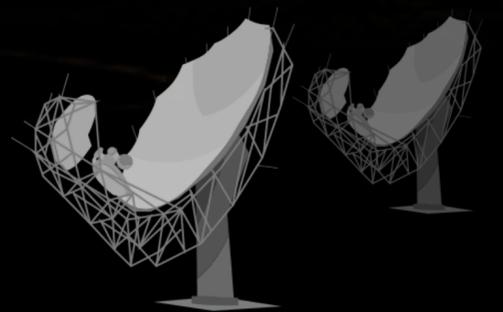




# Introduction to Radio Astronomy



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Astronomy Niche Area,  
Department of Mathematical Sciences,  
University of South Africa



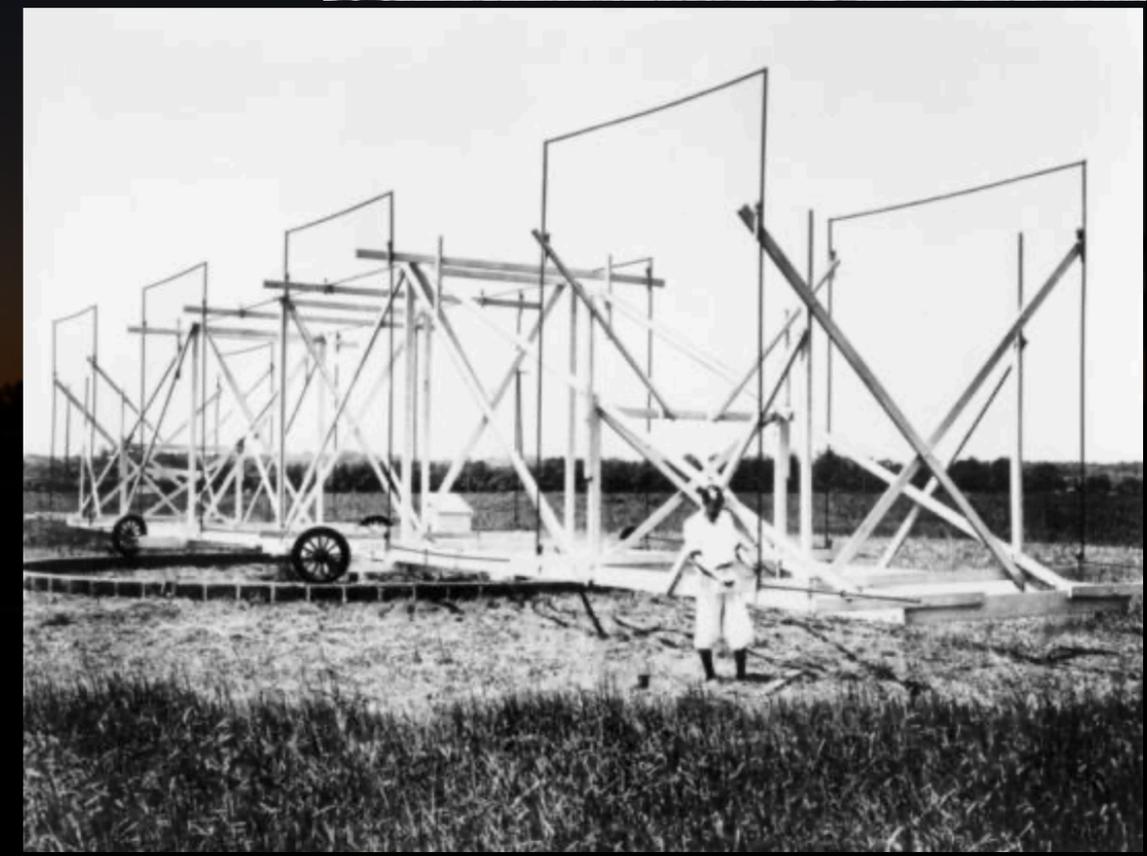


# Overview

- RAD1 (Intro to radio astronomy and radio telescopes)
- RAD2 (Single-dish data processing)
- RAD3 (Single-dish data processing)
- RAD4 (Radio interferometry)
- RAD5 (Interferometric data processing)
- RAD6 (Interferometric data processing)

# History of radio astronomy

- 1932 - Karl Jansky (Bell Telephone Labs) ~20 MHz detected Galactic emission
- 1938 - Grote Reber built a 10m parabolic telescope and mapped the Galaxy at 160 MHz
- 1950's - Discrete sources detected
- 1960's - High resolution interferometry
- 1970's/80's - Interferometric imaging array (e.g. VLA)
- 2000s - Development of software-based receivers
- 2020s - Start of SKA, conceived in 1991, first MoU in 2000



# EM Spectrum

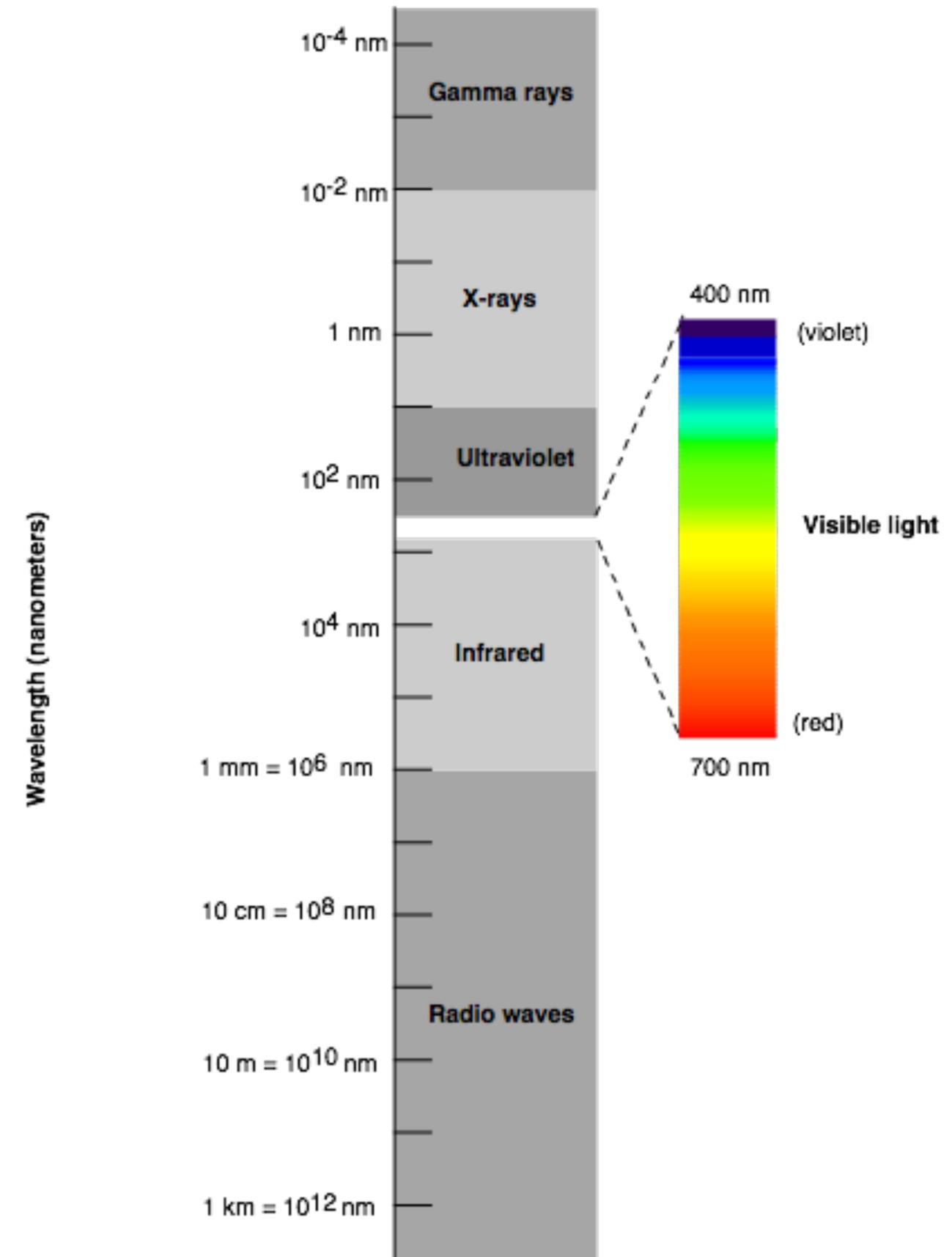
Radio Waves => electromagnetic waves  
with  $\lambda = 0.3\text{mm} - 100\text{km}$   
(1 THz - 3 kHz)

Most radio telescopes and interferometers  
> 500 MHz (0.6 m)

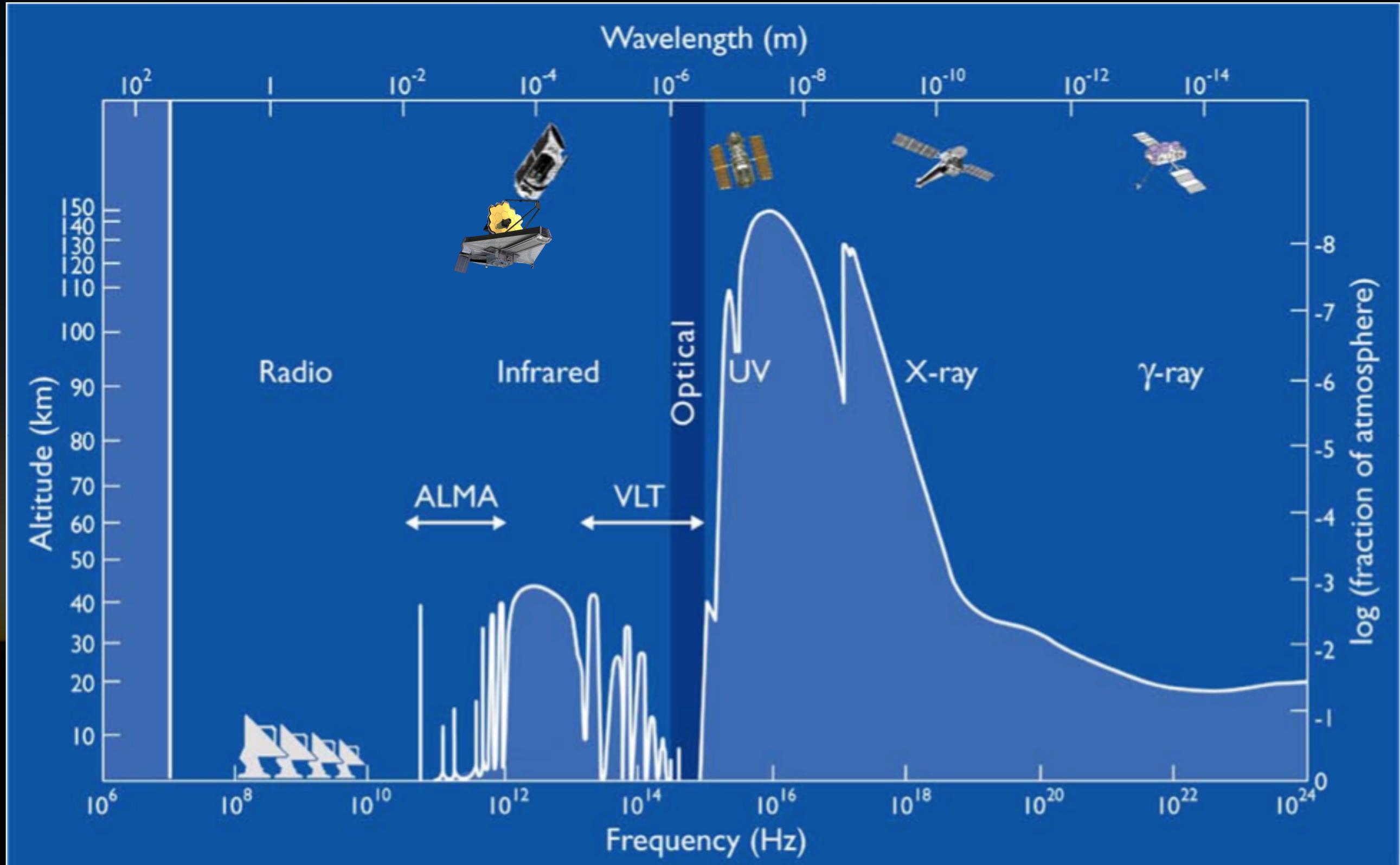
**Microwaves** (1 cm - 30 m)  
(30 GHz - 10 MHz)

**Millimetre** (1 mm to 10 mm)  
(300 GHz - 30 GHz)

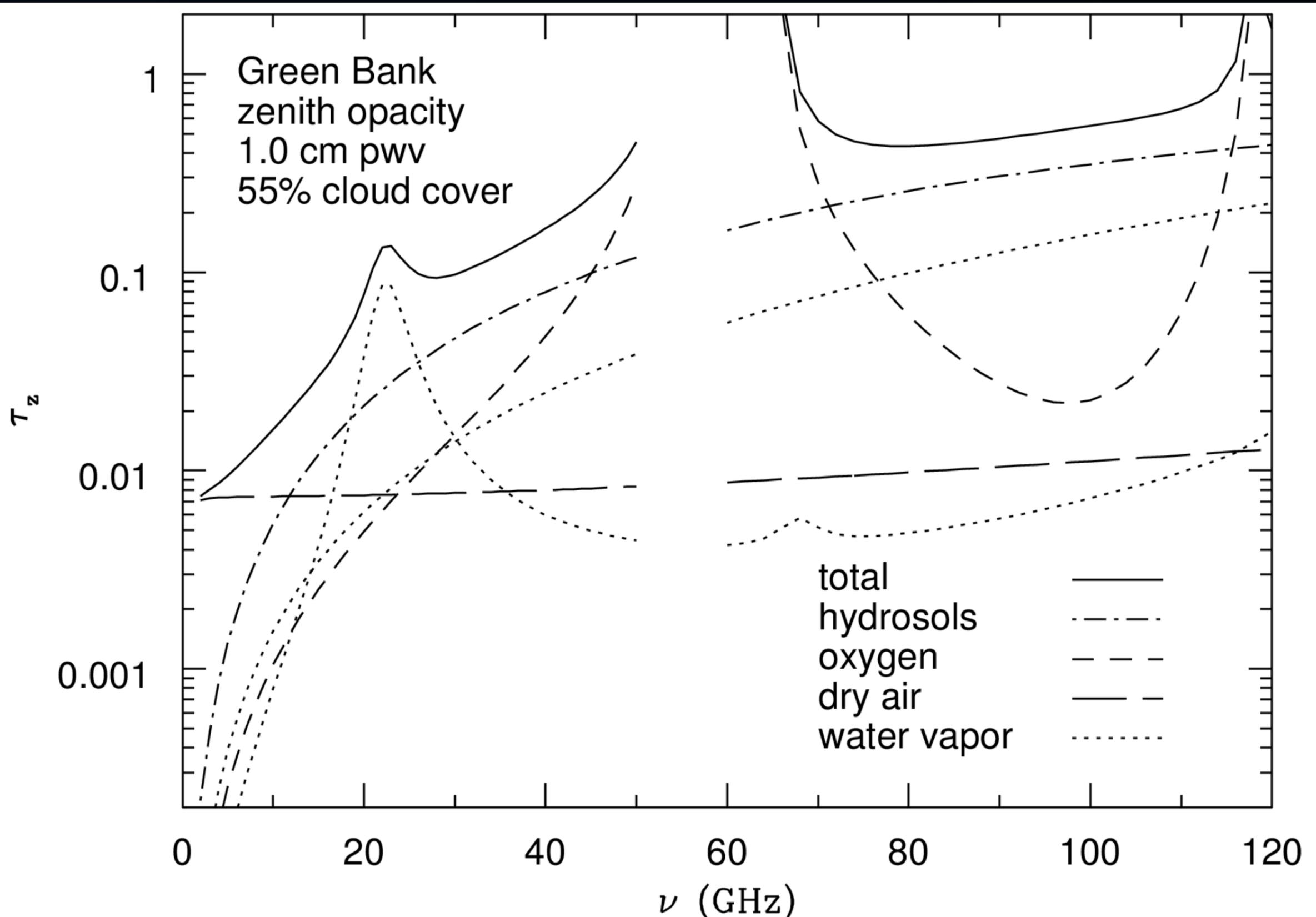
**Sub-millimetre** (< 1 mm, up to 0.4 mm)  
(> 300 GHz)



# Why should we care about the radio band?



# Opacity in radio bands





# Bands and naming conventions



## High Frequency (mm/sub-mm):

JCMT  
 $\lambda \sim 2000 - 345 \mu\text{m}$   
 $\nu \sim 150 - 870 \text{ GHz}$

ALMA  
 $\lambda \sim 3\text{mm} - 400 \mu\text{m}$   
 $\nu \sim 84 - 720 \text{ GHz} (40 - 950 \text{ GHz})$

## Low Frequency:

LOFAR  
 $\lambda \sim 1 - 20 \text{ m}$   
 $\nu \sim 10 - 240 \text{ MHz}$   
(10-90, 110-240)

## Large Radio Telescopes $\nu > 500 \text{ MHz}$ : GBT ( $\nu \sim 0.32 - 100 \text{ GHz}$ )

L Band	18 cm	1.40 GHz
S Band	13 cm	2.3 GHz
C Band	6 cm	5.0 GHz
X Band	3.5 cm	8.4 GHz
U Band	2.5 cm	15 GHz
K Band	1.3 cm	22 GHz
Ka Band	0.9 cm	32 GHz
Q Band	0.7 cm	43 GHz





How much energy does a radio photon carry?

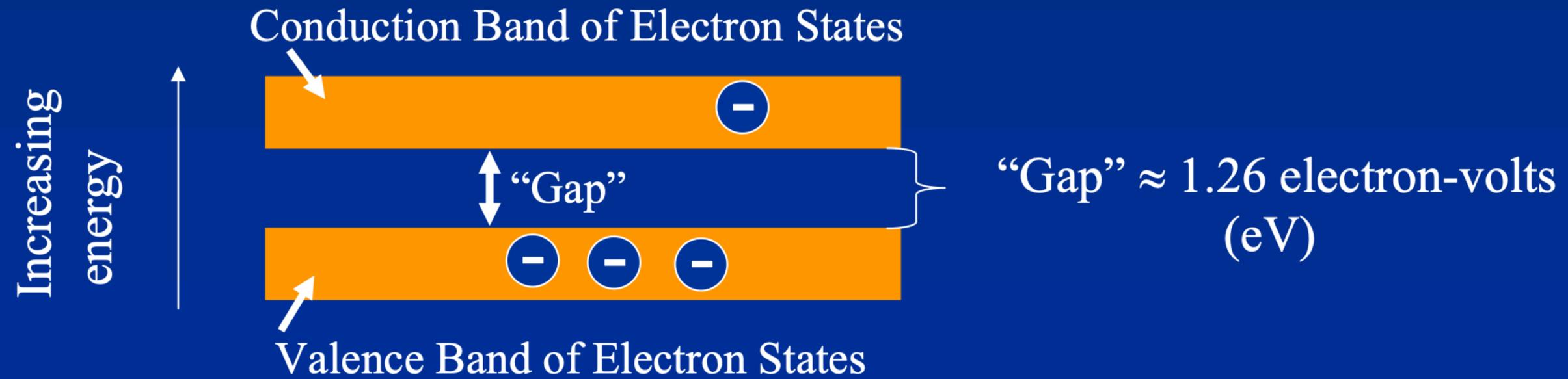


## Energies

	$\lambda$	$E$	$T (= h\nu/k)$
Optical photons	600nm	$\sim 2\text{eV}$	20,000 K
Radio photons	1m	$\sim 10^{-6}\text{eV}$	0.012 K

$\Rightarrow$  photon-counting is not an option in radio ast.

CCD



$E = 1.26$  electron Volts

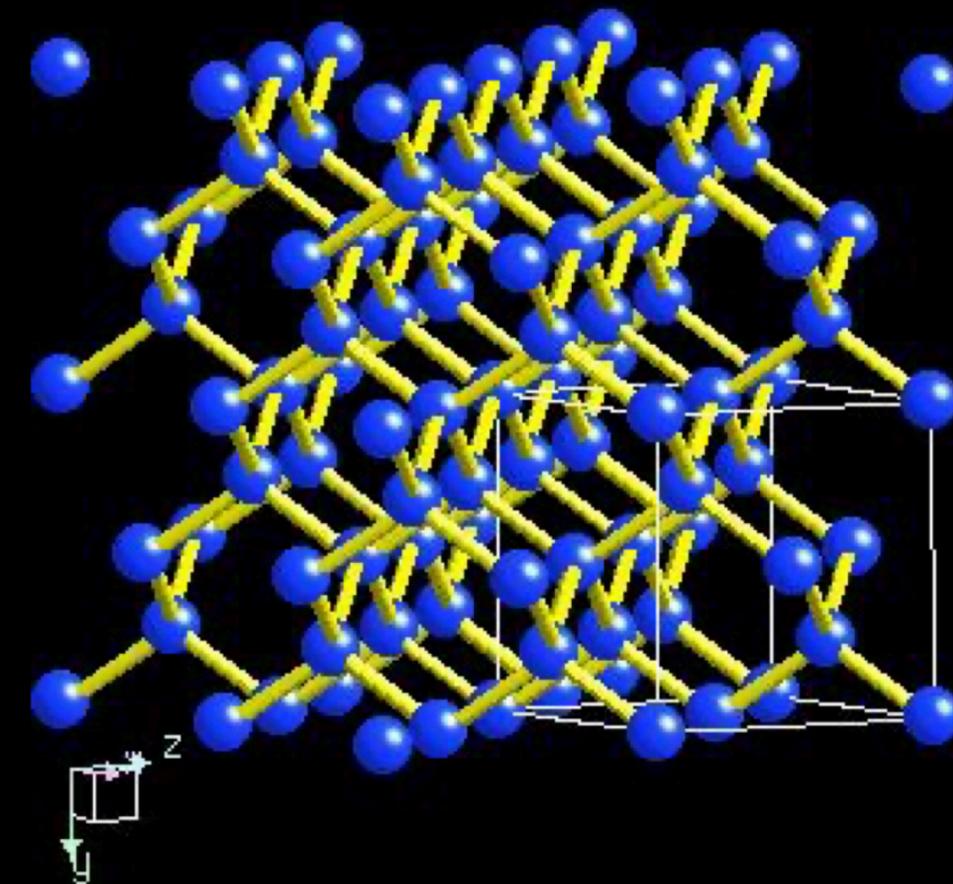
- $1 \text{ eV} = 1.602 \times 10^{-12} \text{ erg} = 1.602 \times 10^{-12} \text{ Joule}$

$$\lambda = \frac{hc}{E} = \frac{(6.624 \times 10^{-27} \text{ erg} - \text{sec}) \cdot \left(3 \times 10^8 \frac{m}{\text{sec}}\right)}{1.26 \text{ eV} \times \left(1.602 \times 10^{-12} \frac{\text{erg}}{\text{eV}}\right)}$$
$$= 9.84 \times 10^{-7} \text{ m} = 984 \text{ nm}$$

⇒ To Energize Electron in Si Lattice Requires

$$\lambda < 984 \text{ nm} \cong 1 \mu\text{m}$$

Silicon





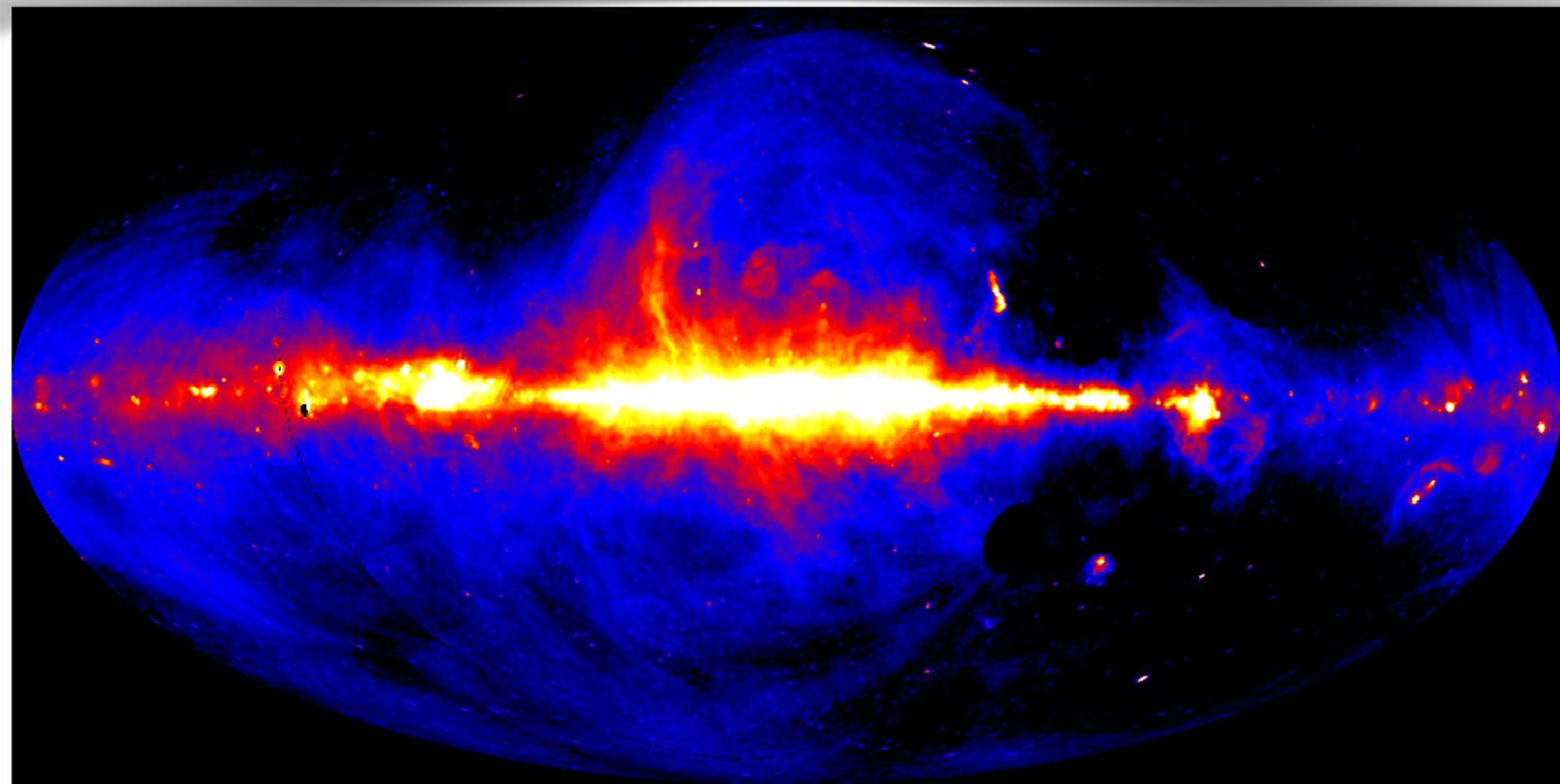
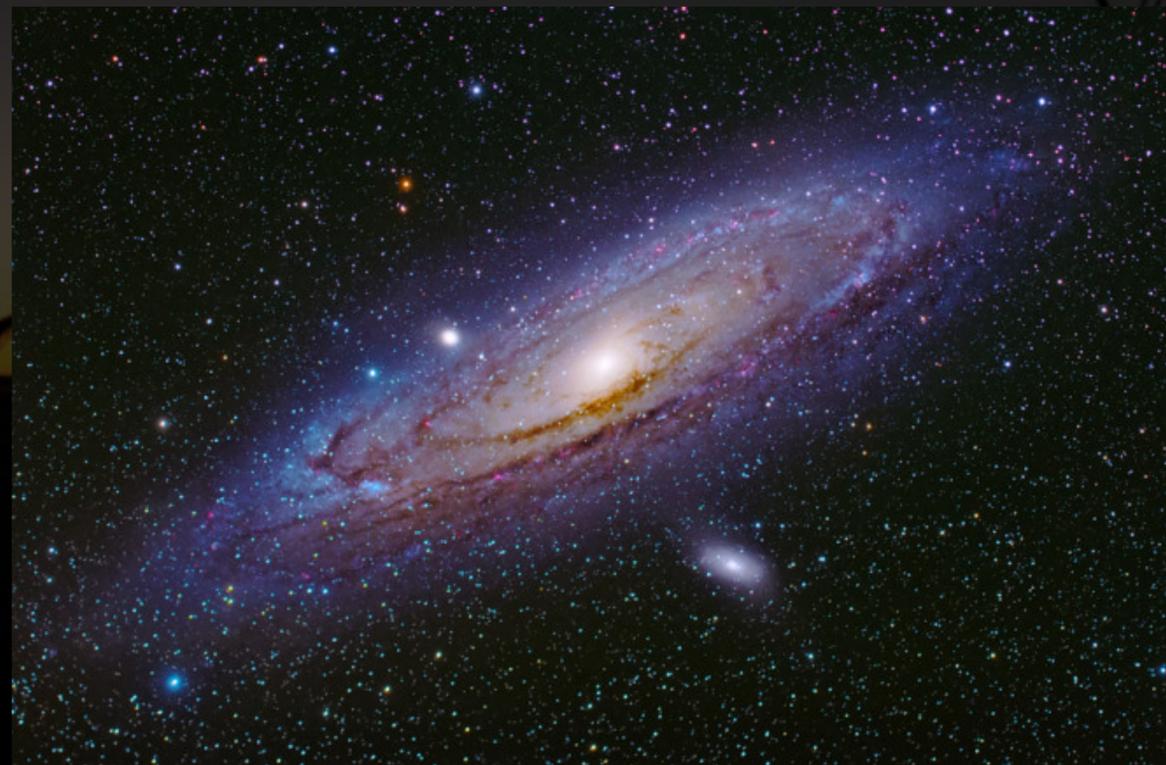
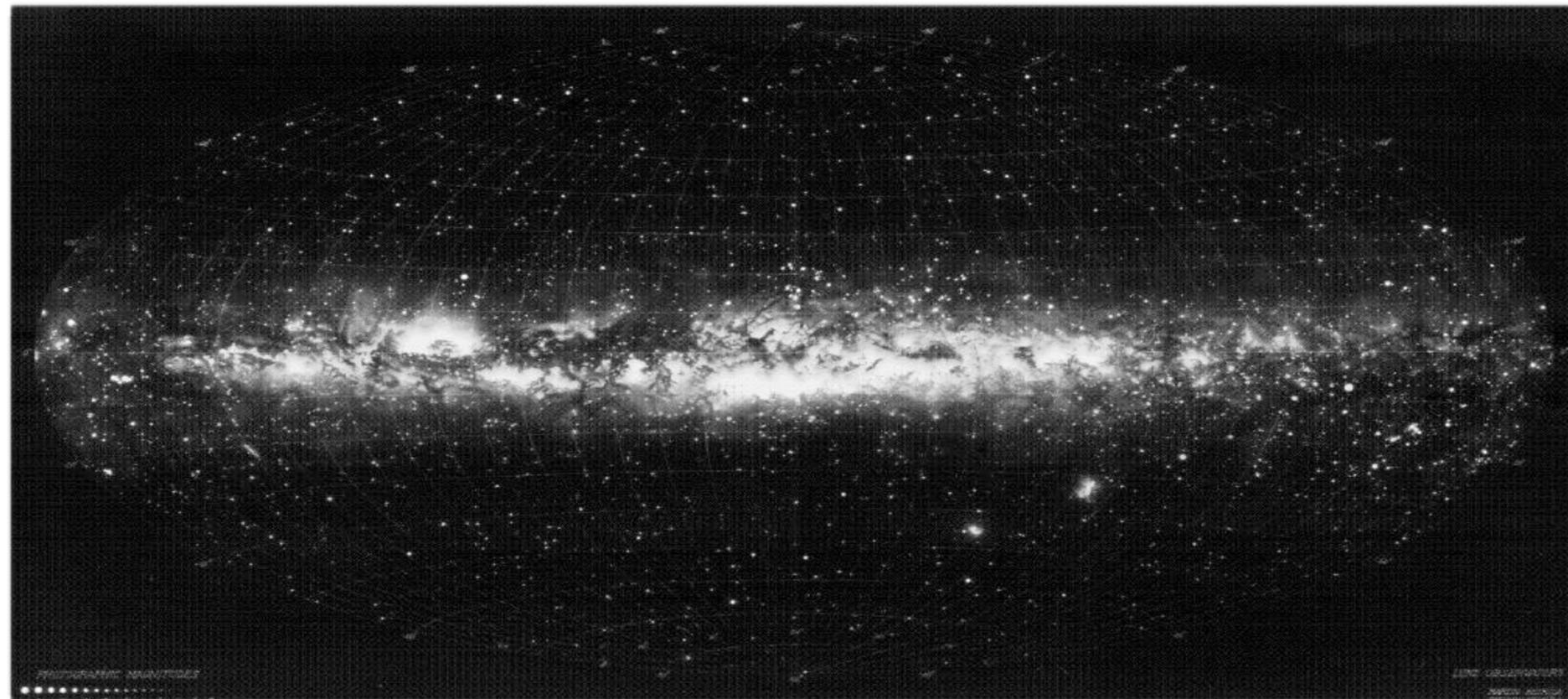
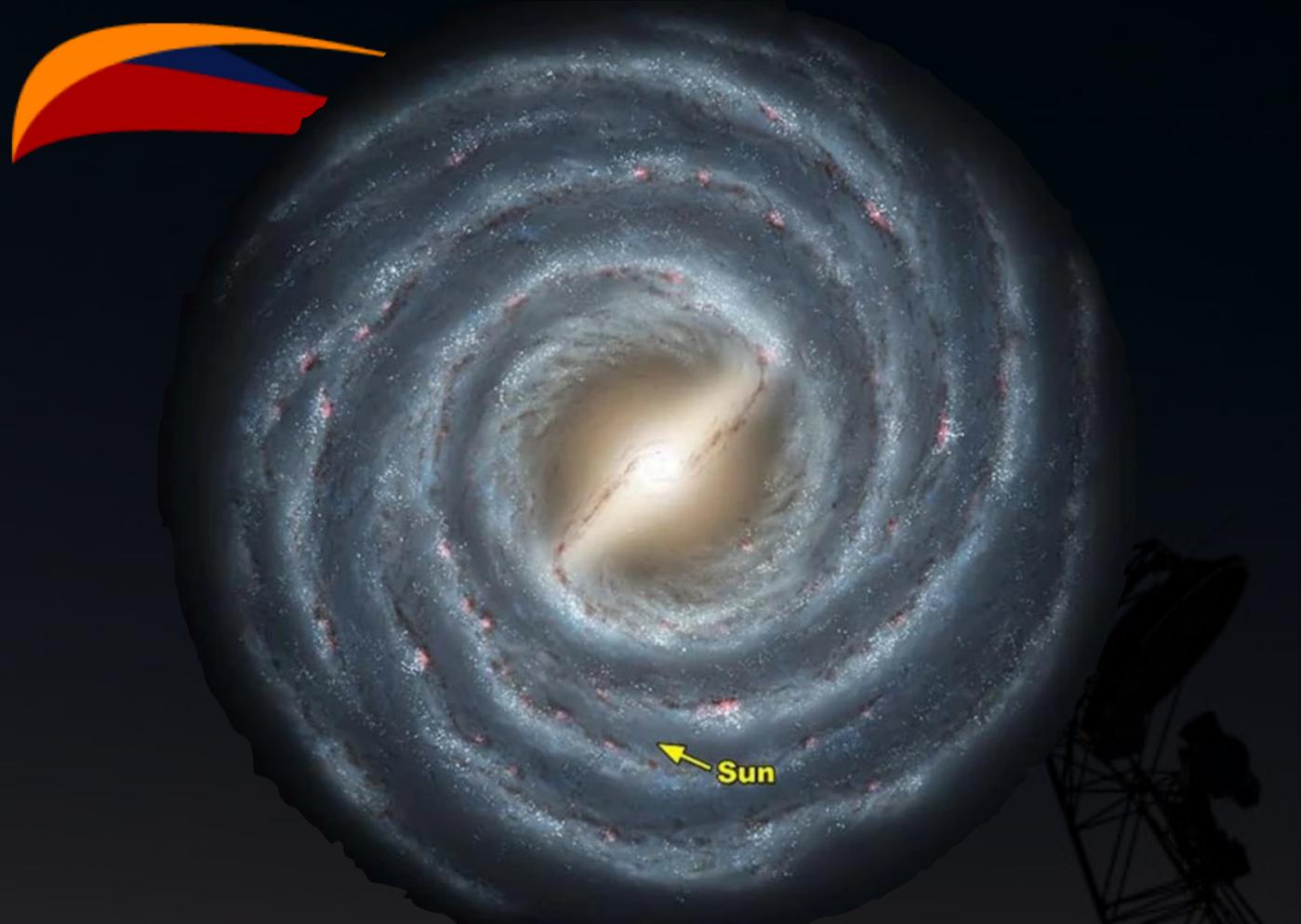
What do we measure in radio observations?





Photon counting in the radio is not usually an option, we must think classically in terms of measuring the source electric field

=> i.e. measure the voltage oscillations induced in a conductor (antenna) by the incoming EM-wave.



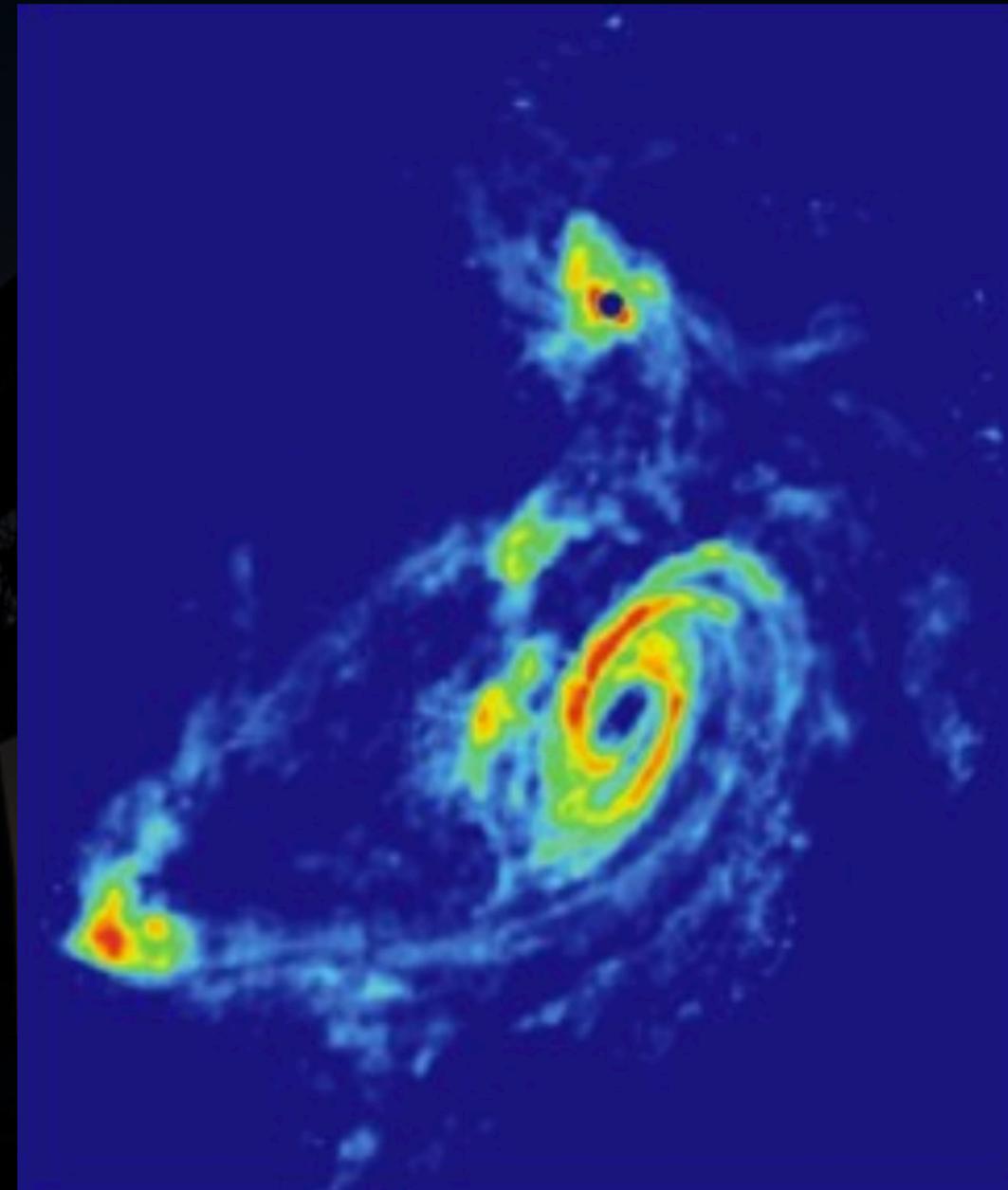
Incomplete picture without radio data....



Centaurus A galaxy



What do you see in the optical image?





How are radio emissions from astronomical objects produced?



# Radio Emission Processes

---

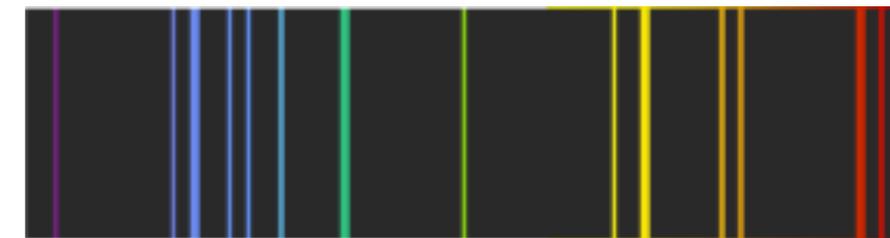
- Electromagnetic emission can be divided into two types:

## Continuum emission



=> emission over a very broad frequency range  
usually due to the acceleration of charged particles moving with a wide-range of energy

## Spectral line emission



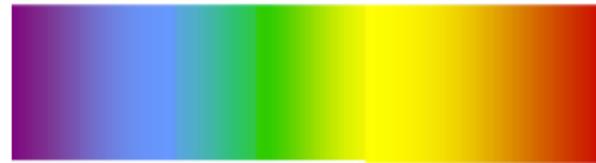
=> emission over a very narrow frequency range  
usually due to the discrete transitions in the internal energy states of atoms or molecules

# Radio Emission Processes

$$B_\nu = \frac{2kT\nu^2}{c^2} = \frac{2kT}{\lambda^2} \quad (h\nu \ll kT)$$

- Continuum emission

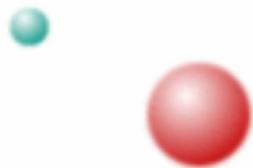
Radio astronomy is cool 😎



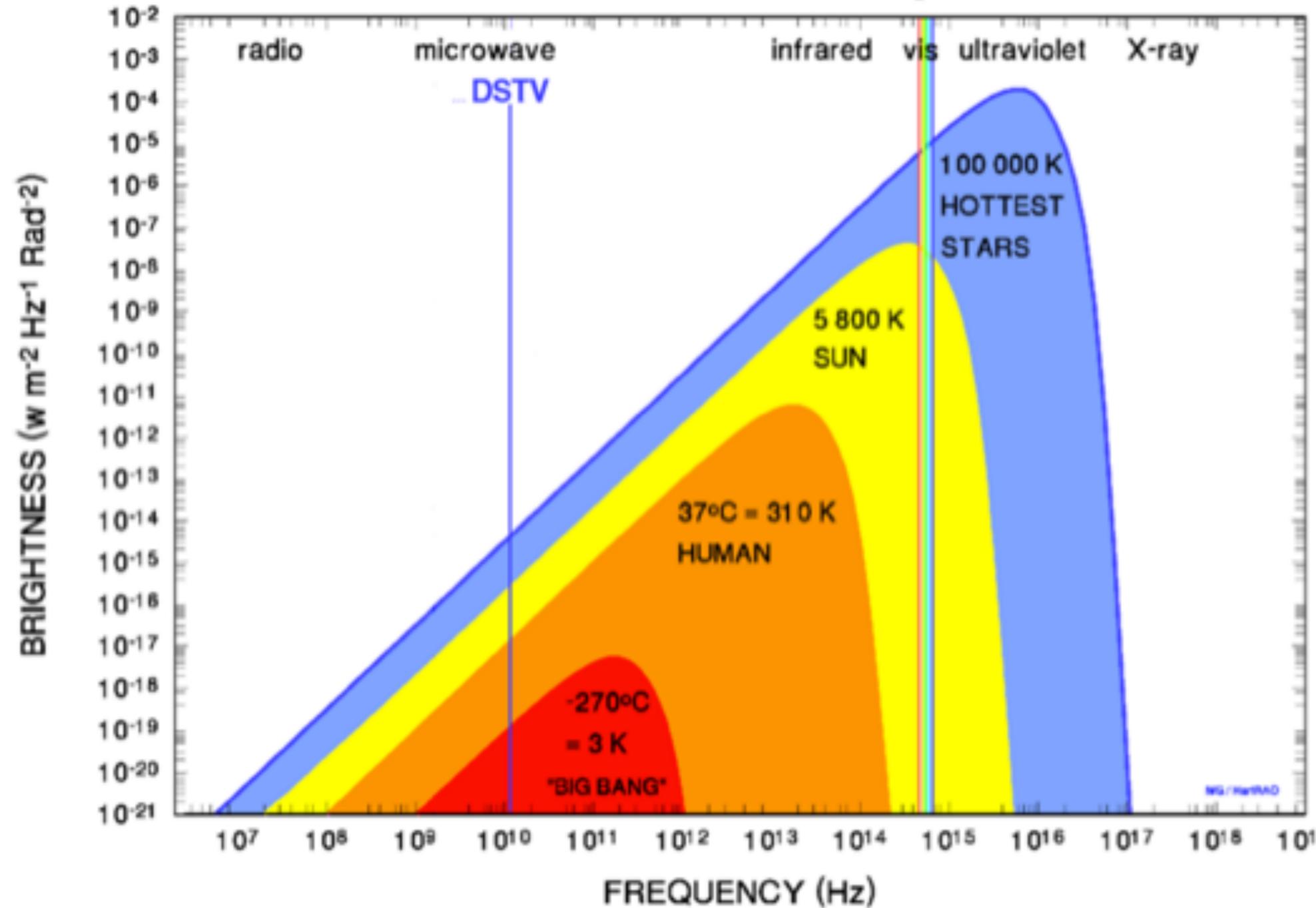
## Thermal Emission

=> Black body radiation for objects with temperature  $T \sim 3\text{-}30\text{ K}$  (CMB radiation peaks at  $T = 2.7\text{ K}$ ,  $0.001\text{ metres}$ ,  $300\text{ GHz}$ ).

=> Bremsstrahlung (free-free) emission: deflection of a charged particle (electron) in the electric field of another charged particle (ion)



$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$



# Radio Emission Processes

- Continuum emission

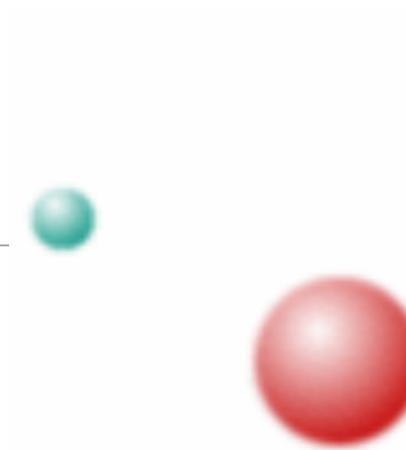
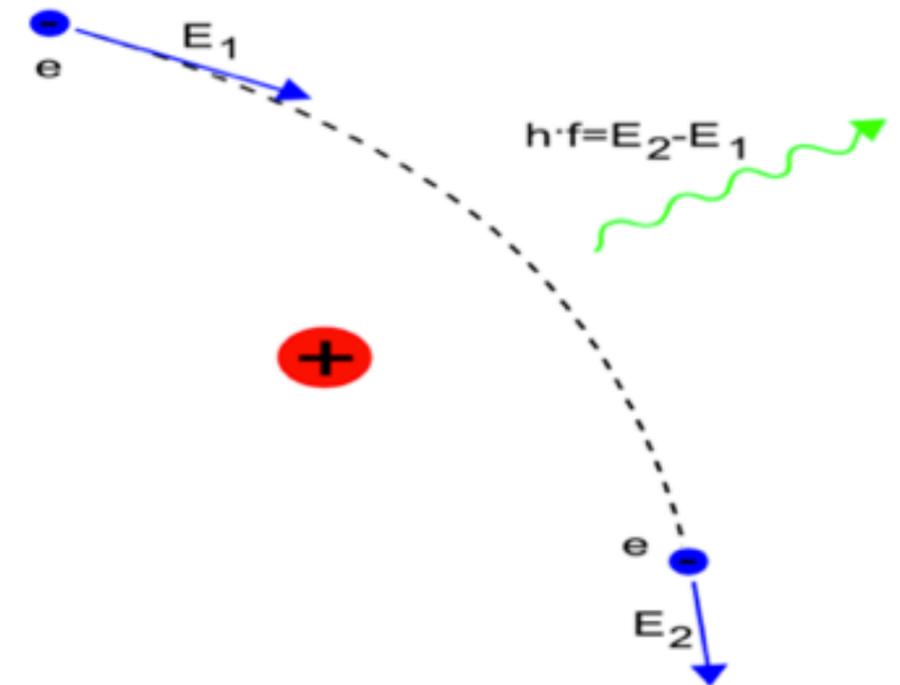


Radio astronomy is **cool** 😎

## Thermal Emission

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# Radio Emission Processes

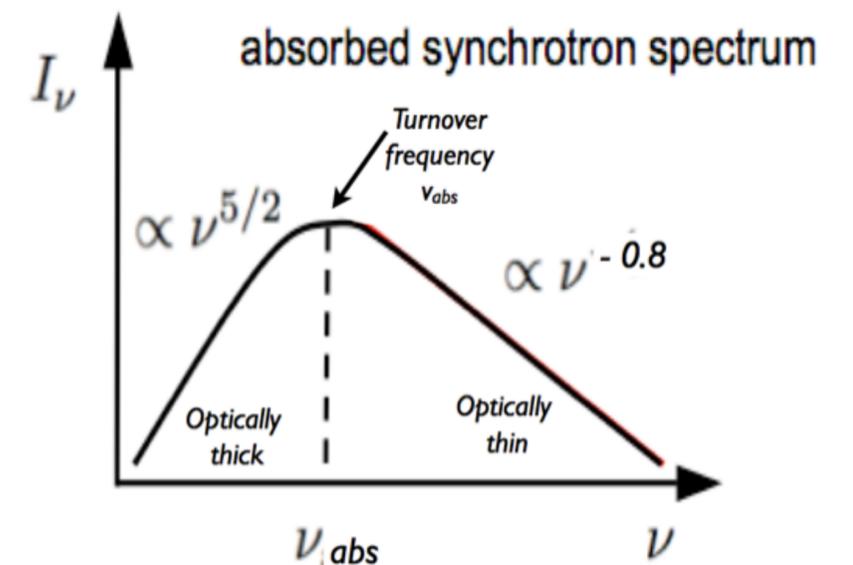
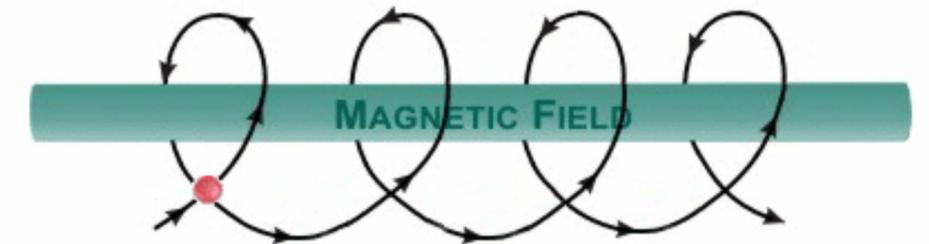
- Continuum emission



## Non-thermal Emission

=> Synchrotron radiation: relativistic electrons spiraling around weak magnetic field lines.

=> Since synchrotron radiation is strongest at low frequencies (long wavelength) it can be detected with **radio telescopes**.



# Radio Emission Processes

- Spectral Line Emission



## Neutral hydrogen HI (21 cm)

=> Most NB spectral line in the radio.

=> spin-flip transition between high-energy state and low-energy state of the H atom (aligned vs opposed spins for p+ and e-).

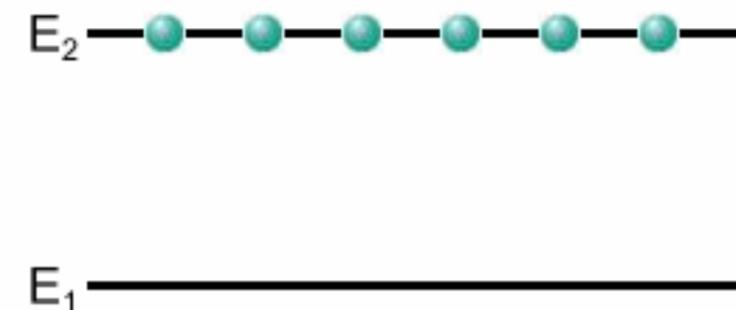
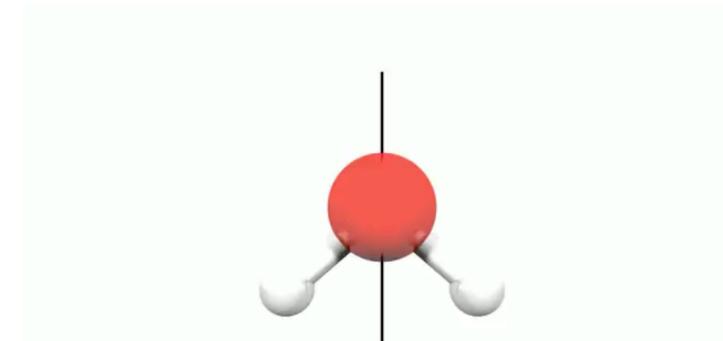
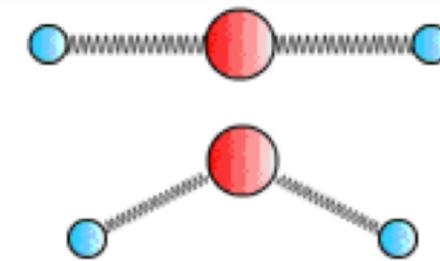
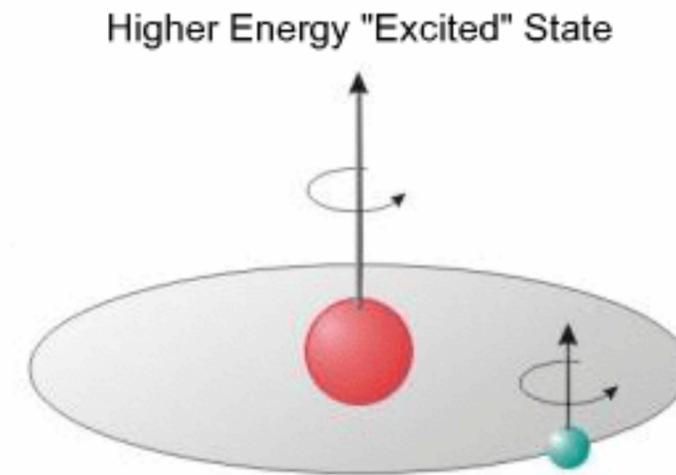
=> Although this transition is rare - there is just so much H in the ISM !

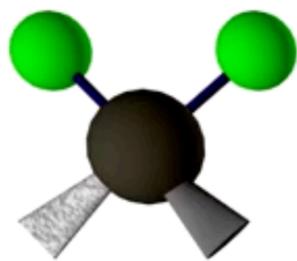
## Molecular lines (CO, CS, CN,...)

=> Produced by changes in the vibrational or rotational states of their electrons (due to collisions or interactions)

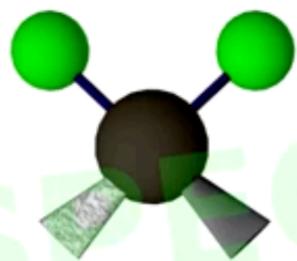
## Maser emission (OH, H<sub>2</sub>O, SiO,...)

=> Amplification of incident radiation passing through clouds of gas

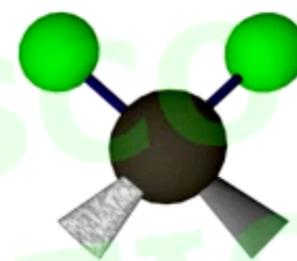




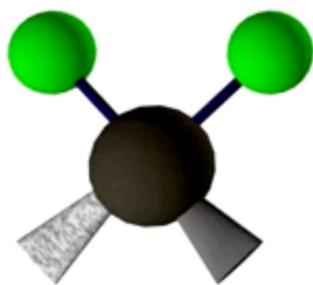
**SYMMETRIC  
STRETCHING**



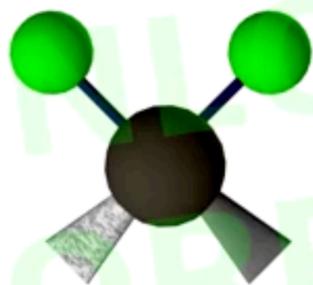
**ANTISYMMETRIC  
STRETCHING**



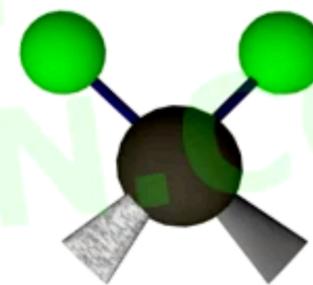
**ROCKING**



**WAGGING**



**TWISTING**



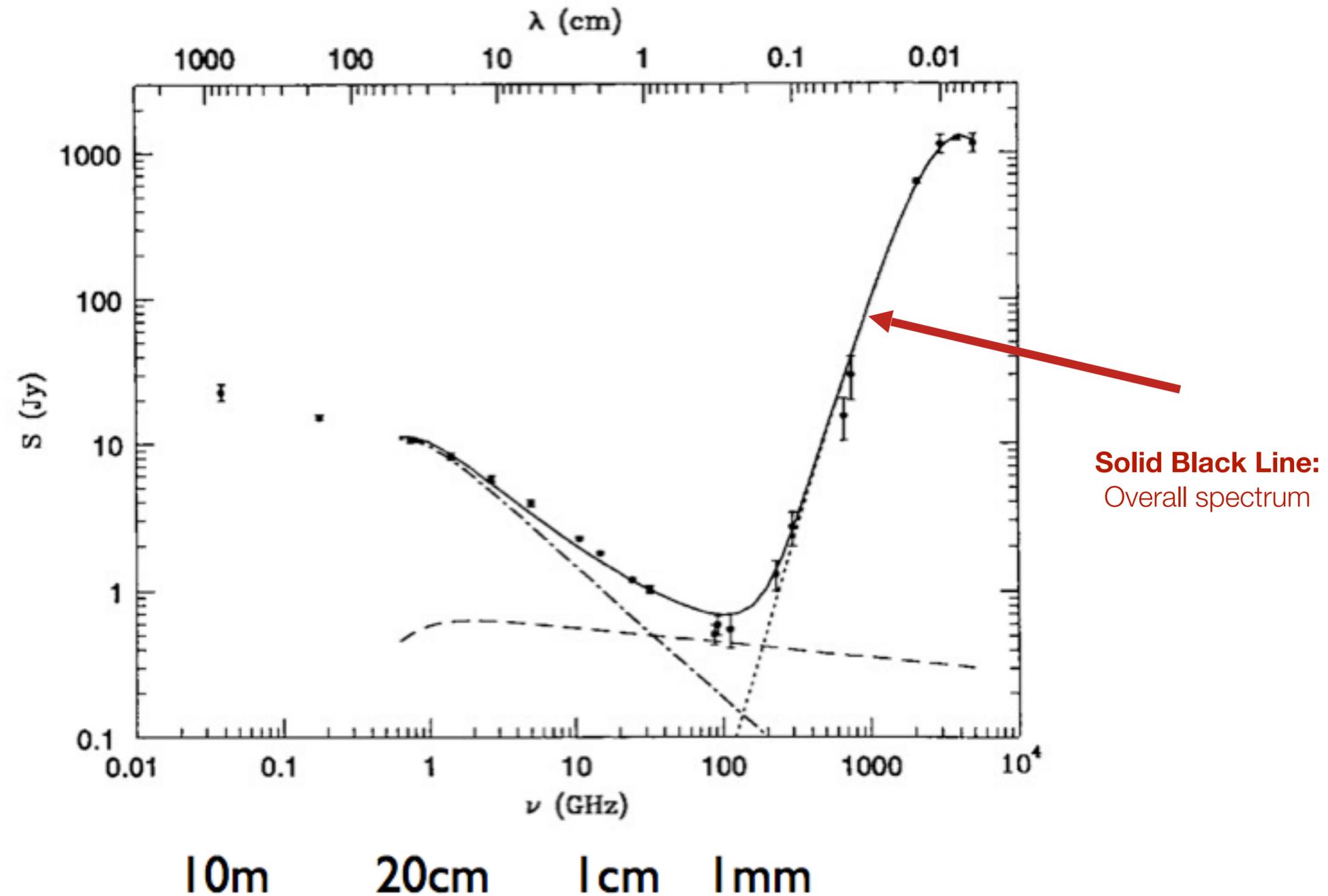
**SCISSORING**

# Radio Emission Processes

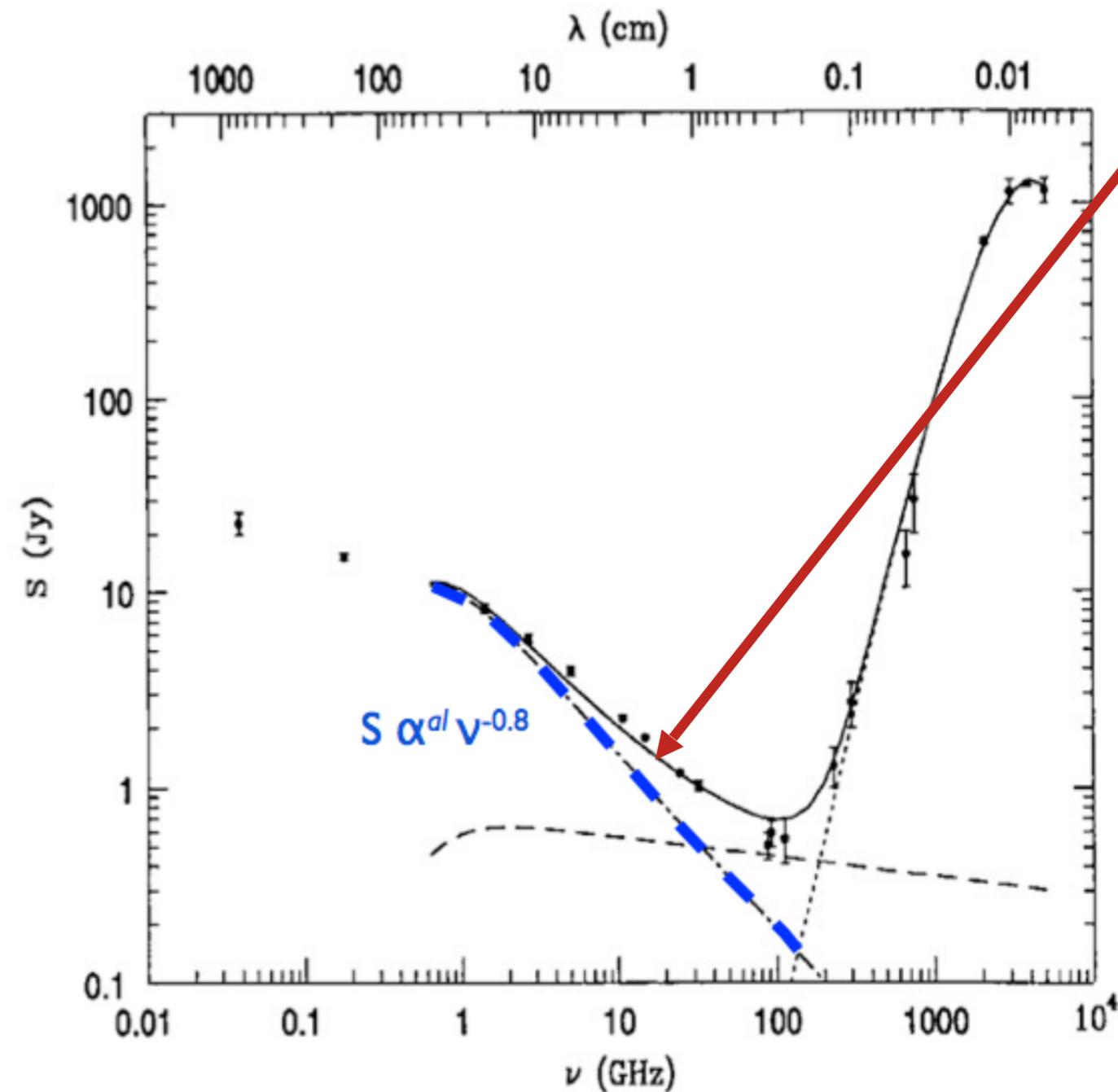
Wavelength	Spectral Line	Continuum
<p><b>meter, cm, mm</b></p>	<p>Neutral Hydrogen (HI) 21 cm fine structure line - <b>neutral gas</b></p> <p>Hydrogen recombination lines - <b>ionised gas</b></p> <p>OH, H<sub>2</sub>O, SiO Masers - <b>dense warm molecular gas</b></p> <p>Molecular rotation lines - <b>cold molecular gas</b></p>	<p>Thermal Bremsstrahlung (free-free emission) - <b>HII regions</b></p> <p>Synchrotron Radiation - <b>jets in radio galaxies, pulsars, shocks in supernovae, cosmic ray electrons in the magnetic fields of normal galaxies etc., acceleration of electrons in stellar and planetary systems</b></p> <p>Thermal emission from dust - <b>cold dense gas</b></p>
<p><b>sub-mm (and FIR)</b></p>	<p>Molecular rotation lines - <b>warm, dense gas</b></p> <p>Solid state features (silicates) - <b>dust</b></p> <p>Hydrogen recombination lines - <b>ionised HII regions</b></p>	<p>Thermal emission - <b>warm dust</b></p>

# Radio Emission Processes

Example: the radio spectrum of a “normal” star forming galaxy like M82



# Radio Emission Processes

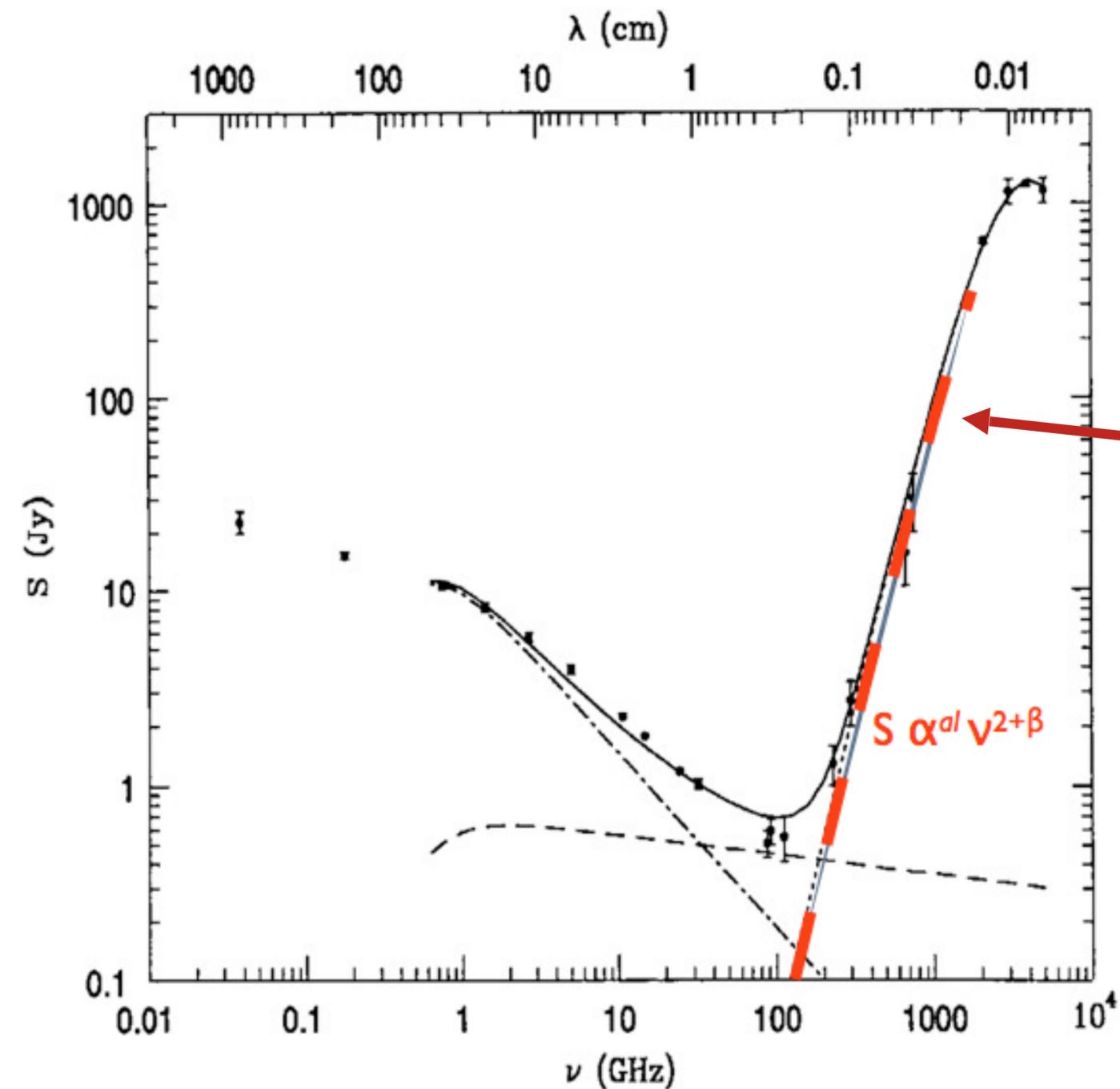


**Blue Line is a steep spectrum.**

synchrotron emission:

cosmic ray electrons accelerated in M82's magnetic field.

# Radio Emission Processes

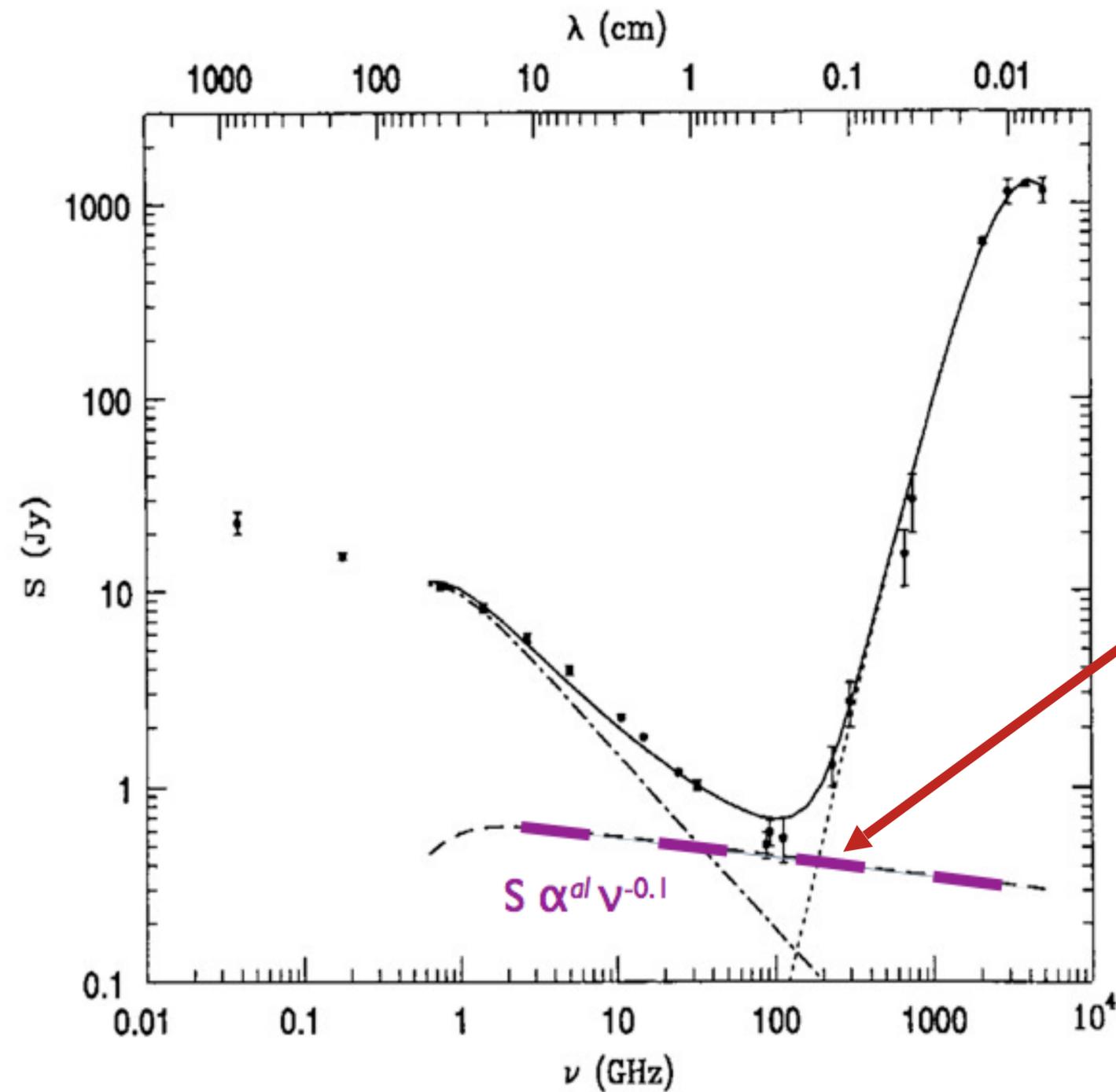


**Red line.**  
thermal BB emission:

- dust heated up by the uv-  
photons from massive  
stars.

The same stars that  
produced the supernovae

# Radio Emission Processes



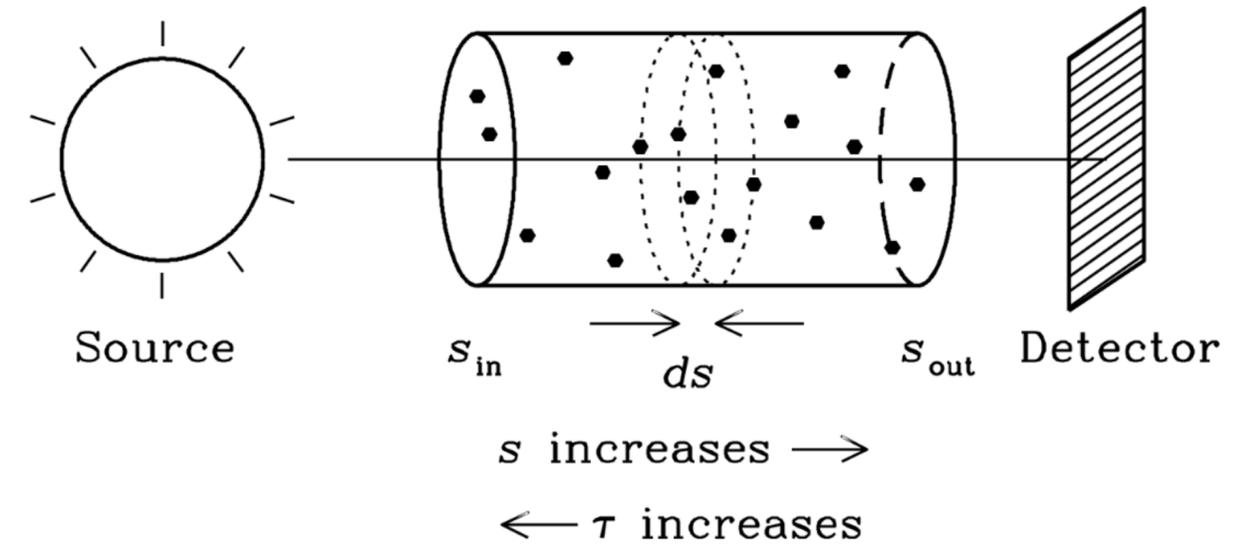


# Propagation of radio waves



# Radiative transfer

- ▶ Absorption coefficient
- ▶ Emission coefficient



Absorption coefficient:

$$\kappa \equiv \frac{dP}{ds} \quad \frac{dI_\nu}{I_\nu} = -\kappa ds$$

$$\frac{I_\nu(s_{out})}{I_\nu(s_{in})} = \exp \left[ - \int_{s_{in}}^{s_{out}} \kappa(s') ds' \right]$$

$$\tau \equiv - \int_{s_{out}}^{s_{in}} \kappa(s') ds' \quad \text{so} \quad \frac{I_\nu(s_{out})}{I_\nu(s_{in})} = \exp(-\tau)$$

Emission coefficient

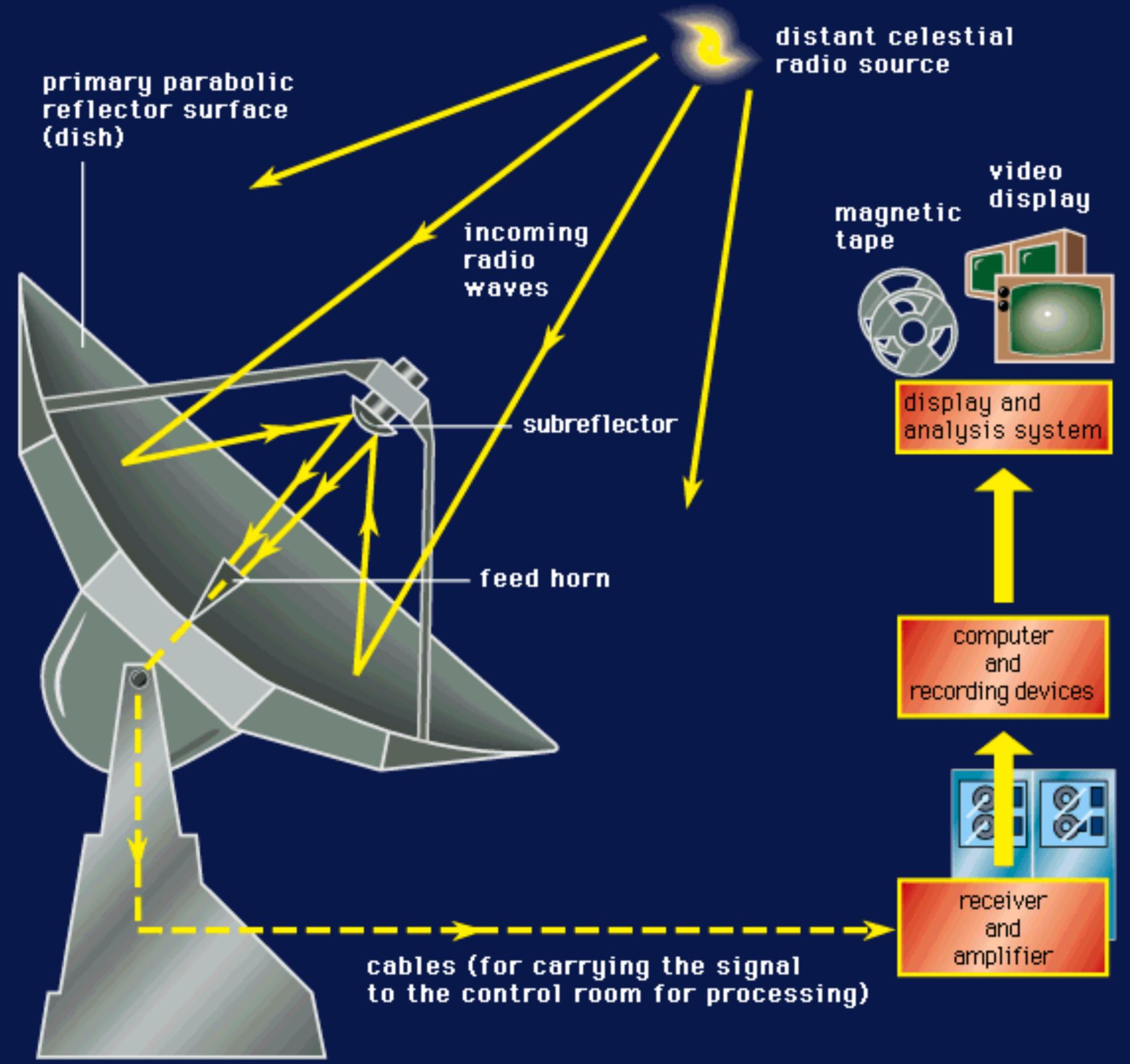
$$j_\nu \equiv \frac{dI_\nu}{ds}$$

Radiative transfer equation

$$\frac{dI_\nu}{ds} = -\kappa I_\nu + j_\nu$$



# How radio telescopes work?

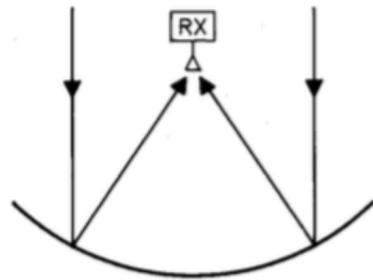


# Reflector antennas

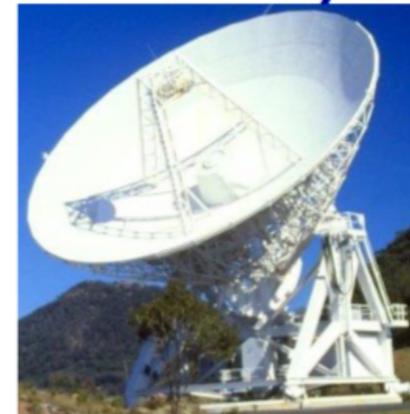
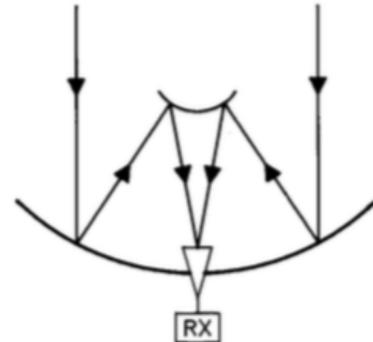
GMRT



Prime Focus



On-axis Cassegrain (best for array receivers)

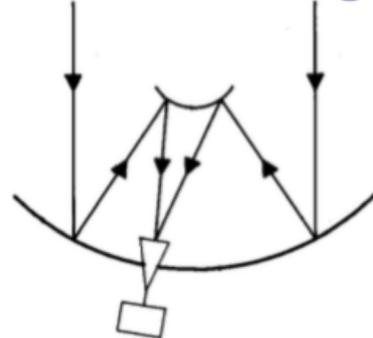


ATCA,  
Mopra

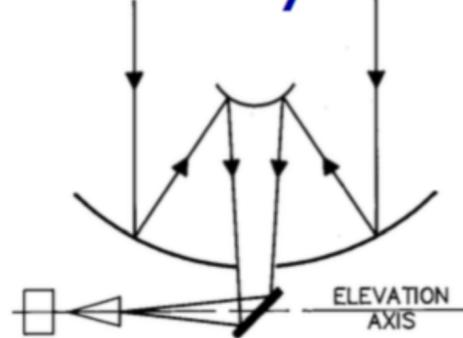
VLA,  
ALMA



Offset Cassegrain



Nasmyth

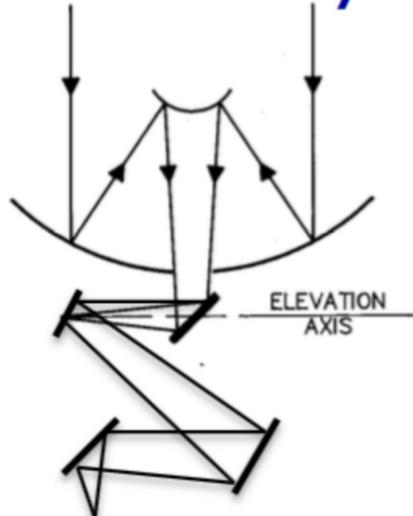


CARMA,  
CSO

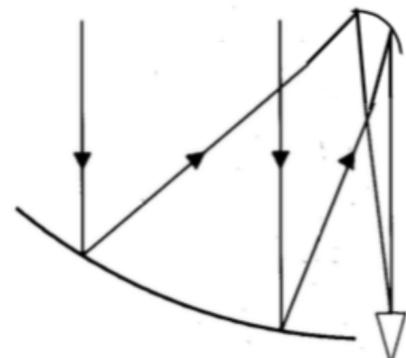
SMA



Bent Nasmyth



Dual offset Gregorian



GBT

Receivers do not tilt in elev.

Cleanest beam, minimizes standing waves, polarization asymmetry compensated -- Mizugutch et al. (1976)



# Reflector antenna efficiencies

Response pattern (primary beam):  $A(\nu, \theta, \phi) = A(\nu, \theta, \phi)/A_0$

Effective area (on-axis):  $A_0 = \eta A = (\text{aperture efficiency})(\pi R^2)$

where  $\eta = \eta_{\text{surface}} \eta_{\text{blockage}} \eta_{\text{spillover}} \eta_{\text{taper}} \eta_{\text{radiation}} \eta_{\text{misc}}$

$\eta_{\text{surface}} = \exp(-(4\pi\sigma/\lambda)^2)$        $\sigma = \text{rms surface error (Ruze 1966)}$

$= 0.44$  for  $\sigma = \lambda/14$  (VLA at 43 GHz)       $\sigma_{\text{VLA}} \sim 500 \mu\text{m}$

$= 0.79$  for  $\sigma = \lambda/26$  (VLA at 22 GHz)       $\sigma_{\text{ALMA}} \sim 25 \mu\text{m}$

$\eta_{\text{blockage}} = \text{blockage efficiency (feed legs and subreflector)}$

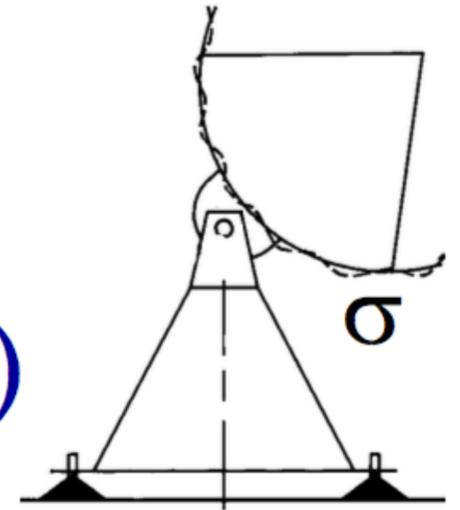
$\eta_{\text{spillover}} = \text{feed spillover efficiency}$

$\eta_{\text{taper}} = \text{feed taper efficiency}$

}  $\eta_{\text{illumination}} = 0.8$  for -10dB taper

$\eta_{\text{radiation}} = \text{metal reflection efficiency } (\sim 0.99 \text{ per Al mirror})$

$\eta_{\text{misc}} = \text{diffraction, phase, focus error, polarization efficiencies}$

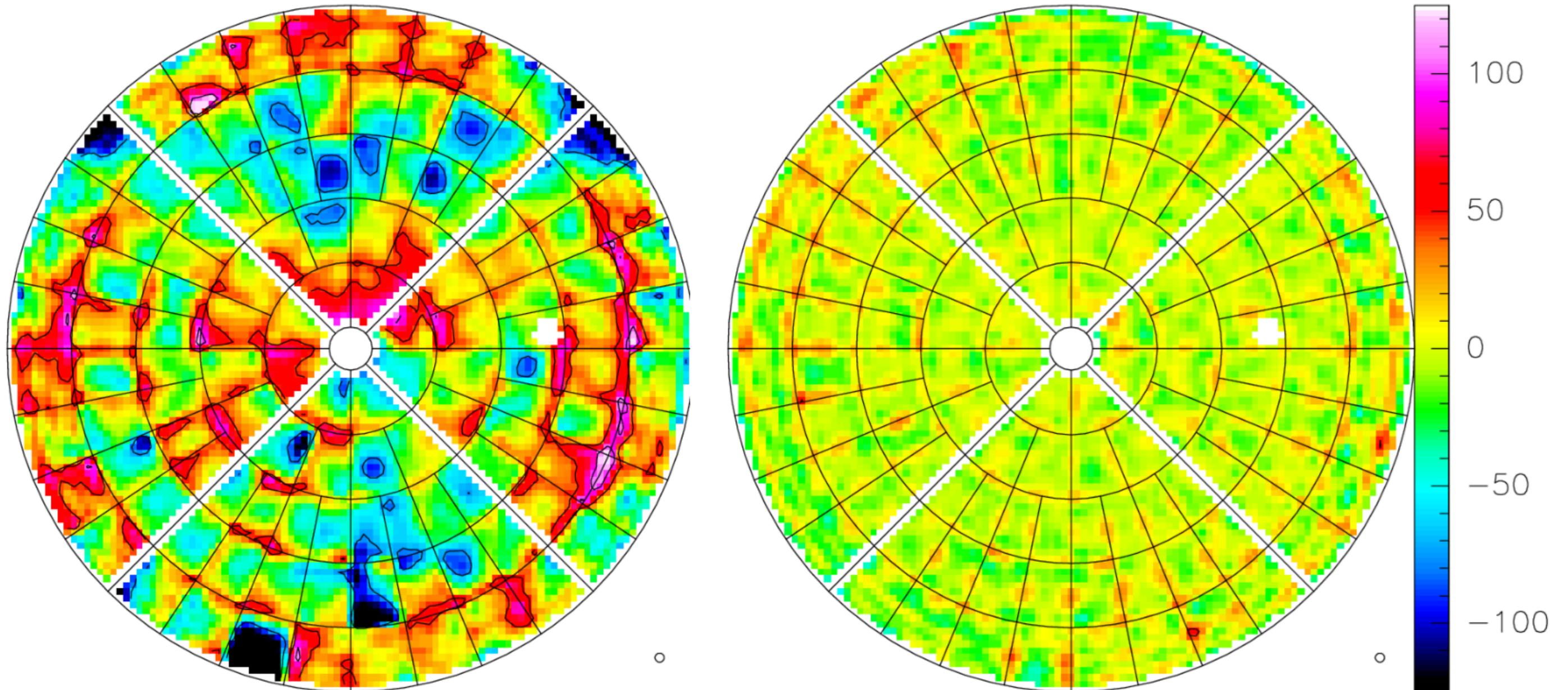


# Holography: ALMA surface panel adjustment

Phase map converted to path length error from ideal paraboloid

Before adjustment ( $43\mu\text{m}$ )

After adjustment ( $11\mu\text{m}$ )





# Amplifiers and mixers

Let's compare an amplifier and a mixer:

I. Amplifiers are 2-port devices: one input and one output



Example: NRAO Cryogenic Low Noise Amplifiers (LNAs) using Heterostructure Field Effect Transistors (HFETs) used on the VLA, VLBA, GBT:

- Operate at ~15 K
- $T_{noise} \sim 5 hf/k$   
(i.e. 5 x quantum limit)
- M. Pospieszalski (2012)  
(MIKON conference)

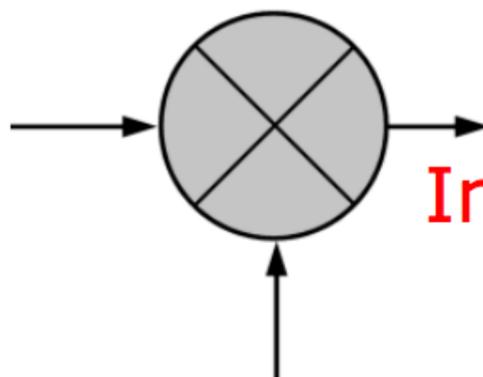


# What is a mixer?

Mixers are 3-port devices: LO and RF inputs, and IF output.

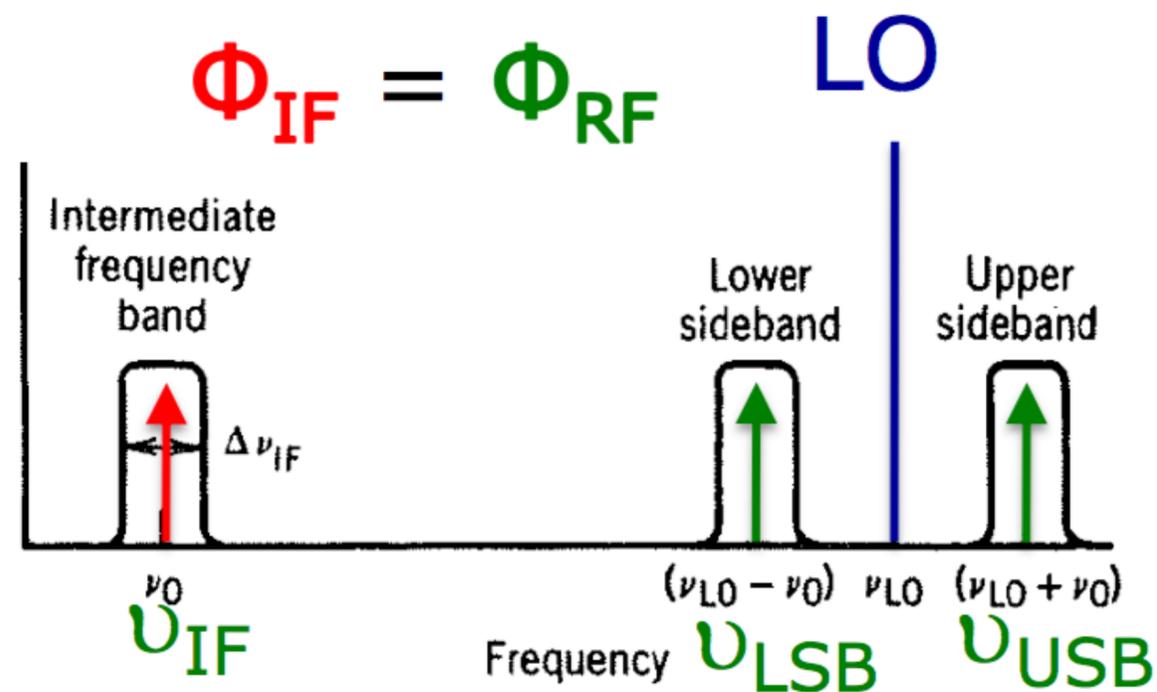
- Invented around WWI for radio direction finding (see IEEE Microwave Magazine Sept. 2013 special issue).
- They multiply the LO & RF signals and transfer the phase from the RF to the IF by “heterodyning”. Typically the IF contains signals from two sidebands.
- They are key components for interferometers!!

RF input  
= “Radio”  
Frequency



IF output =  
Intermediate Freq.

LO = Local Oscillator



$$\sin(2\pi f_1 t) \sin(2\pi f_2 t) = \frac{1}{2} \cos[2\pi(f_1 - f_2)t] - \frac{1}{2} \cos[2\pi(f_1 + f_2)t]$$



# Calibrating single-dish telescope data

- Convert from power densities to antenna temperatures
- Correct bandpass and pointing errors
- Derive Kelvin to Jansky conversion factor
- Apply to target

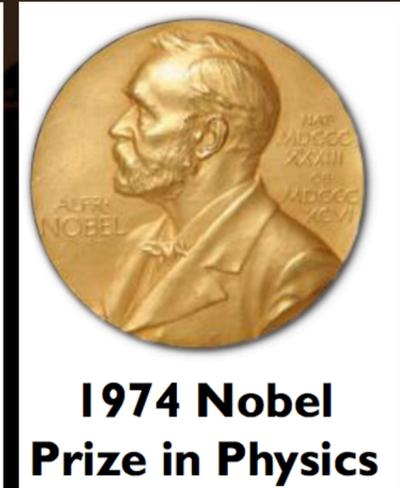
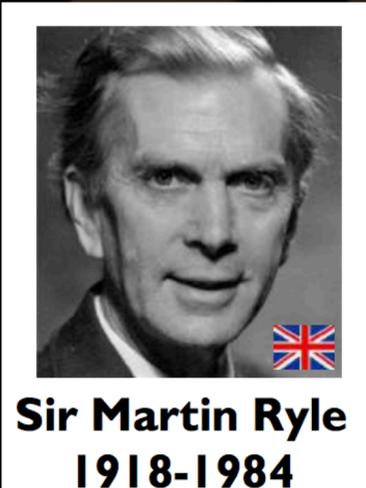
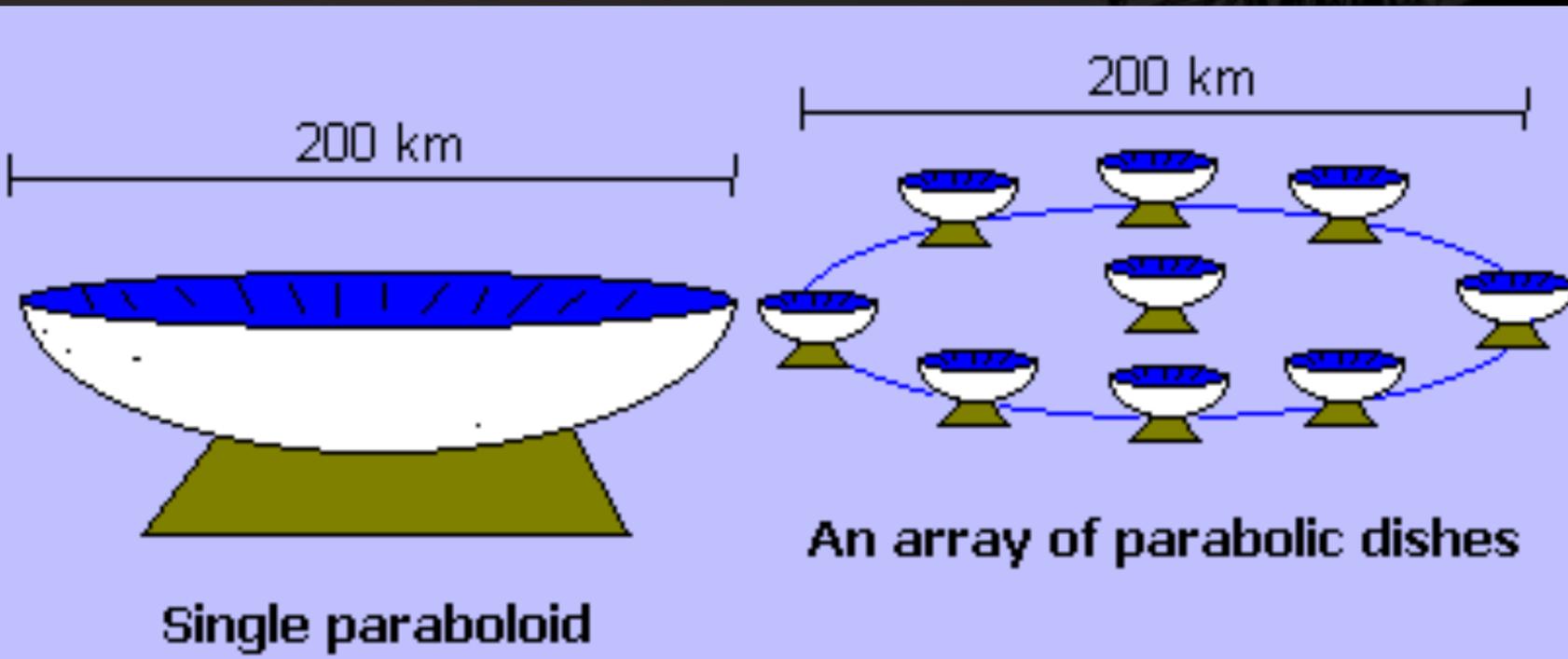
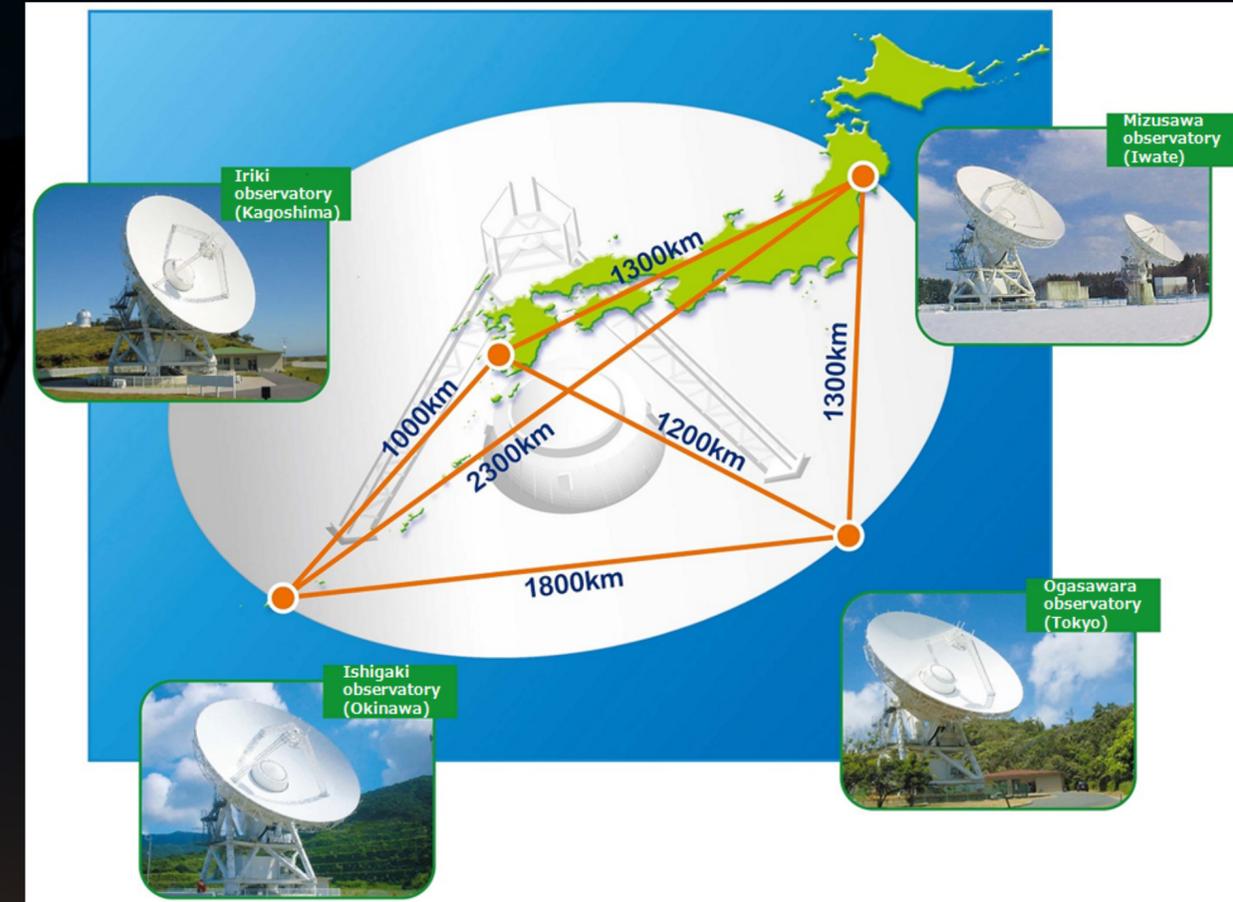
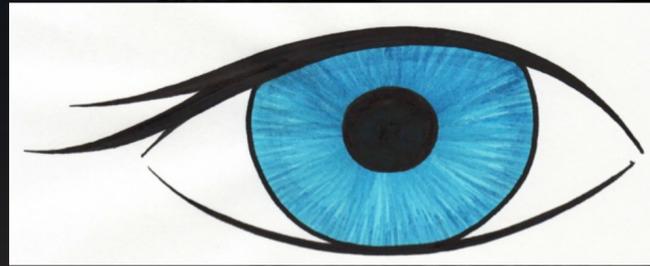
$$T_s = T_{\text{cmb}} + T_{\text{rsb}} + \Delta T_{\text{source}} + [1 - \exp(-\tau_A)]T_{\text{atm}} + T_{\text{spill}} + T_r + \dots$$



# Radio interferometry

$$\theta \sim \lambda/D \sim \lambda/B$$

<b>Eye</b>	D ~ 1mm	$\lambda = 600\text{nm}$	$\theta \sim 2'$
<b>GBT</b>	D = 100m	$\lambda = 6\text{cm}$	$\theta \sim 2'$
<b>HST</b>	D = 2.4m	$\lambda = 500\text{nm}$	$\theta \sim 50 \text{ mas}$



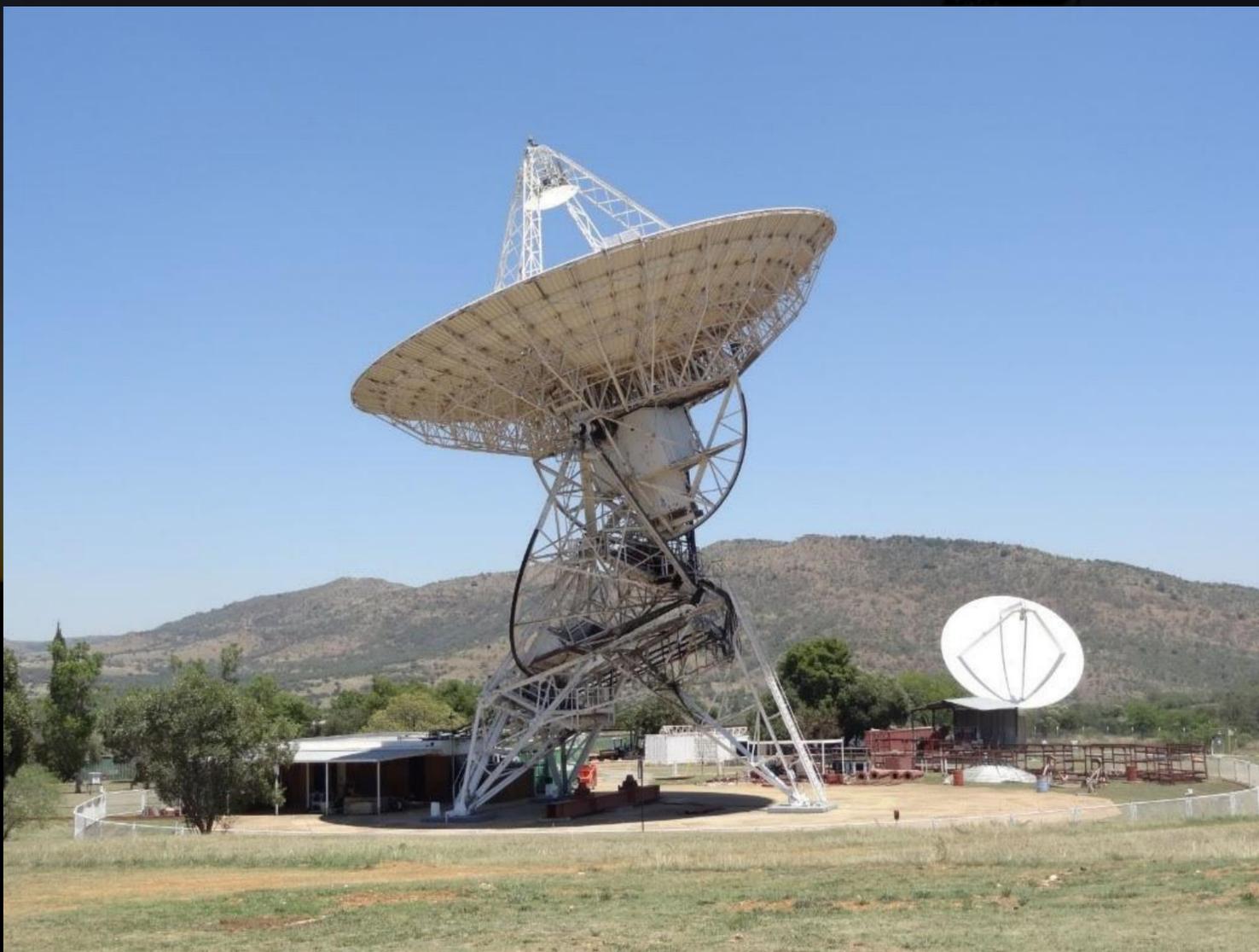


# Radio astronomy facilities in Africa





# HartRAO/SARAO telescopes

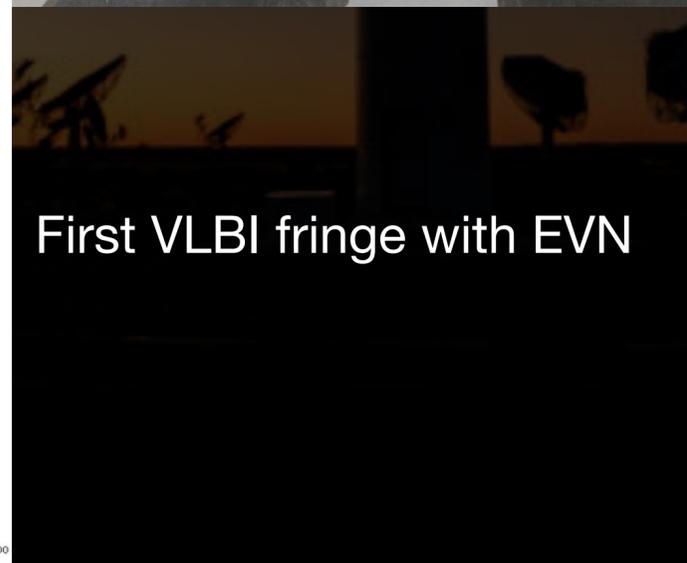
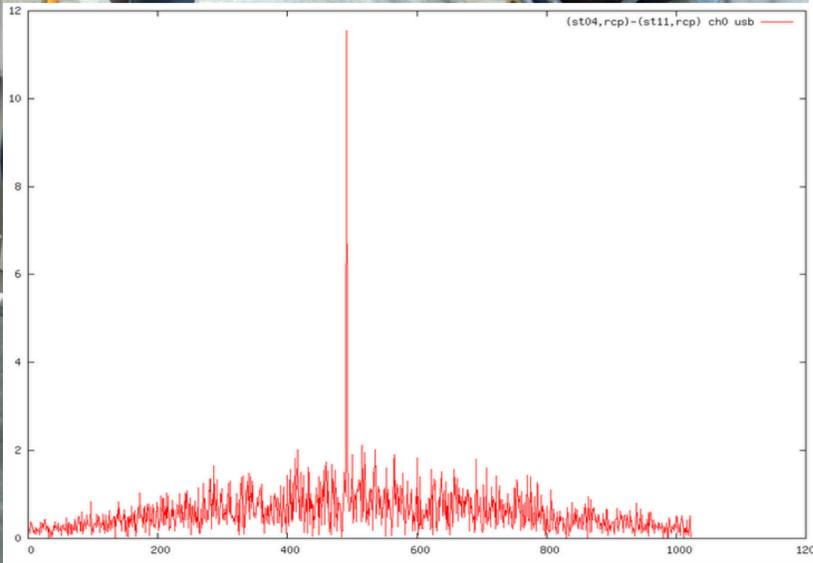
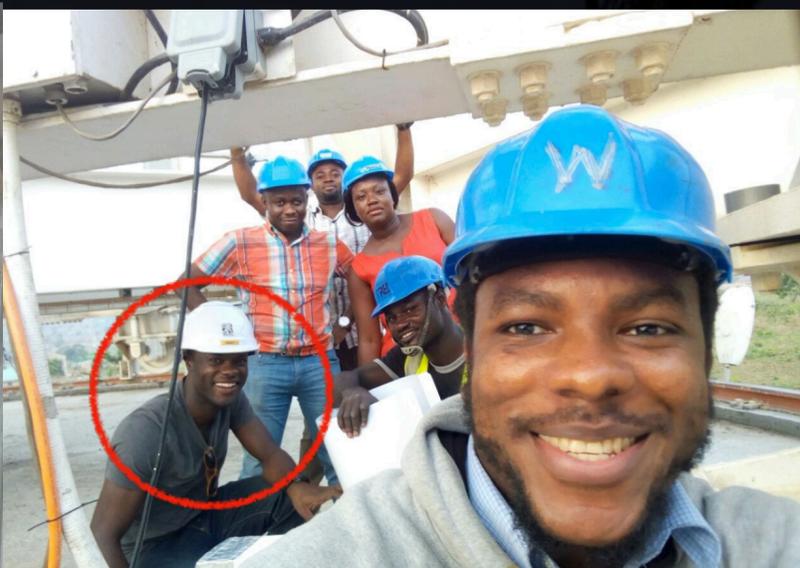


## HartRAO 26m telescope, 15m XDM and 13.2m VGOS

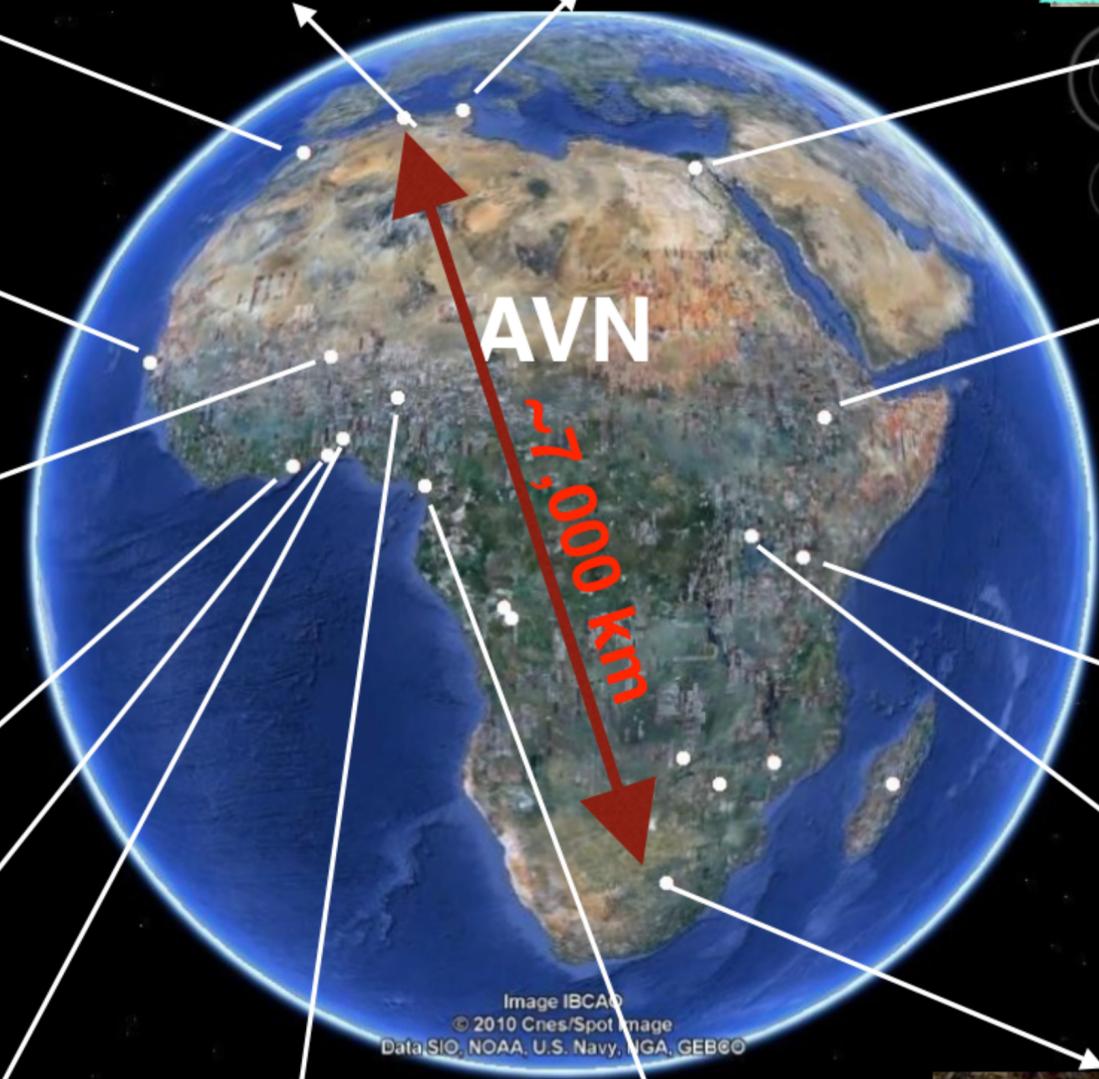
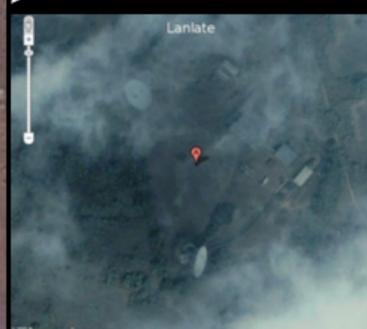
- Still up and running (Single-dish and VLBI with EVN/LBA)
- Bearing failure may happen in the near future
- Impact of the slow failing bearing already seen in data
- 15m eXperiment Development Model (XDM: 2007) used for geodetic observations
- 13.2m VGOS antenna, not yet fully operational

# Ghana 32m radio telescope

- Ambient C-band dual-polarization receiver
- Maser monitoring observations
- Successful fringe tests with EVN (5 GHz) and single baseline test with HartRAO 26m (6.7 GHz)
- H-maser clock installation expected in few months



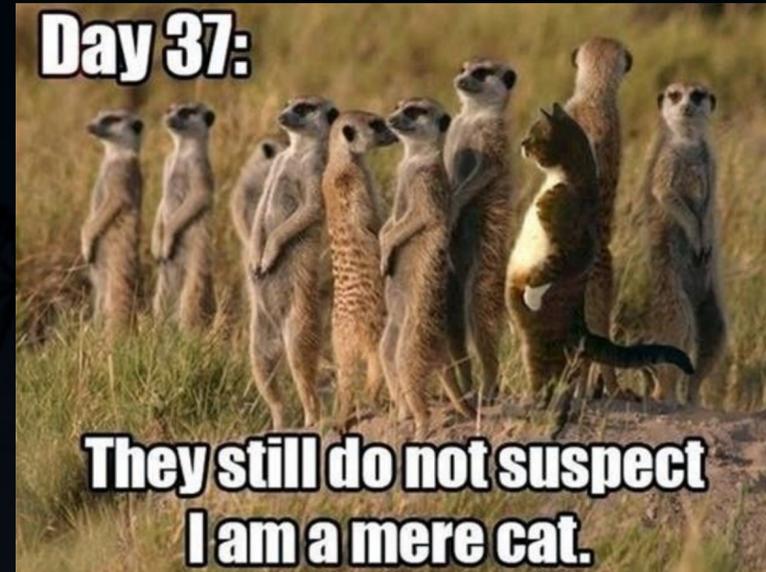
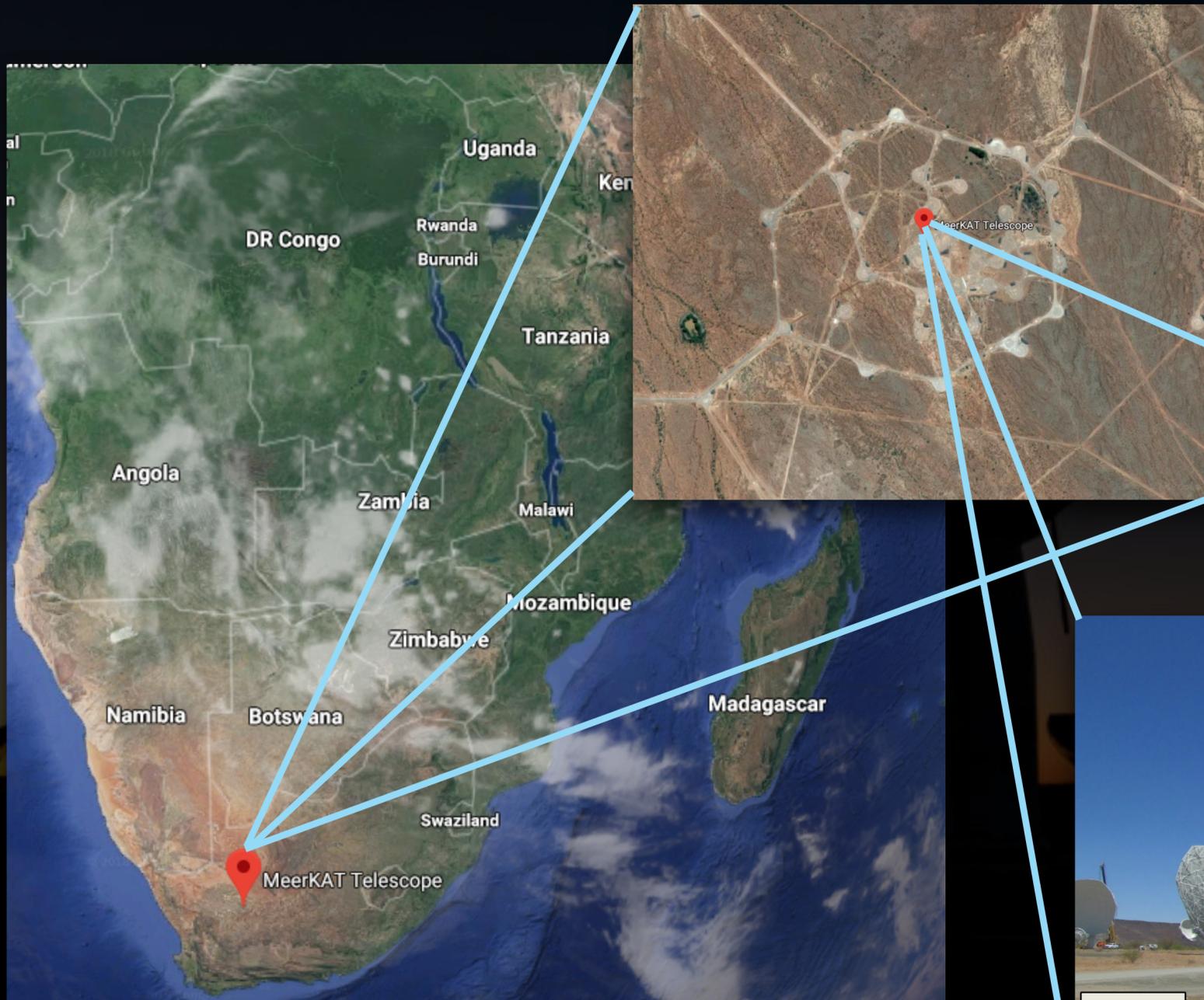
First VLBI fringe with EVN



Ultimate goal

African VLBI Network

# MeerKAT telescope





# Scientific Output from African Radio Facilities

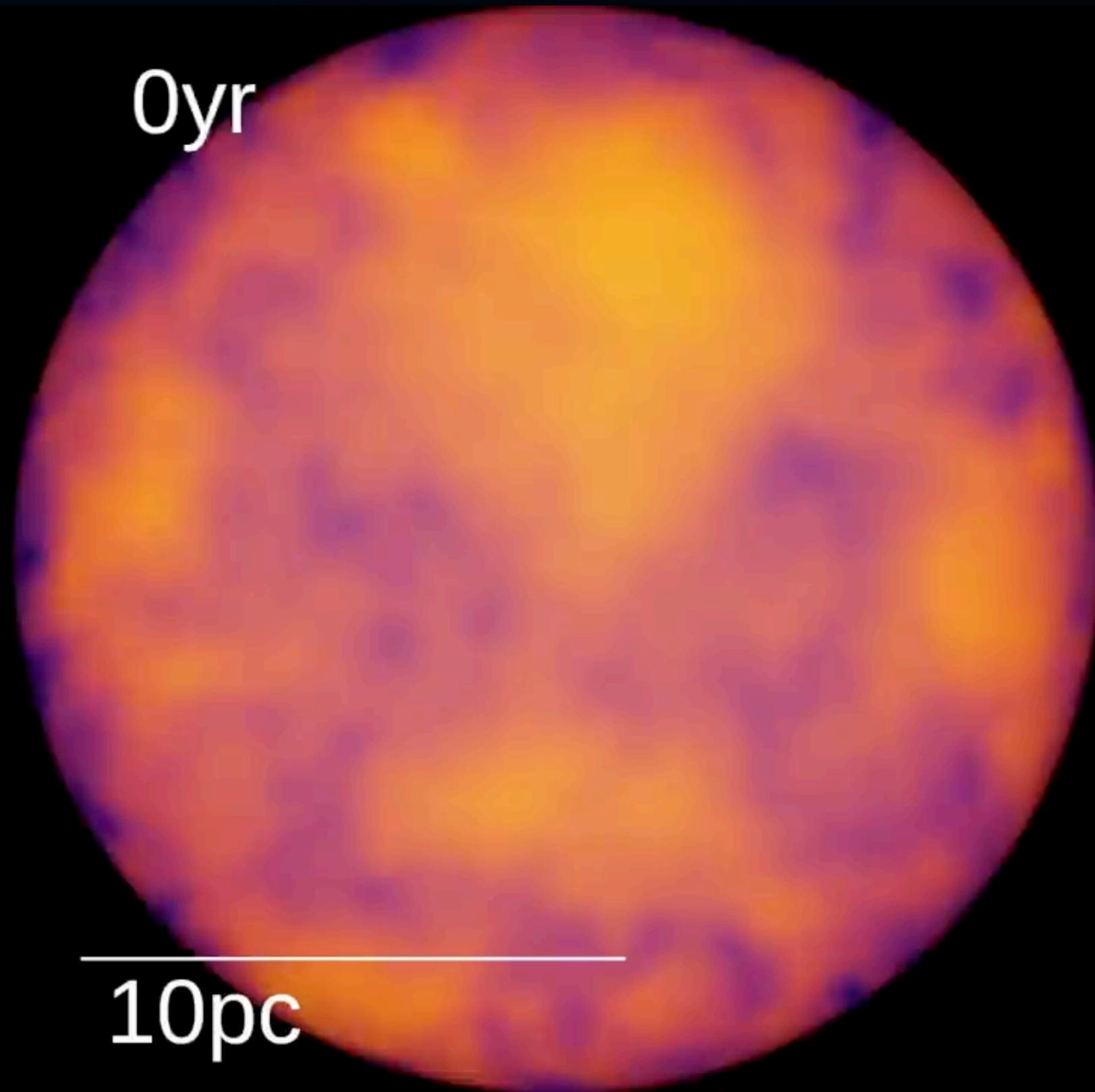




# Star formation

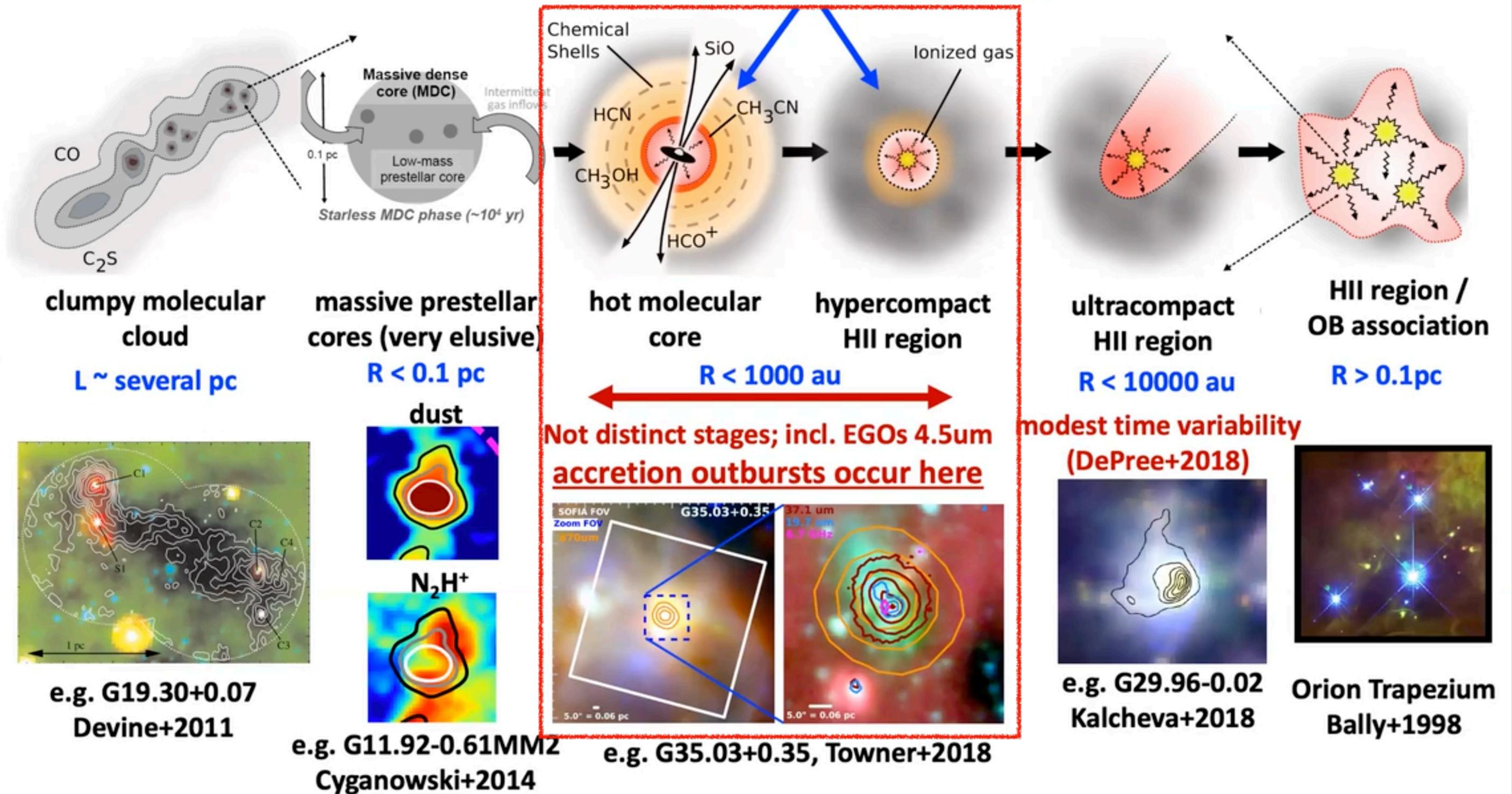


# Star formation

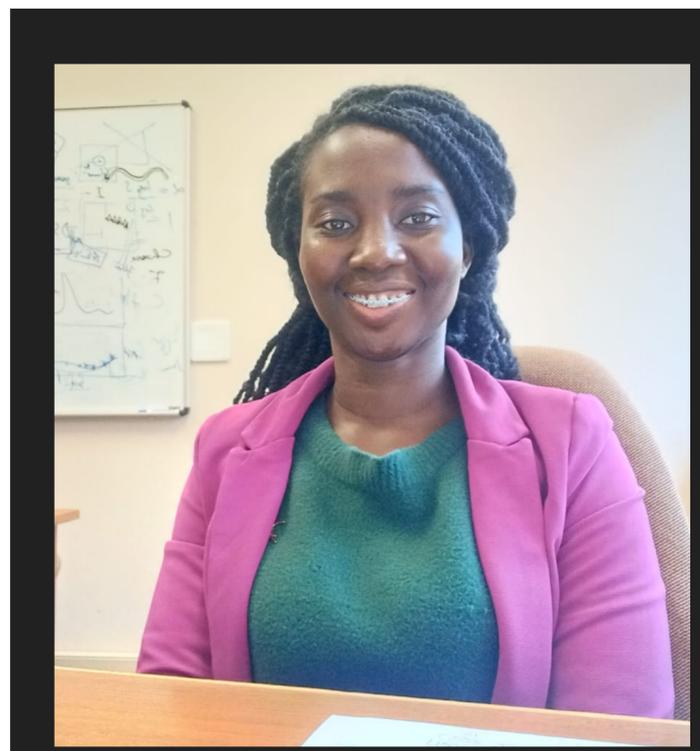
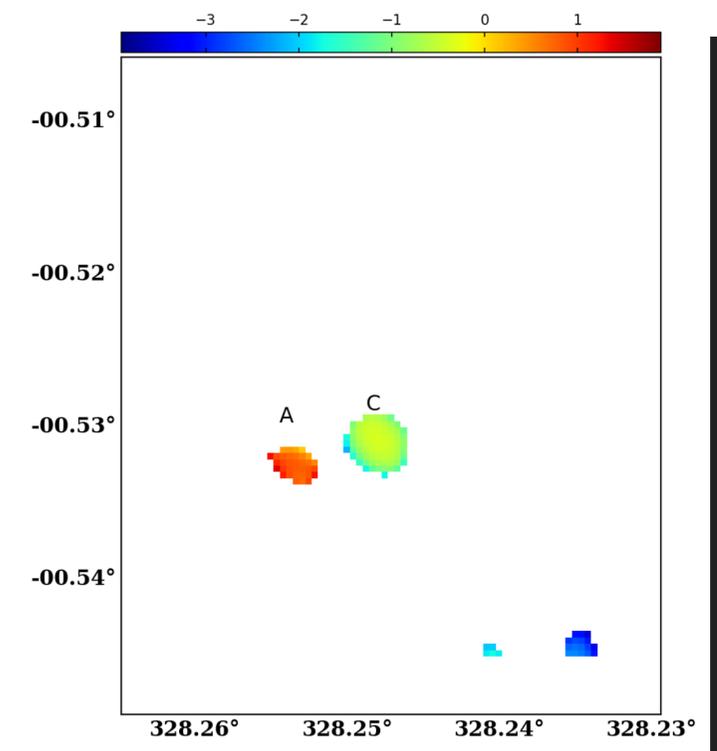
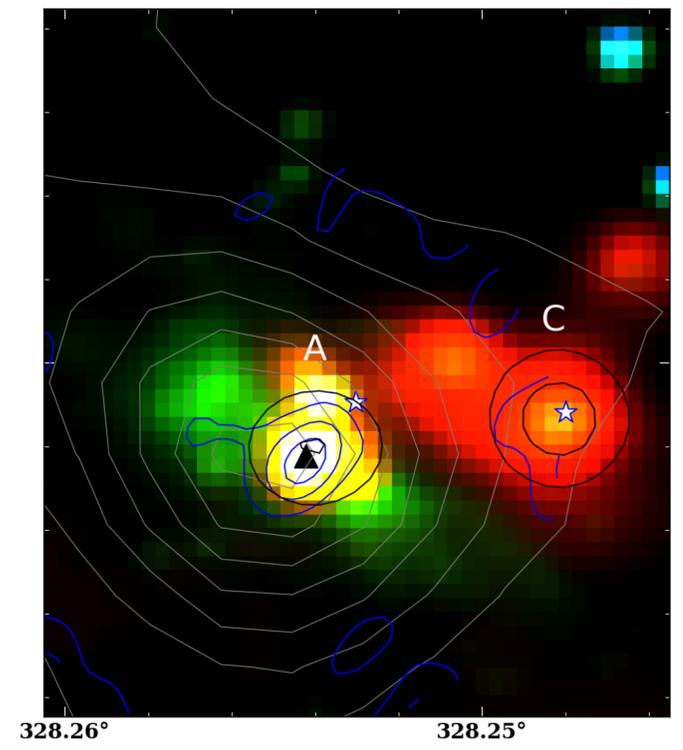
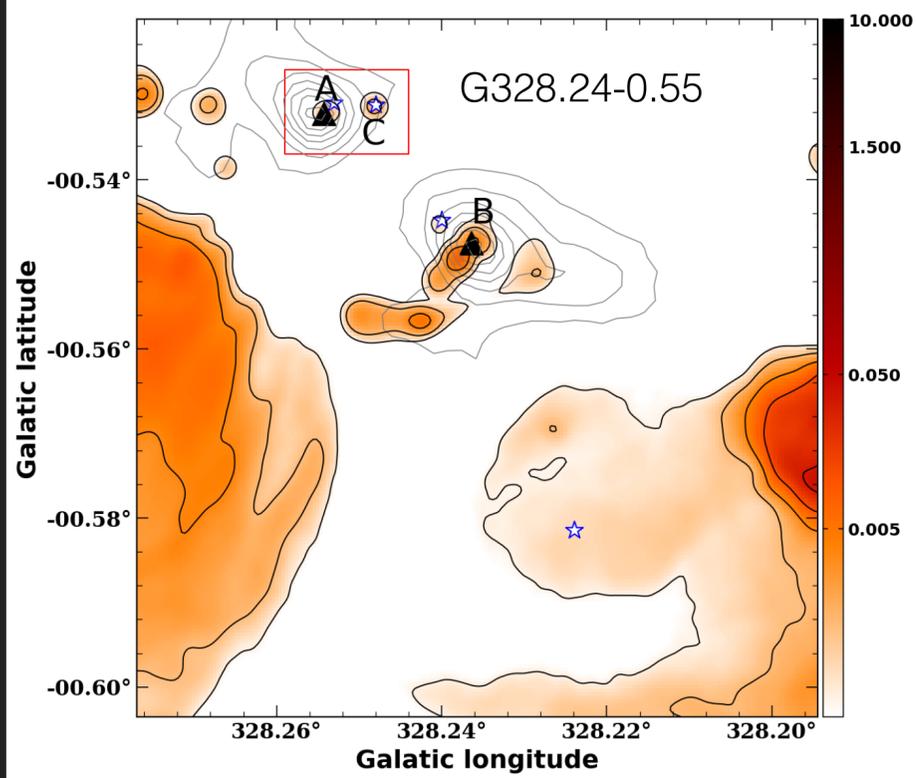
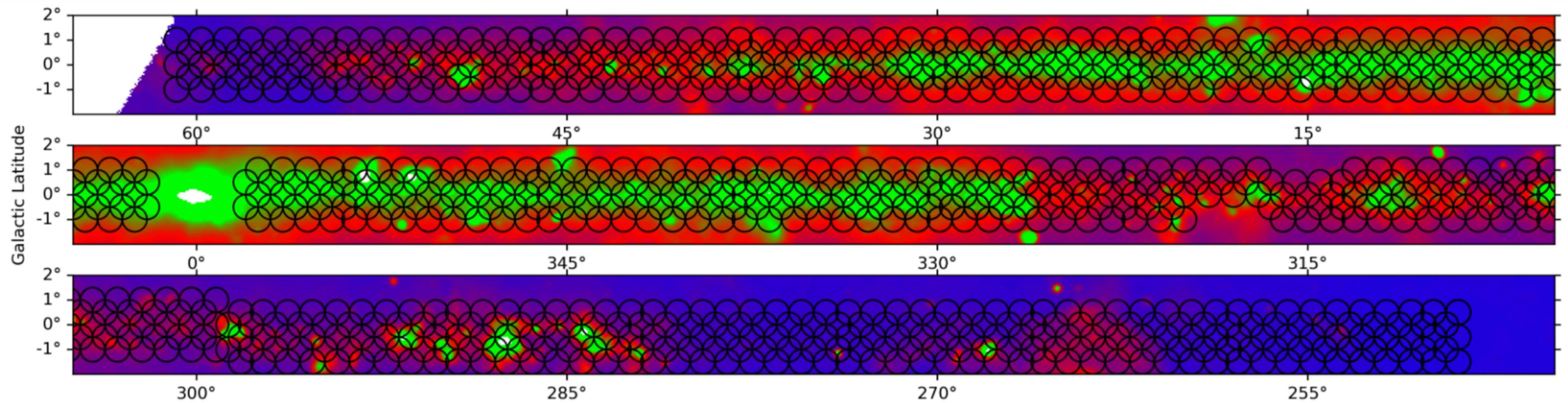


# Evolutionary stages of high-mass stars

## COMs: Complex Organic Molecules



# Capitalize on the tremendous sensitivity of MeerKAT $\sim 5 \mu\text{Jy}/\text{beam}$

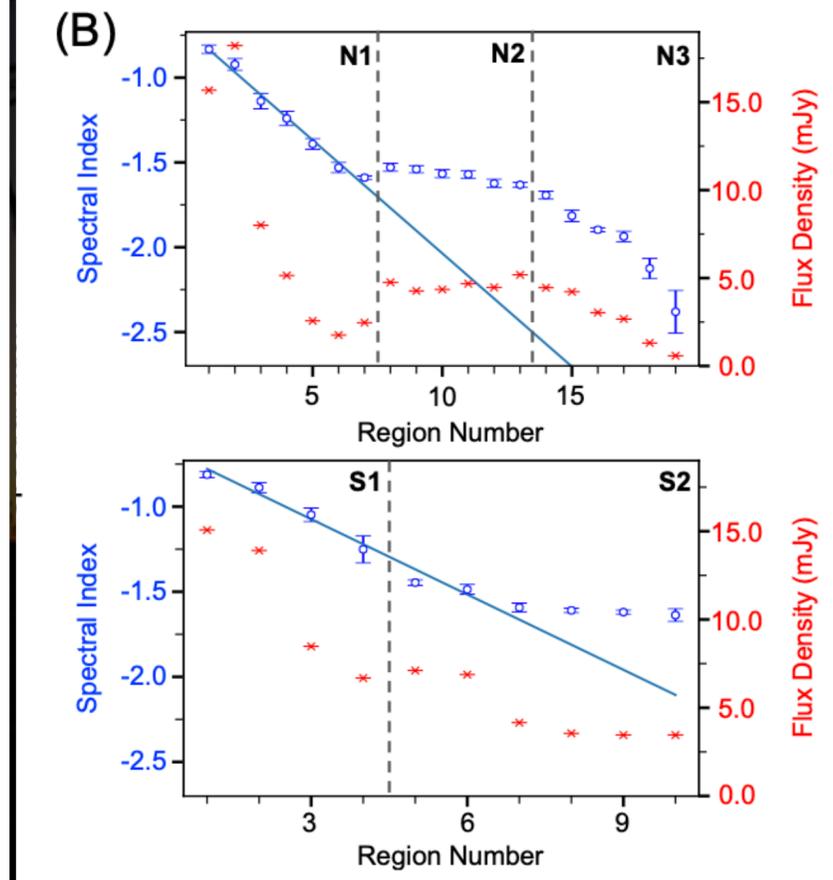
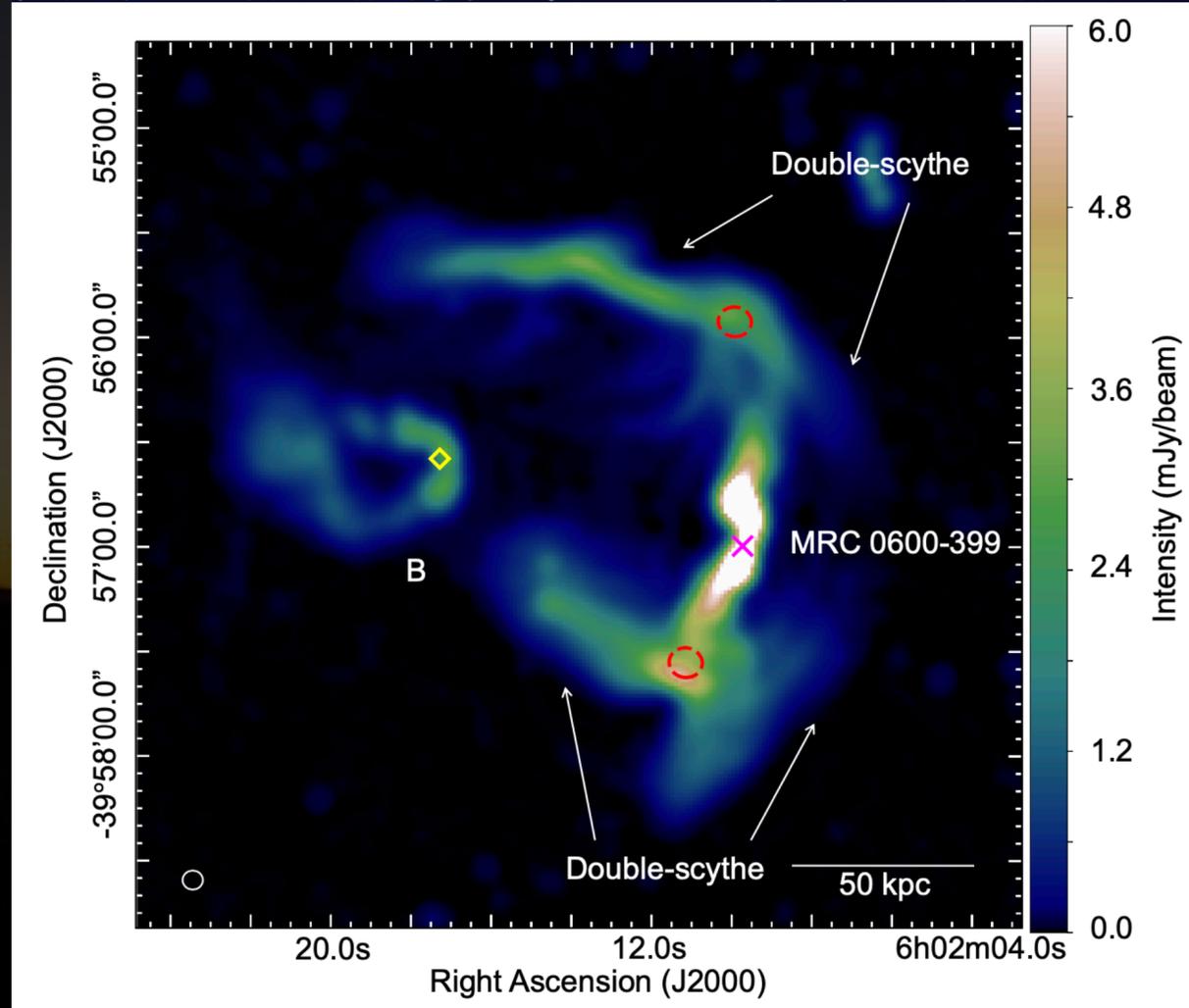
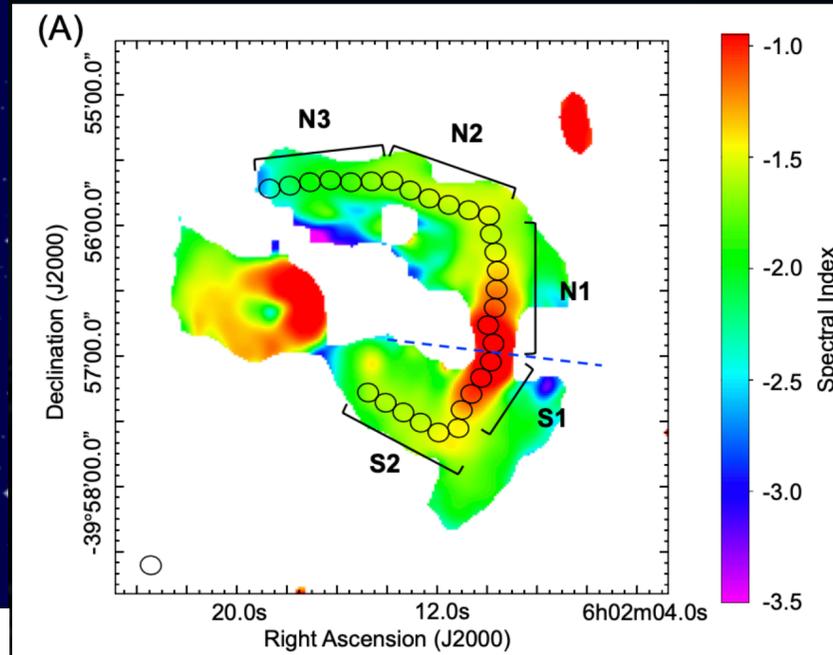
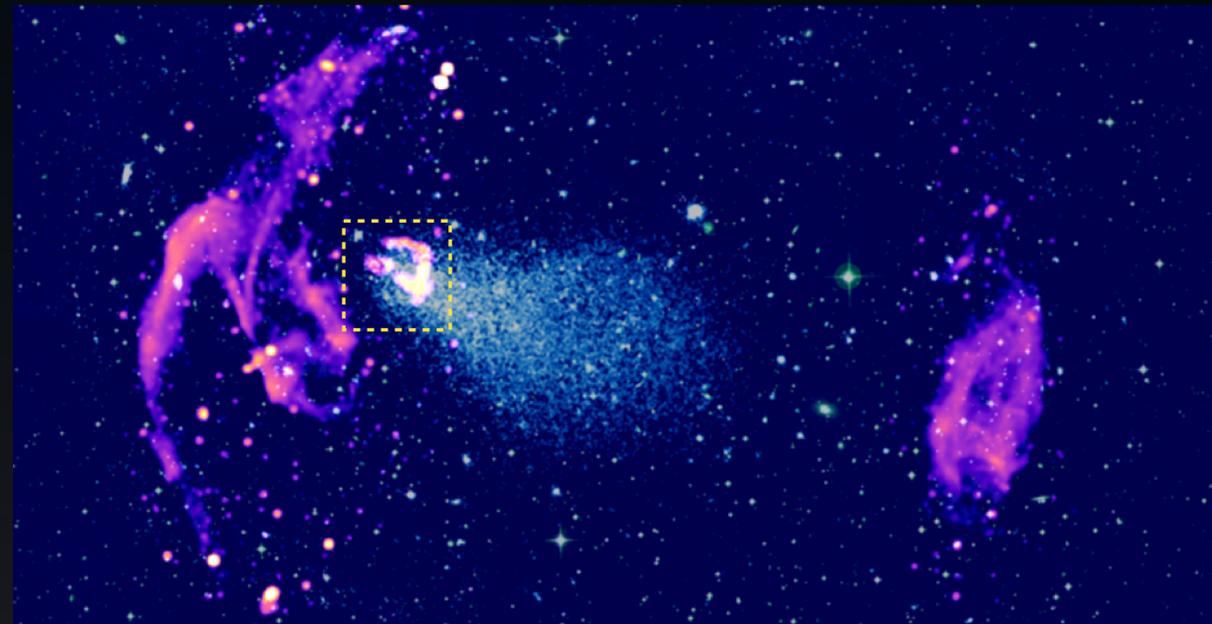




# Galaxy Cluster and Intra-cluster Magnetic Field



# Galaxy Cluster and Intra-cluster Magnetic Field



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nature > articles > article

Article | Published: 05 May 2021

**Jets from MRC 0600-399 bent by magnetic fields in the cluster Abell 3376**

James O. Chibueze , Haruka Sakemi , Takumi Ohmura , Mami Machida, Hiroki Akamatsu, Takuya Akahori, Hiroyuki Nakanishi, Viral Parekh, Ruby van Rooyen & Tsutomu T. Takeuchi

Nature 593, 47–50 (2021) | Cite this article

3029 Accesses | 2 Citations | 212 Altmetric | Metrics

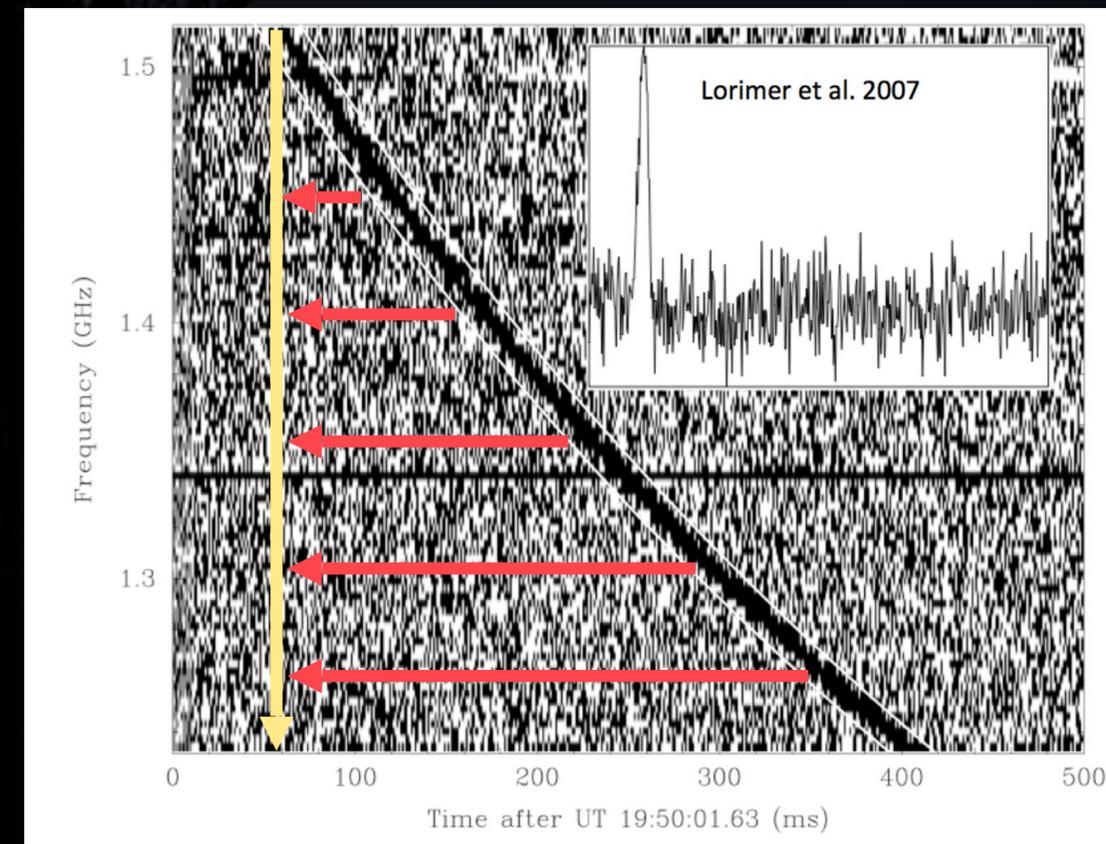


# Fast Radio Bursts (FRBs)

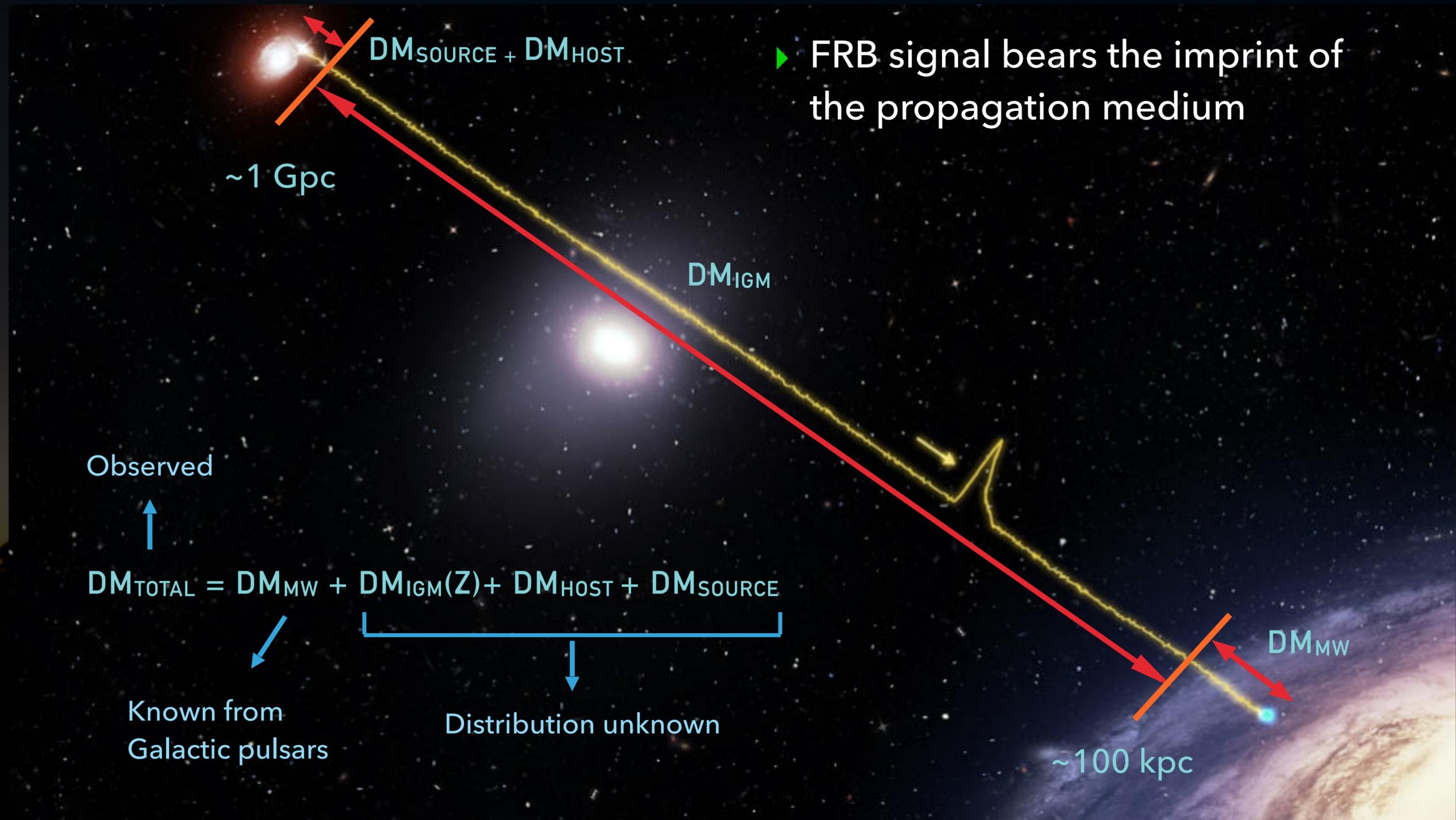


## FRBS IN A NUTSHELL

- ▶ Millisecond duration bursts with microsecond sub-structures
- ▶ Extremely energetic events ( $< 10^{44}$  erg s $^{-1}$ ) from  $z_{\text{spec}} \sim 0.03$  to 0.66
- ▶  $\sim 10,000$  events/sky/day
- ▶ Some repeat!
- ▶  $DM = \int n_e dl$  pc cm $^{-3}$   $\rightarrow$  proxy for distance
- ▶ Detected from 110 MHz to 8 GHz.

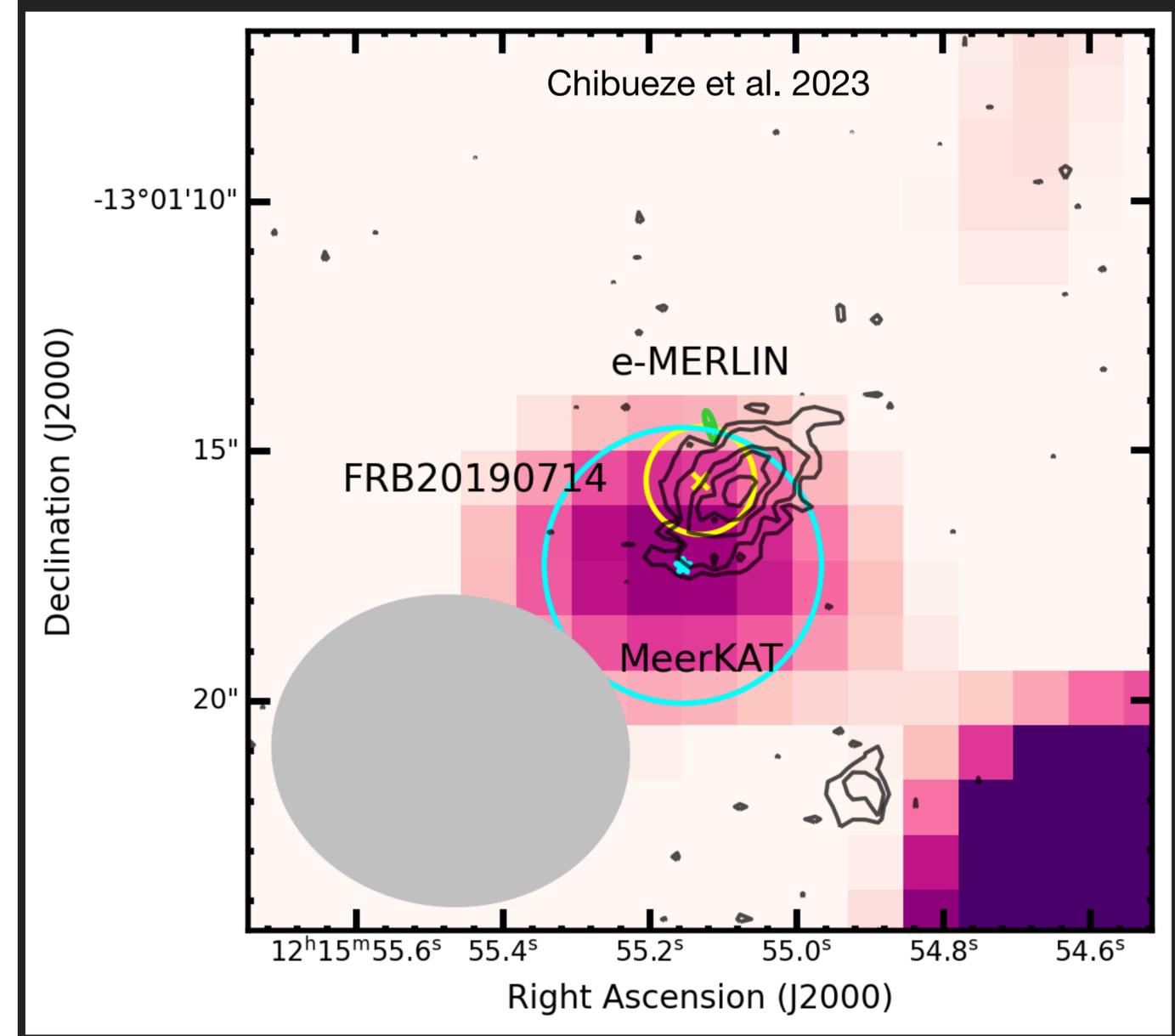
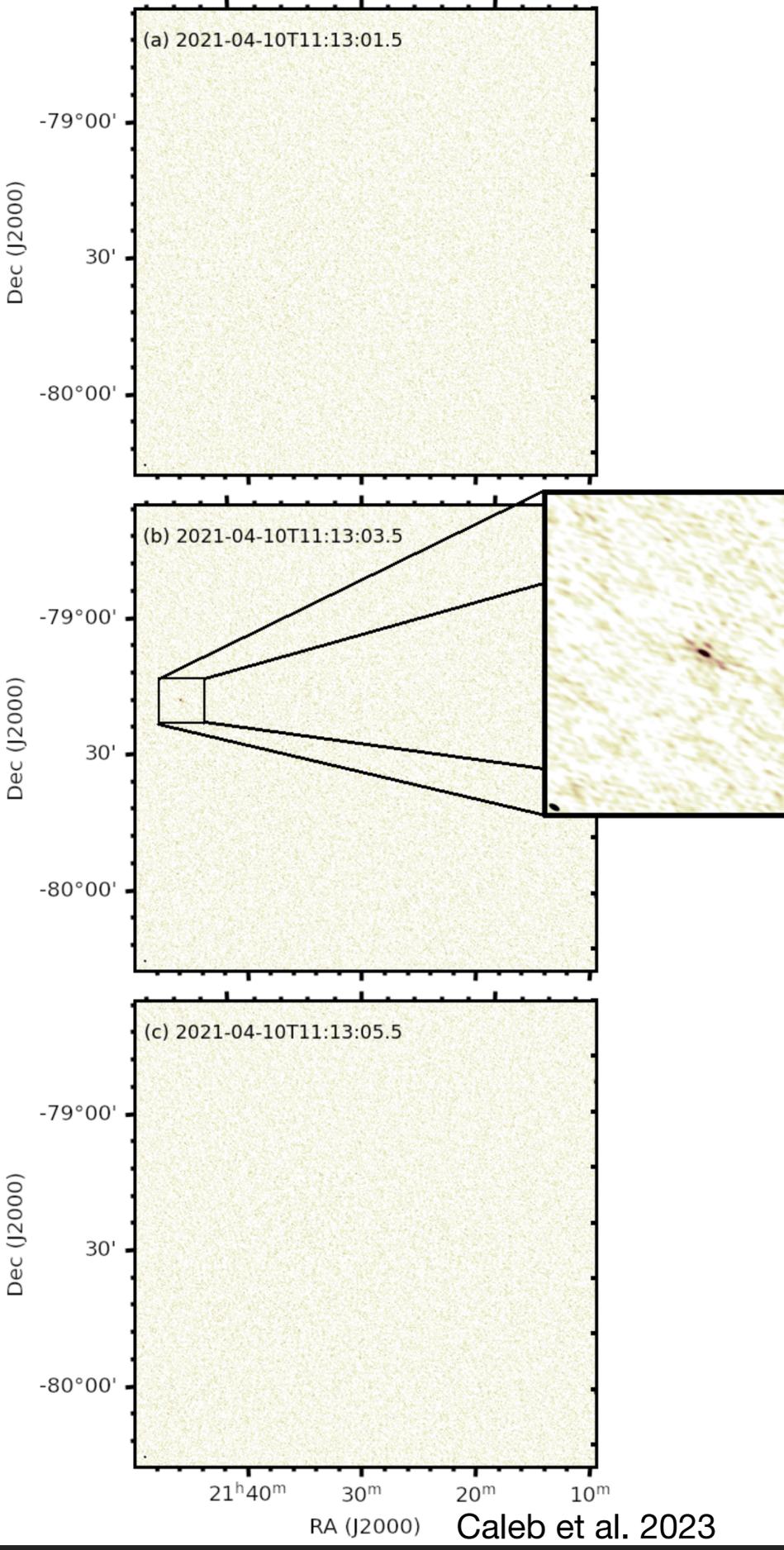


# FRBS IN A NUTSHELL

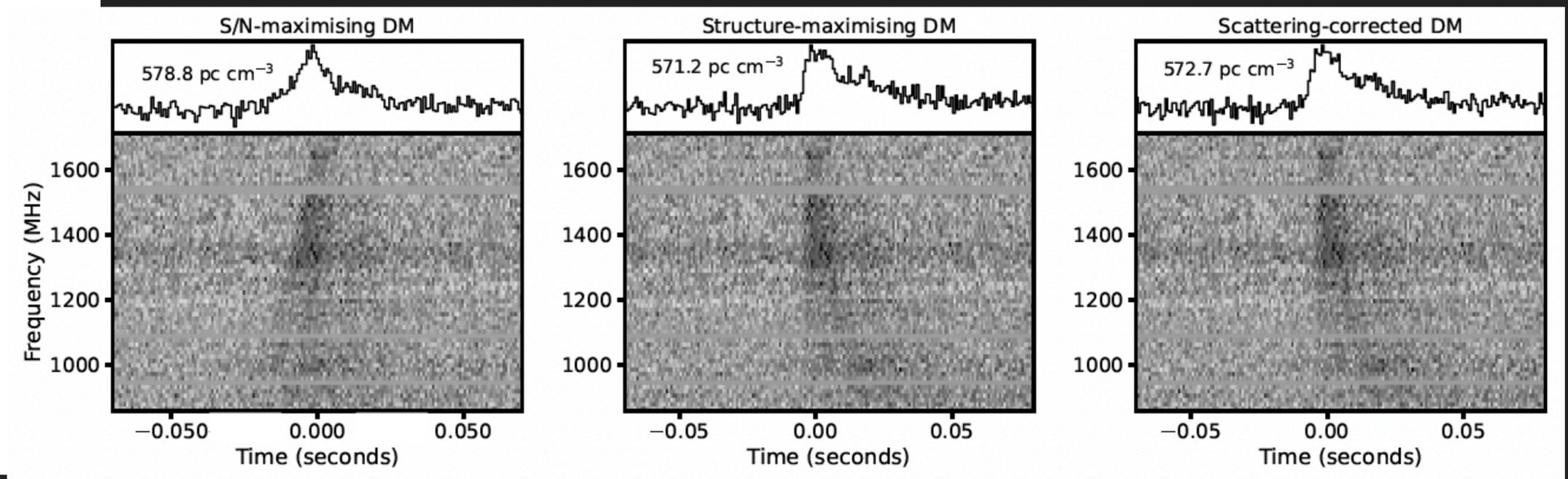


## PUTTING IT ALL TOGETHER: OBSERVATIONS

- ▶ ~600 known FRBs of which ~20 repeat (published)
- ▶ Repeaters and non-repeaters have same underlying DM and fluence distributions (*CHIME FRB catalog 2021*)
- ▶ Repeater pulses are intrinsically broader in width and narrower in bandwidth (*Pleunis et al. 2021*)
- ▶ Repeater bursts show complex time-frequency structures (*Pleunis et al. 2021, Hessels et al. 2019*)
- ▶ *Global landscape of polarimetric properties is diverse*



MeerKAT's detection of FRBs and radio continuum associated with FRBs



# PUTTING IT ALL TOGETHER: FRB MODELS

- ▶ Magnetospheric origin
- ▶ Shock wave models

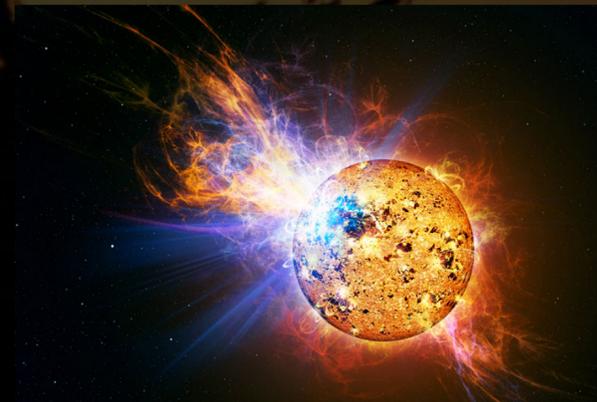
## Magnetars:

- ▶ Young magnetar from SLSN
- ▶ Magnetar from CCSN
- ▶ Magnetar from DNS merger



## Pulsars:

- ▶ Pulsar giant flares
- ▶ Young SNR pulsars



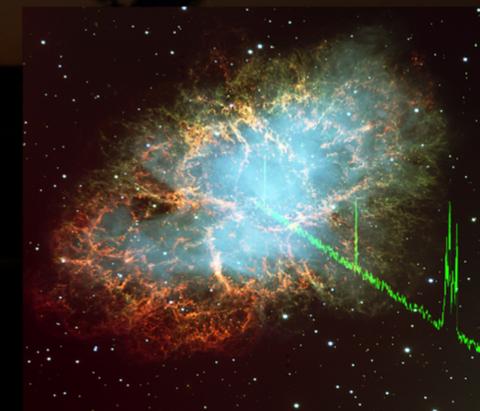
## White dwarfs:

- ▶ WD from WD-WD merger
- ▶ White dwarf collapse



## Compact-object mergers:

- ▶ NS-NS merger
- ▶ WD-WD merger
- ▶ NS-BH merger
- ▶ BH-BH merger



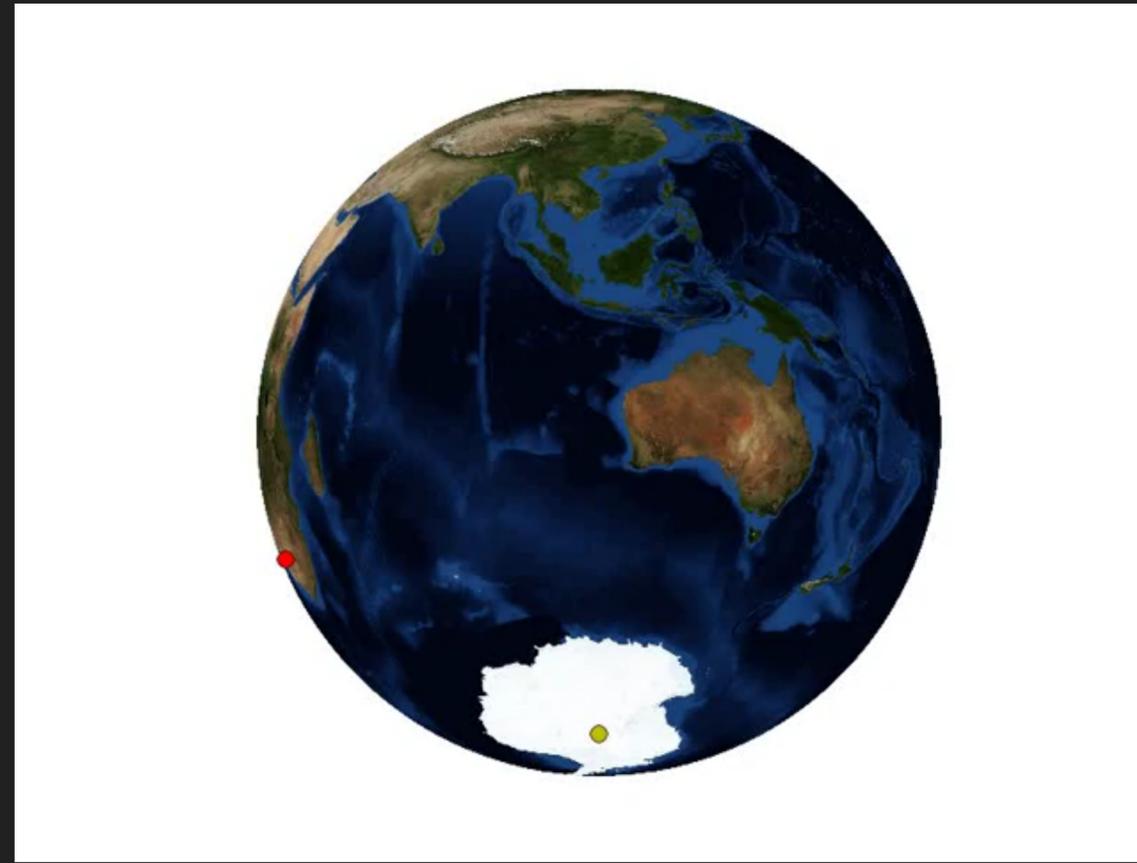
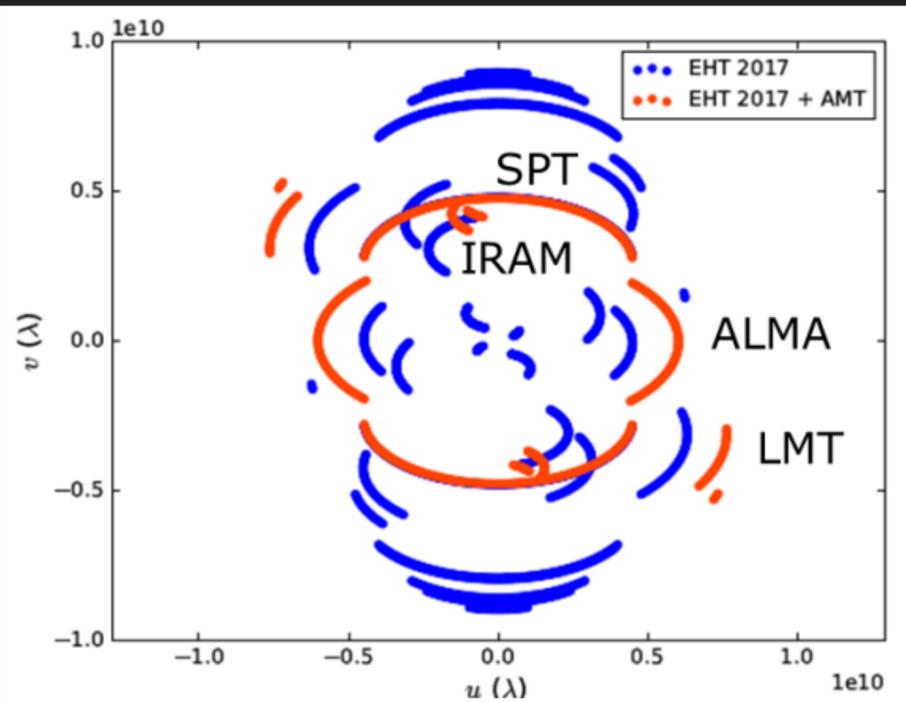


Future facilities and efforts to spread radio astronomy across all of Africa

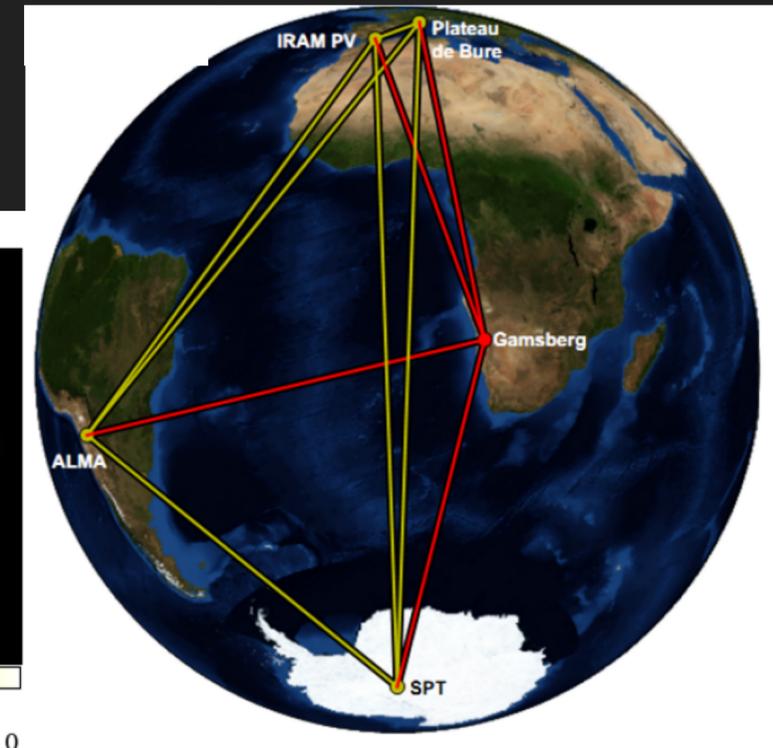
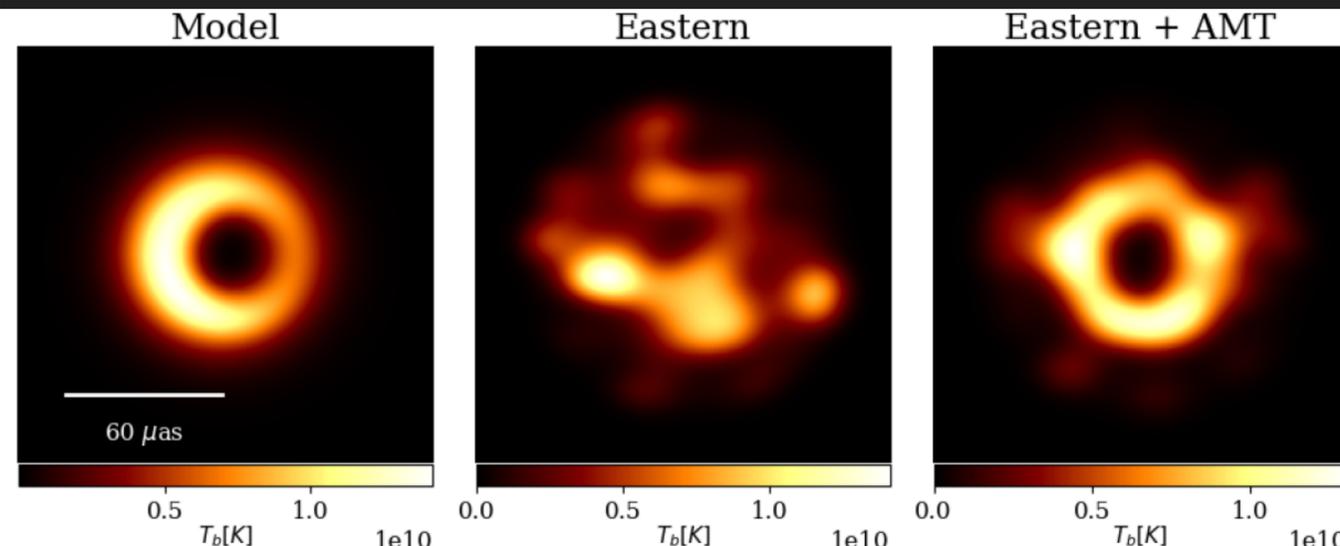
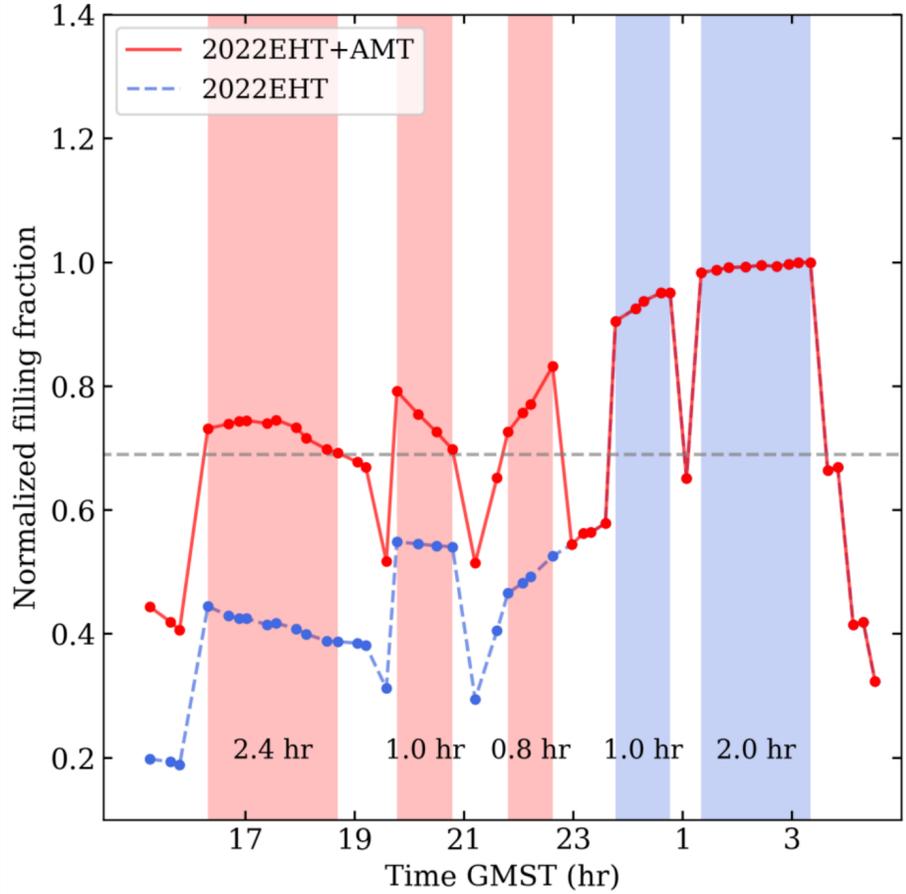




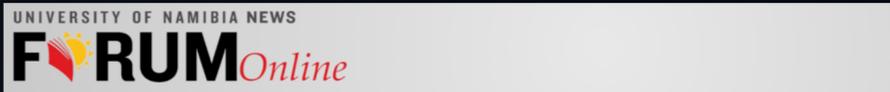
# African Millimeter Telescope (AMT) as part of EHT and AVN



Earth as seen from Sgr A\*



# African Millimeter Telescope (AMT)



ALL NEWS CAMPUS NEWS RESEARCH & INNOVATION CAREERS CONNECT UNAM CARES ALUMNI ARTS & CULTURE

Astronomers receive ERC Synergy Grant to make colour movies of black holes and build new telescope in Africa



- Co-Is
- Elina Lindfors Univ. Turku
  - Michael Backes Univ. Namibia

13.8M€ (+12M€ from RU)

## PIs

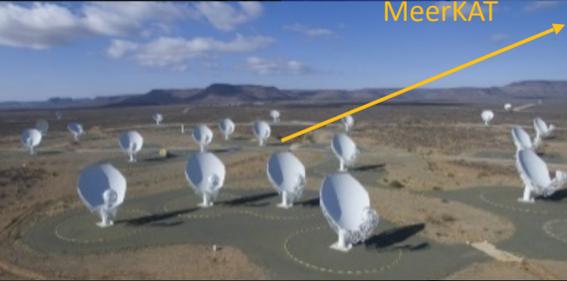
- Heino Falcke Radboud Univ.
- Sera Markoff Univ. Amsterdam
- Rob Fender Oxford Univ.



Mt. Gamsberg



H.E.S.S.



MeerKAT



Gamsberg (Namibia)



# African Millimeter Telescope (AMT)

- International Science Committee formed (RU, UNAM, Wits, NWU, Metsähovi, Turku, Oxford, CEA, ASTRON, MIT, Grenoble Alpes, ...)



- Site quality being tested
- SEST to be upgraded to NOEMA (electronics, surface stability, etc.)
- Preliminary Design Review passed in 2019
- First-light instruments:
  - 67-116GHz (EHT)
  - 211-275GHz (EHT)
- Additions:
  - 275-373GHz (ngEHT)
  - 35-50GHz (EVN)
  - 23GHz (SKA, EVN)

# Square Kilometre Array (SKA)

## SKA– Key Science Drivers: The history of the Universe

Testing General Relativity  
(Strong Regime, Gravitational Waves)

Cosmic Dawn  
(First Stars and Galaxies)

Cradle of Life  
(Planets, Molecules, SETI)

Galaxy Evolution  
(Normal Galaxies  $z \sim 2-3$ )

Cosmic Magnetism  
(Origin, Evolution)

Cosmology  
(Dark Energy, Large Scale Structure)

Exploration of the Unknown

Extremely broad range of science!

The need to grow human capacity in radio astronomy and interferometry on the African continent is enormous considering that SKA-era is in the horizon.



# African Radio Astronomy Network (ARAN)

## North-West University 4-dish interferometer



# North-West University 4-dish interferometer

- 3.7m dishes
- C-band 6.45 ~ 6.75 GHz
- Dual polarization
- Only one polarization in use
- Practical/hands-on tools
- Commissioning and verification is ongoing
- Role out to the rest of Africa

# The ARAN Goal



# The ARAN - Nigeria



Ross A. Burns, PhD  
DIRECTOR  
Observing facility support, web contact person



James O. Chibueze, PhD  
DIRECTOR  
Procurement and Logistics, spokesperson



Gordon MacLeod, PhD MBA  
DIRECTOR  
Legal matters and finance, strategy



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Website : [www.nasrdacbss.com](http://www.nasrdacbss.com)



## MEMORANDUM OF UNDERSTANDING

Between

**CENTRE for BASIC SPACE SCIENCE,  
NIGERIA**

and

**GLOBAL EMERGING RADIO ASTRONOMY FOUNDATION**

1. Centre for Basic Space Science (hereafter referred to as CBSS), Nsukka, an activity centre of the National Space Research and Development Agency incorporated under the NASRDA Act, 2010 and having its principal office at Obasanjo Space Centre, Umaru Musa Ydar'adua express way, P.M.B. 437, Lugbe, Abuja, Nigeria and the Global Emerging Radio Astronomy Foundation (hereafter referred to as GERA), incorporated under the Canada Not-For-Profit Corporations Act (Act No S.C. 2009, c. 23), having its principal office at 5841 87A Street NW Edmonton AB T6E 5W6, Canada, wish to collaborate on a pre-agreed basis, in order to install a 3-m class radio telescope for education and training purposes.
2. The purpose of this Memorandum of Understanding (MoU) is to establish a framework within which co-operation may develop between the two institutions for the purpose of purchasing and installing a 3-m class radio telescope in Nigeria. This will occur within the context of the regulations and policies of each institution, subject to the availability of resources and on a pre-agreed basis.



We can only bring the benefits of the massive investments in radio astronomy on the continent, if we all work together coherently  
- James O. Chibueze