Radio Astronomy Intro, part 1

Greg Taylor

University of New Mexico

Astronomy 423/539 at UNM

Radio Astronomy

Course Goals

- To understand how radio astronomical instrumentation functions and is used in practice.
- To understand some of the exciting science carried out at radio wavelengths.
- To understand the main astrophysical processes which give rise to radio emission
- A chance to see and work with real radio data from the Very Large Array, the Very Long Baseline Array, and the Long Wavelength Array

- Your goals?

Course Outline

- Exploring the Invisible Universe
- Some basic information (radiative transfer, thermal emission, the radiometry equation)
- Signals and noise, receivers
- Antennas – Our Connection to the Universe
- The Two-Element Interferometer
- Aperture Synthesis techniques
  - Connected element interferometers (VLA)
  - Very Long Baseline Interferometry (VLBA)
  - Long Wavelength Interferometry (LWA)
- Synchrotron Emission and Magnetic Fields
- Active Galactic Nuclei and their Jets
- See the Syllabus for more details
- TA: Megan Lewis

Course Methods

- **Materials will be posted at:** http://www.phys.unm.edu/~gbtaylor/astr423/
- **Weekly homework assignments**
- **Reading assignments (2 books, both available from me)**
- **Lectures**
  - **Powerpoint slides (will be posted)**
  - **Traditional chalkboard lectures (not posted)**
  - **data reduction tutorials (~1 or 2, not posted)**
- **Two mid-term exams**
- **Observing projects with the VLA & LWA (schedules by Feb 10 !)**
- **A day at the VLA/LWA touring (TBD)**
- **Homework analyzing our VLA data and LWA data**
- **Written and oral reports based on the observations**
- **Grad students will be expected to do some extra work (present a hw solution, schedule observations, etc. - meet me to discuss)**
- **No final exam**

How to Use a Radio Telescope

1. Come up with a great idea
2. Write a compelling proposal
3. Submit your great proposal for review
4. Wait a while
5. Schedule the observations
6. Watch the observations take place
7. Calibrate the data
8. Make images and perform detailed analysis
9. Write up your results and submit them for publication

How we will use the VLA/LWA

1. Come up with a great idea (start thinking about this now!)
2. Write a compelling proposal (<300 words; Homework #1)
3. Submit your great proposal for review (proposals due Feb 1)
4. Wait a while (TAC decision on Feb 3; 2 hours VLA observing and 10 hours of LWA observing time to allocate)
5. Schedule the observations (by Feb 10 for VLA and Feb 17 for LWA)
6. Watch the observations take place (tough with dynamic scheduling)
7. Calibrate the data (homework)
8. Make images and perform detailed analysis (homeworks & project)
9. Write up your results and submit them for publication (for a grade)

How we will use the LWA

1. We have ~10 hours of LWA time available
2. We will have a class homework observing pulsars
    1. Take some data and practice RFI excision techniques
    2. Learn how to do a dispersion/period search
    3. Discover new aspects of pulsars at long wavelengths!

The Very Large Array

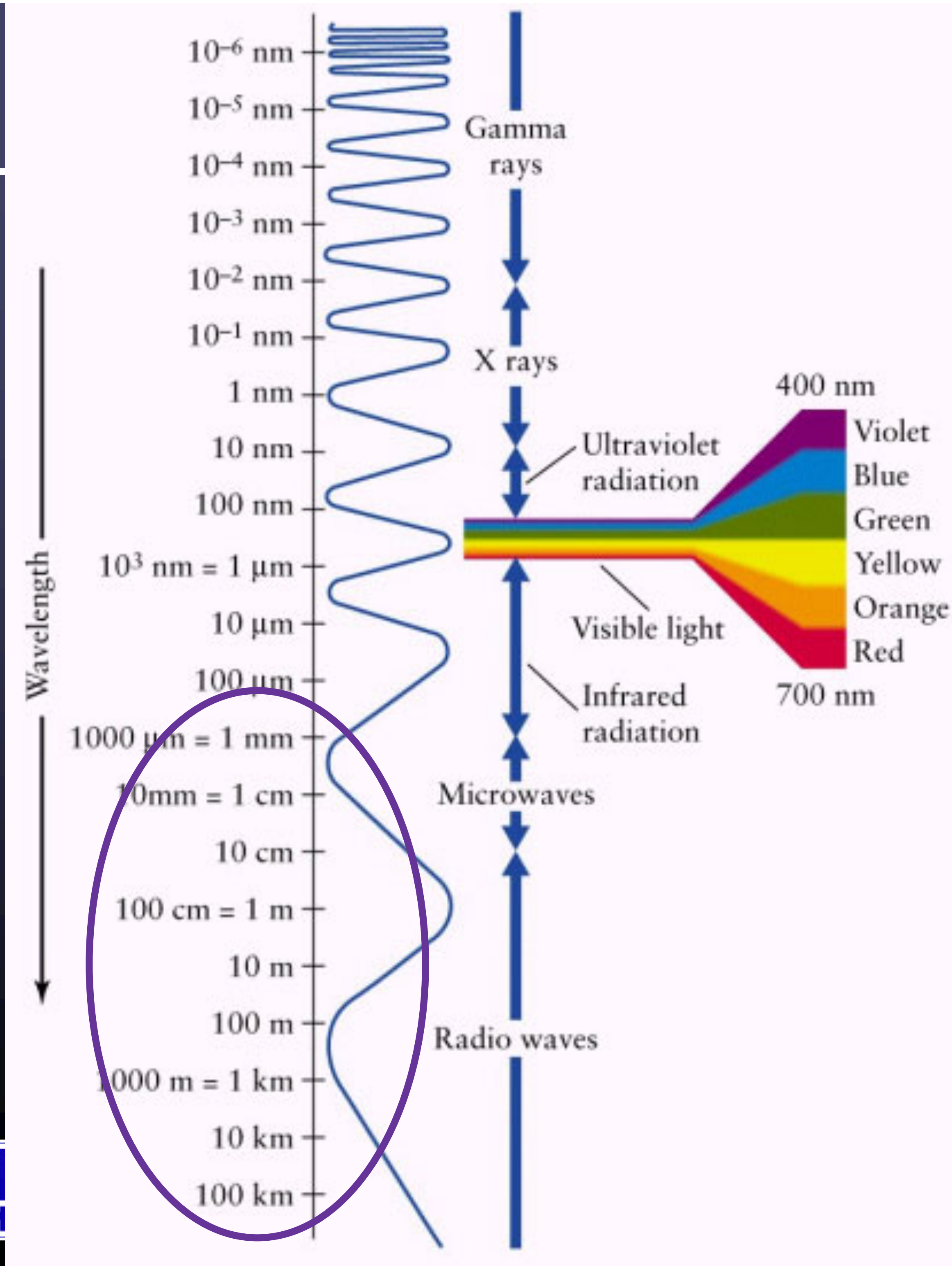
- In February the VLA will be in A config

Angular resolution ~ 0.3” at 5 GHz,
sensitivity = 13 microJy/beam in 10 minutes @ 5 GHz
Frequency range: 1 to 50 GHz

Observing Constraints

- VLA time should be in the range 20h – 24h LST so targets should be between RA 18:00:00 and 02:00:00 and Declination > -10:00:00
- VLA frequency 76 MHz – 18 GHz (no K,Q for us)
- VLA+LWA observing is also possible at 76 MHz
- LWA time can be at any LST, DEC > -10:00:00
- LWA observations can be with 1 or 2 stations
- LWA Frequency range 5-88 MHz

The FULL Electromagnetic Spectrum



EM Radiation – basic properties

- speed of light = c = λ ν

c = constant = 3 x 10^{10} cm/s = 3 x 10^5 km/s

λ has units of length (cm) - we will use c.g.s. units (mostly)

ν has units of 1/s (Hz)

- Photons carry energy depending on their frequency (or wavelength)

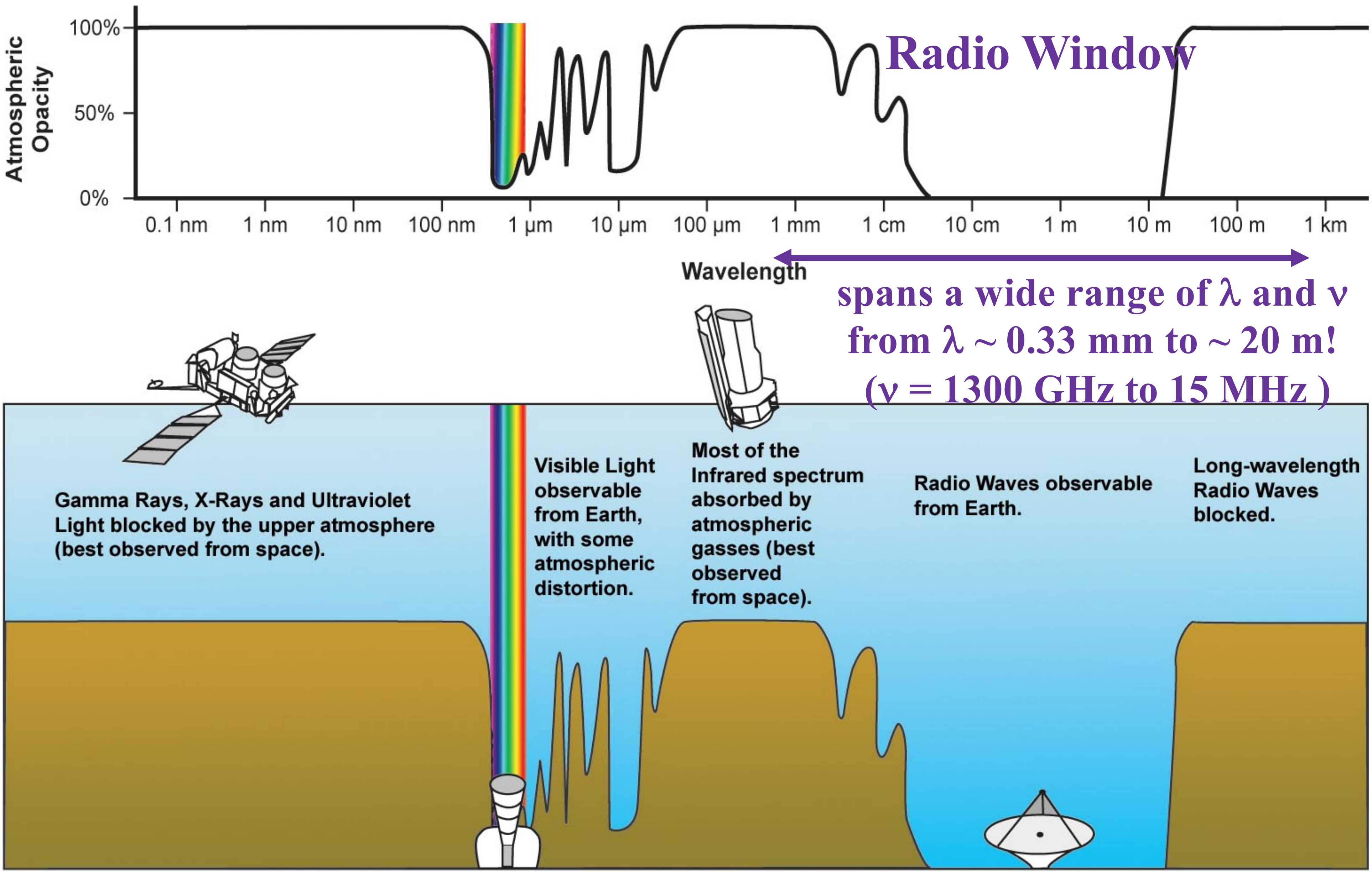
$$E = h\nu$$

h = 6.63 x 10^{-27} erg s, ν is frequency, E energy

h = 4.14 x 10^{-15} eV s

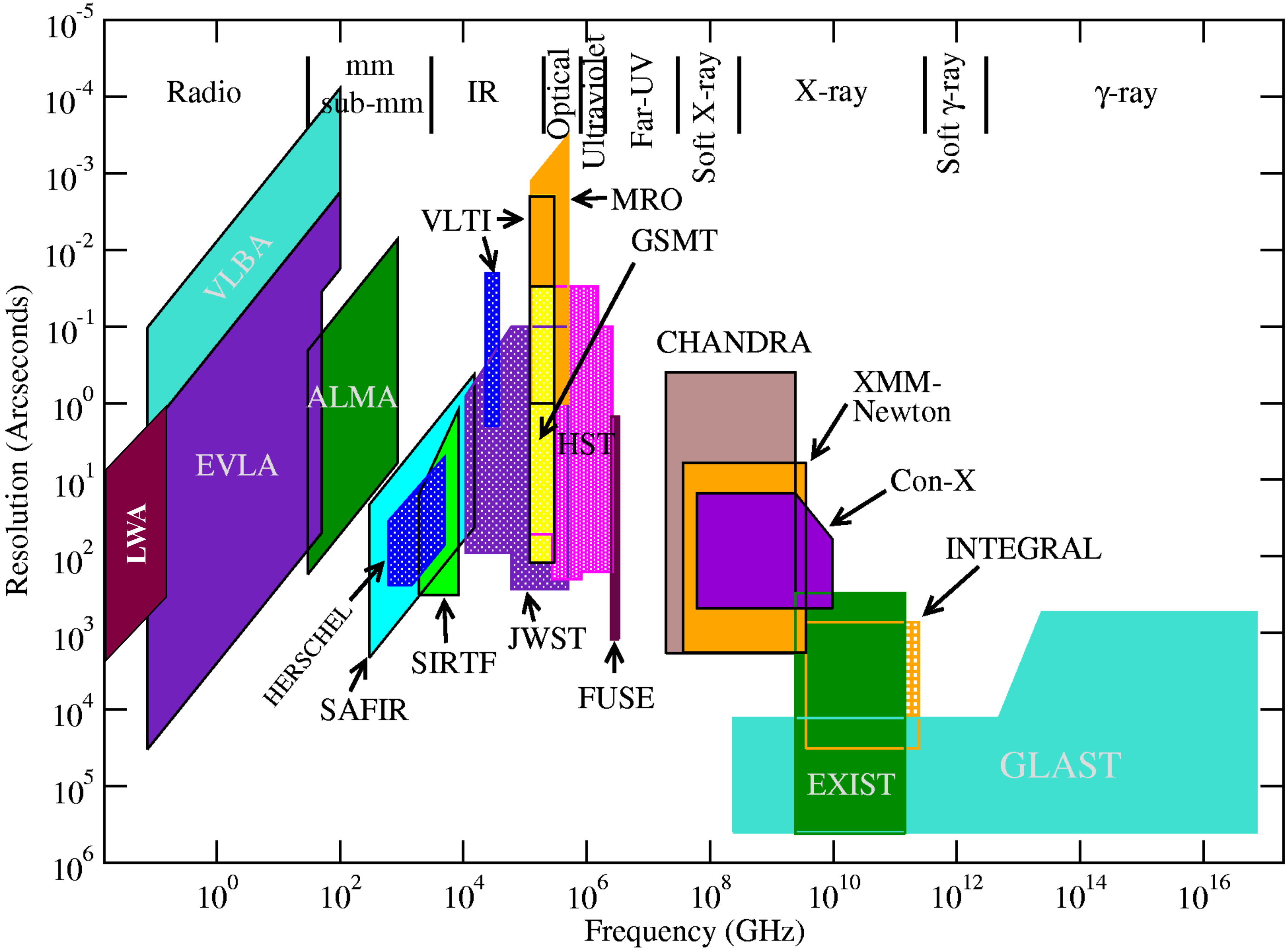
- *note: "high energy" astronomers (X-ray, Gamma Ray) usually use the corresponding energy rather than wavelength, i.e., 10 keV, 2 GeV*

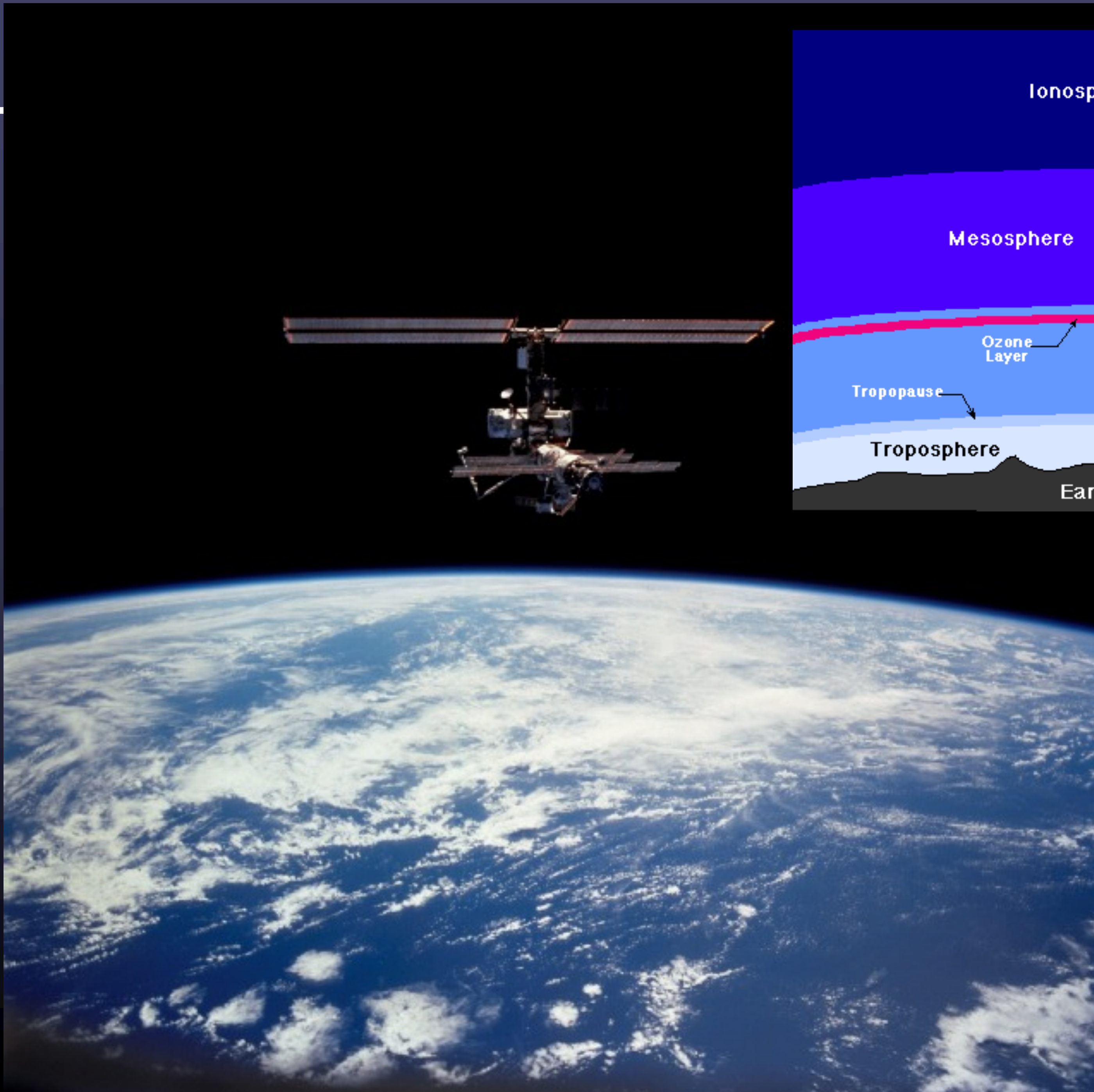
For example: 10^{17} Hz = 0.4 keV

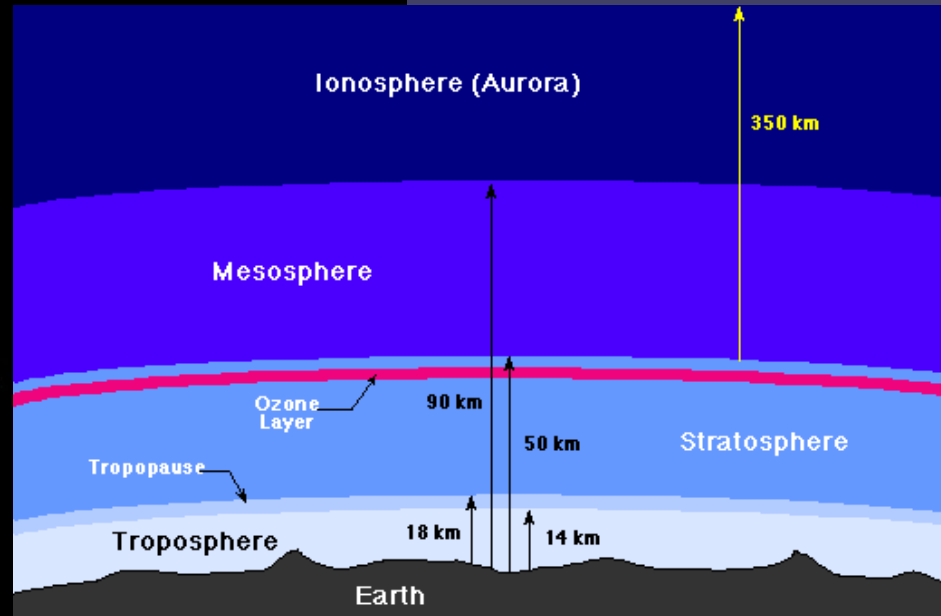


Radio Window

spans a wide range of λ and ν from λ ~ 0.33 mm to ~ 20 m!
(ν = 1300 GHz to 15 MHz)


Radio
mm
sub-mm
IR
Optical
Ultraviolet
Far-UV
Soft X-ray
X-ray
Soft γ-ray
γ-ray
VLBA
EVLA
LWA
ALMA
VLTI
MRO
GSMT
HST
JWST
SIRTF
HERSCHEL
SAFIR
FUSE
CHANDRA
XMM-
Newton
Con-X
INTEGRAL
EXIST
GLAST
Resolution (Arcseconds)
Frequency (GHz)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}




Ionosphere (Aurora)
350 km
Mesosphere
Ozone Layer
90 km
50 km
Stratosphere
Tropopause
Troposphere
18 km
14 km
Earth

Radio
High frequency cut off

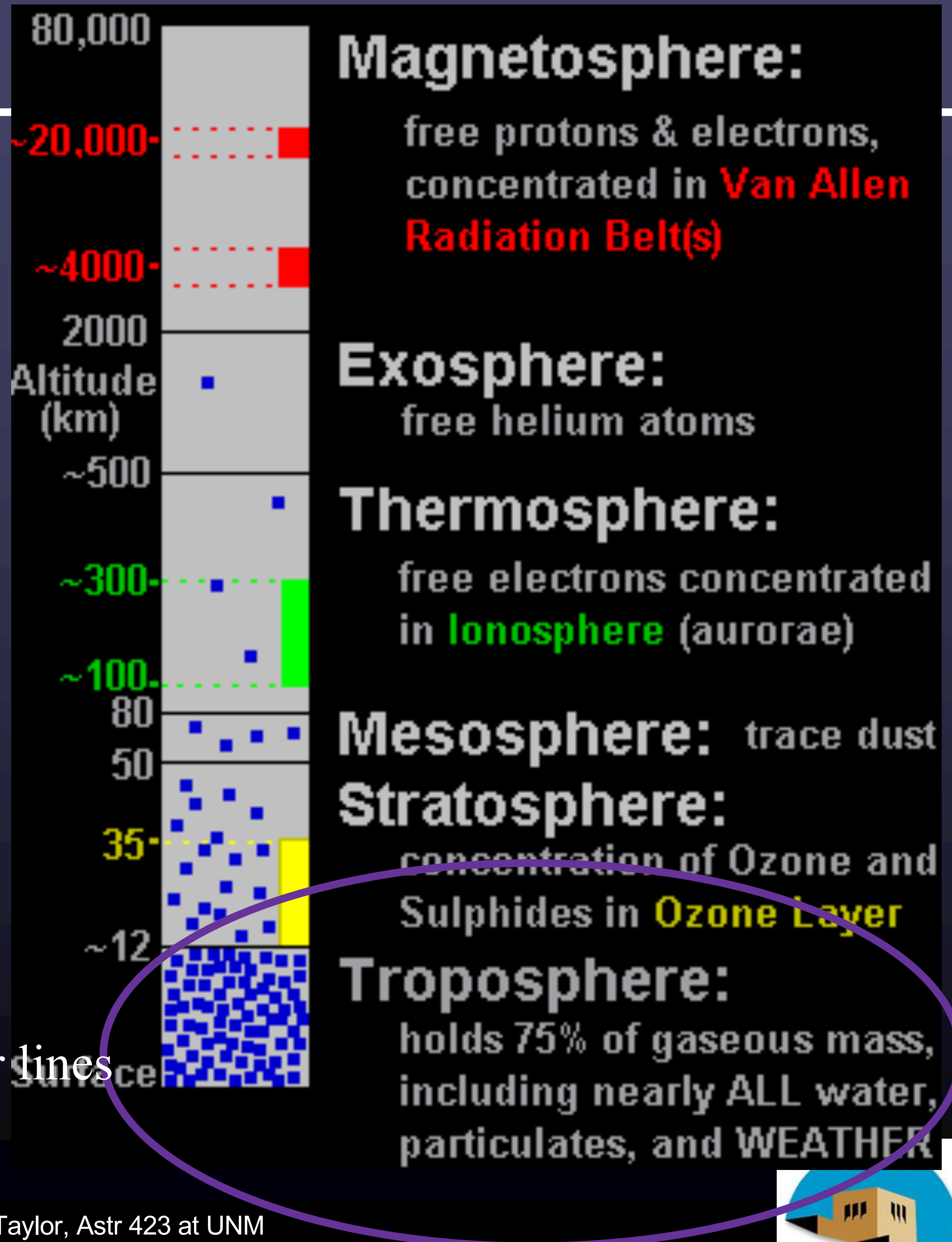
- due to the troposphere layers

- H_2O, O_2 absorb incoming "high frequency" radio photons

- particularly bad spectral windows include:

H_2O at 22.2 GHz (1.35 cm)
183 GHz (1.63 mm)
O_2 at 60 GHz (5 mm)
119 GHz (2.52 mm)

- water/oxygen "band" features are closely spaced absorption lines
- high frequencies good for molecular lines



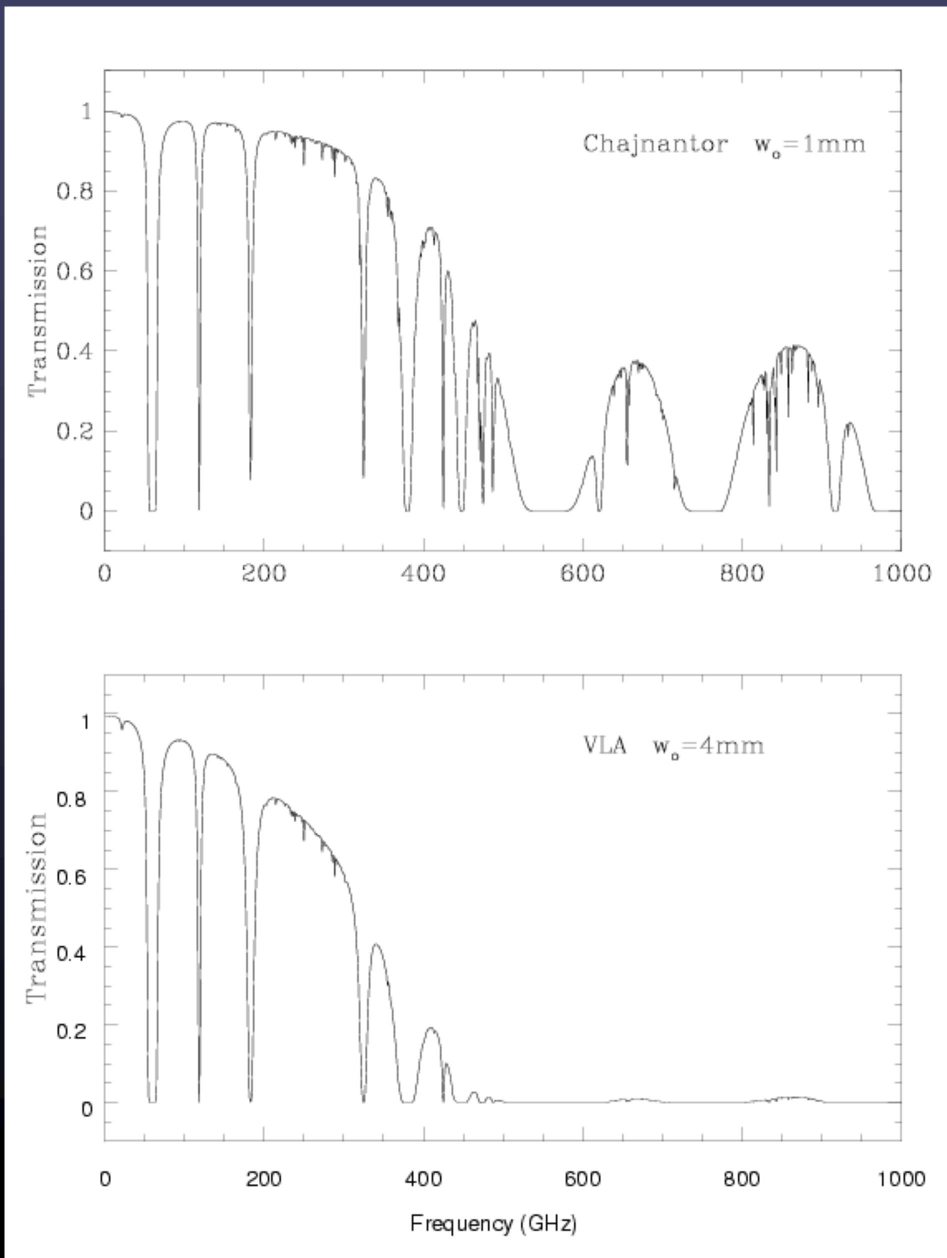
High Frequency Observing

Because the main culprit for high frequency radio astronomy is WATER VAPOR in the atmosphere, you **can** improve your observing conditions!

- go to HIGH or DRY locations:

The University of New Mexico

Atmospheric Opacity at the VLA and ALMA sites



Transmission of the atmosphere from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

⇒atmosphere little problem for λ > cm (most VLA bands up to 15 GHz)

⇒ some problems from 20 to 50 GHz

The University of New Mexico

Highest, driest telescope site: (~ 16,400 feet)
Atacama desert, Northern Chile

Site of millimeter array telescope: ALMA

ALMA, now complete

66 ALMA Antennas now at high site.

Radio
Low frequency cut off

- due to the ionospheric layers

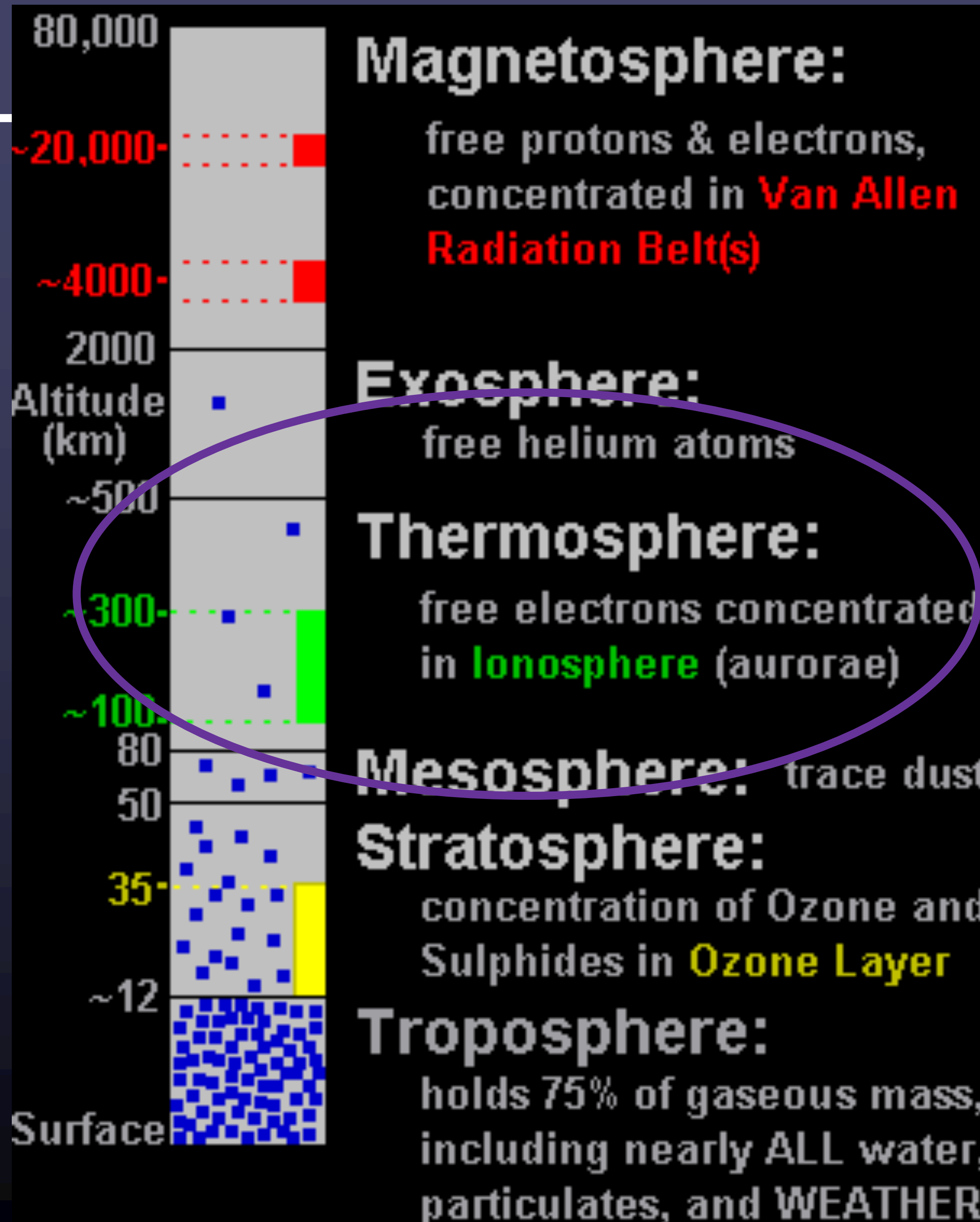
- free electrons in the ionosphere start to absorb low frequency radio radiation IF the frequency is LESS than the *plasma frequency*

$$\nu_p = 8.97\, n_e^{1/2}$$

where n_e is the electron density (cm^{-3}) and ν_p is in kHz

-n_e does depend on solar activity! and day/night, location on Earth

-e.g., at night ν=4.5 MHz (66 m) daytime ν=11 MHz (27 m)



Astrophysics Talks

UNM Center for Astrophysics Research and Technologies
seminar series
Thursdays @ 2pm in PandA 190
next talk Jan 28: Tim Braun… on "TBD"

NRAO Colloquium Series
Fridays @ 11am in PandA 190 broadcast from the Scientific Operations Center in Socorro
next talk ?

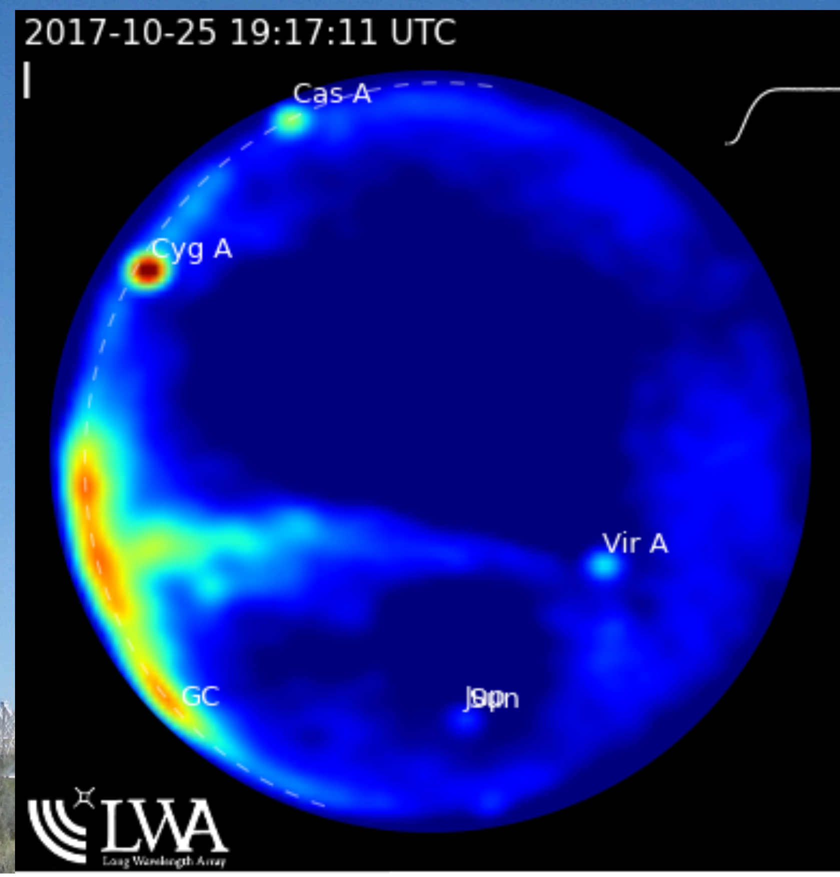
UNM Colloquium Series
Fridays @ 3:30pm over Zoom

LWA Long Wavelength Array

The LWA Radio Observatory Staff

Faculty and Staff

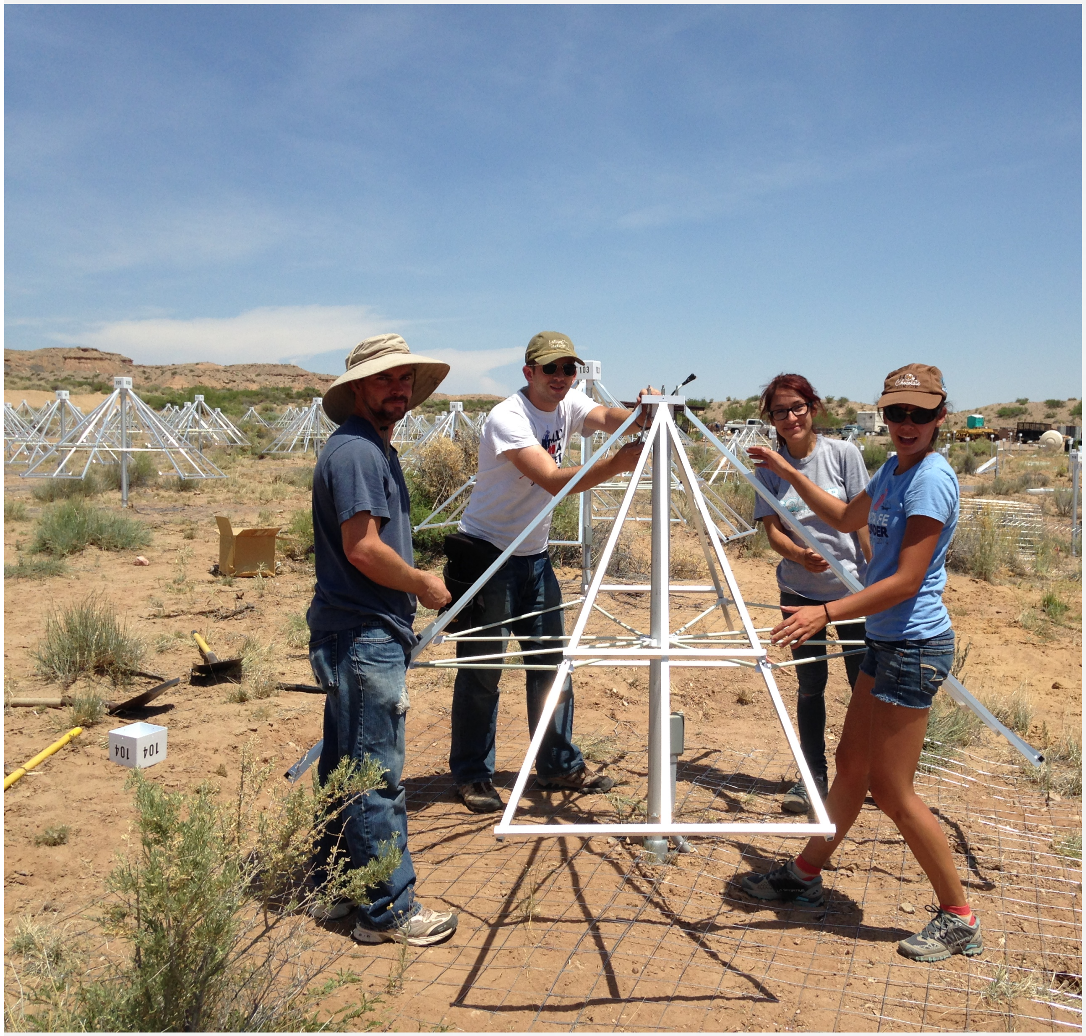
Greg Taylor (UNM)
Jayce Dowell (UNM)
Ylva Pihlstrom (UNM)
Ken Obenberger (AFRL/UNM)
Frank Schinzel (NRAO/UNM)
Kevin Stovall (SNL/UNM)



Grads	Students	Undergrads
Seth Bruzewski		
Chris DiLullo		
Pratik Kumar		Cameron Zamora
Evan Sheldahl		
Craig Taylor		
Savin Varghese		

LWA-SV

Construction 2015



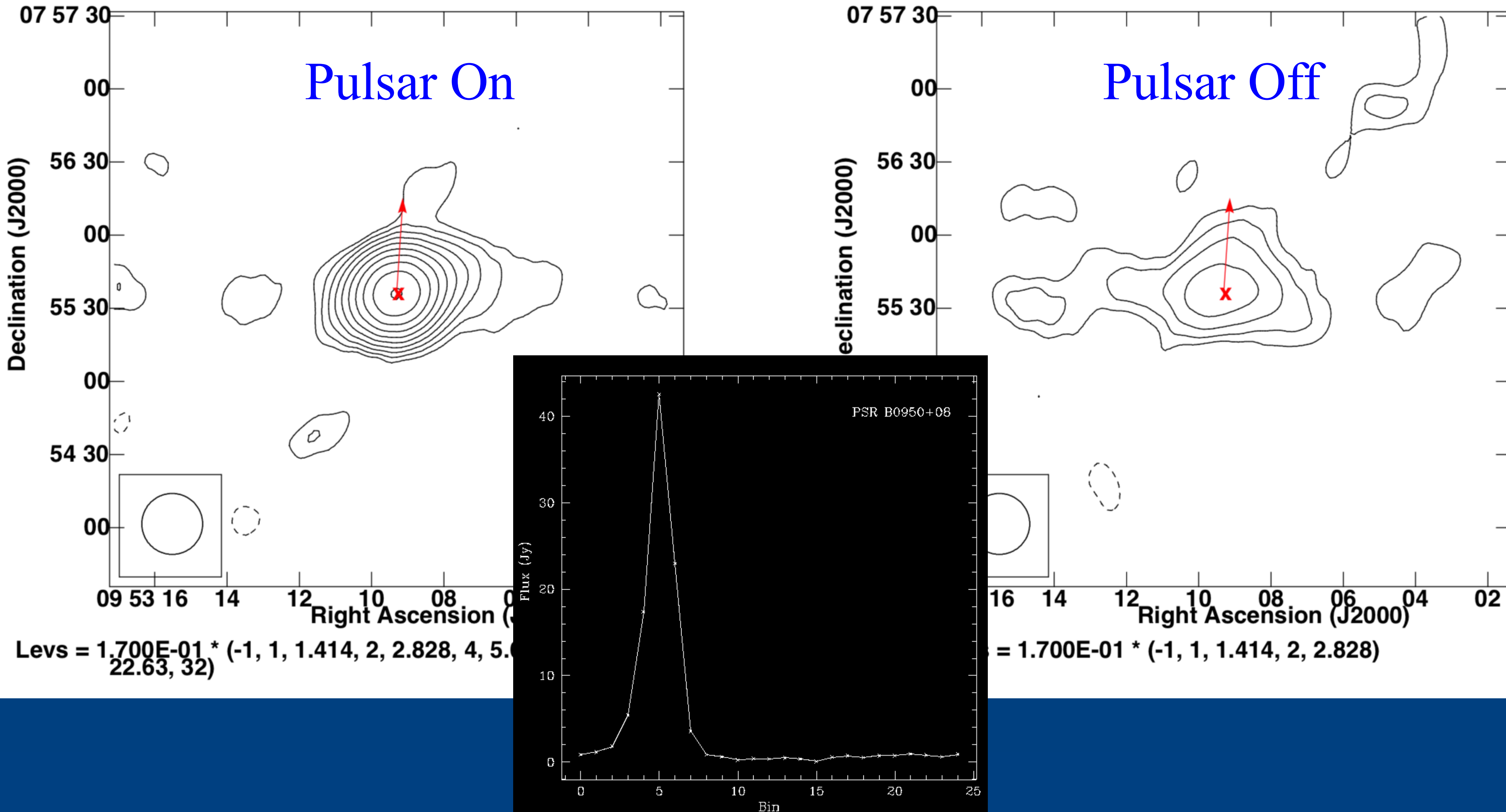
Advanced Digital Processor

VLA 50-86 MHz

New 4 band feeds (MJP)
4 meter band: 50-86 MHz
All 28 installed by 2019

ELWA – Discovery of a Pulsar Wind Nebula around B0950+08

Ruan et al. 2020



Long Wavelength Array (LWA)

Frequency Range: 10-88 MHz
First station ("LWA-1") completed April 2011

Second NM station ("LWA-SV" completed July 2017

Next up: "LWA-NA" mini-station (64 dipoles)

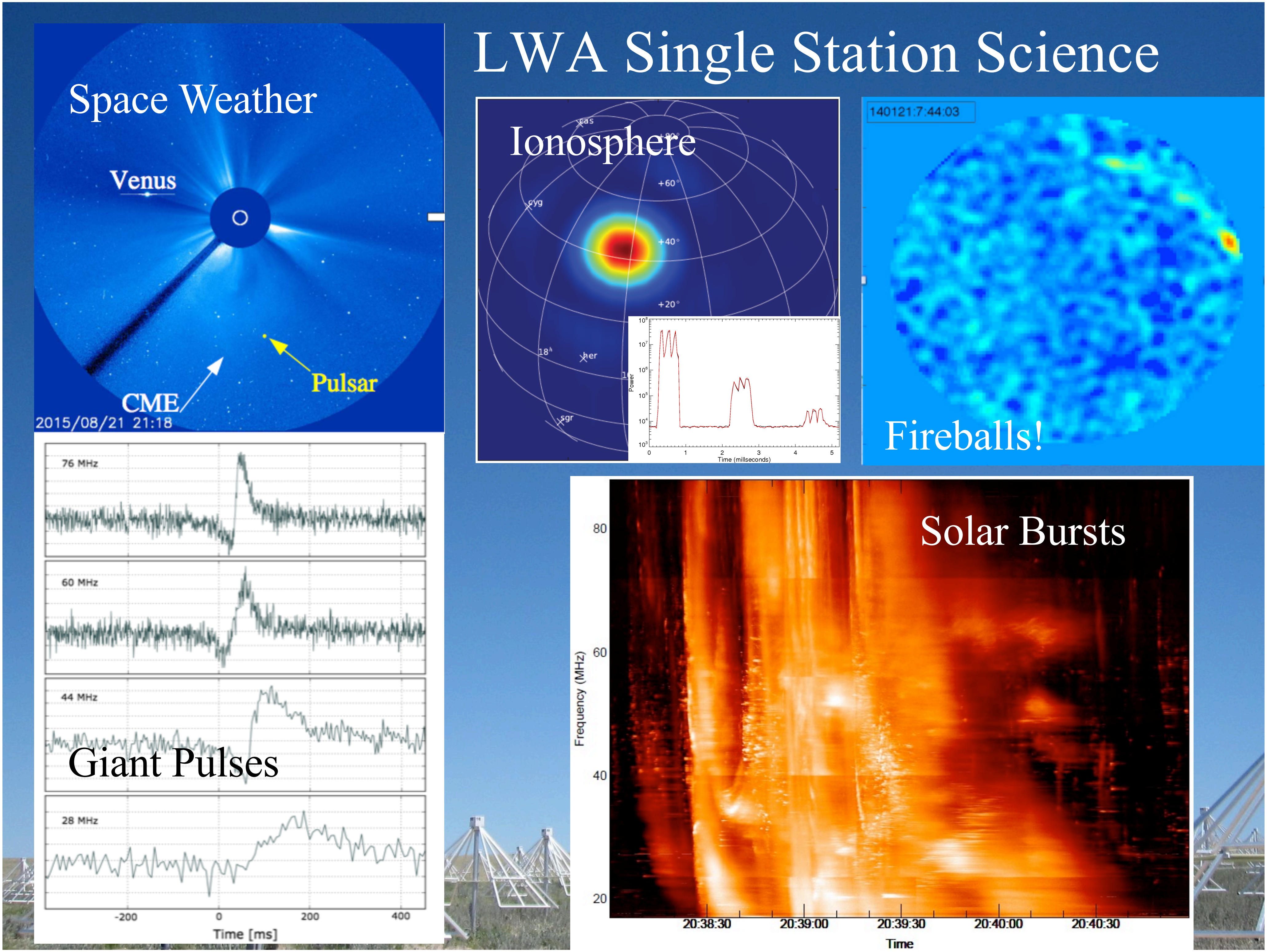
2020 Funded by AFRL

2021 Construction of LWA-NA

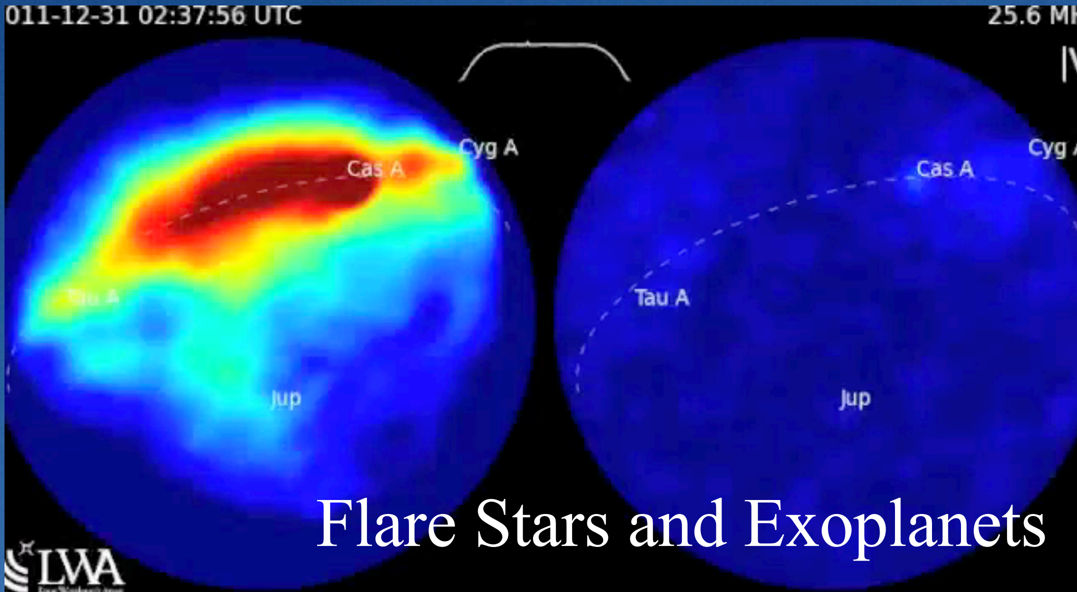
2021 Beamforming at OVRO-LWA

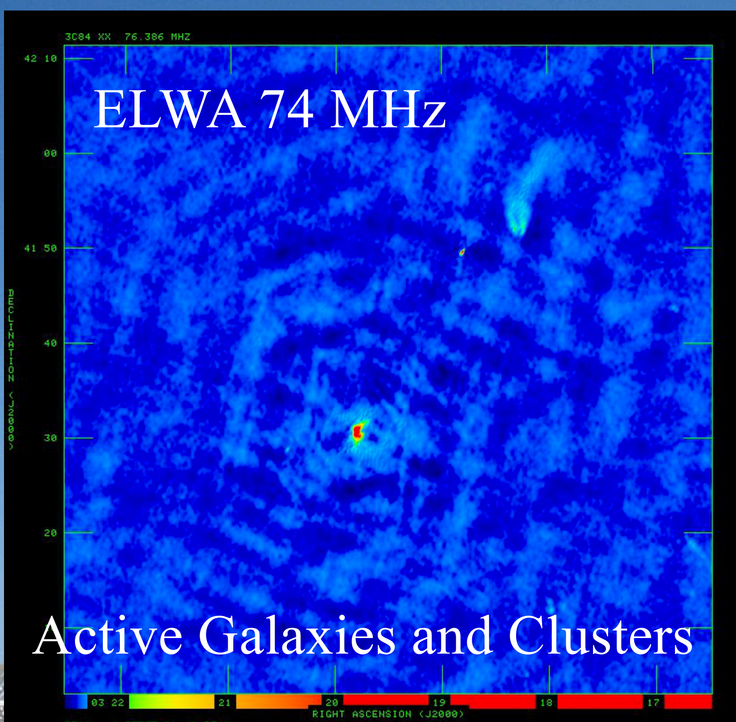
LWA swarm – 1" resolution

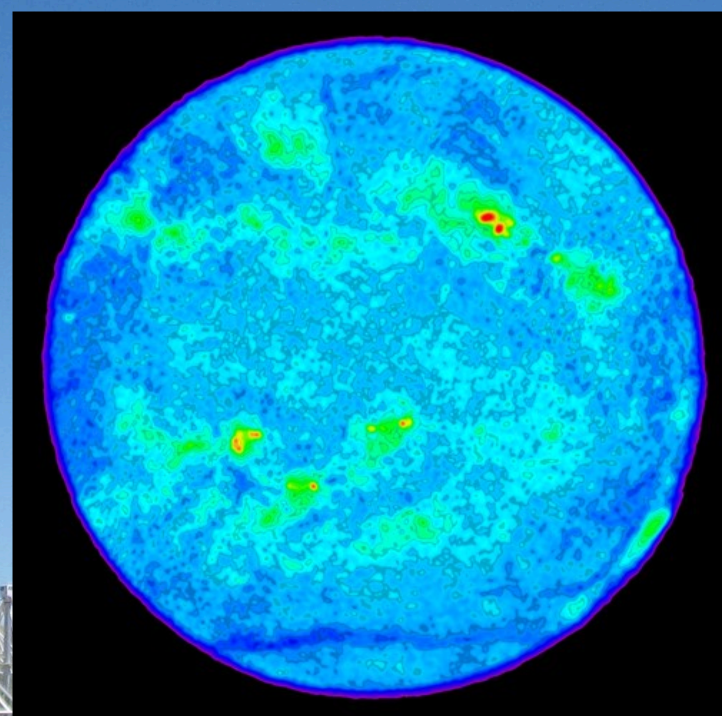
LWA Single Station Science



LWA Swarm Science



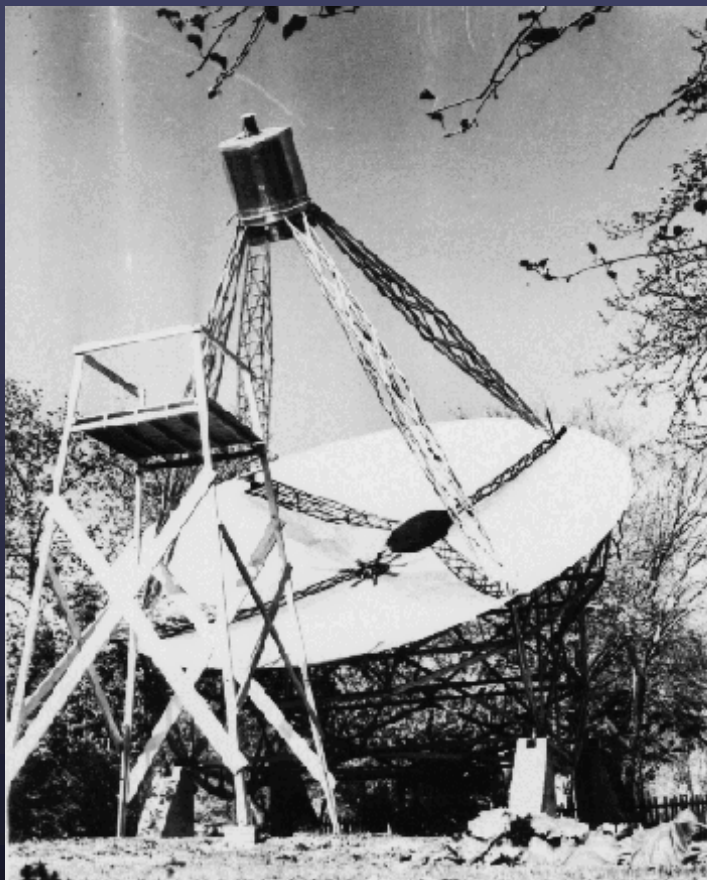


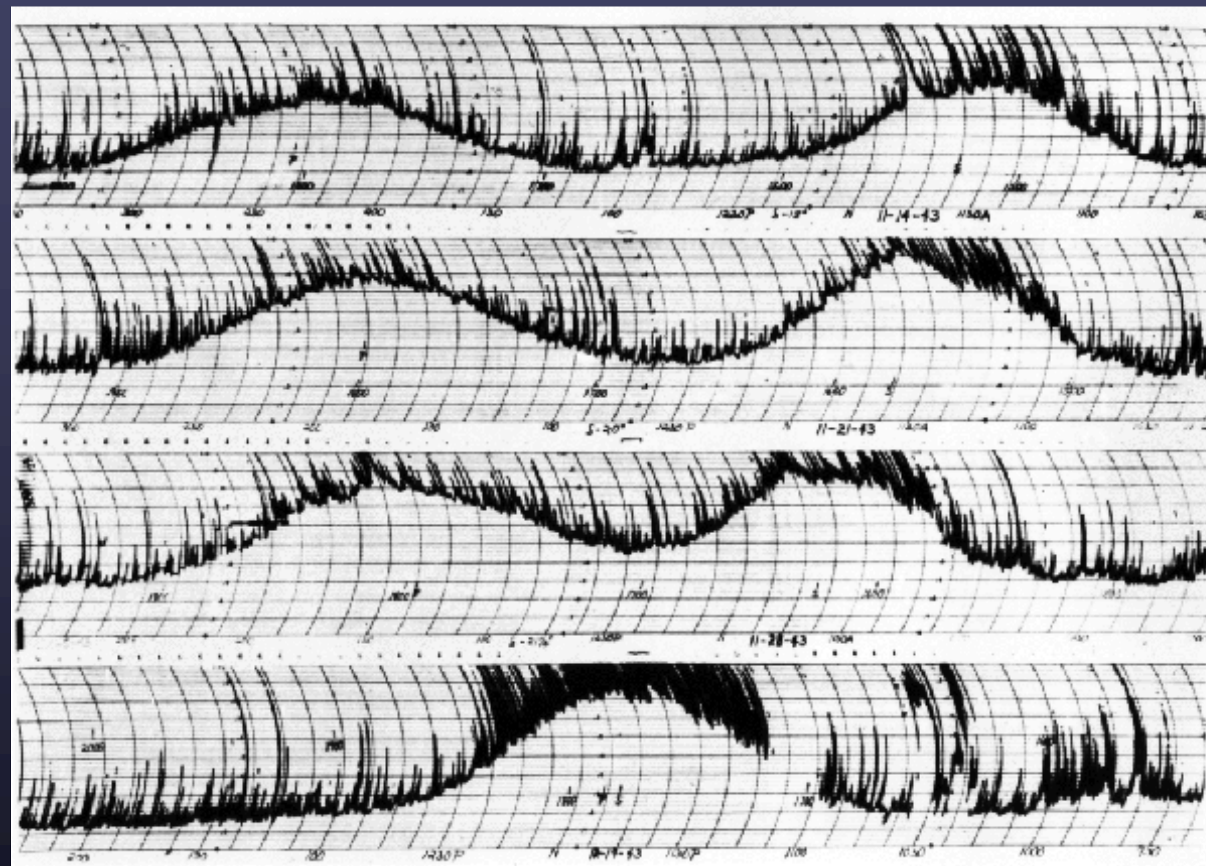


Imaging Solar Bursts

From S. White

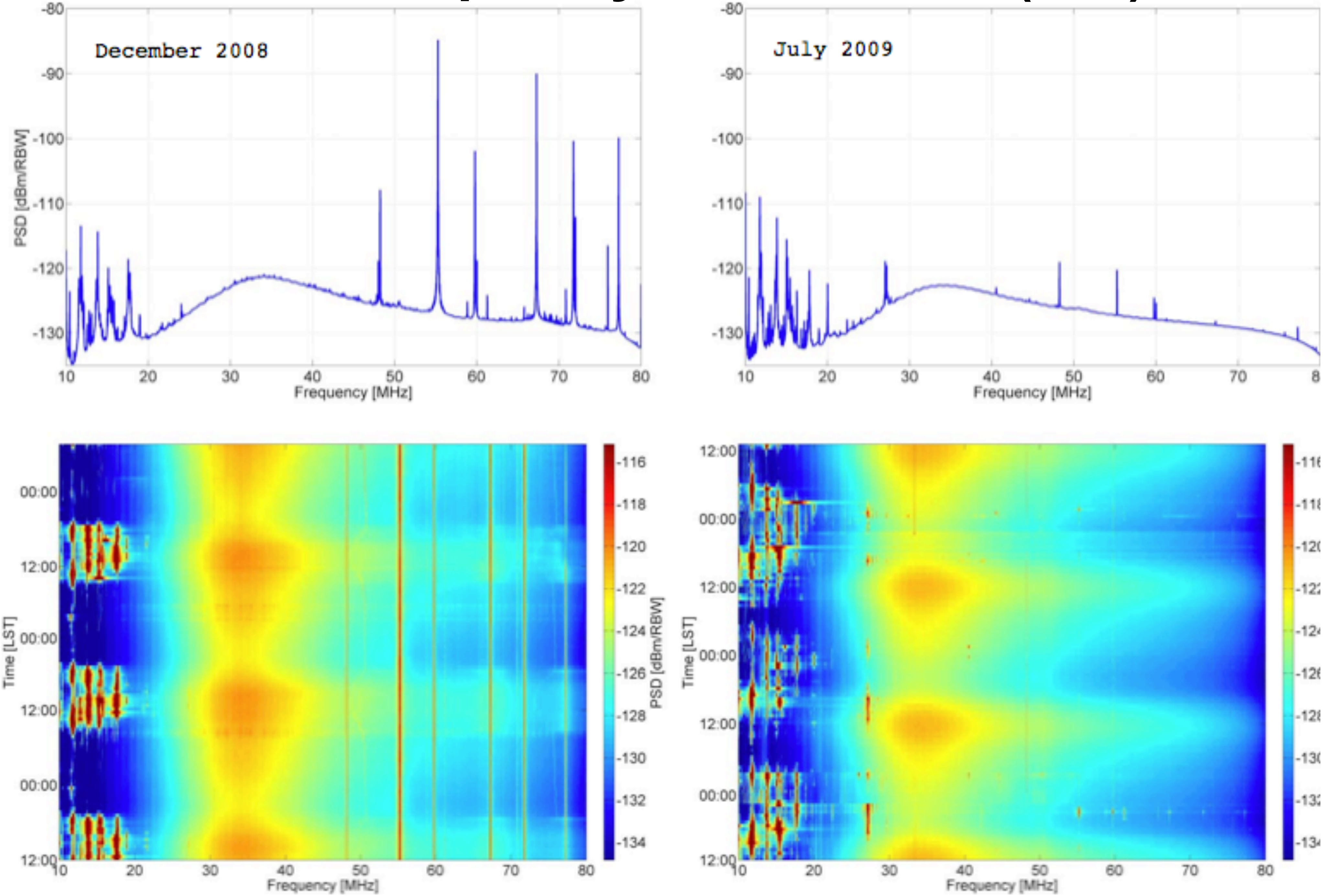
Radio Frequency Interference





Grote Reber's telescope and Radio Frequency Interference in 1938

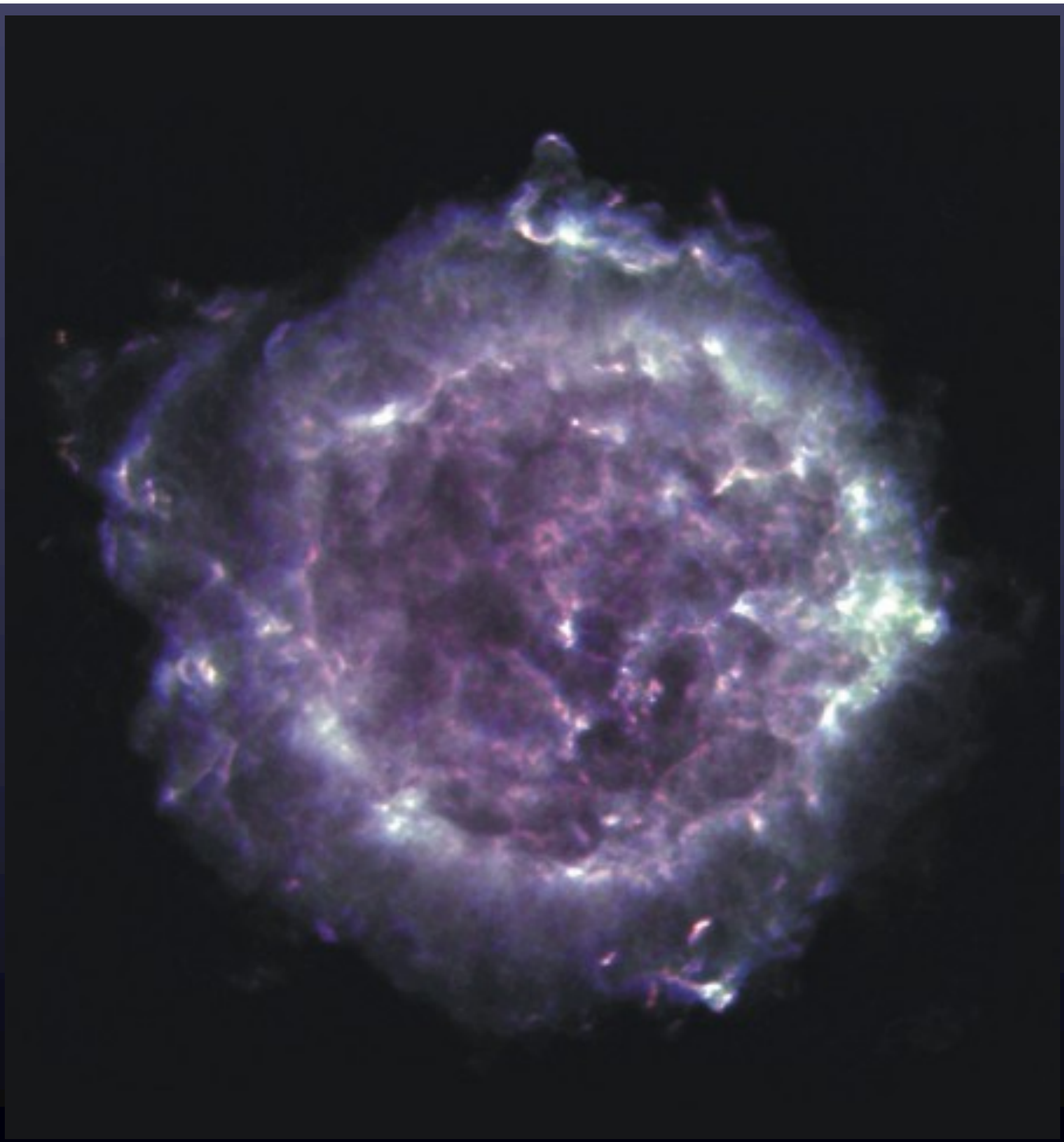
Radio Frequency Interference (RFI)



The Radio Sky

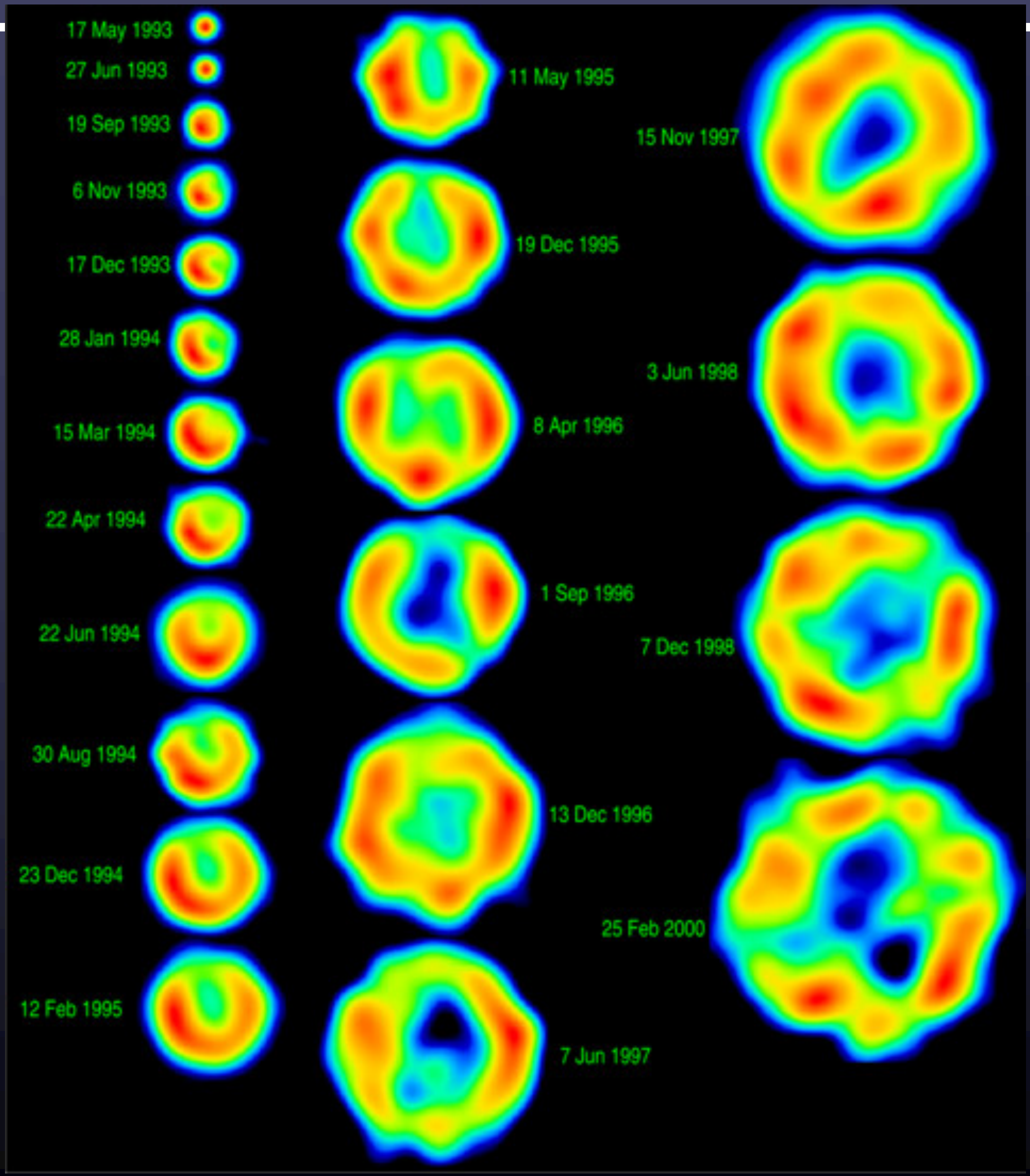
5 GHz image from 300 ft,Condon et al.

Supernovae



Cass A
Rudnick et al.

A Young Supernova



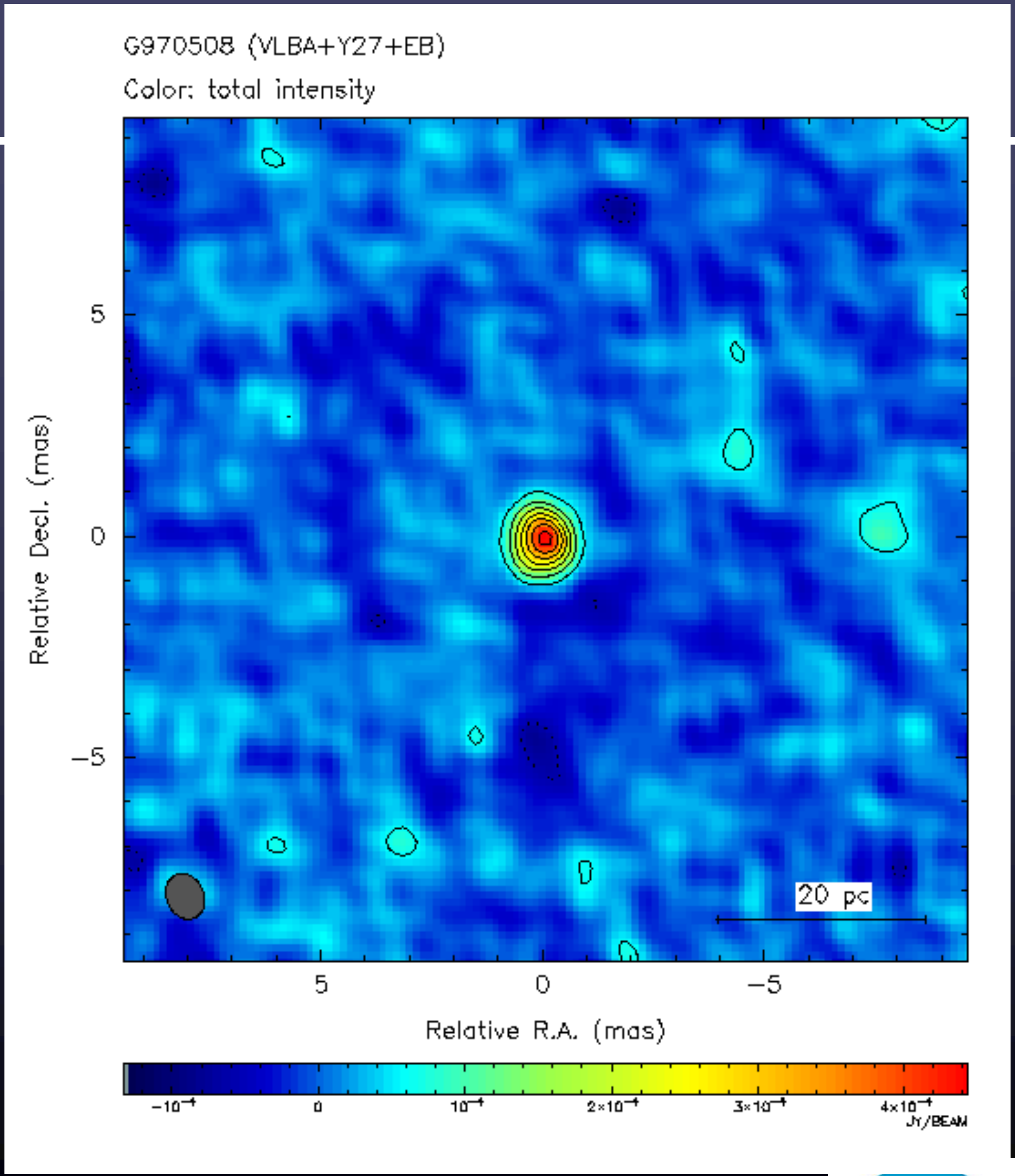
SN 1993J
Rupen et al.

Gamma Ray Bursts

GRB 970508

- First GRB Afterglow detected in the radio
- Size < 10^{19} cm (3 lt years)
- absolute position to < 1 mas
- Distance > 10000 lt years

Taylor et al 1997

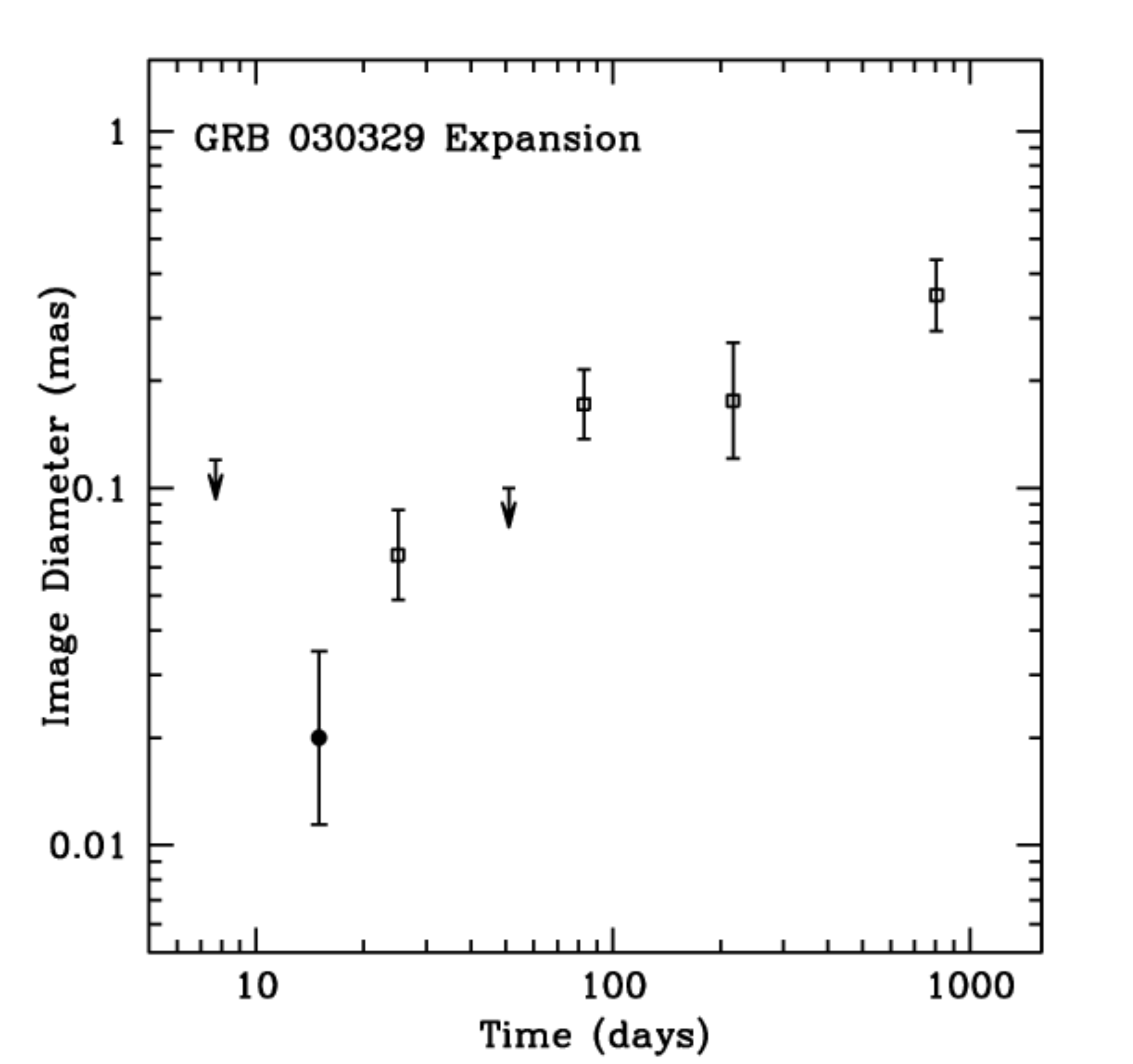


Relativistic
Expansion v ~ 0.96c

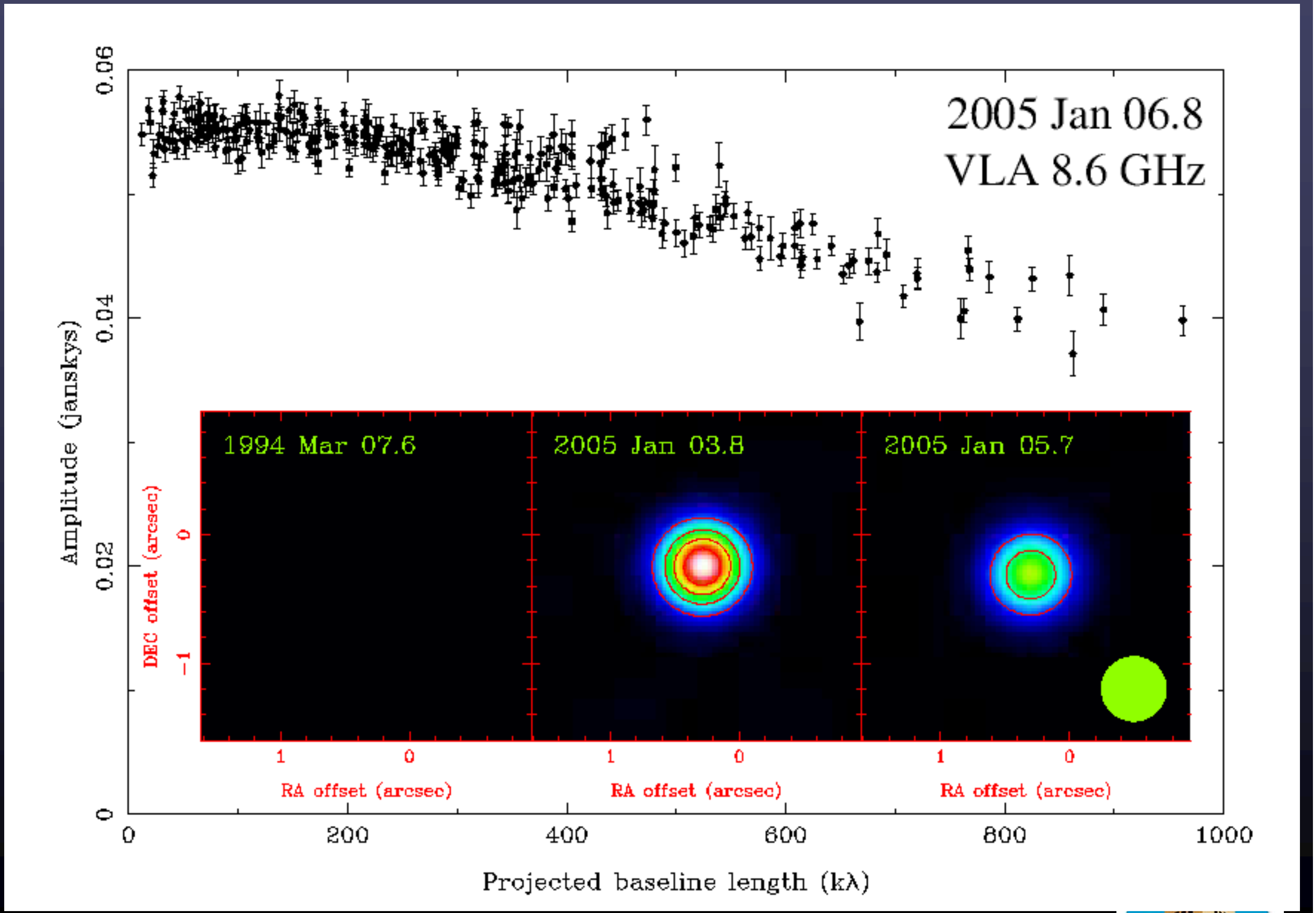
E ~ 10^53 ergs
(isotropic equivalent)

R ~ (E/n)^1/8

Pihlstrom et al 2007

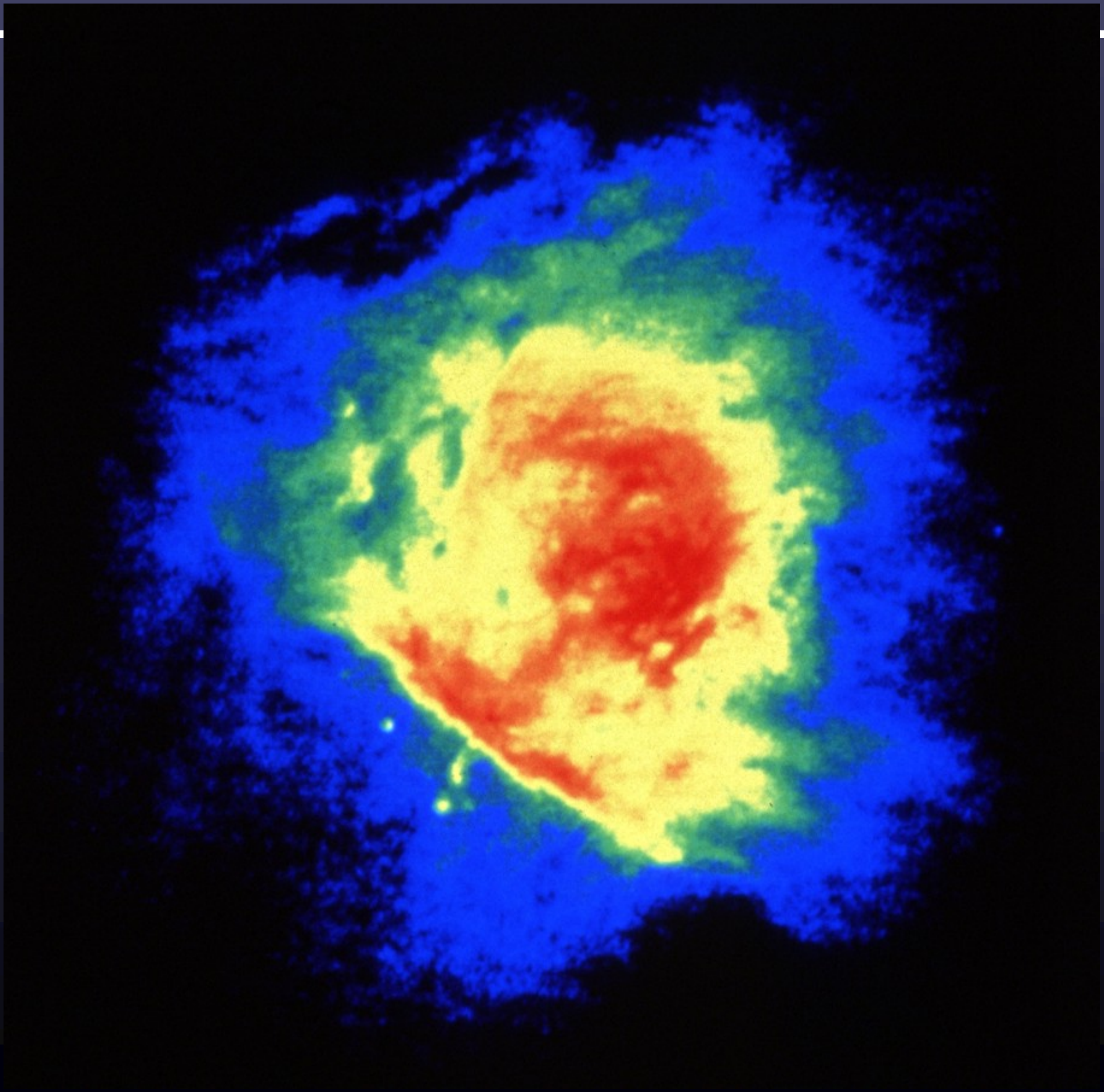


Giant Flare from the Magnetar SGR 1806-20



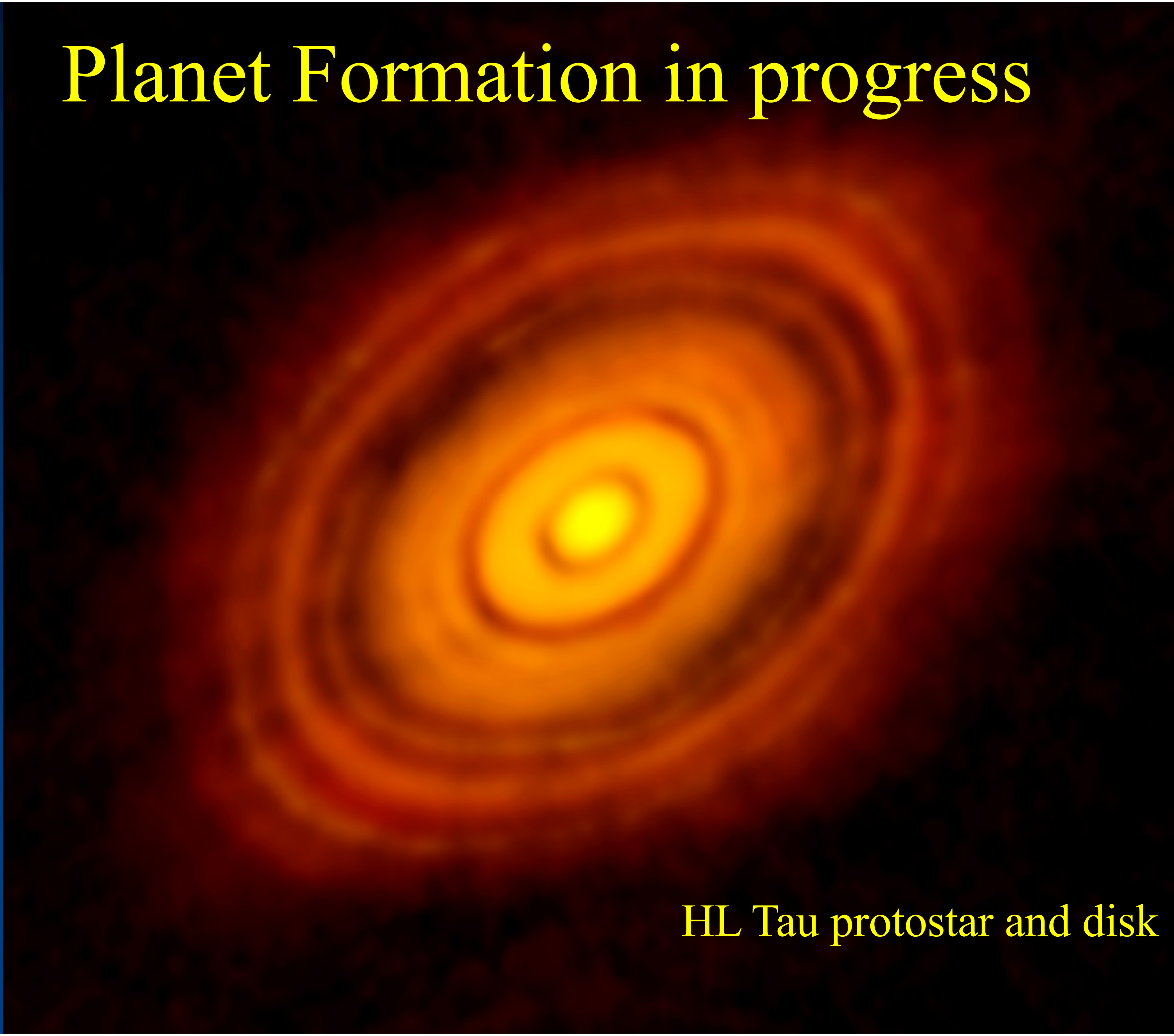
Gaensler et al 2005

Star forming regions - Orion nebula (M42)



Yusef-Zadeh et al.

Planet Formation in progress



HL Tau protostar and disk

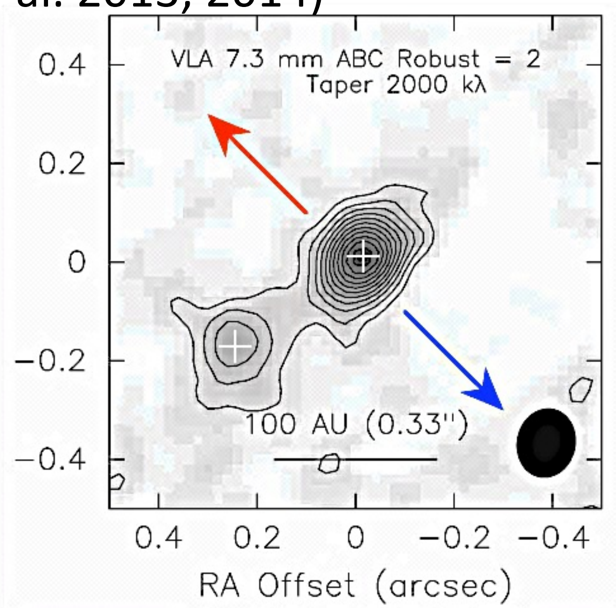
Discovery/Origins: Proto-stars, planets, disks

Star and planet formation with the VLA

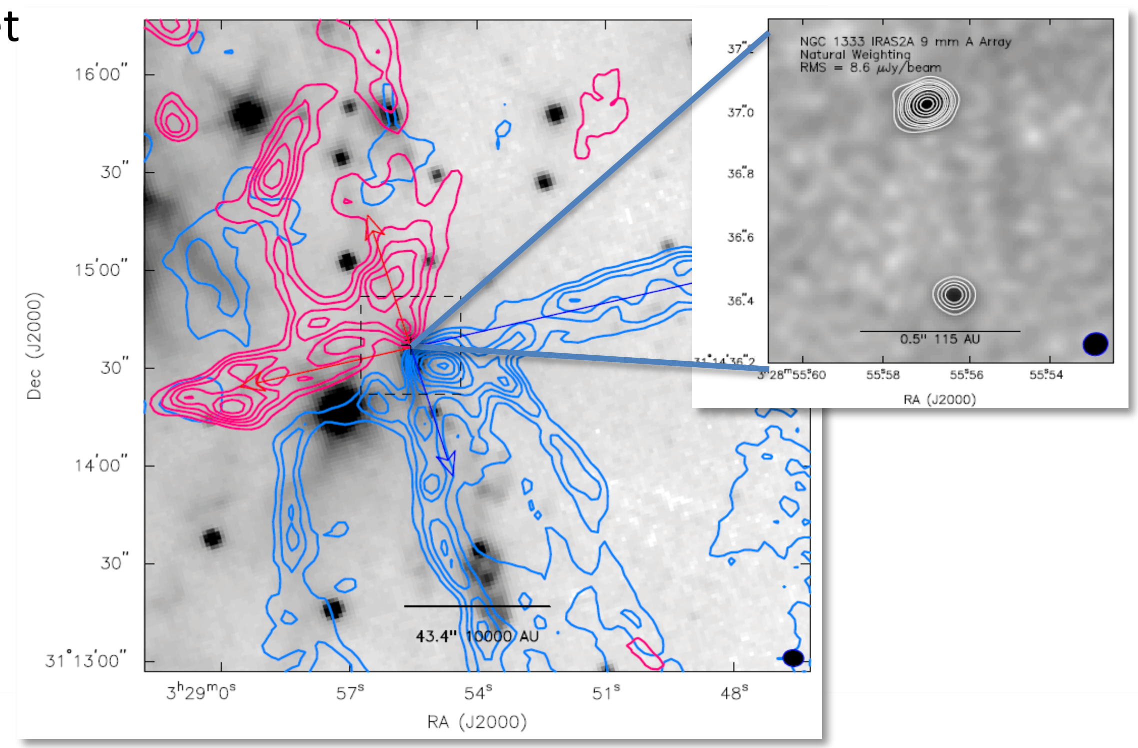
VLA @ λ ~ 1cm provides three key capabilities

1. Imaging to 40mas resolution
2. Dense cores, optically-thick in mm: ‘terrestrial planet formation zone’ < 10AU
3. Sensitive to cm-sized dust grains: pebbles to rocks

Origin of stellar multiplicity (Tobin et al. 2013, 2014)



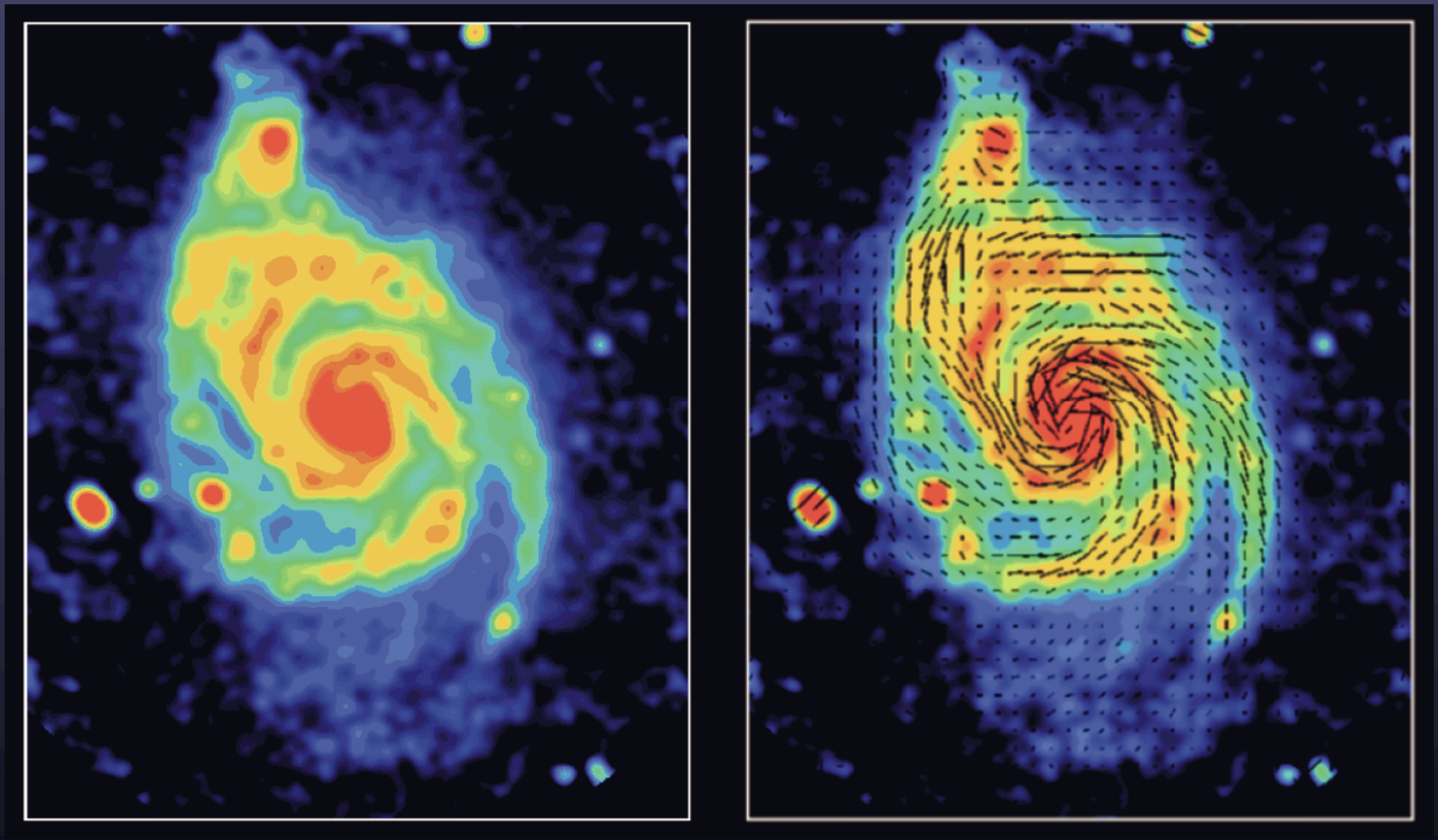
L1165: binary aligned in disk plane, perpendicular to outflow ⇒ protostellar *disk fragmentation*



NGC1333 IRAS2A: double, misaligned outflows ⇒ *turbulent fragmentation* of dense core during collapse (Tobin et al. 2015)

Normal Galaxies

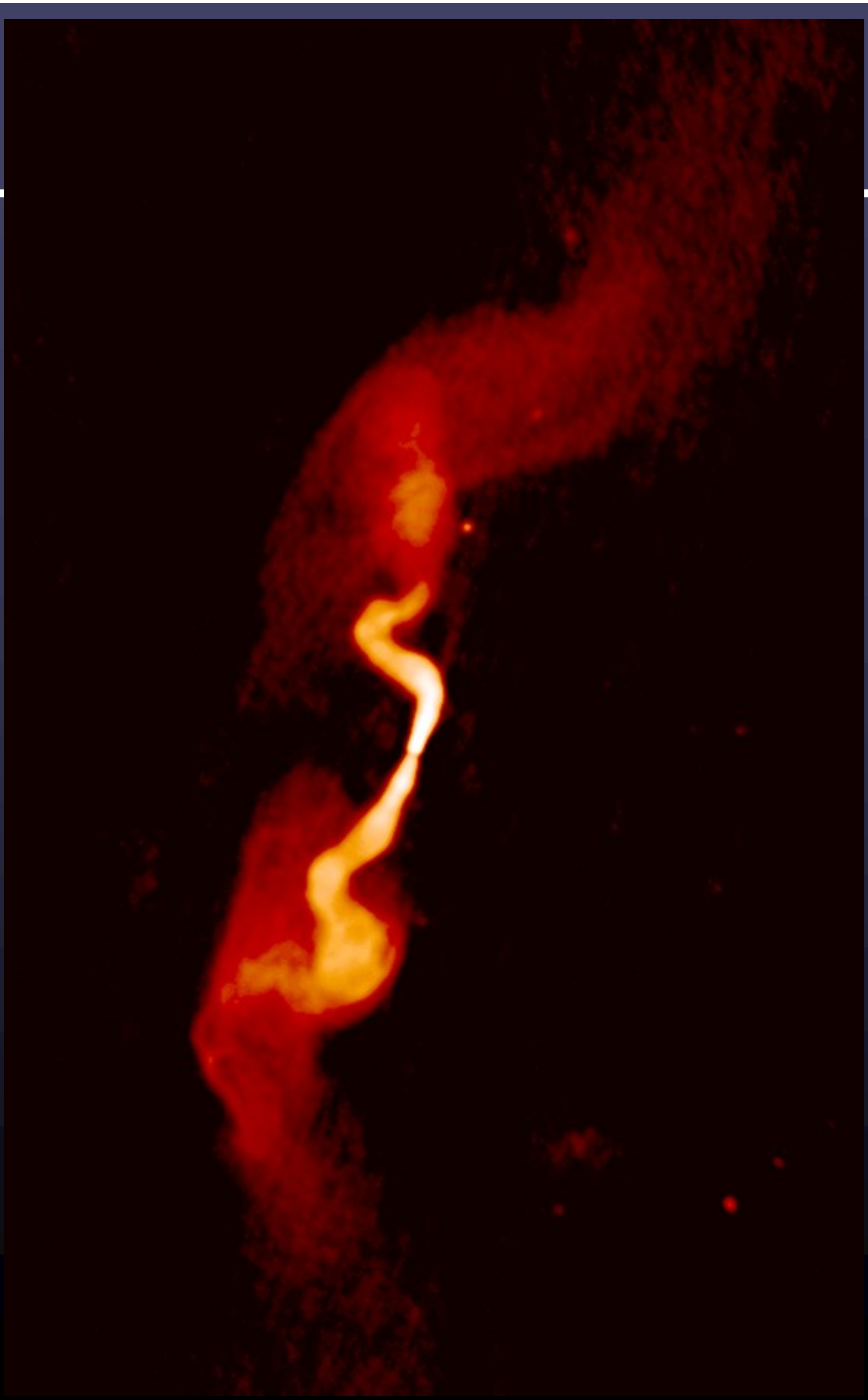
M51



Beck et al

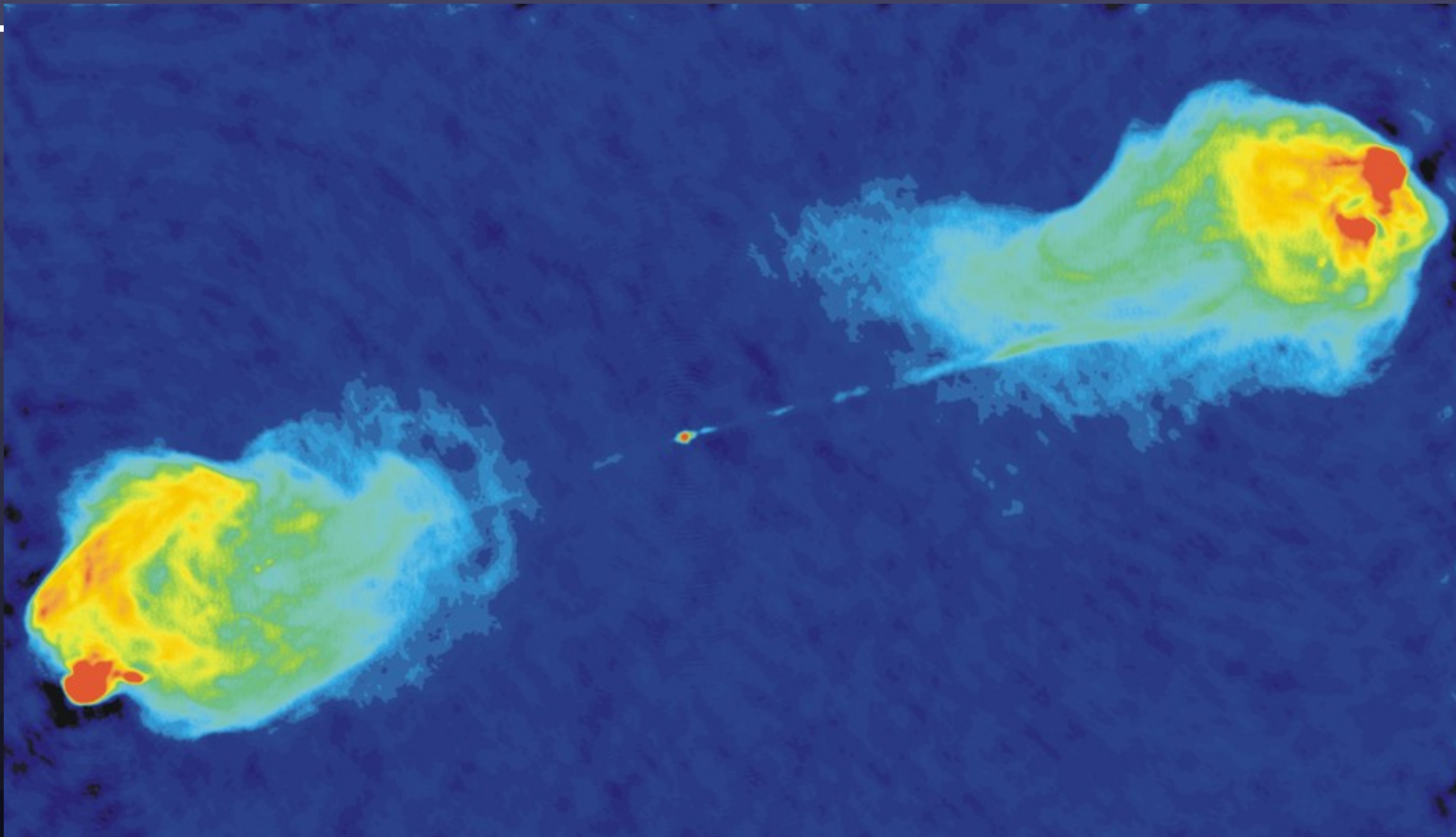
3C31

Active galaxy

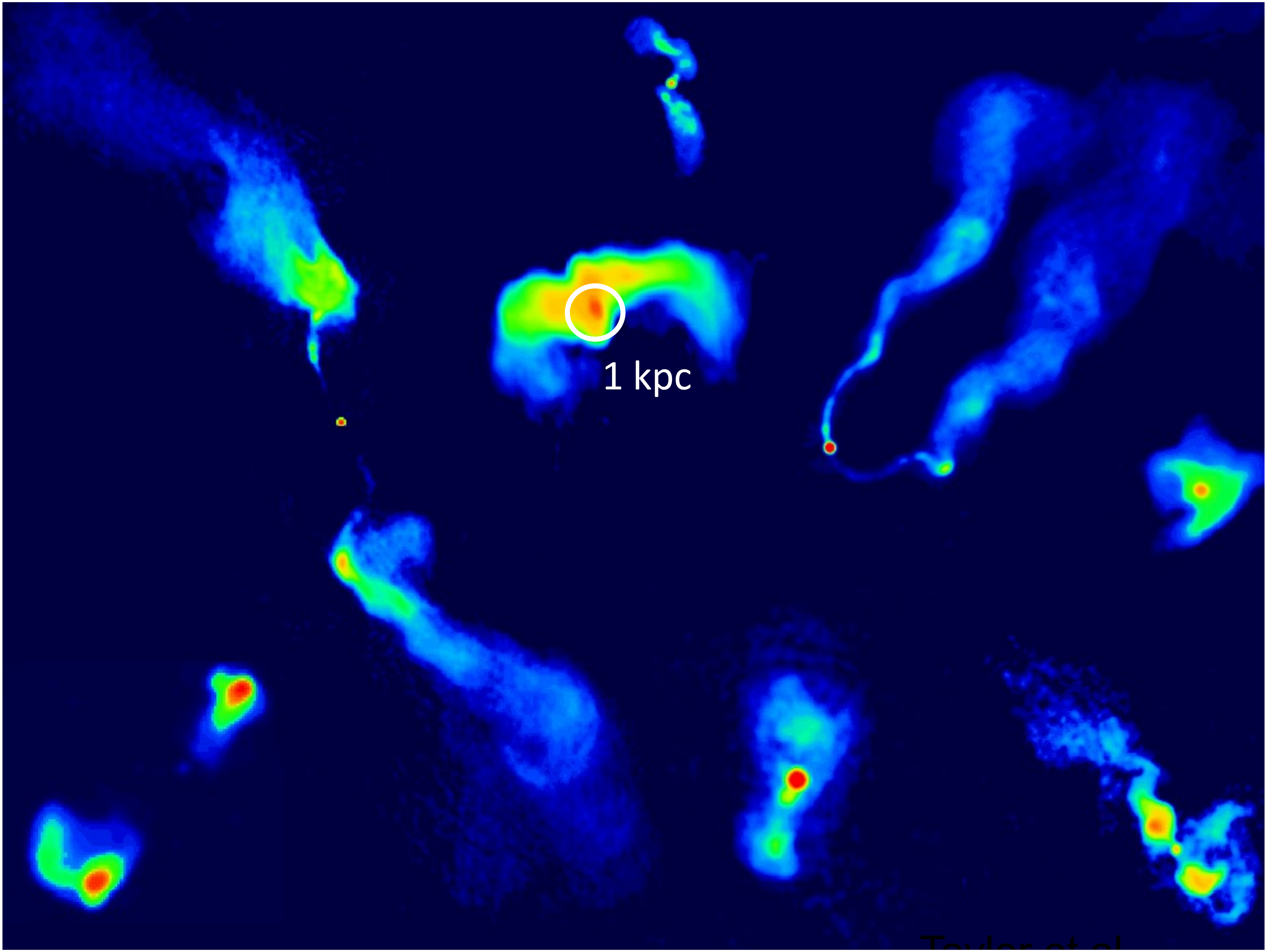


Laing et al.

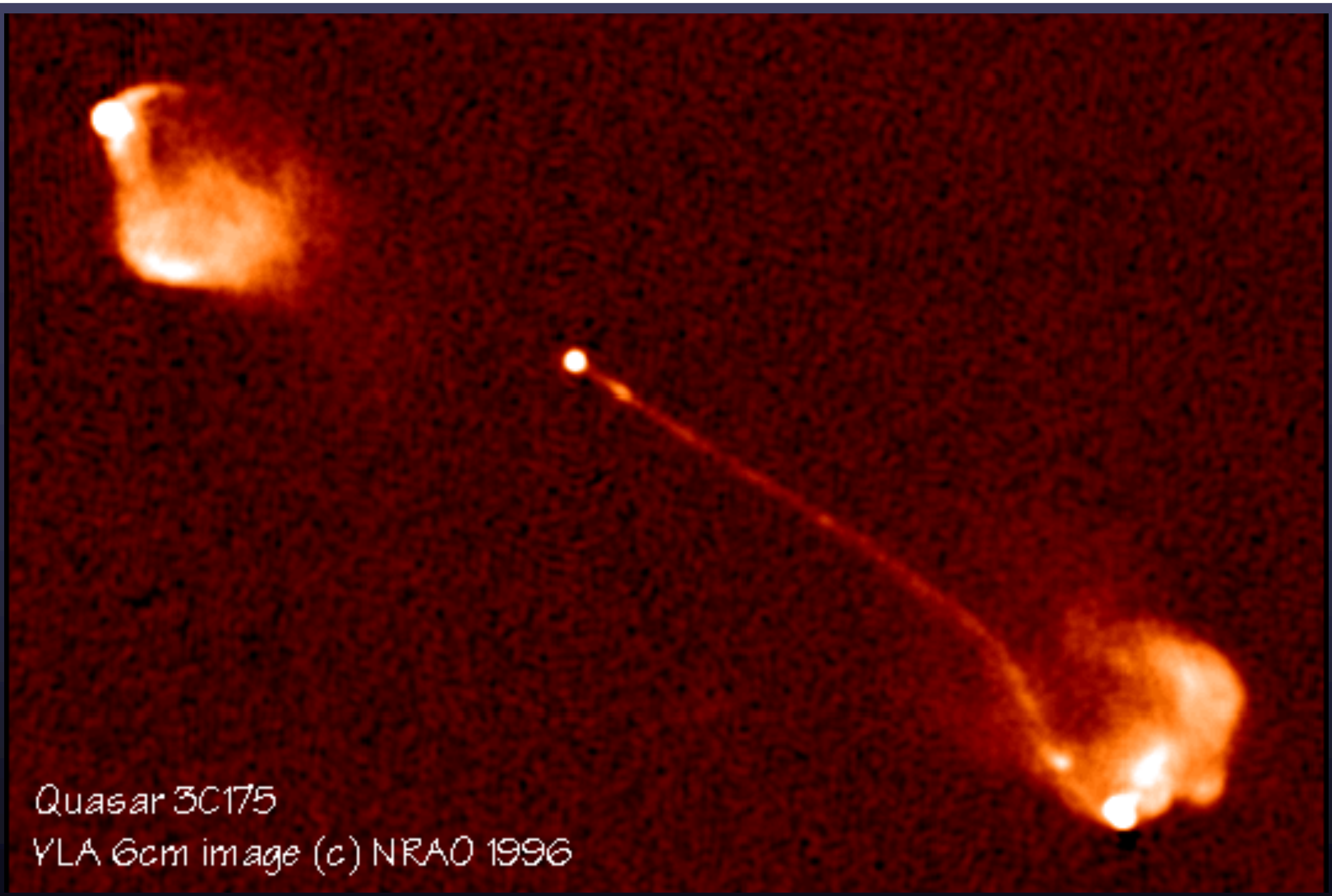
Cygnus A – prototypical radio galaxy -- FR II



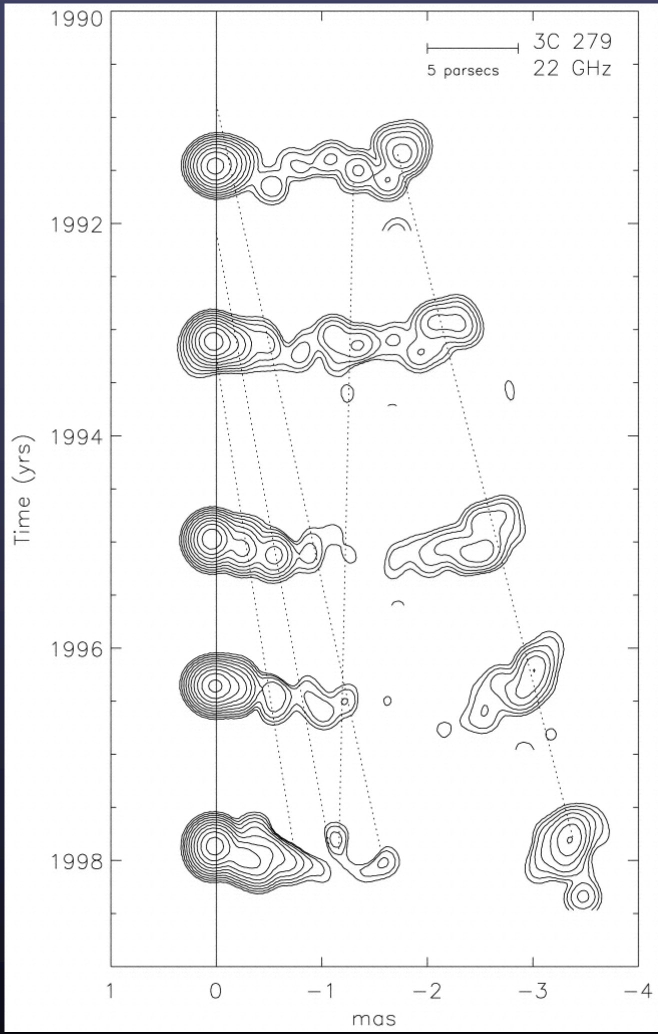
Carilli et al.

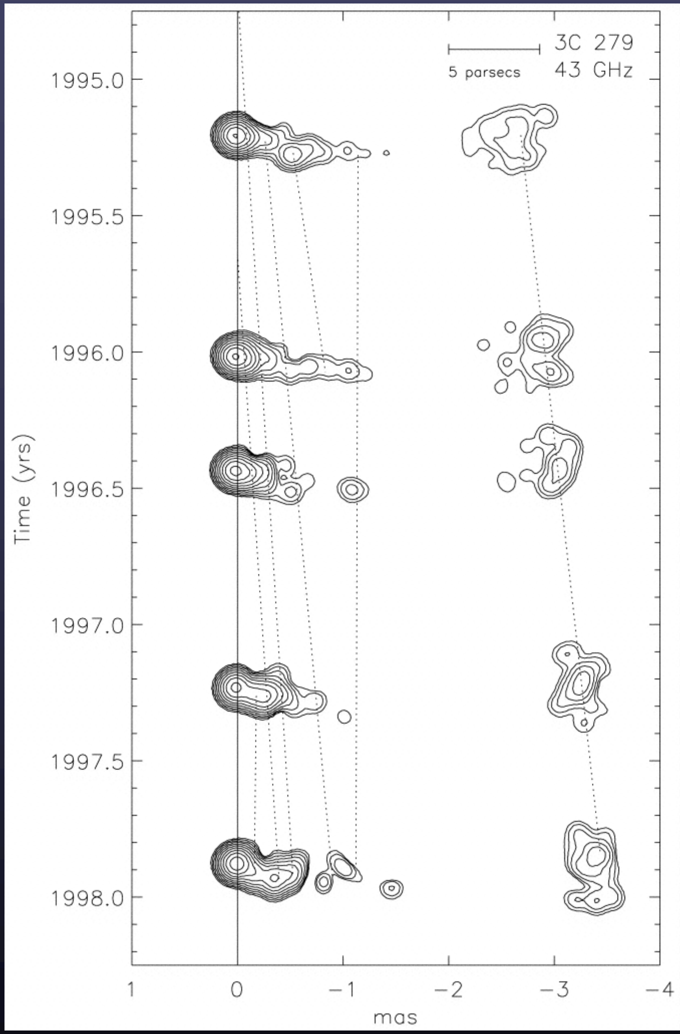

1 kpc

Quasar



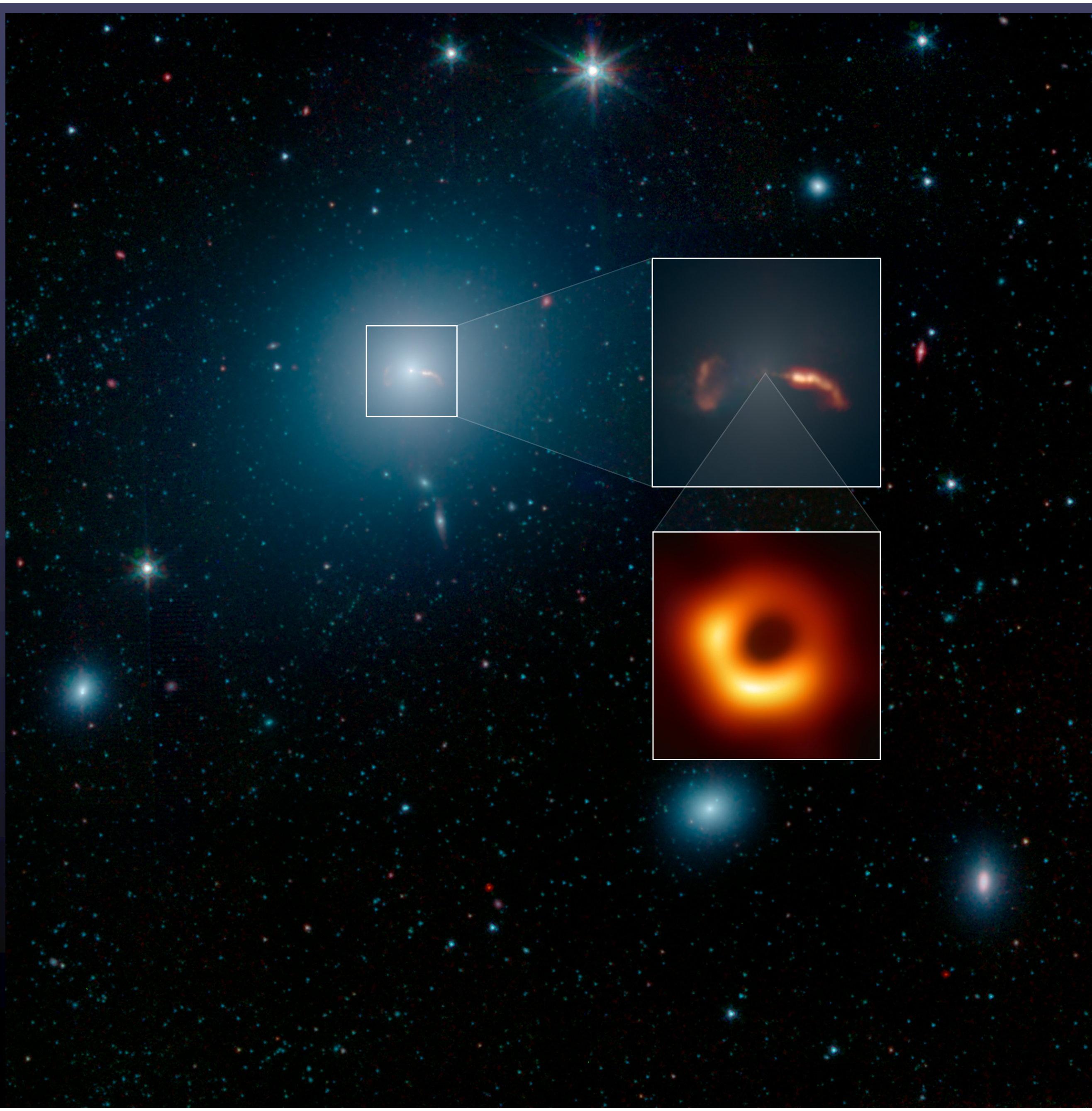
3C279 Quasar with the VLBA





Wehrle et al. 2001, ApJS, 133, 297

M87 Radio Galaxy

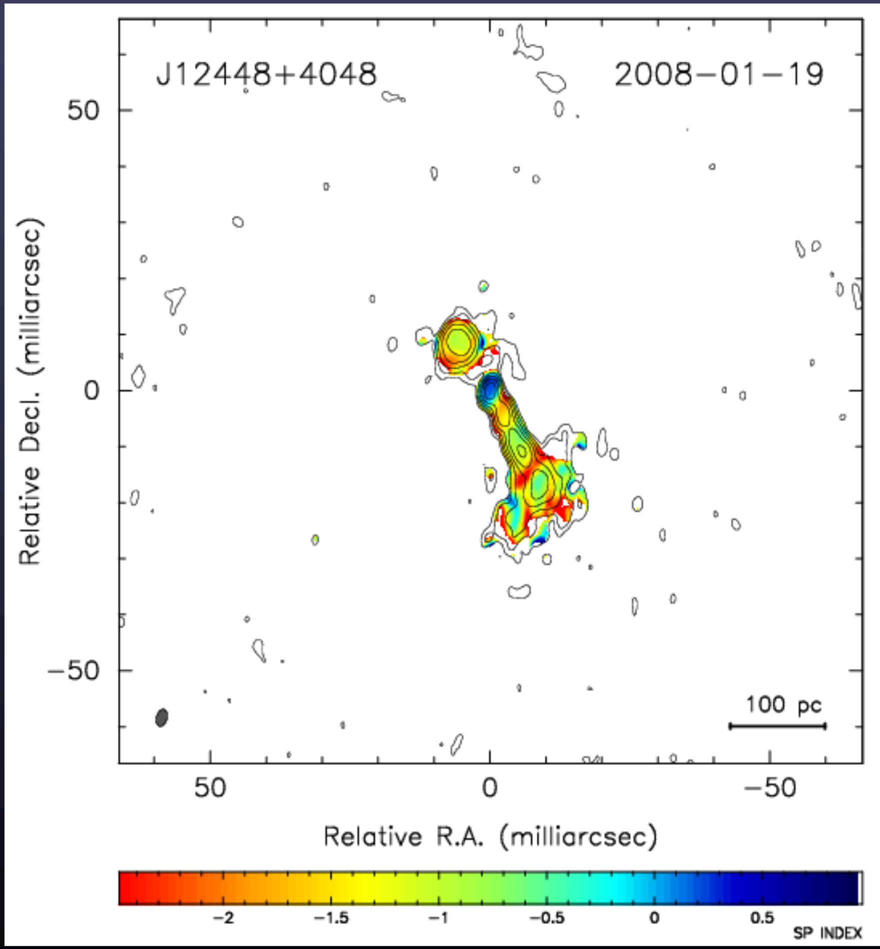


NRAO

The University of New Mexico

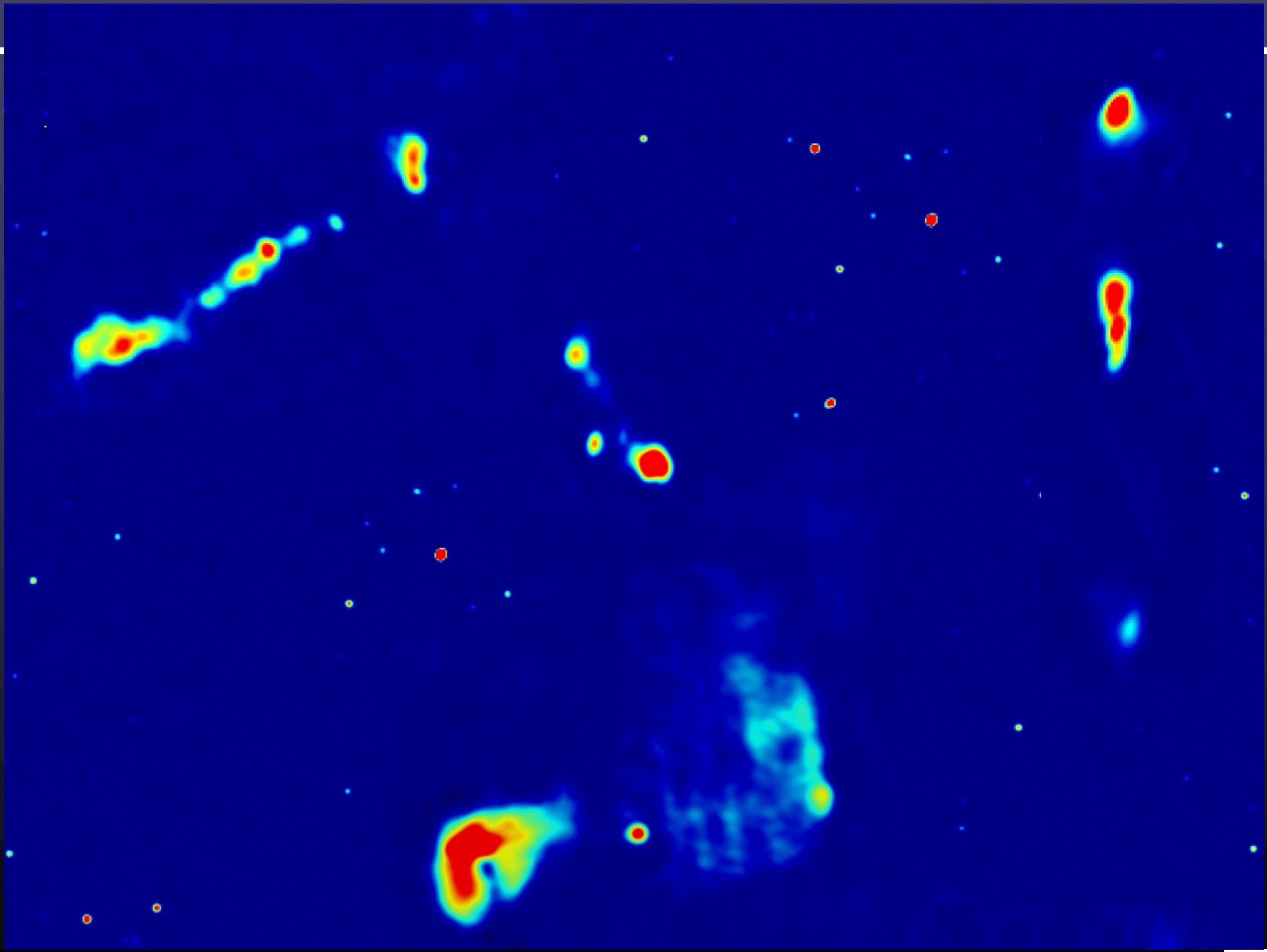
J12448+4048

Baby radio galaxy



Tremblay et al. 2011

Compact Symmetric Objects (CSOs)



Why so many types of Active Galactic Nuclei?

We see AGN :

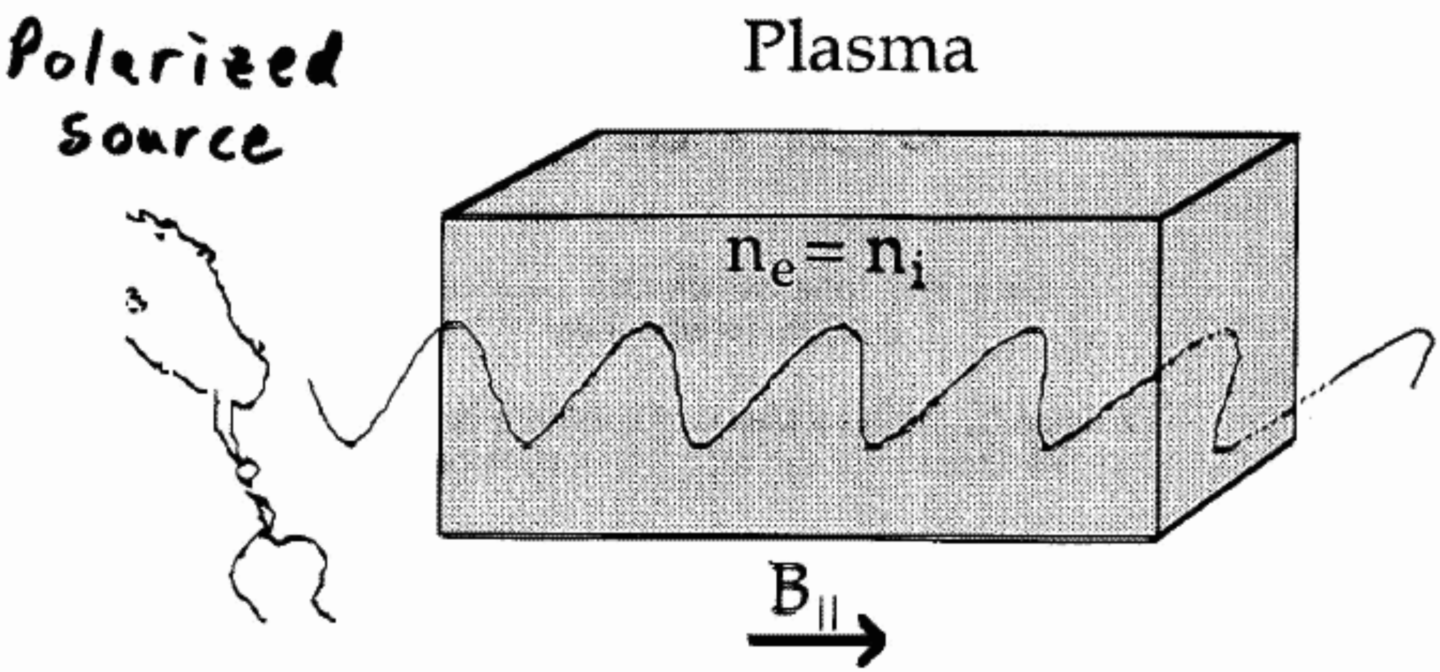
- from different orientations
- at different evolutionary stages
- in different environments
- with different instruments

Synchrotron Emission depends on the distribution of both relativistic particles and magnetic fields.

Why we care about the environment:

- a black hole alone does not make for an AGN
- what are the fueling rates and fueling mechanisms?
- how is the jet collimated?
- what is the ambient magnetic field strength & topology?
- environment plays a key role in unified schemes
- investigate torus chemistry and physics
- Disturbed morphologies may indicate interactions with surrounding gas
- look for inflows/outflows
- use gas kinematics to weigh the central engine

Faraday Rotation

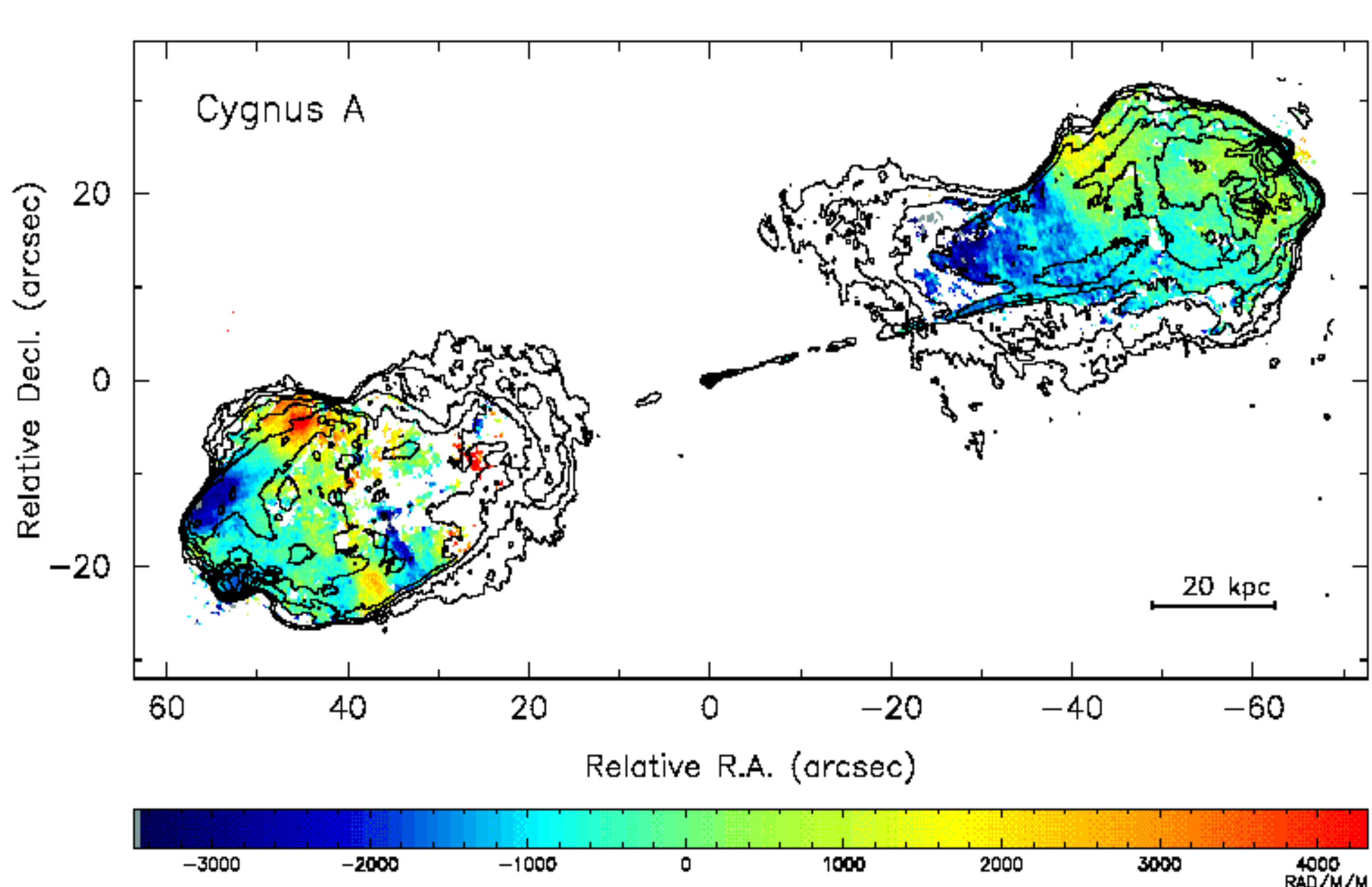


$$\Psi = \Psi_0 + \mathrm{RM}\,\lambda^2$$

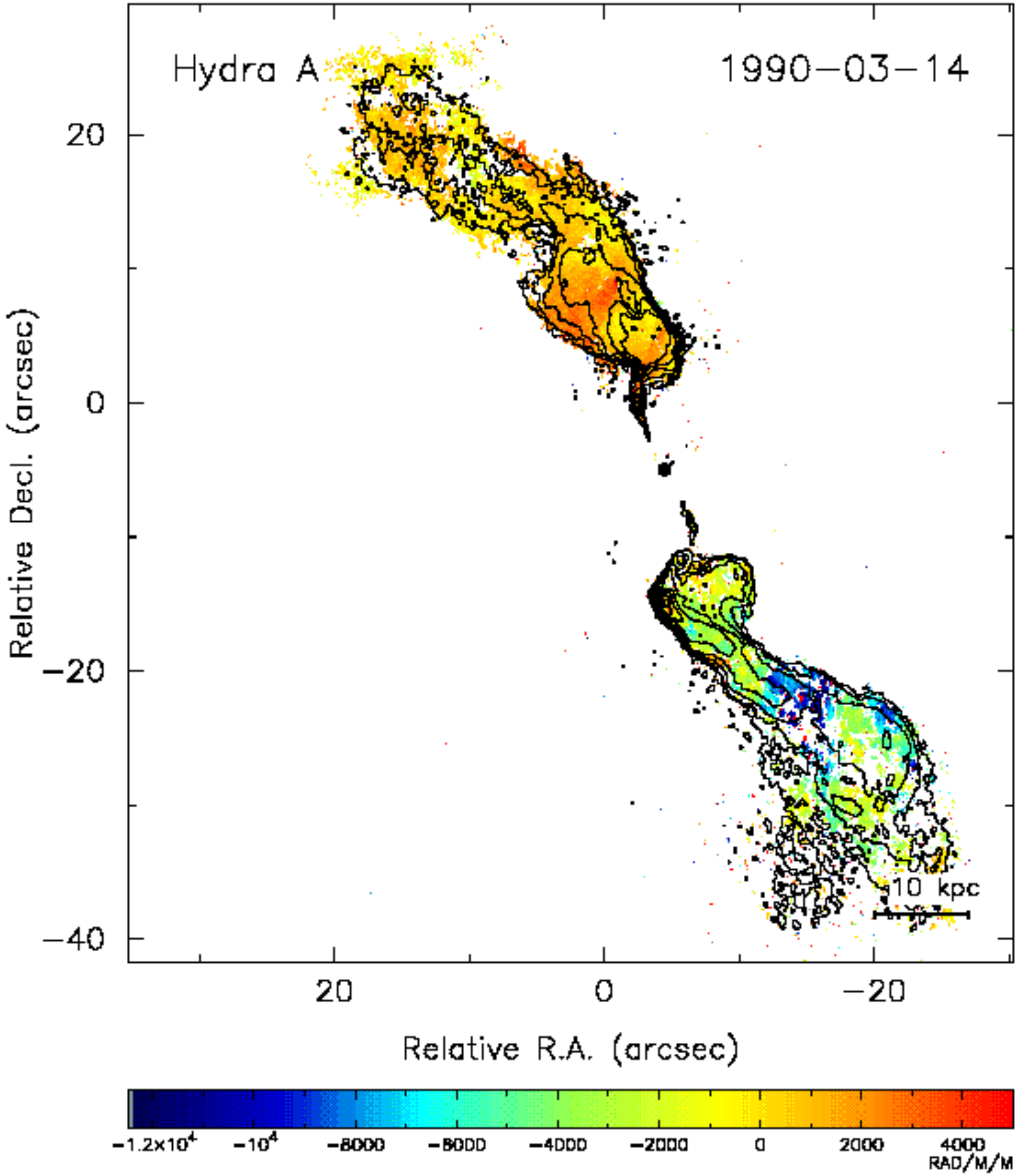
kpc
μGauss

$$\mathrm{RM} = 812 \int_0^L n_e B_{||}\, dl \ \text{radians/m}^2$$

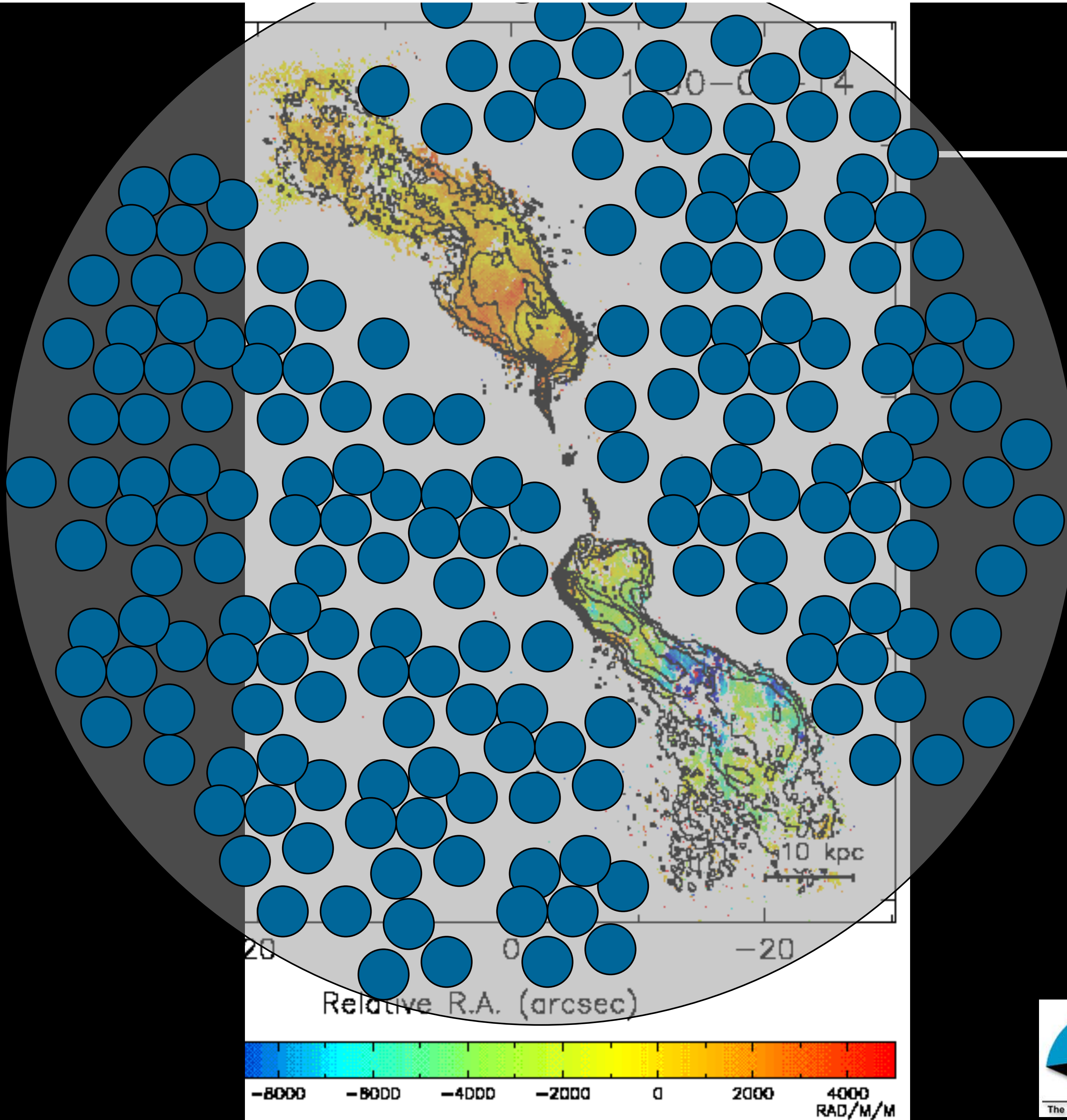
cm^{-3}

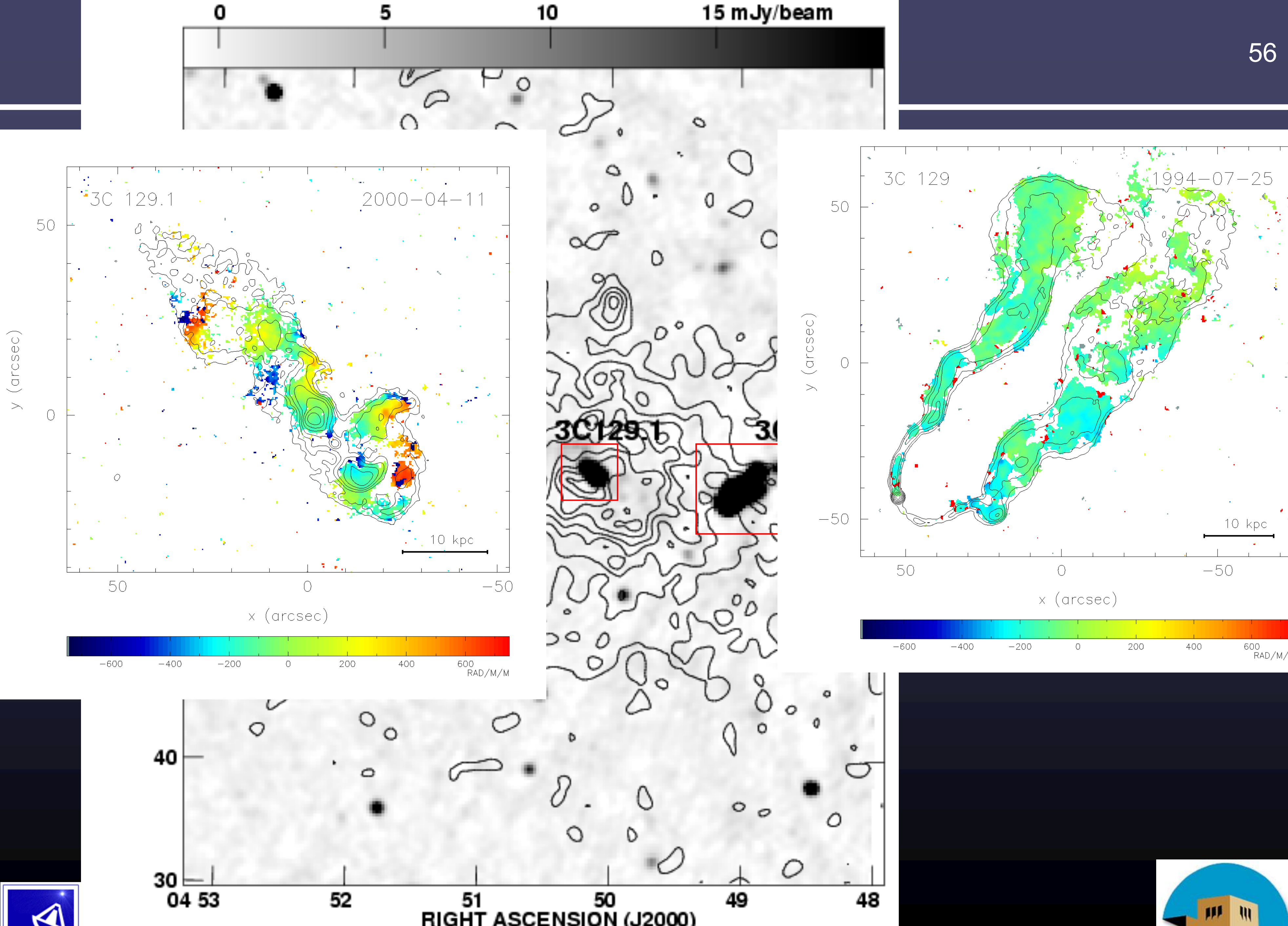


Carilli & Taylor 2002 (ARA&A)



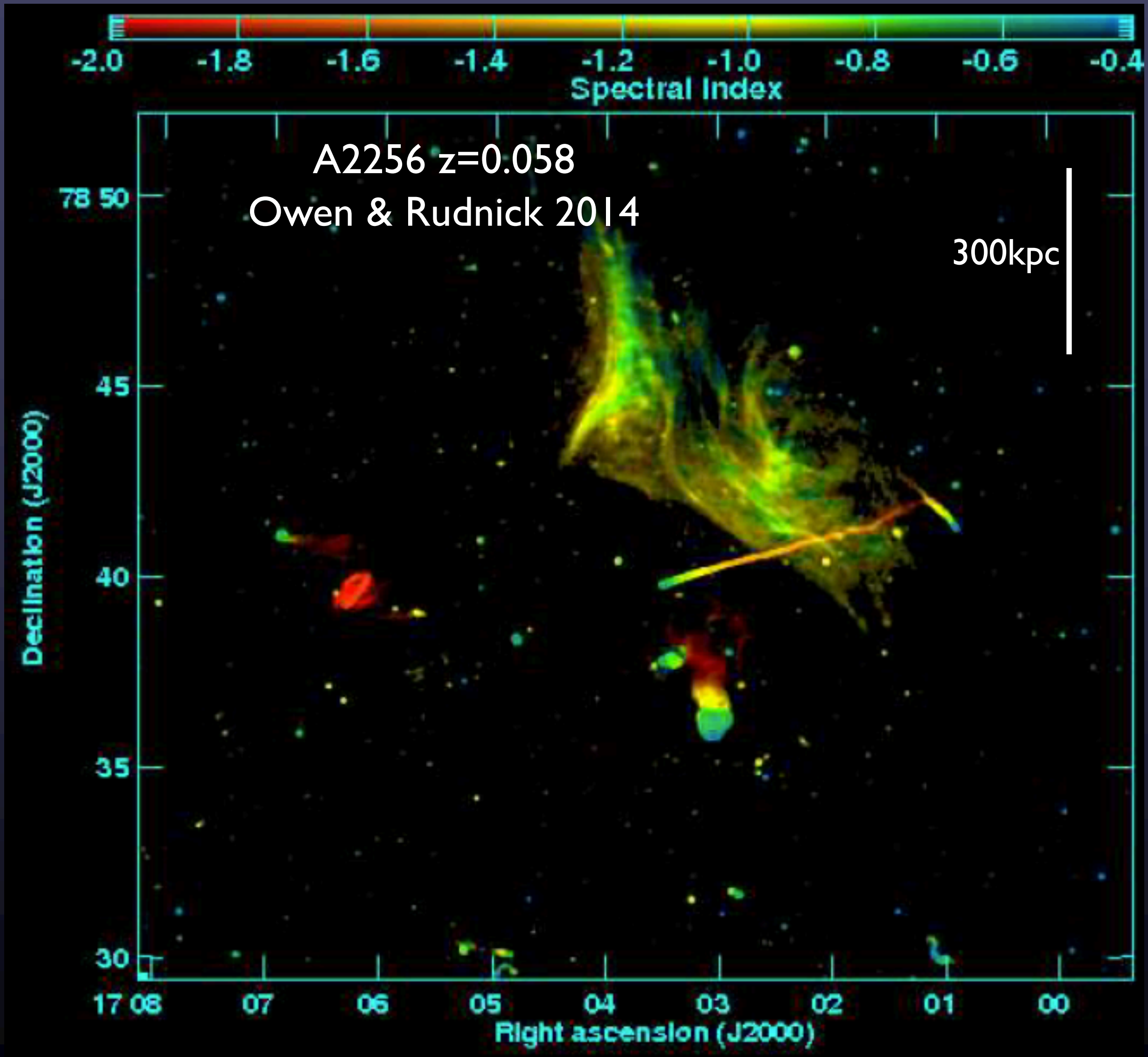
Carilli & Taylor 2002 (ARA&A)


10 kpc
20
0
−20
Relative R.A. (arcsec)
−8000
−6000
−4000
−2000
0
2000
4000
RAD/M/M


0
5
10
15 mJy/beam
3C129.1
3C
40
30
04 53
52
51
50
49
48
RIGHT ASCENSION (J2000)
3C 129.1
2000-04-11
y (arcsec)
x (arcsec)
10 kpc
RAD/M/M
3C 129
1994-07-25
y (arcsec)
x (arcsec)
10 kpc
RAD/M/M
The University of New Mexico

Frontiers of Plasma Physics: VLA imaging of cluster radio emission on scales 0.1kpc to 1 Mpc

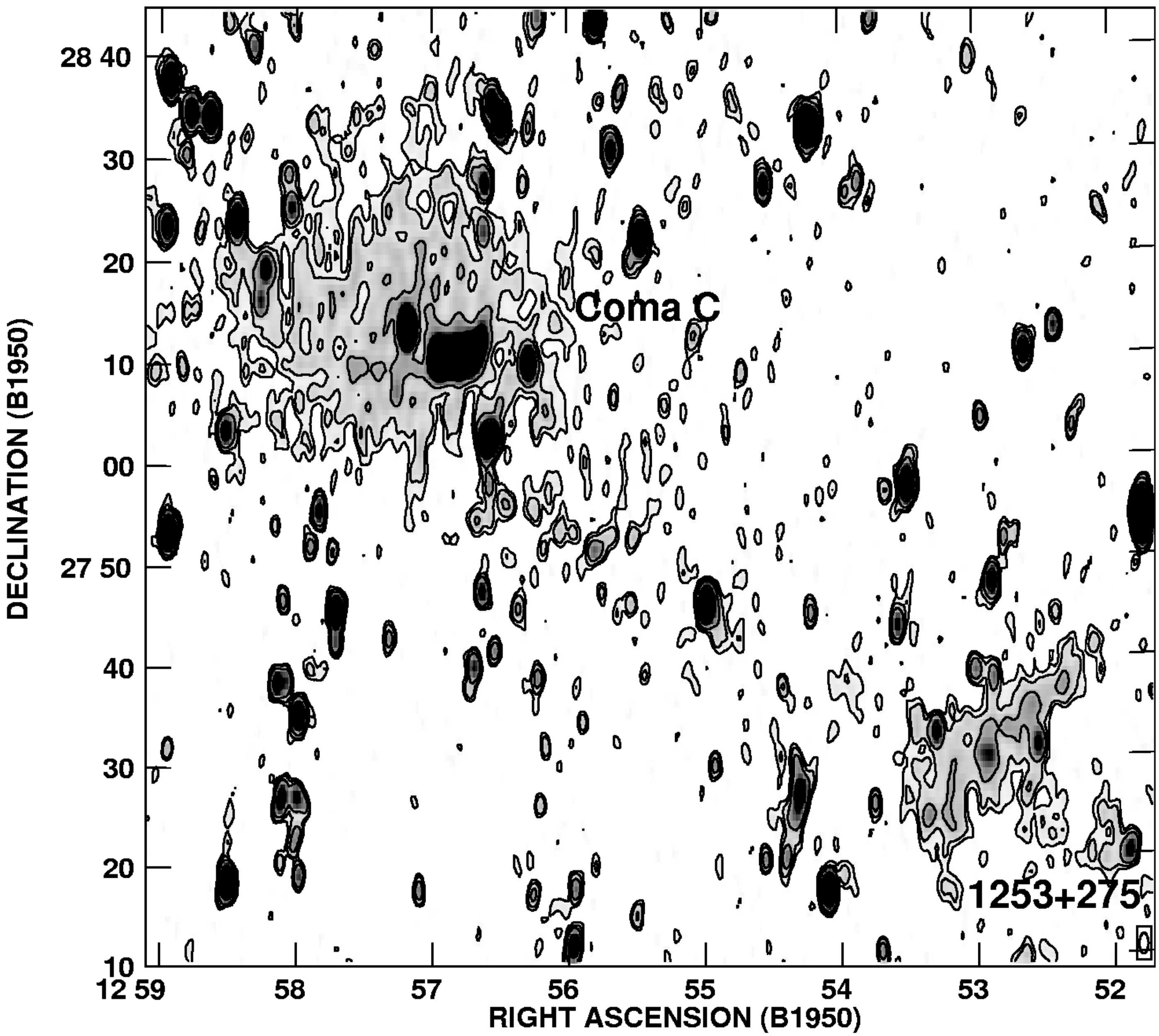
- 1 – 8 GHz
- rms~2.5uJy
- Frac. Pol. up to 70%
- RM ~ 100 rad m^{-2}
- *Laboratory for plasma physics on largest scales:* Halos, jets, lobes, relics, Xray gas…



Feretti et al. 1998

WSRT at 90cm

B ~ 0.4 μG



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Further Reading

http://www.nrao.edu/whatisra/mechanisms.shtml
http://www.nrao.edu/whatisra/
http://www2.jpl.nasa.gov/radioastronomy/
www.nrao.edu

Synthesis Imaging in Radio Astronomy
ASP Vol 180, eds Taylor, Carilli & Perley

This lecture is on the course web page:

http://www.phys.unm.edu/~gbtaylor/astr423/lectures