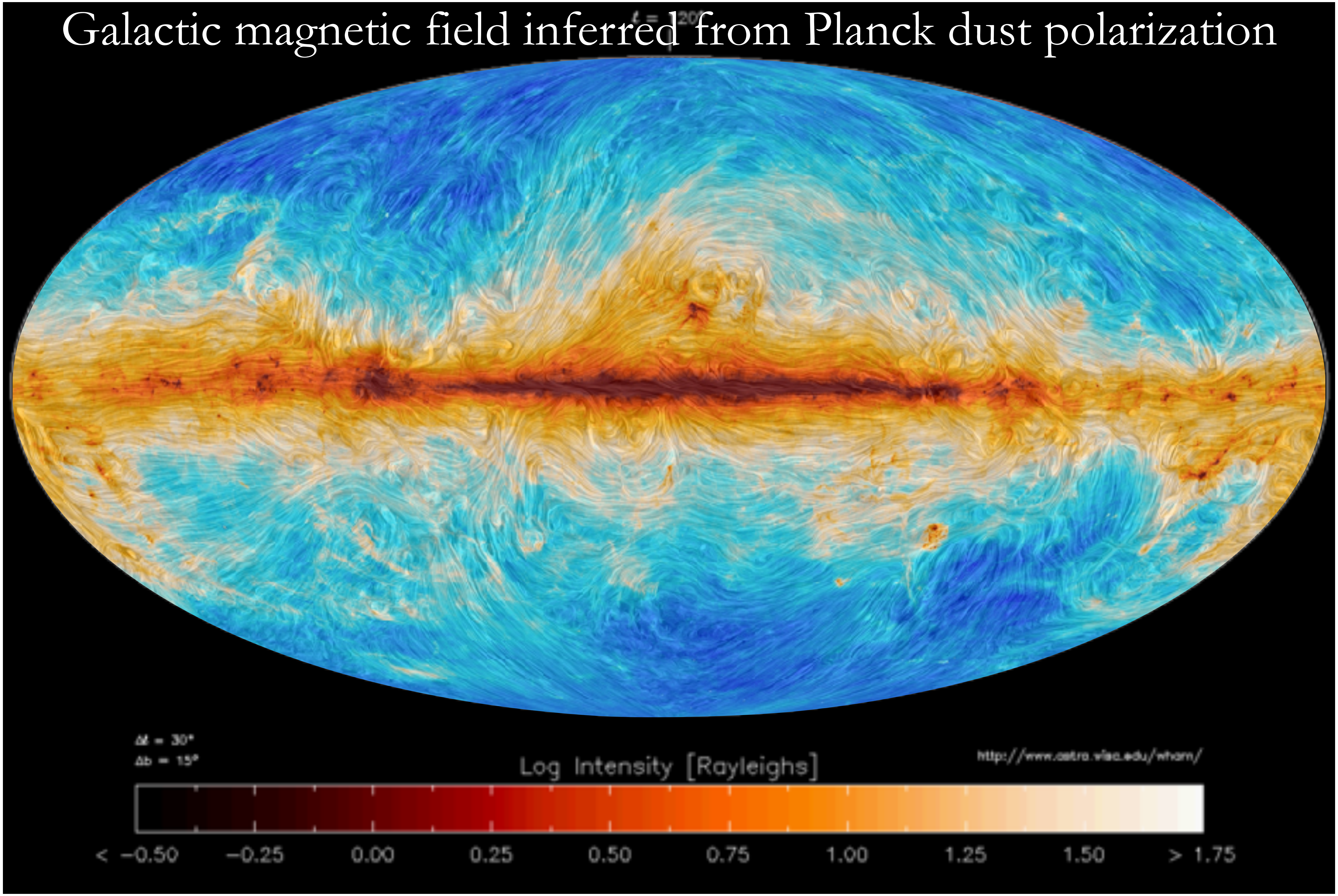
Interstellar Medium



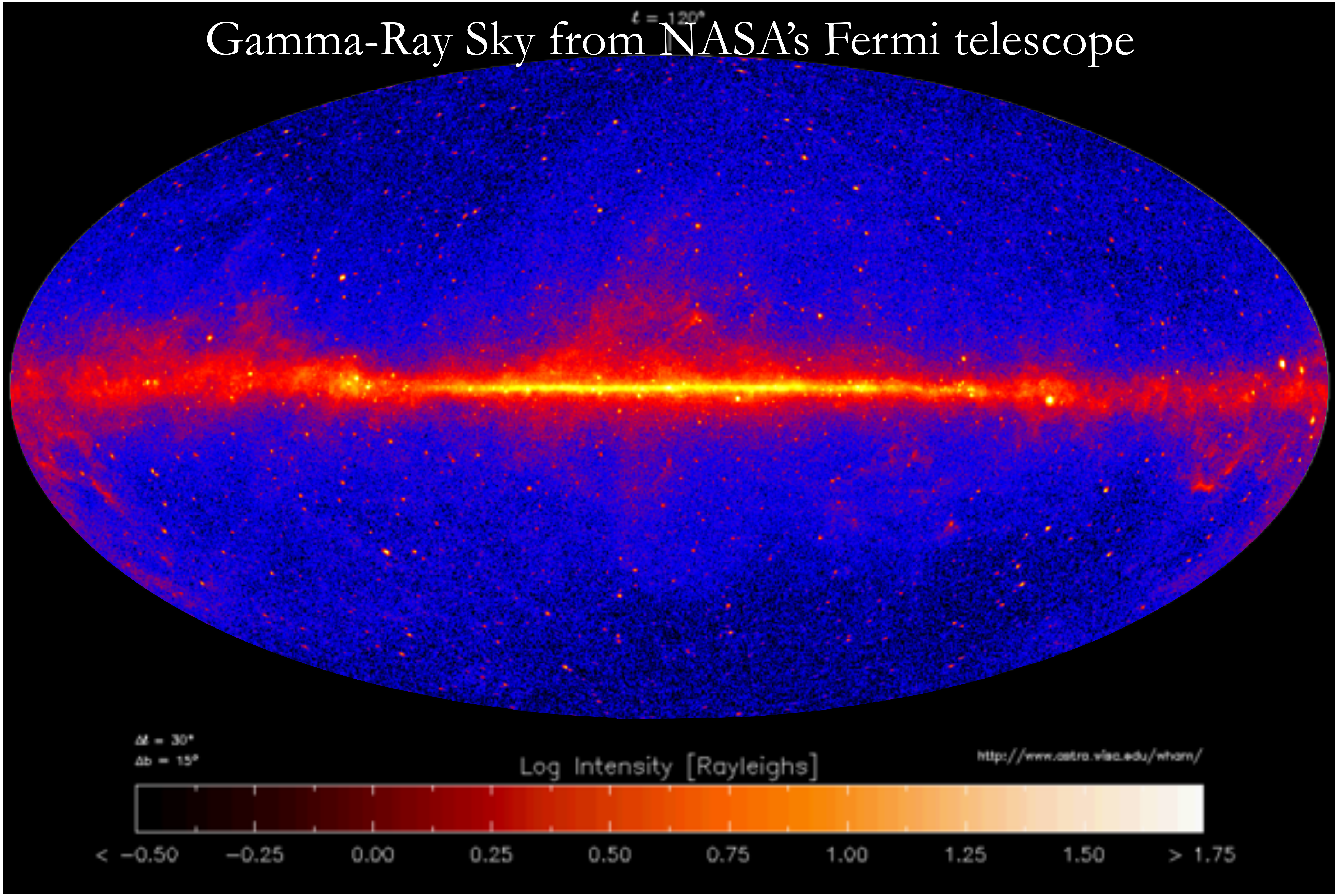
Hα survey

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)

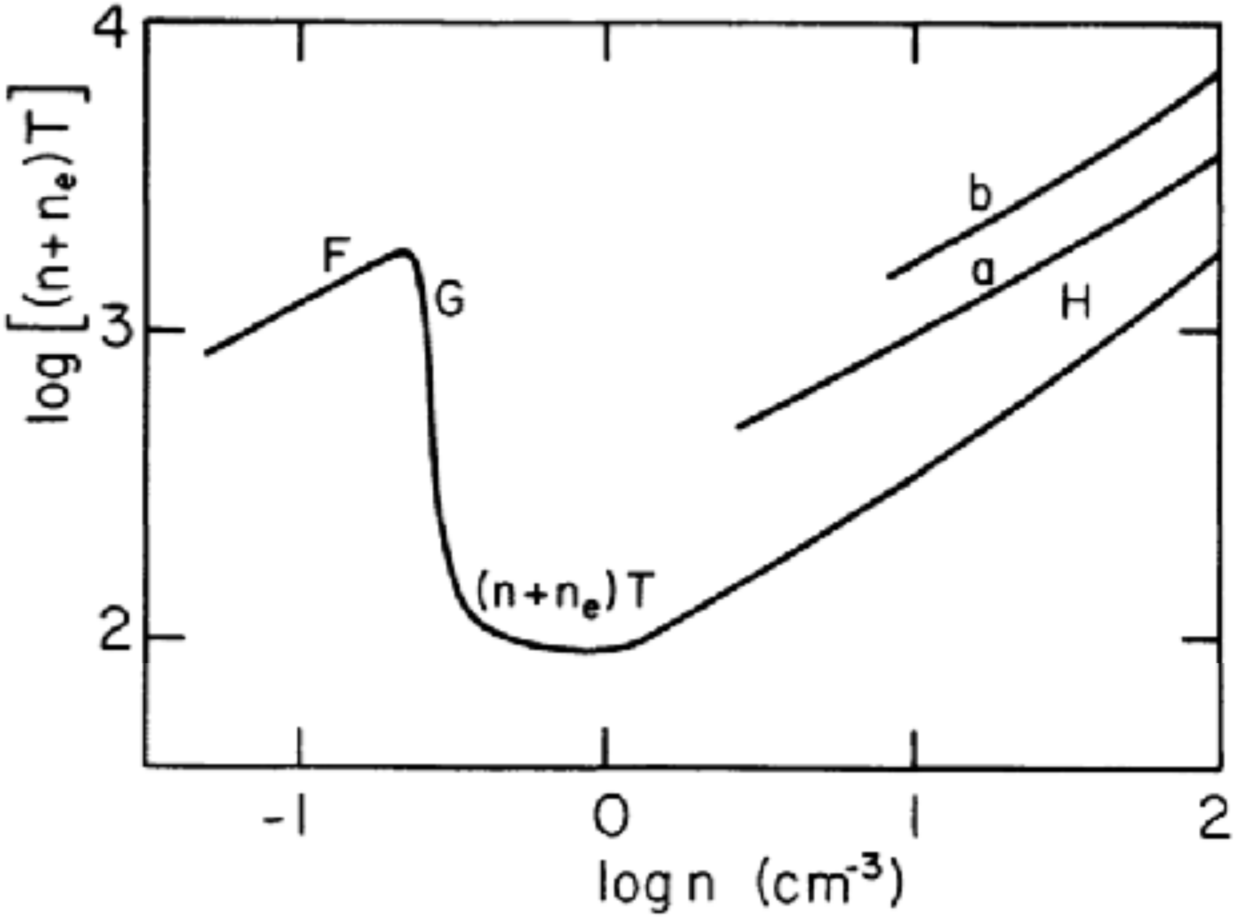
1% dust (metals, graphites, silicates) $\longleftarrow$ important plasma component; also, is ~0.1% mass of Galaxy but responsible for ~30-50% of bolometric luminosity

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

warm component $n \sim 0.1 - 1 \text{ cm}^{-3}$ $T \gtrsim 10^3$ K

cold component $n \gtrsim 10 \text{ cm}^{-3}$ $T \lesssim 100$ K

hot (coronal) component $n \lesssim 0.01 \text{ cm}^{-3}$ $T \gtrsim 10^5$ K

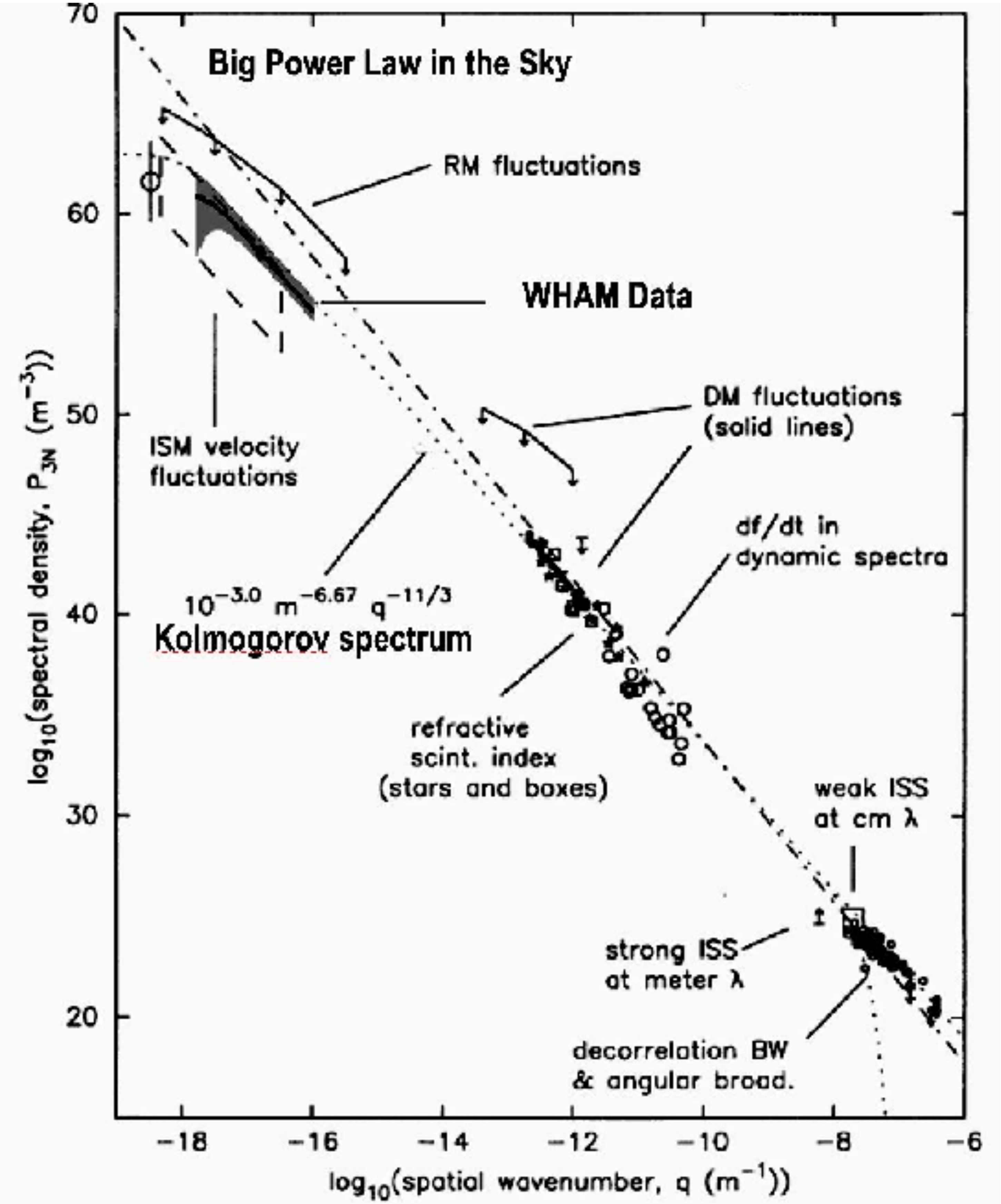


Crab nebula, young SNR

Interstellar Medium

Turbulence

"Great Power Law in the Sky"

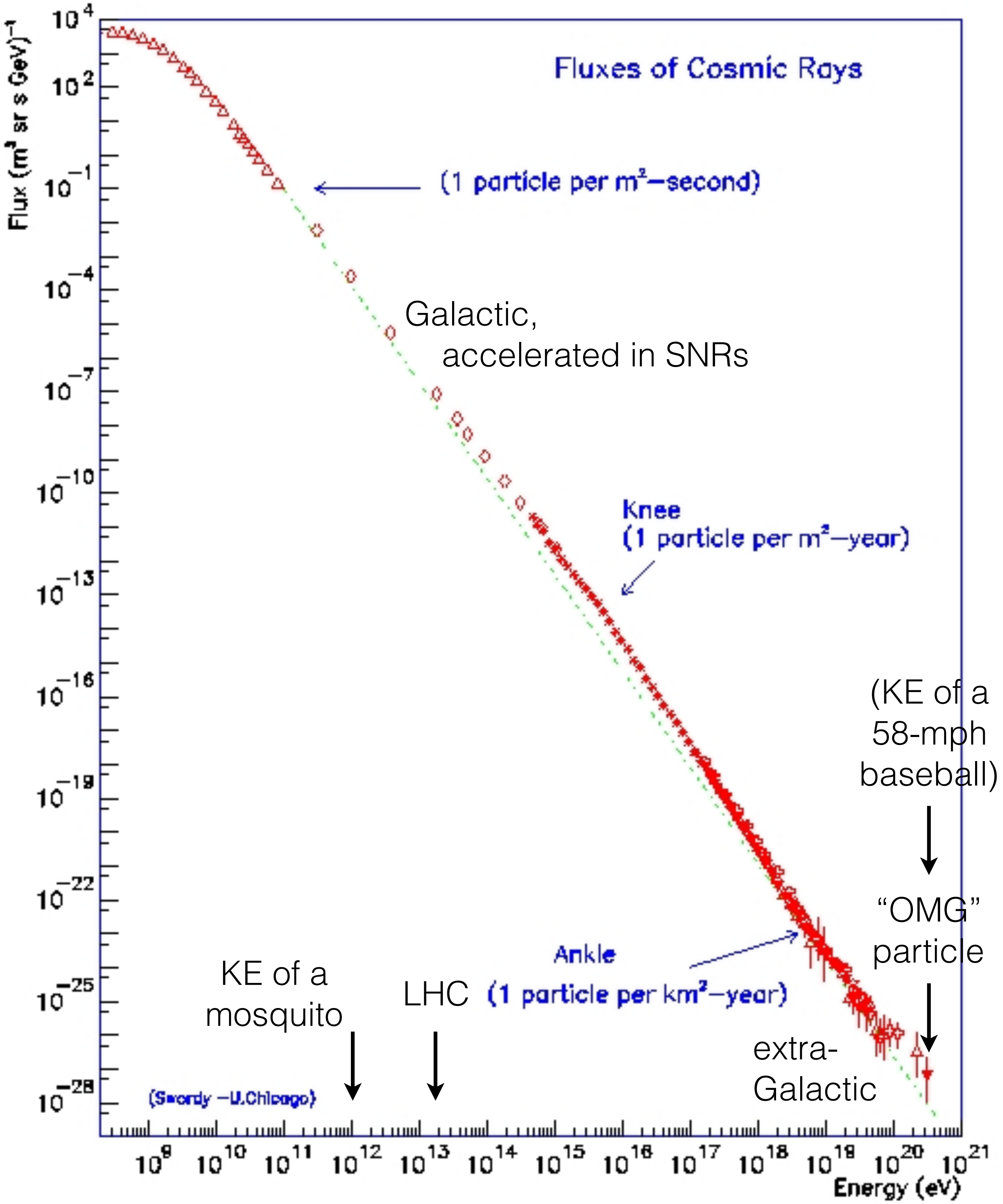


Armstrong, Cordes, Rickett 1981, Nature
Armstrong, Rickett, Spangler 1995, ApJ

Interstellar Medium

Cosmic Rays

2nd great power law in the sky



Galactic, accelerated in SNRs

(KE of a 58-mph baseball)

“OMG” particle

KE of a mosquito

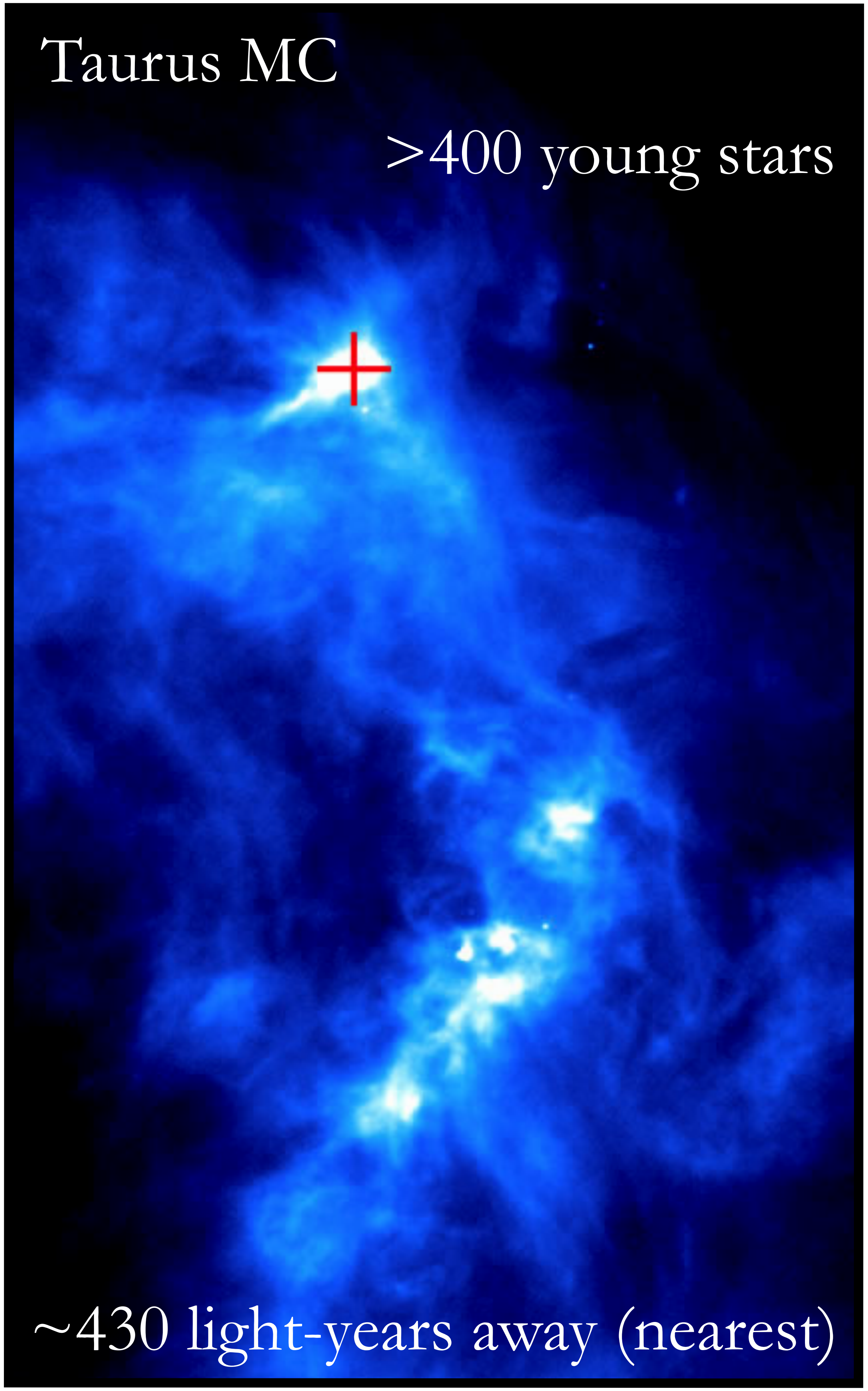
LHC

extra-Galactic

Interstellar Medium

what makes studying the ISM both fascinating and difficult:

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



Molecular Clouds

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!

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

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

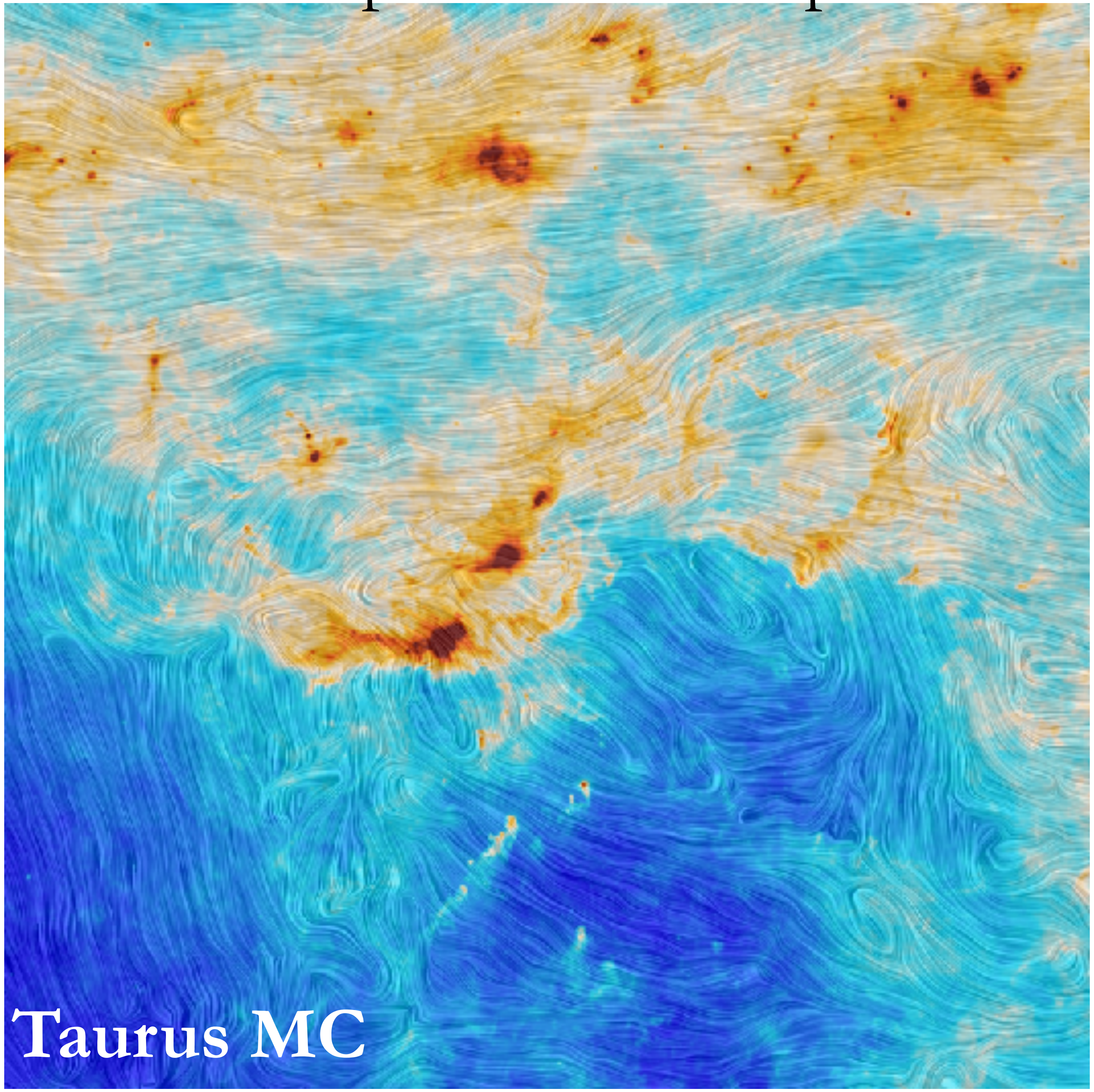
$$t_{\mathrm{coll},in} \sim 1\ \mathrm{mth}$$

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

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

Molecular Clouds

Planck dust polarization map



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

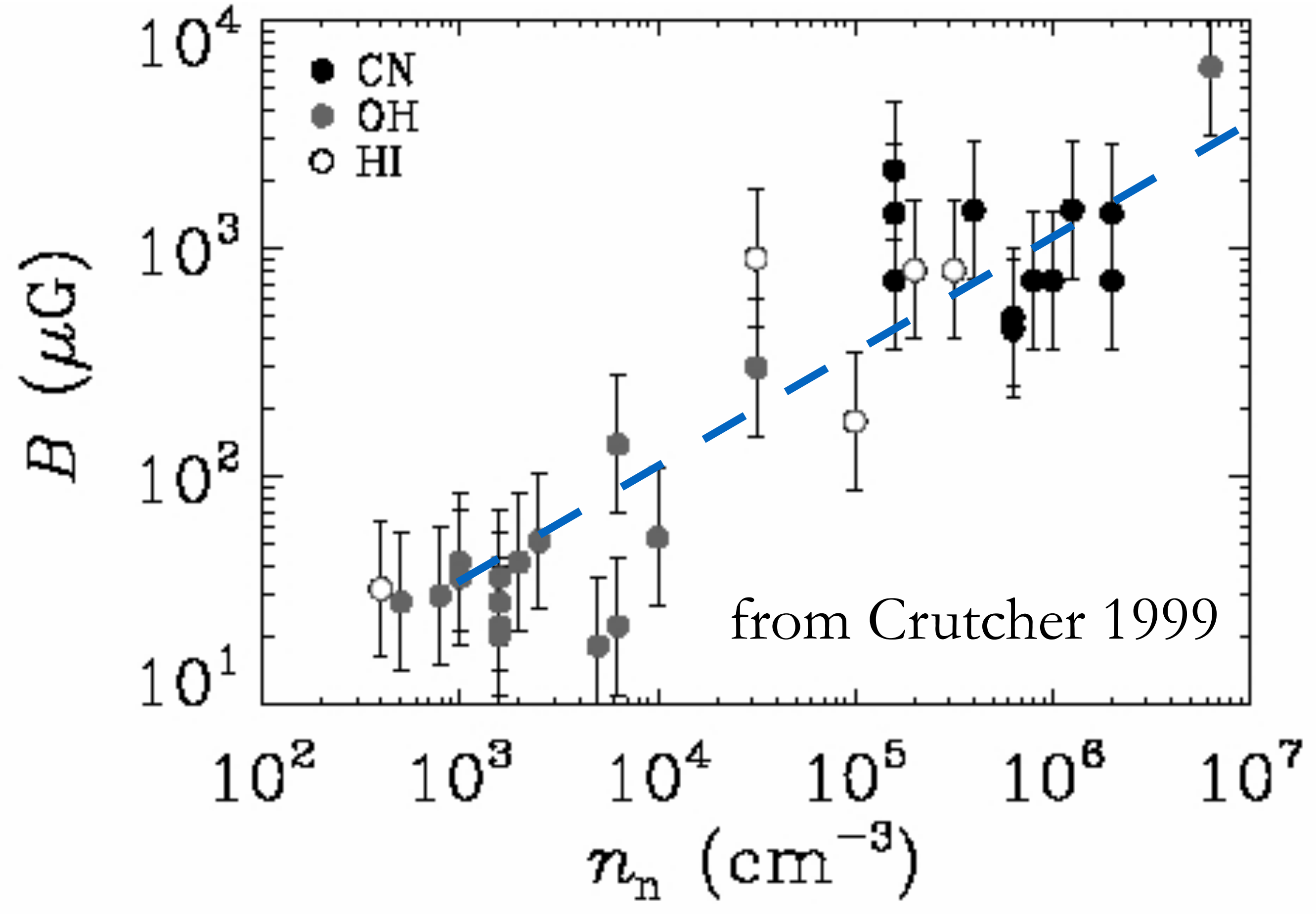
$$\beta \sim 0.01 - 0.1$$

$$M_A \sim 1$$

turbulence, magnetic fields, and gravity in rough energy equipartition

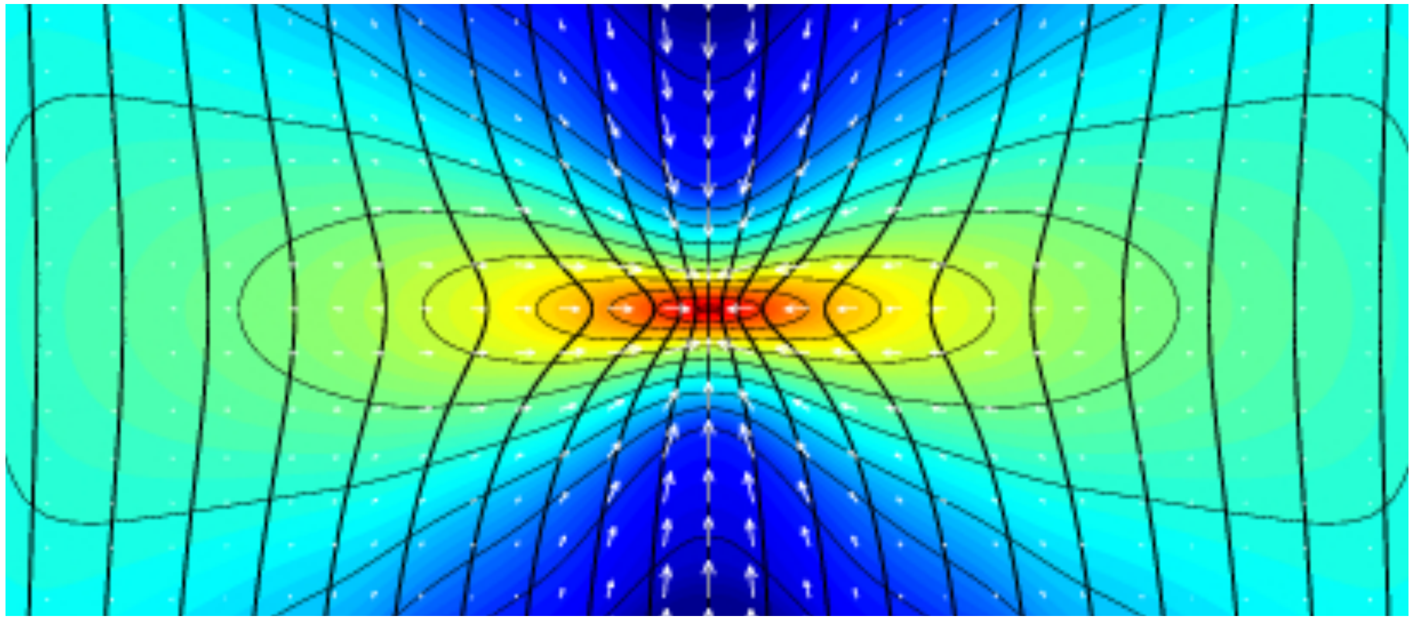
Protostellar Cores

Zeeman observations



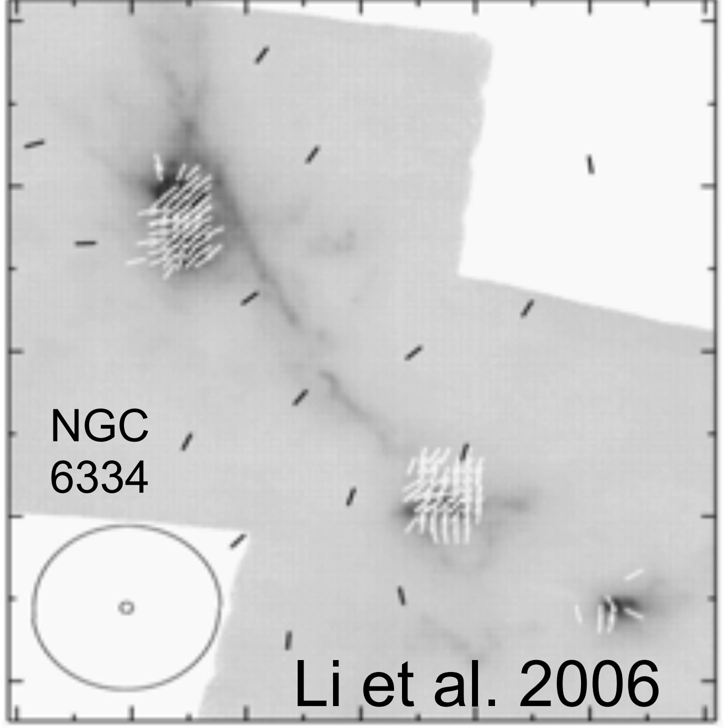
from Crutcher 1999

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



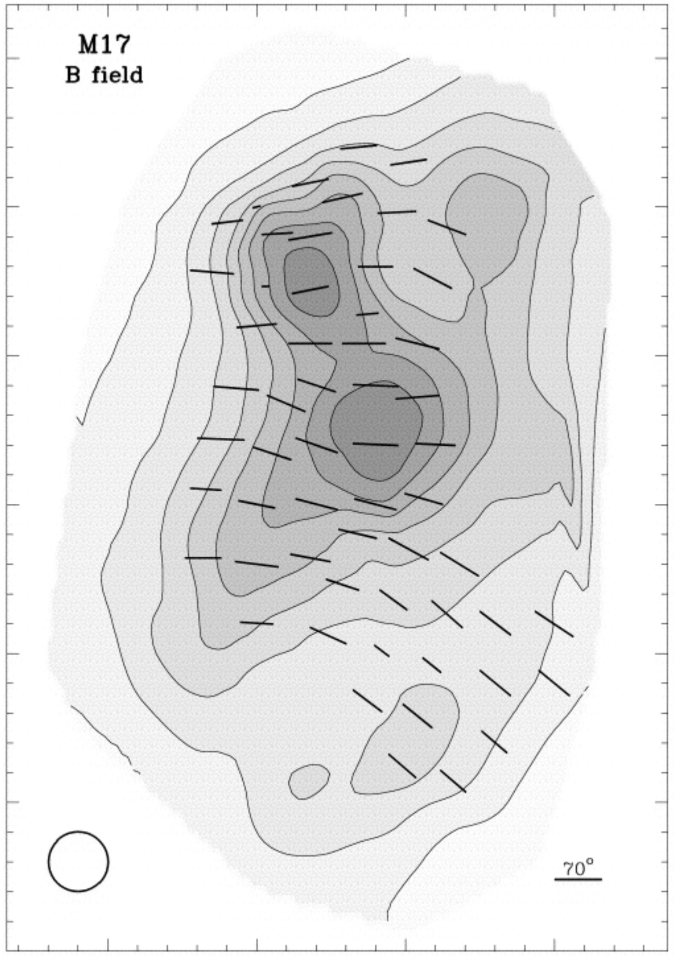
Protostellar Cores

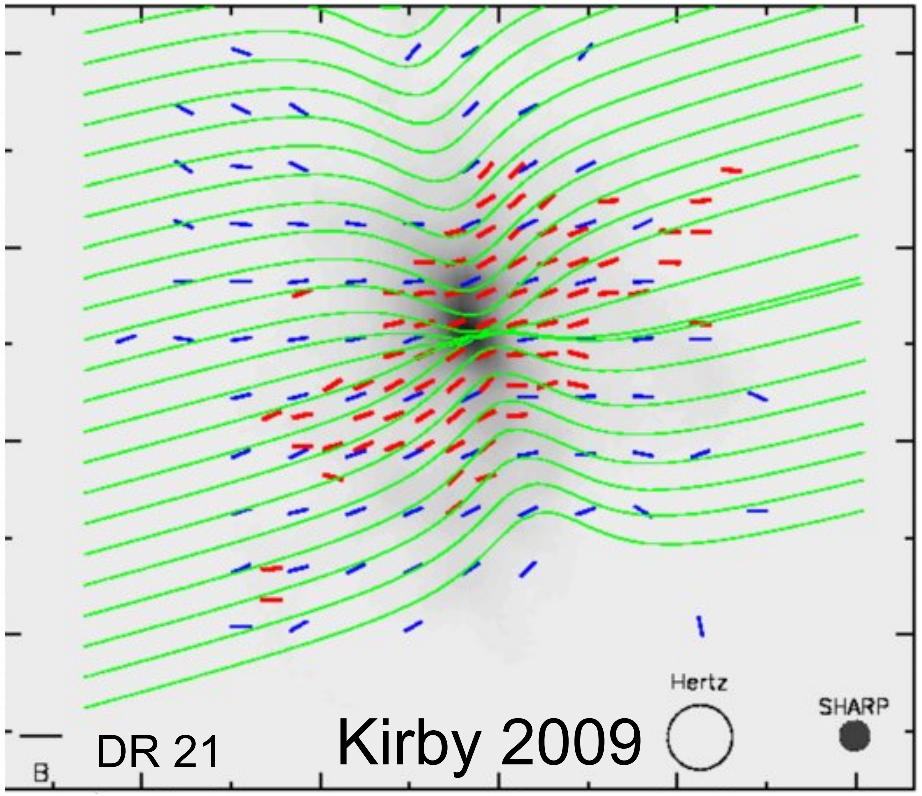
Dotson et al. 2008



Li et al. 2006

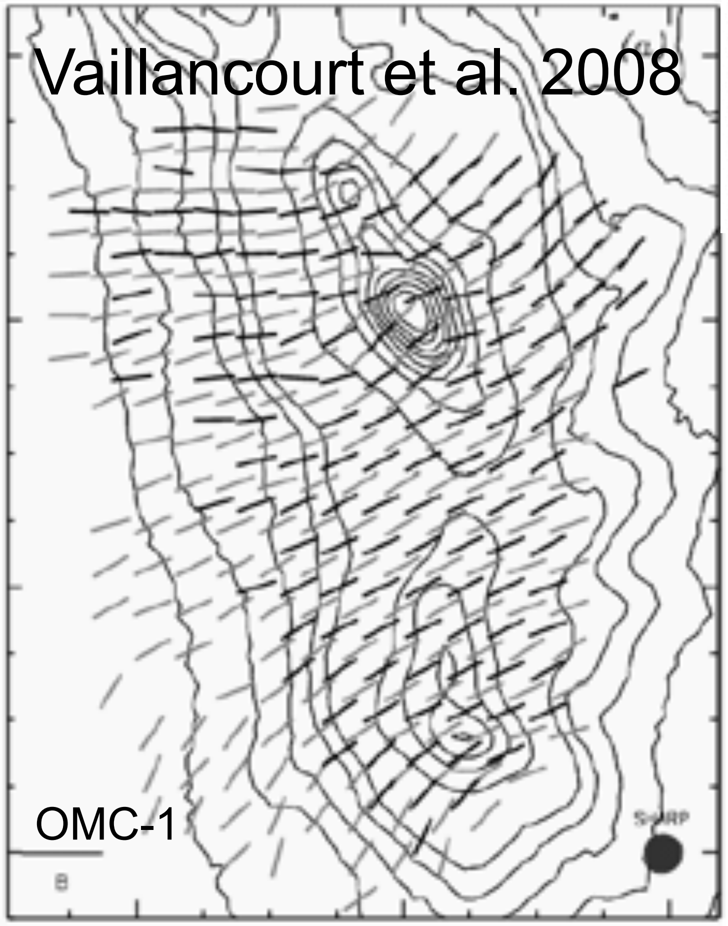
Houde et al 2002

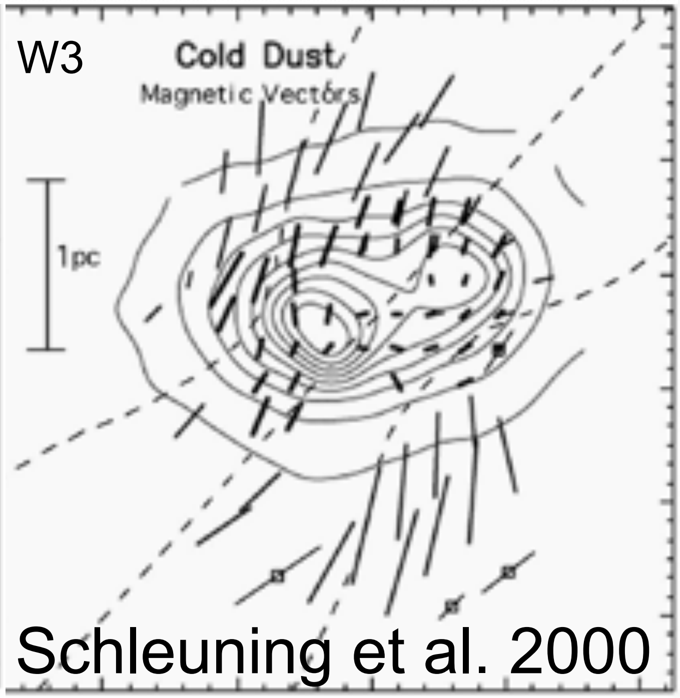




Kirby 2009

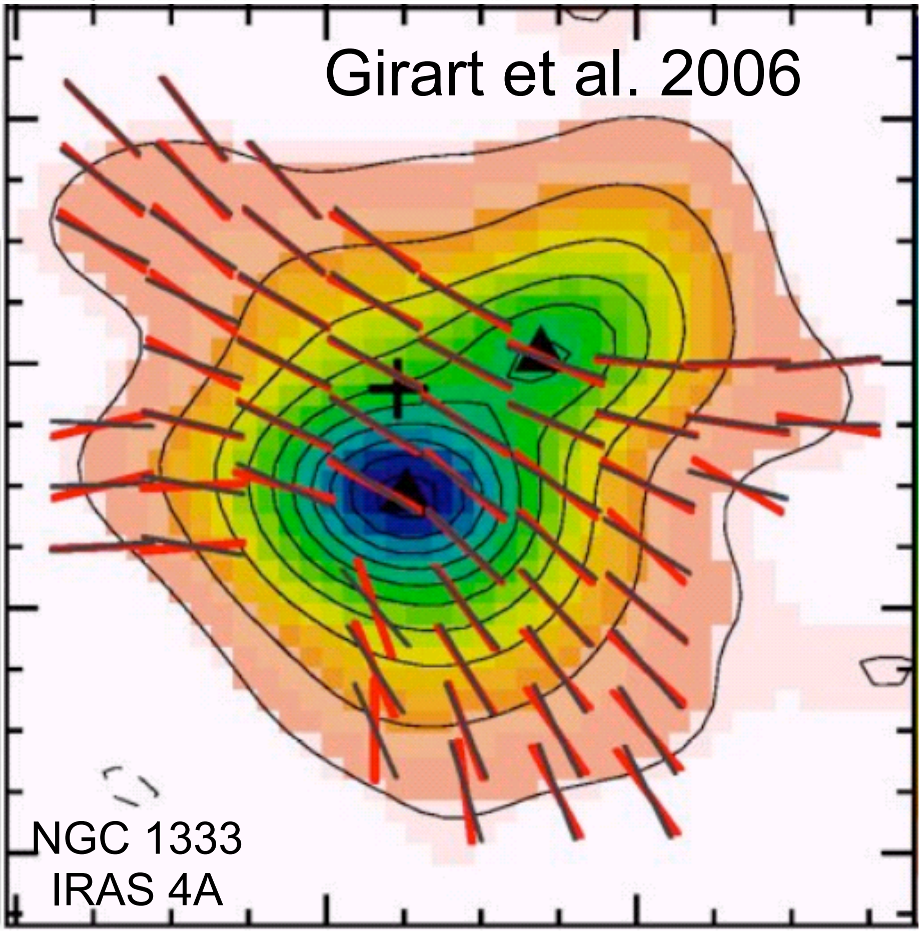
Vaillancourt et al. 2008





Schleuning et al. 2000

Girart et al. 2006



Protoplanetary Disks

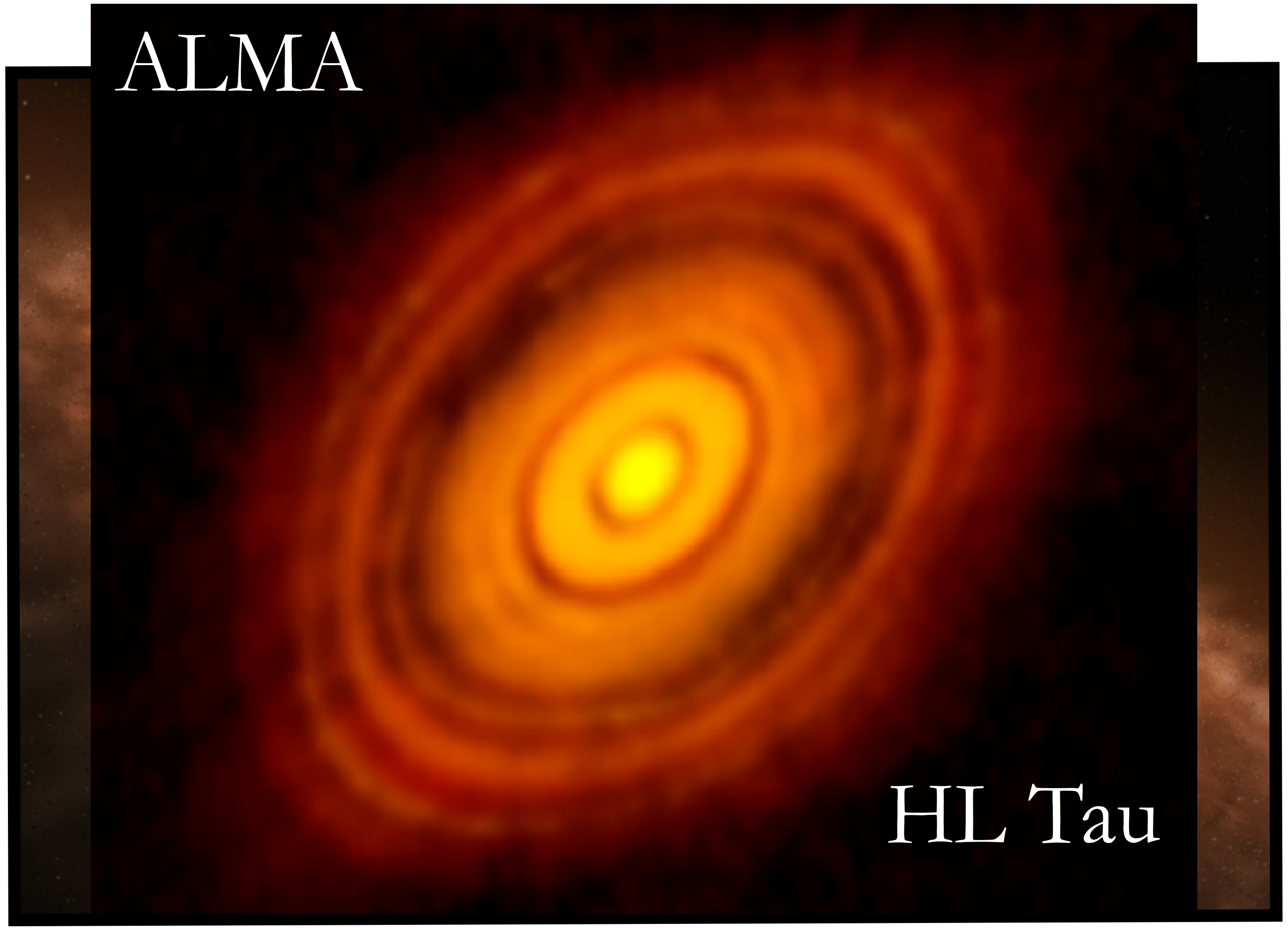
Keplerian disks of gas and dust, evolving on ~yr to ~Myr timescales

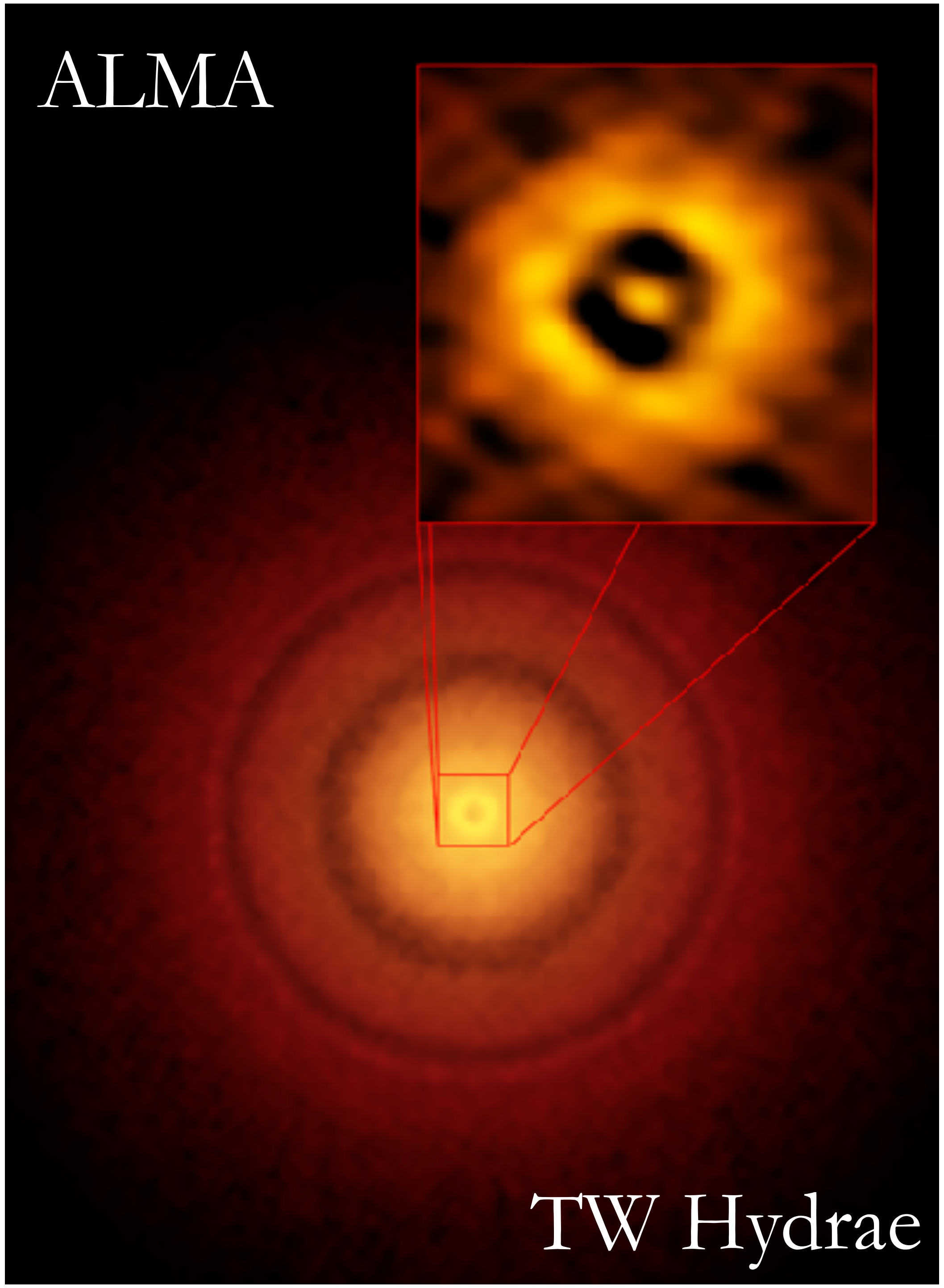
$$n_n \sim 10^{9-15}\ \mathrm{cm}^{-3}$$

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

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

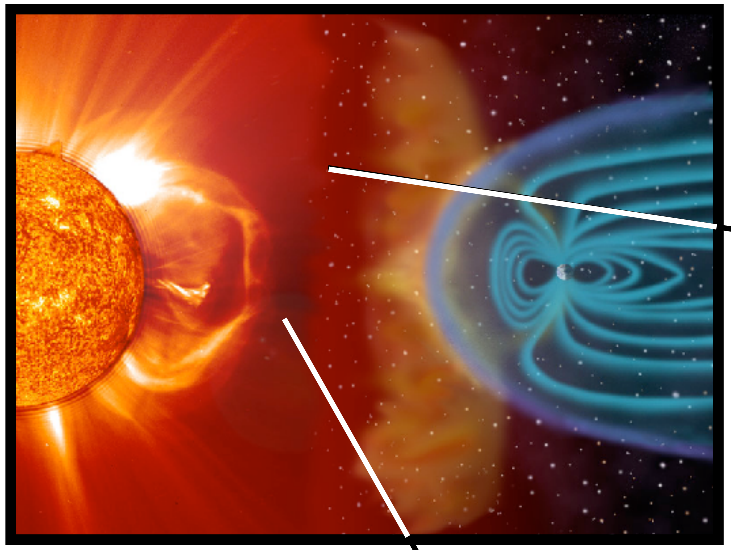
$$B \sim 0.01 - 1\ \mathrm{G}\ ??$$





Solar Wind

$$\dot{M} \sim 10^{-14}\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$$



at $r \sim 1$ au...

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

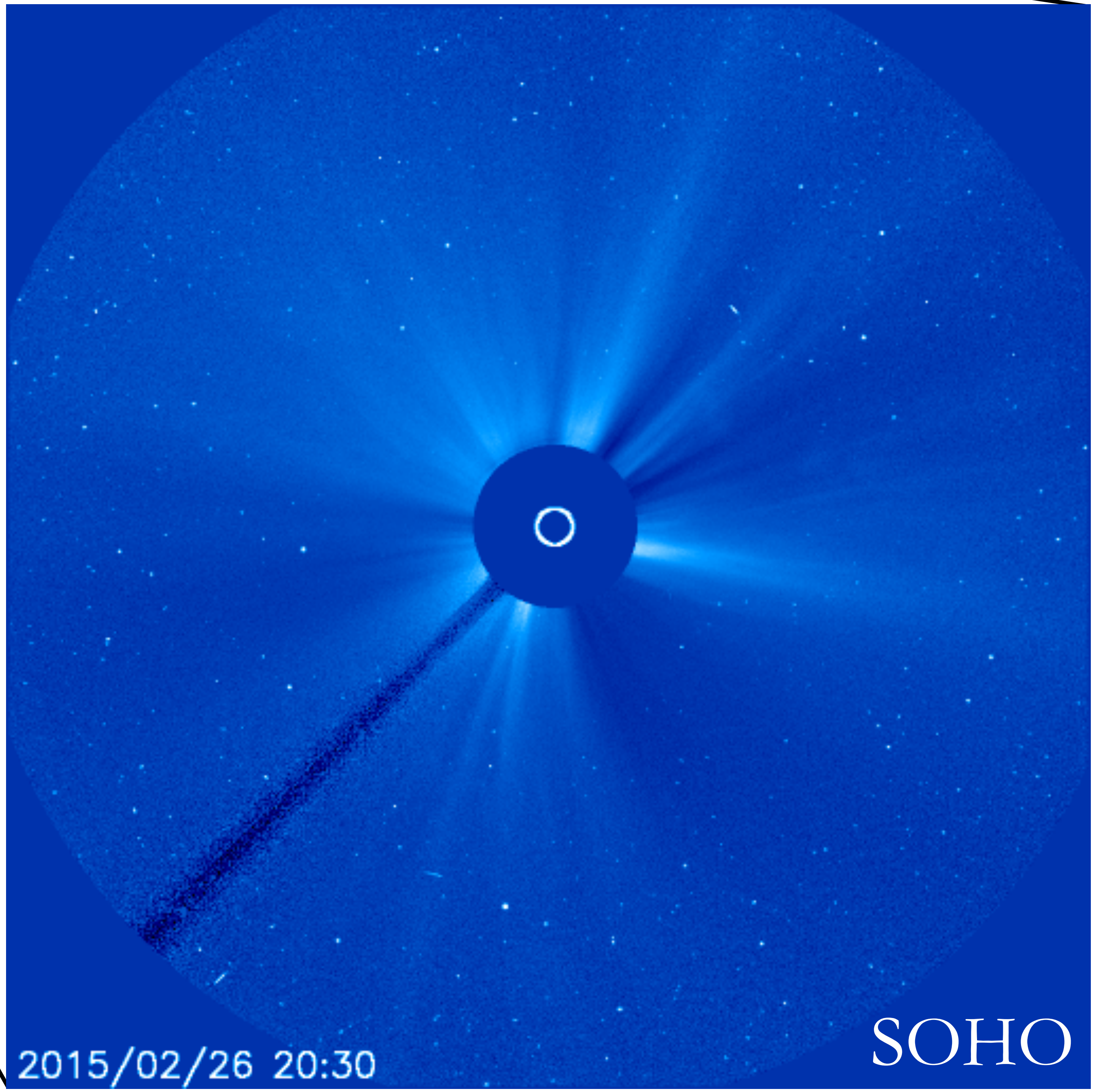
$k_B T \sim 10\ \mathrm{eV}$

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

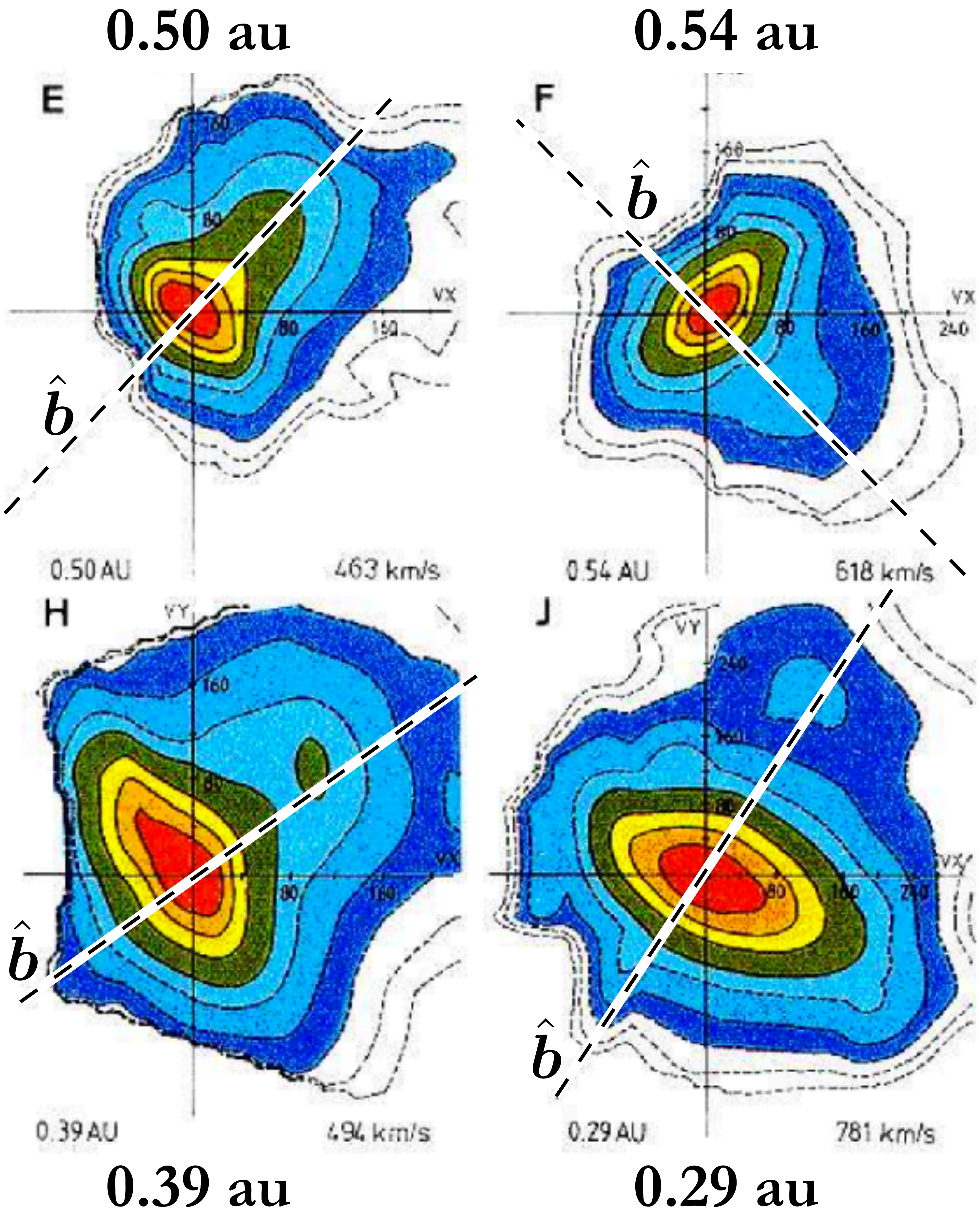
$\lambda_{\mathrm{mfp}} \sim 1\ \mathrm{au}$

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

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



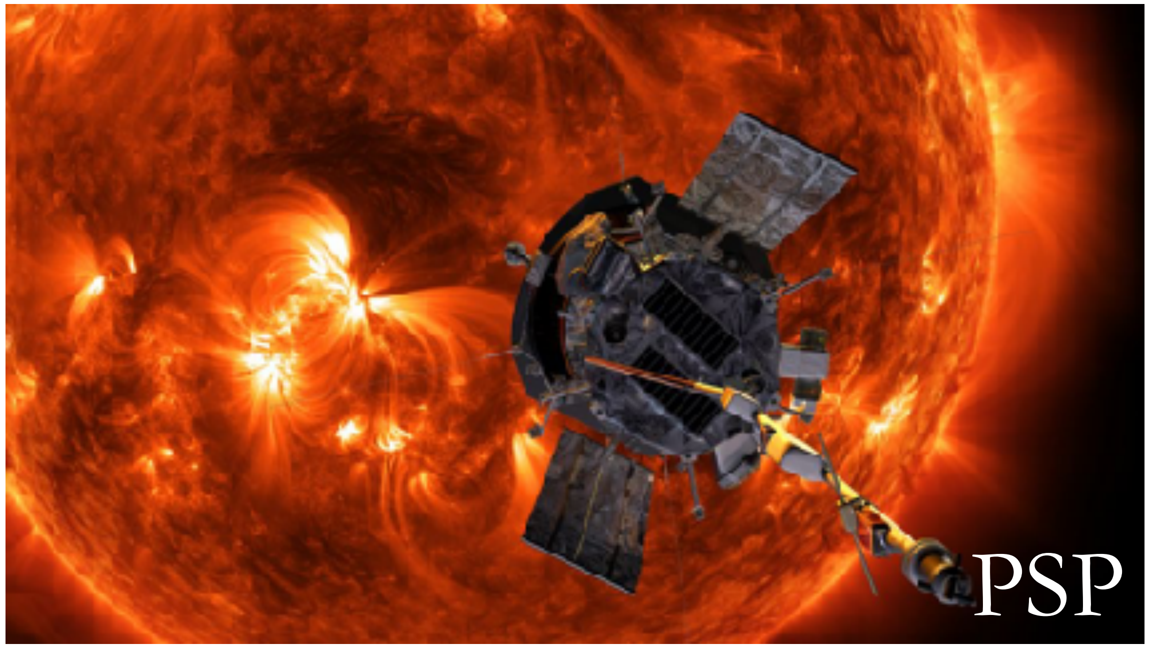
You can easily see departures isotropy of particle distribution in the collisionless solar wind.



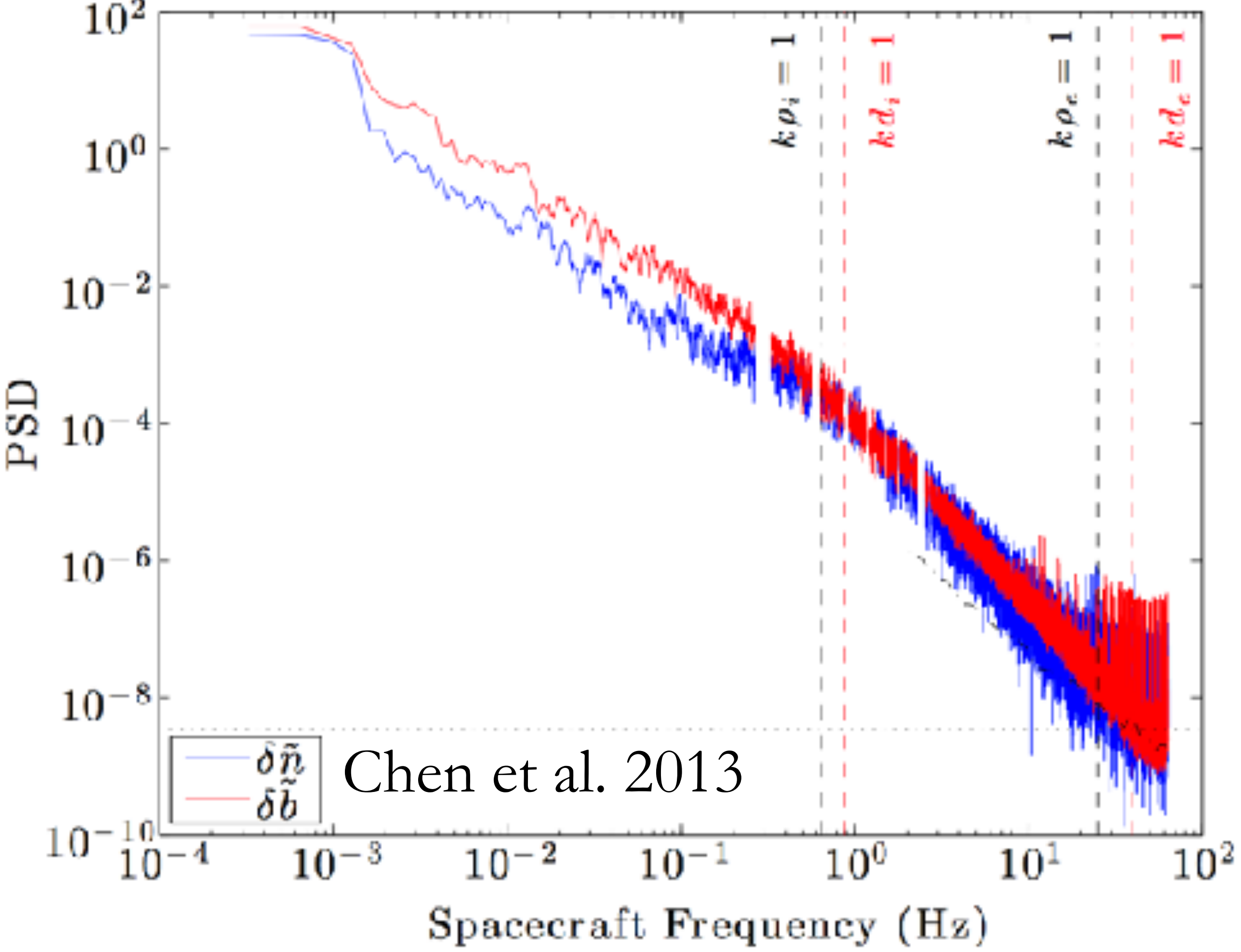
Marsch (2006)

many spacecraft measuring particle velocity distribution functions and electromagnetic fields in the solar wind (SW)…

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 (now at L1)
Parker Solar Probe: launched Aug 2018, has made two passes of Sun, will come within ~9 R☉ of solar surface (at 430,000 mph)



excellent laboratory for studying plasma kinetics and turbulence



Chen et al. 2013

Solar Corona

NASA's GSFC, SDO AIA Team

$$T \sim 100 - 250 \text{ eV } (\sim 1 - 3 \text{ MK})$$

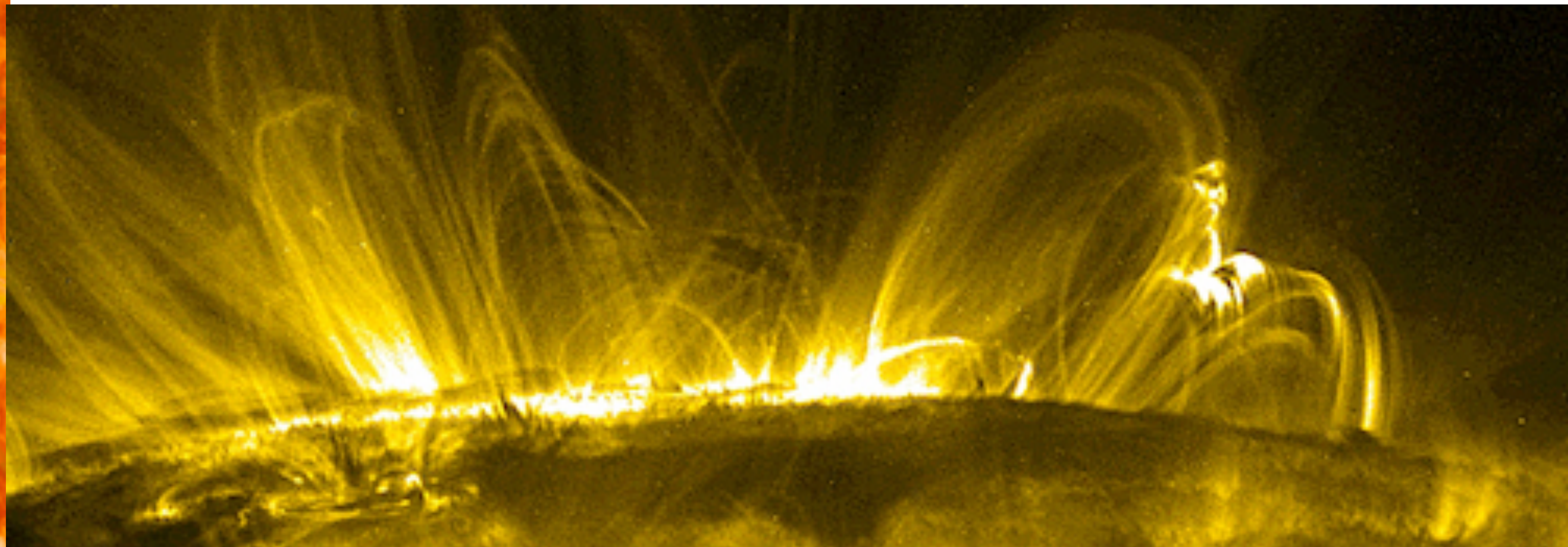
photosphere is ≈5800 K

$$n_{\mathrm{H}} \sim 10^{8-9} \text{ cm}^{-3}$$

($\sim 10^7$ times less dense than photosphere)

$$B \sim 1 - 10 \text{ G}$$

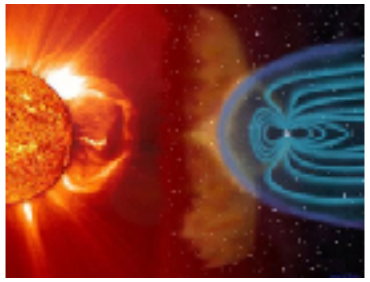
$$\beta \lesssim 0.01$$

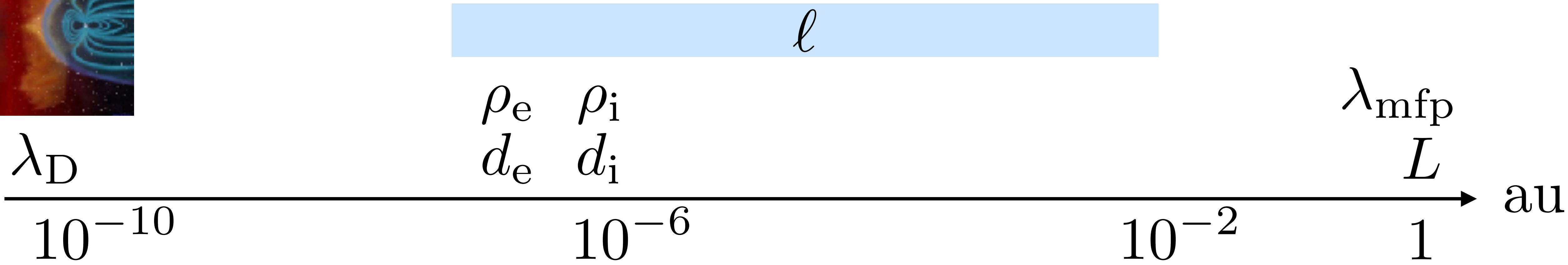


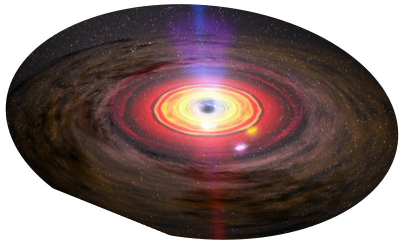
What were the common themes?

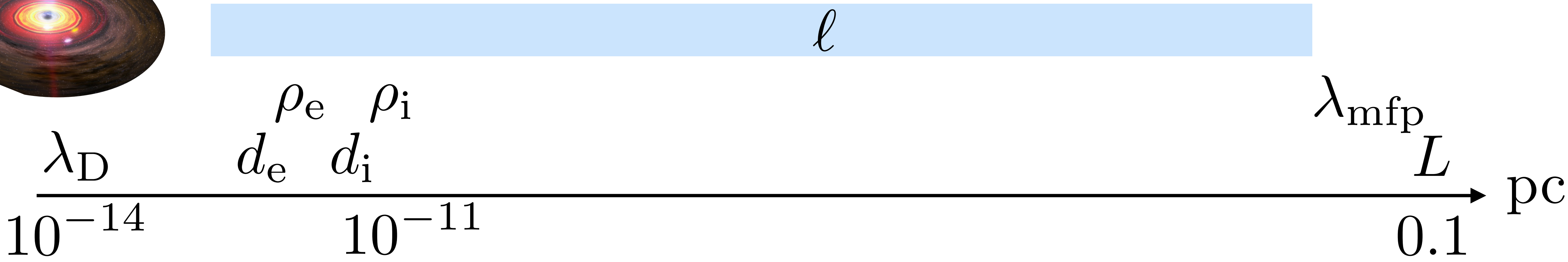
(other than plasma and magnetic fields)

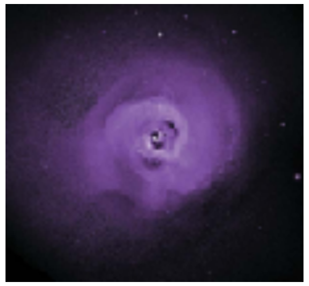
huge scale separations!

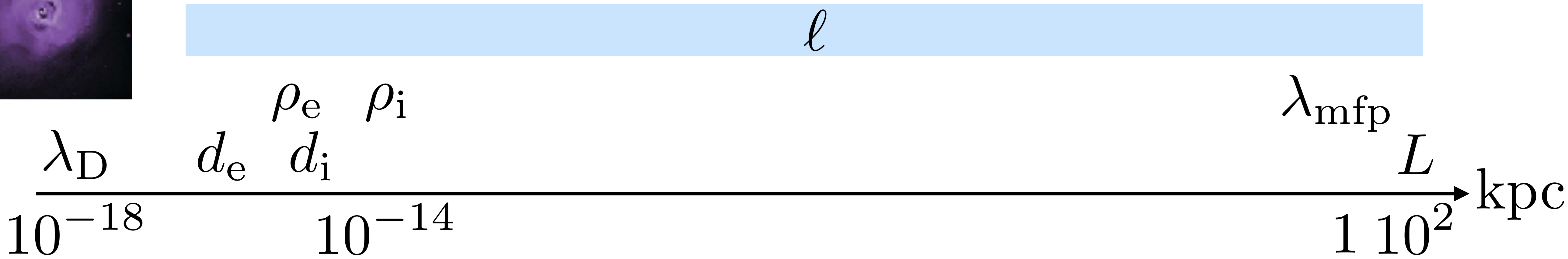



ℓ
ρ_e ρ_i
d_e d_i
λ_{mfp}
L
λ_D
au
10^{-10}
10^{-6}
10^{-2}
1




ℓ
ρ_e ρ_i
λ_{mfp}
λ_D
d_e d_i
L
pc
10^{-14}
10^{-11}
0.1




ℓ
ρ_e ρ_i
λ_{mfp}
λ_D
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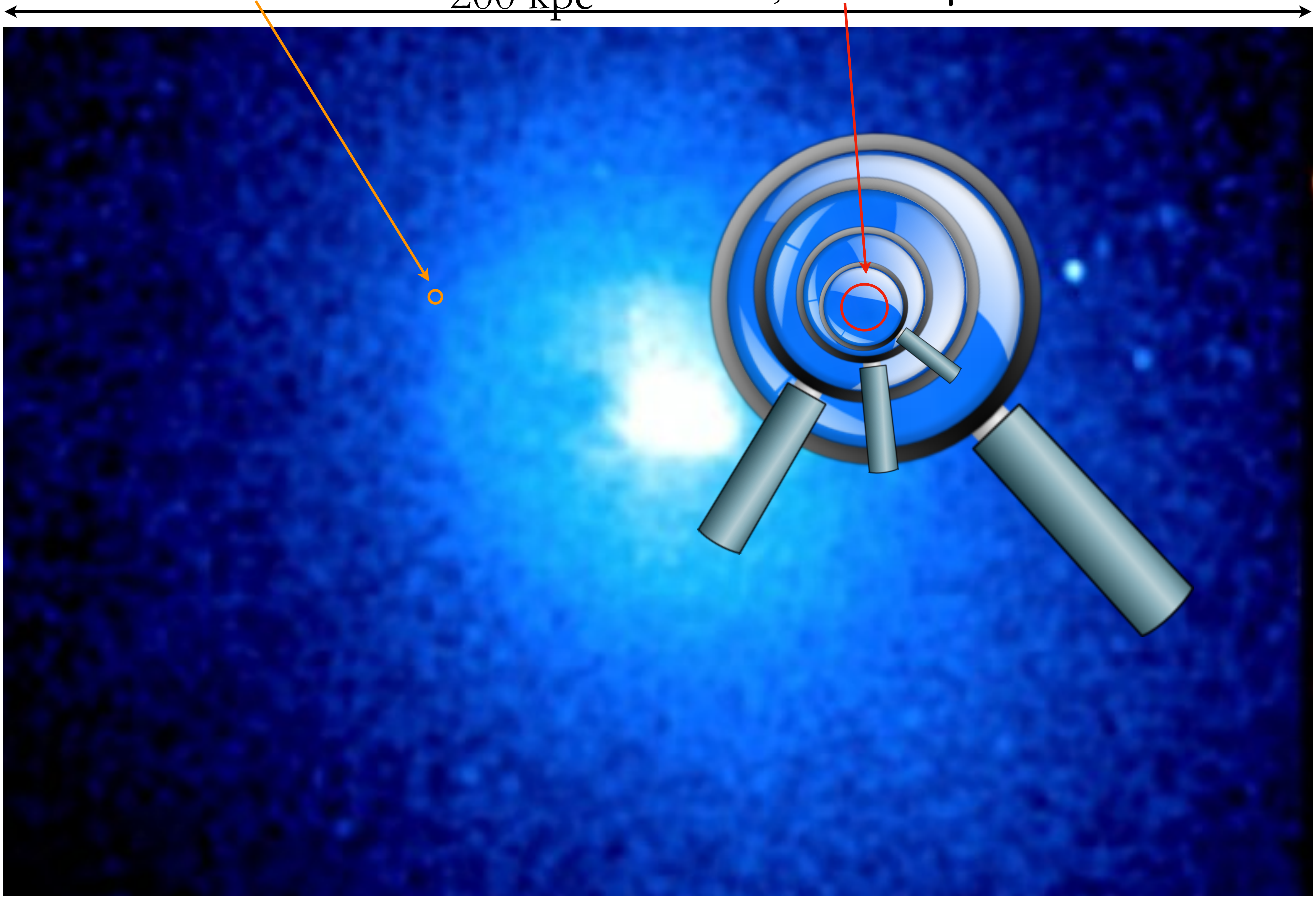
kpc
10^{-18}
10^{-14}
$1 \; 10^2$

(Some) Outstanding Questions in Plasma Astrophysics

1. Cosmic magnetogenesis and dynamo



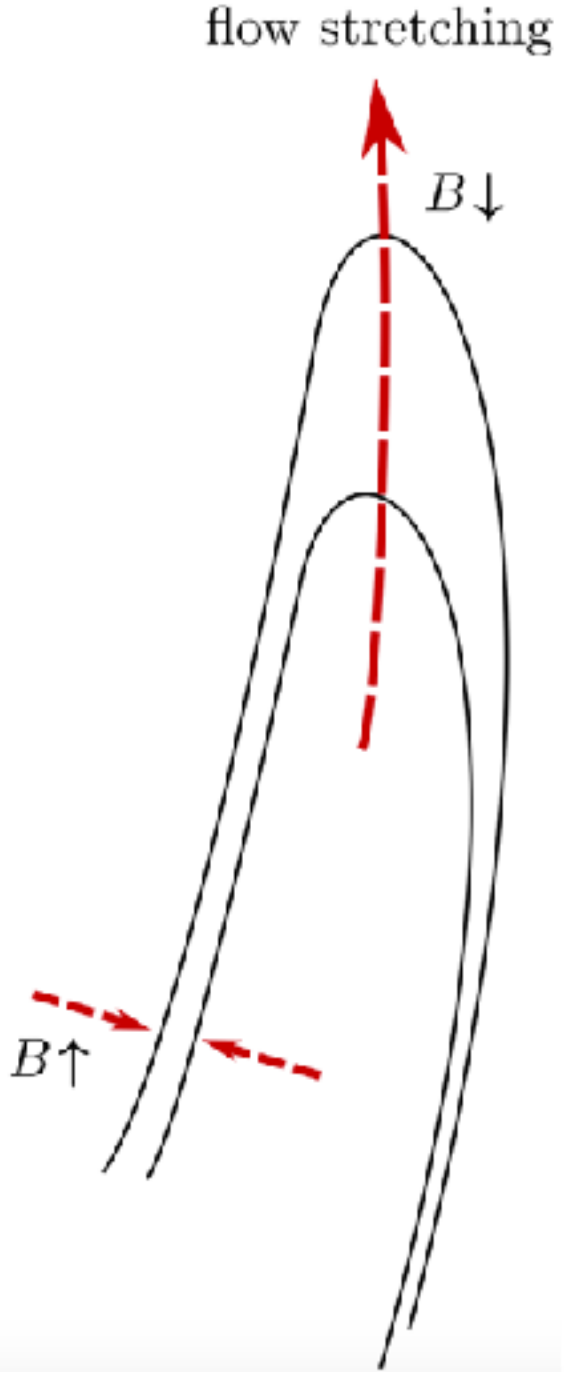
ion Larmor orbit
if $B \sim 10^{-18}$ G

200 kpc

ion Larmor orbit
now, with $B \sim \mu\mathrm{G}$

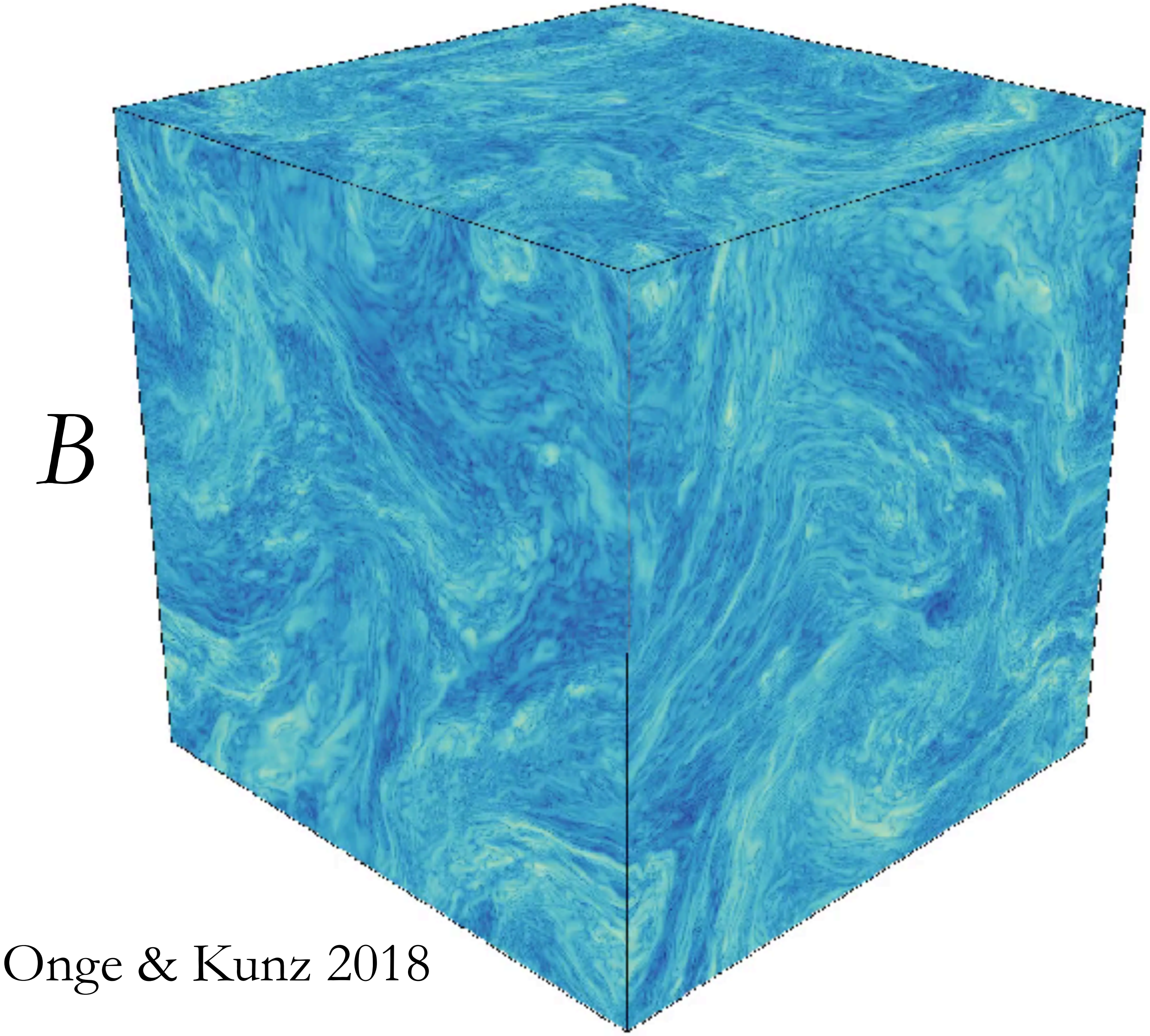
$v_{\mathrm{A}} \sim u_{\mathrm{rms}}$
~ 160 km s^{-1}

natural to attribute intracluster magnetic field to **fluctuation ("turbulent") dynamo** (Batchelor 1950; Zel'dovich et al. 1984; Childress & Gilbert 1995), whereby a succession of random velocity shears stretches the field and leads on the average to its growth to dynamical strengths.



Zel'dovich *et al.* 1986
Schekochihin *et al.* 2004

frontier: turbulent dynamo in collisionless plasma



St-Onge & Kunz 2018

(Some) Outstanding Questions in Plasma Astrophysics

1. Cosmic magnetogenesis and dynamo
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 ($n \sim 1\ \mathrm{cm}^{-3}$, $B \sim 1\ \mu\mathrm{G}$).

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

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

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

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

recognized early on (Babcock & Cowling 1953)
rigorously incorporated into theory of star formation (Mouschovias 1979+)

let's make the Sun…

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

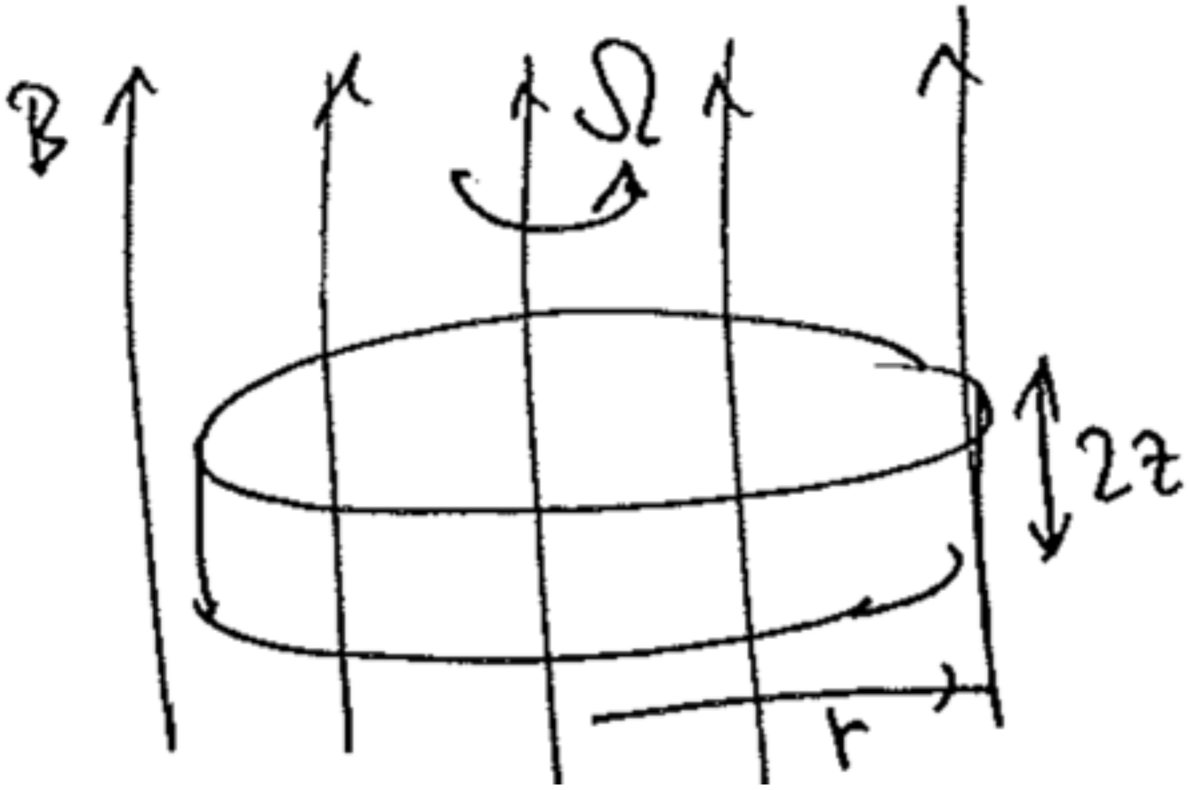
Conserve angular momentum during contraction:

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

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

(see Mouschovias 1991a)

Magnetic Braking (see Mouschovias & Paleologou 1979, 1980)



$$M = \rho_{\rm disk} \times \pi R^2 \times 2Z$$

$$\Phi_B = B \times \pi R^2$$

$$I_{\rm disk} = \frac{1}{2} M R^2 = \rho_{\rm disk} \pi R^4 Z$$

$$I_{\rm ext} = \rho_{\rm ext} \pi R^4 \times v_{\rm A,ext} \tau_{\rm b}$$

$$\frac{I_{\rm disk}}{I_{\rm ext}} = \frac{\rho_{\rm disk}}{\rho_{\rm ext}} \frac{Z}{v_{\rm A,ext} \tau_{\rm b}} \quad \Longrightarrow \quad \tau_{\rm b} = \left(\frac{\pi}{\rho_{\rm ext}}\right)^{1/2} \frac{M}{\Phi_{\rm B}}$$

matches results from exact time-dependent MHD solution

(Some) Outstanding Questions in Plasma Astrophysics

1. Cosmic magnetogenesis and dynamo
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 (GR, RT, kinetics,…) (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 (sunspots; 1645-1715)
8. Supernovae (~10^{51} erg KE) and gamma-ray bursts (~10^{51} erg ~10^{44} J beamed)
9. Cosmic-ray spectrum and non-thermal particle acceleration (up to ~10^{20} eV!)
10. Magnetospheres of compact objects (e.g., pulsars, black holes)
11. Jet/outflow launching and collimation (wide variety…)
12. Magnetic reconnection in realistic environments (rate, onset, particle acceleration, cross-scale coupling, relativistic effects…)