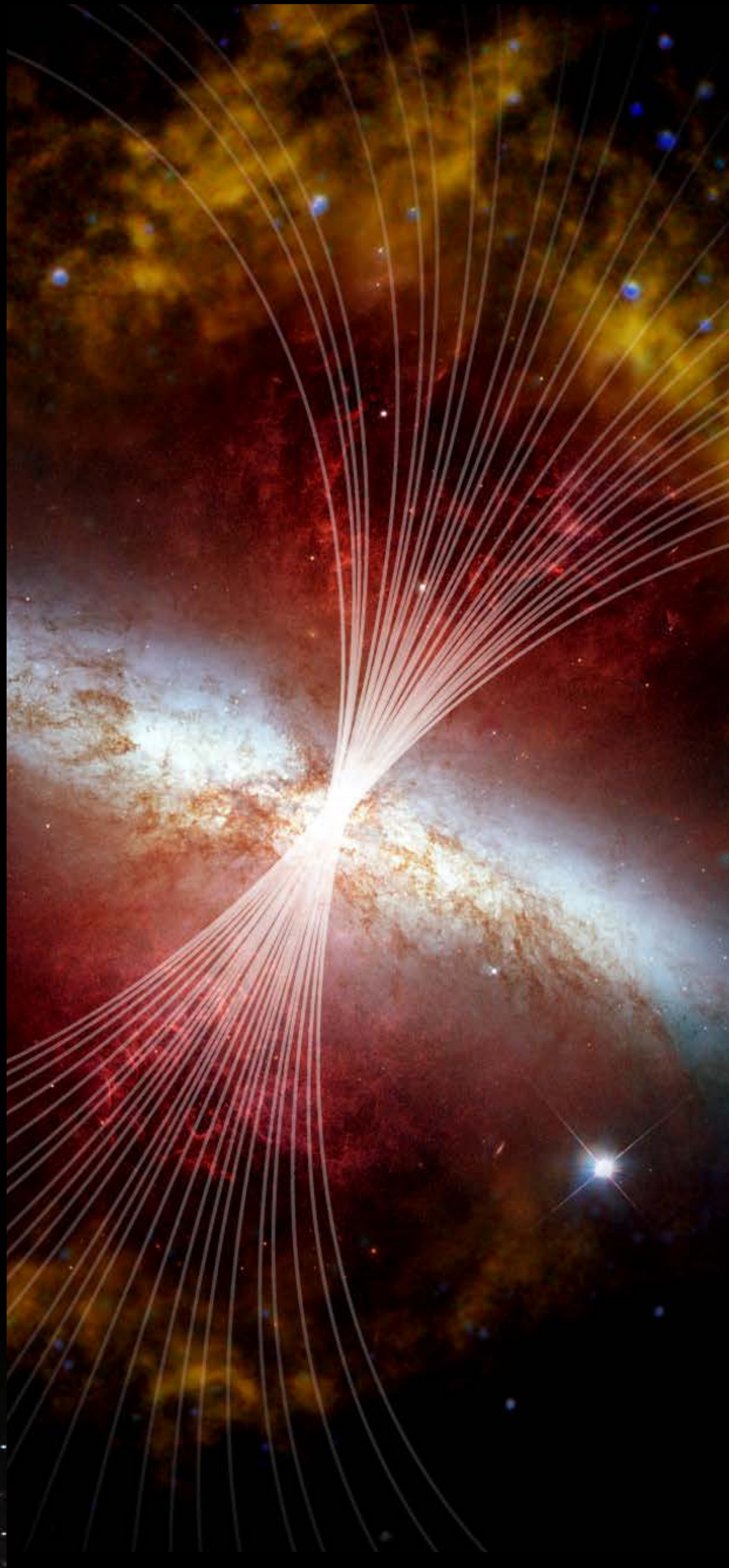

EXTRAGALACTIC MAGNETISM WITH SOFIA: FIRST RESULTS

Enrique Lopez Rodriguez

KIPAC/Stanford

LEGACY TEAM

Team Member	Affiliation
Enrique Lopez-Rodriguez (co-PI)	**KIPAC, Stanford University, USA**
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Karl Gordon	Space Telescope Science Institute (STScI), USA
Lucas Grosset	KIPAC, Stanford University, USA

Team Member	Affiliation
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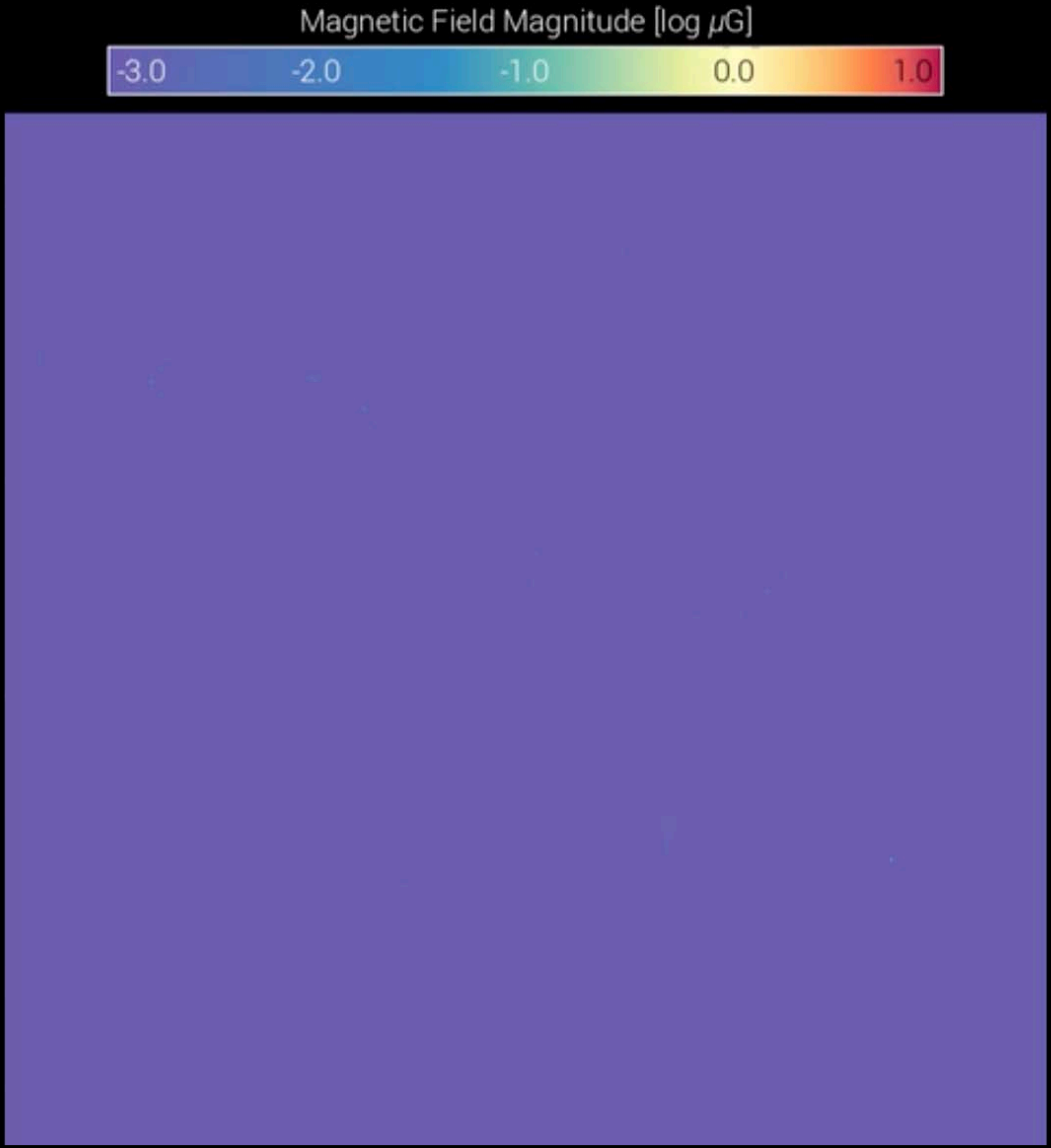
Sergio Martinez Alvarez	KICC, Cambridge, UK —> KIPAC/Stanford, USA
Evangelia Ntormousi	University of Crete, Greece
William T. Reach	SOFIA Science Center, NASA Ames, USA
Julia Roman-Duval	Space Telescope Science Institute, USA
Alejandro Serrano Borlaff	NASA Ames, USA
Kandaswamy Sugramanian	Inter-University Centre for Astronomy and Astrophysics, India
Konstantinos Tassis	University of Crete, Greece
Ngoc Tram Le	SOFIA Science Center, NASA Ames, USA
Ellen Zweibel	University of Winsconsin, USA

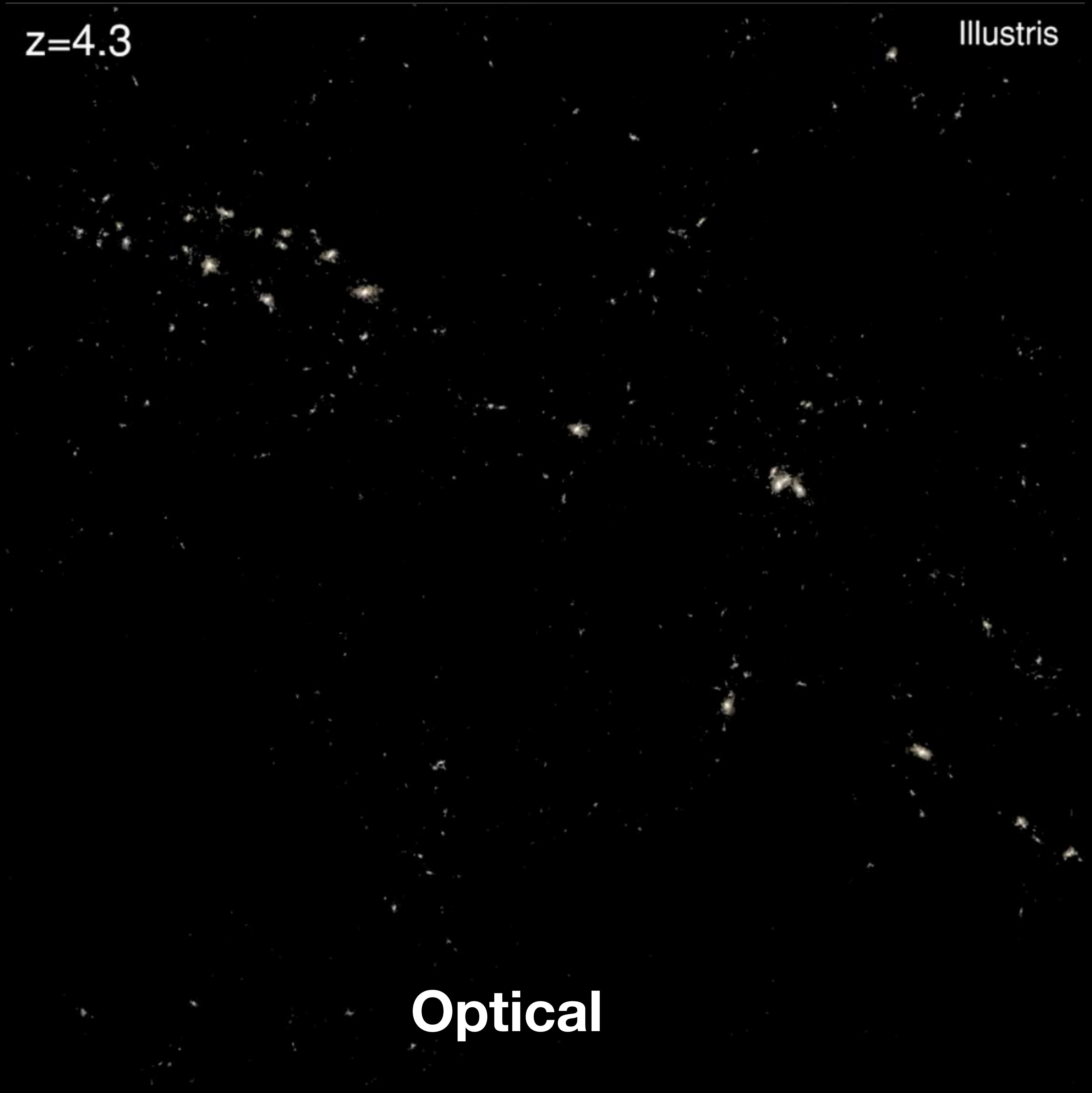
THE ROLE OF MAGNETIC FIELDS IN GALAXY EVOLUTION

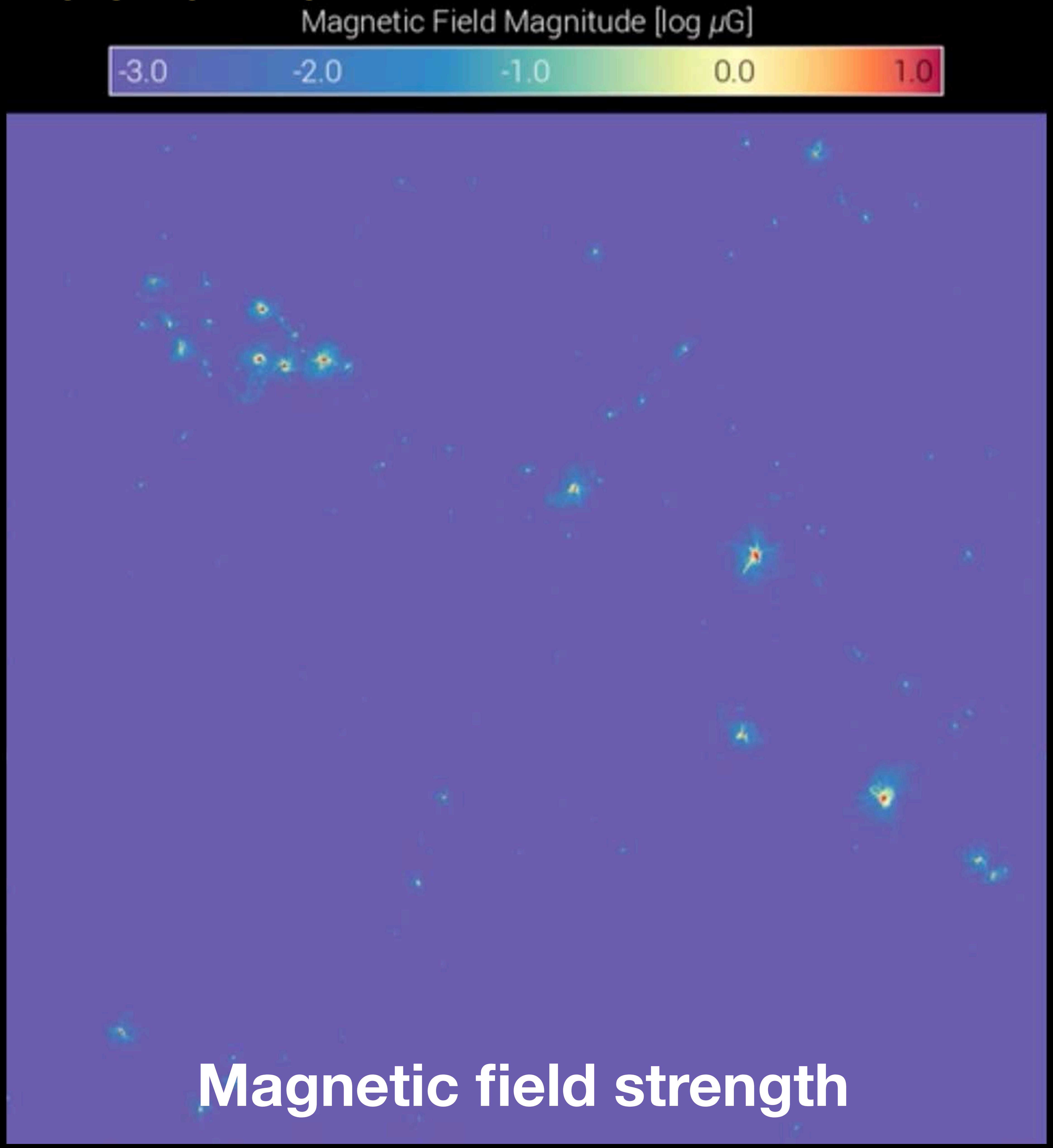
Stage 1: Field seeds

- Generation of seed fields by Biermann battery, Weibel instability, or plasma fluctuations (B~10^{-18}-10^{-9} G)

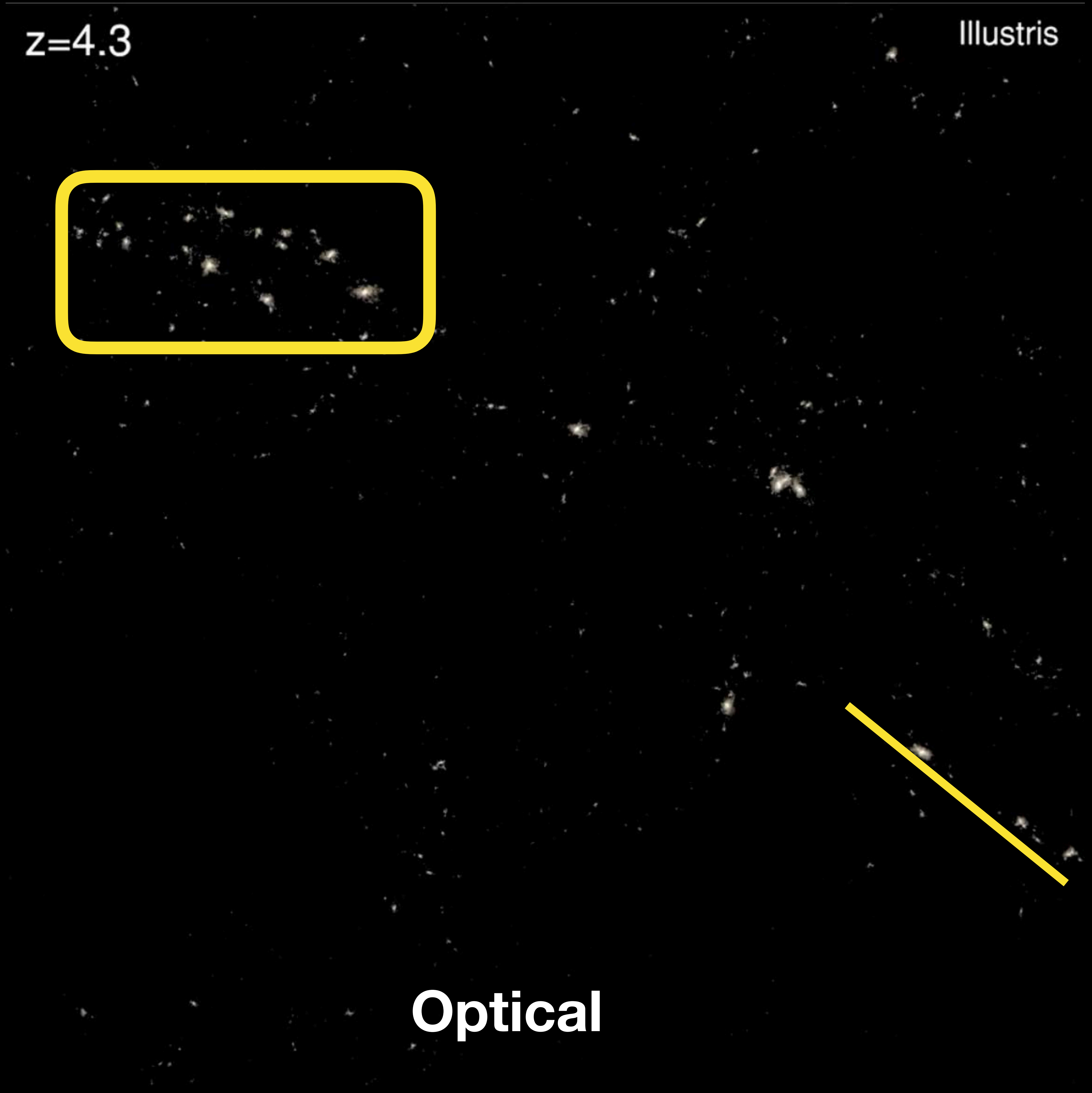


LARGE SCALE STRUCTURES

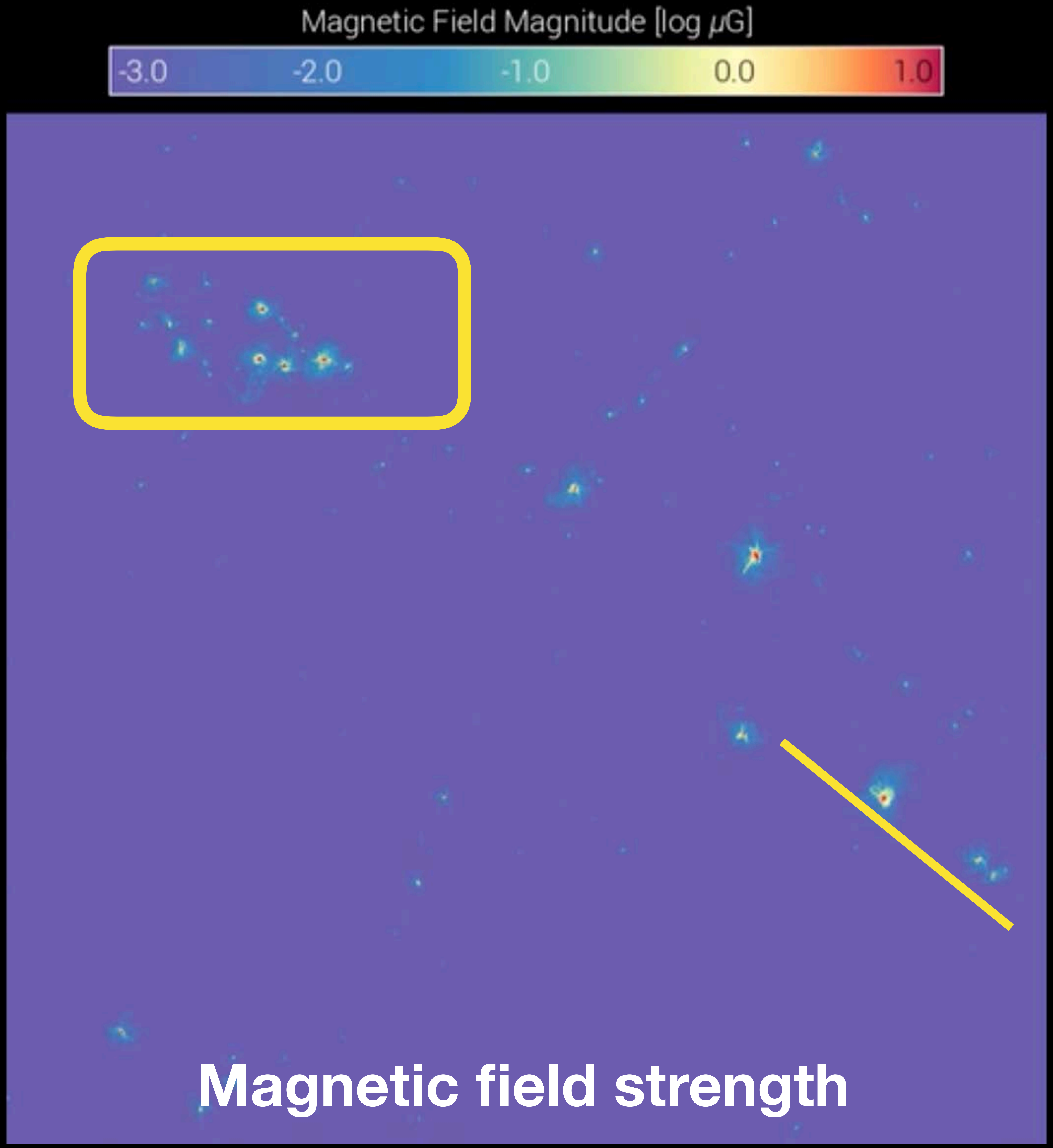




LARGE SCALE STRUCTURES

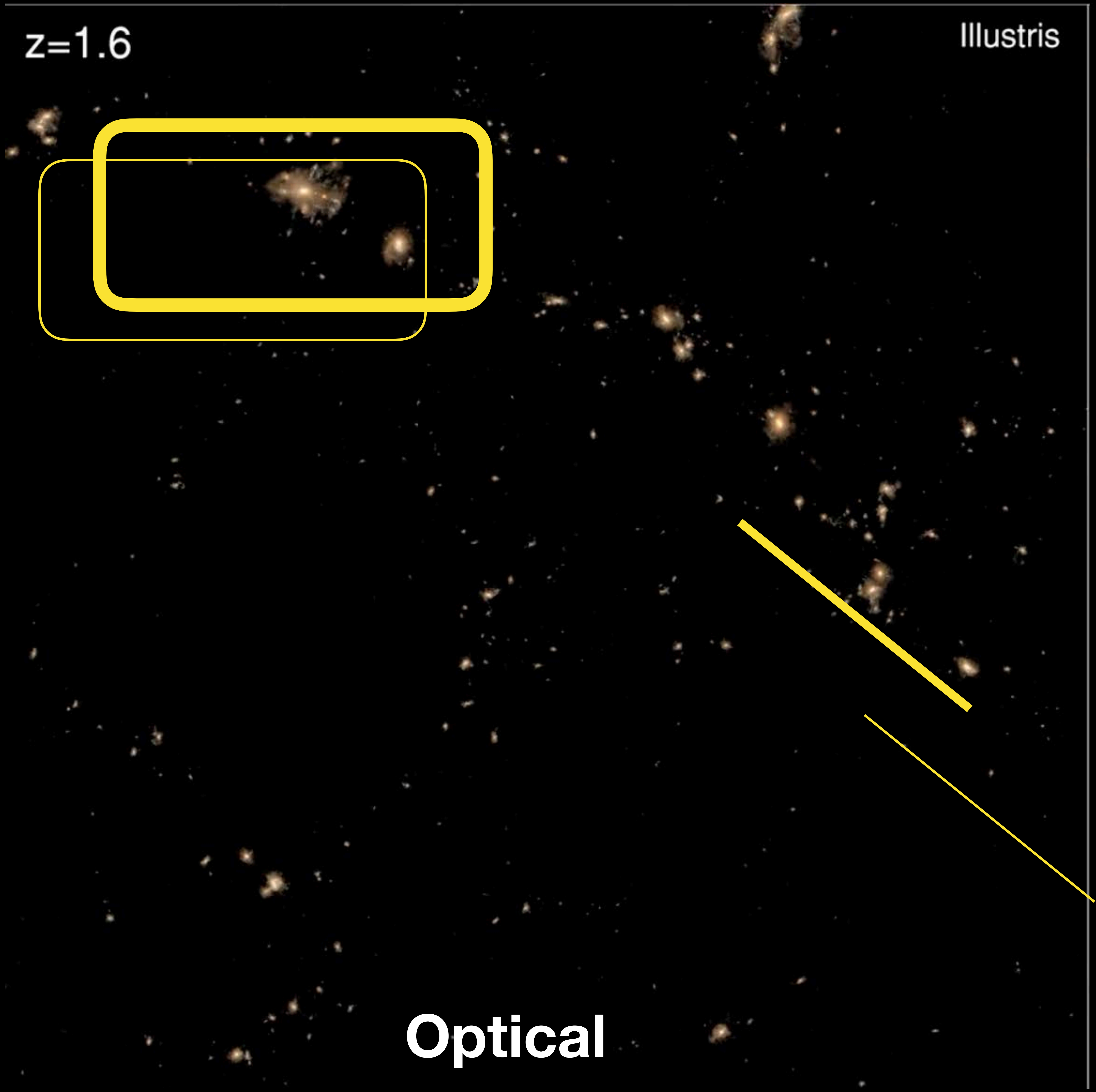


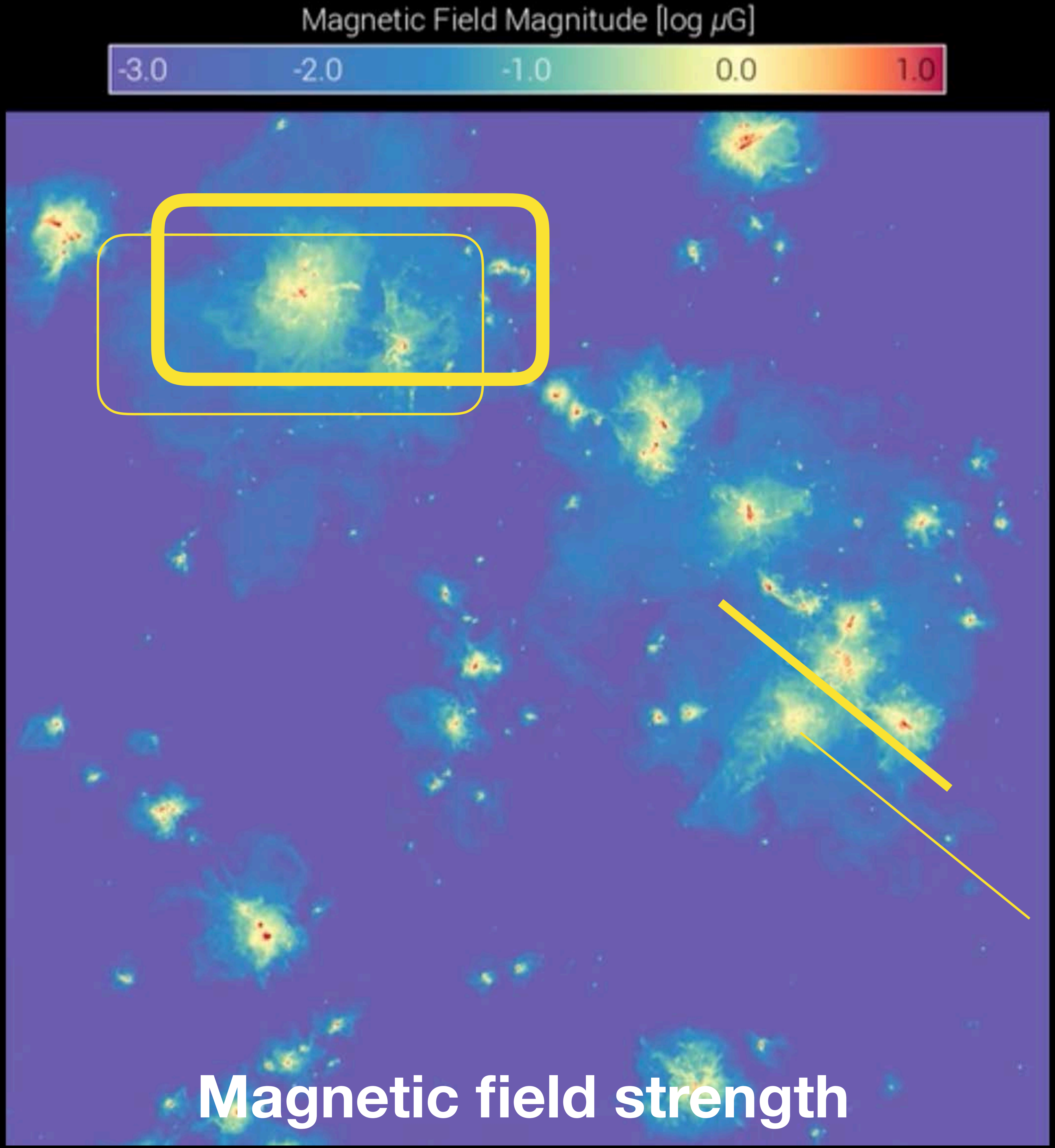
Optical



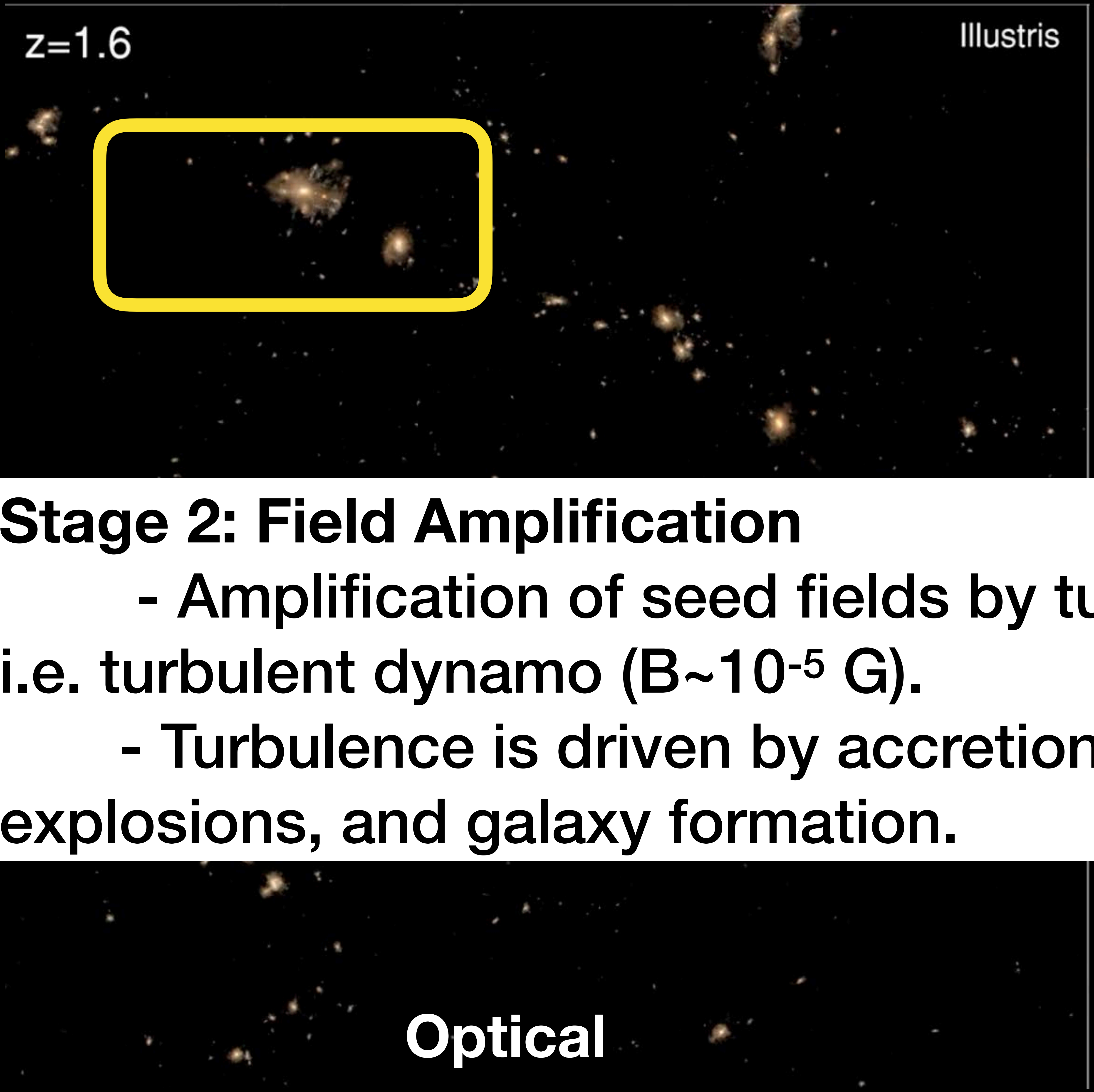
Magnetic field strength

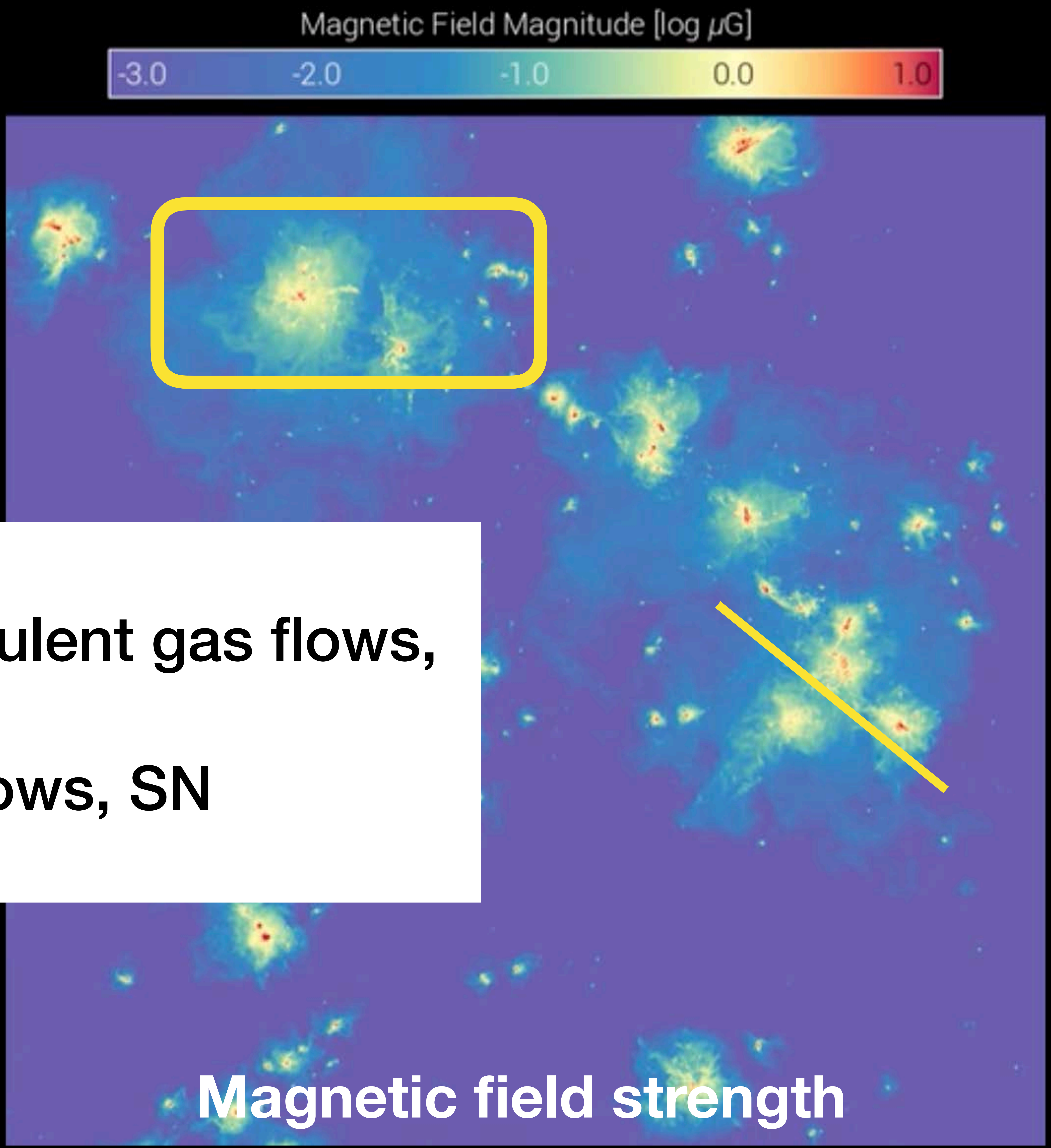
PEAK OF STAR FORMATION ACTIVITY





STAGE 2: FIELD AMPLIFICATION

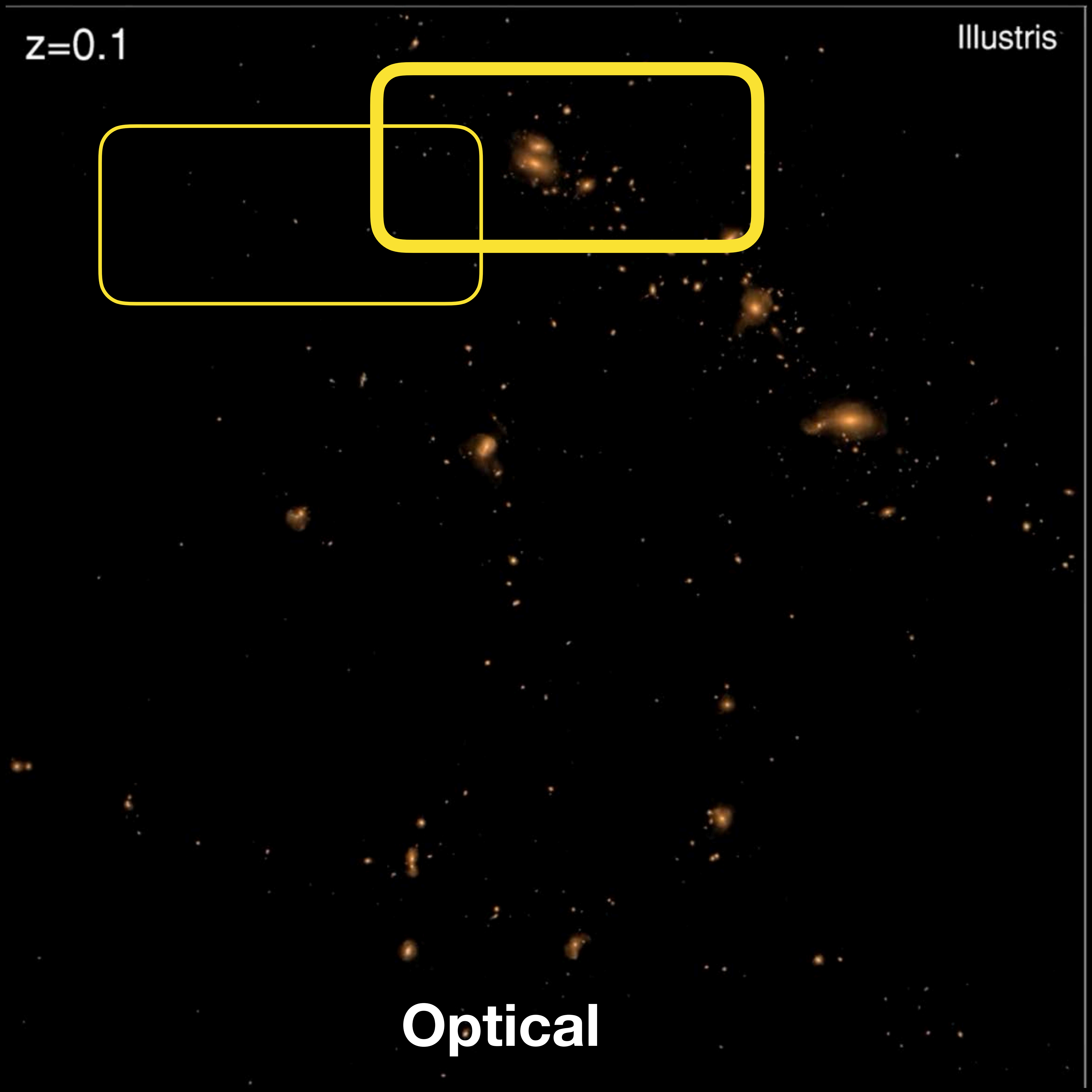




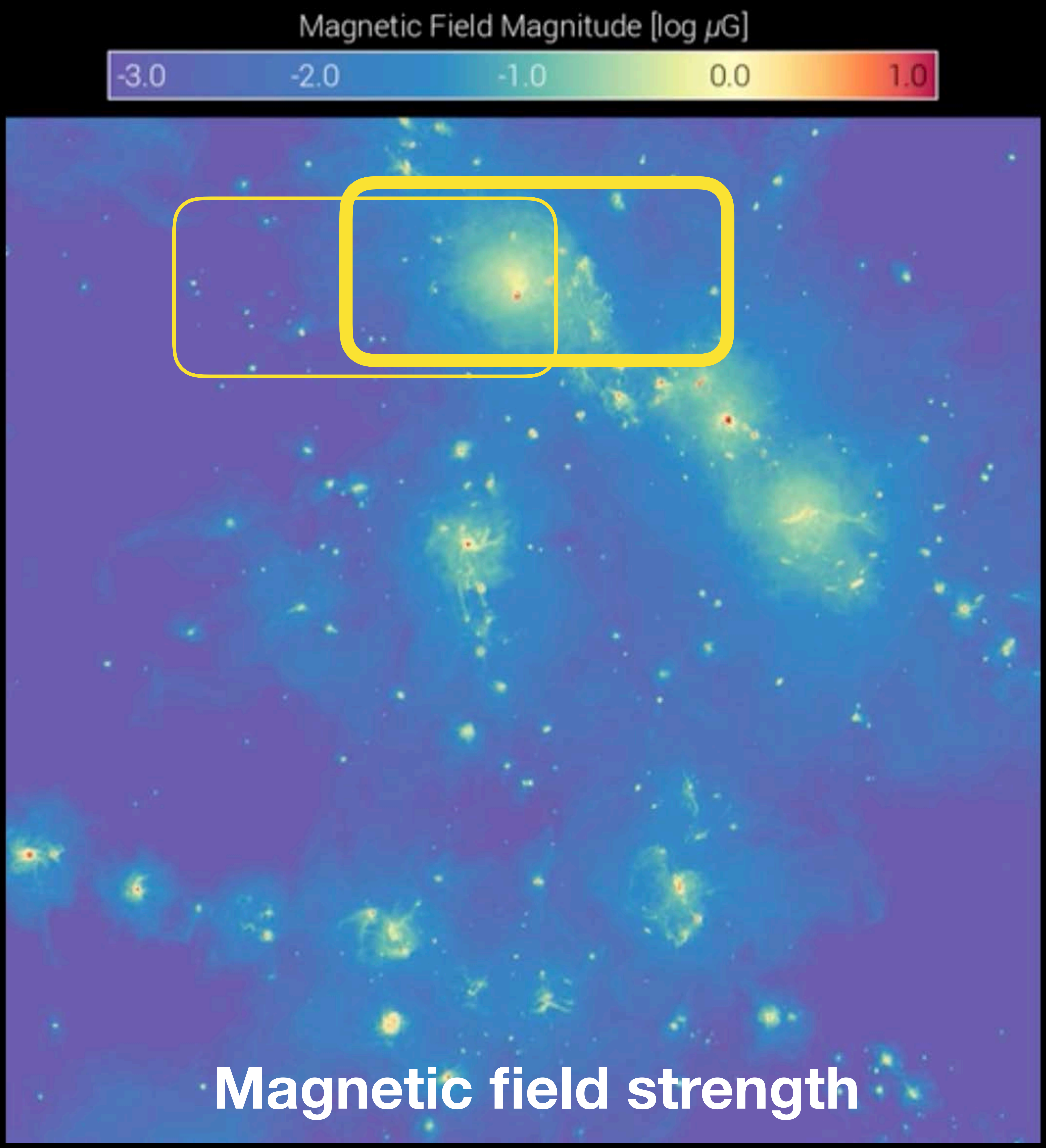
Stage 2: Field Amplification

- Amplification of seed fields by turbulent gas flows, i.e. turbulent dynamo ($B \sim 10^{-5}$ G).
- Turbulence is driven by accretion flows, SN explosions, and galaxy formation.

PRESENT-DAY GALAXIES

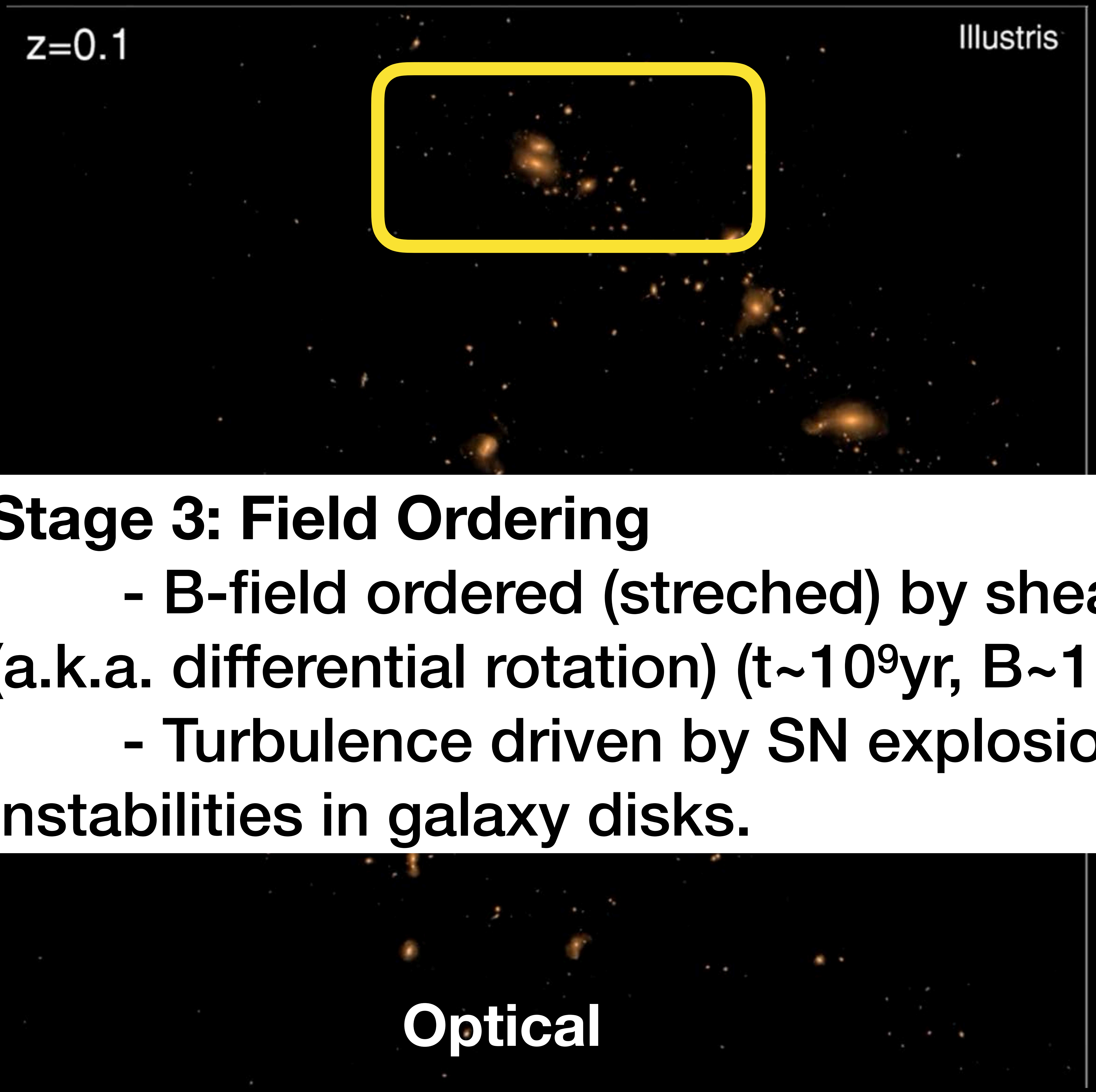


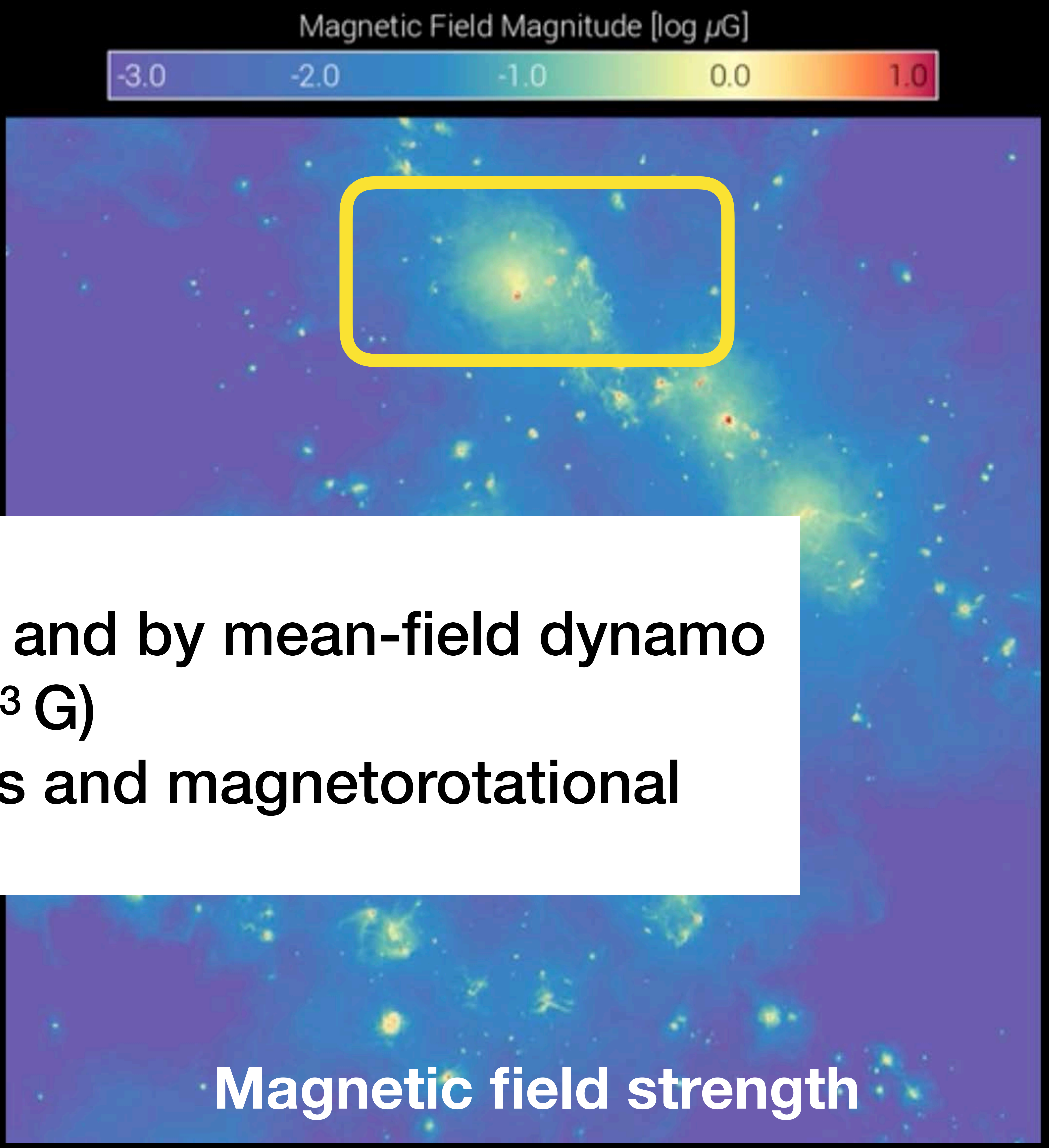
Optical



Magnetic field strength

STAGE 3: FIELD ORDERING



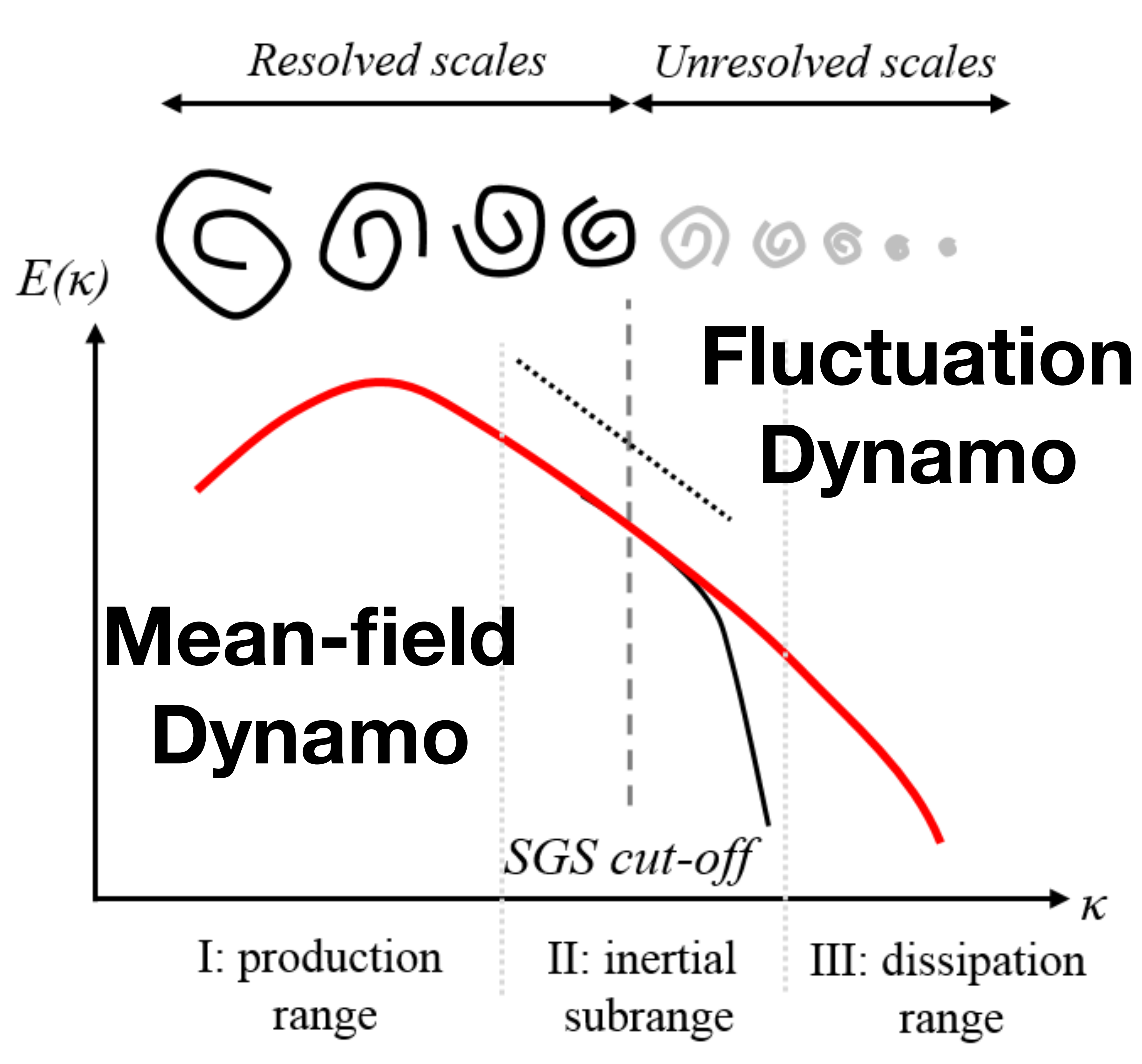


Stage 3: Field Ordering

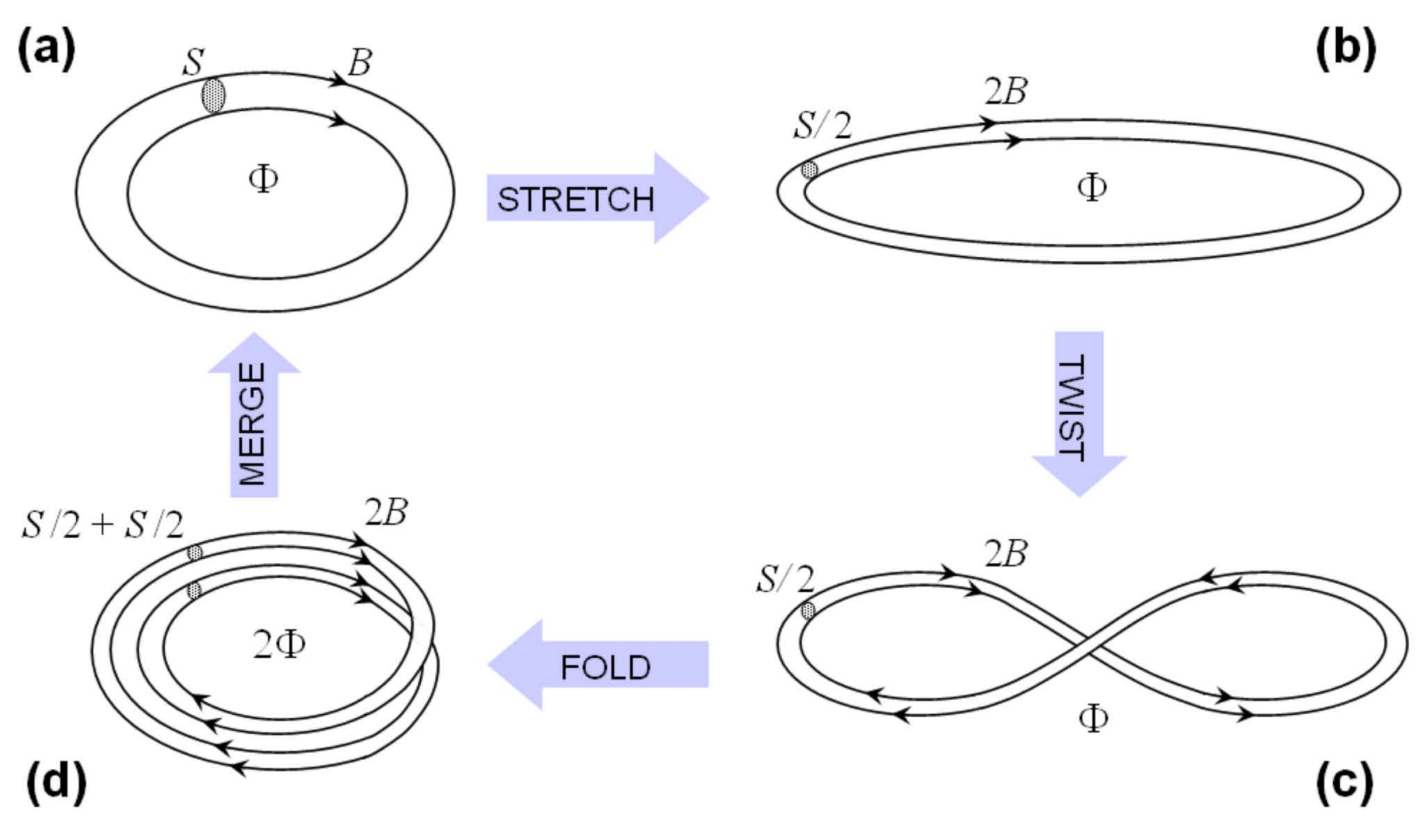
- B-field ordered (streched) by shear and by mean-field dynamo (a.k.a. differential rotation) ($t \sim 10^9$ yr, $B \sim 10^{-3}$ G)
- Turbulence driven by SN explosions and magnetorotational instabilities in galaxy disks.

TURBULENT DYNAMOS

Turbulent cascade
(Dissipation)



B-field amplification
(electromagnetic induction)



Turbulent coherent length of ~50-100 pc driven by SN explosions in spiral galaxies
(e.g. Haverkorn 2008, Brandenburg &Subramanian 2005)

OPEN QUESTIONS

- How did the evolution of galaxies in mergers affect magnetic fields?

- Is the circumgalactic medium magnetized?

- How has the magnetic field been amplified by interaction/SF in galaxies?

- What is the structure of the magnetic field around an active nucleus?

SURVEY OF MAGNETIC FIELDS IN GALAXIES WITH SOFIA (SALSA)

GOAL:

First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.

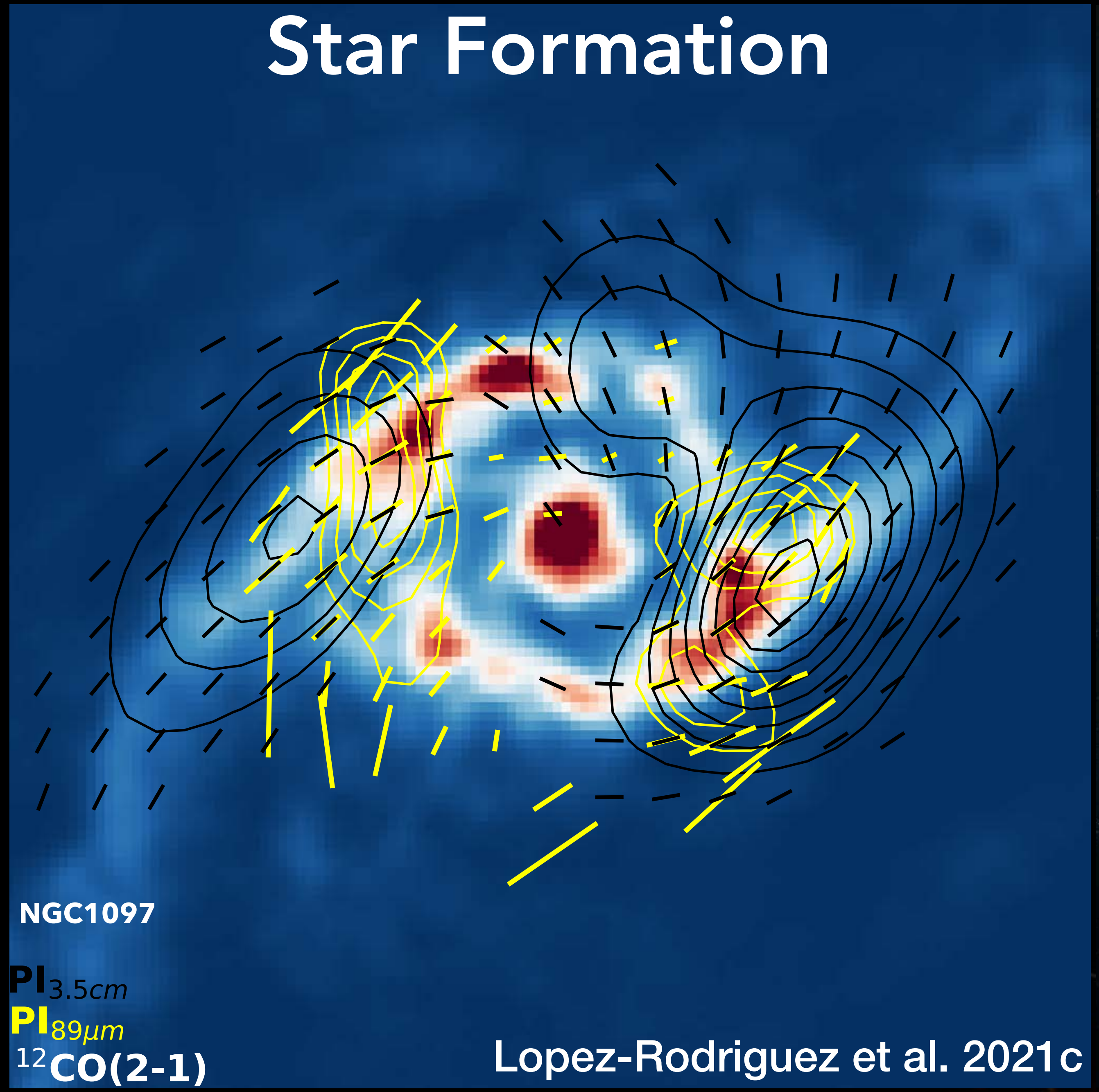
SURVEY OF MAGNETIC FIELDS IN GALAXIES WITH SOFIA (SALSA)

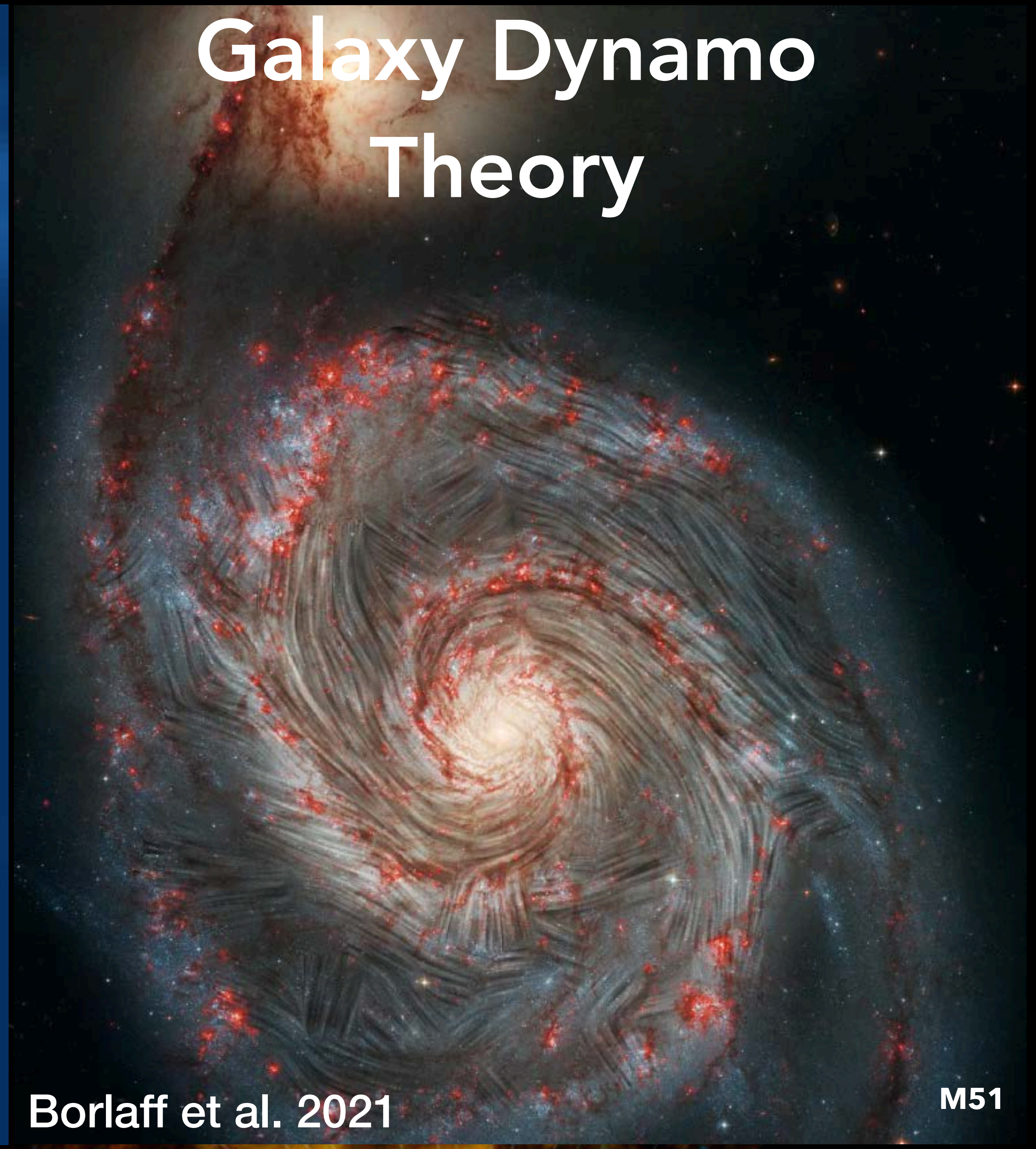
GOAL:

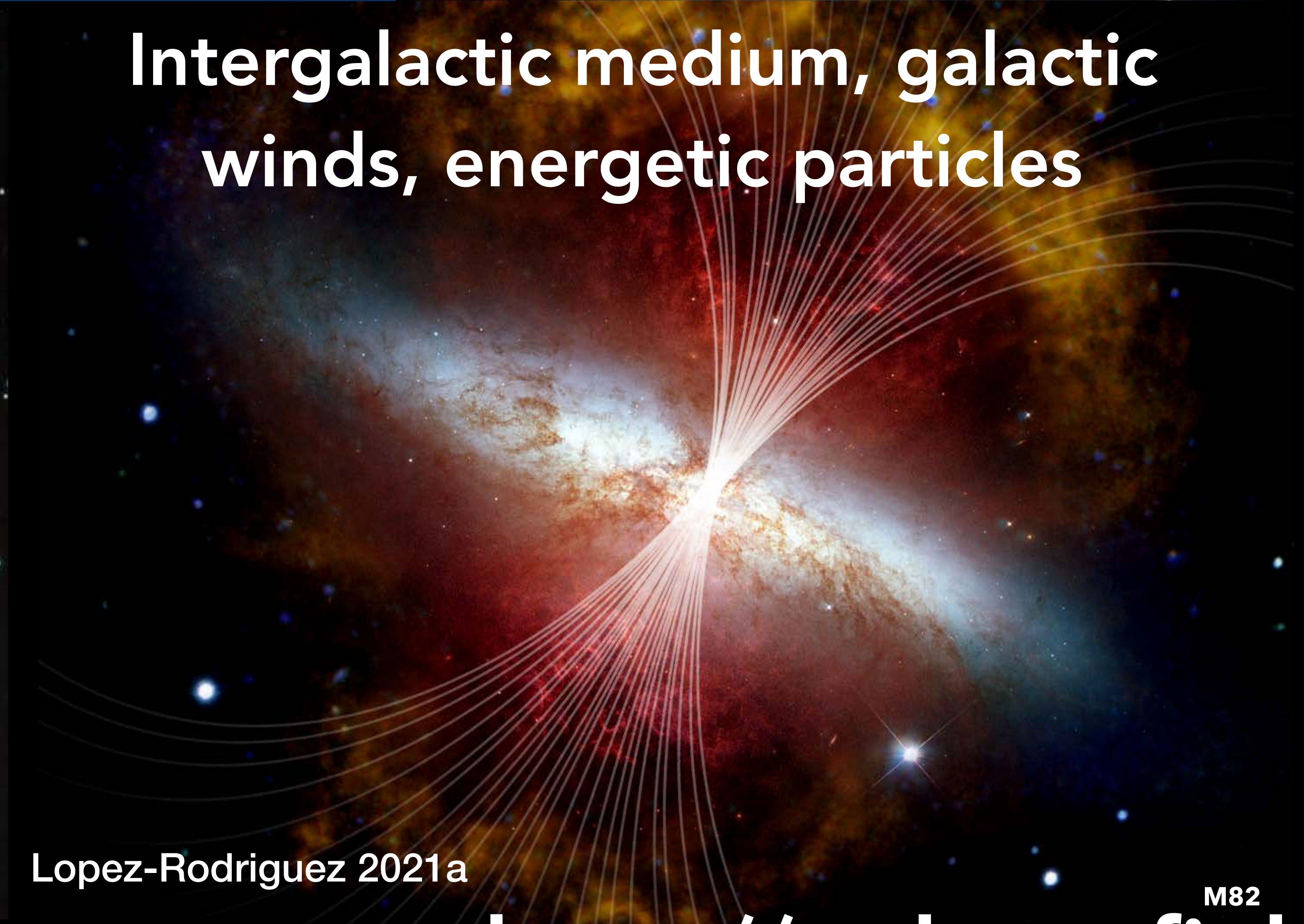
First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.

ISM Phase	Instrument	Tracers
Dense and cold	FIR/HAWC+/ SOFIA	Continuum dust total/polarized emission of aligned dust B-field orientation
Warm and diffuse	Radio/VLA/ Effersberg	Synchrotron emission B-field orientation/direction/strength
Molecular gas (CO)	Sub-mm/ALMA	Line emission morphology Velocity field Velocity dispersion (turbulent kinetic energy)
Neutral gas (HI)	21cm (varios telescopes)	Line emission morphology Velocity field Velocity dispersion (turbulent kinetic energy)

KEY SCIENCE TOPICS OF THE LEGACY PROGRAM



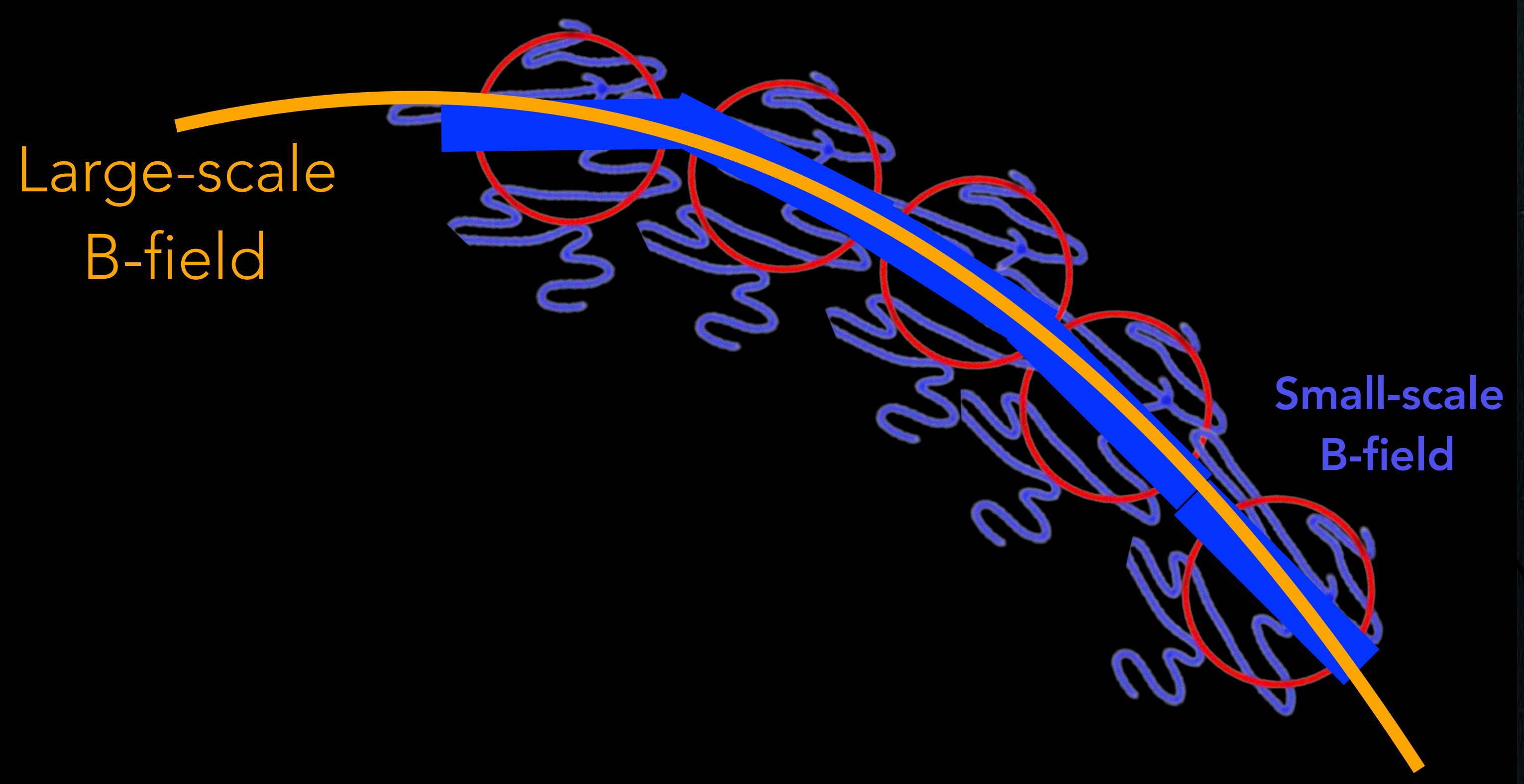


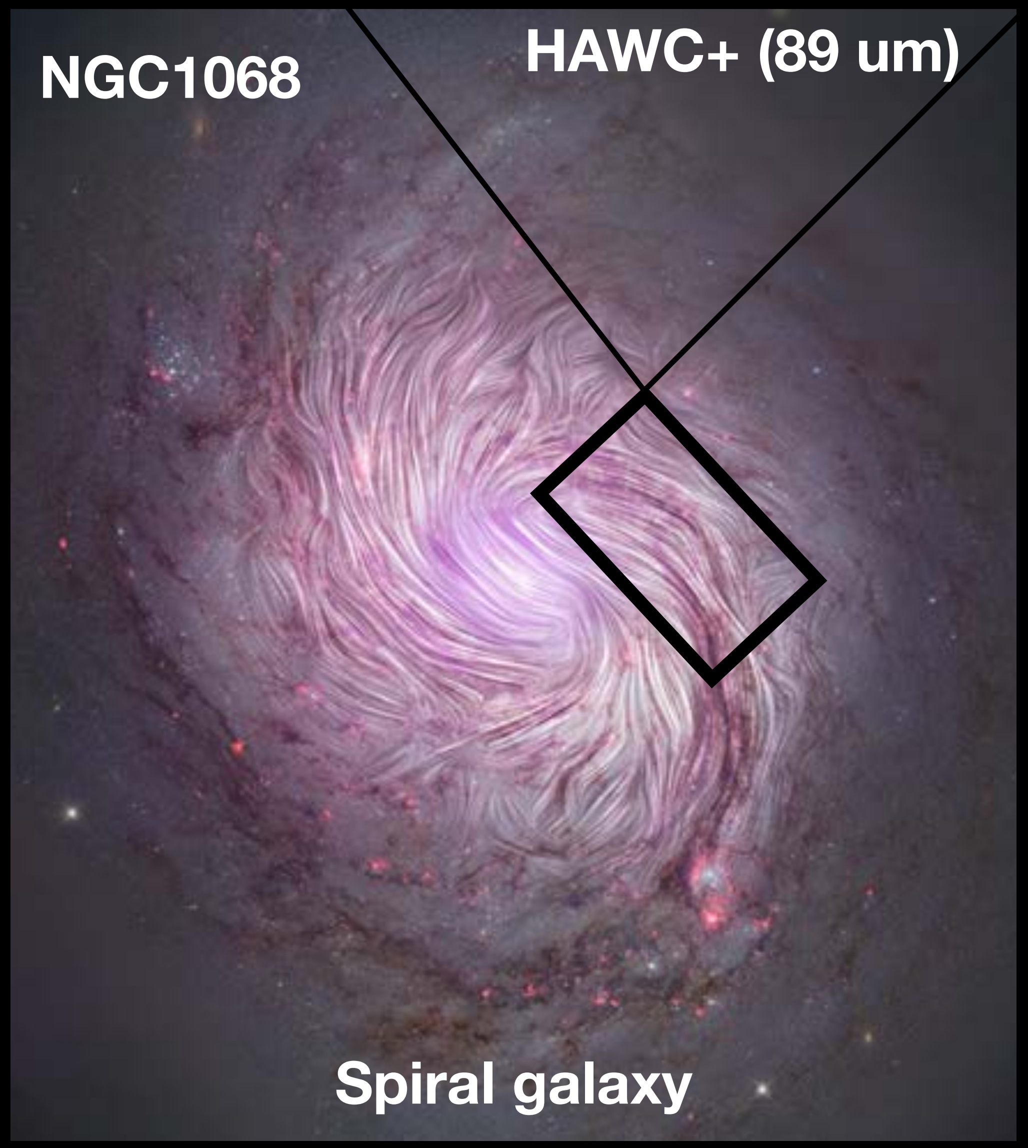


http://galmagfields.com/

ORDERED MEAN-FIELD DYNAMO

Ordered mean-field dominates
(galactic dynamo)





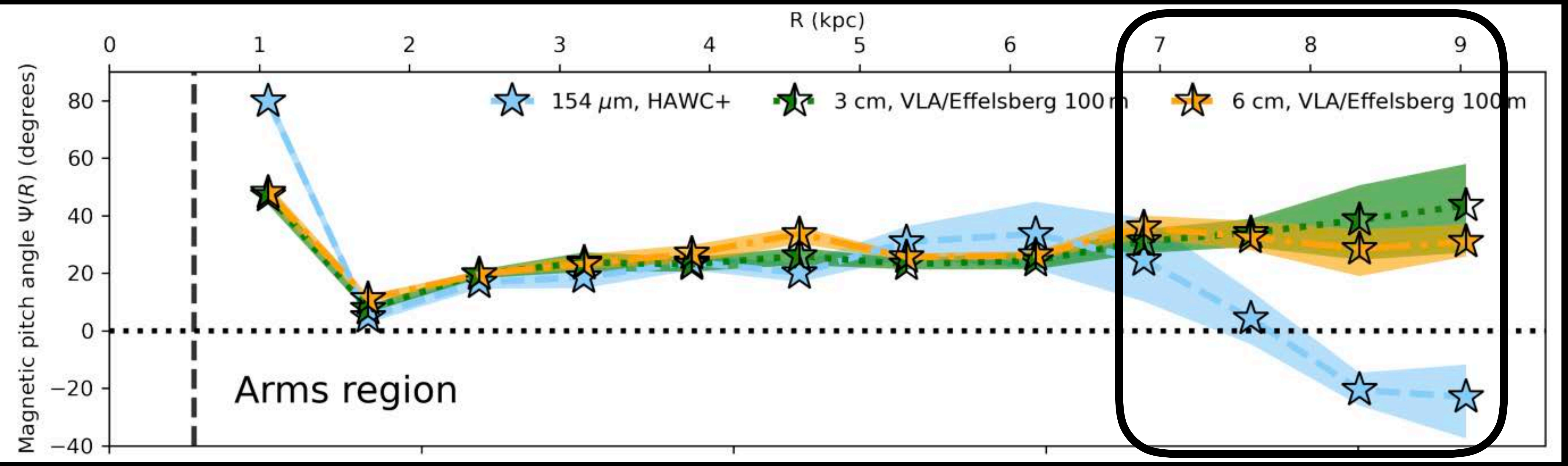
Lopez-Rodriguez et al. 2020

Borlaff et al. 2021

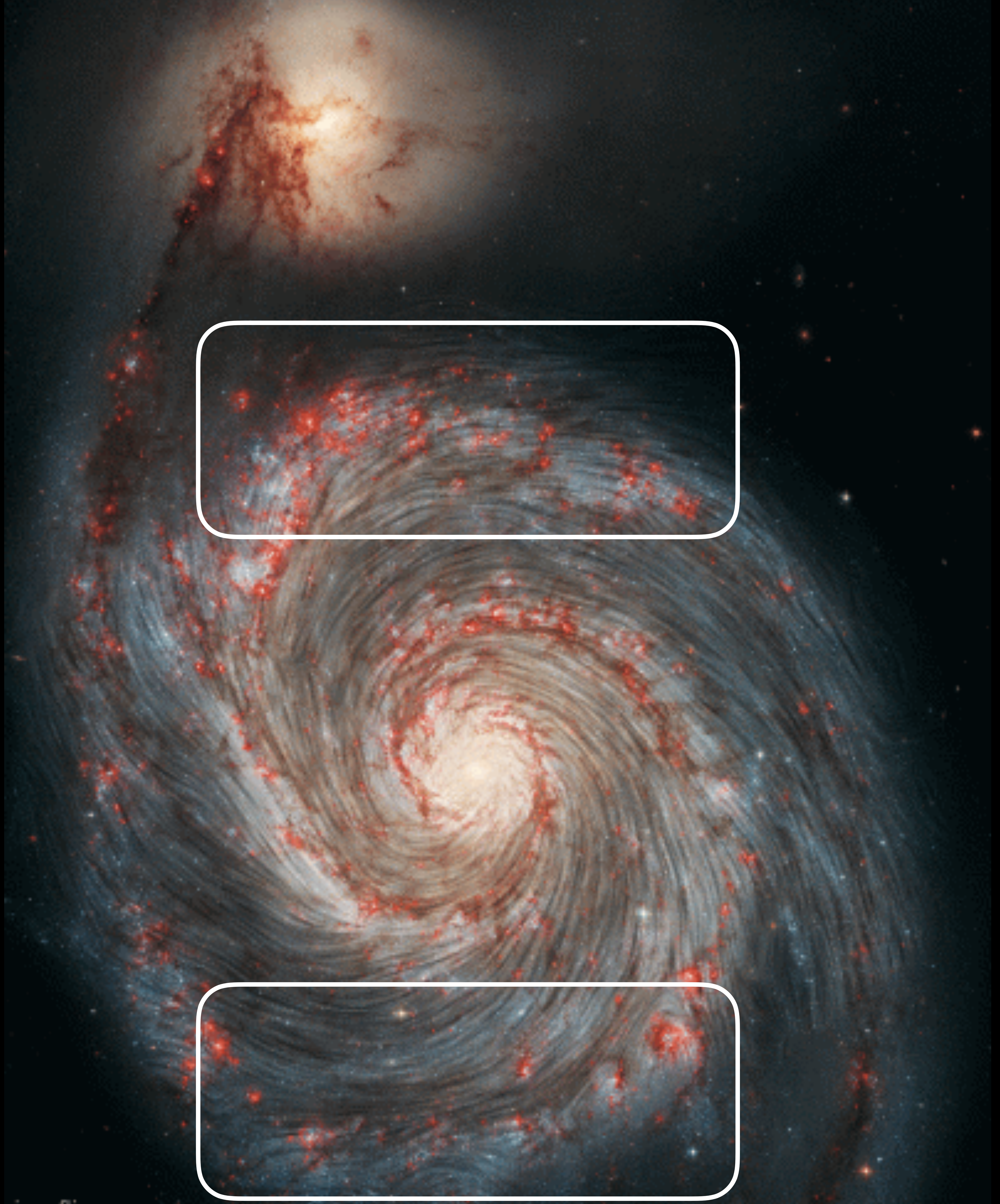
M51

SPIRAL GALAXY WITH COMPANION

- Far-IR and radio do not necessarily trace the same B-field component along the LOS



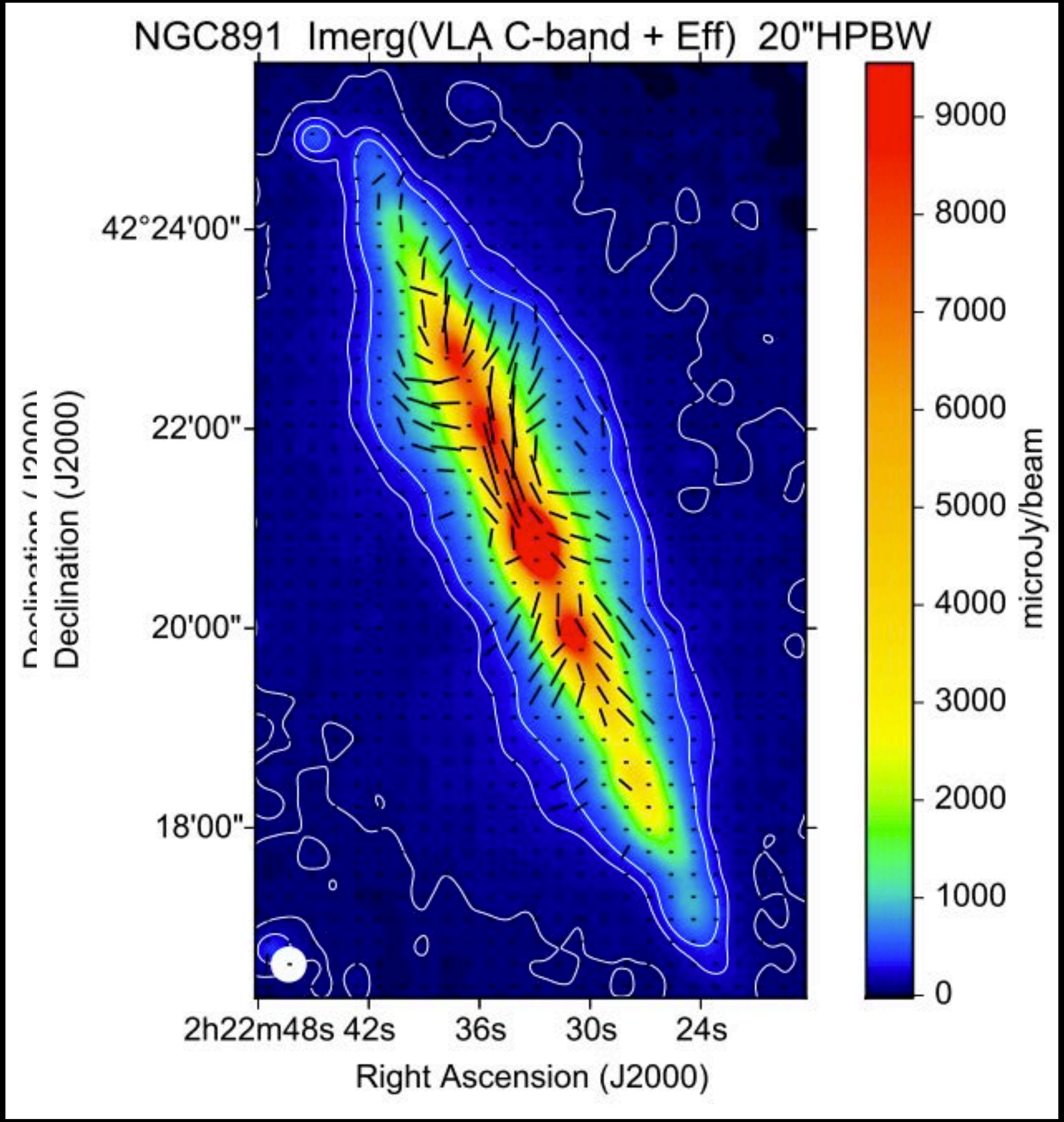
Borlaff et al. 2021



RADIO AND FIR OBSERVATIONS TRACE DIFFERENT GALACTIC SCALE HEIGHTS

Radio

h ~ 1-2 kpc



Krause et al. (2018,2020)

RADIO AND FIR OBSERVATIONS TRACE DIFFERENT GALACTIC SCALE HEIGHTS

Radio

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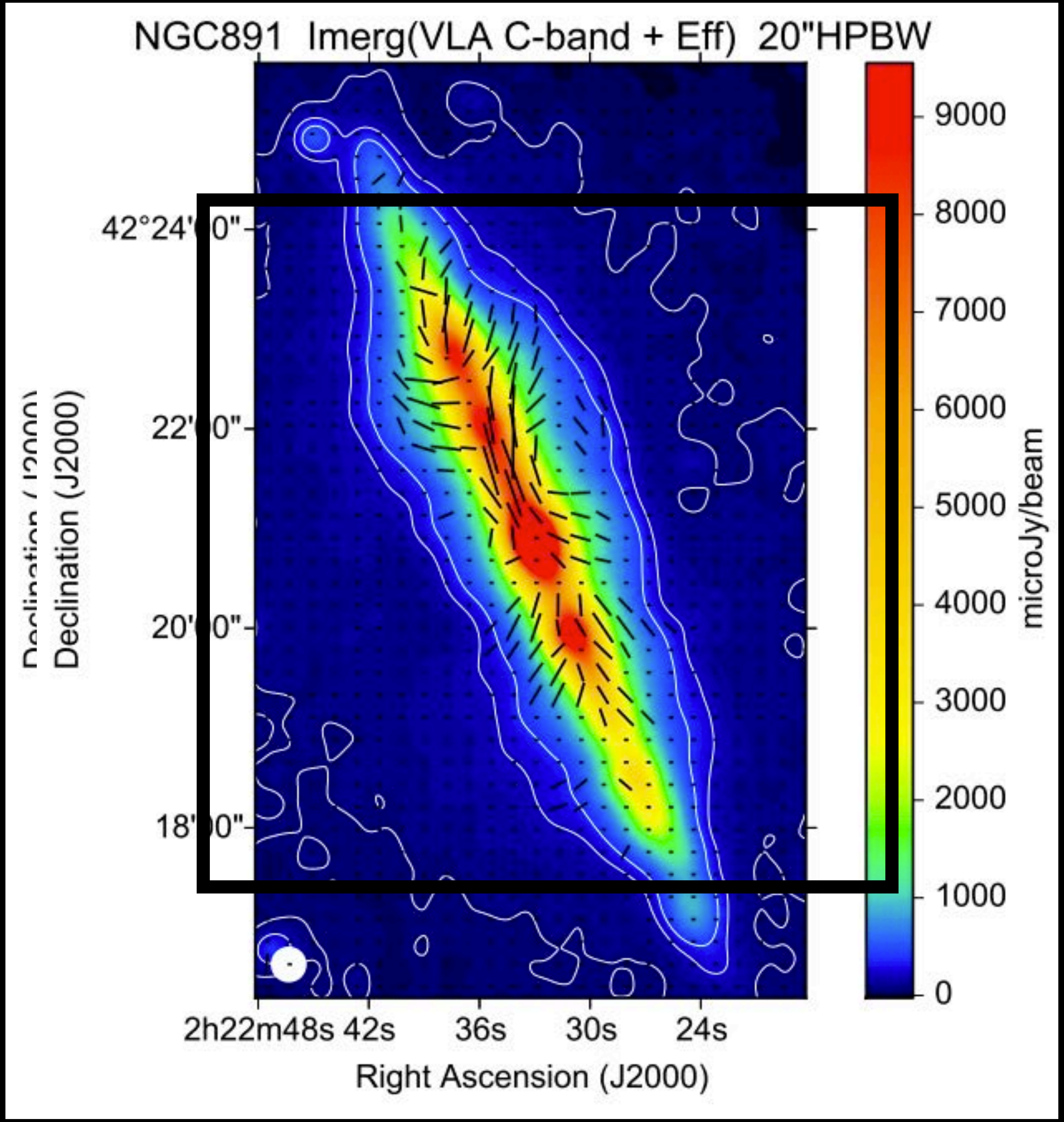
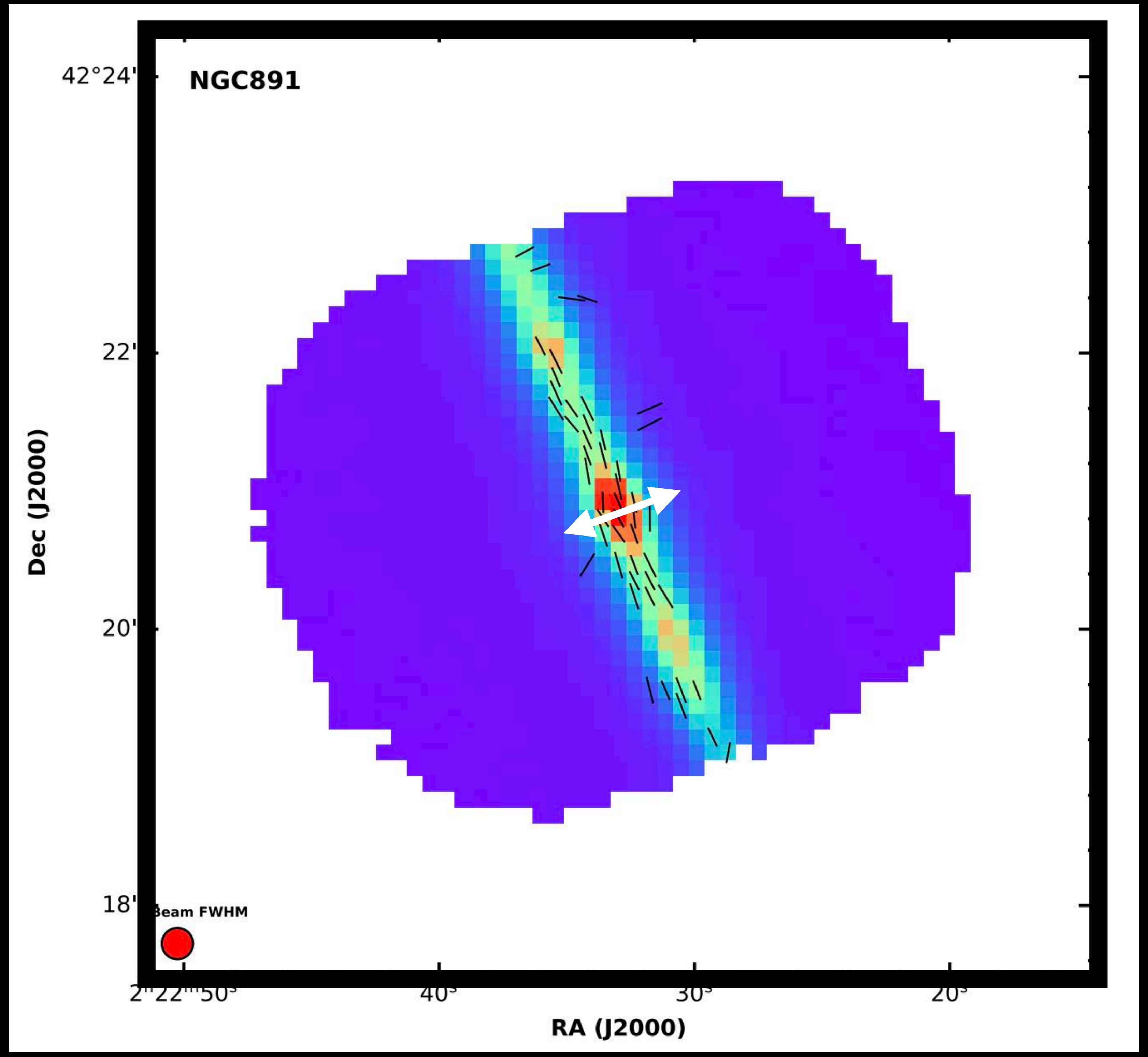


Krause et al. (2018,2020)

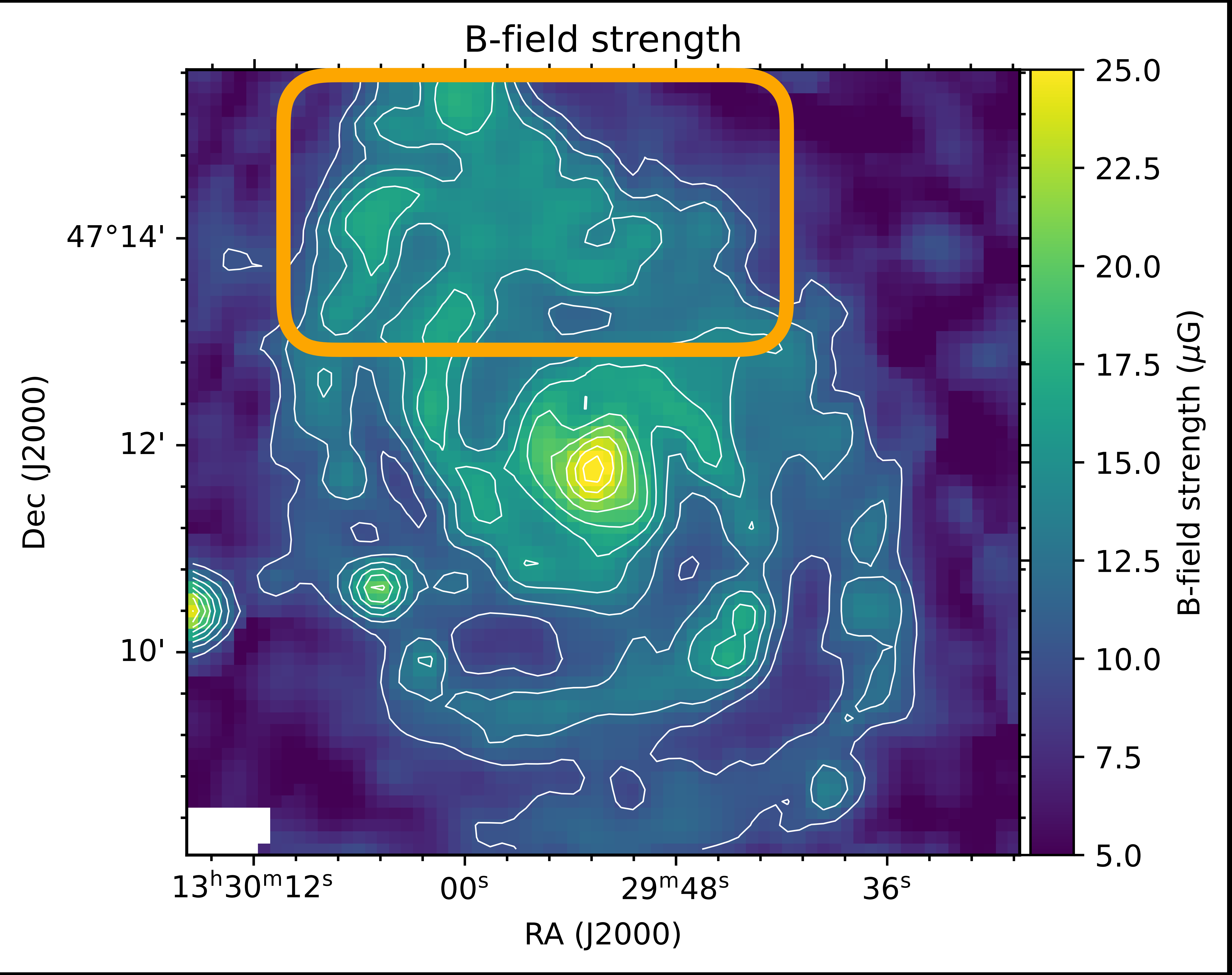
FIR

h < 0.5 kpc

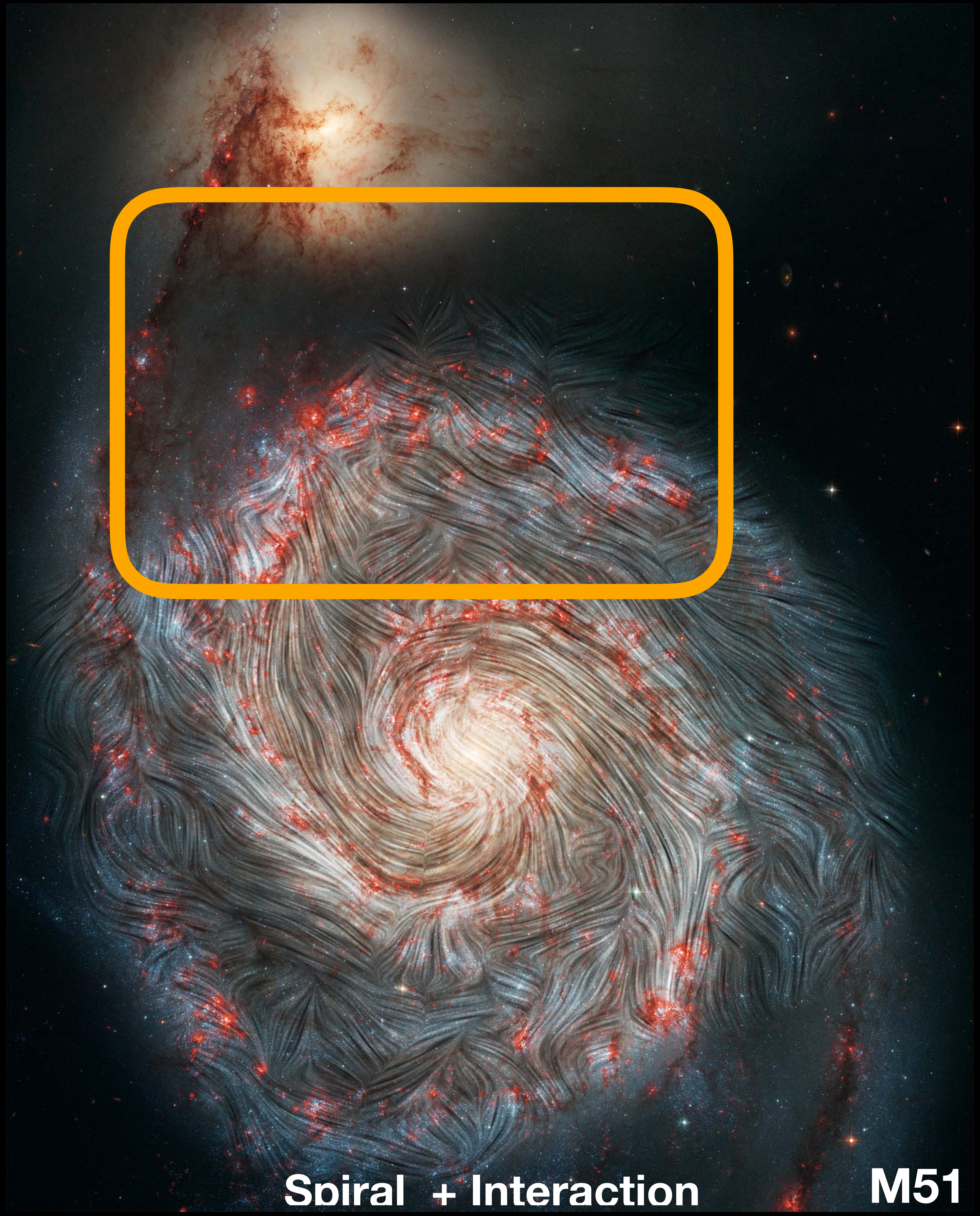


Jones et al. (2020) FWHM (HAWC+): 13.6”

B-field amplification due to galaxy interaction and/or star formation activity



Fletcher et al. 2011

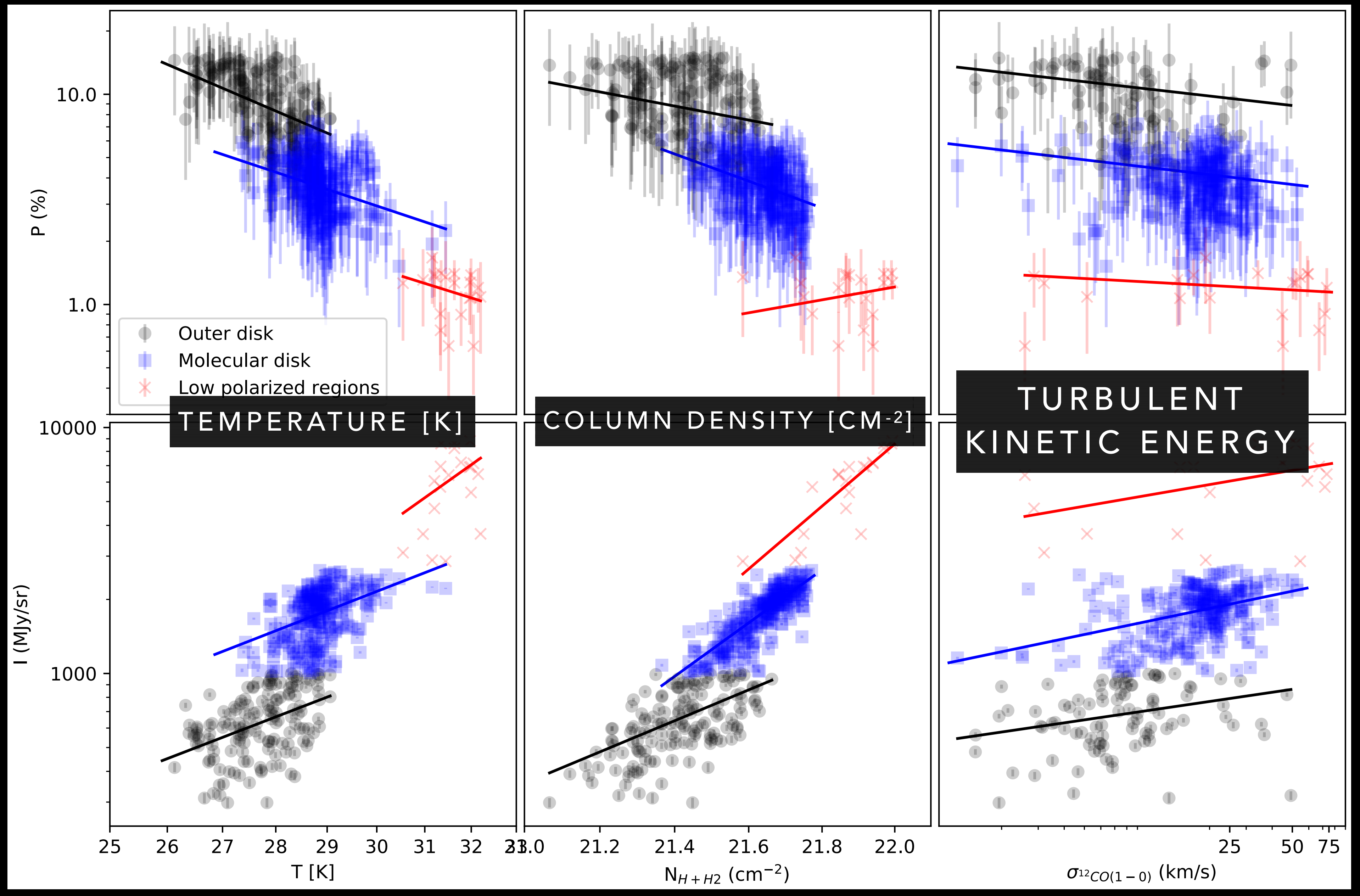


Borlaff et al. 2021


Ordered mean-field dominates
(galactic dynamo)
Large-scale
B-field
Small-scale
B-field
NGC1068
Spiral galaxy
Lopez-Rodriguez et al. 2020
M51
Spiral + Interaction
Borlaff et al. 2021
Fluctuation dynamo dominates
(SF, galaxy interaction)
Large-scale
B-field
Small-scale
B-field

CENTAURUS A
MERGER GALAXY AND ACTIVE NUCLEI

- Distorted B-field across the warped disk.
- B-field arises from fluctuation dynamos.
- Large turbulence kinetic energy and fast rotating disk.



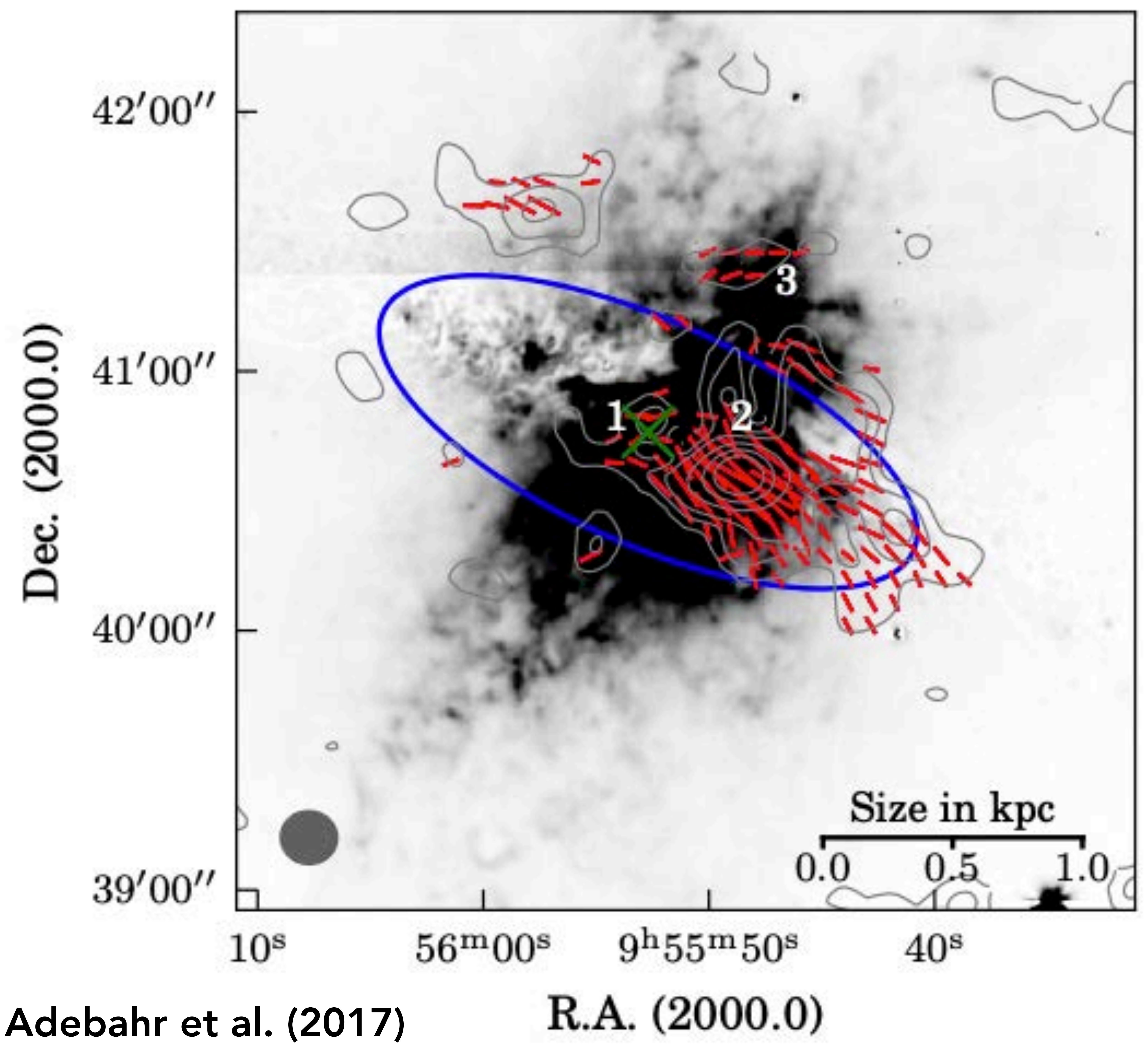
Lopez-Rodriguez (2021b, Nature Astronomy)

B-FIELD AMPLIFICATION DUE TO TURBULENCE DYNAMO DRIVEN BY MERGER

B-FIELD IN STARBURST GALAXIES: RADIO POLARIMETRIC OBSERVATIONS

Radio (18 and 22 cm)

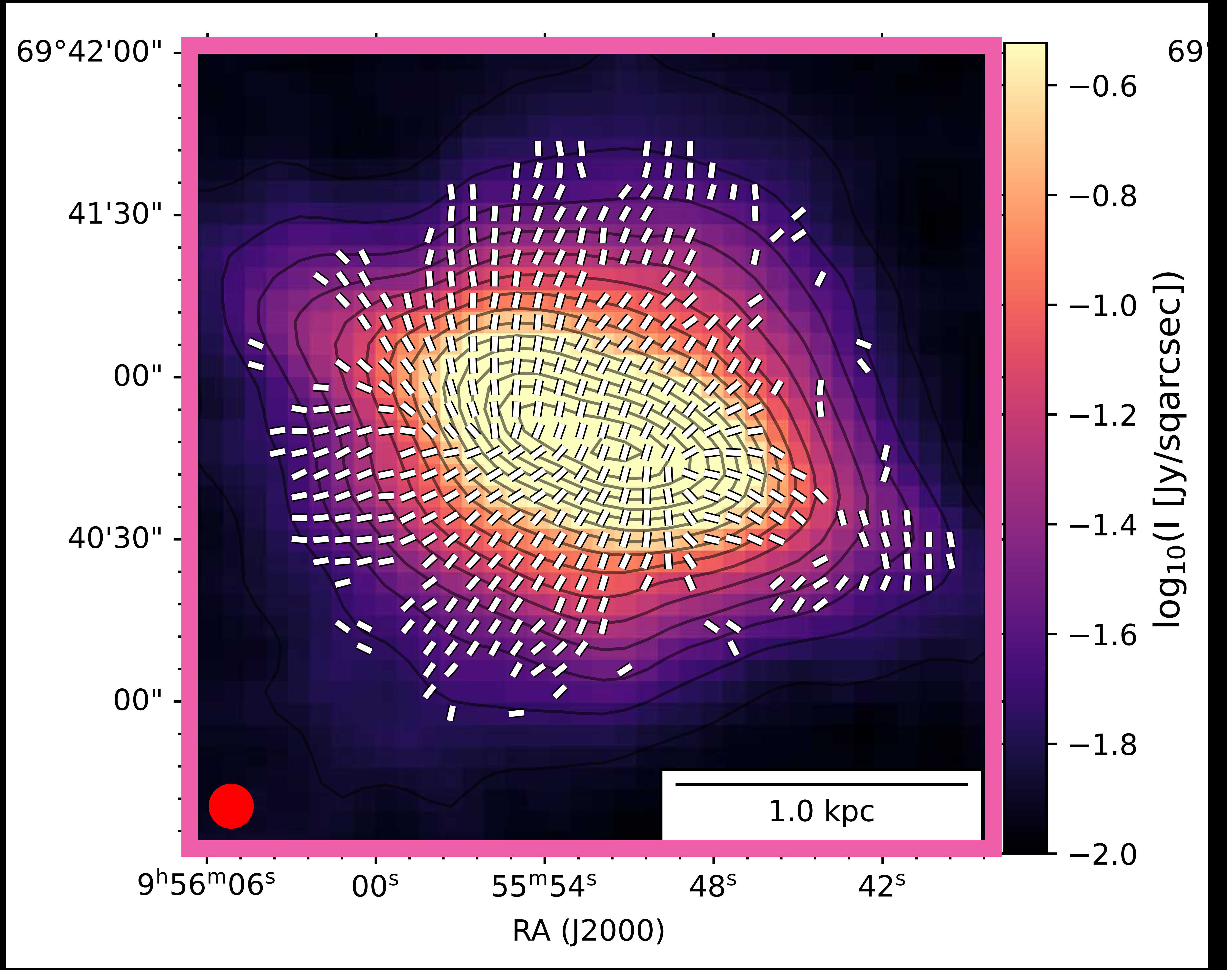
Polarization arising from synchrotron emission.
Magnetized bar due to remnant galactic dynamo.
Hints of helical B-field in the starburst region.



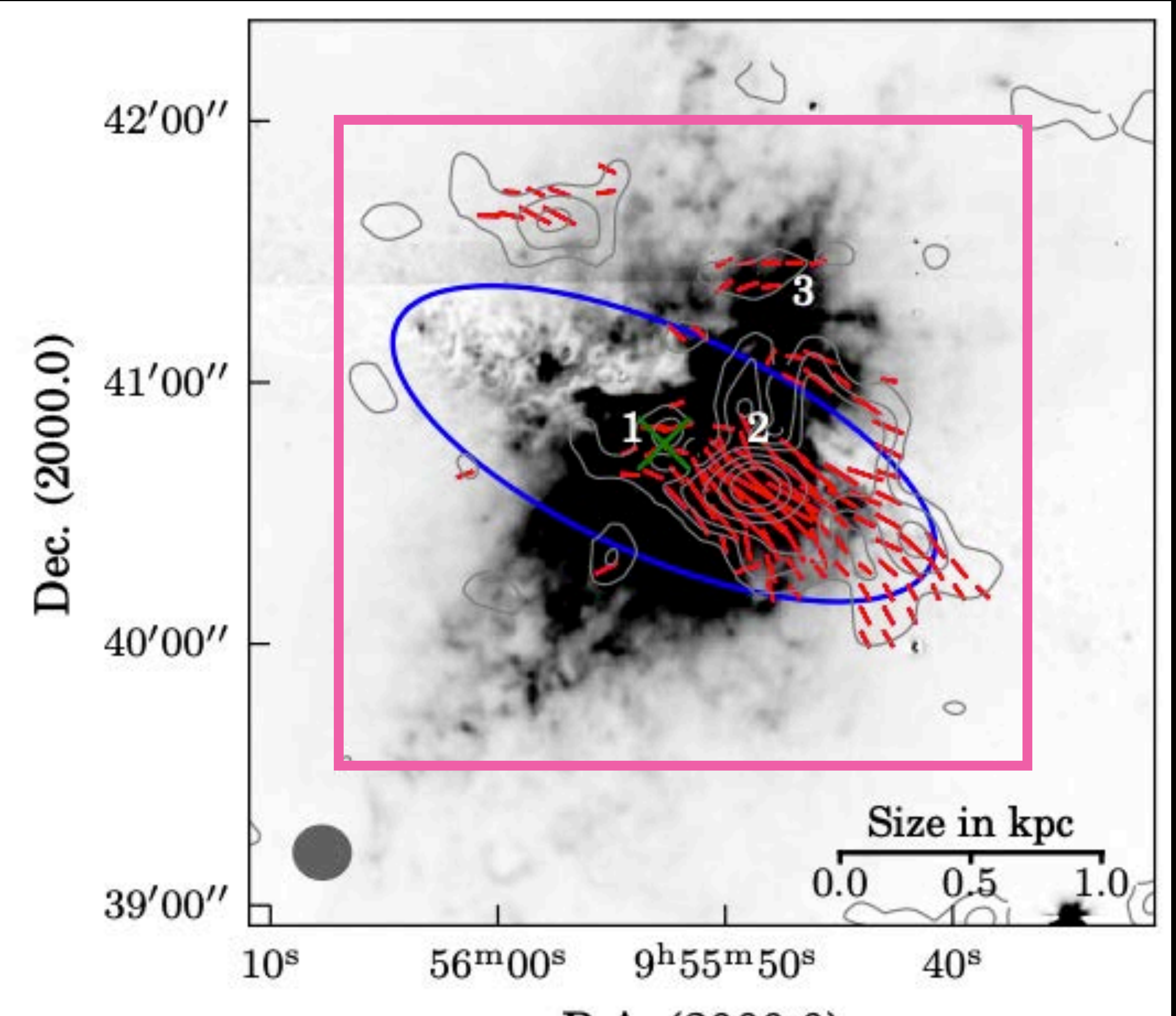
Adebahr et al. (2017)

B-FIELD TRACED BY RADIO AND FIR POLARIMETRIC OBSERVATIONS

FIR (89 um)



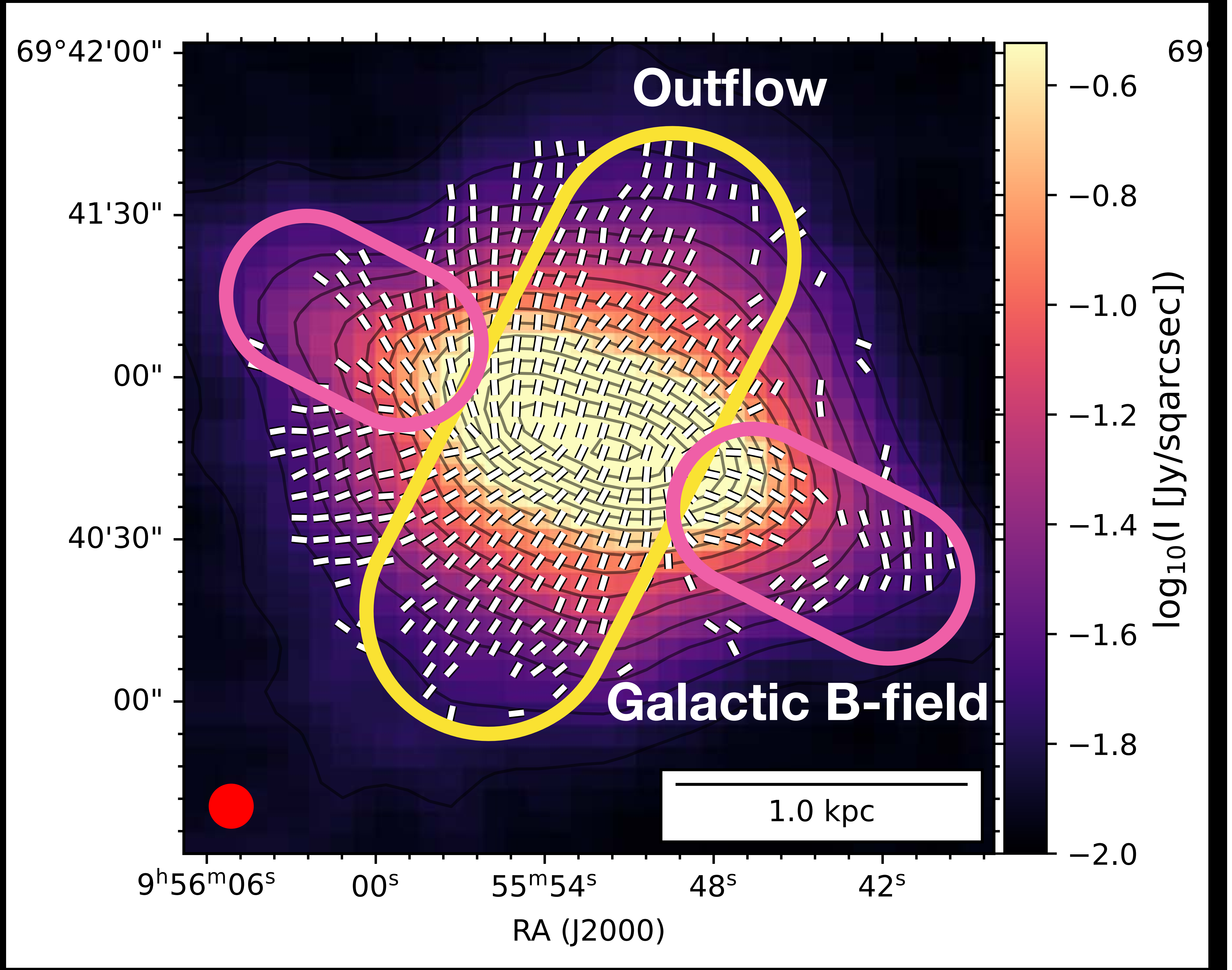
Radio (18 and 22 cm)



Adebahr et al. (2017)

FIR POLARIZATION TRACES THE B-FIELD ALONG THE OUTFLOW AND DISK

FIR (89 um)



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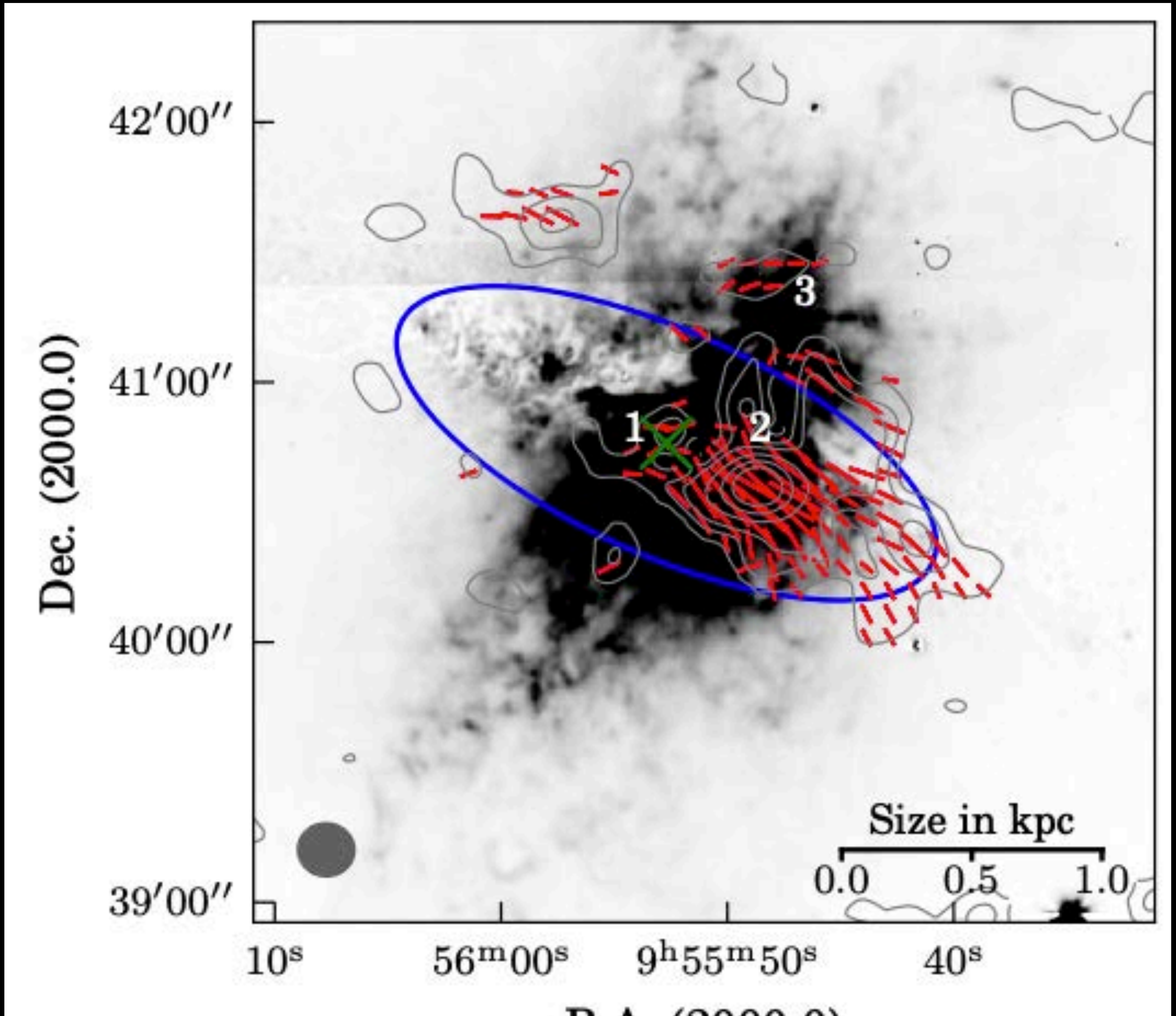
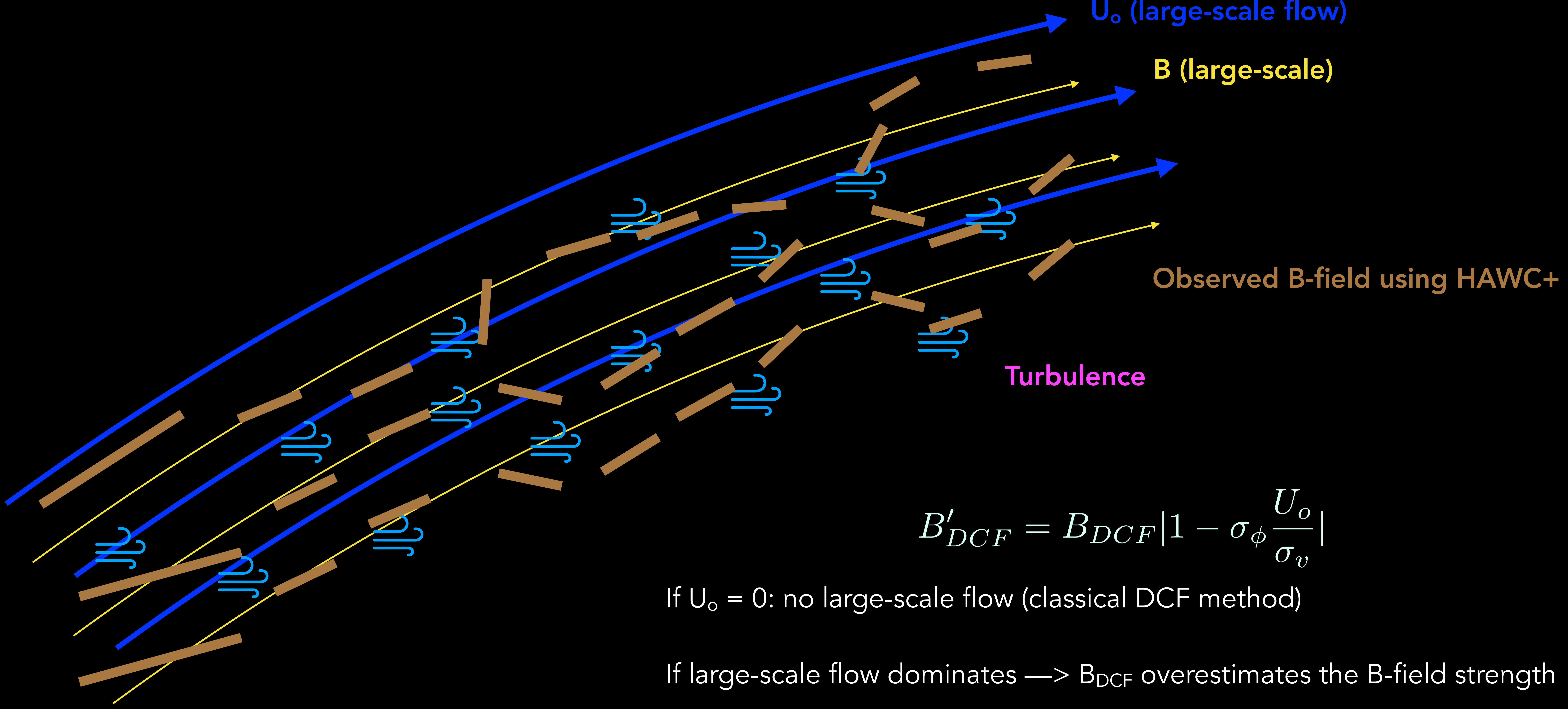


Adebahr et al. (2017)

LARGE-SCALE FLOW ALONG THE GALACTIC OUTFLOW



$$B'_{DCF} = B_{DCF}|1 - \sigma_\phi \frac{U_o}{\sigma_v}|$$

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

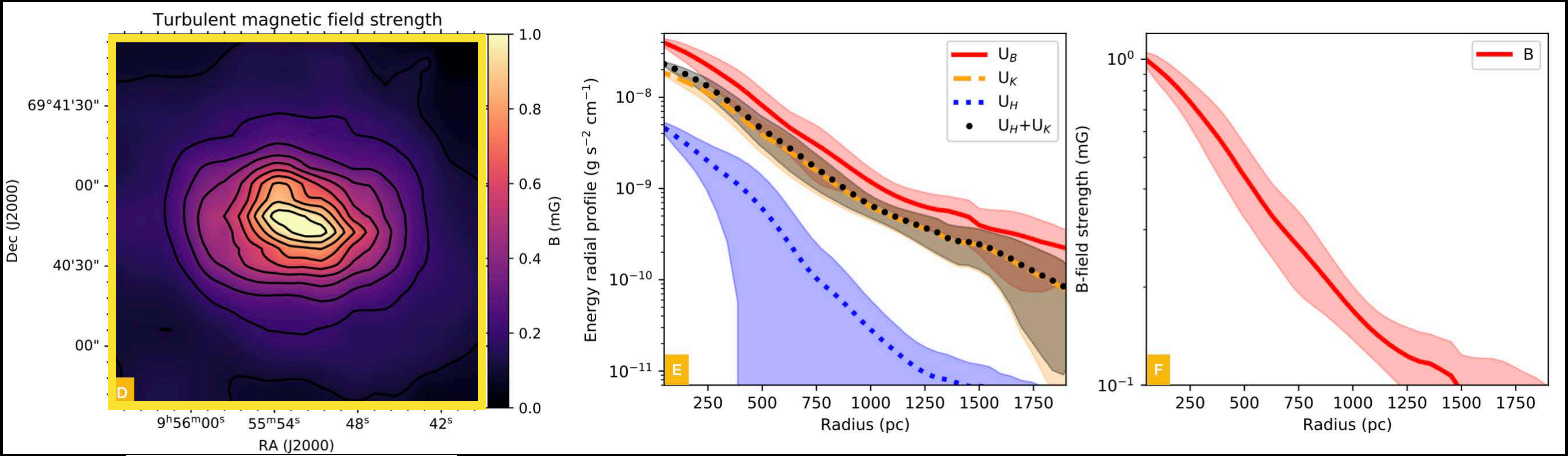
If large-scale flow dominates —> B_{DCF} overestimates the B-field strength

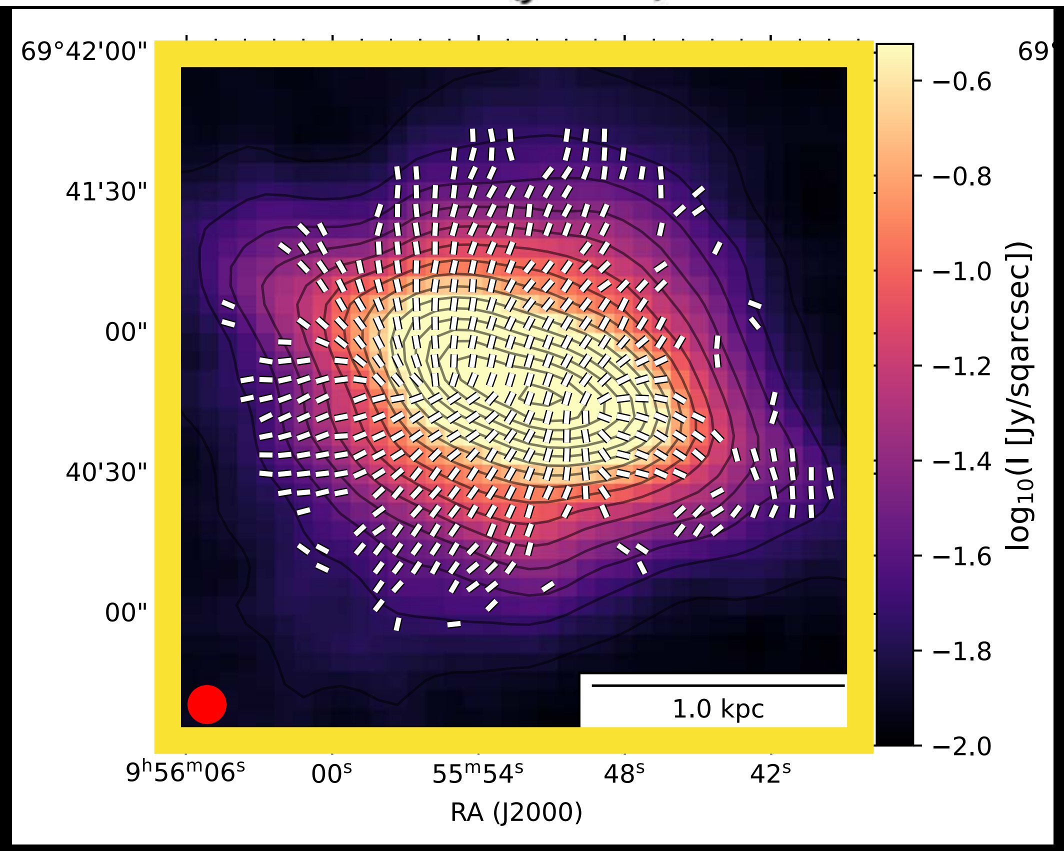
If turbulence dominates —> B_{DCF} underestimates the B-field strength

TURBULENT MAGNETIC AND KINETIC ENERGIES ARE IN CLOSE EQUIPARTITION

Energy budget:

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



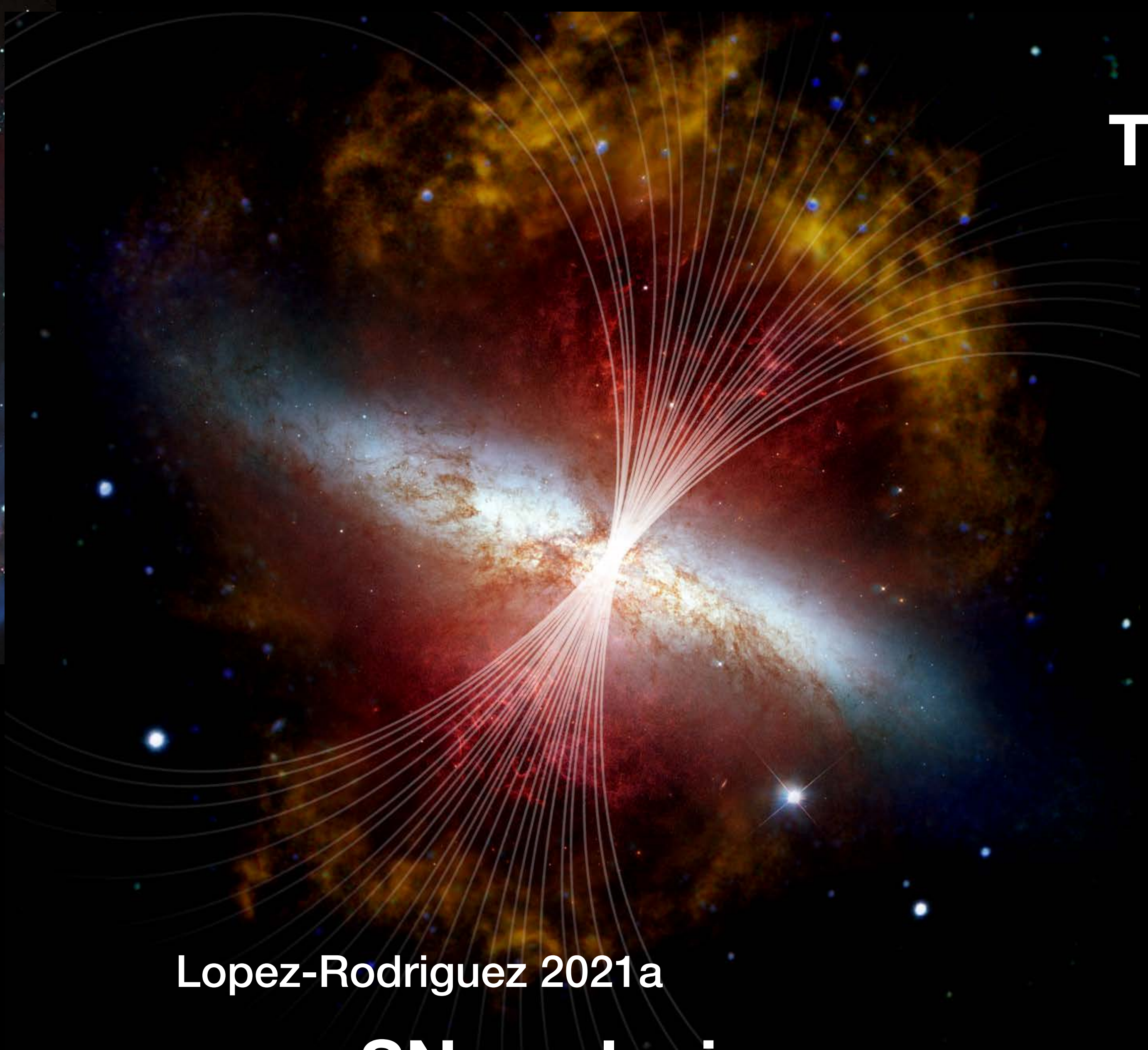


Turbulent dynamo

Mergers

B-field amplification

Turbulent dynamo



SN explosions

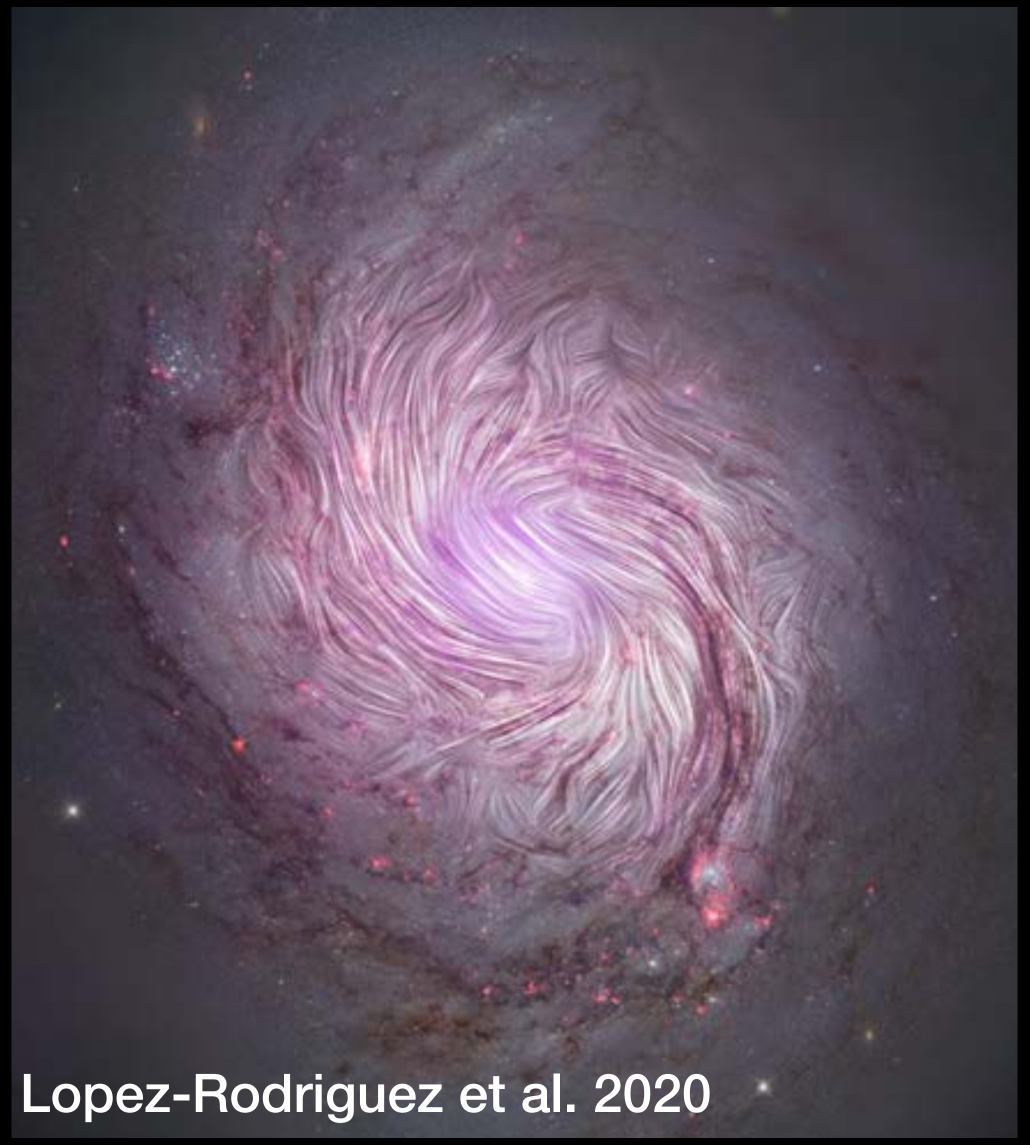
Permeate IGM with B-fields

Turbulent + Mean-field dynamo

Interaction, SF, galactic dynamo

SF disturbs/amplify mean-field

Mean-field dynamo



SF, galactic dynamo

Saturated B-field close equipartition with turbulent kinetic energy in the ISM

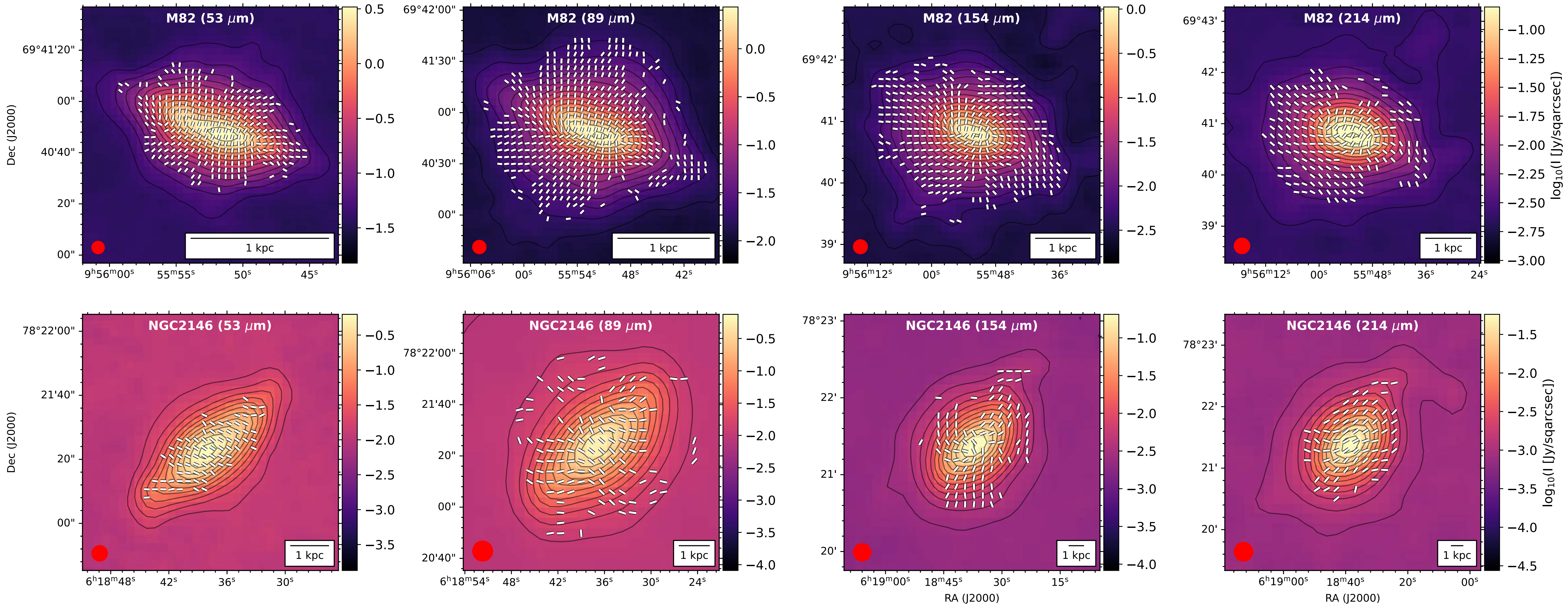
GALAXY SAMPLE

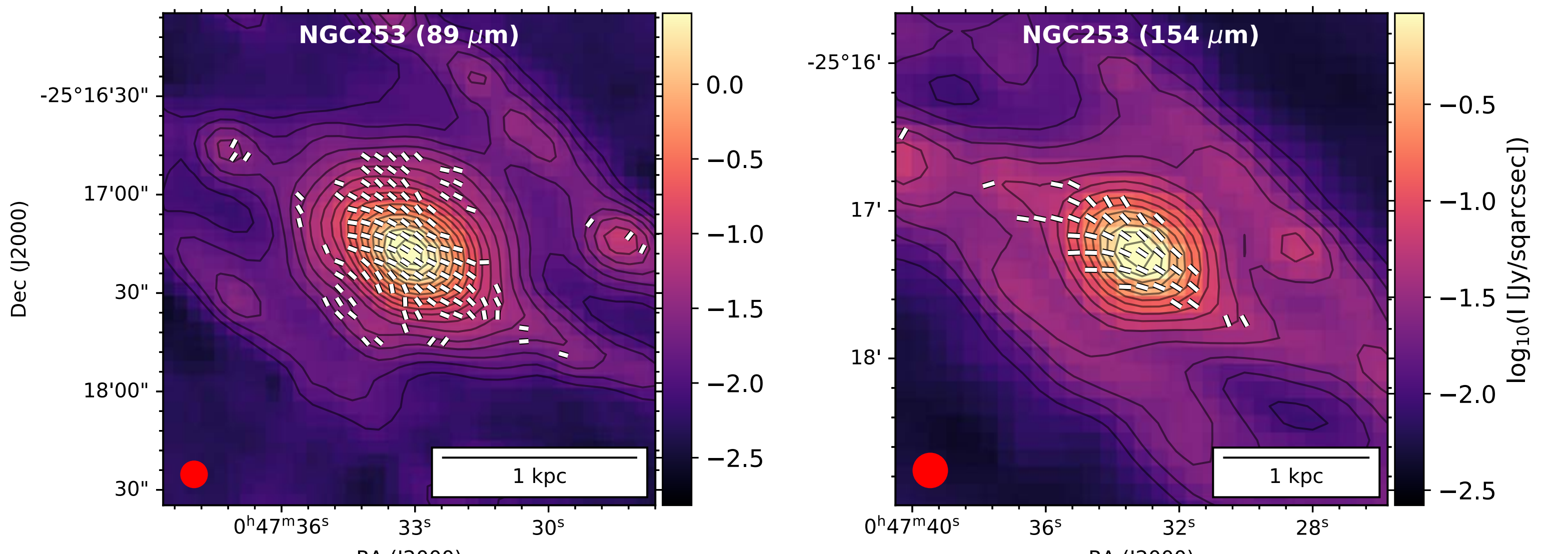
All galaxies have available radio polarimetric observations, molecular and neutral gas maps, and Herschel observations.

NAME	TYPE	DISTANCE (Mpc)	HAWC+ EXIST	HAWC+ REQUEST	ON-SOURCE TIME (h)
ANTENNAE (NGC 4038/9)	Interacting	20	-	D	6.75
CENTAURUS A	S0 (AGN)	3.42	**AC**	D	3.00
CIRCINUS	SAb (AGN)	4.2	**ACD**	-	-
M 51	Sb	8.6	**D***	D	6.75
M 82	Starburst	3.85	**A*D***	A,C,D,E	2, 2, 2, 2
M 83	SABs	5	-	D	6.75
NGC 253	SABc	3.6	**C***	C, D	3, 5
NGC 891	SAb	4.6	**C***	C,D	5,5
NGC 1068	SAb (AGN)	14	**A*C***	A,C,D	7, 3, 5
NGC 1097	SBb	19	**A*C*D***	ACD	5, 6, 7
NGC 2146	Starburst	13	**AC*D*E***	CDE	2, 2, 2
NGC 3627	SABb	16	-	D	6.75
NGC 3628	Sb	18	-	D	6.75
NGC 4631	SBd	13	-	D	6.75
NGC 4736	SAab	7.8	-	D	6.75
NGC 4826	SAab	10	-	C	4.35
NGC 6946	SABcd	3.9	**D***	D	4
NGC 7331	SAb	7.2	-	D	6.75
	MEDIAN	**8.2**	TOTAL ON-SOURCE TIME (h)		130
	STDDEV	**5.8**	**TOTAL REQUESTED TIME (h)**		**157**

Data available at:

Legacy Program website (high-level data products): http://galmagfields.com/

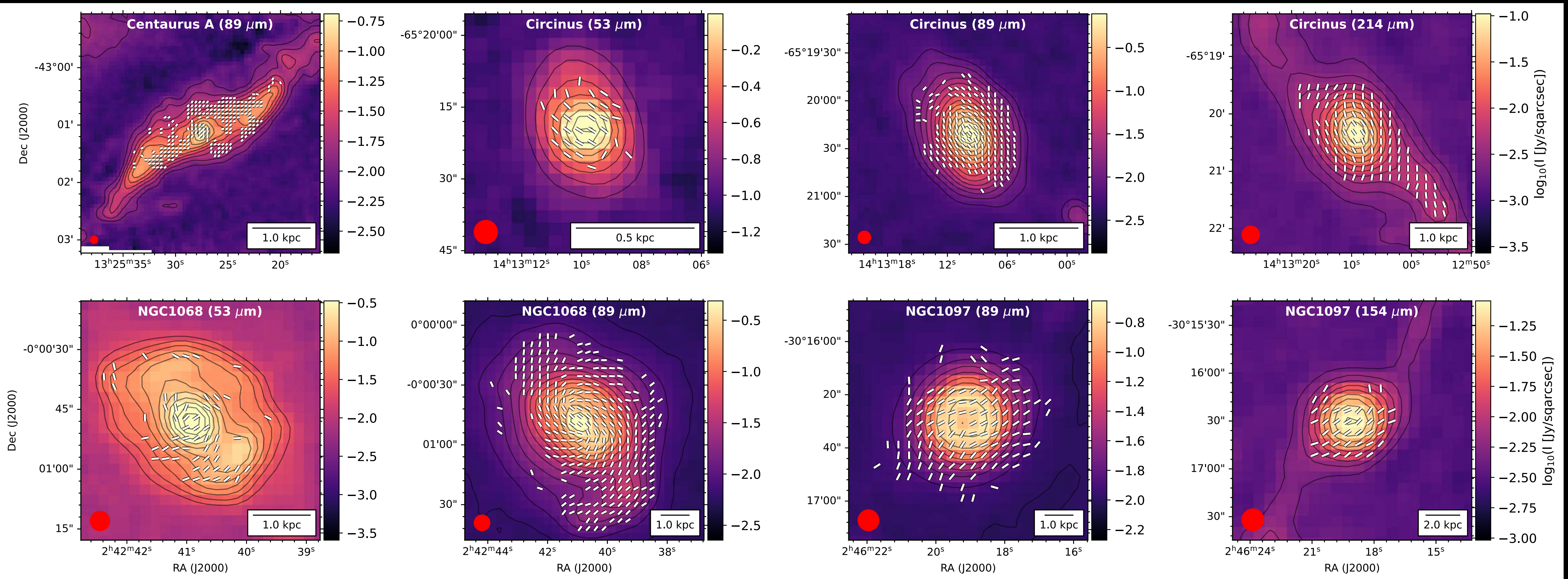


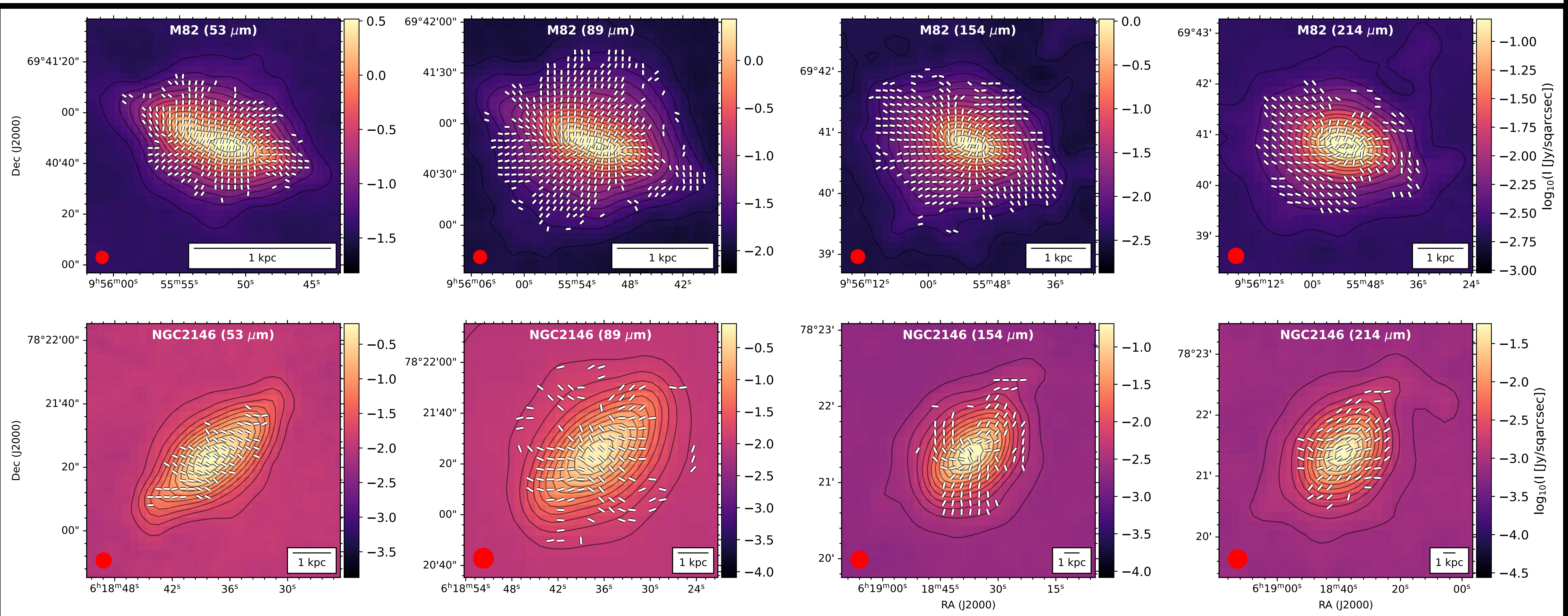


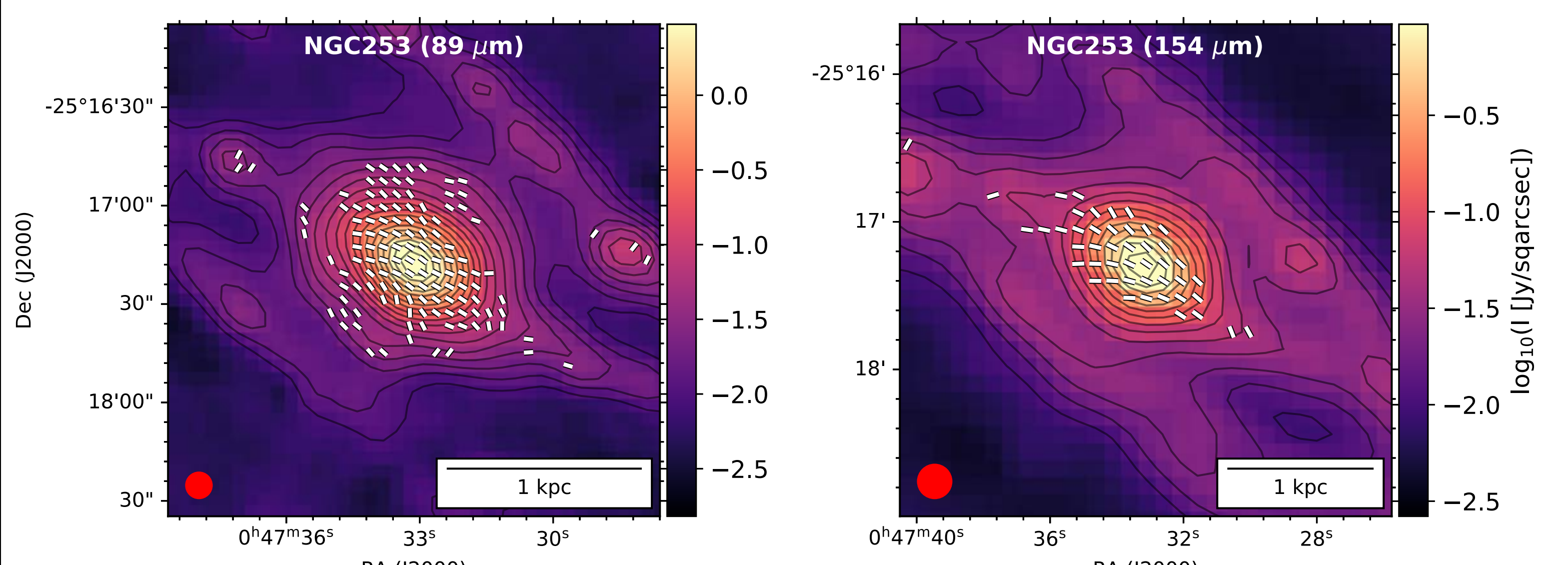
First Data Release

14 galaxies

Starbursts



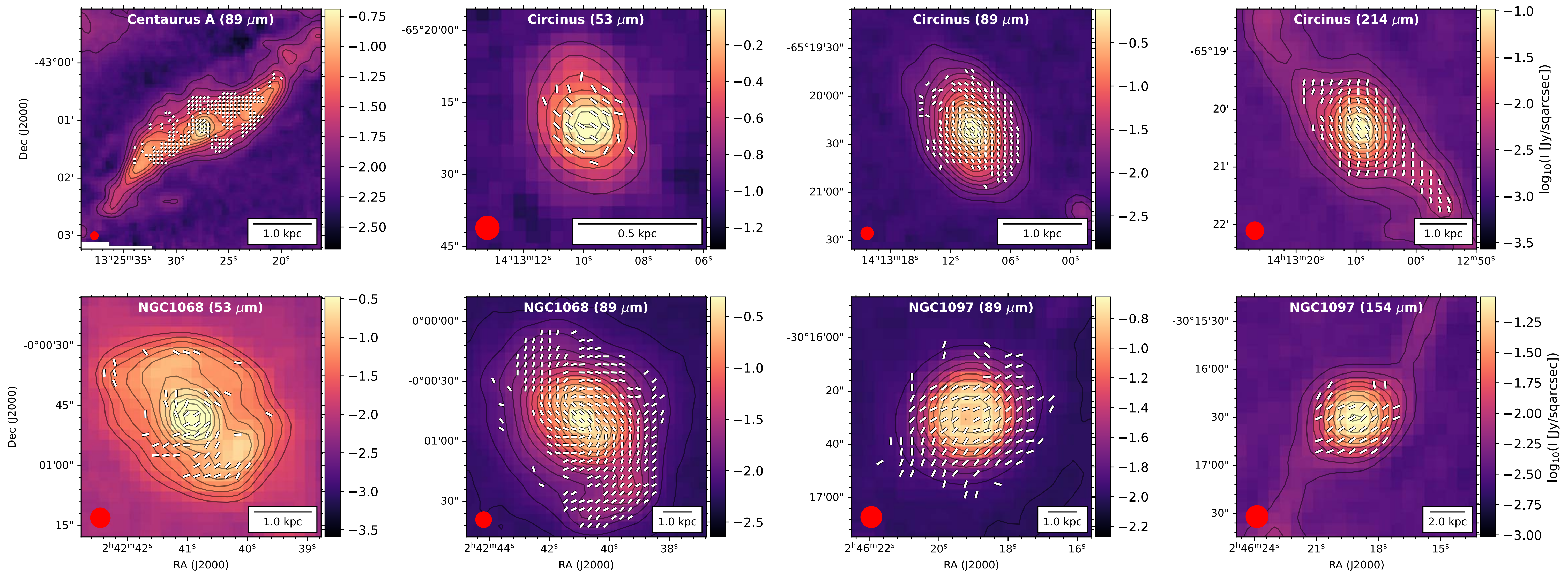


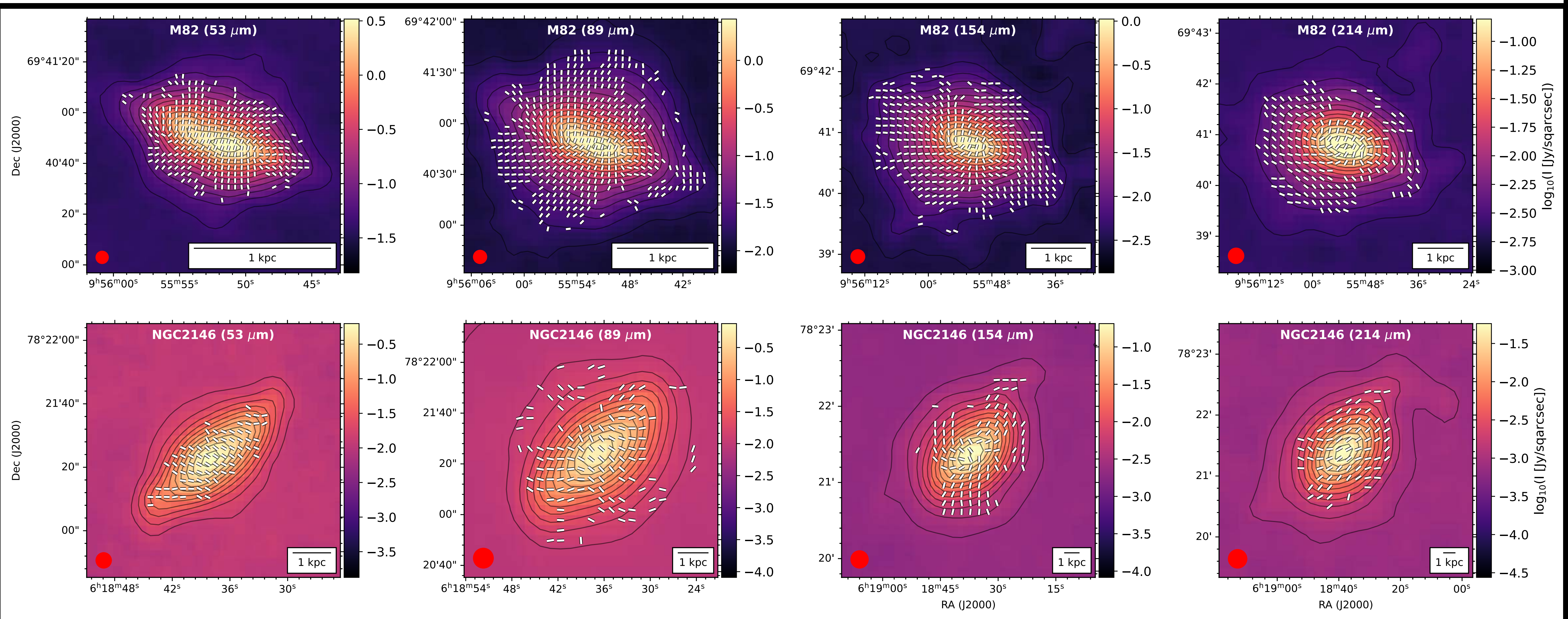


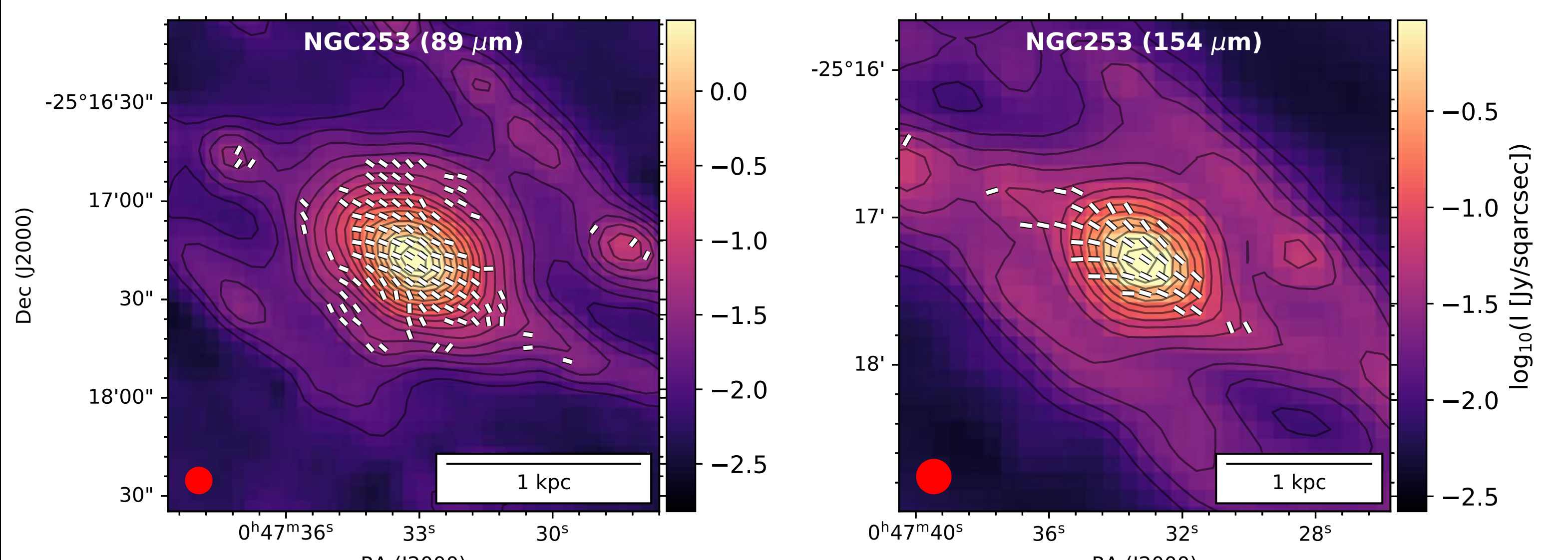
First Data Release

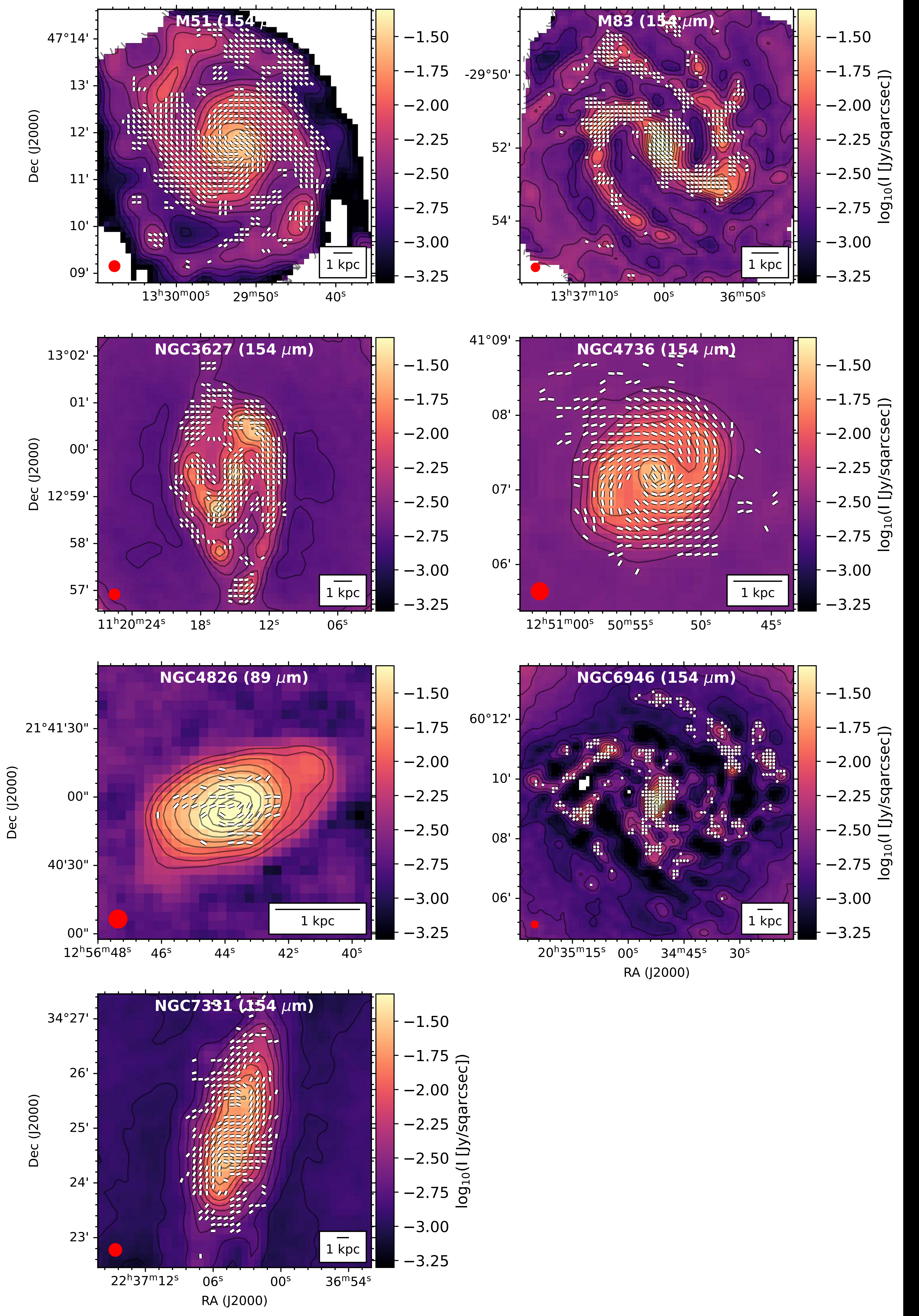
14 galaxies

AGN *Starbursts*









First Data Release

14 galaxies

AGN *Starbursts* *Spirals*

STUDENTS AND SUMMER INTERNS

Iñigo Valenzuela Lombera
+ Susan Clark

Stanford Graduate Student
Physics

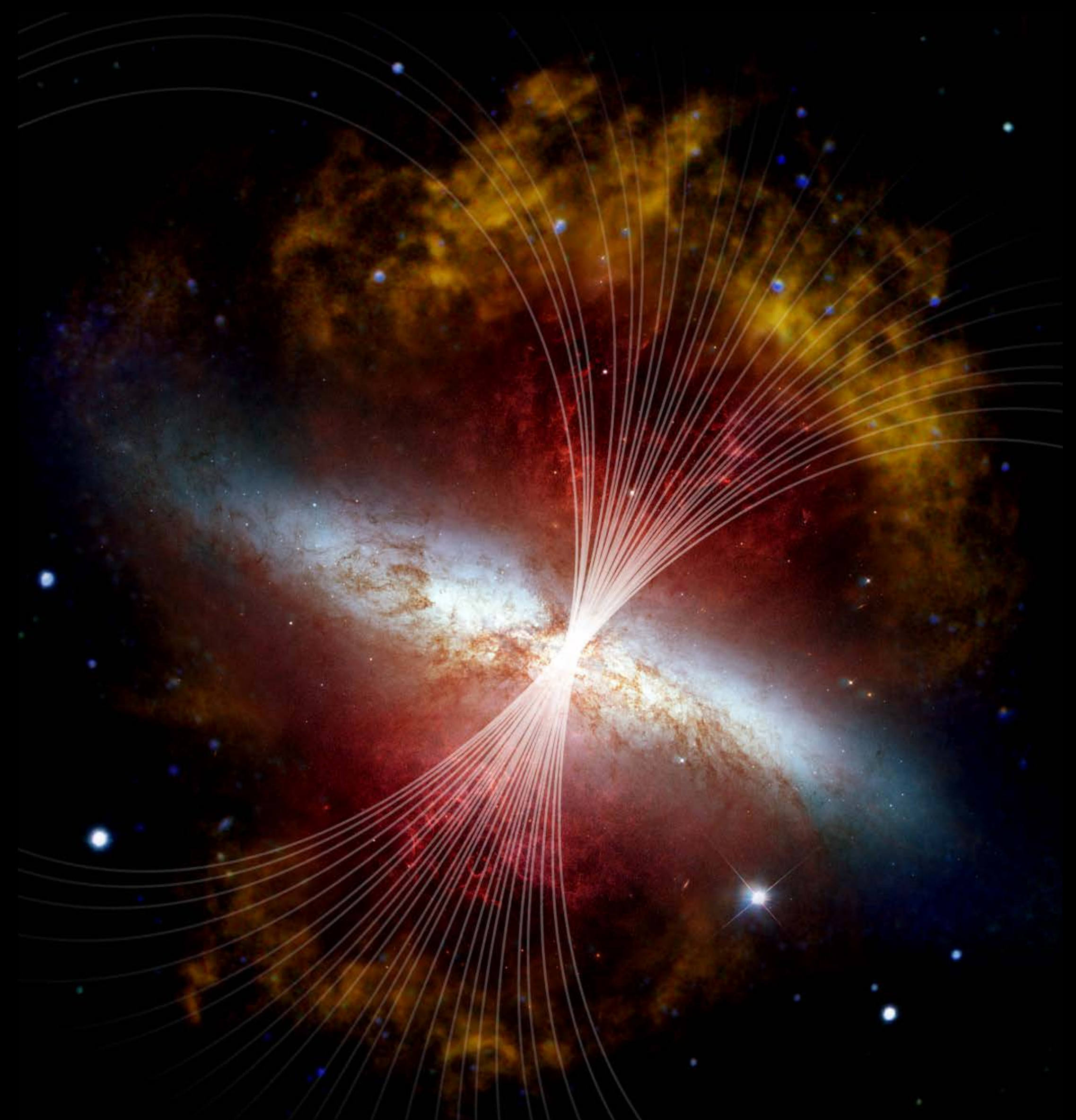
William Jeffrey Surgeny
+ Susan Clark

Stanford Undergrad.

Ifdita Hasan Orney

Stanford Undergrad.
Computer Science

Summer Intern 2022

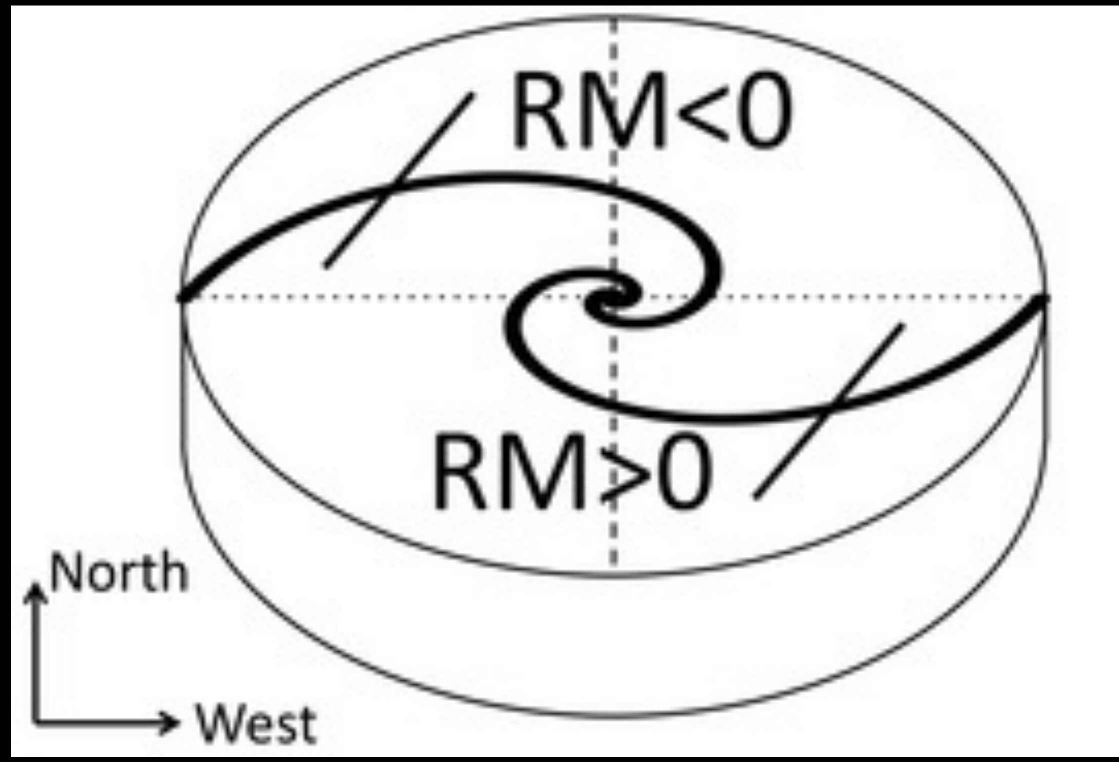


Abraar Salem

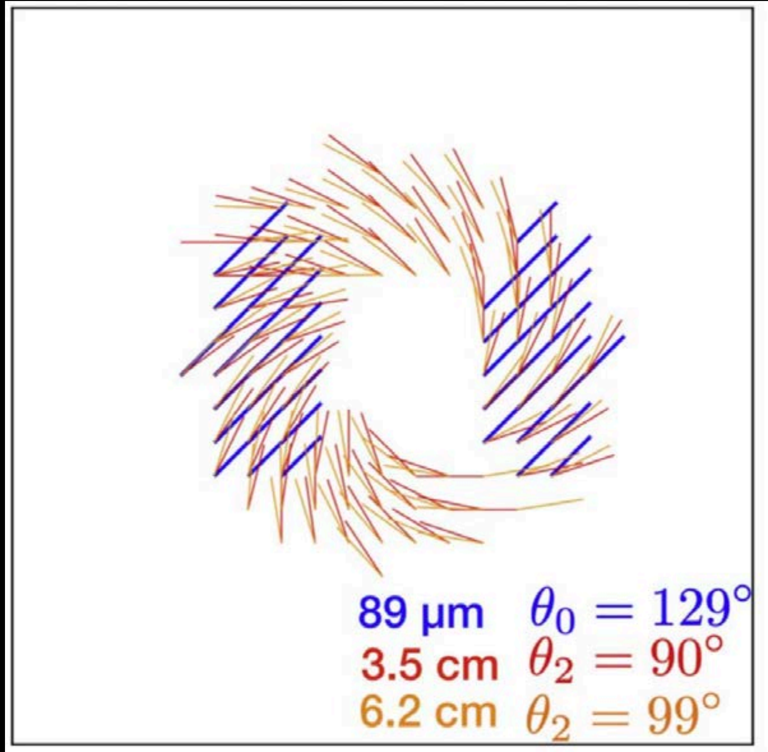
San Francisco State university
Physics

Cal-Bridge Program, Summer 2022

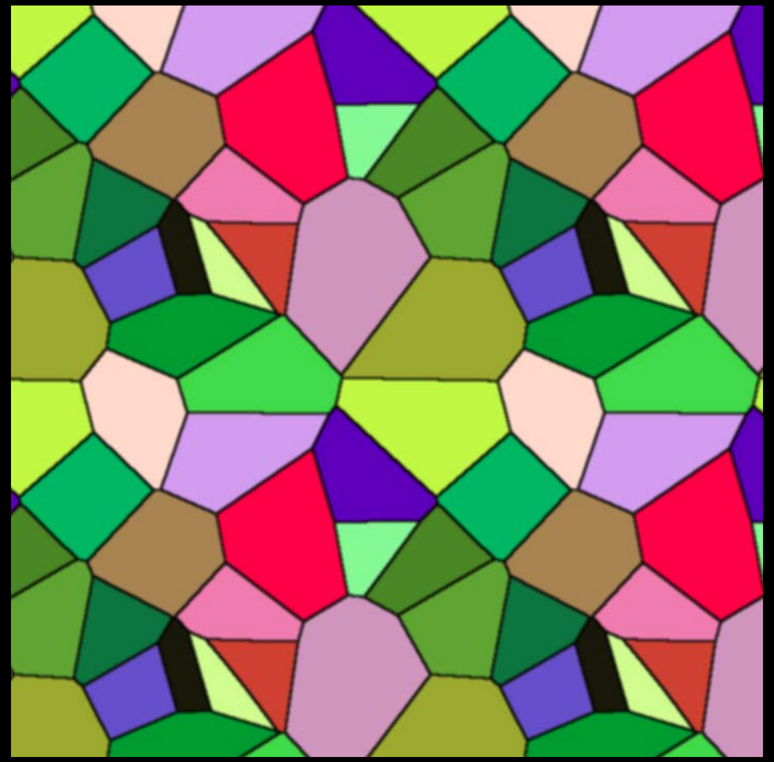
Magnetic field directions
of spiral galaxies



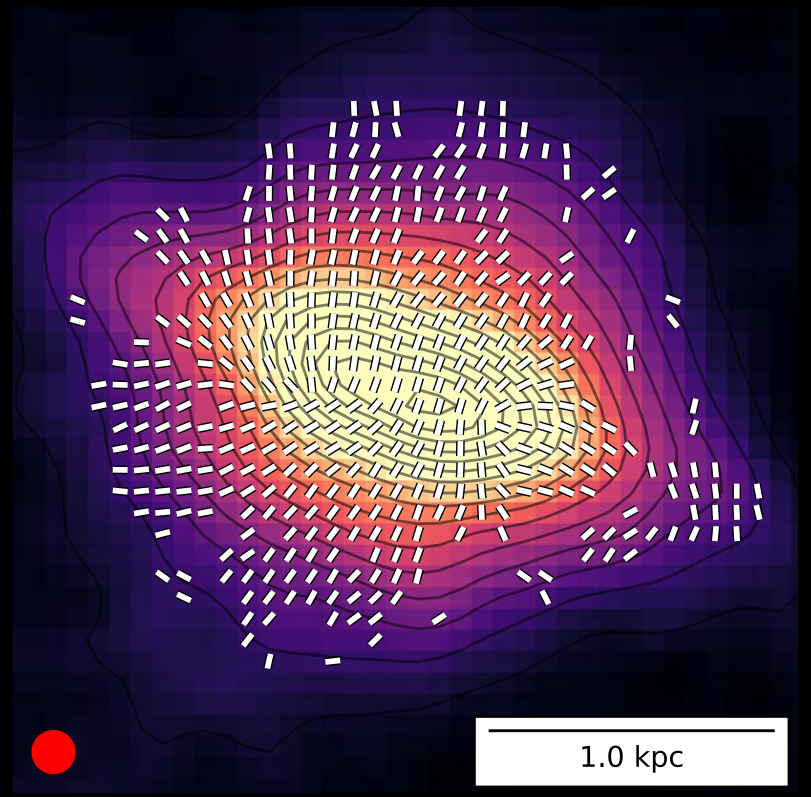
EB decomposition
of B-field in spirals



Voronio algorithm
applied to polarization



B-field orientation
of starbursts



POSTDOCS AND RESEARCHERS

Alejandro Serrano Borlaff

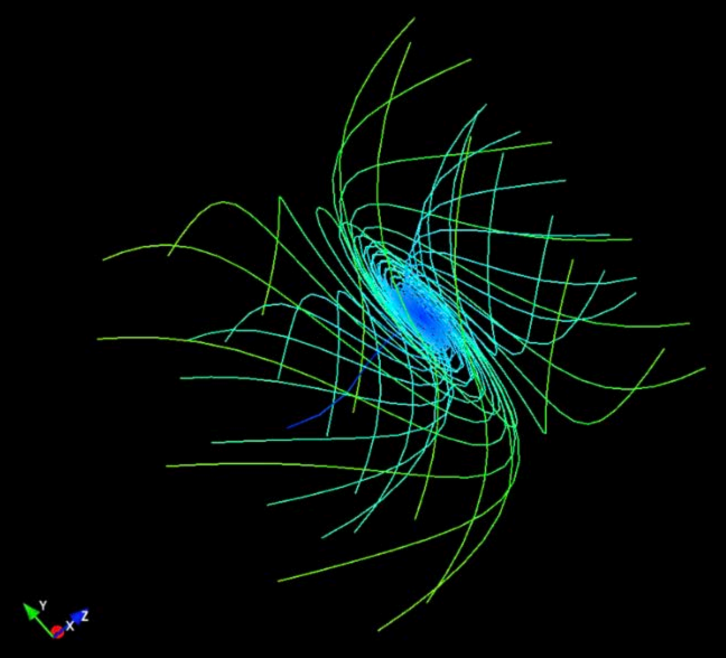
NASA Postdoctoral Program
NASA Ames

M51 (Paper I)
B-field and kinematics
Data analysis tools

Lucas Grosset

Postdoctoral Fellow

B-field morphology
of Circinus



Projected B-field model

Sergio Martin Alvarez

Postdoctoral Researcher
KICC, Cambridge

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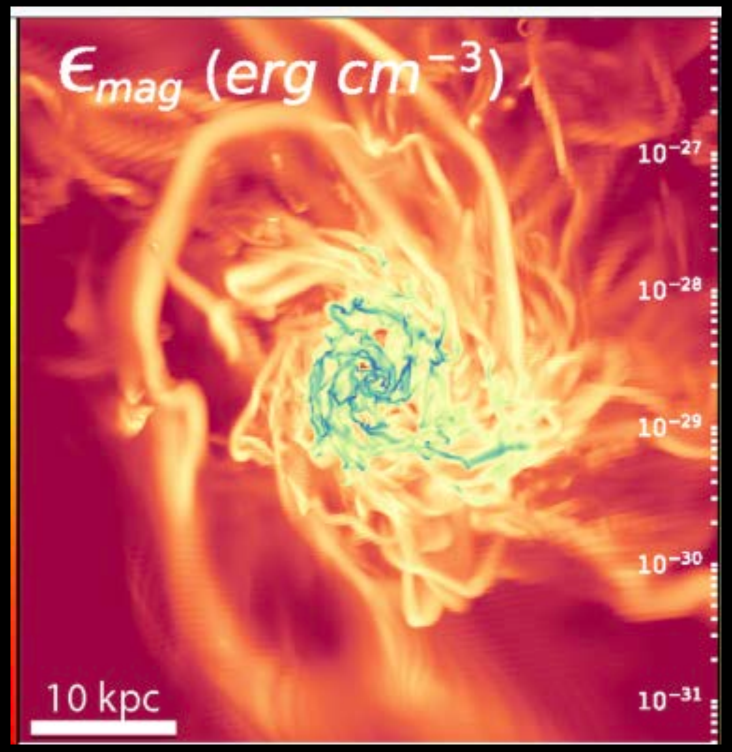
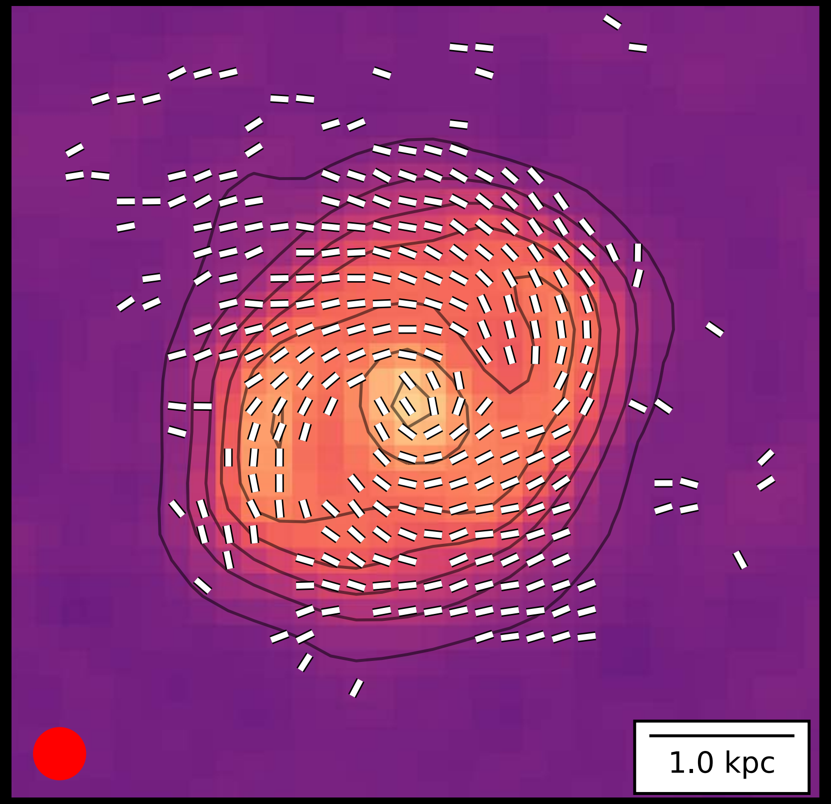
MHD Simulations
of galaxies



Sarah Eftekharzadeh

Instrument Scientist
SOFIA

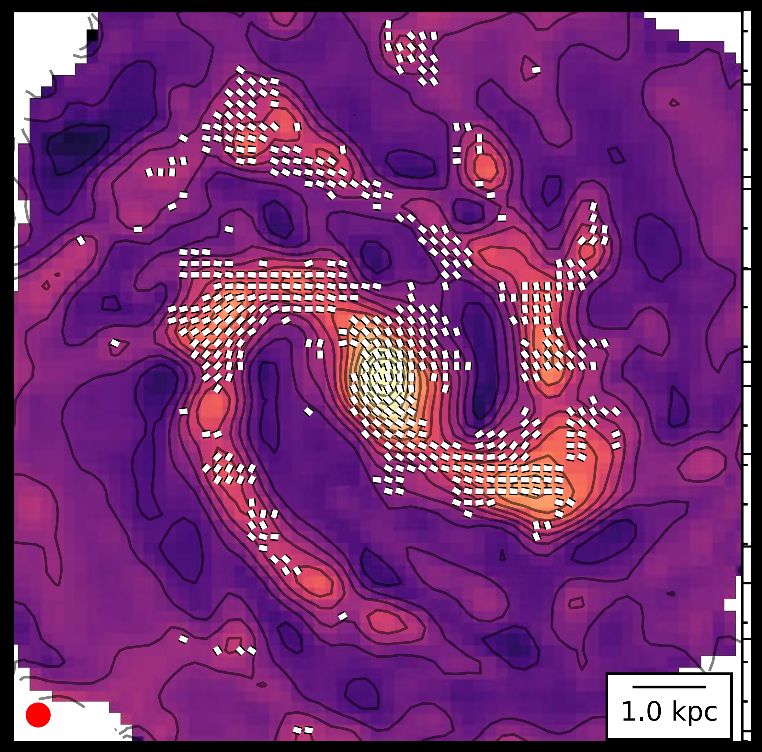
B-fields of the
Unusual NGC 4736



Ignacio del Moral Castro

PhD. Since Feb. 2022
Instituto de Astrofisica de Canarias

B-field vs.
Rotational support
in M83



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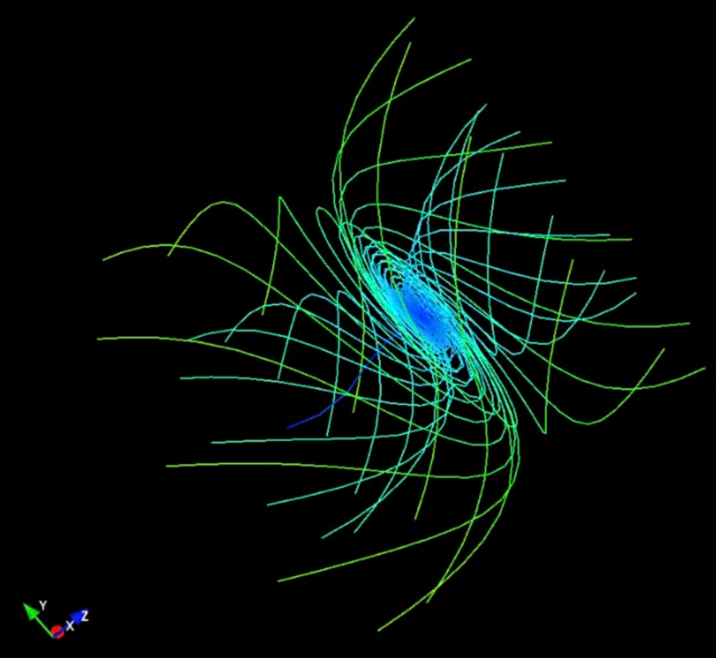

Projected B-field model

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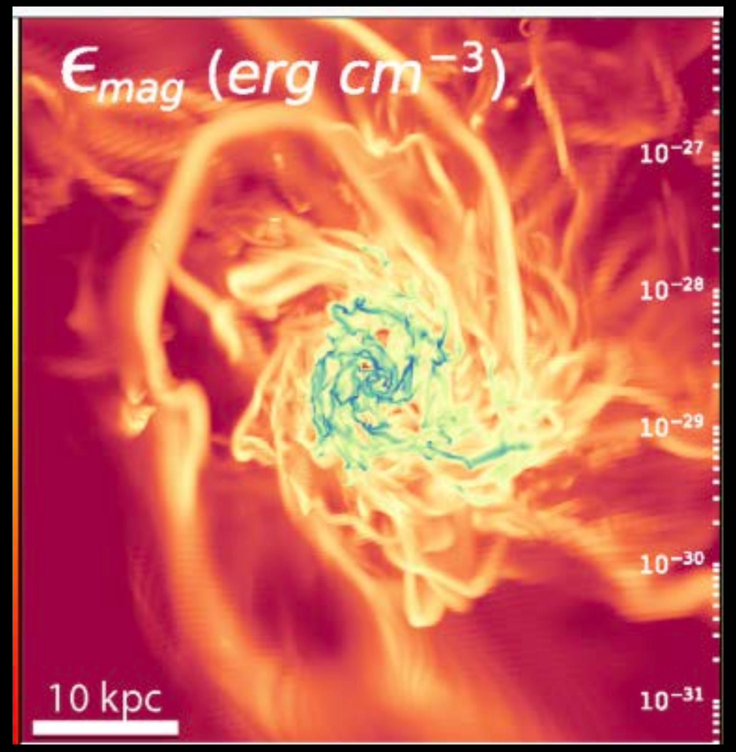

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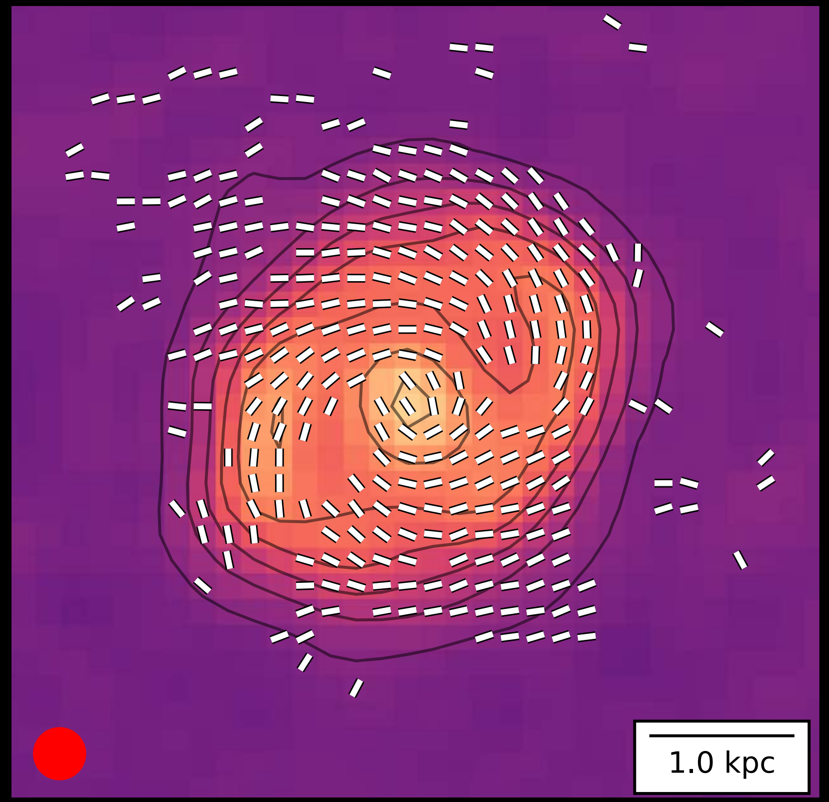

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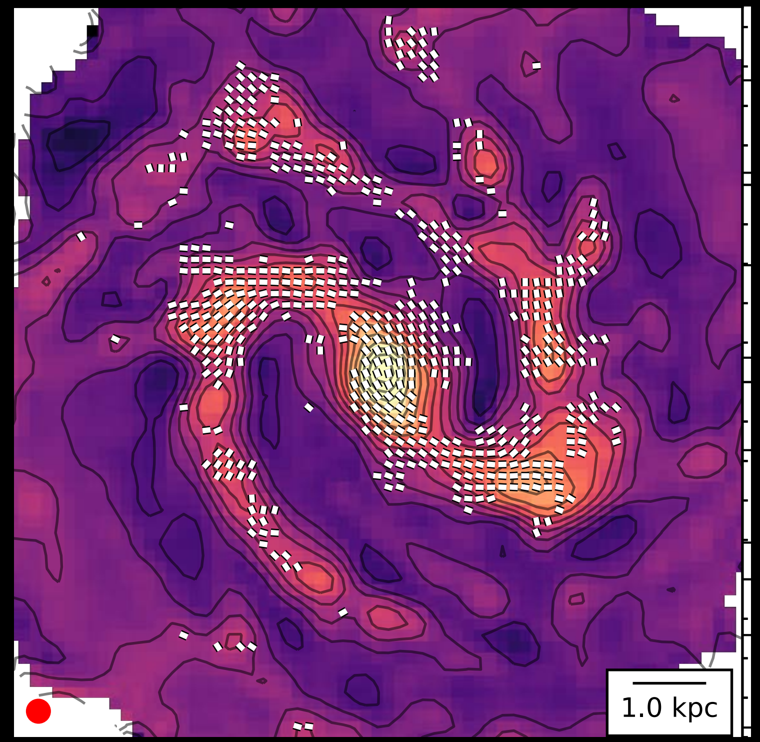

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