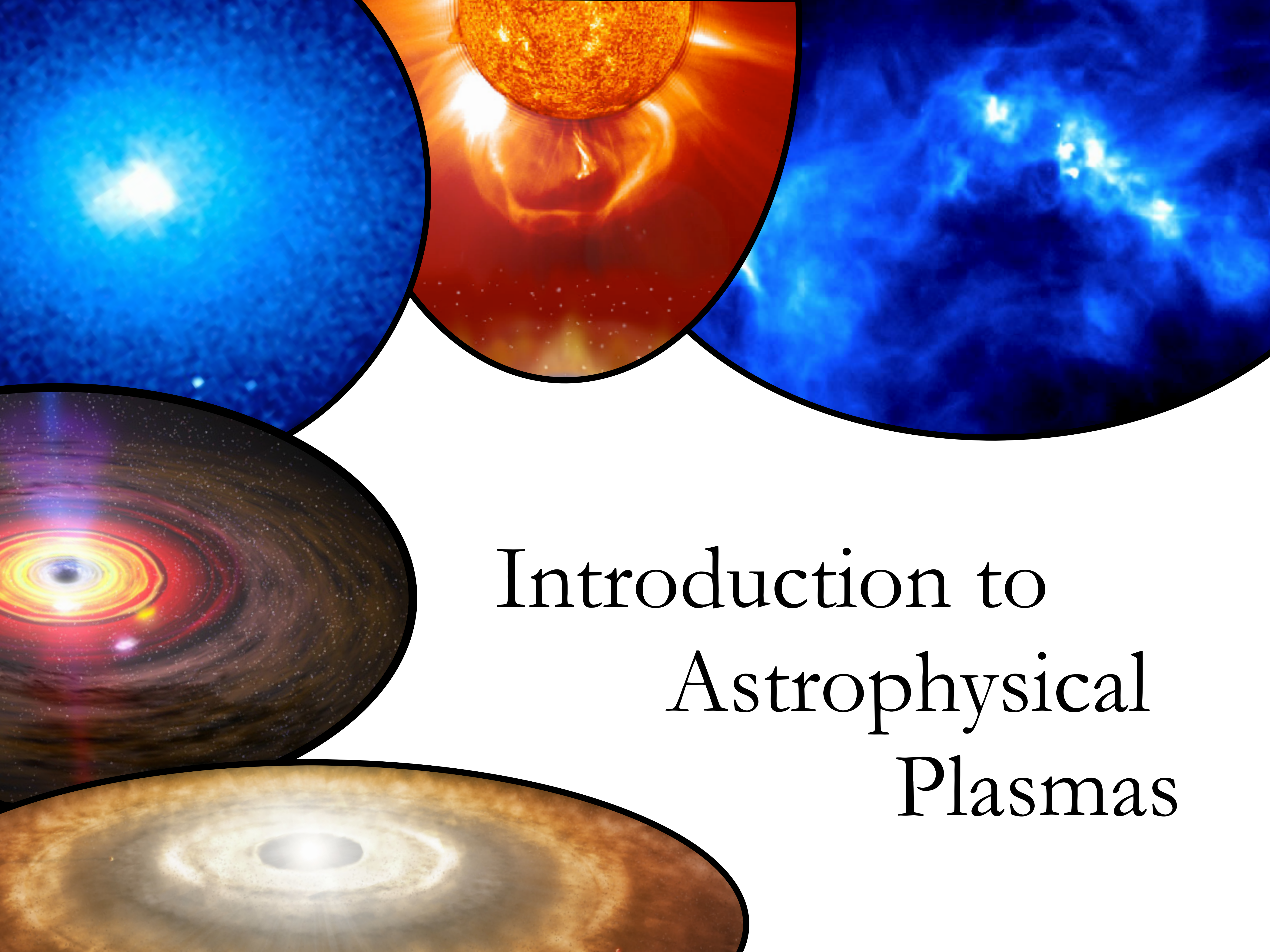


Introduction to Astrophysical Plasmas

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 *loooooooooong*. Again, this is often under-appreciated.

   Degree of ionization only 10^{-10}? 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.

   Collisional mean free path ~1 kpc? Don't worry, pressure-gradient lengthscales can be ~100 kpc.

How are astrophysical plasmas different?

3. **Cosmic magnetism**
   This is tricky. With some notable exceptions, plasma β is often ~10…10^3. 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"!

$$\rho_i \sim \left(\frac{T}{1\ \mathrm{keV}}\right)^{1/2} \left(\frac{B}{10^{-18}\ \mathrm{G}}\right)^{-1}\ \mathrm{kpc}$$

$$\Omega_i \sim \left(\frac{B}{10^{-18}\ \mathrm{G}}\right)\ \mathrm{Myr}^{-1}$$

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

How are astrophysical plasmas different?

4. **Lots of additional physics**
   Want to do plasma astrophysics?
   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 simultaneously 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.

How are astrophysical plasmas different?

6. **Units** (CGS!)
   I haven't used meters, Joules, Newtons, Teslas, etc. for at least 18 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. Isn't 4π so much better?

Note: 1 eV $\approx 10^4$ K

1 yr $\approx \pi \times 10^7$ s

1 km $\mathrm{s}^{-1} \approx 1$ pc Myr^{-1}

1 Tesla $= 10^4$ G

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 H_2 and CO, HCO+, Na+, Mg+, K+…
- Nonthermal ions and electrons (cosmic rays)
  - various acceleration mechanismsay coexist with thermal plasma
  - can coexist with thermal plasma
- Dust grains (charged and neutral)
  - carbonaceous and silicate material, water-ice mantle

What are astrophysical plasmas?

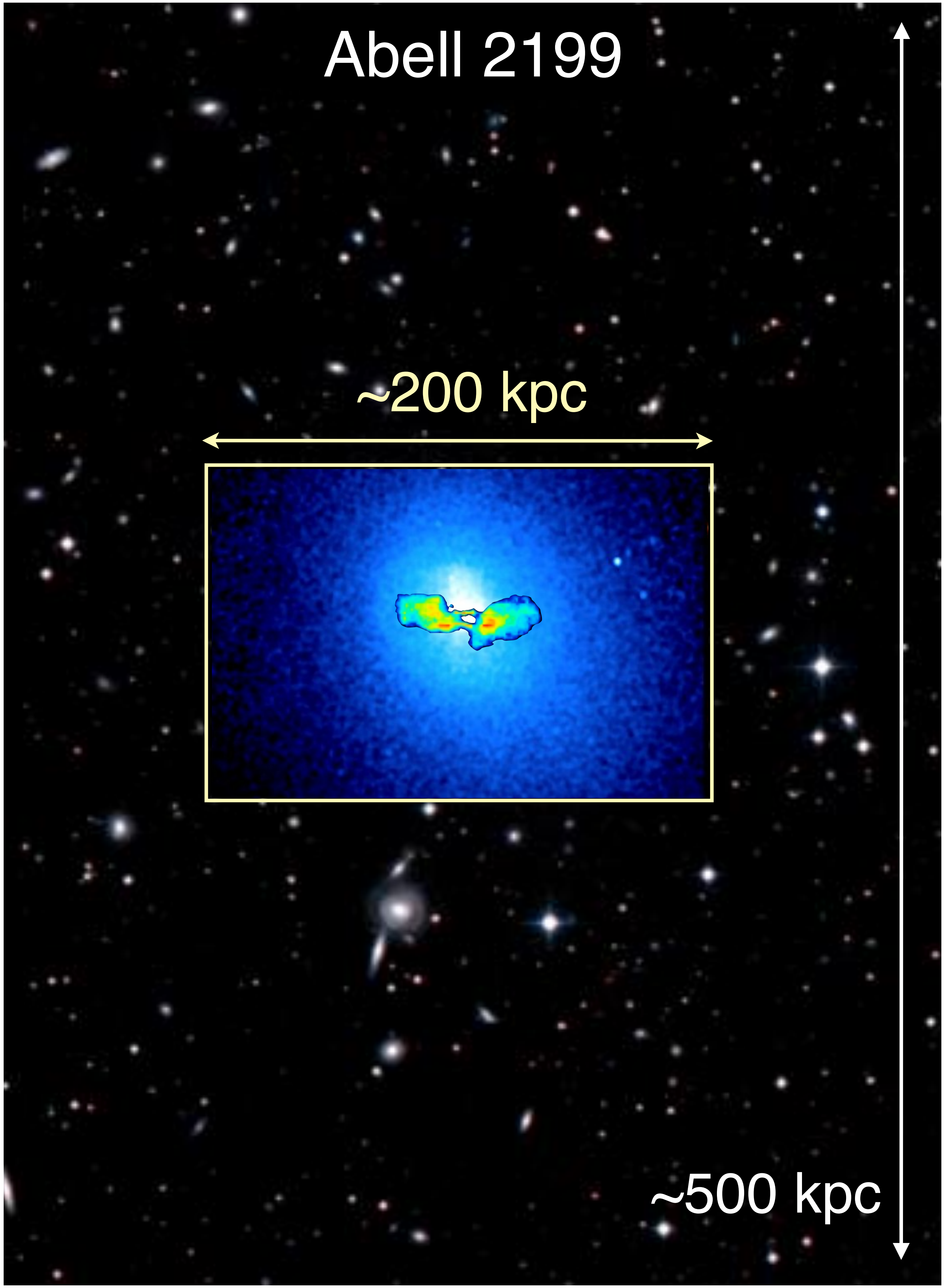
- Electromagnetic fields
  Motion of charged particles creates E&M fields, E&M fields induce charged-particle motion, collisions inform neutrals of E&M fields

- Differences from laboratory plasmas:
  - large-scale gradients and/or flows; lower densities ($n \sim 10^{-3}$ cm^{-3} in a ~Mpc ICM vs $n \sim 10^{14}$ cm^{-3} in a ~1 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

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

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

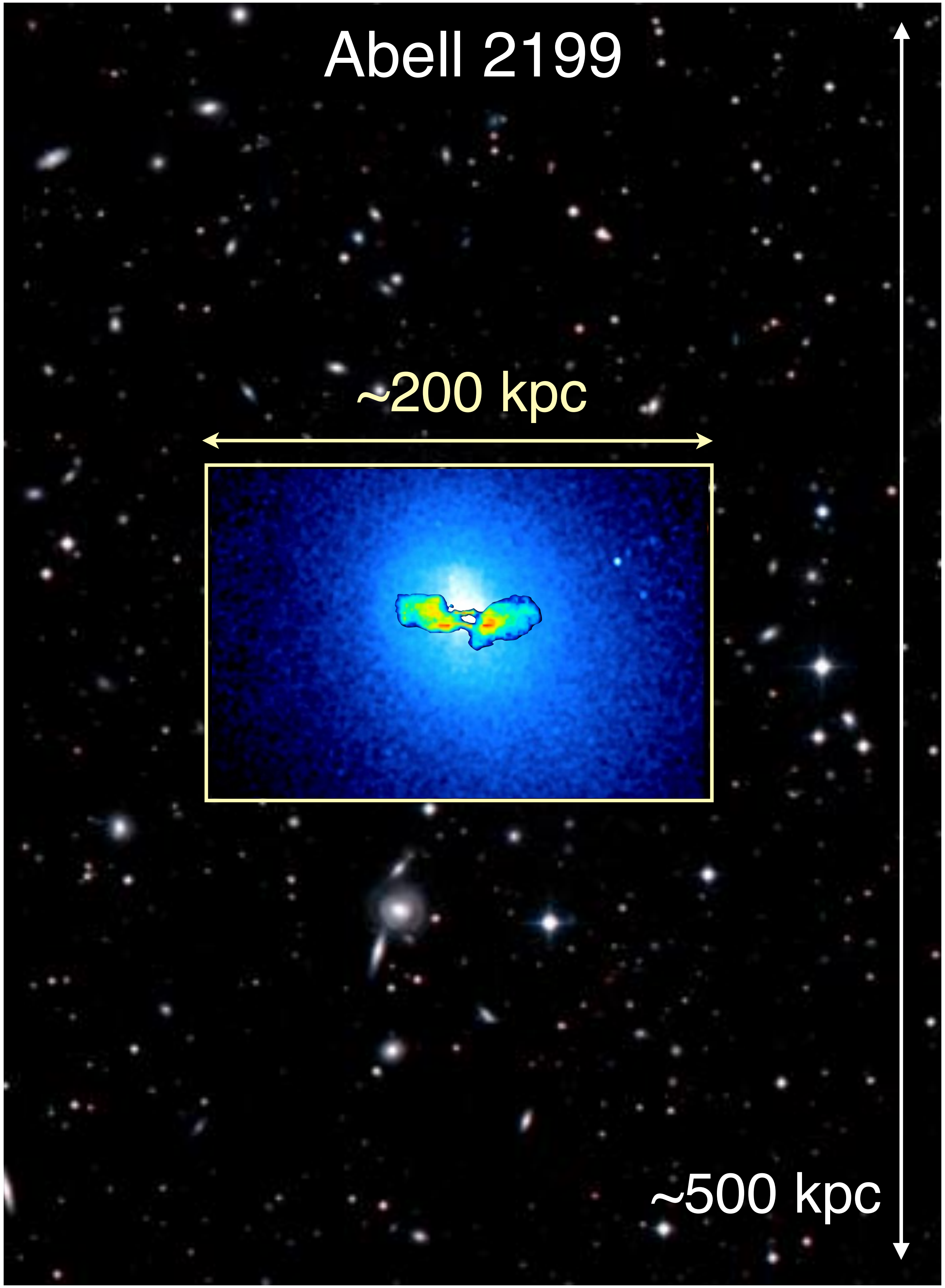
$M \sim 10^{14-15}\ \mathrm{M}_\odot$
in ~ 1 Mpc

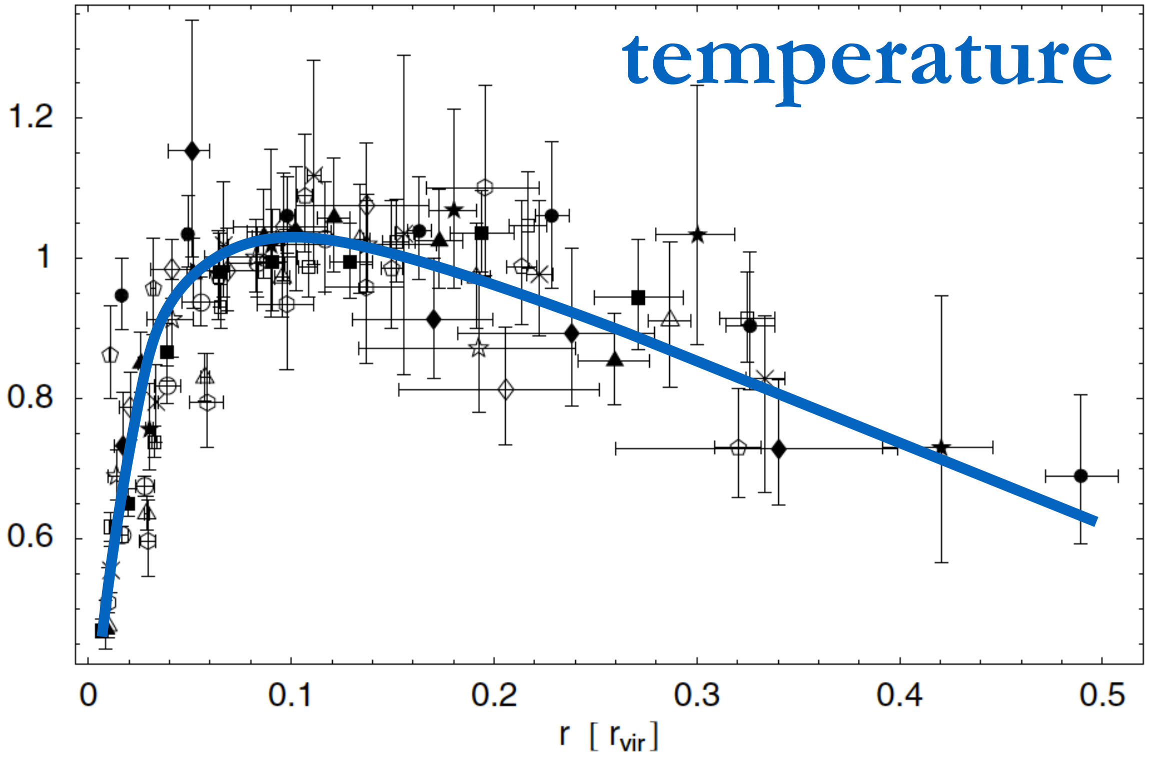
$\sim 84\%$ dark matter

14% thermal plasma
$T \sim 1$–10 keV
$(v_{\mathrm{th,i}} \sim 1000\ \mathrm{km\ s^{-1}})$
$n \sim 10^{-4}$–$10^{-1}\ \mathrm{cm^{-3}}$
$B \sim 1\ \mu\mathrm{G}$

radio (BH &
relativistic plasma)

Intracluster Medium





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

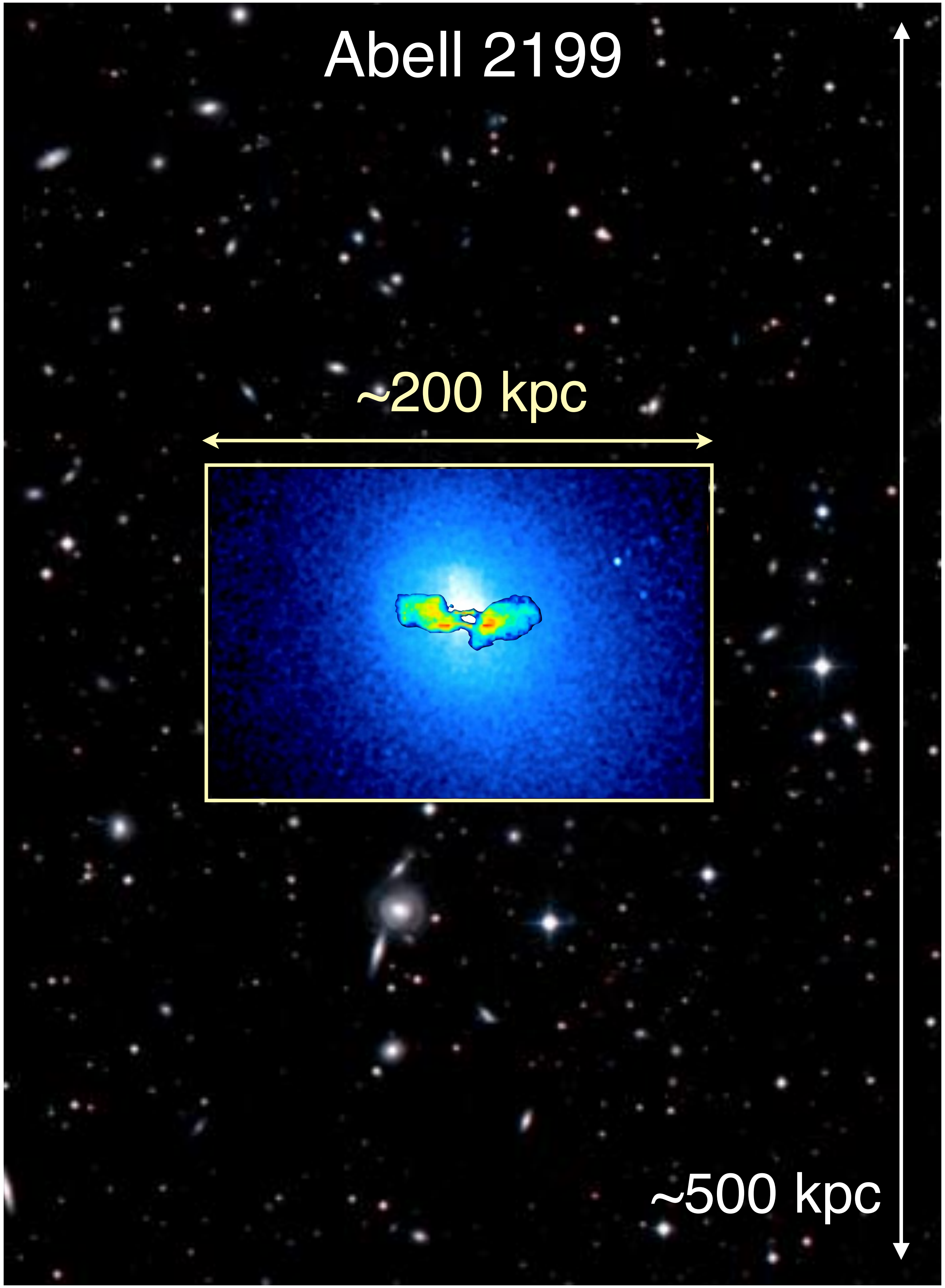
$$t_{\rm dyn} \gtrsim 100 \text{ Myr}$$

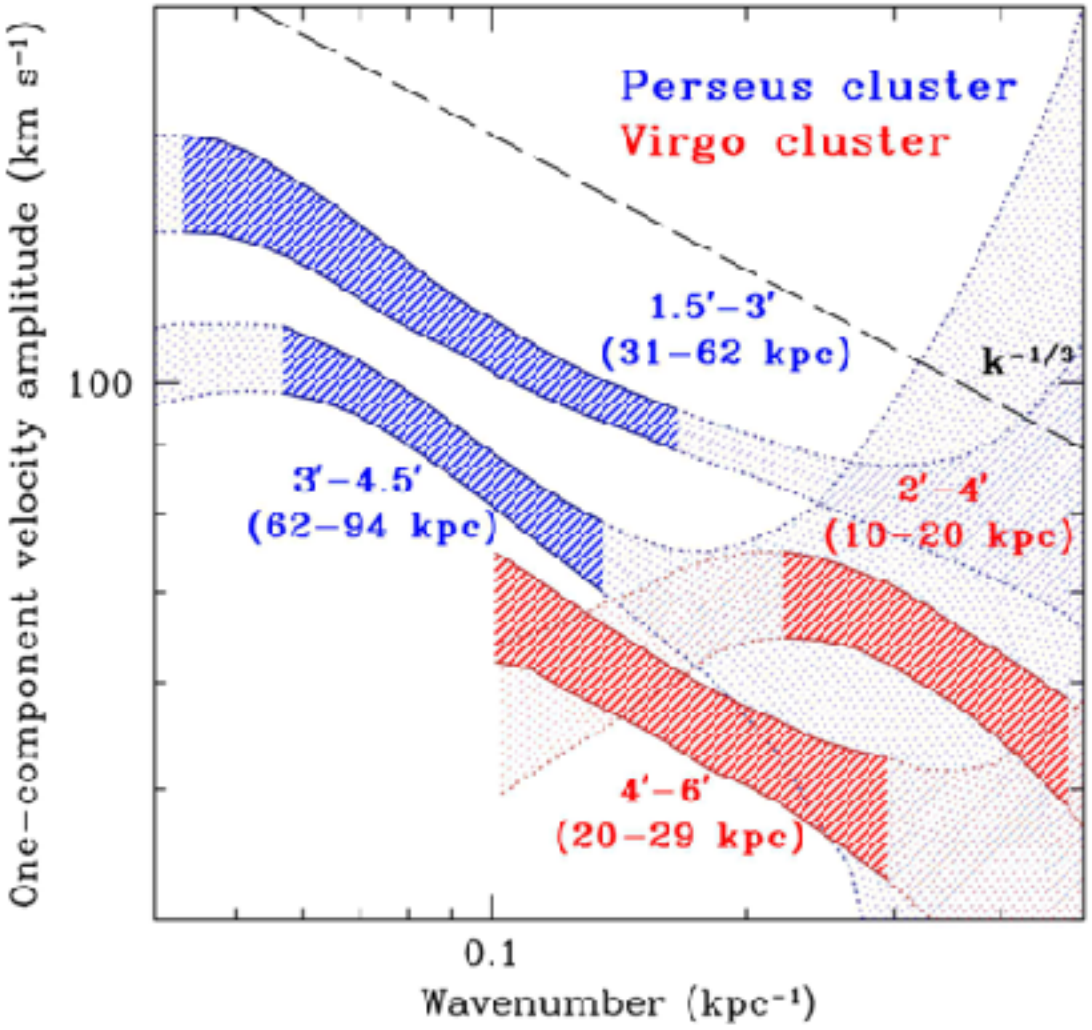
$$t_{\rm ii,coll} \sim 1 - 10 \text{ Myr}$$

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

(ion Larmor orbit ~ size of Jupiter)

Intracluster Medium



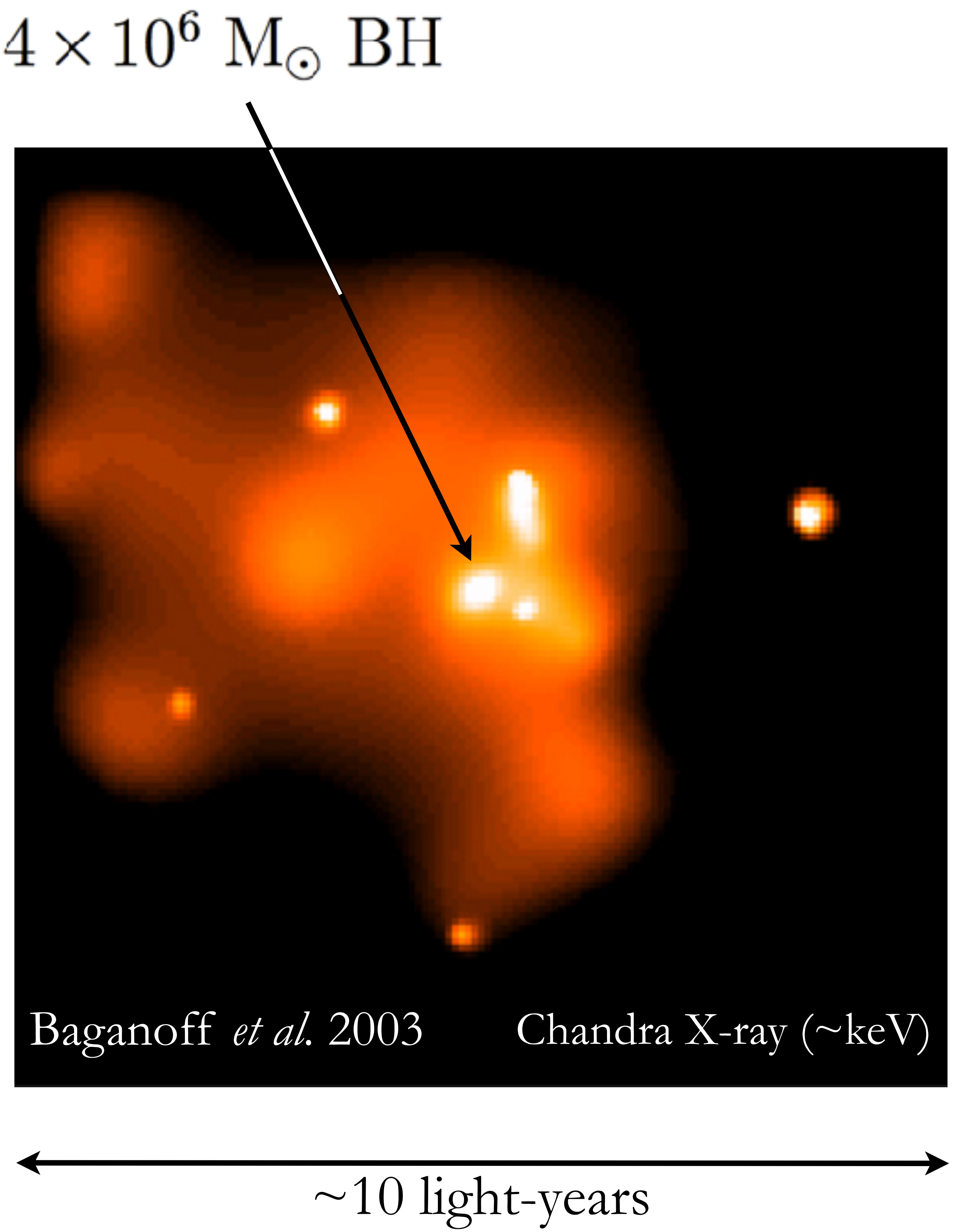


Zhuravleva *et al.* 2014, Nature

subsonic, trans-Alfvénic turbulence

Hitomi, before its death:
$u \approx 160 \text{ km s}^{-1}$

Galactic Center



Baganoff *et al.* 2003

Chandra X-ray (~keV)

~10 light-years

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

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

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

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

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

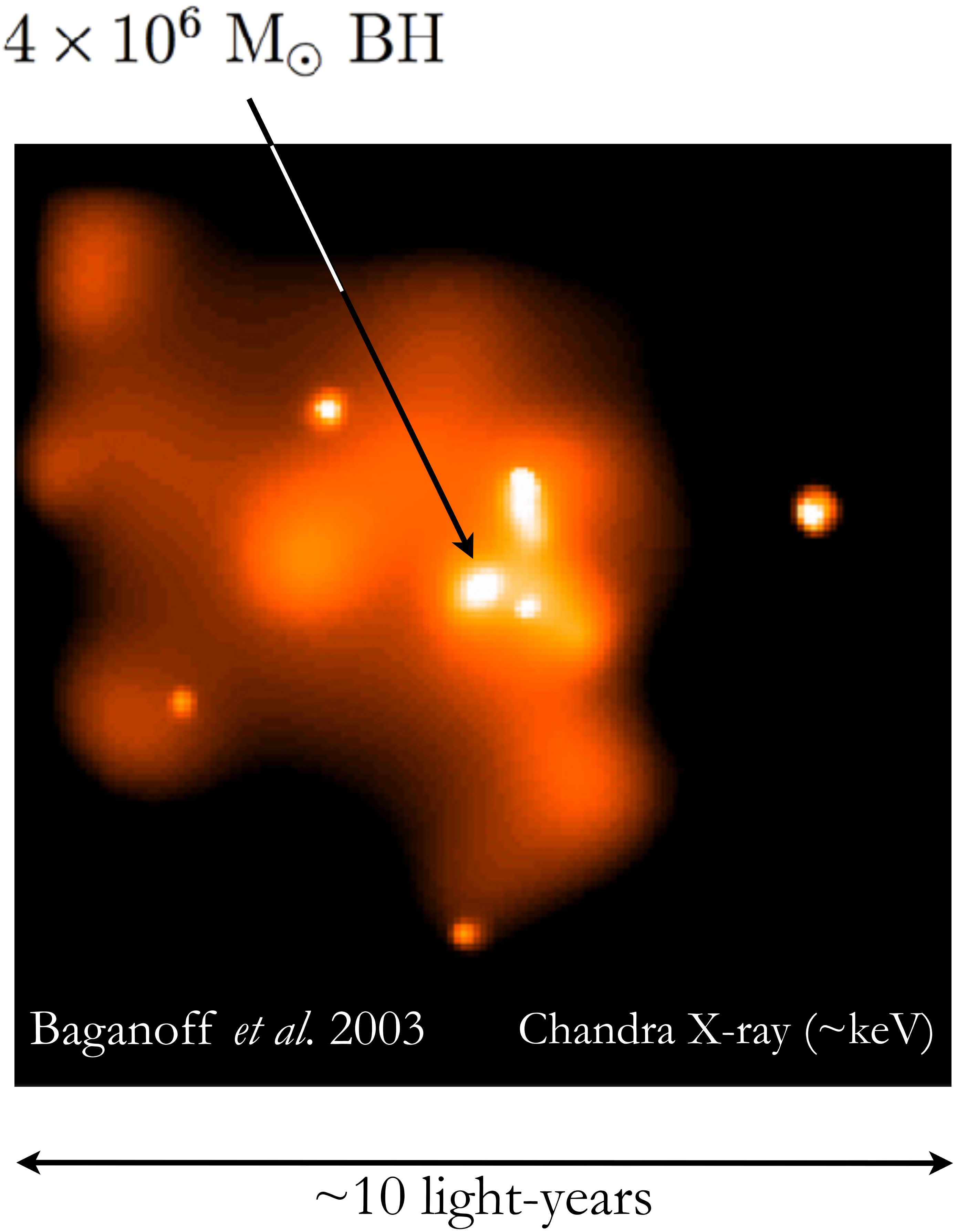
$$t_{\rm dyn} \lesssim 200 \ {\rm yr}$$

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

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

(can drive ion Larmor orbit in ~2 hrs)

Galactic Center



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

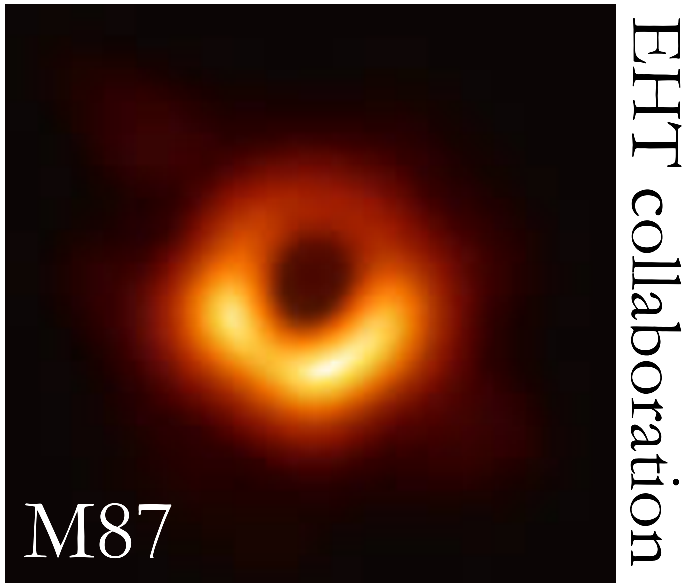
Baganoff *et al.* 2003

Chandra X-ray (~keV)

~10 light-years

get within 10 Schwarzschild radii:

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



M87

EHT collaboration

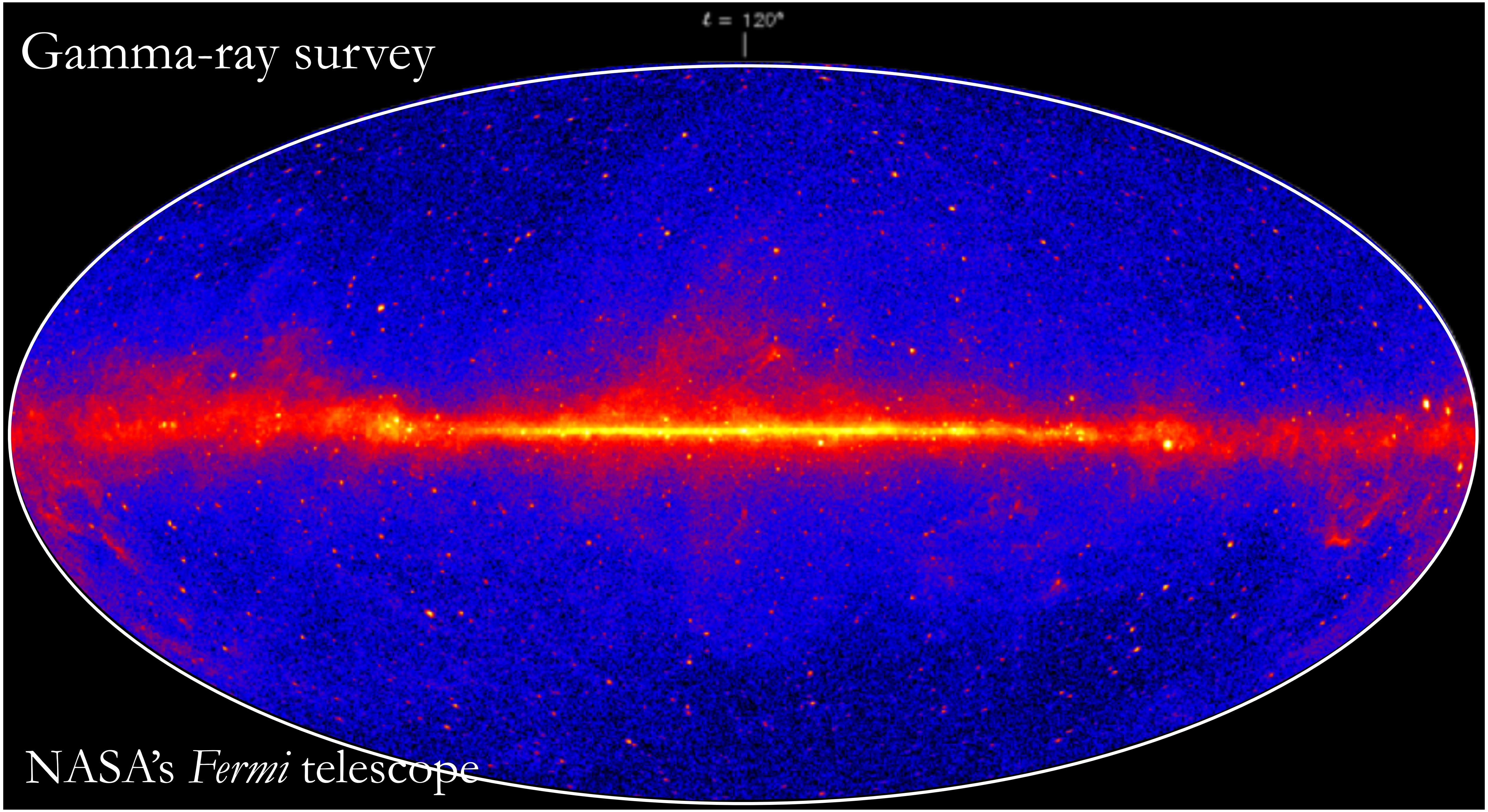
$$t_{\rm dyn} \lesssim 10\ \mathrm{min}$$

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

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

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

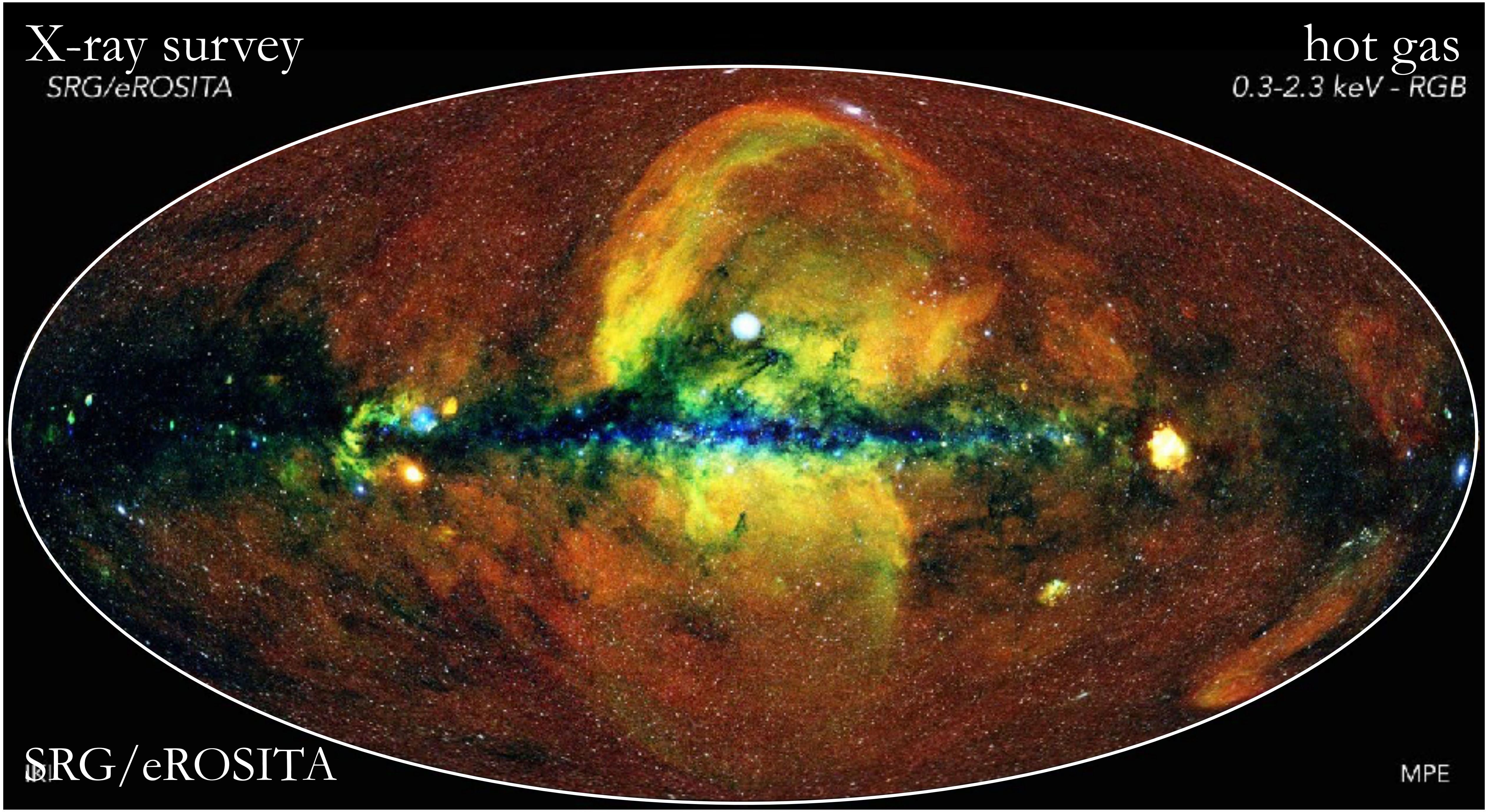
Interstellar Medium



Gamma-ray survey

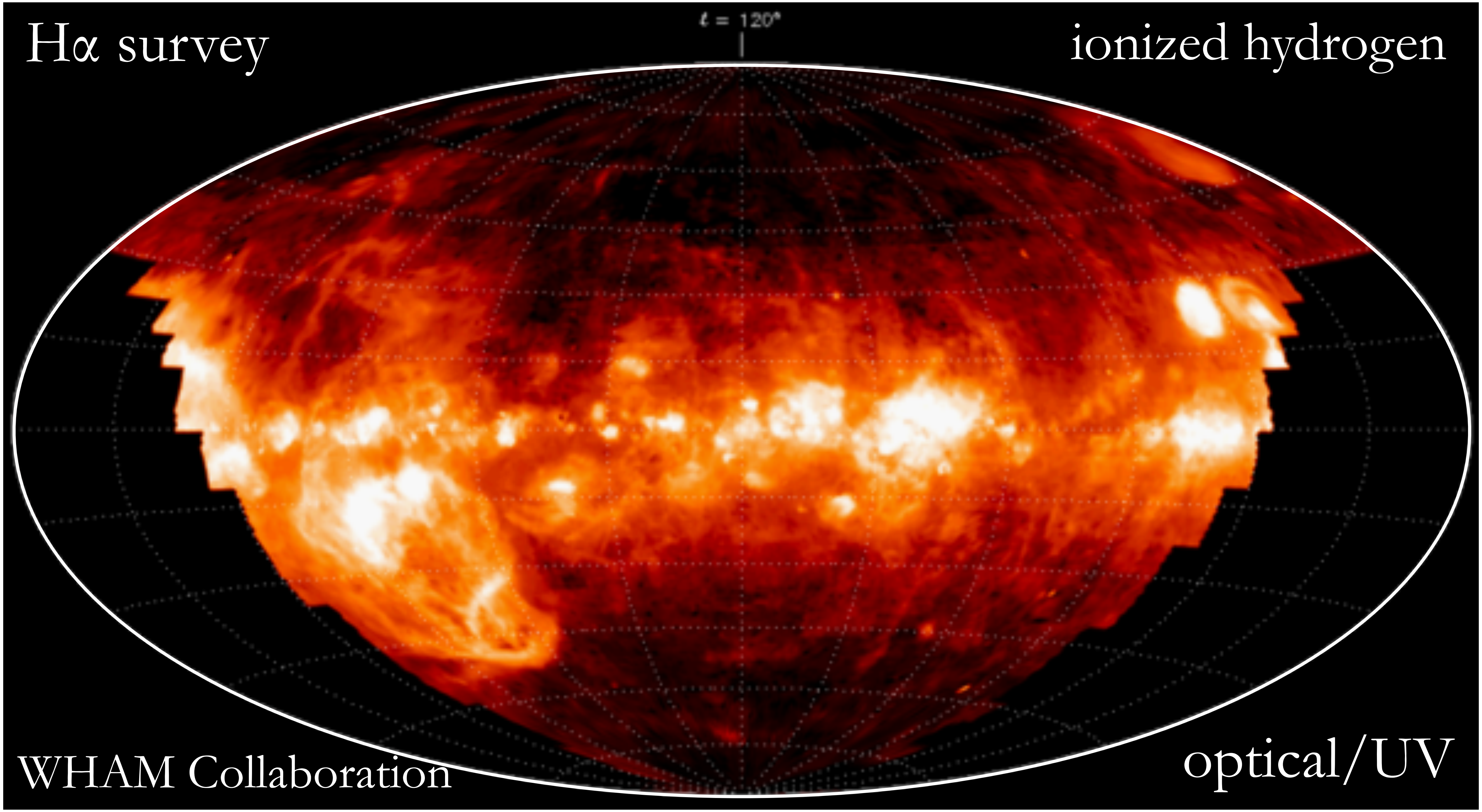
NASA's *Fermi* telescope

Interstellar Medium



gas is 99% of ISM mass; ~74% H, 24% He, 2% “metals” (C, O, N…)

Interstellar Medium



Hα survey

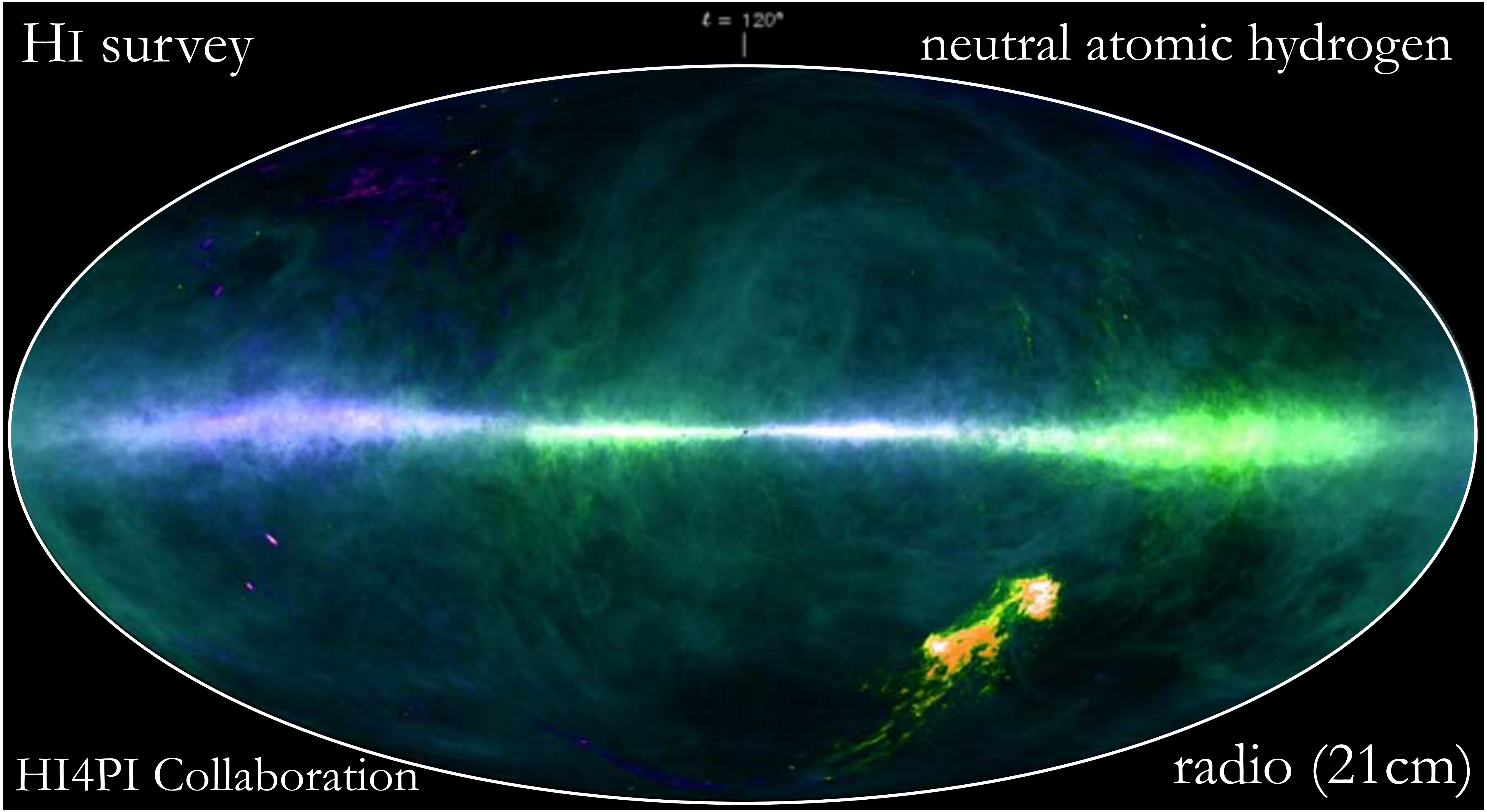
ionized hydrogen

WHAM Collaboration

optical/UV

gas is 99% of ISM mass; ~74% H, 24% He, 2% “metals” (C, O, N…)

Interstellar Medium



HI survey

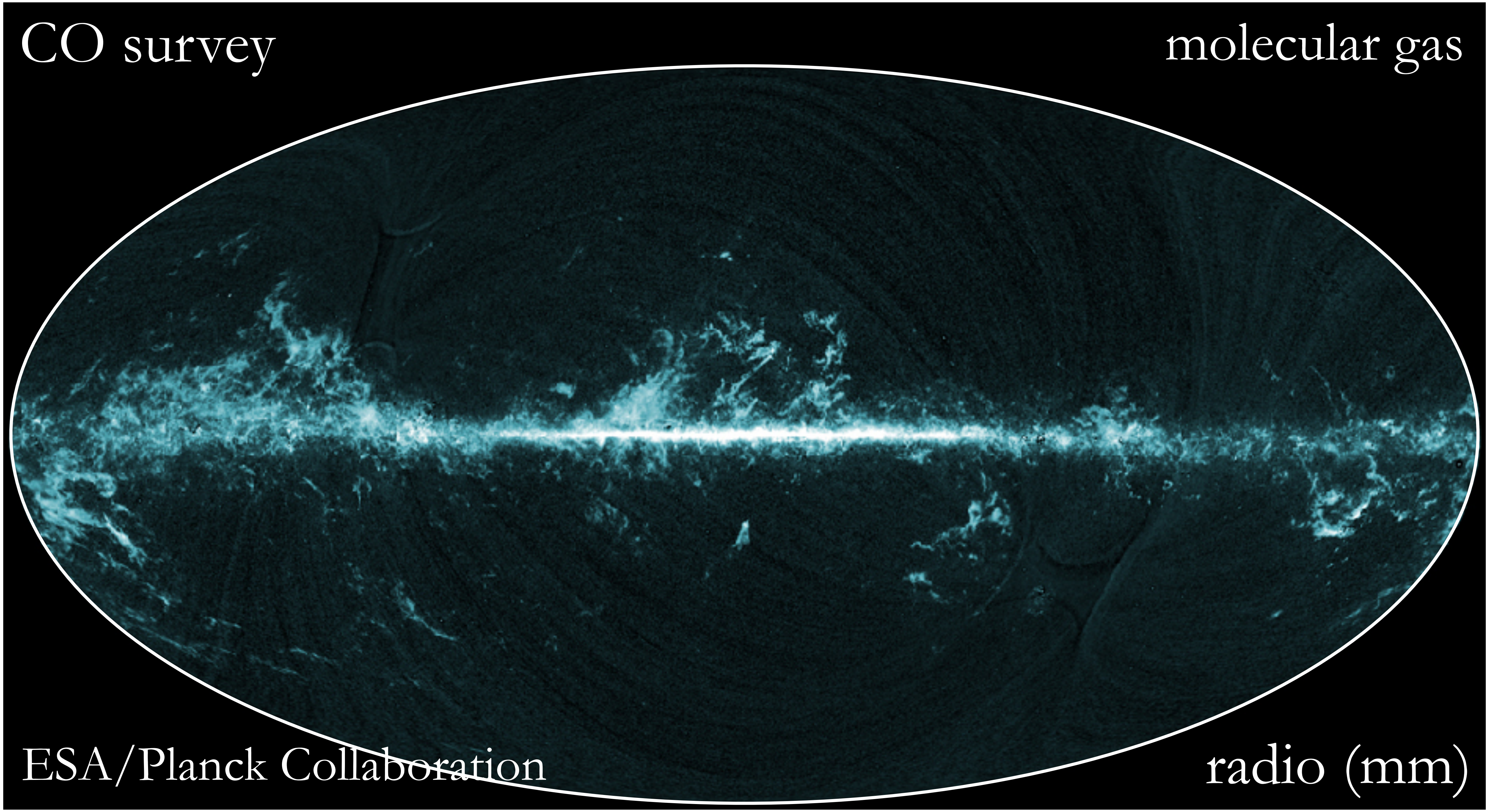
neutral atomic hydrogen

HI4PI Collaboration

radio (21cm)

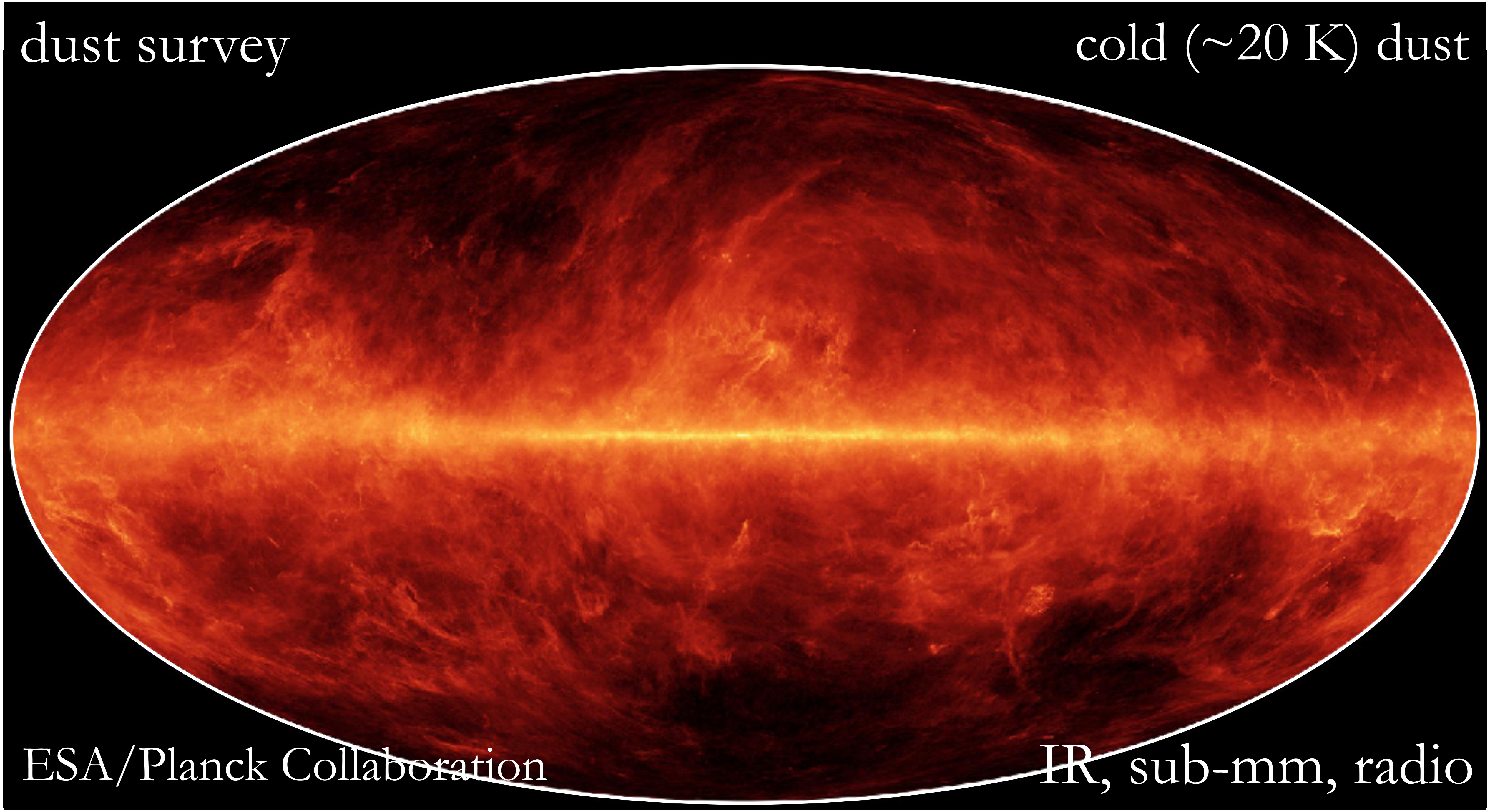
gas is 99% of ISM mass; ~74% H, 24% He, 2% “metals” (C, O, N…)

Interstellar Medium



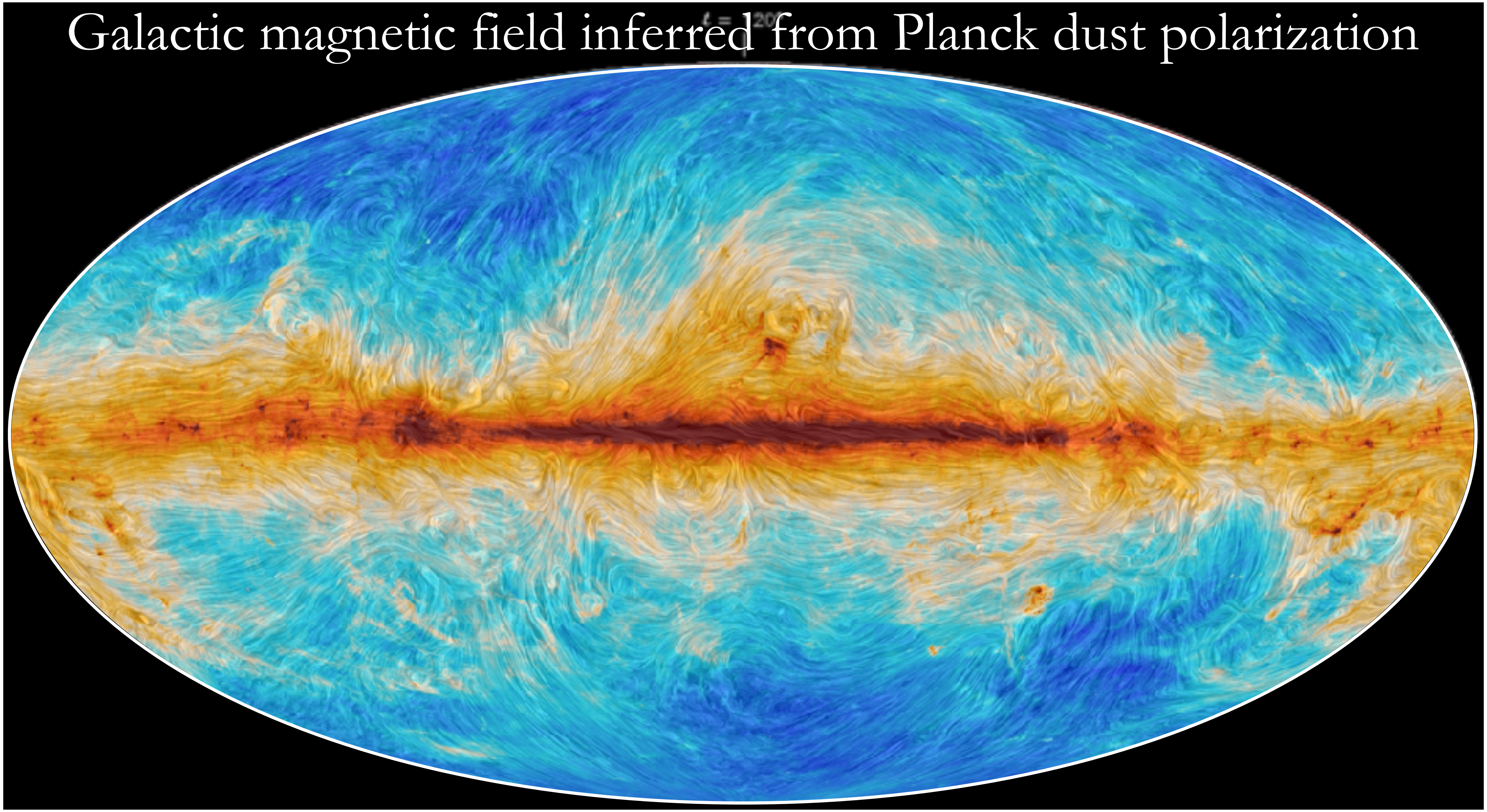
molecules: H_2, CO, HCO^+, HCN, CS, SO, N_2H^+, CH_4, OH, NH_3, H_20, CN…

Interstellar Medium



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

Interstellar Medium



Galactic magnetic field inferred from Planck dust polarization

$B \sim 5\ \mu\mathrm{G}$; 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 ($C \sim 0.2$ km s^{-1}); $n > 100$ cm^{-3}

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

Atomic CNM: $T \sim 60 - 10^3$ K ($C \sim 1$ km s^{-1}c); $n \sim 30$ 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 ~ 50% of the volume near the Galactic midplane

Interstellar Medium

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

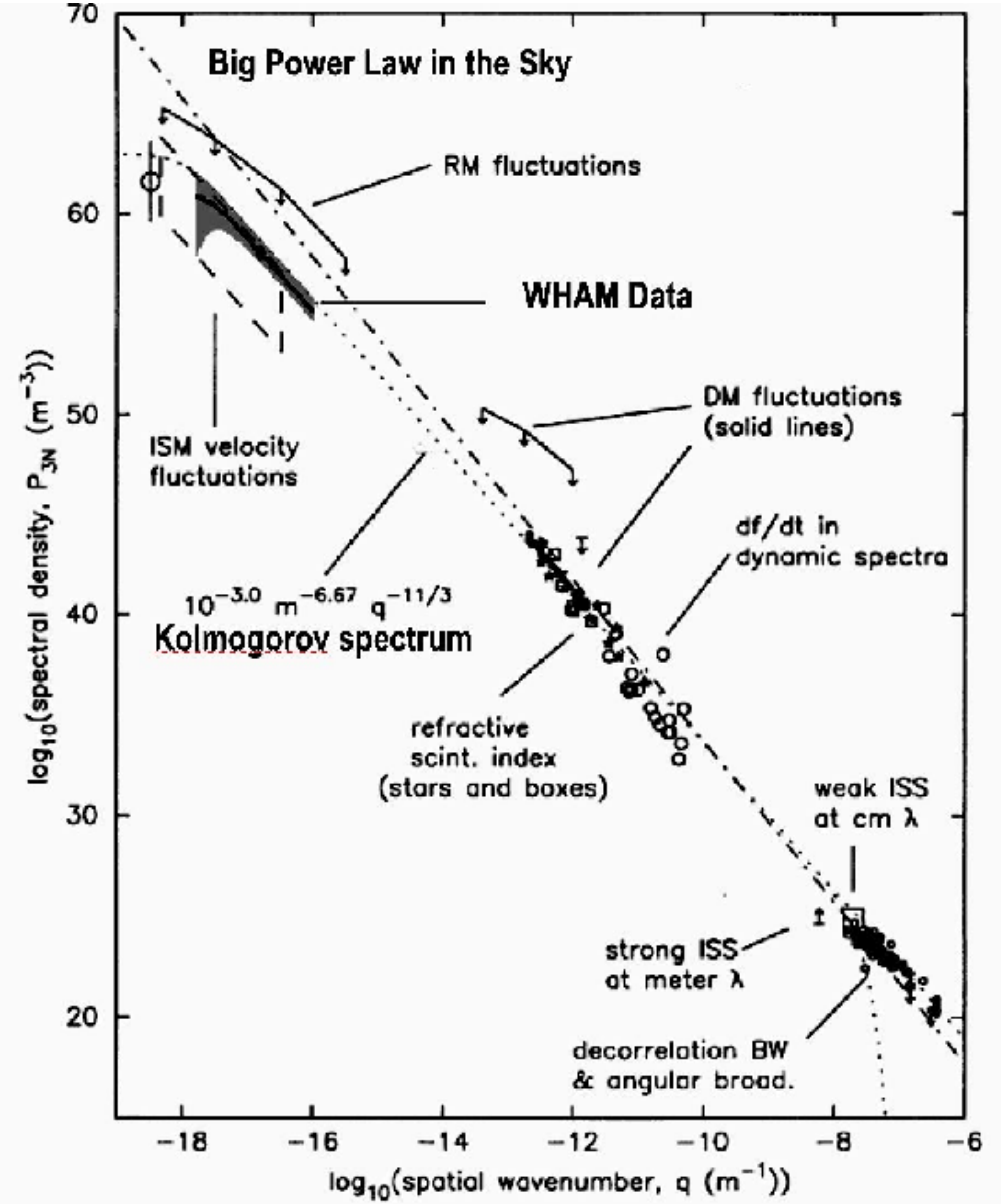
– indiv. supernova remnants, superbubbles, chimneys; ~ 50% volume

Interstellar Medium

Turbulence

“Great Power Law in the Sky”

Crab nebula,
young SNR



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

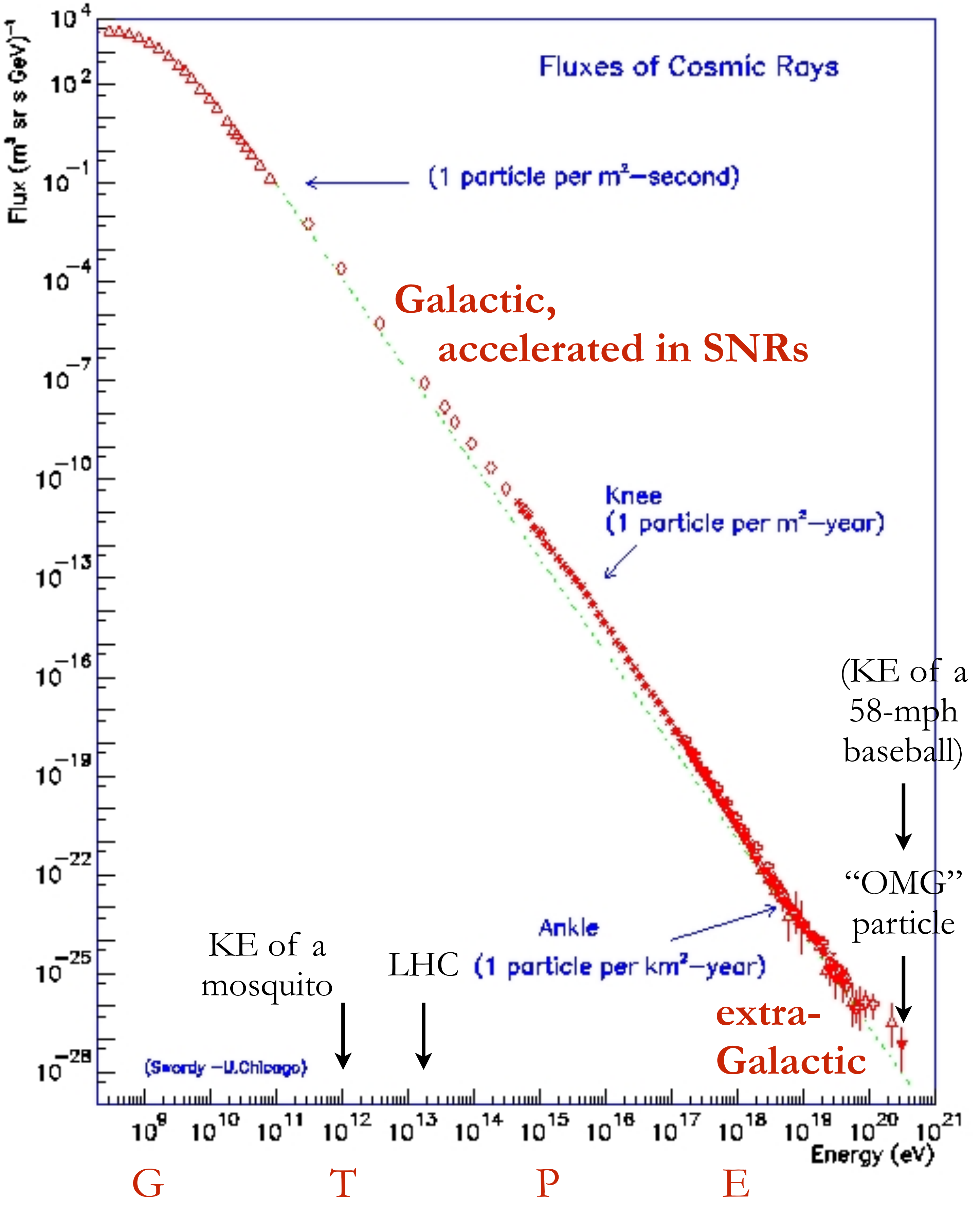
Interstellar Medium

Cosmic Rays

2nd great power law in the sky

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

(direct measurement below GeV
affected by Solar wind modulation)



**Galactic,
accelerated in SNRs**

**extra-
Galactic**

KE of a
mosquito

LHC

(KE of a
58-mph
baseball)

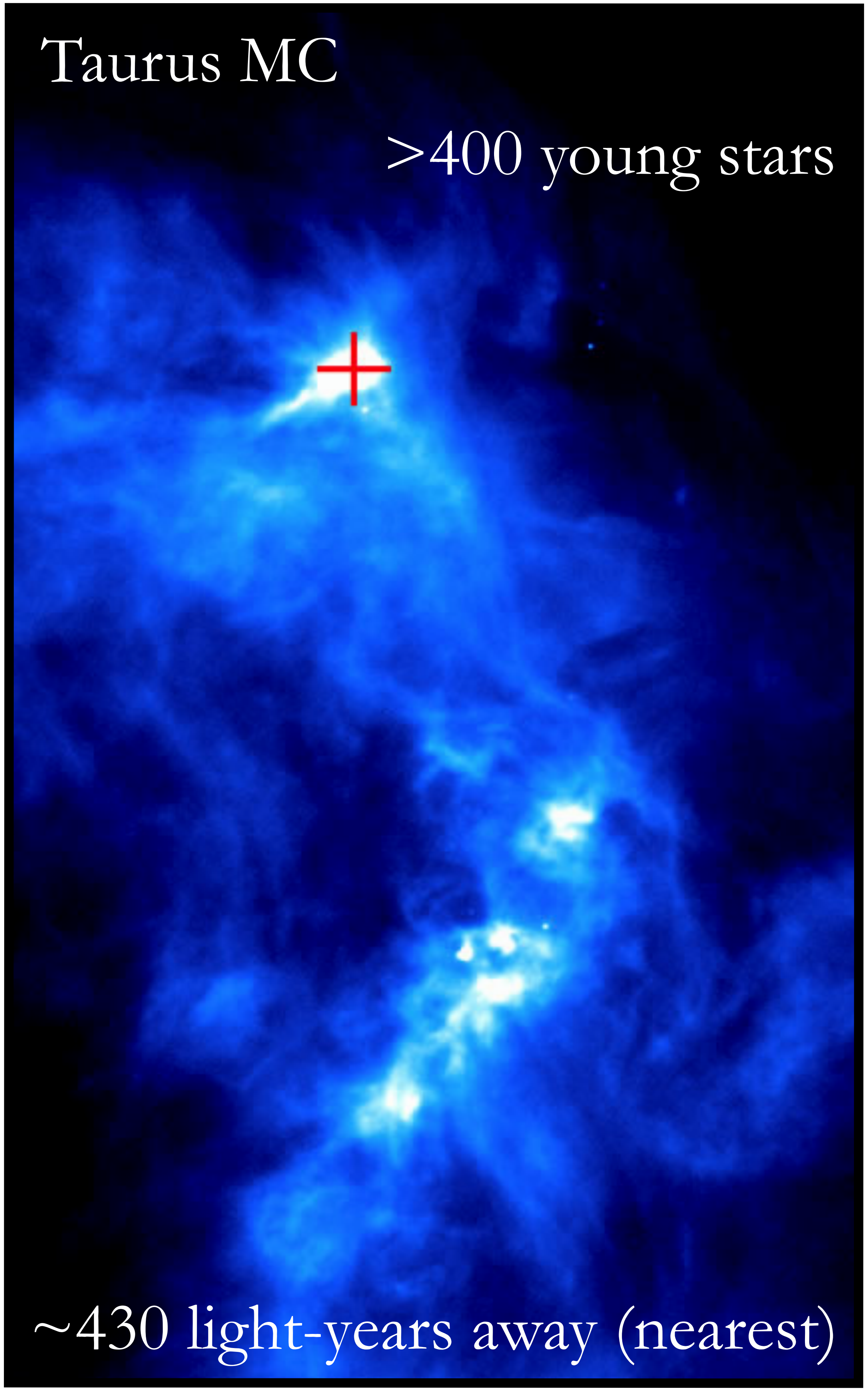
"OMG"
particle

G T P E

Interstellar Medium

what makes studying the ISM both fascinating and difficult:

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



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!

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

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

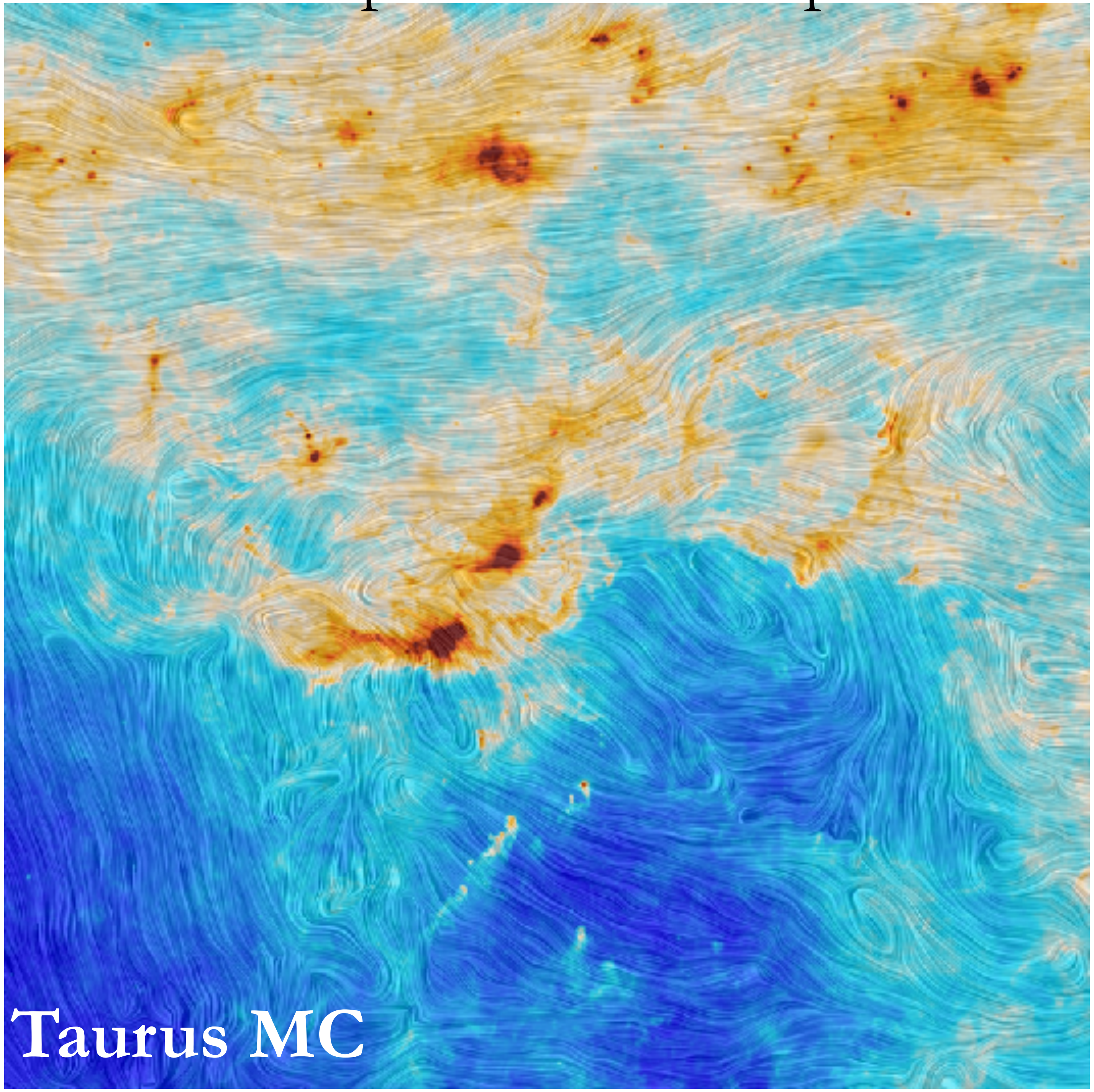
$$t_{\mathrm{coll},in} \sim 1\ \mathrm{mth}$$

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

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

Molecular Clouds

Planck dust polarization map



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

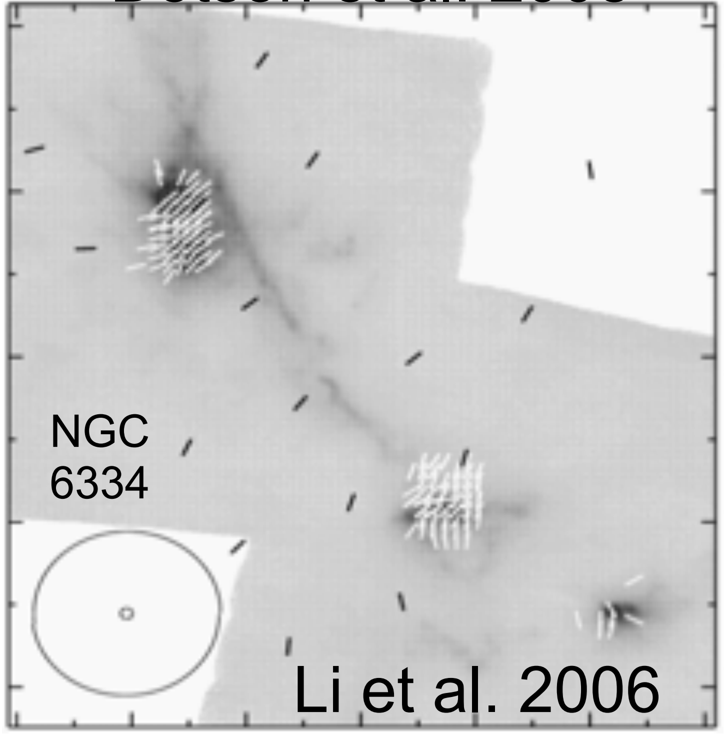
$$\beta \sim 0.01 - 0.1$$

$$M_A \sim 1$$

turbulence, magnetic fields, and gravity in rough energy equipartition

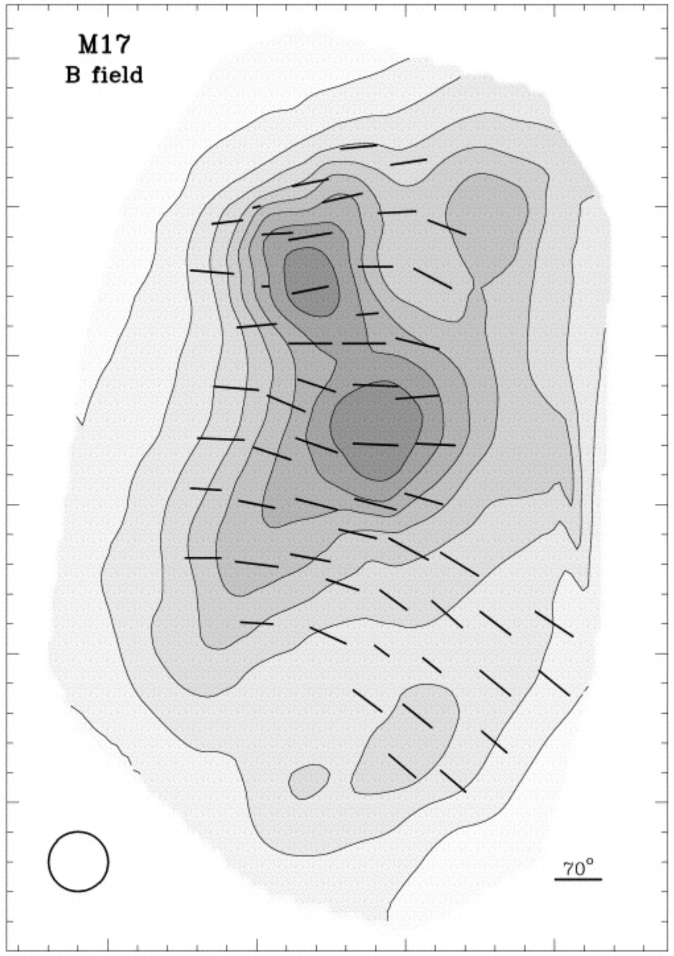
Protostellar Cores

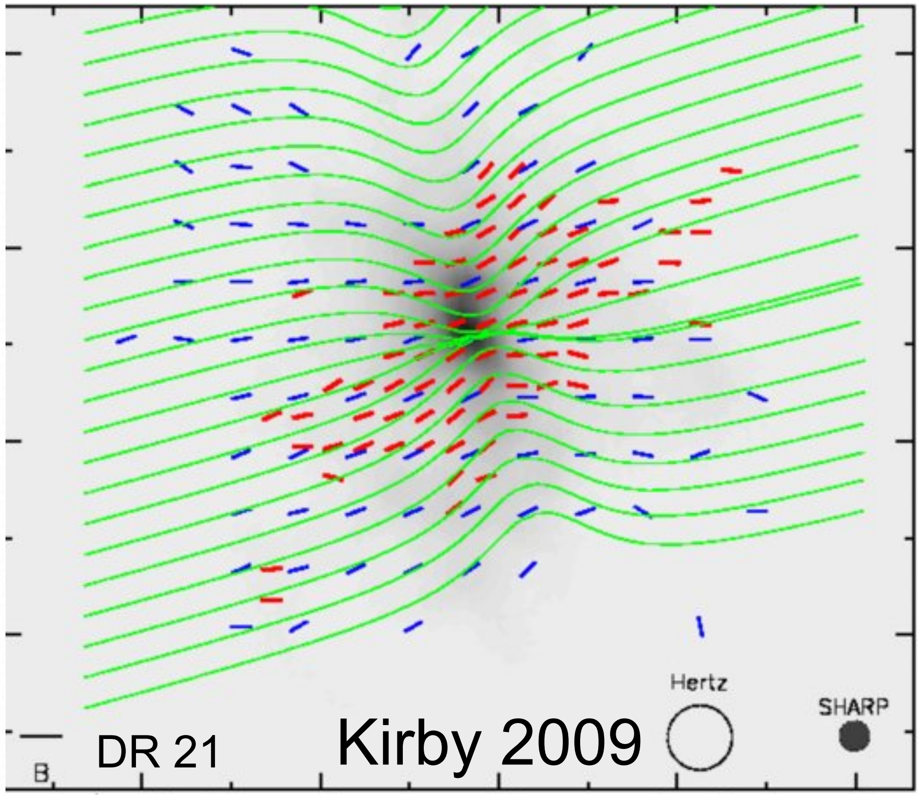
Dotson et al. 2008



Li et al. 2006

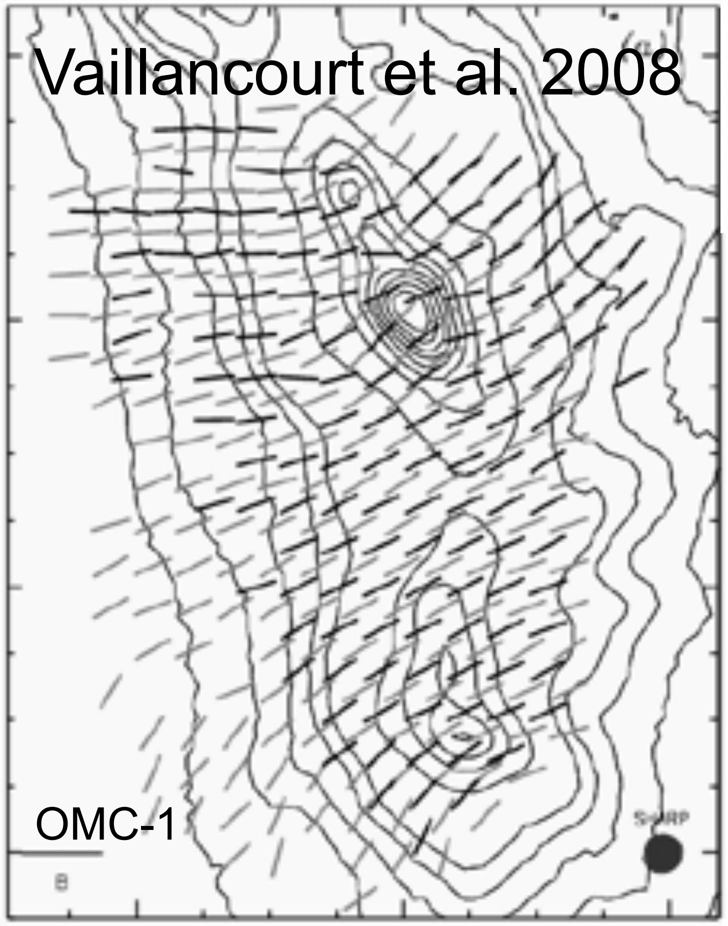
Houde et al 2002

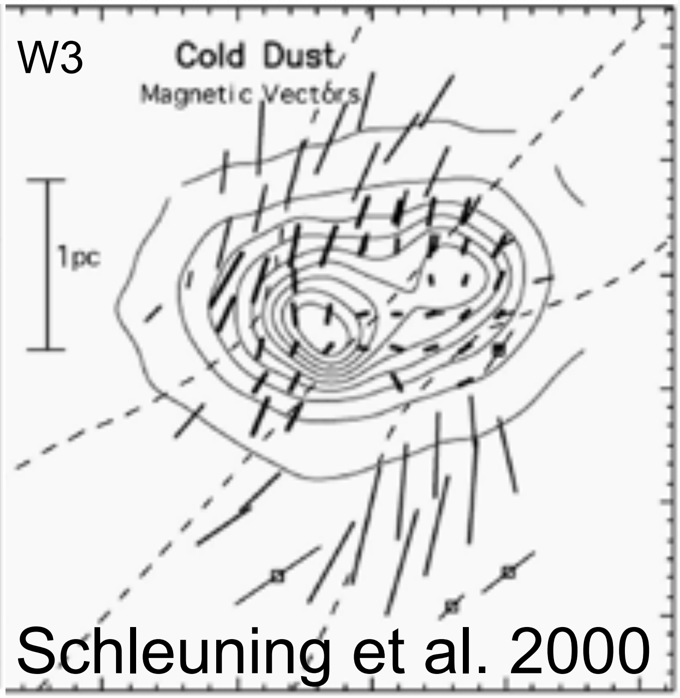




Kirby 2009

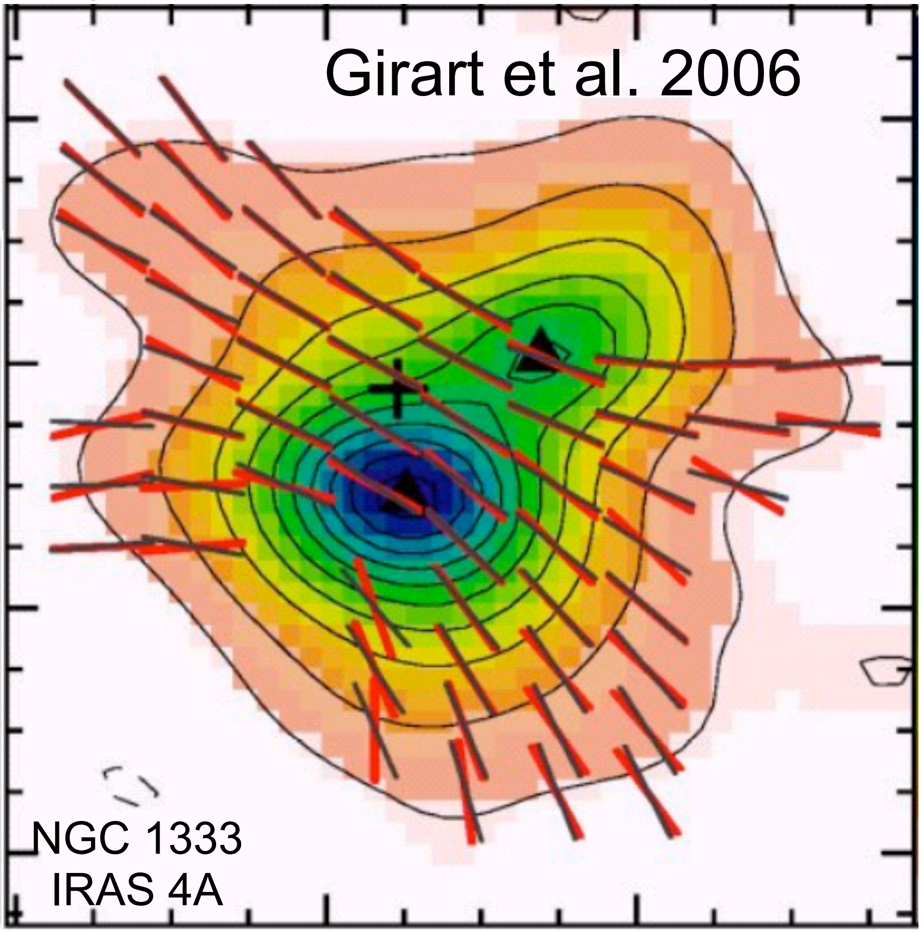
Vaillancourt et al. 2008





Schleuning et al. 2000

Girart et al. 2006



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

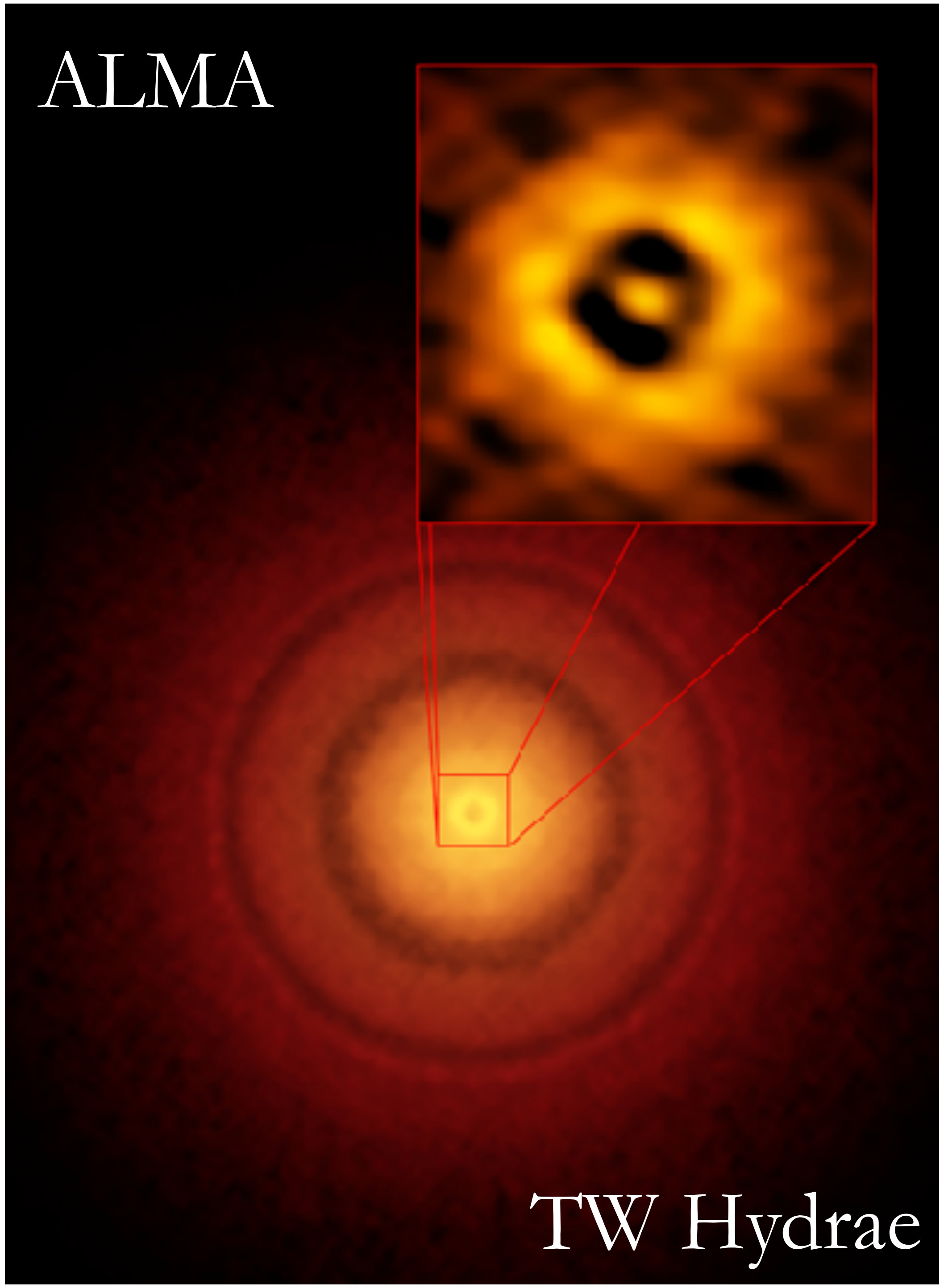
$$T \sim 10^{1-3}\ \mathrm{K}$$

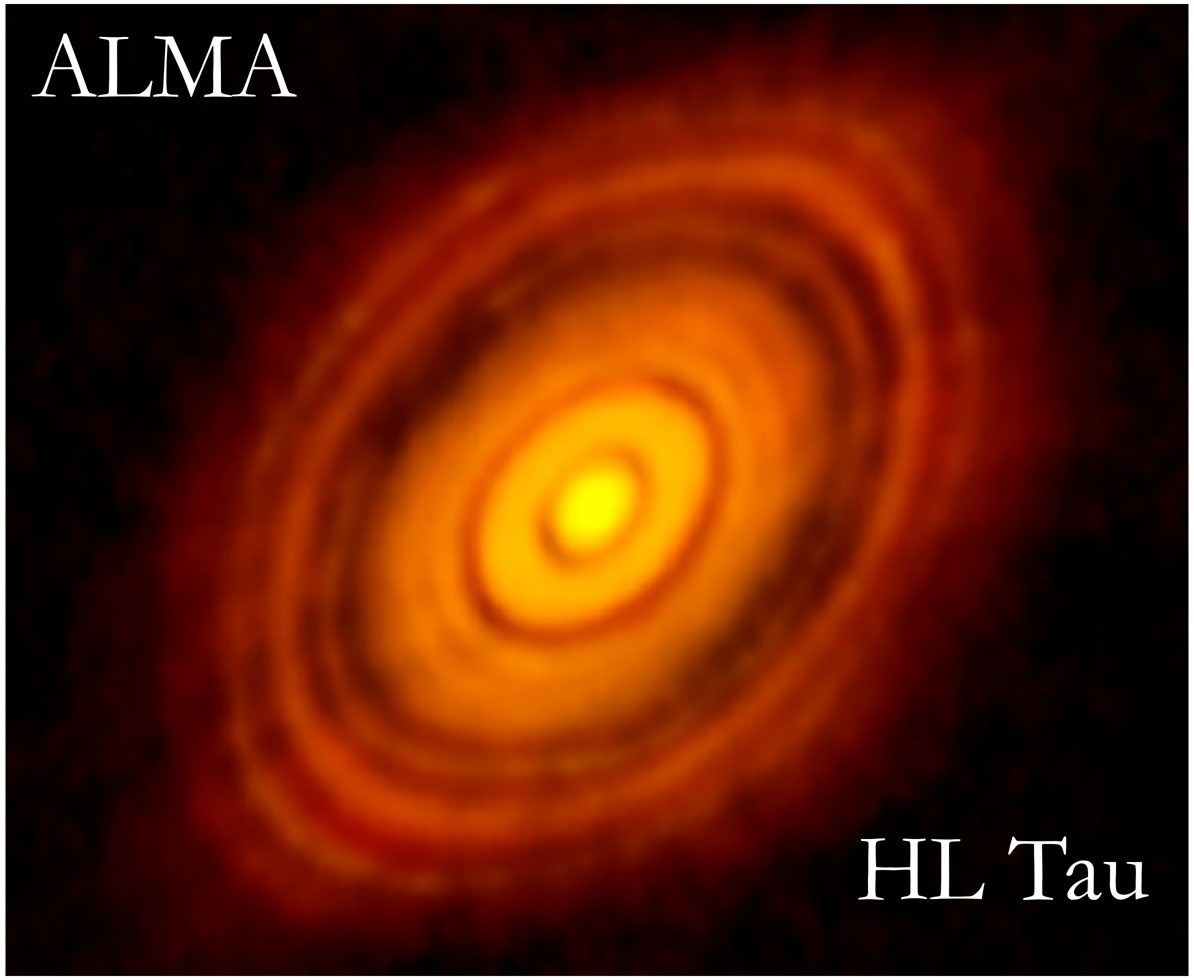
$$x_i \sim 10^{-10} - 10^{-15 \ldots}$$

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

Protoplanetary Disks

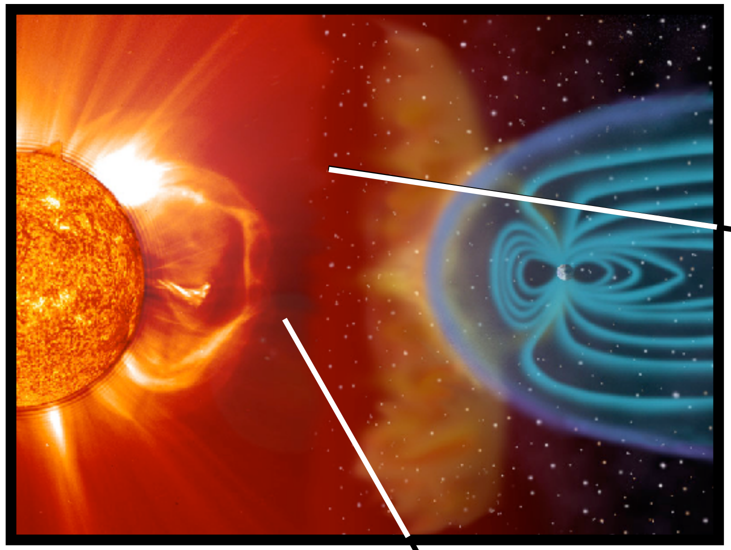
Keplerian disks of gas and dust, evolving on ~yr to ~Myr timescales





Solar Wind

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



at $r \sim 1$ au...

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

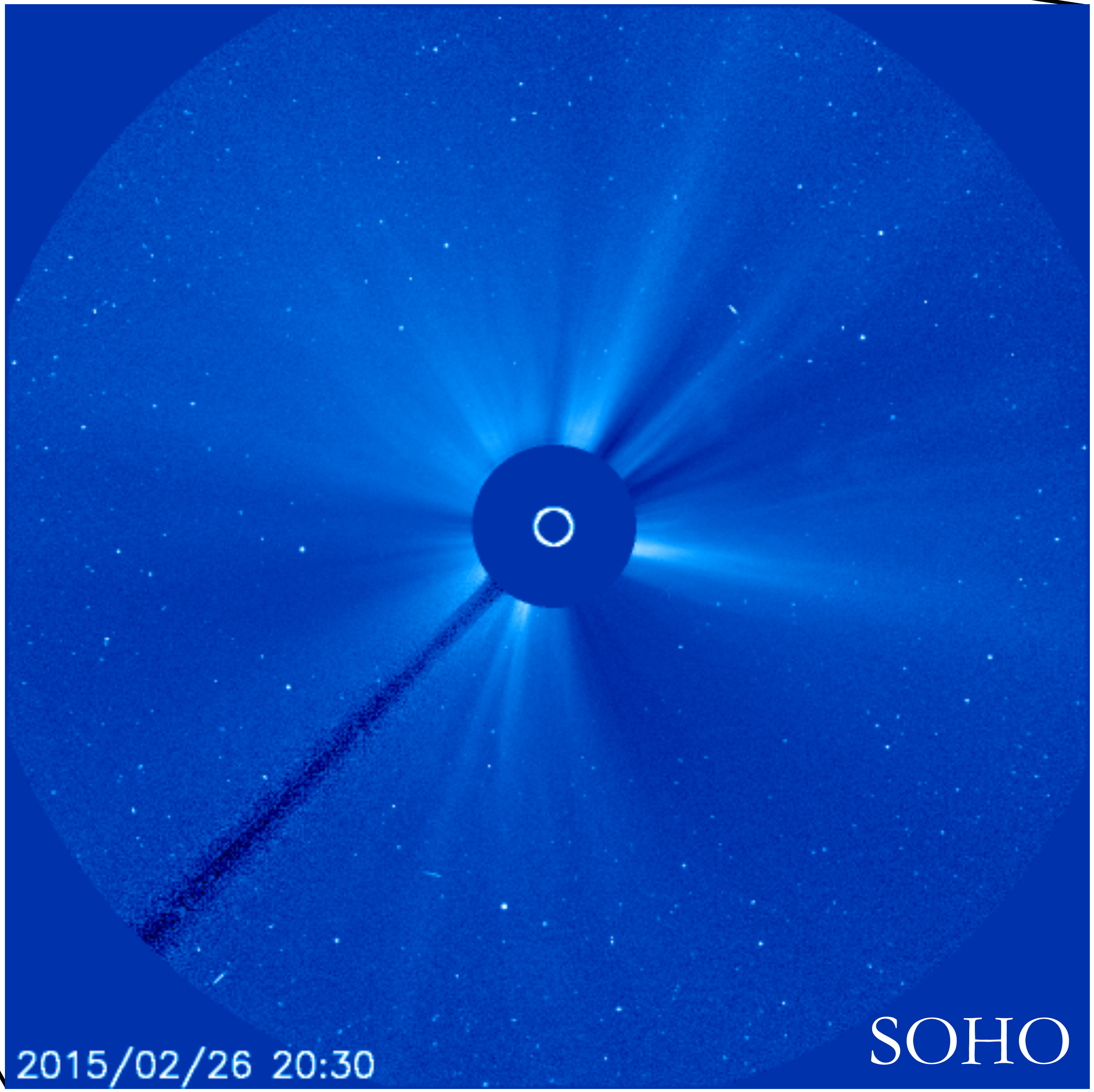
$k_B T \sim 10\ \mathrm{eV}$

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

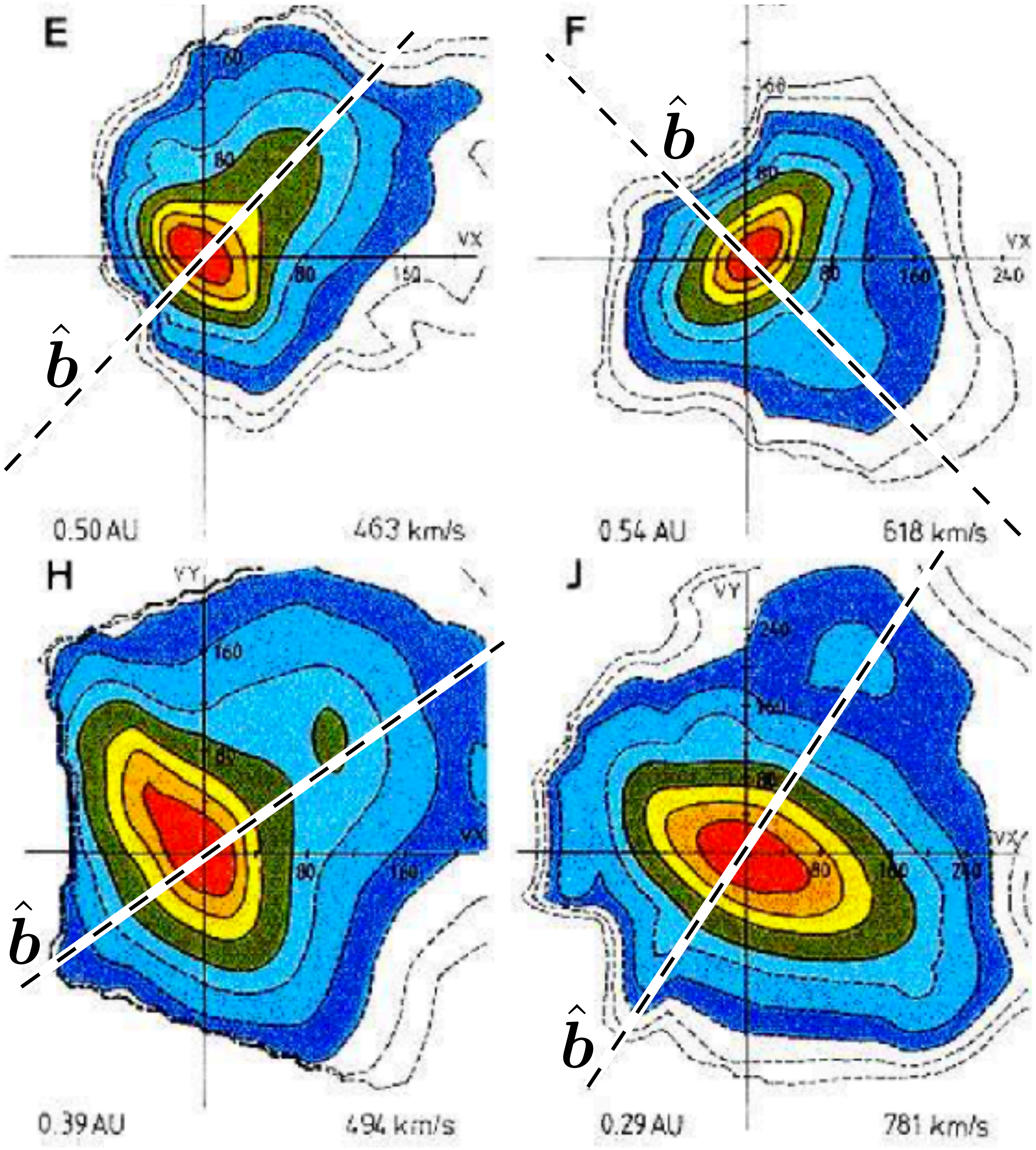
$\lambda_{\mathrm{mfp}} \sim 1$ au

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

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



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



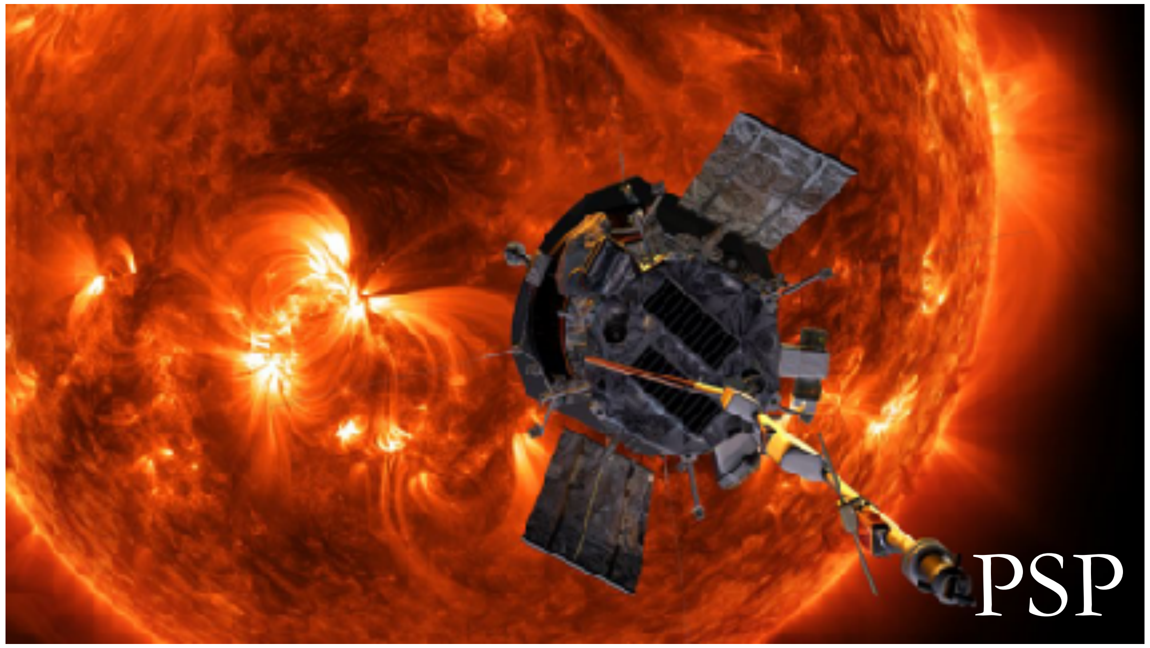
0.50 au **0.54 au**

0.39 au **0.29 au**

Marsch (2006)

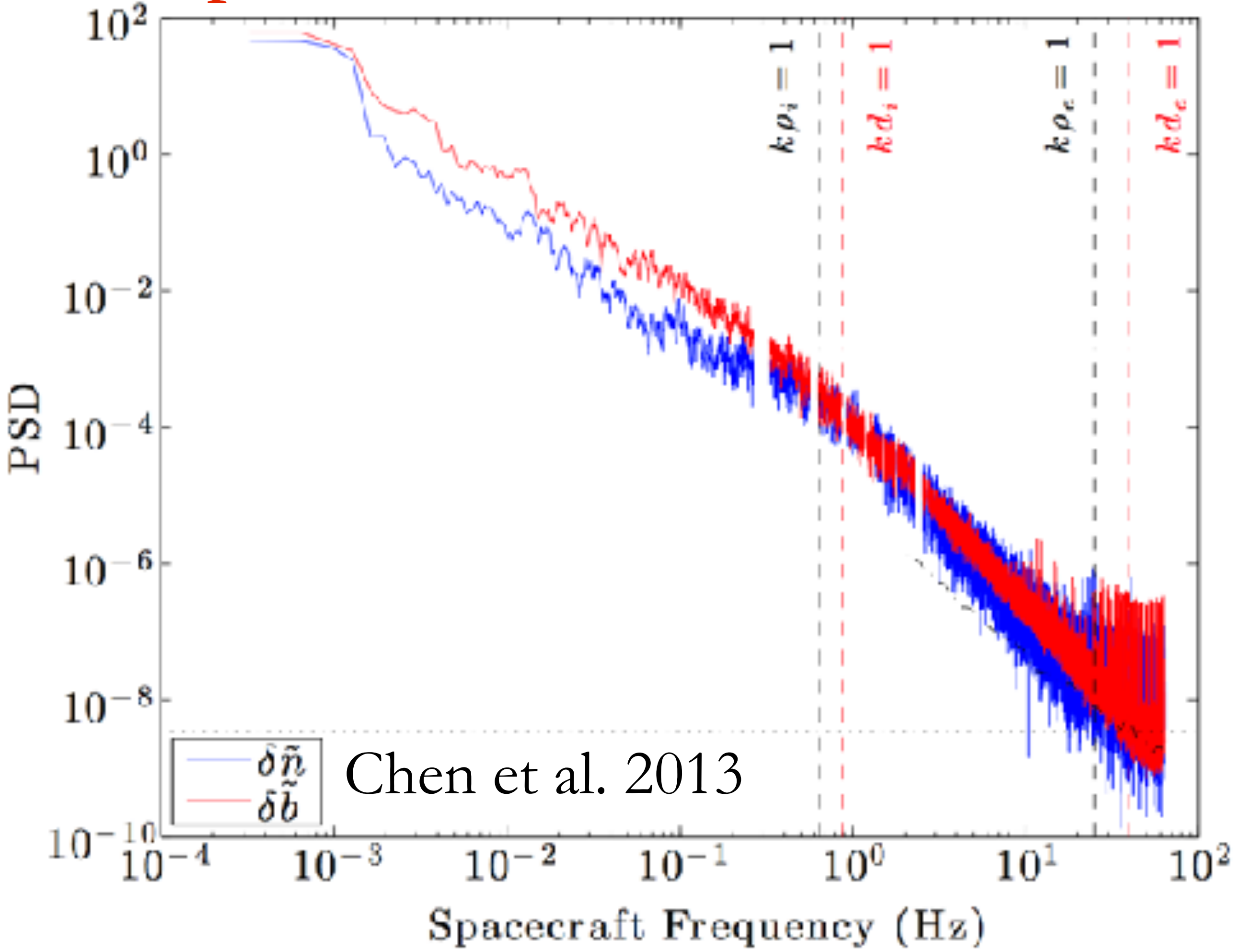
many spacecraft measuring particle velocity distribution functions and electromagnetic fields in the solar wind (SW)…

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, currently on
8th orbit, will come within ~9 $R_\odot$
of solar surface (at 430,000 mph)



http://parkersolarprobe.jhuapl.edu

excellent laboratory for studying plasma kinetics and turbulence



Chen et al. 2013

Solar Corona

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

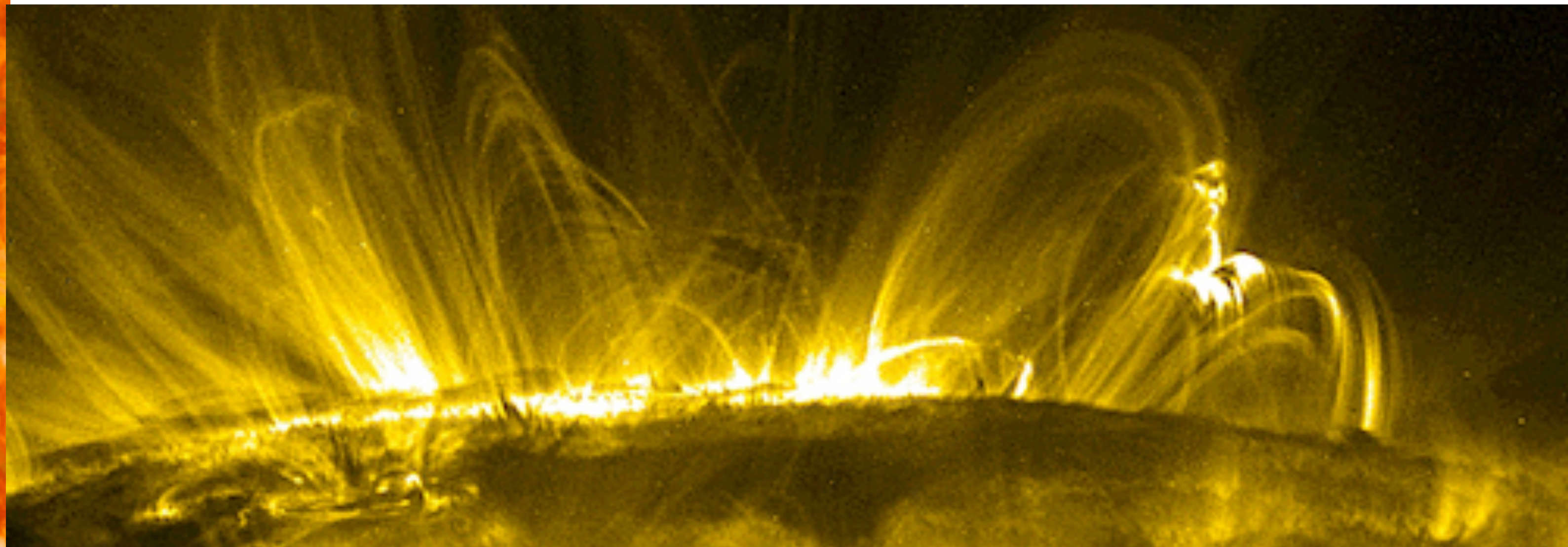
photosphere is $\approx$5800 K

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

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

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

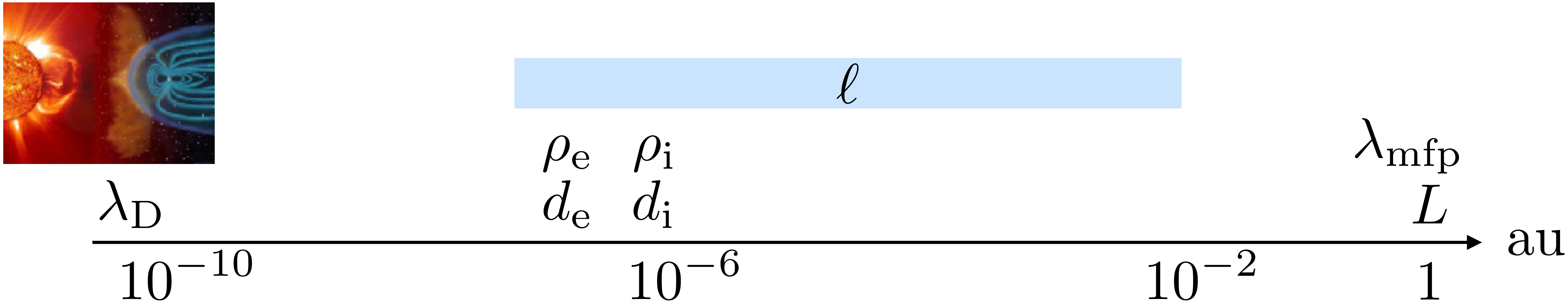
$$\beta \lesssim 0.01$$



What were the common themes?

(other than plasma and magnetic fields)

huge scale separations!


ℓ
ρ_{e} ρ_{i}
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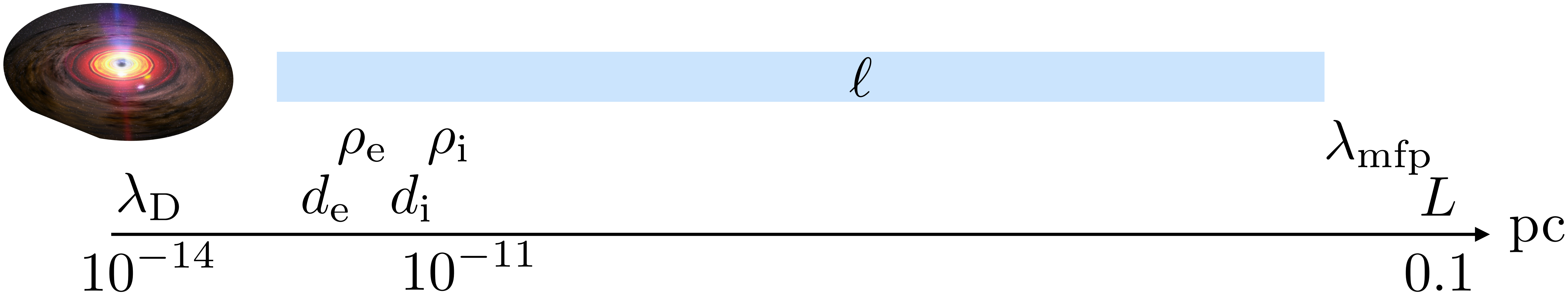
L
au
10^{-10}
10^{-6}
10^{-2}
1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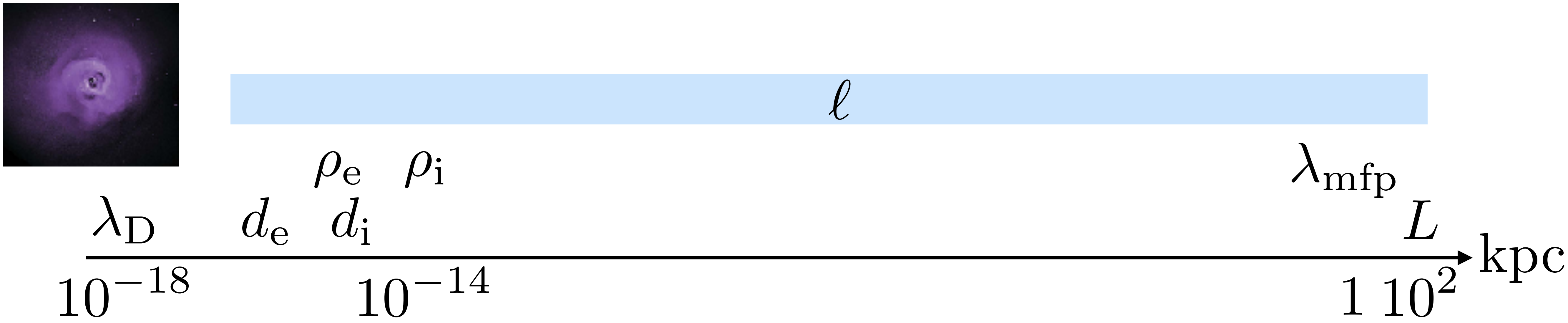
ℓ
ρ_{e} ρ_{i}
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λ_{mfp}
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10^{-18}
10^{-14}
1 10^{2}

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 $\mathrm{M}_\odot$ 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 $\sim$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:

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

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 heating (T_{e} vs T_{i})
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 and non-thermal particle acceleration (up to $\sim 10^{20}$ 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…)

1-hour break

see you at…

PDT	MDT	CDT	EDT	KST	AEST
10am	11am	12pm	1pm	2am	3am