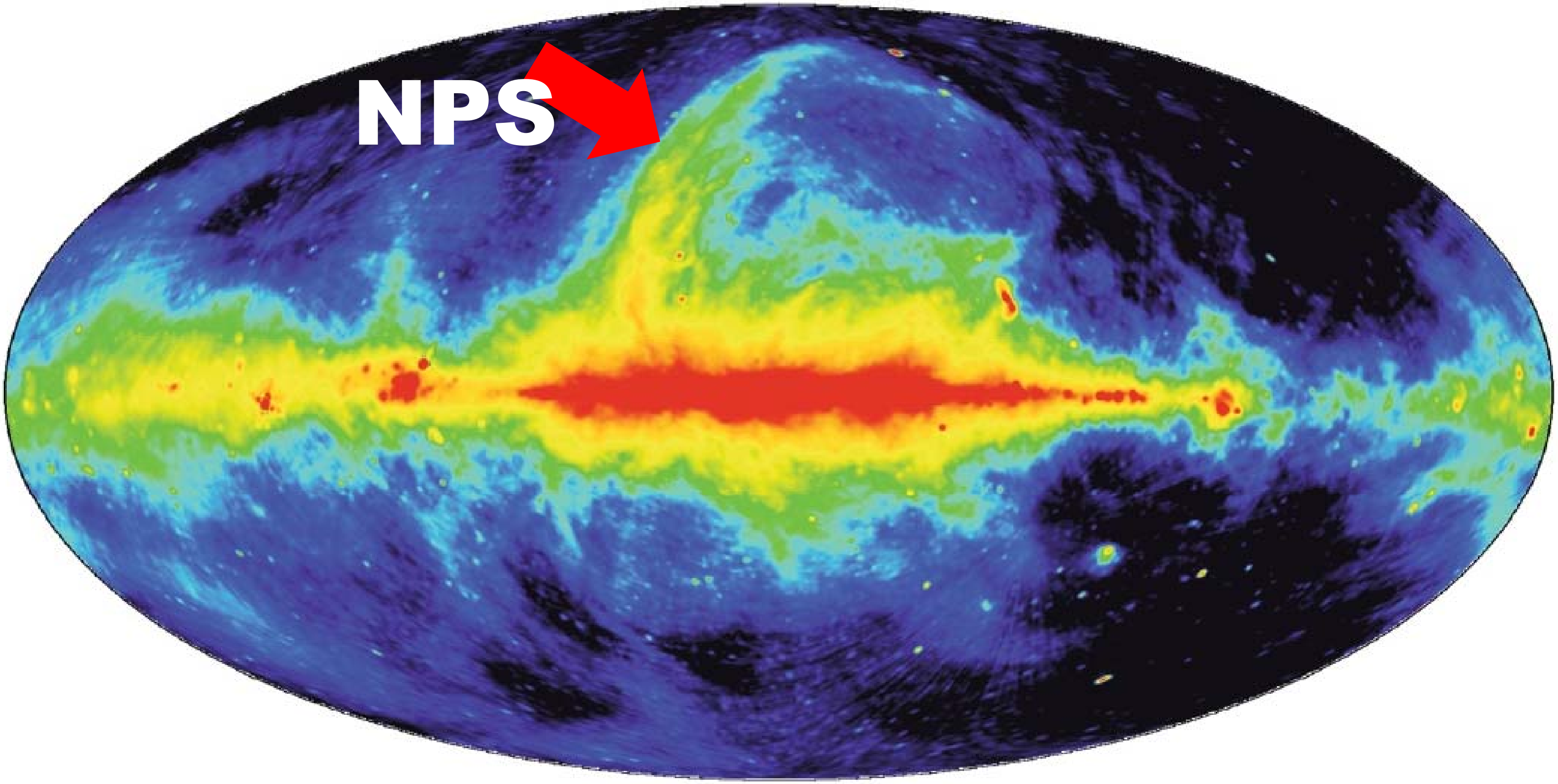
# North Polar Spur
# と銀河中心活動

Yoshiaki SOFUE

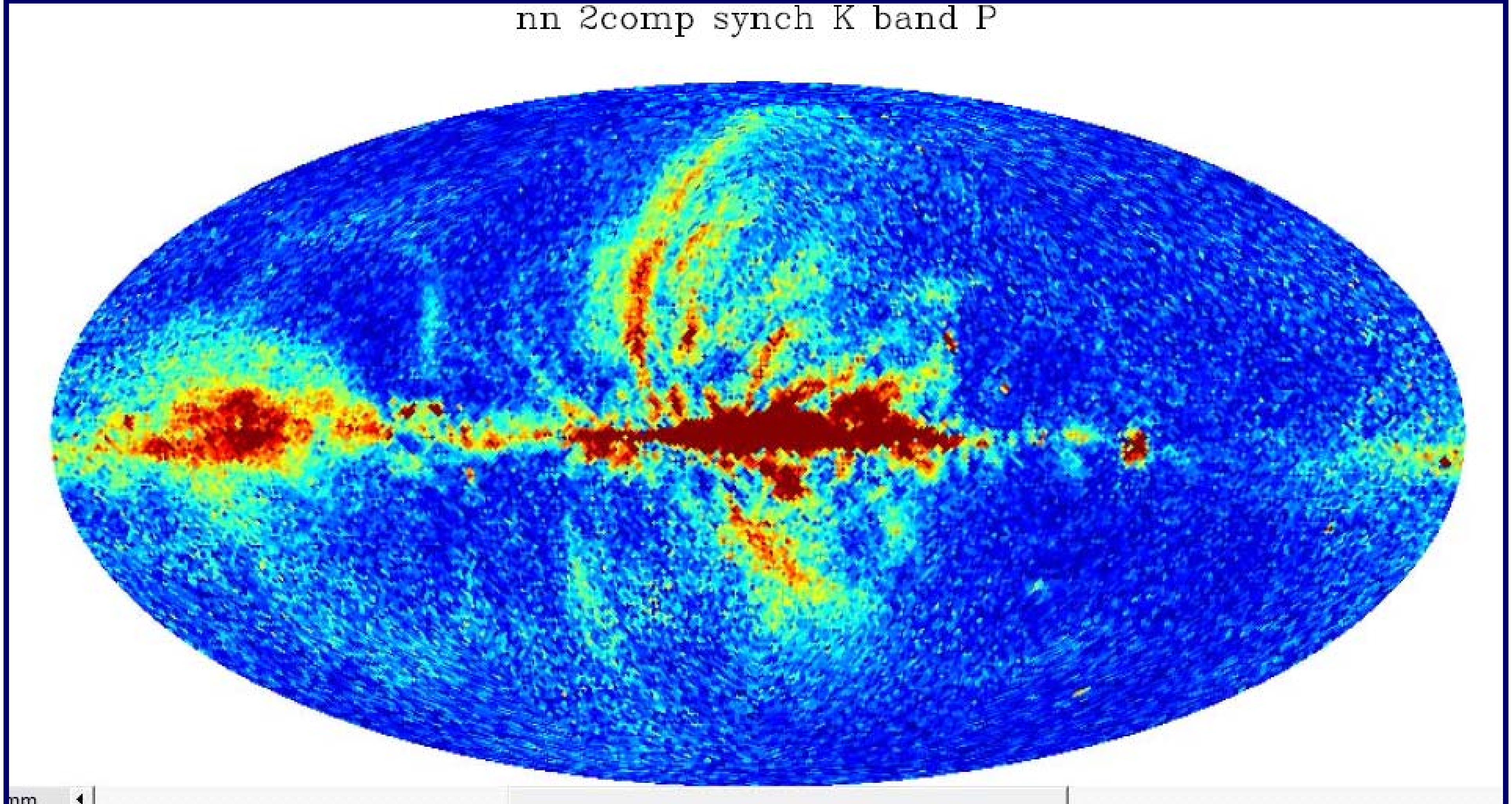
2014@Riken

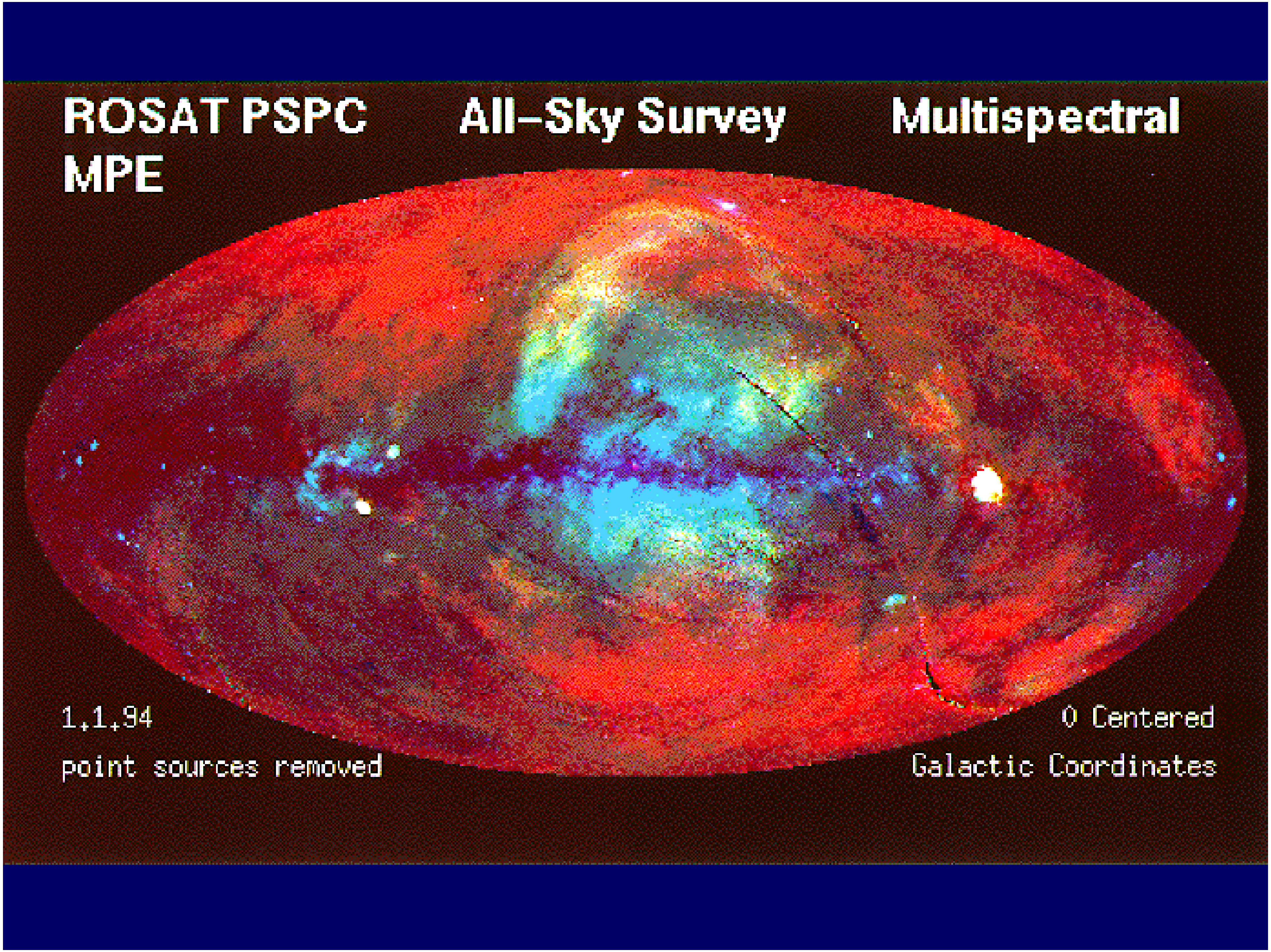
# 1. Introduction

# Radio Sky Bonn/Parkes 408 MHz



# Radio Polarization WMAP 23 GHz




ROSAT PSPC
MPE
All-Sky Survey
Multispectral
1.1.94
point sources removed
0 Centered
Galactic Coordinates

# North Polar Spur =

# SNR?

## (Supernova Remnant)

# GER?

## (Galactic Explosion Remnant)

## or

# Else?

# SNR 説

Oort' suggestion,

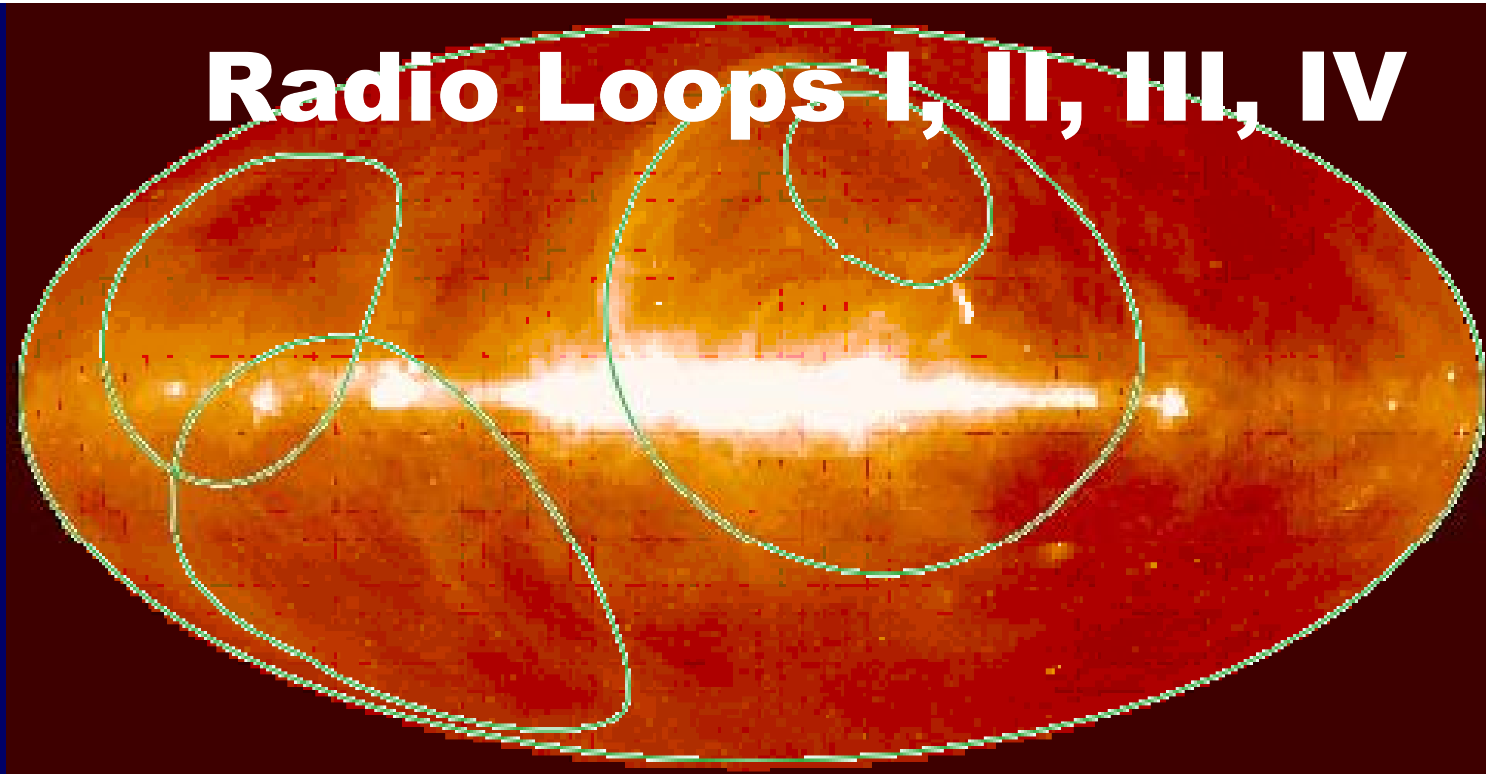
Spoelstra, Berkhuijsen, Salter,

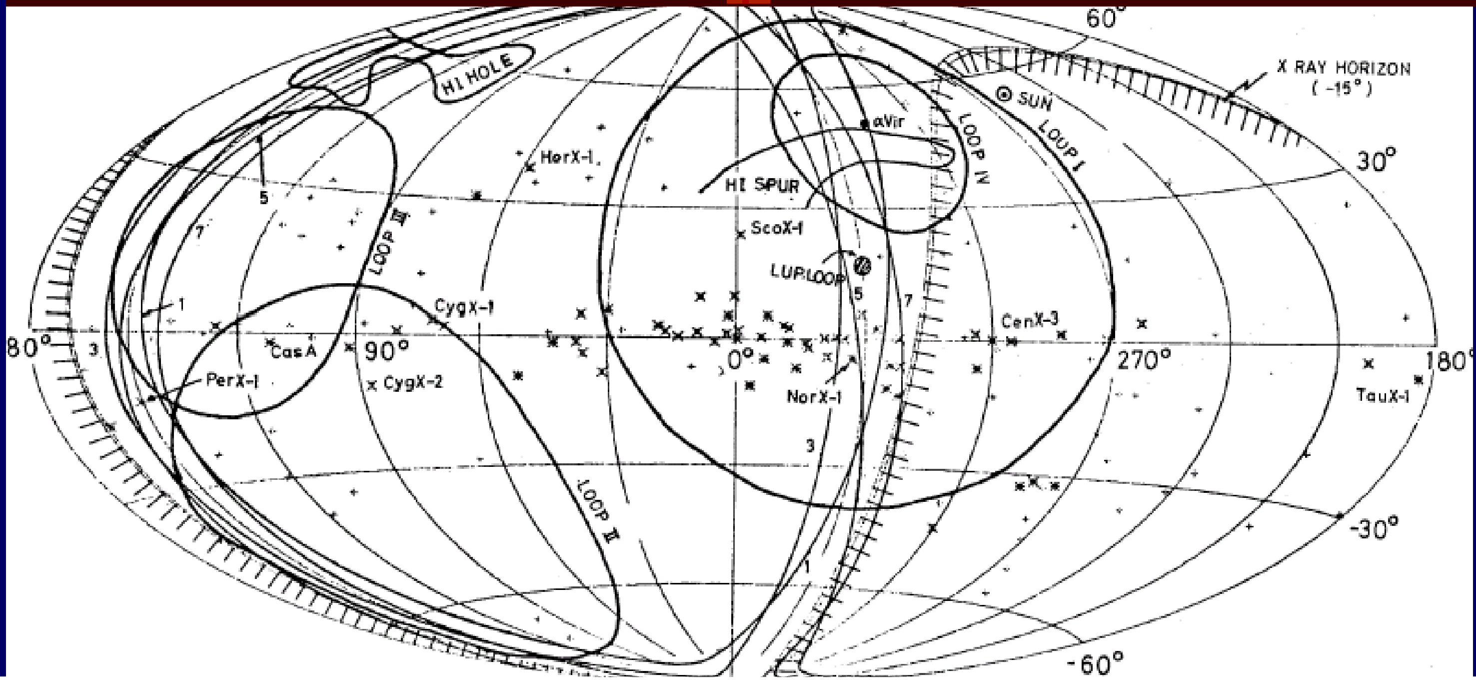
ROSAT Thesis, ....

Japan

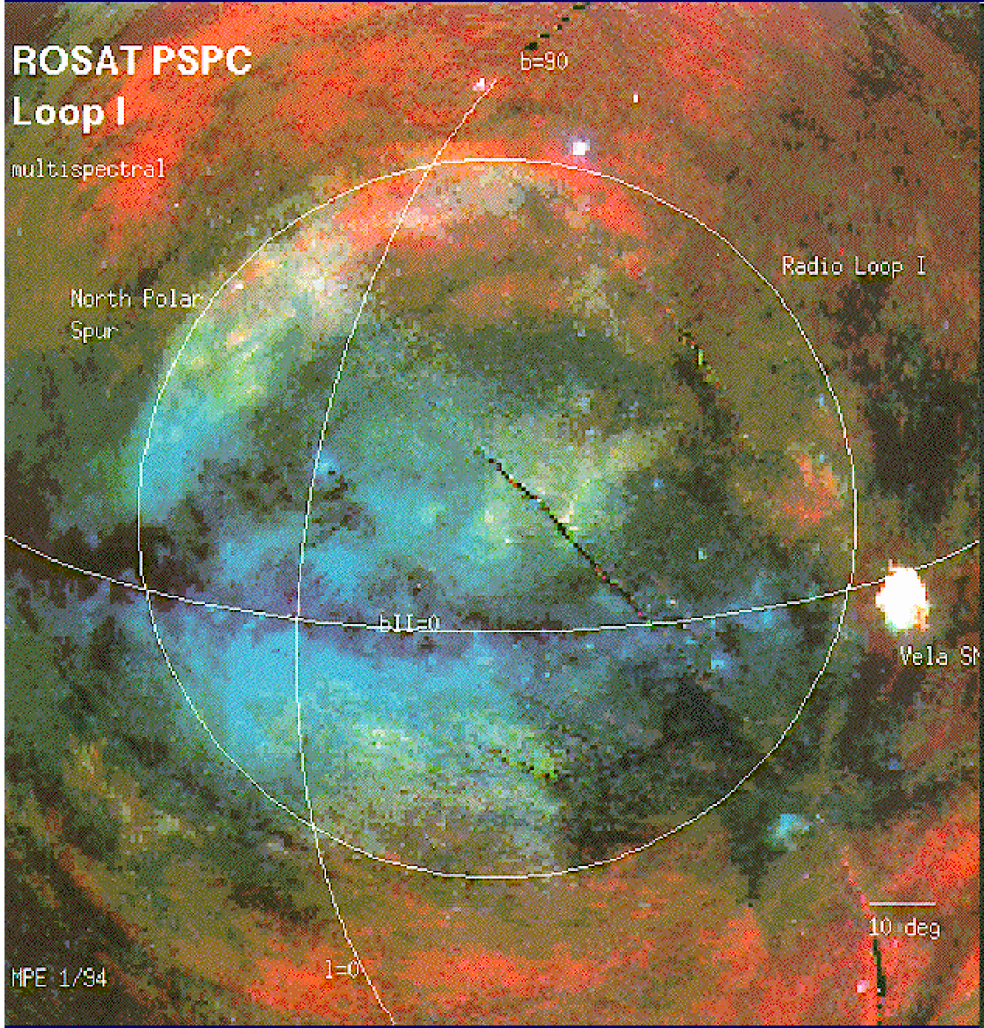
Hayakawa, Oda (Local helix), et al.

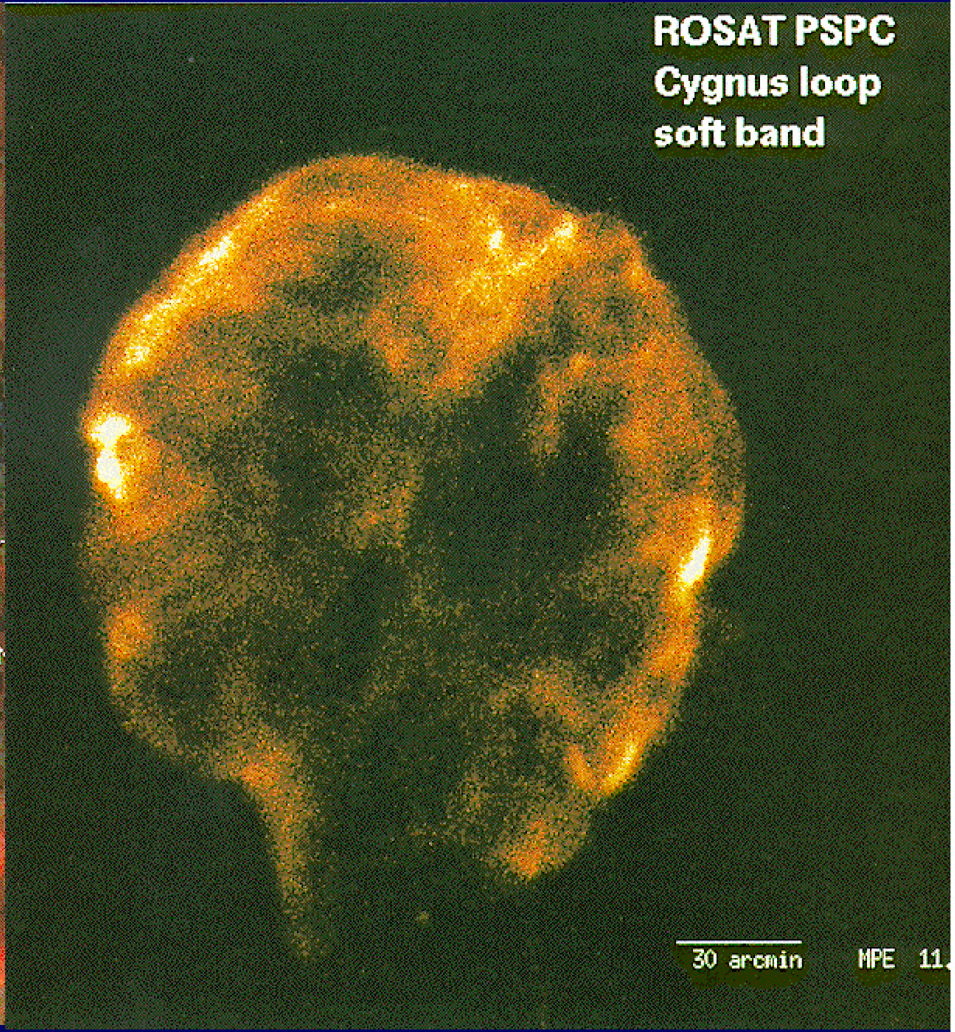
# Radio Loops I, II, III, IV






**Hayakawa 1977**


ROSAT PSPC
Loop I
multispectral
b=90
Radio Loop I
North Polar
Spur
bII=0
Vela
10 deg
MPE 1/94
l=0


ROSAT PSPC
Cygnus loop
soft band
30 arcmin
MPE

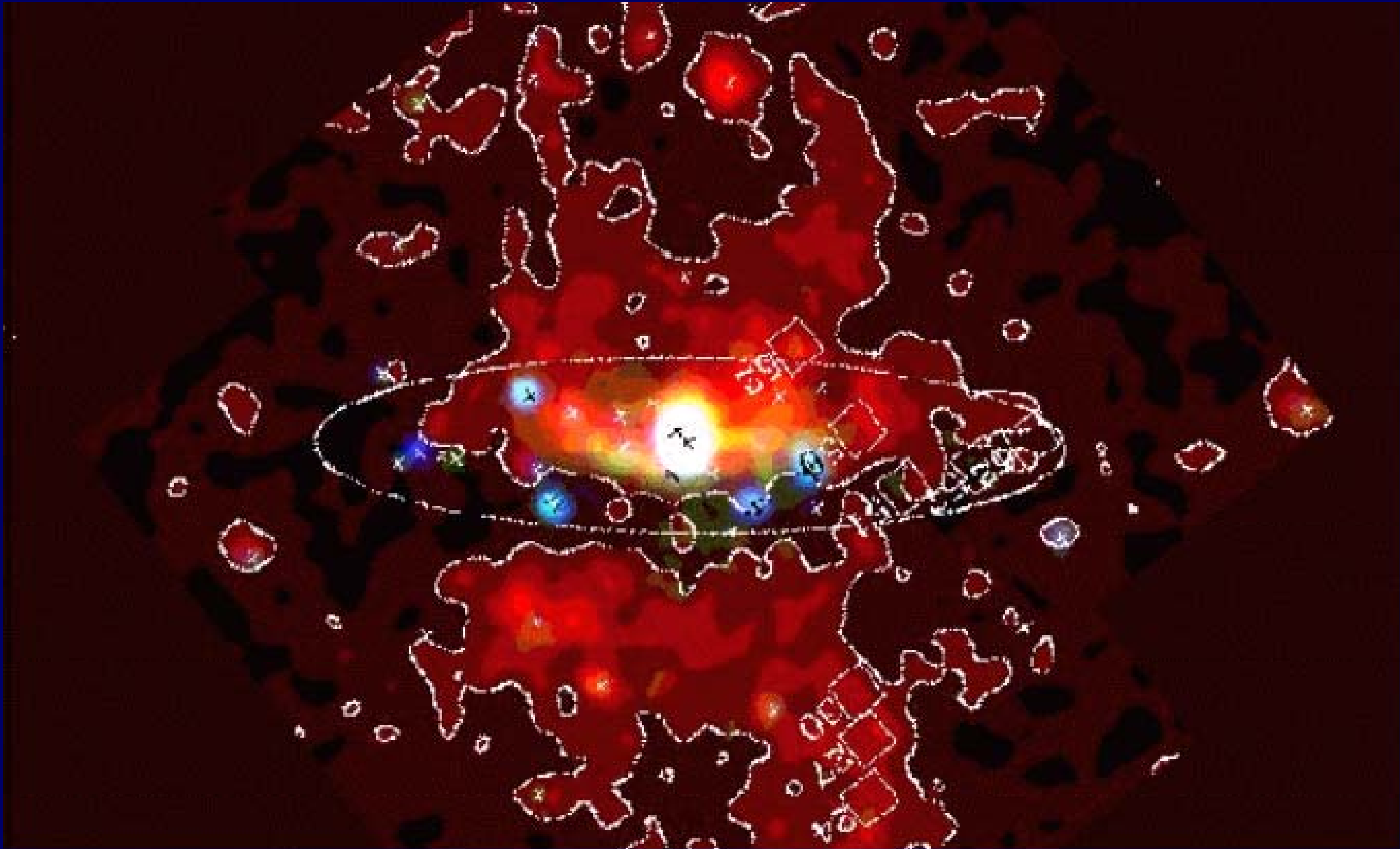
# GER 説

Sofue 1970’ ,...

Bland-Hawthorn 2000’, ...

Kataoka et al (2013), + Suzaku sympathy

# NGC 253



# M82

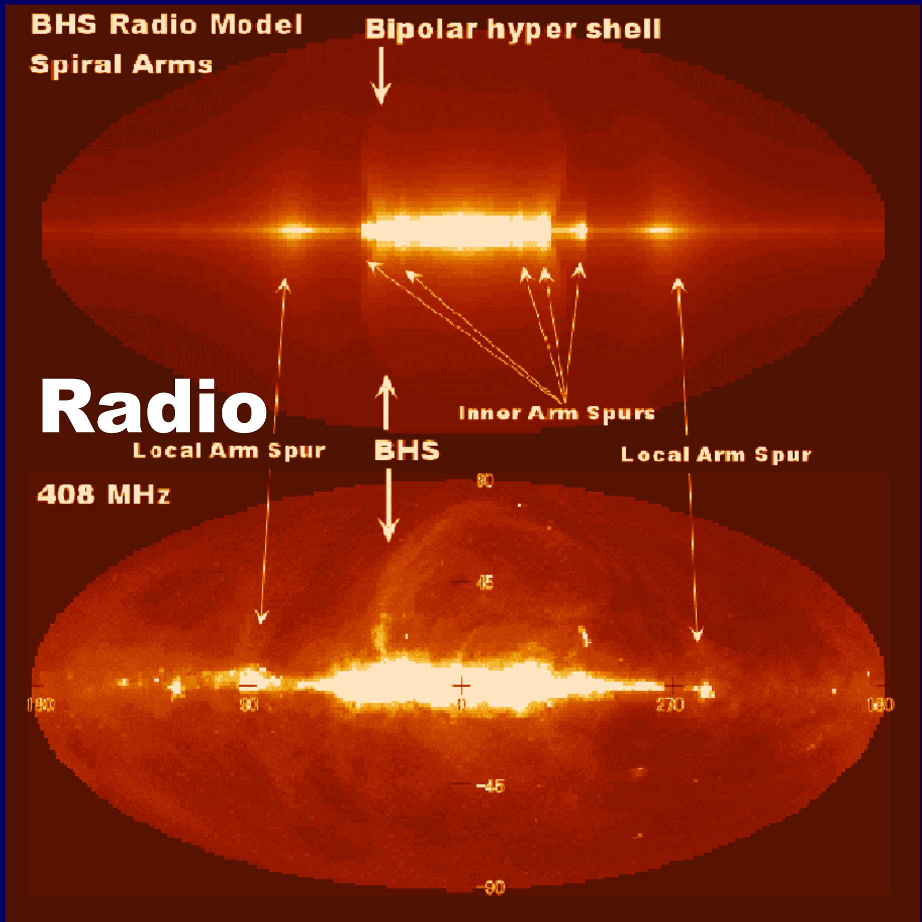
M 82 (NGC 3034)

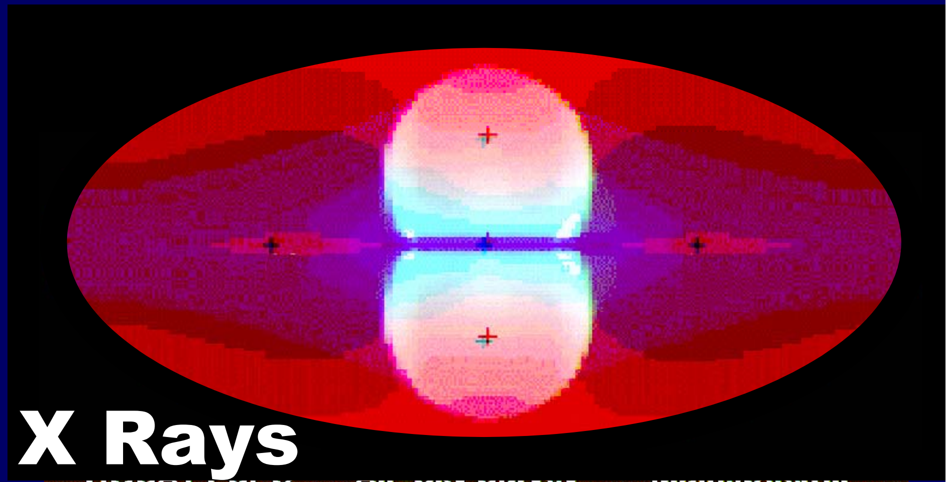
FOCAS (B, V, H$\alpha$ )

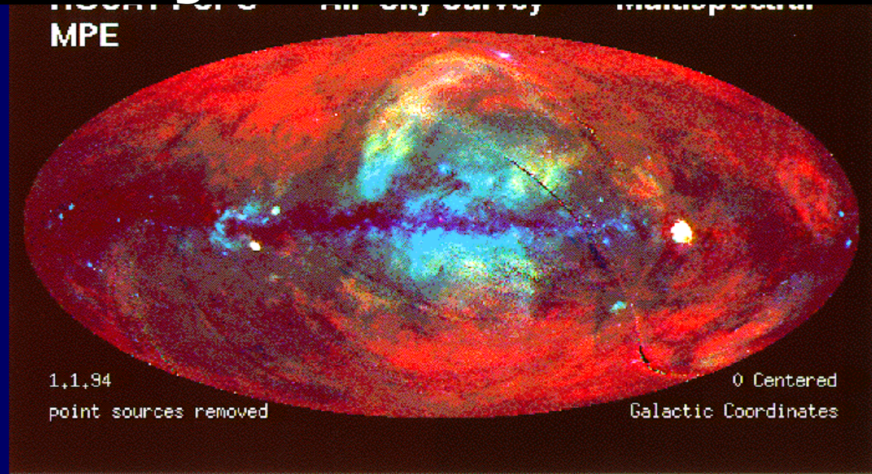
Subaru Telescope, National Astronomical Observatory of Japan

March 24, 2000

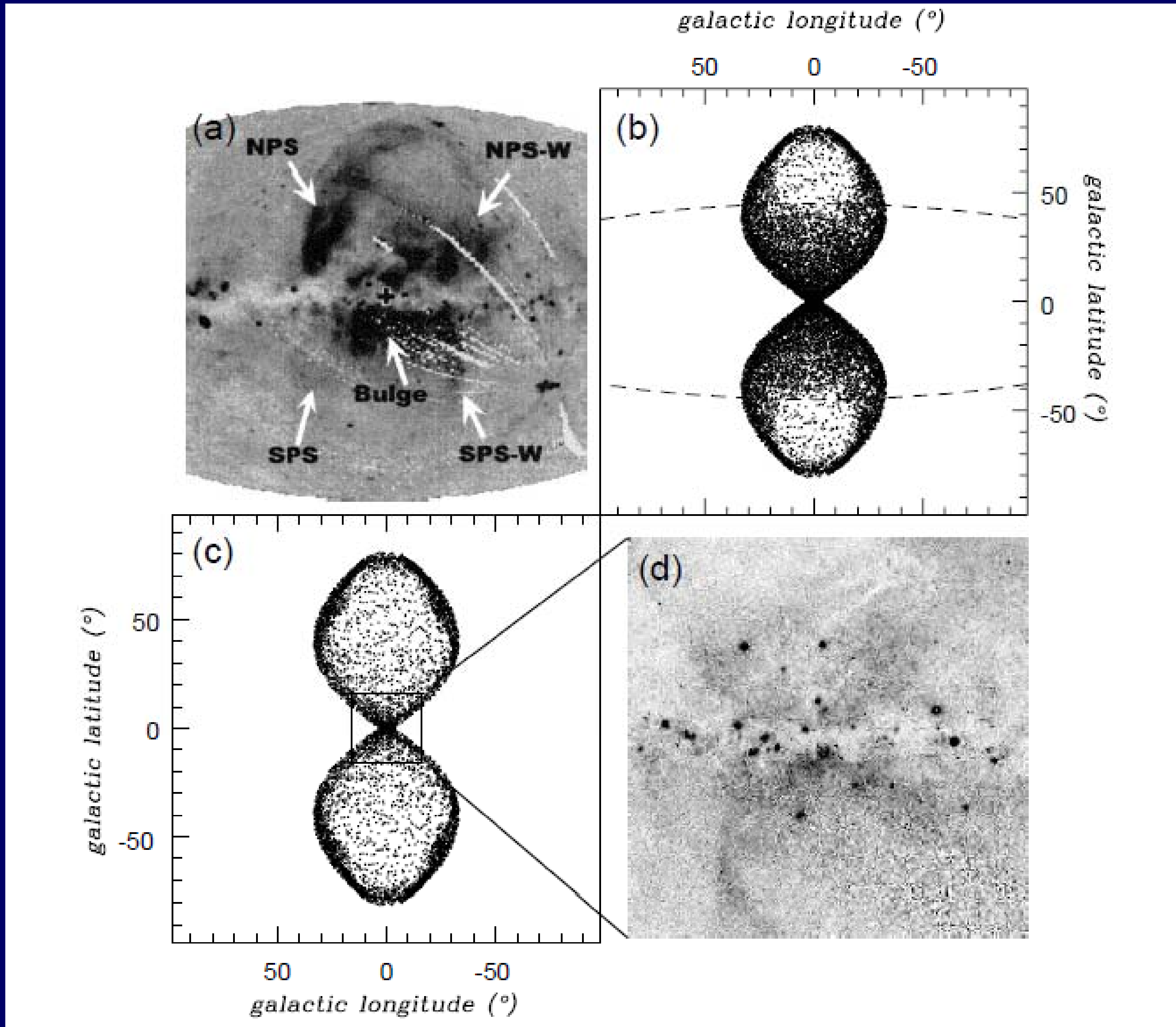
# GER Model


BHS Radio Model
Spiral Arms
Bipolar hyper shell
Radio
Inner Arm Spurs
Local Arm Spur
BHS
Local Arm Spur
408 MHz
90
45
180
90
0
270
180
-45
-90

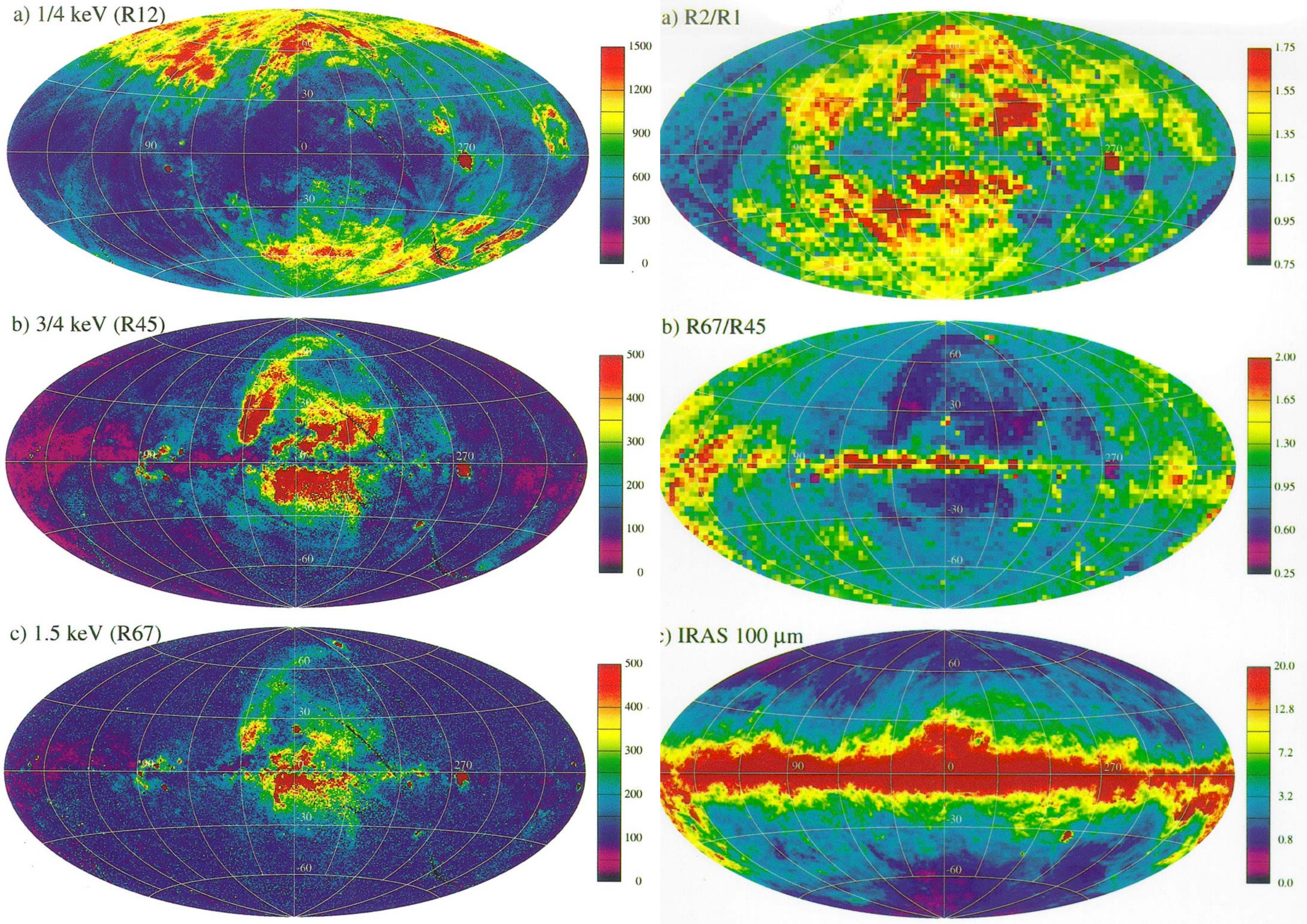

X Rays


MPE
1,1,94
point sources removed
0 Centered
Galactic Coordinates

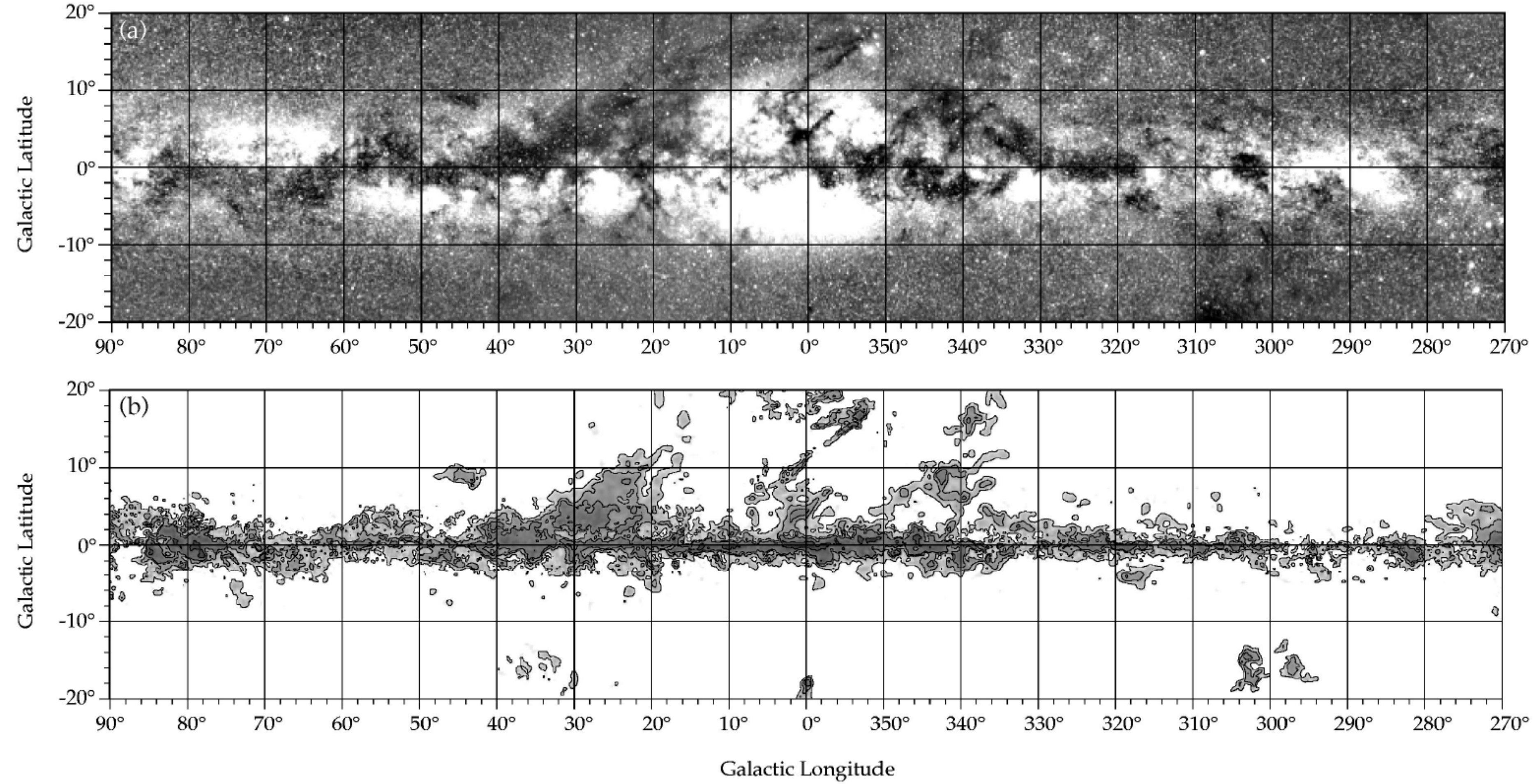
# Bland-Hawthorn and Cohen 2003 Galactic Wind model



# 2. Distance to NPS

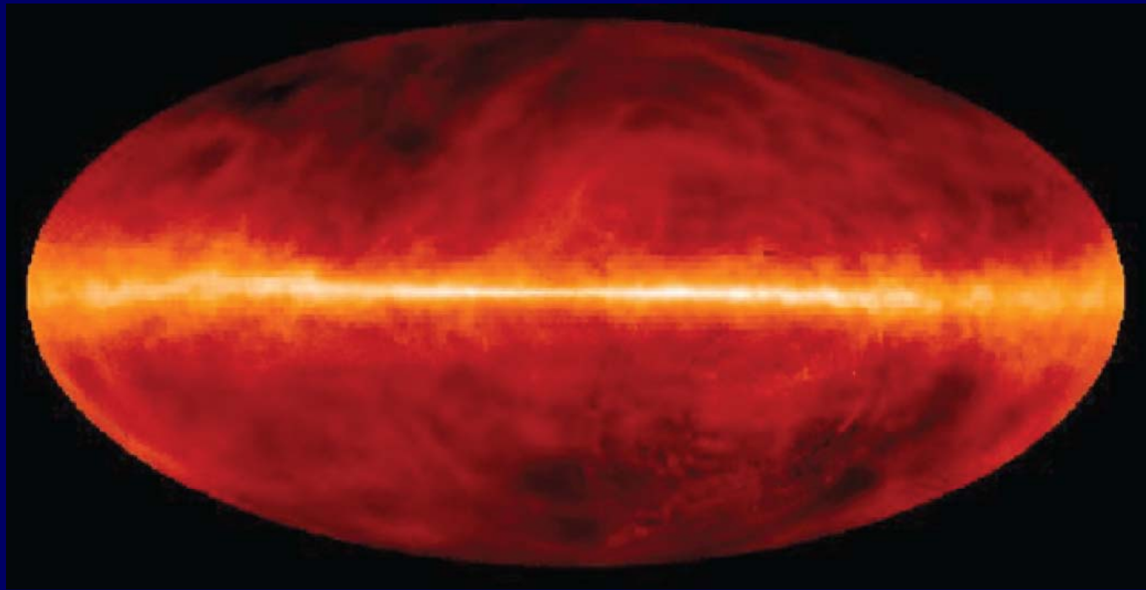



**Snowden et al 1997**



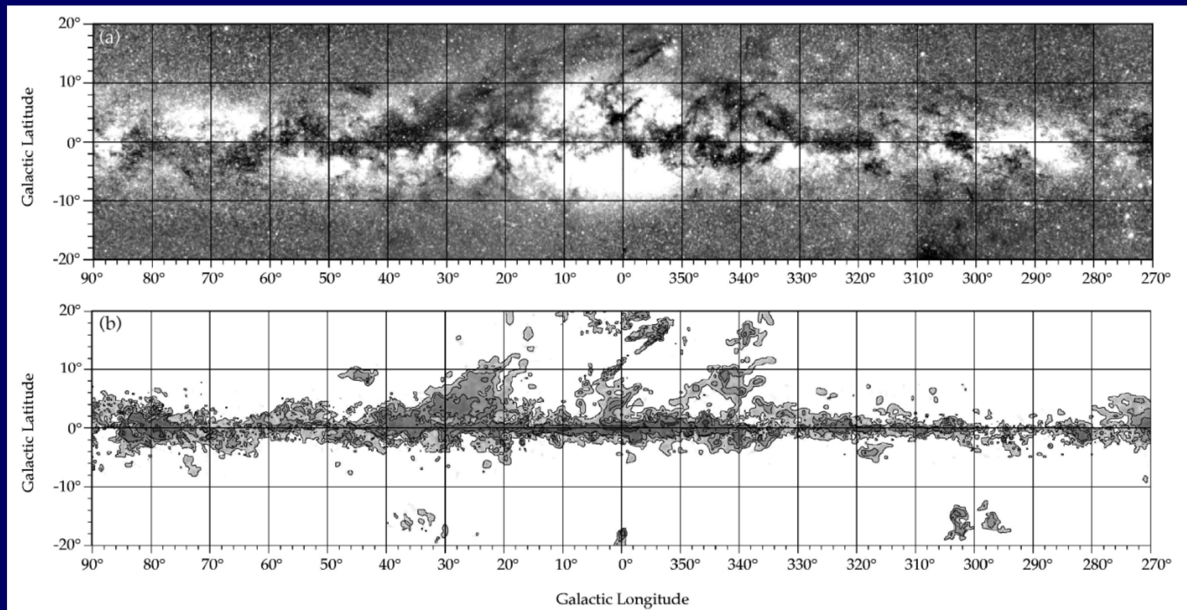
(a)
(b)
Galactic Latitude
Galactic Longitude
20°
10°
0°
-10°
-20°
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
350°
340°
330°
320°
310°
300°
290°
280°
270°

**HI (Kalbera )**



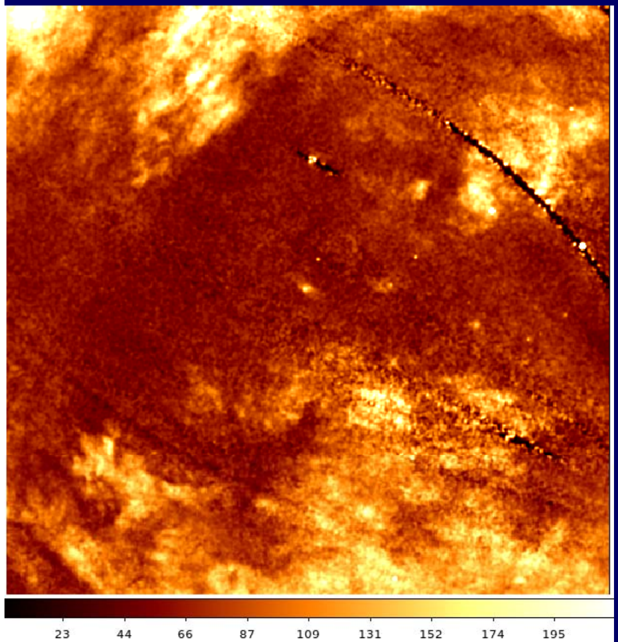
**Dust (COBE)**

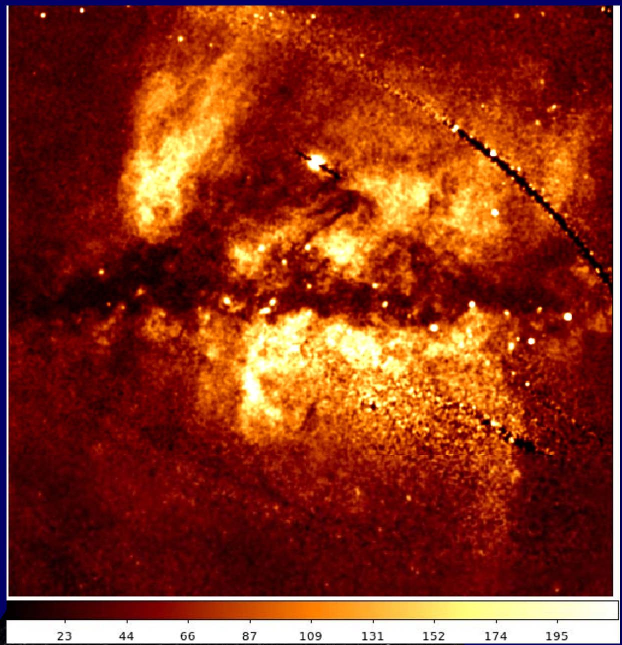
**CO (Dame)**

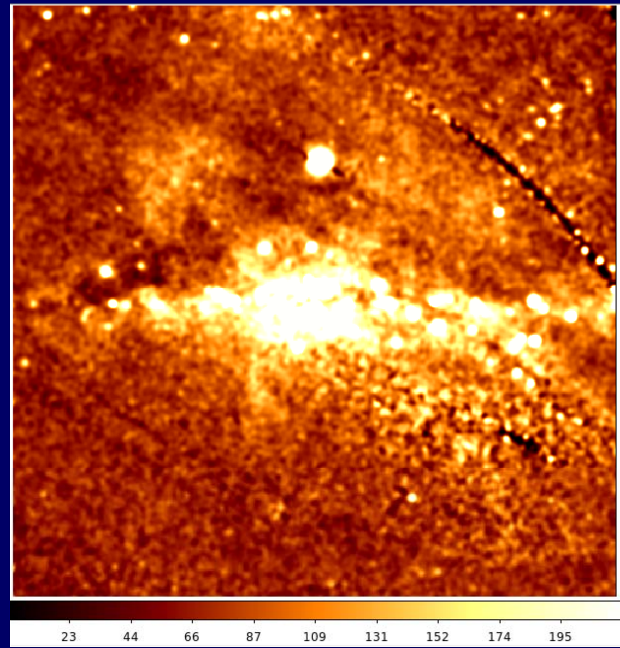


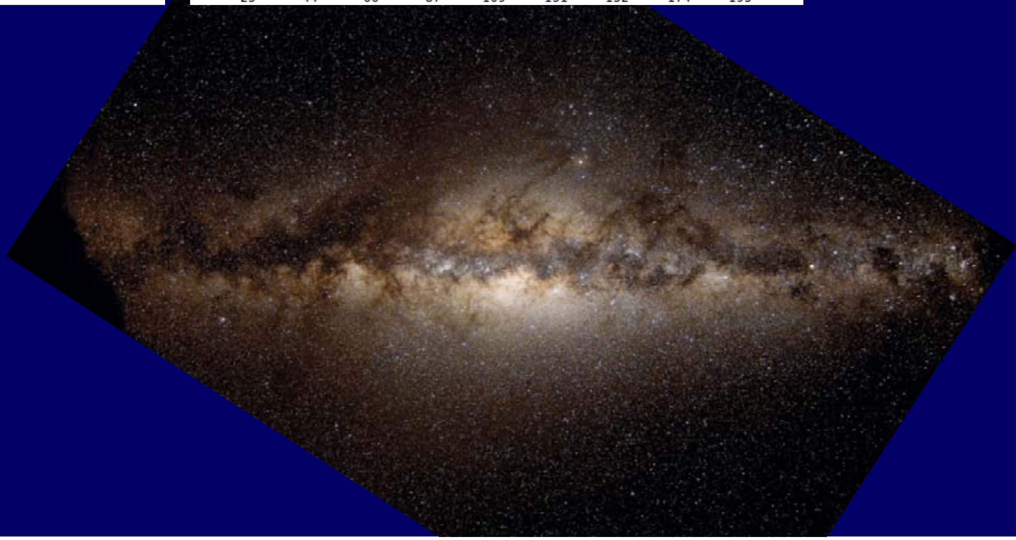
# ROSAT

# R2 (0.2 keV), R5 (0.9 keV), R7(1.6 keV)

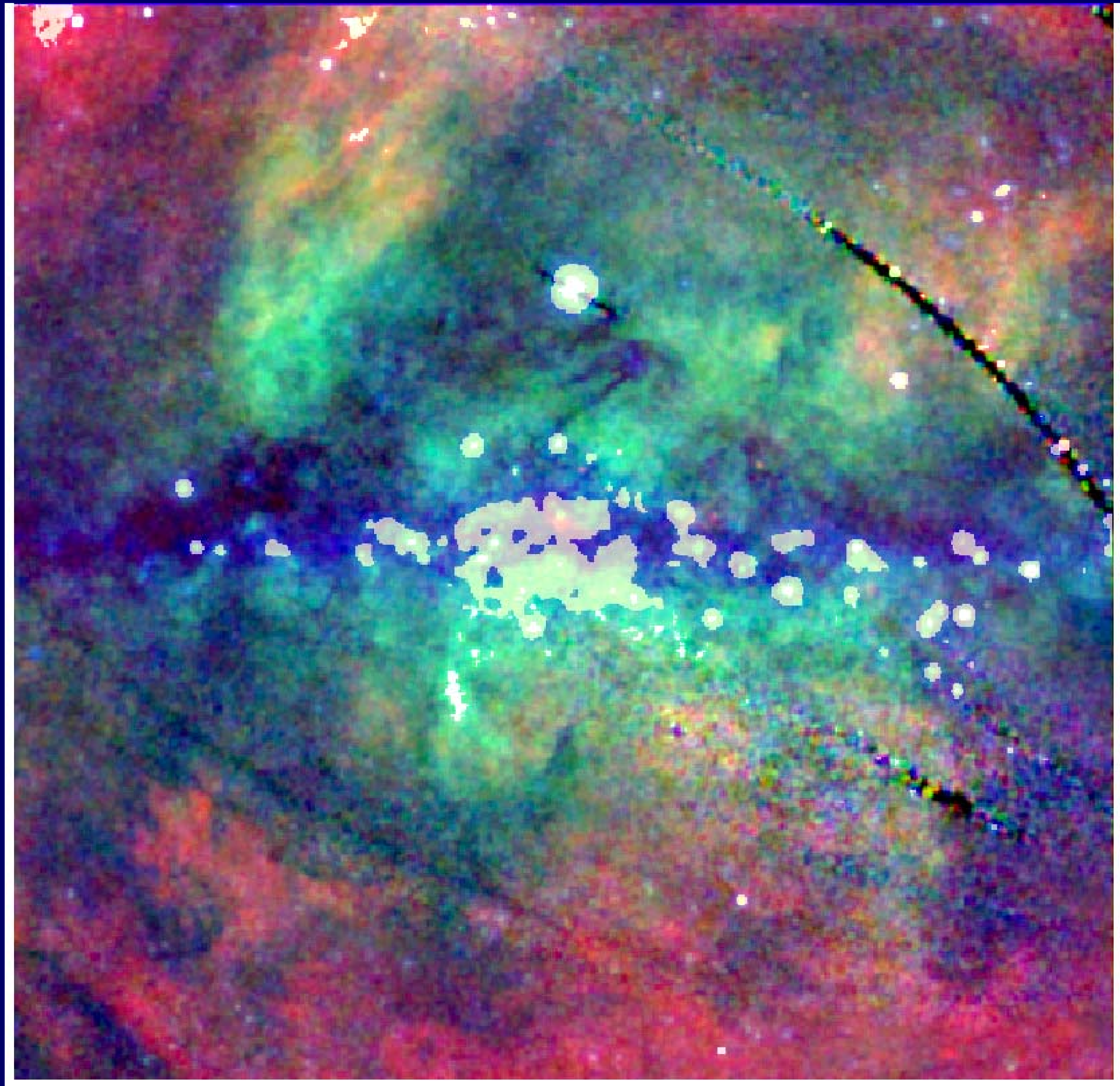


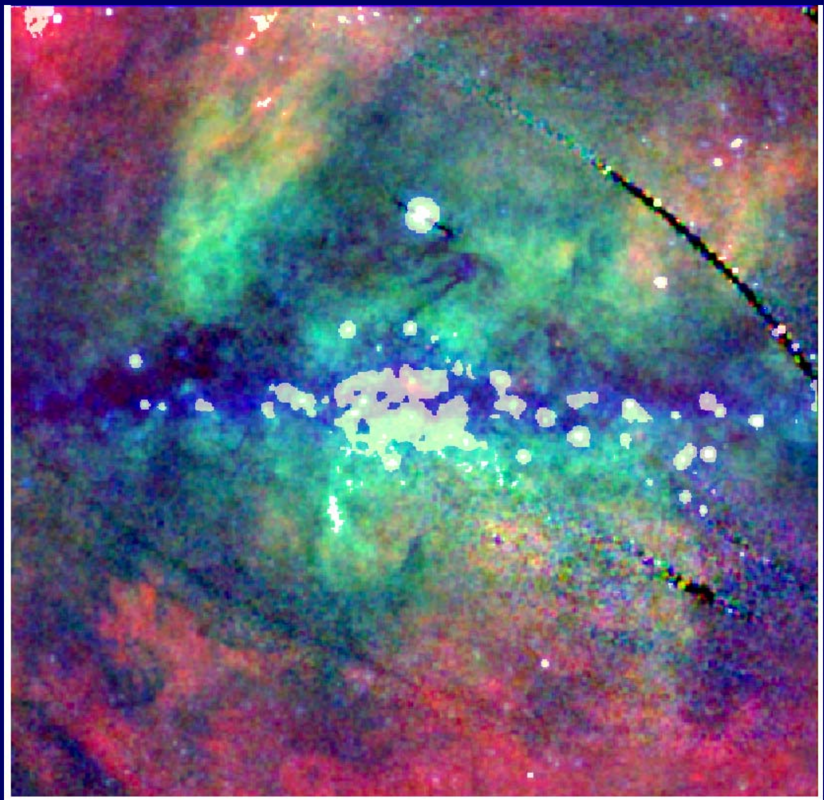



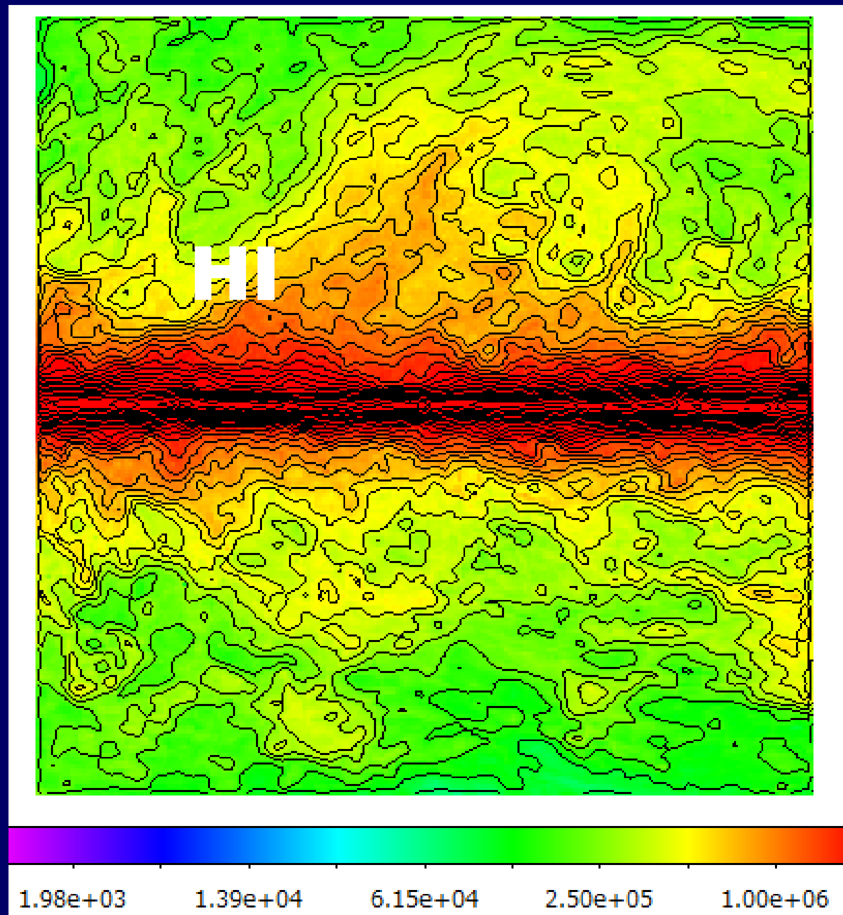



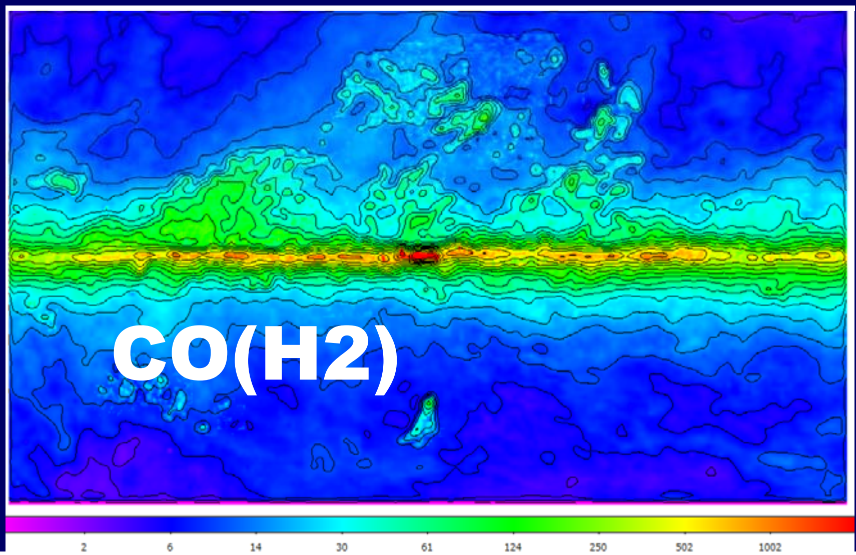



# R2/R5/R7 RGB (l,b +-50d)






HI
1.98e+03
1.39e+04
6.15e+04
2.50e+05
1.00e+06


CO(H2)
2
6
14
30
61
124
250
502
1002

# Tau=1 @

## 0.8 keV:

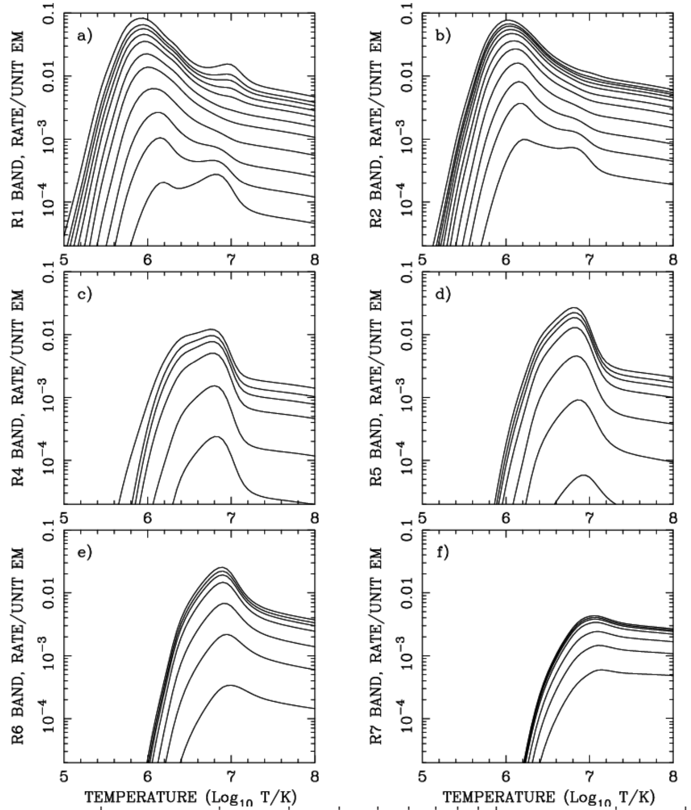
## $N_{H,0}=3\times10^{21}$ H cm$^{-2}$

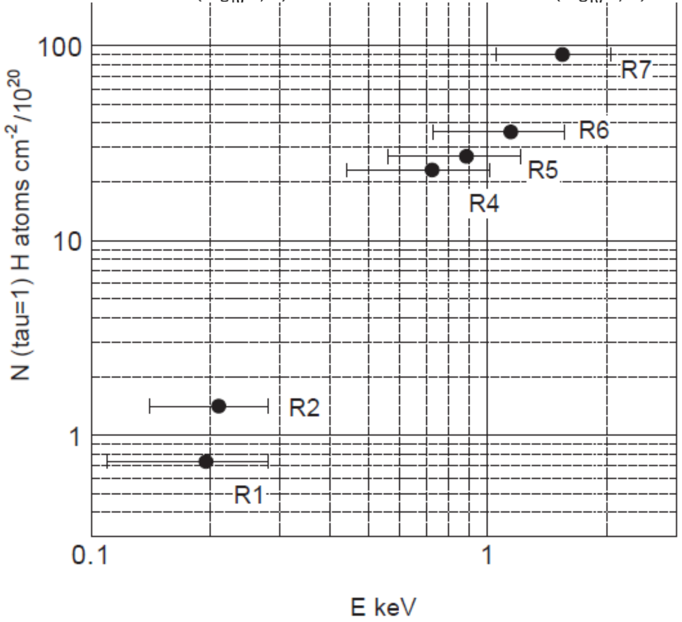
### $=1$ kpc x 1 H cm$^{-3}$

## 1.5 keV:

## $N_{H,0}=9\times10^{21}$ H cm$^{-2}$

### $=3$ kpc x 1 H cm$^{-3}$



## Snowden et al. 1993

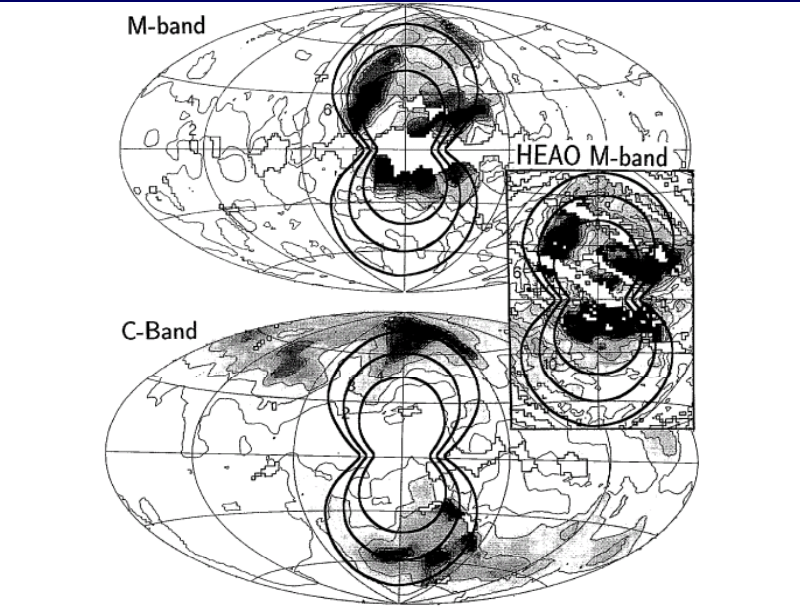
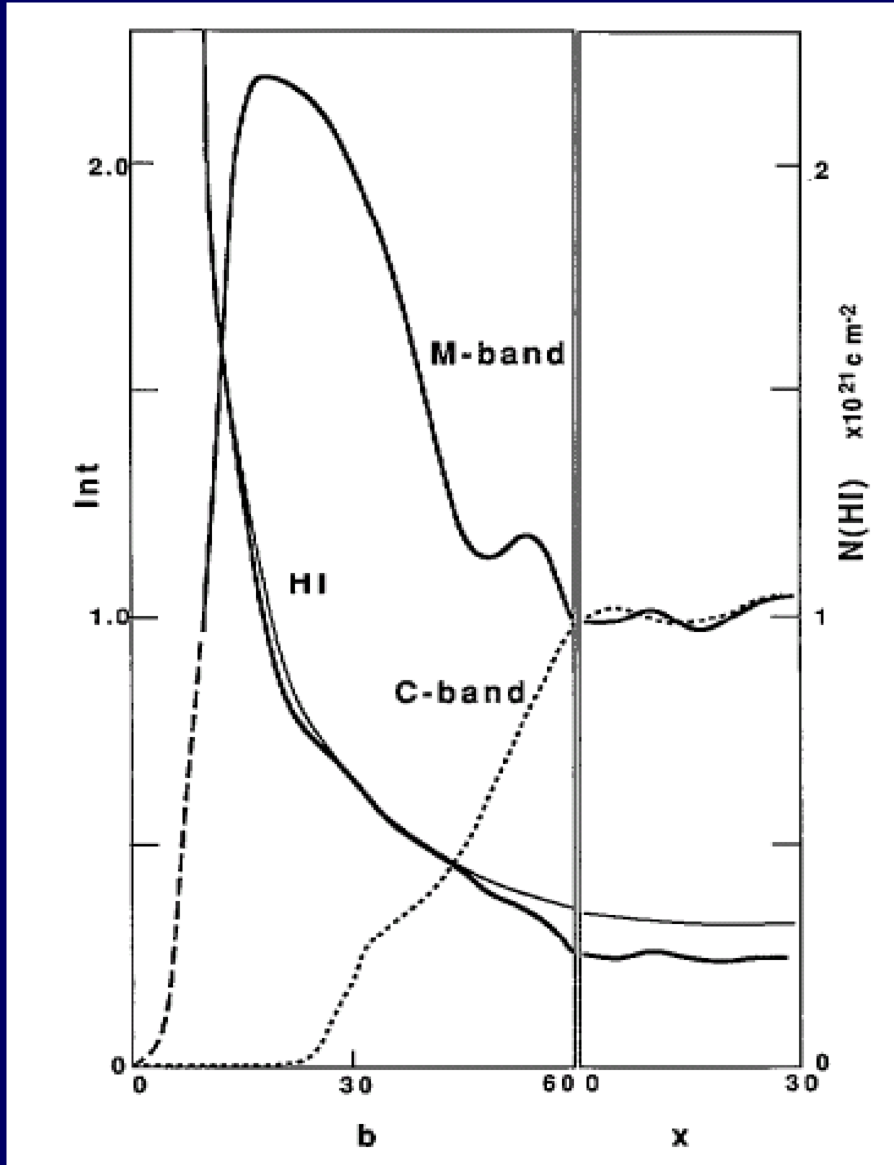
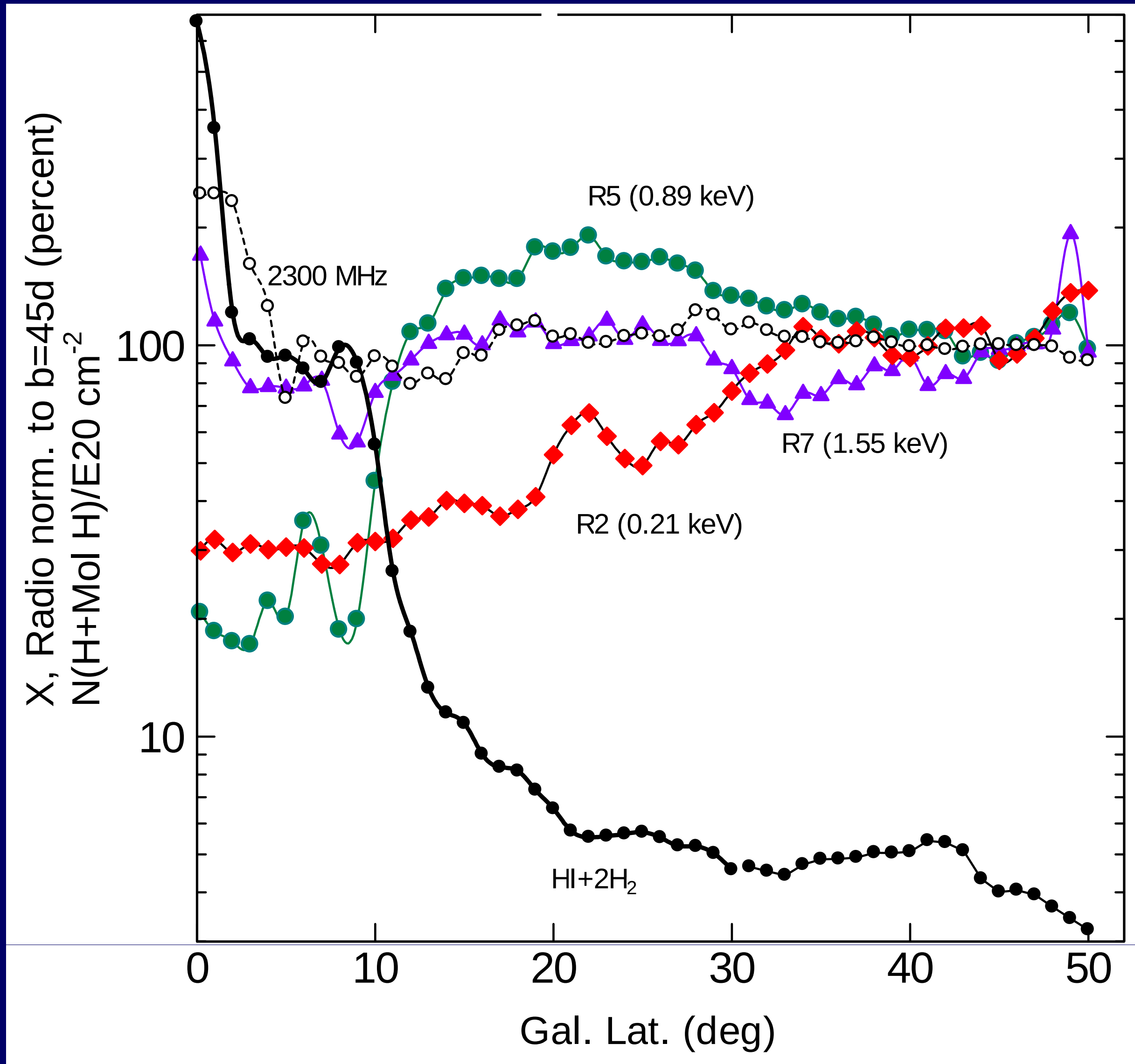


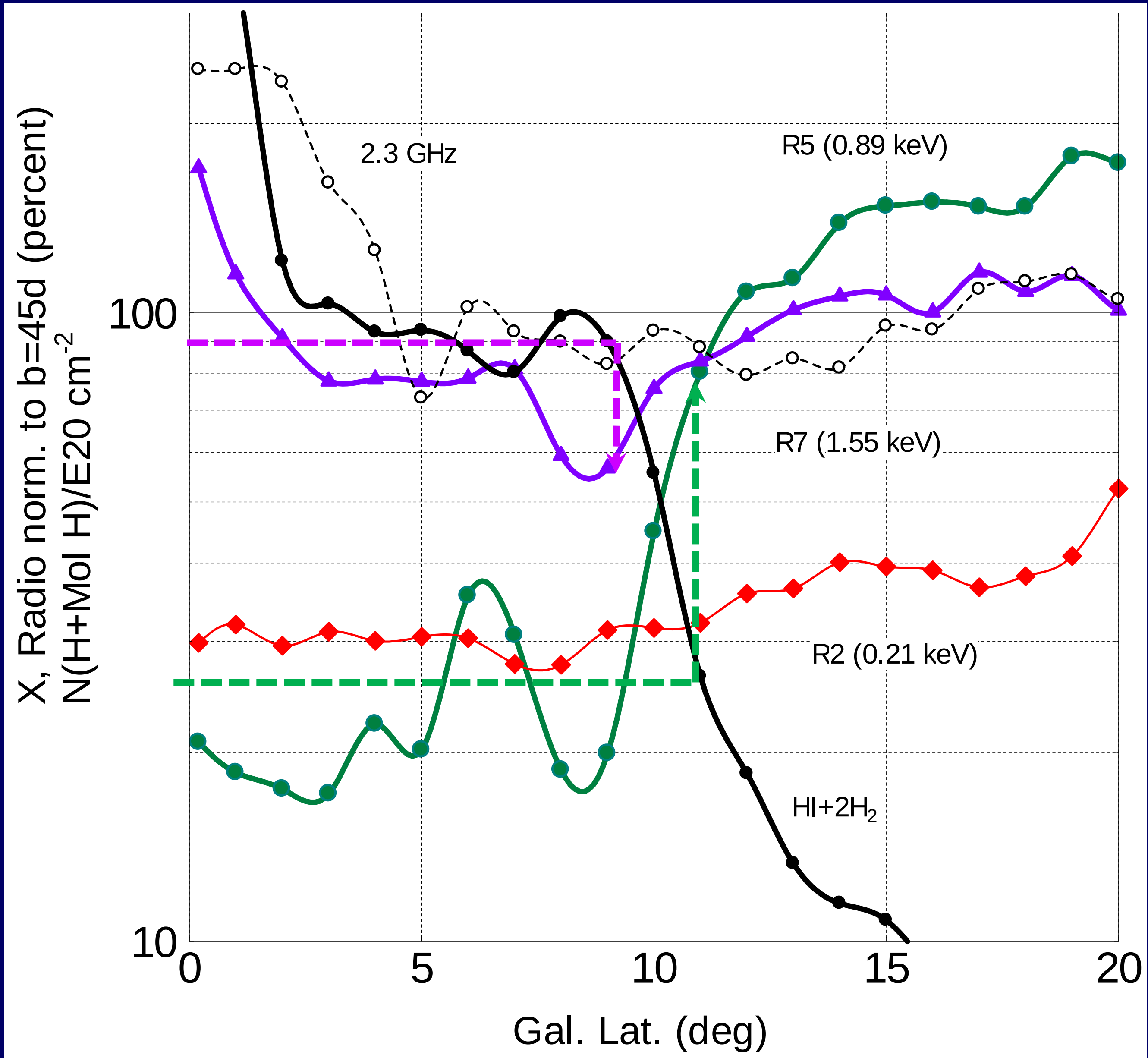

FIG. 1.—Calculated shock front in the Galactic halo at 1, 1.5, and $2 \times 10^7$ yr after an explosion and/or a starburst at the nucleus with a total energy of $3 \times 10^{56}$ ergs. The front is superposed on the *M*- and *C*-band X-ray maps (McCammon et al. 1983).

## Sofue 1994 ApJL



# R2, R5, R7, Radio vs N(H)+2N(H2) Intensities along NPS norm. at b=45





X, Radio norm. to b=45d (percent)
N(H+Mol H)/E20 cm$^{-2}$
100
10
0
5
10
15
20
Gal. Lat. (deg)
2.3 GHz
R5 (0.89 keV)
R7 (1.55 keV)
R2 (0.21 keV)
HI+2H$_2$

# Absorption by Gal. Gas Layer

R5 N>3 E21 H $cm^{-2}$

r > 1 kpc (for n=1 H $cm^{-3}$)

R7 N>9 E 21 H $cm^{-2}$

r> 3 kpc (for n=1 H $cm^{-3}$)

# Kinematic Distance

$V = 7 \pm 3$ km/s

($V_{max} \sim 20$ km/s)

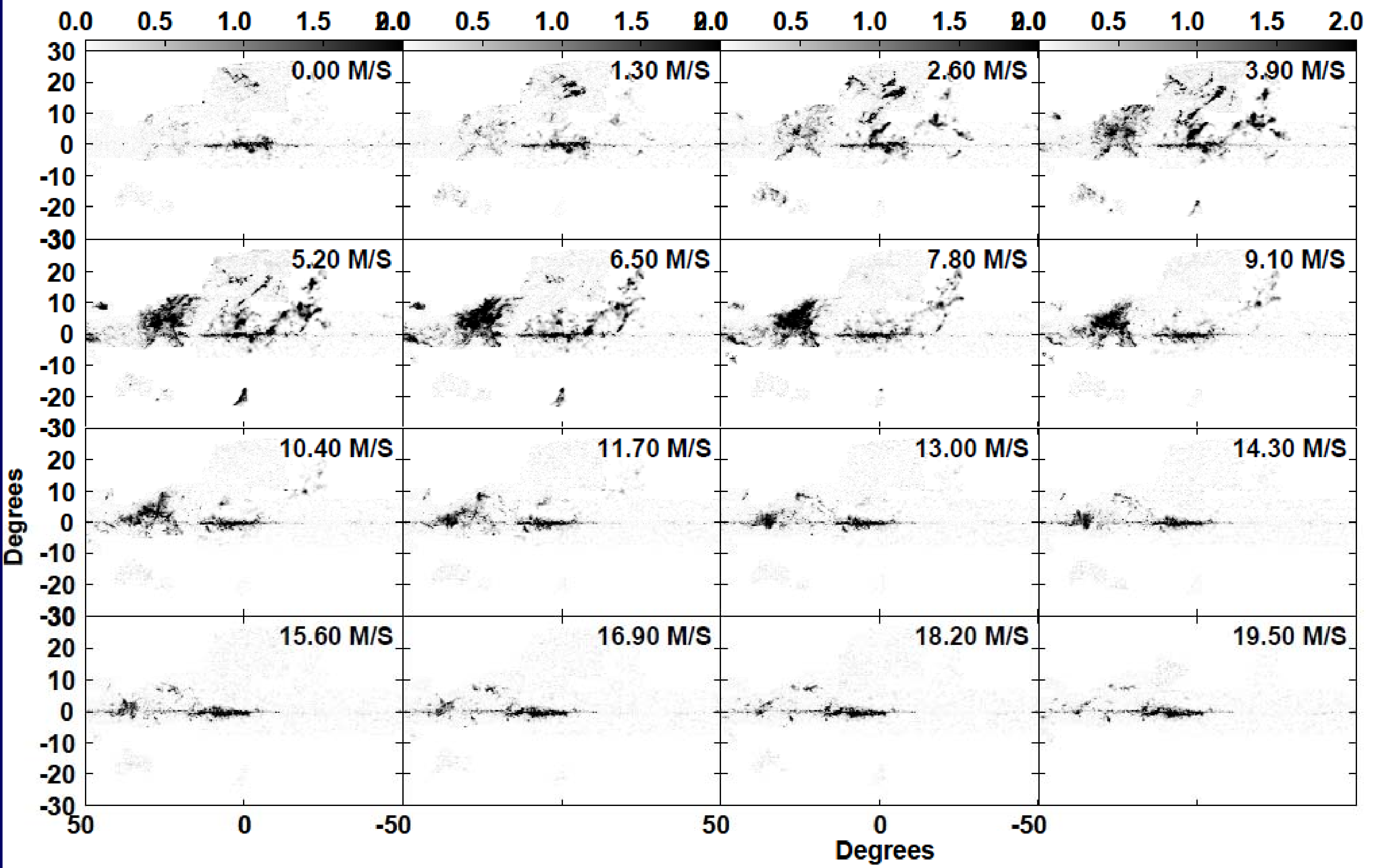
$r = V / A \sin(2l) \cos b$

$r = 0.63 \pm 0.27$ kpc

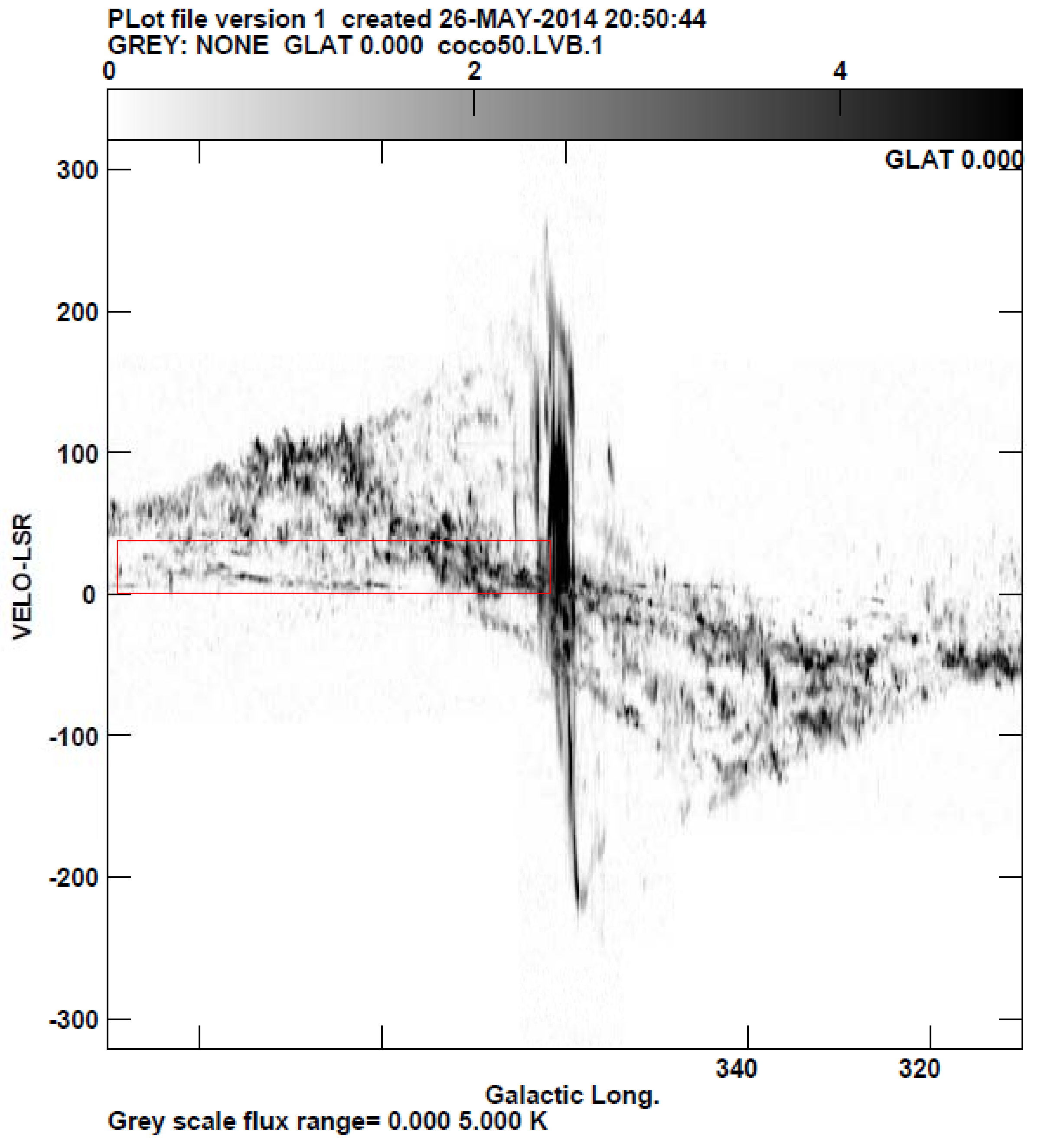
($r_{max} \sim 1.8$ kpc )

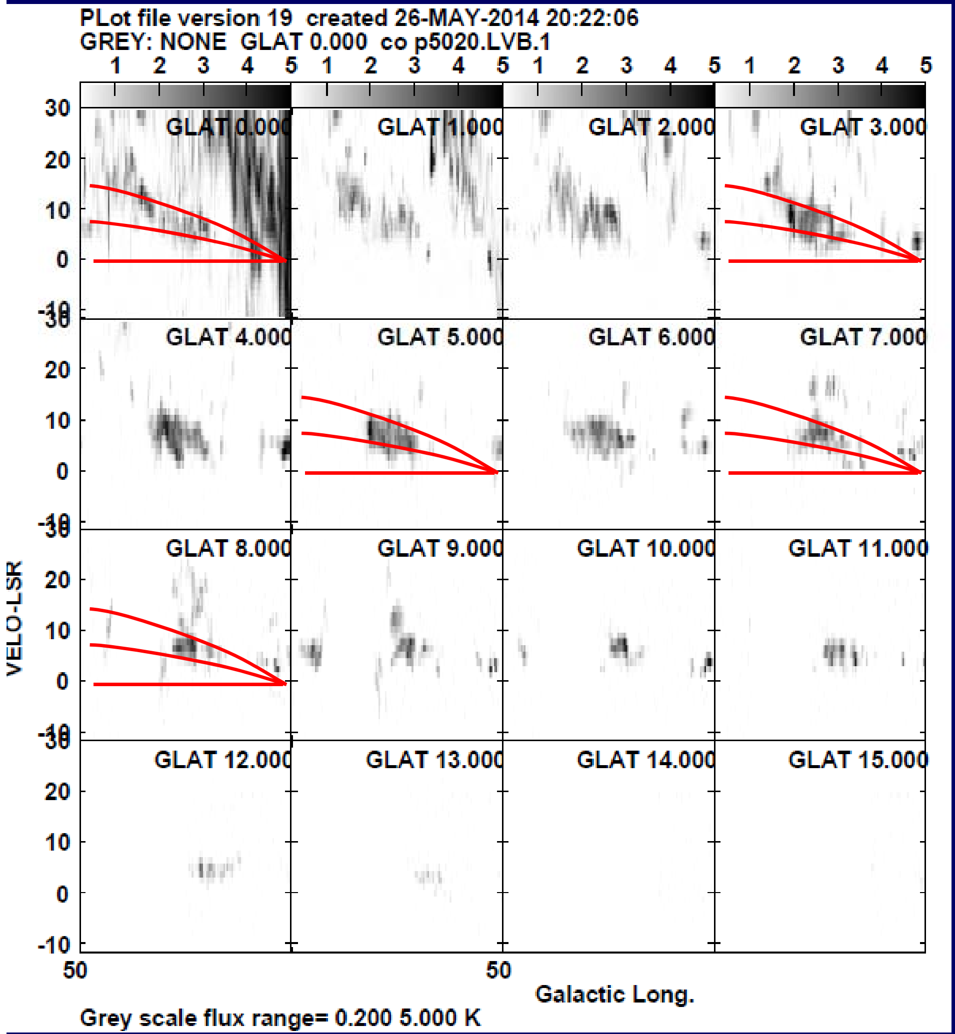
# Kinematic Distance

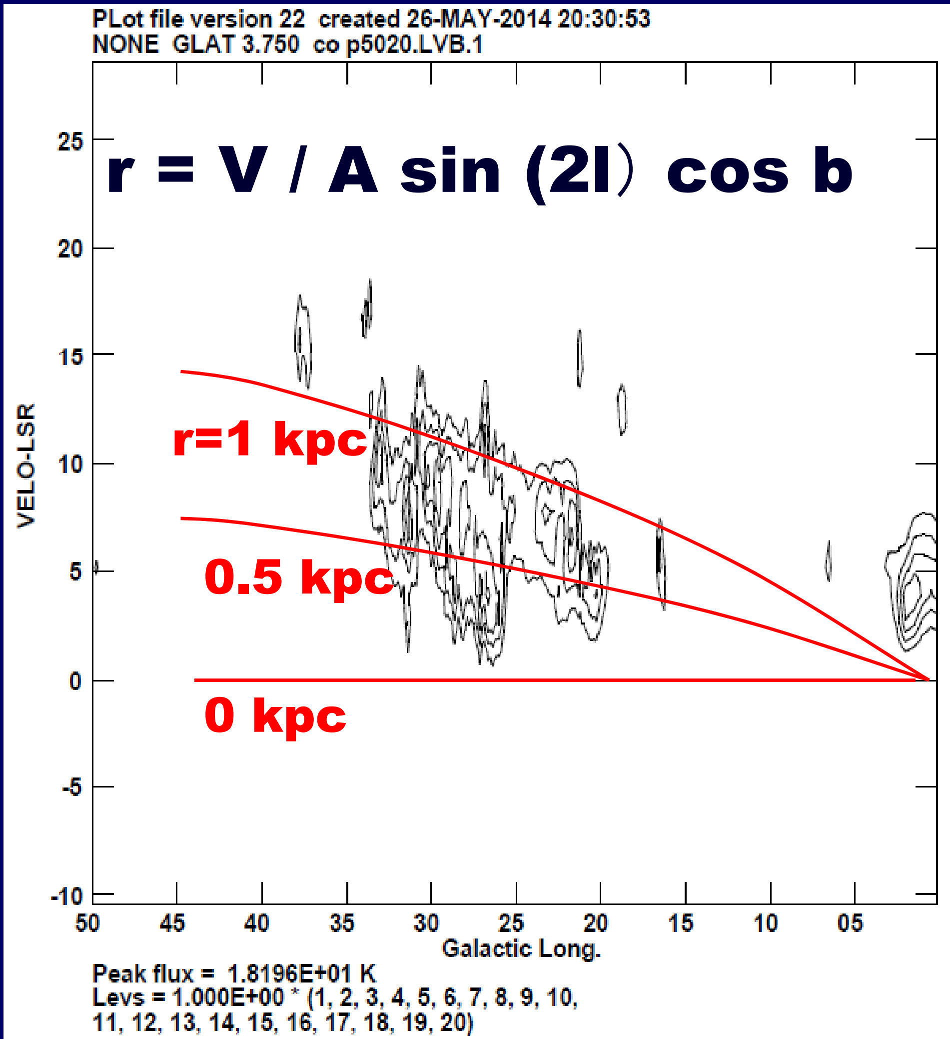
## CO-Velocity Channel maps (Dame et al. 2001)



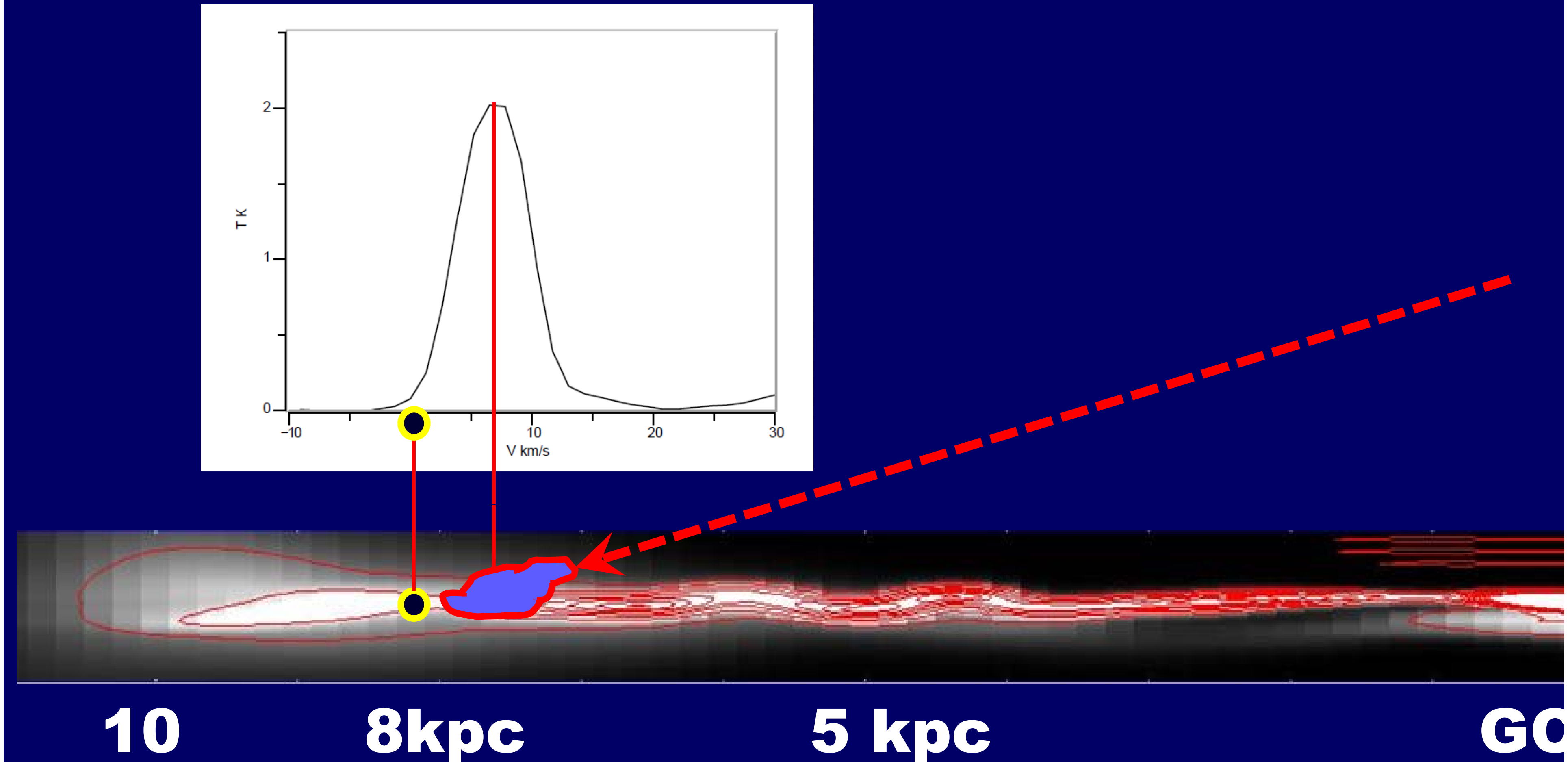
# CO-Long-Velocity




PLot file version 19 created 26-MAY-2014 20:22:06
GREY: NONE GLAT 0.000 co p5020.LVB.1
GLAT 0.000
GLAT 1.000
GLAT 2.000
GLAT 3.000
GLAT 4.000
GLAT 5.000
GLAT 6.000
GLAT 7.000
GLAT 8.000
GLAT 9.000
GLAT 10.000
GLAT 11.000
GLAT 12.000
GLAT 13.000
GLAT 14.000
GLAT 15.000
VELO-LSR
Galactic Long.
Grey scale flux range= 0.200 5.000 K


PLot file version 22 created 26-MAY-2014 20:30:53
NONE GLAT 3.750 co p5020.LVB.1
r = V / A sin (2l) cos b
r=1 kpc
0.5 kpc
0 kpc
VELO-LSR
Galactic Long.
Peak flux = 1.8196E+01 K
Levs = 1.000E+00 * (1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
11, 12, 13, 14, 15, 16, 17, 18, 19, 20)

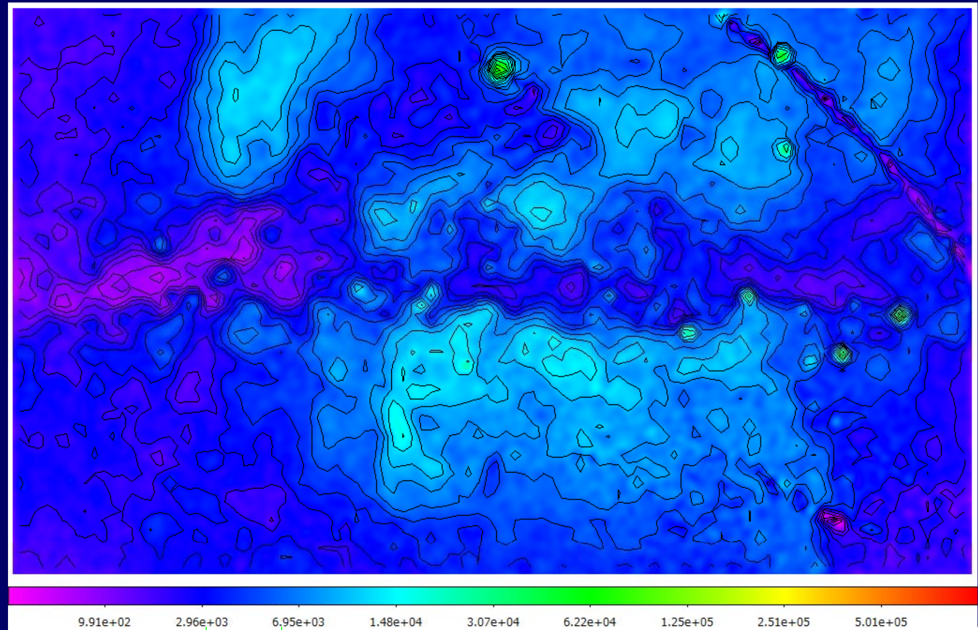
# r>0.63 ±0.27 kpc (r$_{max}$ >1.8 kpc)



# Extinction corrected NPS

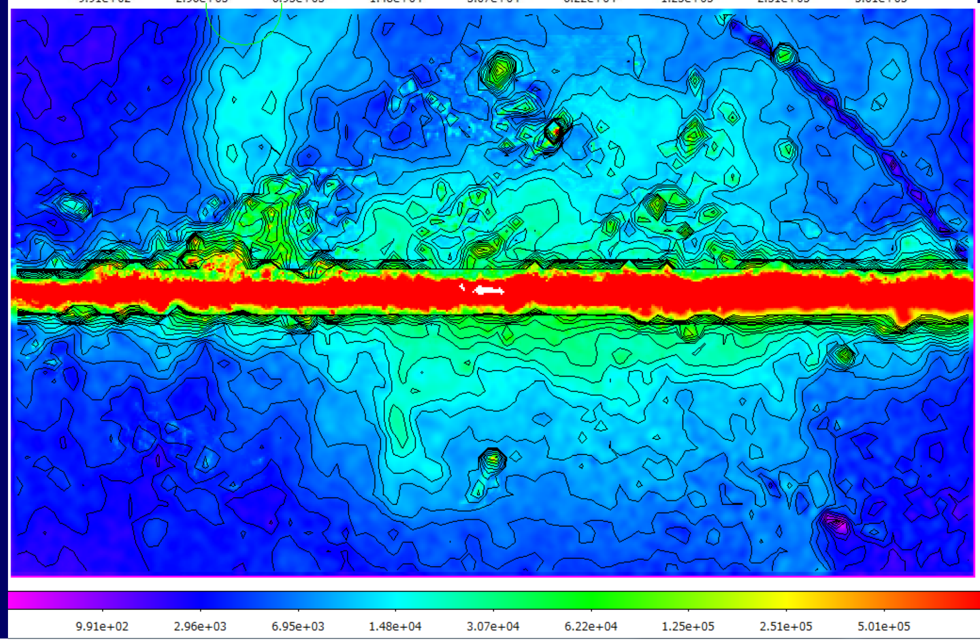
**R5 (0.89 keV)**

**Obs. $I_{R5}$**




$$I_{R5}^{0} = I_{R5}/e^{-N/N_{R5}}$$

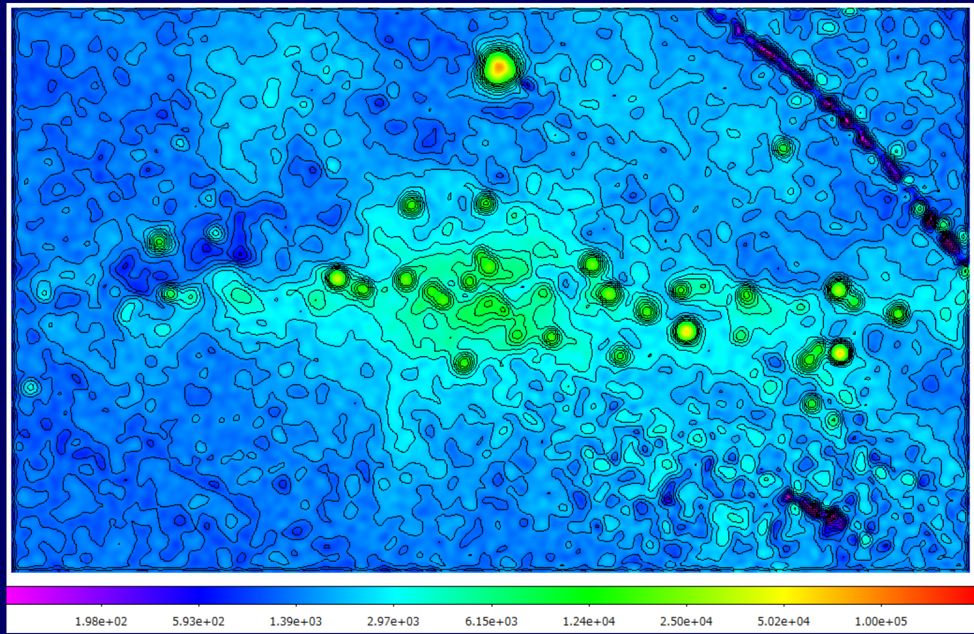
$(N_{R5}=2.7\times 10^{21}\ \mathrm{H\ cm^{-2}})$



# Extinction corrected NPS

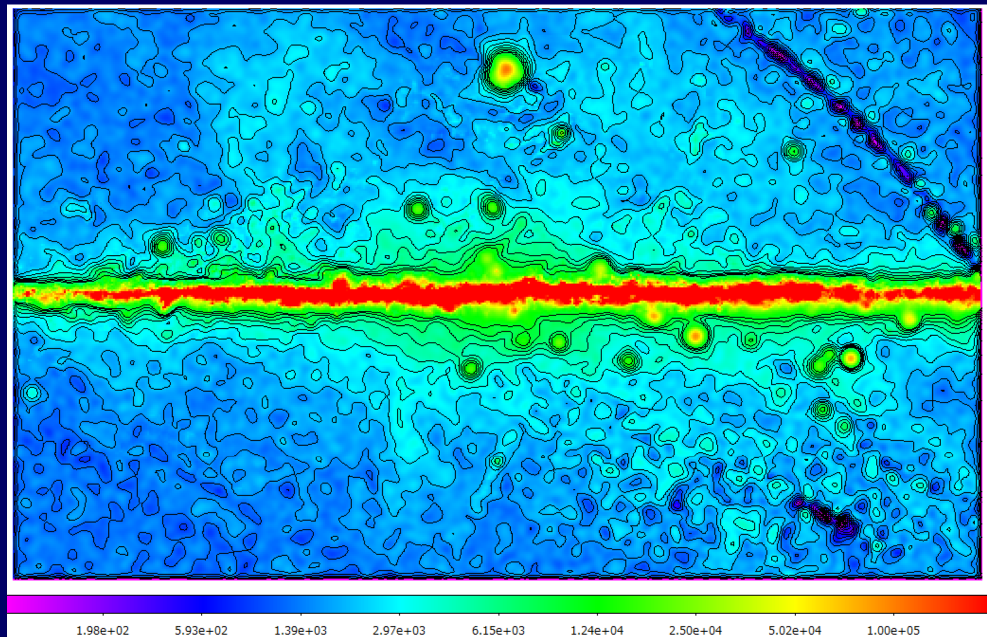
**R7 (1.55 keV)**

**Obs. $I_{R7}$**




$$I_{R7}^{0} = I_{R7}/e^{-N/N_{R7}}$$

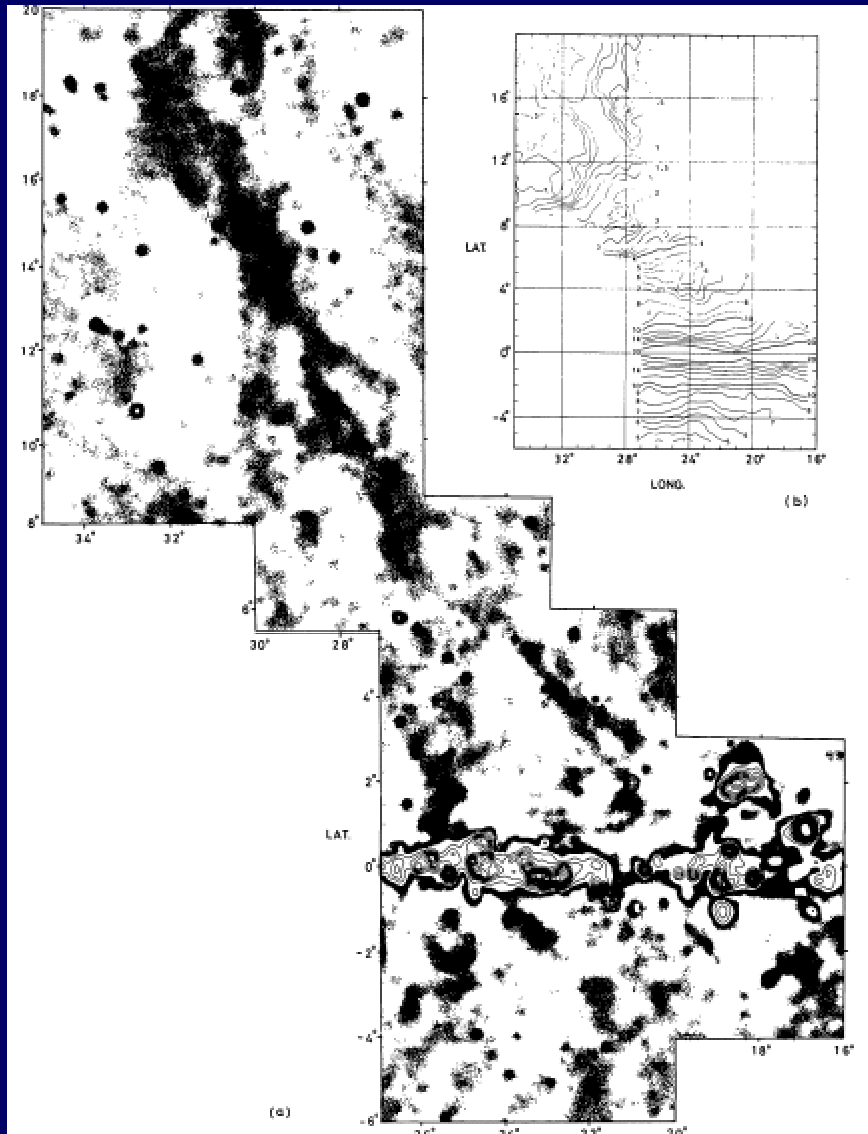
**($N_{R7}$=9.0x $10^{21}$ H $cm^{-2}$)**



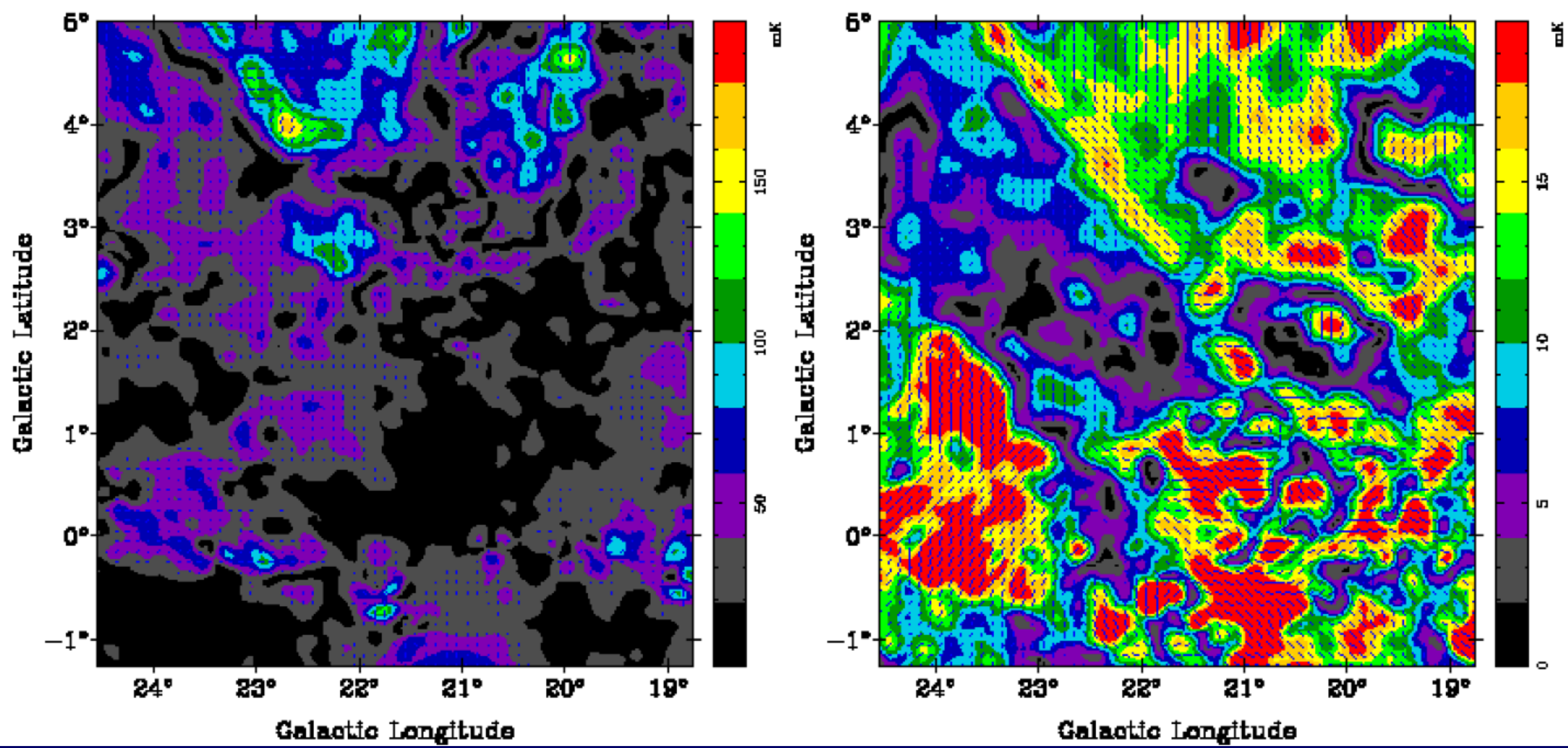
# Other Distances

- Radio polarization
- Optical polarization

# Radio Ridge
# 1420 MHz, Bonn 100m (Sofue et al. 1979)

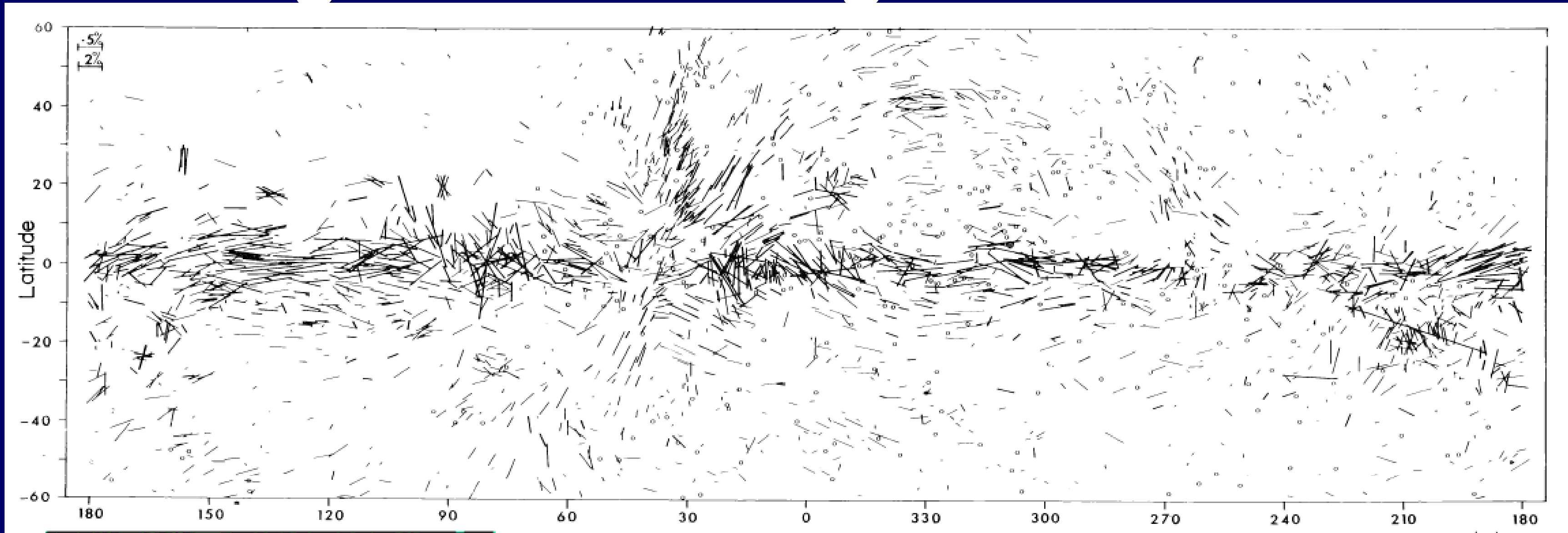


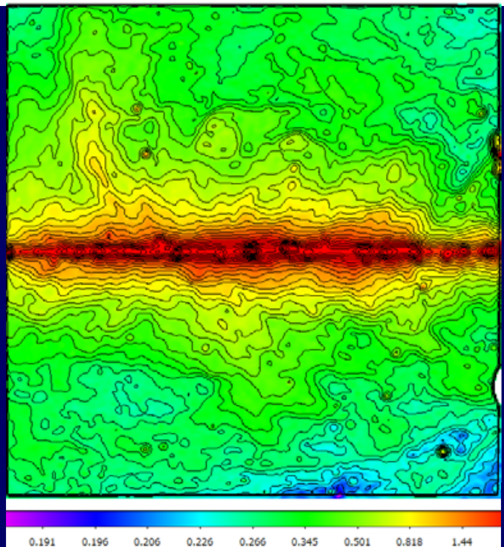
# Small Faraday screening indicates r > 2-3 kpc (Sun et al. 2014)

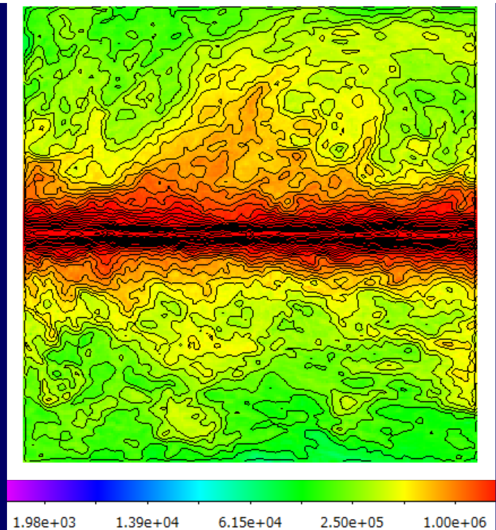


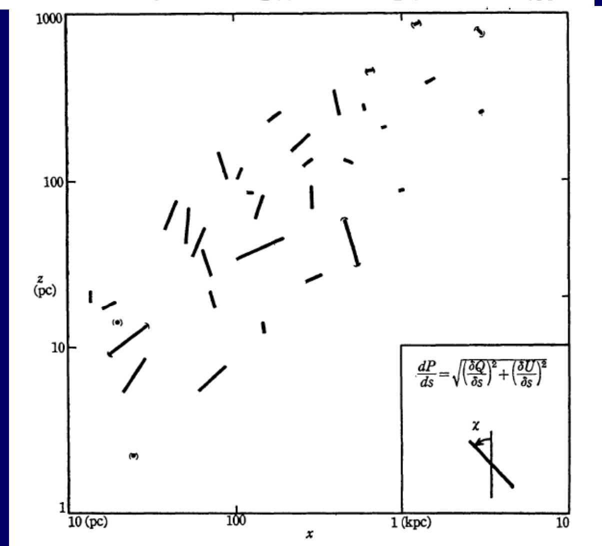

• The low-latitude branch extending from the North Polar Spur is at a distance more than 2–3 kpc. If the branch and the NPS are physically associated, the NPS cannot be local but likely associated with the Galactic bulge, possibly tracing a shock front formed in the Galactic centre.

# Star Pol. Mag. Field (Mathewson 1970)
# // HI Ridge ⊥ Radio Mag.Field




**Radio 2.3 GHz (Jonas)** **HI (Kalbera)** **Diff. Pol. (Sofue)**

# 3. GC Explosion Model

- Sofue 1977

# • Fast MHD (compression) wave

$$\frac{dr}{dt} = V\, p_r/p,$$

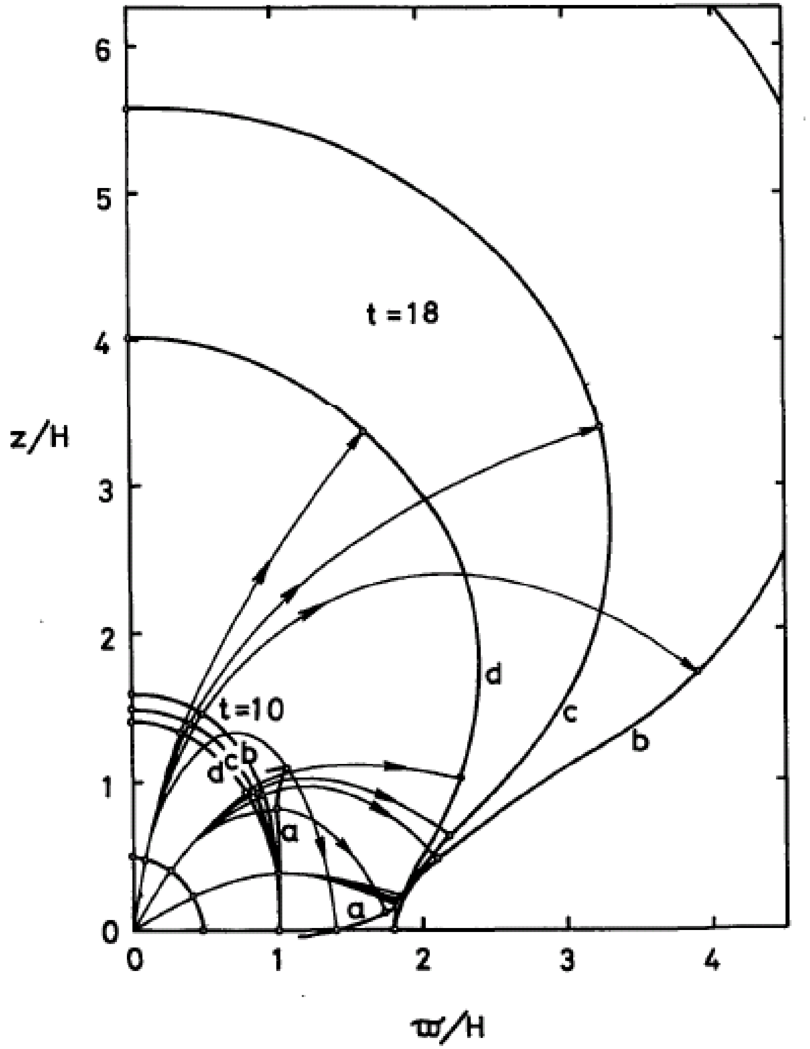
$$\frac{d\theta}{dt} = V\, p_\theta/rp,$$

$$\frac{d\phi}{dt} = V\, p_\phi/rp \sin\theta,$$

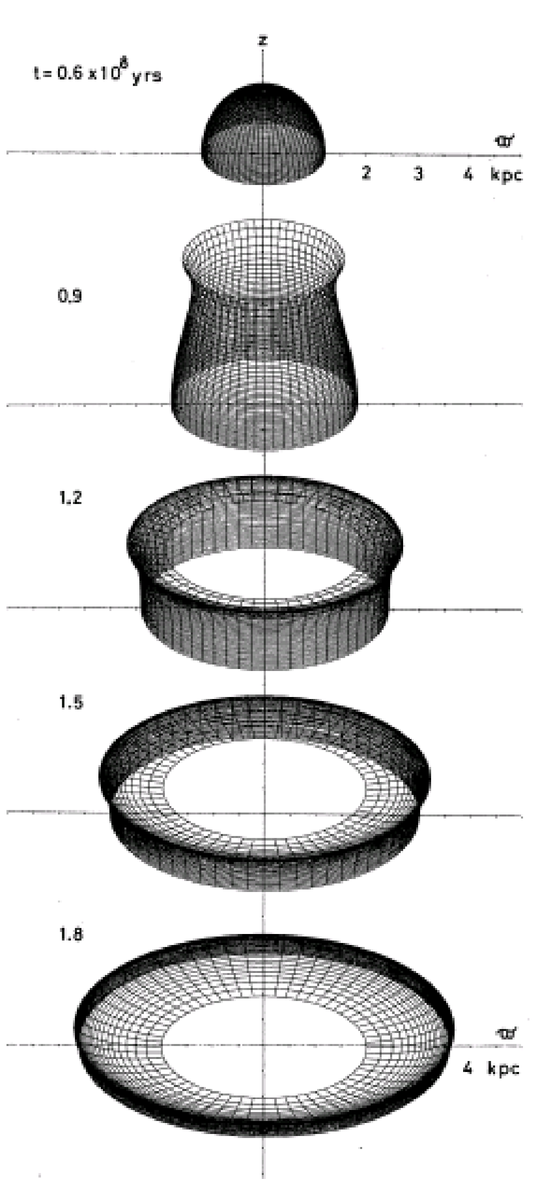
$$\frac{dp_r}{dt} = -p\frac{\partial V}{\partial r} + \frac{V}{rp}(p_\theta^2 + p_\phi{}^2),$$

$$\frac{dp_\theta}{dt} = -\frac{p}{r}\frac{\partial V}{\partial \theta} - \frac{V}{rp}(p_\theta p_r - p_\phi{}^2 \cot\theta),$$

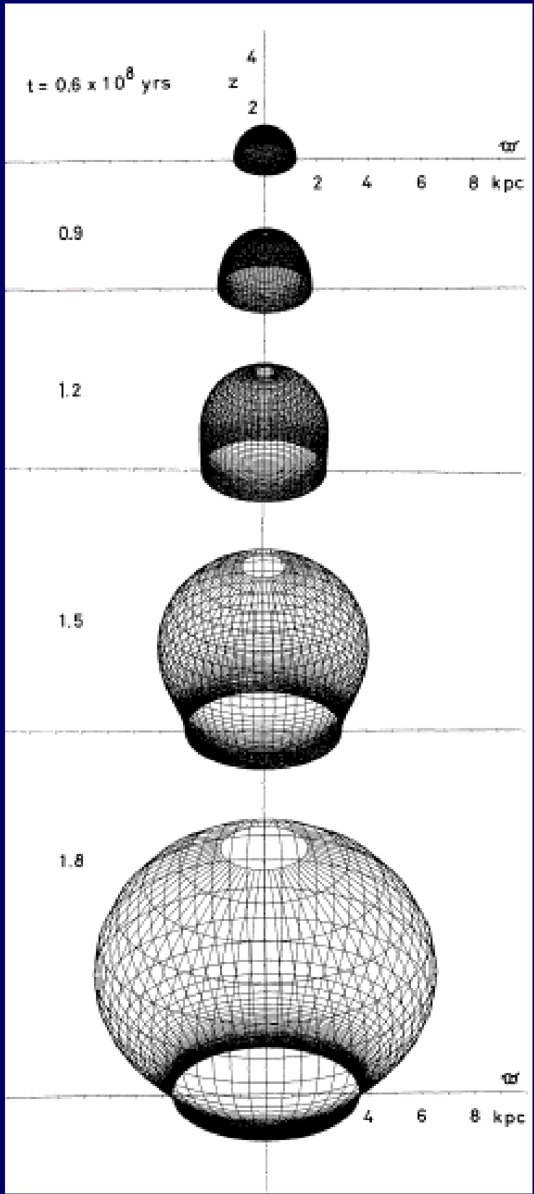
$$\frac{dp_\phi}{dt} = -\frac{p}{\sin\theta}\frac{\partial V}{\partial \phi} - \frac{V}{rp}(p_\phi p_r + p_\phi p_\theta \cot\theta),$$



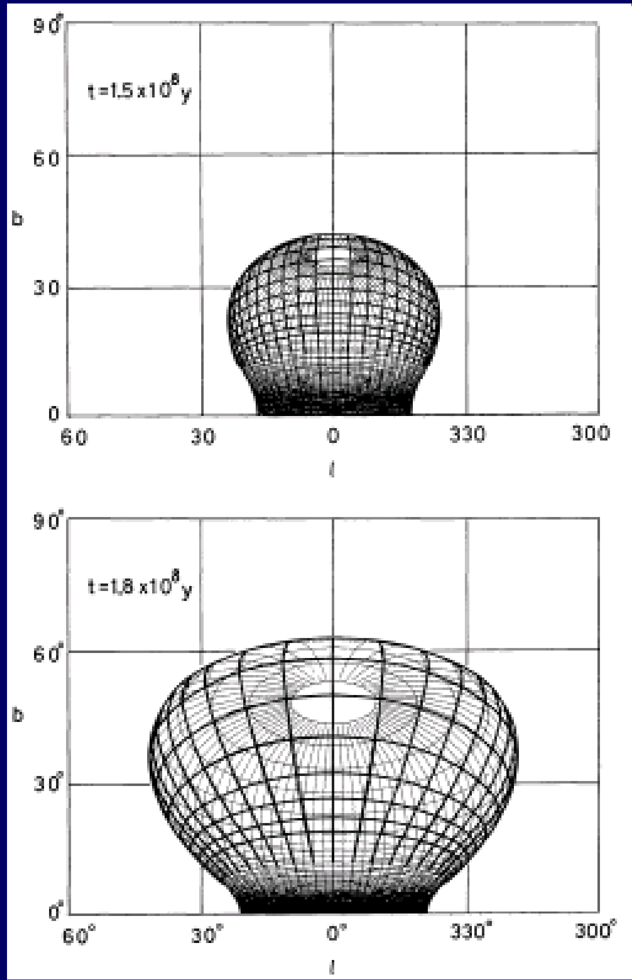
## •Sofue 1977



z
t= 0.6 x10^8 yrs
2 3 4 kpc
0.9
1.2
1.5
1.8
4 kpc

t = 0.6 x 10^8 yrs
z
4
2
2 4 6 8 kpc
0.9
1.2
1.5
1.8
4 6 8 kpc

t =1.5 x10^8 y
90°
60
30
0
b
60 30 0 330 300
l
t =1.8 x10^8 y
90°
60°
30°
0°
b
60° 30° 0° 330° 300°
l

# Radial adiabatic Shock

**Sakashita-Moellenhoff method (Generalized Sedof)**

$$E = \int_0^R \frac{P}{\gamma - 1} 4\pi r^2 dr + \int_0^R \frac{1}{2} \left( \frac{\partial r}{\partial t} \right)^2 \rho_0 4\pi r_0^2 dr_0 .$$

$$E = \frac{1}{3(\gamma+1)^2} \left( \frac{4(2\gamma - 1)}{(\gamma - 1)} JR\ddot{R} + \left\{ \left[ 2IR + \frac{8\gamma}{(\gamma+1)} + 3 \right] J + \frac{2M(\gamma+1)}{(\gamma-1)} \right\} \dot{R}^2 \right).$$

Here,

$$I = \left( \frac{4\pi}{r_0} \frac{d\rho_0}{dr_0} \right)_R ,$$

$$J = \int_0^R \rho_0 4\pi r_0^2 dr_0 ,$$

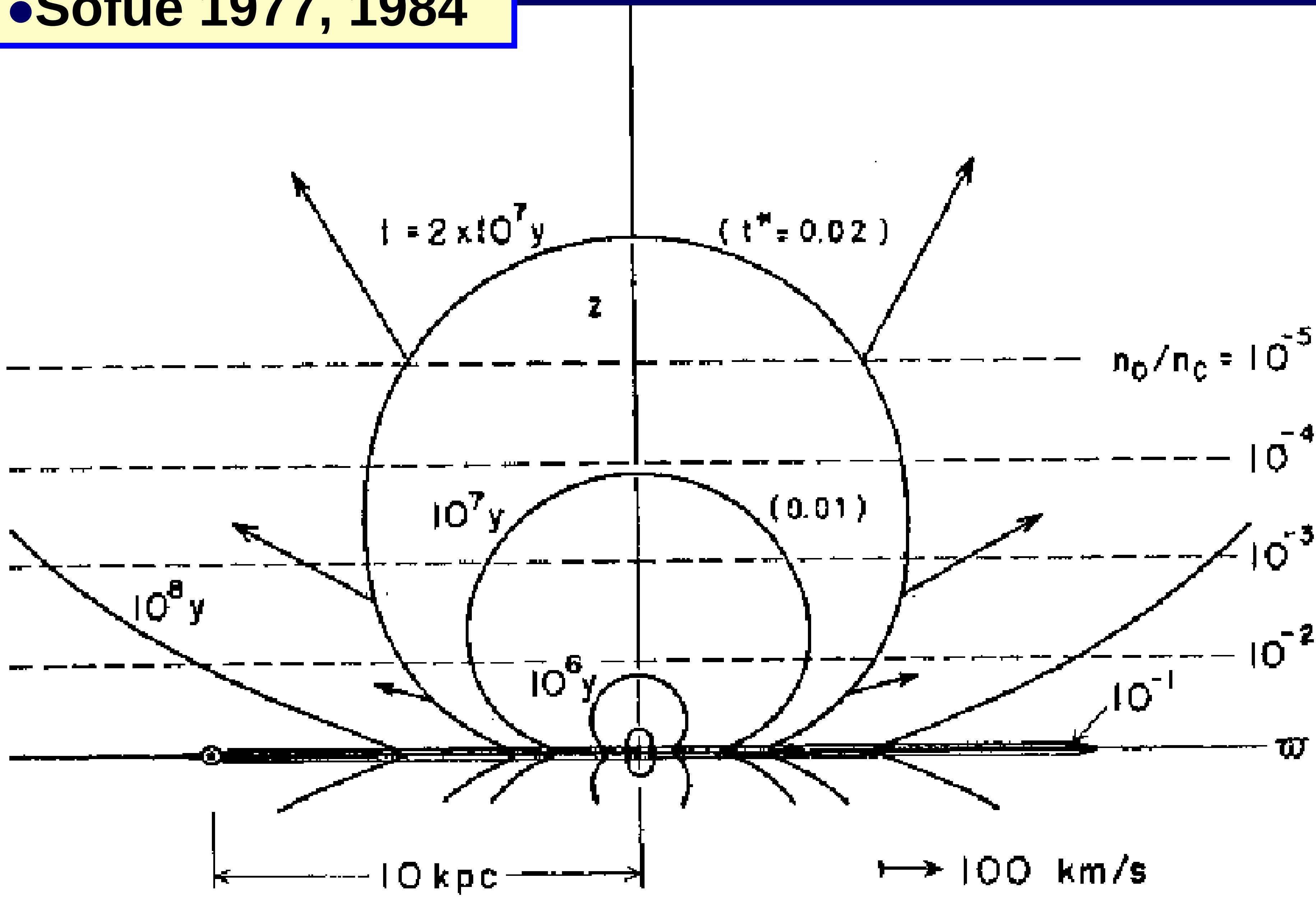
and

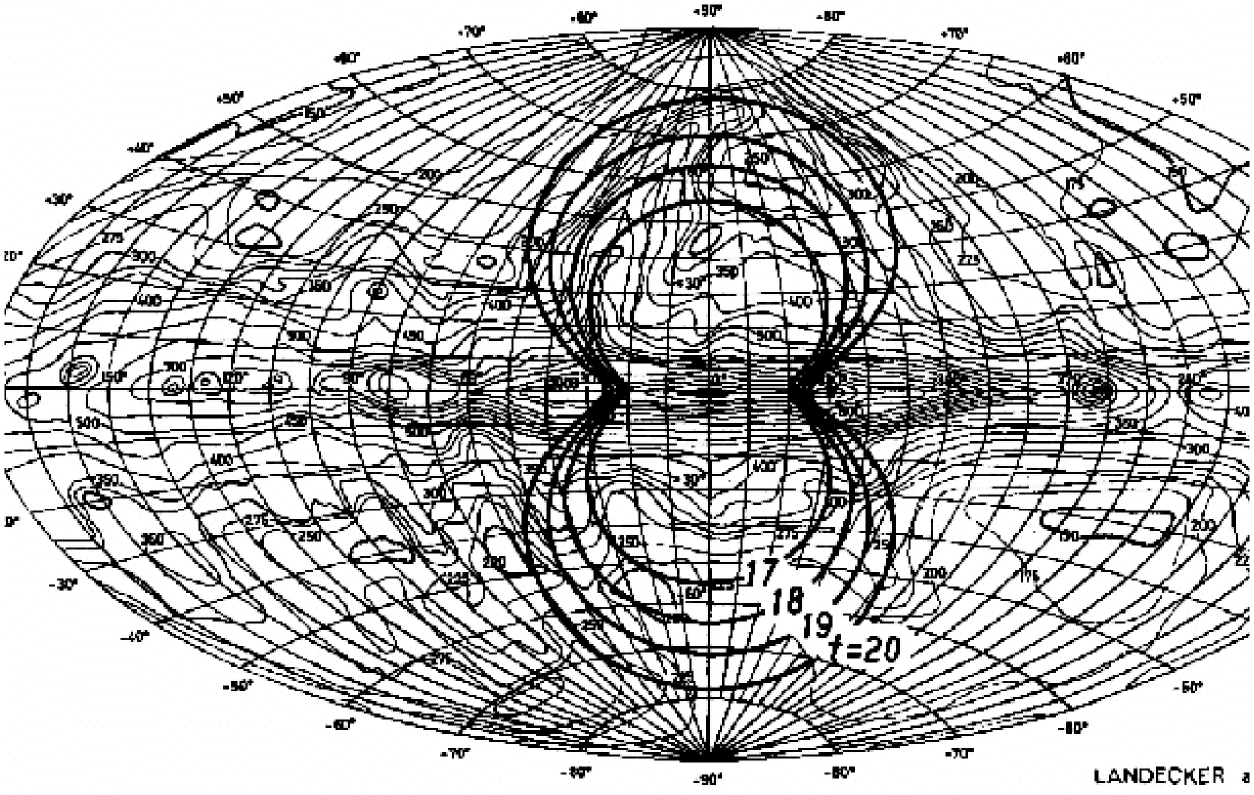
$$M = \rho_0 \frac{4\pi}{3} R^3 .$$

$$\rho_0 = \rho_1 \exp(-z/z_1) + \rho_2 \exp(-z/z_2) + \rho_3 .$$

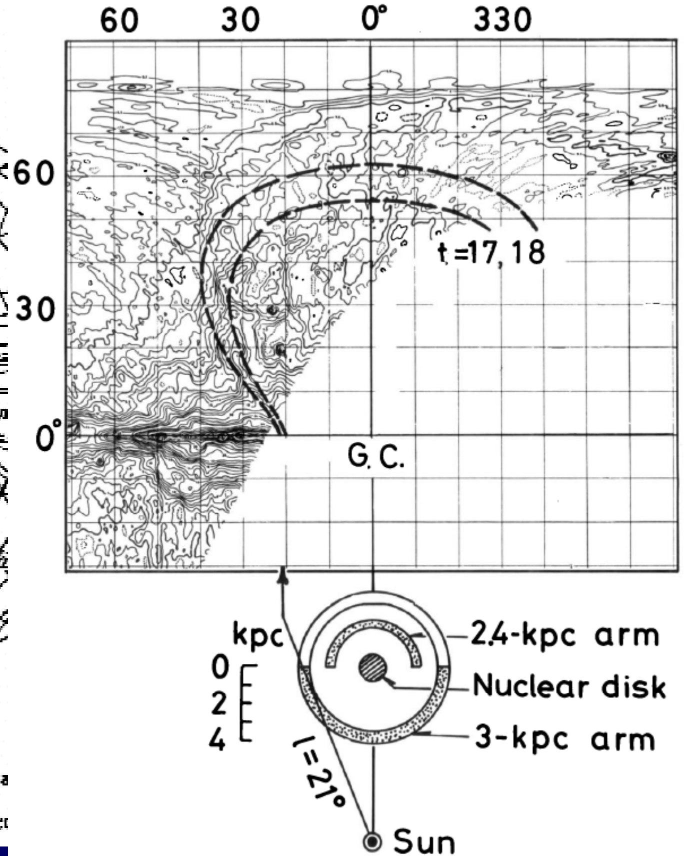
# Bipolar Hyper Shell Model

- Sofue 1977, 1984



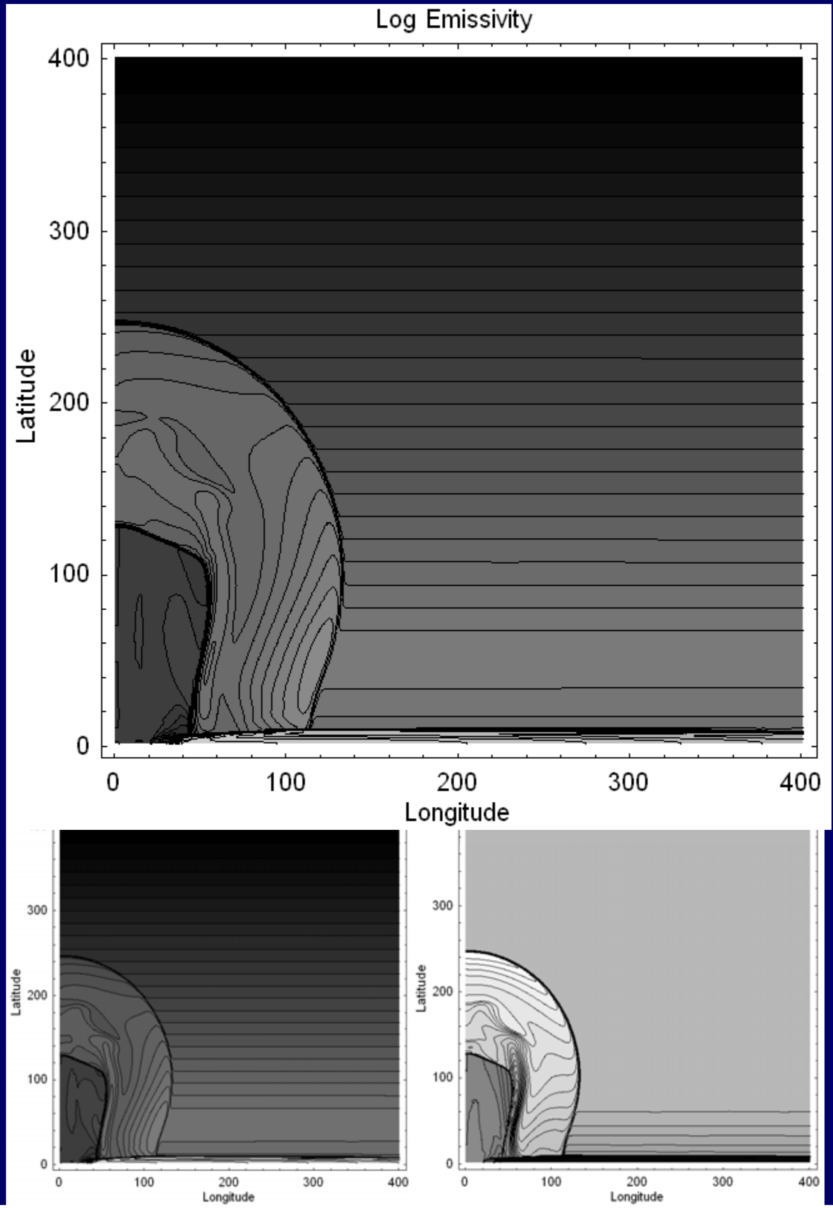


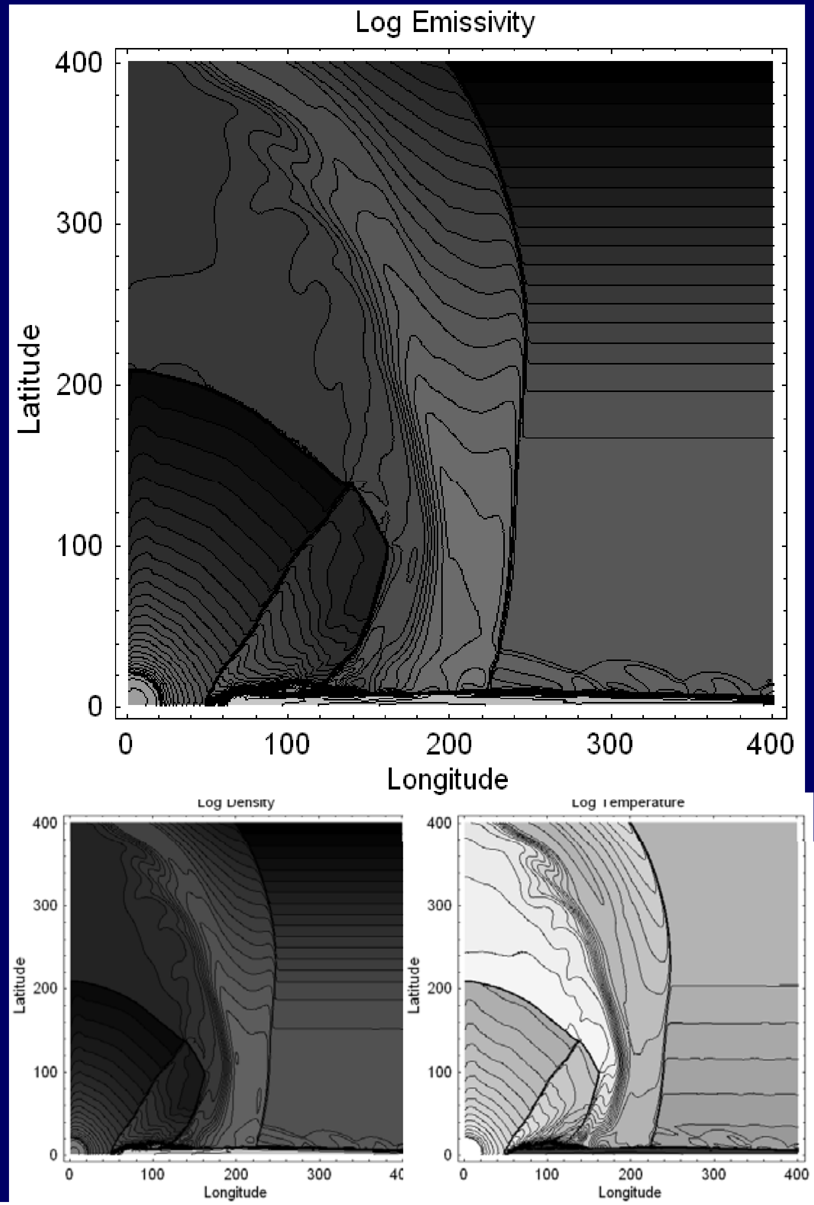

. 8. The same as Figure 7, but for the front at $t = 17 - 20.10^7$ years superposed on the 150 MHz map by Landec




- Sofue 1977

# Numerical Hydrodynamics:
# Sofue & Habe 2013 (in prepa)



$E \sim 10^{55\text{-}56}$ ergs($10^{4-5}$ SN)

$t \sim 10^{6\text{-}7}$ yr

$E \sim 1/2\ Mv^2 \sim 4\pi/3\ \rho r^3 v^2$

$\rho \sim 10^{-3}$ H/cc (Halo)

$r \sim 5$ kpc, $M \sim 10^7 M_\odot$

$v \sim 200\text{-}300$ km/s

$T \sim 10^7$ K $\rightarrow$ Soft X rays

# 4. Simulation of Observed NPS Features

# Radio synchrotron

**Radio emissivity**

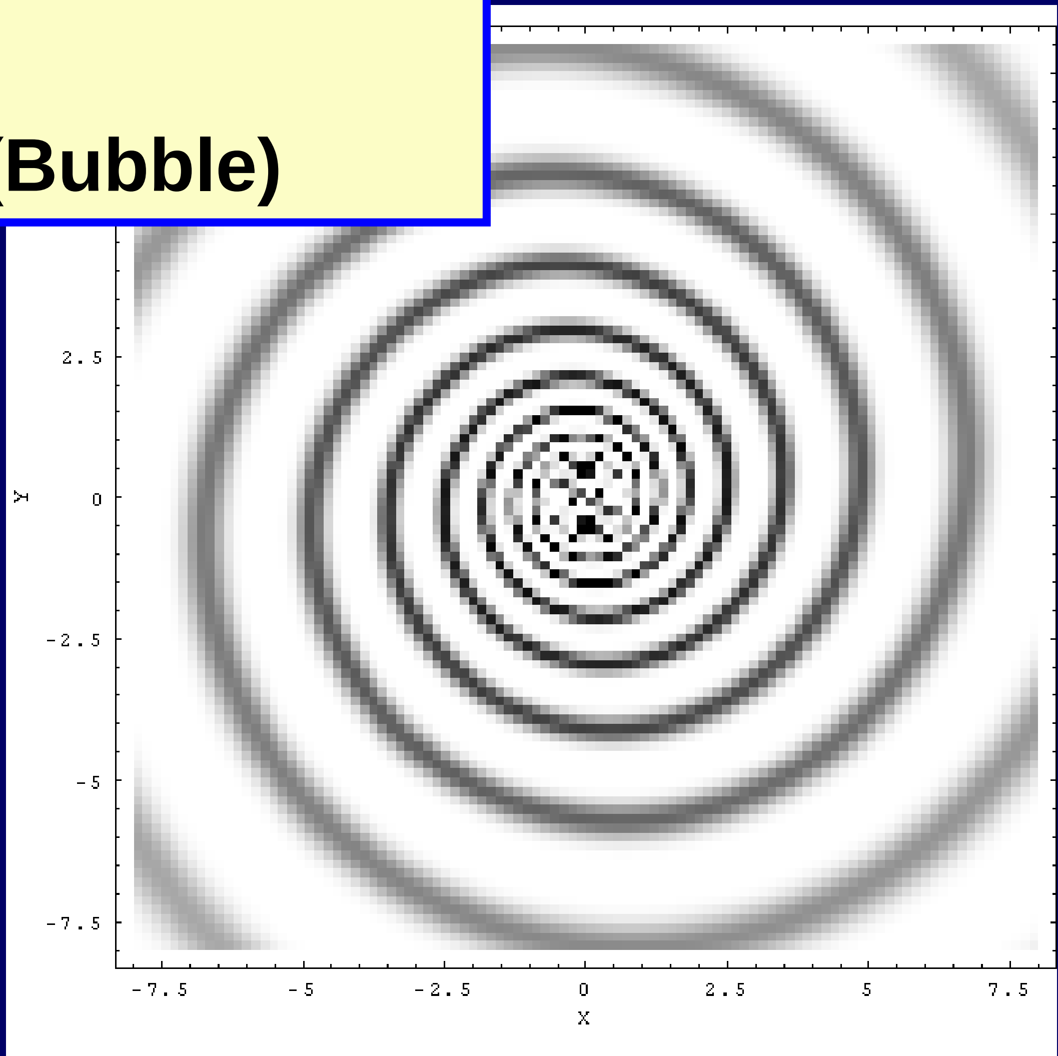
**B-CR equipartition**

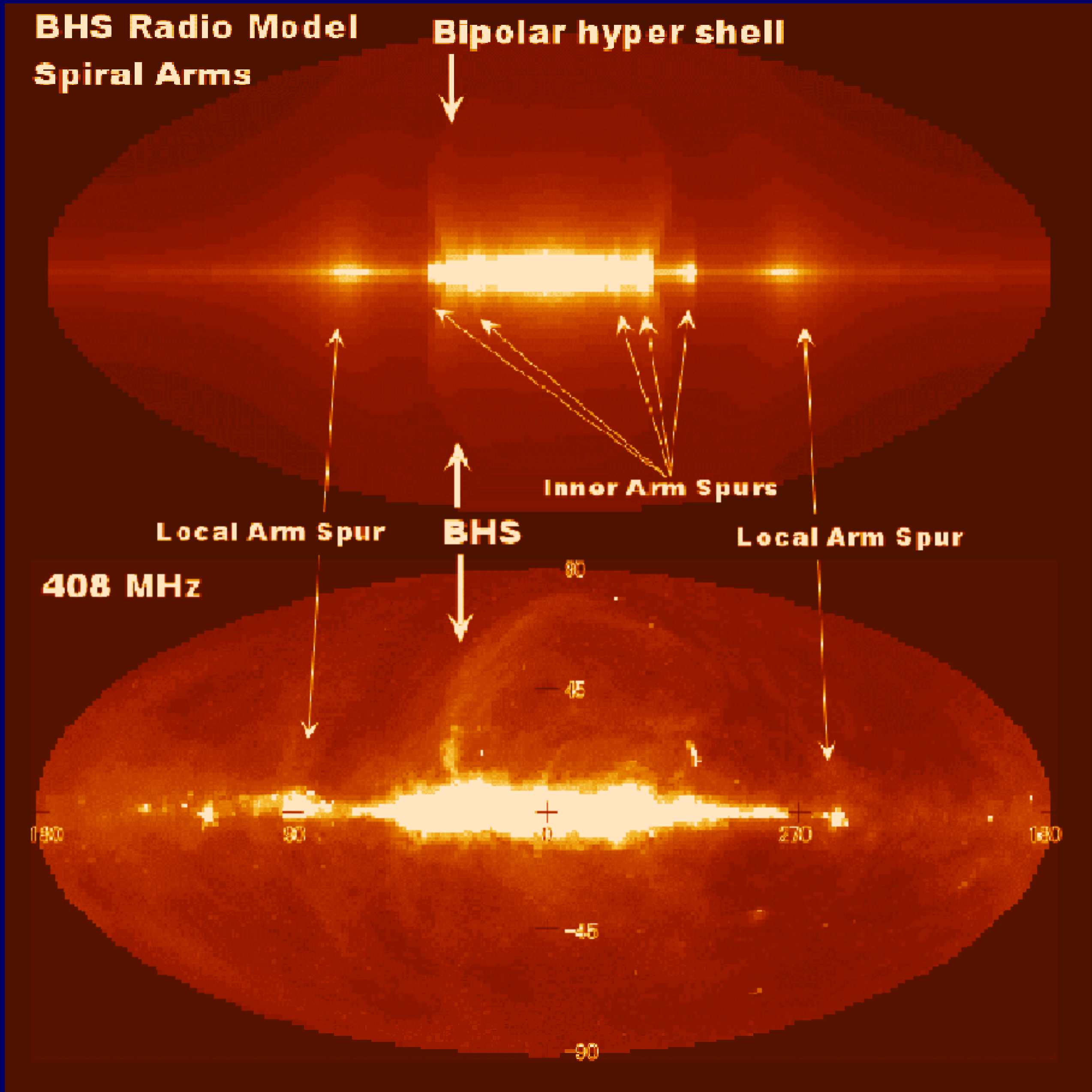
$\varepsilon \propto B^{\gamma} \propto \rho^{\alpha}$

**Radio + X-Ray Emission and Absorption**

**By Disk + Arms**

**+ GC Hyper Shell (Bubble)**






Hz Radio

- Haslam et al 1982

# X-rays @ E=0.2 ～1.5 keV

**Emissivity**

$$\varepsilon \propto \rho^2 T^{0.5}$$

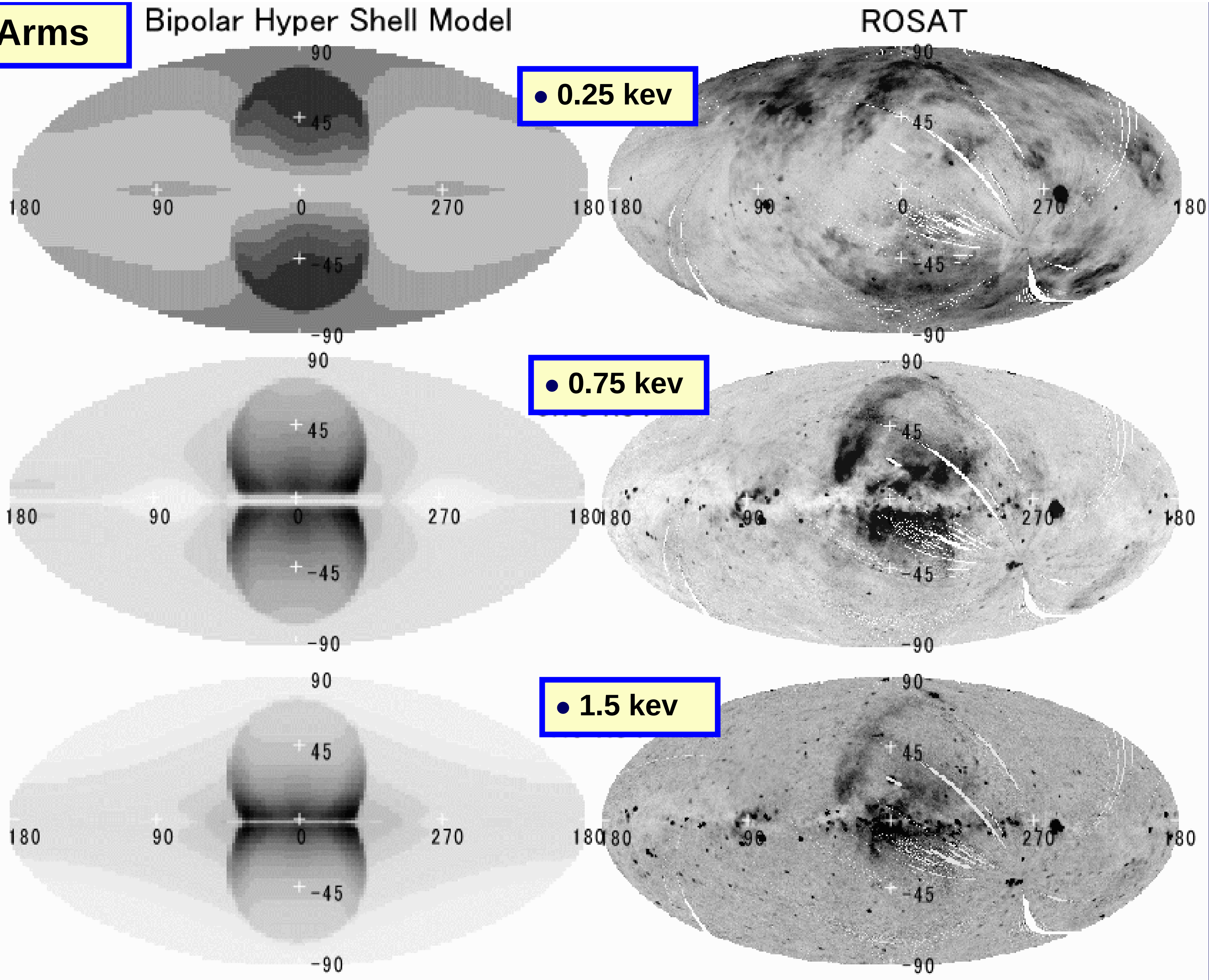
**Transfer:**

**Absorption by metals in HI Disk**

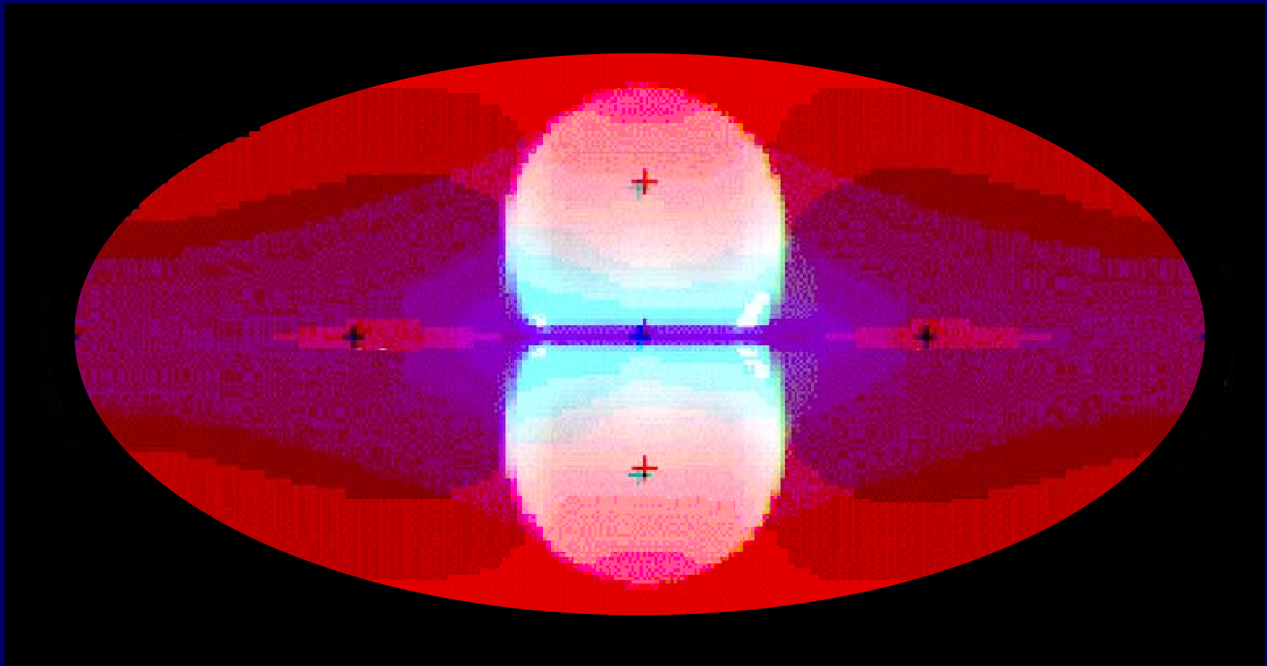
$$dI/ds = \varepsilon - \kappa I$$

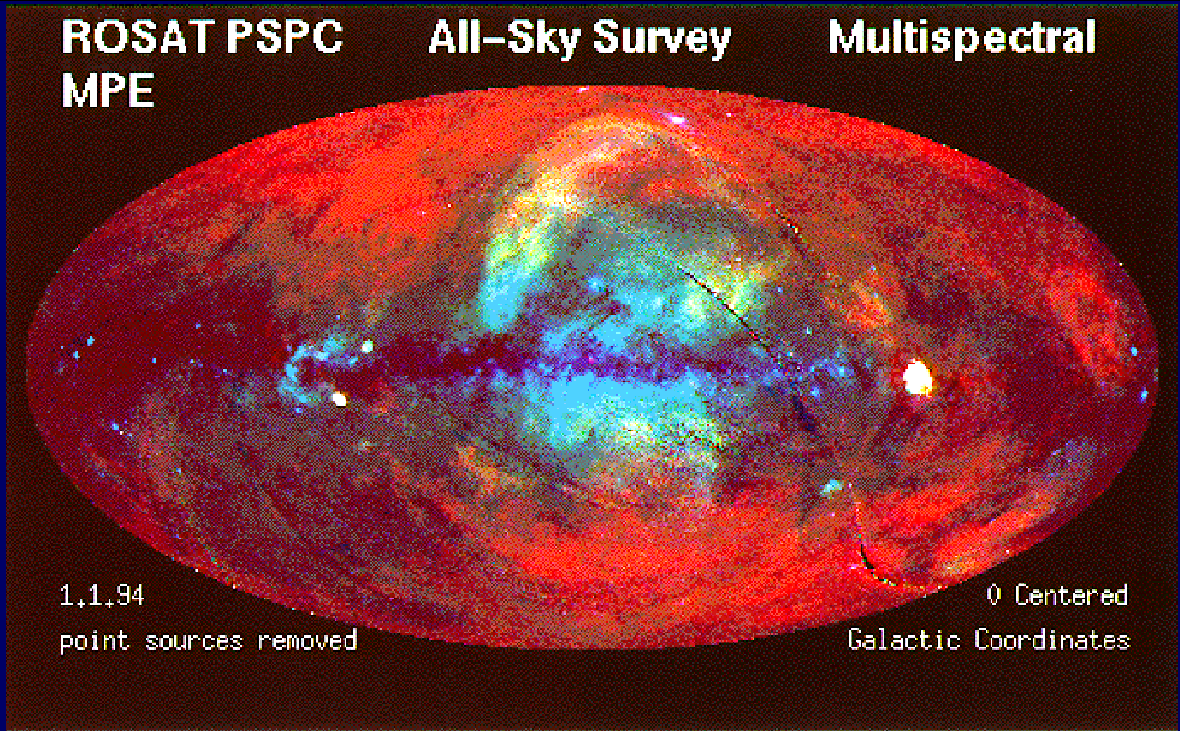
$$\kappa ds = d\tau = n_H ds / N_{H,0}$$

## • Arms

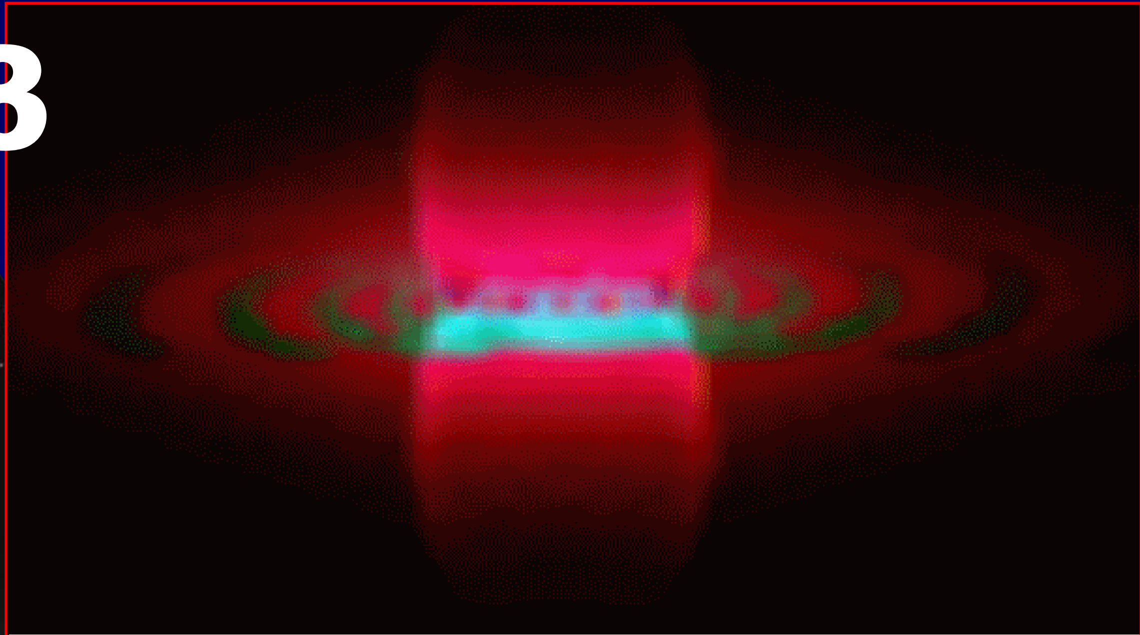


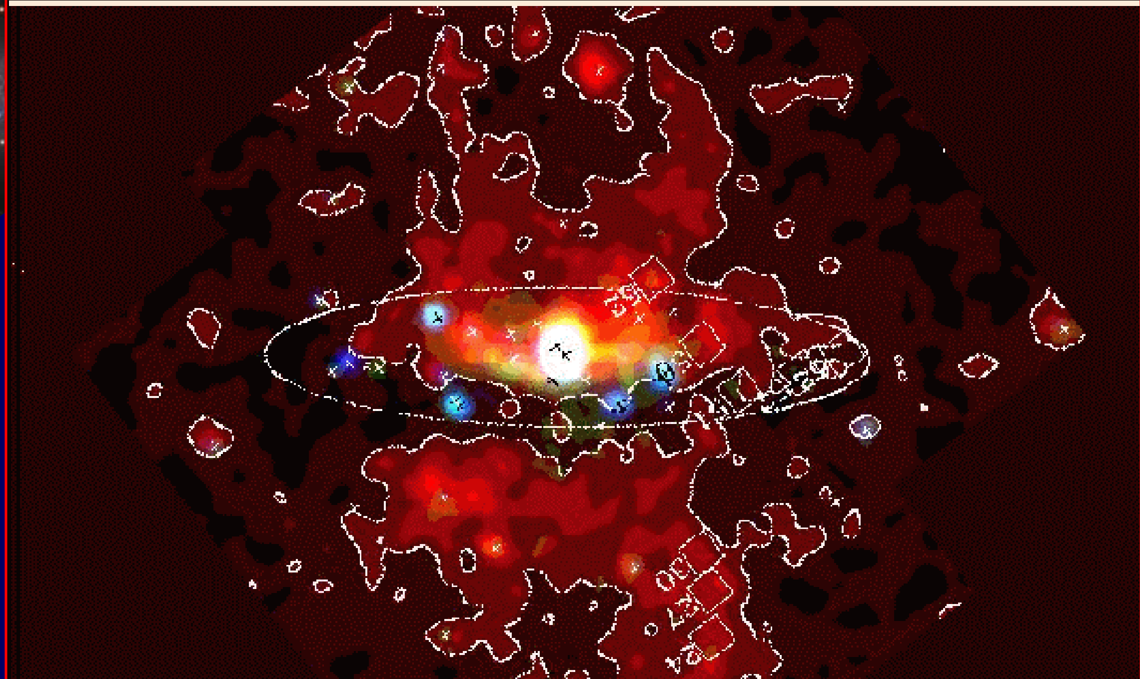
Bipolar Hyper Shell Model
ROSAT
• 0.25 kev
• 0.75 kev
• 1.5 kev
90
45
0
-45
-90
180
90
270
180




ROSAT PSPC
MPE
All–Sky Survey
Multispectral
1.1.94
point sources removed
0 Centered
Galactic Coordinates

# NGC 253





# 5. X vs Gamm

## Fermi Bubble

# Fermi Gamma rays
# 1, 2, 5, 10 GeV



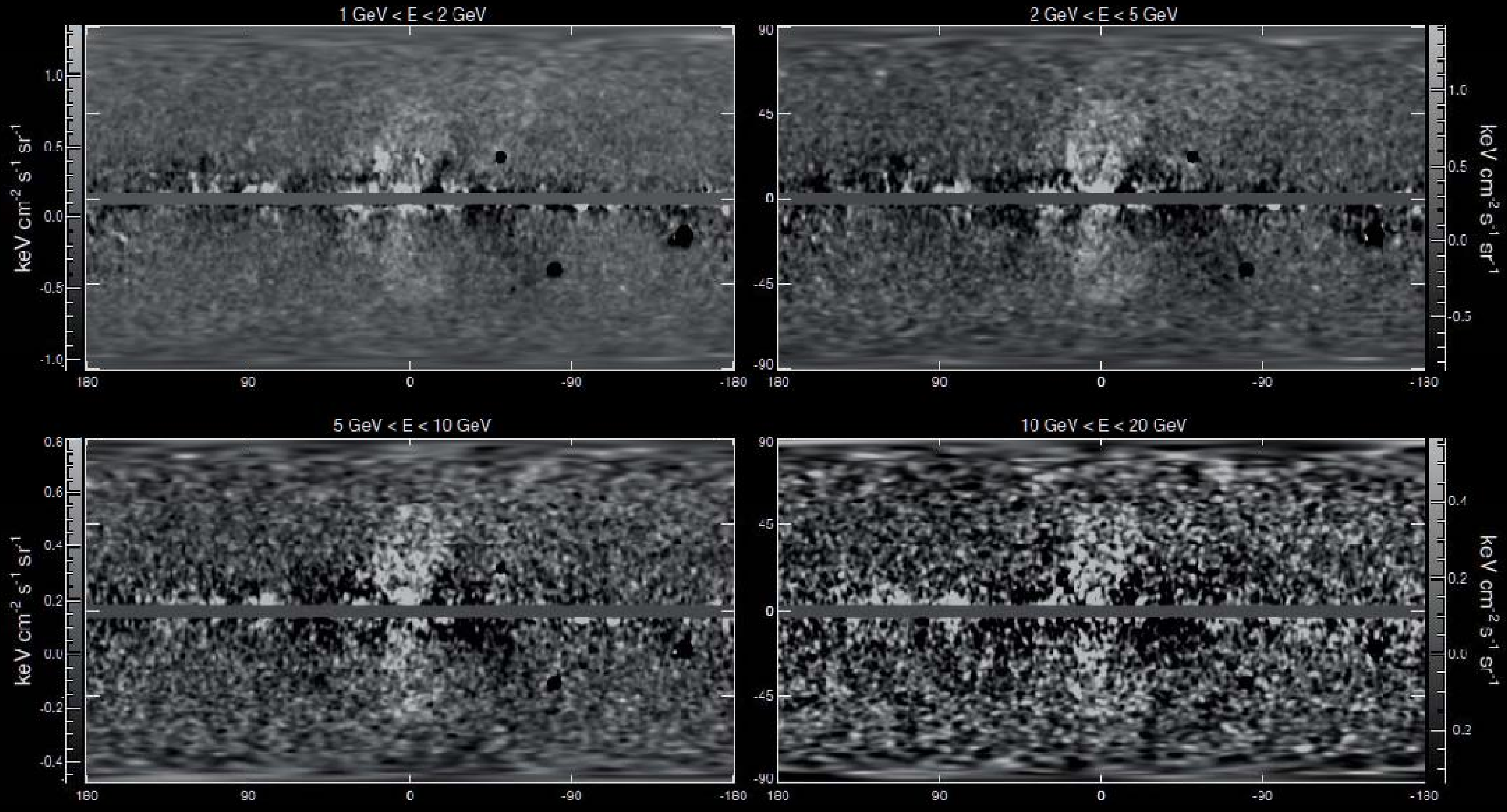
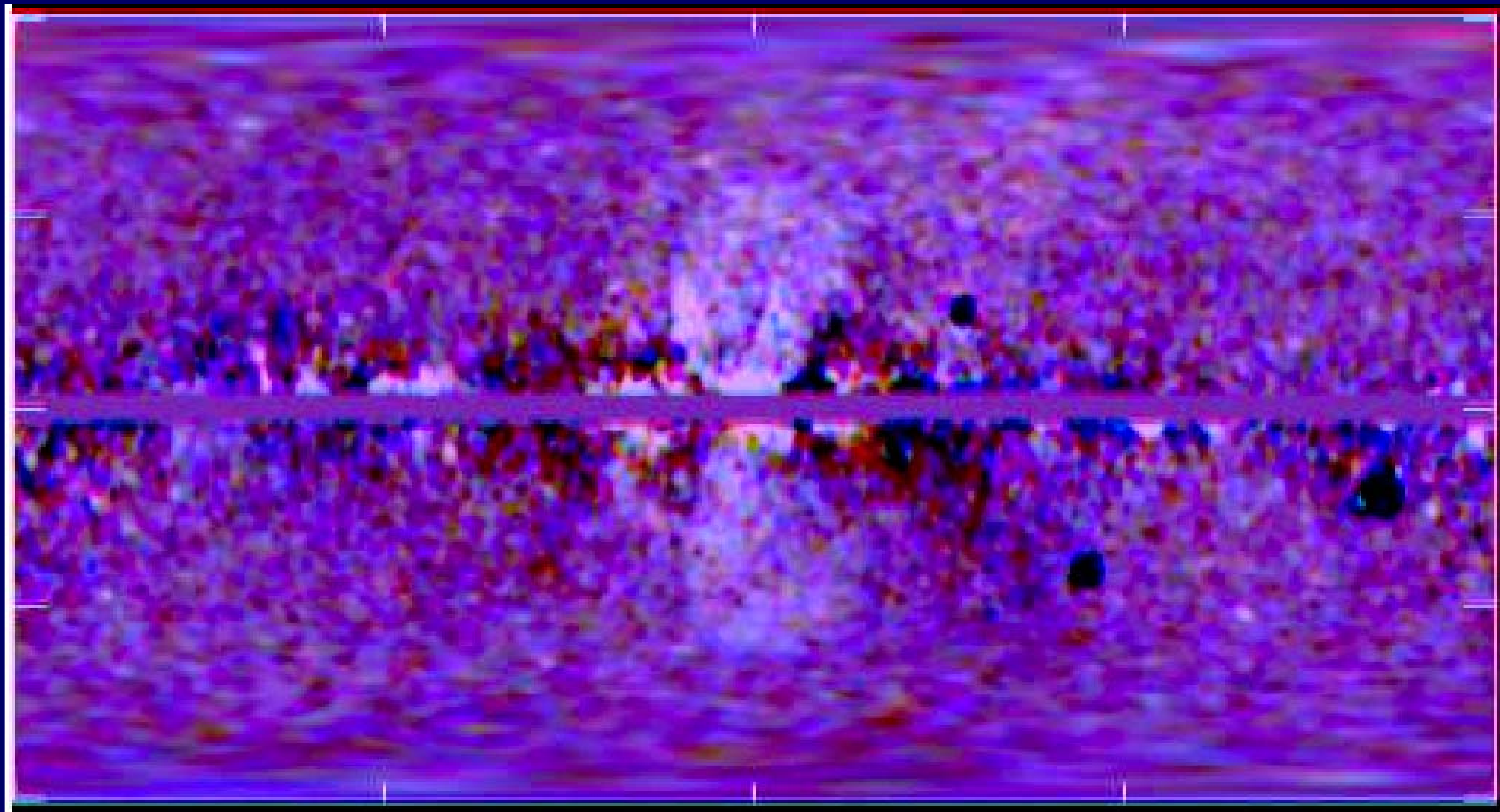
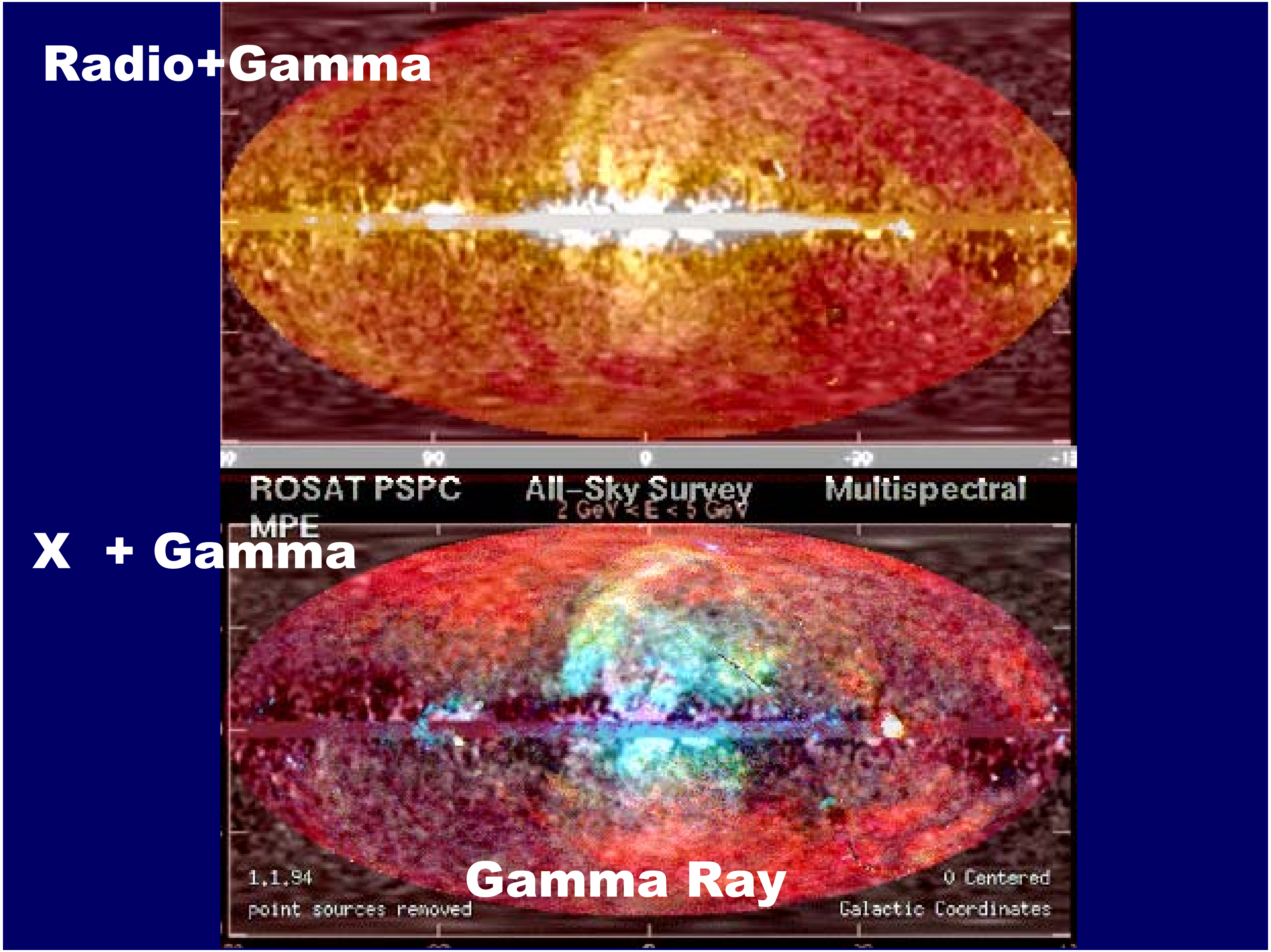


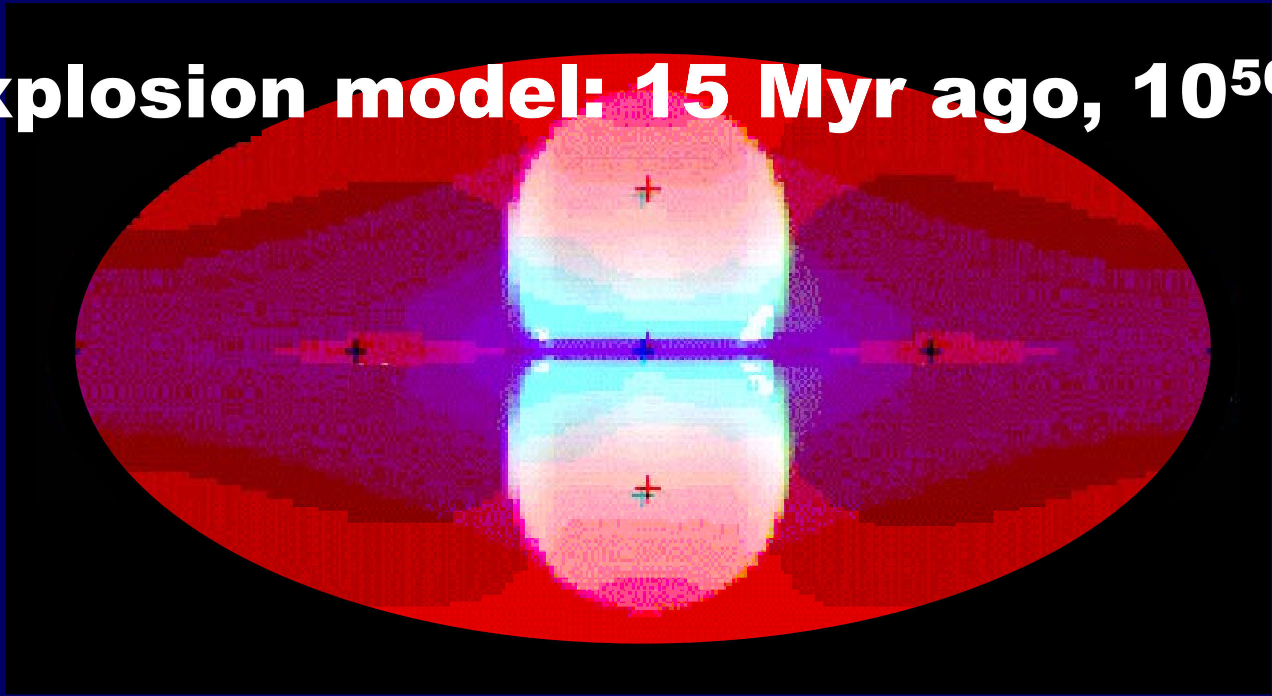

Figure 2. All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in four energy bins (see Section 3.1.1). Two bubble

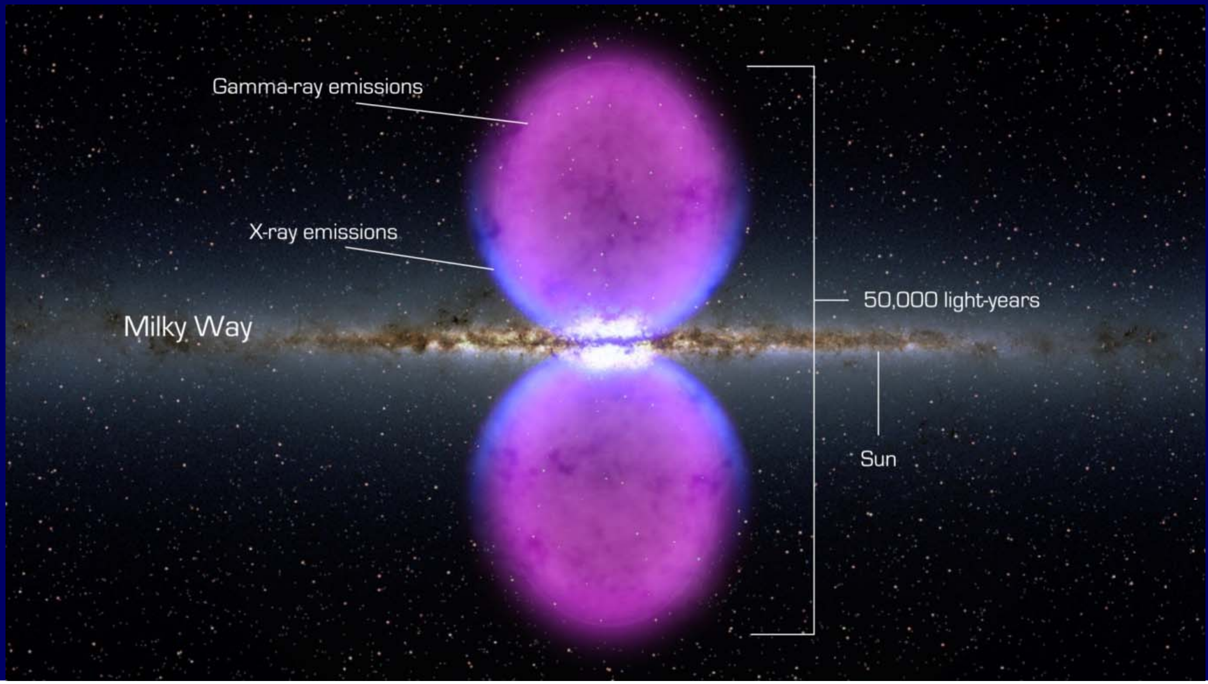


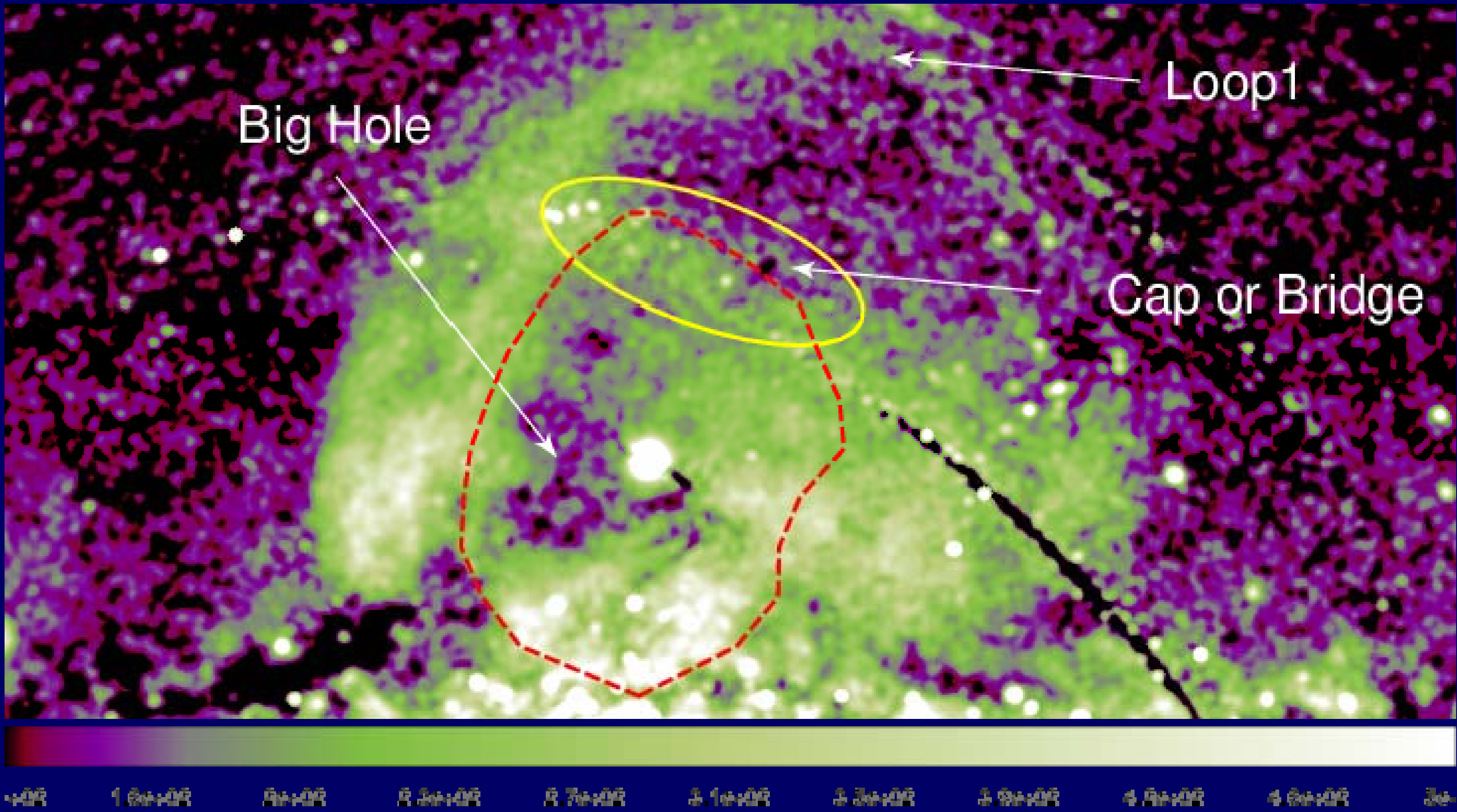


Radio+Gamma
ROSAT PSPC
MPE
All-Sky Survey
2 GeV < E < 5 GeV
Multispectral
X + Gamma
1.1.94
point sources removed
Gamma Ray
0 Centered
Galactic Coordinates

# MW Explosion model: 15 Myr ago, $10^{56}$ ergs








**Kataoka et al. 2013**

# 4. Implications, if NPS=GER

# Galactic Center Explosion (Starburst)?

# If GC Explosion/Starburst,

# t = 15 Myr ago,

# $E = 10^{55\text{-}56}$ ergs.

# Implication

Probing Starburst

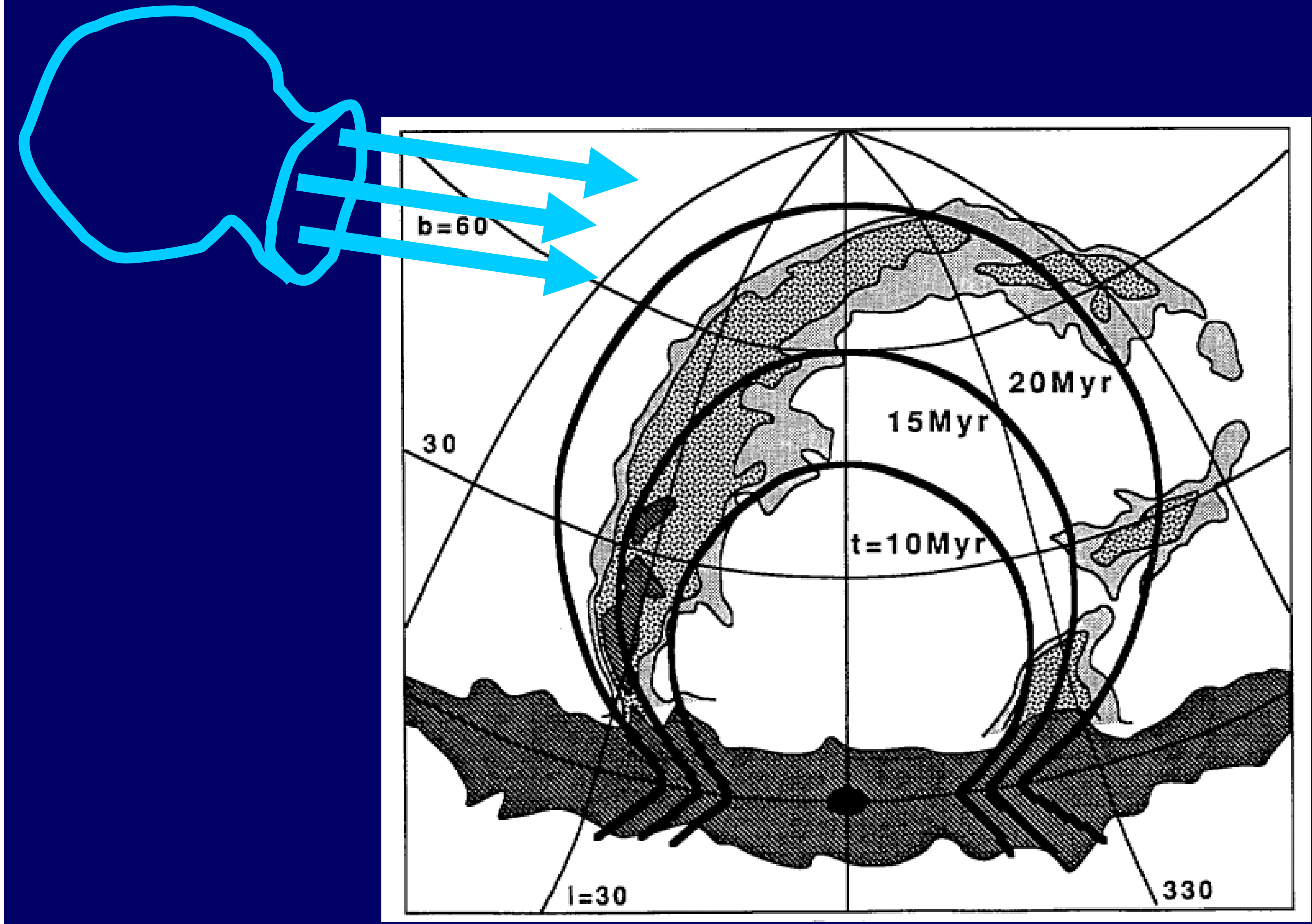
Probing HI disk

Probing Gas Halo

Probing Halo-IG Interface

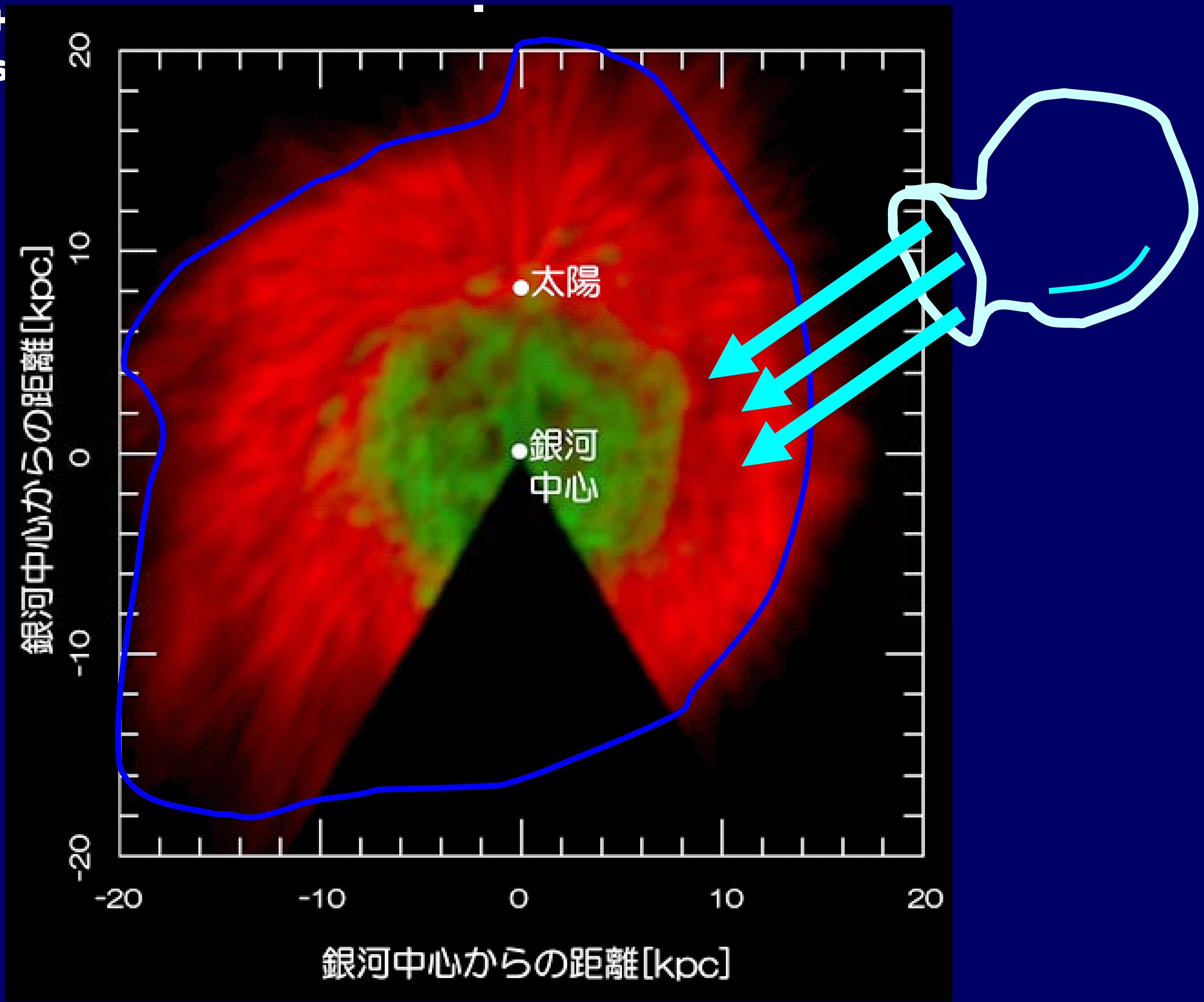
Probing ICM, IGM

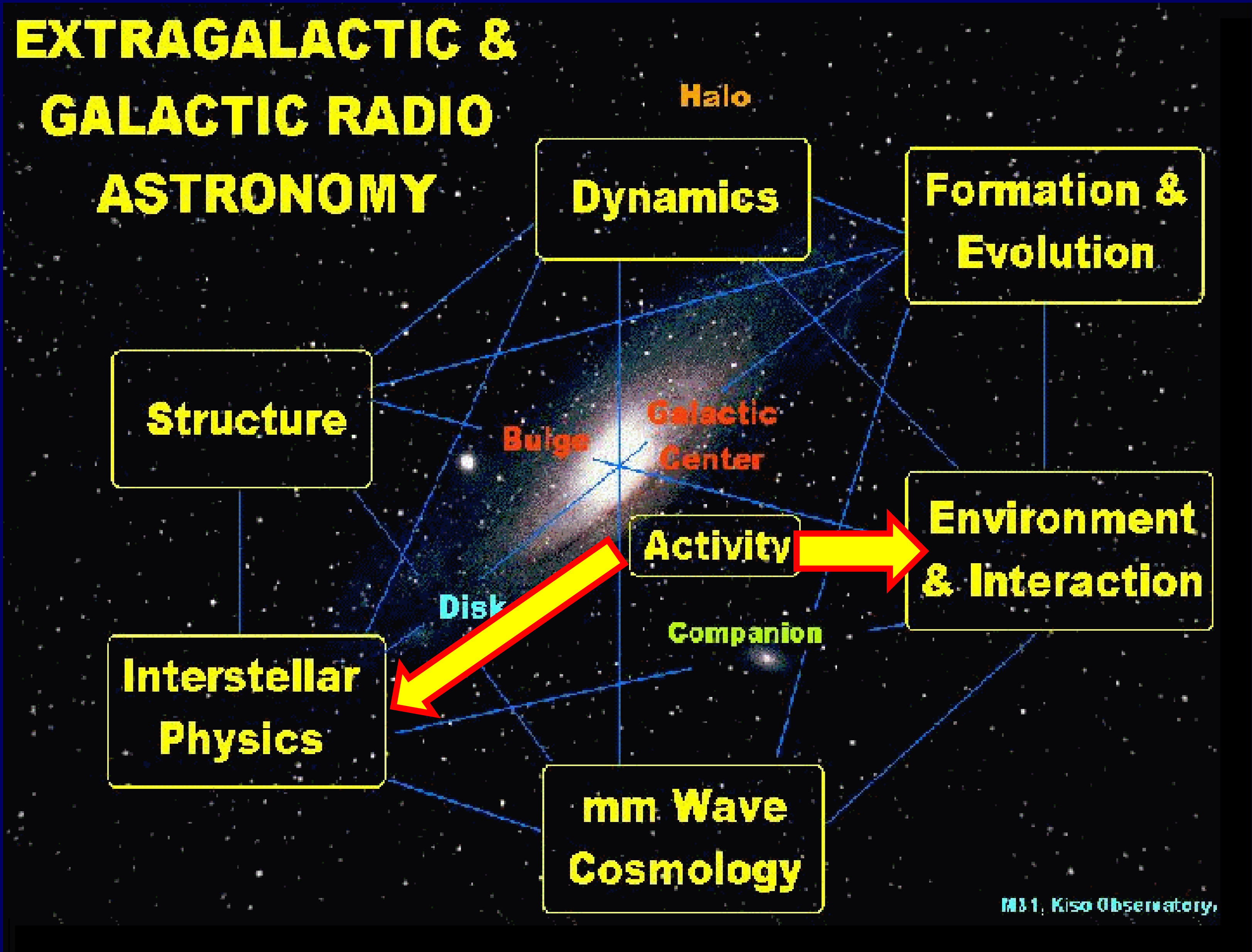
Probing Halo Window



b=60
30
20Myr
15Myr
t=10Myr
l=30
330

HI(red)+
Nakanis
2006




EXTRAGALACTIC &
GALACTIC RADIO
ASTRONOMY
Halo
Dynamics
Formation &
Evolution
Structure
Bulge
Galactic
Center
Activity
Environment
& Interaction
Disk
Companion
Interstellar
Physics
mm Wave
Cosmology
M31, Kiso Observatory