GISM3 - July 30, 2025

Astrophysics Fellowship in Italy

INAF

M-SKAT

Probing the complexity of the ISM at radio wavelengths

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INAF - Osservatorio Astrofisico di Arcetri

Outline

✦ **Part 1- Motivation**

- If complex, why are we interested in the ISM?
- The 3M problem: *Multi-scale, Multi-phase, and Multi-tracer*
- Solving this riddle with radio observations

✦ **Part 2- Looking at the radio window**

- Some historical background
- What are the tools in hand?

✦ **Part 3 - Some probes of the 3M problem**

- The HI in galaxies
- The magnetized content of galaxies (Synchrotron and Faraday rotation)

✦ **Part 4 - Perspectives in the radio band**

The future is bright but challenging (LOFAR2.0, ngVLA, NenuFAR, MeerKAT, Parkes, SRT, …, SKAO)

Disclaimers

- ✦ **I will offer my very biased view:**
  - often galactic means Galactic
  - some key radio signals will be mentioned but won’t be at the party (e.g., molecular lines, RRLs, pulsars, Zeeman splitting)
  - *Radio* telescopes will be mostly sensitive from *cm* to *m* wavelengths

- ✦ **This shows the great potential of radio data for ISM studies, but I had to make choices. Please, no hard feelings!**

- ✦ **Hopefully, this lecture will be understandable for the new comers, yet interesting for the more expert ones.**

Why are we interested in the ISM?

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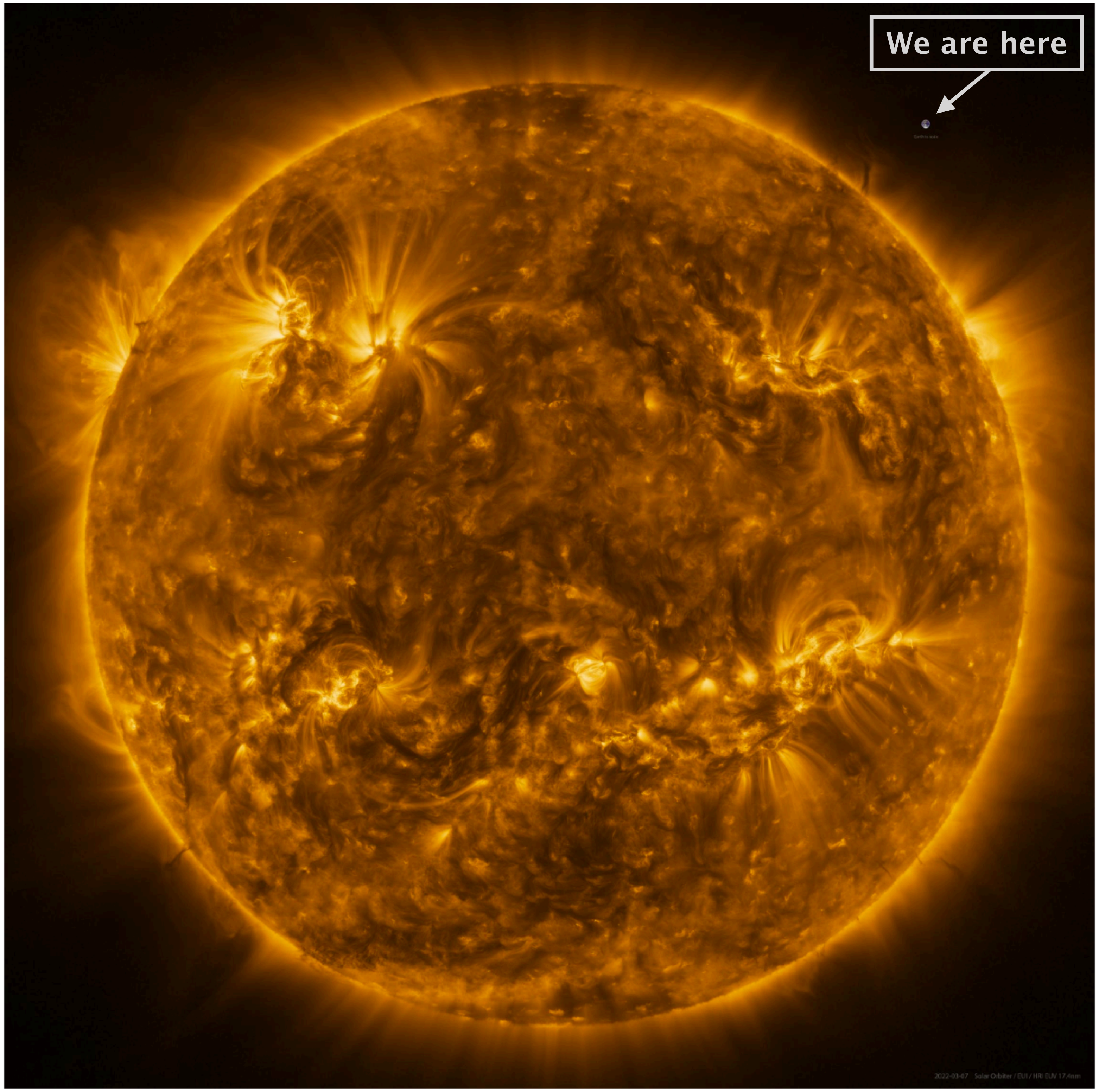
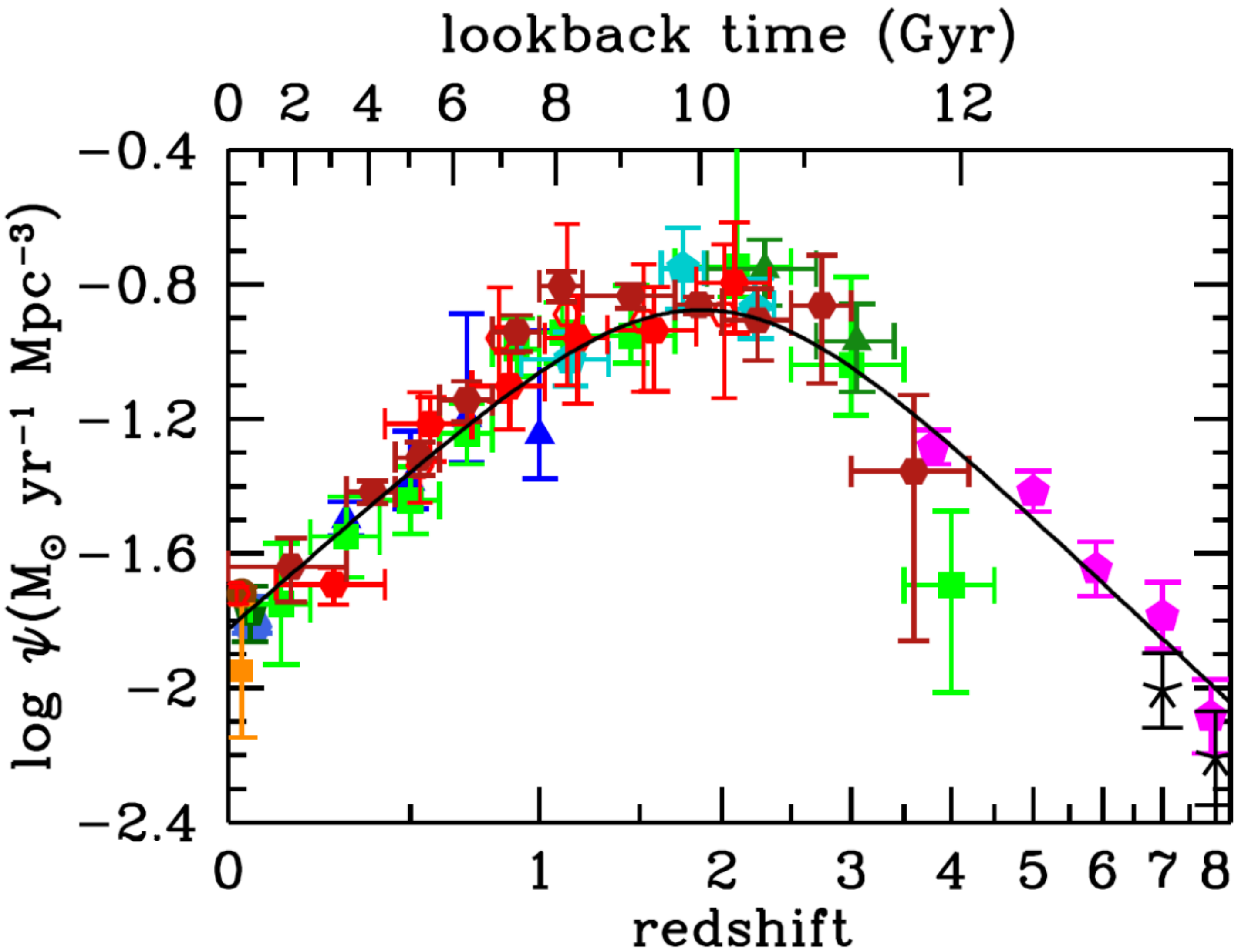
The Sun as seen by the Solar Orbiter in the UV (ESA)



First and foremost, the ISM is where the formation of stars and planets is seeded

Why are we interested in the ISM?

Star formation rate (SFR) density



- Cold gas in the early universe
- Rapid accretion and mergers
- Weak feedback (e.g., AGNs, Supernovae)

- Cosmic noon (z~2), build up of stellar masses and metal enrichment

- For the opposite reasons, after cosmic noon the quenching era starts

(Madau & Dickinson 2014, collection of FUV and FIR data)

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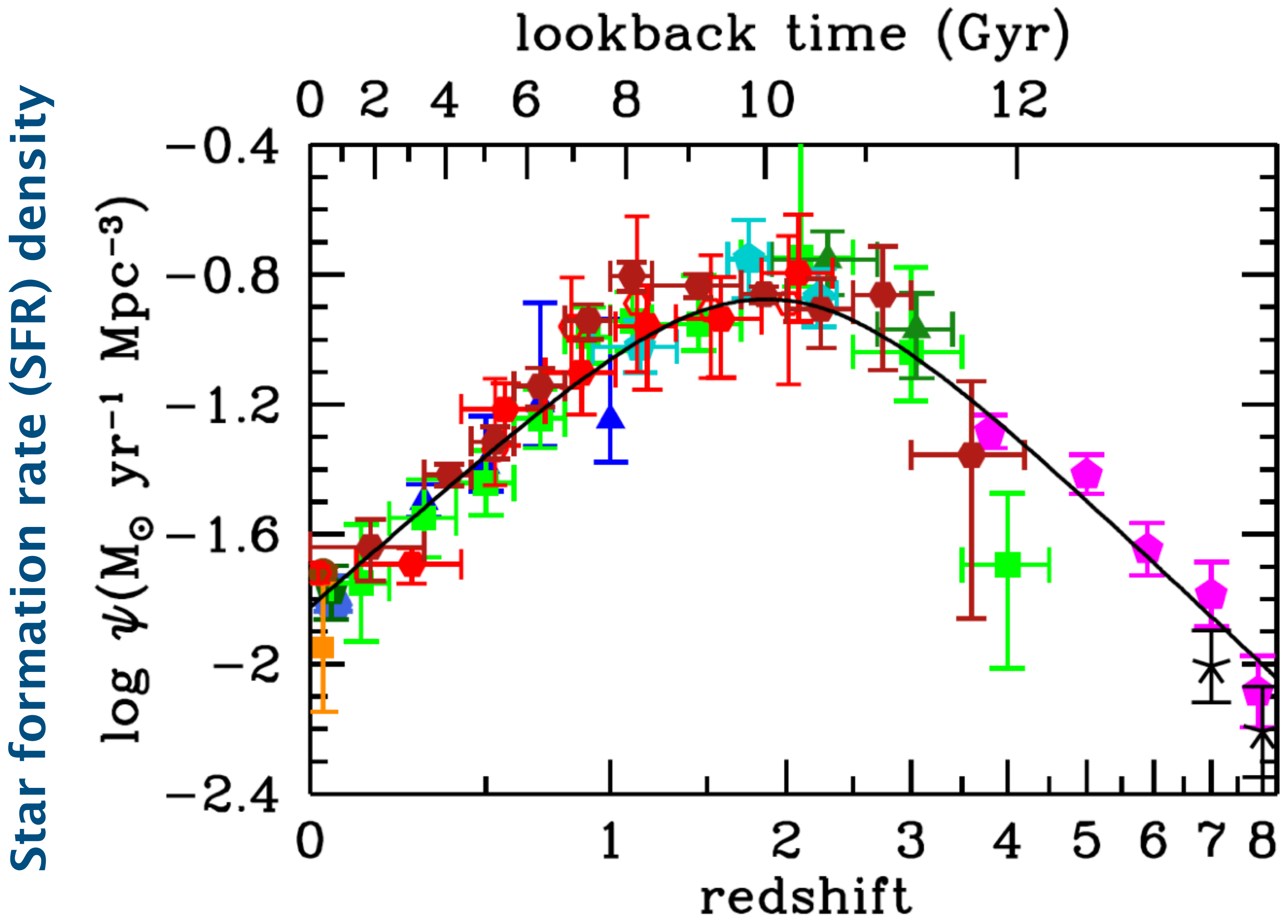

- **Cold gas in the early universe**
- **Rapid accretion and mergers**
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- **Cosmic noon (z~2), build up of stellar masses and metal enrichment**

- **For the opposite reasons, after cosmic noon the quenching era starts**

(…) “This trend is primarily determined by gas accretion and feedback processes at galactic scales” (…)

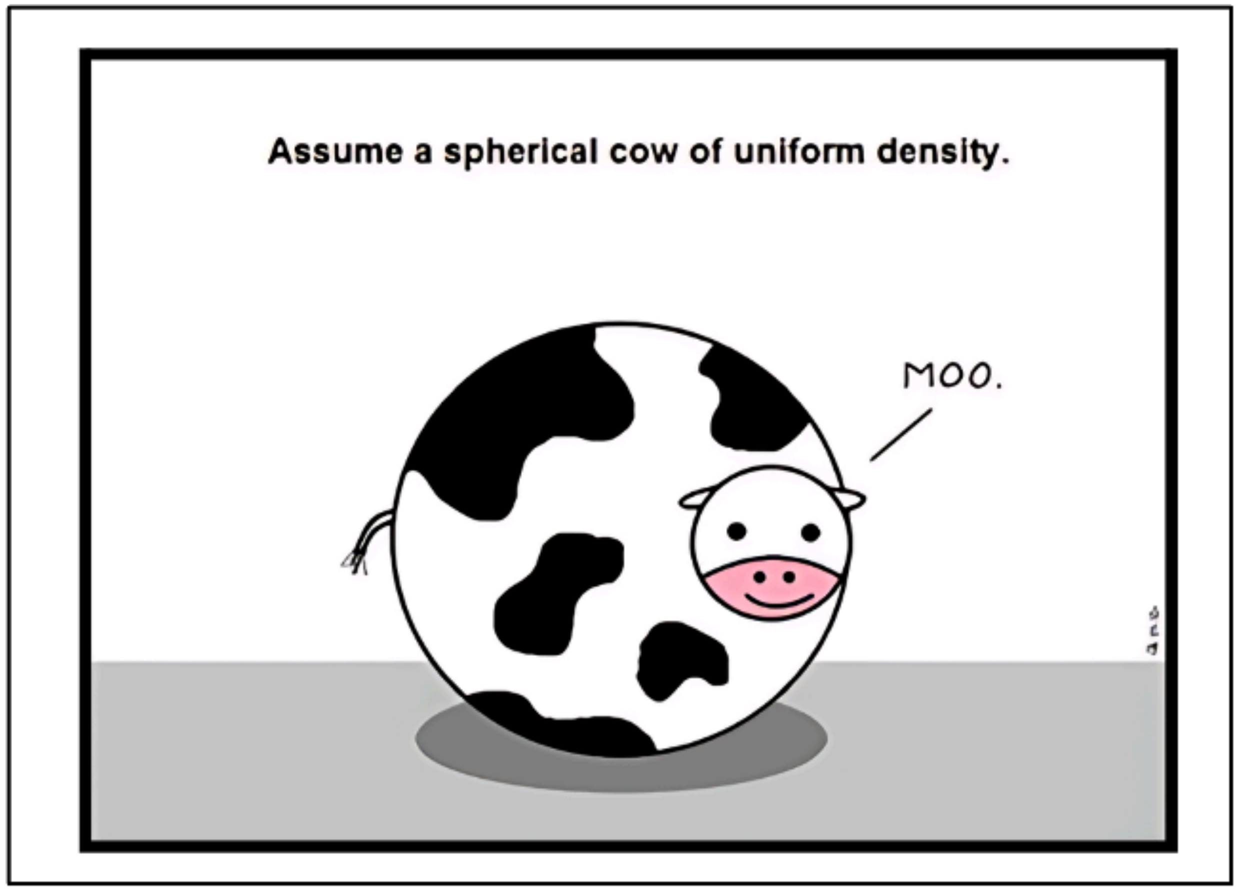
(…) “painstaking all this vast effort has been, it does miss a crucial point” (…)

(…) “the inner working of galaxies rooted in the physics of the **interstellar medium”** (…)

(…) “to identify the small-scale mechanisms that determine the rate of <u>conversion of gas into stars</u>” (…)

(Madau & Dickinson 2014, collection of FUV and FIR data)

Why are we interested in the ISM?



- Spherical star forming region of “cold" gas

$$\frac{d^2 r}{dt^2} = -\frac{GM(r)}{r^2}$$

- Collapse in free-fall:

$$t_{\rm ff} \propto \frac{1}{\sqrt{G\rho}} = \frac{1}{\sqrt{G m_{\rm H} n_{\rm H}}}$$

- “Cold" gas in the Milky Way disk: $\sim 10^9\, M_\odot$

Clouds of $\sim 10^6\, M_\odot$ and $n_{\rm H} \sim 100\ {\rm cm}^{-3}$

$t_{\rm ff} \sim 4$ Myr SFR $\sim 250\, M_\odot\, {\rm yr}^{-1}$

(e.g., Zuckerman & Evans 1974, Williams & McKee 1997, McKee & Williams 1997, Krumholz et al. 2005, Elia et al. 2022)

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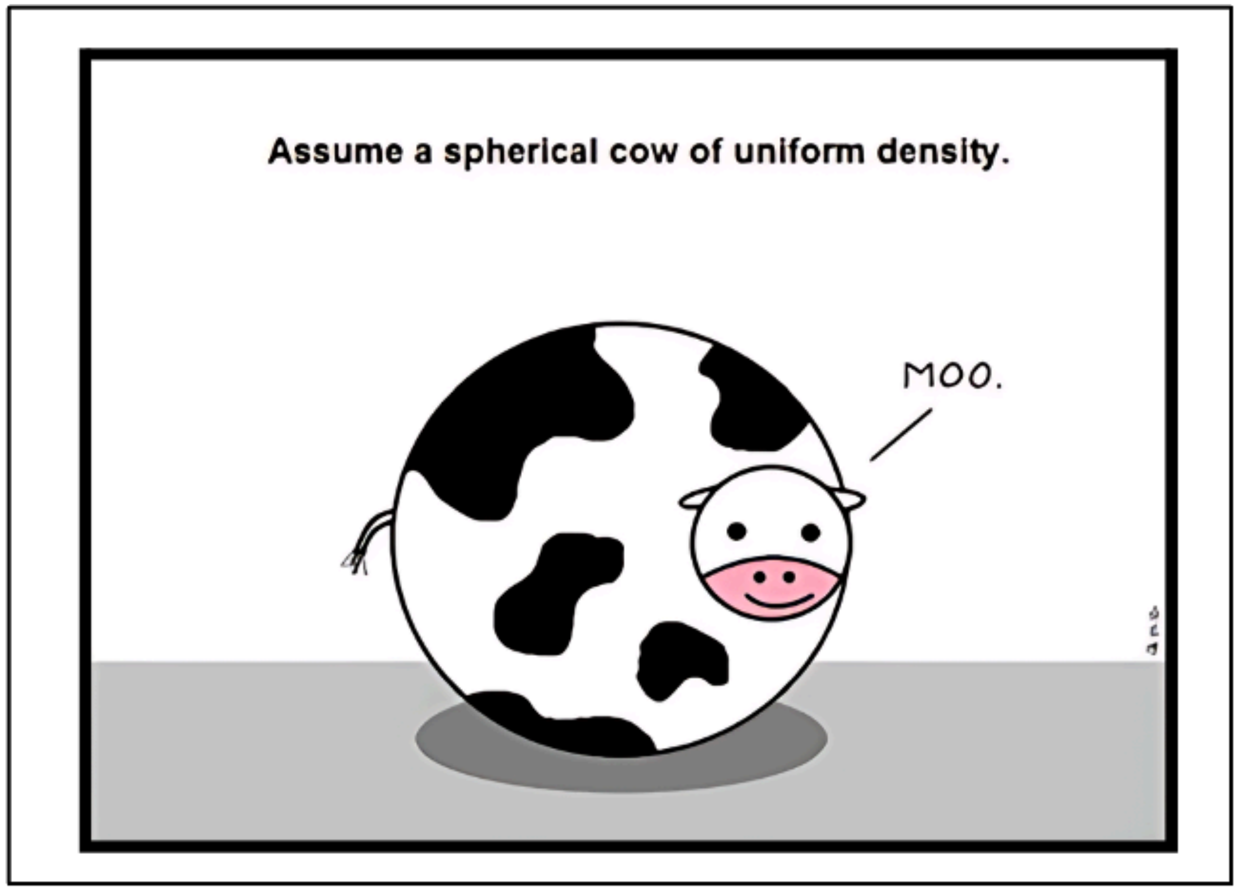

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Observed SFR in the Milky Way ~ 2 solar masses/year

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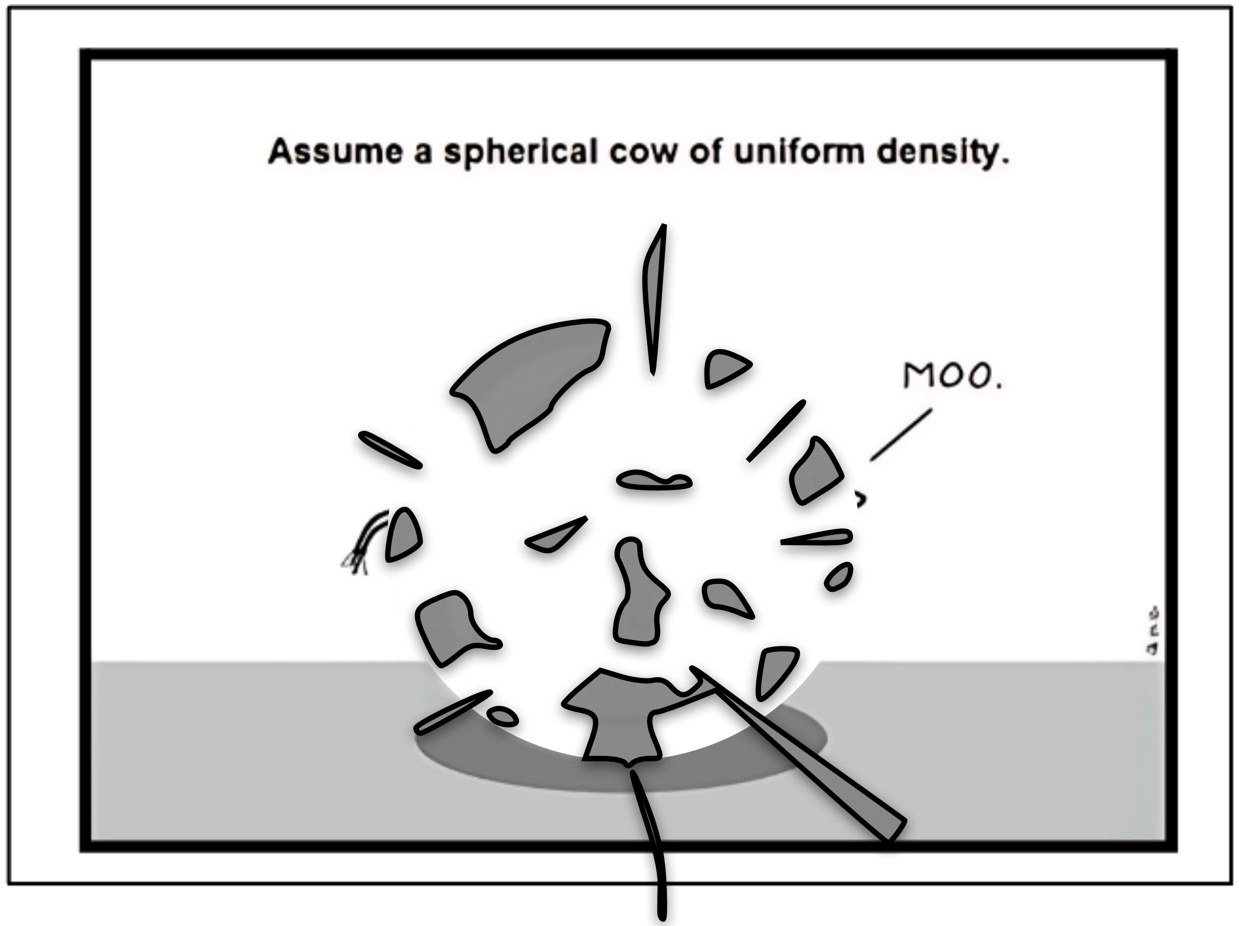

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Observed SFR in the Milky Way ~ 2 solar masses/year

Need to identify those “small-scale” mechanisms!

(e.g., Zuckerman & Evans 1974, Williams & McKee 1997, McKee & Williams 1997, Krumholz et al. 2005, Elia et al. 2022)

The 3M problem: ***Multi-scale, Multi-phase, Multi-tracer***

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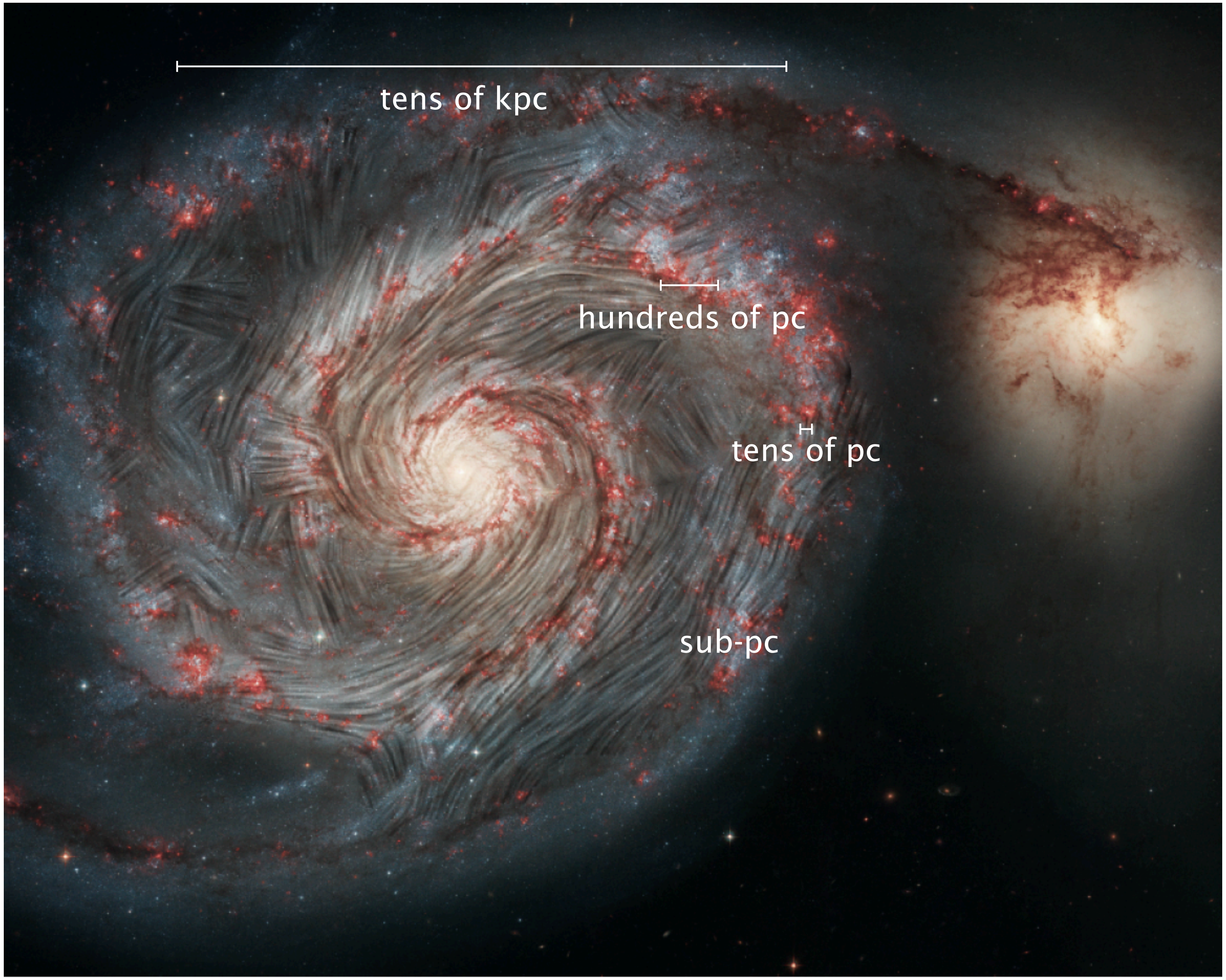
Messier 51 (M51) galaxy - The Whirlpool galaxy - Hubble Space Telescope + SOFIA 154um (Borlaff et al. 2021)



H-alpha is tracing massive star formation

Dark lanes trace dust in the "cold" ISM

Drapery pattern traces magnetic fields in the dust

- ***Multiphase* interactions: gas, magnetic fields, energetic particles—cosmic rays, dust grains, all essential for heating and cooling of the ISM**

- ***Multiscale* problem over more than 8 orders of magnitude: from 1E4 pc to solar-system regions (1E-4 pc)**

The 3M problem: *Multi-scale, Multi-phase, Multi-tracer*

Messier 51 (M51) galaxy - The Whirlpool galaxy - Hubble Space Telescope + SOFIA 154um (Borlaff et al. 2021)

The ISM in galaxies is an open gravitational system,

- energized by galactic-scale motions and stellar feedback (winds, supernovae, cosmic rays),
- turbulent,
- magnetized

Generally, none of these mechanisms can be neglected

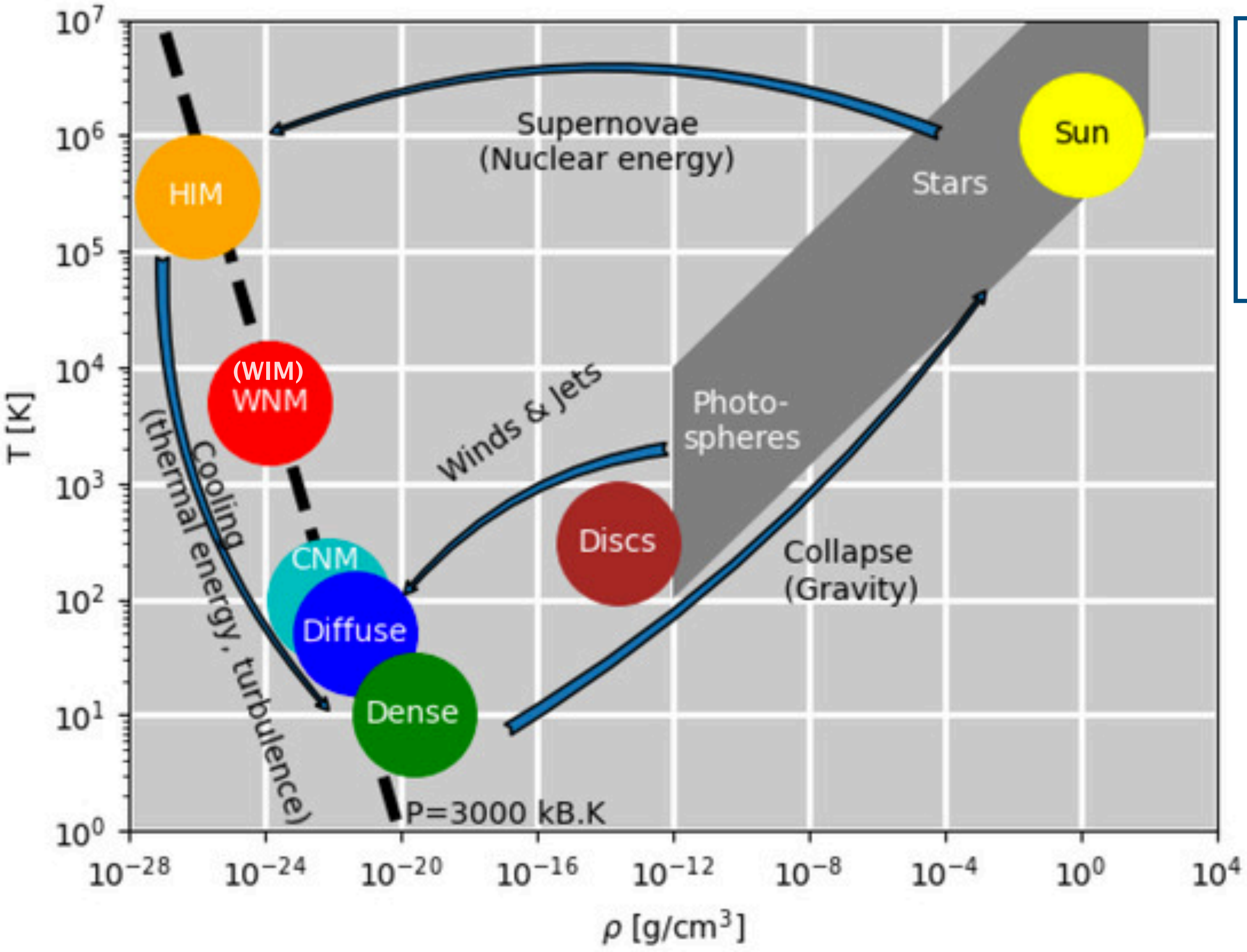
$$U_{\rm cr} \sim U_{\rm mag} \sim U_{\rm tur} \sim U_{\rm th} \; (\sim 1\,{\rm eV\,cm^{-3}})$$

The relative contribution of each dynamical process can depend on the scale

(Draine 2011)

The 3M problem: *Multi-scale, Multi-phase, Multi-tracer*

The ISM matter cycle



- Hot Ionized Medium (HIM) xe = 1
- Warm Ionized Medium (WIM) xe = 1
- Warm Neutral Medium (WNM) xe = 1E-2
- Cold neutral medium (CNM) xe = [1E-4,1E-7]

(Tielens 2005, Ferriere 2020, Lesaffre et al. 2024)

The 3M problem: *Multi-scale, Multi-phase, Multi-tracer*

Data *discretize* the ISM components

A complex puzzle made of multi-tracers through multi-wavelength data:

- **continuum (dust, thermal and non thermal) :** e.g., density, temperature, cosmic rays, magnetic fields
- **emission/absorption spectroscopy (ionized, atomic, molecular) :** e.g., thermodynamics, kinematics, turbulence, magnetic fields, cosmic rays through chemistry
- **direct detections:** cosmic rays
- **transients (e.g., pulsars):** magnetic fields, ionized gas density, turbulence

Solving this riddle with radio observations (?)

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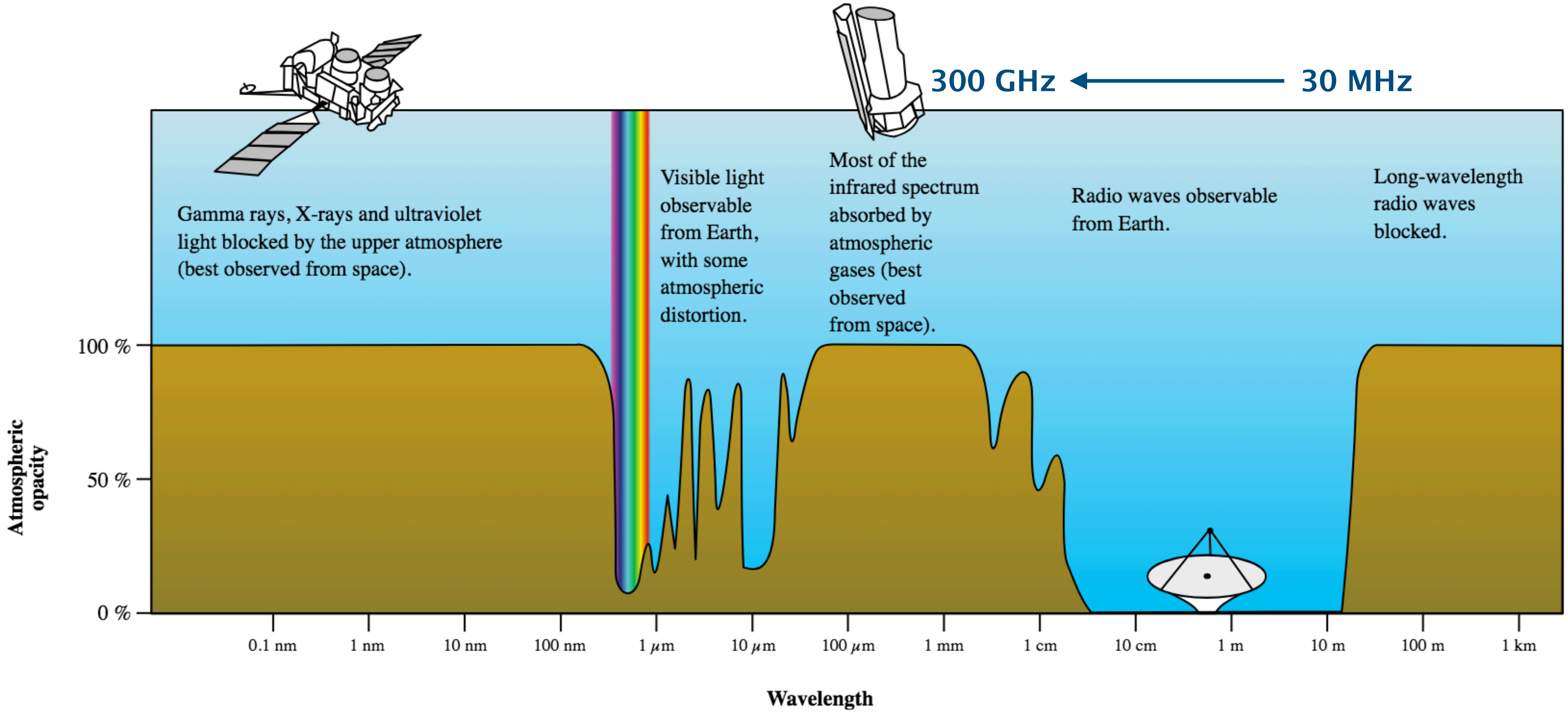
Radio wavelengths can be observed from the ground



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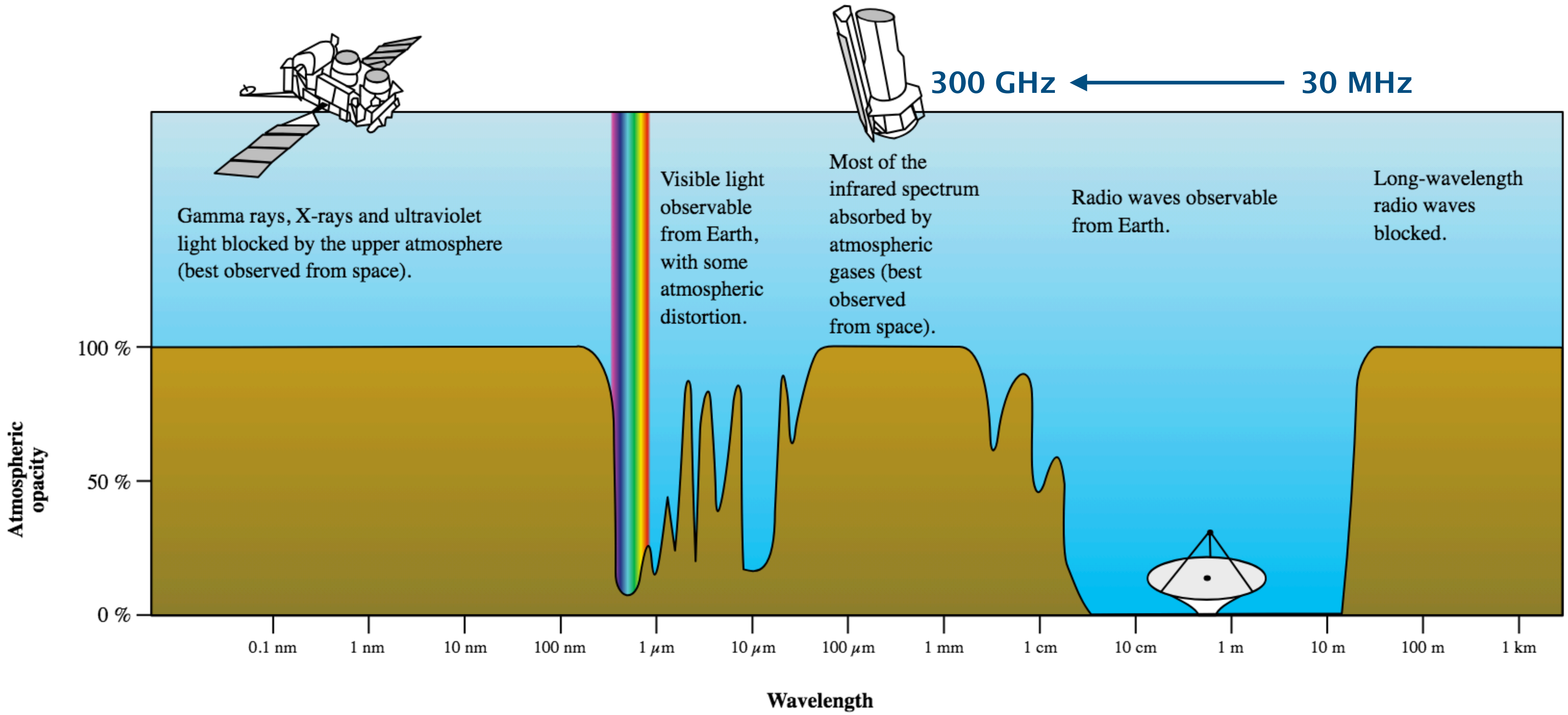

Multi-phase

- **Atomic gas:** HI at 21 cm
- **Ionized gas:** thermal continuum, Radio Recombination Lines (RRLs) from m to cm, Pulsars' dispersion measure (DM)
- **Molecular gas:** hyperfine structure (e.g., OH, CH at 20 cm) rotational lines (e.g., CO at mm), even COMs…

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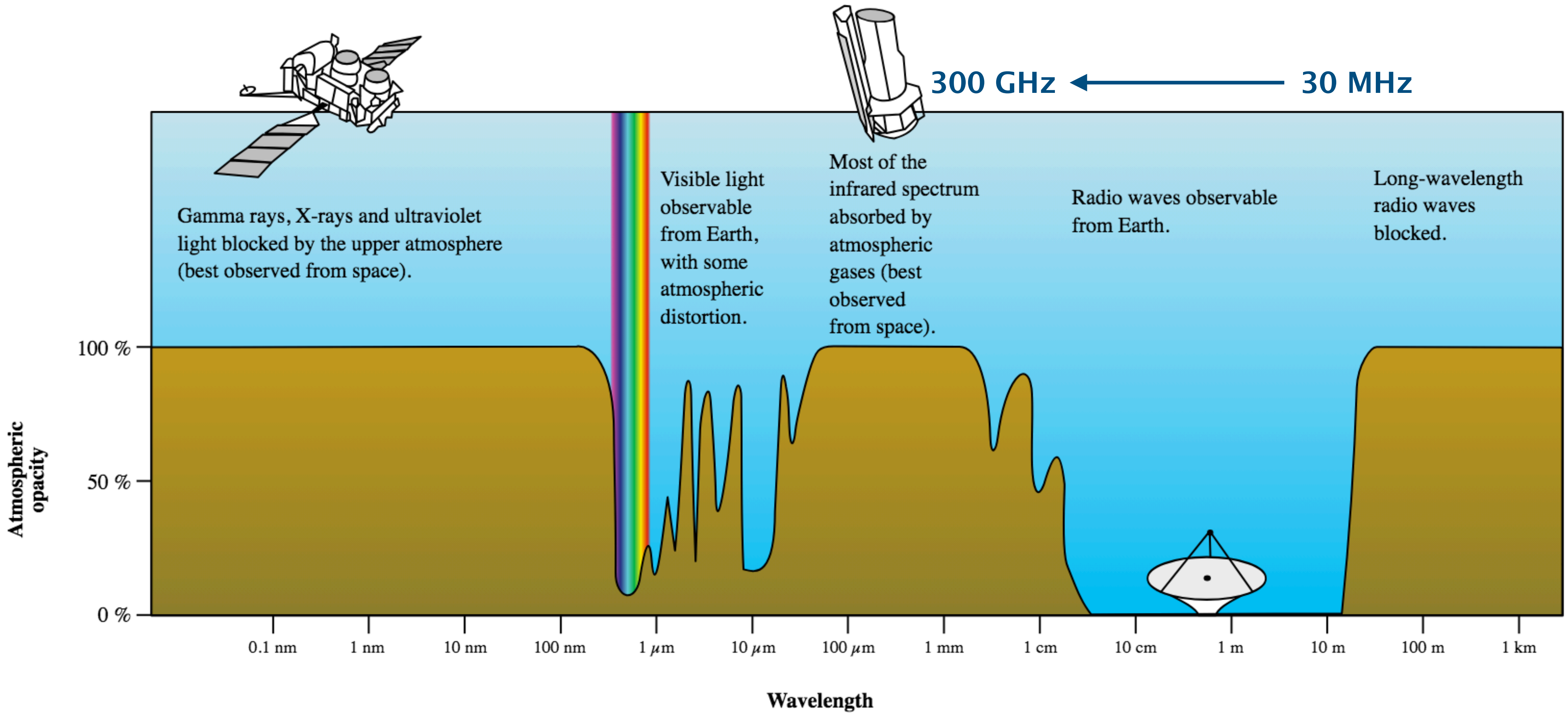

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Multi-tracer

- **Velocity field:** line profiles
- **Density field:** line profiles
- **Magnetic field:** non-thermal continuum (*synchrotron radiation with impact on CRs*), Faraday rotation (*polarization continuum*), Zeeman splitting (*line polarization of HI, OH, and CN*)

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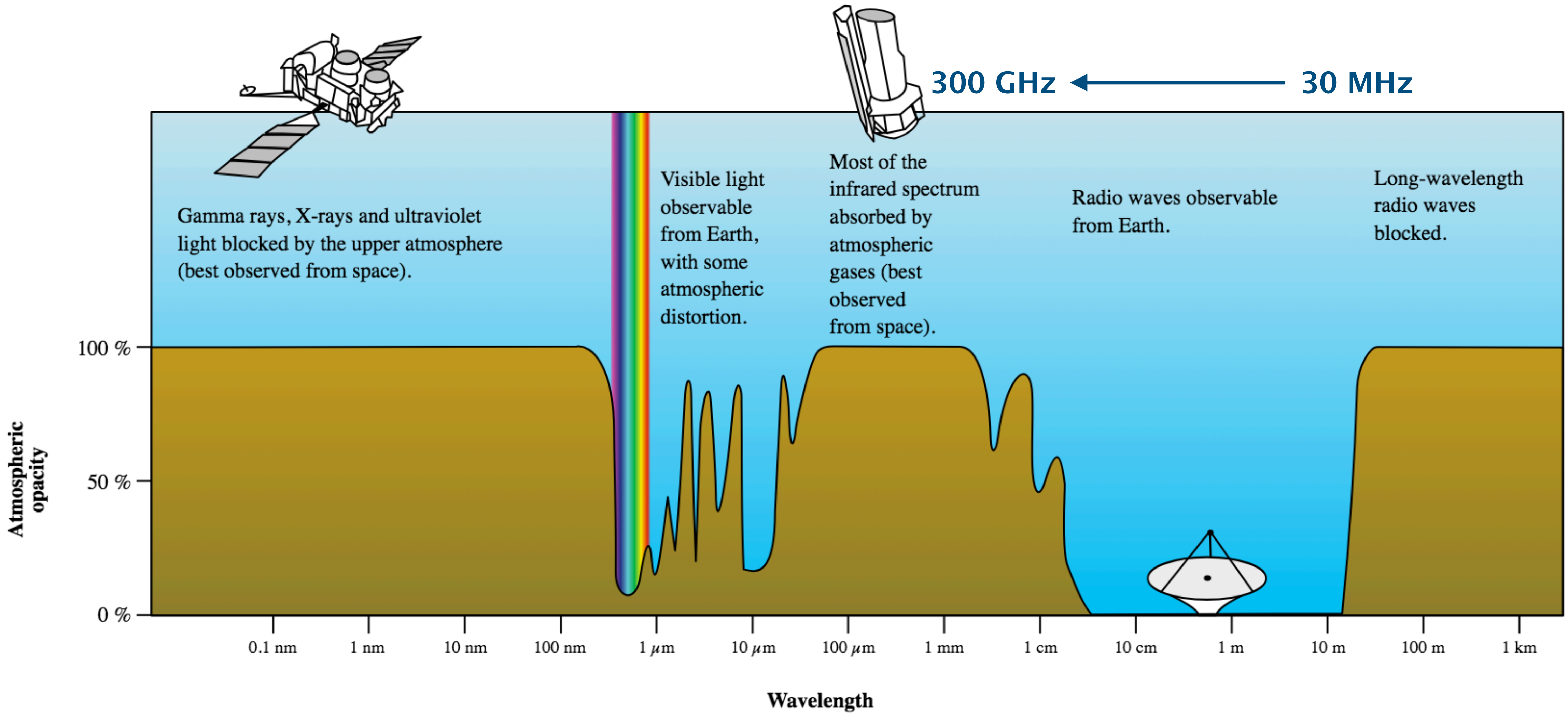

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Multi-scale

- **Large scales:** single dishes
- **Small scales:** radio interferometers

Some historical background

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- **Early 1900s, the ionosphere was discovered as a reflecting medium for radio waves (potential for radio communication). The plasma frequency in the ionosphere is about ~10 MHz (for the diffuse ISM is ~kHz).**

$$\nu > \nu_{\mathrm{p}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

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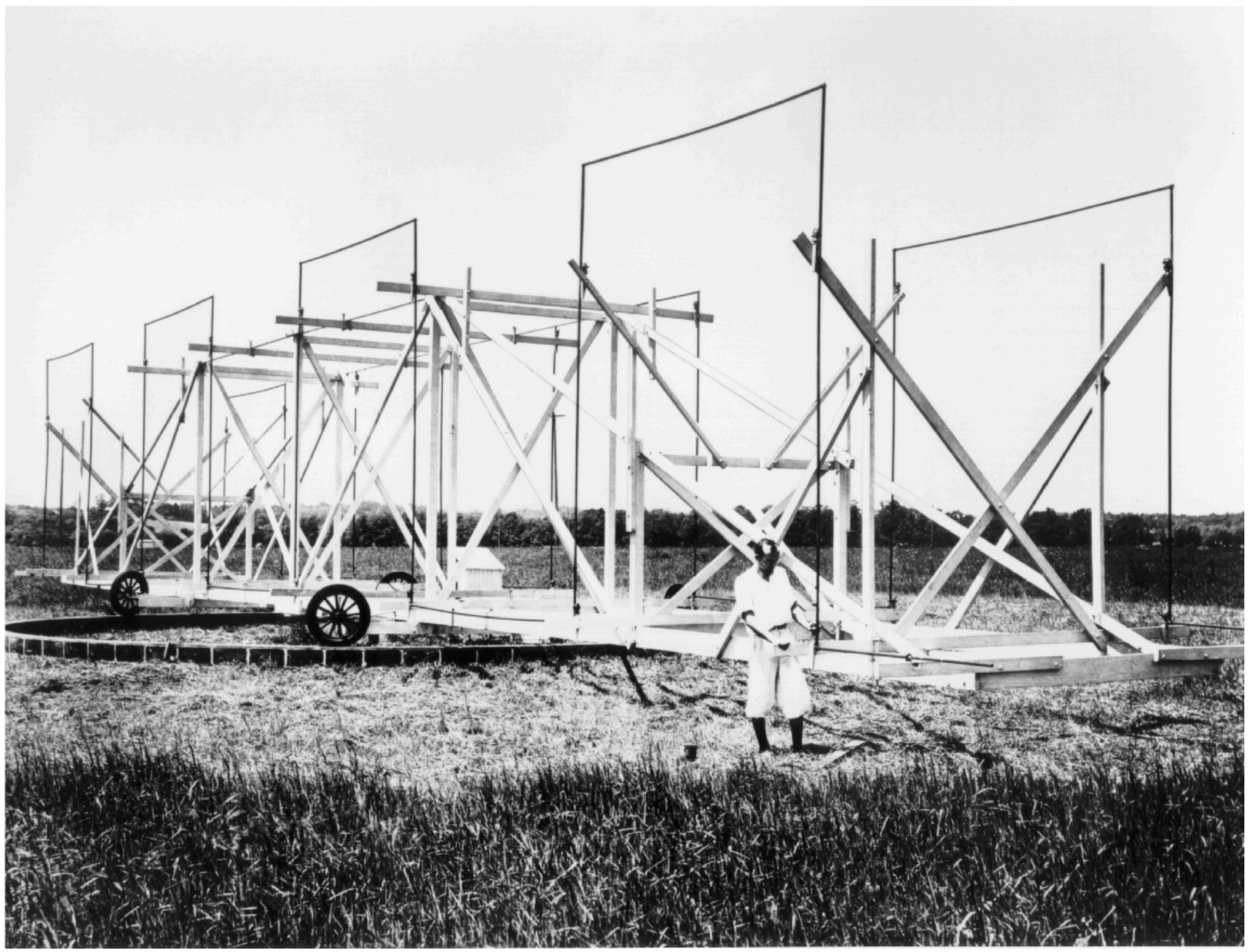

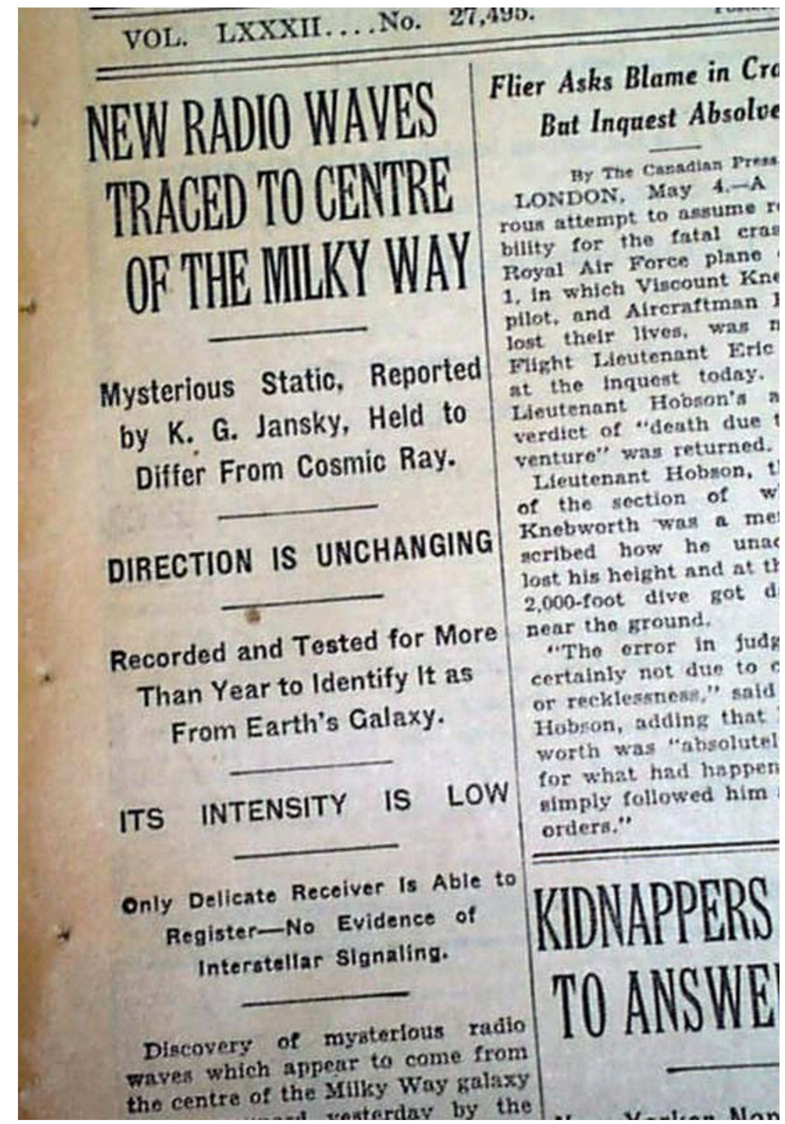
VOL. LXXXII....No. 27,495.

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy

Flier Asks Blame in Cra

But Inquest Absolve

By The Canadian Press

LONDON, May 4.—A

KIDNAPPERS

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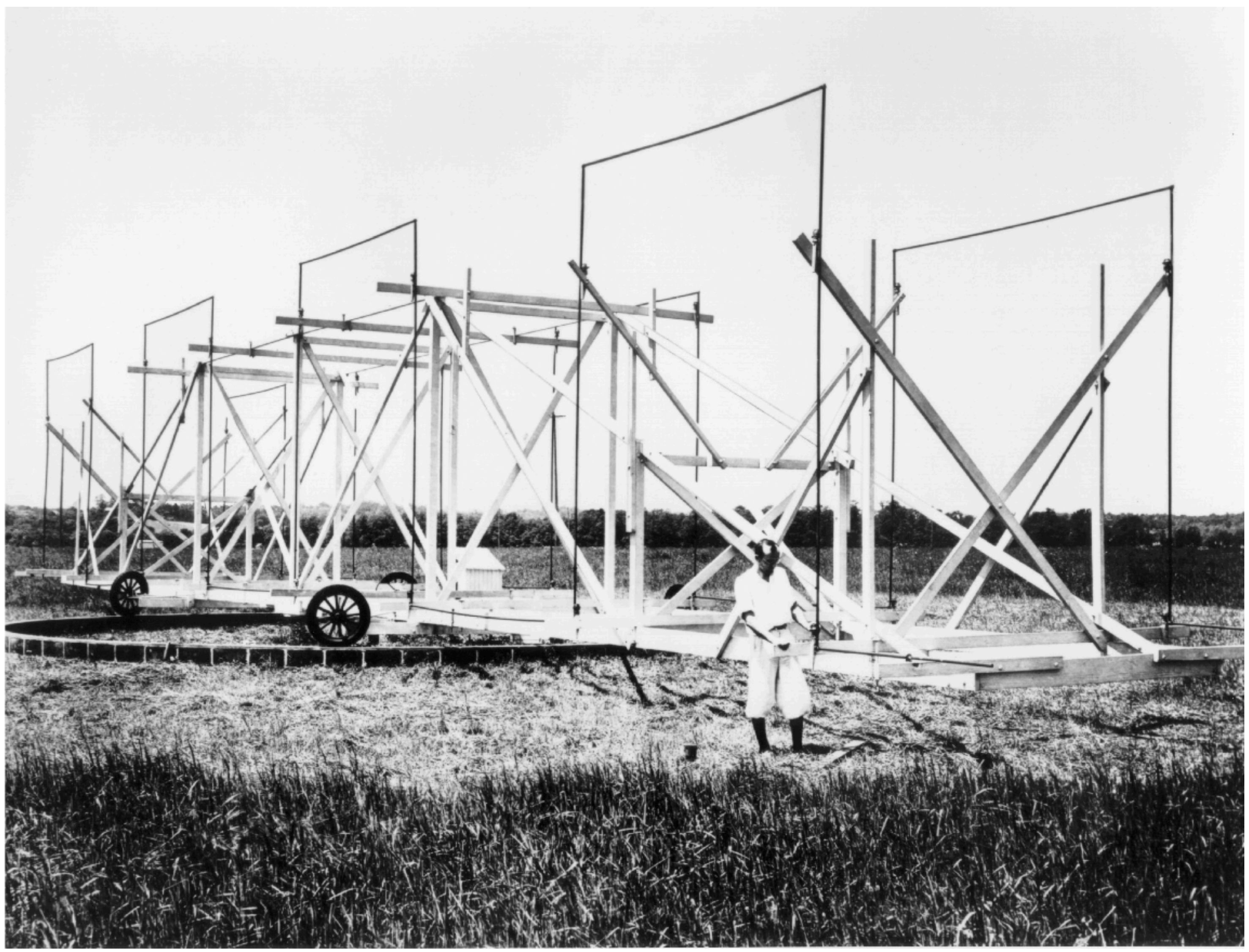

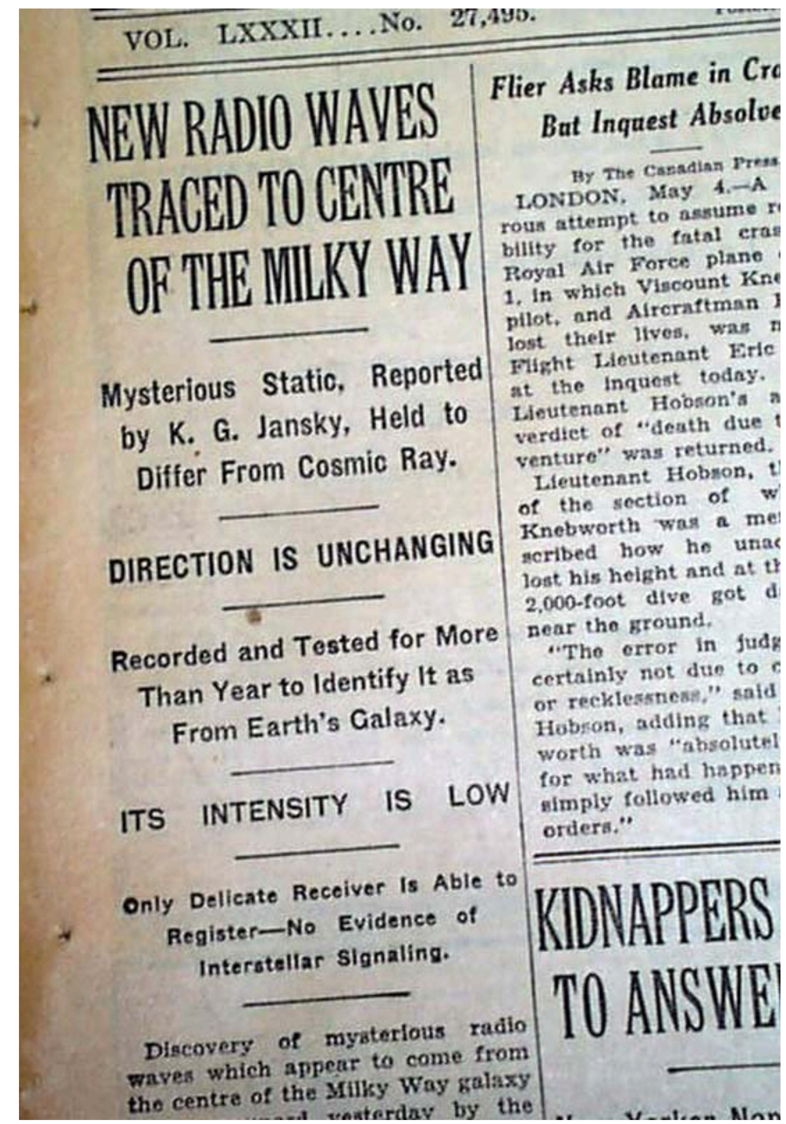

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By The Canadian Press
LONDON, May 4.—A
rous attempt to assume r
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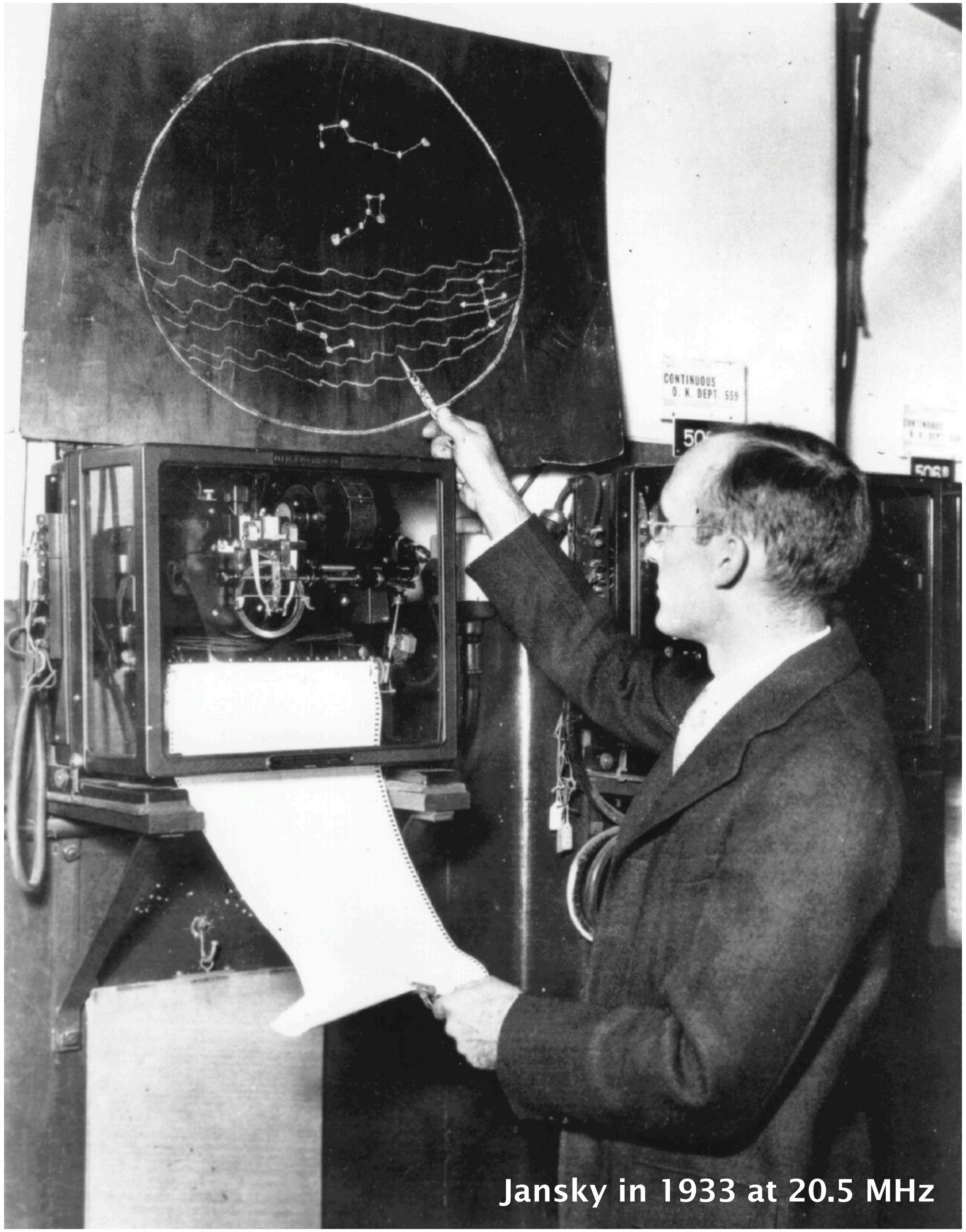
Royal Air Force plane
1, in which Viscount Kne
pilot, and Aircraftman
lost their lives, was
Flight Lieutenant Eric
at the inquest today.
Lieutenant Hobson's
verdict of "death due
venture" was returned.
Lieutenant Hobson,
of the section of
Knebworth was a me
scribed how he una
lost his height and at t
2,000-foot dive got
near the ground.
"The error in jud
certainly not due to
or recklessness," said
Hobson, adding that
worth was "absolute
for what had happen
simply followed him
orders."

KIDNAPPERS TO ANSWE

- "ITS INTENSITY IS LOW" : flux units are Jansky, or $1\,{\rm Jy} = 10^{-26}\,{\rm W\,m^{-2}\,Hz^{-1}}$ (often, Jy/sr converted in K for brightness temperature, Tb)

Some historical background



Jansky in 1933 at 20.5 MHz

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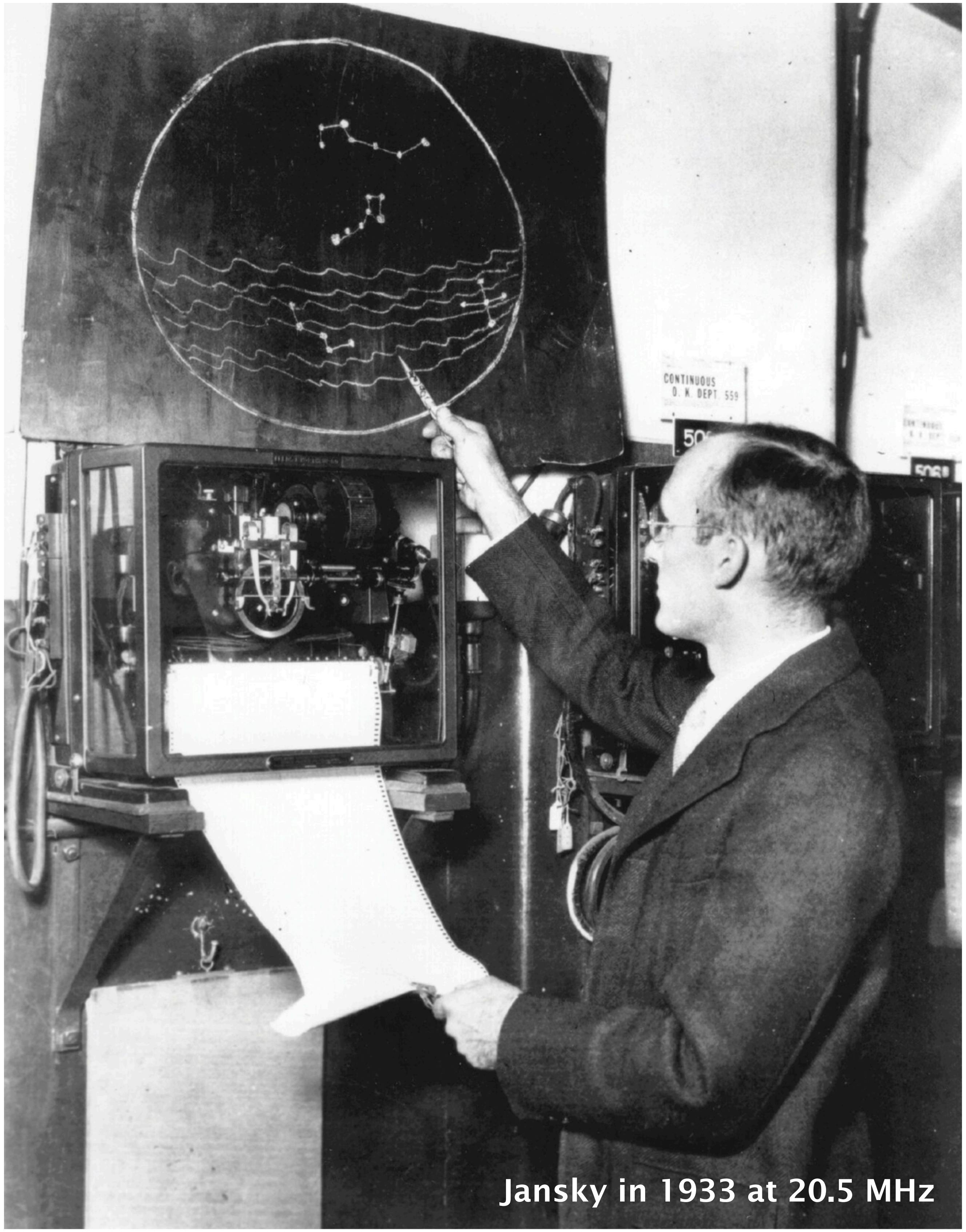

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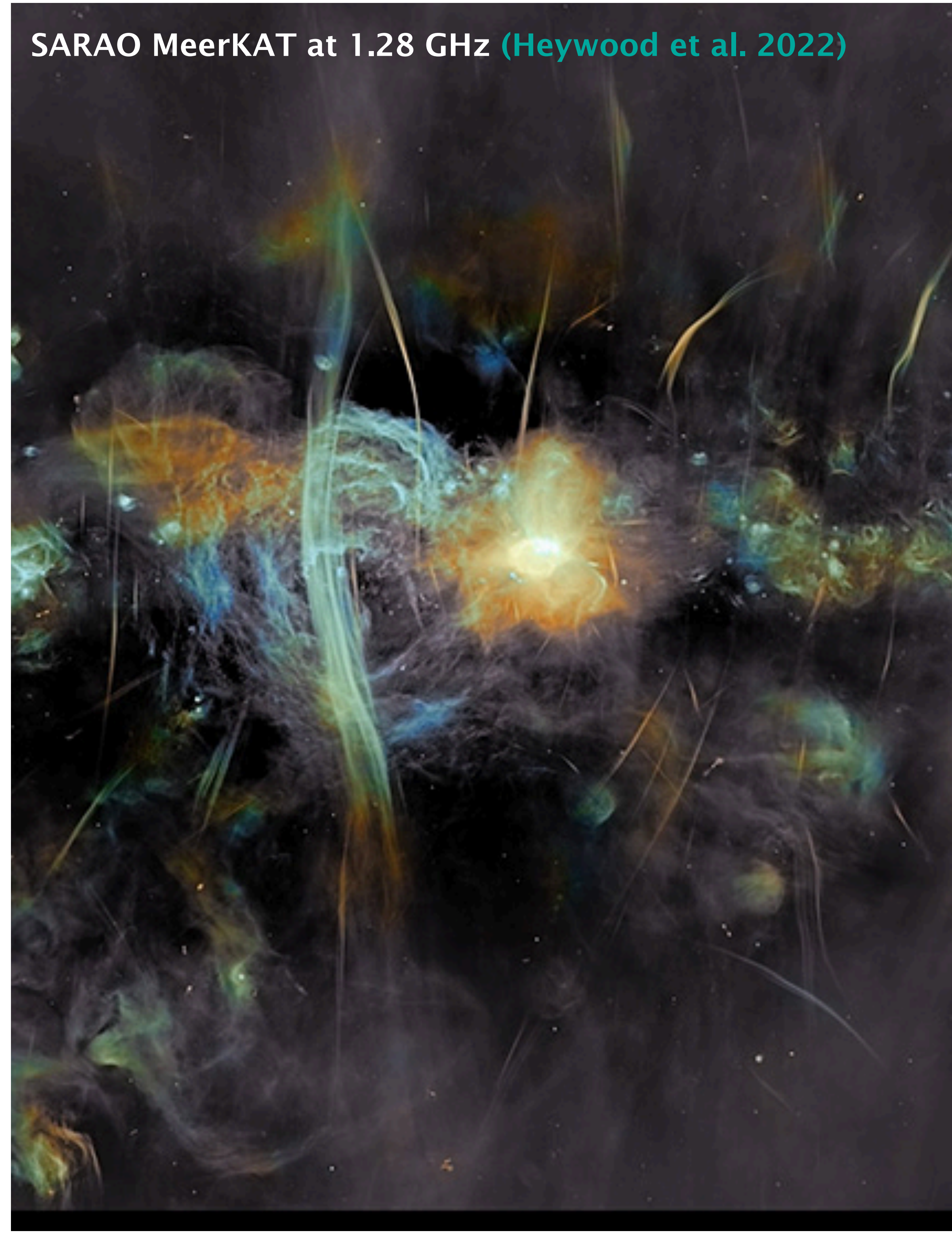

SARAO MeerKAT at 1.28 GHz (Heywood et al. 2022)

What are the tools in hand?

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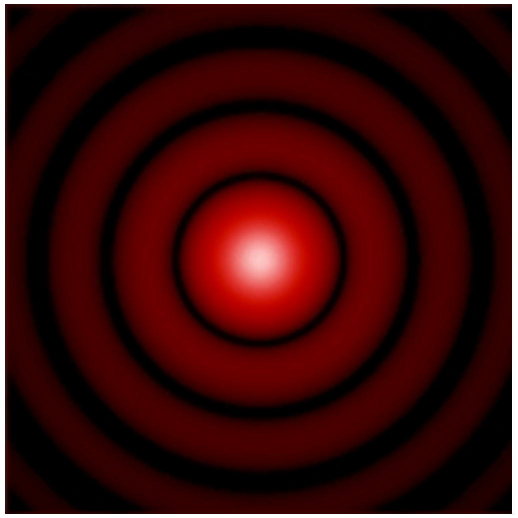
- **The tools are telescopes, which are always *diffraction limited* (due to the finite size of the telescope elements) and characterized by a given *point spread function* (PSF) that defines the *telescope angular resolution*.**

Airy diffraction pattern



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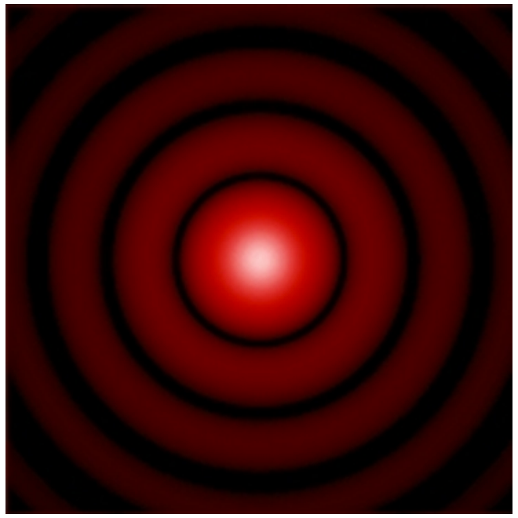

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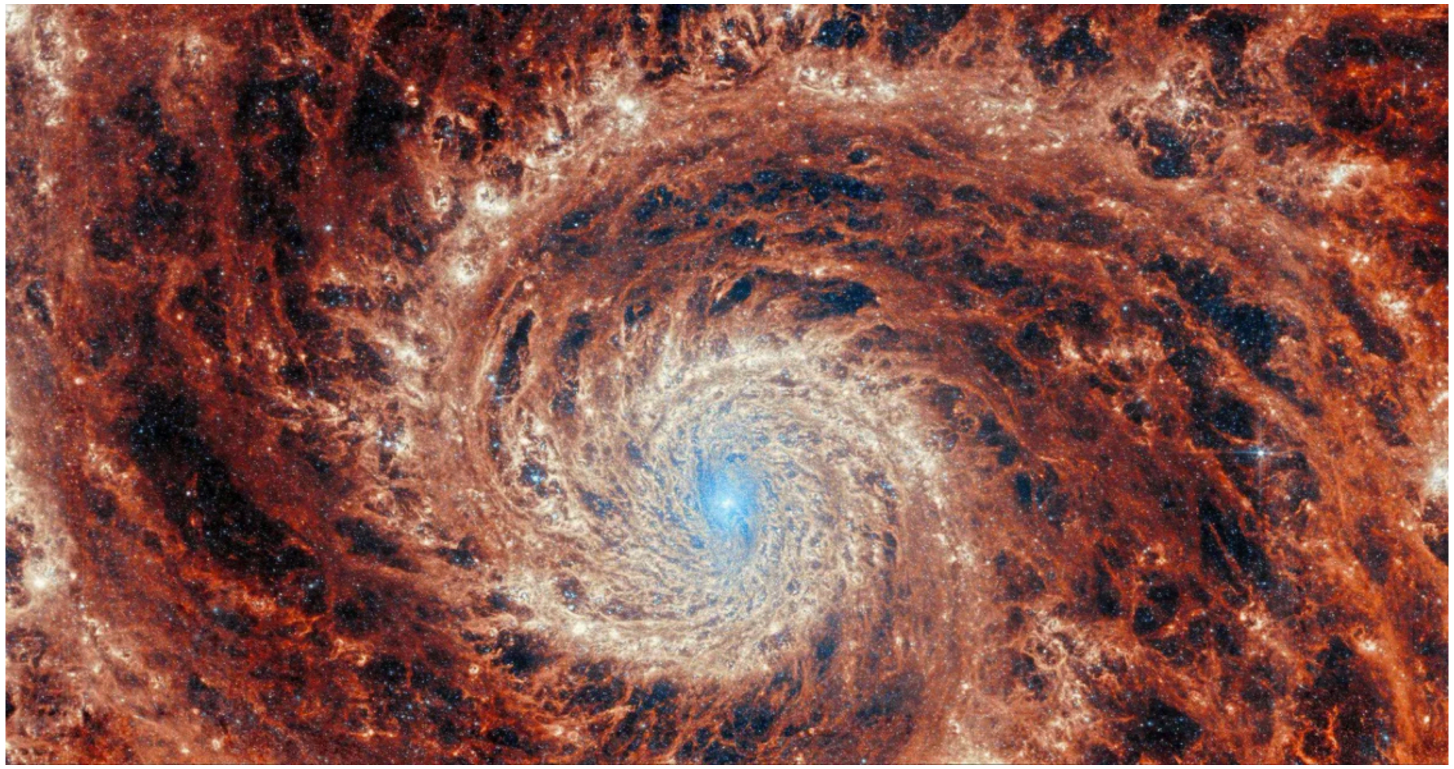
- M51 with NASA/ESA/CSA James Webb Space Telescope in the Infrared (1E-6 m)



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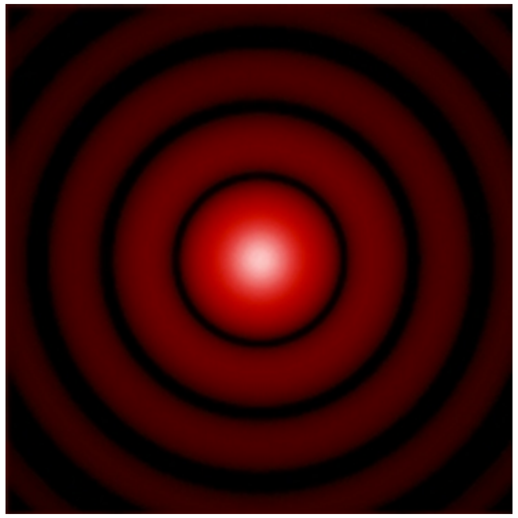

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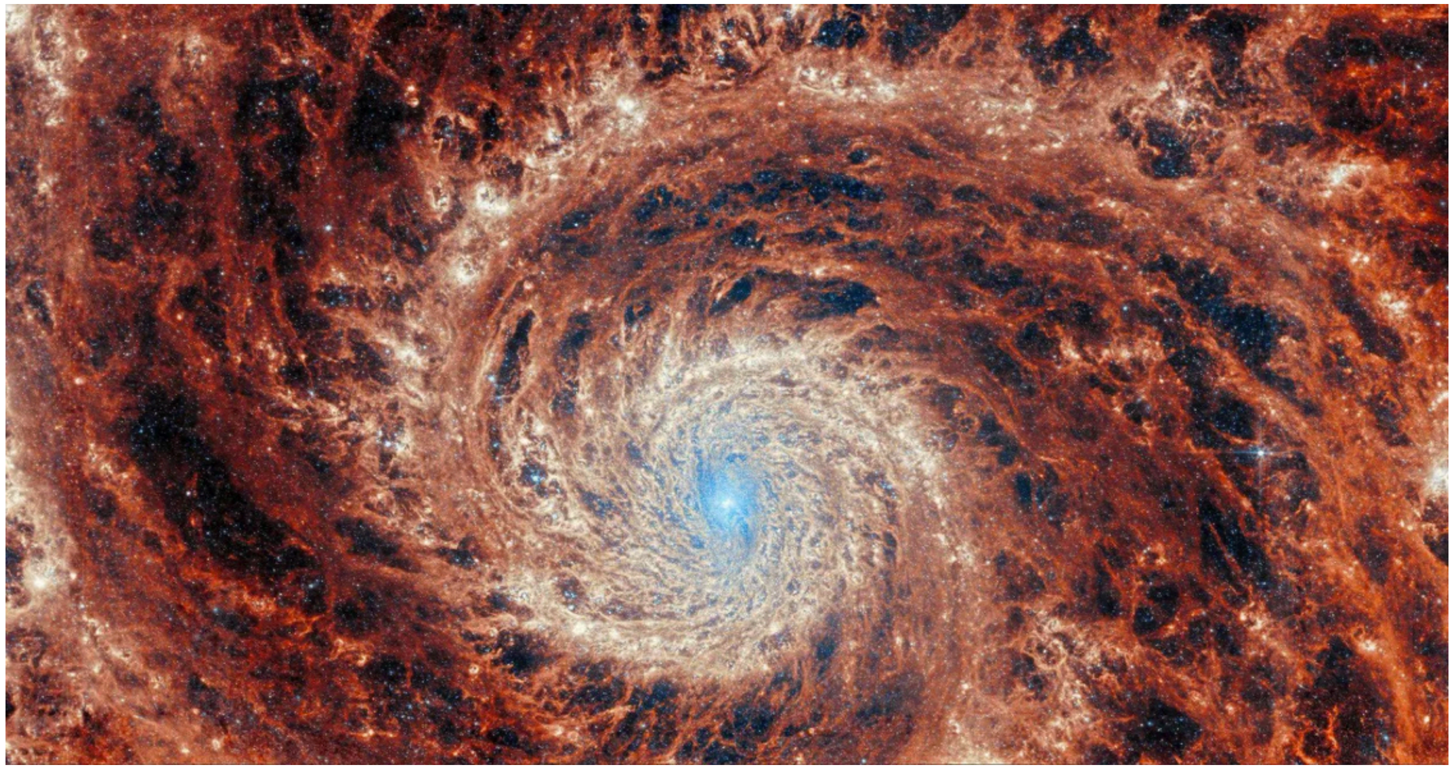


$$\theta_{\mathrm{PSF}}^{\mathrm{JWST}} \approx 0.1''$$

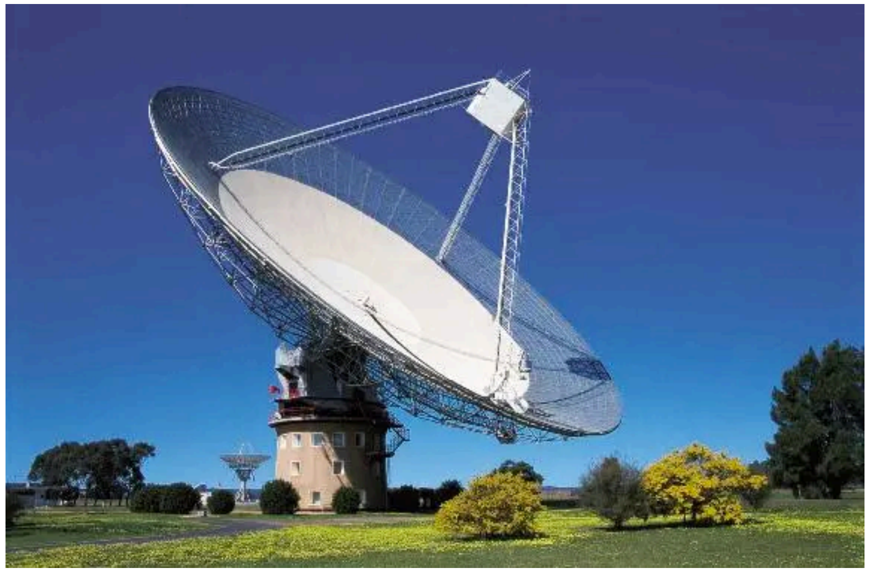
$$D_{21\mathrm{cm}} > 400\,\mathrm{km}$$

The distance to the International Space Station!

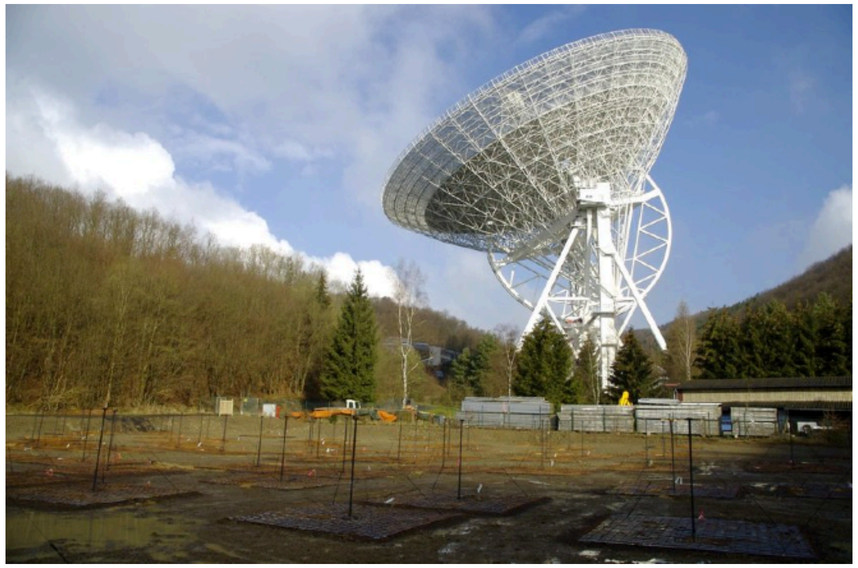
What are the tools in hand?

- Single dishes

IRAM 30m

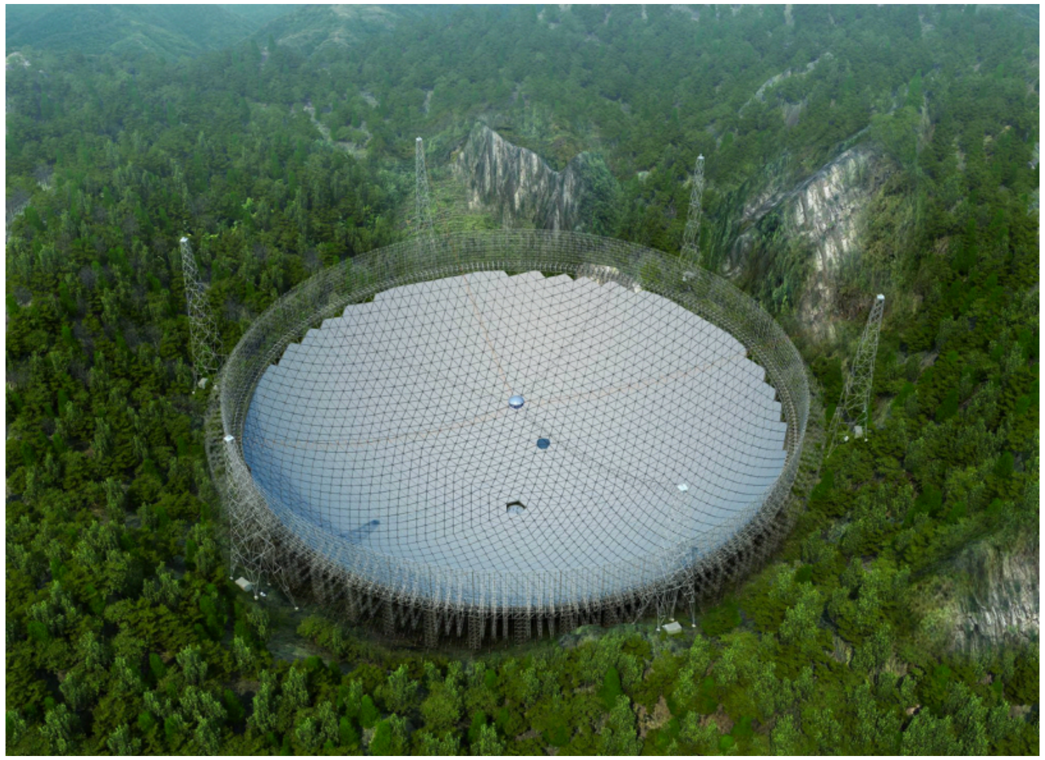


Murriyang Parkes 64m



Effelsberg 100m

Arecibo 300m

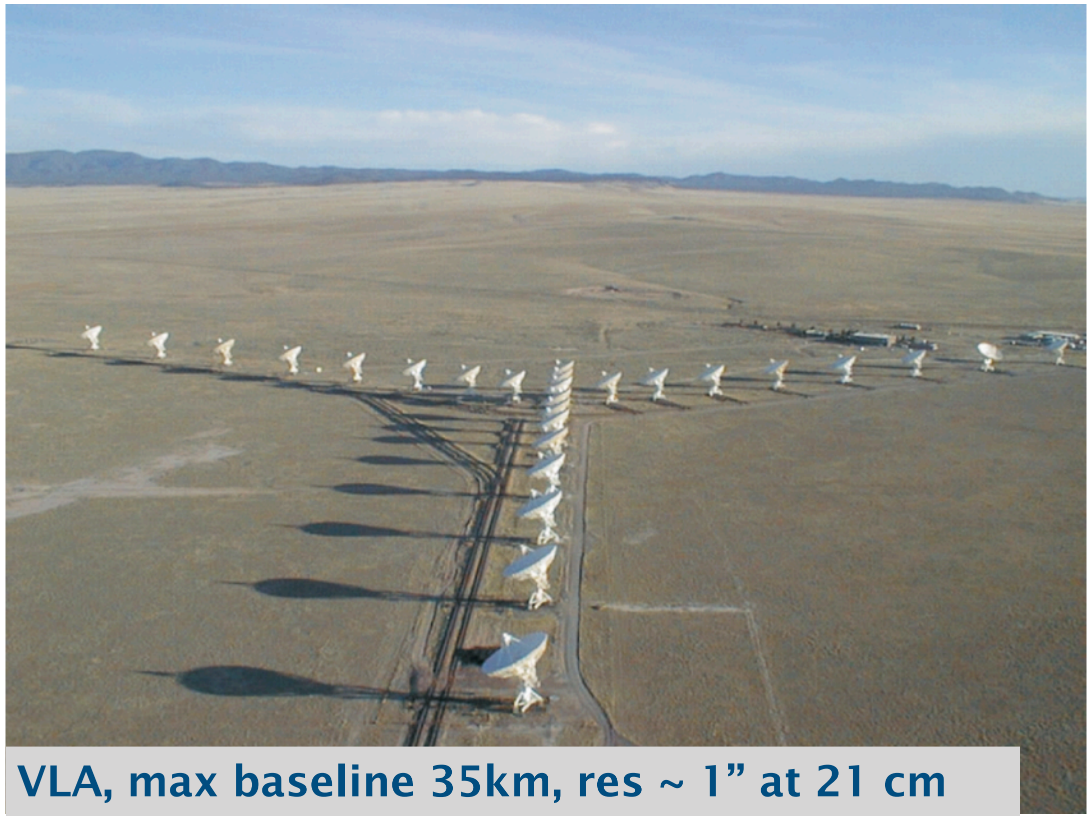


FAST 500m, <u>at best ~1 arcmin at 21 cm</u>

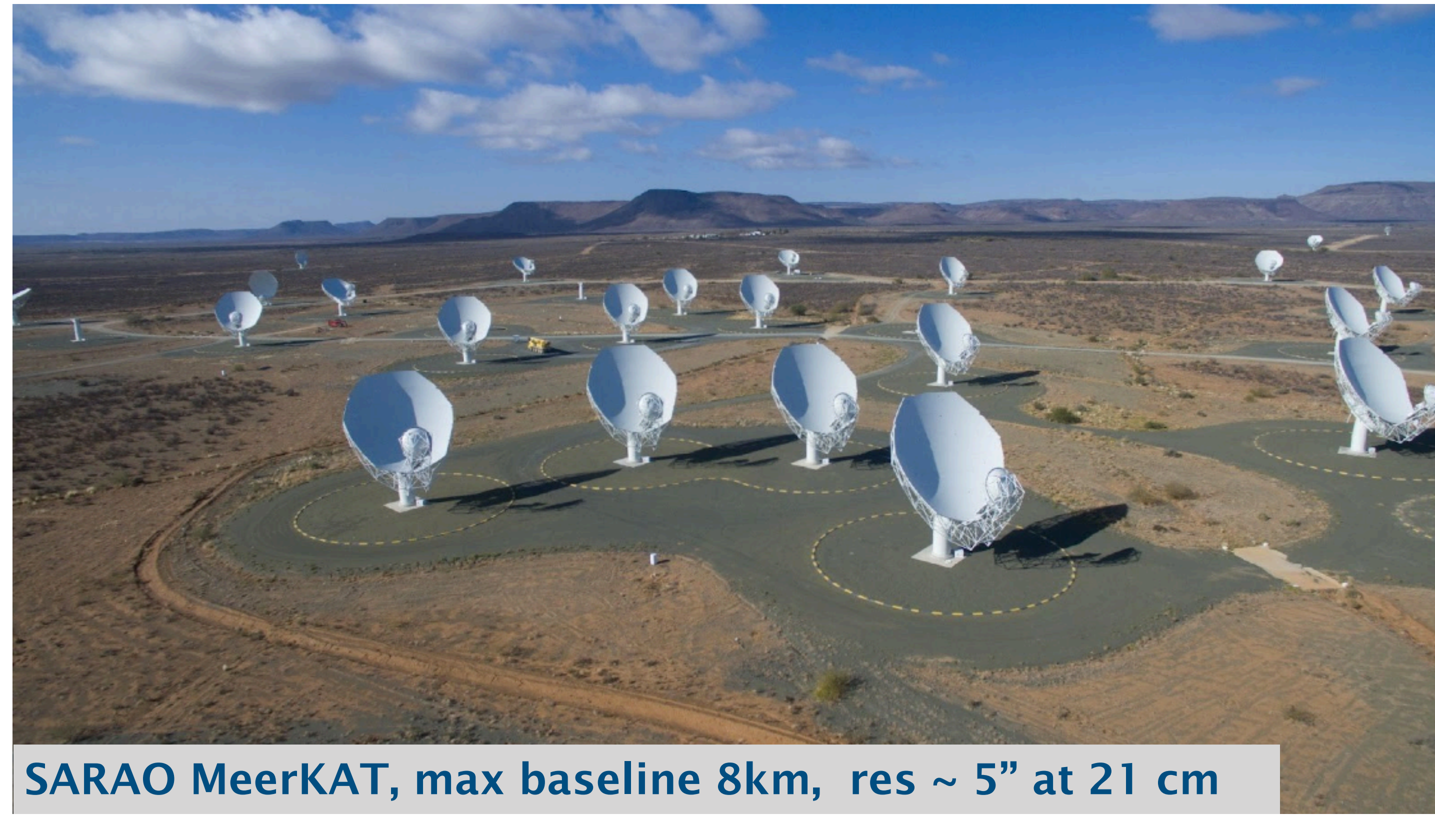
Much worse than an optical amateur 60mm refractor telescope (~ a few arcsec)

What are the tools in hand?

- **Interferometers: use a distributed network of “small” apertures to *synthesize* a larger one** $\theta_{\mathrm{PSF}} \approx \lambda / \texttt{max\_baseline}$

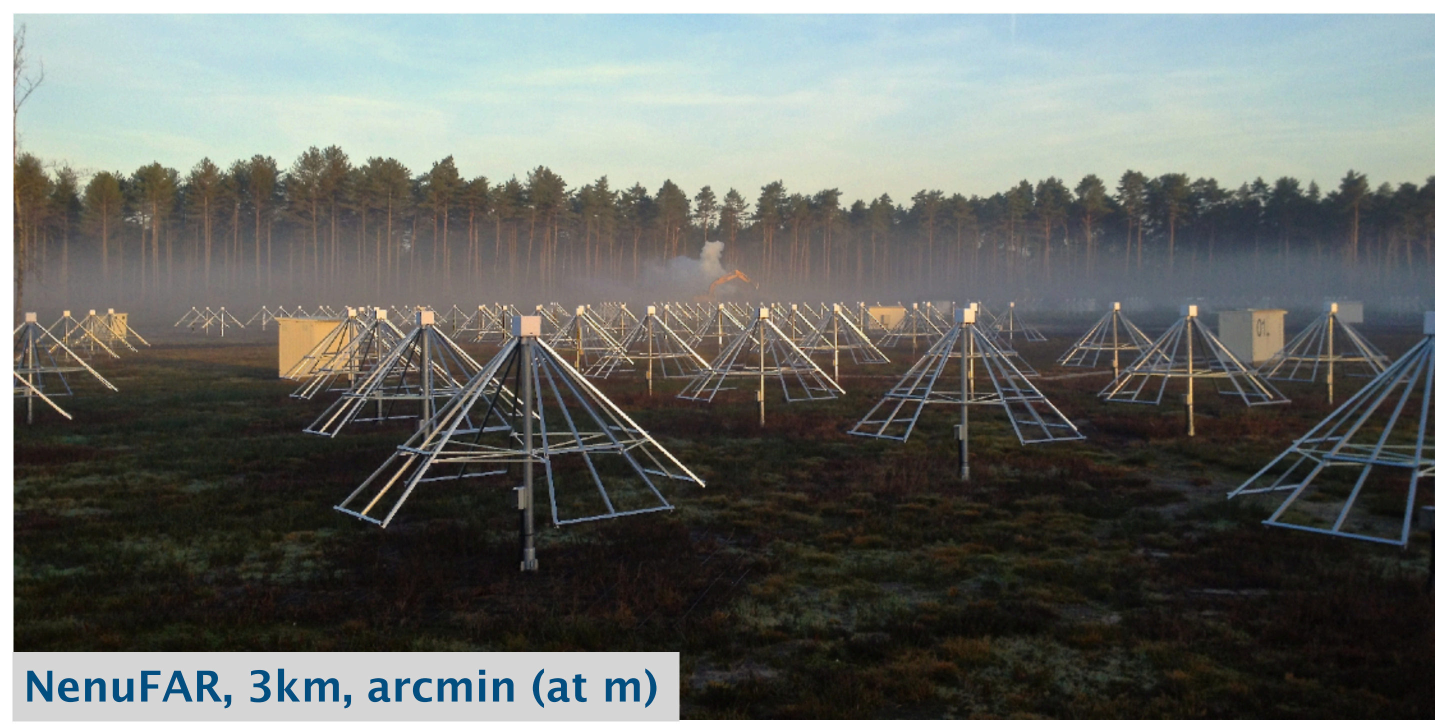


VLA, max baseline 35km, res ~ 1” at 21 cm



SARAO MeerKAT, max baseline 8km, res ~ 5” at 21 cm

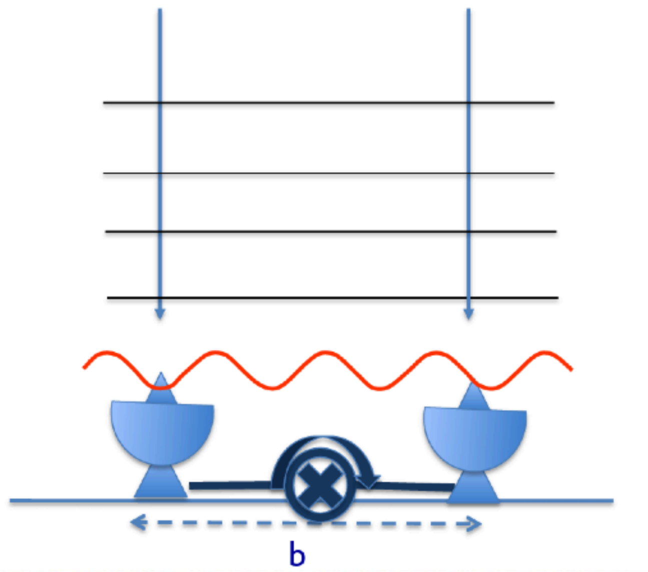
LOFAR, 100 - 1000km, arcsec to sub (at m)



NenuFAR, 3km, arcmin (at m)

What are the tools in hand?

- **Interferometry is great but tricky. It measures the interference pattern between antennas at various baselines (b). It lives in the *visibility space* (Fourier space). Complex number, *visibility*, made of *amplitude* and *phase*.**



Visibility: $$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dx dy$$

True sky: $$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$

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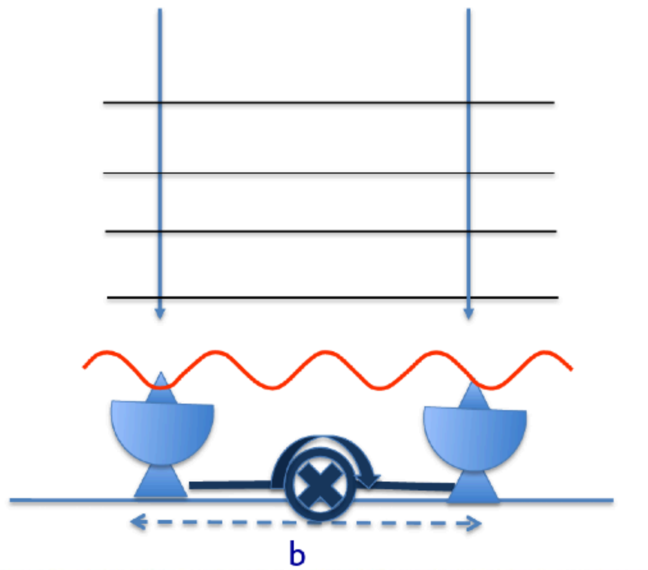

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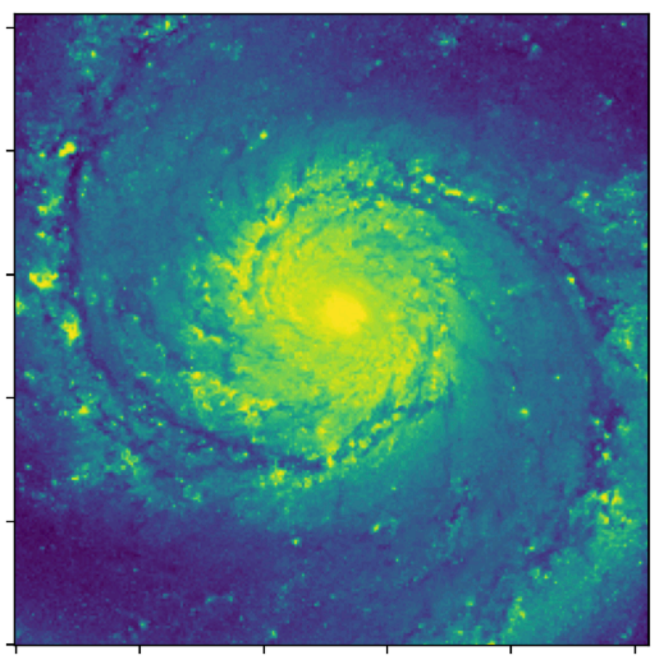
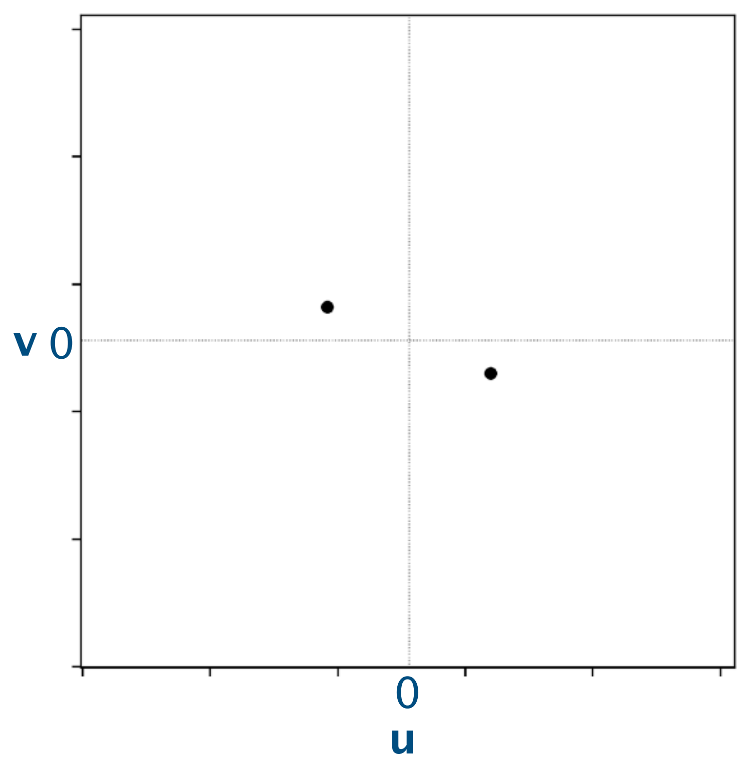
- **Problems start because the uv-plane is sparsely/poorly sampled and the zero spacing will be always missing:**

True sky



*Not at scale

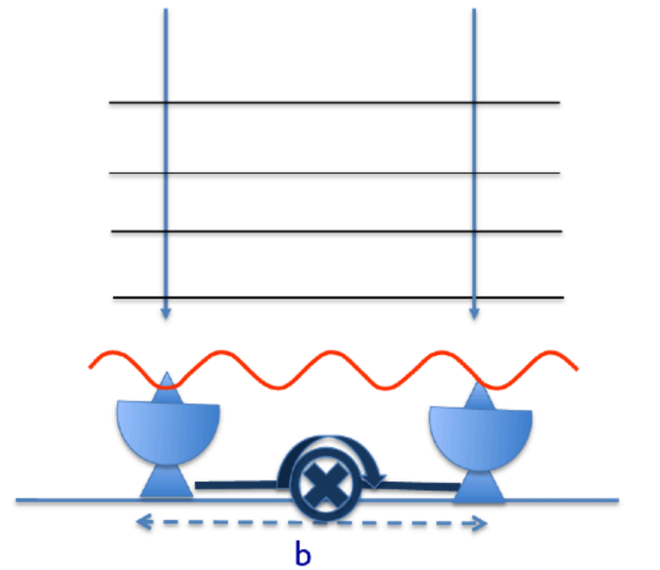
2 antennas (N(N-1))



Observed sky

What are the tools in hand?

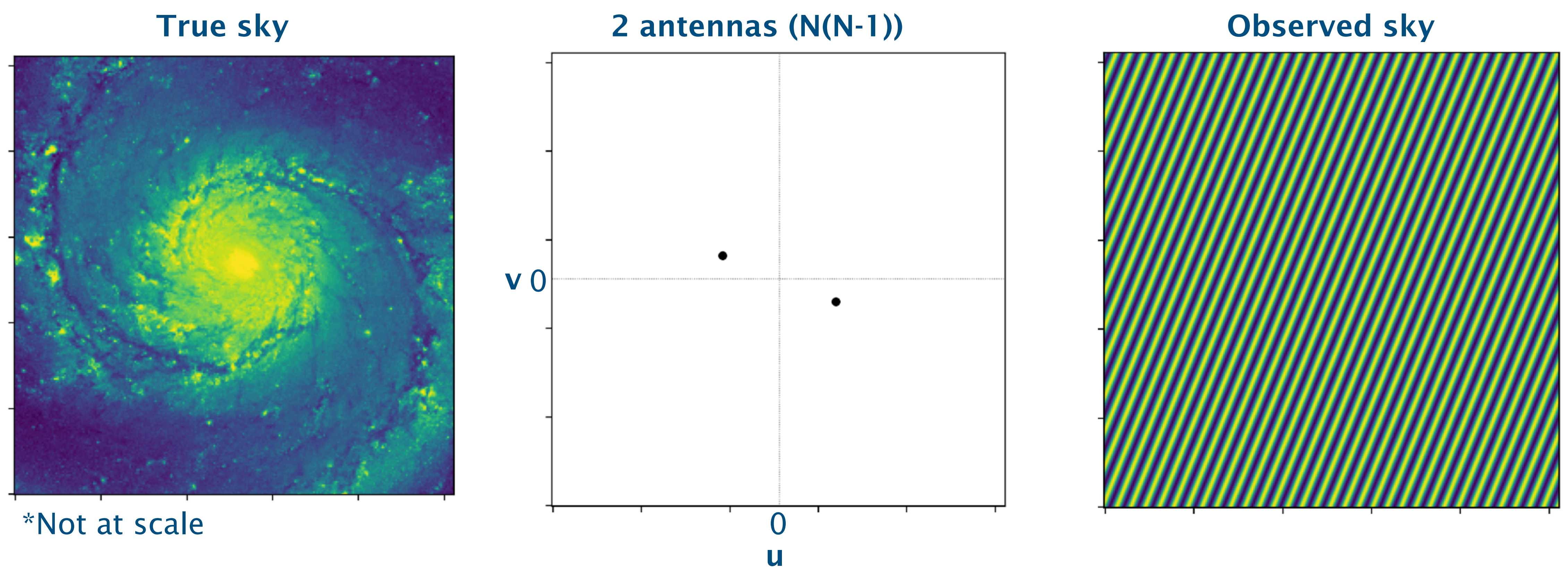
- **Interferometry is great but tricky. It measures the interference pattern between antennas at various baselines (b). It lives in the *visibility space* (Fourier space). Complex number, *visibility*, made of *amplitude* and *phase*.**



Visibility: $$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

True sky: $$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

- **Problems start because the uv-plane is sparsely/poorly sampled and the zero spacing will be always missing:**



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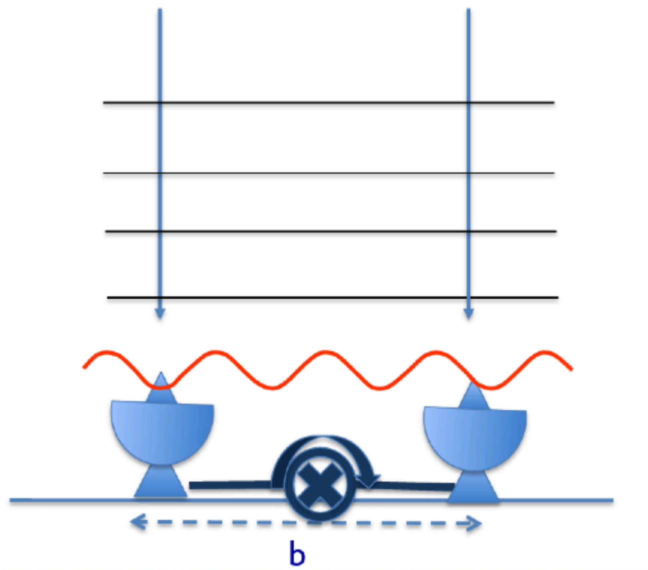

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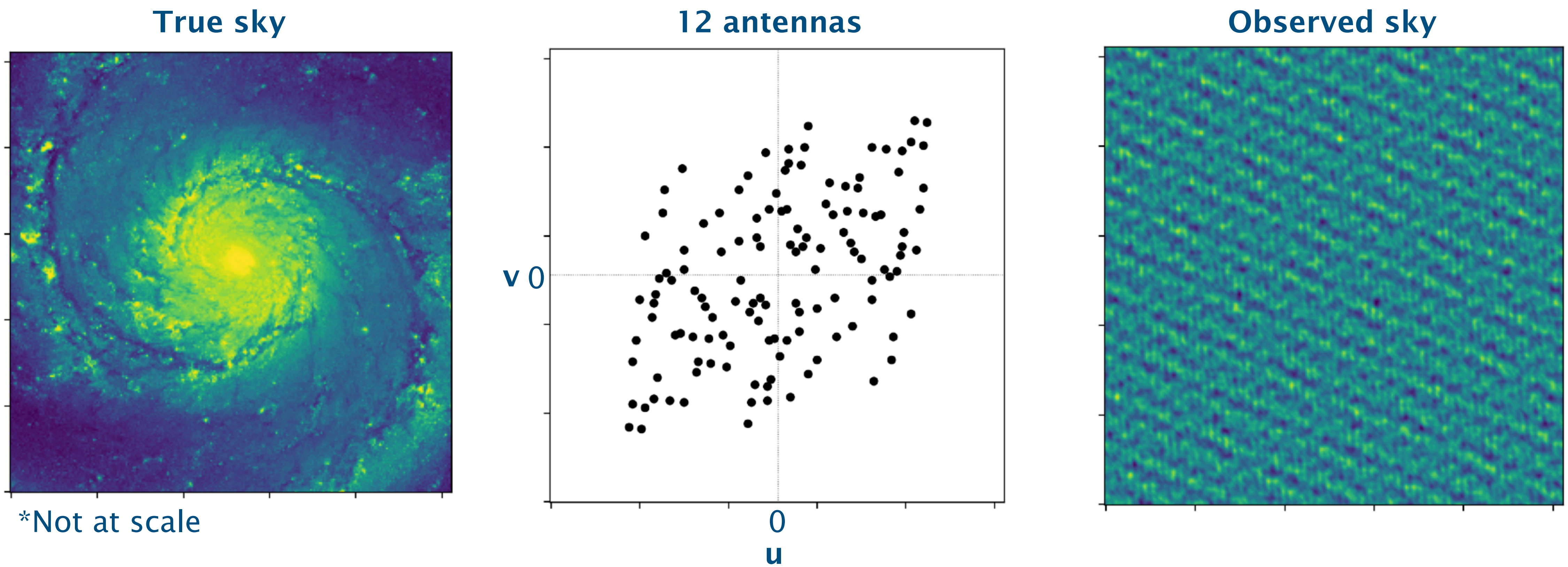

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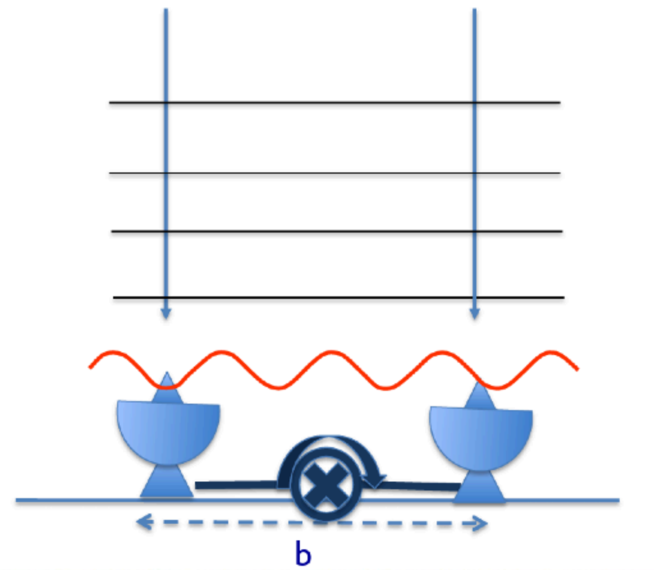

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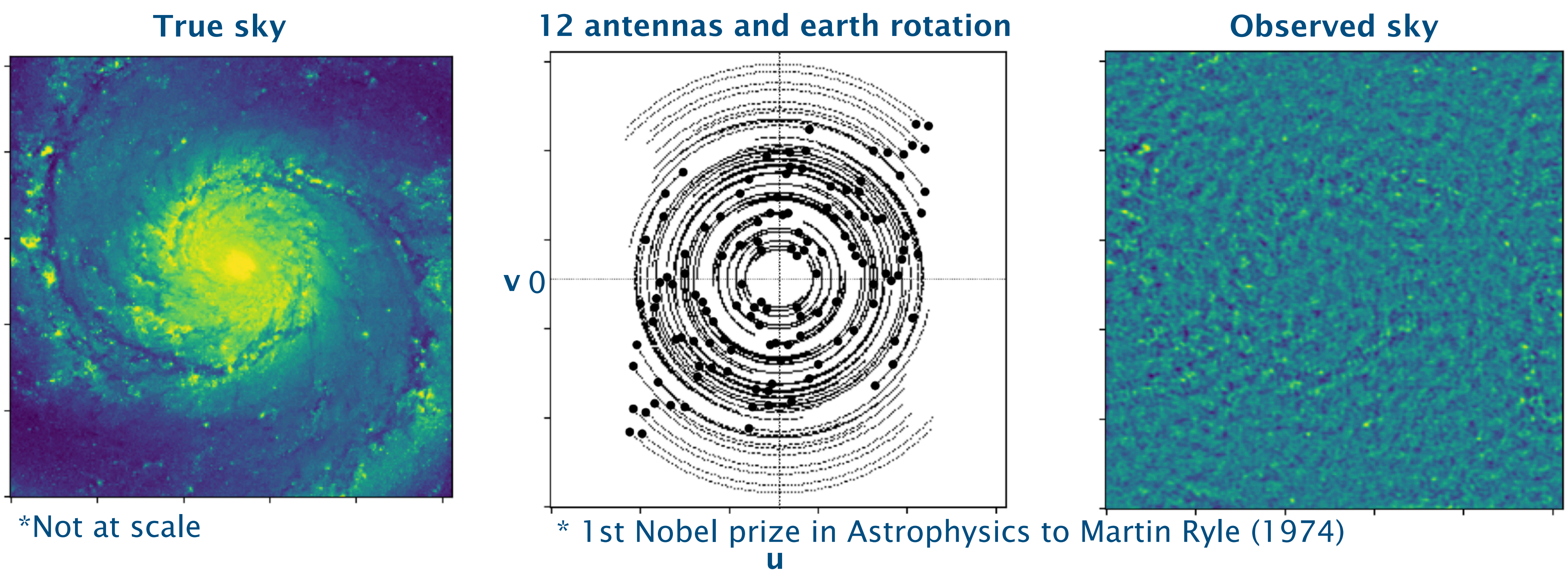

*Not at scale

* 1st Nobel prize in Astrophysics to Martin Ryle (1974)

What are the tools in hand?

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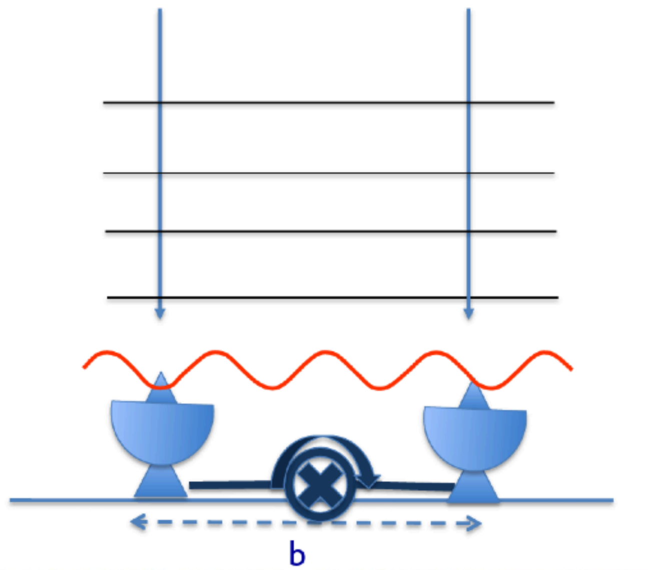

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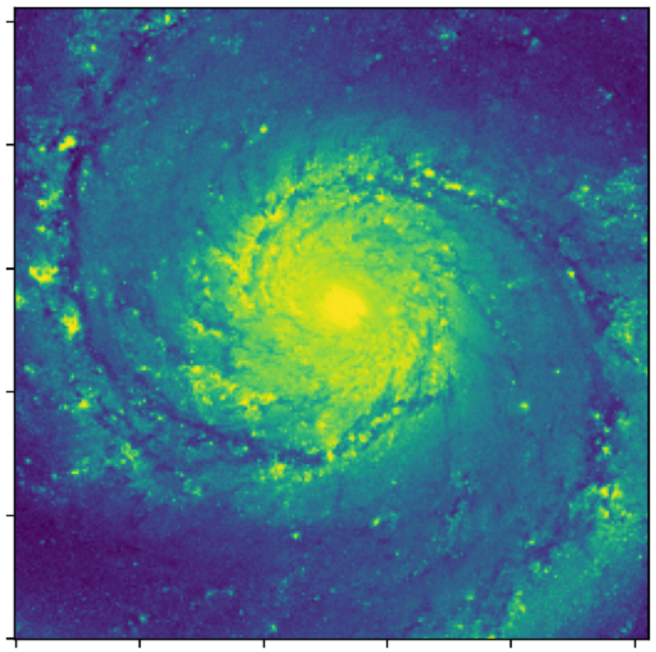
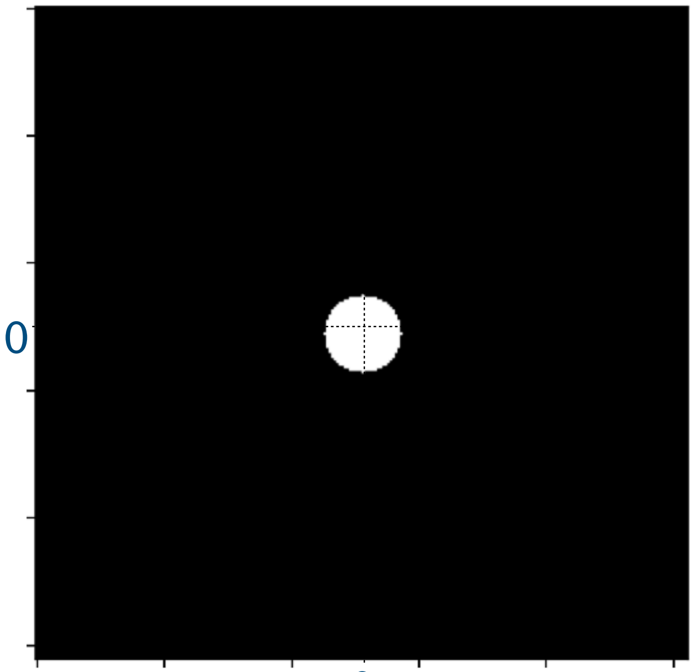
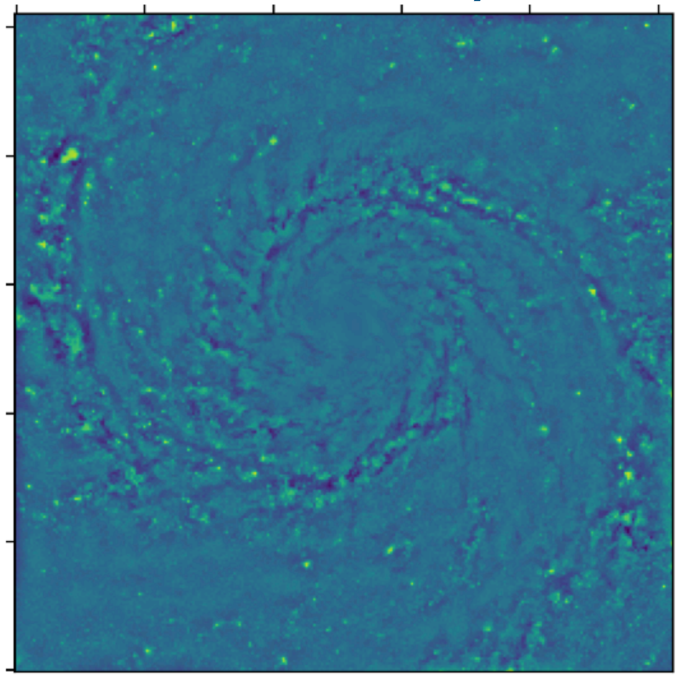


*Not at scale

Eventually…

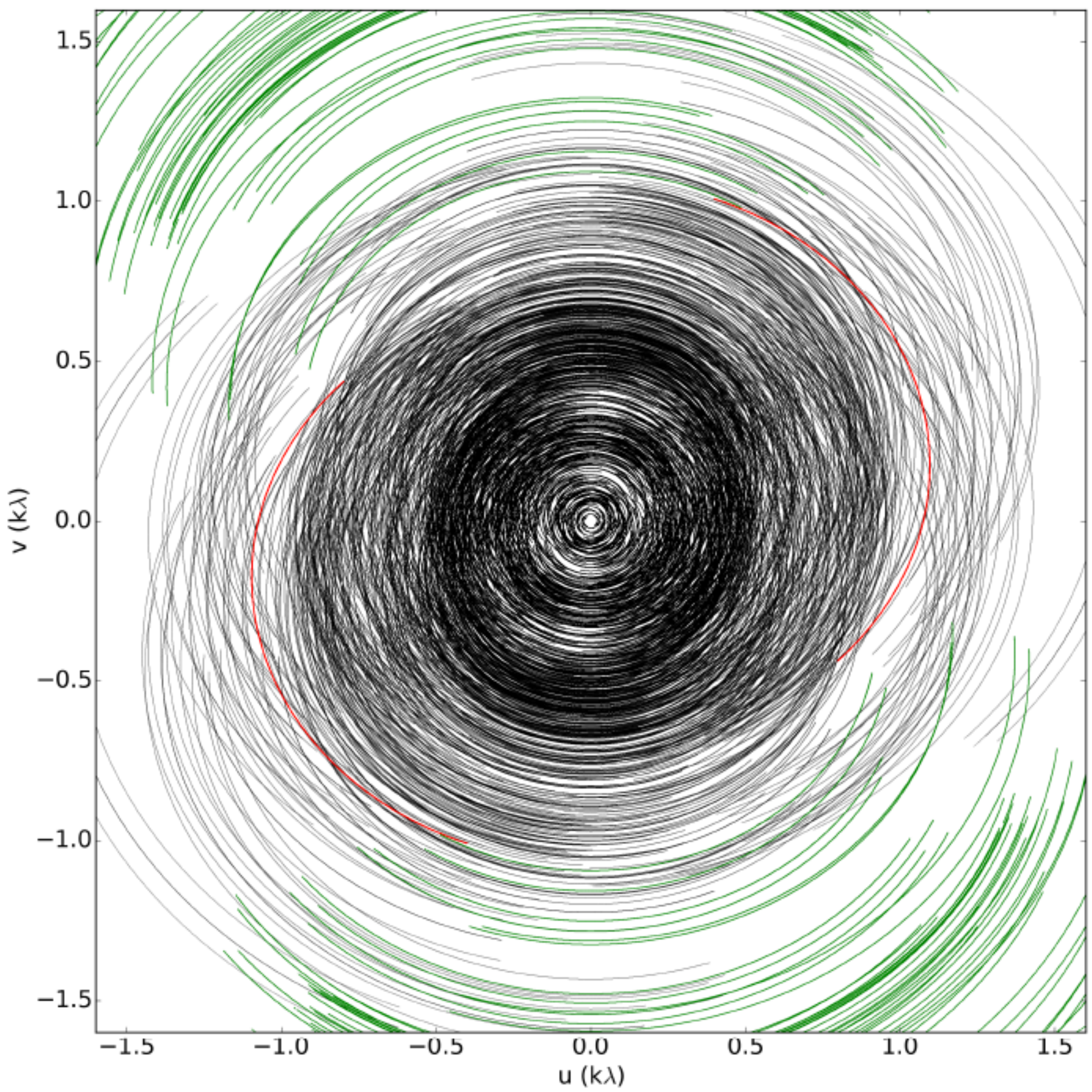


Observed sky



What are the tools in hand?

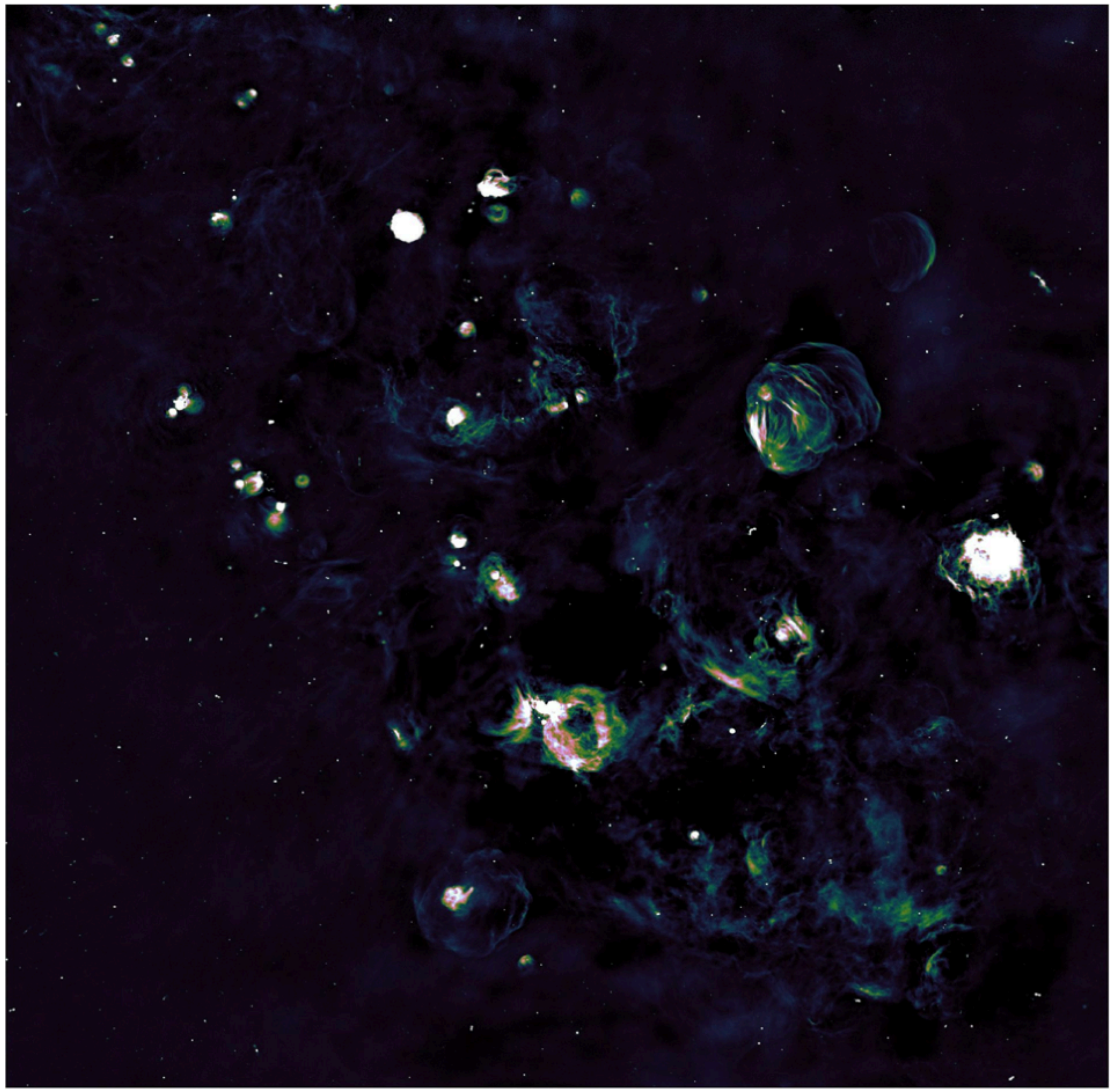
- **Problems start because the uv-plane is sparsely/poorly sampled and the zero spacing will be always missing: the LOFAR case (in black only core stations in the Netherland)**

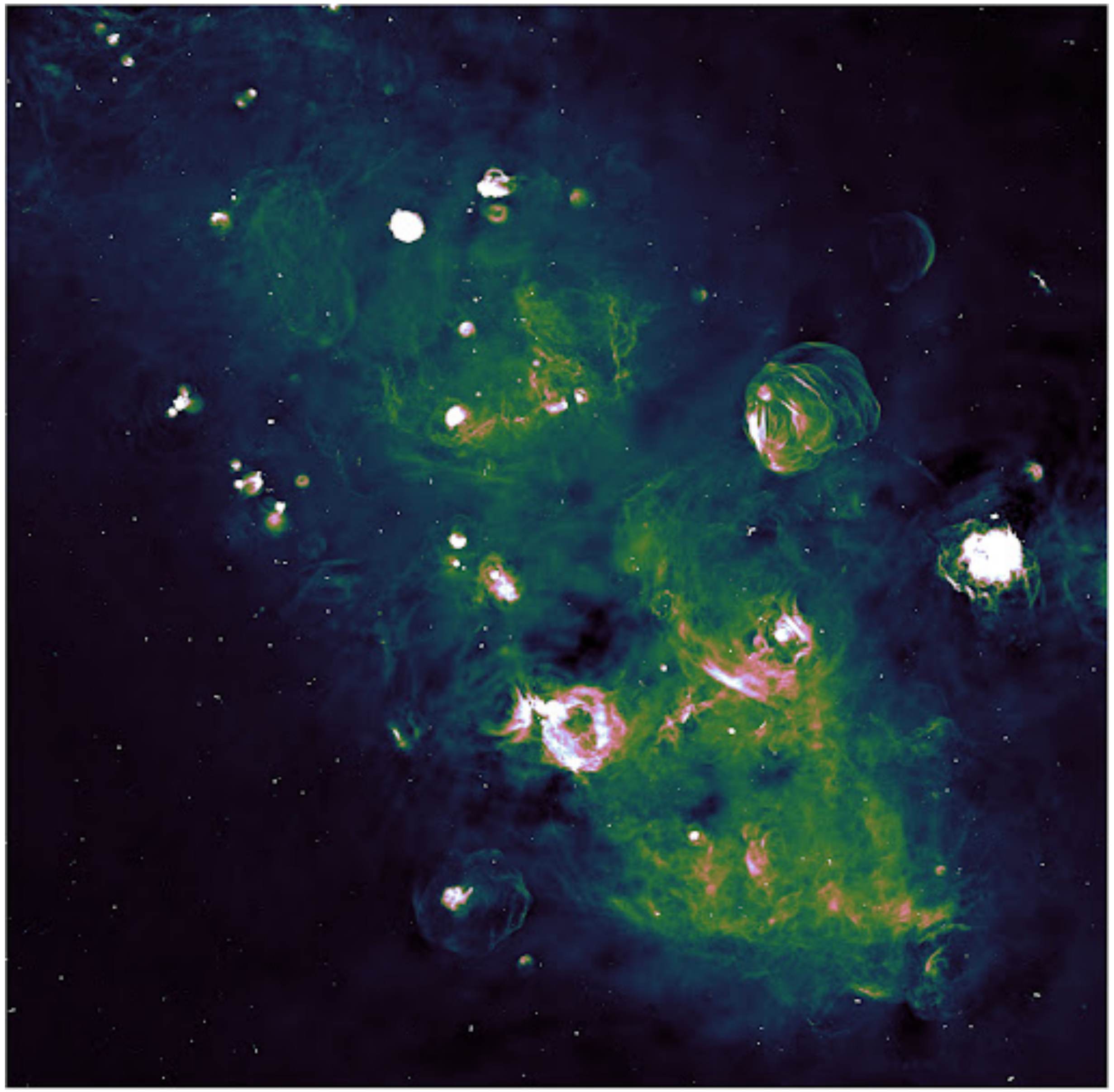


(LOFAR Two-metre Sky Survey, LoTSS, Shimwell et al. 2017)

What are the tools in hand?

- Interferometers tend to miss large angular scales. Often signals combined with single dishes





PEGASUS survey (ASKAP combined with the Murriyang Parkes)

Parts 1 and 2

The radio band holds potential to probe the ISM complexity, crucial to understand star formation and galaxy evolution: spectroscopy, continuum (+polarization) to access the *multi-phase* and *multi-tracer* aspects of ISM.

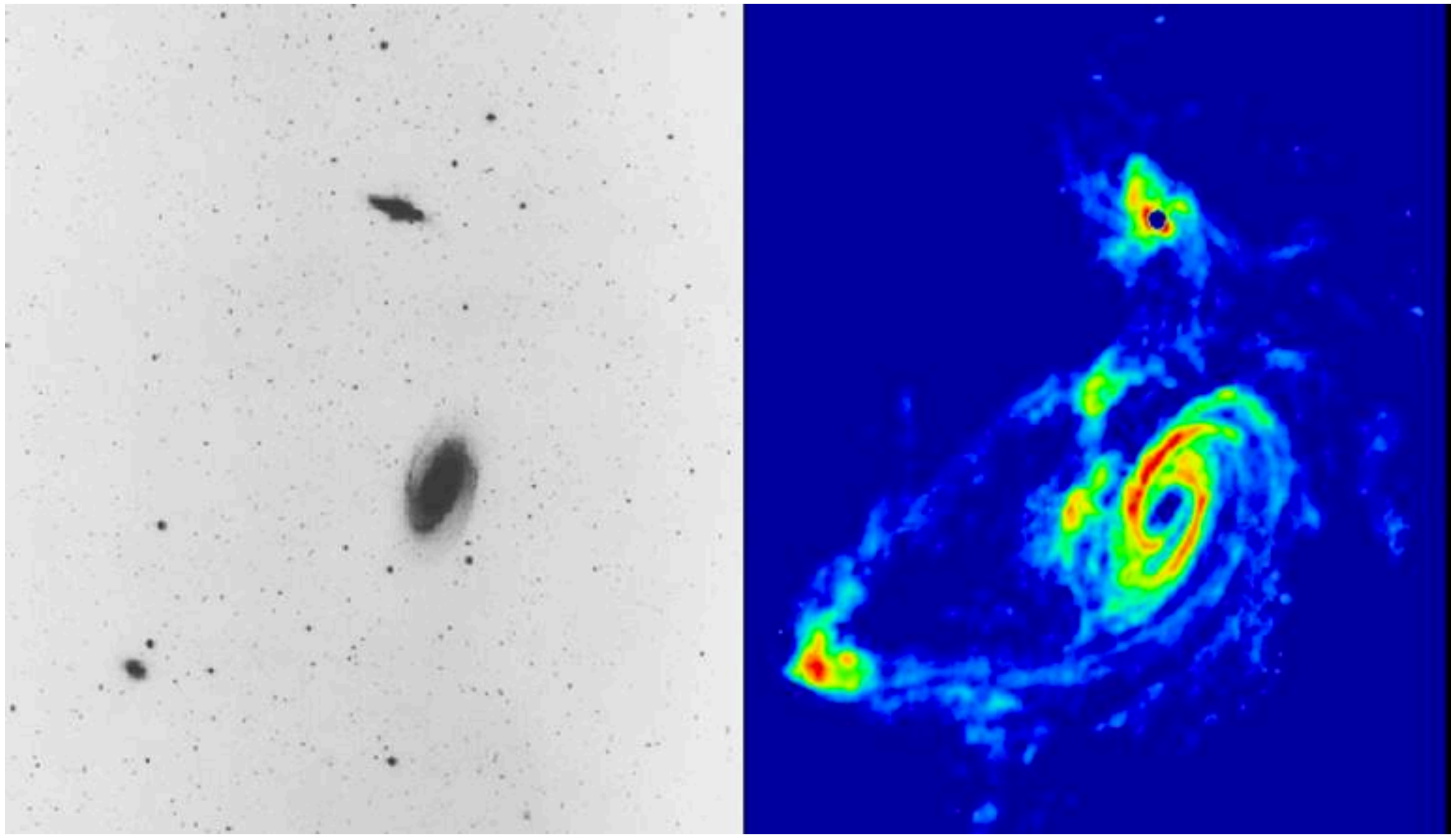
BUT radio observations are challenging: e.g. only interferometers can give access to high angular resolution, although they are tricky business. The *multi-scale* part results in the combination of single-dish and interferometric data

The HI in galaxies

The HI in galaxies

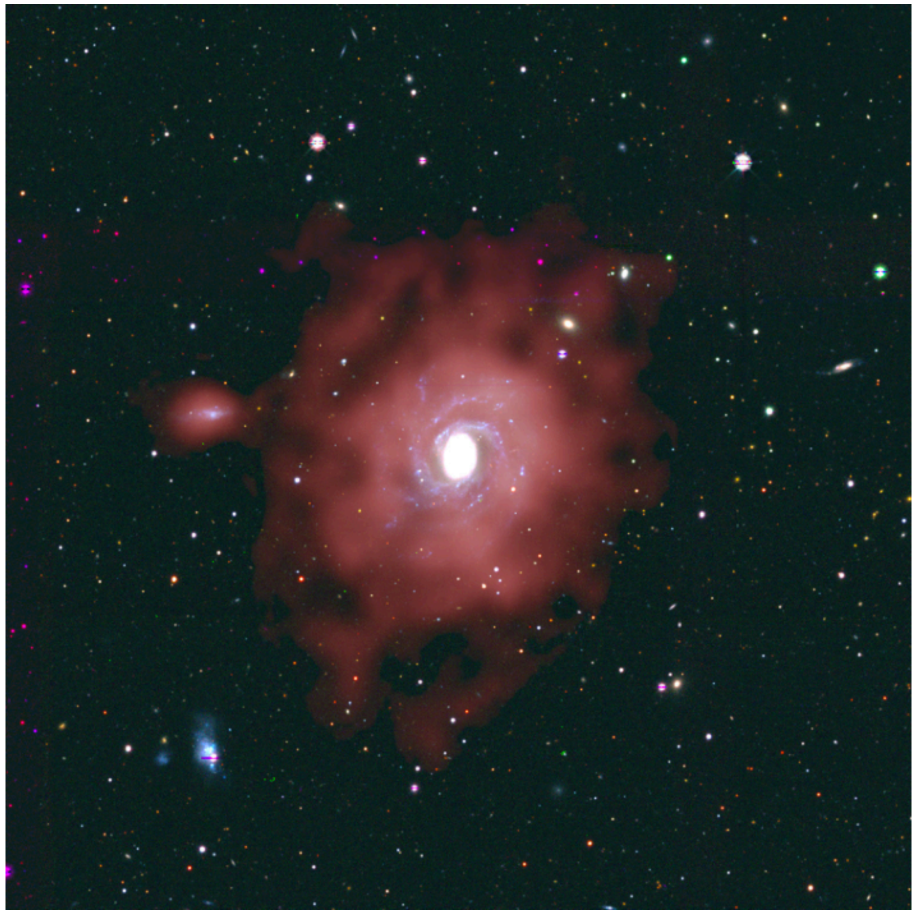
- Atomic hydrogen, being the simplest, is THE most abundant element in the Universe
- It accounts for 70% of the ISM mass, followed by He (28%) and heavier elements (2%). Through the *21cm line* it traces the interstellar reservoir of galactic systems

M81 group



(Yun et al. 1994, Palomar Sky Survey (visible) and VLA (HI at 21 cm))

NGC 4897



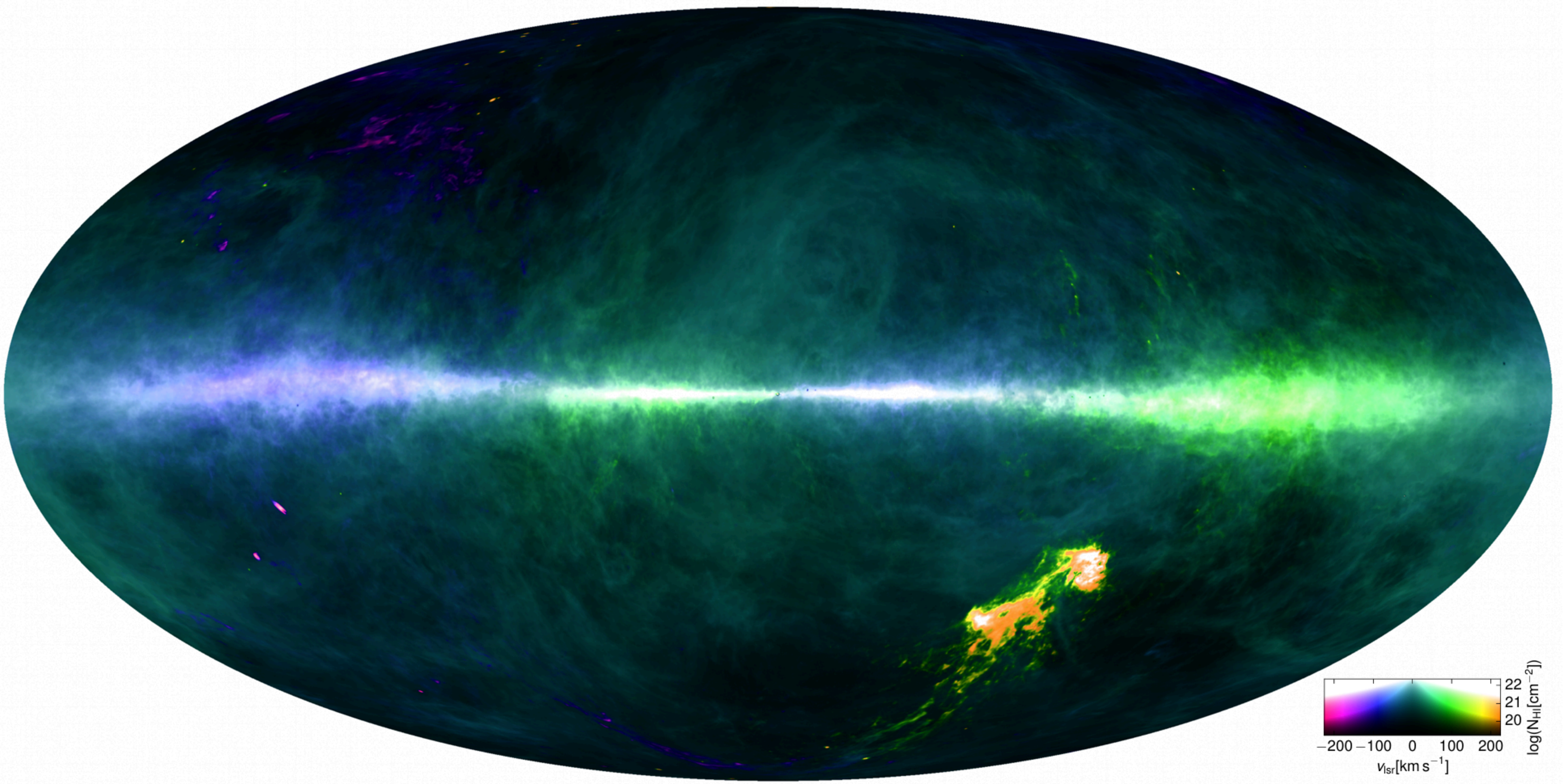
(Wallaby Survey with ASKAP, 2025)

HI extent from tens to hundreds of kpc!

(Lequeux 2005, Draine 2011)

The HI in galaxies

The Milky Way

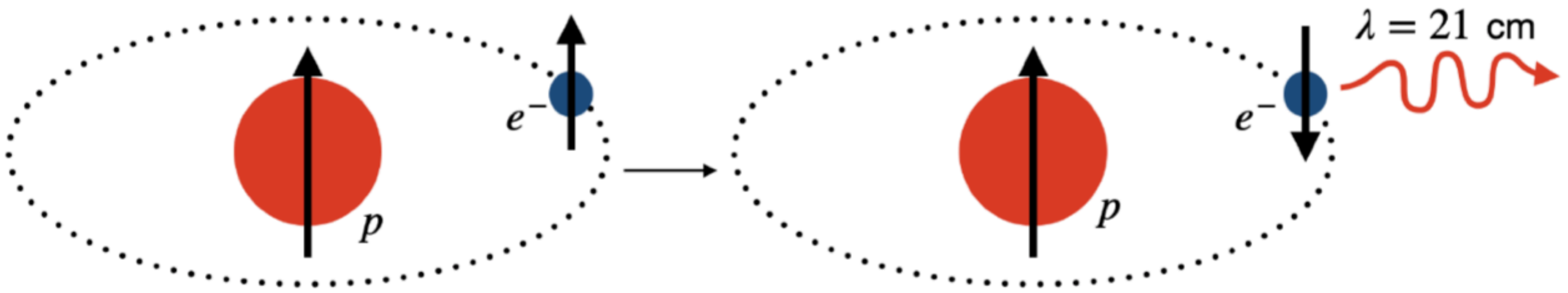


(HI4PI Collaboration 2016, Effelsberg + Murriyang Parkes telescopes)

No single line of sight without HI

The HI in galaxies

- Spectral line from "spin-flip", low energy hyperfine splitting (freq.~1420 MHz) of the HI ground state caused by spin coupling between proton and electron:



$$\frac{n_u}{n_l} = 3e^{-\frac{h\nu_0}{kT_s}}$$

Ts is the spin temperature

- Excitation mechanisms is environment dependent: collisions (e.g., CNM), radio background (cosmic microwave background), Lyman-alpha pumping

- Forbidden transition: $A_{ul} = 2.85\,10^{-15}\,\mathrm{s}^{-1}$ ⟶ $t_{\mathrm{dex}} = 1/A_{ul} \approx 10^7\,\mathrm{yr}$

BUT measurable
(there is a lot of HI out there) !

(Draine 2011)

The HI in galaxies

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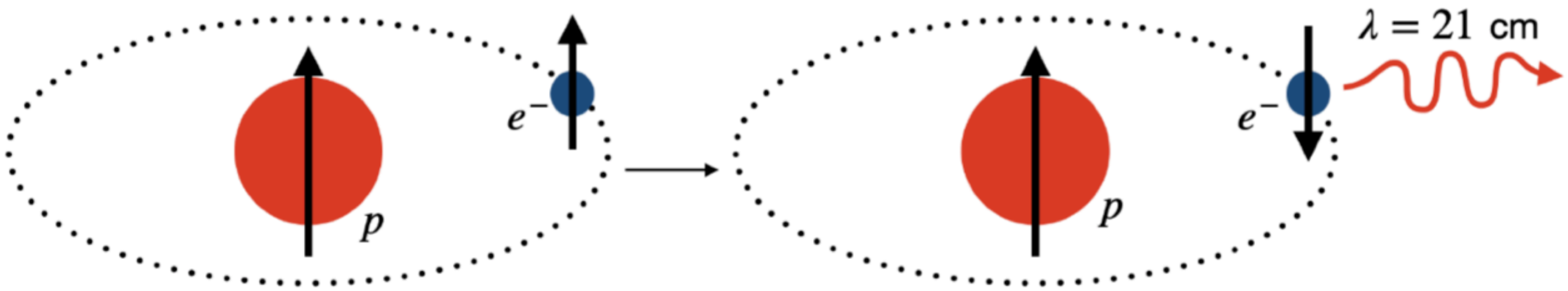

Higher energy state | Lower energy state

$$\frac{n_u}{n_l} = 3e^{-\frac{h\nu_0}{kT_s}}$$

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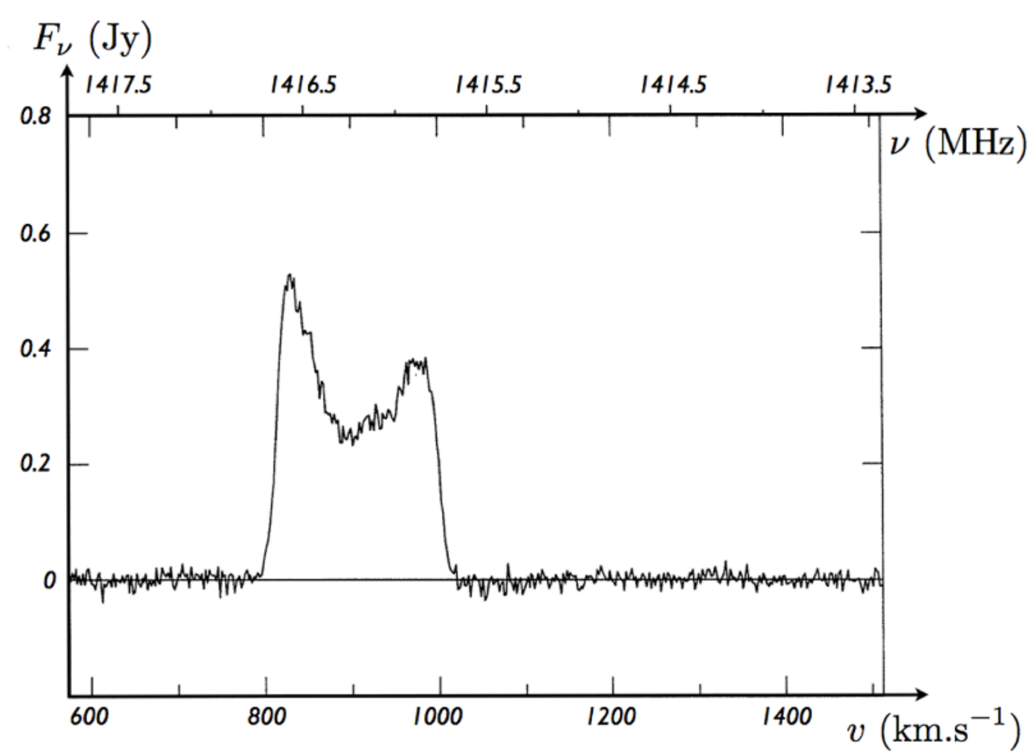
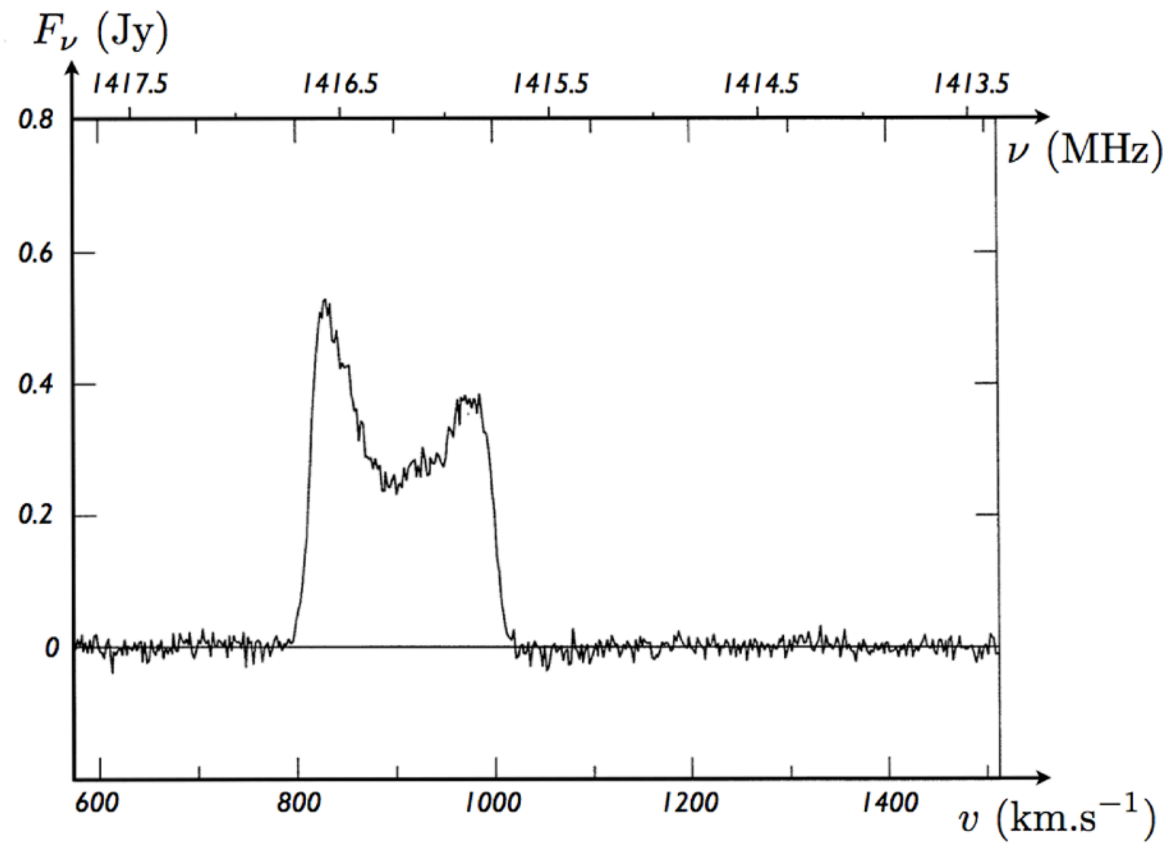


(Green Bank telescope, UGC11707 galaxy, lectures of F. Levrier at LPENS)

- From Doppler shift: kinematics (global and local, e.g., rotation)
- From the integral of the line the amount of HI, or NH
- Challenge to probe small-scale processes in galaxies (blending of the lines within resolution elements)

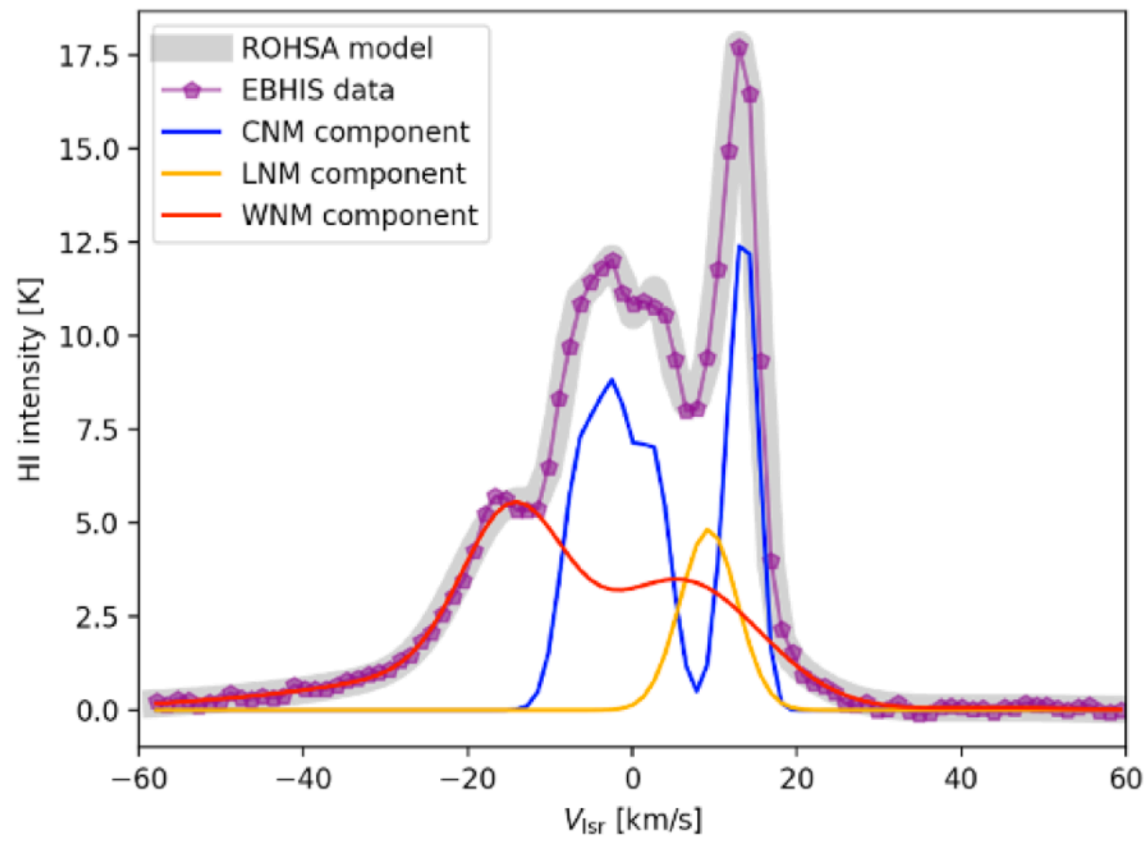
(Draine 2011)

The HI in galaxies



(UGC11707 galaxy)

Milky Way

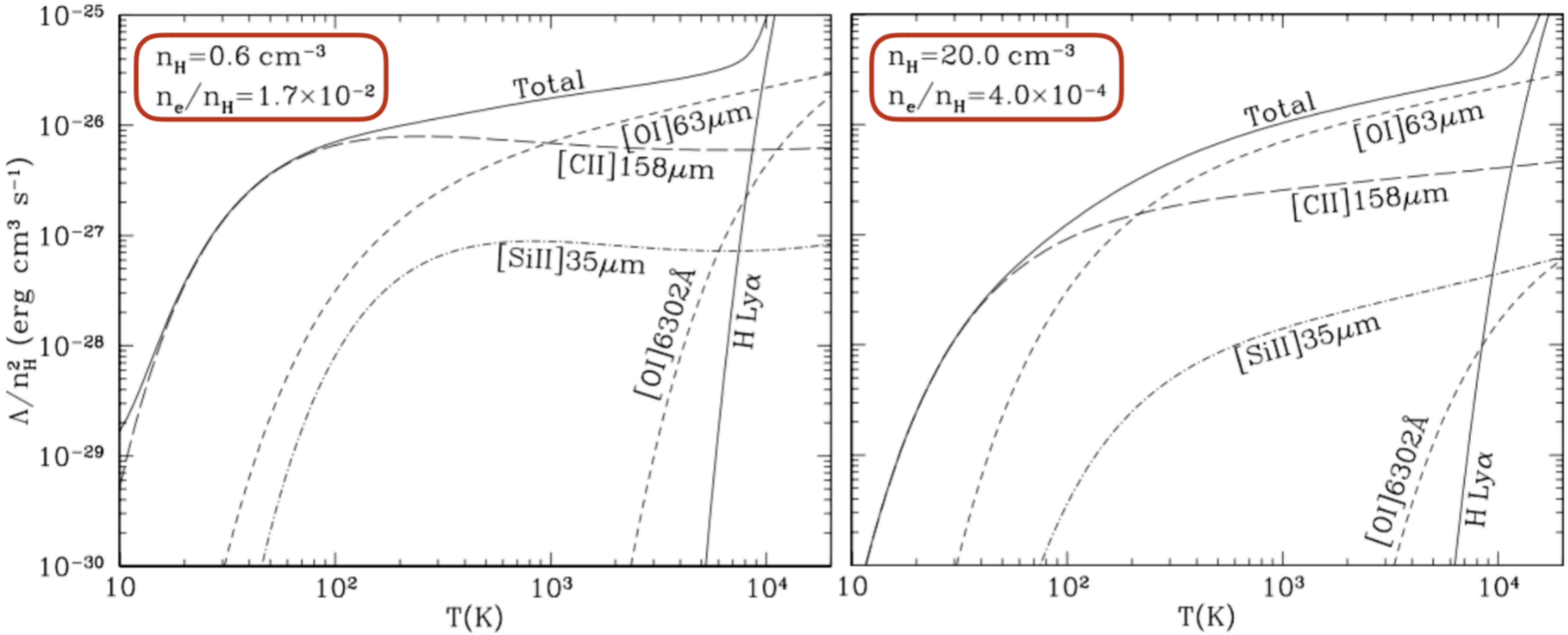


(Bracco et al. 2020)

- Accessing more details in the Milky Way
- Distinct line broadening, from a few to tens of km/s -> *multiphase*

The HI in galaxies

HI traces thermal instability in the ISM (metallicity dependent)

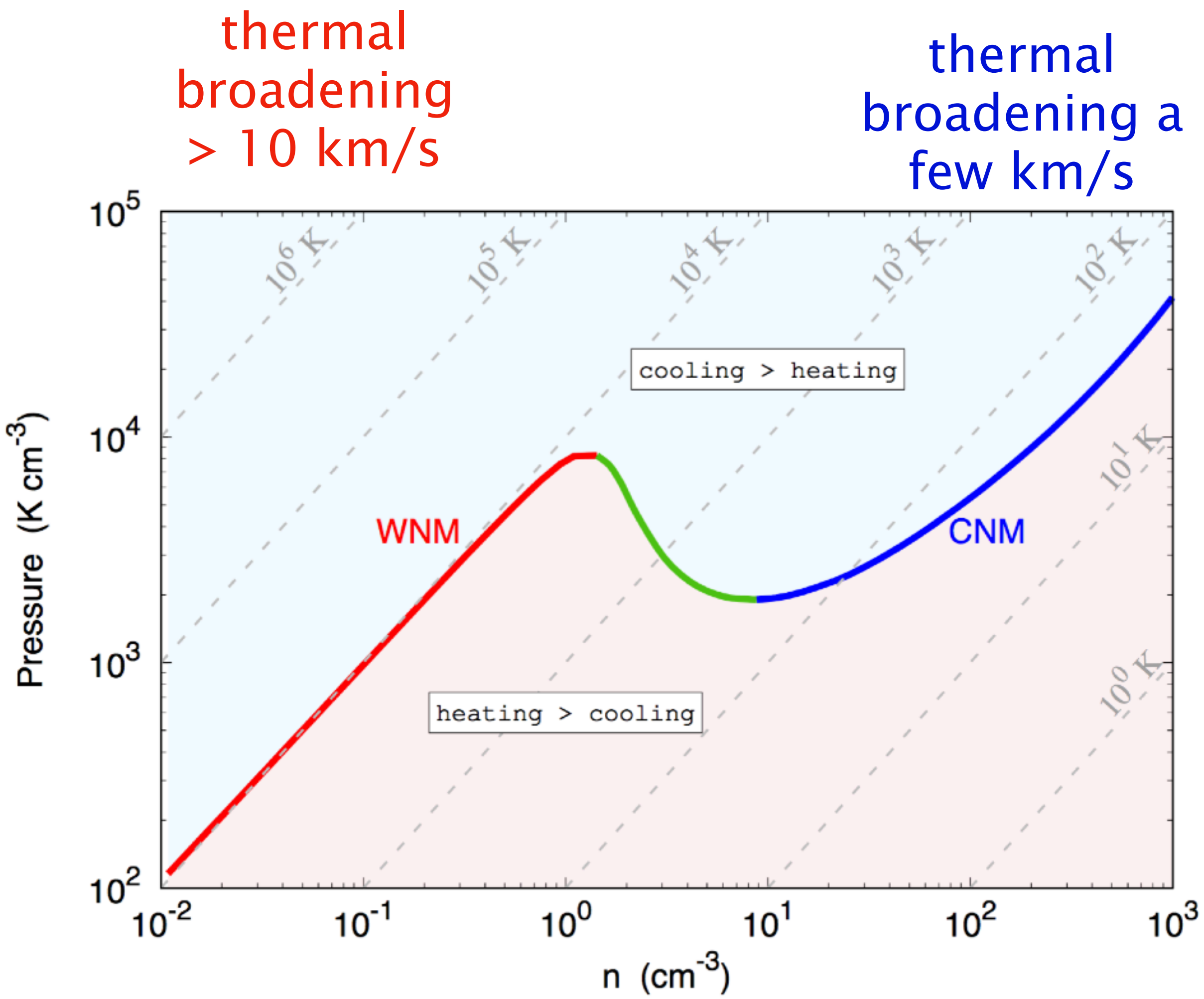


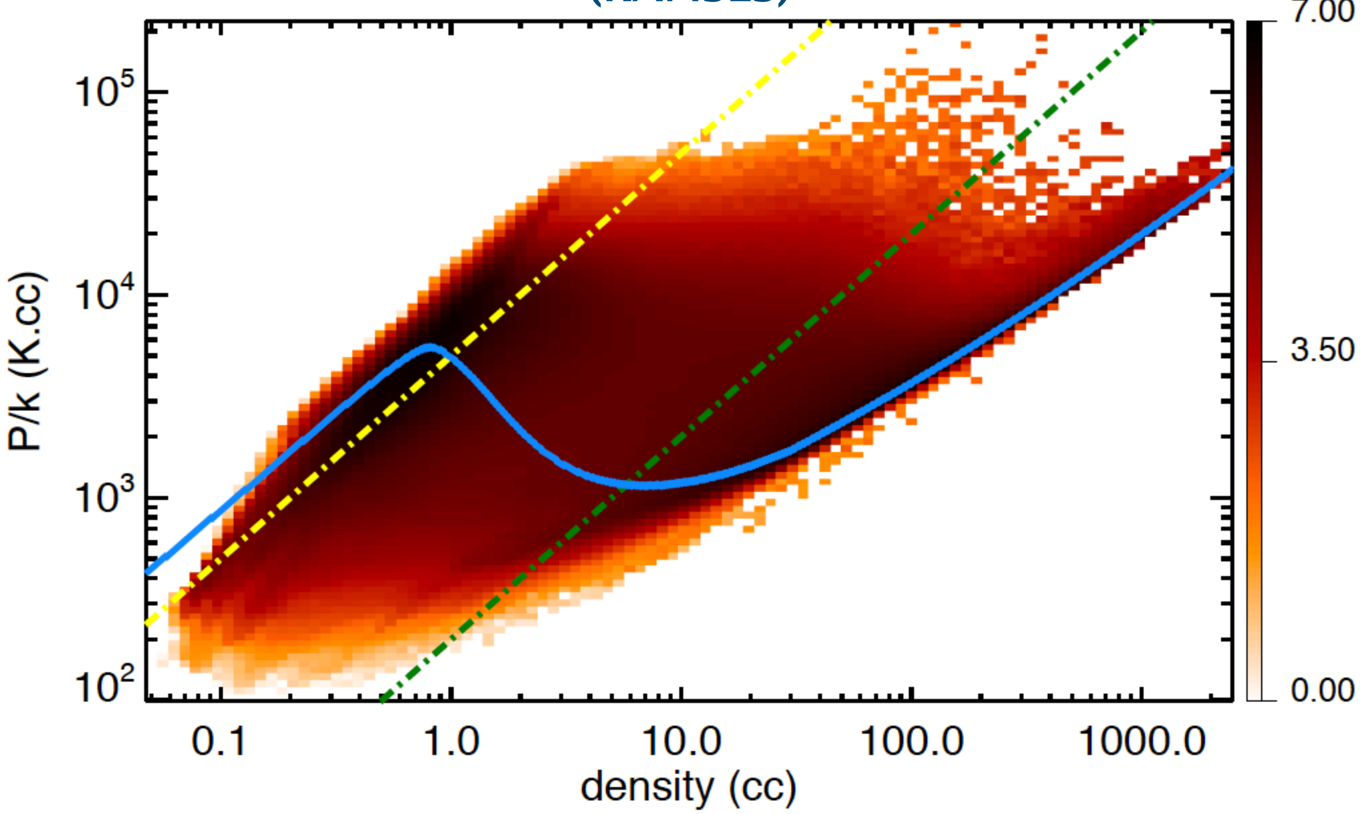
- **<u>Heating</u>:** photoelectric effect on dust grains, cosmic rays, UV and X rays
- **<u>Cooling</u>:** CII and OI line in the colder phase & Lyman-alpha in the warmer phase

Bimodality of thermal pressure states at equilibrium (Wolfire et al. 1995)

(Draine 2011, Tielens 2005)

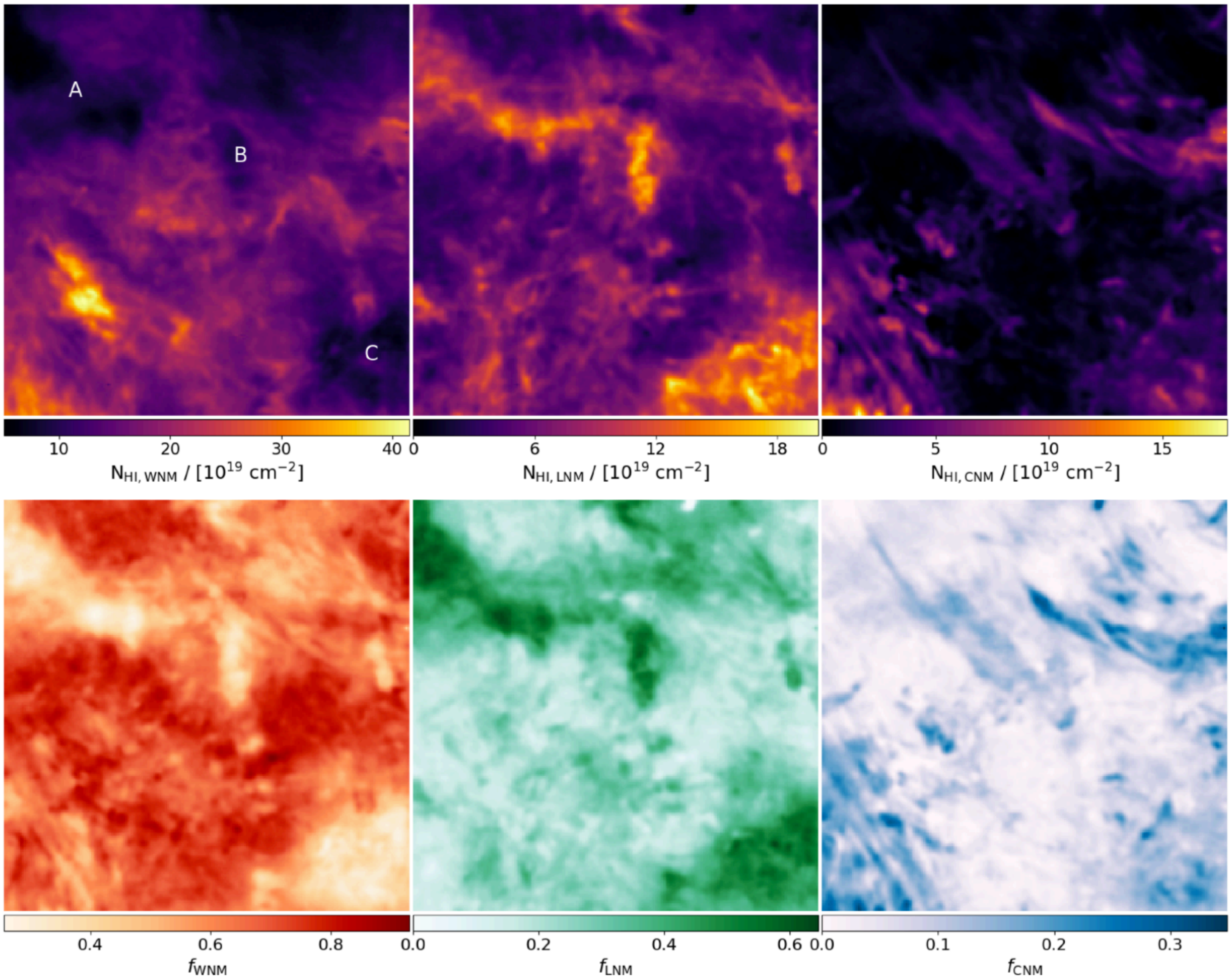
Phase diagram for diffuse ISM





(Godard et al. 2024, Saury et al. 2014)

The HI in galaxies

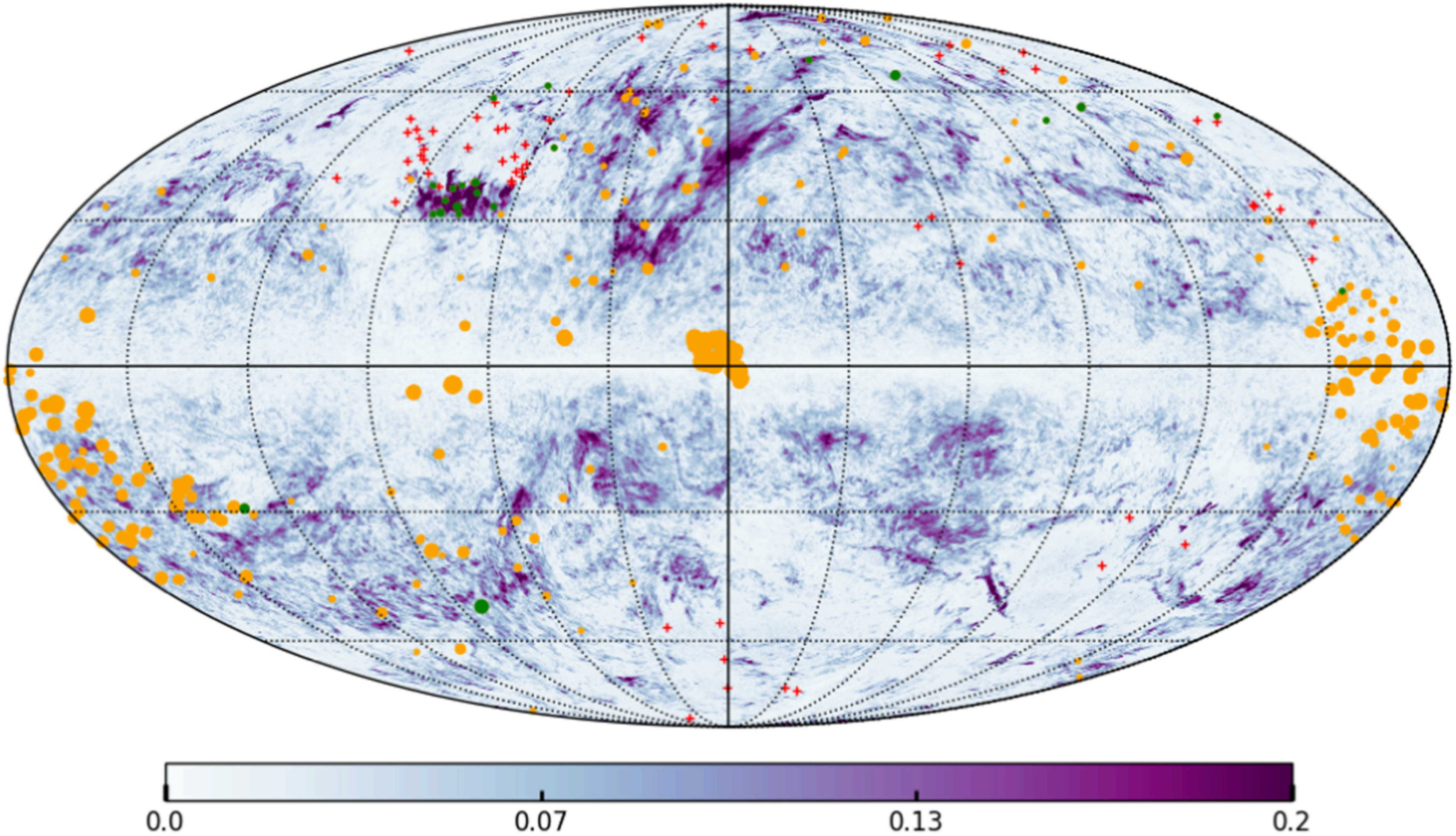


***Multiphase*, thermal and turbulent properties of cold and warm media using HI data**

(Marchal & Miville-Deschênes 2020)

The HI in galaxies

All-sky CNM fraction of the Milky Way



Multiscale, thermal and turbulent properties of cold and warm media using HI data

(Marchal et al. 2024)

The magnetized content of galaxies

The magnetized content of galaxies

- Since its discovery in 1947 in labs, astronomical synchrotron radiation came right after in the 50s.
- The discovery of starlight polarization in 1949—interpreted in terms of interstellar magnetism—paved the way for interstellar synchrotron radiation, cosmic-ray acceleration, and making sense of the radio emission from the 30s.

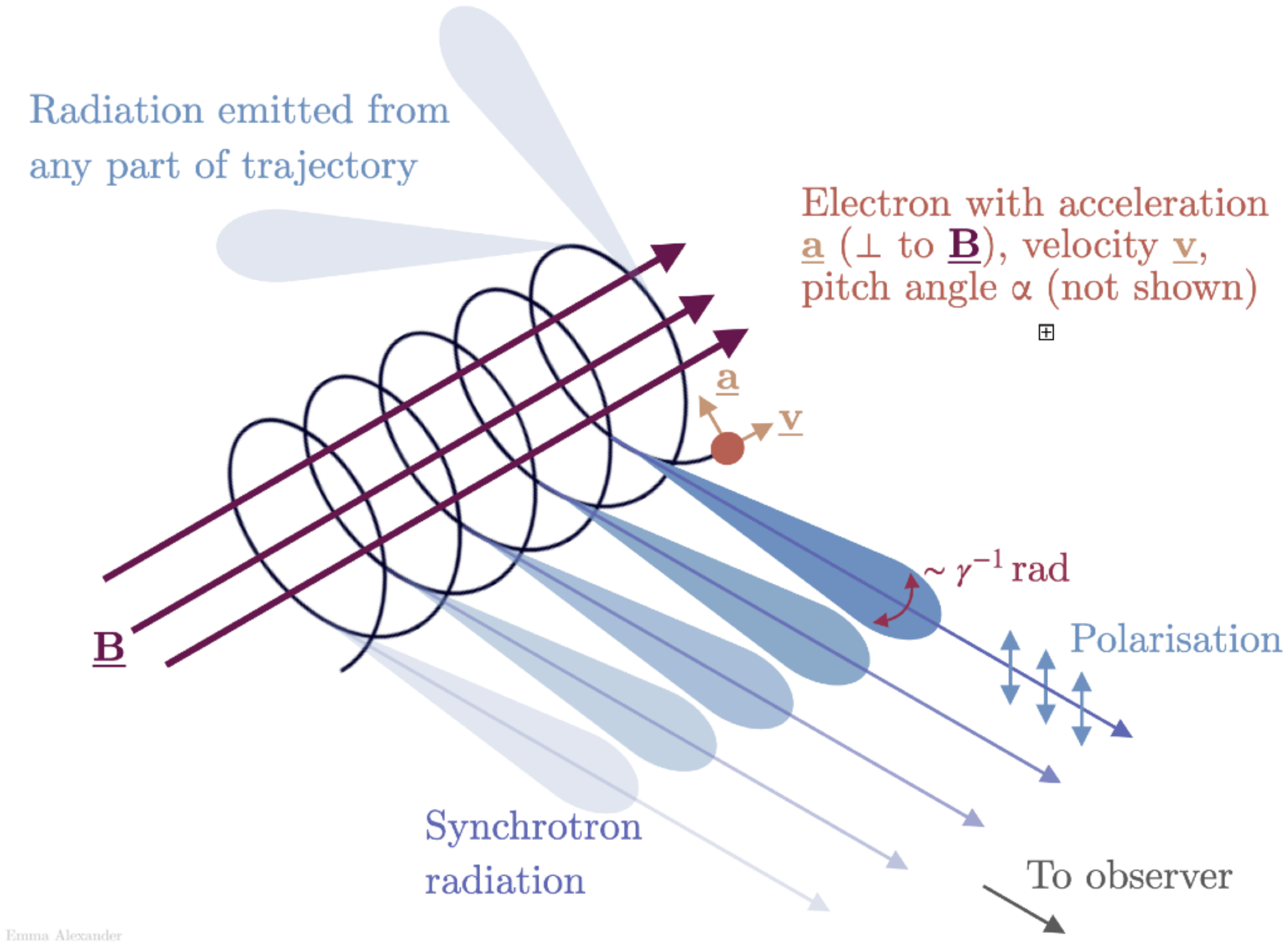
On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

I propose in the present note to discuss a hypothesis on the origin of cosmic rays which attempts to meet in part this objection, and according to which cosmic rays originate and are accelerated primarily in the interstellar space, although they are assumed to be prevented by magnetic fields from leaving the boundaries of the galaxy. The main process of acceleration is due to the interaction of cosmic particles with wandering magnetic fields which, according to Alfvén, occupy the interstellar spaces.

(Wielebinski, “Synchrotron radiation, a basis for modern Astrophysics”)

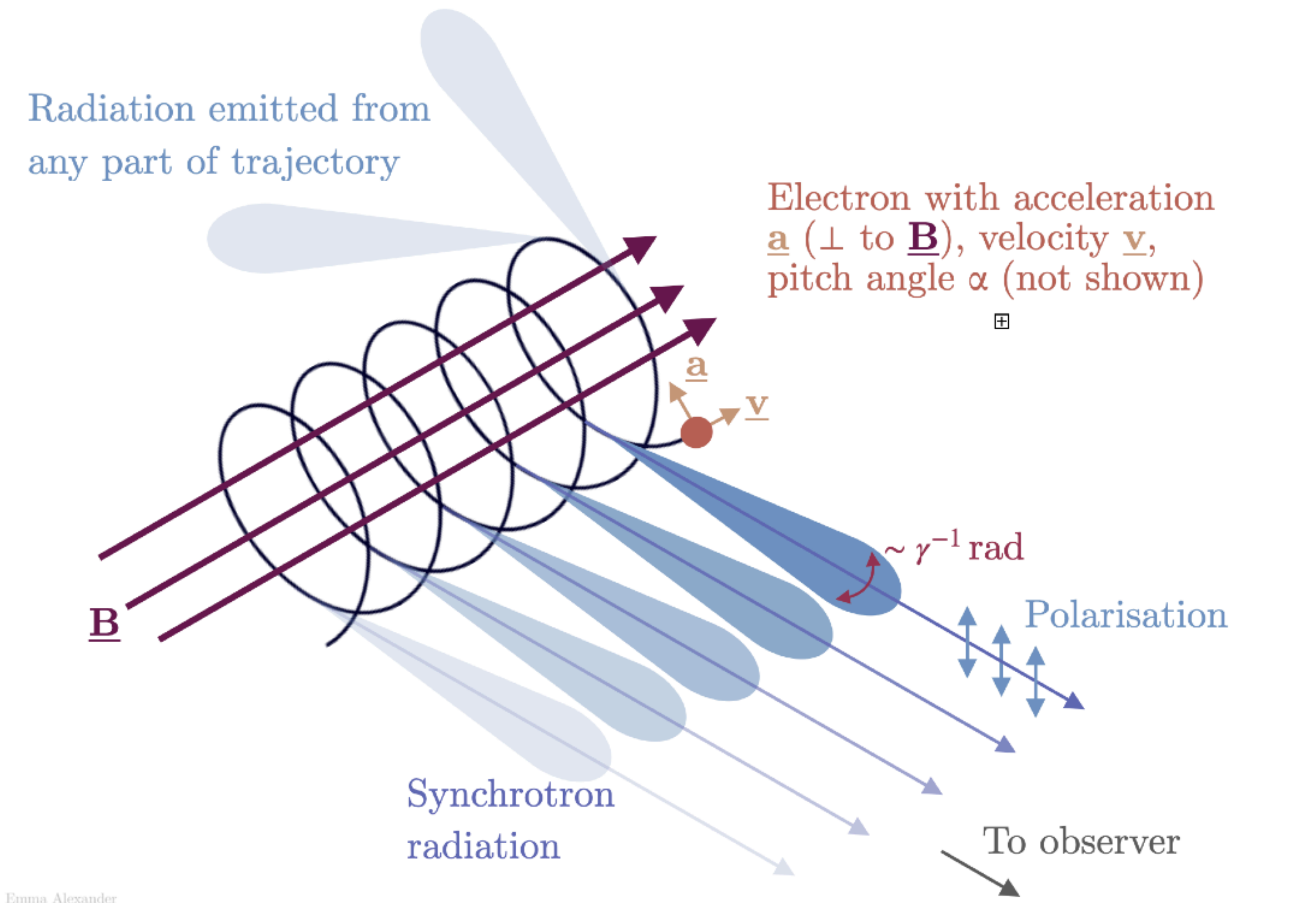
The magnetized content of galaxies



- **Non-thermal radiation generated when relativistic charged particles (CRe) are subject to an acceleration perpendicular to their velocity caused by the ambient magnetic field.**

(Longair 2011)

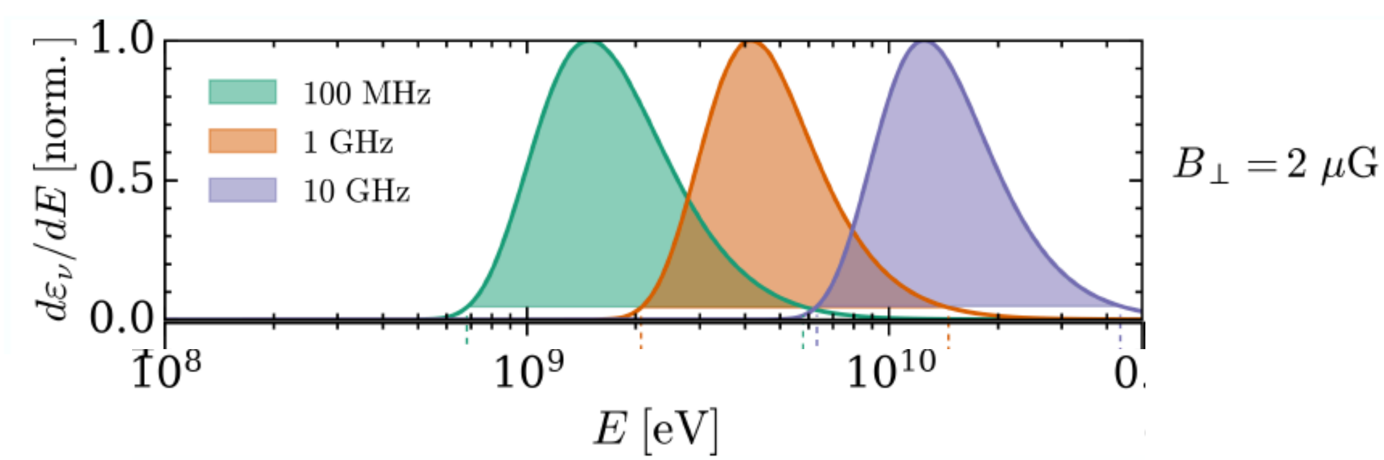
The magnetized content of galaxies



- Non-thermal radiation generated when relativistic charged particles (CRe) are subject to an acceleration perpendicular to their velocity caused by the ambient magnetic field.
- This is a *broad-band continuum emission* as the synchrotron emissivity [erg/s/cm3/Hz/sr] is a function of the energy distribution of CRe and the magnetic-field strength

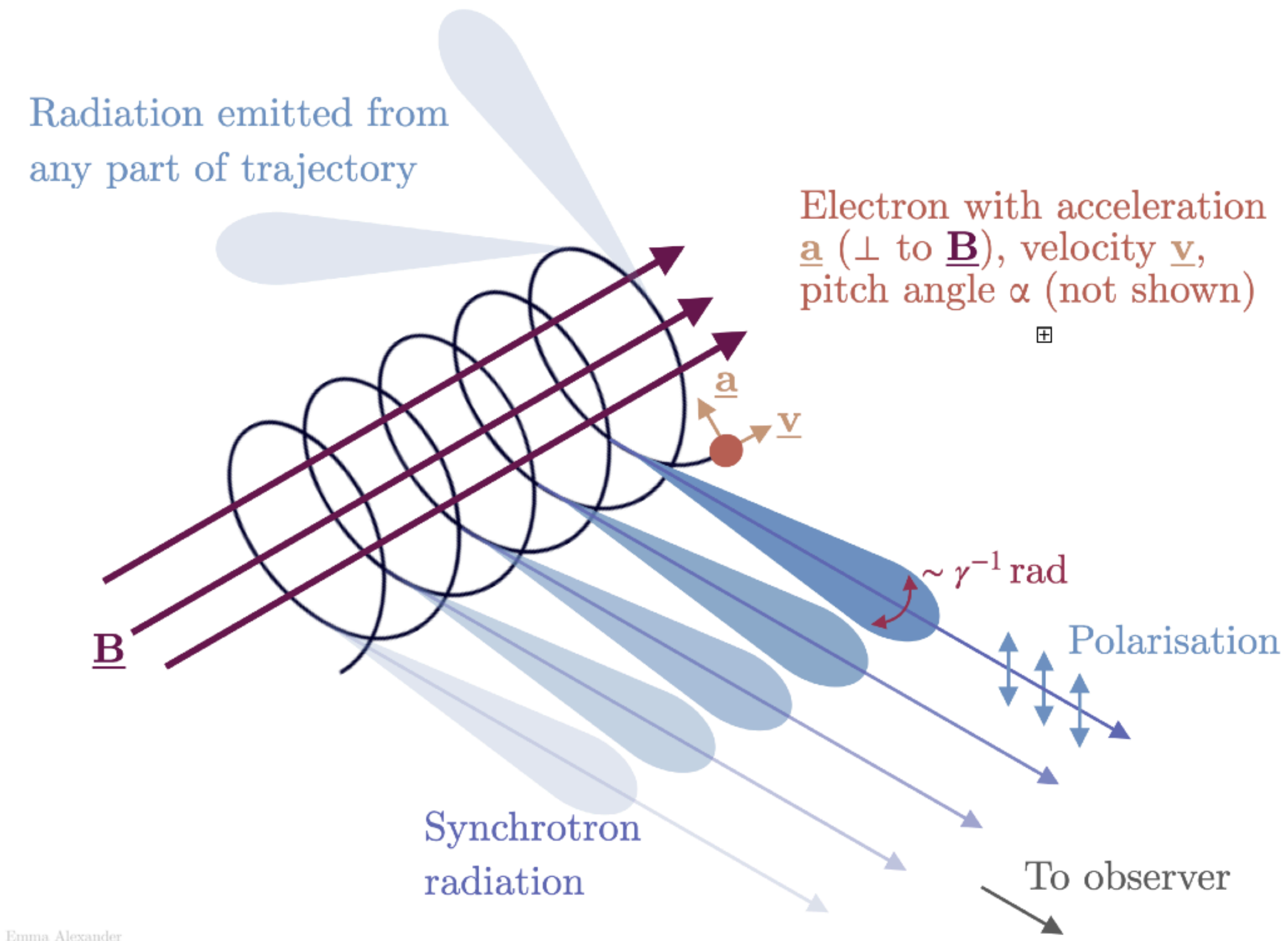
$$\epsilon_\nu \approx \int j_e(E) F(\nu, E, \vec{r}, B_\perp) \mathrm{d}E$$

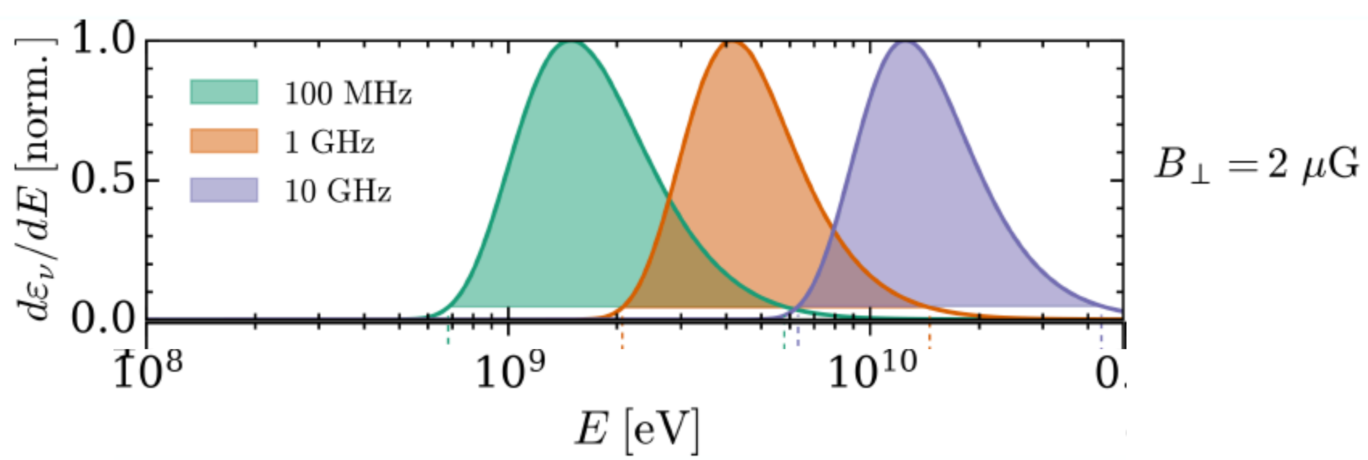
- Strong linear polarization (~70%)



(Longair 2011, Padovani et al. 2021)

The magnetized content of galaxies





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- Strong linear polarization (~70%)

- We measure Stokes parameters I, Q, U

$$I_\nu \propto \int \epsilon_\nu(\vec{r}) d\vec{r}$$

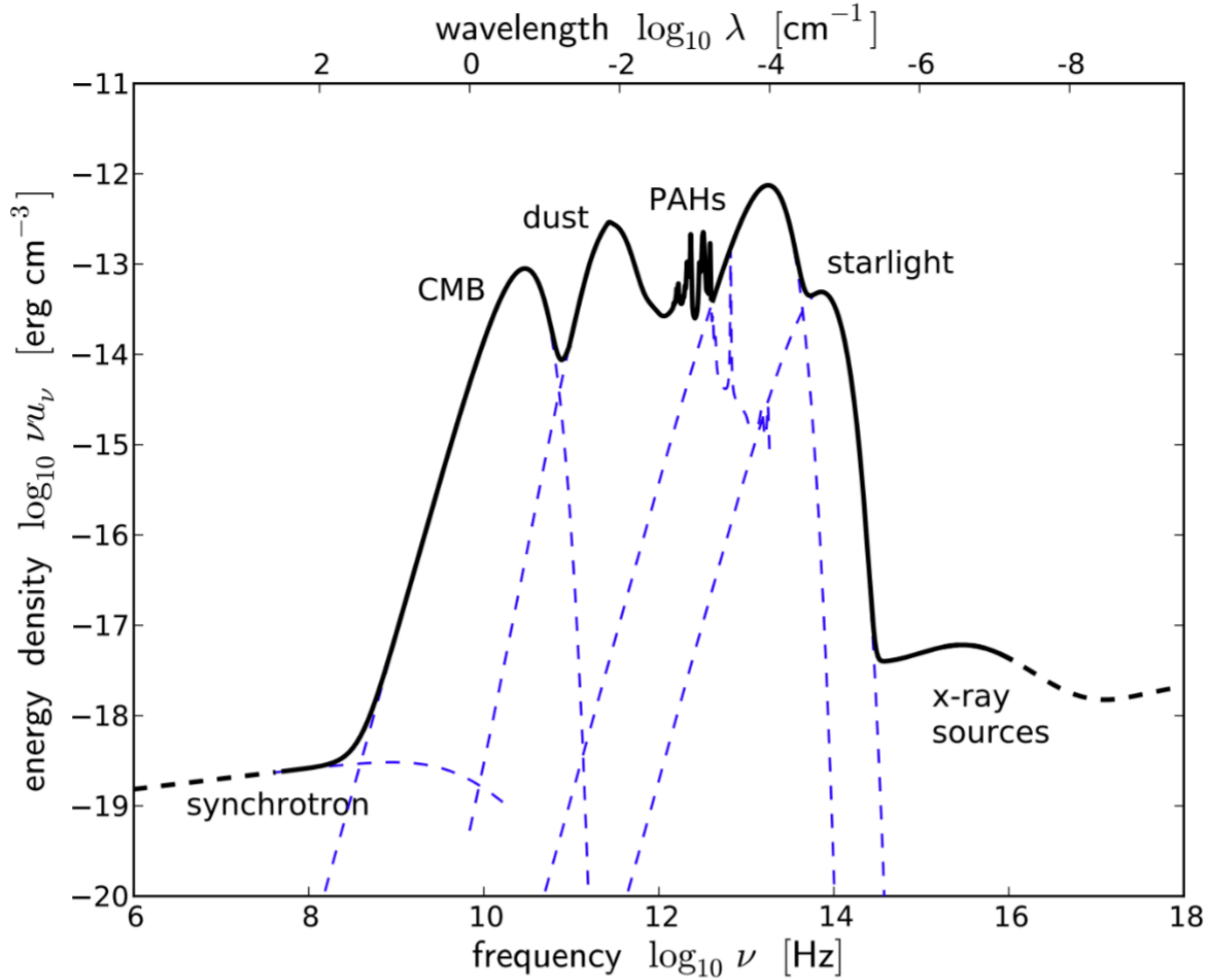
- From total intensity -> CRe properties
- From polarization -> magnetic field properties

$$P = Q + iU \quad \psi = 0.5 \tan^{-1}(U/Q)$$

(Longair 2011, Padovani et al. 2021)

The magnetized content of galaxies

Interstellar radiation field

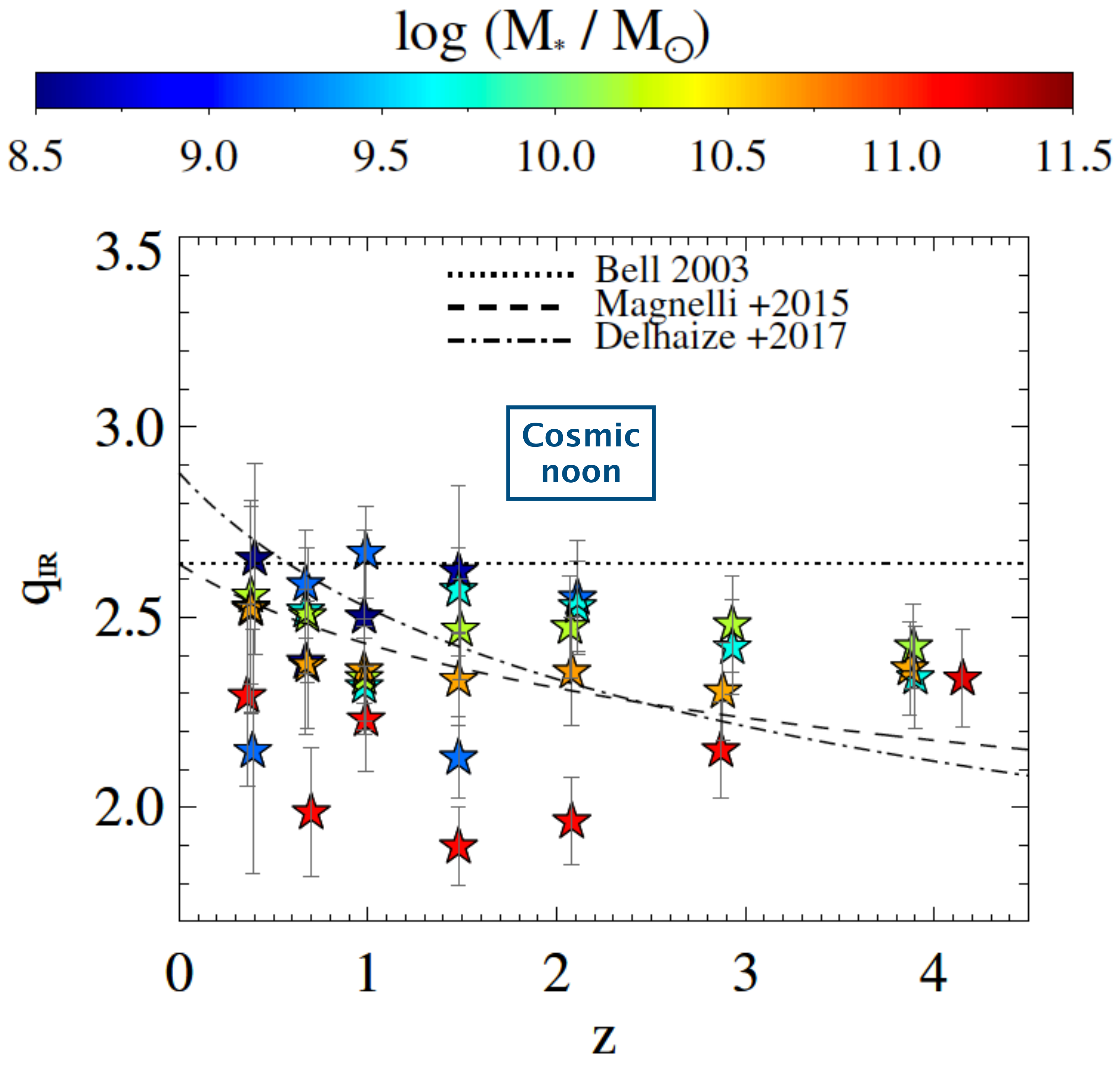


(Klessen & Glover 2016)

The magnetized content of galaxies

Infrared-radio correlation as a tracer of the star-formation rate of galaxies

Ratio between IR and Radio luminosities

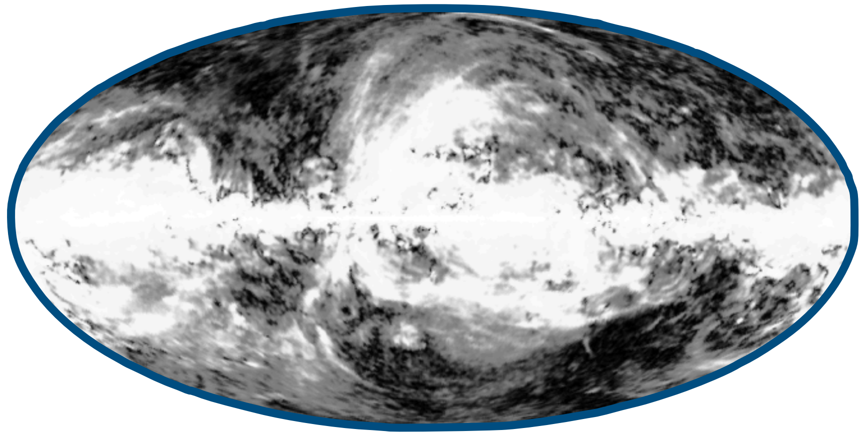


(Delvecchio et al. 2021)

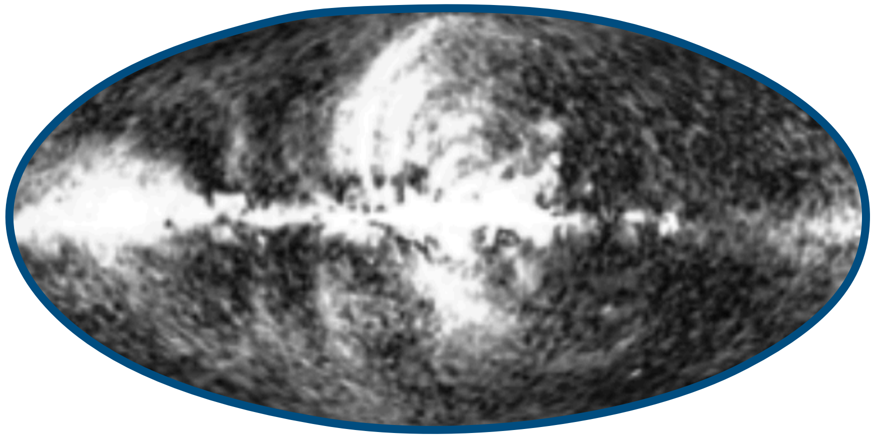
The magnetized content of galaxies

- Polarization has never been observed at 70% of total intensity.
- There are v*arious mechanisms of depolarization* (vectors do not sum up as positive scalars)
- I will focus on *Faraday rotation,* which is key for the *magnetized* and *multiphase* ISM

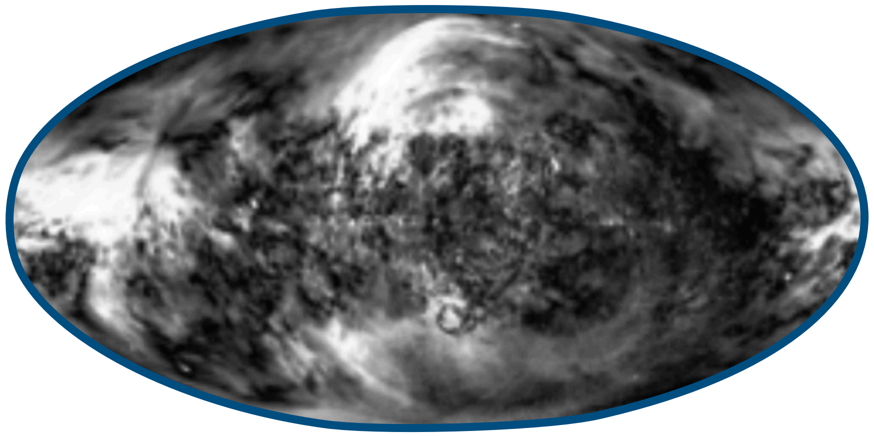
353 GHz (Planck)



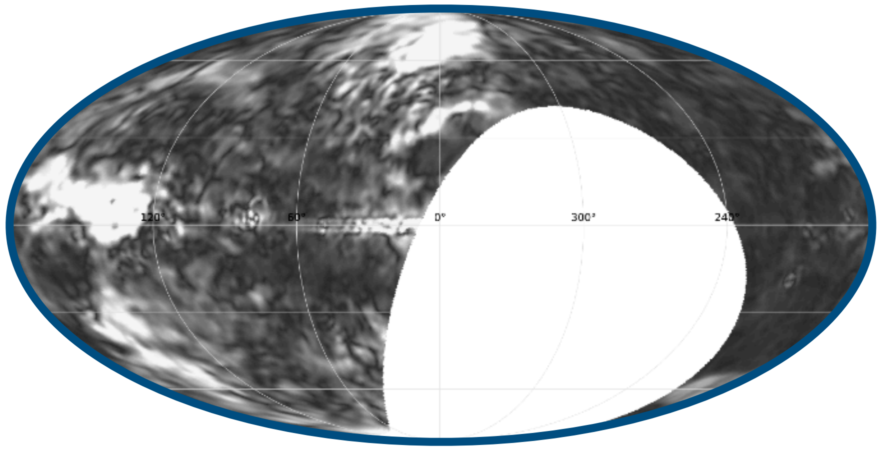
23 GHz (WMAP)



1.4 GHz (DRAO+Villa Elisa)



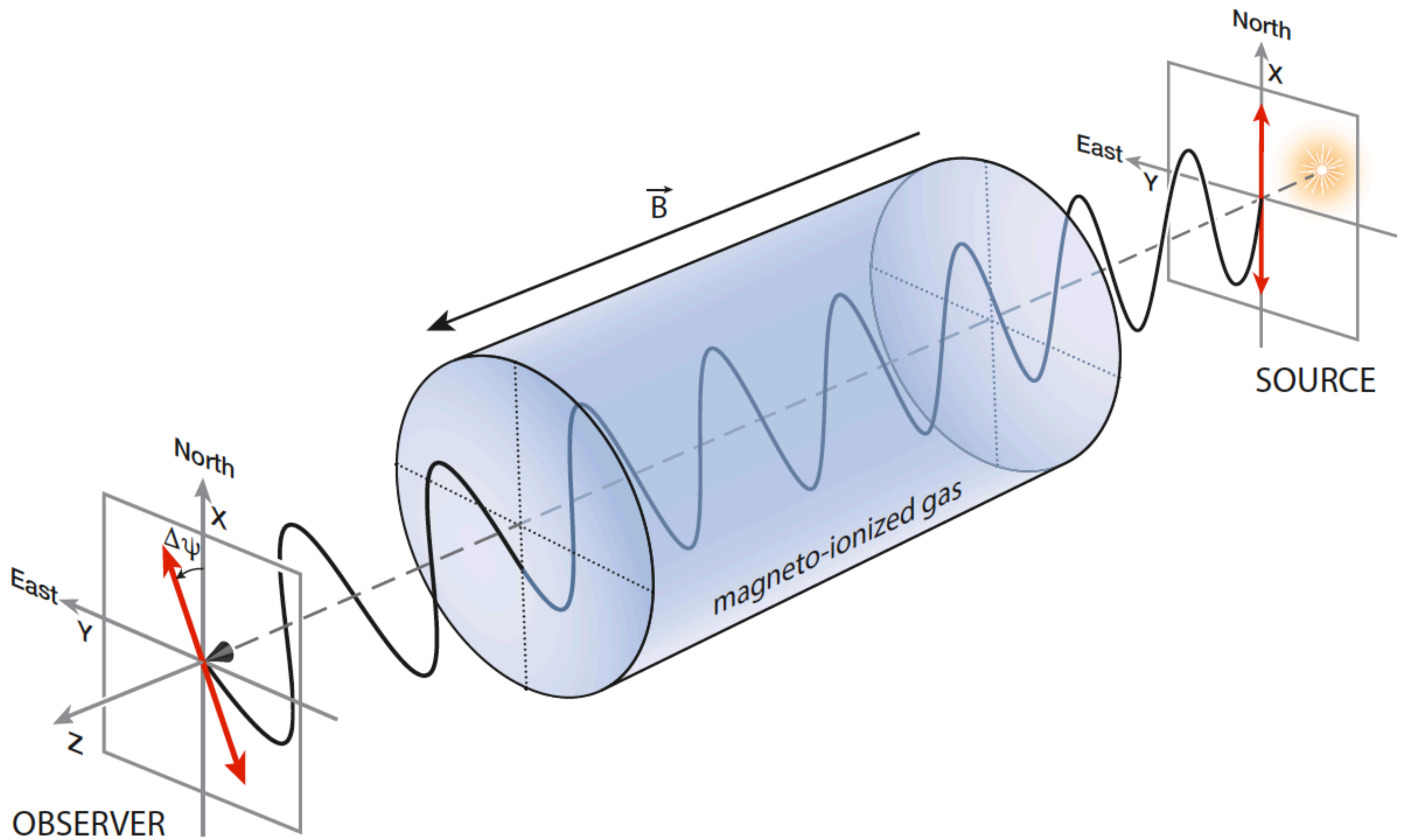
0.610 GHz (DRAO)



Low P | Large P

(Planck 2018 results. XII. 2020, Hinshaw et al. 2008, Wolleben et al. 2006, Testori et al. 2008, Ordog et al. in prep.)

The magnetized content of galaxies



Observed quantities

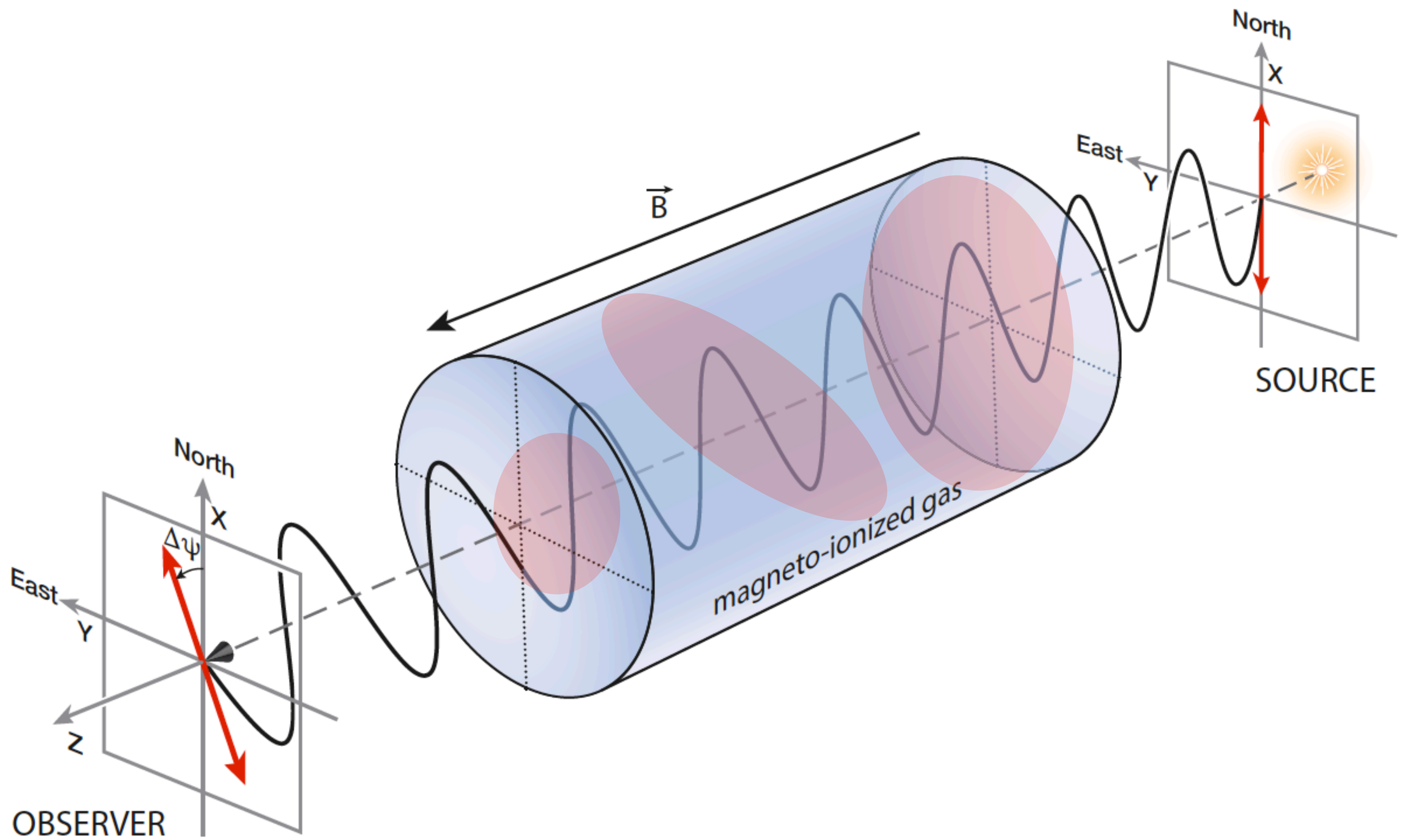
$$P(\lambda^2) = Q(\lambda^2) + \mathrm{i}U(\lambda^2)$$
$$\psi_{\mathrm{pol}} = 0.5\tan^{-1}(U/Q)$$

Derived quantities

$$\hat{P}_{\mathrm{eff}} = P_0 e^{2i(\psi_{\mathrm{pol}} + \mathrm{RM}\lambda^2)}$$
$$\Delta\psi_{\mathrm{pol}} = RM\lambda^2 \propto \lambda^2 \int n_e \vec{B} \cdot \mathrm{d}\vec{l}$$

(Ferrière et al. 2021)

The magnetized content of galaxies



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In practice, *beam averaging* and *line-of-sight complexity* depolarize signals

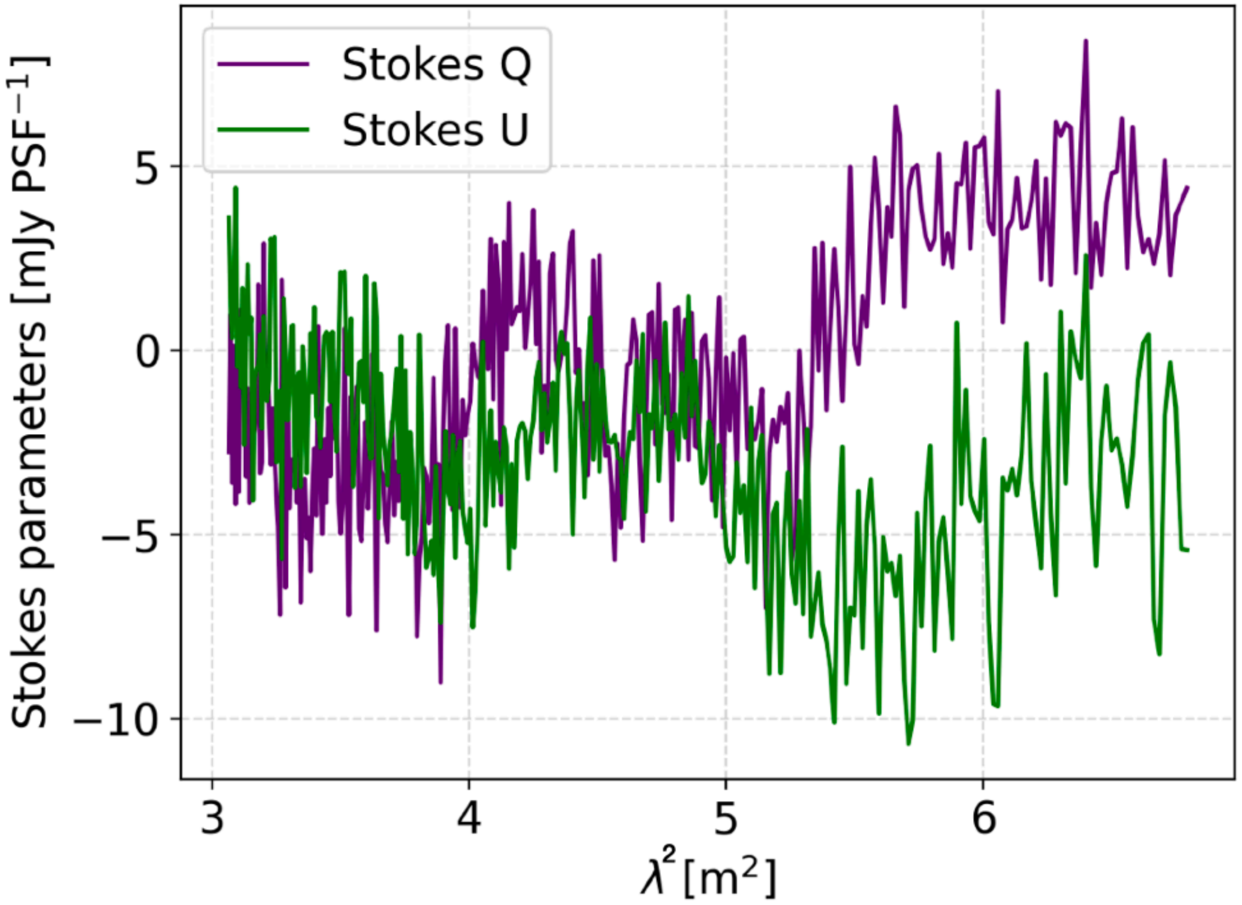
(Ferrière et al. 2021, Sokoloff et al. 1998)

The magnetized content of galaxies

- **Faraday tomography captures this complexity and allows us to study the *multiscale, multiphase, magnetized* ISM**

MEASURED

$$P(\lambda^2) = \int_{-\inf}^{\inf} F(\phi) e^{2i\phi\lambda^2} \mathrm{d}\phi$$



*one single line of sight

(Burn 1966, Brentjens & de Bruyn 2005, Jelić et al. 2015, Bracco et al. 2020)

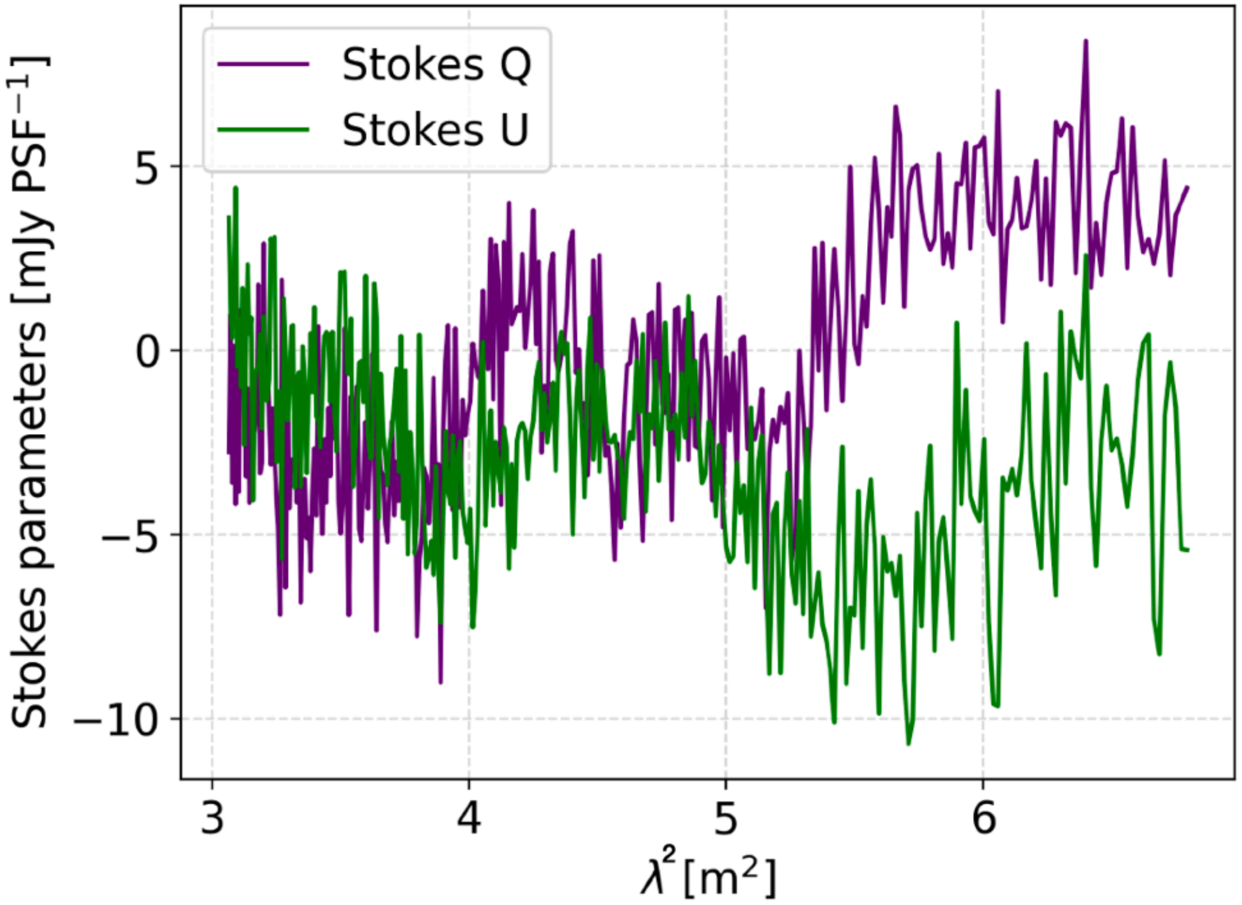
The magnetized content of galaxies

- **Faraday tomography captures this complexity and allows us to study the *multiscale, multiphase, magnetized* ISM**

- **Gain in signal-to-noise and direct information on physical quantities (e.g., magnetic field direction)**

MEASURED
$$P(\lambda^2) = \int_{-\inf}^{\inf} F(\phi) e^{2i\phi\lambda^2} \mathrm{d}\phi$$

DERIVED
$$F(\phi) \propto \int_{-\inf}^{\inf} P(\lambda^2) e^{-2i\phi\lambda^2} \mathrm{d}\lambda^2$$



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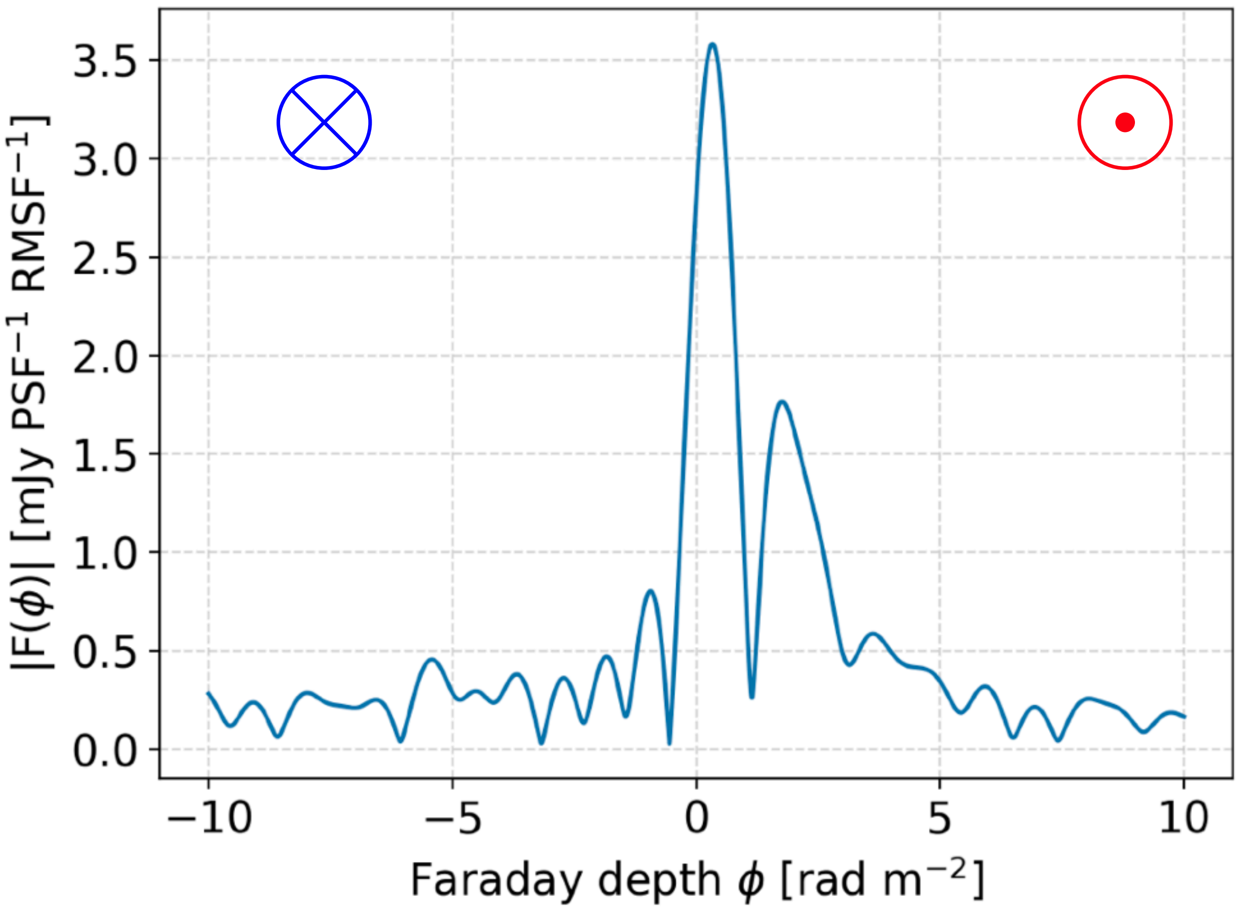

(Burn 1966, Brentjens & de Bruyn 2005, Jelić et al. 2015, Bracco et al. 2020)

The magnetized content of galaxies

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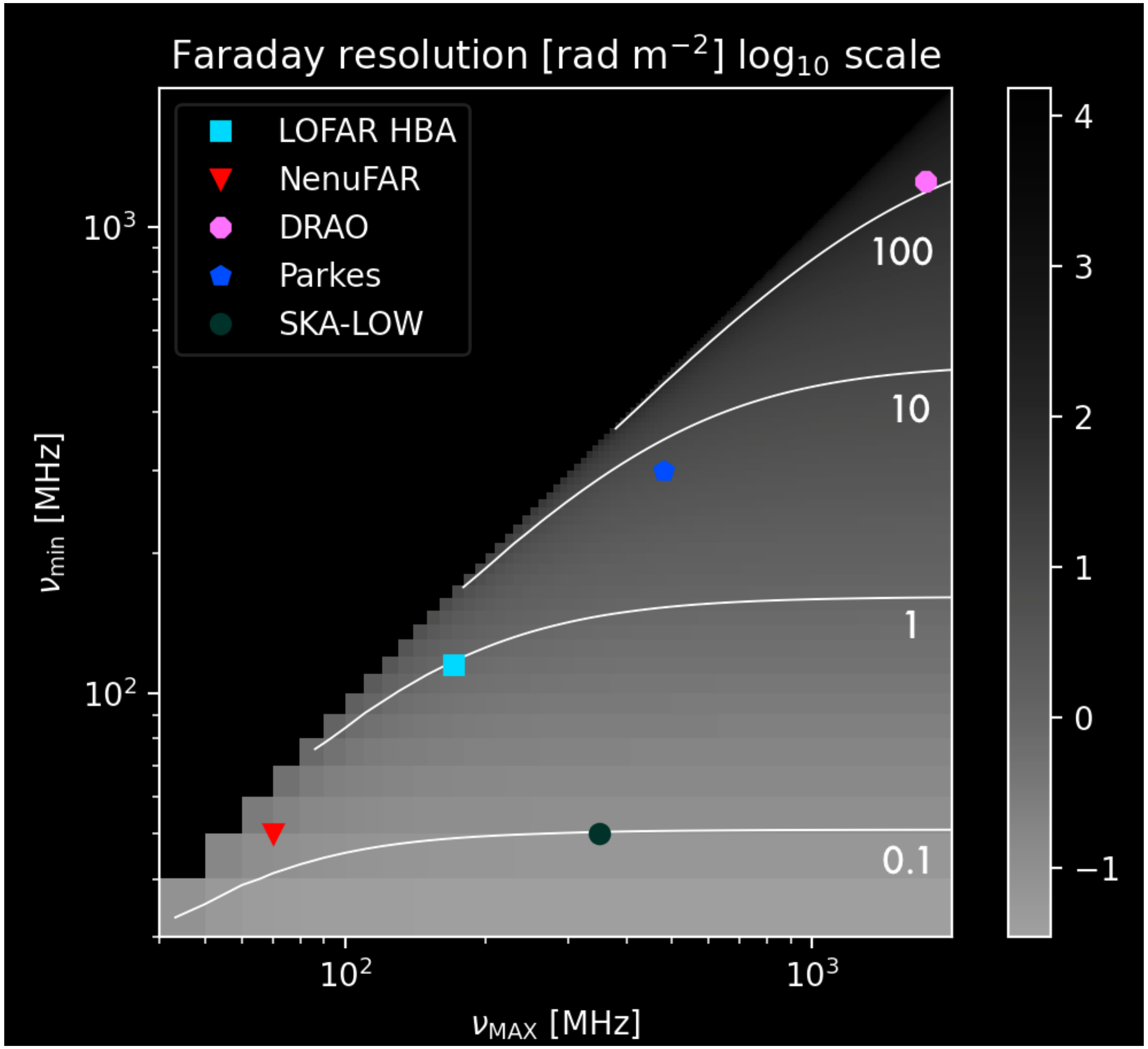
Moon size

- **The LOFAR case between 100 and 200 MHz (LOFAR Two meter Sky Survey, LoTSS)**

(Erceg et al. 2022)

The magnetized content of galaxies

- **Faraday tomography captures this complexity and allows us to study the *multiscale, multiphase, magnetized* ISM**



	CNM	WNM	WIM	HIM
T [K]	80	5 000	8 000	10^6
n_H [cm^{-3}]	30	0.4	0.2	0.005
n_e [cm^{-3}]	0.02	0.01	0.2	0.006
C_s [km s^{-1}]	0.7	6	10	120
V_A [km s^{-1}]	1.7	15	20	130
ω_e [kHz]	8	5.5	25	4
$\|\Omega_e\|$ [Hz]	90	90	90	90
r_e [km]	0.6	5	6	60
τ_e	9 min	5 d	12 hr	45 yr
λ_e	5 $R_\oplus$	1.3 AU	0.17 AU	0.3 pc
L [pc]	10	30	30	100
V [km s^{-1}]	3	10	10	30
Re	4×10^{10}	10^7	5×10^7	10^2
Re$_m$	7×10^{14}	3×10^{18}	5×10^{18}	5×10^{22}
P$_m$	2×10^4	3×10^{11}	10^{11}	5×10^{20}
RM **(B|| ~ 5 uG) rad m-2**	**< |1|**	**< |2|**	**< |5|**	**< |5|**

(Ferrière 2020)

The future is bright but challenging

(skao.int)

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- The case of the Square Kilometre Array Observatory (SKAO)
- A project started in early 1990s and now approaching completion (>1 GEuro)
- The largest radio interferometer between *50 MHz* and *15 GHz* (maybe more in the future)
- Two instruments: SKA-Low [50 MHz, 350 MHz] (right) and SKA-Mid [350 MHz, 15 GHz] (left)

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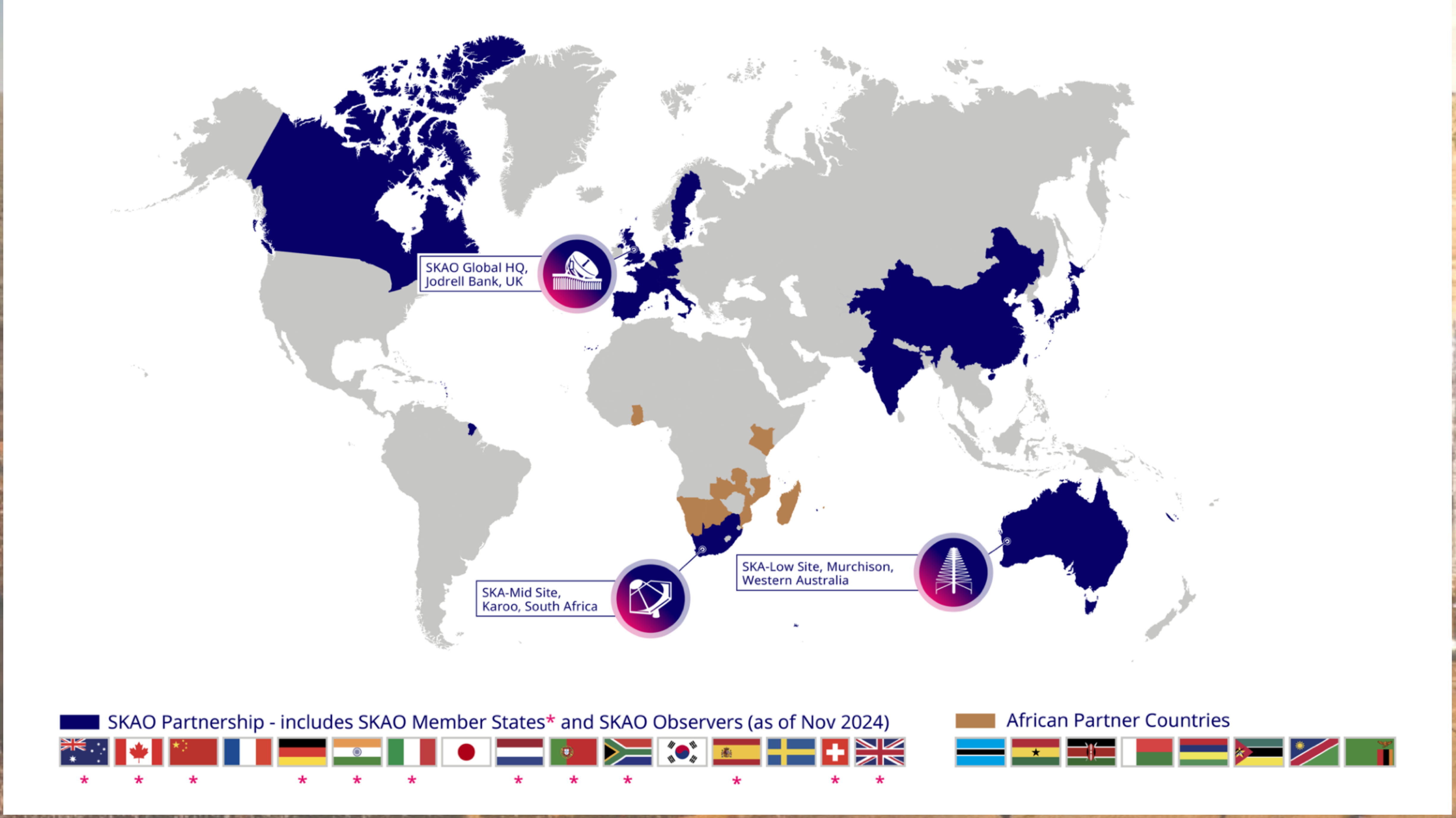

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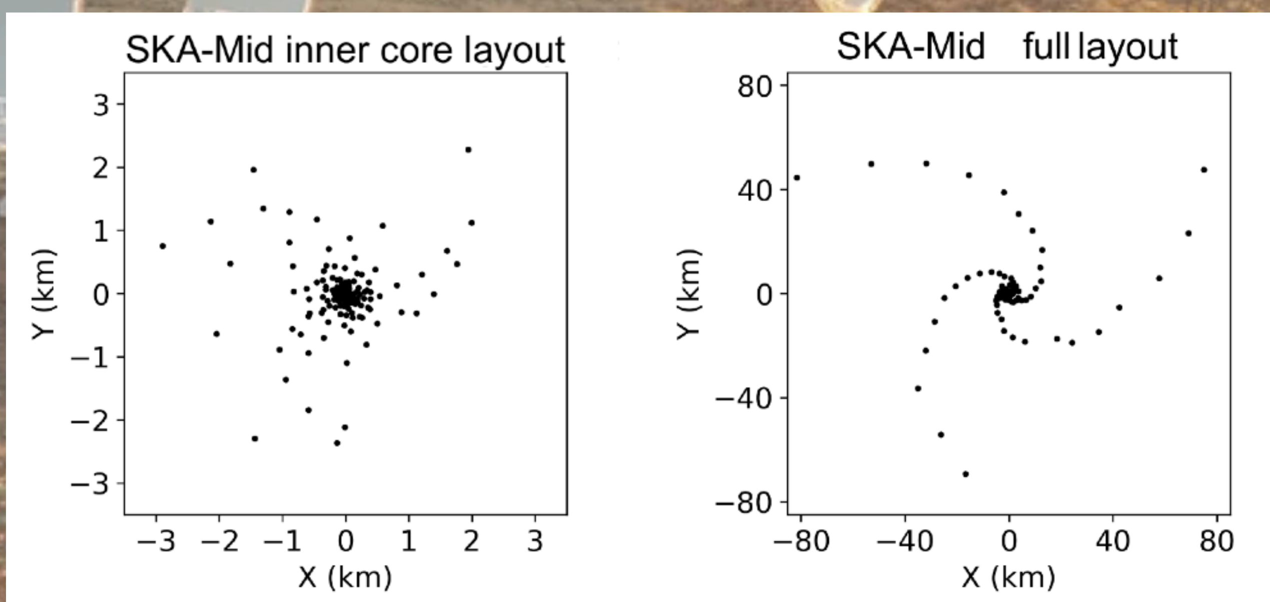
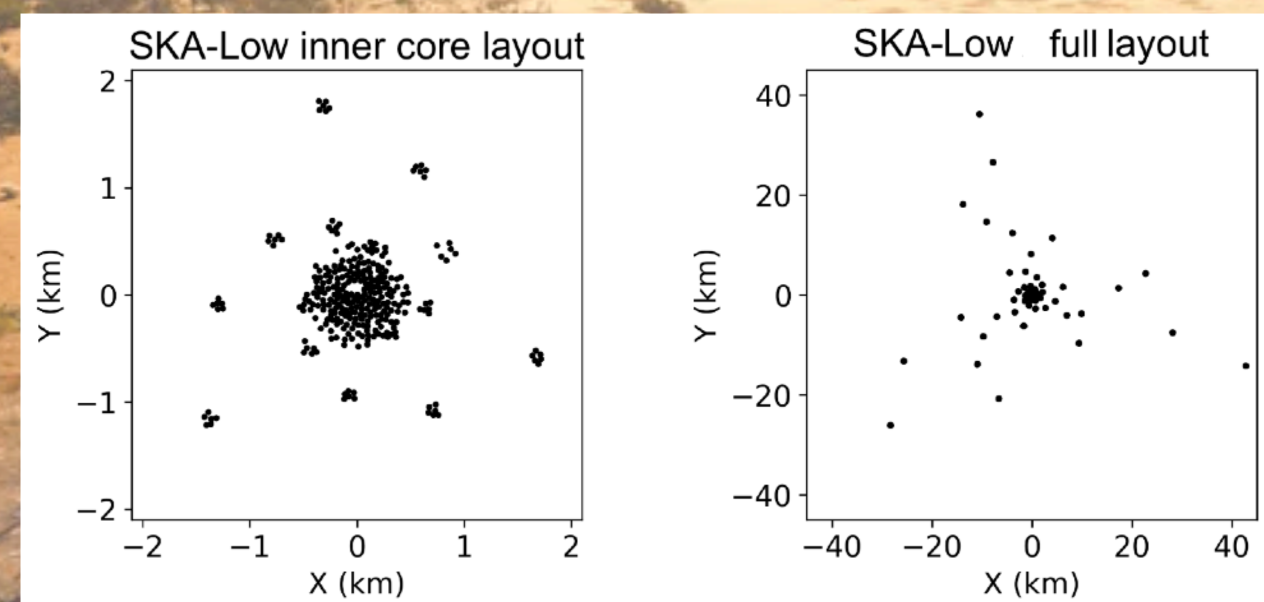
SKA-mid
133 single dishes of 15-m diameter
64 single dishes of 13.5-m diameter from MeerKAT
Baselines: random distribution within 2 km in the core;
out to 150 km for the long baselines

SKA-Low
more than 130000 dipoles
across 512 stations of 256 antennas each
Baselines: 1 km diameter core;
out to 75 km for the long baselines





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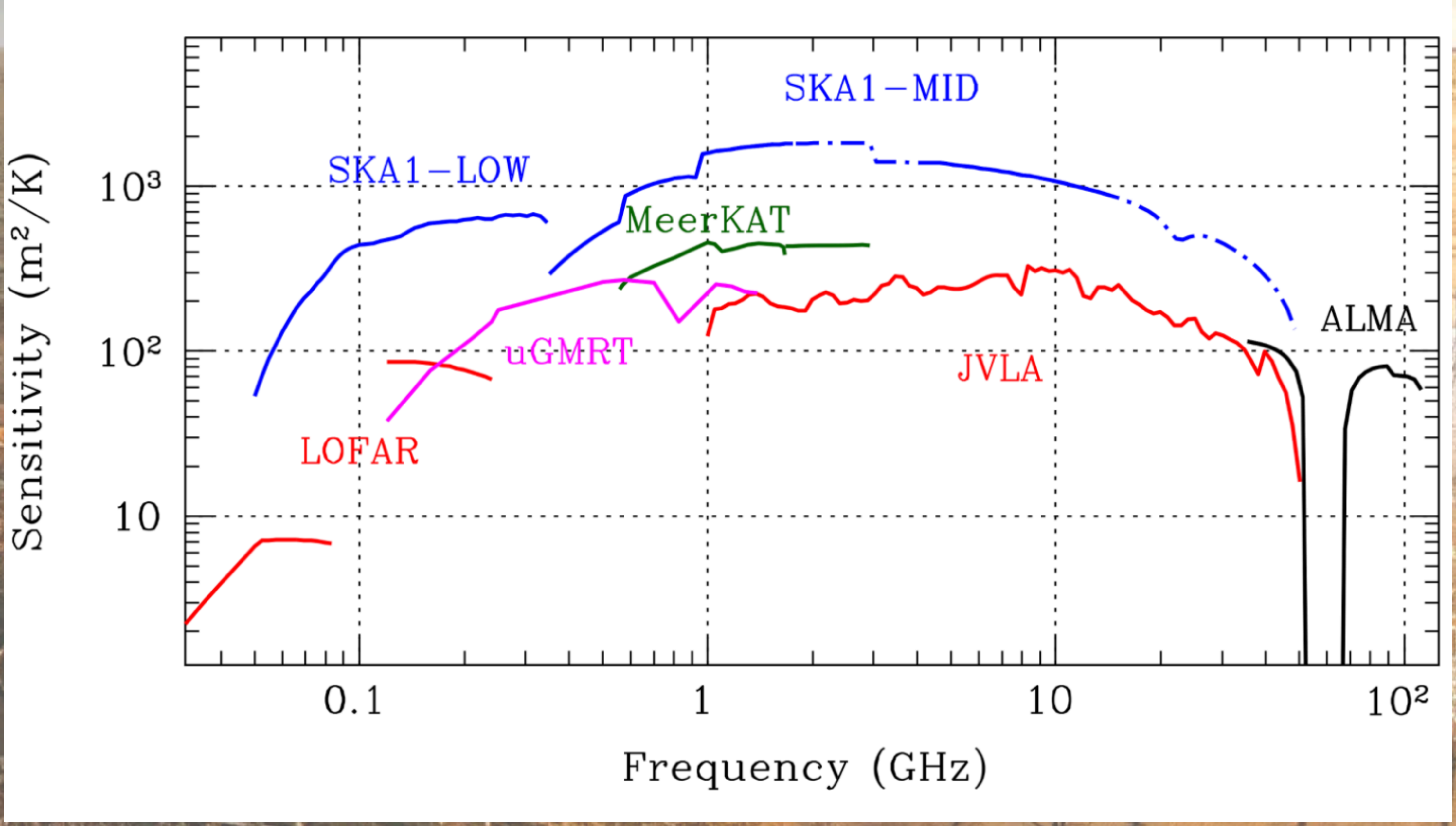

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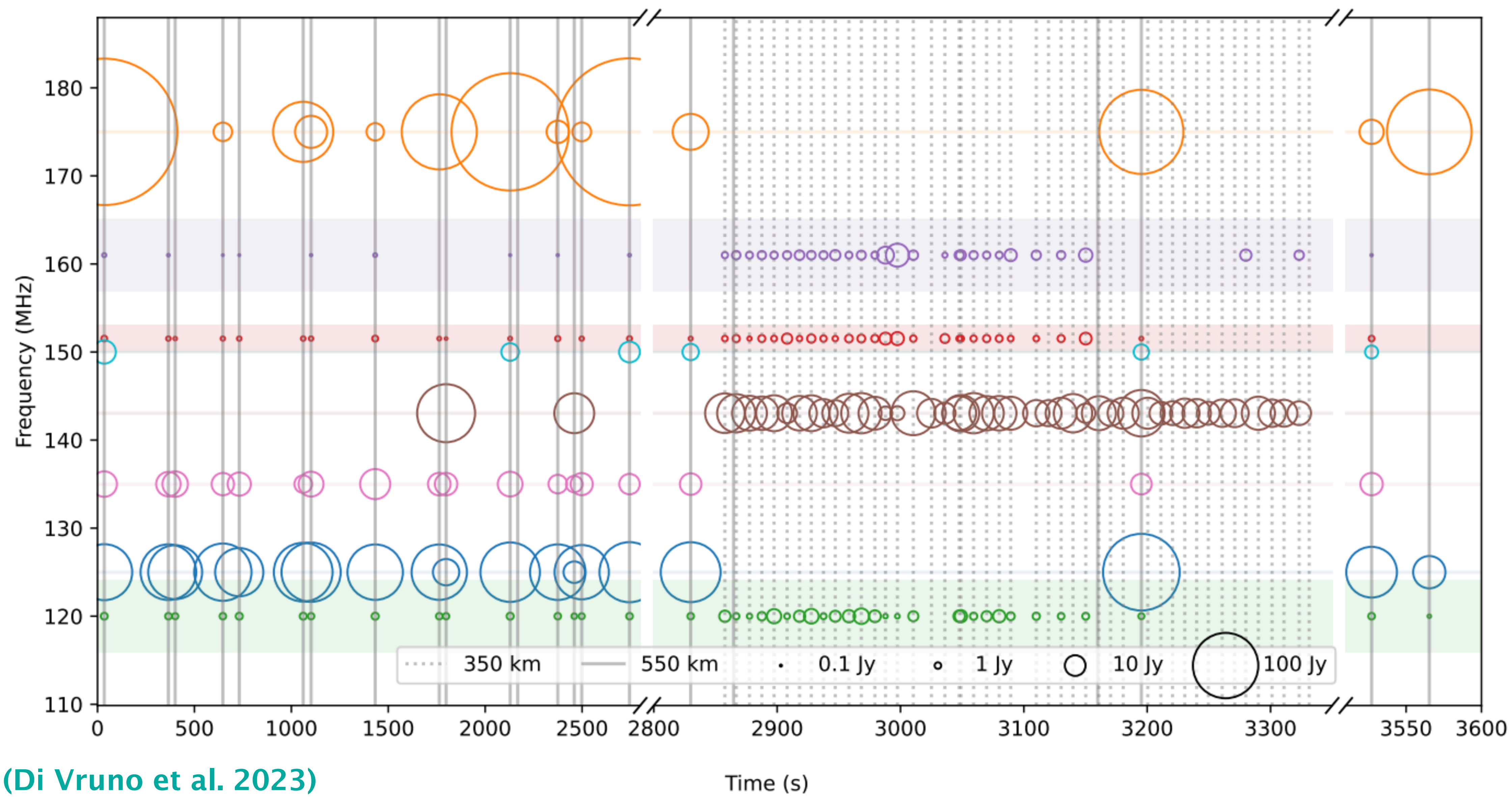
- *Construction challenge*
- *The most sensitive radio telescope, BUT* new sources of Radio Frequency Interference (RFI), contingency plans?

Starlink satellites seen by LOFAR at 150 MHz



(Di Vruno et al. 2023)

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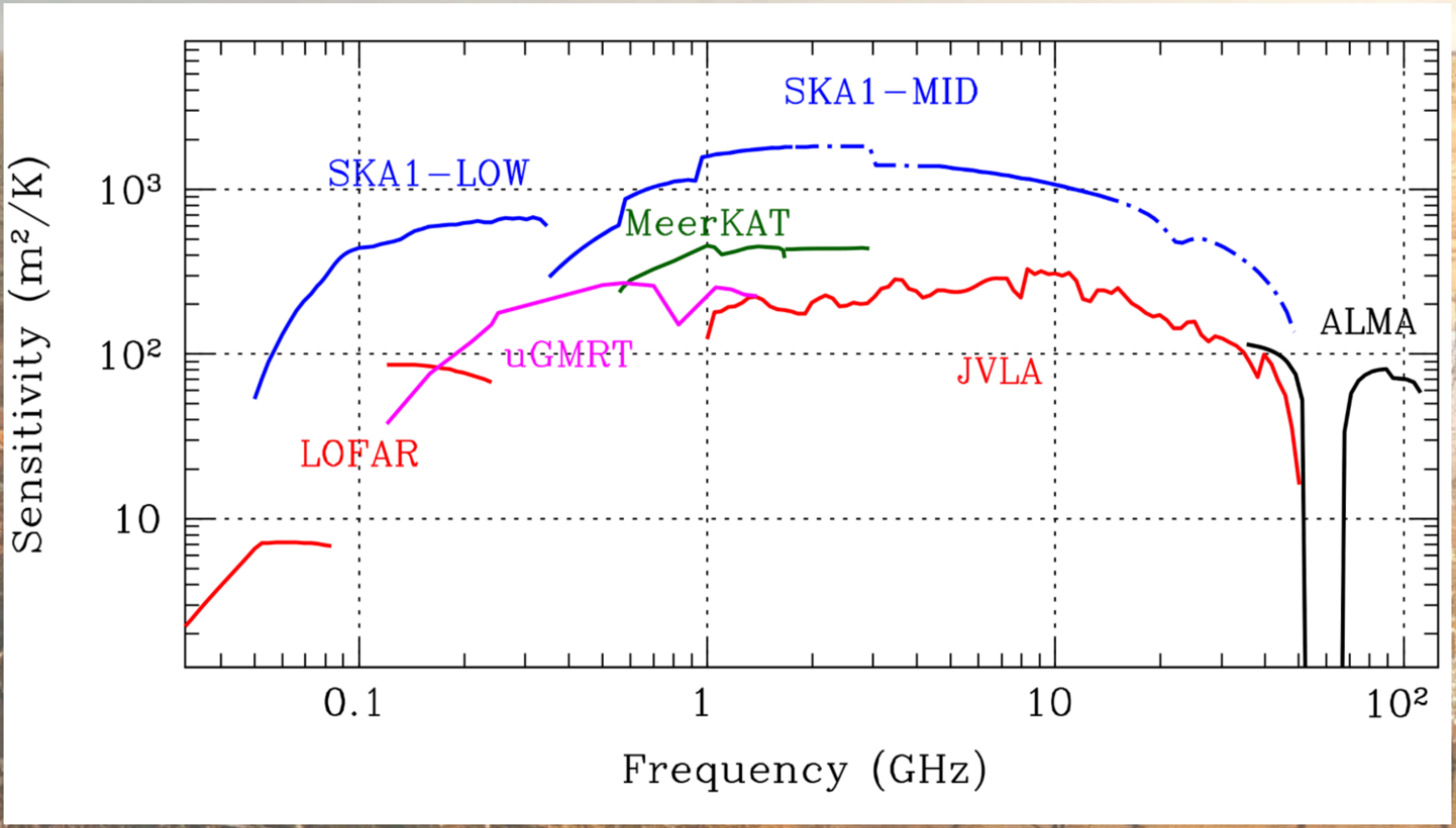
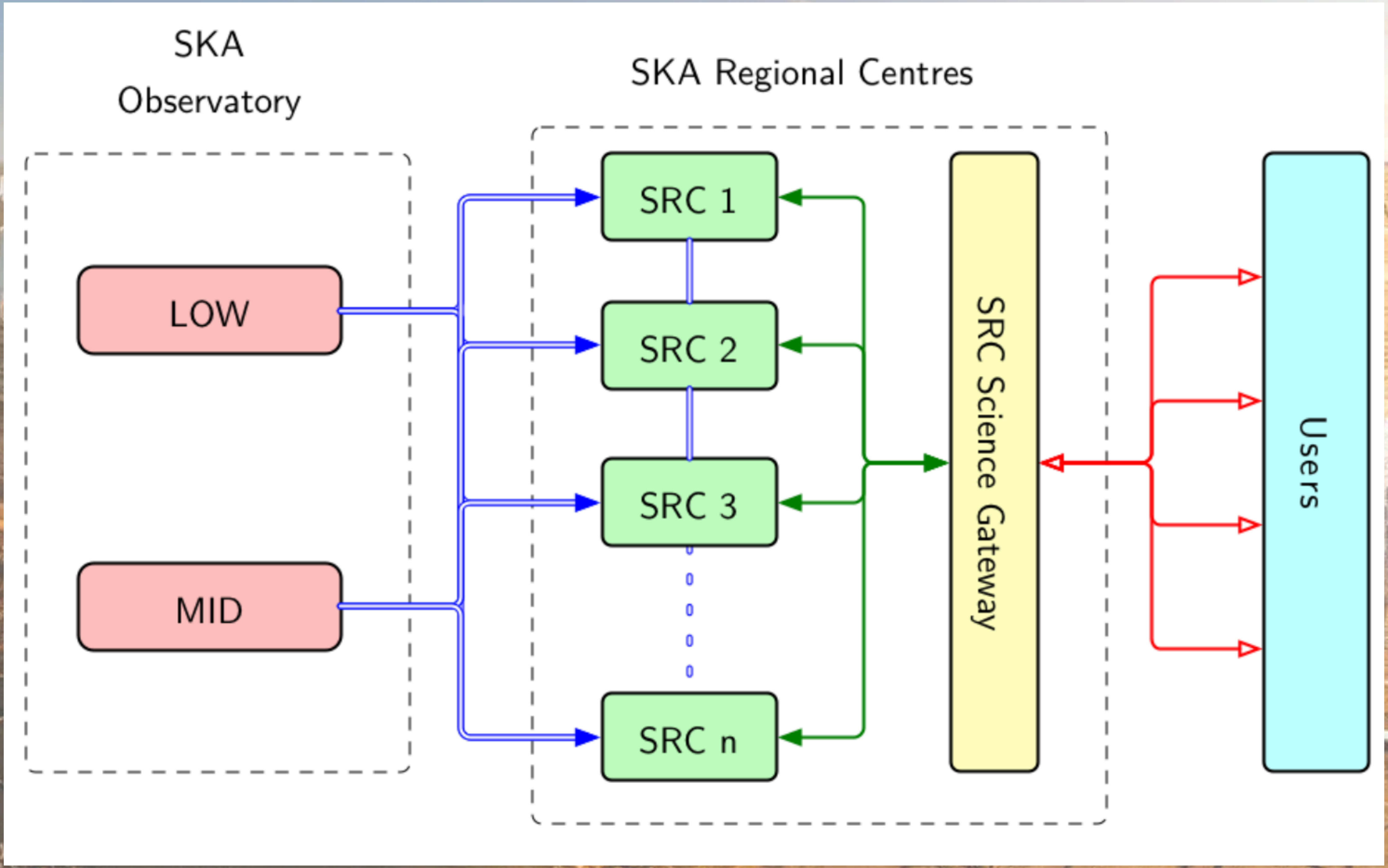
- *The most sensitive radio telescope, BUT at a price …*



The future is bright but challenging

(skao.int)

- Data size: expected 300 PB/year (if more funding is obtained up to 700 PB/year)
- SKA Regional Centre Network (SRCNet): data processing + archive



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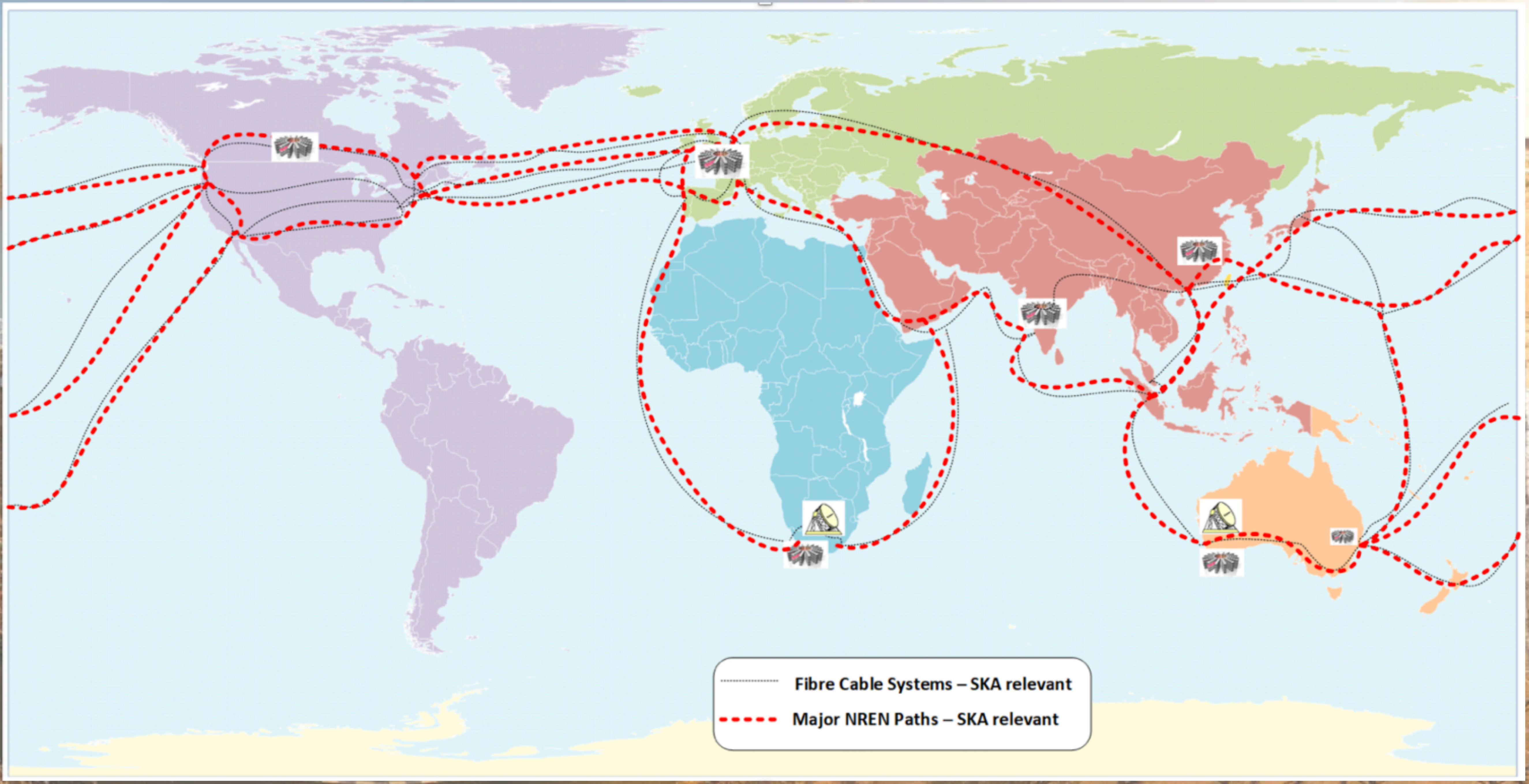

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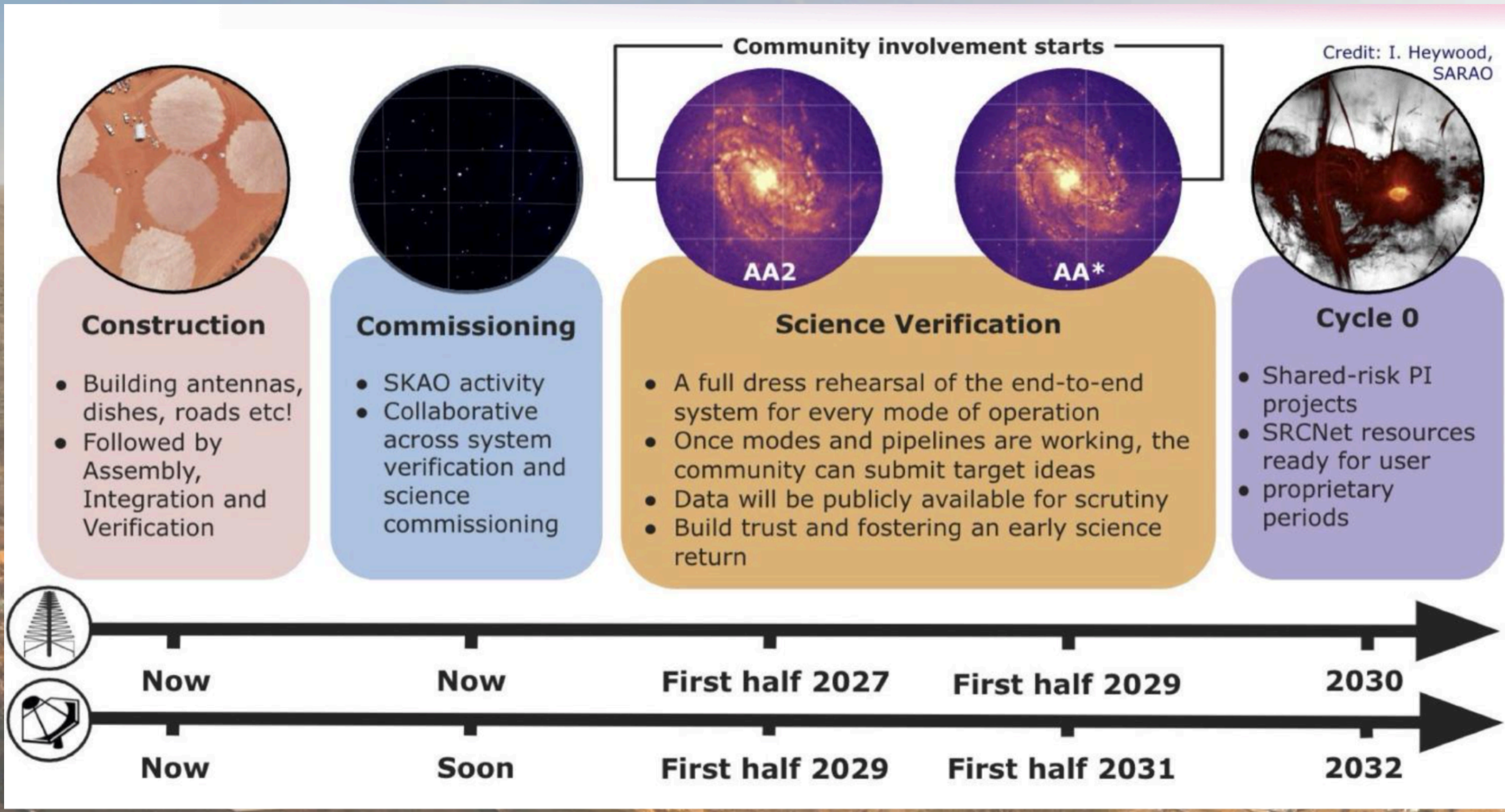

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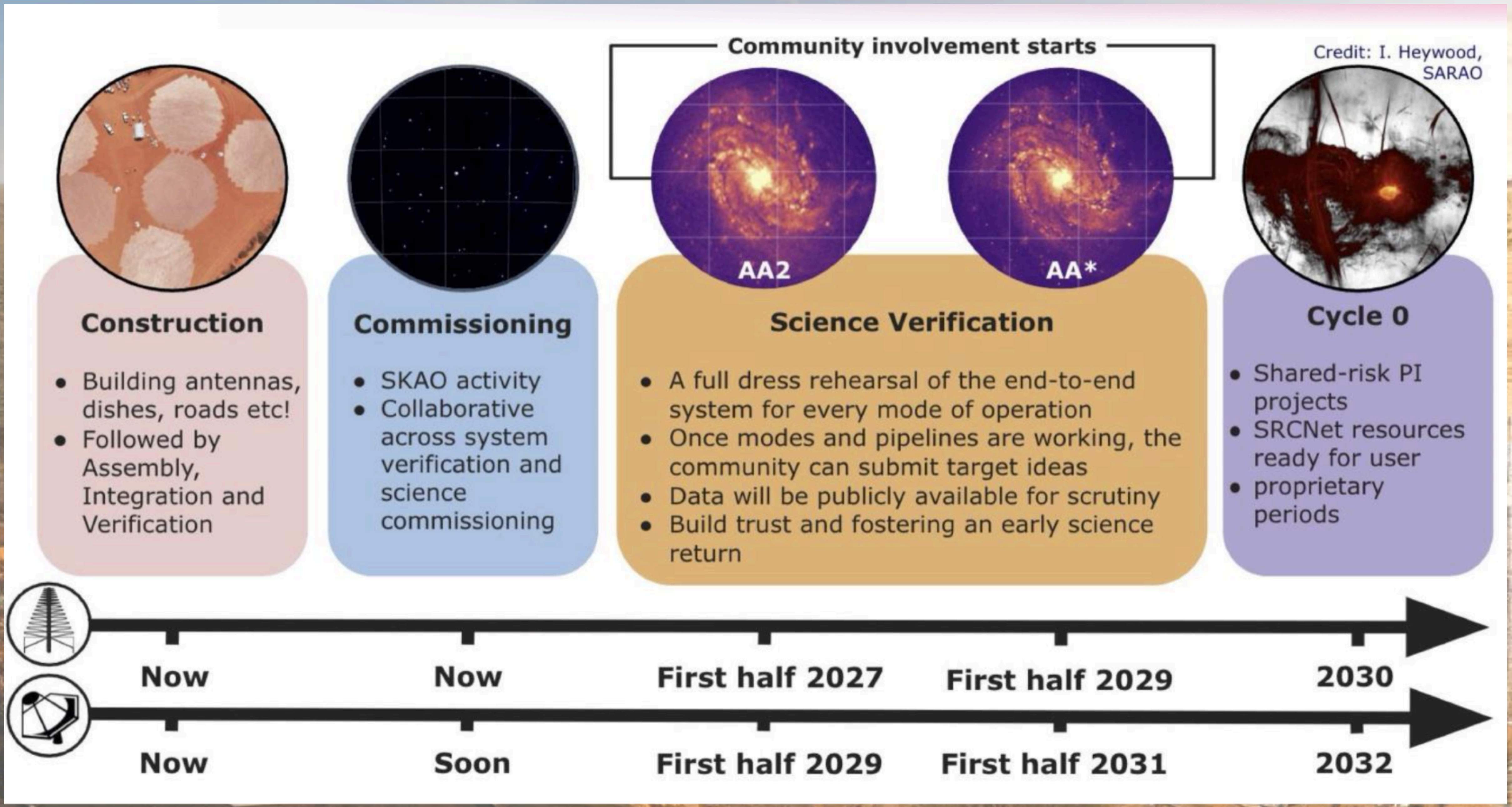

How to contain the environmental footprint of such a large infrastructure (> 18 kt CO2e/yr)?

(Knödlseder et al. 2022)

Concluding remarks

✦ Part 1

- The ISM is where stars and planets form, the ISM is the fuel of galaxies
- The radio window can help address key questions on the ISM: *multiphase, multiscale through multitracer data*

✦ Part 2

- Radio is promising but tricky: angular resolution problem and challenge of interferometric data handling

✦ Part 3

- The HI in galaxies
- The multiphase and magnetized ISM with synchrotron and Faraday rotation

✦ Part 4

The future is bright but challenging with next generation radio telescopes (e.g., LOFAR2.0, ngVLA, SKAO)

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