CHANNELING ASTROPHYSICAL MAGNETIC FIELDS TO THE CIRCUMGALACTIC MEDIUM

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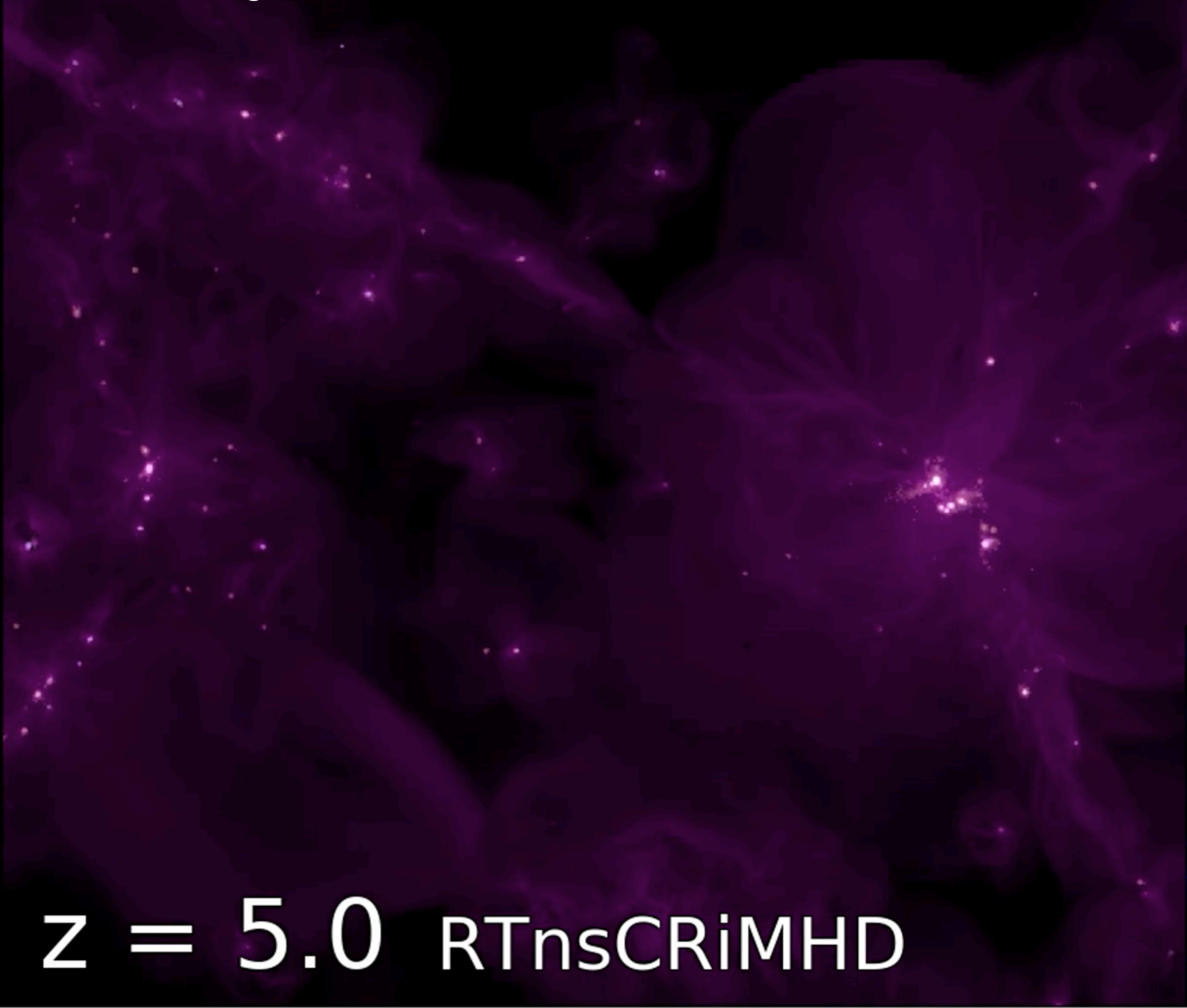
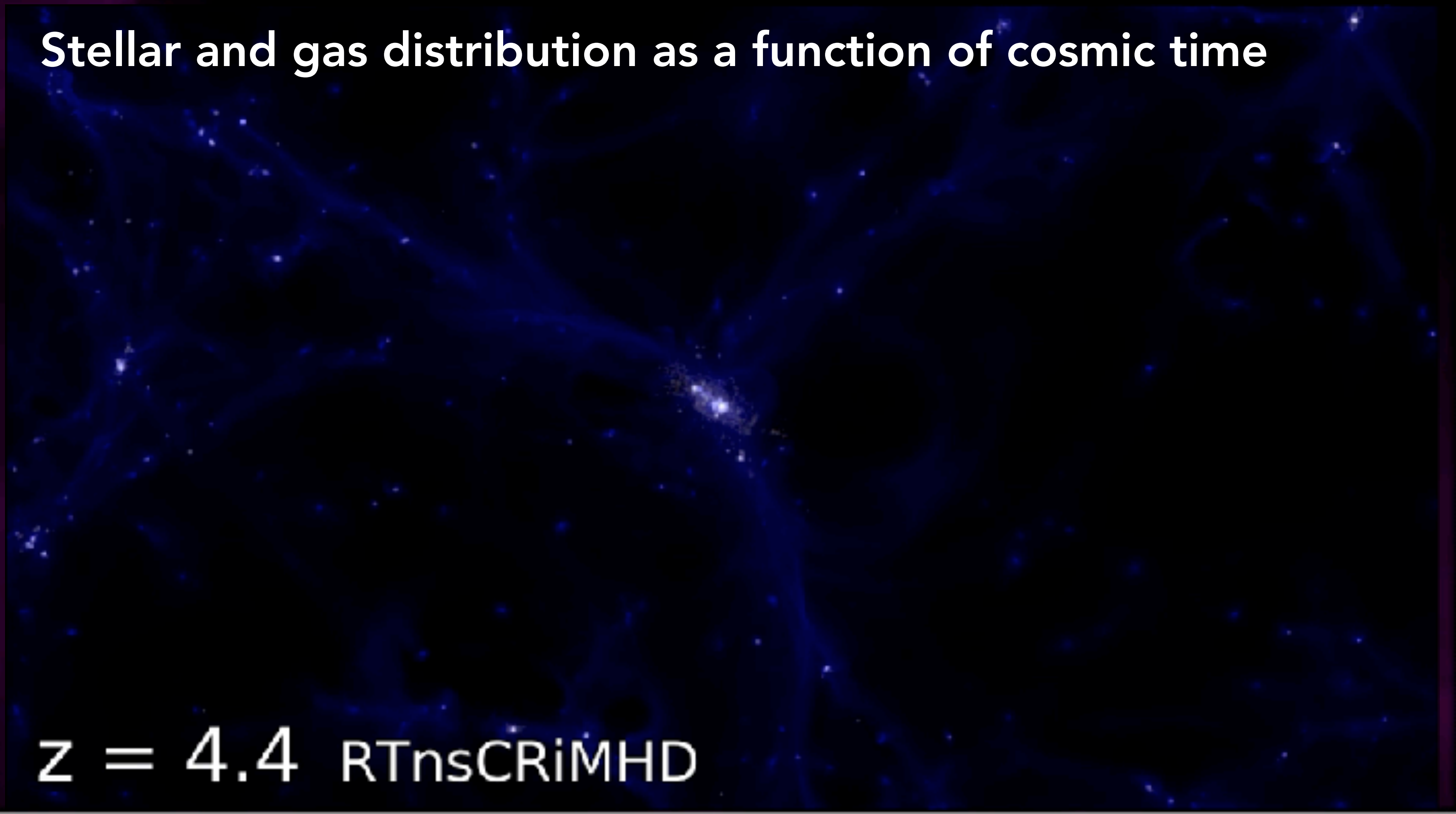
Stellar and gas distribution as a function of cosmic time

Martin-Alvarez et al. (2022: Pandora Project I)

Stellar and Magnetic Field distribution as a function of cosmic time

Martin-Alvarez et al. (2022: Pandora Project I)





Is the circumgalactic medium magnetized?

- What are the physical mechanisms driving the B-field into the CGM?
- How much B is driven away?

THE ROLE OF STARBURST IN GALAXY EVOLUTION: M82 AS CANONICAL EXAMPLE

'Galactic winds are the primary mechanism by which energy and metals are recycle in galaxies and deposited into the IGM'

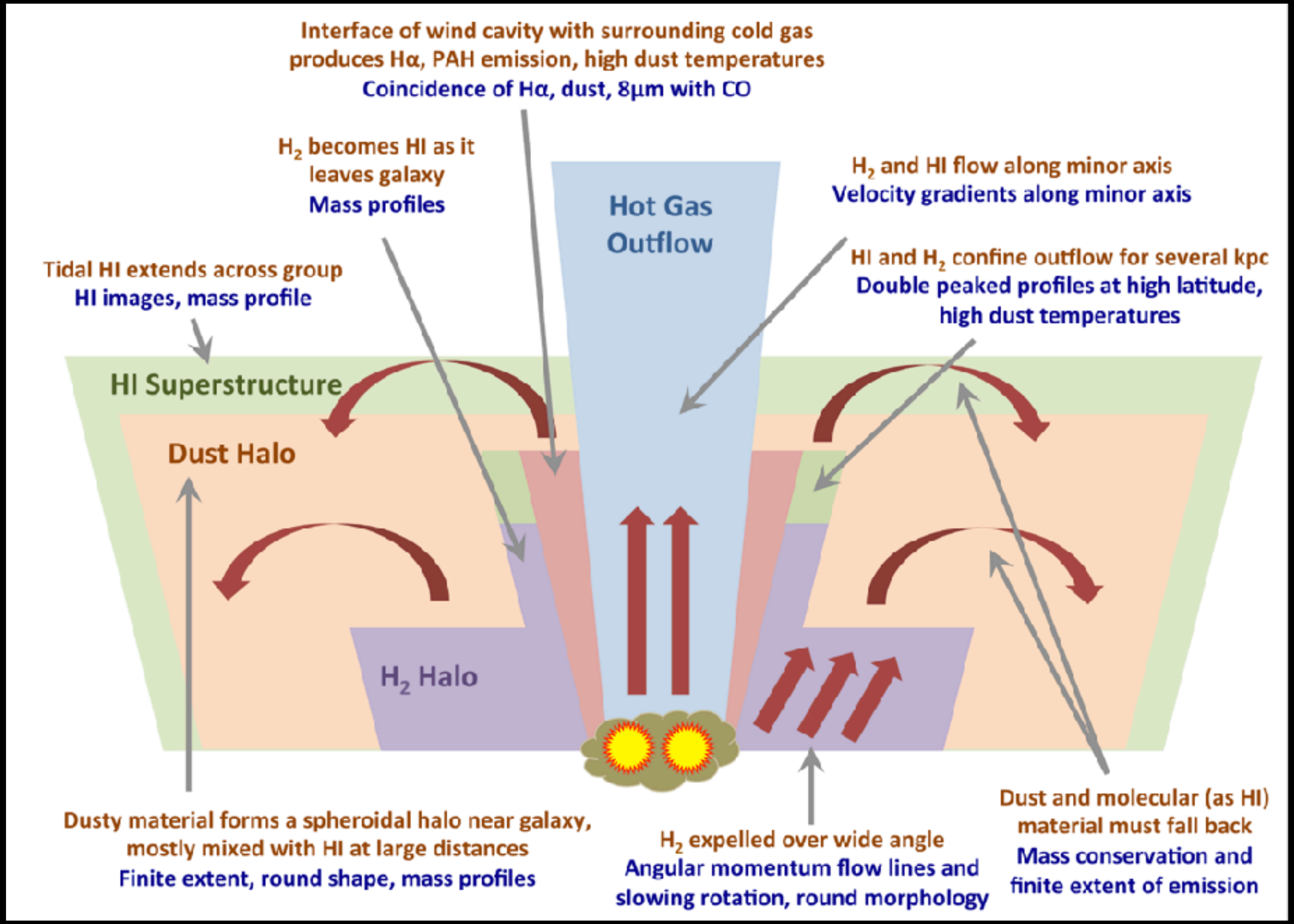
Veilleux, Cecil & Bland-Hawthorn's ARAA Review (2005)

D = 3.85 Mpc (20 pc/", Vacca et al. 2015)

Bipolar superwind driven by extreme star formation regions.

Galactic wind is extended and perpendicular to the galactic plane up to ~10 kpc.

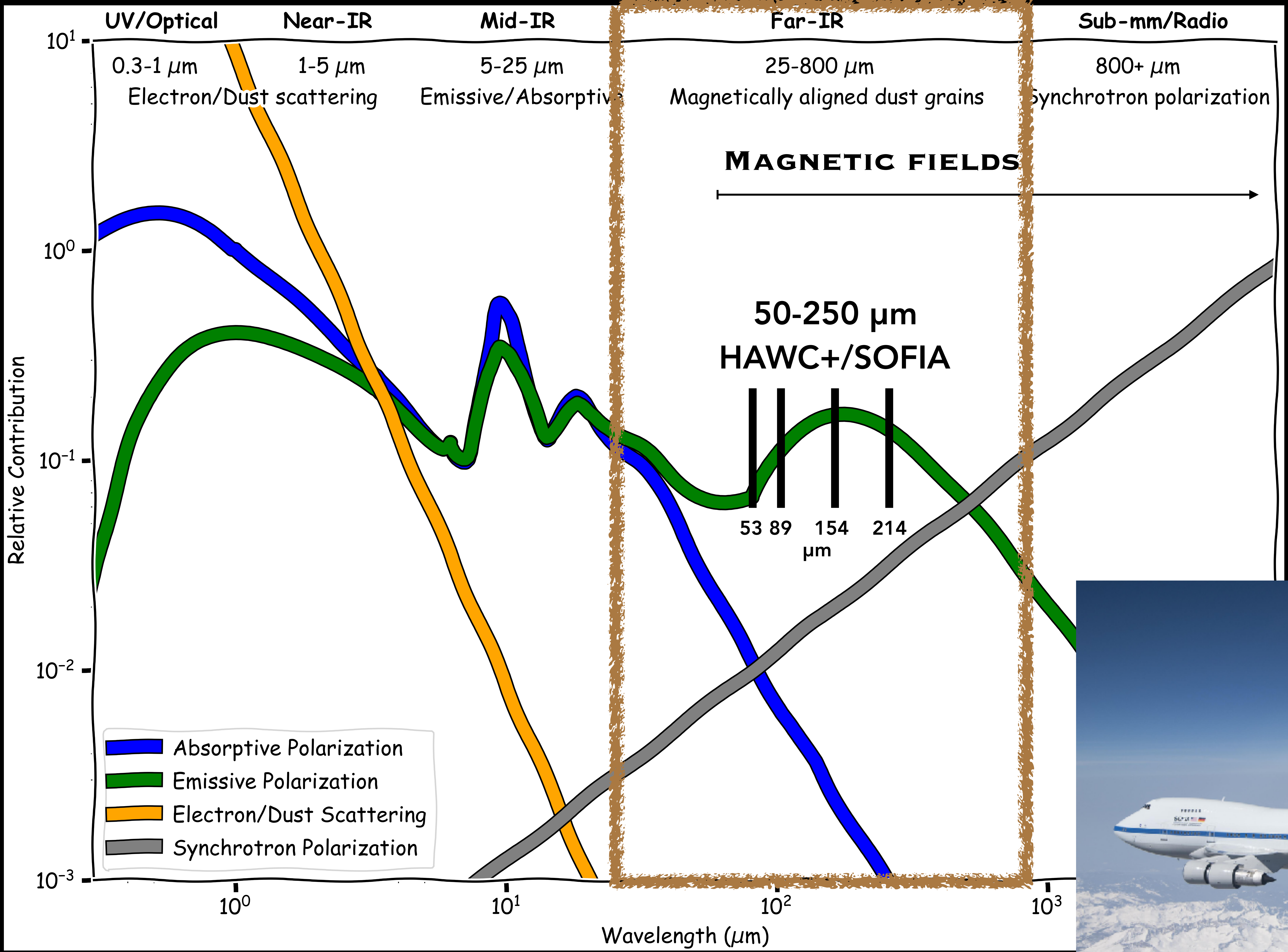
Credit: NASA



Not to scale

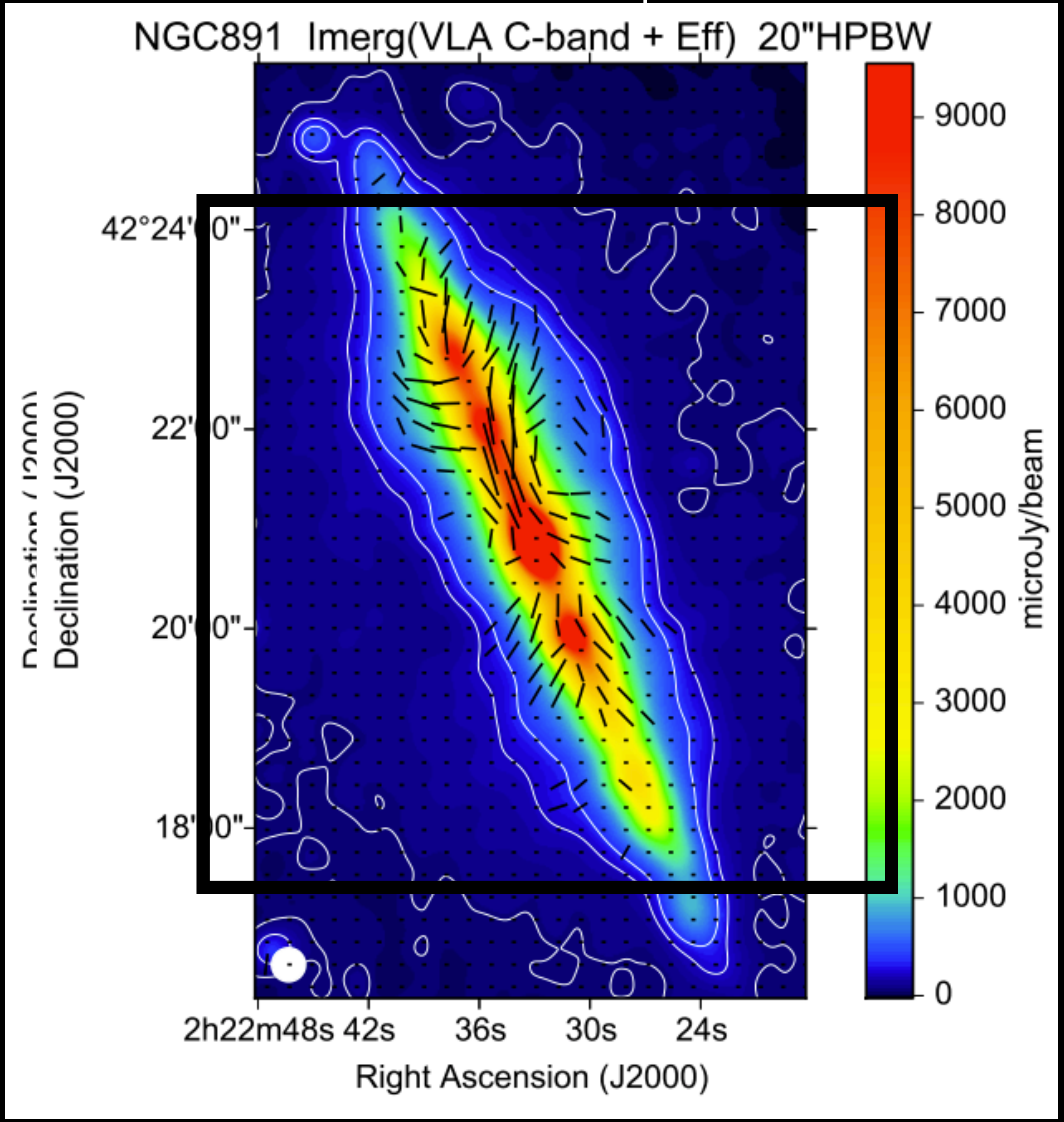
Leroy et al. (2015)

OUR APPROACH: THERMAL POLARIZED EMISSION FROM DUST



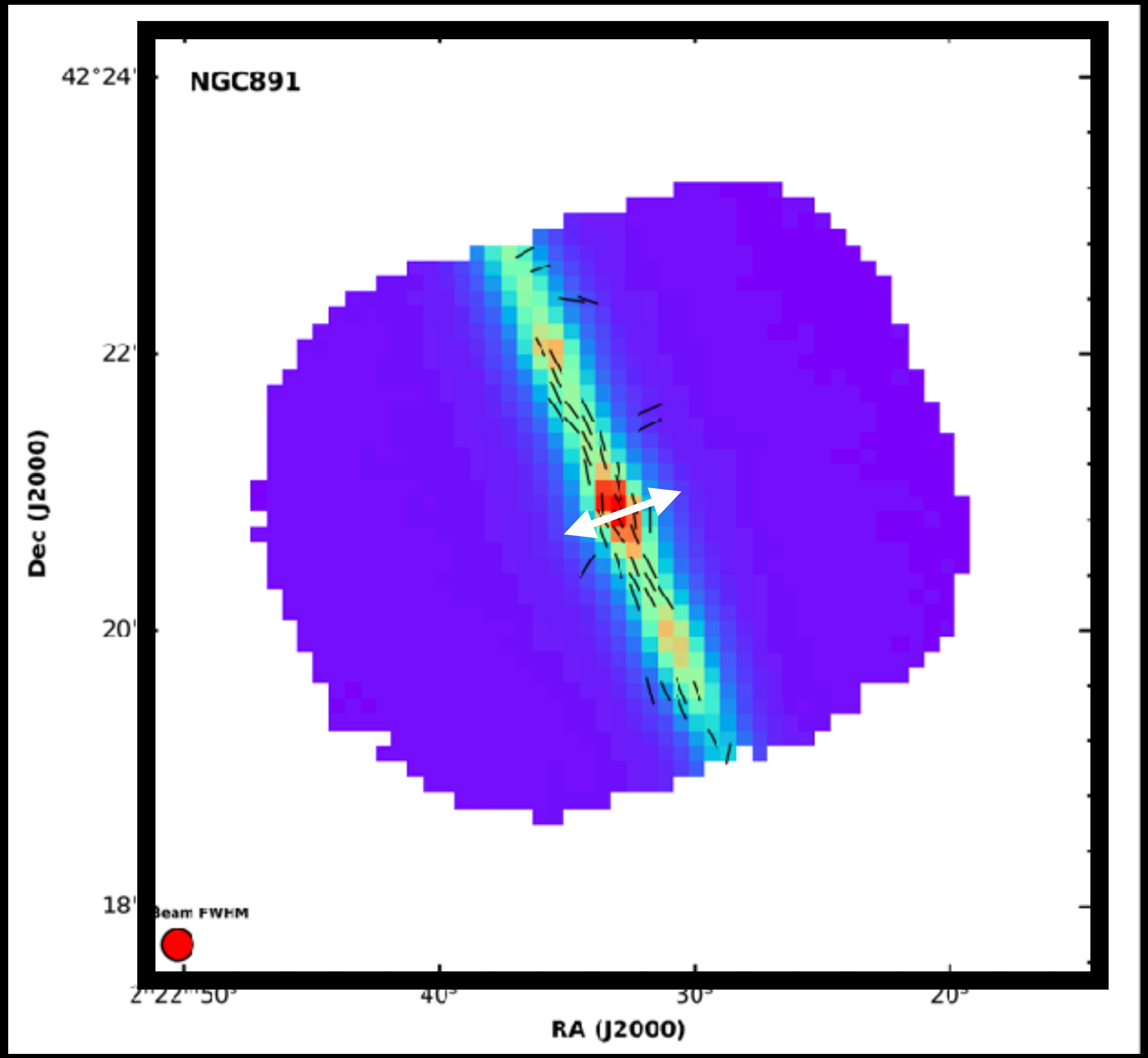
What are we measuring at Radio and FIR wavelengths?

Radio: warm and diffuse ISM
h ~ 1-2 kpc



Krause et al. (2018,2020)

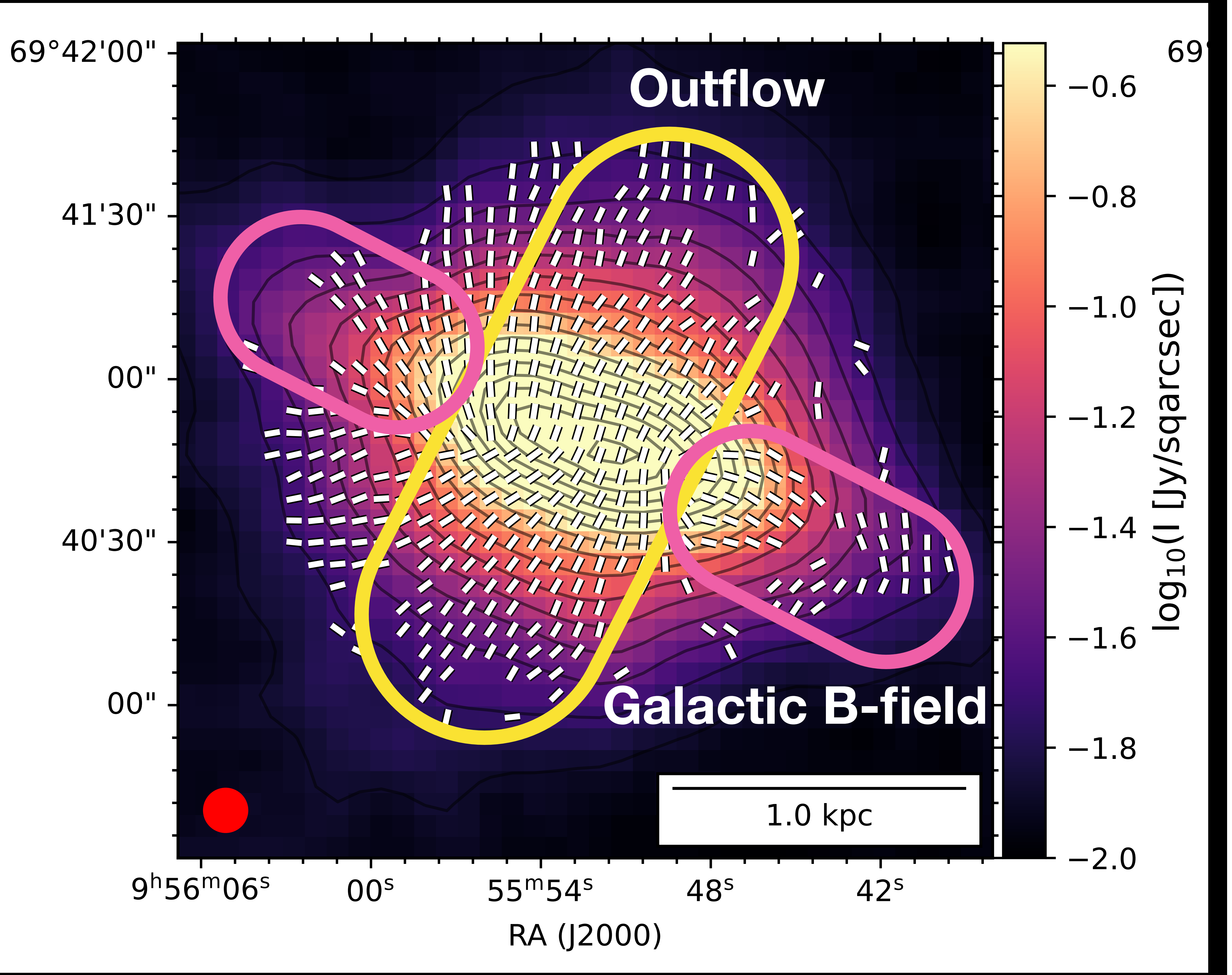
FIR: cold and dense ISM
h < 0.5 kpc



Jones et al. (2020) FWHM (HAWC+): 13.6"

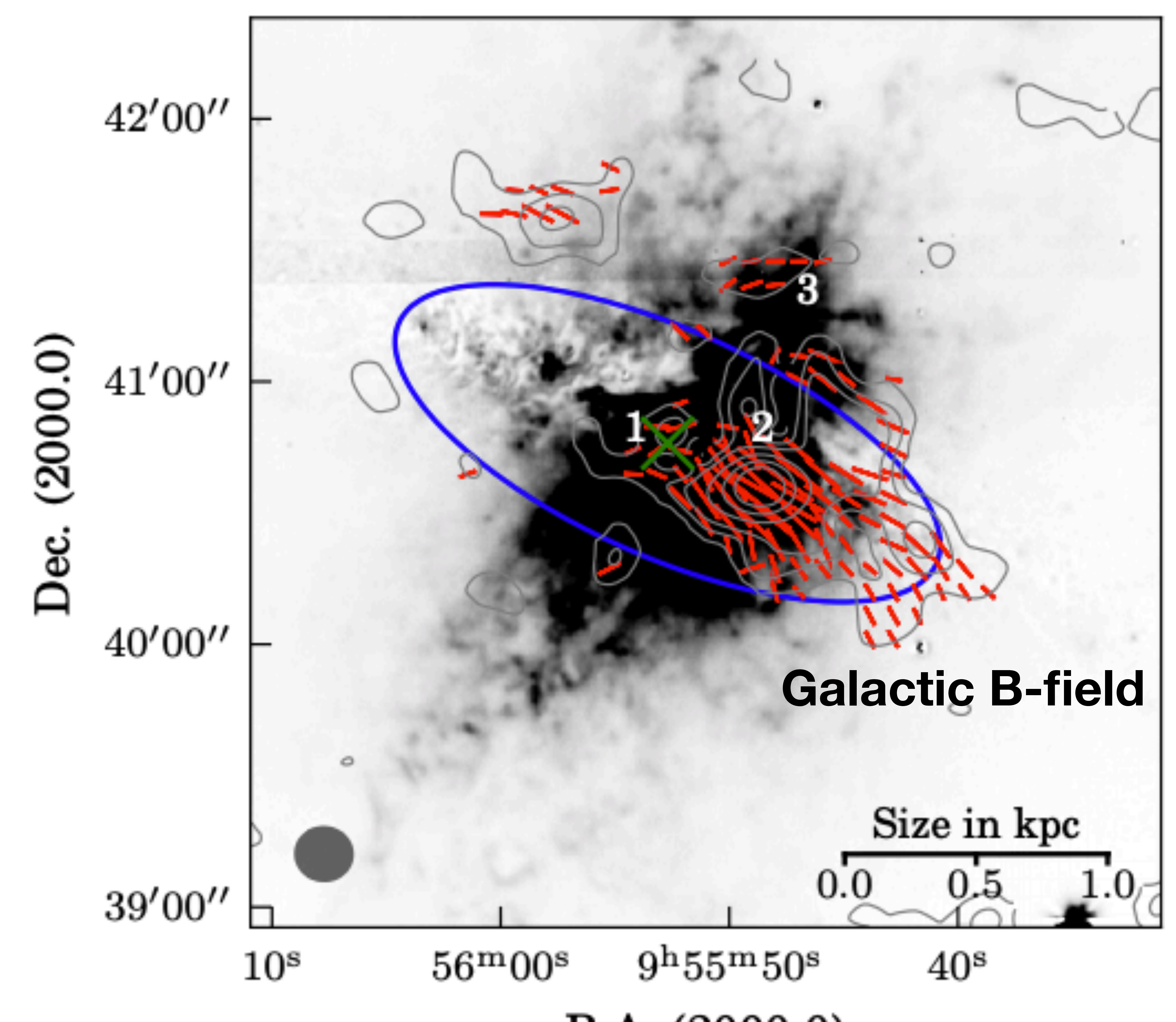
FIR polarization traces the B-field along galactic outflows

FIR (89 um)



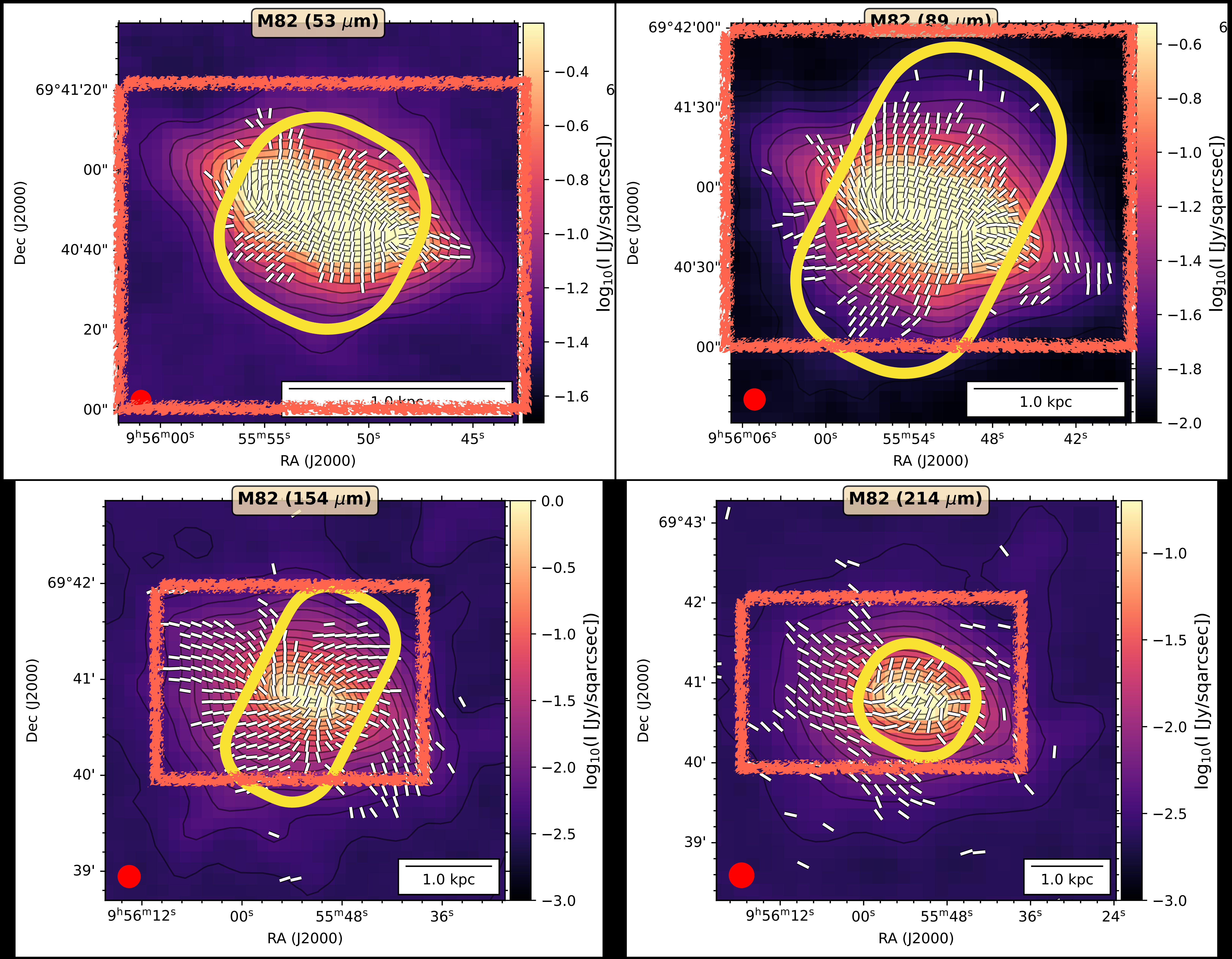
Lopez-Rodriguez et al. (2021, 2022b: SALSA IV)

Radio (18 and 22 cm)



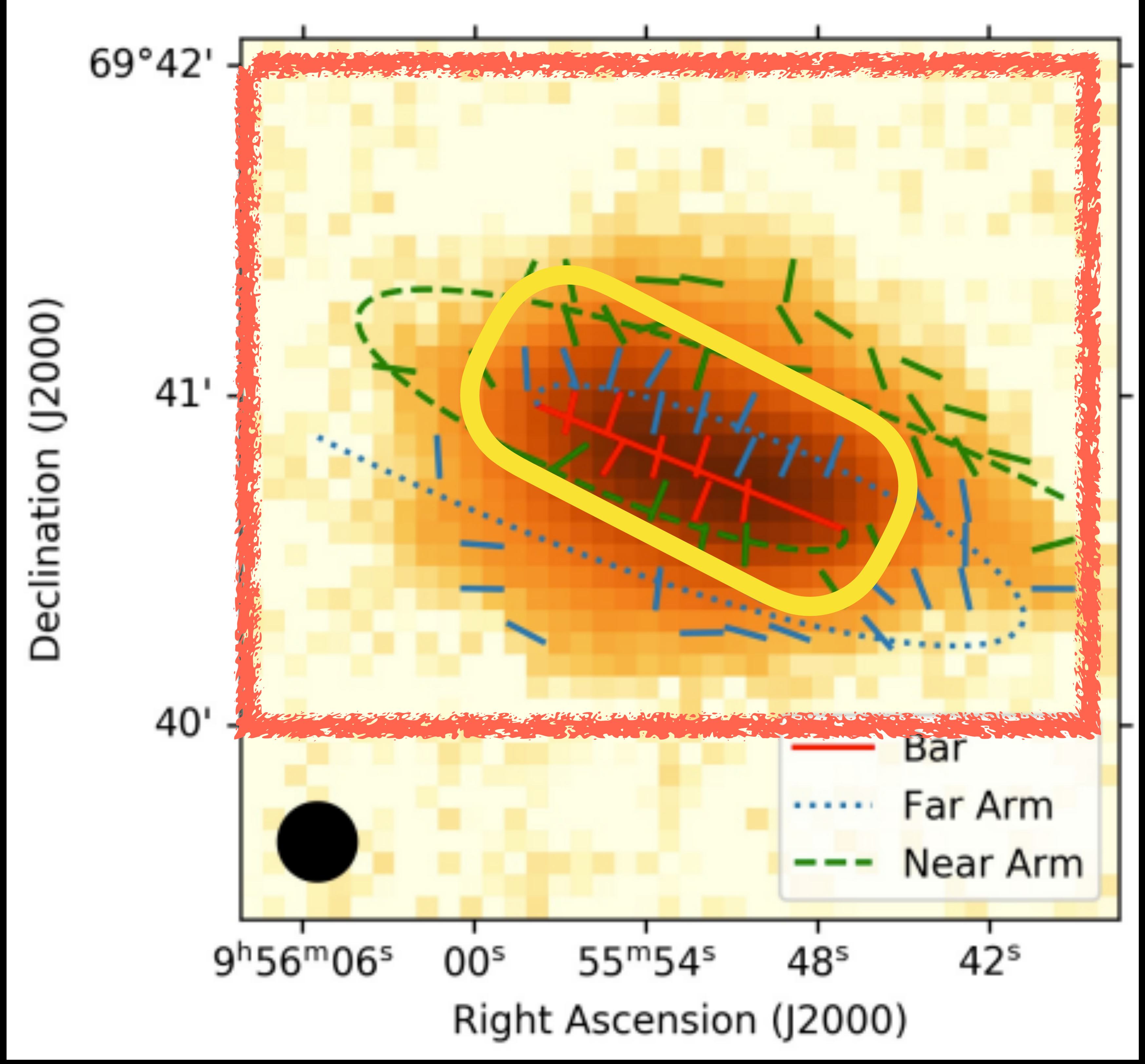
Adebahr et al. (2017)

B-FIELDS IN THE COLD-PHASE OF THE GALACTIC OUTFLOW



Lopez-Rodriguez et al. (2022b)

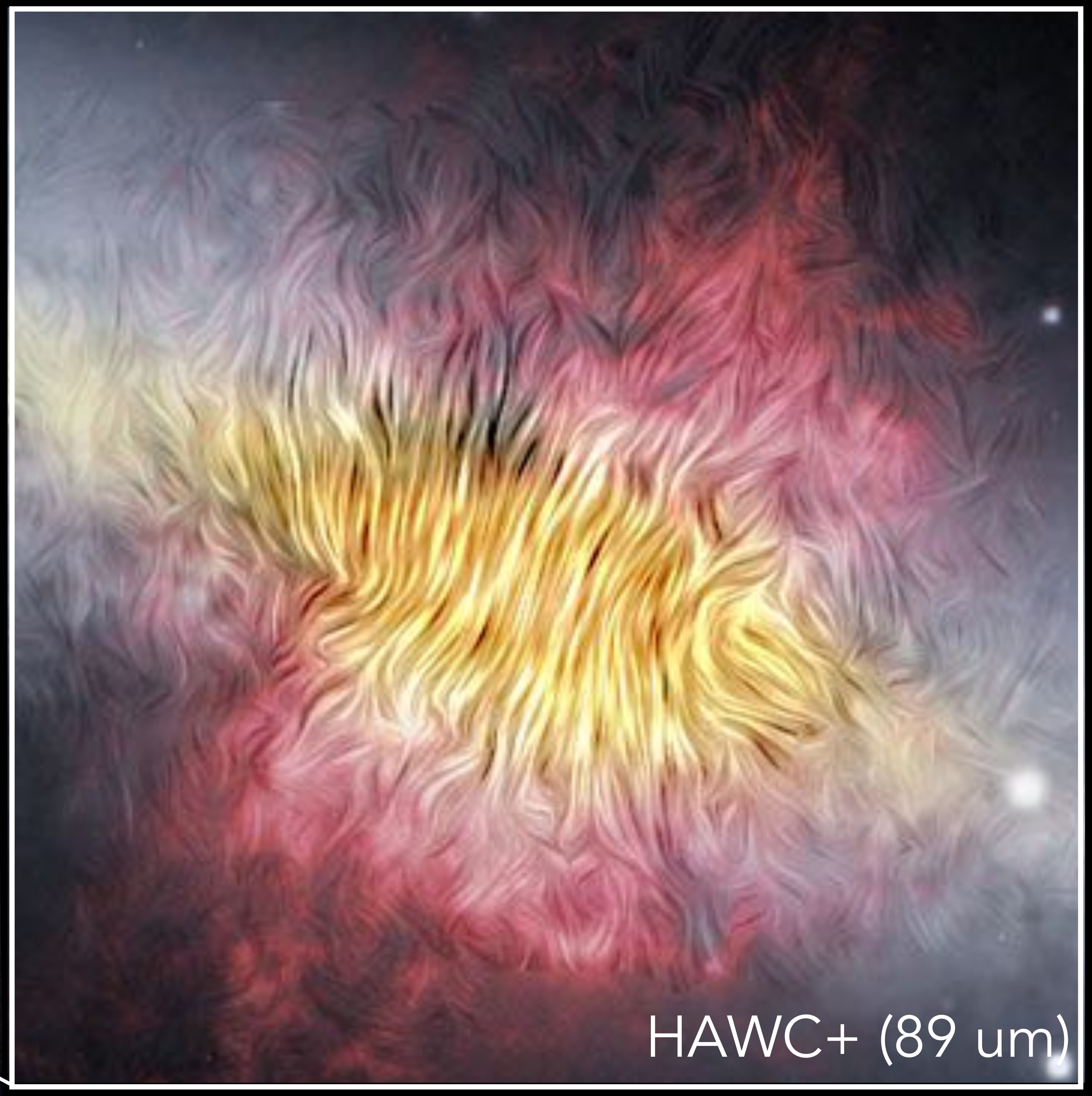
FIR (850 um)



Pattle et al. (2021)

ANALYSIS

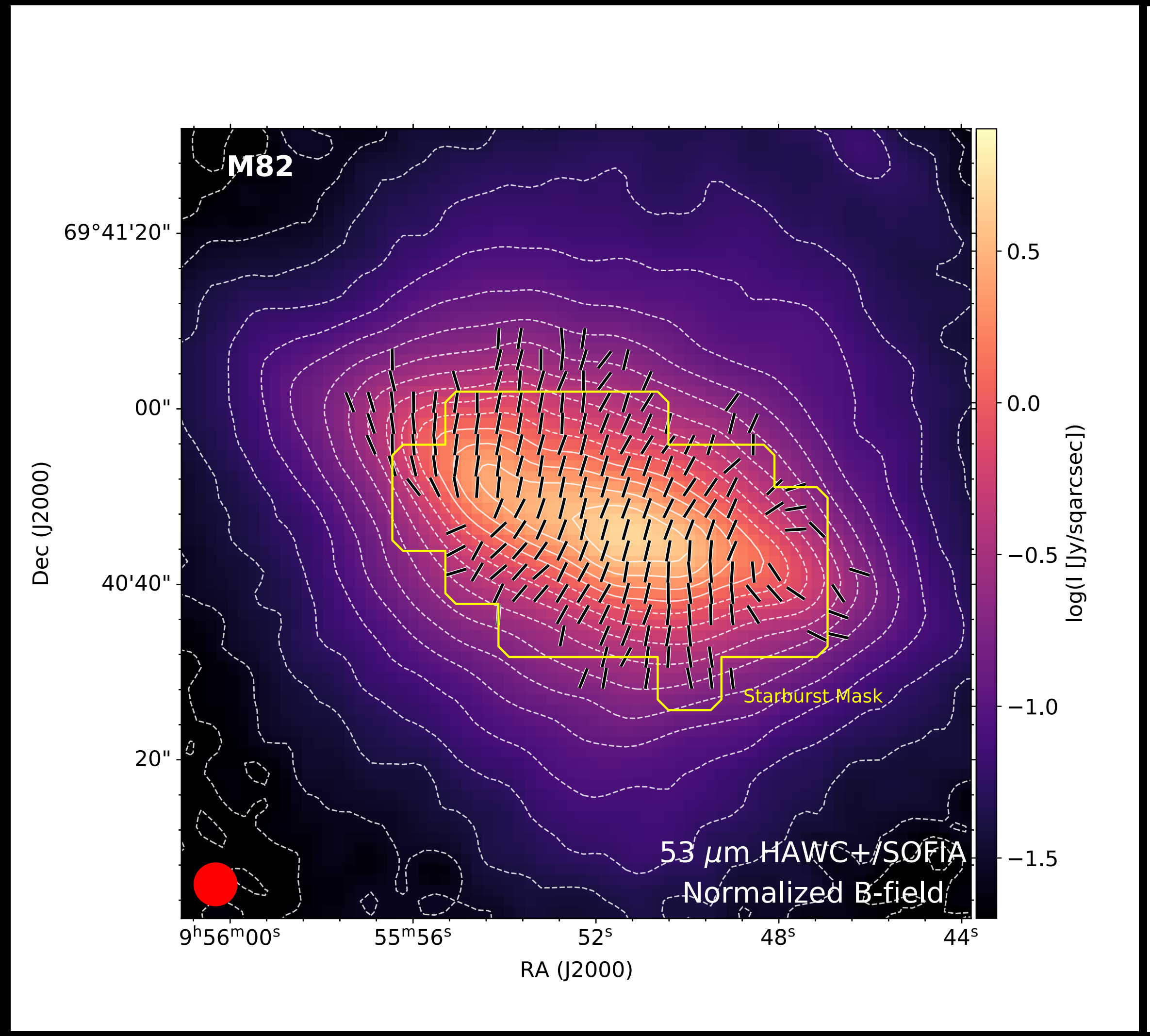
- What is the energetic balance between B-field and gas kinematics in the wind?
- What does the B-field look like along the galactic wind and in the halo?
- Is the B-field ‘open’ (galactic outflow) or ‘closed’ (galactic fountain)?



Lopez-Rodriguez et al. (2021)

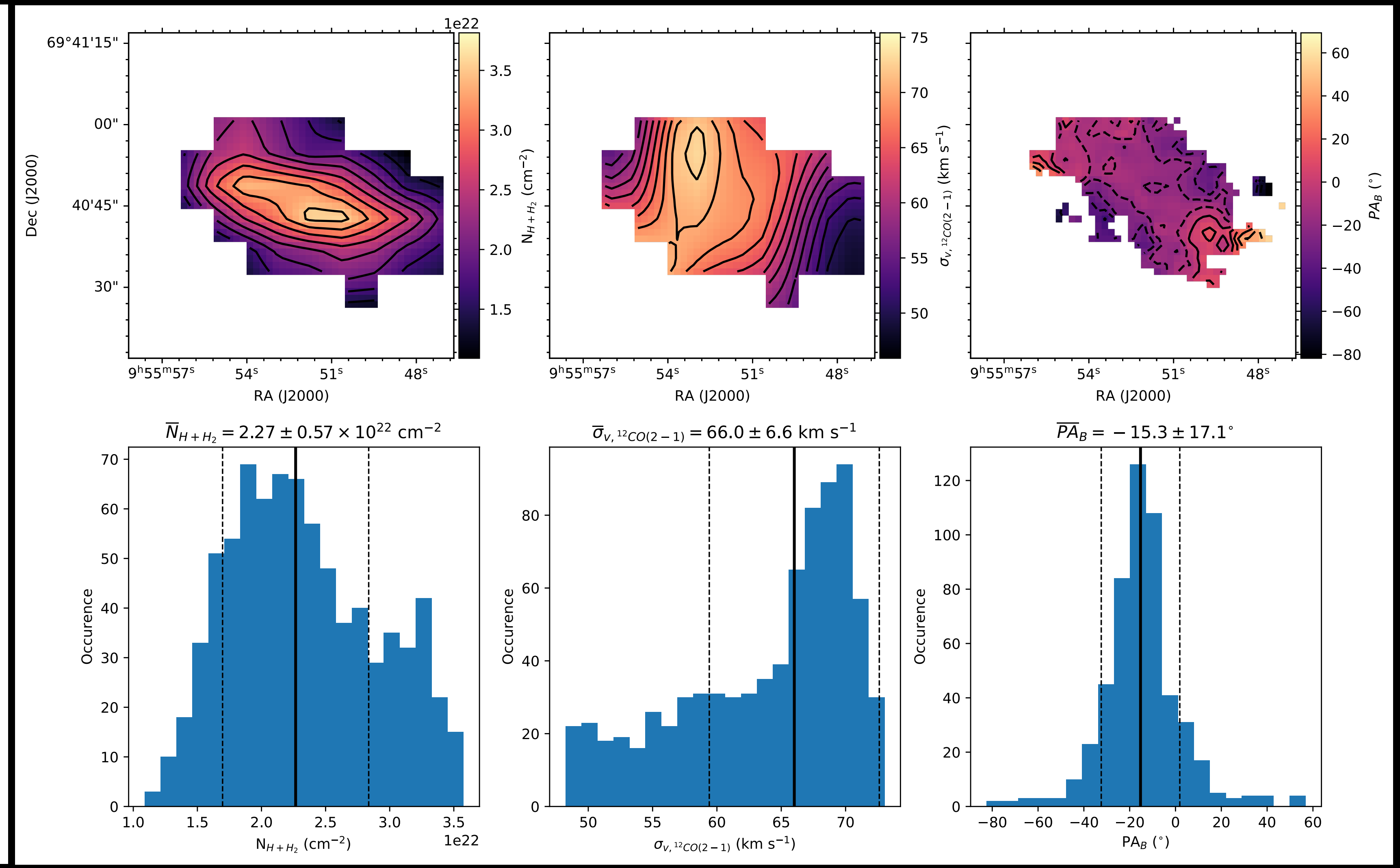
ESTIMATION OF THE B-FIELD STRENGTH USING A MODIFIED VERSION OF THE DCF METHOD

Magnetic field orientation in the plane of the sky



Jones et al. (2019). Contursi et al. (2013)

Column Density   CO(2-1) Velocity dispersion   B-field orientation



Jones et al. (2019)   Leroy et al. (2015)   Jones et al. (2019)

Mass Density (ρ)

Angular Dispersion $\left[\frac{\langle B_t^2 \rangle}{\langle B_0^2 \rangle}\right]$

Velocity Dispersion (σ_v)

$$B_{ADF} = \sqrt{4\pi\rho}\,\sigma_v \left[\frac{\langle B_t^2 \rangle}{\langle B_0^2 \rangle}\right]^{-1/2}$$

B_{ADF} = 1.04 ± 0.17 mG

Large-Scale Flow (U_0)

U_o = 396±87 km/s

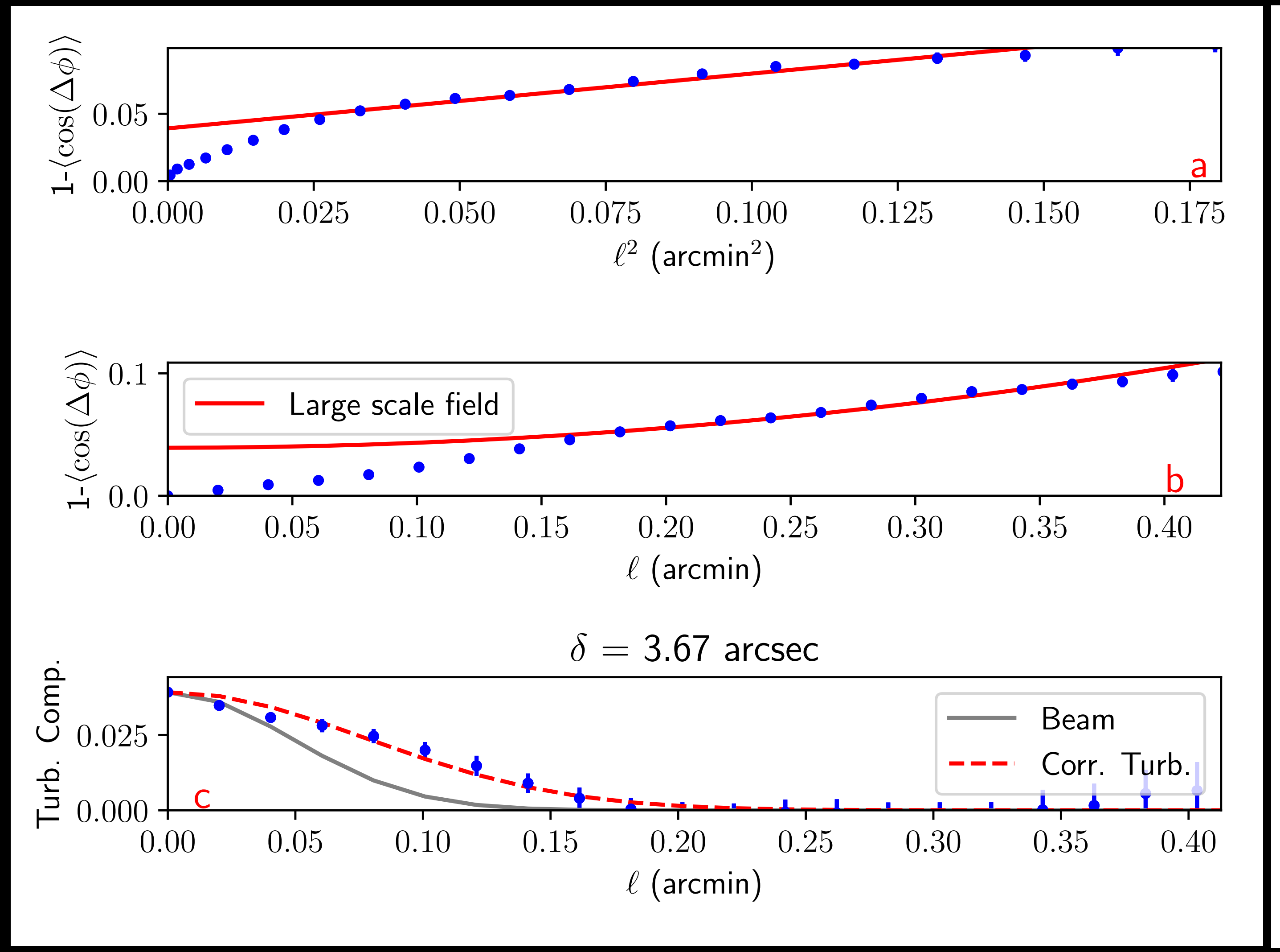
Leroy et al. (2015)

$$B'_{ADF} = B_{ADF} \left| 1 - \sigma_\phi \frac{U_0}{\sigma_v} \right|$$

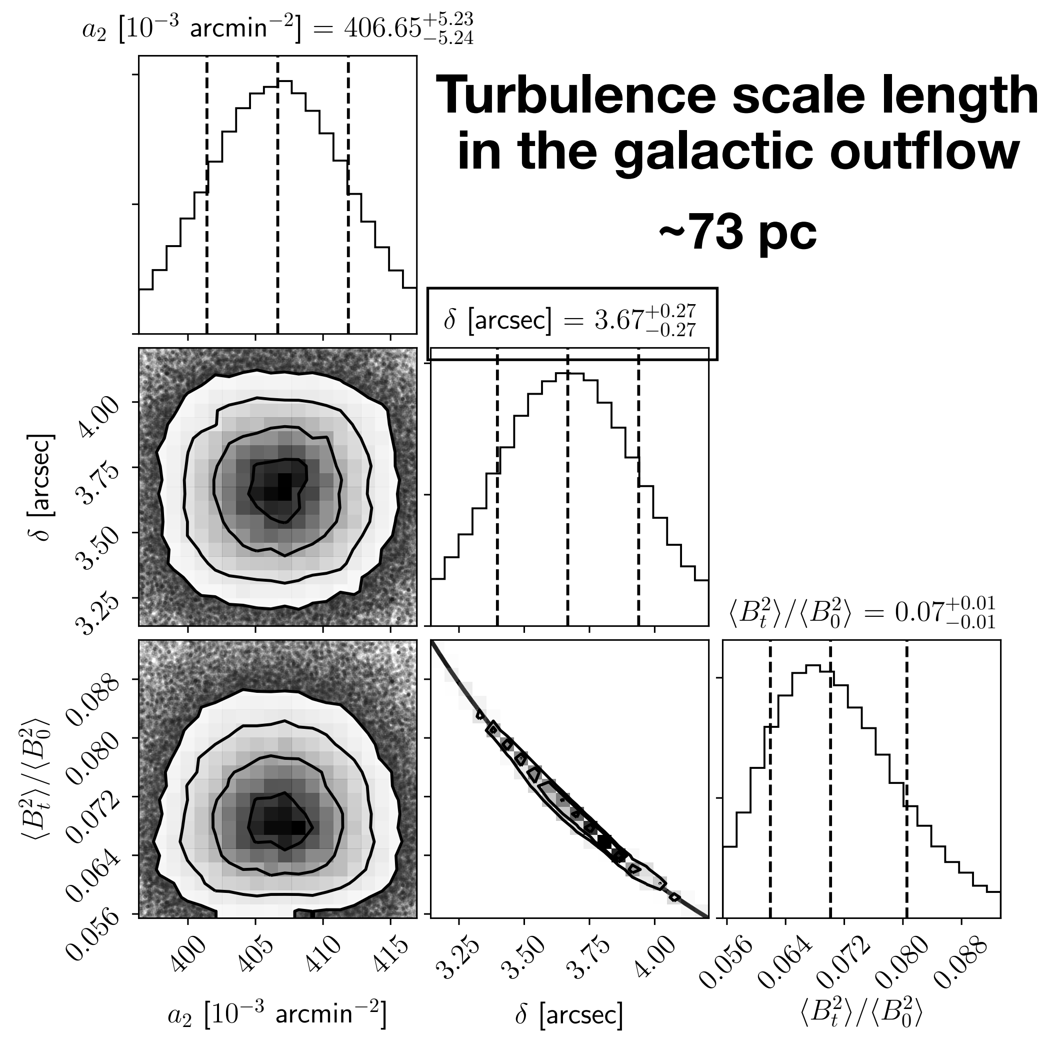
Correction of ~25%.

B'_{ADF} = 0.77 ± 0.17 mG

Angular dispersion function



Posteriors



Mean B-field strength in the starburst mask (873x510 pc²)

~1 mG for the star-forming region, and ~μG weak diffuse component (Adebahr et al. 2007)

~220-240 μG dense core taking into account energy loses (Lacki & Beck 2013)

<1.6 mG using hydrostatic and magnetic equipartition (Thompson et al. 2006)

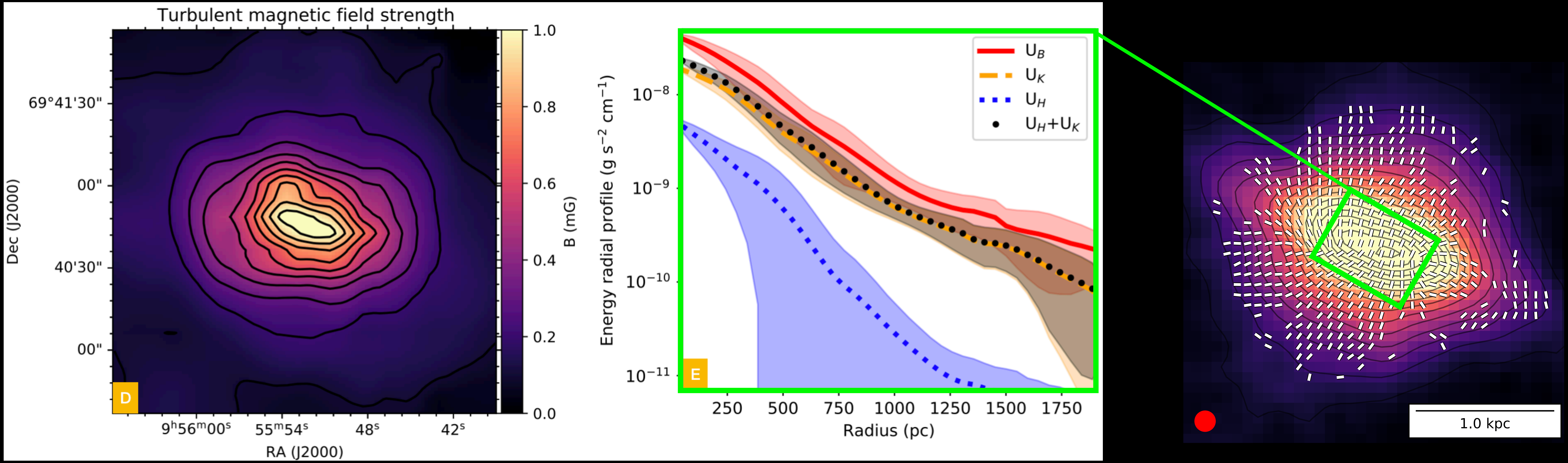
The turbulent kinetic and magnetic energy are in equipartition in the outflow

Energy budget:

- The beta parameter defines the entrainment between kinetic, thermal, and magnetic energies: $\beta' = \frac{U_K + U_H}{U_B}$

Our method:

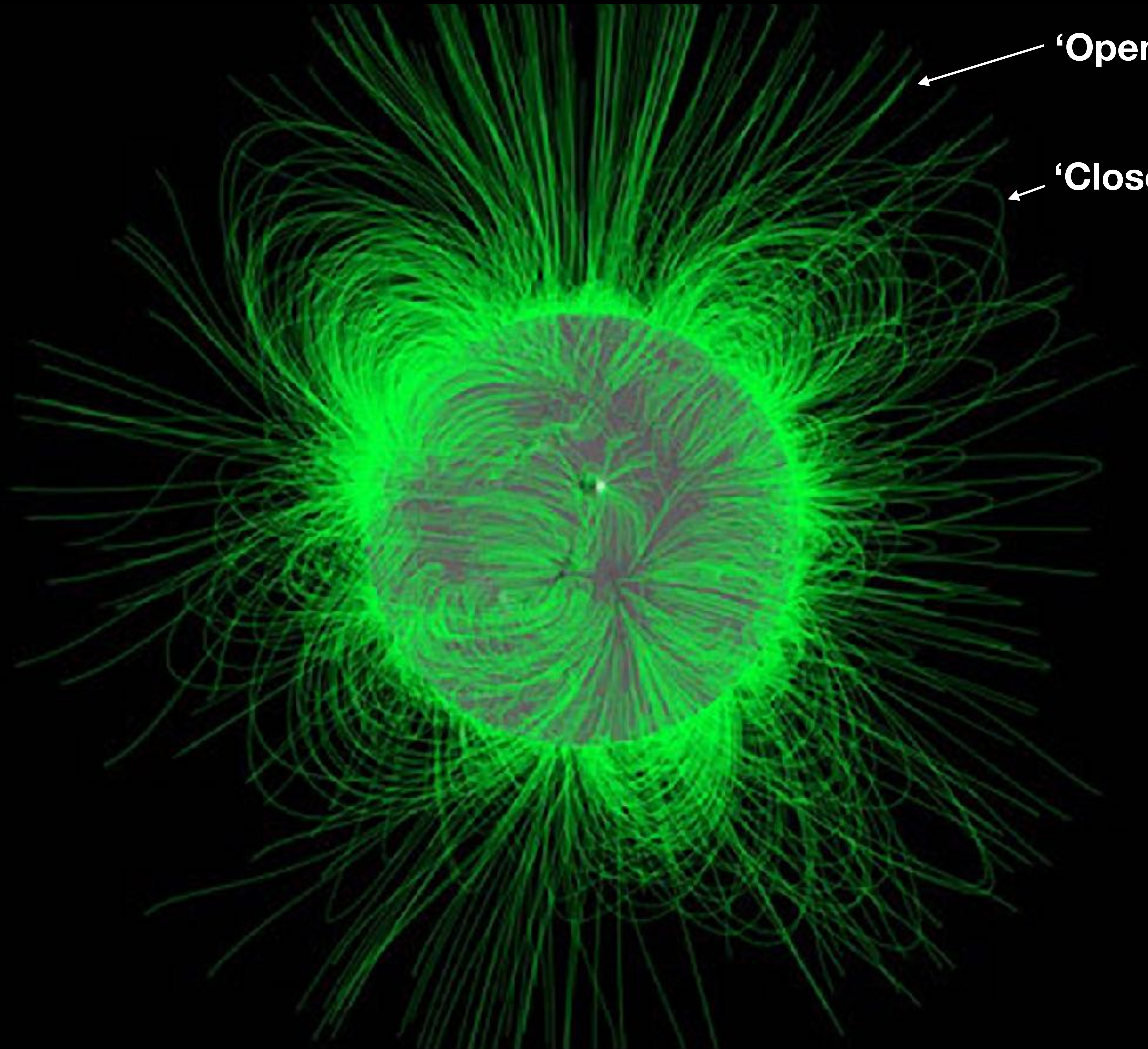
- The corrected DCF (i.e., large-scale flow) method provides the mean B-field strength within the starburst mask.
- The energy balance shows that **turbulent magnetic and kinetic energies are in close equipartition:** $\beta' = 0.56 \pm 0.23$



Lopez-Rodriguez et al. (2021)

POTENTIAL FIELD EXTRAPOLATION

The potential field extrapolation is commonly used in solar physics to estimate the B-fields above the corona.

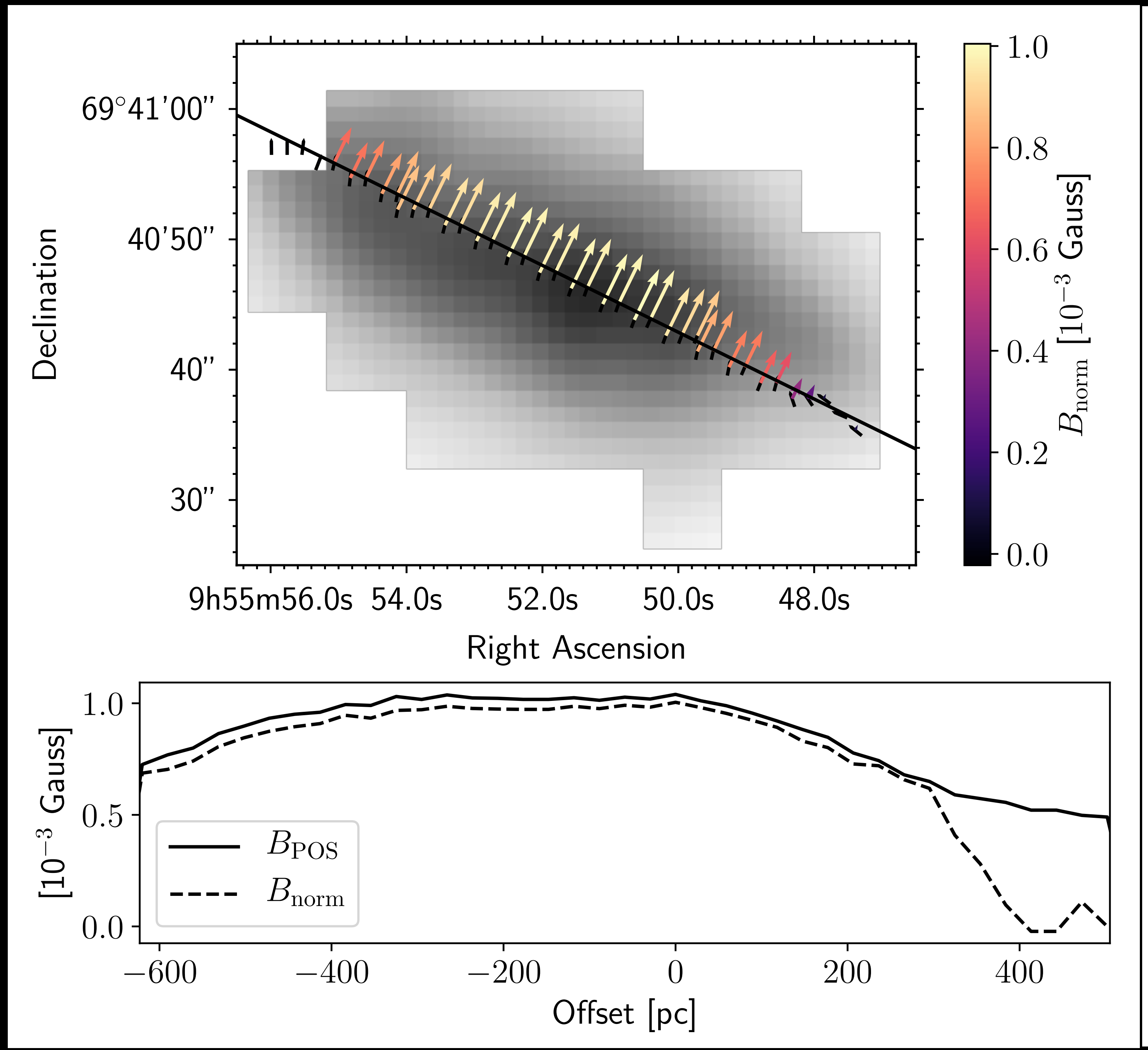


POTENTIAL FIELD EXTRAPOLATION: B-FIELD LINES ARE 'OPEN'

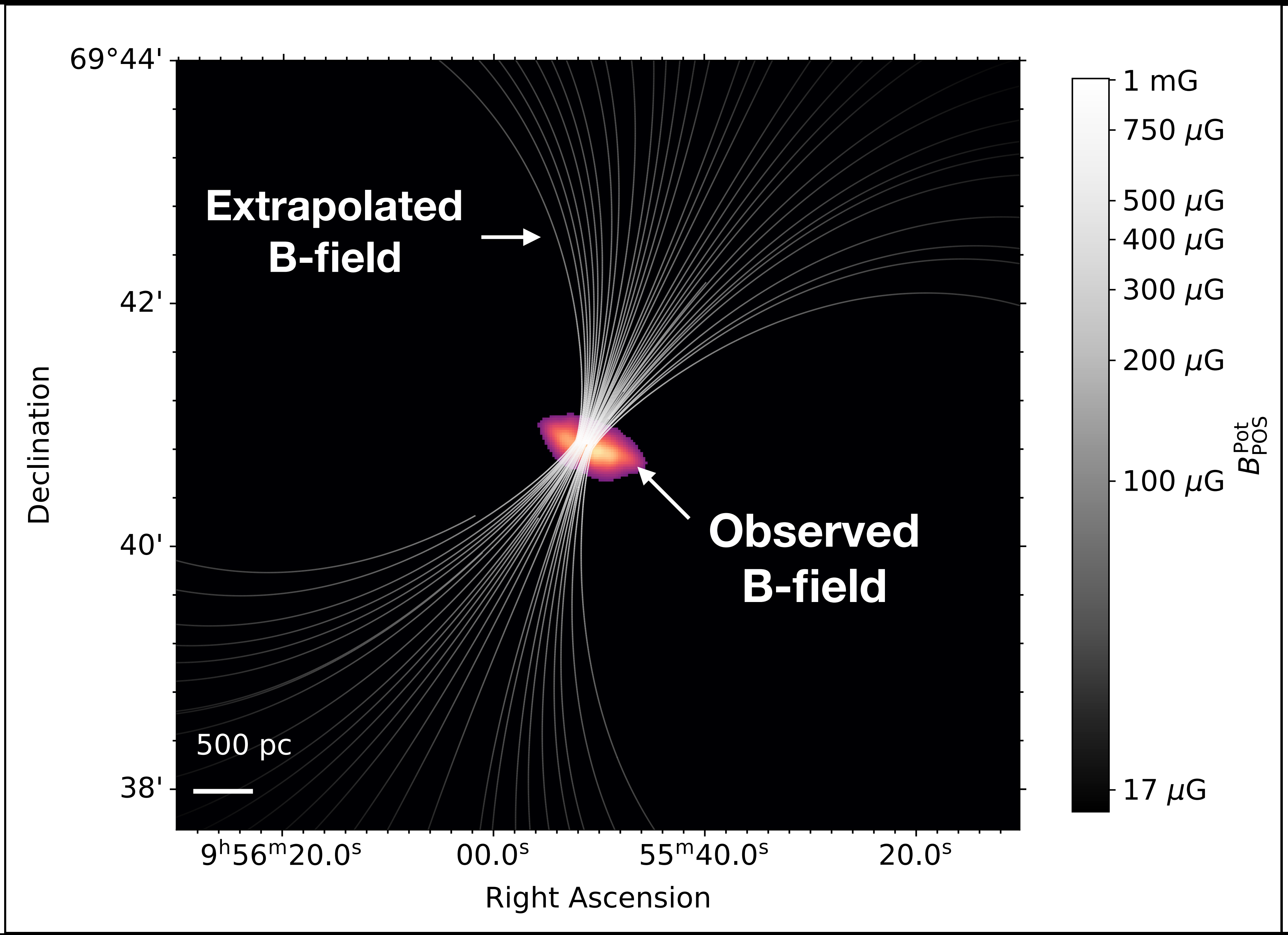
This (very simplified) method:

- Solves the Laplace equation with two boundary conditions:
  1. The B-field strength and orientation in the central plane of the starburst mask.
  2. The B-field strength at infinity is zero.

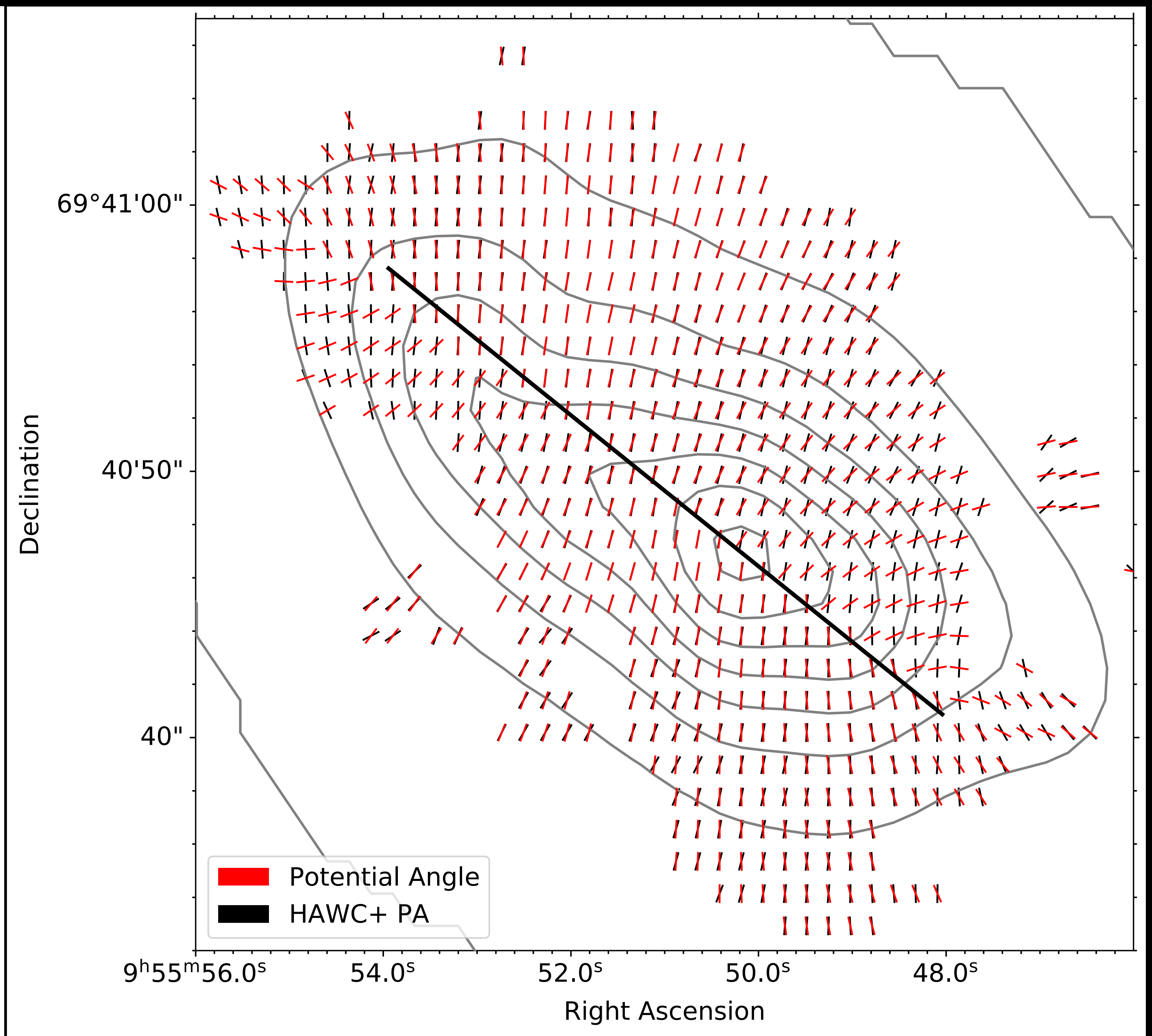
The magnetic field in the central plane of the starburst mask



Extrapolated B-field strength and orientation



Observed vs. extrapolated B-field orientation



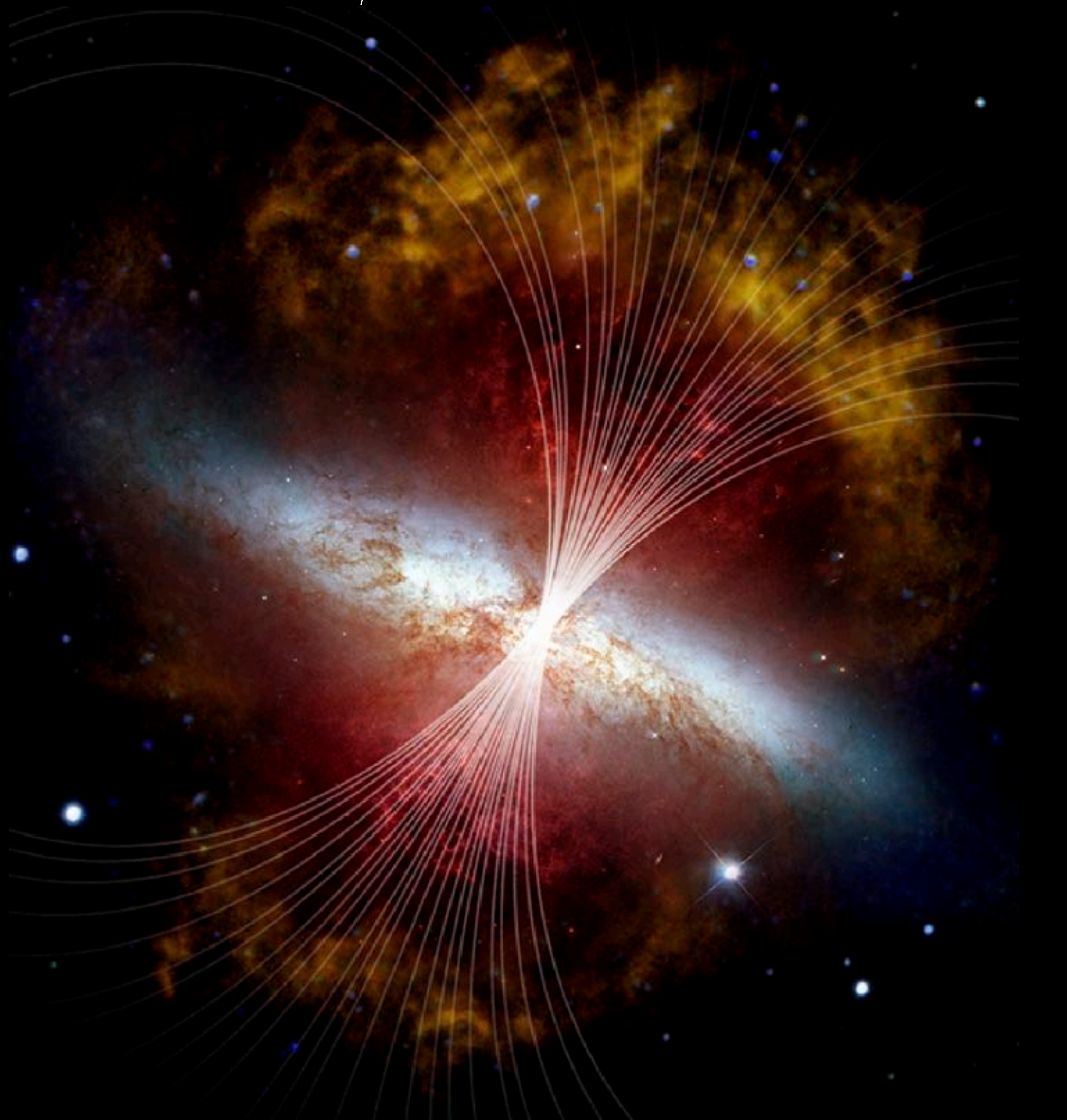
Absolute angular difference <10°

MAGNETIC FIELD ALONG THE GALACTIC OUTFLOW

R < 2 kpc (measured):

- Turbulent kinetic and turbulent B-field energies are in close equipartition: $U_K \sim U_{BPF}$.

$$\beta' = 0.56 \pm 0.23$$



R ~ 6.6 kpc (extrapolated):

- U_K (clouds) > U_{BPF}
- U_K (ambient; diffuse gas) << U_{BPF}

$$B \leq 15\ \mu G \text{ at r} \geq 6.6 \text{ kpc}$$

$$U_B \leq 8.9 \times 10^{-12} \text{ g s}^{-2} \text{ cm}^{-1}$$

Magnetic fields are 'open'

Galactic outflows permeate the CGM and IGM with astrophysical B-fields.

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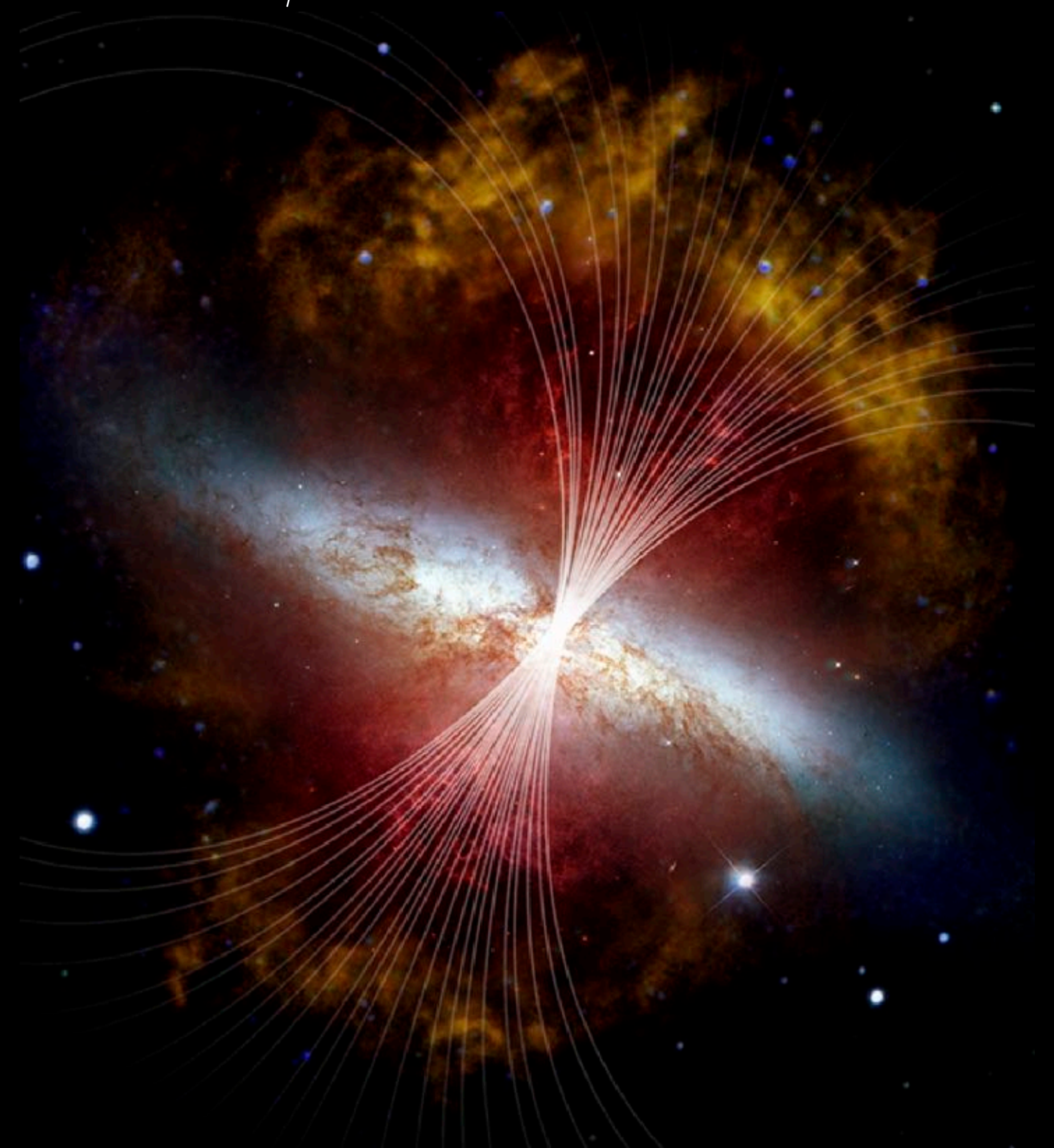

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Magnetic fields are 'open'

Galactic outflows permeate the CGM and IGM with astrophysical B-fields.

Astrophysical B-fields in the IGM from galactic outflows:

$$B \propto r^{-1} ---> B_{1Mpc} \sim 9.9 \times 10^{-8} \text{ G B}_{10\text{Mpc}} \sim 9.9 \times 10^{-9} \text{ G}$$

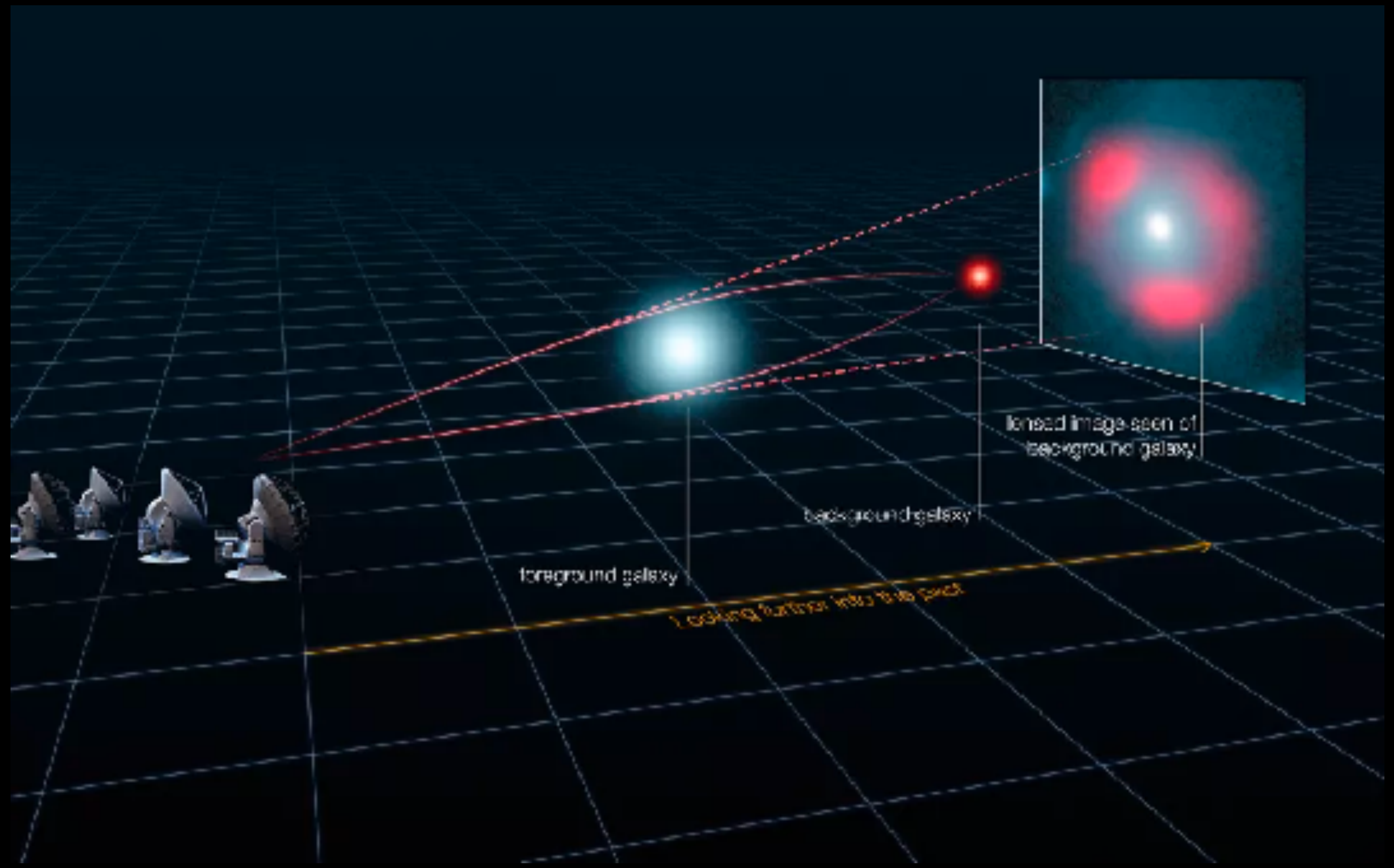
$$B \propto r^{-2} ---> B_{1Mpc} \sim 6.5 \times 10^{-10} \text{ G B}_{10\text{Mpc}} \sim 6.5 \times 10^{-12} \text{ G}$$

Are we measuring astrophysical B-fields in clusters/IGM/voids?

- Galactic outflows
- Active galactic nuclei

Near-Future: B-fields at high redshift using sub-mm polarimetry

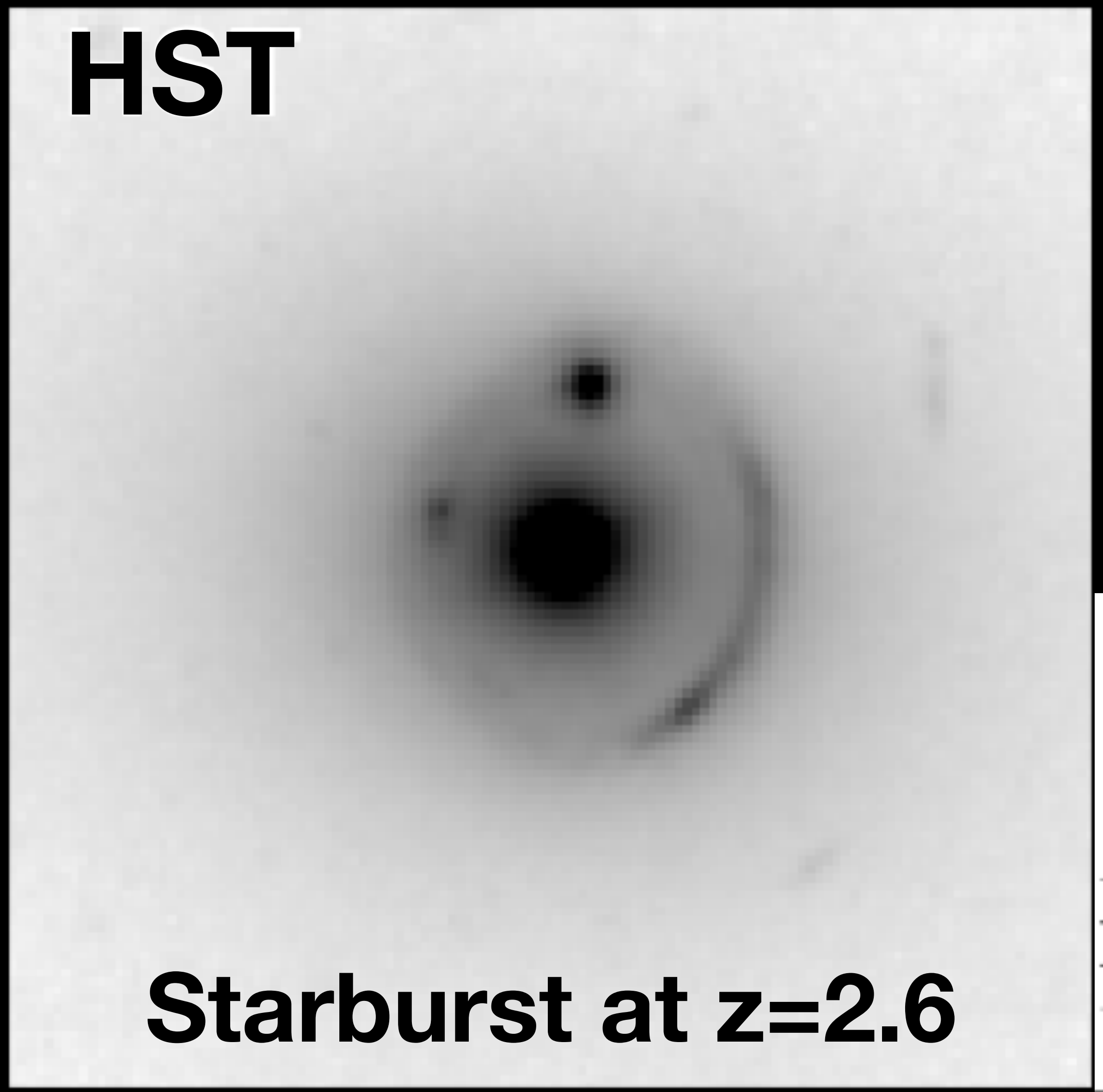
Gravitationally lensed dusty star-forming galaxies at z = 1-6

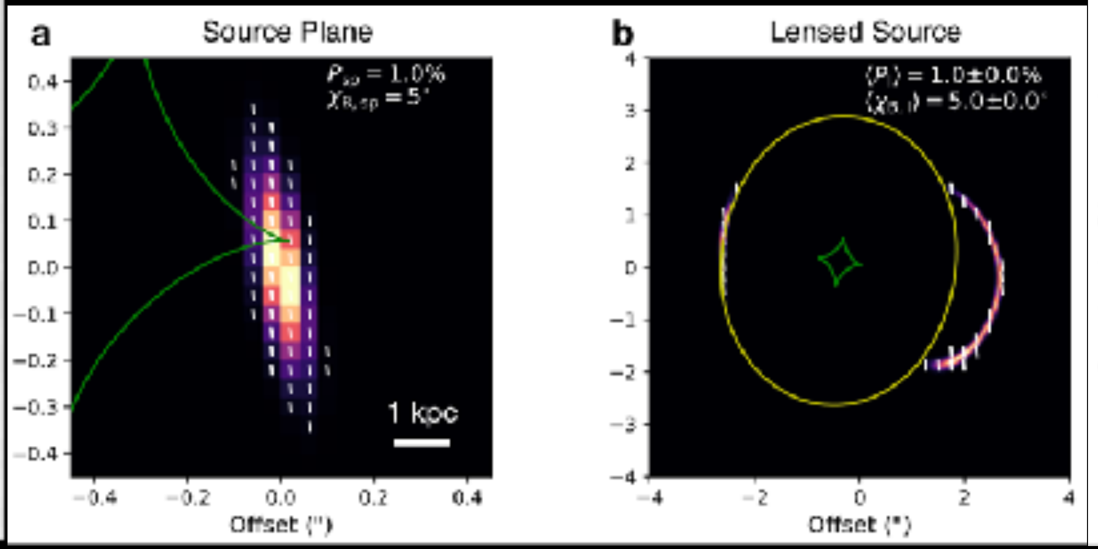


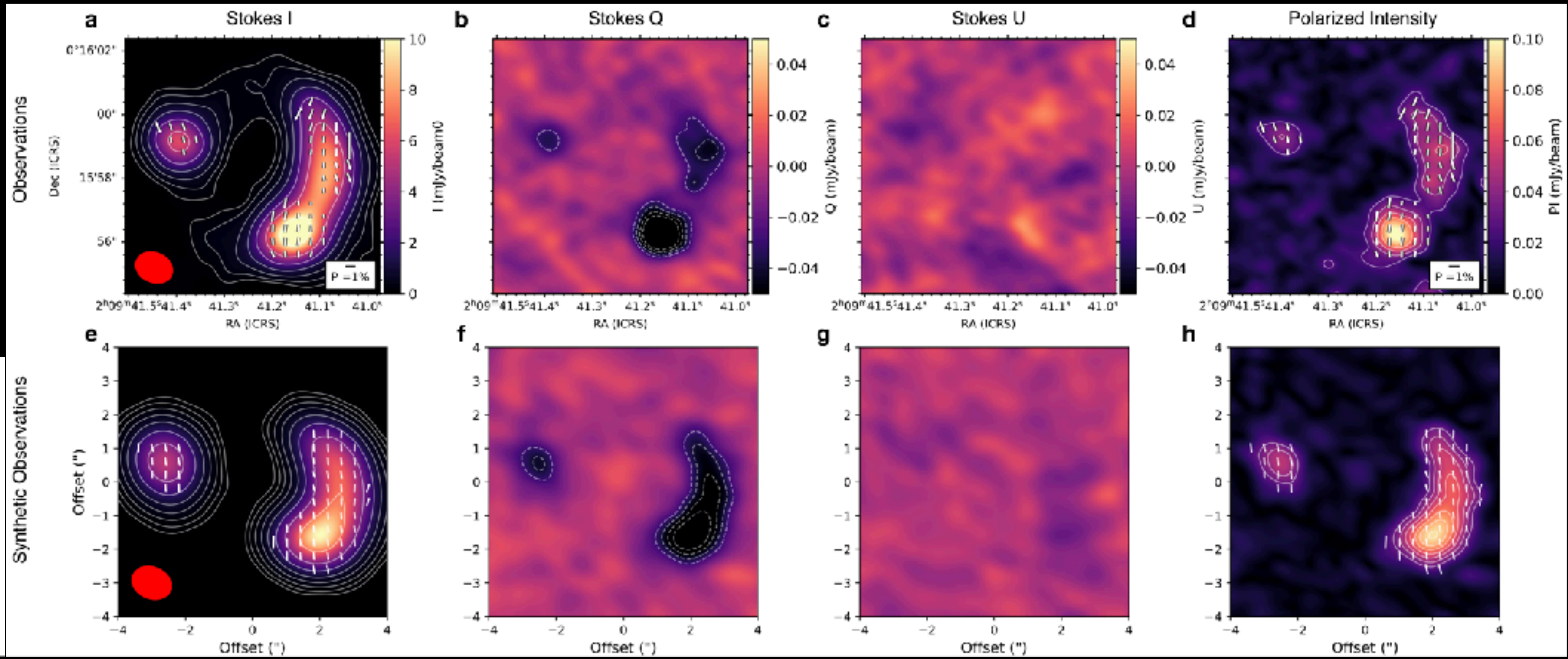
2 kpc-scale ordered B-field parallel to a fast rotating disk in a starburst at 3Gyr after Big Bang.

ALMA polarimetric observations

860 um (dust continuum polarization) at 0.5″ resolution







Geach, Lopez-Rodriguez et al. (in prep.)

Gravitational lensing polarimetric model

Extra slides

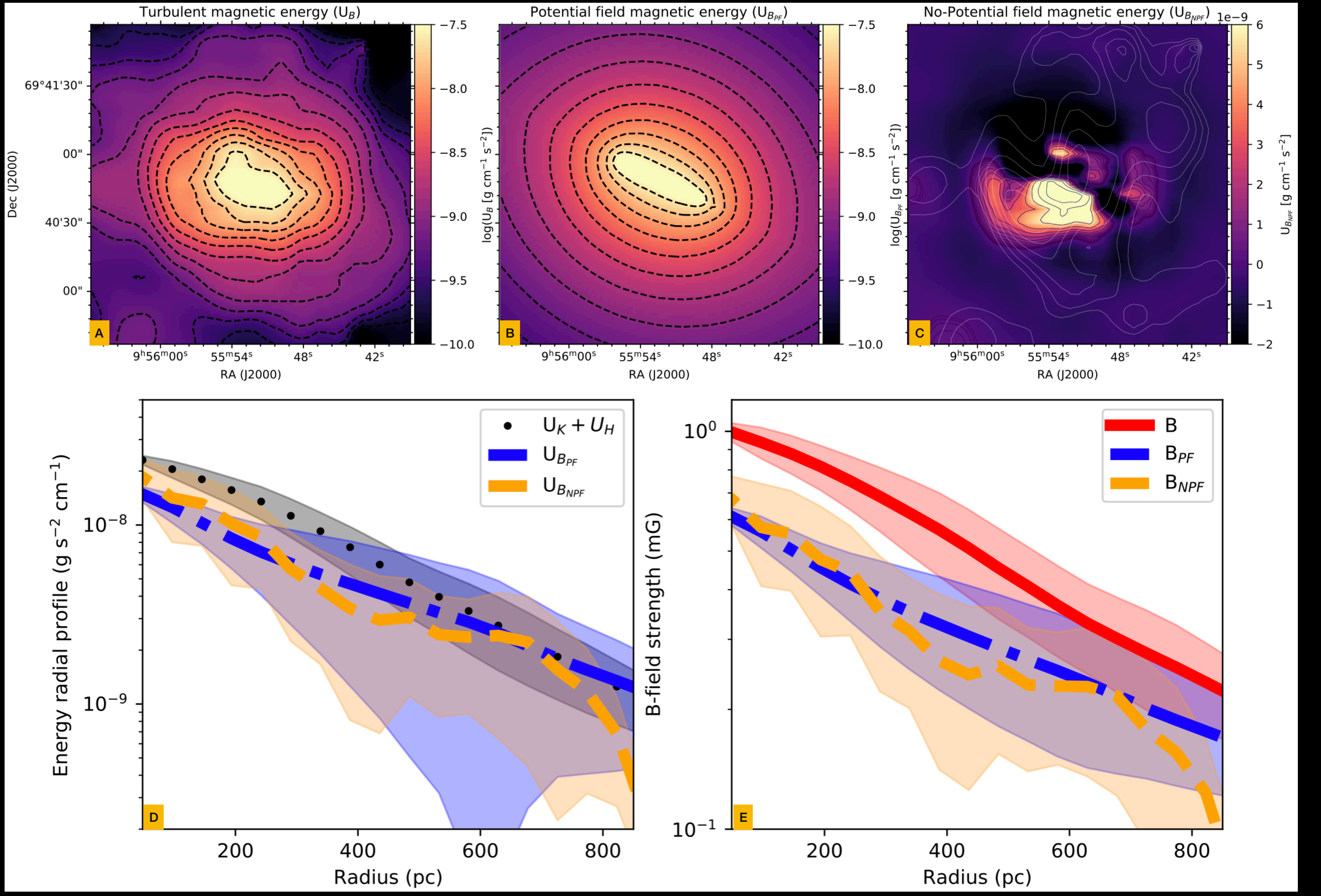
MAGNETIC FIELD ALONG THE GALACTIC OUTFLOW

Central 300 pc radius (measured):

- B-field energy arises from two different physical components:
    1. Large-scale (anisotropic turbulent) B-field associated with the galactic outflow (potential field)
    2. Small-scale turbulent B-field associated with a bow-shock-like pattern (non-potential field)
- Now:
    - $U_K \geq U_{BPF}$ and $U_K \geq U_{BNPF}$ —> The turbulent kinetic energy in slightly larger than each of the individual turbulent magnetic fields within the starburst region.

300 pc > R < 2 kpc (measured):

- Turbulent kinetic and turbulent B-field energies are in close equipartition: $U_K \sim U_{BPF}$.
- No contribution of the small-scale B-field.



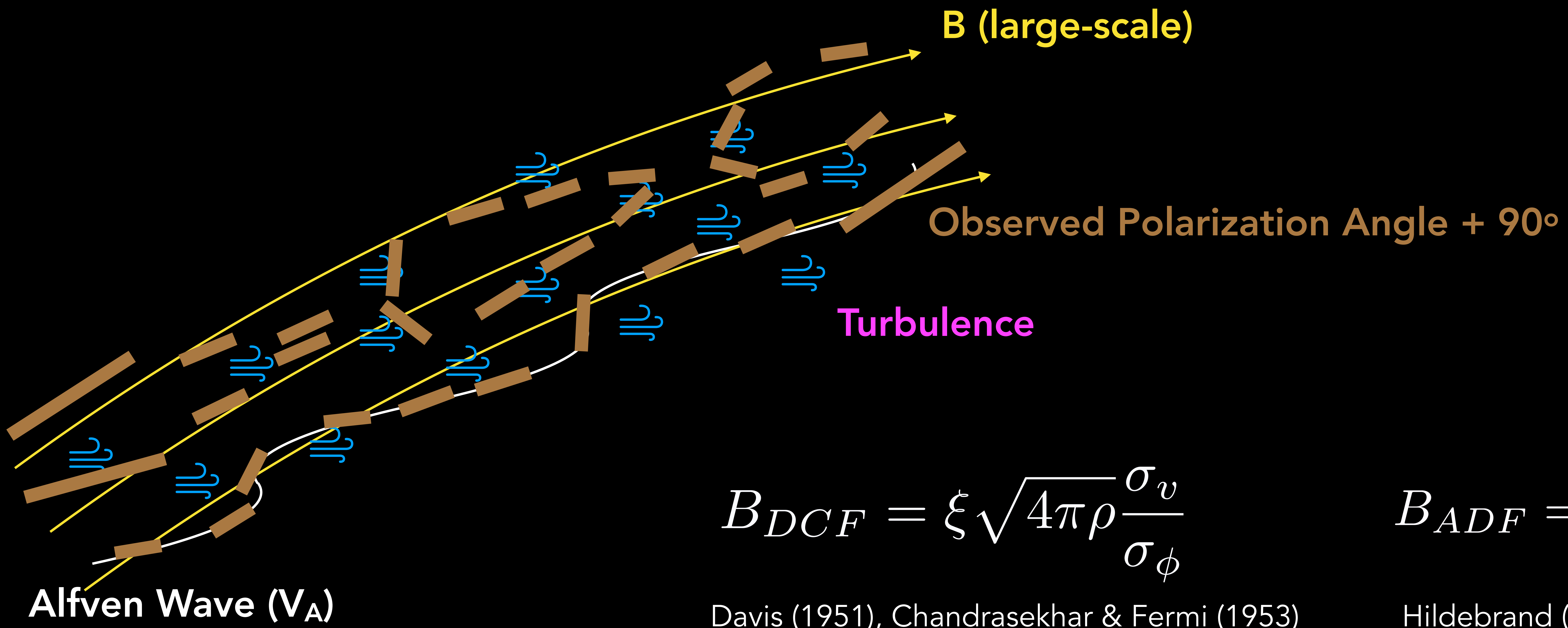
DAVIS-CHANDRASEKHAR-FERMI (DCF) + ANGULAR DISPERSION FUNCTION METHODS

This method assumes:

- For a steady-state with no large-scale flows, the Alfven wave (V_A, velocity of a transverse magnetohydrodynamical wave) is related to the observed dispersion of polarization angles.
- B-field is a composition of large-scale and turbulent components.
- Two-point structure function (i.e. dispersion function) to describe the angular dispersion as a function of angular scale.

We obtain:

- Turbulence-to-large-scale magnetic energies: $\frac{< B_t^2 >}{< B_o^2 >}$
- B-field strength of the turbulent component in the plane-of-the-sky.



$$B_{DCF} = \xi \sqrt{4\pi\rho} \frac{\sigma_v}{\sigma_\phi}$$

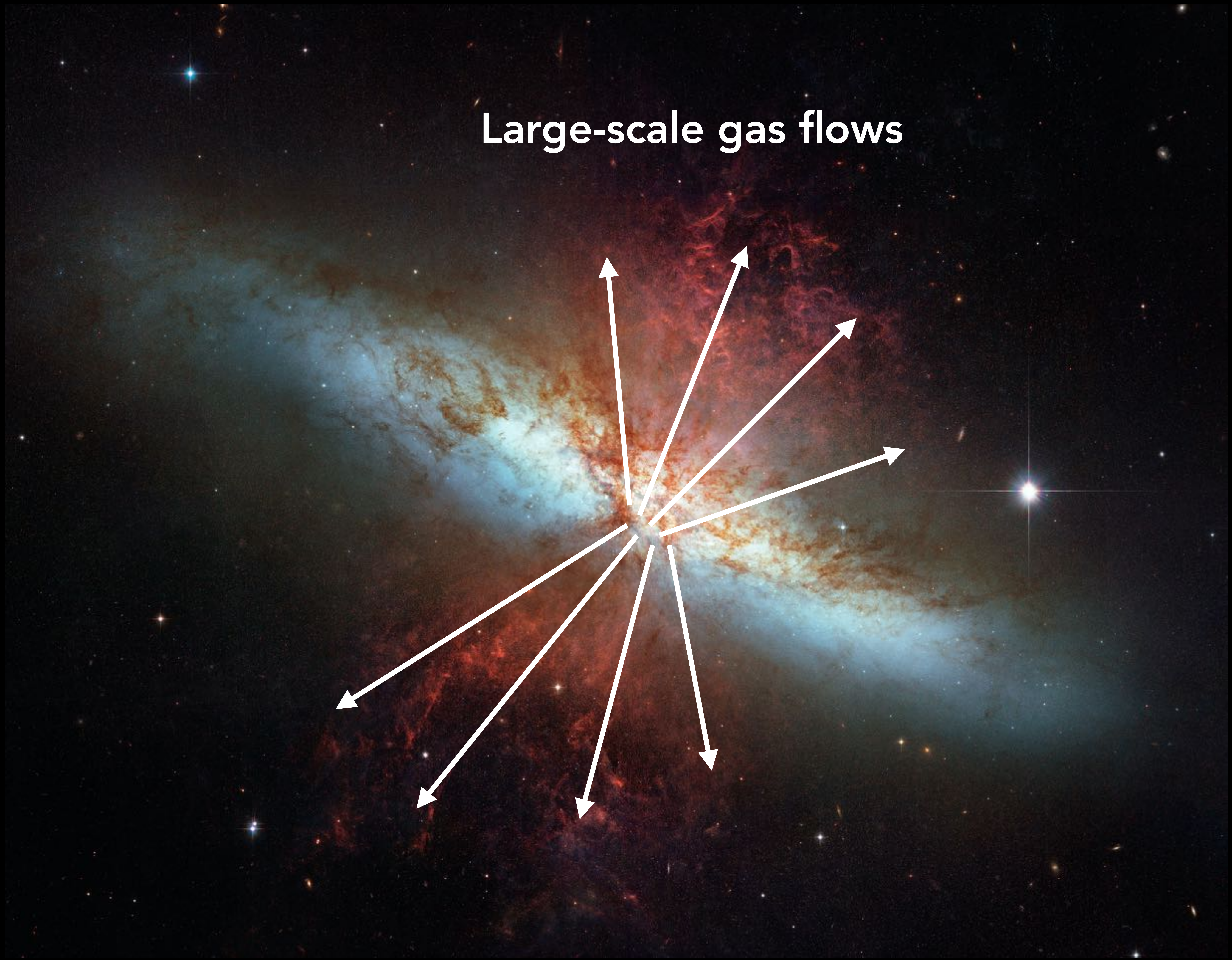
Davis (1951), Chandrasekhar & Fermi (1953)

ξ factor: Ostriker et al. (2001)

$$B_{ADF} = \sqrt{4\pi\rho}\sigma_v \left[\frac{< B_t^2 >}{< B_o^2 >} \right]^{-1/2}$$

Hildebrand (2009), Houde et al. (2009, 2011)

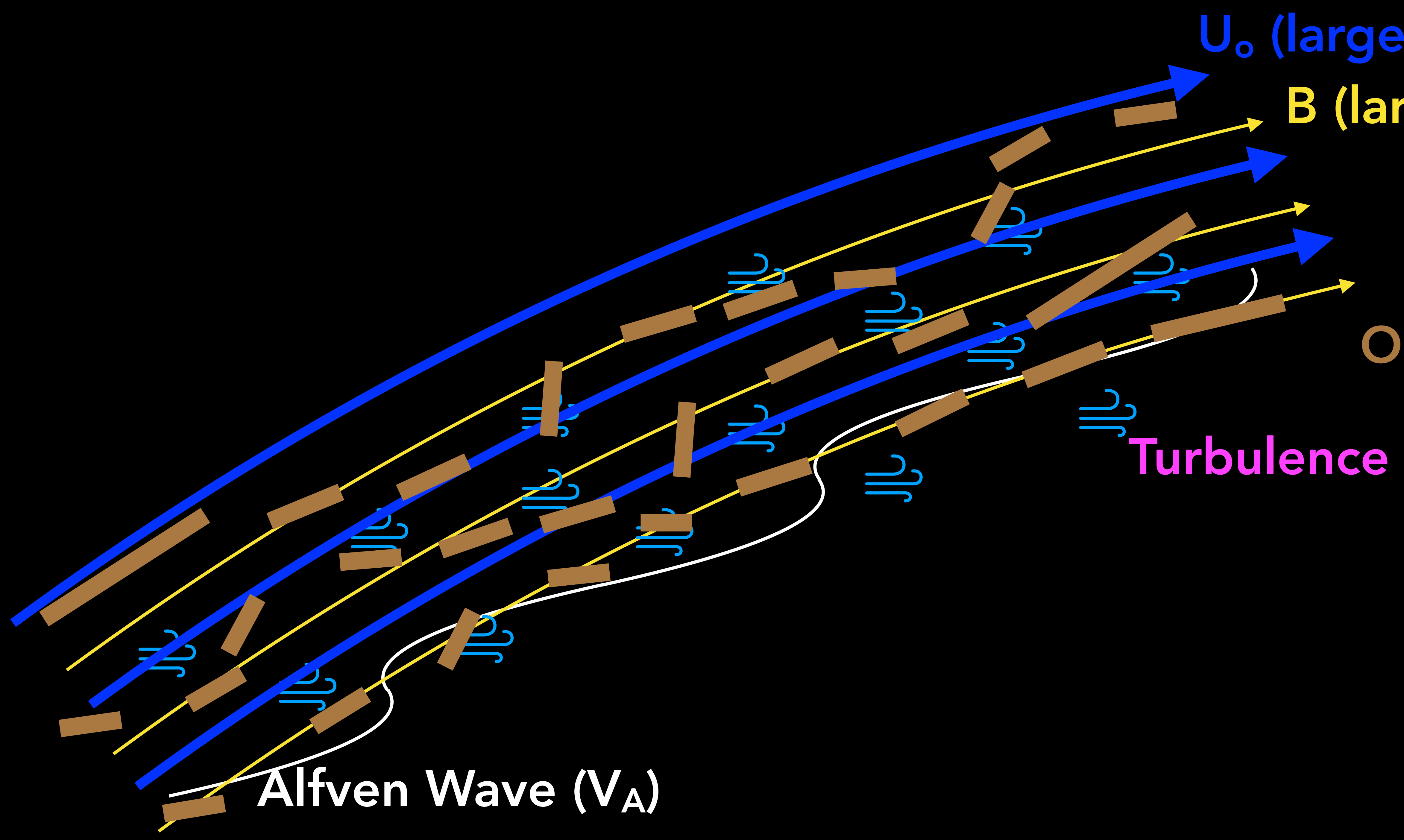
BUT… WE HAVE A BIG PROBLEM USING THE DCF METHOD IN M82



THE EFFECT OF GALACTIC OUTFLOWS IN THE DCF METHOD

This method assumes:

- Steady large-flow in the same direction as the magnetic field orientation.
- Two waves ($V_A + U_o$ and $V_A - U_o$) can satisfy the wave equation.
  - FIR polarimetric observations have a 180º ambiguity, no direction is estimated, only orientation.



$$(V_A \pm U_o)^2 \propto \frac{\sigma_v^2}{\sigma_\phi^2} \rightarrow \boxed{B'_{DCF} = B_{DCF}|1 - \sigma_\phi \frac{U_o}{\sigma_v}|}$$

If U_o = 0: no large-scale flow (classical DCF method)

If large-scale flow dominates —> B_{DCF} overestimates the B-field strength

If turbulence dominates —> B_{DCF} underestimates the B-field strength

DCF Method:

$$B_{DCF} = \xi \sqrt{4\pi\rho} \frac{\sigma_v}{\sigma_\phi}$$

Davis (1951), Chandrasekhar & Fermi (1953)

ξ factor: Ostriker et al. (2001)

ENERGY BALANCE AND MAP OF THE MAGNETIC FIELD STRENGTH

Energy budget:

- The entrainment between kinetic, thermal, and magnetic energies are defined by the beta parameter: $\beta' = \frac{U_K + U_H}{U_B}$

This method assumes:

- Corrected DCF method provides the mean B-field strength within the starburst mask.
- The energy map should satisfy that the beta parameter within the mask $\beta' = 0.56 \pm 0.23$