Thermal sources

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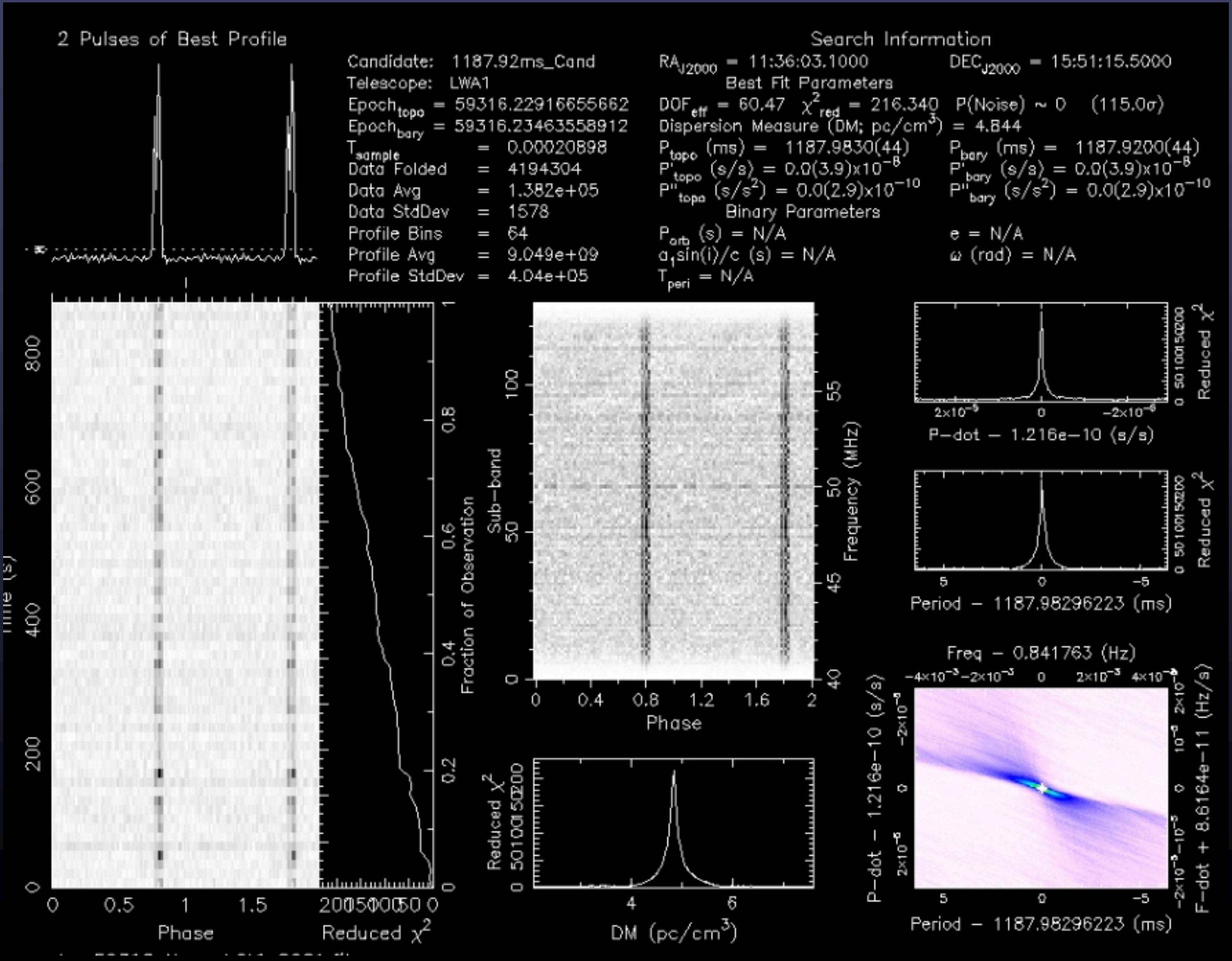
Astronomy 423 at UNM

Radio Astronomy

HW9 Pulsars



Search Information

Candidate: 1187.92ms_Cand
Telescope: LWA1
Epoch_{topo} = 59316.2291665562
Epoch_{bary} = 59316.2346355891 2
T_{sample} = 0.00020898
Data Folded = 4194304
Data Avg = 1.382e+05
Data StdDev = 1578
Profile Bins = 64
Profile Avg = 9.049e+09
Profile StdDev = 4.04e+05

RA_{J2000} = 11:36:03.1000
DEC_{J2000} = 15:51:15.5000

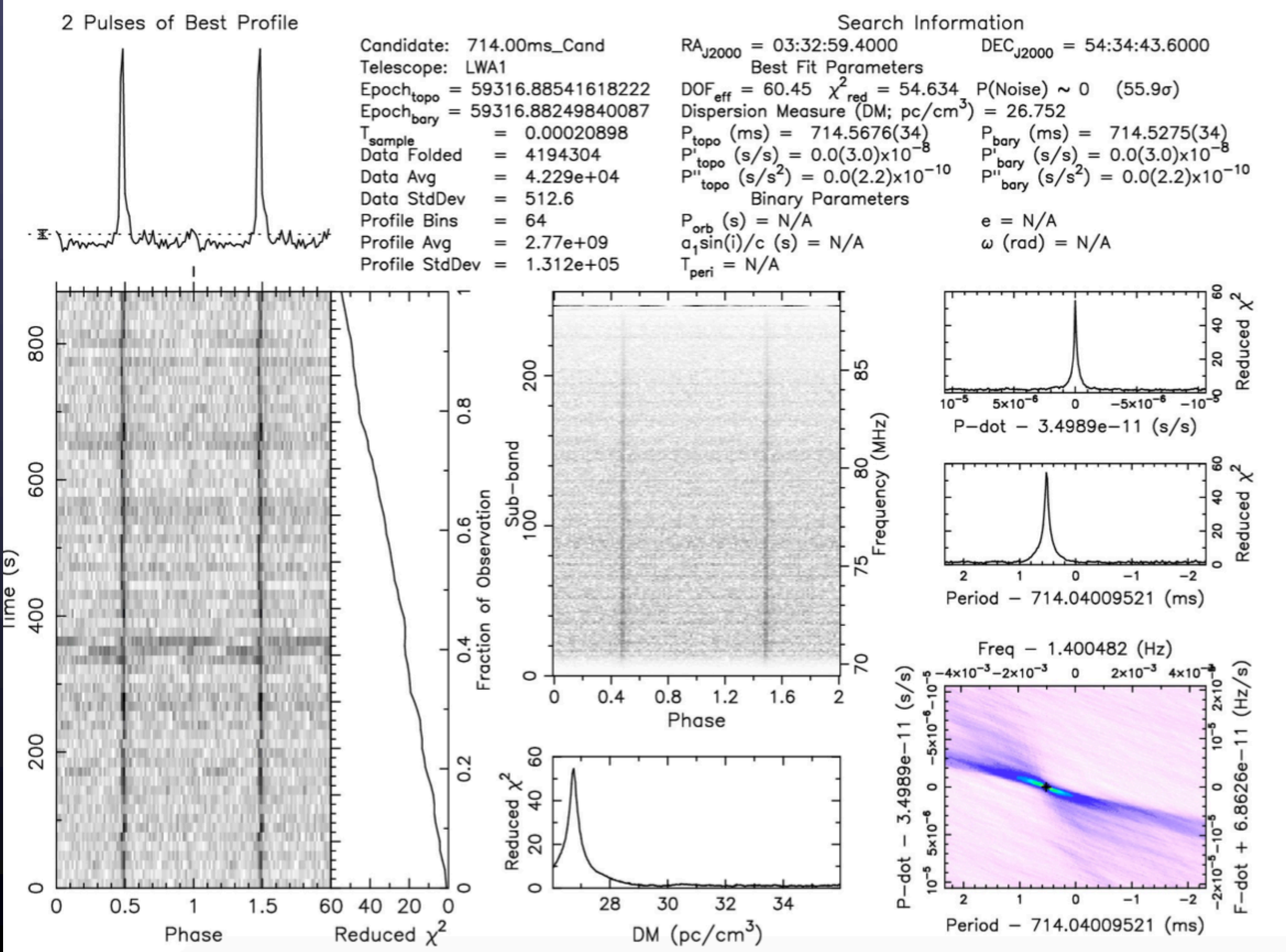
Best Fit Parameters

DOF_{eff} = 60.47 χ^2_{red} = 216.340 P(Noise) ~ 0 (115.0σ)
Dispersion Measure (DM; pc/cm^3) = 4.844
P_{topo} (ms) = 1187.9830(44)
P_{bary} (ms) = 1187.9200(44)
P'_{topo} (s/s) = $0.0(3.9)\times10^{-8}$
P'_{bary} (s/s) = $0.0(3.9)\times10^{-8}$
P''_{topo} (s/s^2) = $0.0(2.9)\times10^{-10}$
P''_{bary} (s/s^2) = $0.0(2.9)\times10^{-10}$

Binary Parameters

P_{orb} (s) = N/A
e = N/A
$a_1\sin(i)/c$ (s) = N/A
ω (rad) = N/A
T_{peri} = N/A

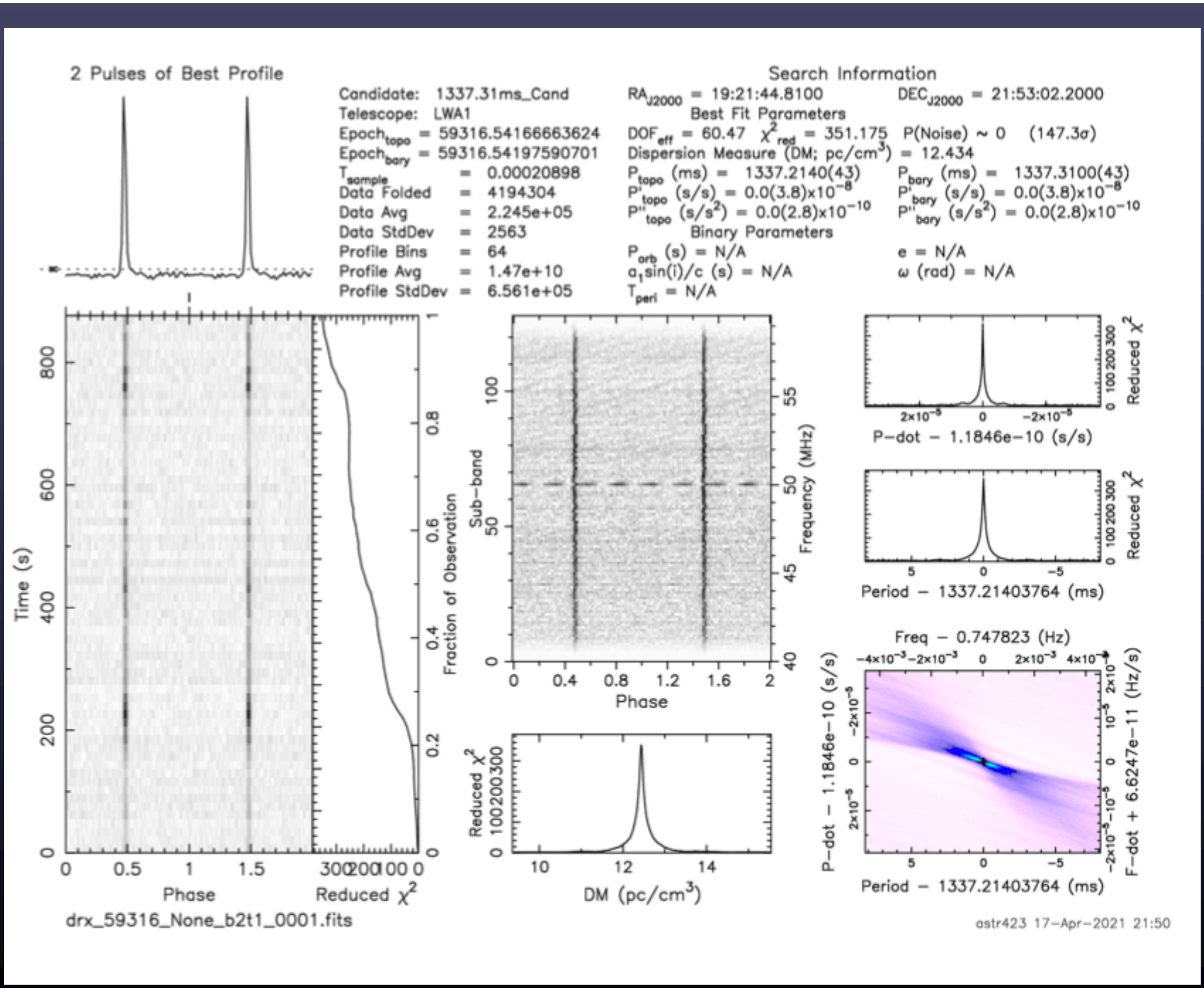
HW9 Pulsars



Candidate: 714.00ms_Cand
Telescope: LWA1
$\mathrm{Epoch_{topo}}$ = 59316.88541618222
$\mathrm{Epoch_{bary}}$ = 59316.88249840087
$\mathrm{T_{sample}}$ = 0.00020898
Data Folded = 4194304
Data Avg = 4.229e+04
Data StdDev = 512.6
Profile Bins = 64
Profile Avg = 2.77e+09
Profile StdDev = 1.312e+05

Search Information
$\mathrm{RA_{J2000}}$ = 03:32:59.4000 $\mathrm{DEC_{J2000}}$ = 54:34:43.6000
Best Fit Parameters
$\mathrm{DOF_{eff}}$ = 60.45 χ^2_{red} = 54.634 P(Noise) ~ 0 (55.9σ)
Dispersion Measure (DM; pc/cm^3) = 26.752
$\mathrm{P_{topo}}$ (ms) = 714.5676(34) $\mathrm{P_{bary}}$ (ms) = 714.5275(34)
$\mathrm{P'_{topo}}$ (s/s) = 0.0(3.0)x10^{-8} $\mathrm{P'_{bary}}$ (s/s) = 0.0(3.0)x10^{-8}
$\mathrm{P''_{topo}}$ (s/s^2) = 0.0(2.2)x10^{-10} $\mathrm{P''_{bary}}$ (s/s^2) = 0.0(2.2)x10^{-10}
Binary Parameters
$\mathrm{P_{orb}}$ (s) = N/A e = N/A
$a_1\sin(i)/c$ (s) = N/A ω (rad) = N/A
$\mathrm{T_{peri}}$ = N/A

HW9 Pulsars



Search Information

Candidate: 1337.31ms_Cand
Telescope: LWA1
Epoch_{topo} = 59316.54166663624
Epoch_{bary} = 59316.54197590701
T_{sample} = 0.00020898
Data Folded = 4194304
Data Avg = 2.245e+05
Data StdDev = 2563
Profile Bins = 64
Profile Avg = 1.47e+10
Profile StdDev = 6.561e+05

RA_{J2000} = 19:21:44.8100
DEC_{J2000} = 21:53:02.2000

Best Fit Parameters

DOF_{eff} = 60.47 χ^2_{red} = 351.175 P(Noise) ~ 0 (147.3σ)
Dispersion Measure (DM; pc/cm^3) = 12.434
P_{topo} (ms) = 1337.2140(43)
P_{bary} (ms) = 1337.3100(43)
P'_{topo} (s/s) = 0.0(3.8)x10^{-8}
P'_{bary} (s/s) = 0.0(3.8)x10^{-8}
P''_{topo} (s/s^2) = 0.0(2.8)x10^{-10}
P''_{bary} (s/s^2) = 0.0(2.8)x10^{-10}

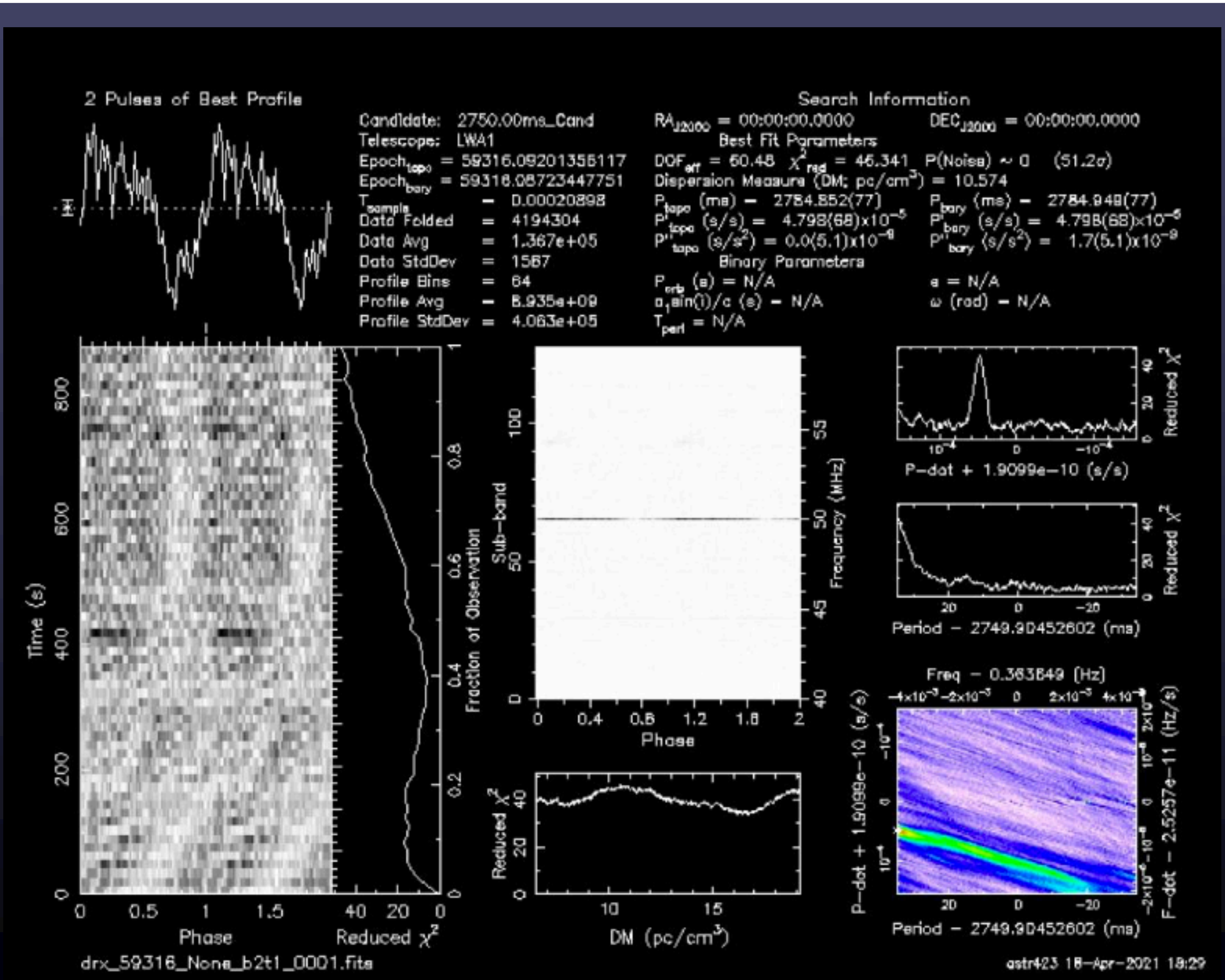
Binary Parameters

P_{orb} (s) = N/A
$a_1\sin(i)/c$ (s) = N/A
T_{peri} = N/A
e = N/A
ω (rad) = N/A

drx_59316_None_b2t1_0001.fits

astr423 17–Apr–2021 21:50

HW9 Pulsars



2 Pulses of Best Profile

Candidate: 2750.00ms_Cand
Telescope: LWA1
$\mathrm{Epoch_{topo}}$ = 59316.09201356117
$\mathrm{Epoch_{bary}}$ = 59316.08723447751
$\mathrm{T_{sample}}$ = 0.00020898
Data Folded = 4194304
Data Avg = 1.367e+05
Data StdDev = 1567
Profile Bins = 64
Profile Avg = 8.935e+09
Profile StdDev = 4.063e+05

Search Information

$\mathrm{RA_{J2000}}$ = 00:00:00.0000
$\mathrm{DEC_{J2000}}$ = 00:00:00.0000

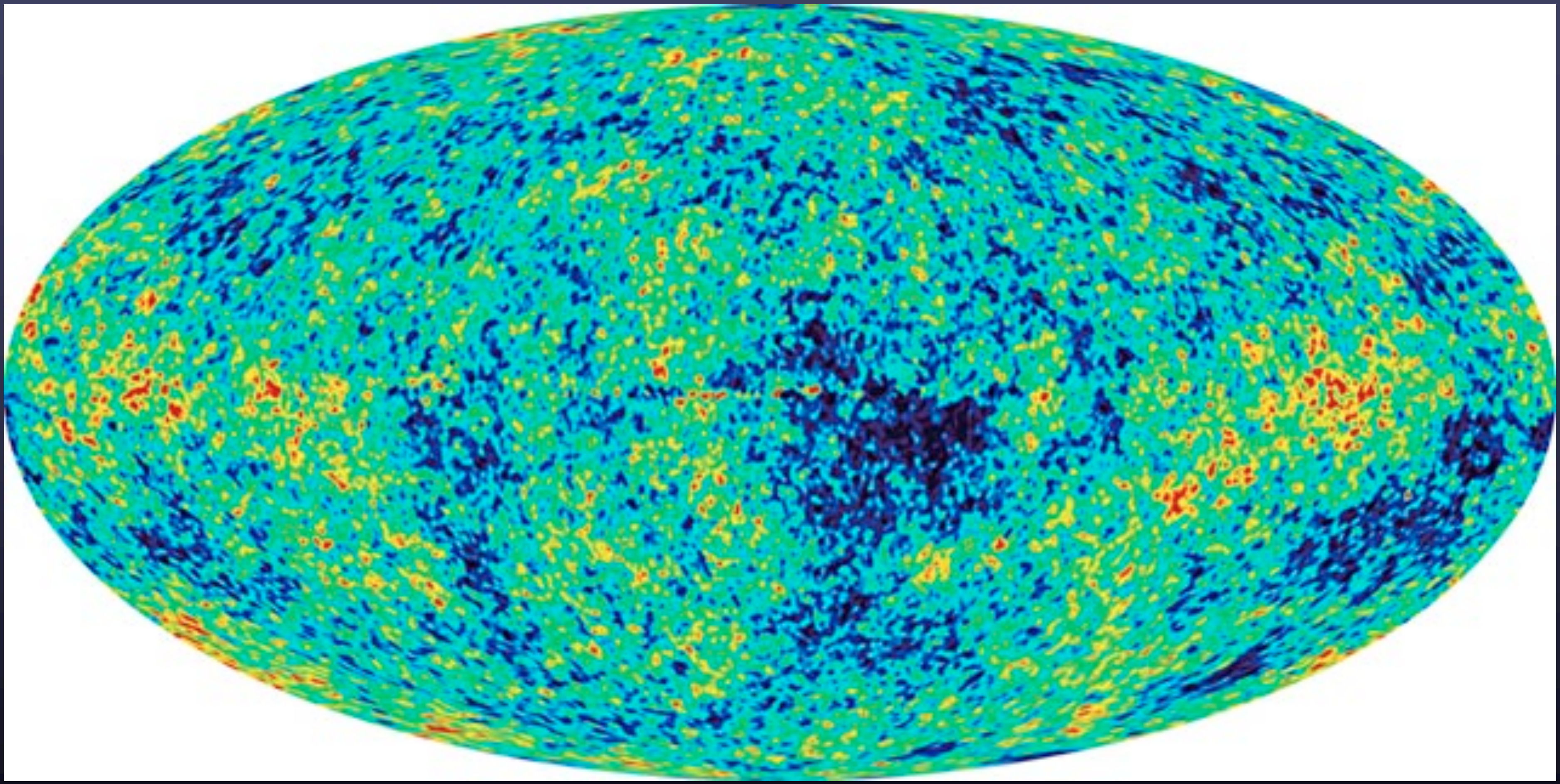
Best Fit Parameters

$\mathrm{DOF_{eff}}$ = 60.48 χ^2_{red} = 46.341 P(Noise) ~ 0 (51.2σ)
Dispersion Measure (DM; pc/cm^3) = 10.574
$\mathrm{P_{topo}}$ (ms) = 2784.852(77)
$\mathrm{P_{bary}}$ (ms) = 2784.948(77)
$\mathrm{P'_{topo}}$ (s/s) = 4.798(68)x10^{-5}
$\mathrm{P'_{bary}}$ (s/s) = 4.798(68)x10^{-5}
$\mathrm{P''_{topo}}$ (s/s^2) = 0.0(5.1)x10^{-9}
$\mathrm{P''_{bary}}$ (s/s^2) = 1.7(5.1)x10^{-9}

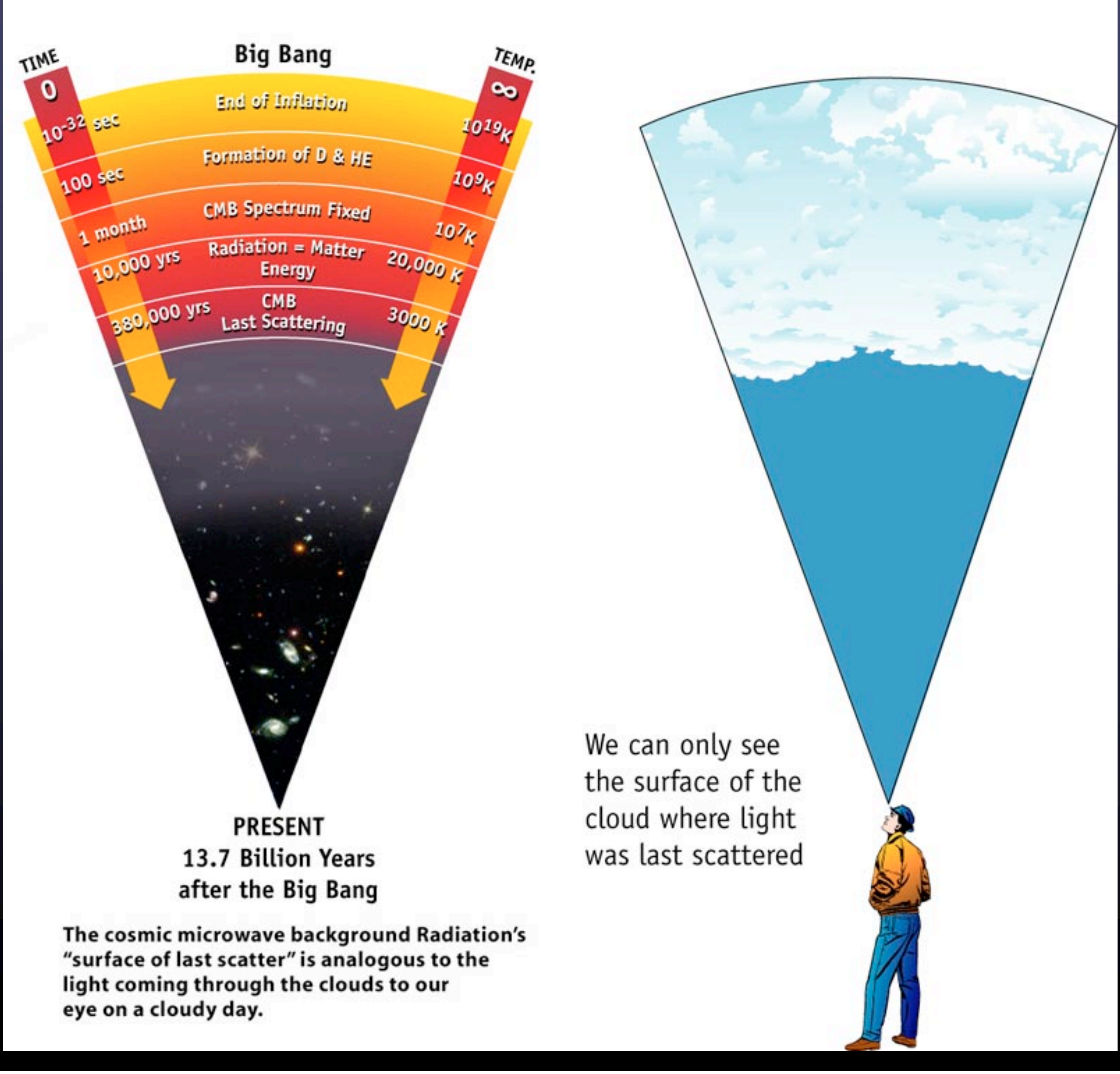
Binary Parameters

$\mathrm{P_{orb}}$ (s) = N/A
e = N/A
$a_1$sin(i)/c (s) = N/A
ω (rad) = N/A
$\mathrm{T_{peri}}$ = N/A

The Microwave Background



The Microwave Background

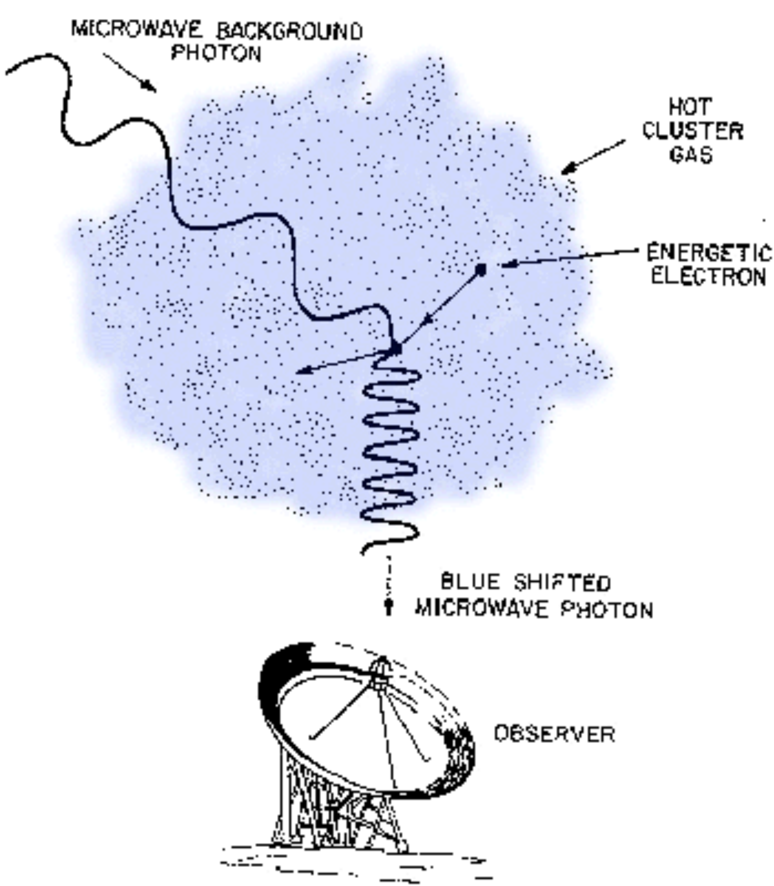


We can only see the surface of the cloud where light was last scattered

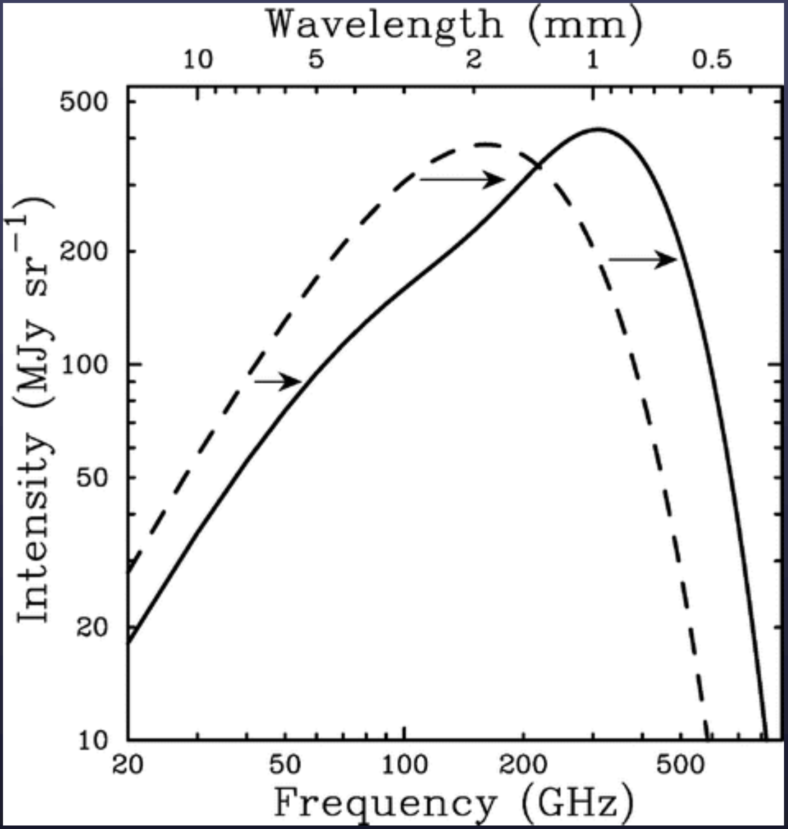
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

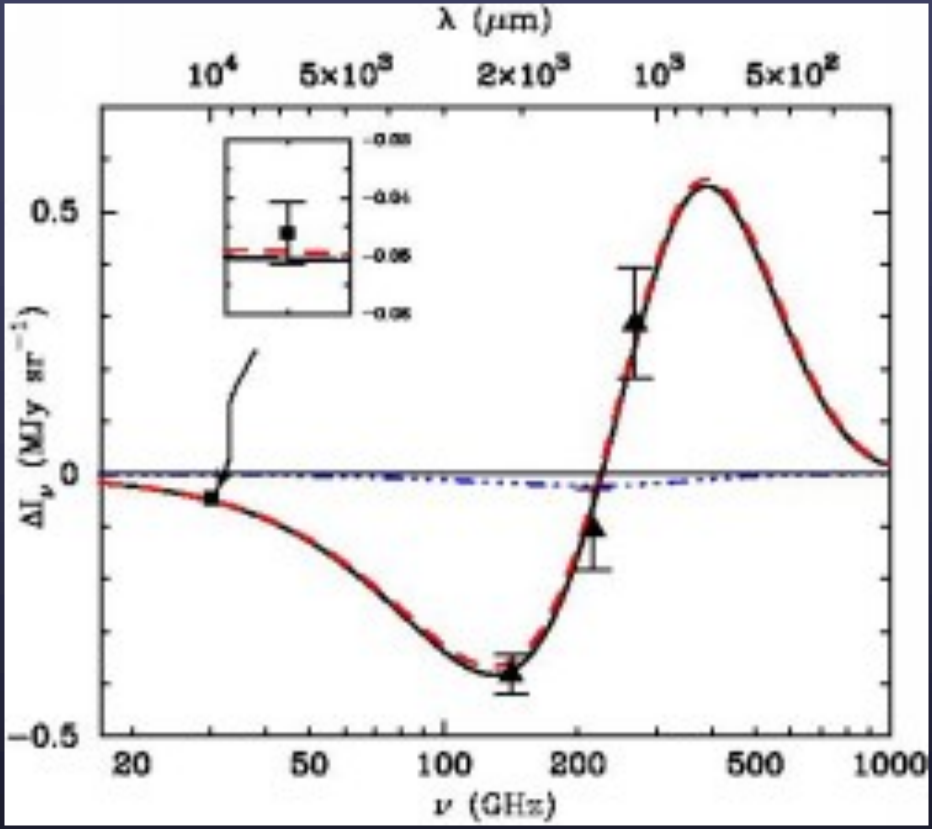
Sunyaev-Zeldovich effect

- The Sunyaev-Zeldovich effect
  - Photons of the CMB are scattered to higher frequencies by hot electrons in galaxy clusters, causing a negative brightness **decrement**.
  - Decrement is proportional to integral of electron pressure through the cluster, or electron density if cluster is isothermal.
  - Electron density and temperature can be estimated from X-ray observations, so the linear scale of the cluster is determined.
  - This can be used to measure the cluster distance and combined with z to get H_0.



Sunyaev-Zeldovich effect





SZ images

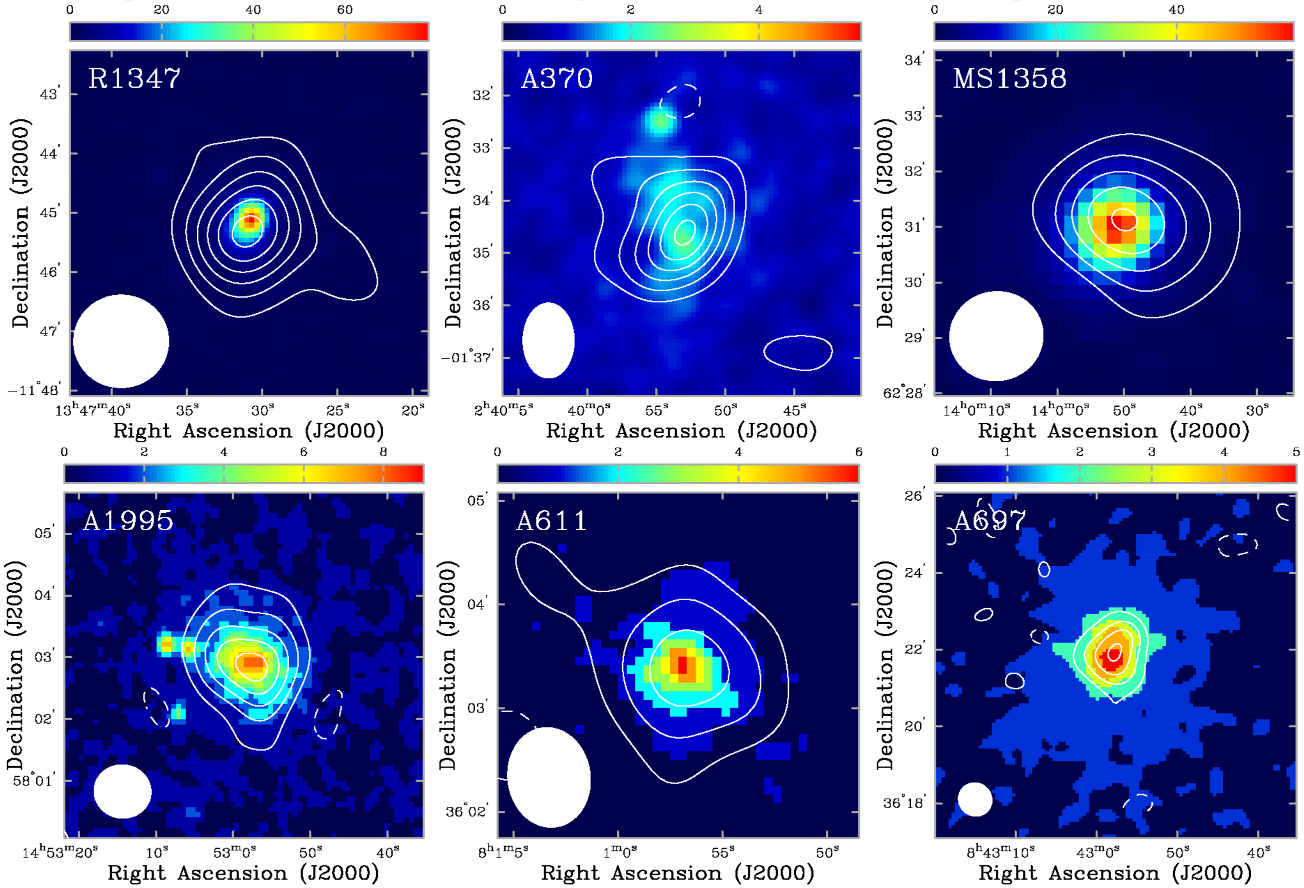
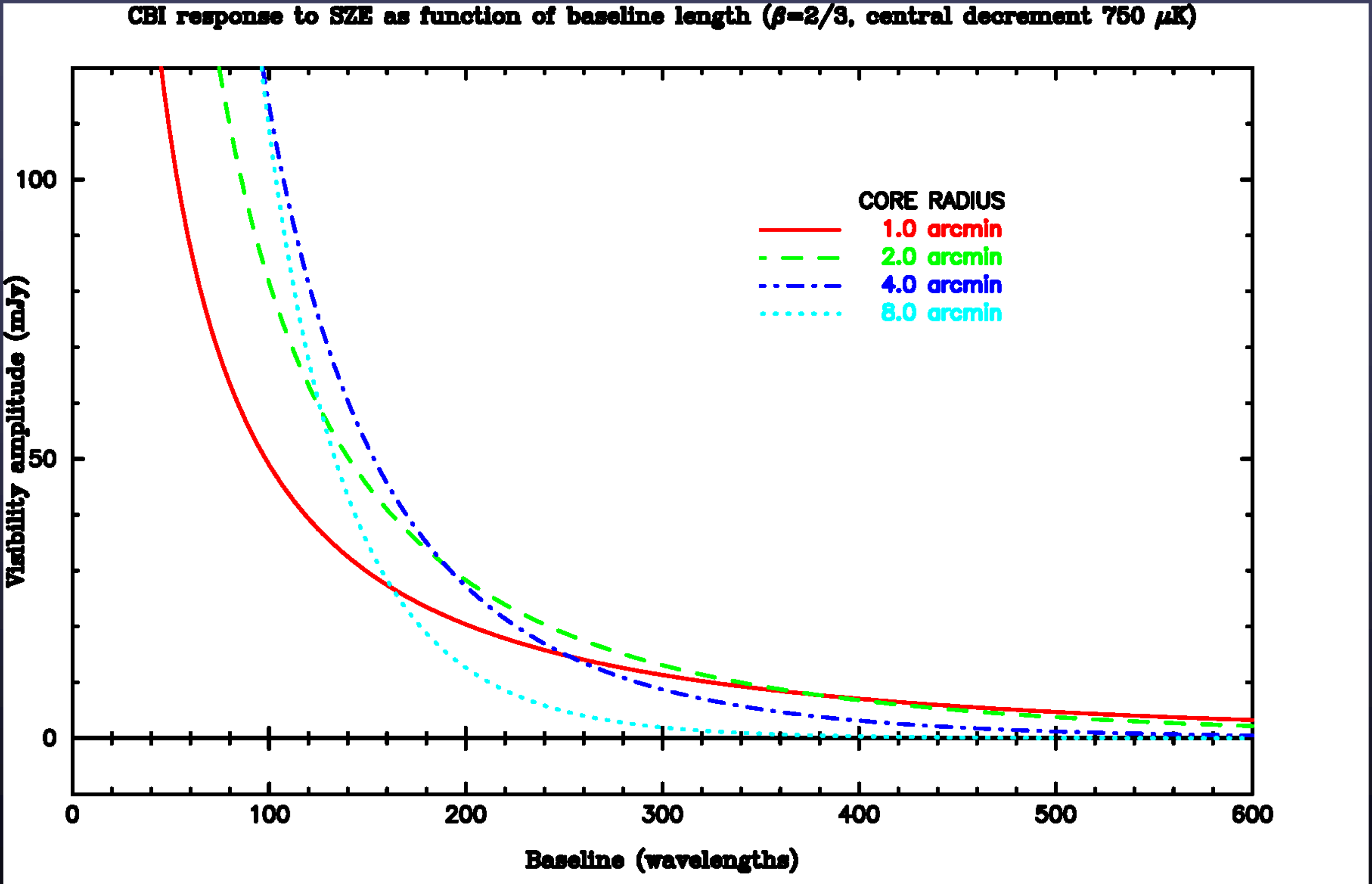


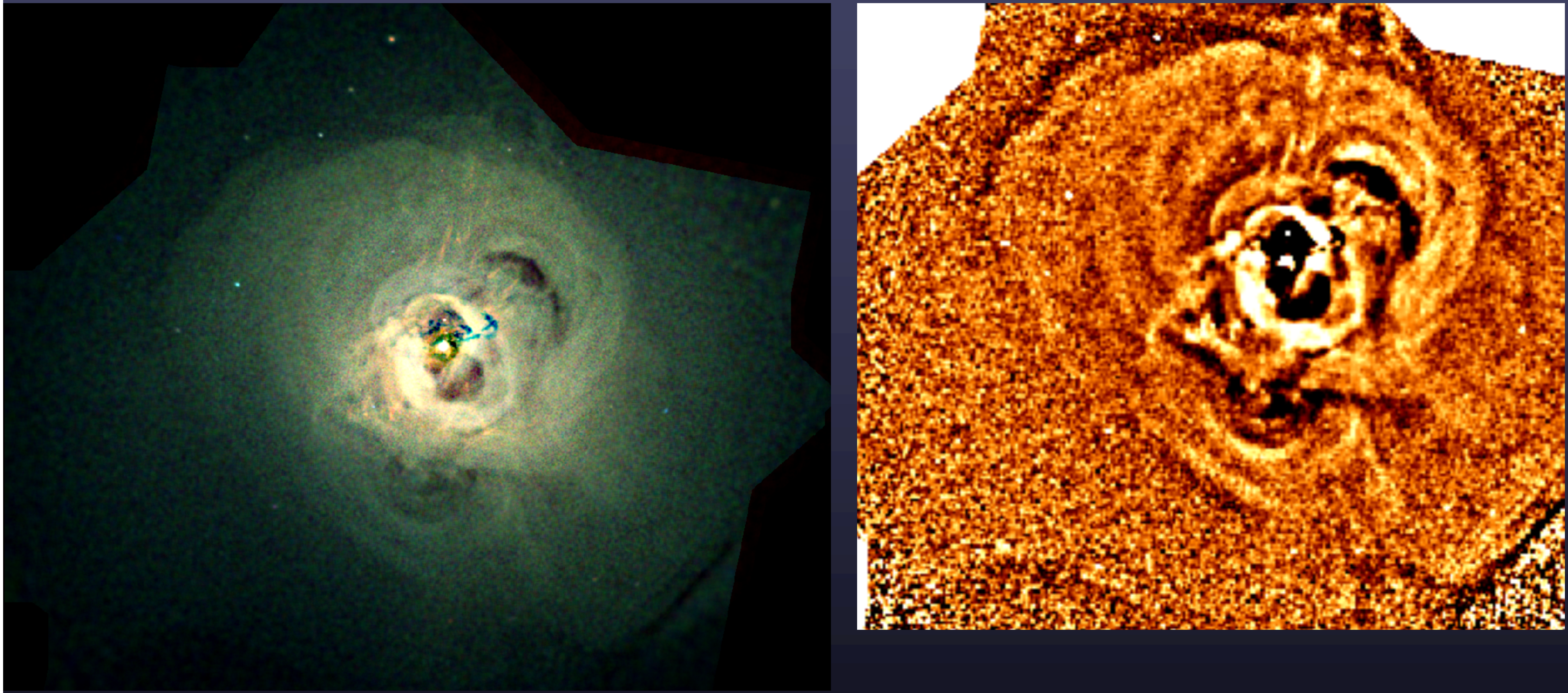
Fig. 2.—SZE (contours) and X-ray (color scale) images of each cluster in our sample. Negative contours are shown as solid lines. The contours are multiples of 2 σ and the FWHM of the synthesized beams are shown in the bottom left corner. The X-ray color scale images are raw counts images smoothed with Gaussians with $\sigma = 15''$ for PSPC data and $\sigma = 5''$ for HRI data. There is a color scale mapping for the counts above each image. The 30 GHz image statistics are summarized in Table 4.

Reese et al. astro-ph/0205350

SZ profiles


CBI response to SZE as function of baseline length (β=2/3, central decrement 750 μK)
Visibility amplitude (mJy)
Baseline (wavelengths)
0
50
100
0
100
200
300
400
500
600
CORE RADIUS
1.0 arcmin
2.0 arcmin
4.0 arcmin
8.0 arcmin

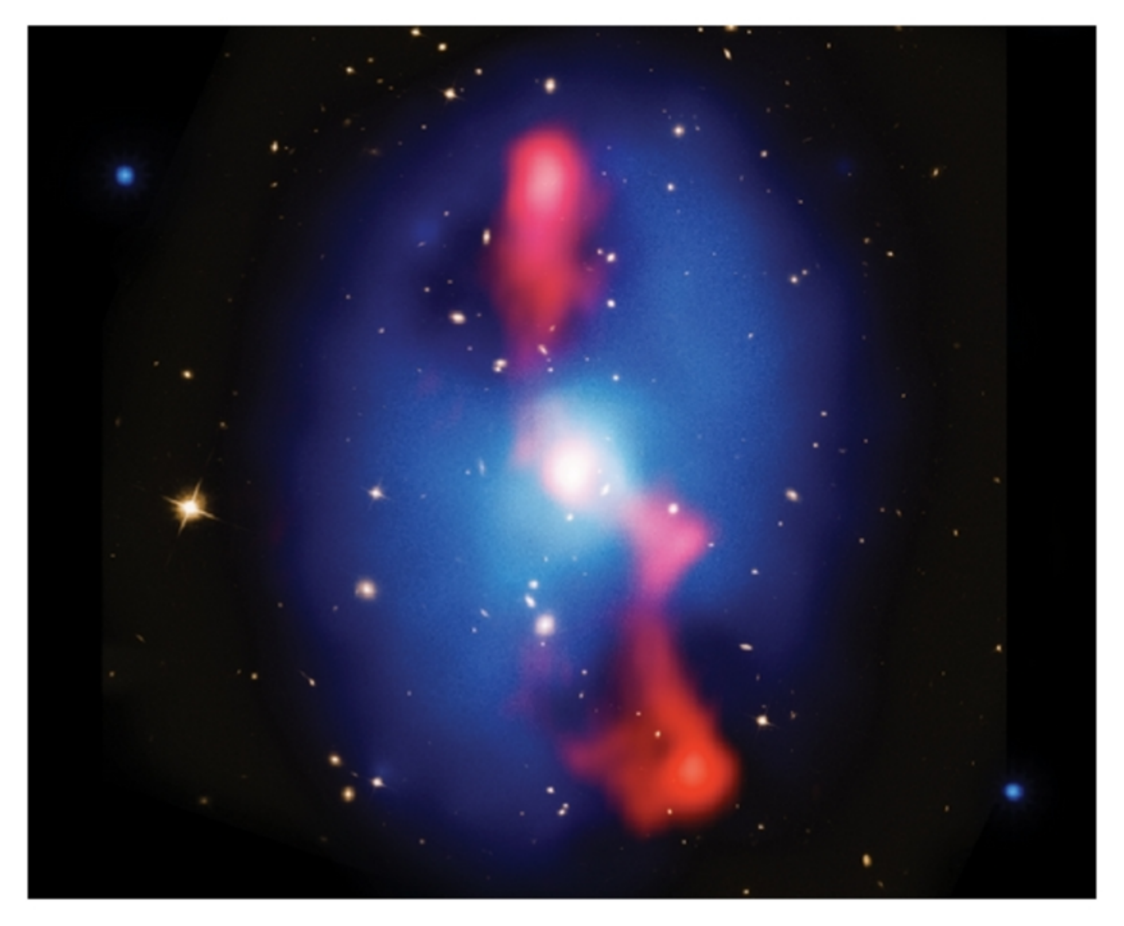
Clusters of Galaxies



Chandra 900 ks image of Perseus cluster, unsharp-masked at right (Fabian et al. 2006)

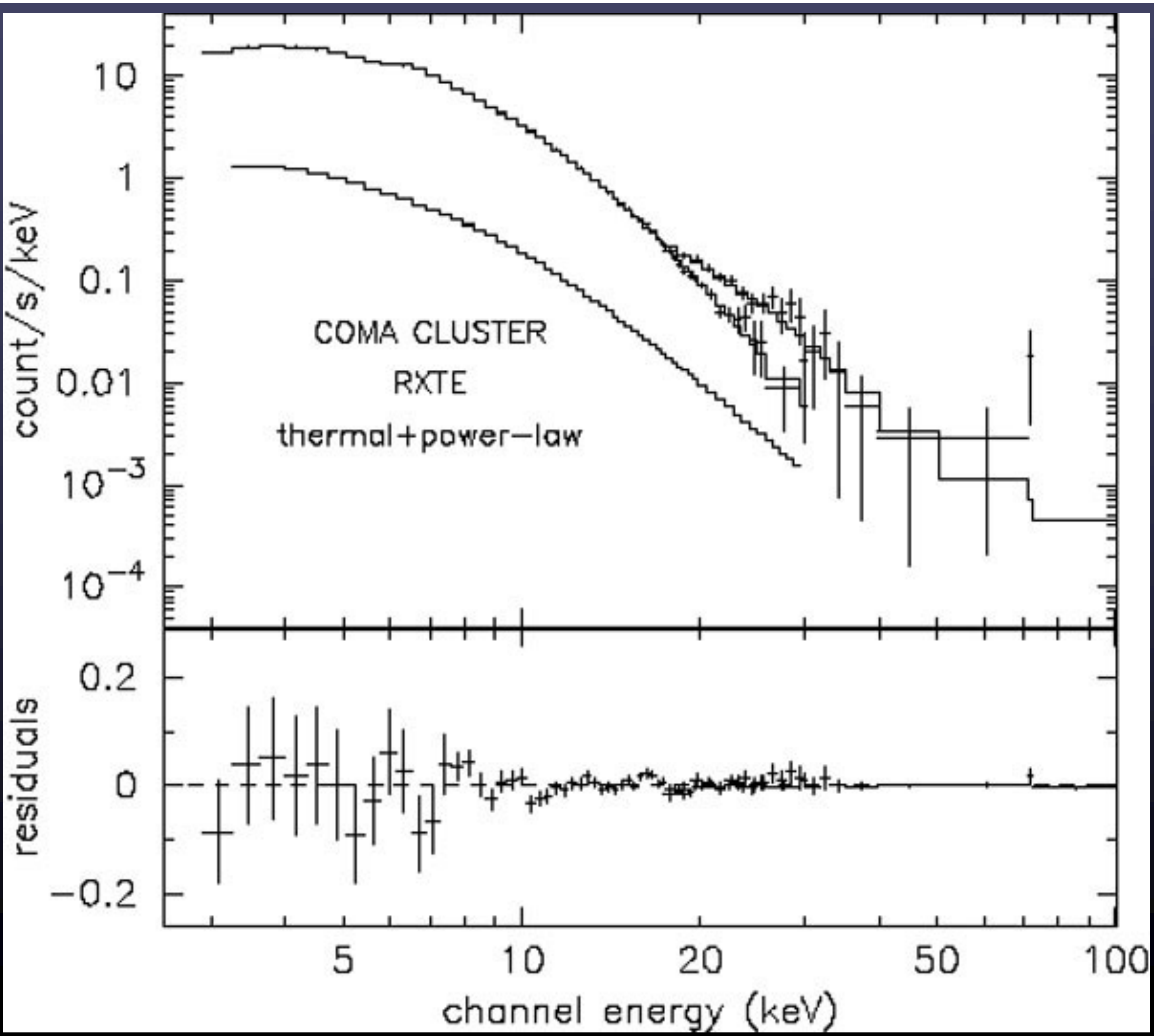
Clusters of Galaxies

800 kpc

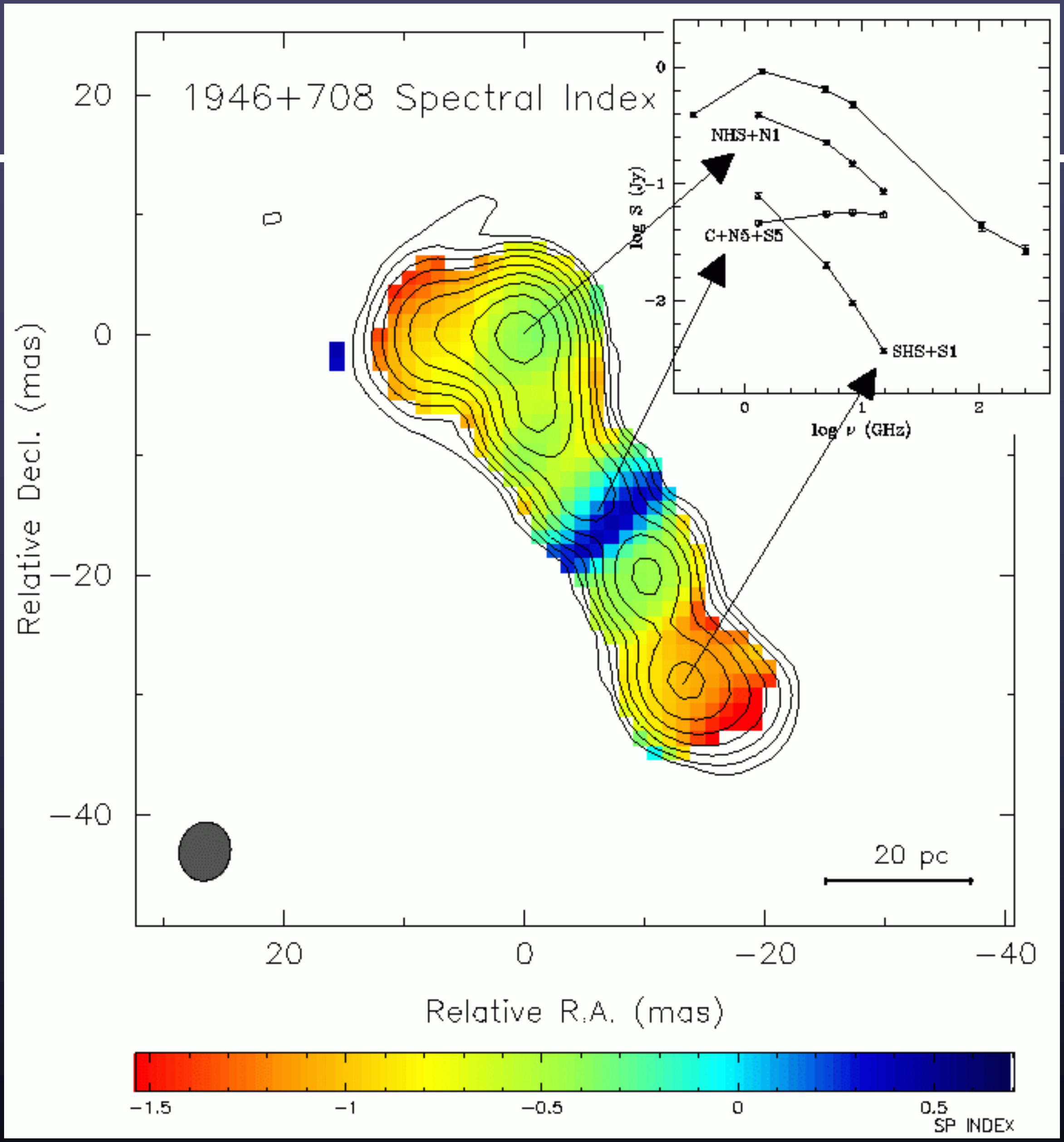


MS0735+7421 in radio (red) and X-rays (blue) – Gitti et al.

Thermal Emission from Clusters



Free-free absorption in 1946+708



Peck & Taylor (2001)

Spectral index map from 1.3/5 GHz VLBI observations

free-free optical depth:

$\tau_{ff} \sim T^{-3/2}\, n_e^{2} \nu^{-2}\, d$

$N_e \sim 8 \times 10^{22}$ cm^{-2}

ionization ~ 10%

Hydra A

Taylor (1996)

core:

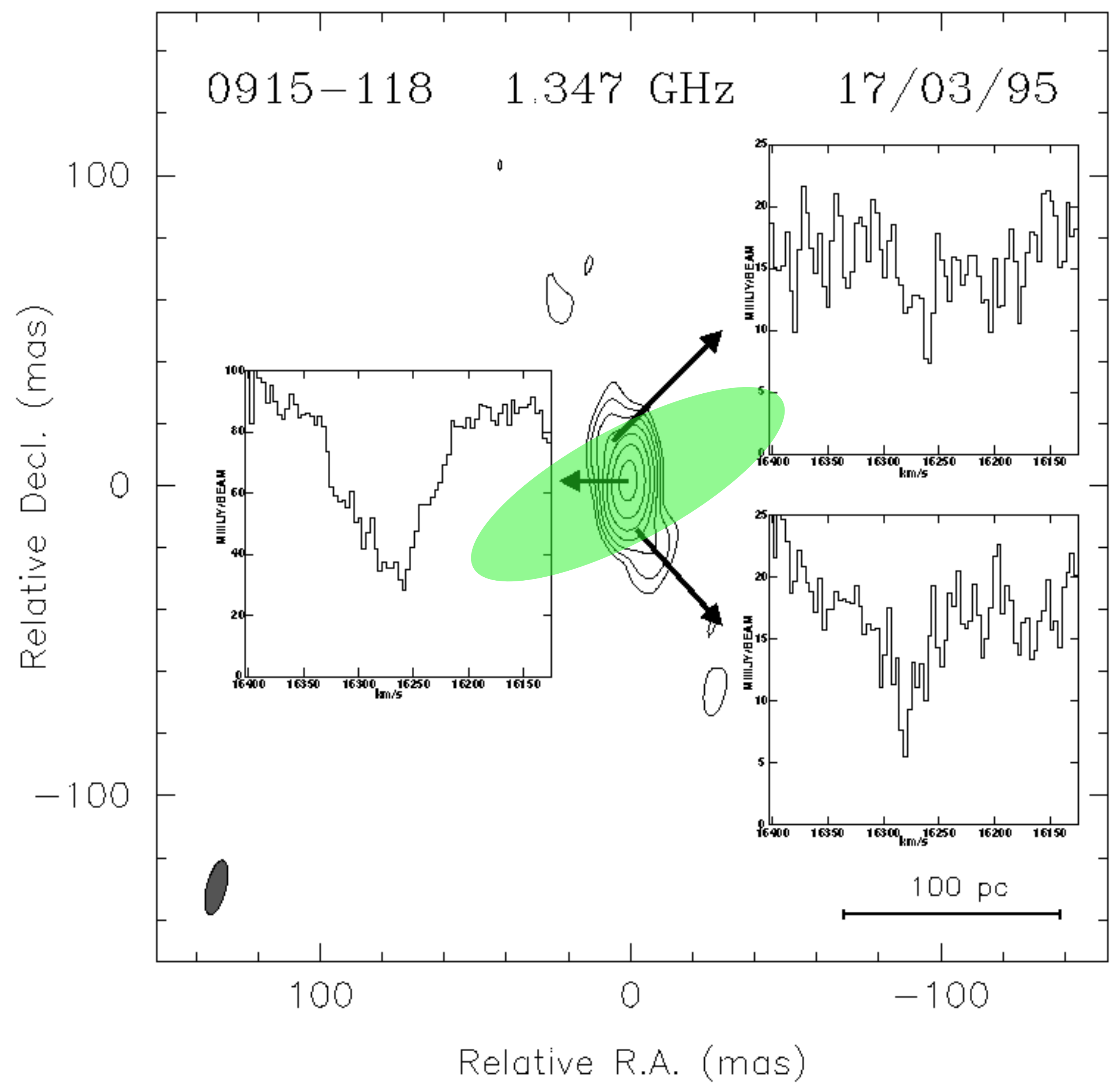
$\tau \sim 0.8$

FWHM = 80 km/s

$N_H = 1 \times 10^{24}$ cm^{-2}

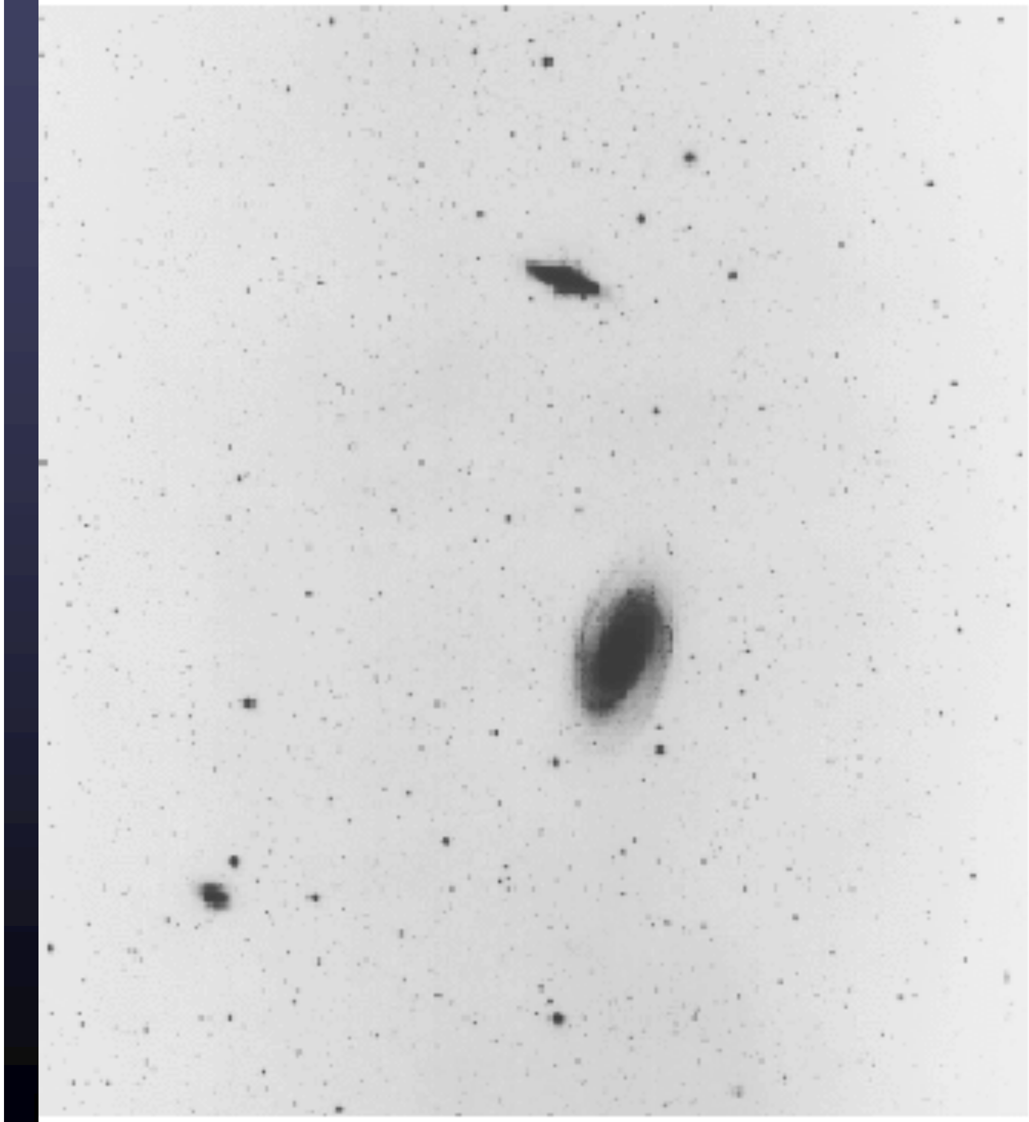
for $T_{spin} = 8000$ K

$M \sim 2 \times 10^7 M_{sun}$
for r=50 pc

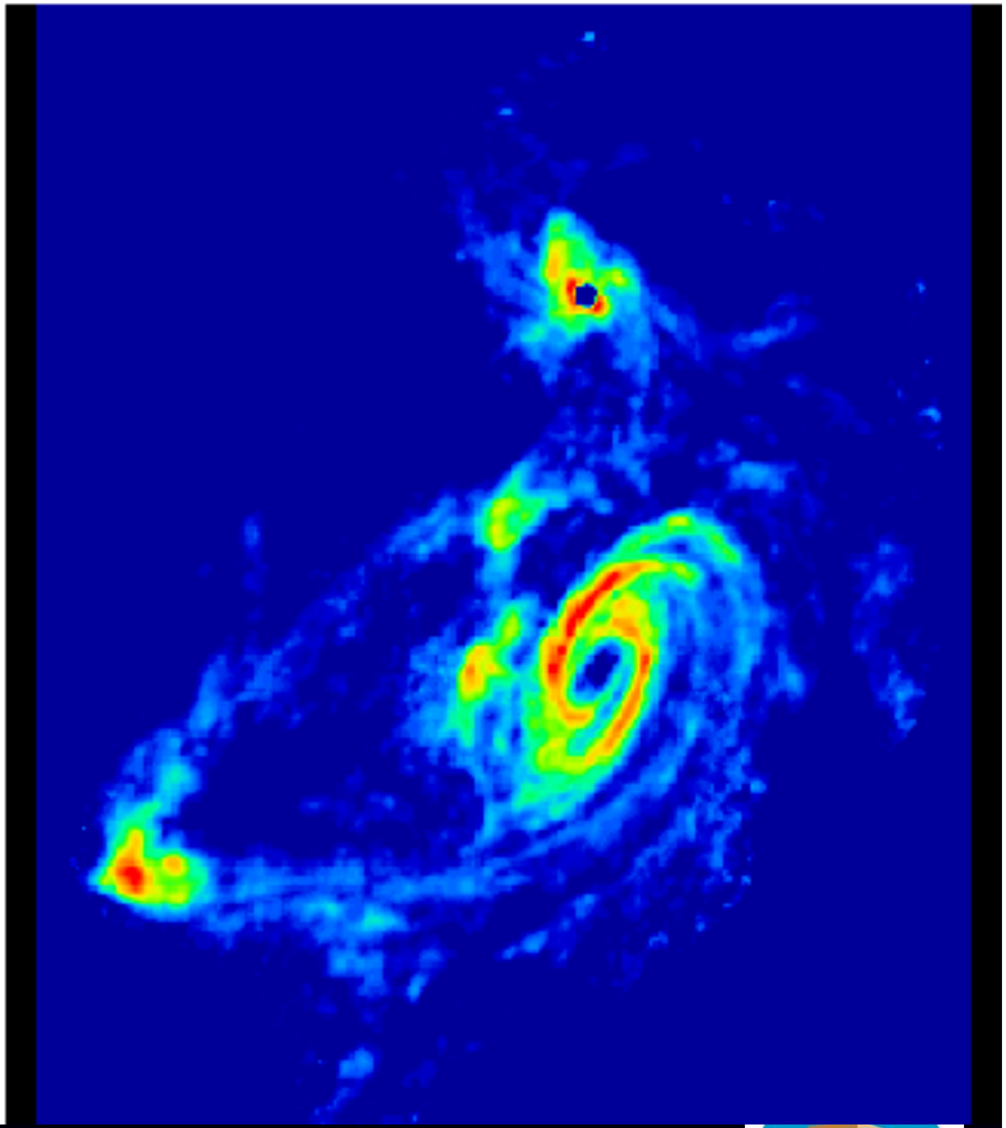


TIDAL INTERACTIONS IN M81 GROUP

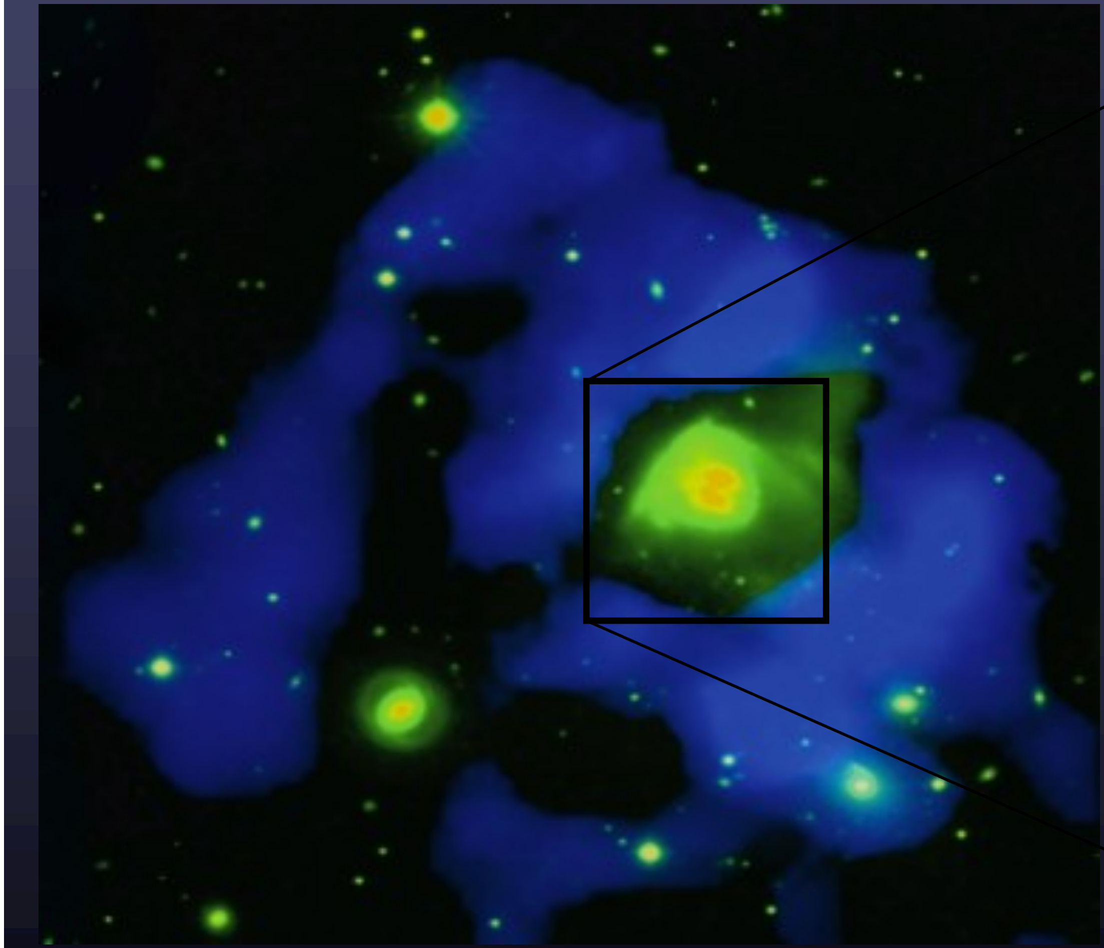
Stellar Light Distribution



21cm HI Distribution



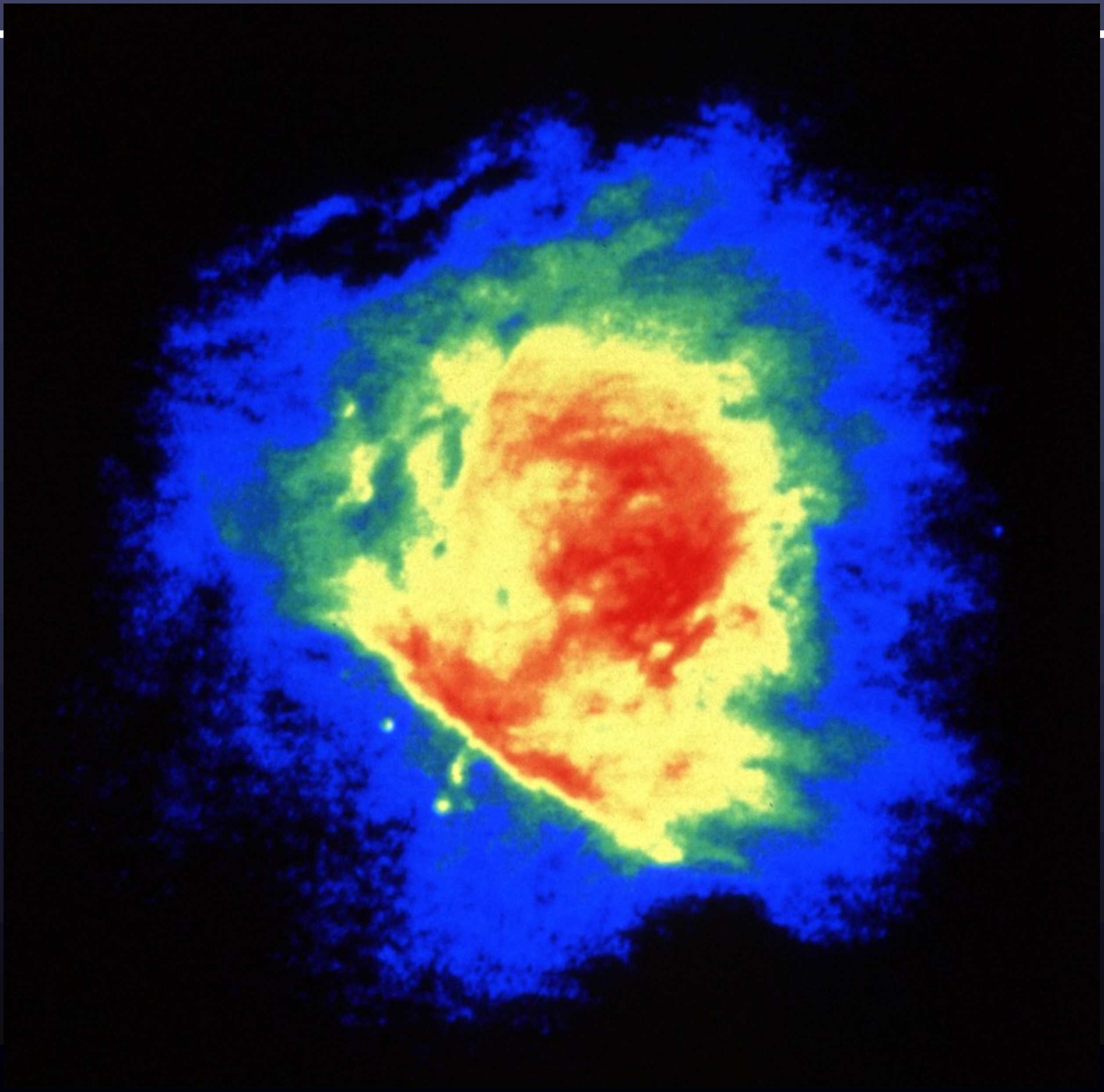
Arp 220 - A starburst Galaxy



HI image from the VLA

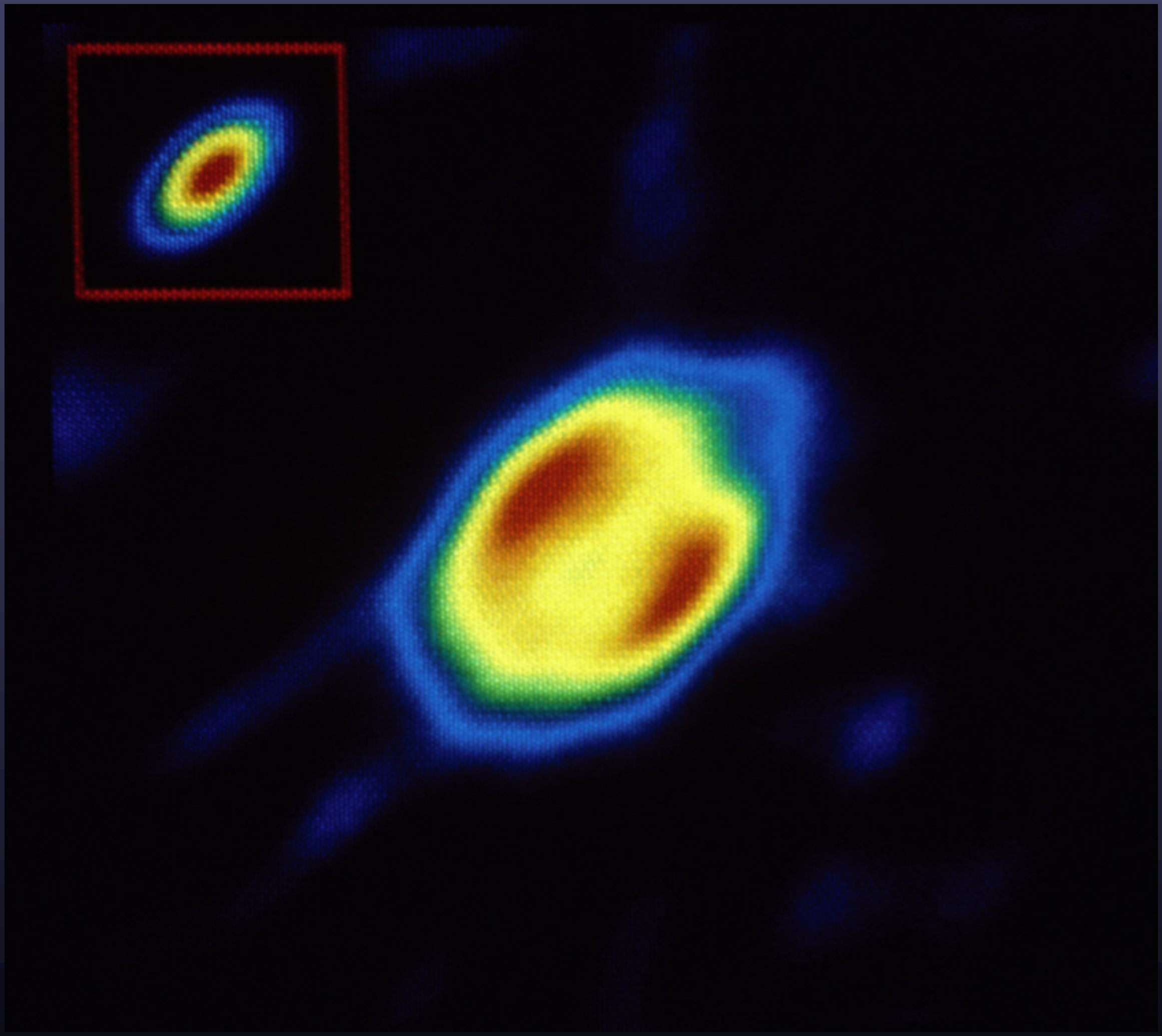
HST/NICMOS image

Star forming regions - Orion nebula (M42)



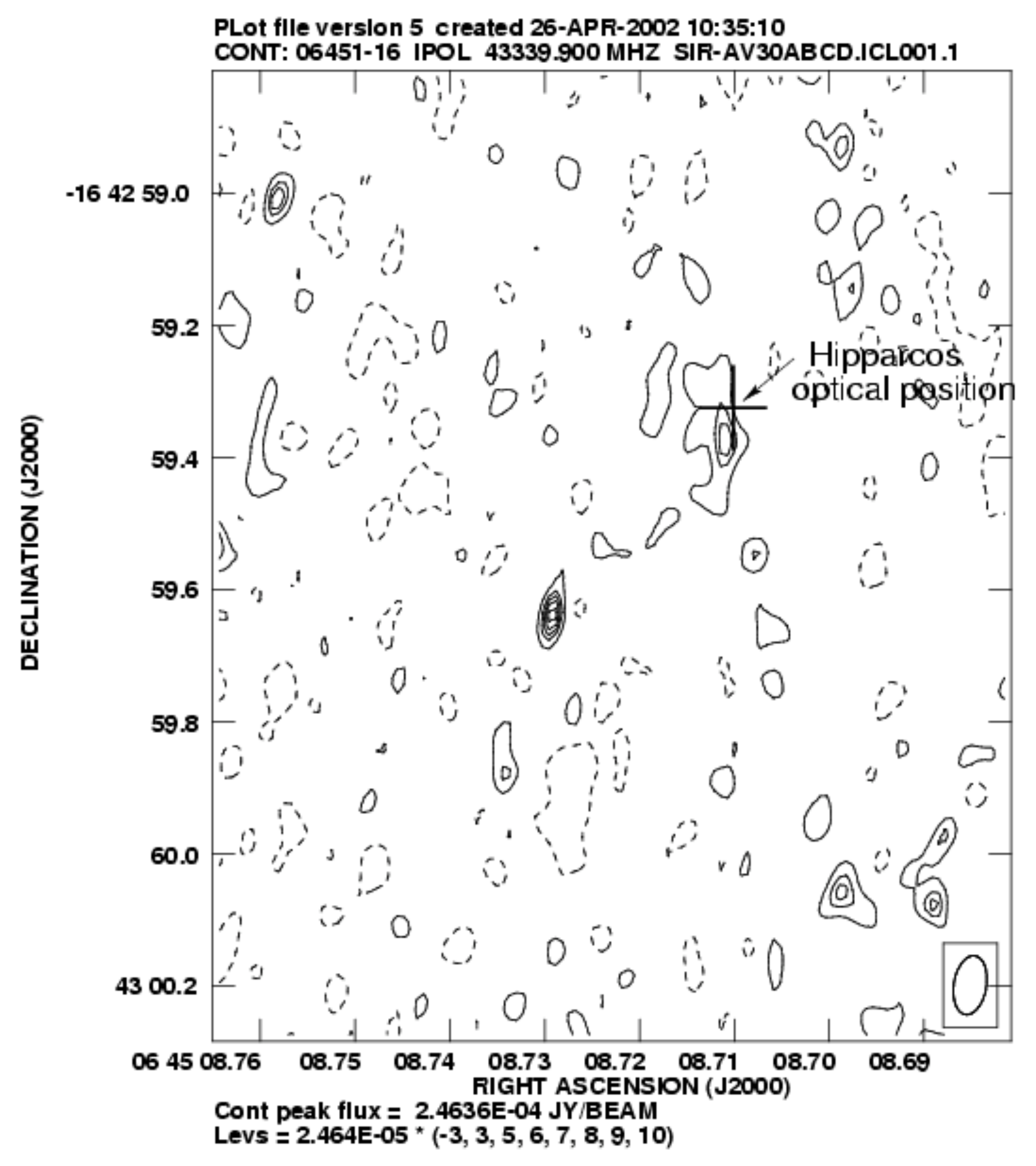
Yusef-Zadeh et al.

Planetary Nebulae - NGC 7027

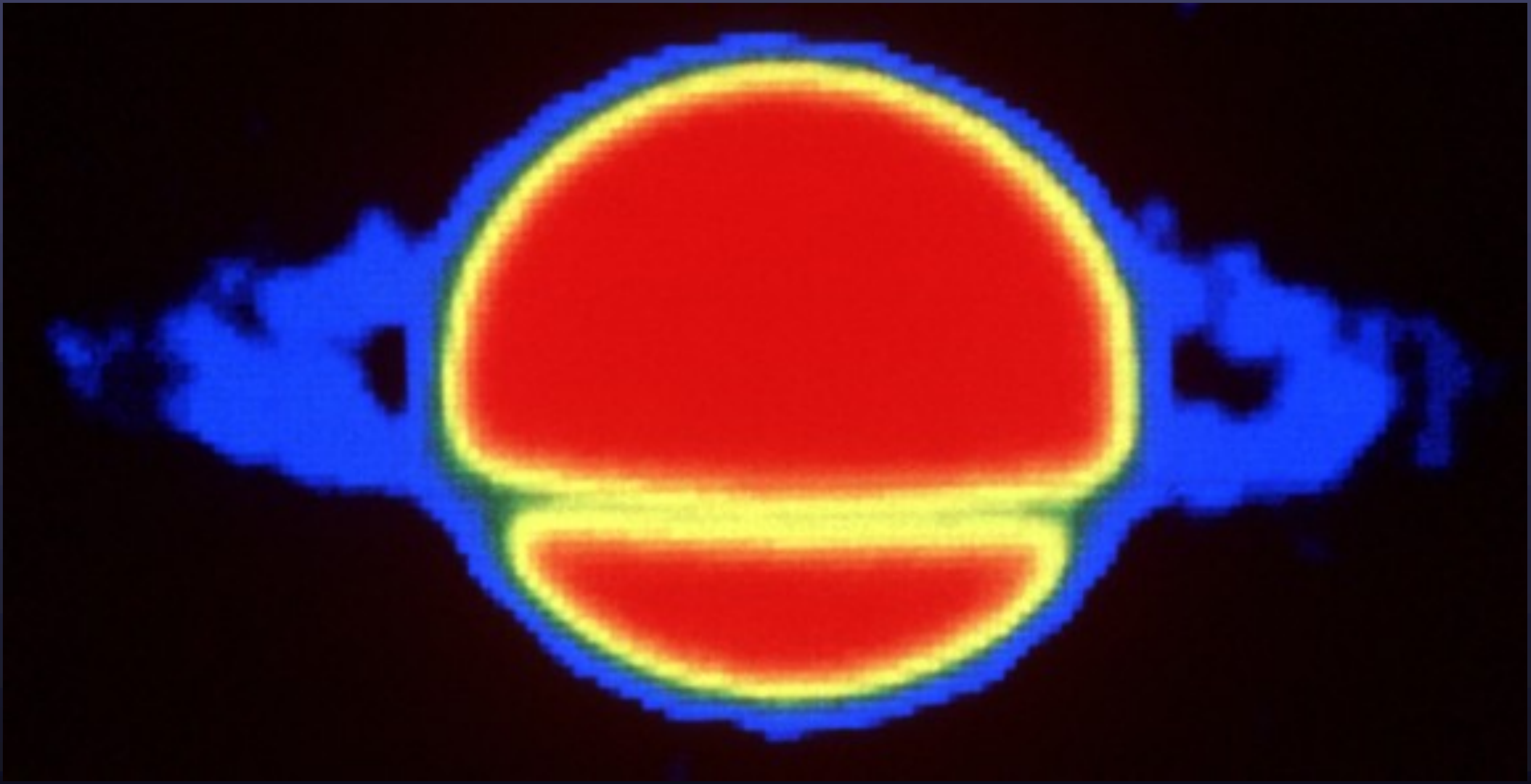


Hjellming
et al.

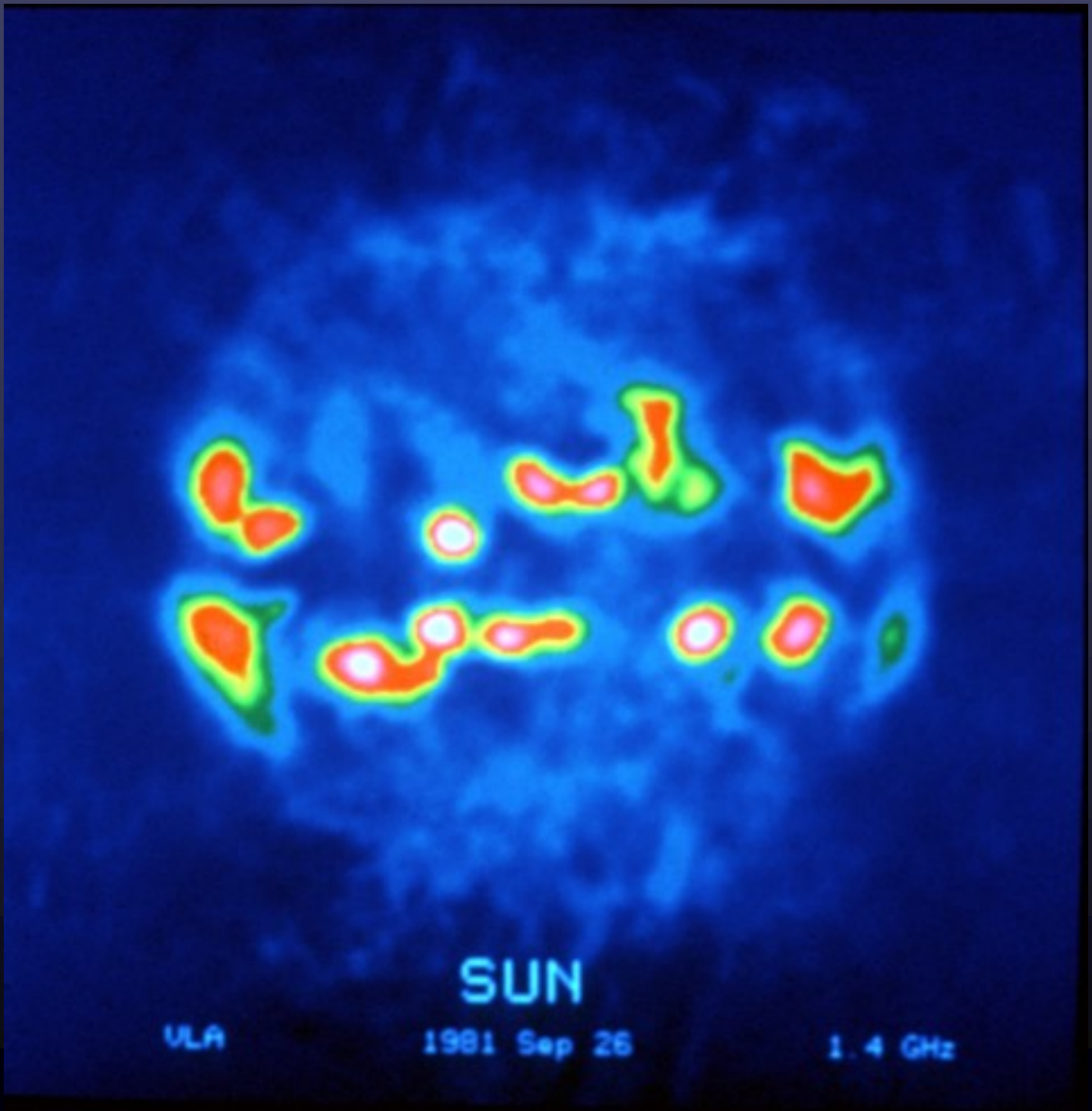
Sirius at 43 GHz with the VLA



Saturn



Solar activity in the radio



Thermal Sources

- The Cosmic Microwave Background
- Dust
- Planets, comets, asteroids
- Emission lines (HI, CO, other atomic and molecular)
- Stellar winds and outflows
- Sun (Quiet Sun) and other stars
- Supernovae
- HII regions
- Starburst galaxies (thermal component from HII regions)
- Clusters of galaxies (free-free)
- Clusters of galaxies - Sunyaev-Zeldovich effect
- Accretion disks

Further Reading

http://www.nrao.edu/whatisra/mechanisms.shtml
http://www.nrao.edu/whatisra/
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

Review for Midterm #2

- Everything since midterm #1

Exam 2 Equations

Constants and astronomical quantities:

Speed of light	$c = 3 \times 10^{10}$ cm s^{-1}
Planck's constant	$h = 6.626 \times 10^{-27}$ erg s
Gravitational constant	$G = 6.67 \times 10^{-8}$ cm^3 g^{-1}s^{-2}
Stefan-Boltzmann's constant	$\sigma = 5.67 \times 10^{-5}$g s^{-3} K^{-4}
Boltzmann's constant	$k = 1.38 \times 10^{-16}$ erg K^{-1}
Mass of the Sun	$M_\odot = 1.99 \times 10^{33}$ g
Surface temperature of the Sun	$T_\odot = 5800$ K
Mass of a hydrogen atom	$M_H = 1.67 \times 10^{-24}$ g
Mass of an electron	$m_e = 9.11 \times 10^{-28}$ g
Astronomical unit	1 AU = 1.496×10^{13} cm
Parsec	1 pc = 3.26 ly = 3.086×10^{18} cm = 206,265 AU
1 Jy	10^{-23} erg s^{-1} cm^{-2} Hz^{-1}
Conversion Kelvin (K) to Celsius (C)	T[K]=T[C]+273
Conversion Celsius (C) to Fahrenheit (F)	T[F]=$\frac{9}{5}$T[C]+32
1 radian	206,265 arcseconds

Useful equations:

$\lambda_{max} = \frac{0.29 cm K}{T}$ Wien's Law and $F = \sigma T^4$ Stefan - Boltzmann Law

$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$ Planck Function

$T_b = \frac{\lambda^2 S_\nu}{2k\Omega}$ Brightness Temperature

$K.E. = 3/2kT$ (per particle) and $V = \sqrt{(3kT/m)}$ (average velocity of particle)

$\theta = 1.02\lambda/D$ (in radians) resolution for diameter or max baseline length,D

$V = \frac{\lambda_{obs}-\lambda_0}{\lambda_0}c$ doppler velocity

$\nu_G = \frac{eB}{2\pi m} = 2.8\frac{B}{\mathrm{Gauss}}$MHz gyro frequency

$\nu_c = 1.5\gamma^2\nu_G$ synchrotron characteristic frequency

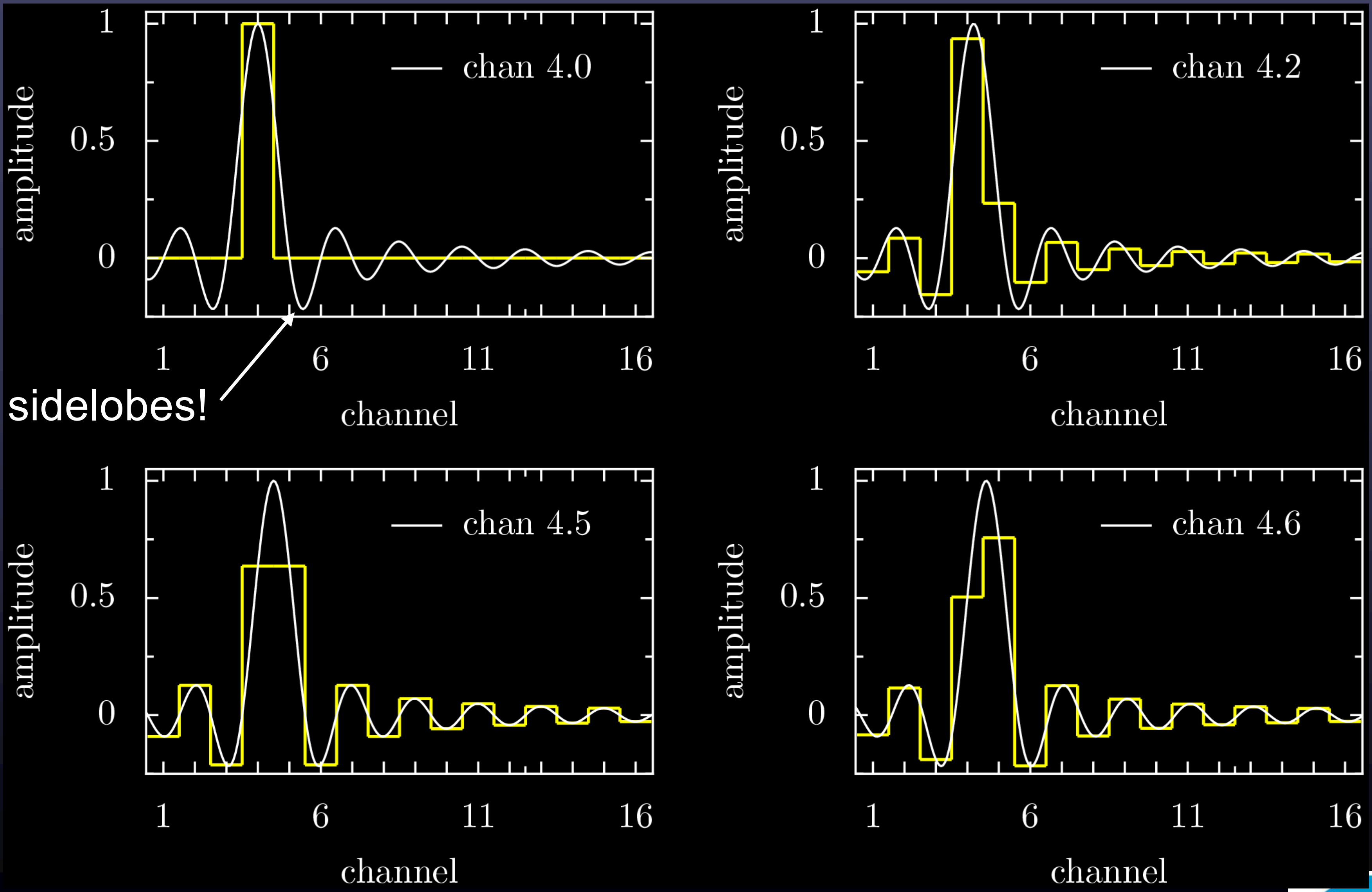
Synchrotron Lifetime = $\frac{16.4 yr}{B^2\gamma}$ where B is in Gauss

$T_b(s) = T_{back}(s_0)e^{-\tau_\nu(s)} + T_{emit}(1 - e^{-\tau_\nu(s)})$ radiative transfer
$\tau(\nu) = 8.235 \times 10^{-2}\nu^{-2.1}T_e^{-1.35}EM$ free-free optical depth
$EM = \int n_e^2 ds$ emission measure
$RM = 812\int Bn_e ds$ rad m^{-2} rotation measure

Practical Spectral Line Correlators

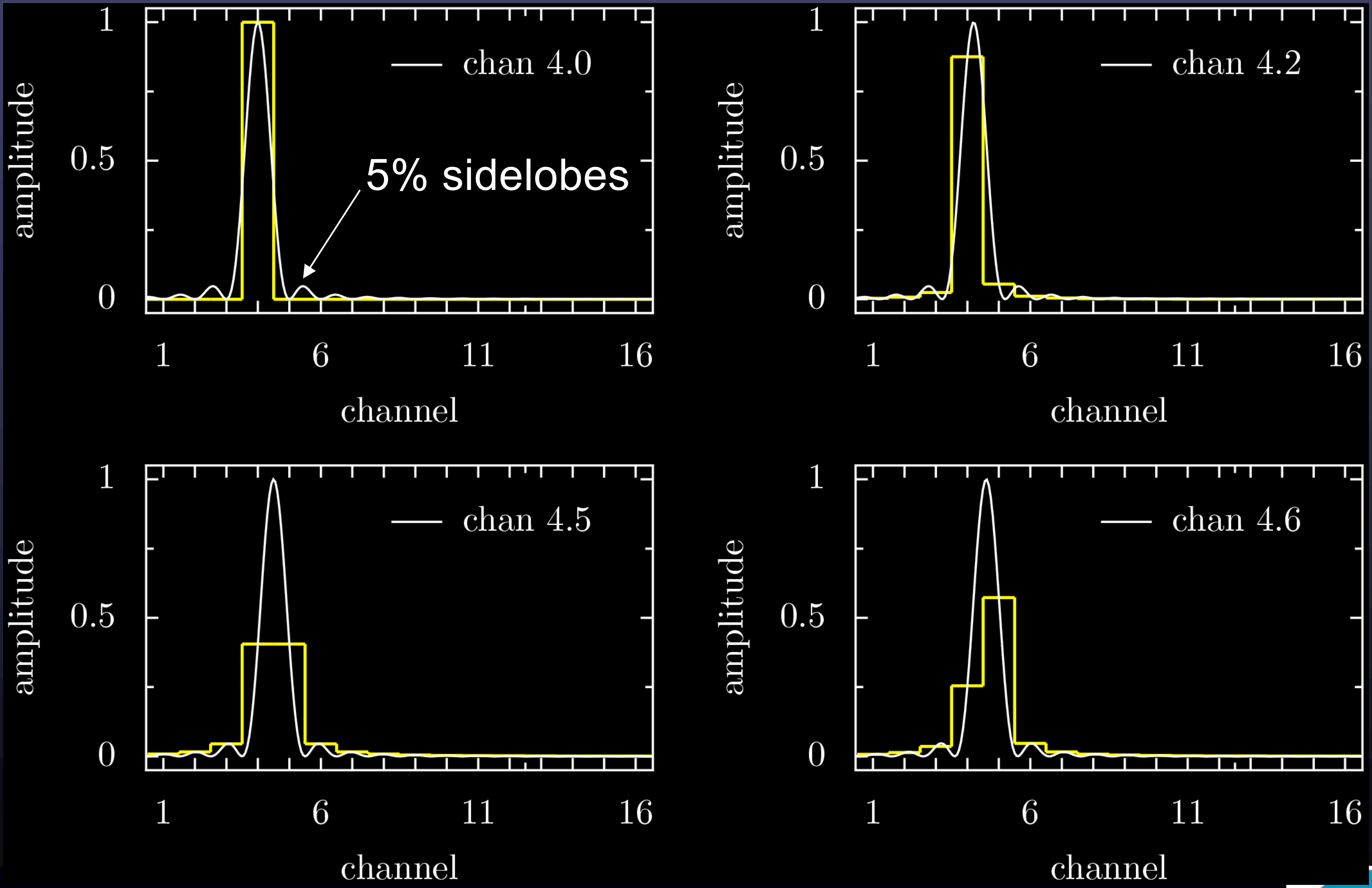
- The FX architecture
  - F : Replace filterbank with digital Fourier transform
  - X : Use a complex-correlator for each frequency channel
  - Then integrate
- The XF architecture
  - X : Measure correlation function at many lags
  - Integrate
  - F : Fourier transform
- Other architectures possible

XF Spectral Response (2)

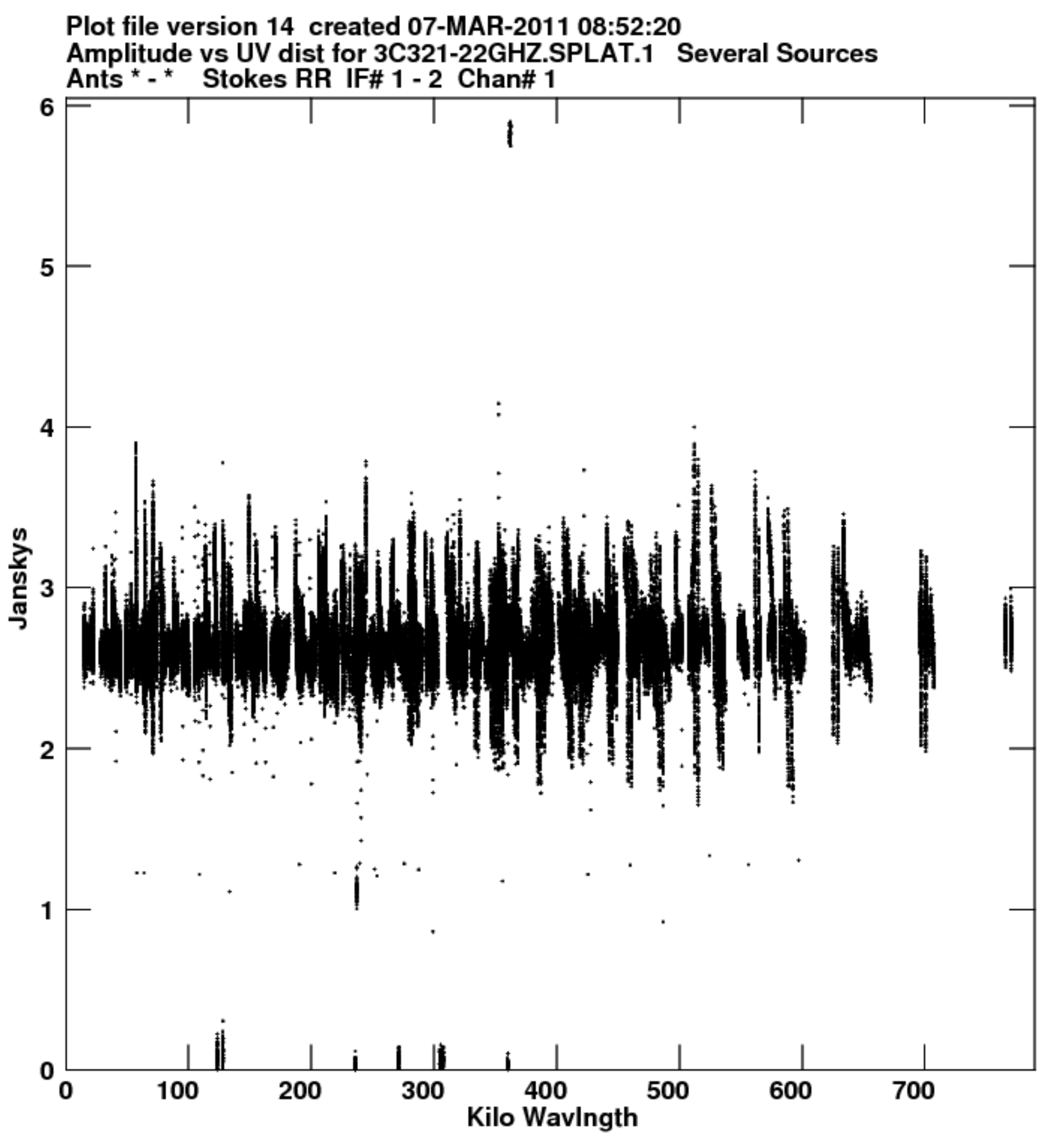


22% sidelobes!

FX Spectral Response (2)



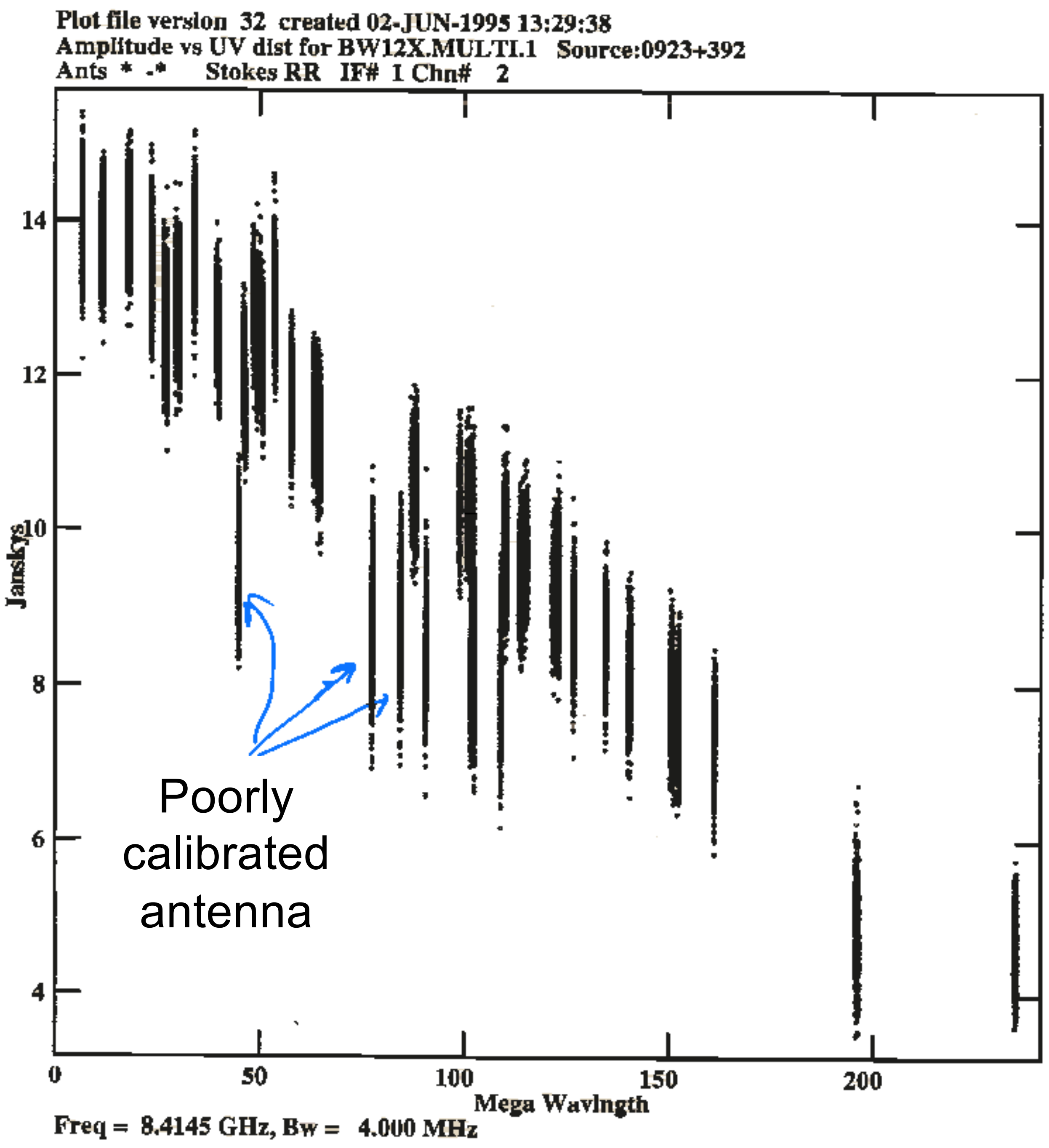
A Data Editing Example



Editing

- Typical calibrator visibility function after a priori calibration
  - Calibrator is resolved
  - Will need to image
  - One antenna low
  - Use calibrator to fix

- Shows why flux scale (gain normalization) should only be set by a subset of antennas



Poorly calibrated antenna

Calibration Summary

- Determining calibration is as important as determining source structure—can’t have one without the other
- Calibration dominated by antenna-based effects, permits separation of calibration from astronomical information
- Calibration formalism algebra-rich, but can be described piecemeal in comprehendible segments, according to well-defined effects
- Calibration determination is a single standard fitting problem
- Calibration an iterative process, improving various components in turn
- Point sources are the best calibrators
- Observe calibrators according requirements of components
- Data examination and editing an important part of calibration

What is Polarized Light?

- Light is oscillating electric and magnetic fields
- Polarization is labeled by the shape of the trace of the tip of the **E** vector
- Each polarization has an orthogonal state
- Incoherent light can contain many polarization states

Stokes Parameters describe partially polarized light

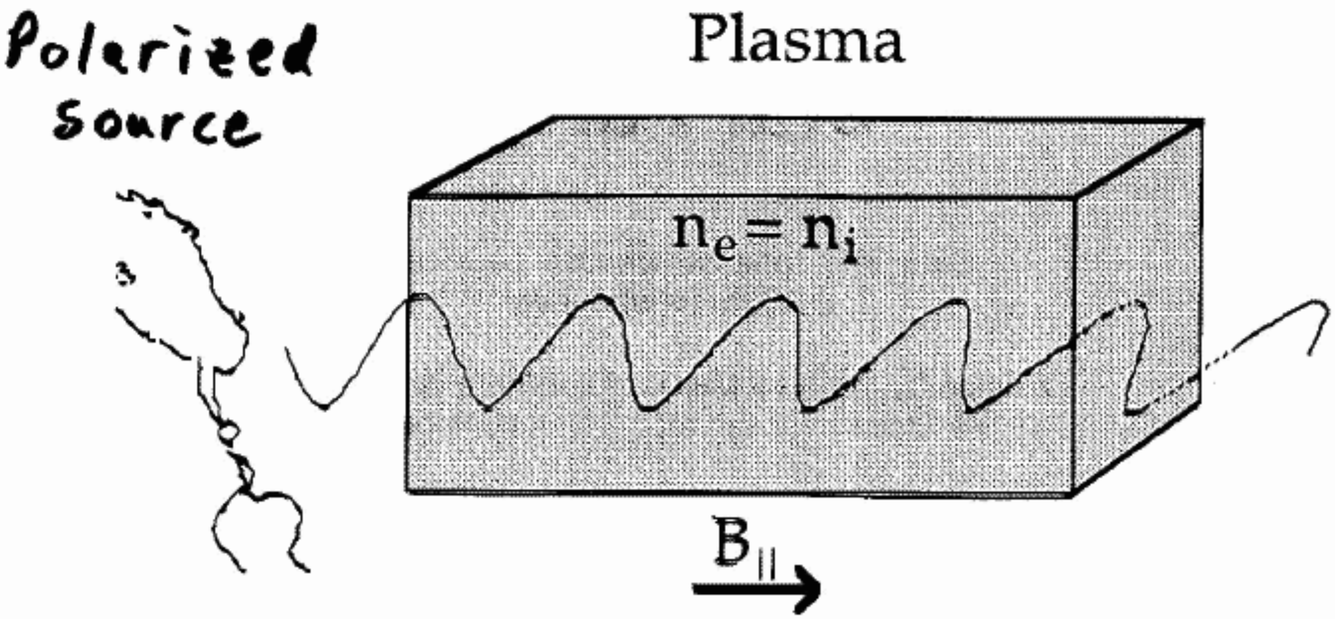
$I = RR + LL$
$Q = RL + LR$
$U = i(LR - RL)$
$V = LL - RR$

For circular feeds

Alternate representation:

• pol. angle (EVPA)	$\phi = 0.5 \text{ atan } (U/Q)$
• polarized intensity	$p = \text{sqrt}(Q^2 + U^2)$
• fractional linear	$m = p / I$
• fractional circular	$v = \lvert V \rvert / I$

Faraday Rotation



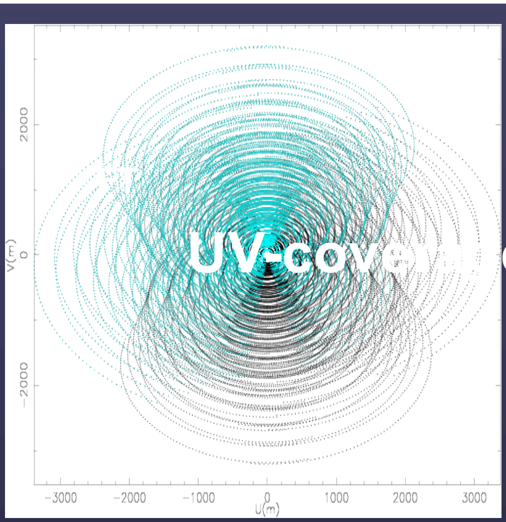
$$\Psi = \Psi_0 + \mathrm{RM}\,\lambda^2$$

$$\mathrm{RM} = 812 \int_0^{\overset{\text{kpc}}{L}} \underset{\text{cm}^{-3}}{n_e}\, \overset{\mu\text{Gauss}}{B_{||}}\, dl \text{ radians/m}^2$$

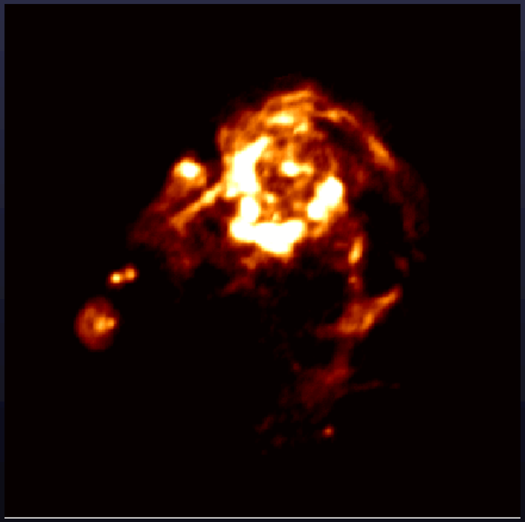
The Dirty Image

The PSF

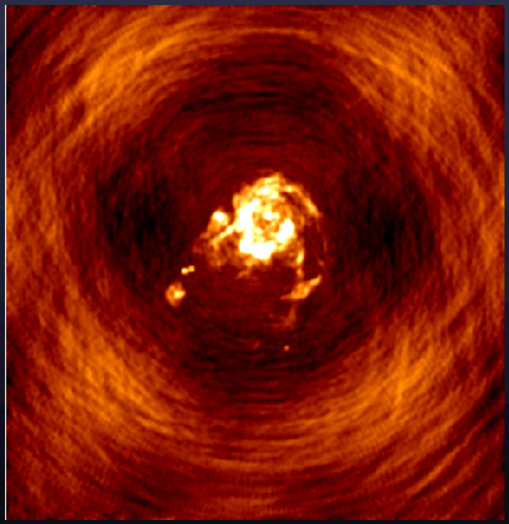
↔



UV-coverage



→



The

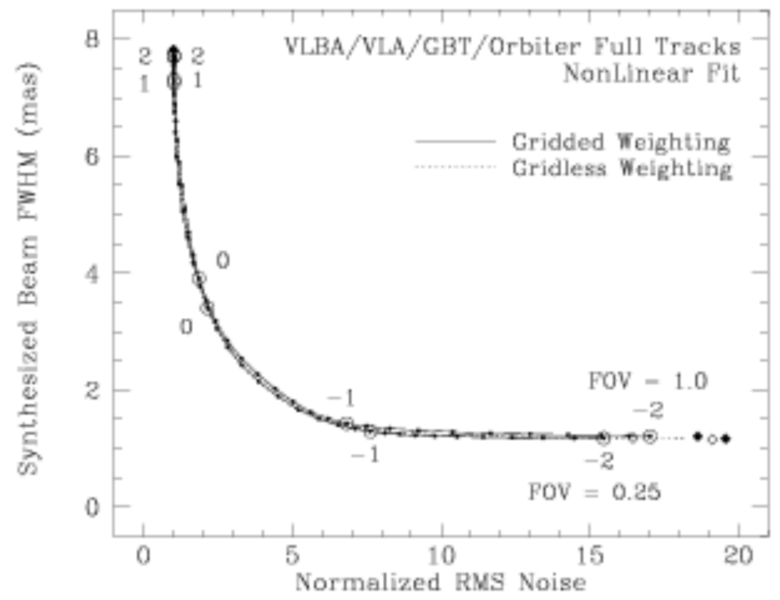
Dirty Image

...Weighting

- **Robust/Briggs weighting:**

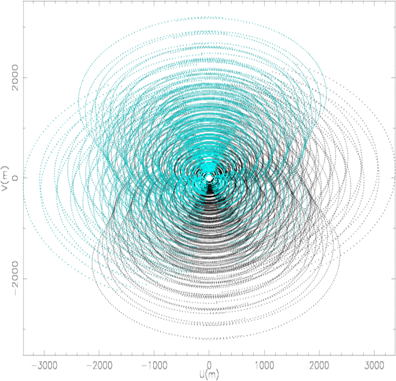
$$W_k = 1/[S.\rho(u_k, v_k) + \sigma_k^2]$$

- **Parameterized filter – allows continuous variation between optimal resolution (uniform weighting) and optimal noise (natural weighting).**



The missing information

- **As seen earlier, not all parts of the uv-plane are sampled – the 'invisible distribution'**

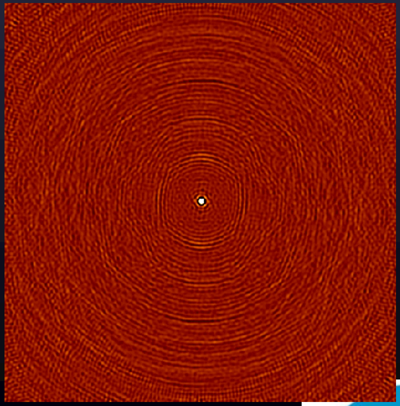


1. “Central hole” below u_{min} and v_{min}:

- Image plane effect: Total integrated power is not measured.
- Upper limit on the largest scale in the image plane.

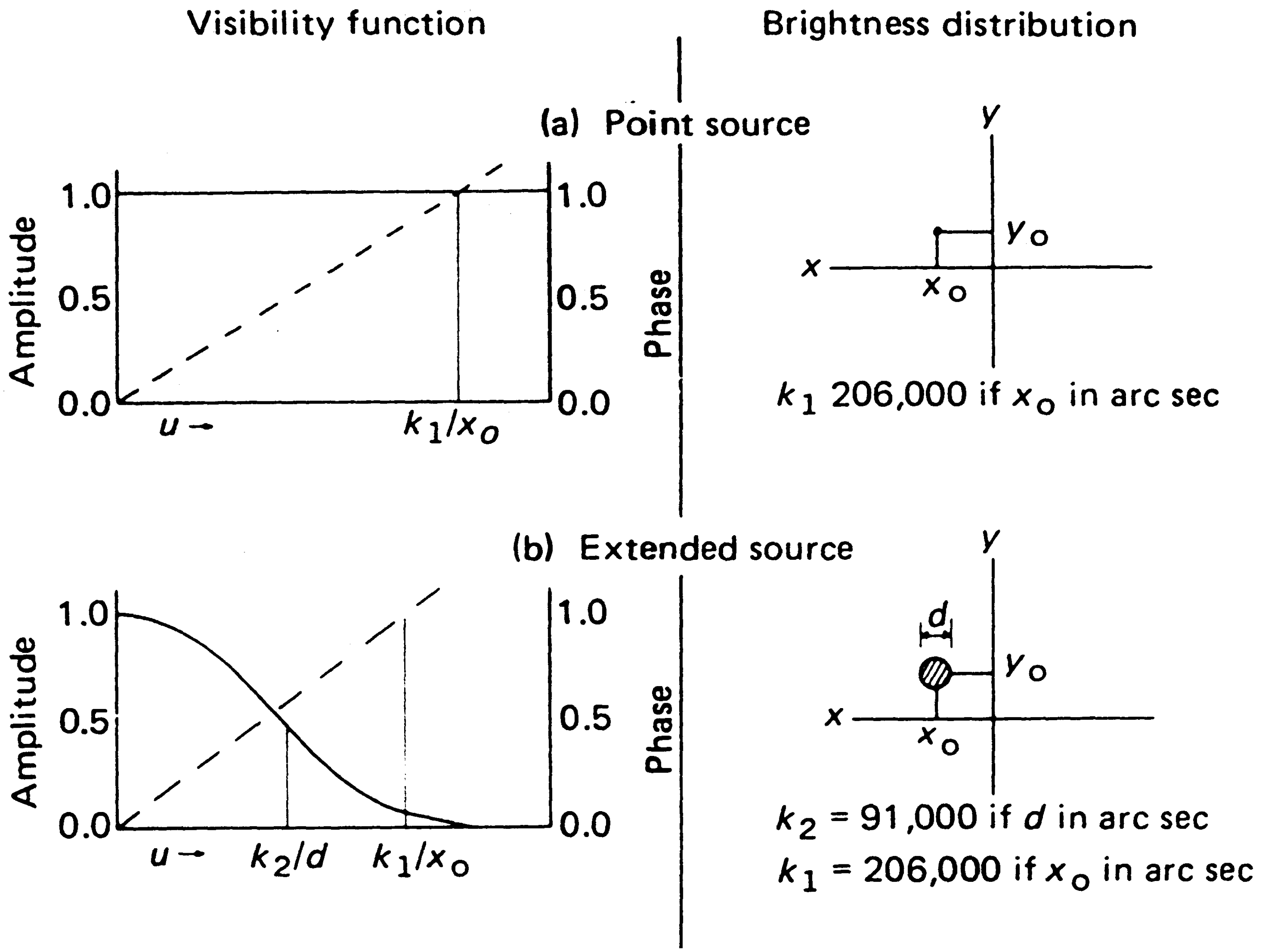
2. No measurements beyond u_{max} and v_{max}:

- Size of the main lobe of the PSF is finite (finite resolution).



3. Holes in the uv-plane:

- Contribute to the side lobes of the PSF.


Visibility function
Brightness distribution
(a) Point source
Amplitude
Phase
1.0
0.5
0.0
1.0
0.5
0.0
$u \rightarrow$
k_1/x_o
y
x
y_o
x_o
k_1 206,000 if x_o in arc sec
(b) Extended source
Amplitude
Phase
1.0
0.5
0.0
1.0
0.5
0.0
$u \rightarrow$
k_2/d
k_1/x_o
y
x
d
y_o
x_o
k_2 = 91,000 if d in arc sec
k_1 = 206,000 if x_o in arc sec

Why does self-calibration work?

- self-calibration preserves the *Closure Phase* which is a good observable even in the presence of antenna-based phase errors

$$\begin{aligned}\Phi_{ijk} &= \theta_{ij} + \theta_{jk} + \theta_{ki} \\ &= \theta_{ij}^{\text{true}} + \left(\phi_i - \phi_j\right) + \theta_{jk}^{\text{true}} + \left(\phi_j - \phi_k\right) + \theta_{ki}^{\text{true}} + \left(\phi_k - \phi_i\right) \\ &= \theta_{ij}^{\text{true}} + \theta_{jk}^{\text{true}} + \theta_{ki}^{\text{true}}\end{aligned}$$

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Advantages and disadvantages of self-calibration

- Advantages
  - Gains are derived for correct time, not by interpolation
  - Gains are derived for correct direction on celestial sphere
  - Solution is fairly robust if there are many baselines
- Disadvantages
  - Requires a sufficiently bright source
  - Introduces more degrees of freedom into the imaging so the results might not be robust and stable
  - Position information may be lost

Model fitting

- Imaging as an Inverse Problem
  - In synthesis imaging, we can solve the **forward problem**: given a sky brightness distribution, and knowing the characteristics of the instrument, we can predict the measurements (visibilities), within the limitations imposed by the noise.
  - The **inverse problem** is much harder, given limited data and noise: the solution is rarely unique.
  - A general approach to inverse problems is **model fitting**. See, e.g., Press et al., *Numerical Recipes*.
    1. Design a model defined by a number of adjustable parameters.
    2. Solve the forward problem to predict the measurements.
    3. Choose **a figure-of-merit** function, e.g., rms deviation between model predictions and measurements.
    4. Adjust the parameters to **minimize the merit function**.
  - Goals:
    1. Best-fit values for the parameters.
    2. A measure of the goodness-of-fit of the optimized model.
    3. Estimates of the uncertainty of the best-fit parameters.

Inspecting Visibility Data

- Fourier imaging

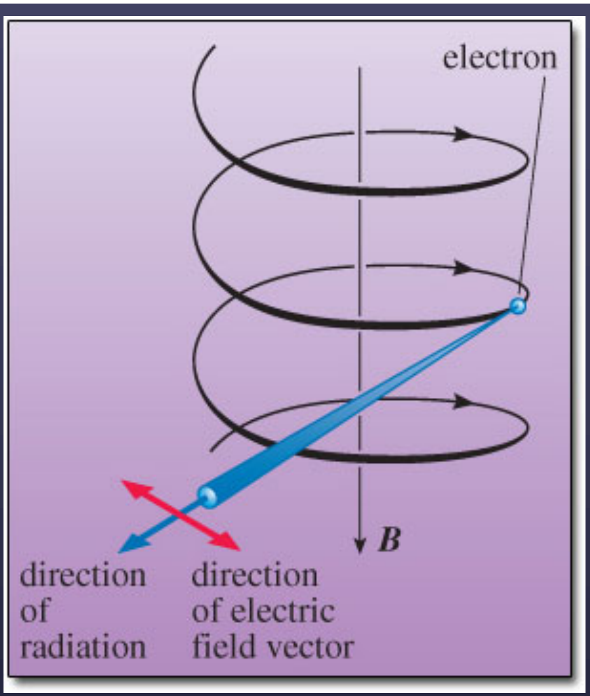
$$V(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathcal{A}(l,m) I(l,m) \exp[-2\pi i(ul + vm)]\, dl\, dm$$

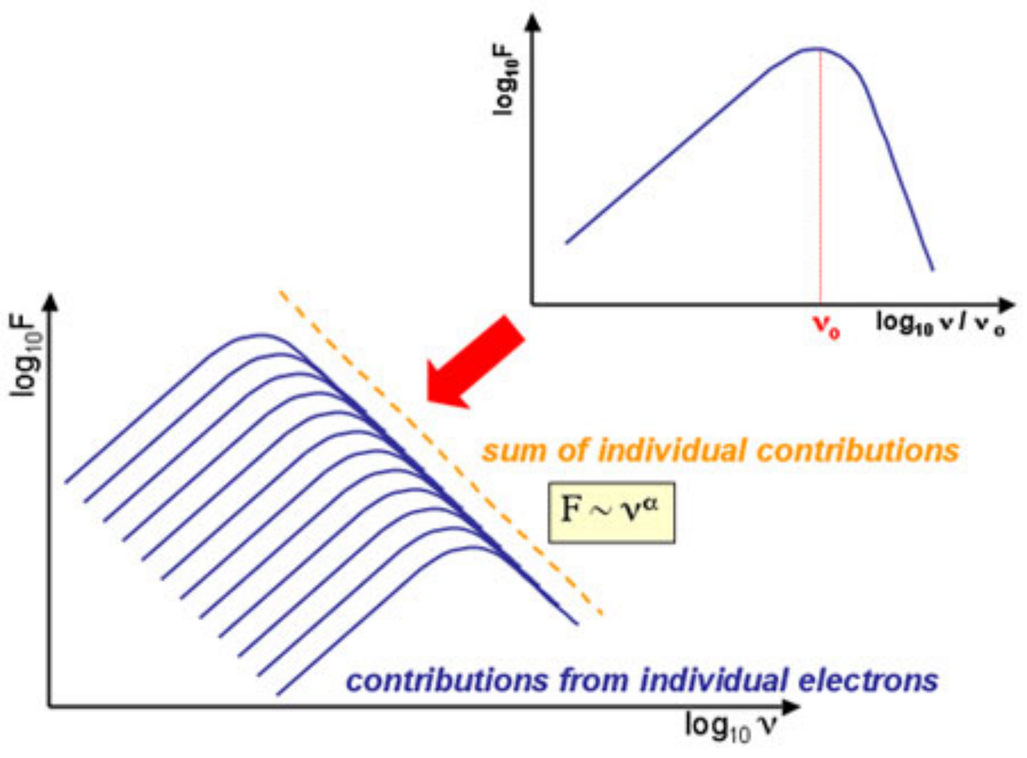
- Problems with direct inversion
  - Sampling
    - Poor (*u*,*v*) coverage
  - Missing data
    - e.g., no phases (speckle imaging)
  - Calibration
    - Closure quantities are independent of calibration
  - Non-Fourier imaging
    - e.g., wide-field imaging; time-variable sources (SS433)
  - Noise
    - Noise is uncorrelated in the (*u*,*v*) plane but correlated in the image

Non-Thermal Sources

- Man-made signals (RFI)
- Cosmic ray air showers
- Solar Flares (Active Sun), also flare stars and brown dwarfs
- Planetary magnetospheres
- Lightning (from storms on planets and locally as RFI)
- Planetary Radar/Spacecraft telemetry
- Supernova Remnants
- Gamma-ray Bursts and their afterglows
- Pulsars
- Magnetar flares
- Masers
- X-ray binaries/microquasars
- Normal galaxies (cosmic ray population)
- Active Galaxies (including Quasars, Blazars, etc.)
- Intracluster medium (halos and relics)
- Dark-matter decay

Synchrotron Emission





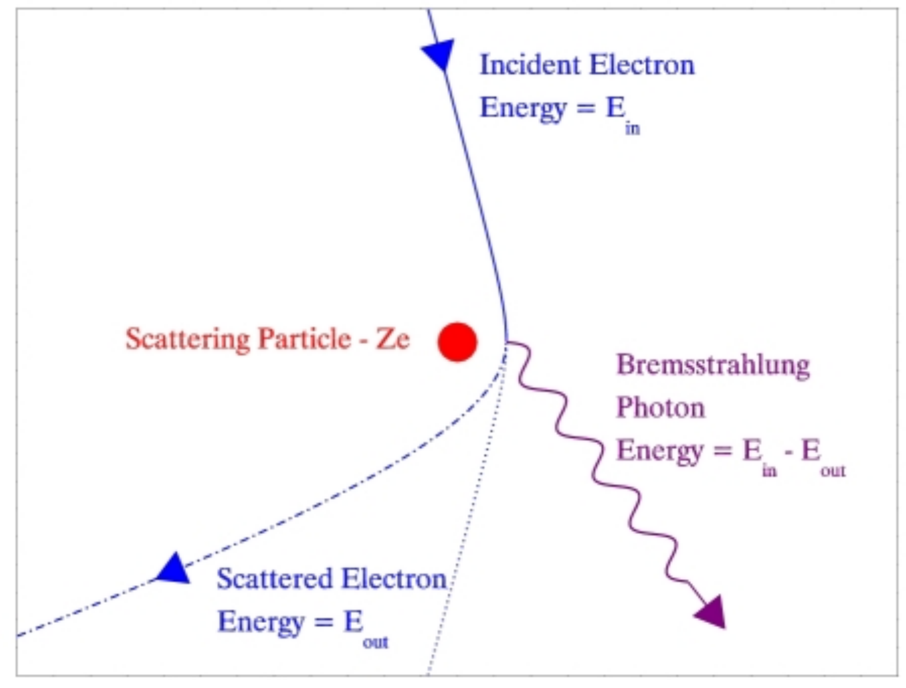
$$\nu_G = \frac{eB}{2\pi m} = 2.8\frac{B}{\text{Gauss}}\text{MHz gyro frequency}$$

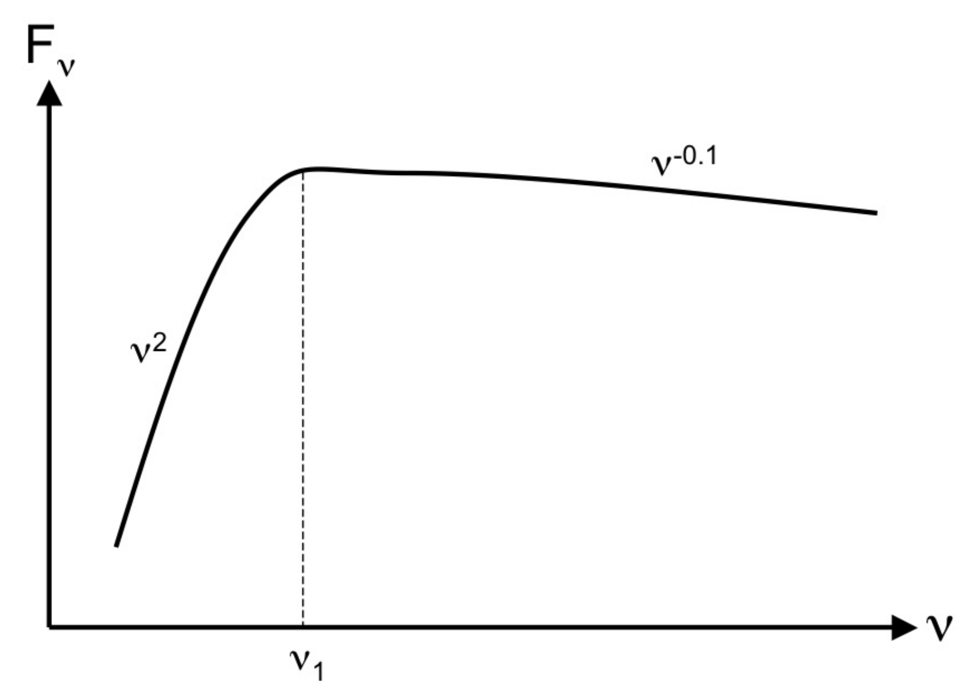
$$\text{Synchrotron Lifetime} = \frac{16.4yr}{B^2\gamma} \text{ where B is in Gauss}$$

Thermal Sources

- The Cosmic Microwave Background
- Dust
- Planets, comets, asteroids
- Emission lines (HI, CO, other atomic and molecular)
- Stellar winds and outflows
- Sun (Quiet Sun) and other stars
- Supernovae
- HII regions
- Starburst galaxies (thermal component from HII regions)
- Clusters of galaxies - free-free emission
- Clusters of galaxies - Sunyaev-Zeldovich effect
- Accretion disks?

Free-Free Emission





$$\tau(\nu) = 8.235 \times 10^{-2}\, \nu_{\mathrm{GHz}}^{-2.1} T_e^{-1.35}\, \mathrm{EM}$$