

Introduction to
Astrophysical
Plasmas

What are astrophysical plasmas?

- Thermal ions and electrons (and neutrals):
 - may be fully ionized, e.g., EUV-photoionized or collisionally ionized if warm/hot; mostly H
 - may be poorly ionized with trace ions/electrons, e.g., FUV-irradiated or cosmic-ray irradiated; mostly H₂ and CO, HCO⁺, Na⁺, Mg⁺, K⁺...
- Nonthermal ions and electrons (cosmic rays)
 - various acceleration mechanisms
 - can coexist with thermal plasma
- Dust grains (charged and neutral)
 - carbonaceous and silicate material, water-ice mantle

What are astrophysical plasmas?

- Electromagnetic fields

Motion of charged particles creates E&M fields, E&M fields drive charged-particle motion, collisions inform neutrals of E&M fields

- Differences from laboratory plasmas:

- large-scale gradients and/or flows; lower densities

- ($n \sim 10^{-3} \text{ cm}^{-3}$ in a $\sim \text{Mpc}$ ICM or $n \sim 1 \text{ cm}^{-3}$ in the $\sim \text{kpc}$ ISM versus $n \sim 10^{14} \text{ cm}^{-3}$ in a $\sim 1 \text{ m}$ fusion device)

- ionization fraction can be very low (but still behaves like a plasma)

- typically no physical boundaries

- gravity can be important! (main confinement mechanism)

- other physics (chemistry, radiation, relativity...) can also be important

A warning on units...

meters, Joules, Newtons, Teslas, etc. are generally not used by astrophysicists and plasma astrophysicists (though are by laboratory and fusion plasma physicists)

Note: $1 \text{ eV} \approx 10^4 \text{ K}$ $1 \text{ km s}^{-1} \approx 1 \text{ pc Myr}^{-1}$
 $1 \text{ yr} \approx \pi \times 10^7 \text{ s}$ $1 \text{ Tesla} = 10^4 \text{ G}$

$$\beta \equiv \frac{\text{gas pressure}}{\text{magnetic pressure}} = \frac{8\pi P}{B^2}$$

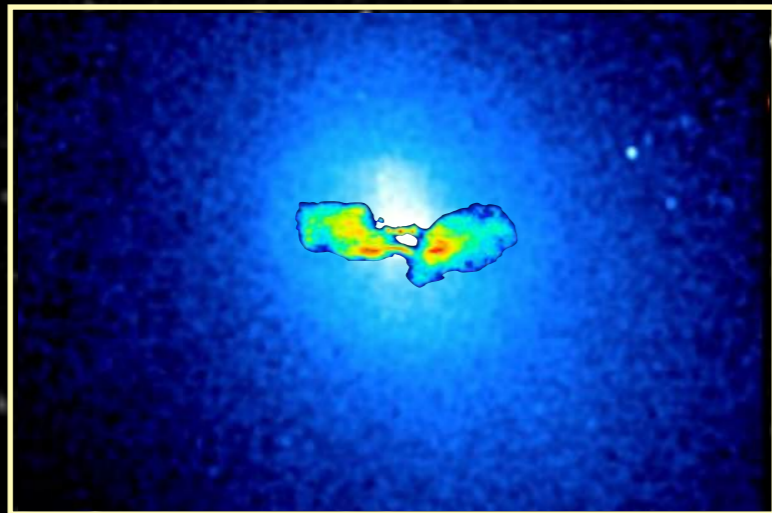
now for some astrophysical examples,
with a focus on the plasma properties

start big and work our way down

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

Abell 2199

~ 200 kpc



~ 500 kpc

Clusters of Galaxies

$\sim 10^{2-3}$ galaxies

$M \sim 10^{14-15} M_{\odot}$
in ~ 1 Mpc

$\sim 84\%$ dark matter

14% thermal plasma

$T \sim 1-10$ keV

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

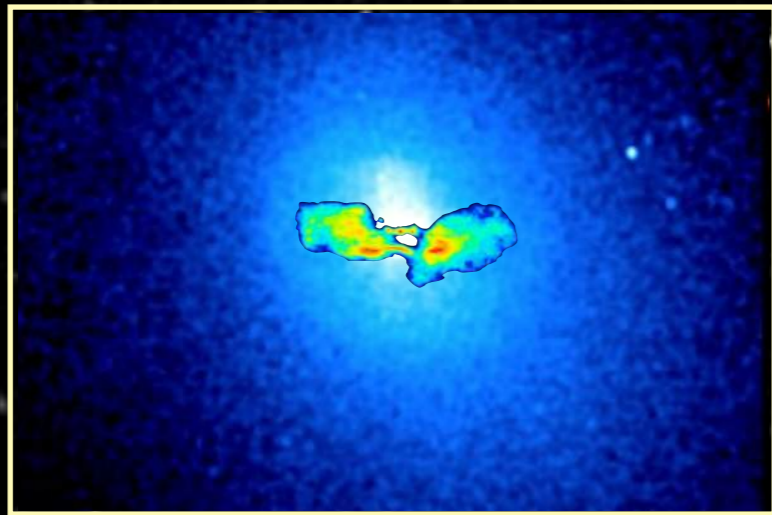
$n \sim 10^{-4}-10^{-1} \text{ cm}^{-3}$

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

radio (BH &
relativistic plasma)

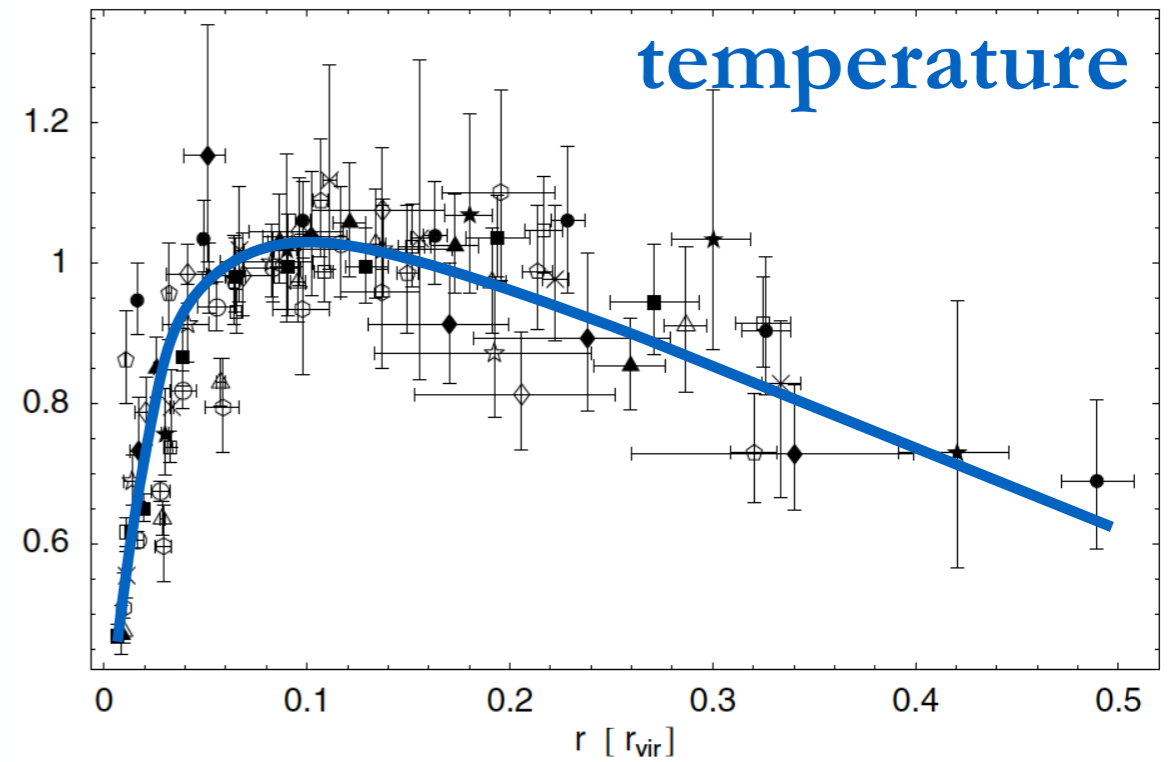
Abell 2199

~200 kpc



~500 kpc

Intracluster Medium



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

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

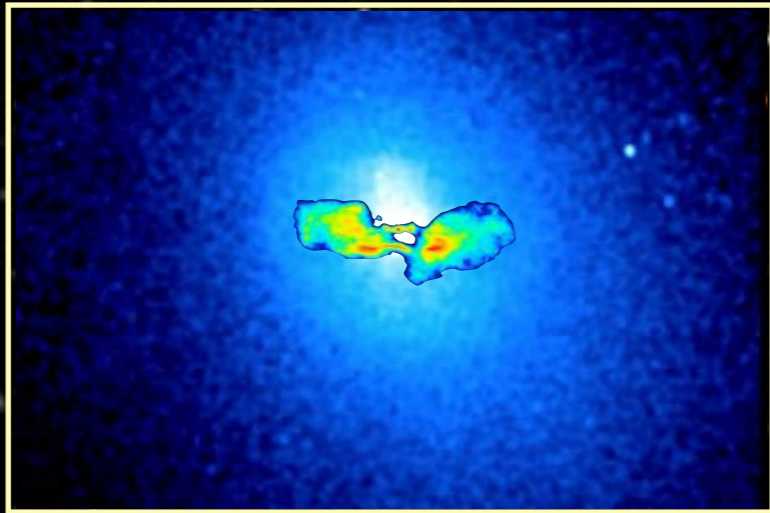
$$t_{\text{ii,coll}} \sim 1 - 10 \text{ Myr}$$

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

(ion Larmor orbit \sim size of Jupiter)

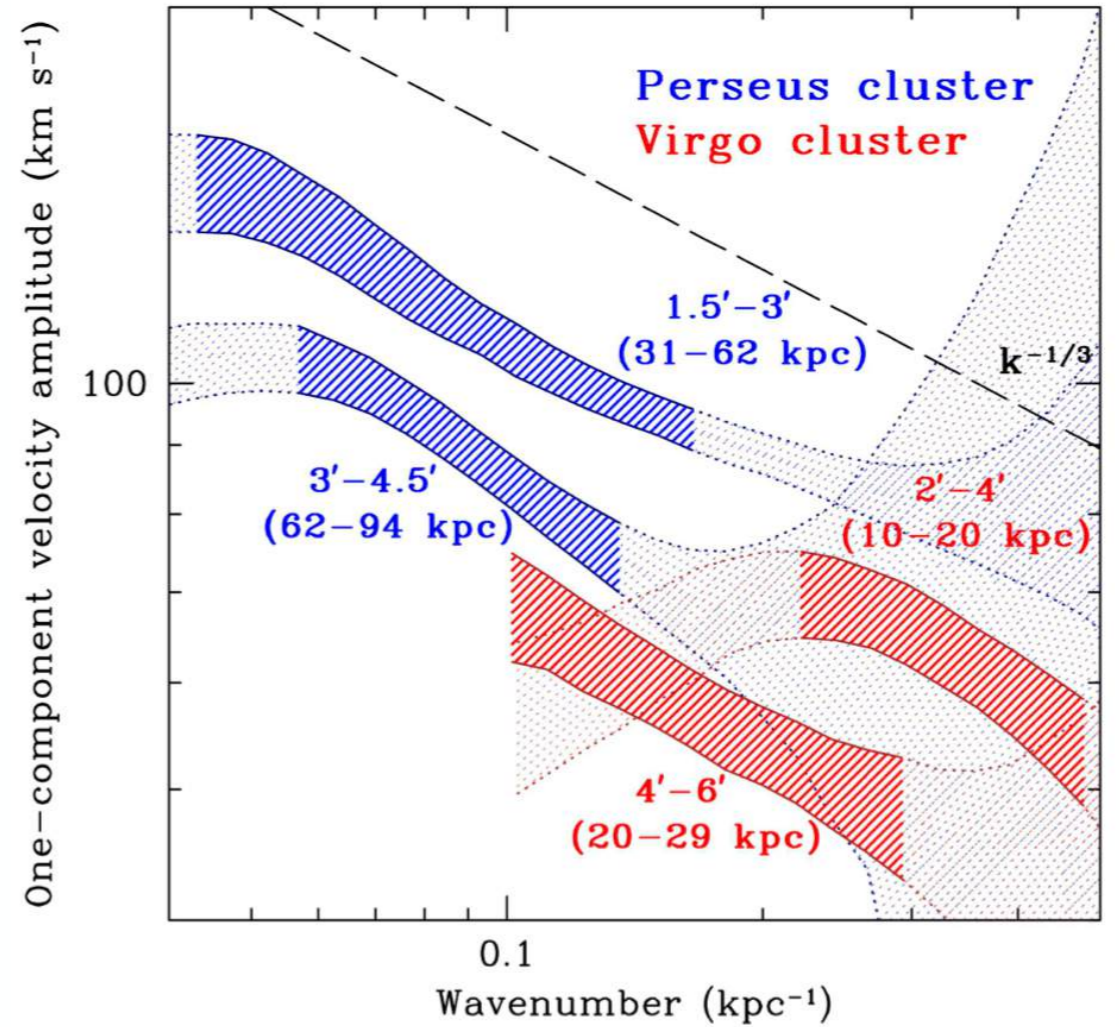
Abell 2199

~200 kpc



~500 kpc

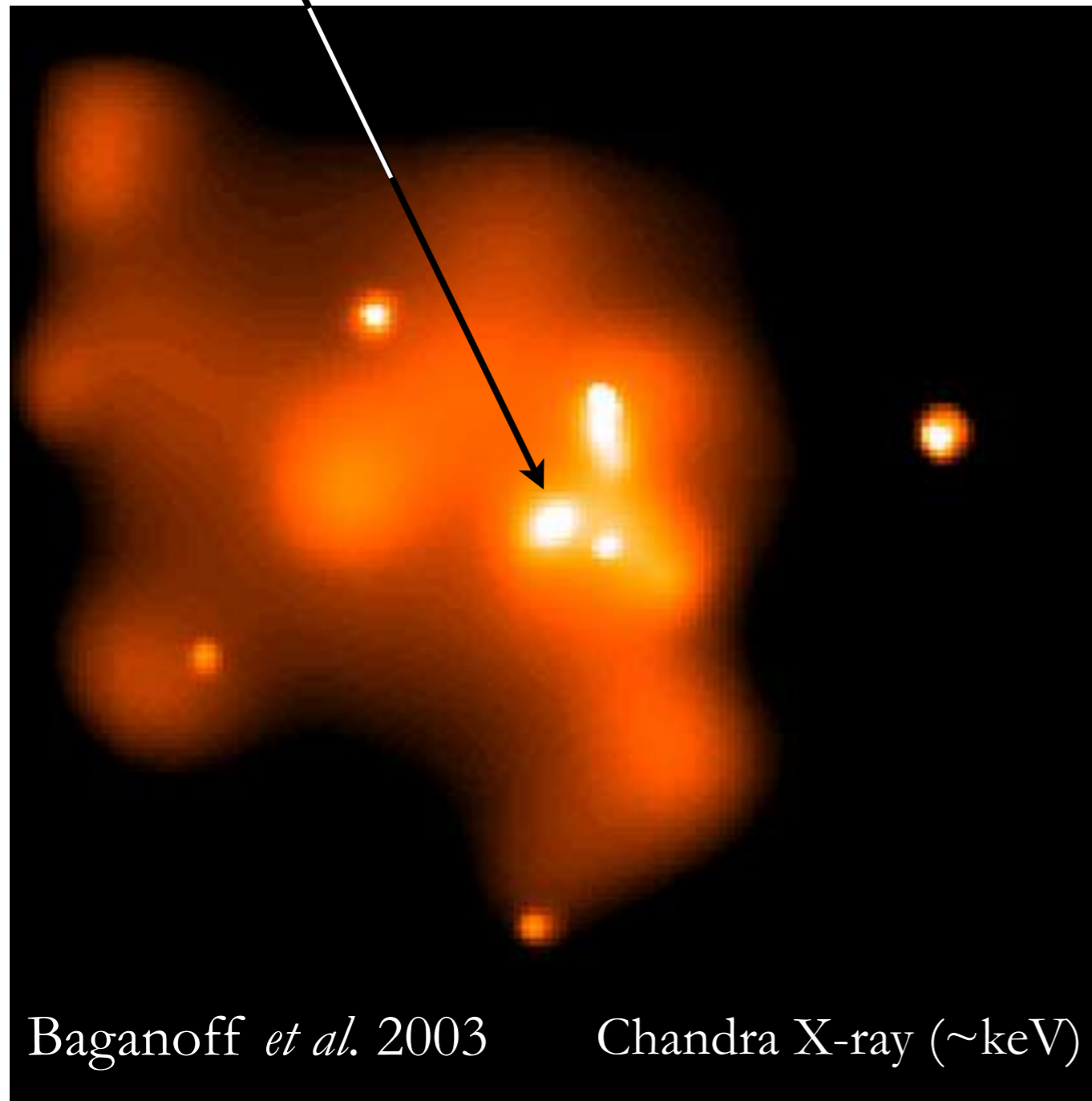
Intracluster Medium



Zhuravleva *et al.* 2014, Nature

subsonic, trans-Alfvénic
turbulence measured:
 $u \approx 100 - 300 \text{ km s}^{-1}$

$4 \times 10^6 M_{\odot}$ BH



← ~10 light-years →

Galactic Center

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

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

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

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

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

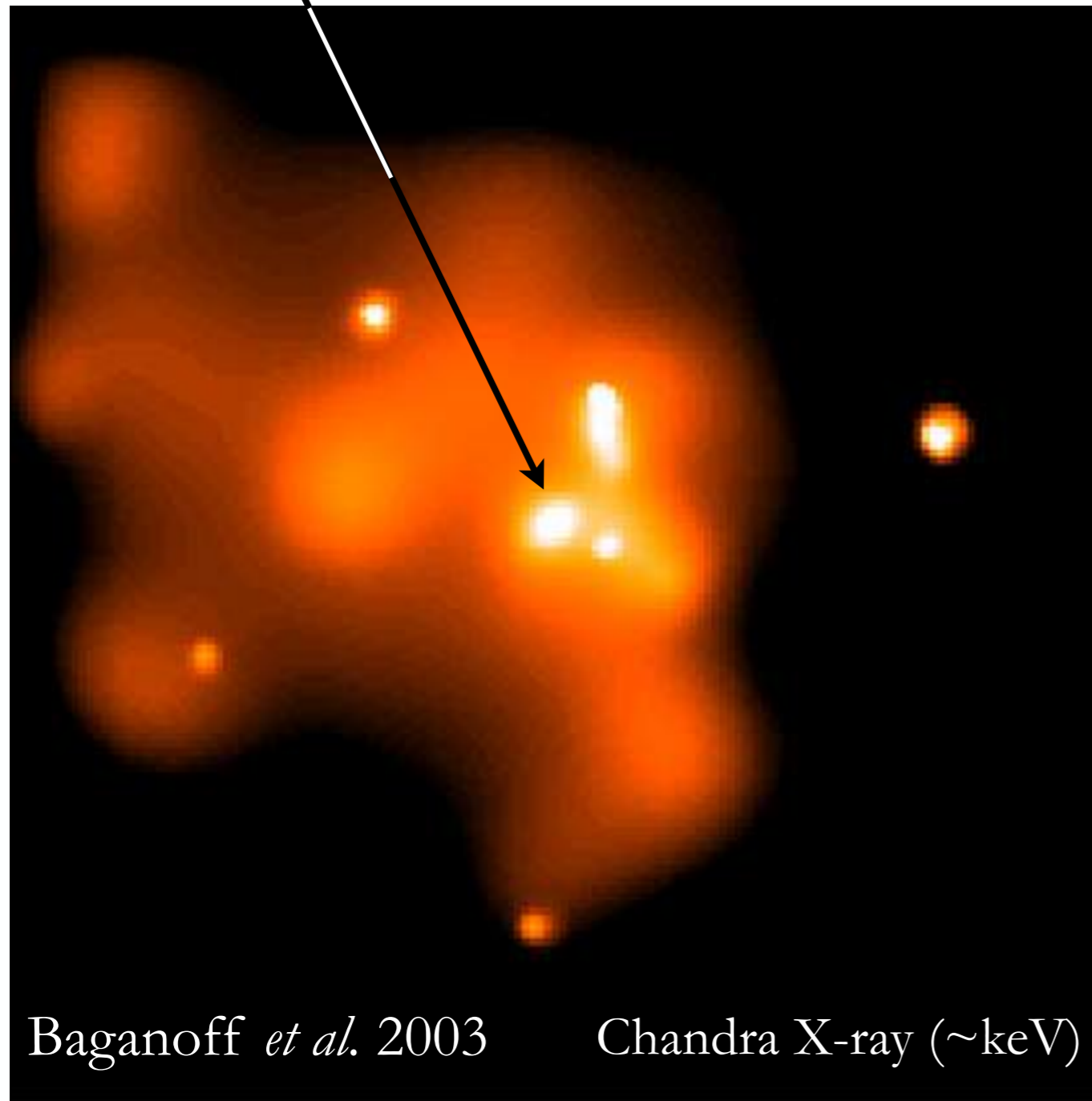
$$t_{\text{dyn}} \lesssim 200 \text{ yr}$$

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

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

(can drive ion Larmor orbit in ~2 hrs)

$4 \times 10^6 M_{\odot}$ BH

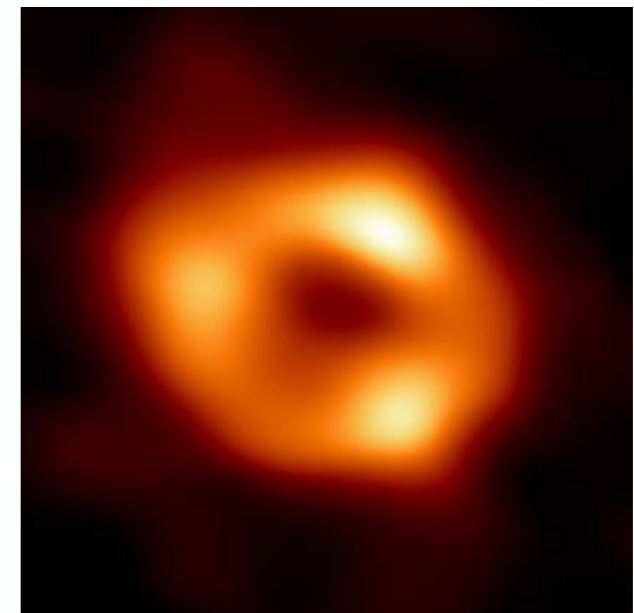


~ 10 light-years

Galactic Center

get within 10 Schwarzschild radii:

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



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

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

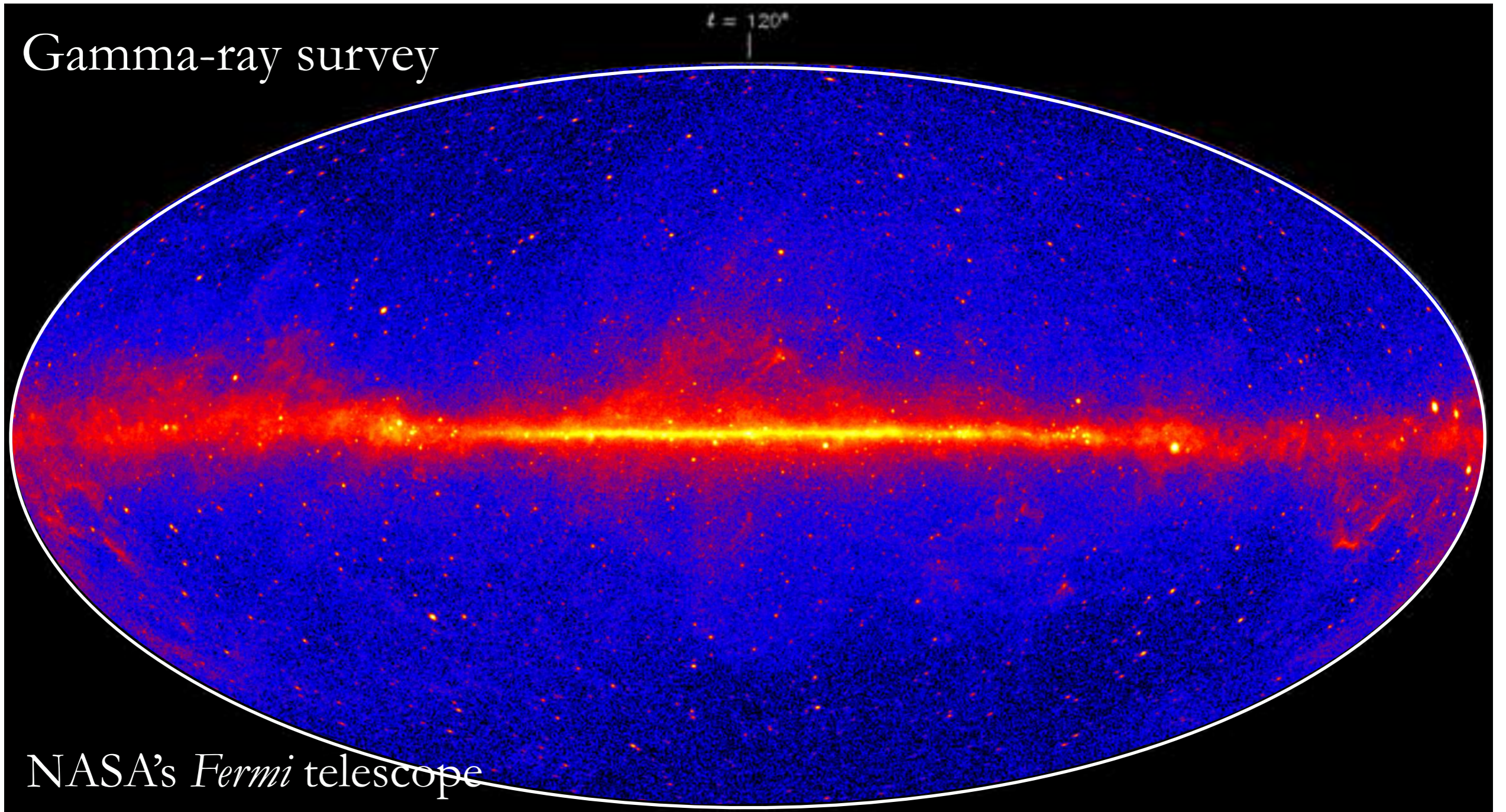
$$t_{\text{gyr,i}} \sim 100 \mu\text{s}$$

fun facts: Schwz. radius of Sun ~ 3 km
Schwz. radius of GC ~ 0.1 au

Interstellar Medium

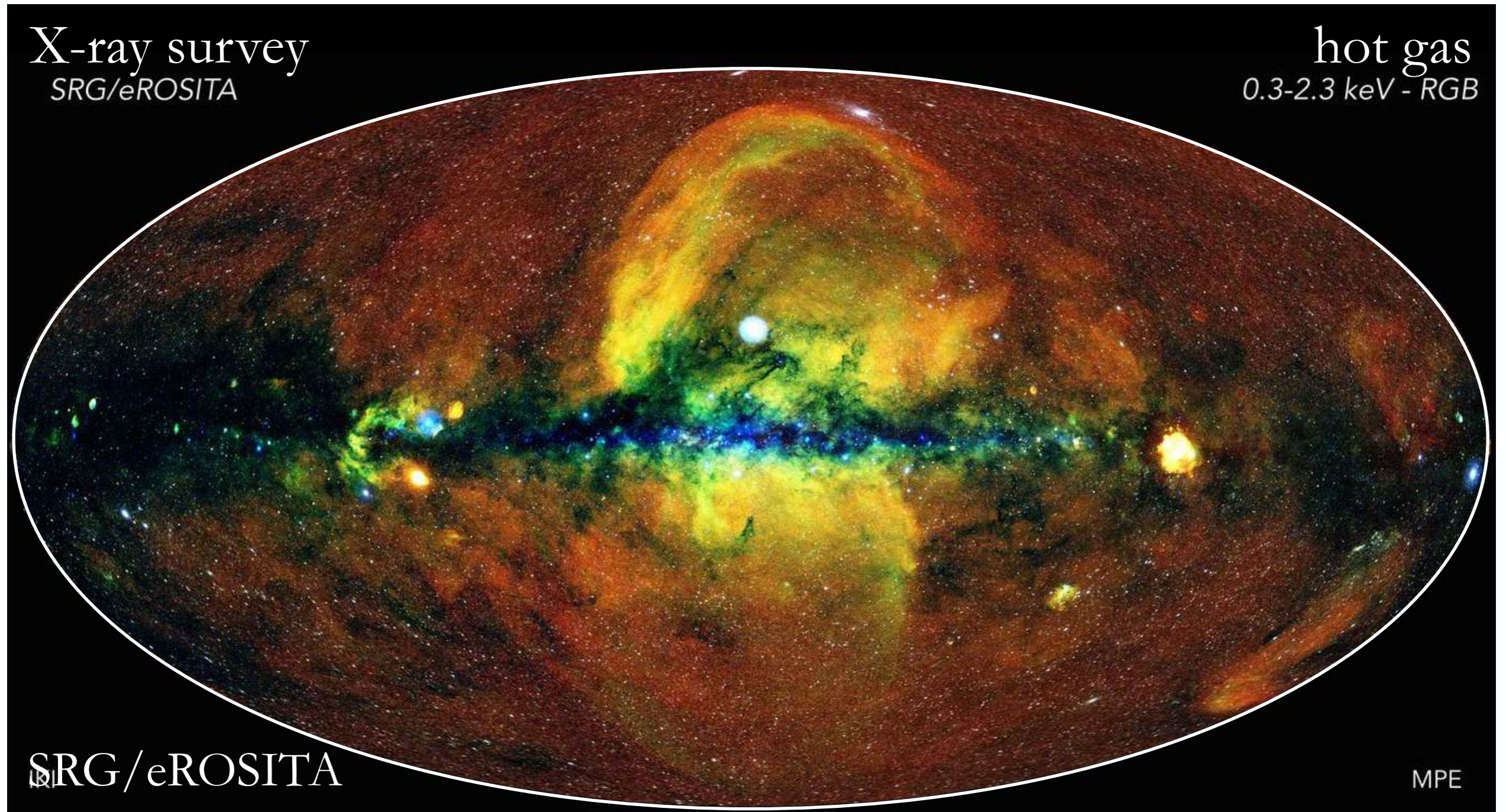
Gamma-ray survey

$l = 120^\circ$



NASA's *Fermi* telescope

Interstellar Medium

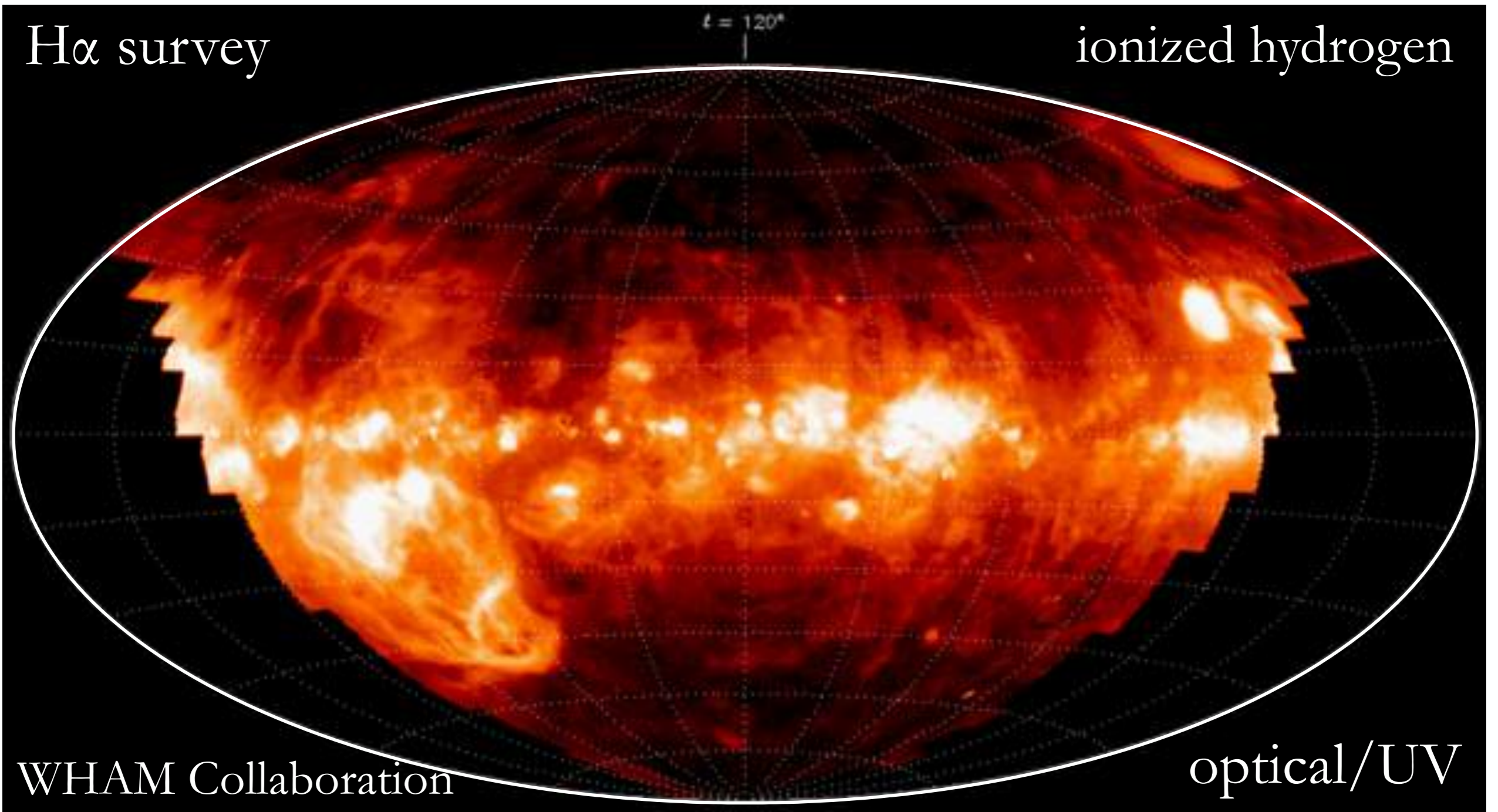


gas is 99% of ISM mass; $\sim 74\%$ H, 24% He, 2% “metals” (C, O, N...)

Interstellar Medium

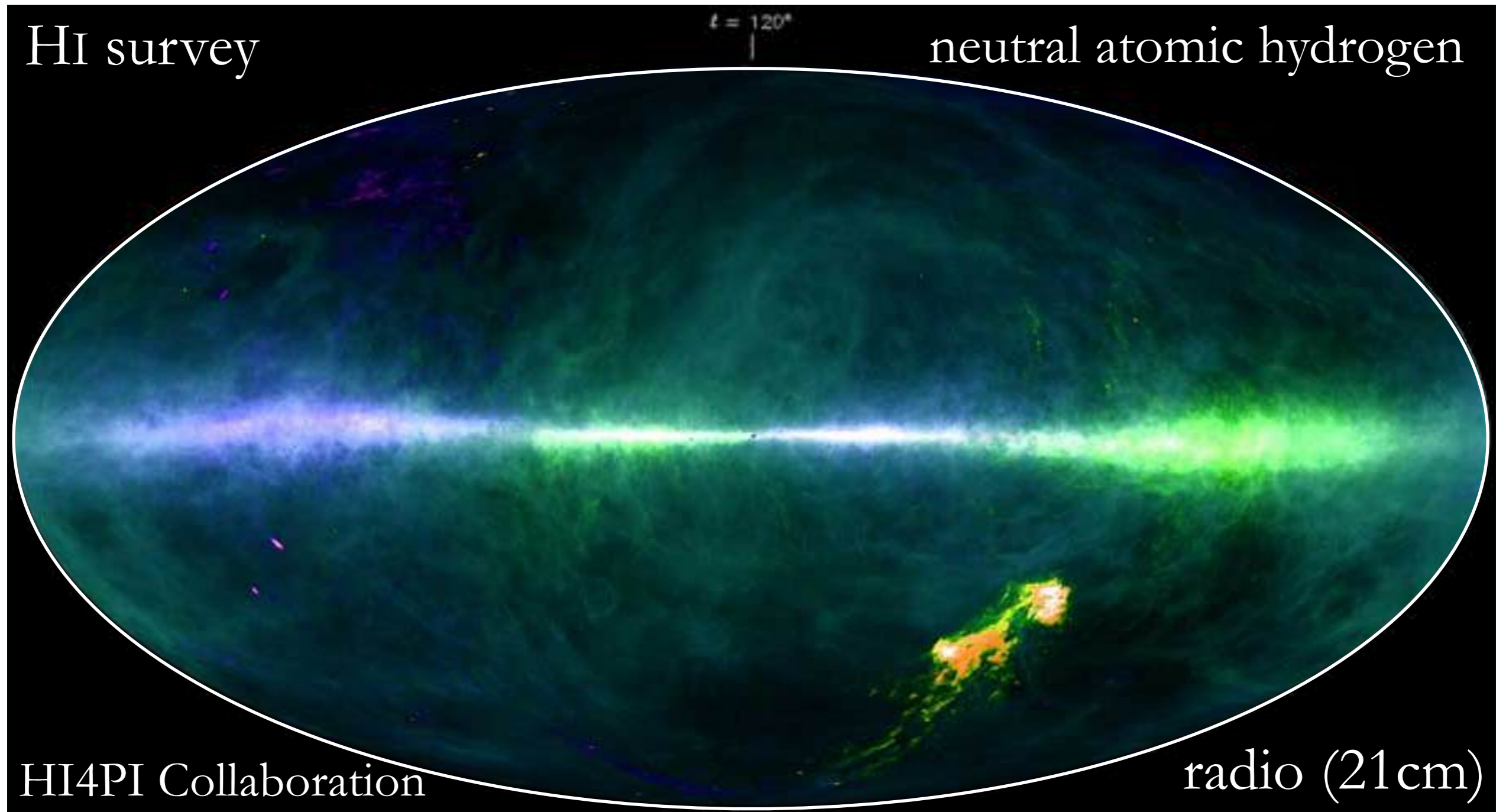
H α survey

ionized hydrogen



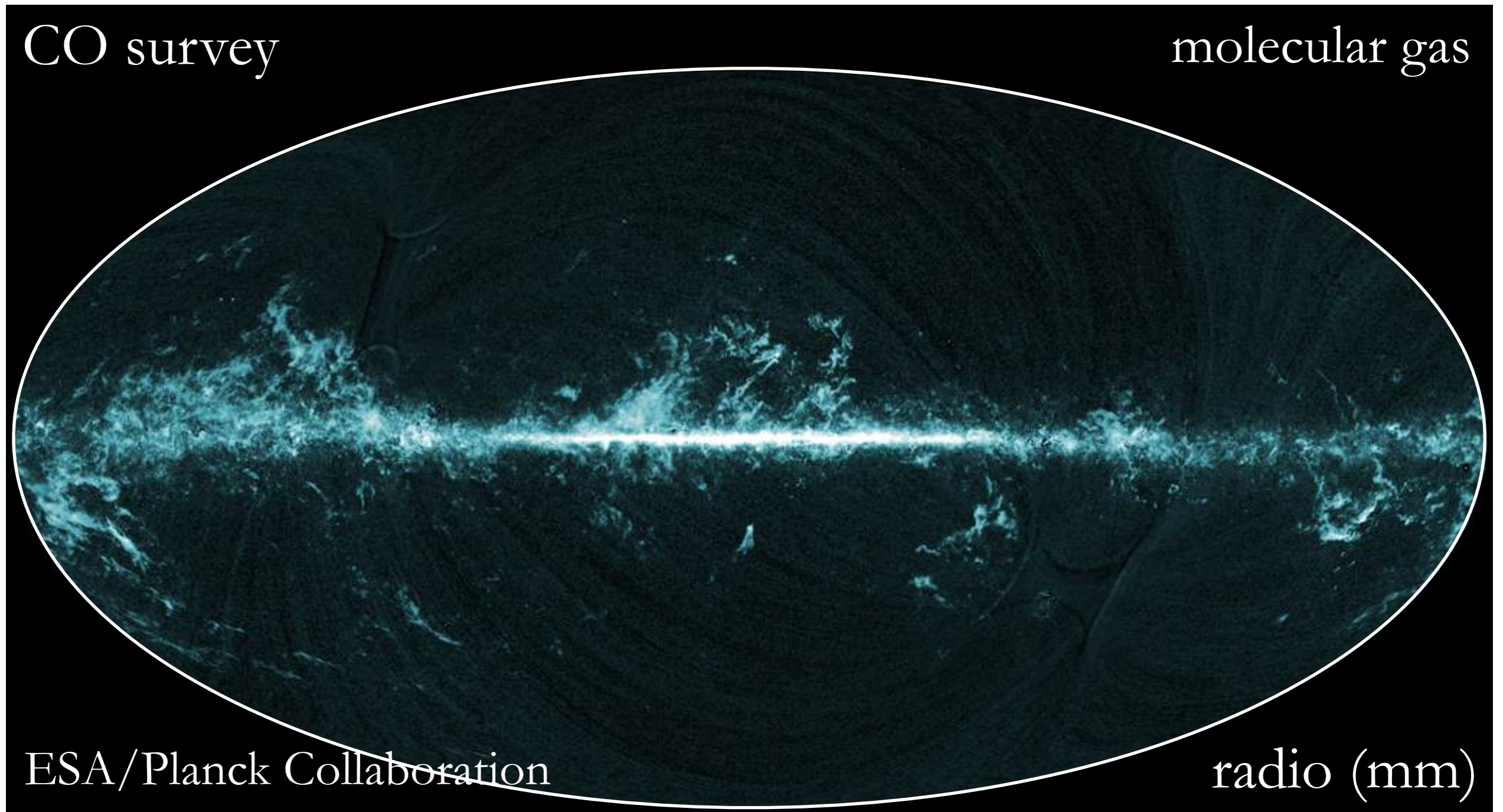
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Interstellar Medium



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Interstellar Medium

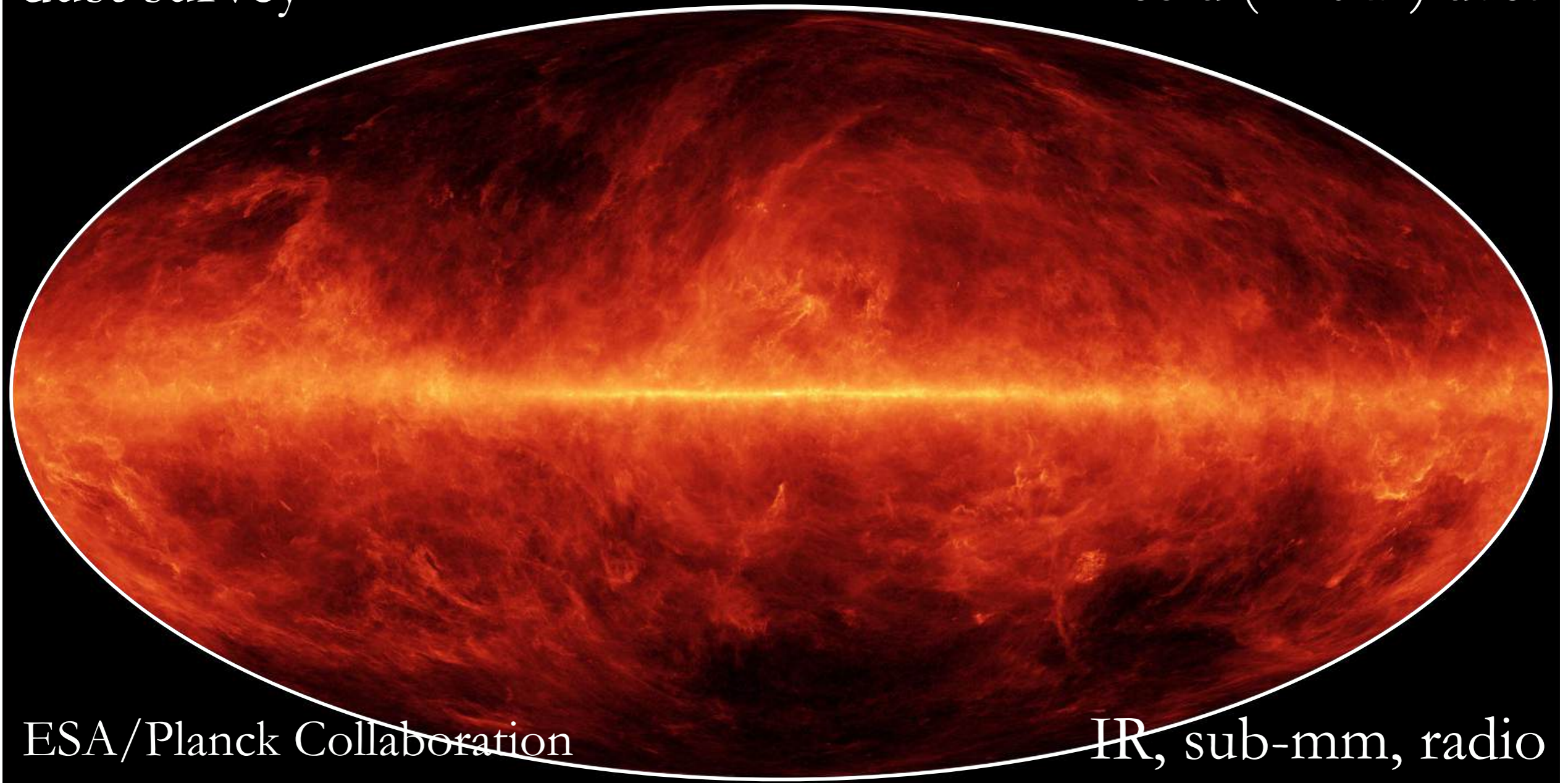


molecules: H_2 , CO , HCO^+ , HCN , CS , SO , N_2H^+ , CH_4 , OH , NH_3 , H_2O , CN ...

Interstellar Medium

dust survey

cold (~ 20 K) dust



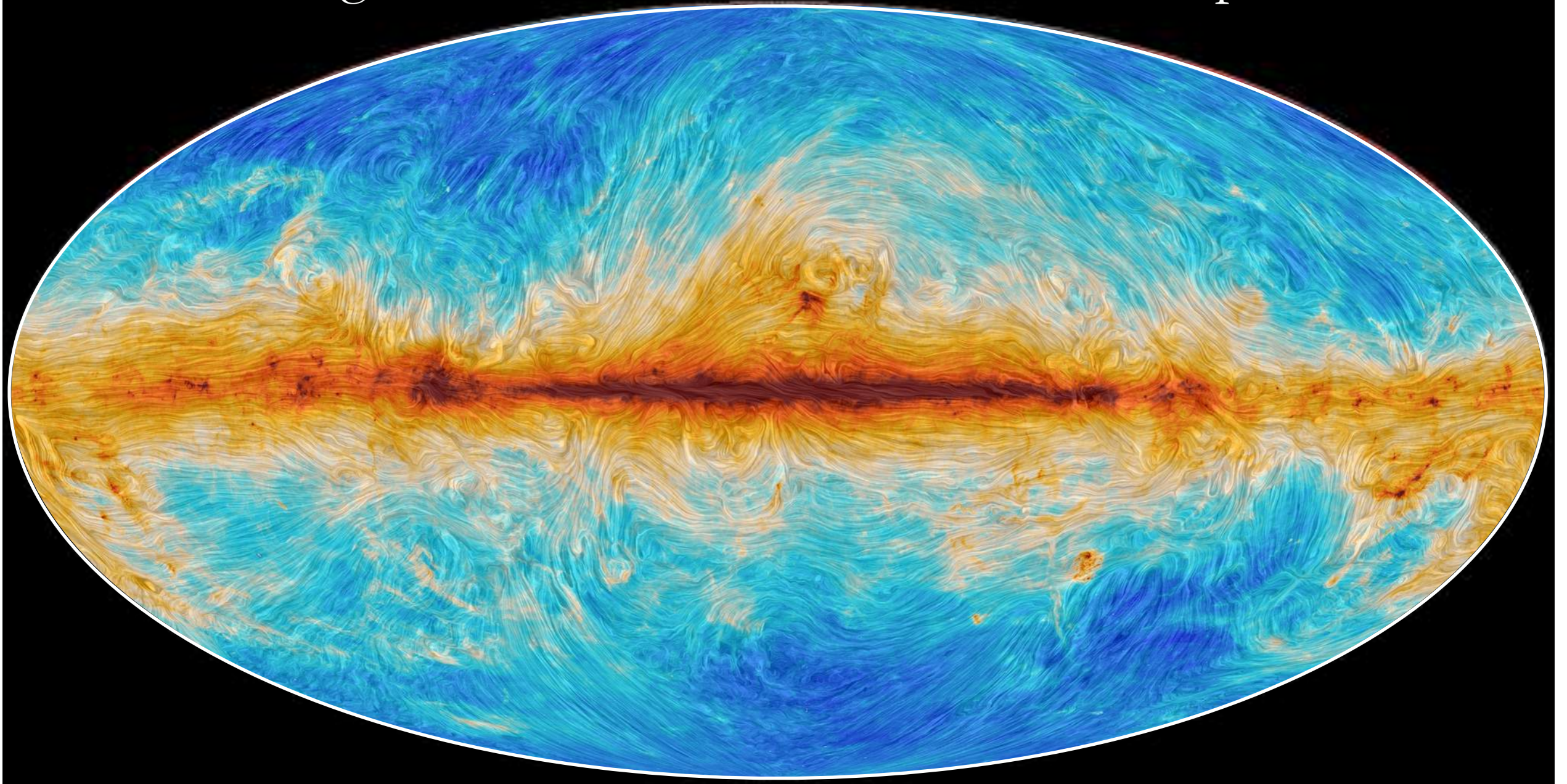
ESA/Planck Collaboration

IR, sub-mm, radio

dust is 1% of ISM mass, $\sim 0.1\%$ mass of Galaxy
but responsible for $\sim 30-50\%$ of bolometric luminosity

Interstellar Medium

Galactic magnetic field inferred from Planck dust polarization



$B \sim 5 \mu\text{G}$; known from Zeeman splitting, synchrotron emission, polarization of dust emission and extinction (assumed aligned $\perp B$)

Interstellar Medium

Multi-phase gas, both in chemistry and thermodynamics:

- atomic, ionized, molecular
- hot, warm, cold
- e.g., WIM = warm ionized medium, CNM = cold neutral medium

Molecular gas: $T \sim 10 - 20$ K ($c_s \sim 0.2$ km s⁻¹); $n > 100$ cm⁻³

- can be self-gravitating; all star formation is in molecular gas
- turbulence very important because $u_{\text{turb}} \sim 1$ km s⁻¹ $\gg c_s$

Atomic CNM: $T \sim 60 - 10^3$ K ($c_s \sim 1$ km s⁻¹); $n \sim 30$ cm⁻³

- organized in dense clouds, sheets, and filaments; $L \sim 1 - 10$ pc

Atomic WNM: $T \sim 5000 - 8000$ K; $n \sim 0.3$ cm⁻³

- diffuse: fills $\sim 50\%$ of the volume near the Galactic midplane

Interstellar Medium

Diffuse WIM: $T \sim 8000$ K; $n \sim 10^{-3 \dots -2}$ cm $^{-3}$

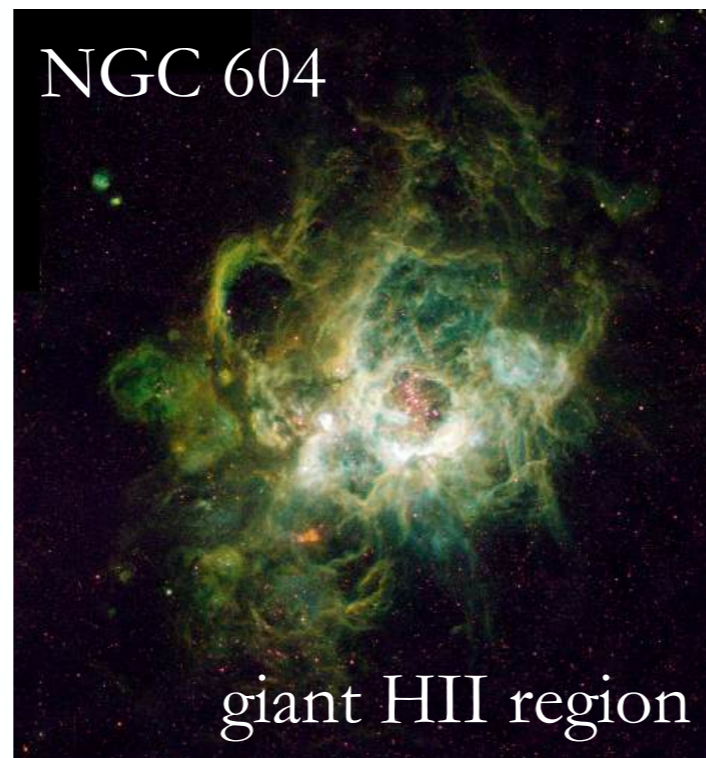
– diffuse: mostly found at high $|z| \sim$ kpc

HII region WIM: $T \sim 6000 - 10^4$ K; $n \sim 10 - 10^4$ cm $^{-3}$

– found near young massive stars and clusters

Hot ionized medium: $T \sim 5 \times 10^5 - 10^7$ K; $n \sim 10^{-3 \dots -2}$ cm $^{-3}$

– indiv. supernova remnants, superbubbles, chimneys; $\sim 50\%$ volume



Interstellar Medium

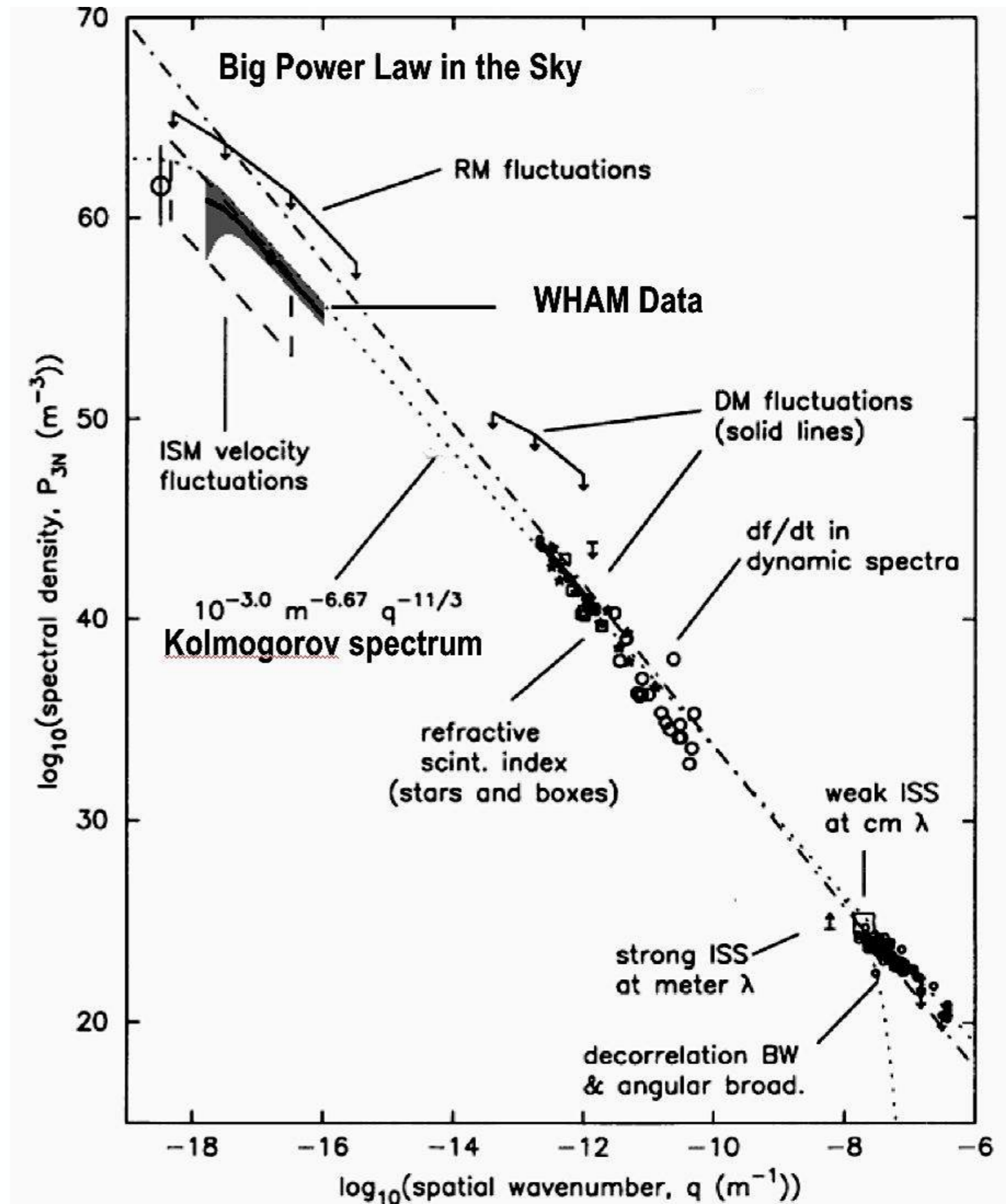
Turbulence

“Great Power Law in the Sky”

Crab nebula,
young SNR



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



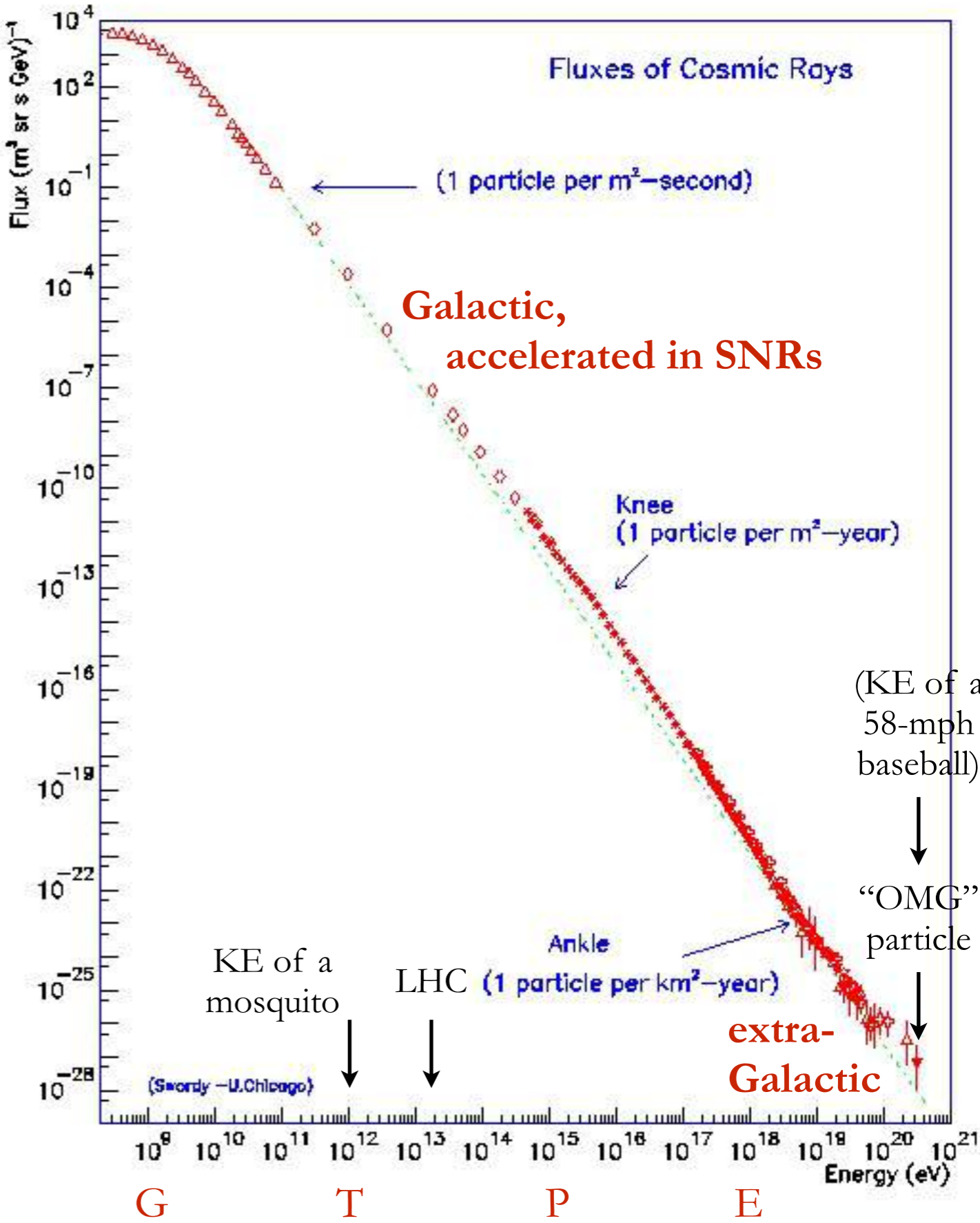
Interstellar Medium

Cosmic Rays

2nd great power law in the sky

$$d\Phi/dE \propto E^{-2.7}$$

(direct measurement below GeV
affected by Solar wind modulation)



Interstellar Medium

what makes studying the ISM both fascinating and difficult:

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

Taurus MC

>400 young stars



~430 light-years away (nearest)

Molecular Clouds

part of the “cold phase” of the ISM

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

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

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

low degree of ionization!

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

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

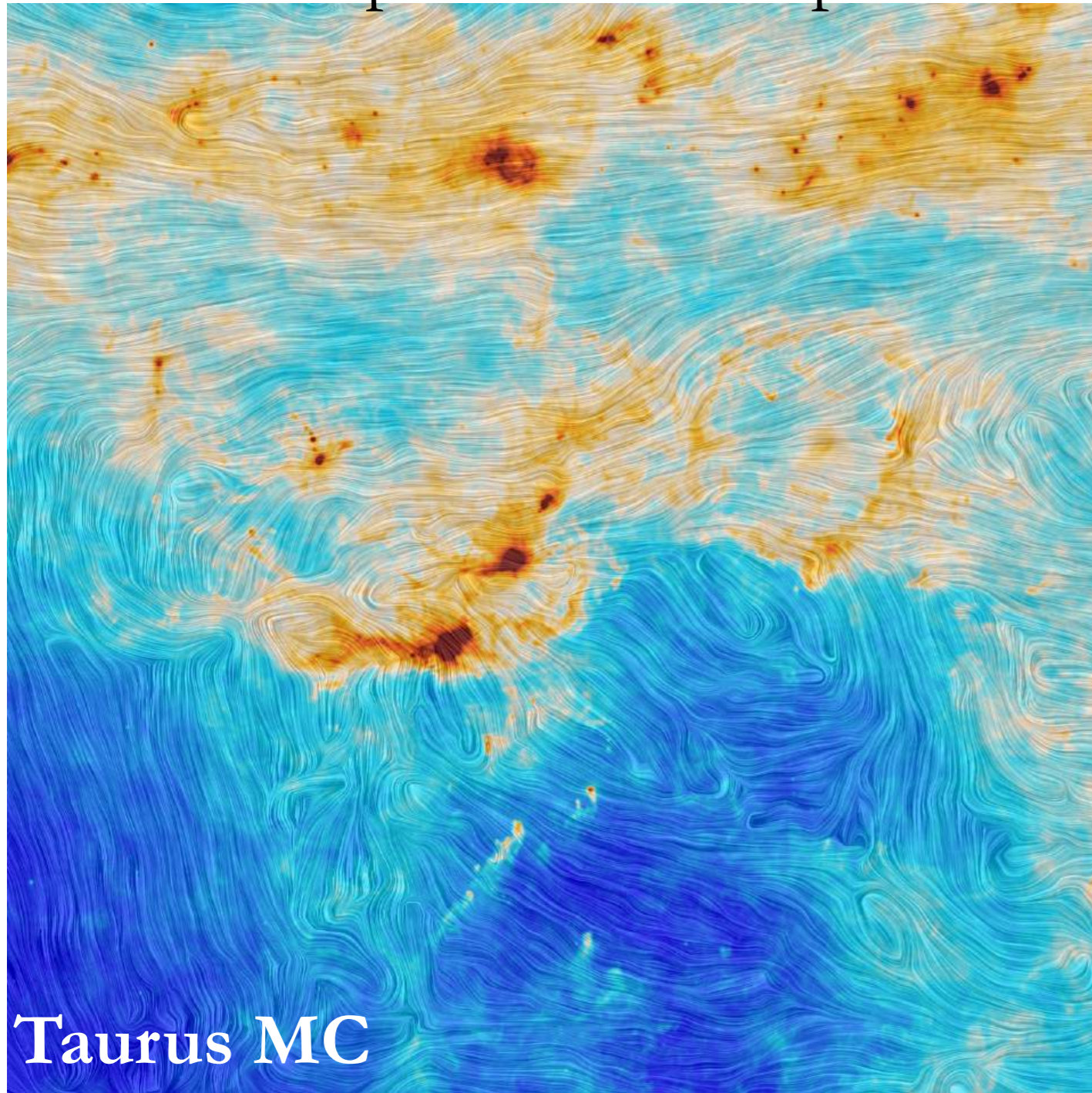
$$t_{\text{coll},in} \sim 1 \text{ mth}$$

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

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

Molecular Clouds

Planck dust polarization map



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

$$\beta \sim 0.01 - 0.1$$

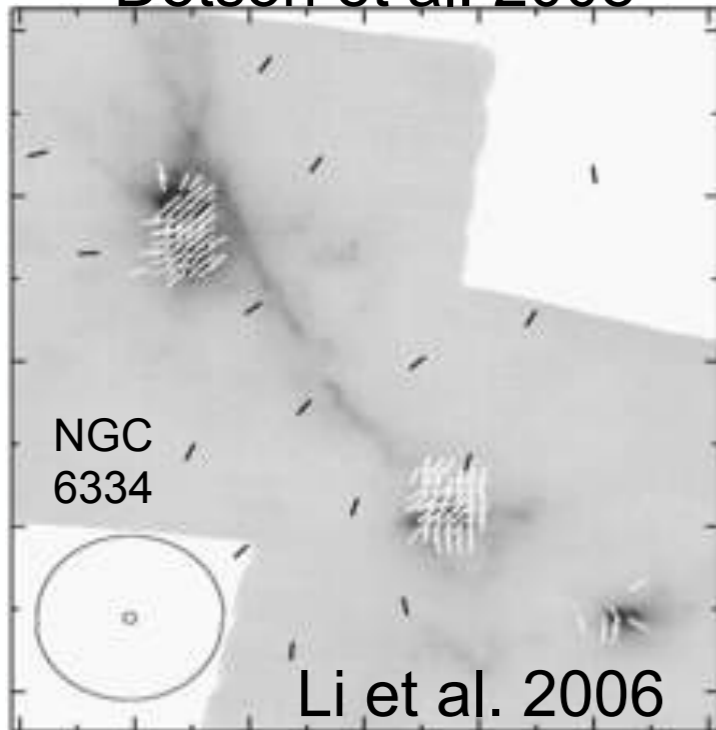
$$M_A \sim 1$$

turbulence, magnetic fields,
and gravity in rough
energy equipartition

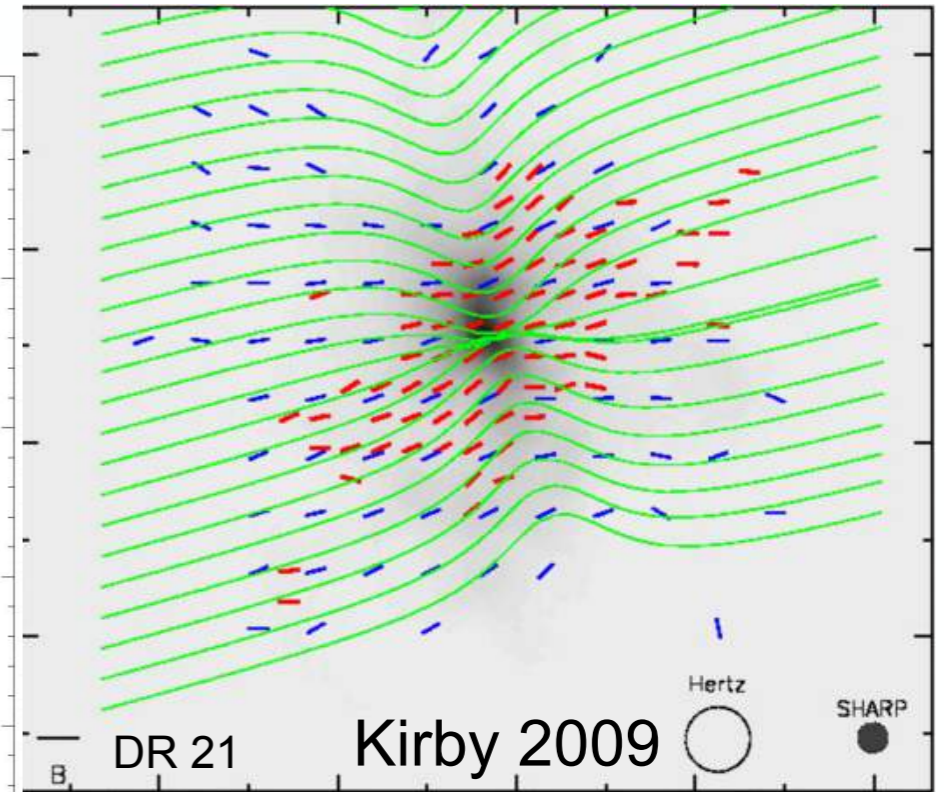
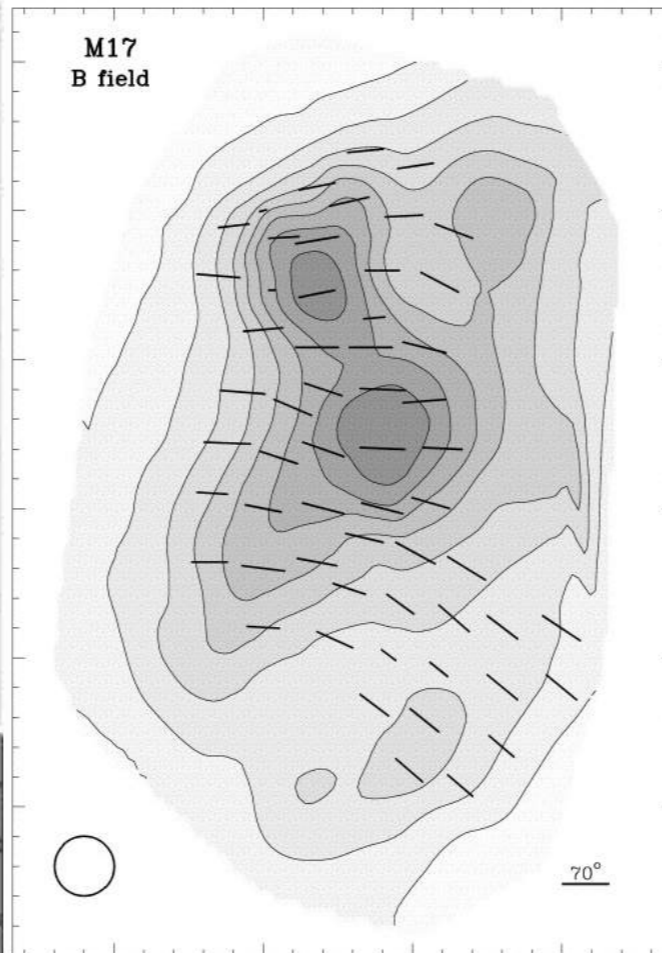
(elongated dust grains, oriented \perp to \mathbf{B} , emit polarized light in the FIR & sub-mm)

Protostellar Cores

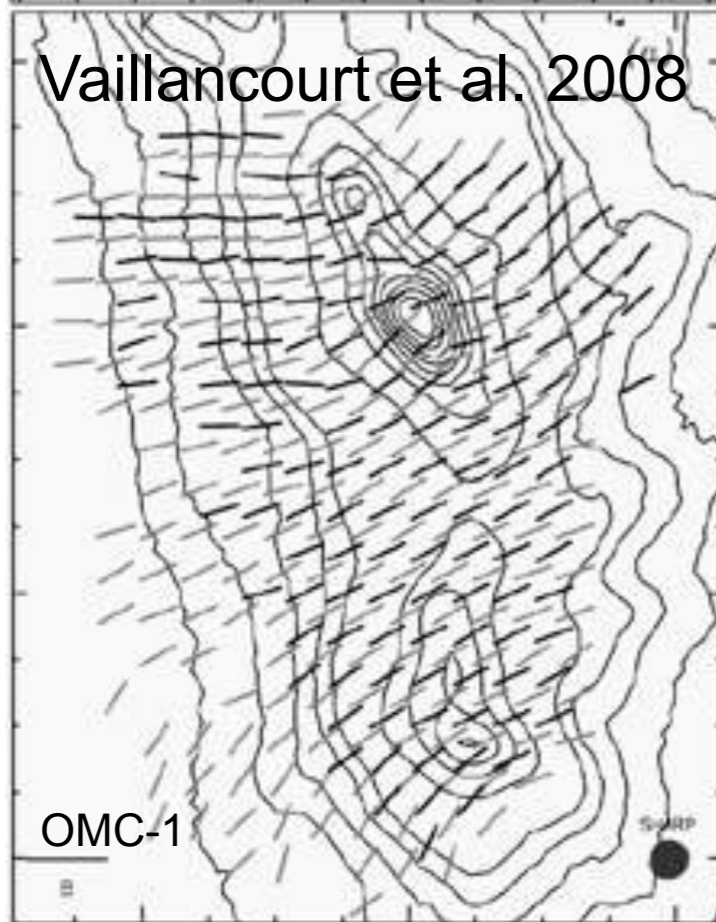
Dotson et al. 2008



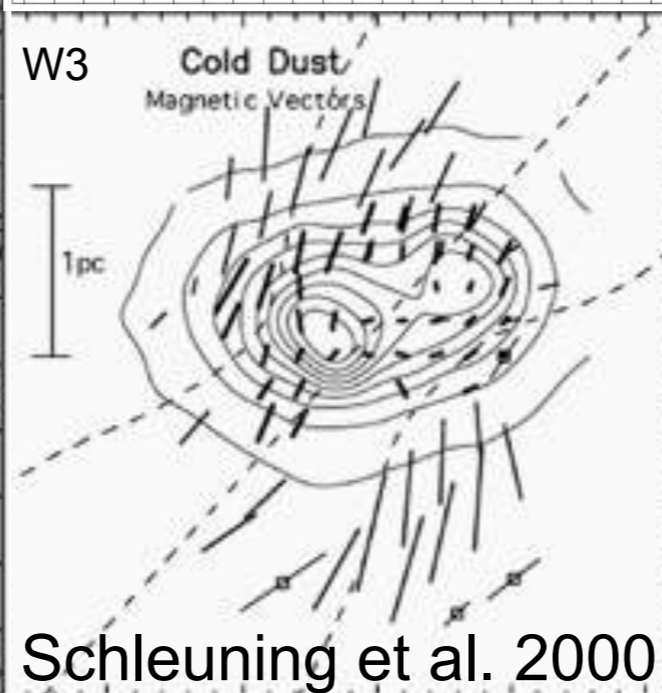
Houde et al 2002



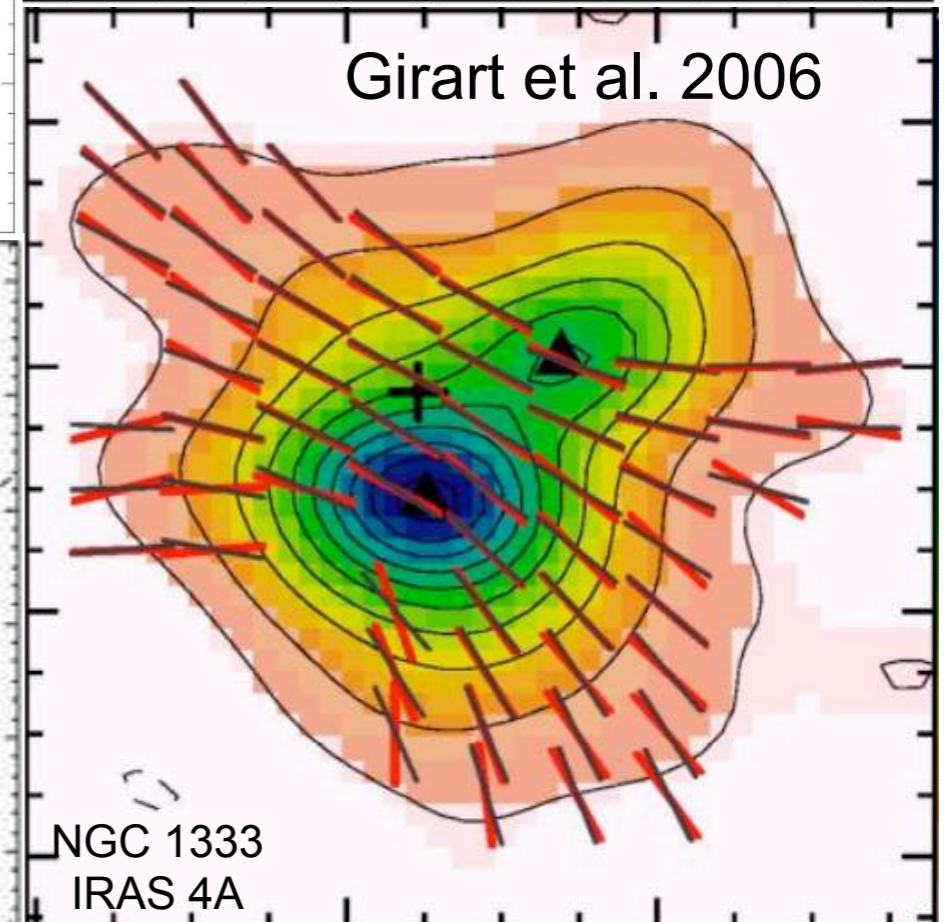
Vaillancourt et al. 2008



W3



Girart et al. 2006



Protoplanetary Disks

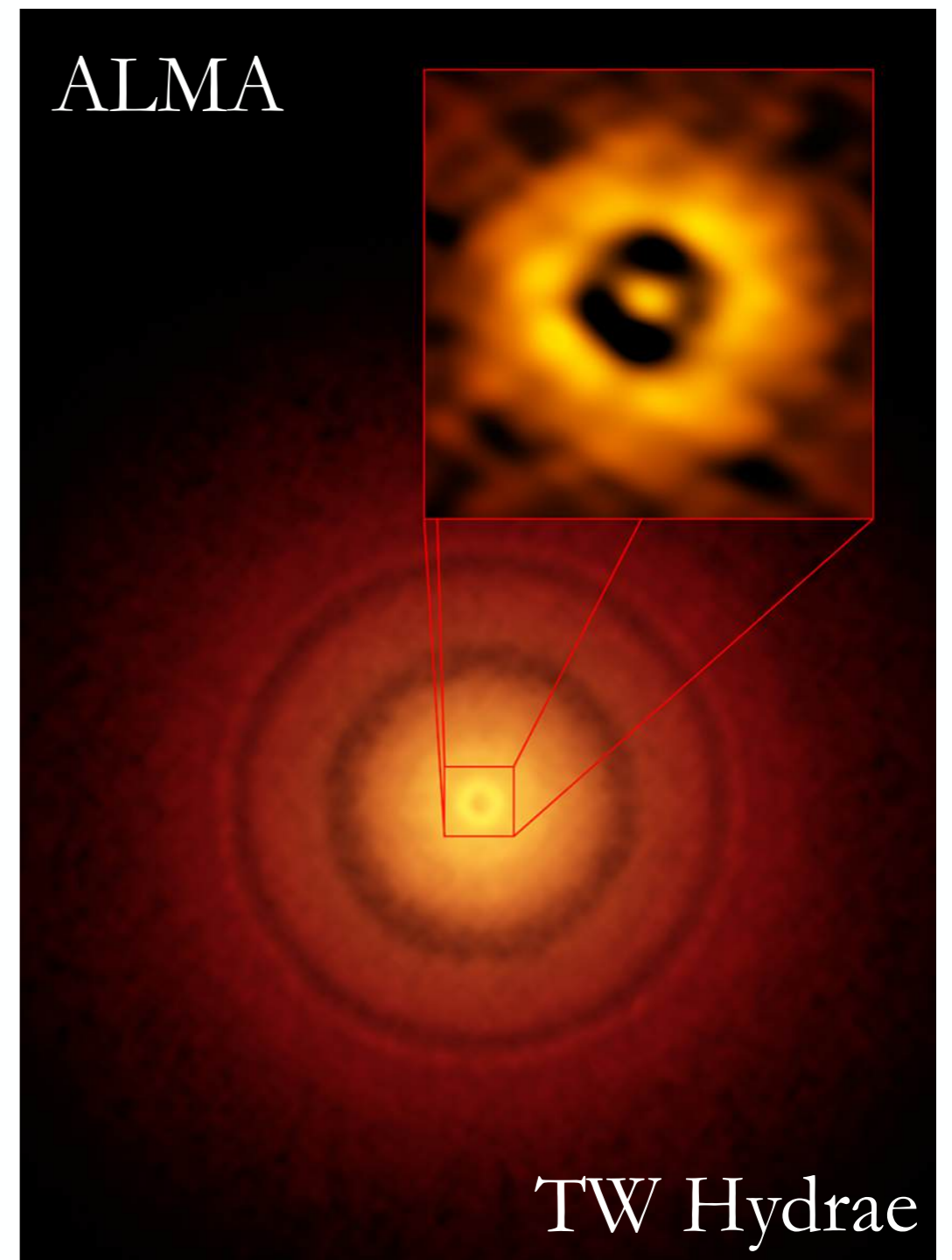
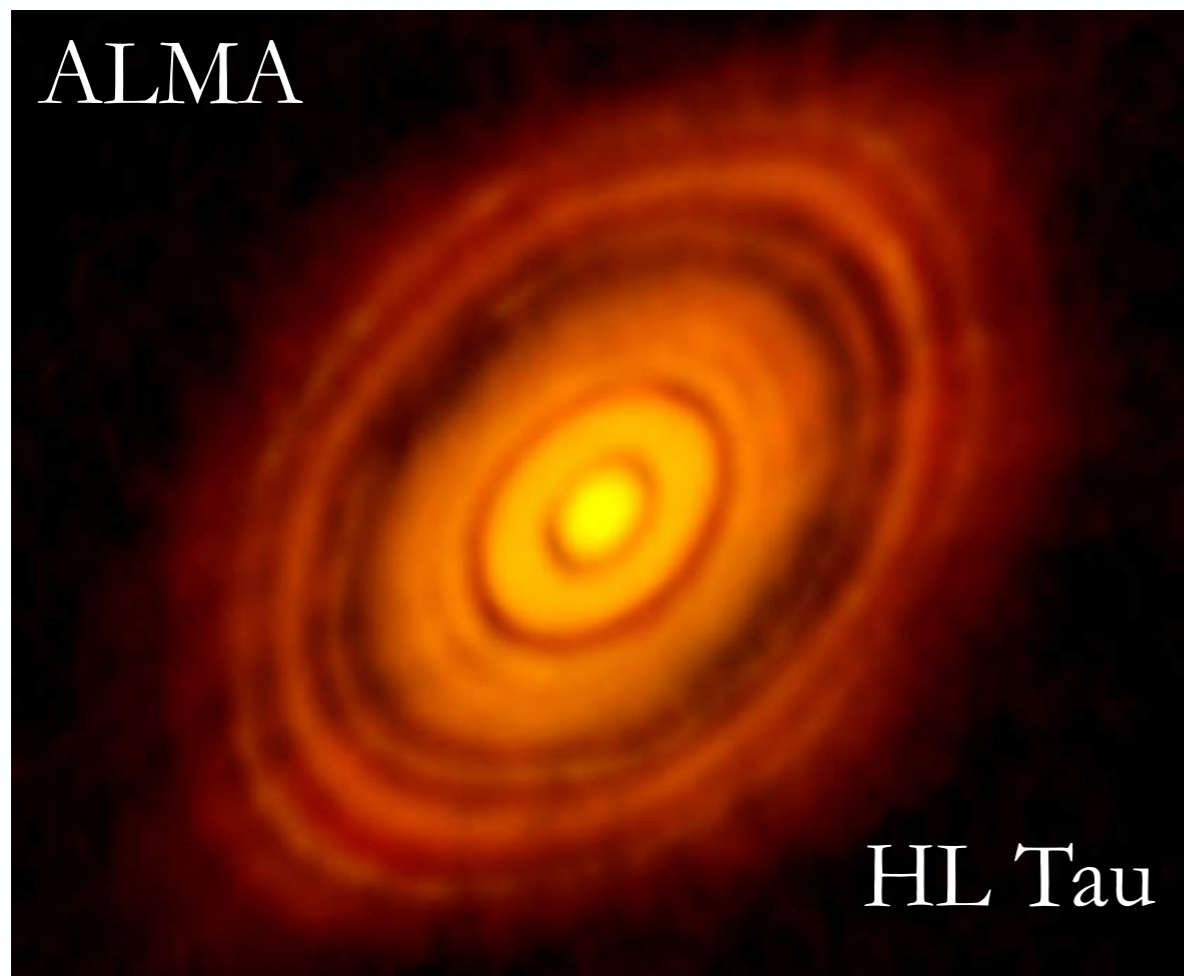
$$n_n \sim 10^{9-15} \text{ cm}^{-3}$$

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

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

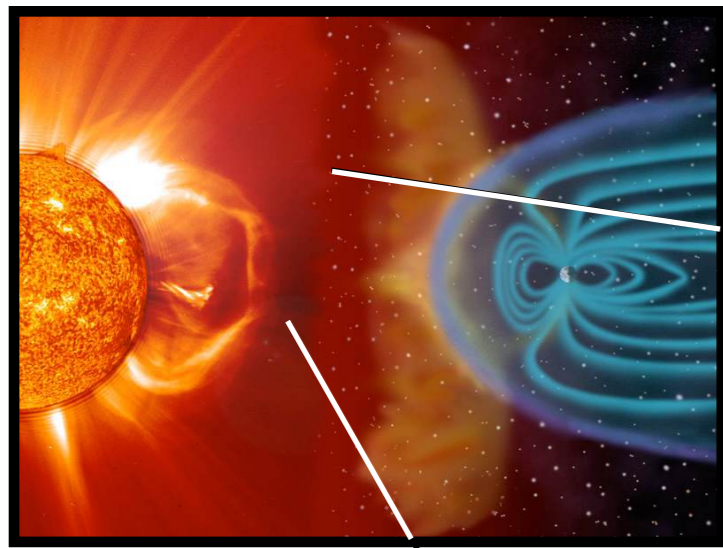
$$B \sim 0.01 - 1 \text{ G} ??$$

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



Solar Wind

$$\dot{M} \sim 10^{-14} M_{\odot} \text{ yr}^{-1}$$



at $r \sim 1$ au...

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

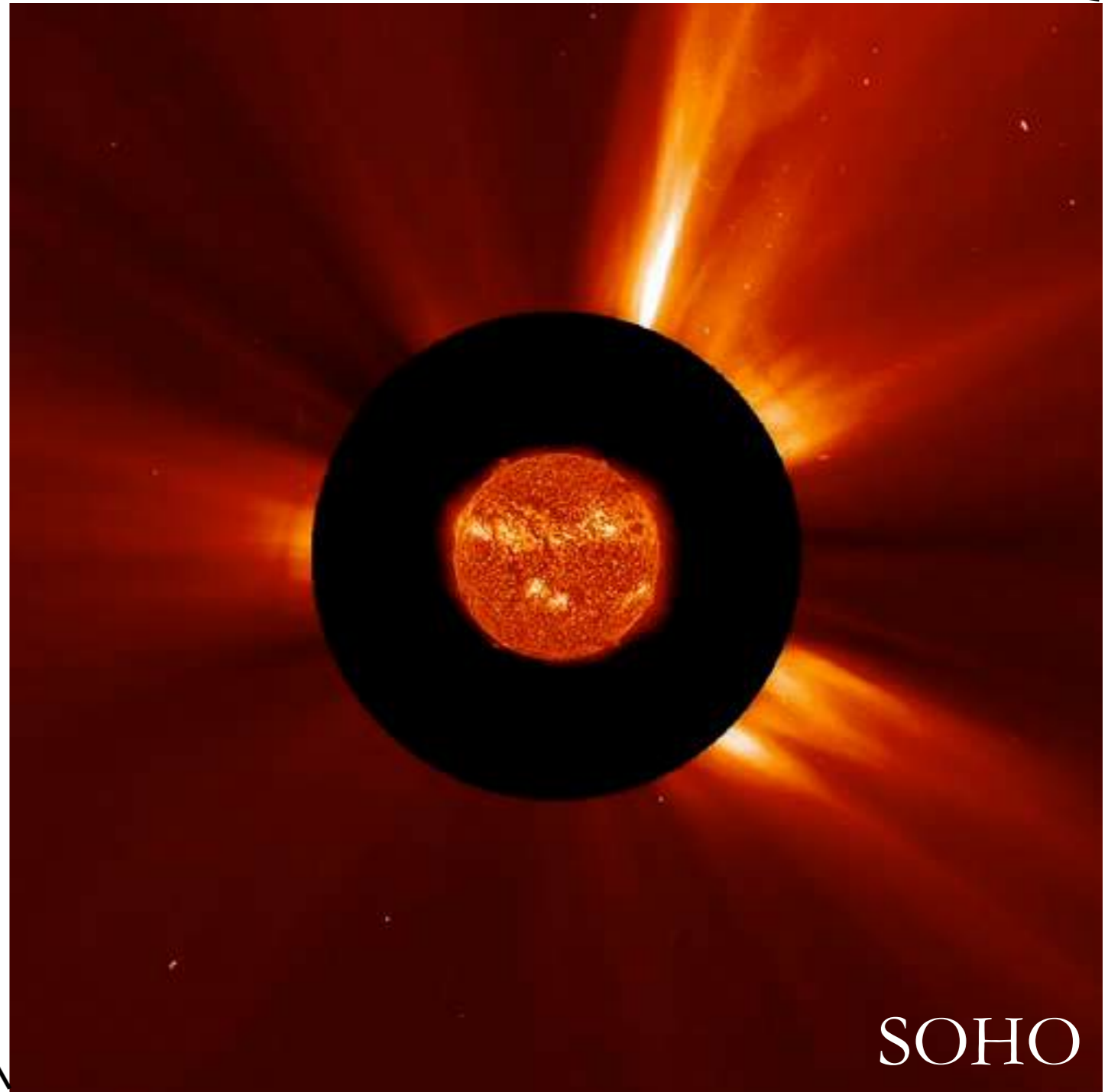
$$k_B T \sim 10 \text{ eV}$$

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

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

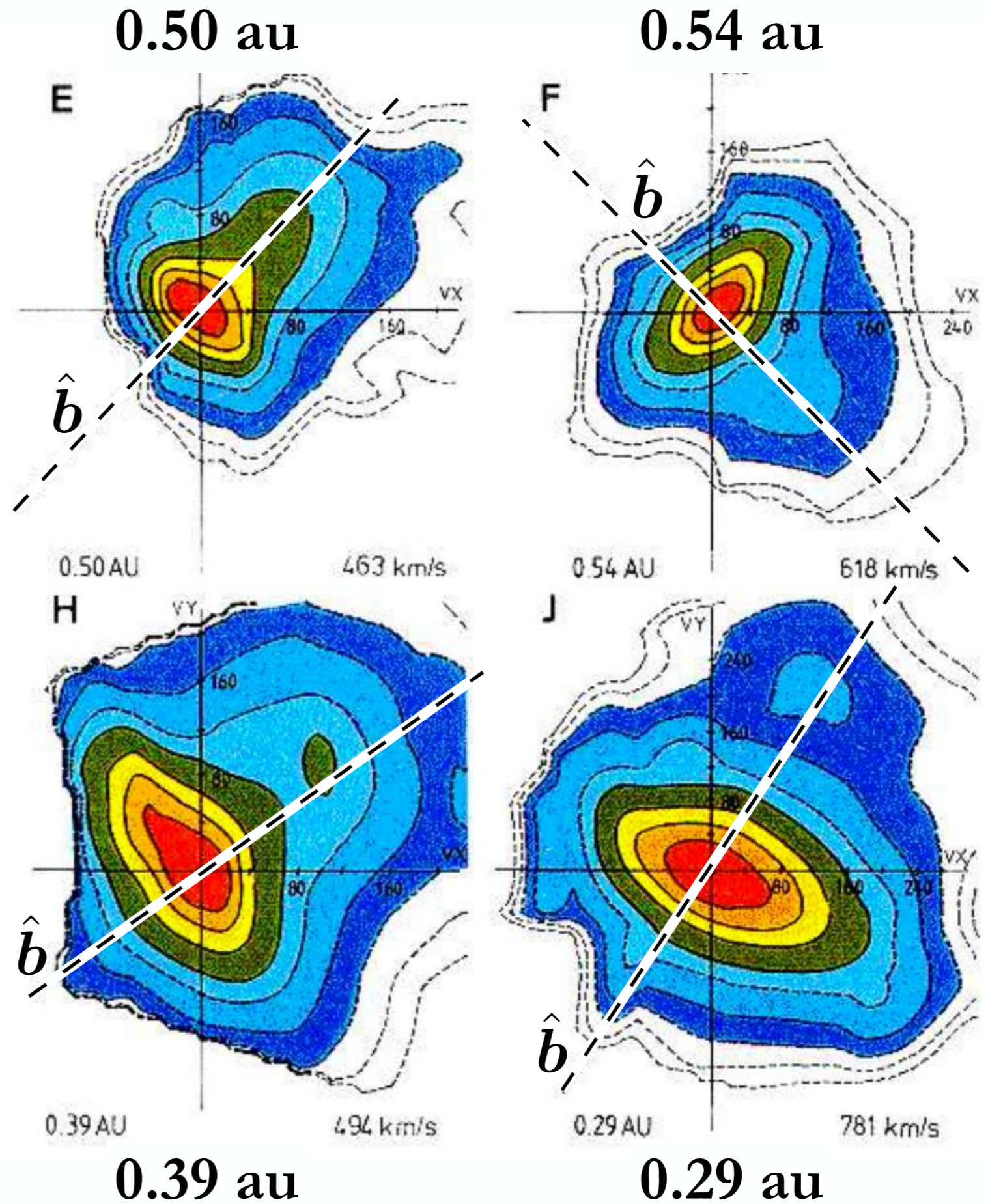
$$\rho_i \sim 10^{-6} \text{ au}$$

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



SOHO

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



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)

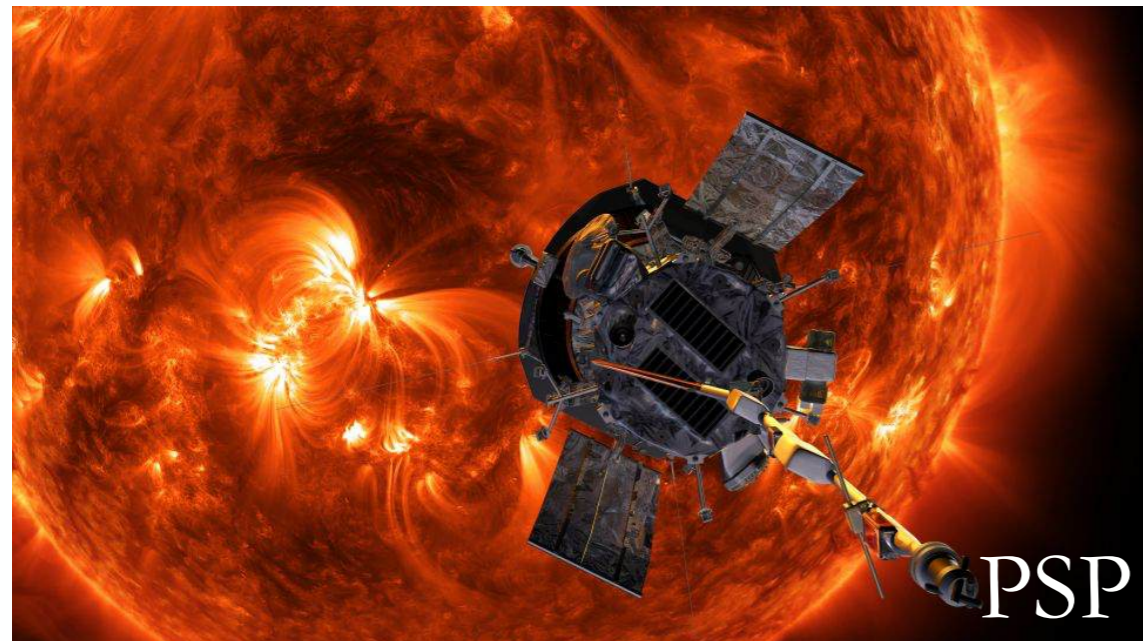
Voyager 1 & 2: recently passed boundary between SW & ISM

CLUSTER: “formation flying” spacecraft

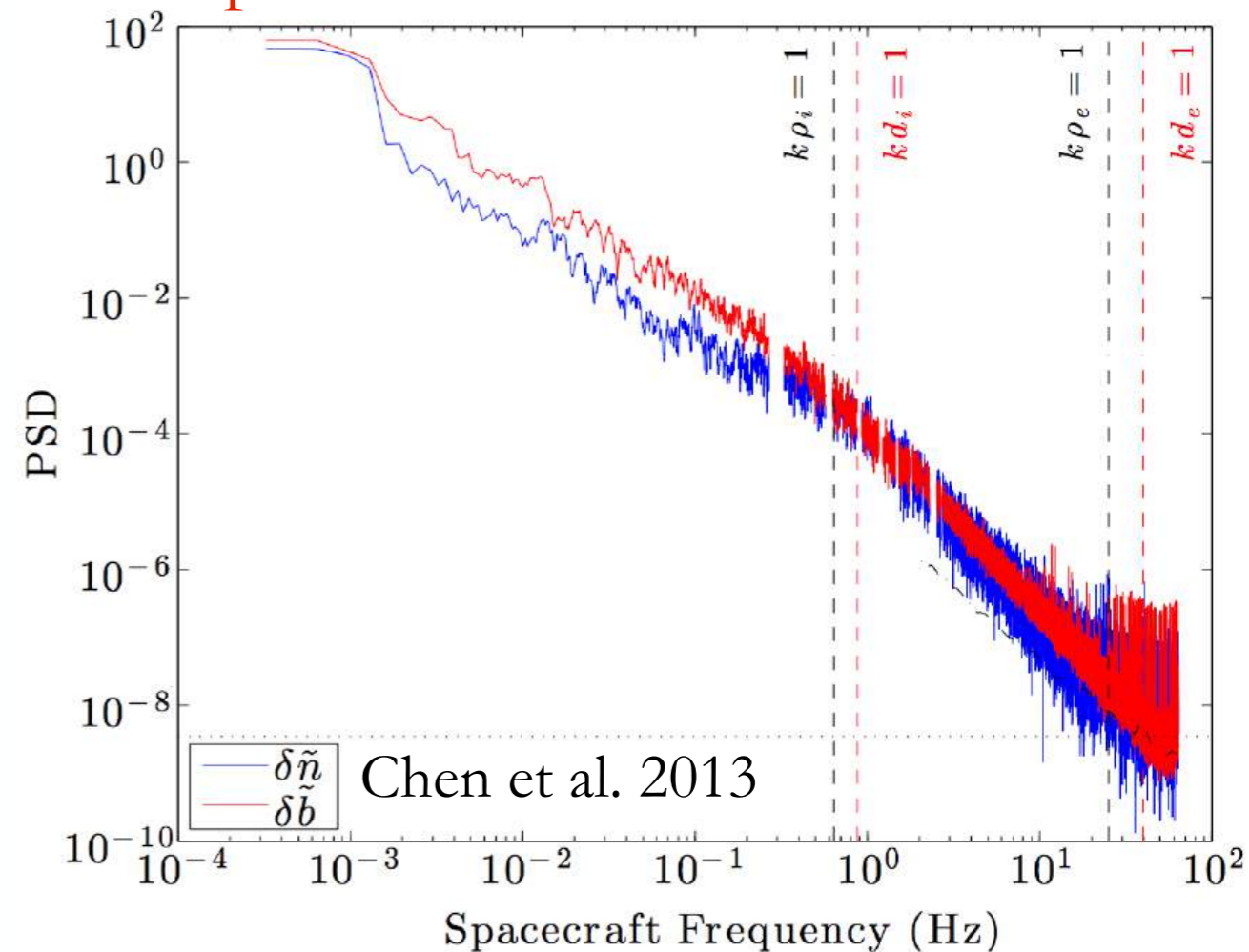
STEREO A & B: focus on CMEs

Wind: near-Earth SW (now at L1)

Parker Solar Probe: launched Aug 2018, currently on 27th orbit, has come within $\sim 9 R_{\odot}$ of solar surface (at 430,000 mph)



excellent laboratory for studying plasma kinetics and turbulence



Solar Corona

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

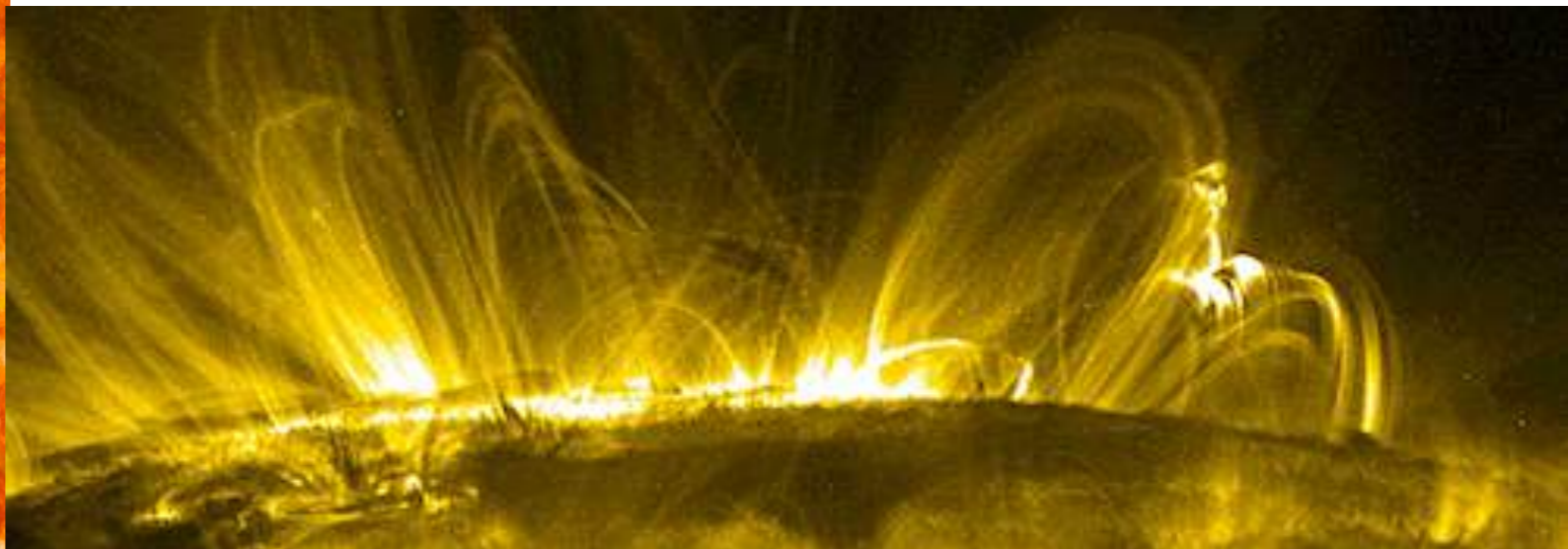
photosphere is $\approx 5800 \text{ K}$

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

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

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

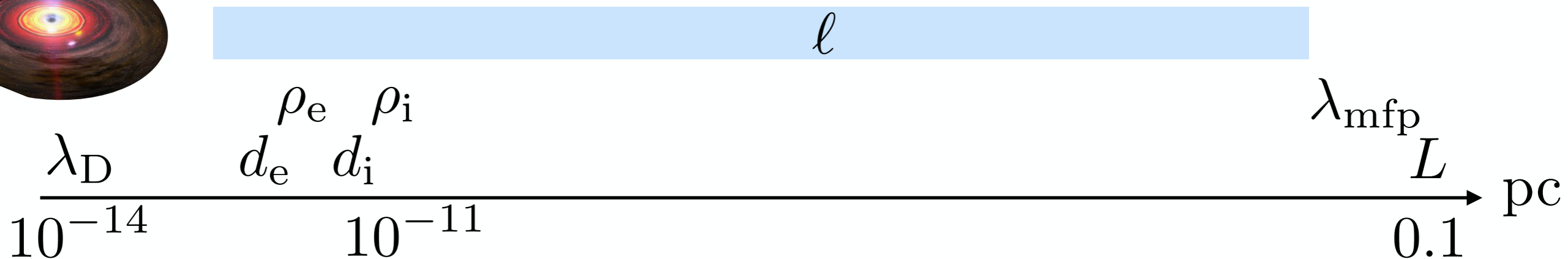
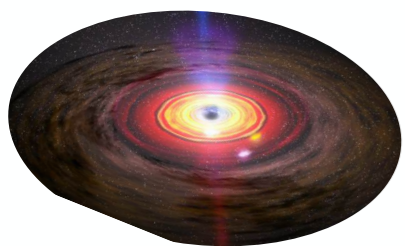
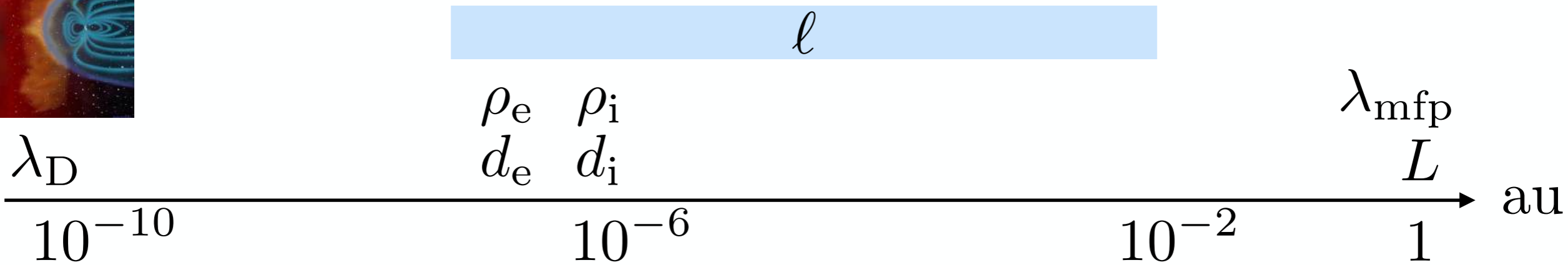
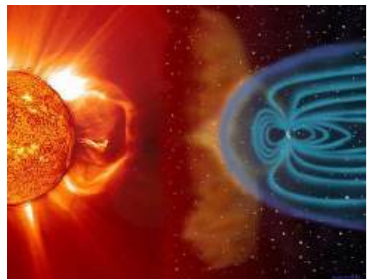
$$\beta \lesssim 0.01$$



What were the common themes?

(other than plasma and magnetic fields)

huge scale separations!



Some (unsolved/partially solved) 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 $1 M_{\odot}$ blob of interstellar medium ($n \sim 1 \text{ cm}^{-3}$, $B \sim 1 \mu\text{G}$).

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

Conserve magnetic flux ($\Phi_B \propto Br^2 = \text{const}$) and mass ($M \propto nr^3 = \text{const}$)
during spherical contraction $\implies B \propto n^{2/3}$
 $\implies B_{\odot} \sim 10^{10} \text{ G!!!}$ (actual field is $\sim 1 \text{ G}$)

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)

rigorously incorporated into theory of star formation (Mouschovias 1979+)

let's make the Sun...

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

Conserve angular momentum during contraction:

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

must shed a lot of angular momentum!

Some (unsolved/partially solved) 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, radiation, 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 energization (T_e vs T_i , non-thermal particles)
7. 11-year solar cycle and the Maunder minimum (sunspots; 1645-1715)
8. Supernovae ($\sim 10^{51}$ erg KE) and gamma-ray bursts ($\sim 10^{51}$ erg $\sim 10^{44}$ J beamed)
9. Cosmic-ray spectrum, transport, and acceleration (up to $\sim 10^{20}$ eV!)
10. Magnetospheres of compact objects (pulsars, black holes); emission mechanisms
11. Jet/outflow launching and collimation (wide variety...)
12. Magnetic reconnection in realistic environments
(rate, onset, particle acceleration, cross-scale coupling, relativistic effects...)