UNIVERSITY OF AMSTERDAM

Master Astronomy and Astrophysics - 5214RAAS6Y




Radio Astronomy

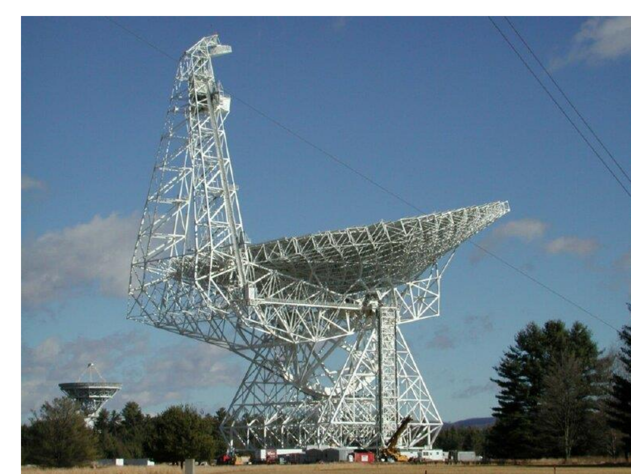
Lecture 3

Science of Radio Astronomy: Galactic and Solar System

Lecturer: Joeri van Leeuwen (leeuwen@astron.nl)

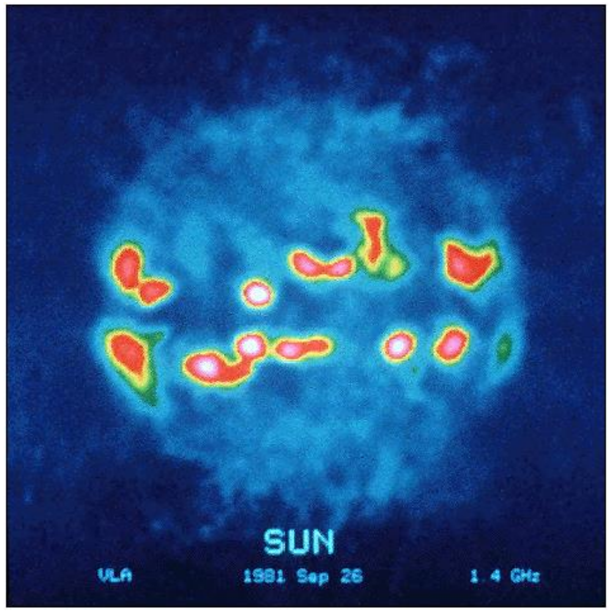
April 8th 2013



Outline

- Solar system: Sun, planets
- Galactic: gas, (proto-)stars, compact objects, exoplanets, seti

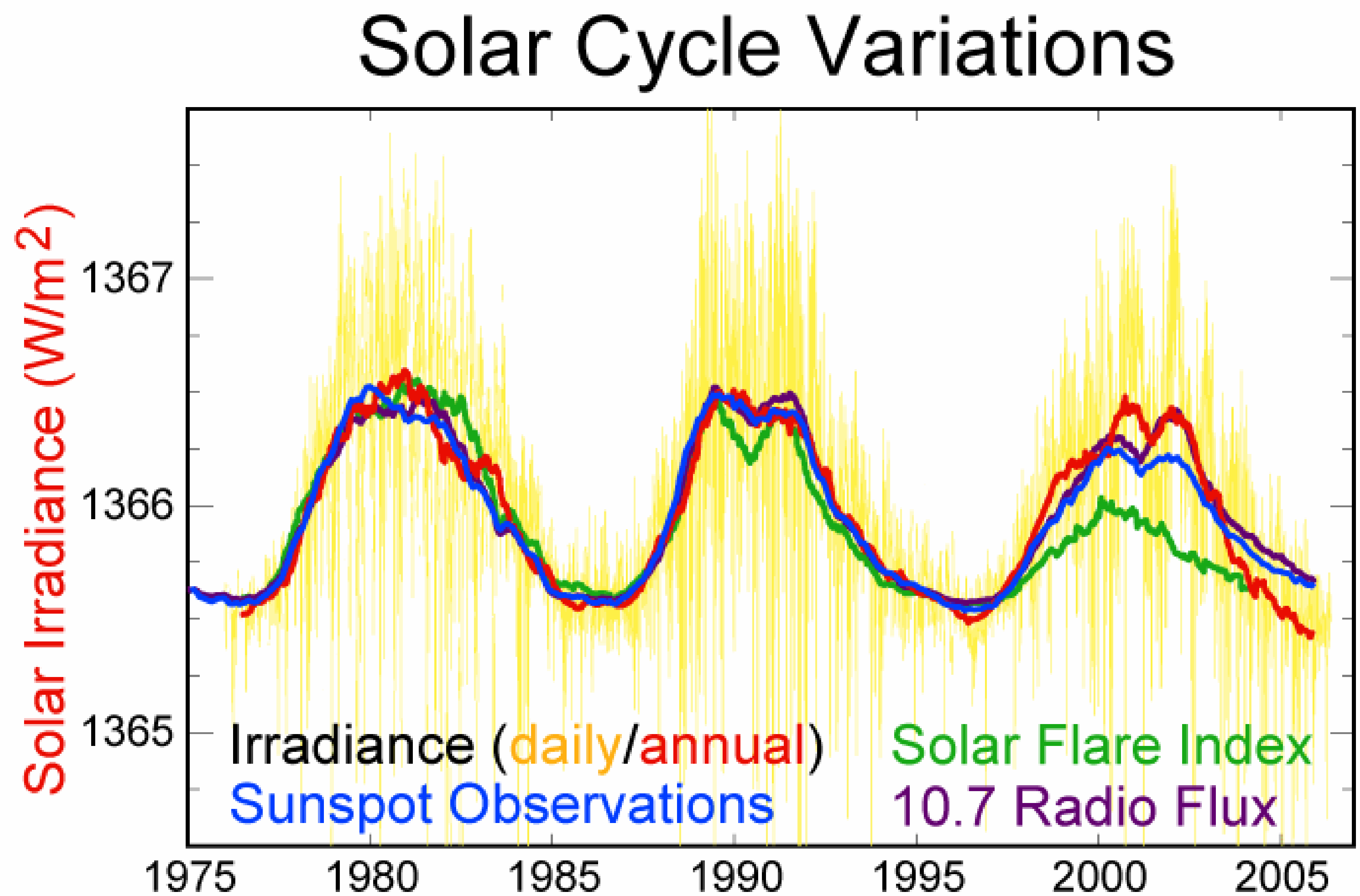


Solar System

- Radio emission can be observed from many bodies in the solar system
- Both the active and quiet sun emit radio waves
- Planets can be observed as thermal sources (black body radiation)
- Magnetic planets have radio emitting radiation belts
- Comets emit 18 cm OH line radiation

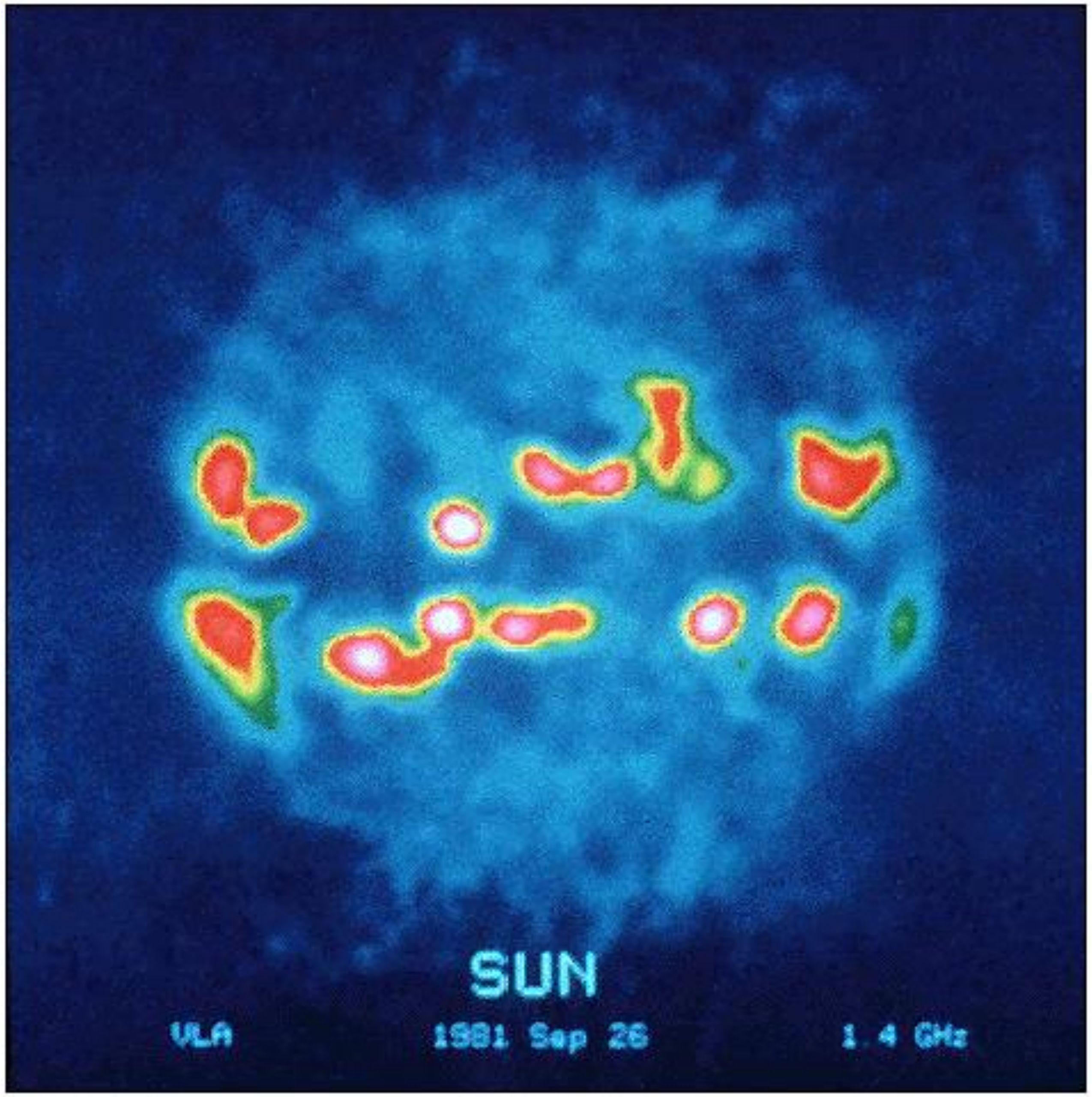
Sun

Radio emission from sun correlates well with solar activity

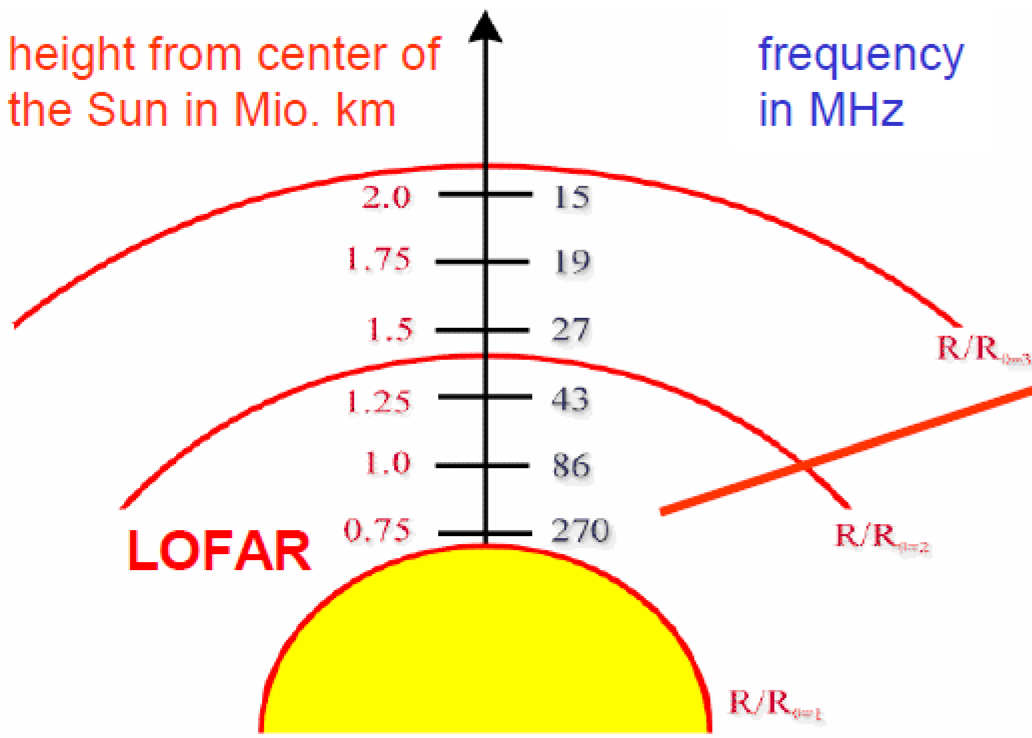


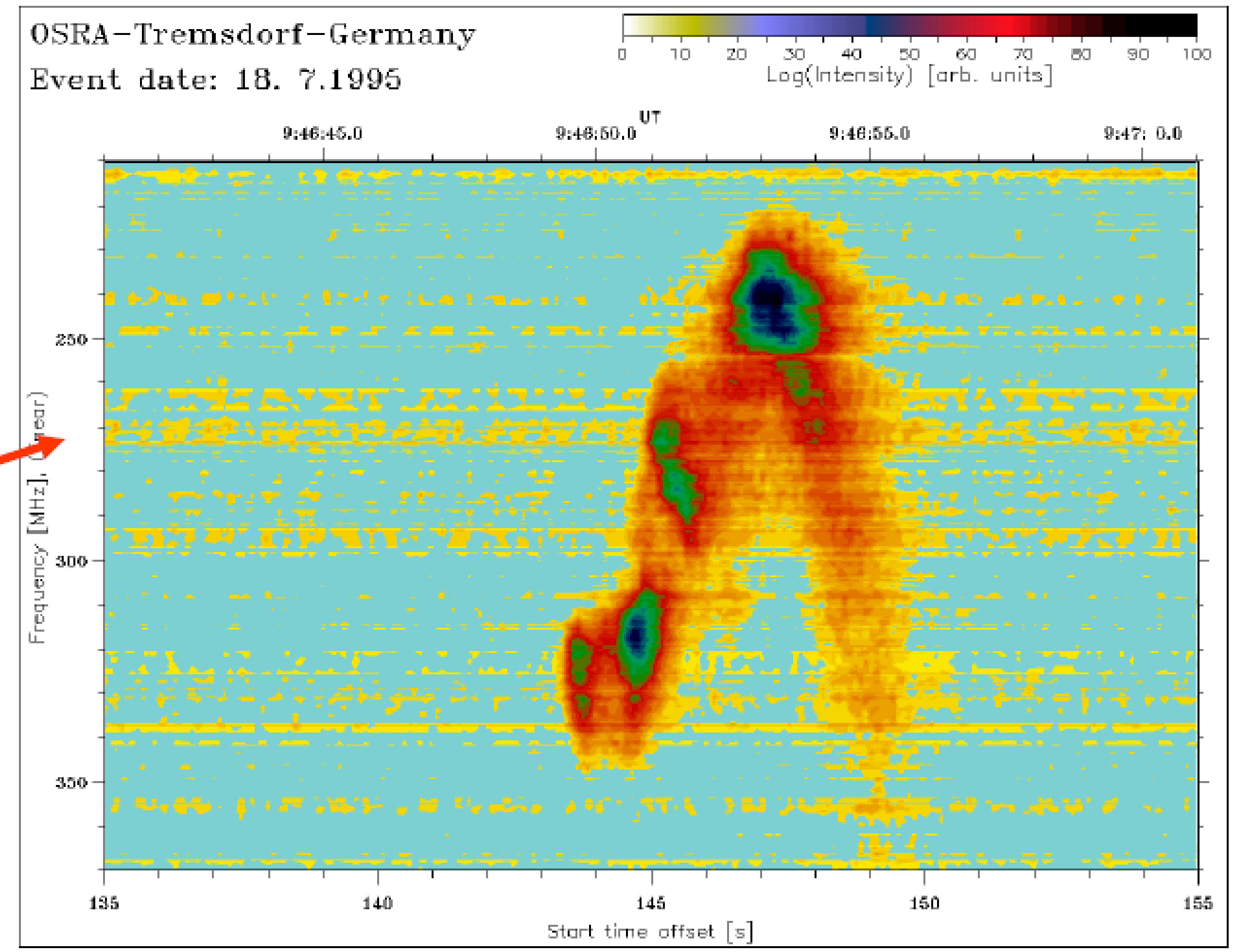
Sun

Radio image of sun showing disk and active regions



Sun





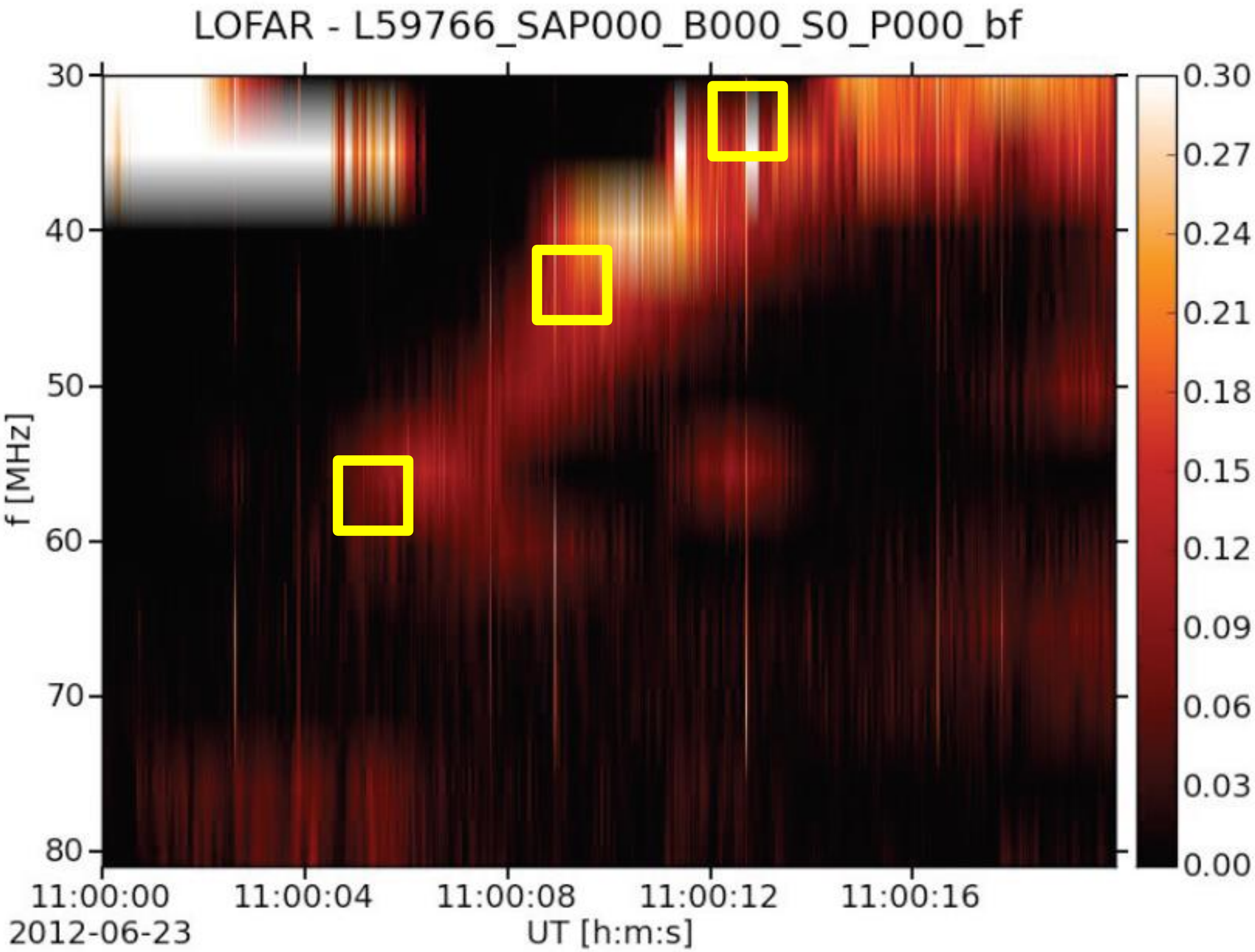
height ≙ frequency

velocity ≙ drift rate

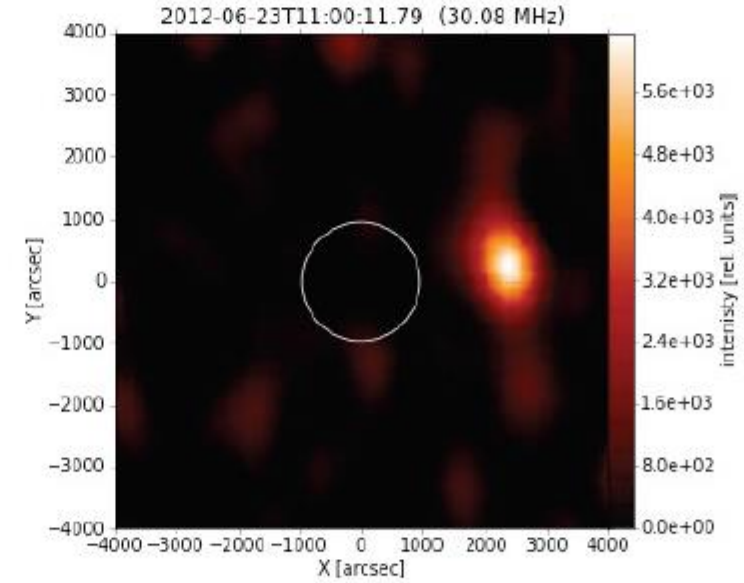
dynamic radio spectrogram ↔ height-time diagram

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{e^2 N_e}{\varepsilon_0 m_e}}$$ plasma frequency

Sun



LOFAR - L59766_SAP000_B000_S0_P000_bf
f [MHz]
UT [h:m:s]
11:00:00
2012-06-23
11:00:04
11:00:08
11:00:12
11:00:16



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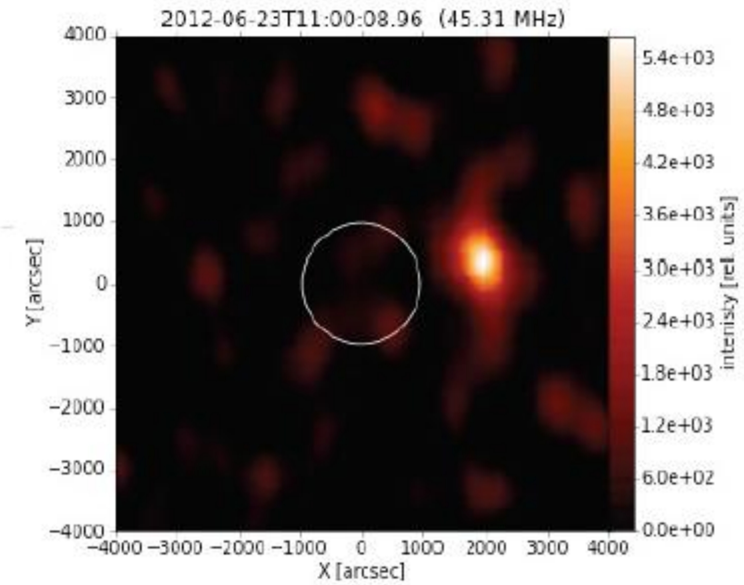
Y [arcsec]
X [arcsec]



2012-06-23T11:00:08.96 (45.31 MHz)
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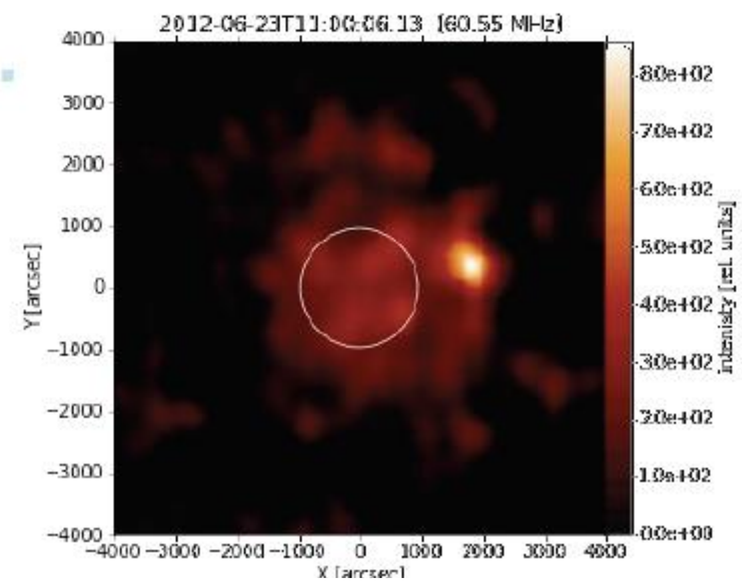
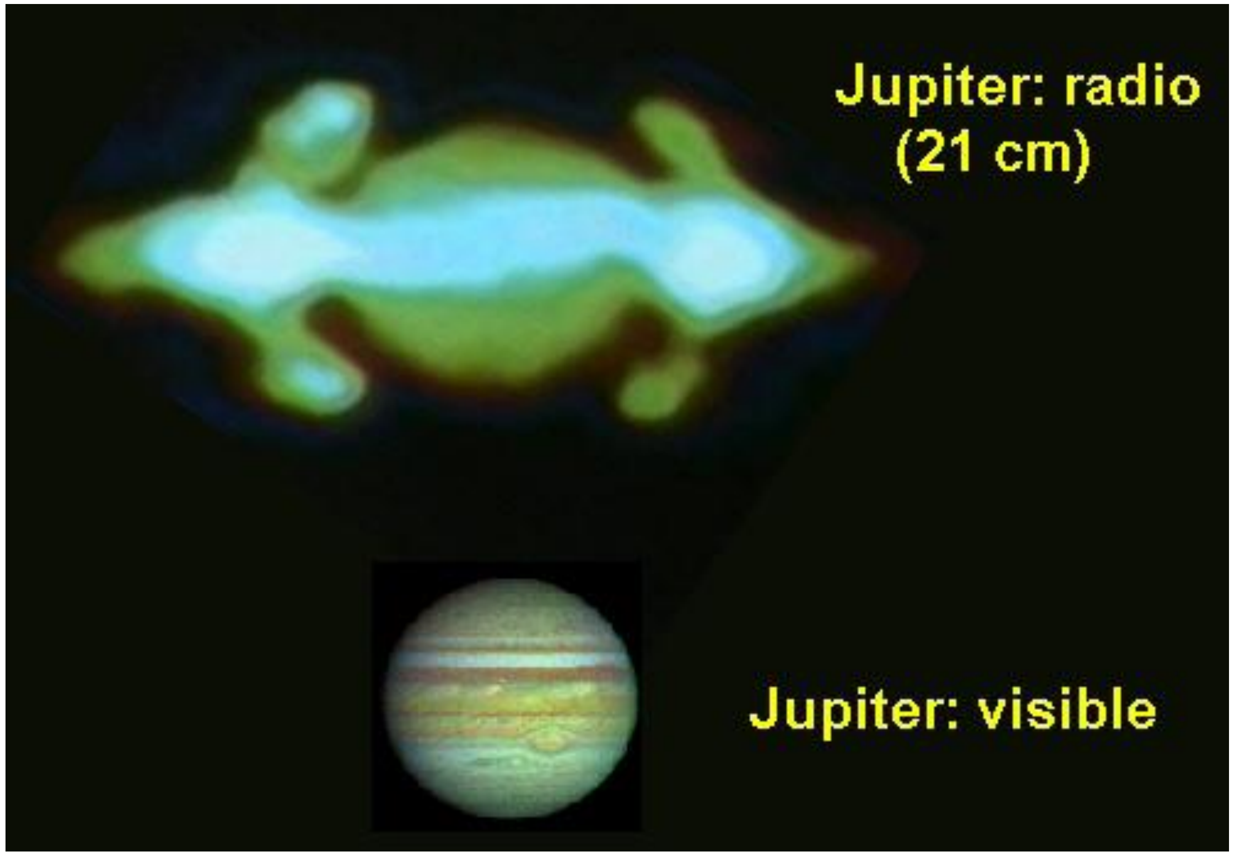
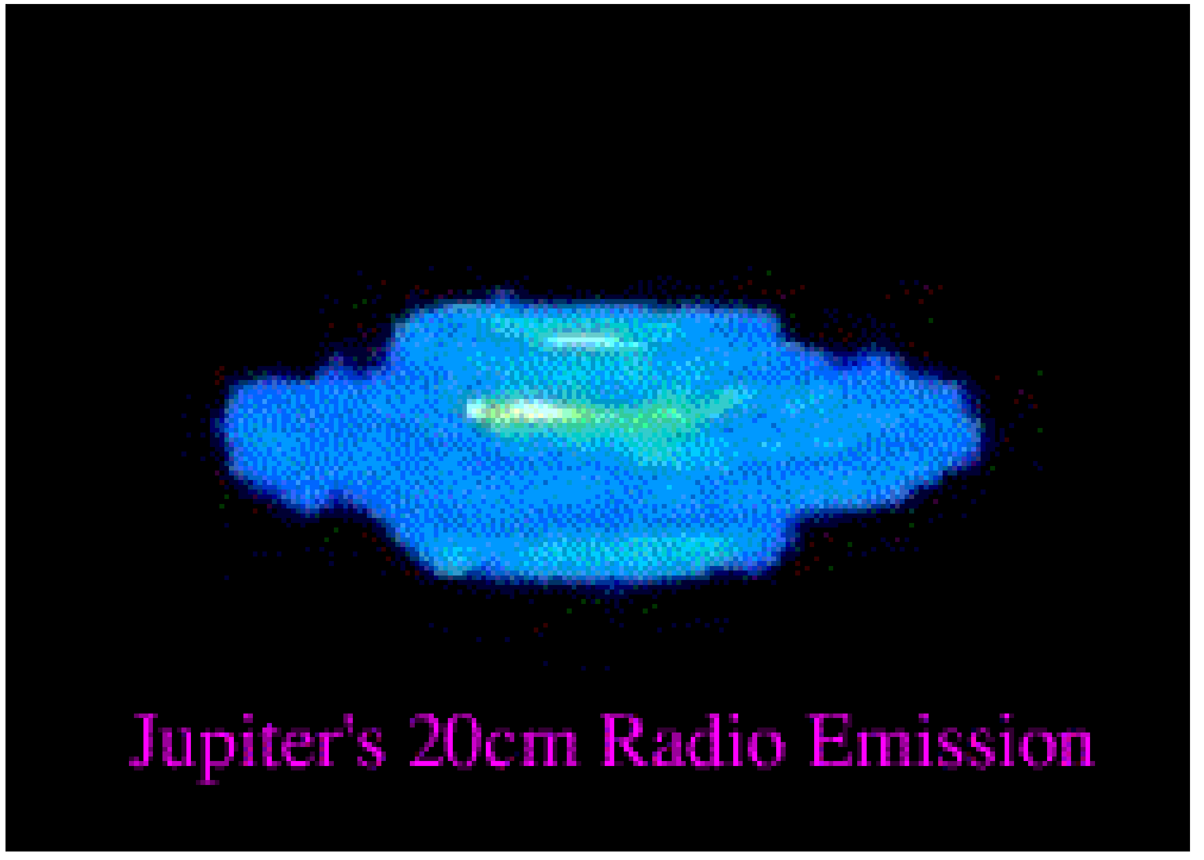


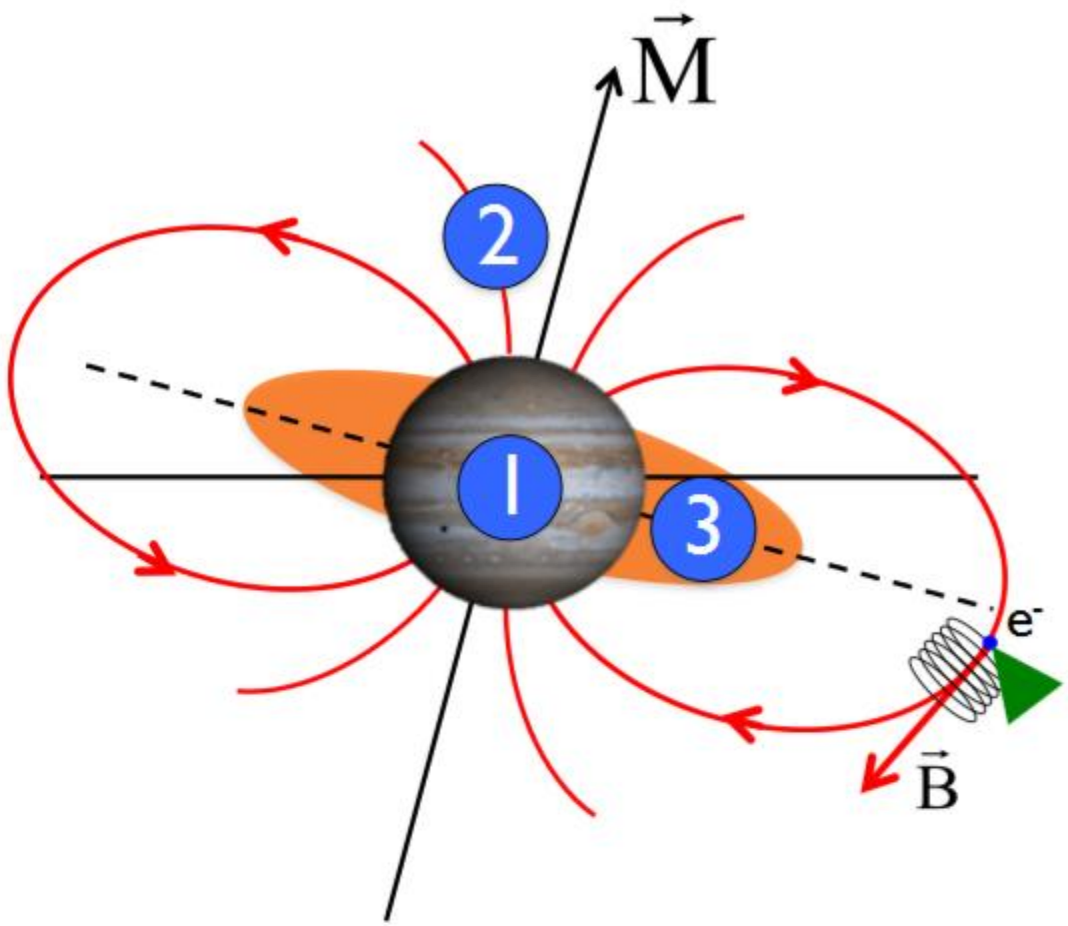
Giant Planets

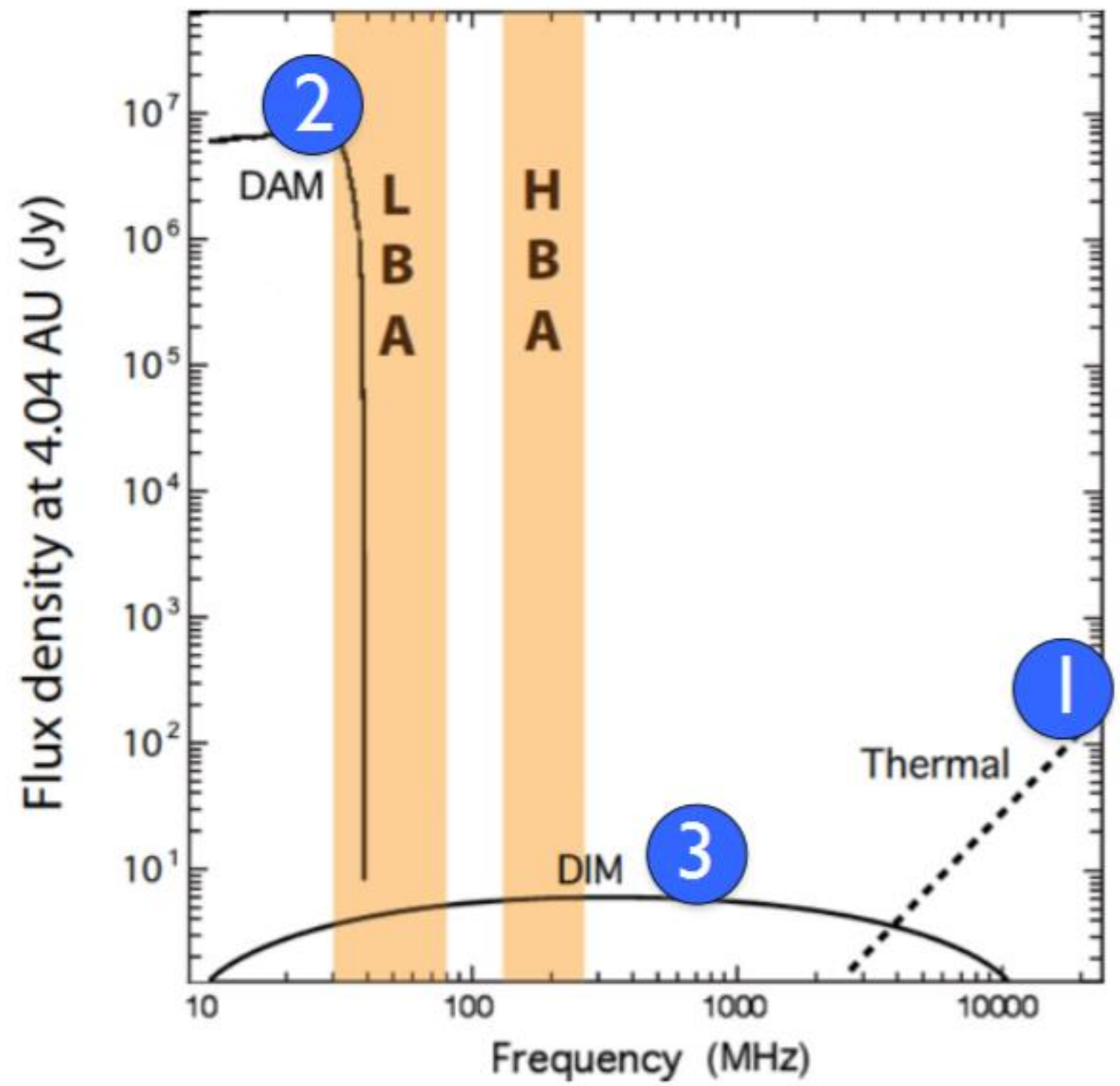
Radio emission from Jupiter's radiation belts





Giant Planets



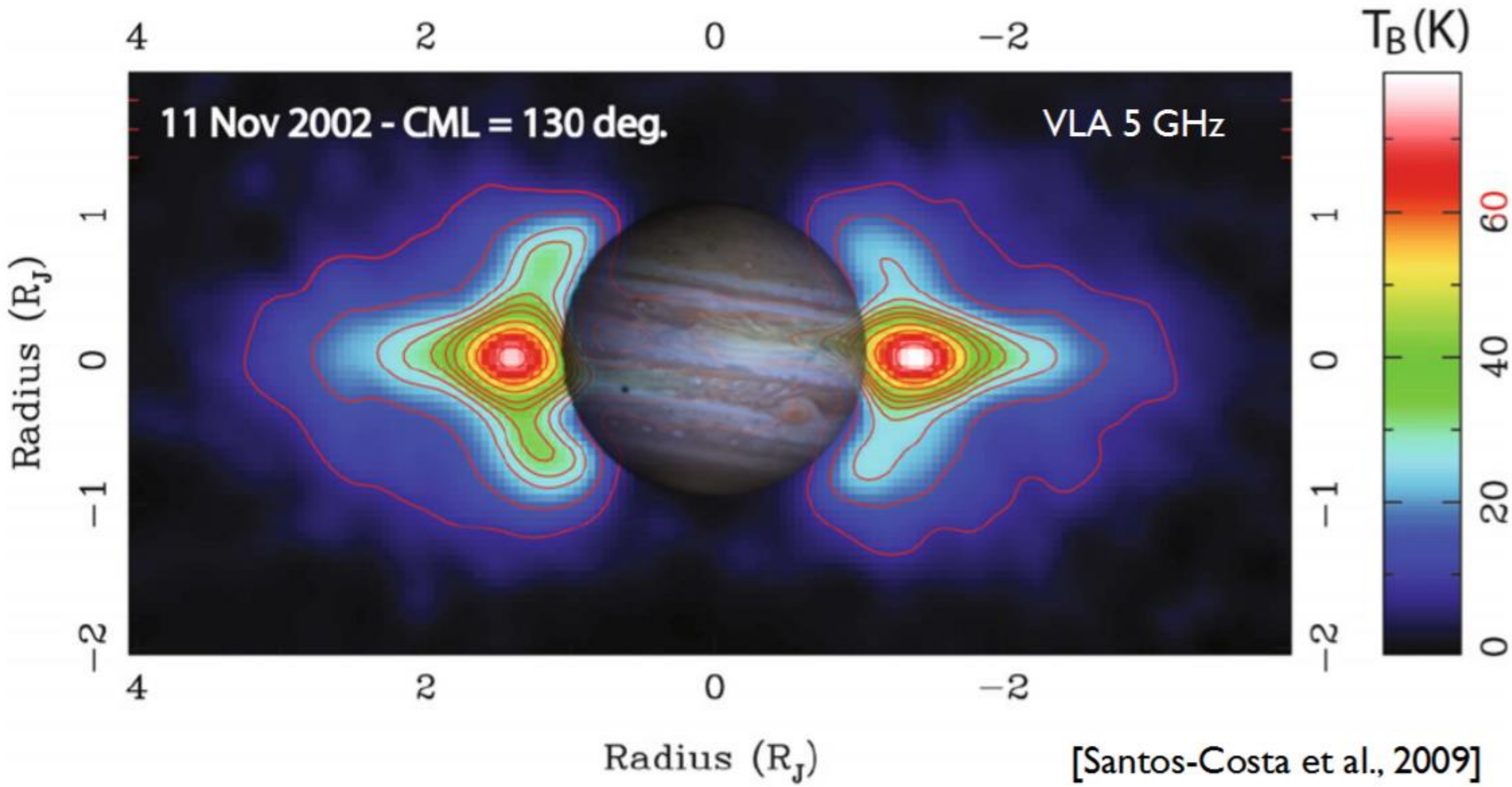


1 Thermal (λ ~ cm)

2 Auroral / Io cyclotron emission (λ ≥ Dm)

3 Radiation belts synchrotron emission (λ = cm-dm-m)

Giant Planets



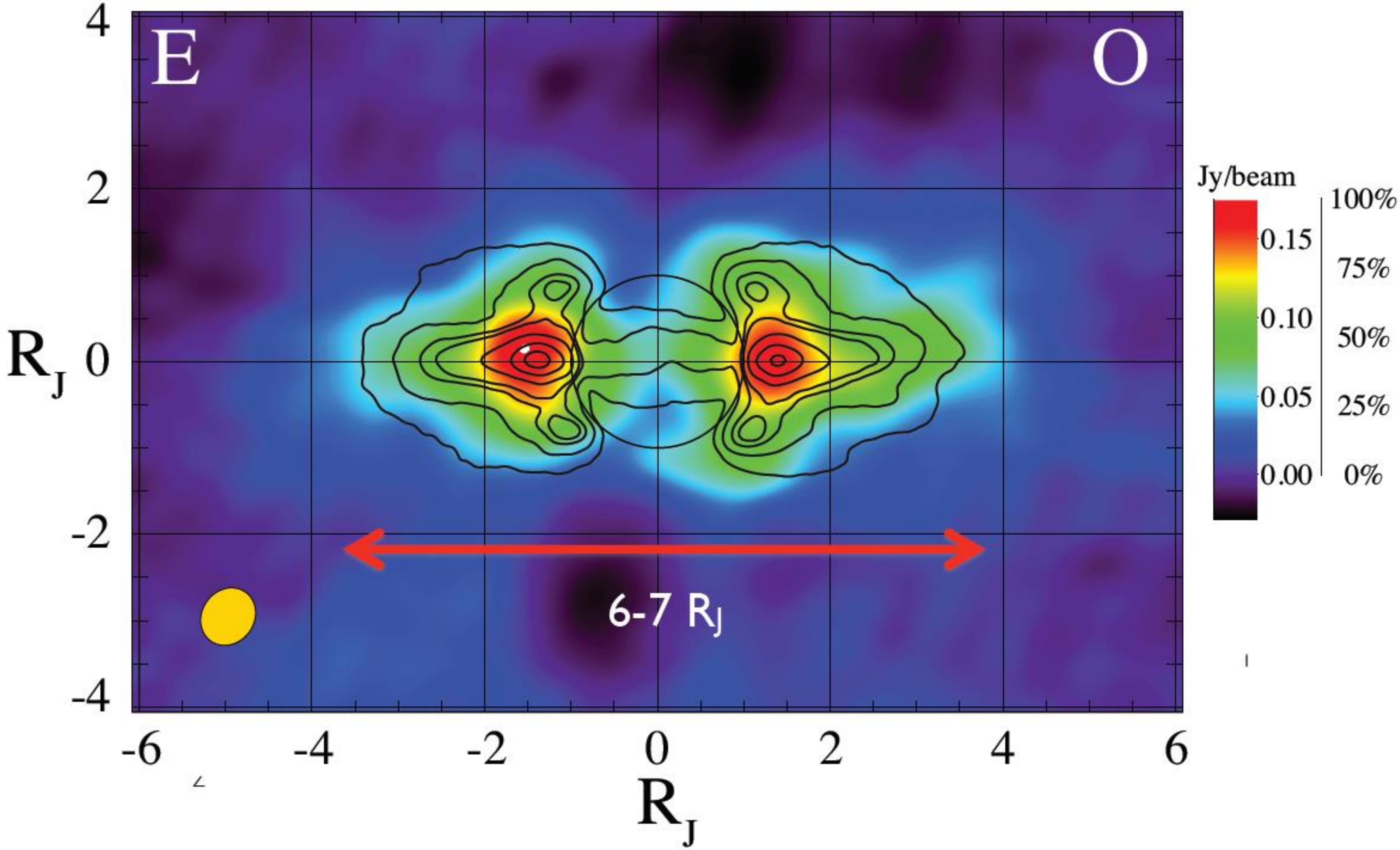
[Santos-Costa et al., 2009]

3 Radiation belts synchrotron emission (λ = cm-dm-m)

- Belts radiating from ~1 to ~3 R_J
- Energetic particles (ions, e- of 100s keV → 10s MeV) trapped near the magnetic equator
- Anisotropic (beamed) and polarized emission (~20-25% linear, <1% circular)

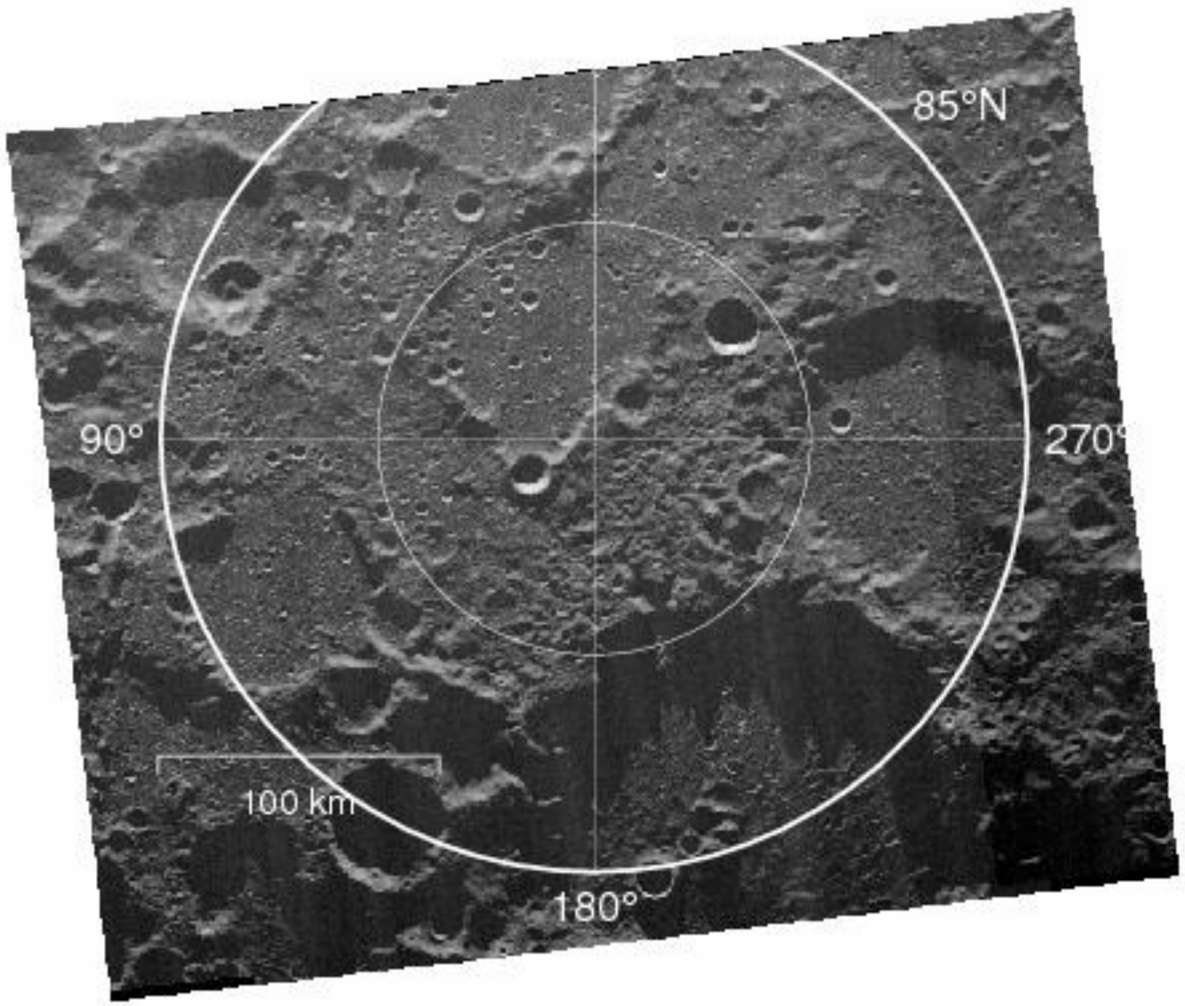
Giant Planets

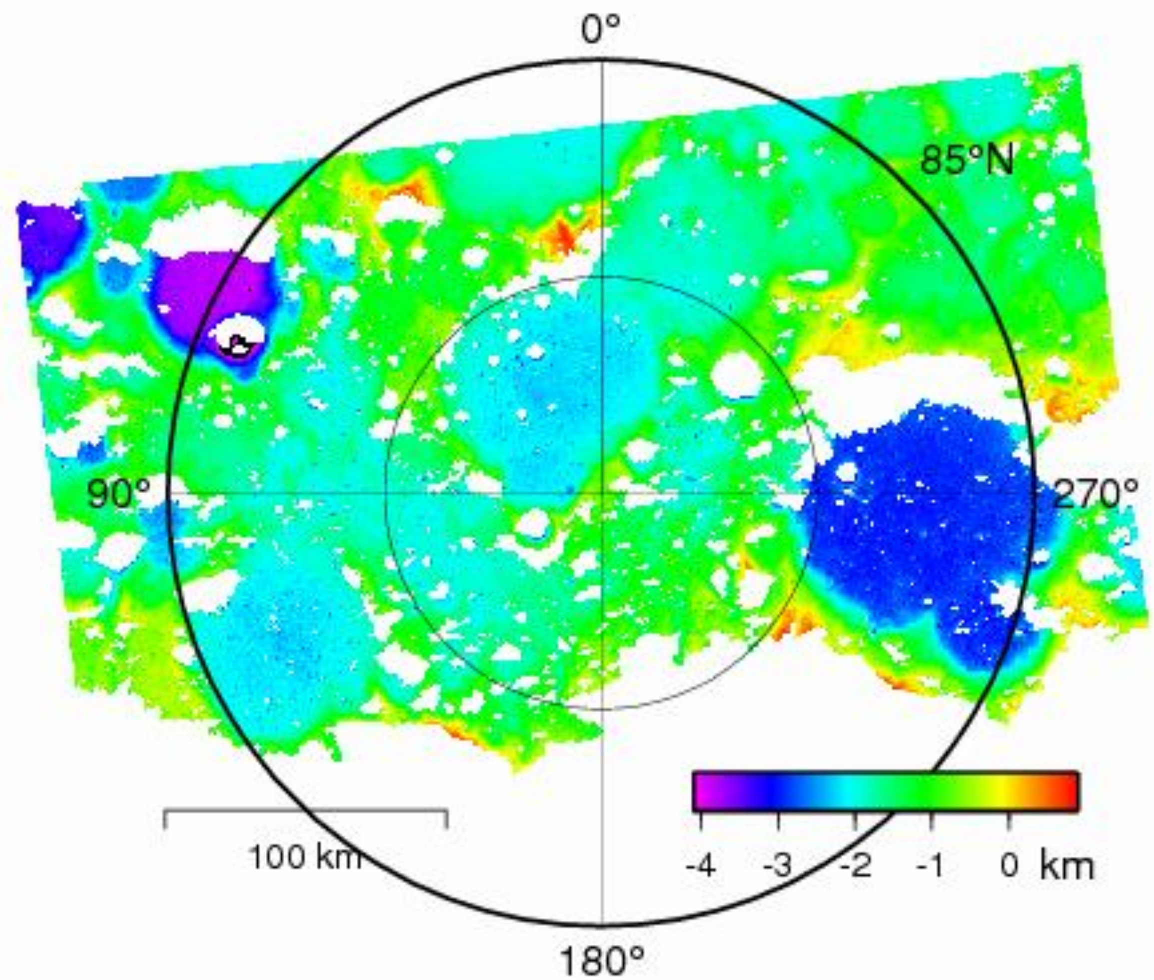
First LOFAR detections:



Moon

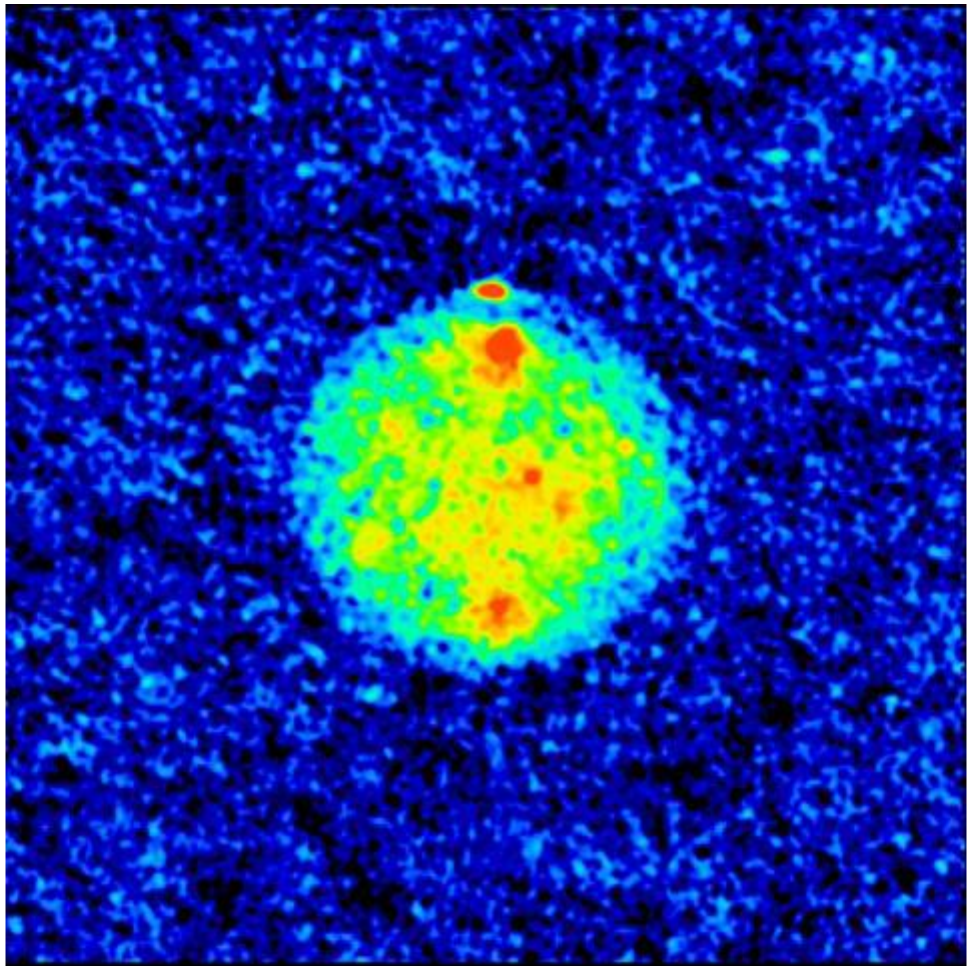
Modern lunar image near the north pole, and elevation in color

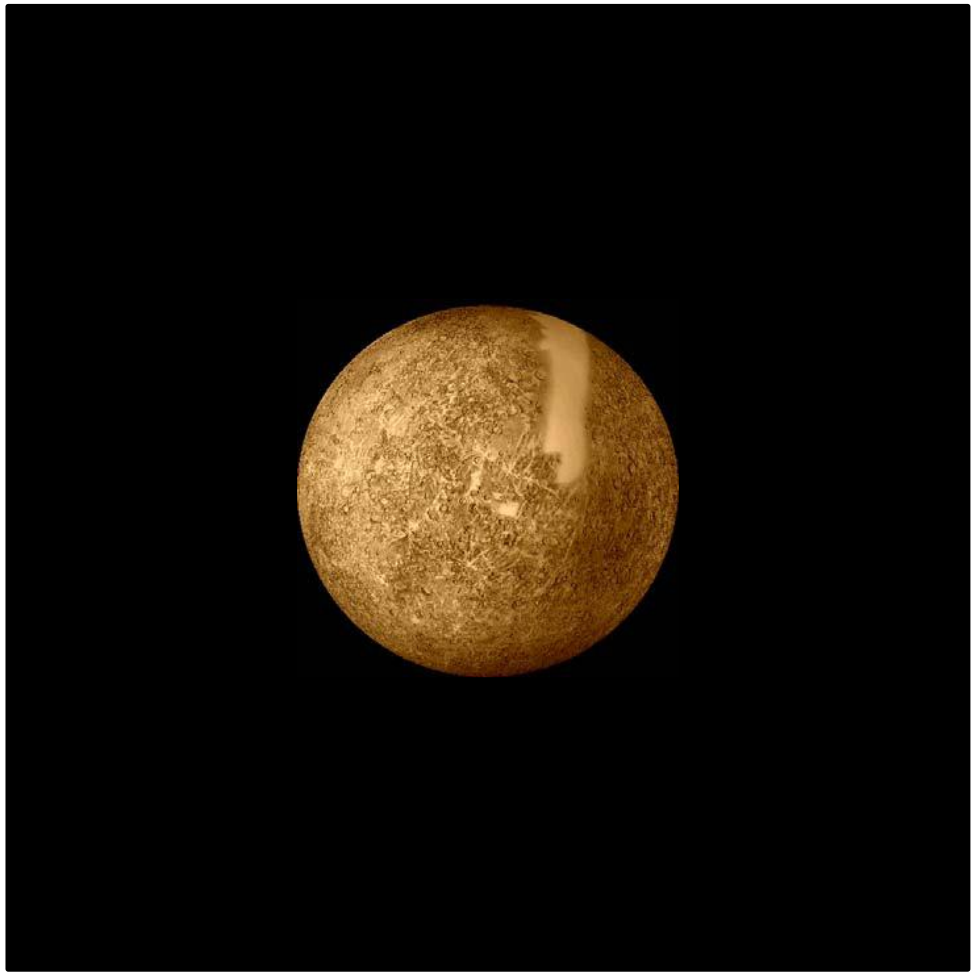




Mercury

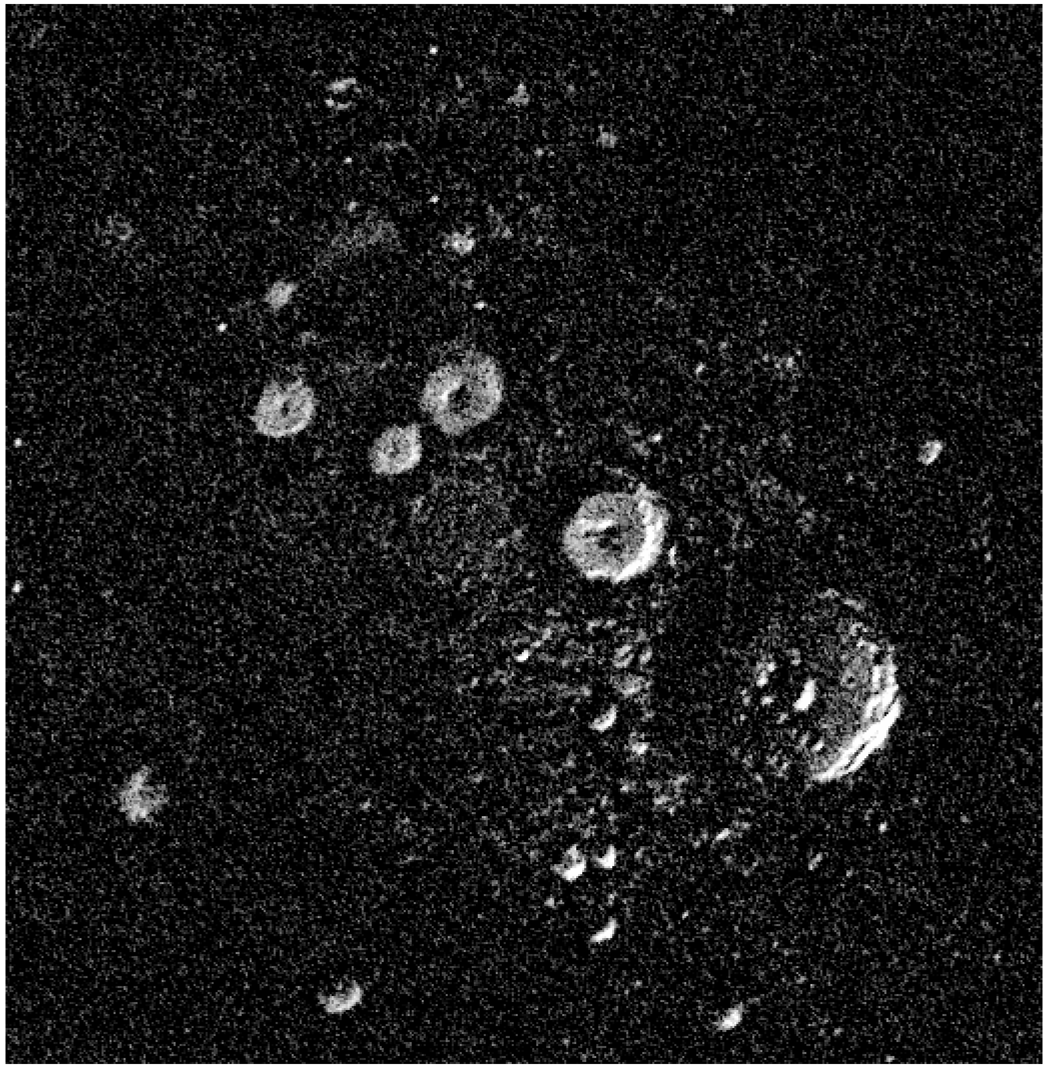
Radar image of Mercury - ice near north pole?





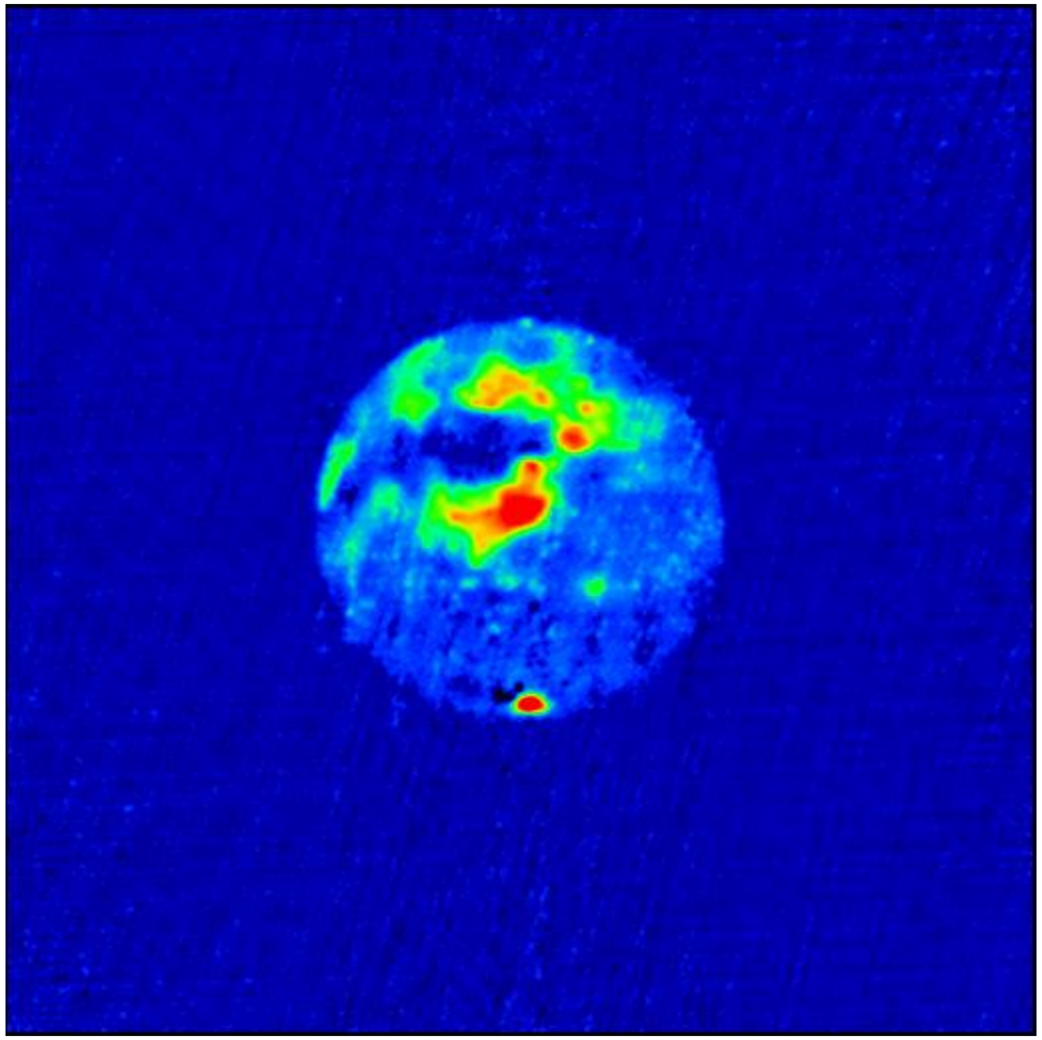
Mercury

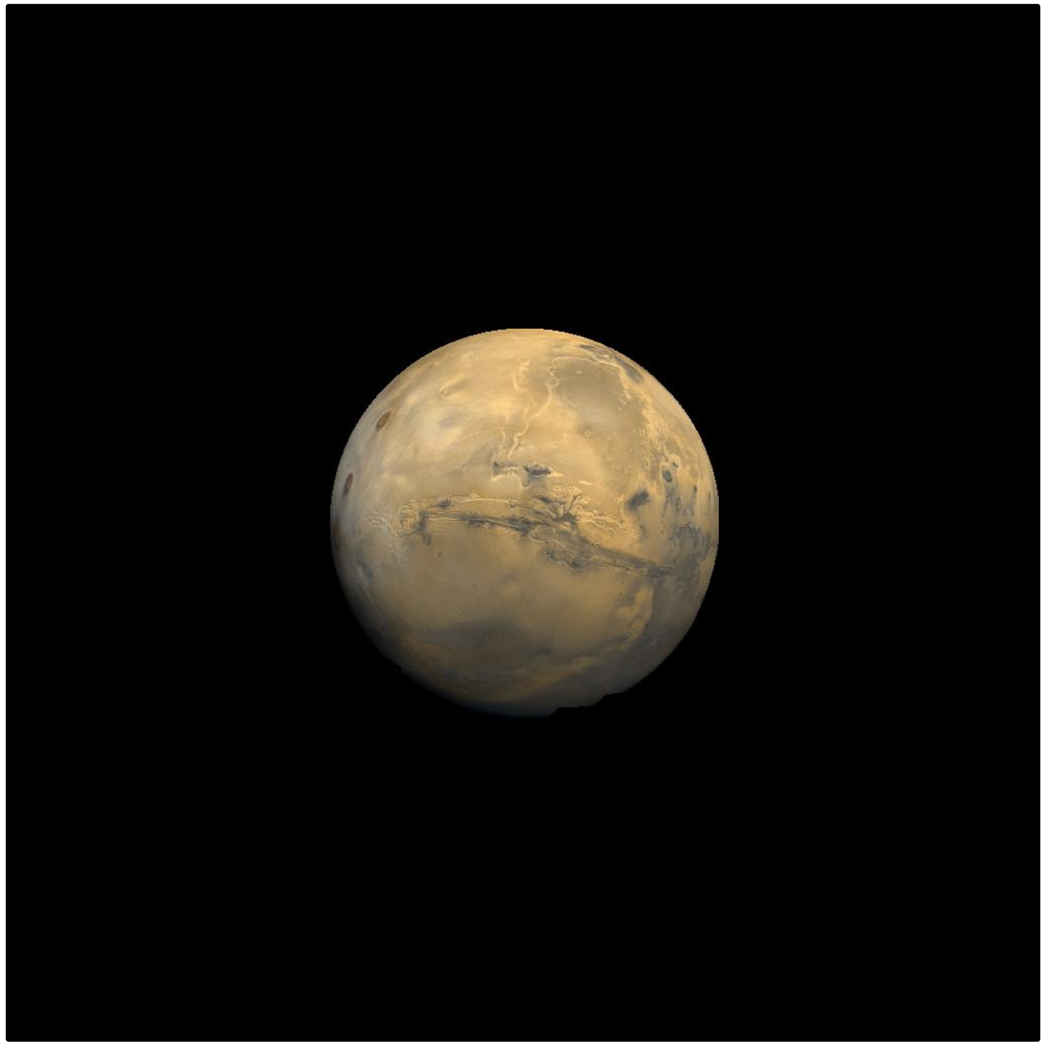
Arecibo delay-Doppler radar image of Mercury's north pole, showing ice deposits (size ~ 300x300 sq. km)



Mars

Radar image of Mars – again likely polar ice





Asteroids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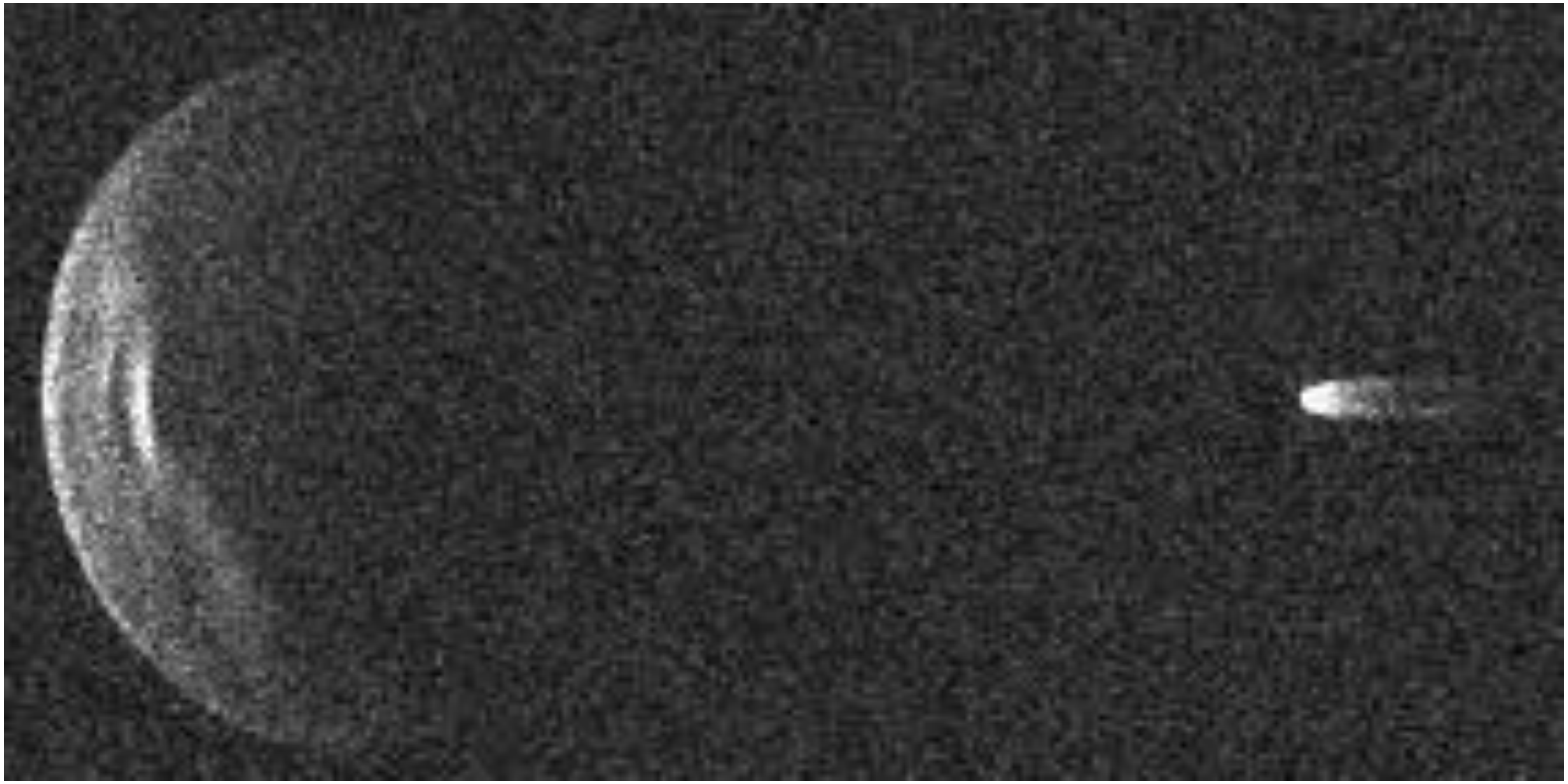
Asteroids

Arecibo delay-Doppler radar image of NEA 1999 JM8 (D ~ 7 km)

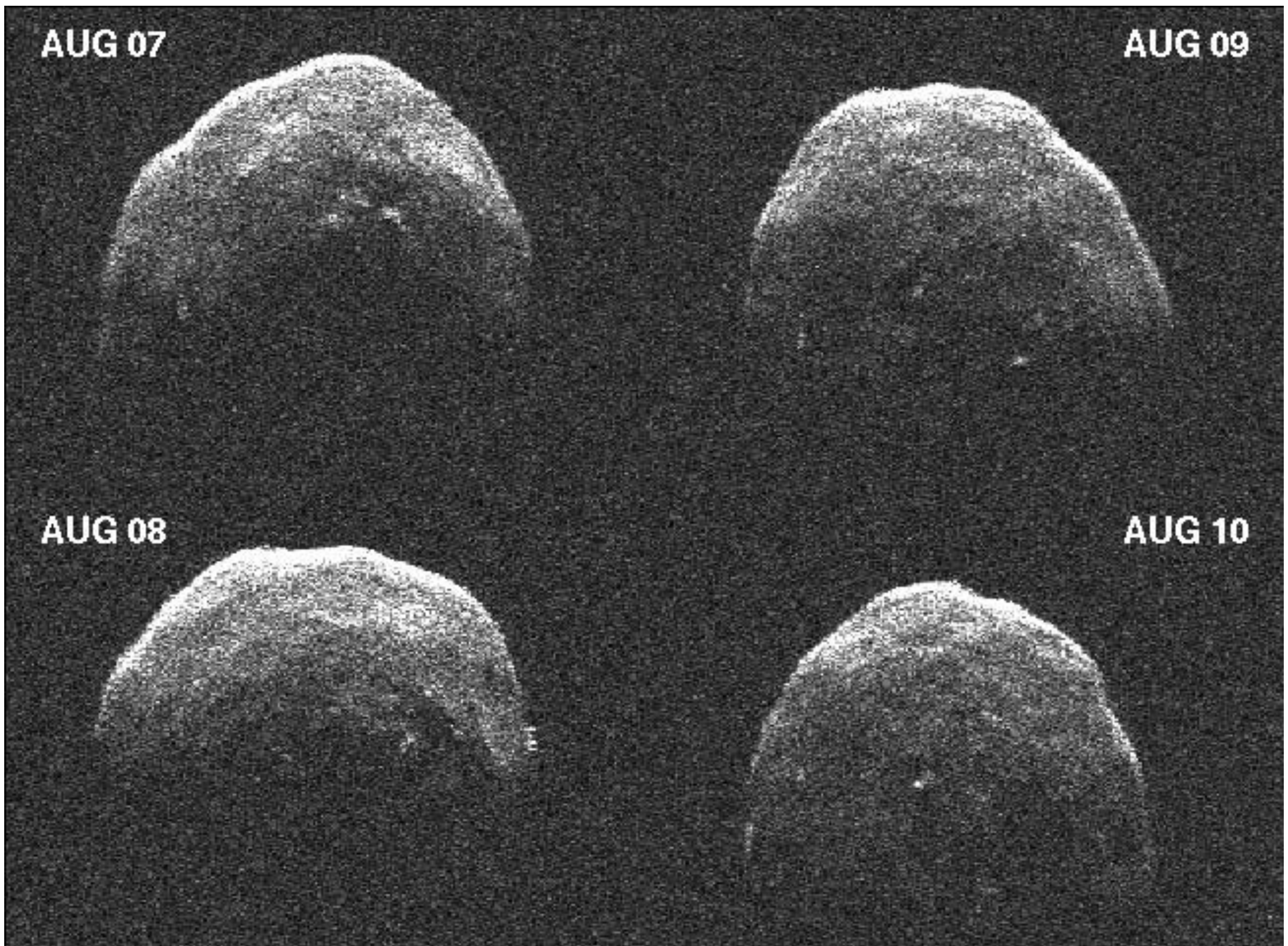
Asteroids

Arecibo delay-Doppler radar image of NEA 1999 KW4 (D ~ 1.5 km)



Asteroids

Arecibo delay-Doppler radar image of NEA 1999 KW4 (D ~ 1.5 km)

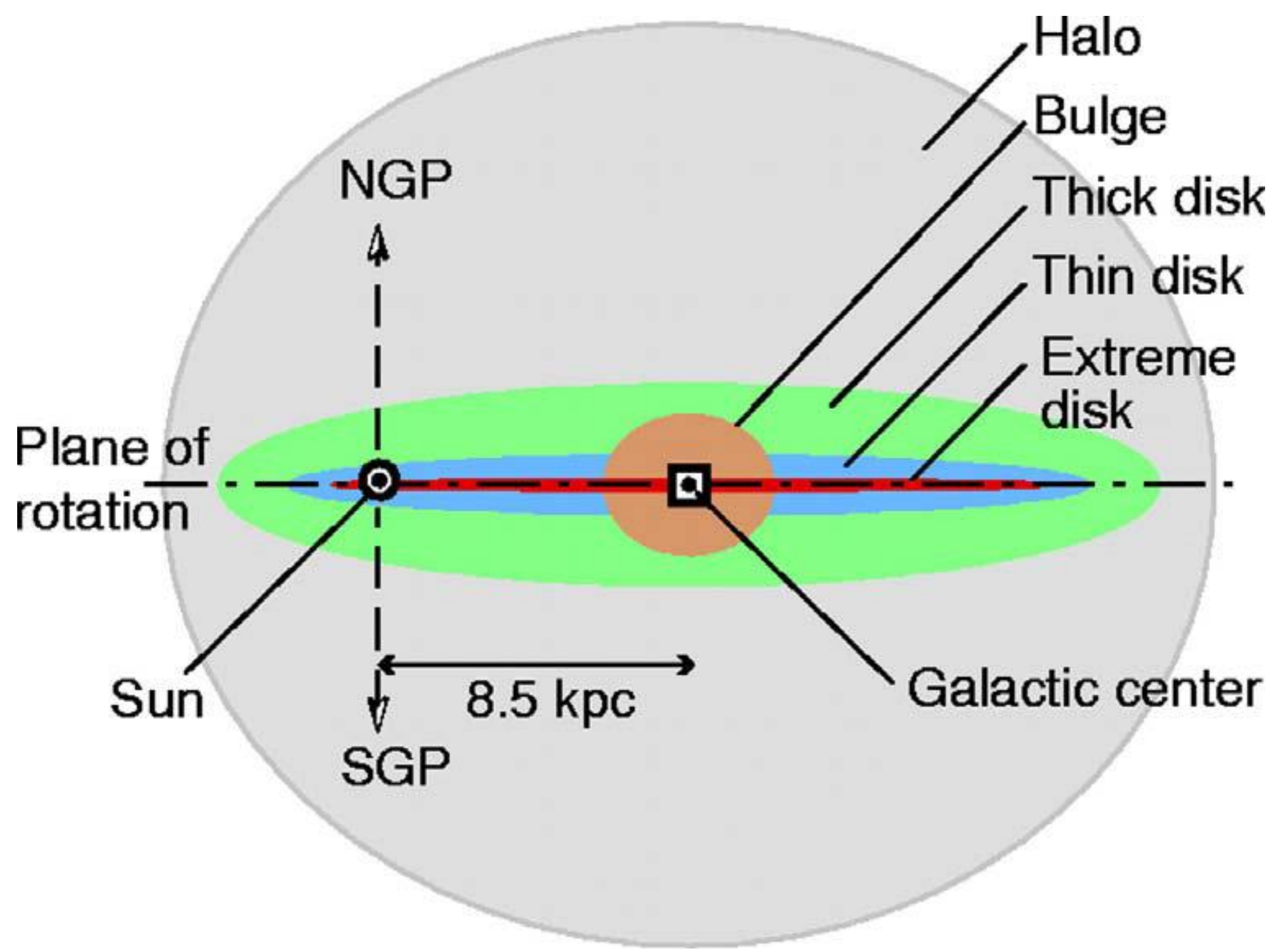


Milky Way

- We observe: diffuse continuum emission from the disk
- 21 cm HI line emission from clouds
- Weak radio emission from all star types
- Radio emission from glowing HII clouds ionized by light from hot, young stars
- Some 275 radio supernova remnants
- Neutron stars observed as pulsars

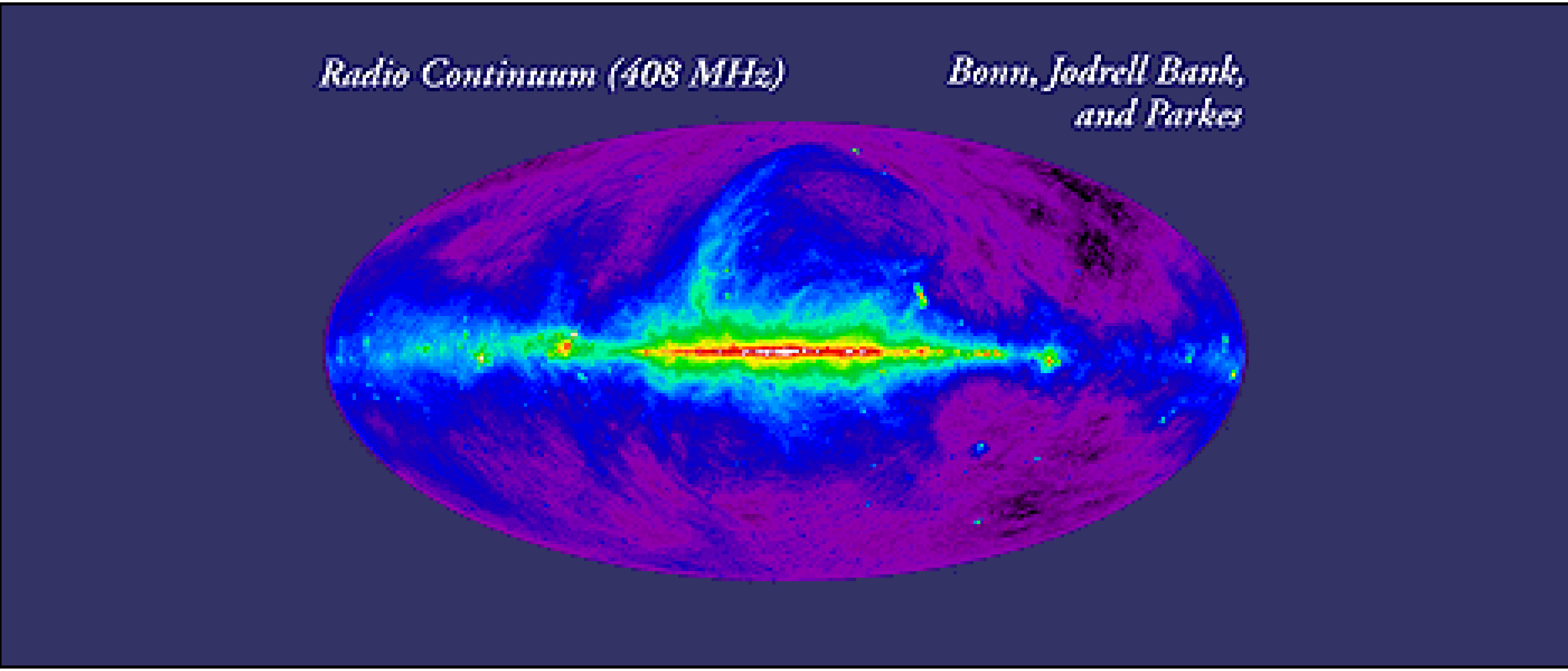
Milky Way

- Sketch shows main structures of MW
- Most objects to be discussed are in thin disk
- Associated with star formation…
- …and star demise
- First, diffuse gas



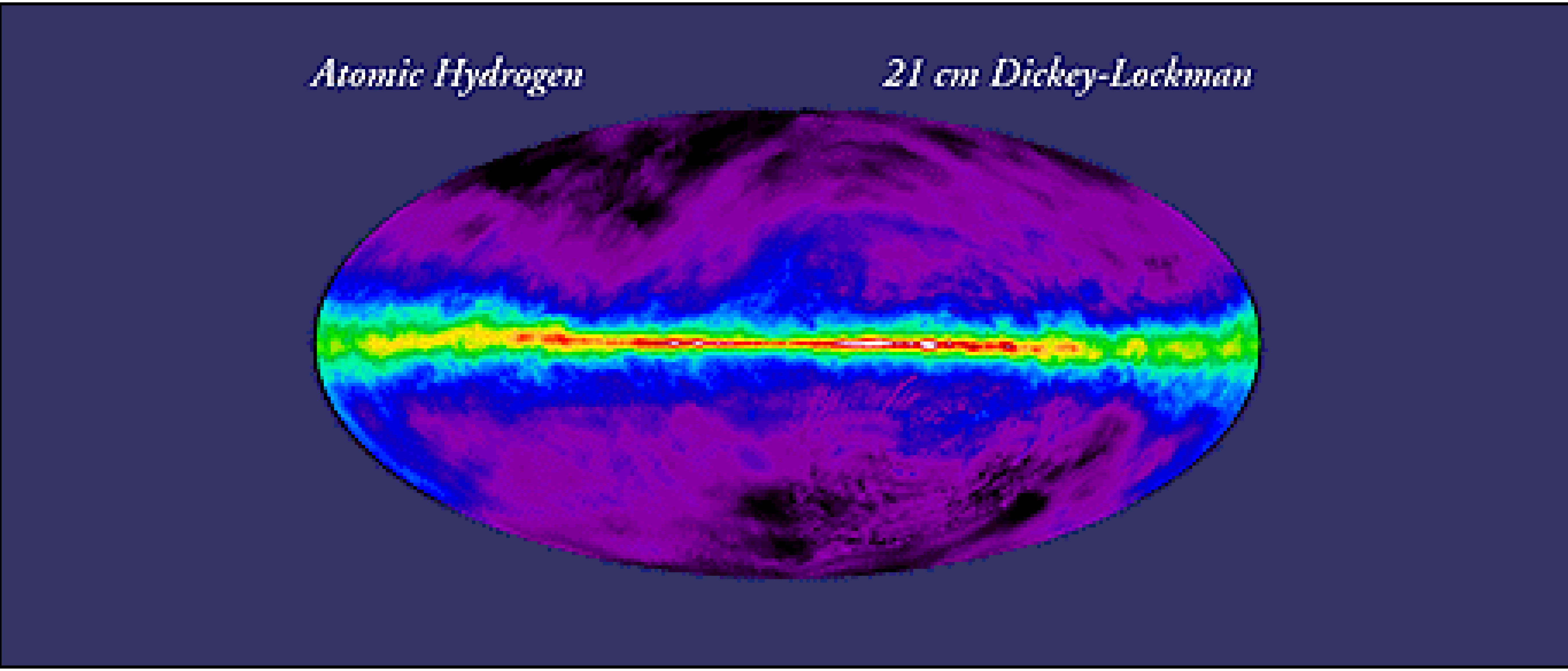
Milky Way

In radio continuum, we see through the whole Milky Way



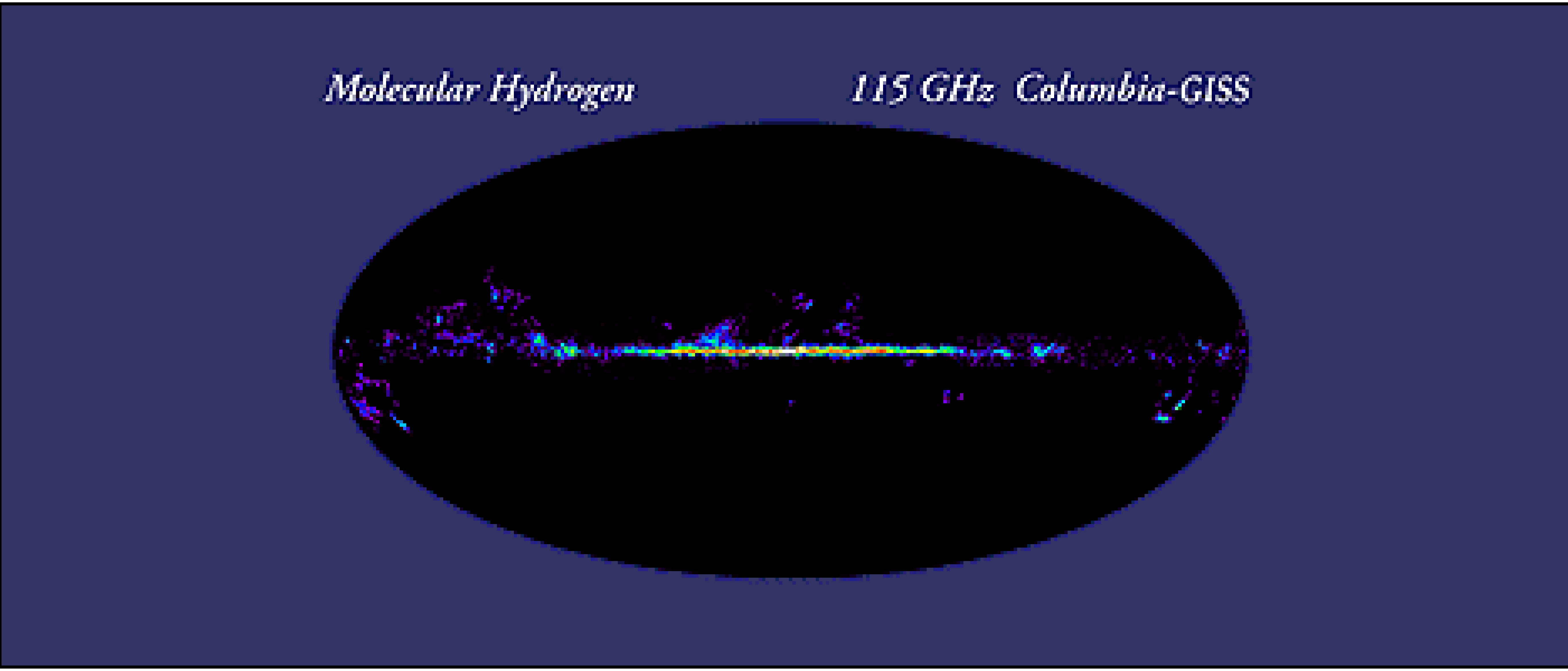
Milky Way

Dust also has no influence on the 21 cm HI line



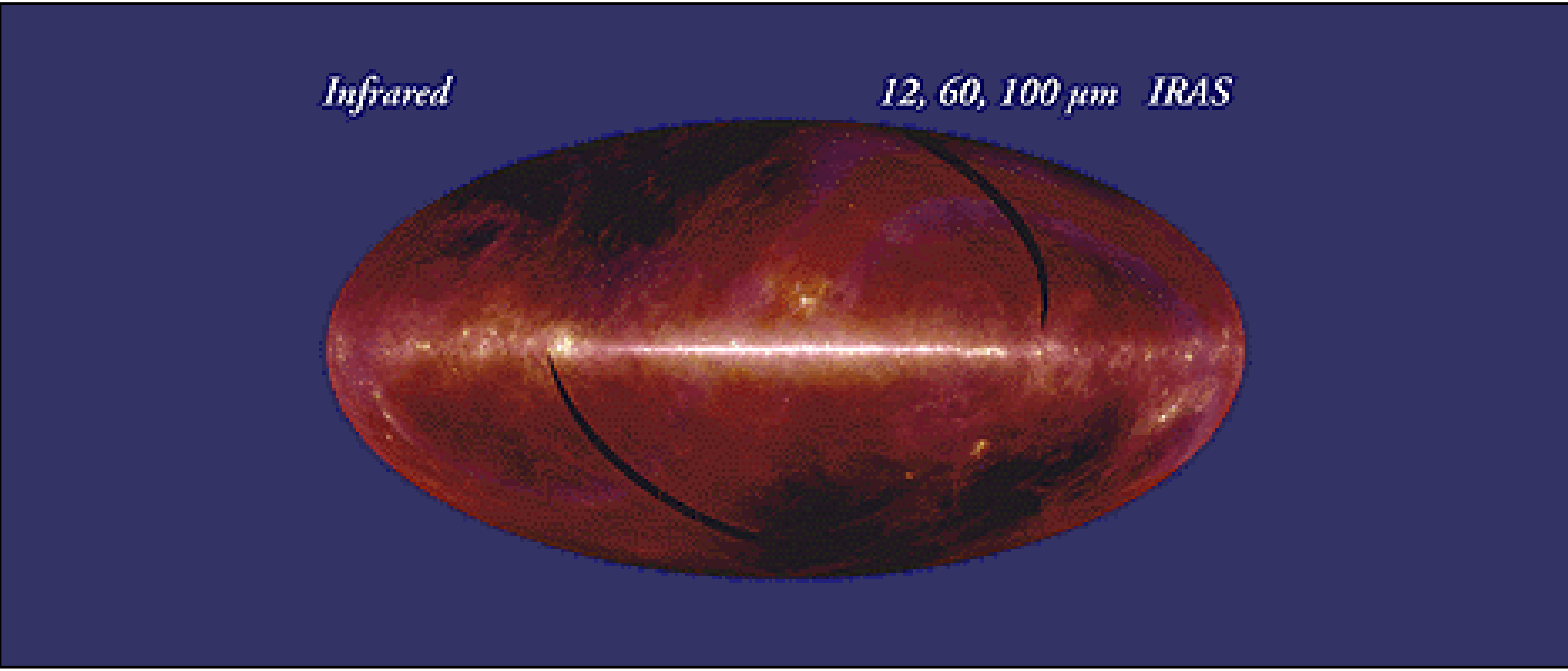
Milky Way

The CO line at 2.6 mm is a surrogate for H_2



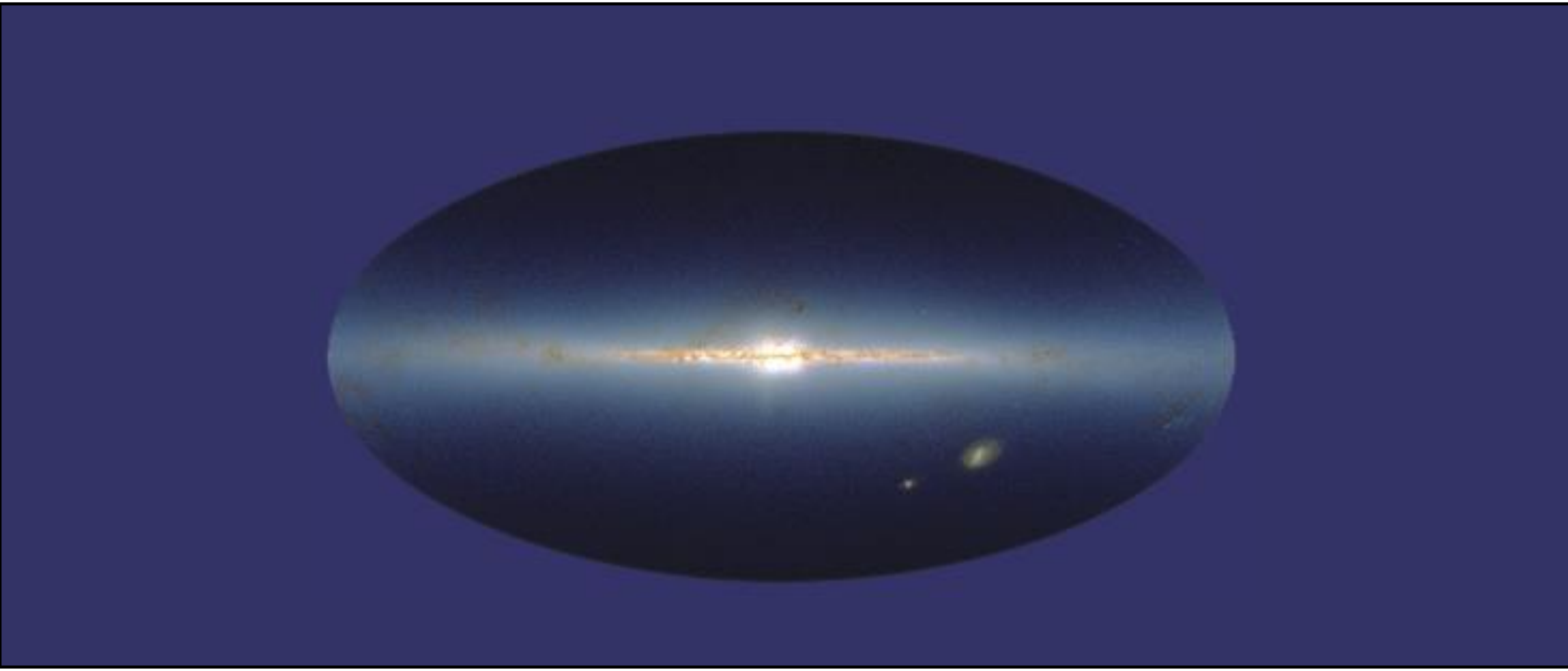
Milky Way

Most IR emission is unblocked (and comes from hot dust)



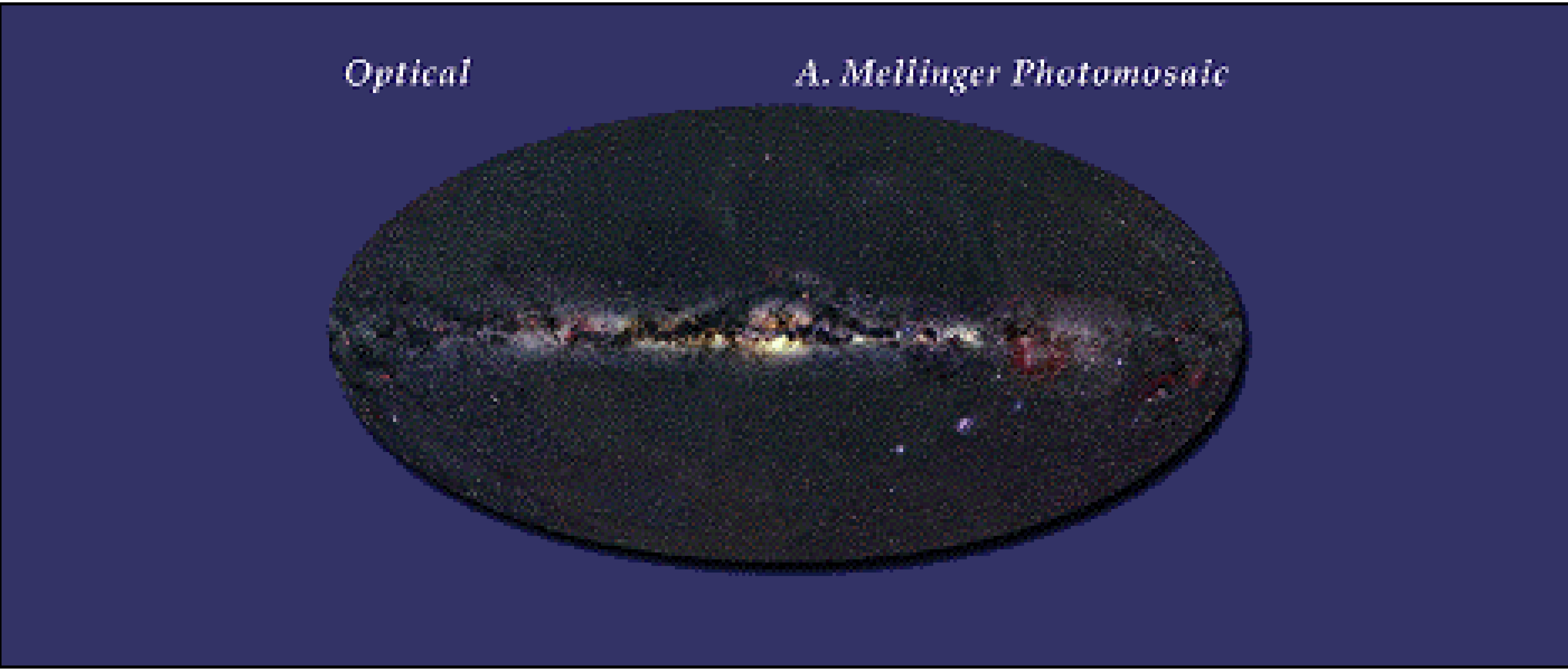
Milky Way

Near IR (2 μm) bulge unobstructed by dust



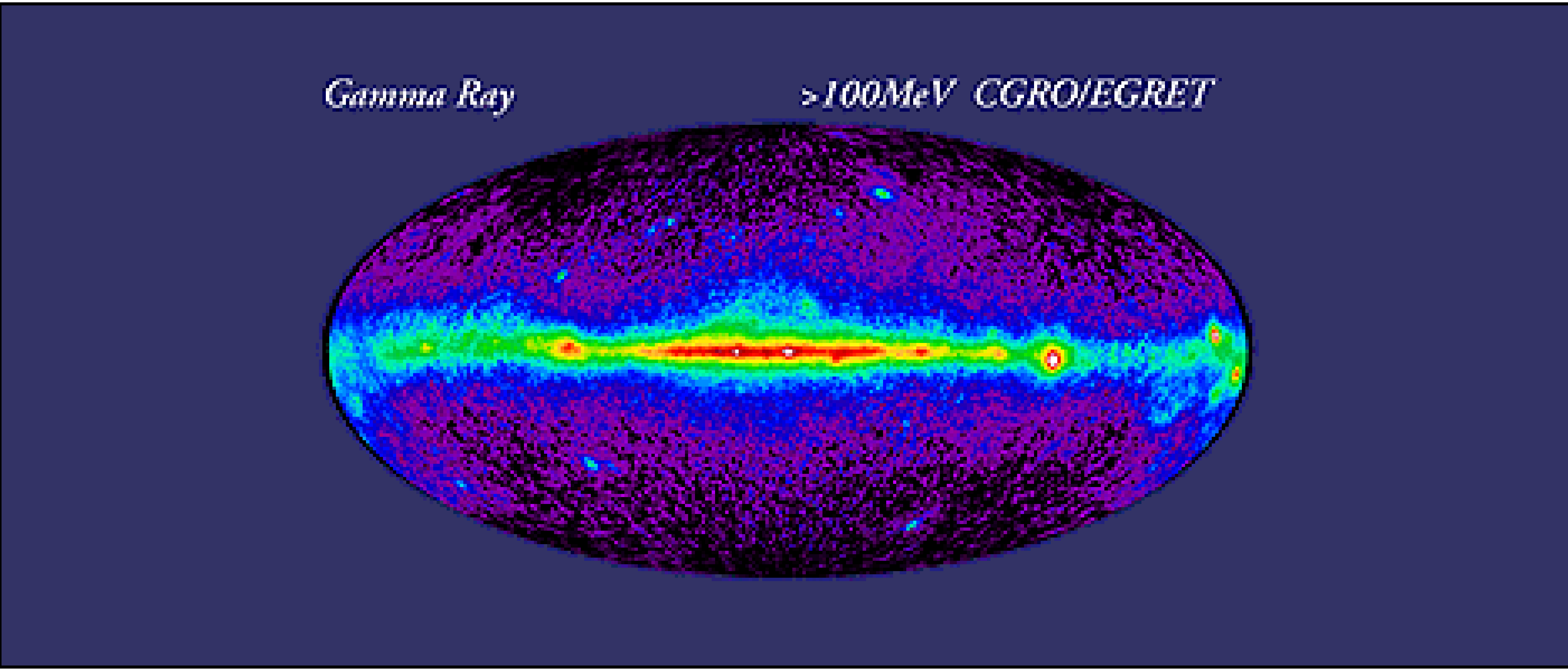
Milky Way

In the galactic plane, little light gets through the dust



Milky Way

High energy γ-rays, unobstructed and closely linked to gas



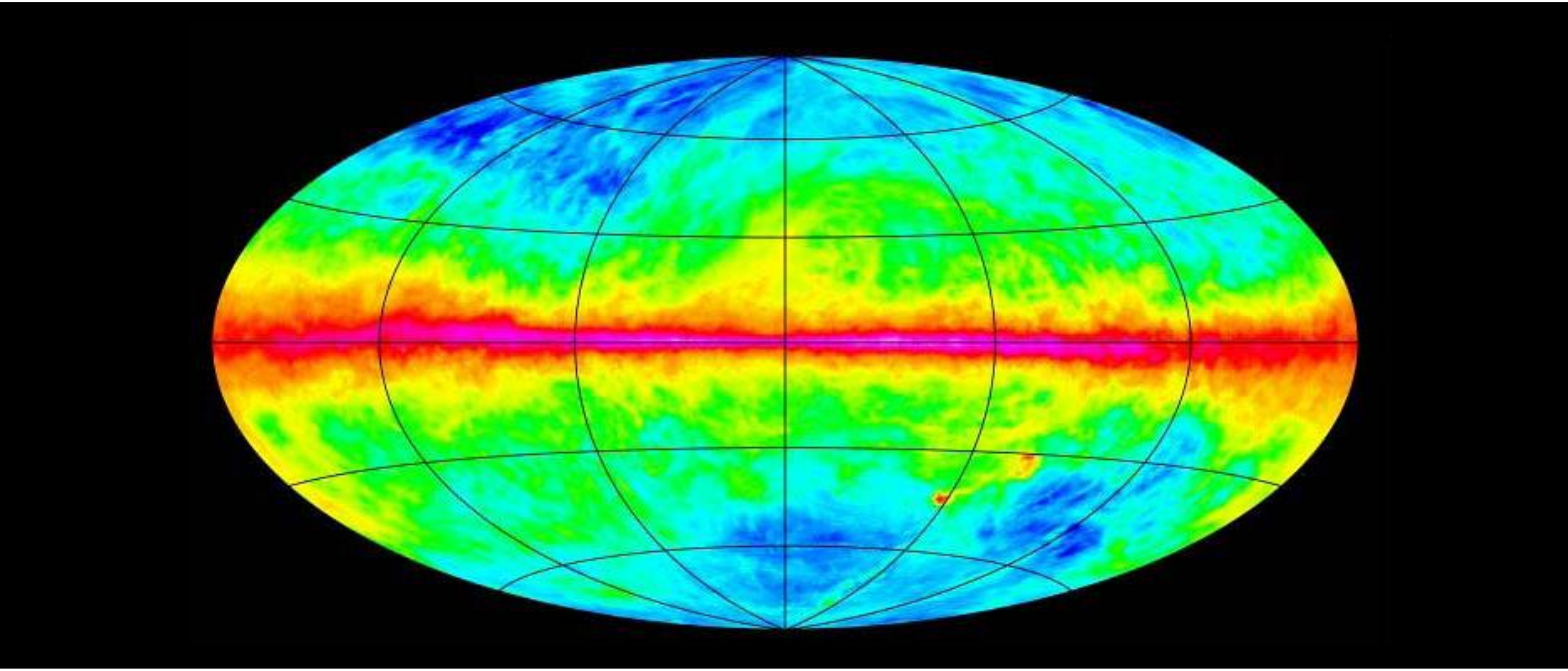
Milky Way

These images show both diffuse and discrete sources:

- The 21 cm HI and 2.6 mm CO mainly come from diffuse clouds of H and H_2
- Much of the 408 MHz radio continuum is from discrete sources (clouds of ionized gas, shocks from supernovae)
- X-ray emission from hot, shocked gas, and from binaries & various stars
- IR from hot dust and cool stars

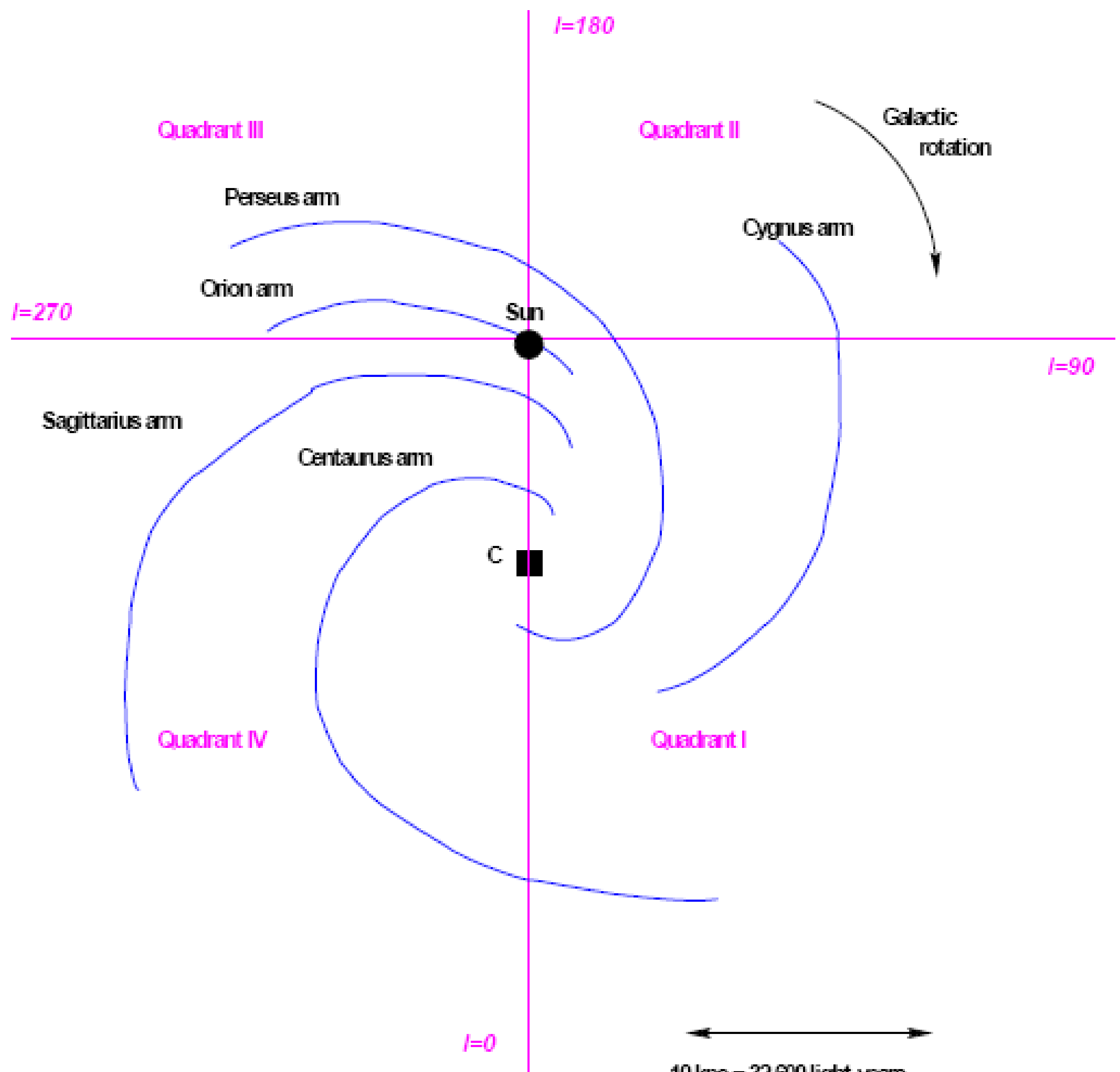
Milky Way

Milky Way is difficult to study as we are in it



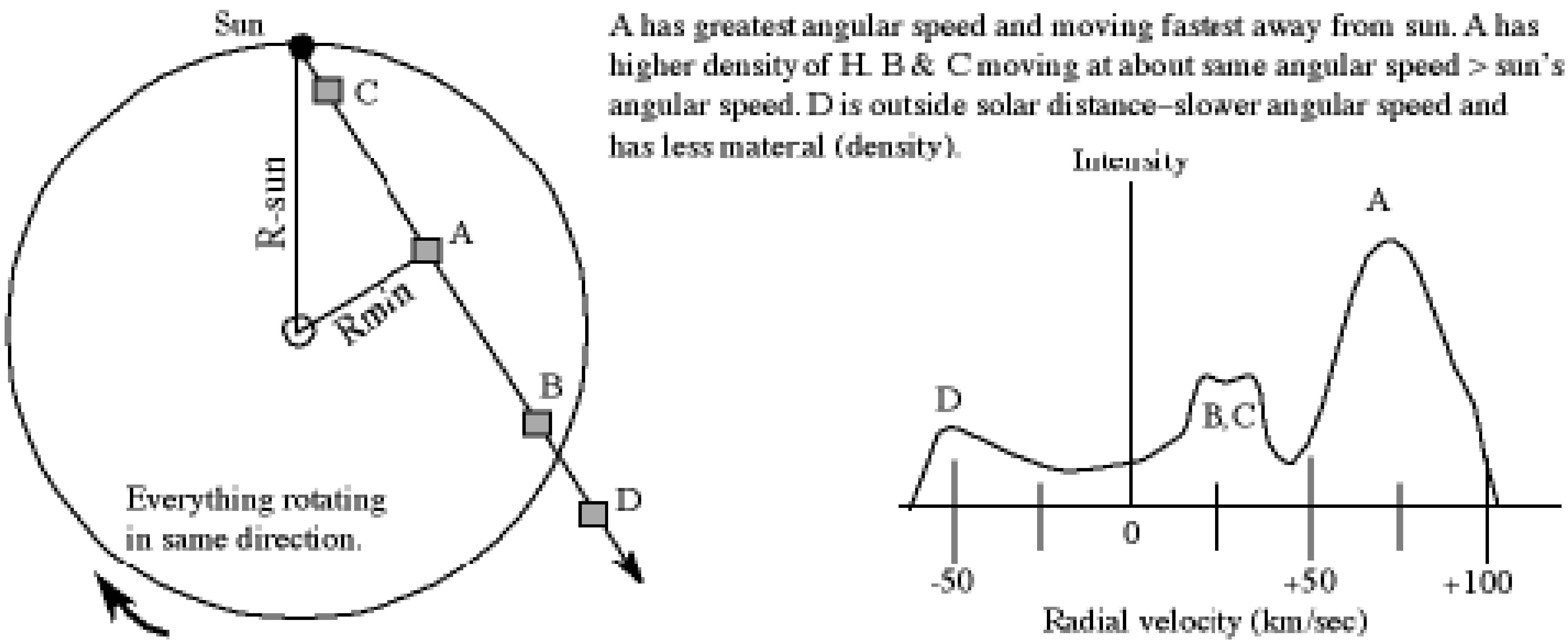
Milky Way

4 quadrants: 4 quadrants:
I & III, gas moves away; II & IV, gas approaches



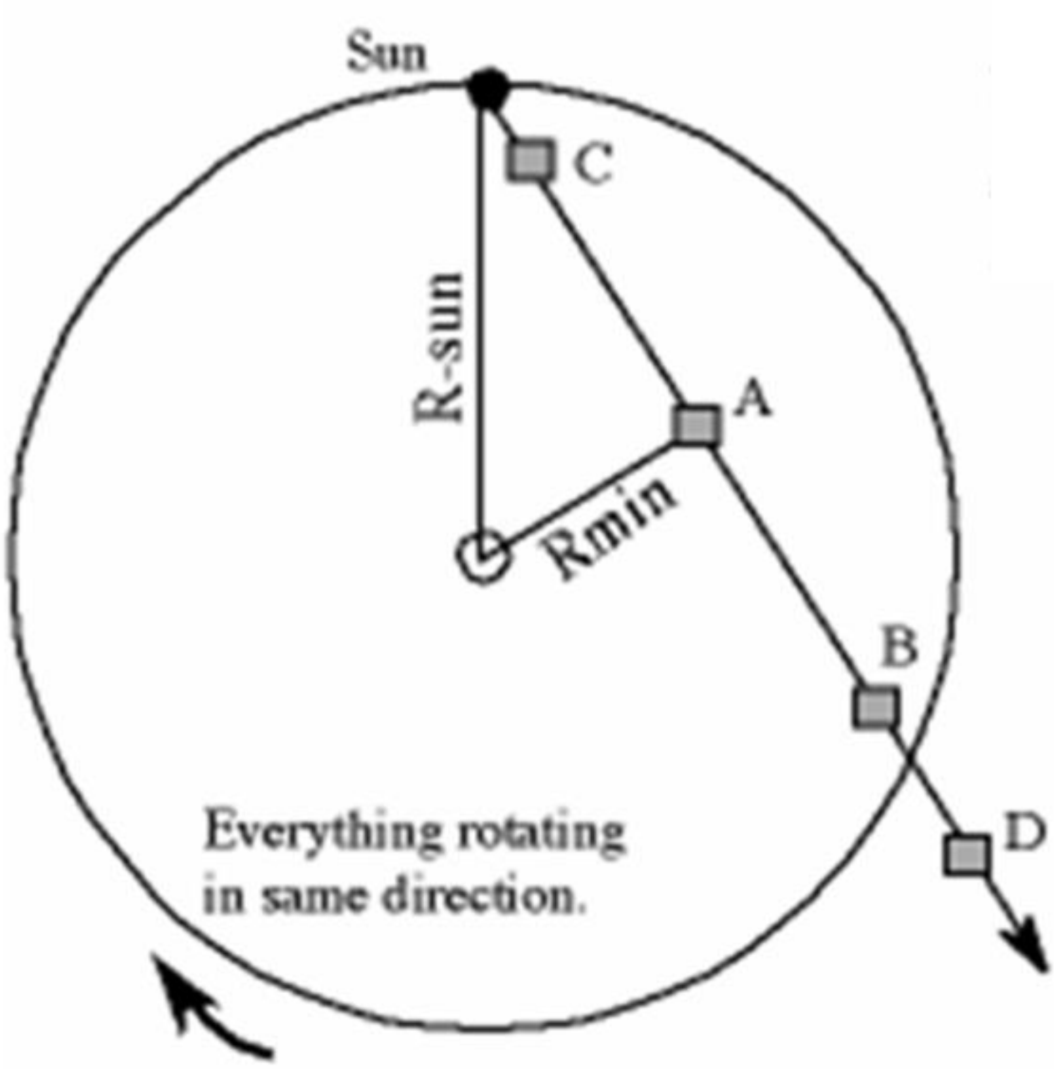
Milky Way

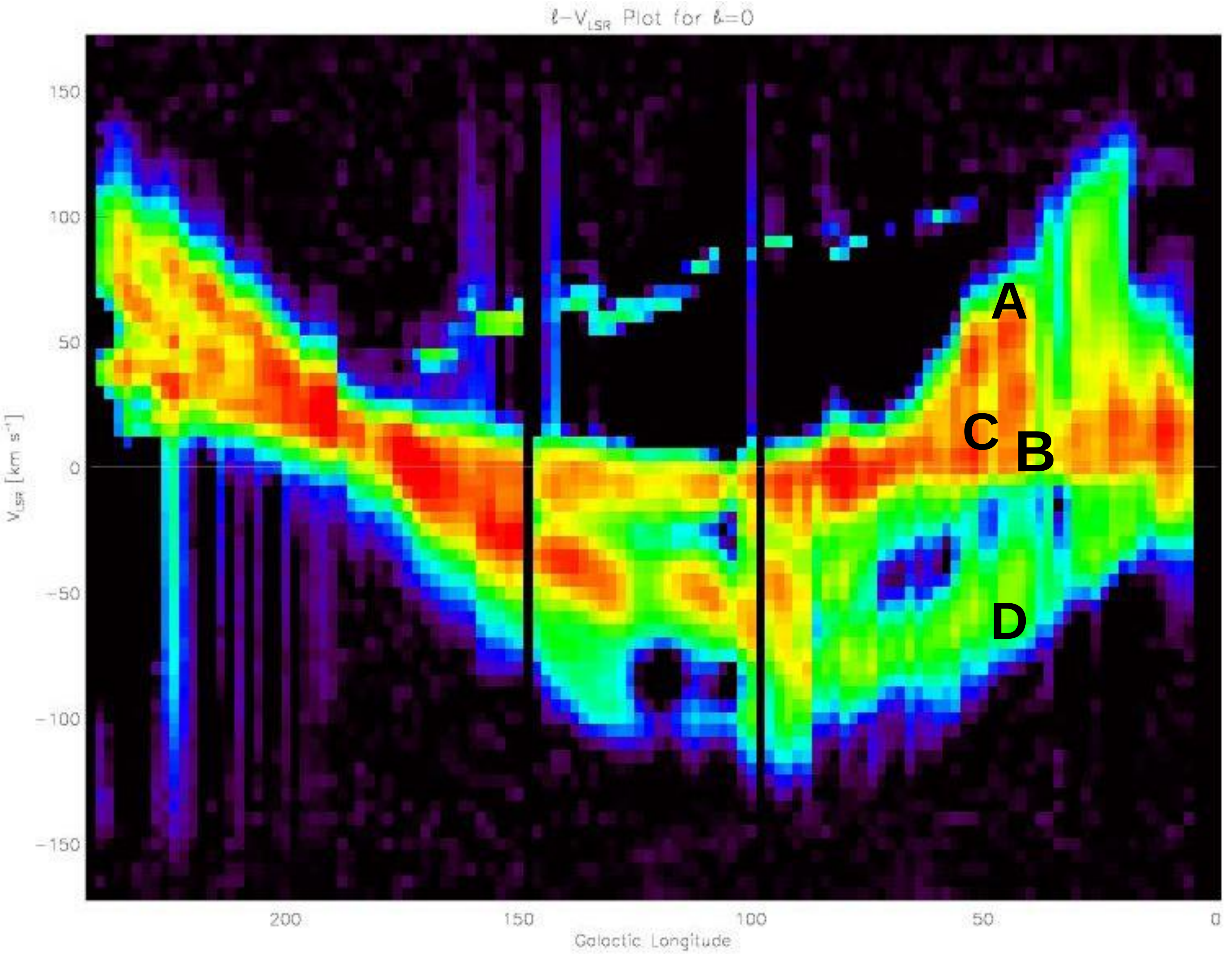
To map motion in Milky Way we must assign peaks to locations



Milky Way

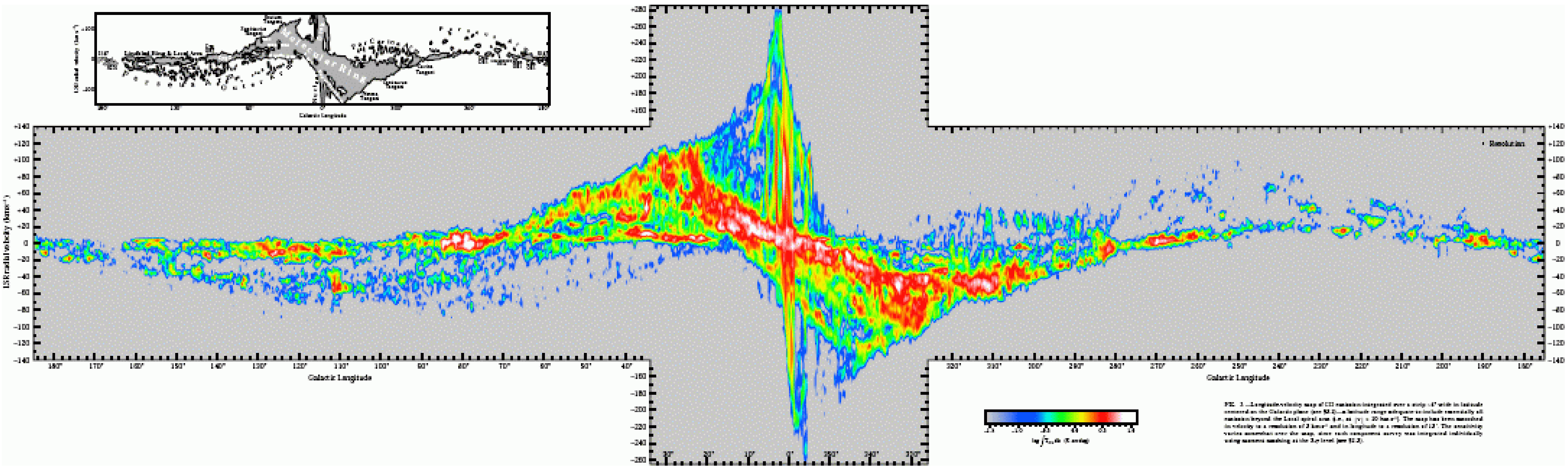
The HI in the Milky Way disk, as position vs. velocity





Milky Way

The line emission (especially HI and CO) gives speed of gas

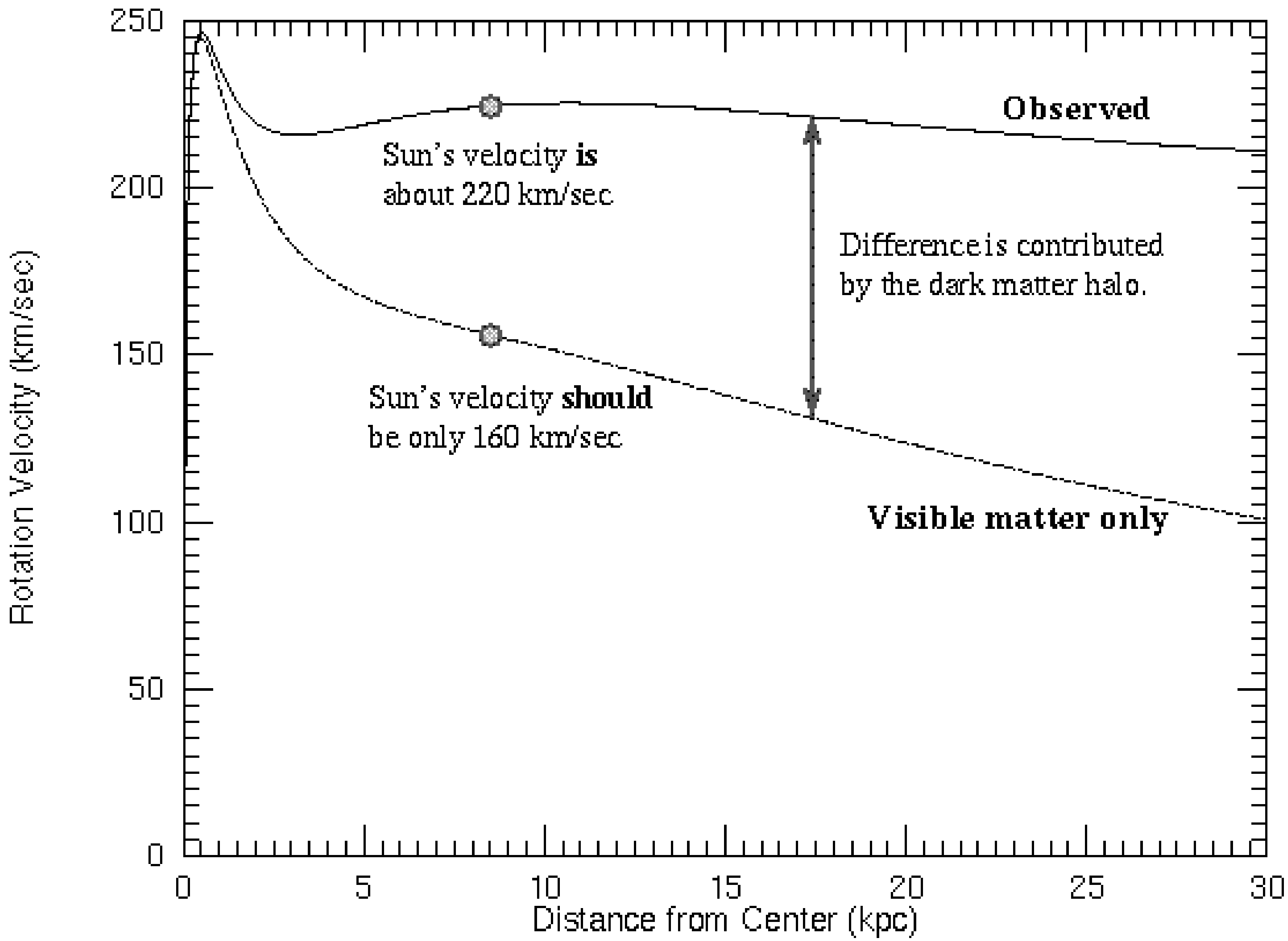


CO in the MW plane, motion relative to Sun

Positive velocity = away from us

Milky Way

Orbital speed in MW is almost constant outside of center



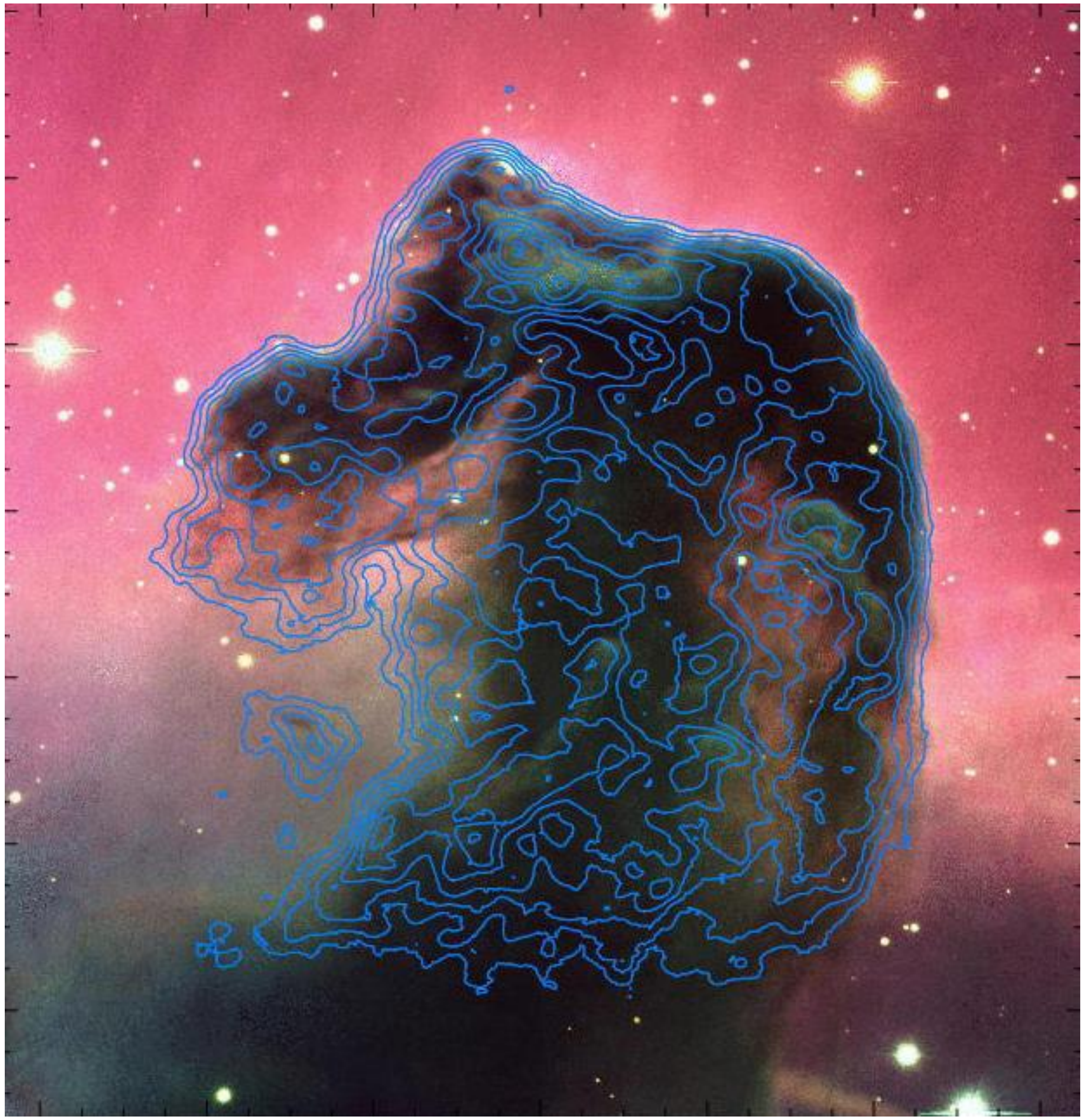
Stellar Lifecycles

Large complexes of dust, H II regions, molecules: cradle of stars

Stellar Lifecycles

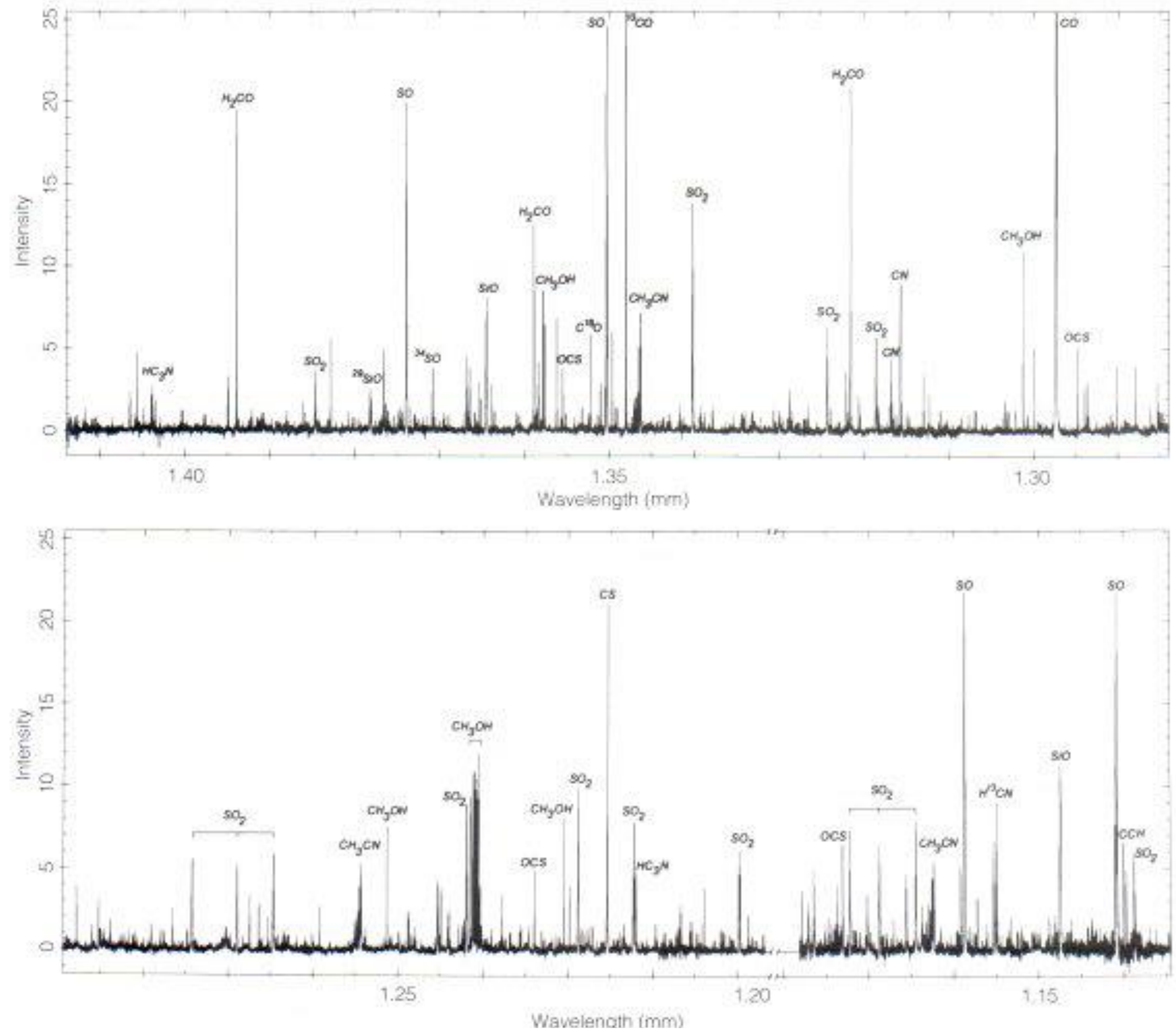
Proto-stars are usually shrouded in dust

Plus molecules like CO



Stellar Lifecycles

Millimeter band is particularly rich in molecular emission

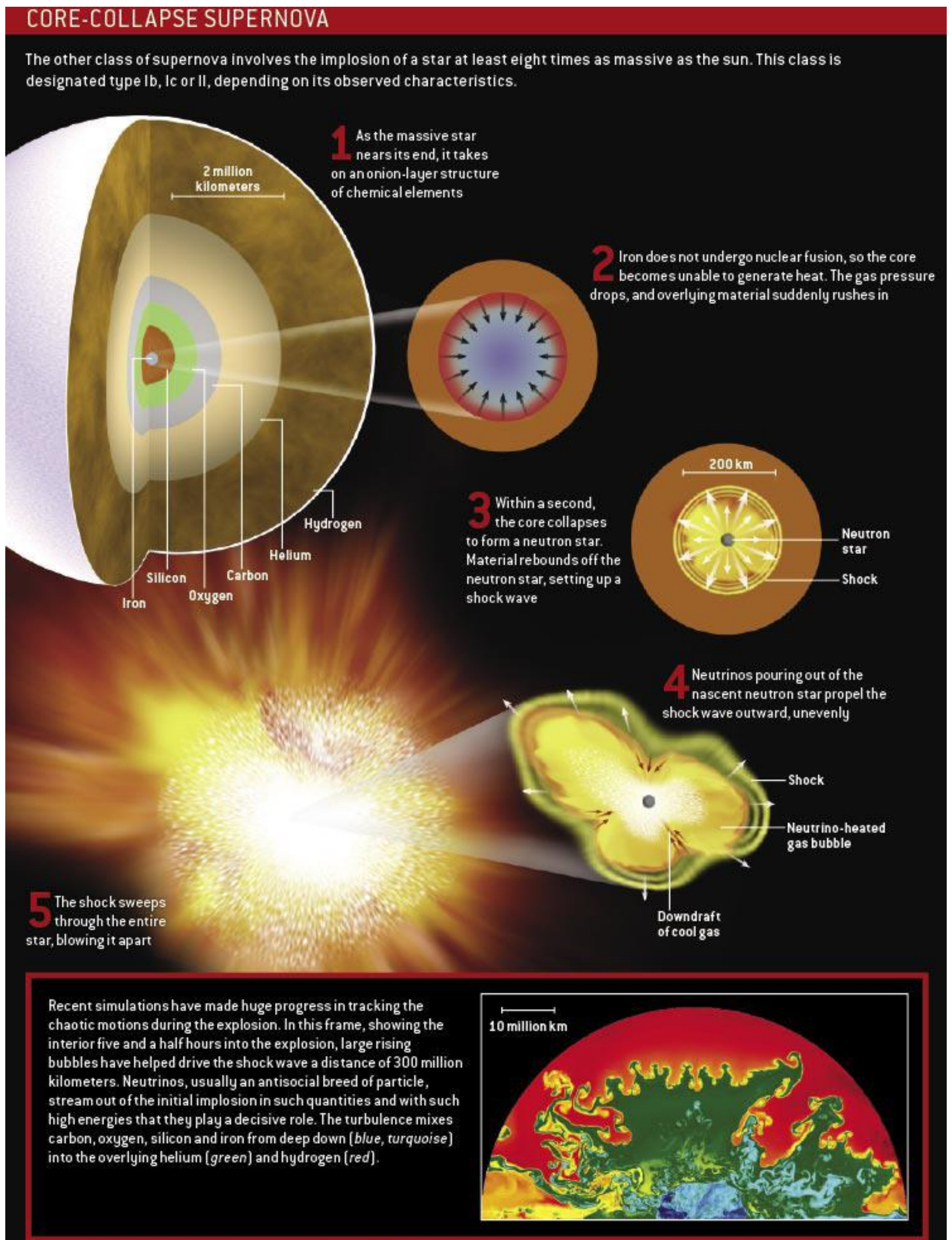


Stellar Lifecycles

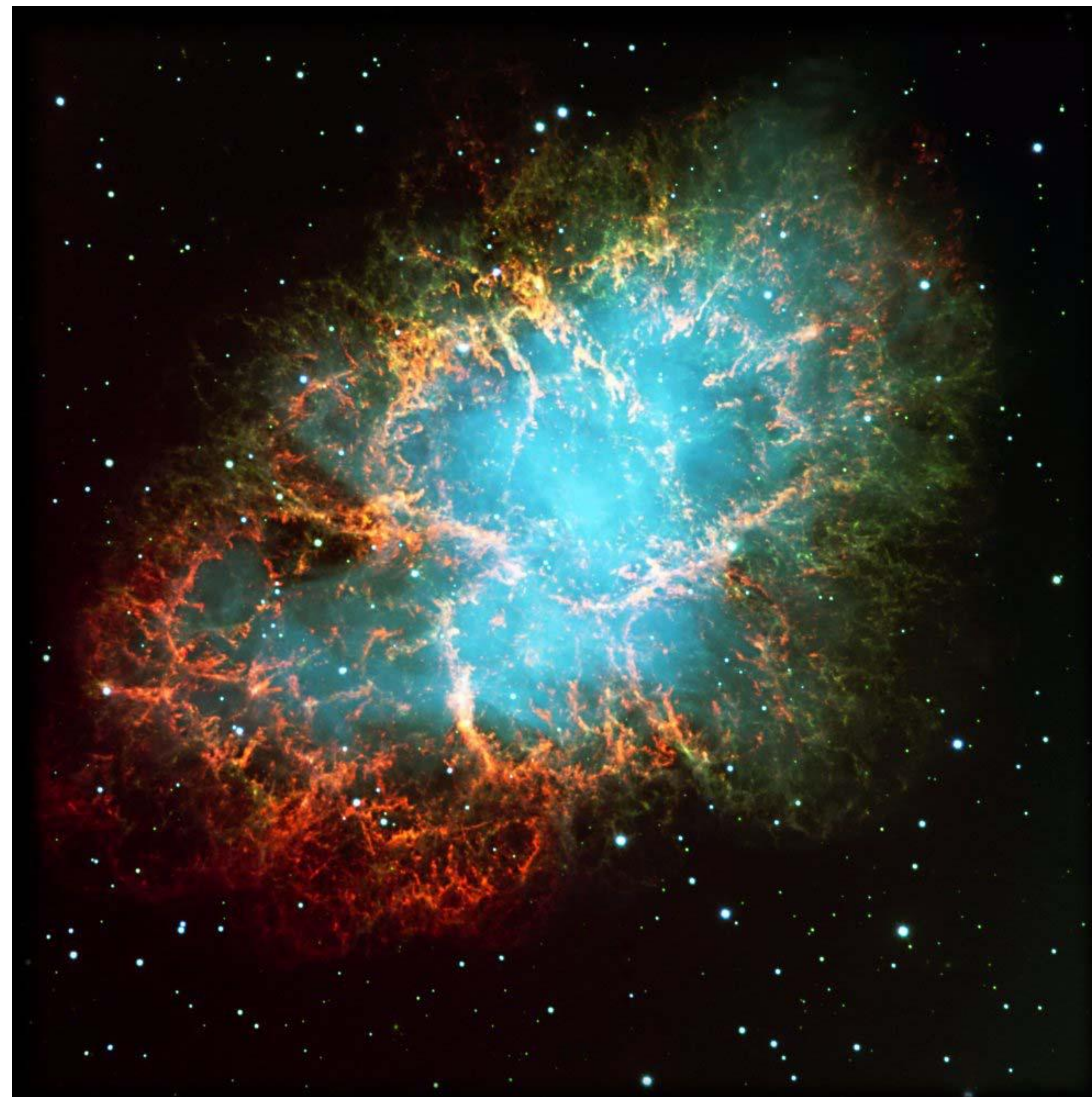
Millimeter band is particularly rich in molecular emission: ALMA now allows for *mm imaging*

Stellar Lifecycles

Massive stars then explode in supernovae

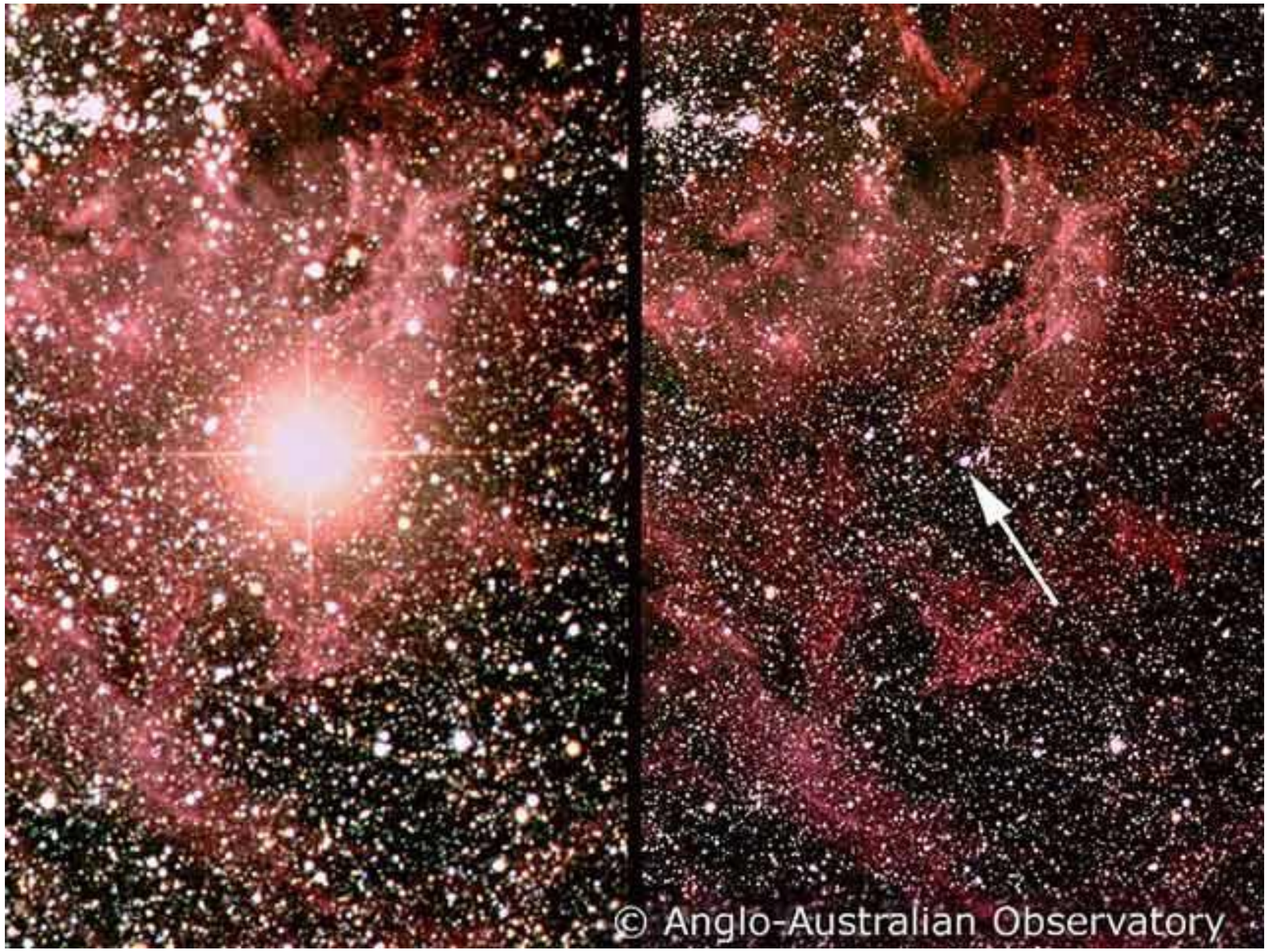


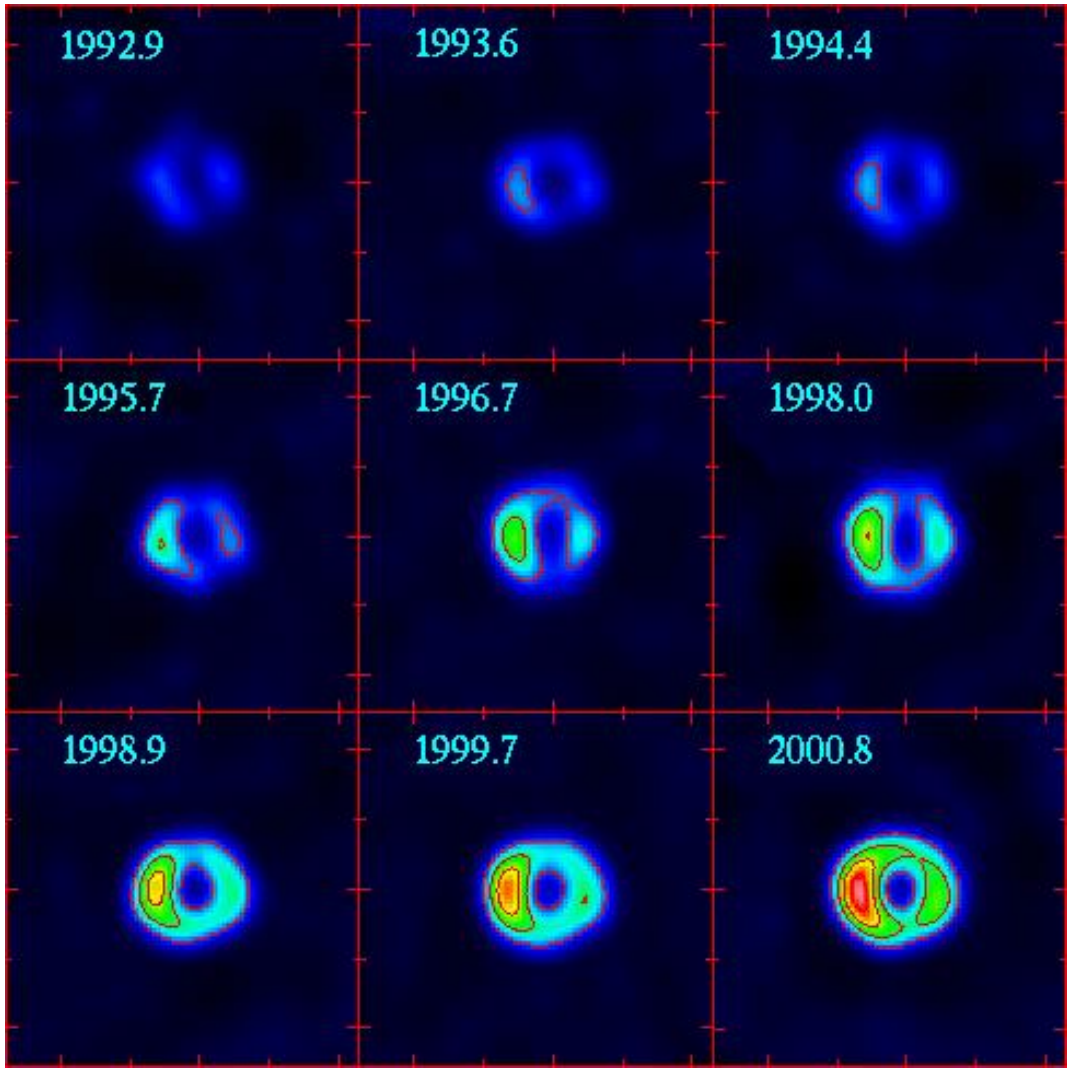
DON DIXON (*illustrations*); KONSTANTINOS KIFONIDIS *Max Planck Institute for Astrophysics* (*simulation*)



Stellar Lifecycles

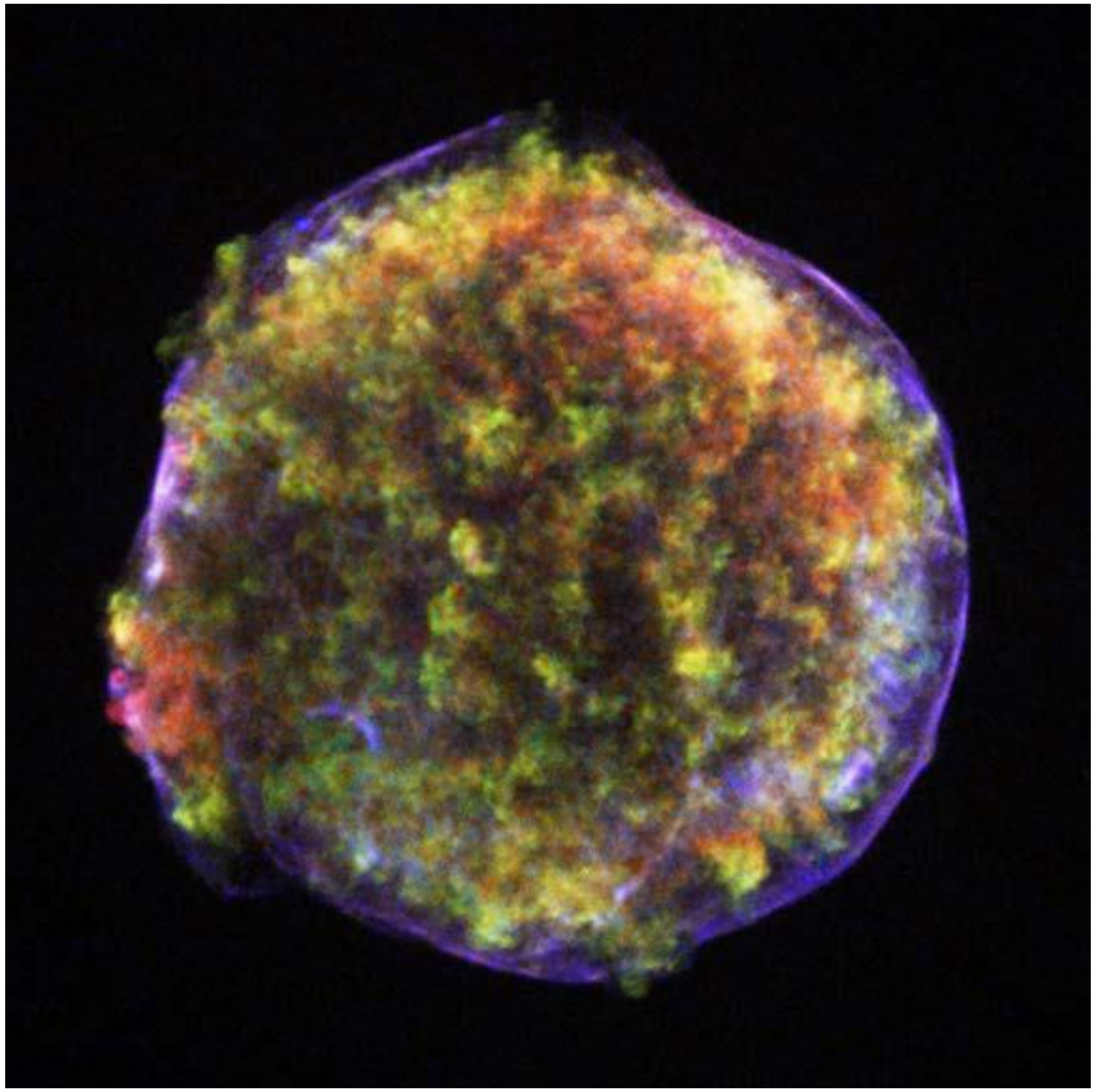
Explosion produces a shell-like shock (cf. SN87a):

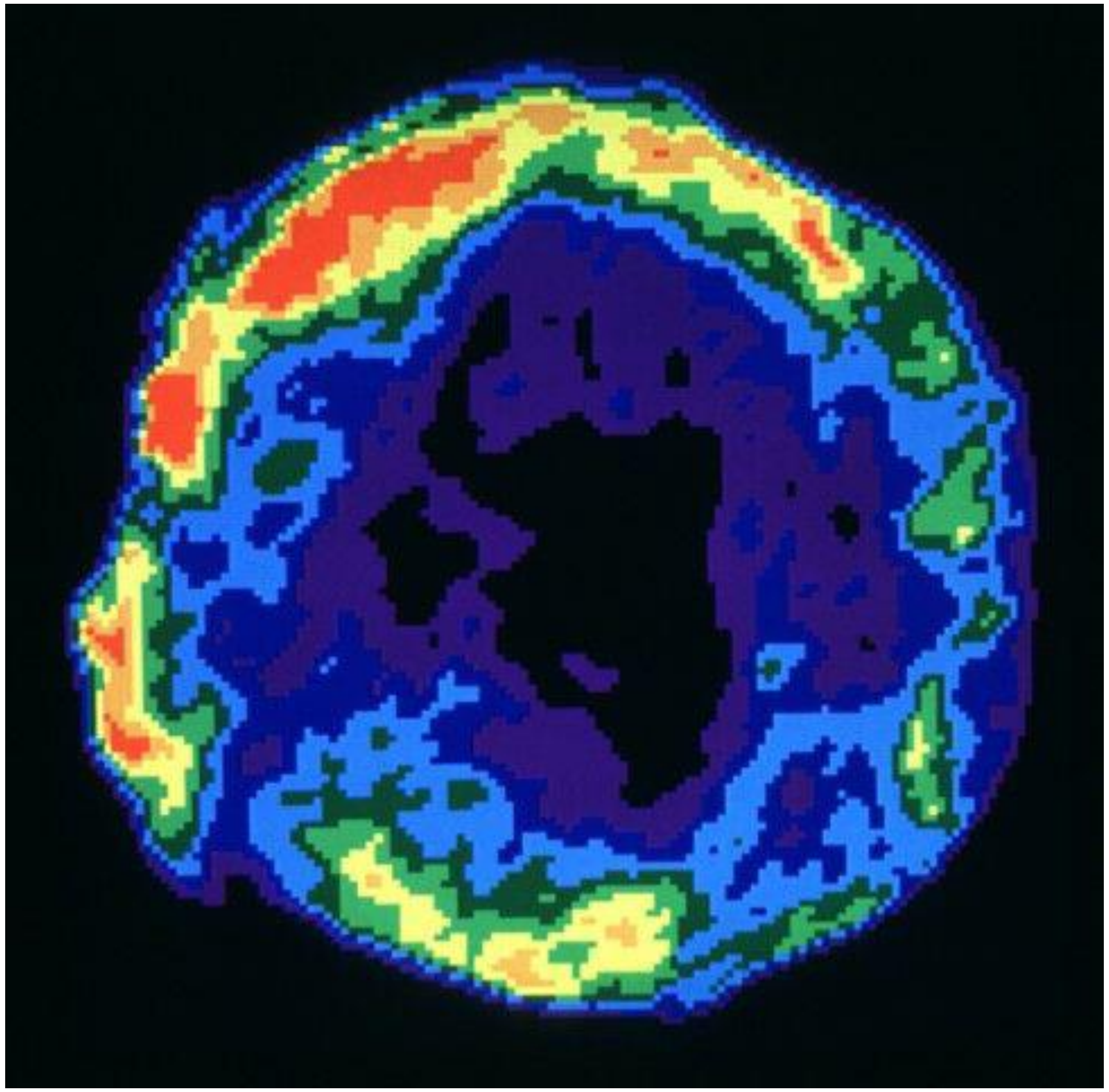




Stellar Lifecycles

Then a supernova remnant. The SNR from the "nova" seen by Tycho in 1572 show (x-ray, radio)





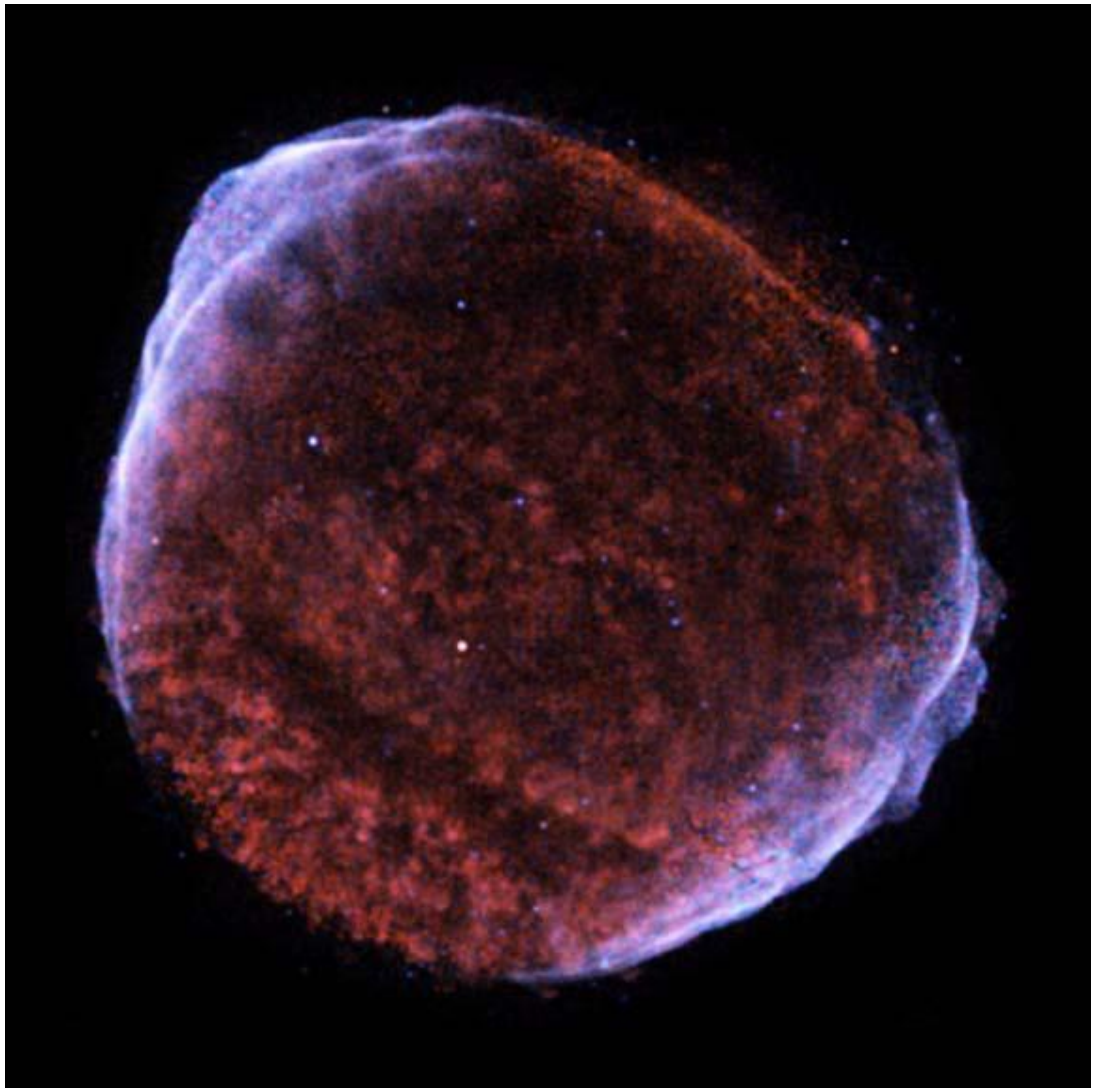
Stellar Lifecycles

Supernova remnant of the SN 1006 AD

X-rays thermal, 10^6K gas (red) heated in shock

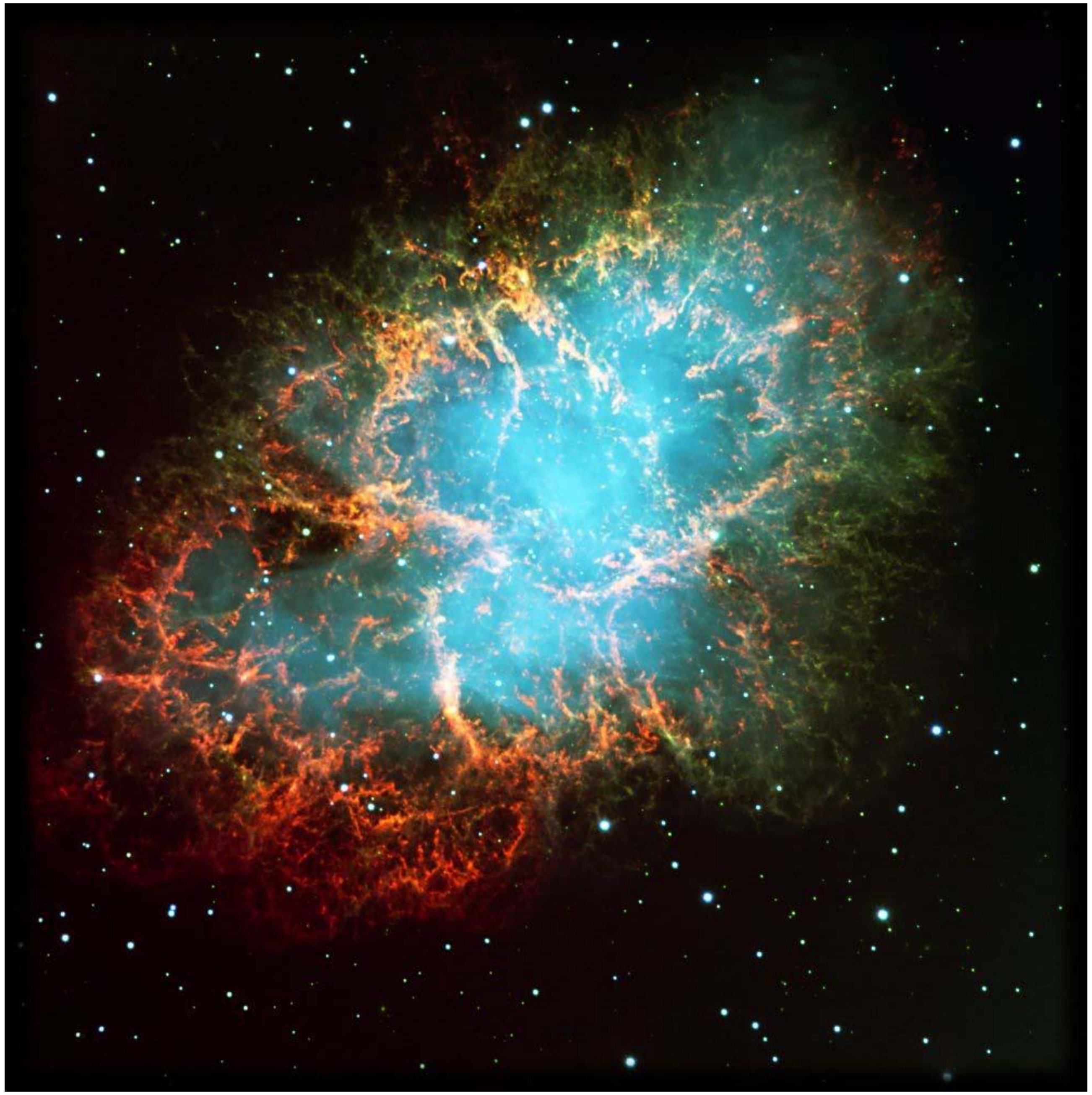
Shock boosts electrons to ~c : synchrotron (blue)

Synchrotron causes radio (next lecture)



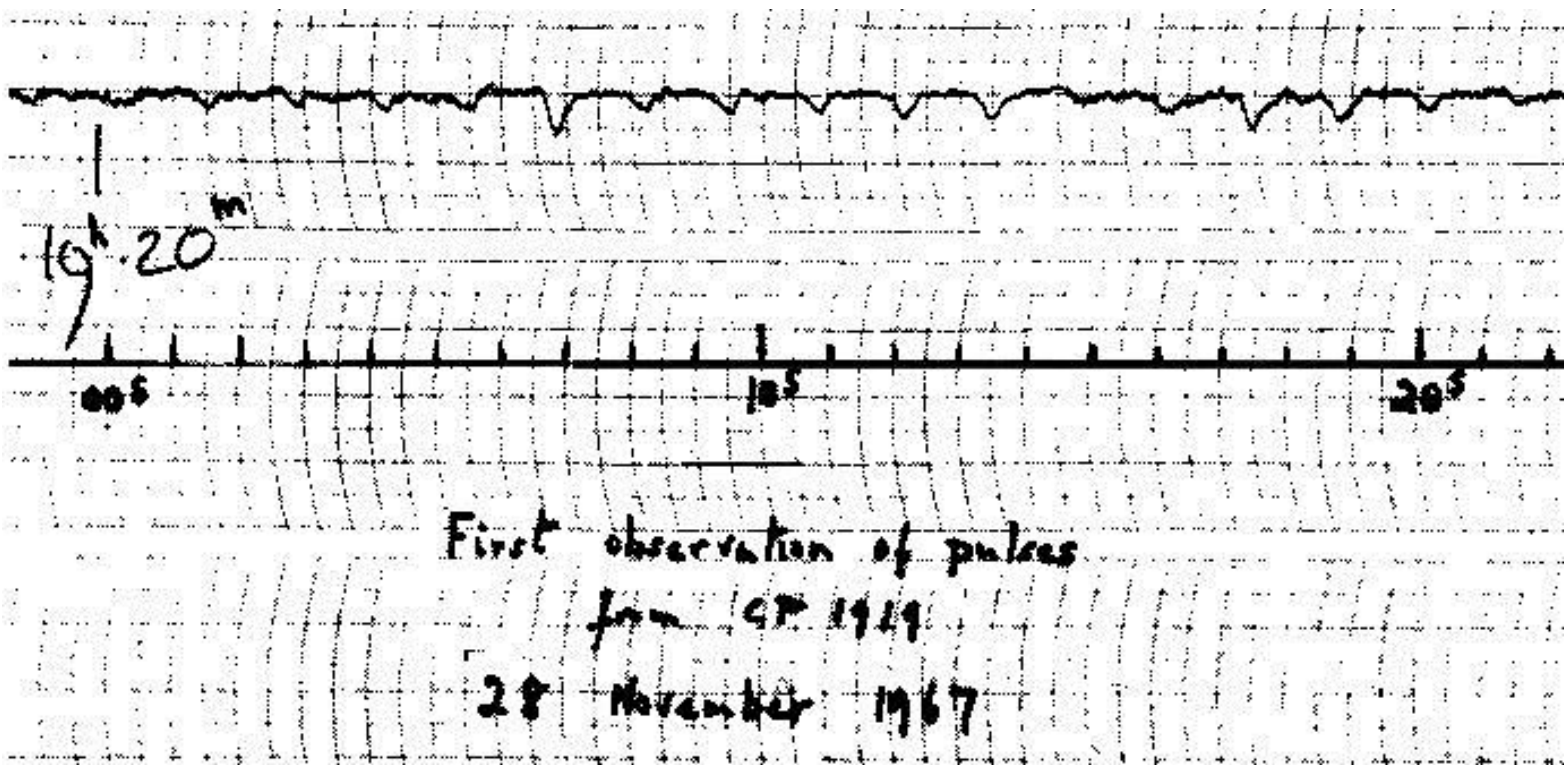
Stellar Lifecycles

Some supernova remants continue to be powered ..
.. but by what?



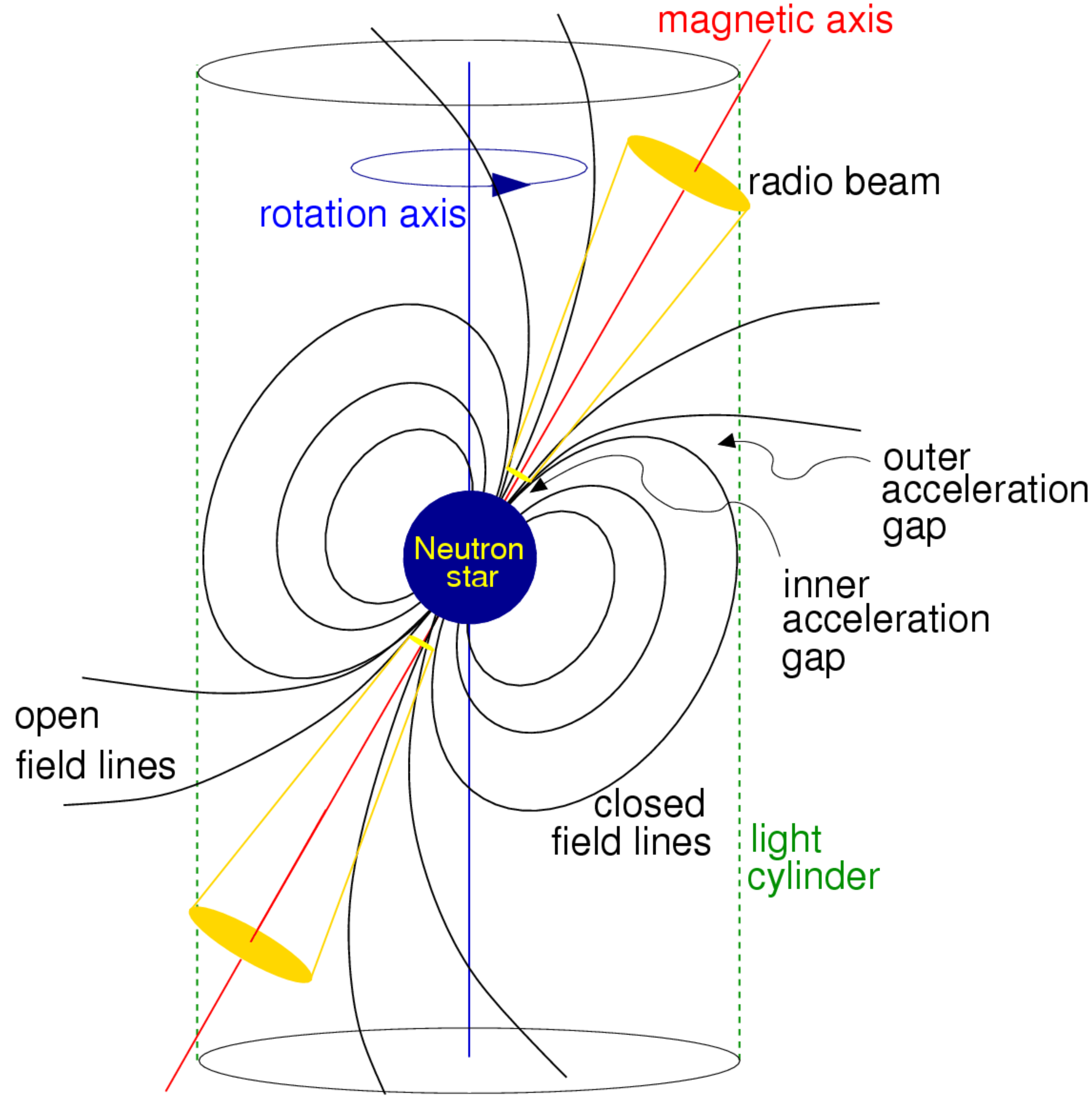
Pulsars

Discovered serendipitously in 1967 during a low-frequency survey of extragalactic radio sources that scintillate in the interplanetary plasma.



Pulsars

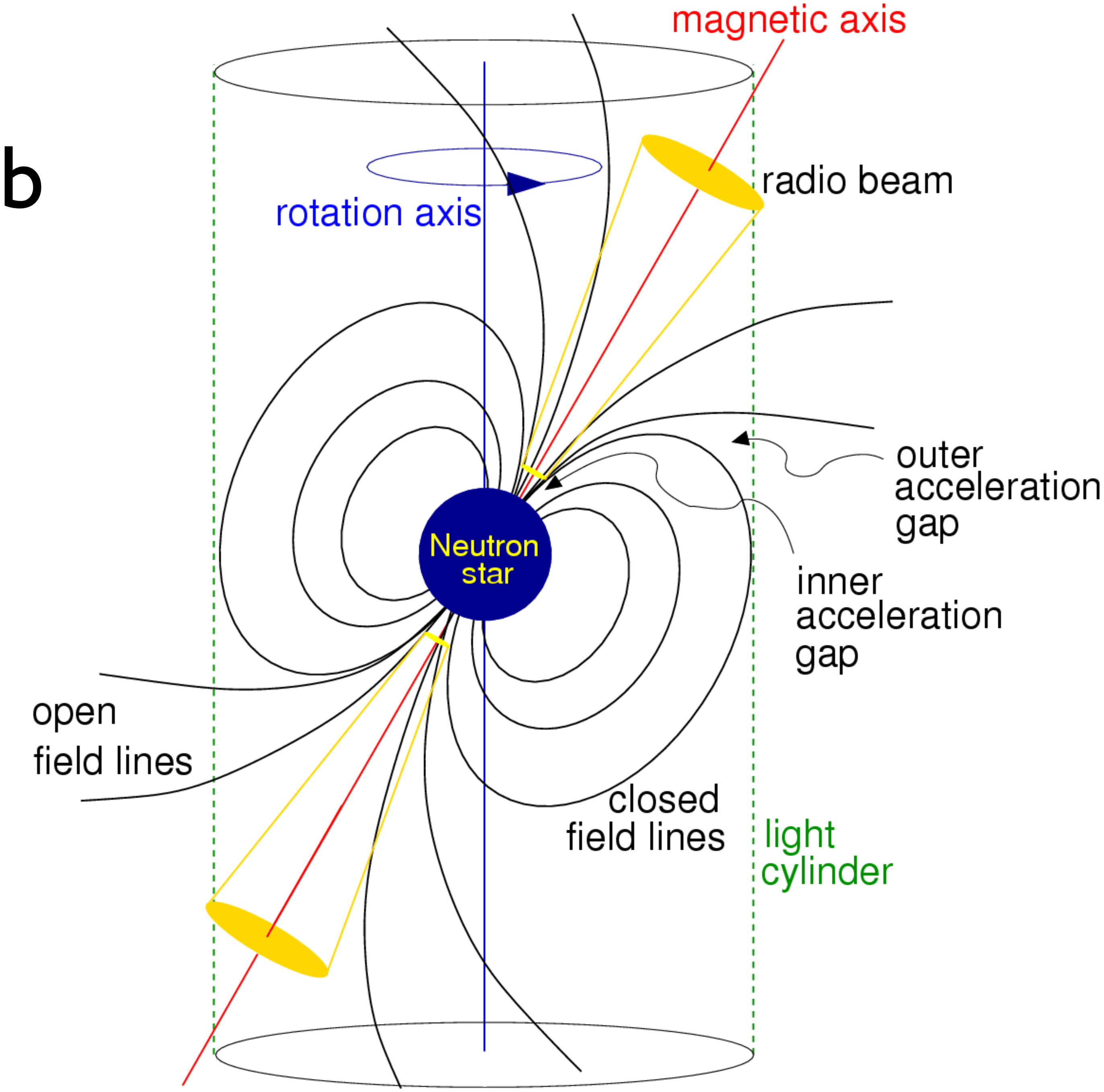
Radio emission generated near polar cap



Pulsars

Radio emission generated near polar cap

Most energy goes in "Poynting flux". For Crab 10^5 Solar luminosities



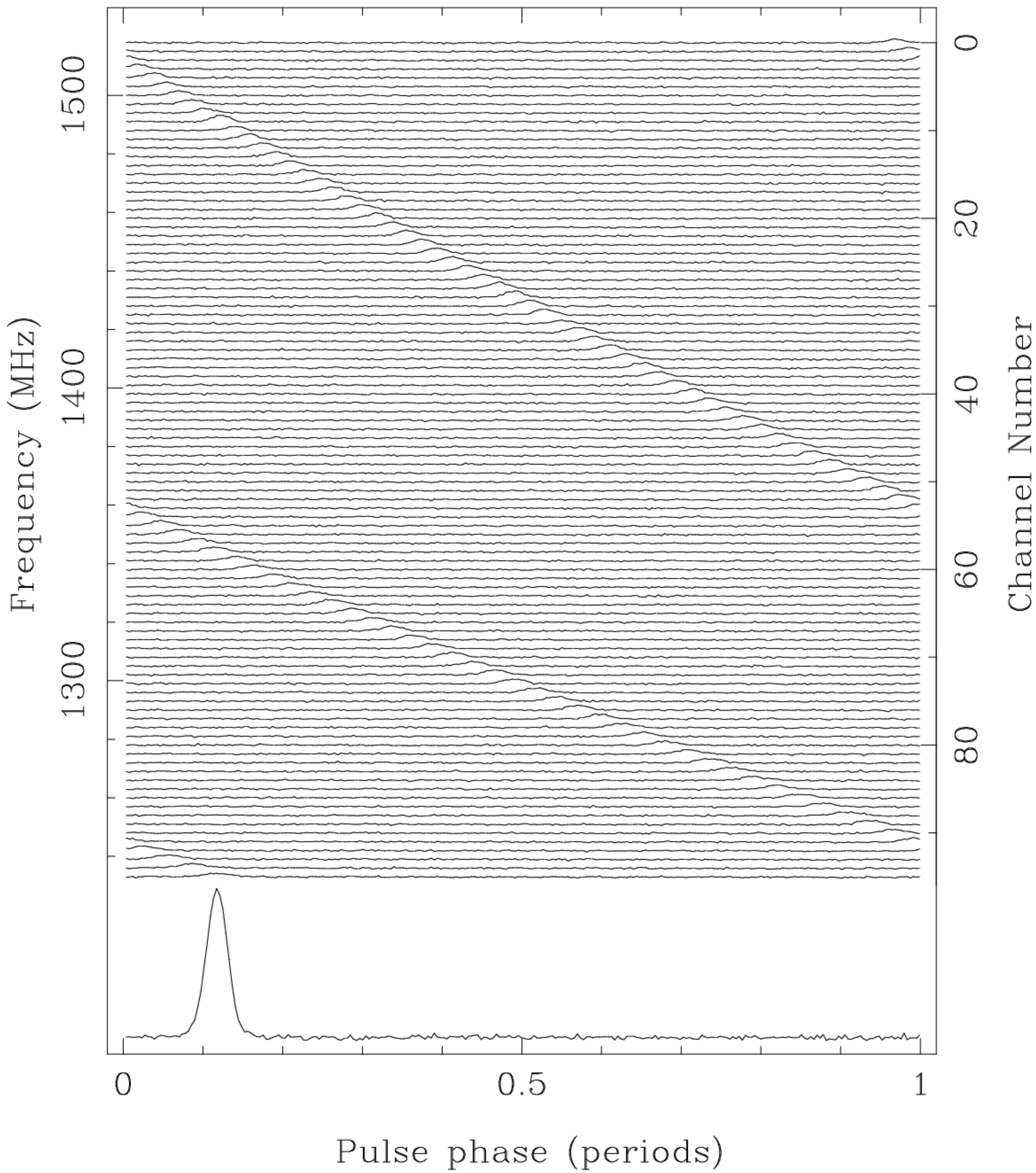
Pulsars & the ISM

With their sharp and short-duration pulse profiles and very high brightness temperatures, pulsars are unique probes of the interstellar medium (ISM). Variable group speed introduces *dispersion delay:*

$$\nu_{\rm p} = \left(\frac{e^2 n_{\rm e}}{\pi m_{\rm e}}\right)^{1/2} \approx 8.97\,{\rm kHz} \times \left(\frac{n_{\rm e}}{{\rm cm}^{-3}}\right)^{1/2}$$

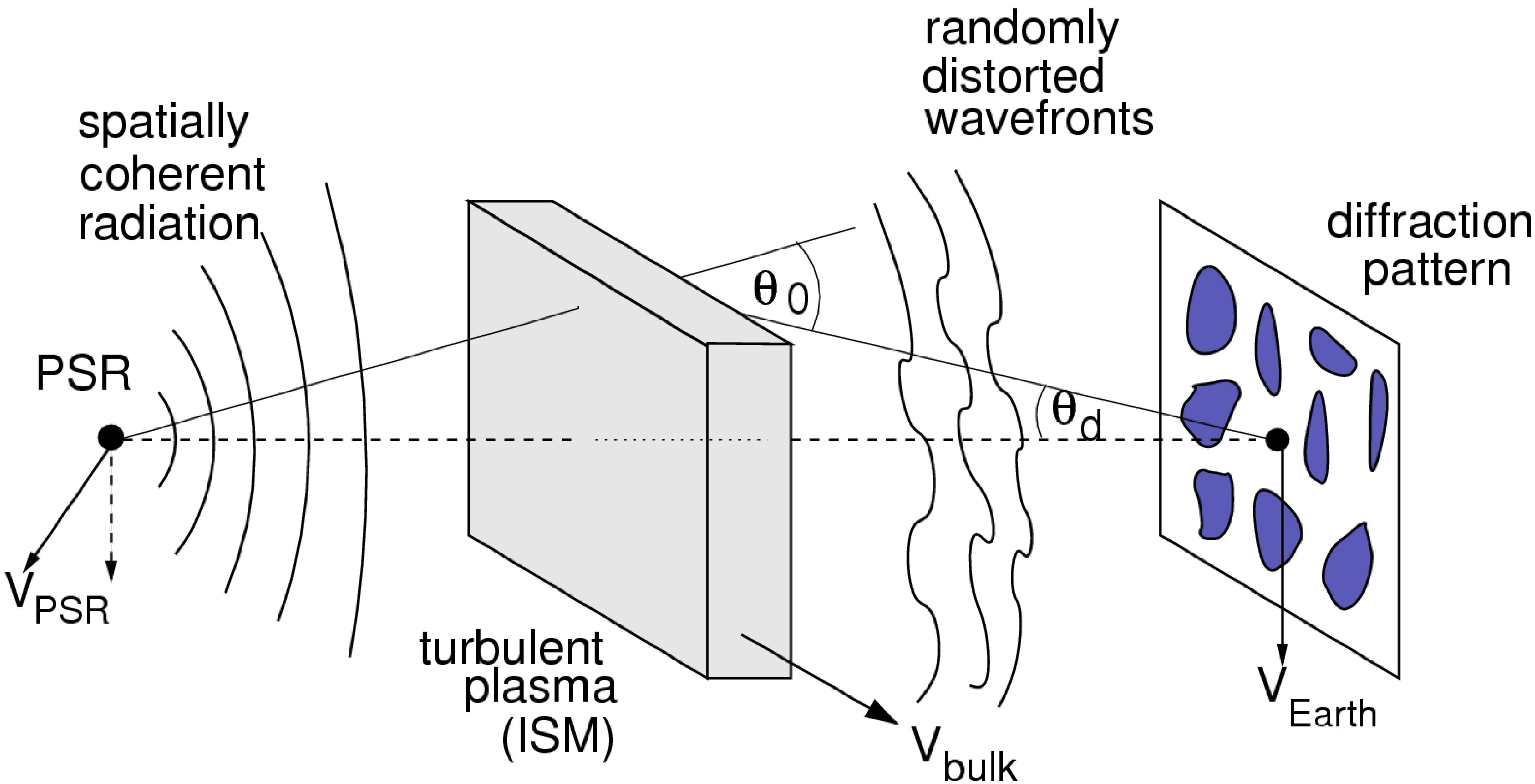
$$v_{\rm g} \approx c\left(1 - \frac{\nu_{\rm p}^2}{2\nu^2}\right)$$

Pulsars & the ISM



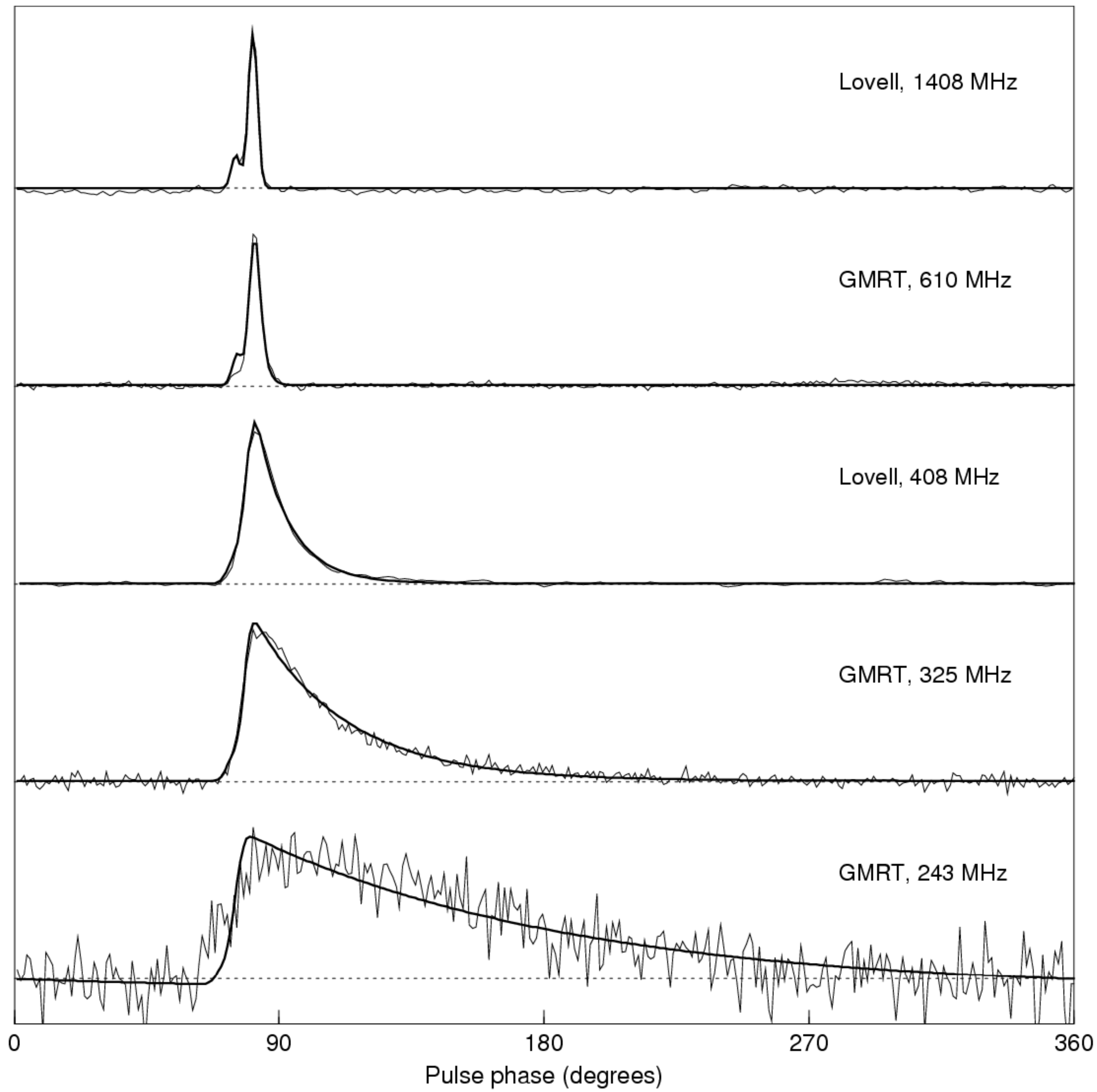
Pulsars & the ISM

Inhomogeneities in the ISM cause small-angle deviations in the paths of the radio waves.



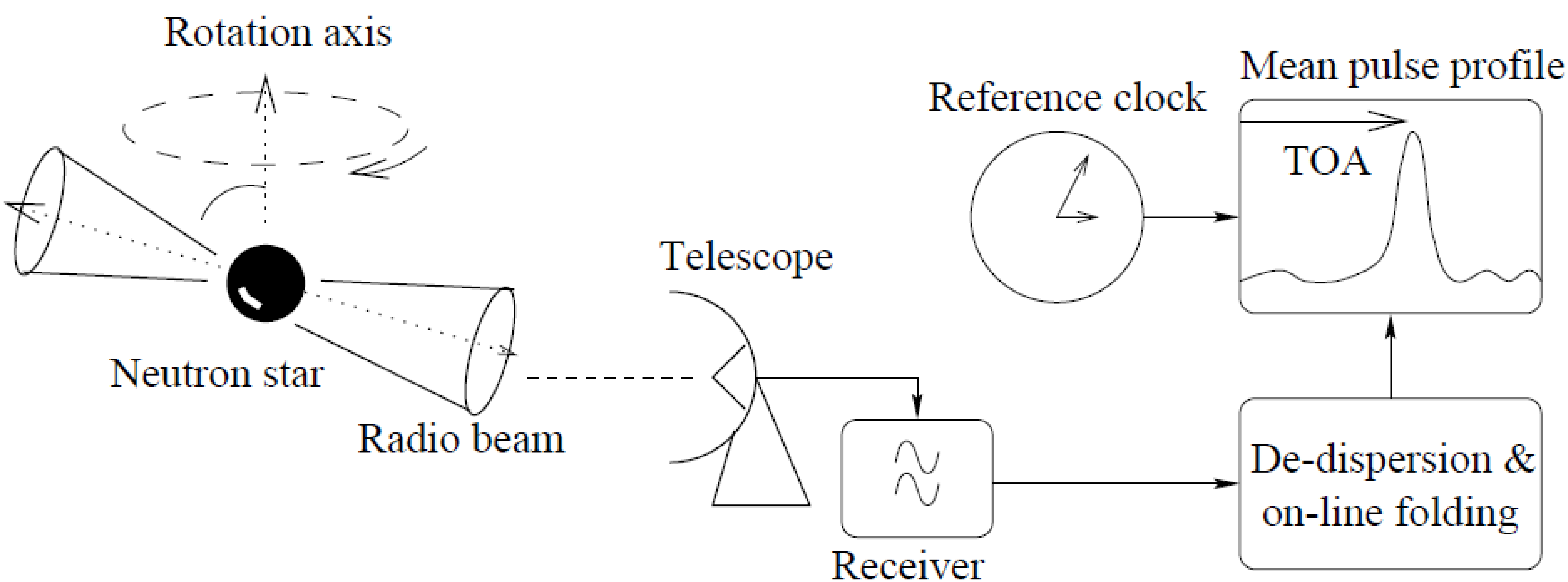
Pulsars & the ISM

These cause scattering tails on pulse profiles



Pulsar Timing

Clock-like stability of pulsars means that precise monitoring of pulsar rotations allows for study of rich variety of physics phenomena



Pulsar Timing

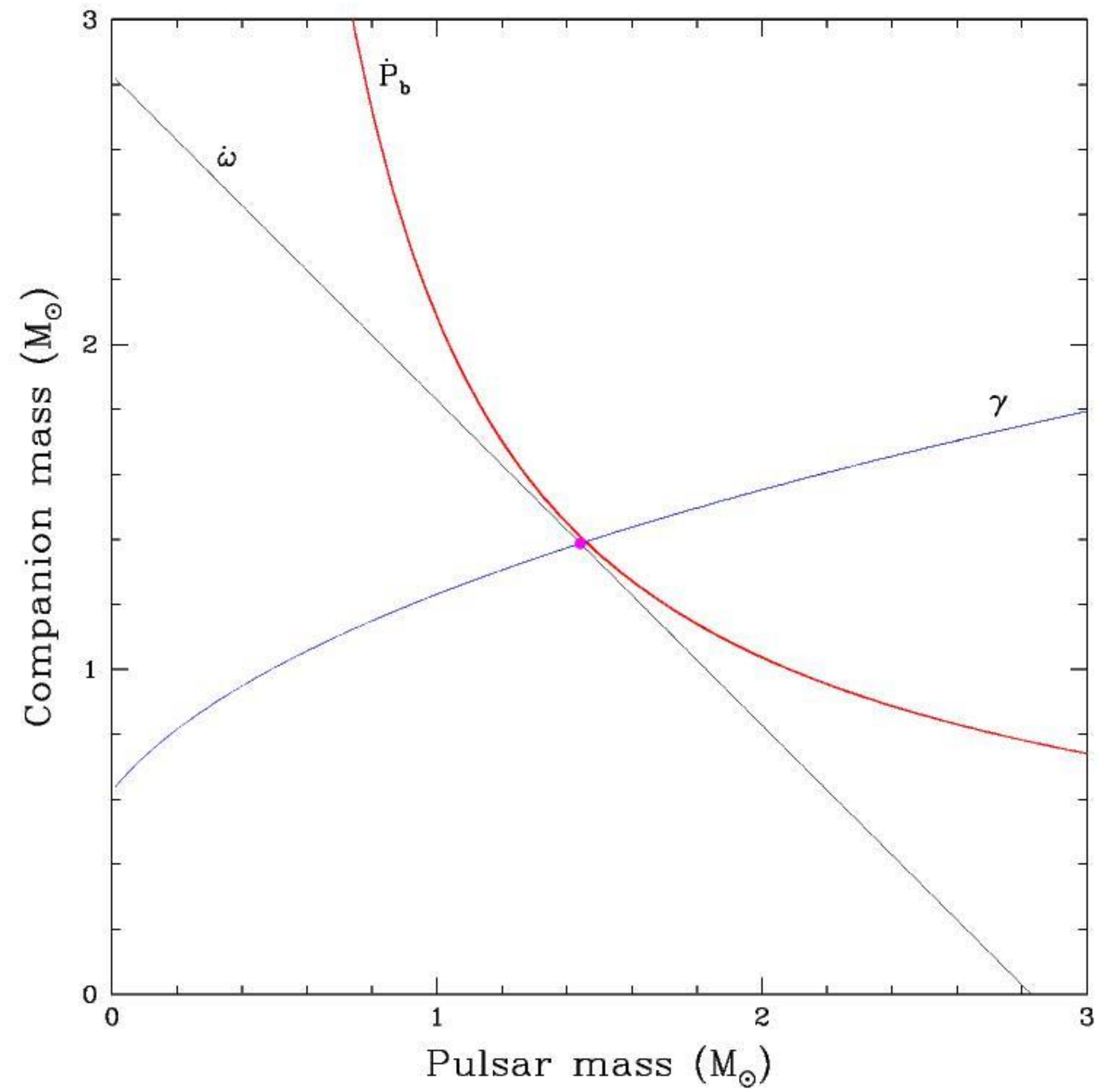
The attainable precision is extreme:

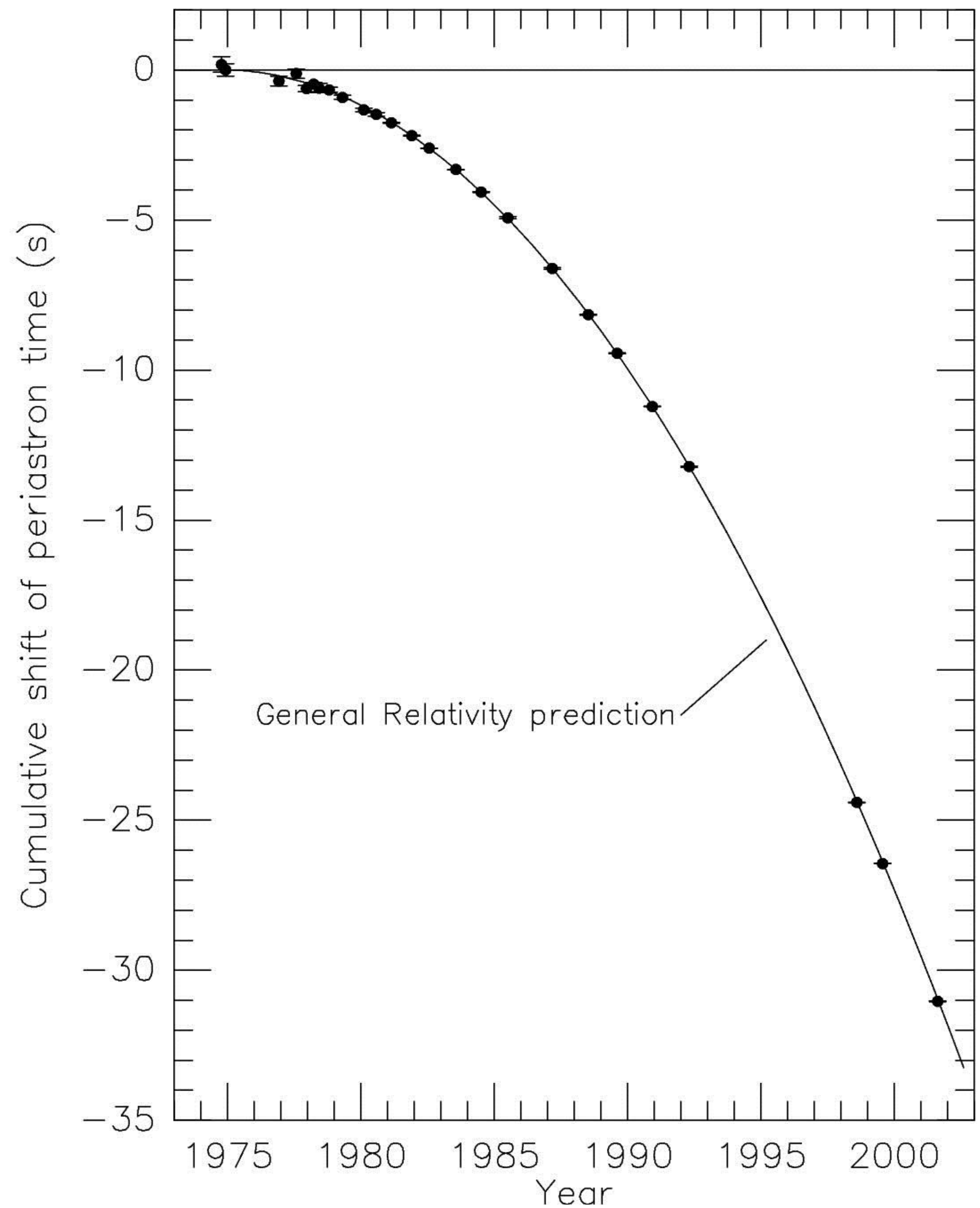
Table 1 PSR J0437–4715 physical parameters

Right ascension, α (J2000) ...	$04^h37^m15^s.7865145(7)$
Declination, δ (J2000)	$-47°15'08''.461584(8)$
μ_α (mas yr^{-1})	121.438(6)
μ_δ (mas yr^{-1})	-71.438(7)
Annual parallax, π (mas)	7.19(14)
Pulse period, P (ms)	5.757451831072007(8)
Reference epoch (MJD)	51194.0
Period derivative, $\dot{P}$ (10^{-20}) ..	5.72906(5)
Orbital period, P_b (days)	5.741046(3)
x (s)	3.36669157(14)
Orbital eccentricity, e	0.000019186(5)
Epoch of periastron, T_0 (MJD)	51194.6239(8)
Longitude of periastron, ω (°) .	1.20(5)
Longitude of ascension, Ω (°) .	238(4)
Orbital inclination, i (°)	42.75(9)
Companion mass, m_2 ($M_\odot$) ...	0.236(17)
$\dot{P}_b$(10^{-12})	3.64(20)
$\dot{\omega}$ (° yr^{-1})	0.016(10)

Pulsar Timing

The attainable precision is extreme:

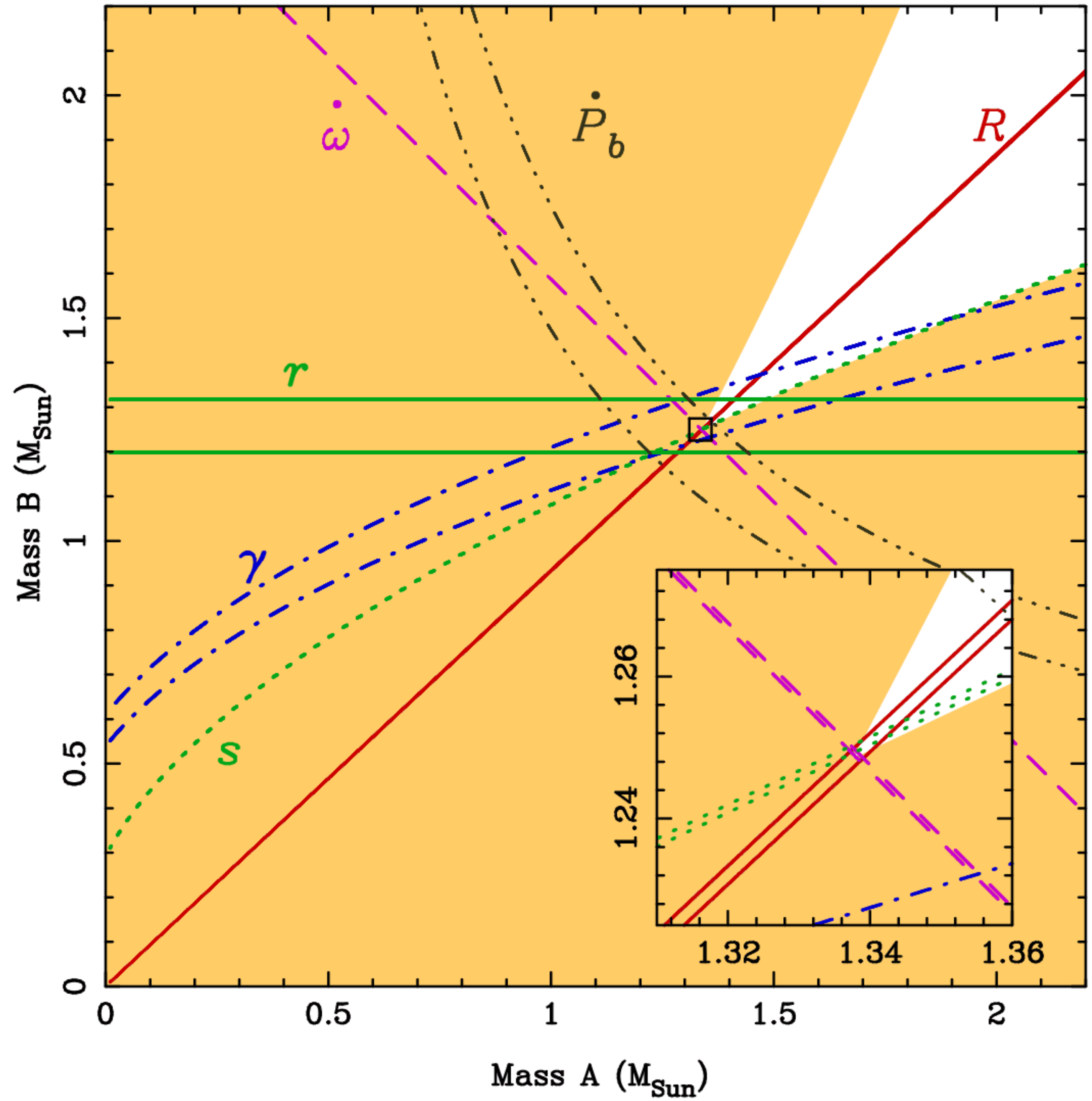




Pulsar Timing

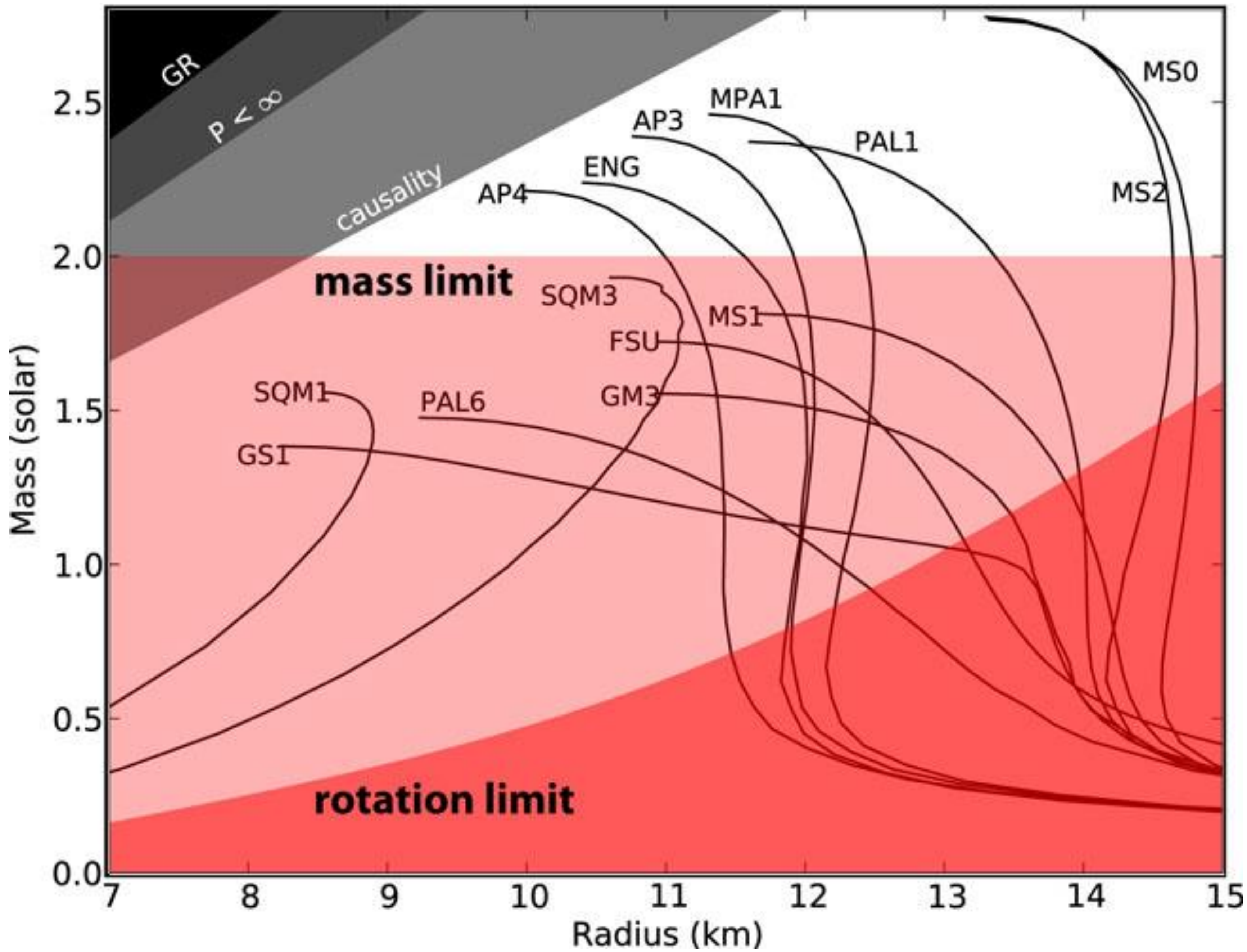
The attainable precision is extreme:

The double pulsar is one of the best tests of general relativity



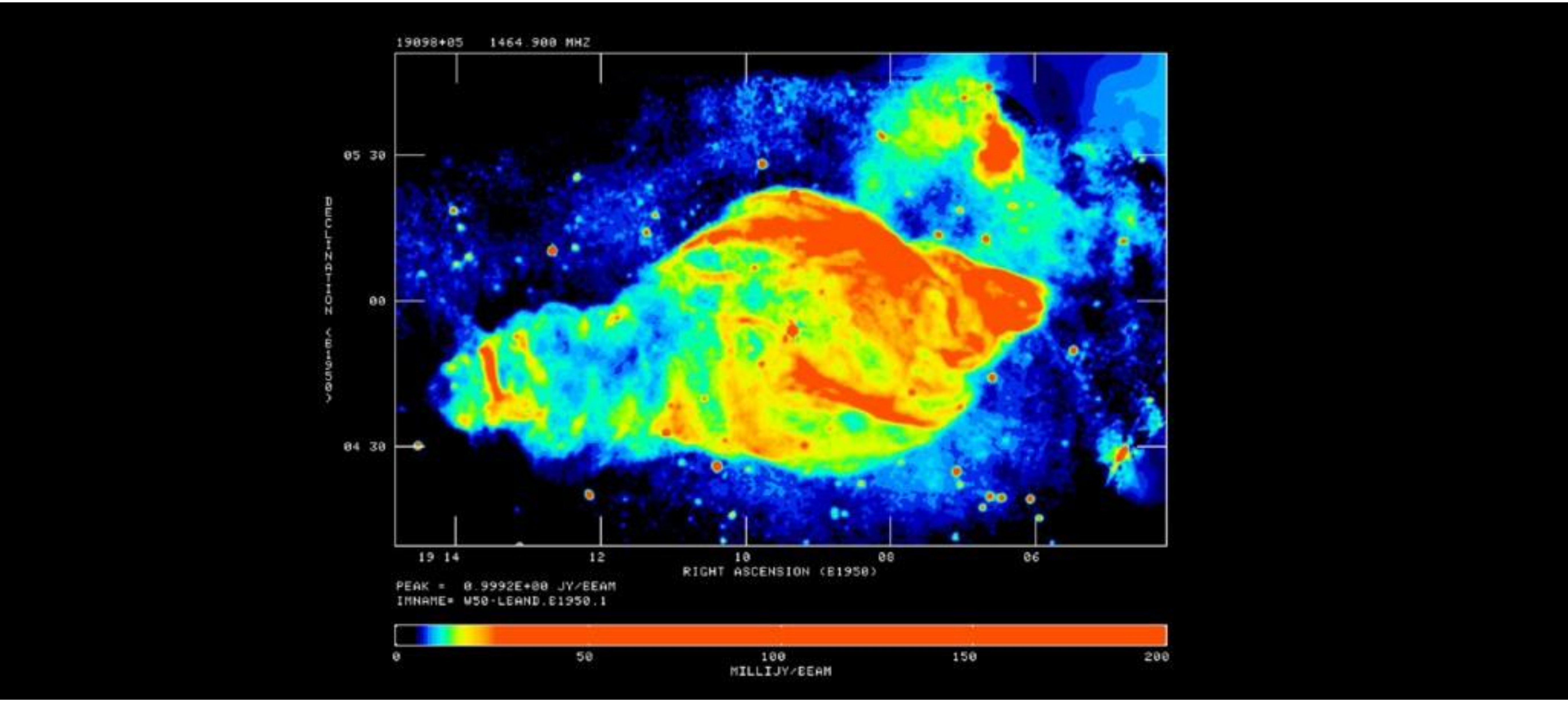
Pulsar Timing

One of the few ways to "weigh" a star, and determine its composition:



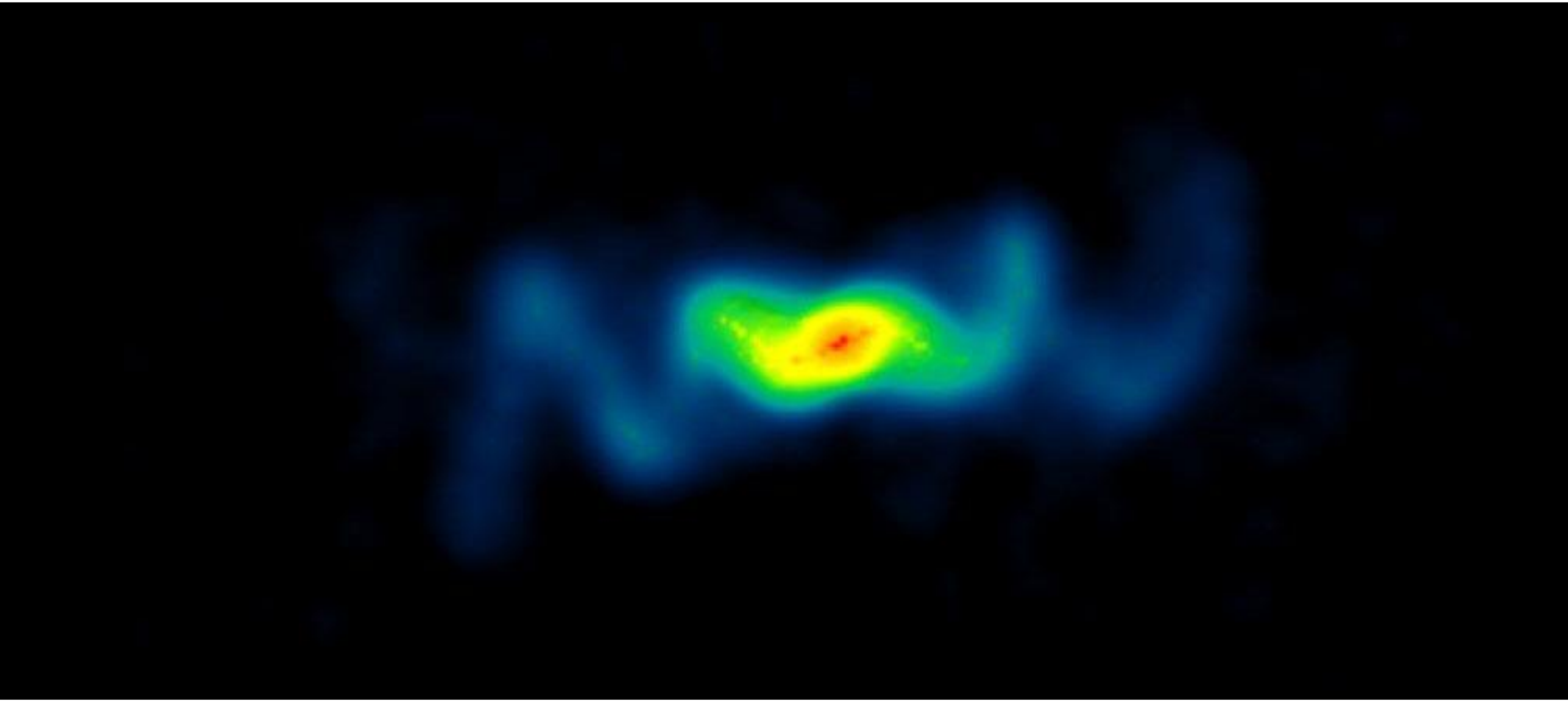
Black Holes

Supernova remnant W50 (~20 kyr) with the central microquasar SS433



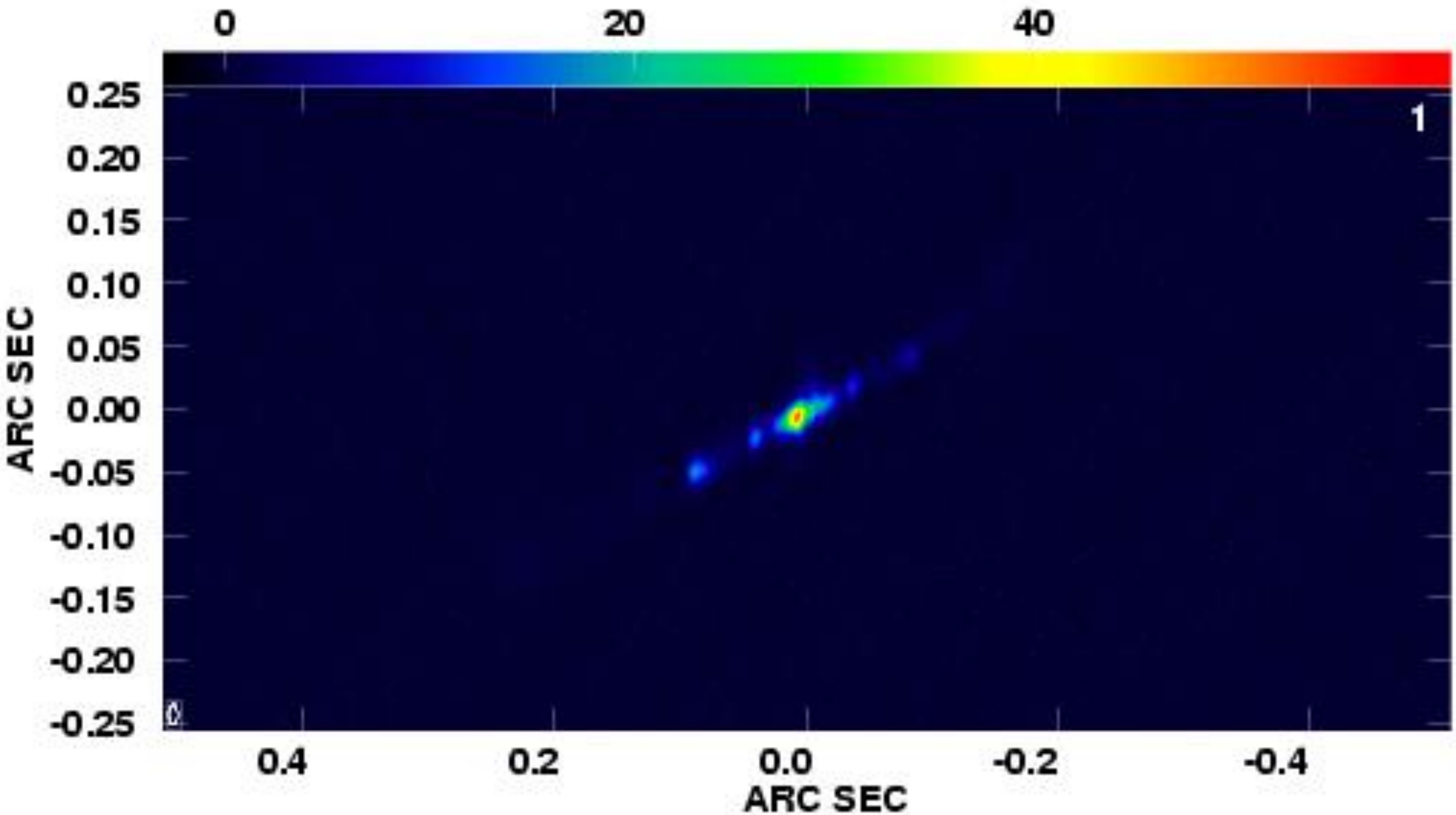
Black Holes

Eclipsing X-ray binary system, compact-object mass indicates black hole



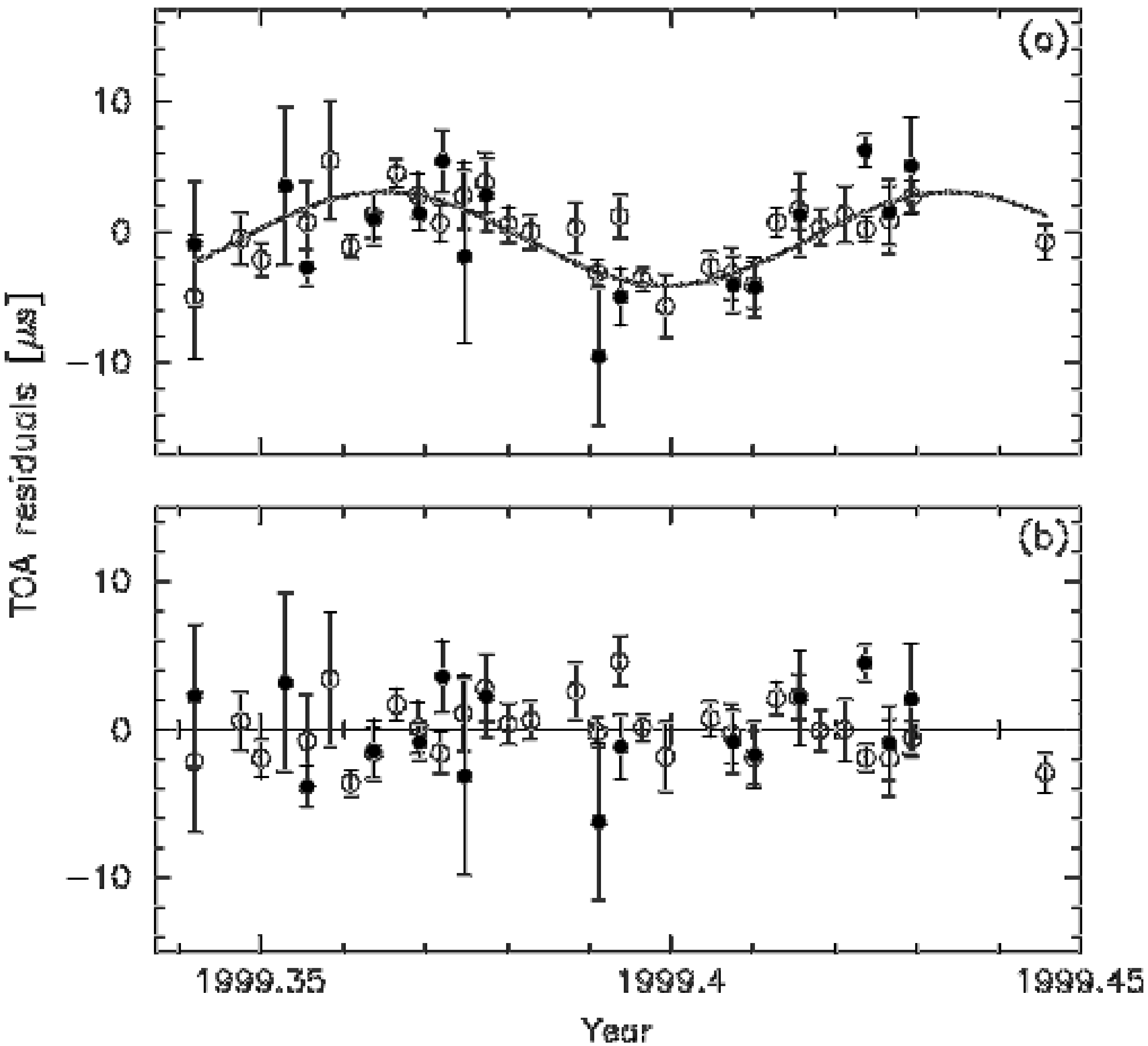
Black Holes

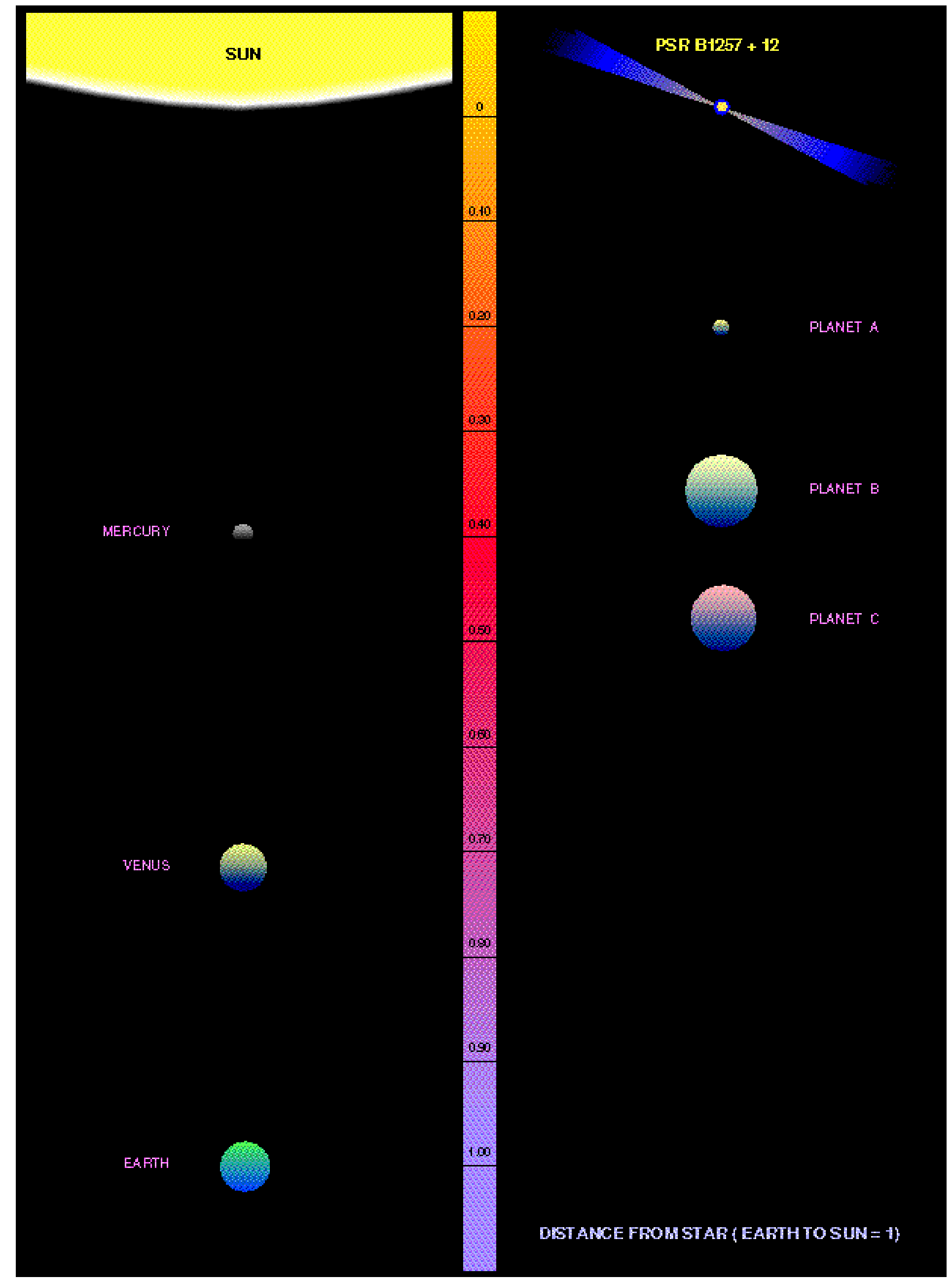
Eclipsing X-ray binary system



Exoplanets

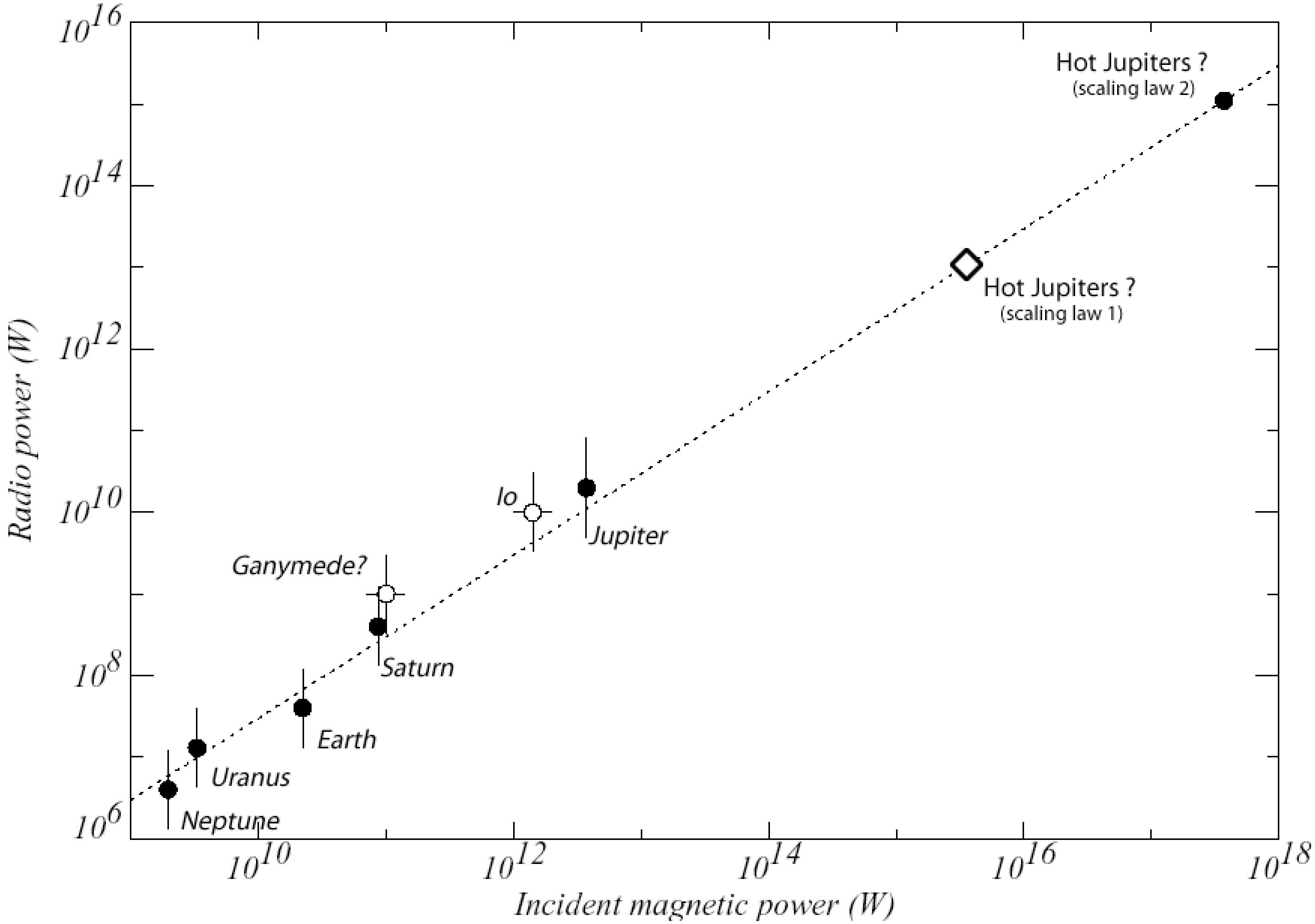
The first extra-solar planets were detected around a pulsar





Exoplanets

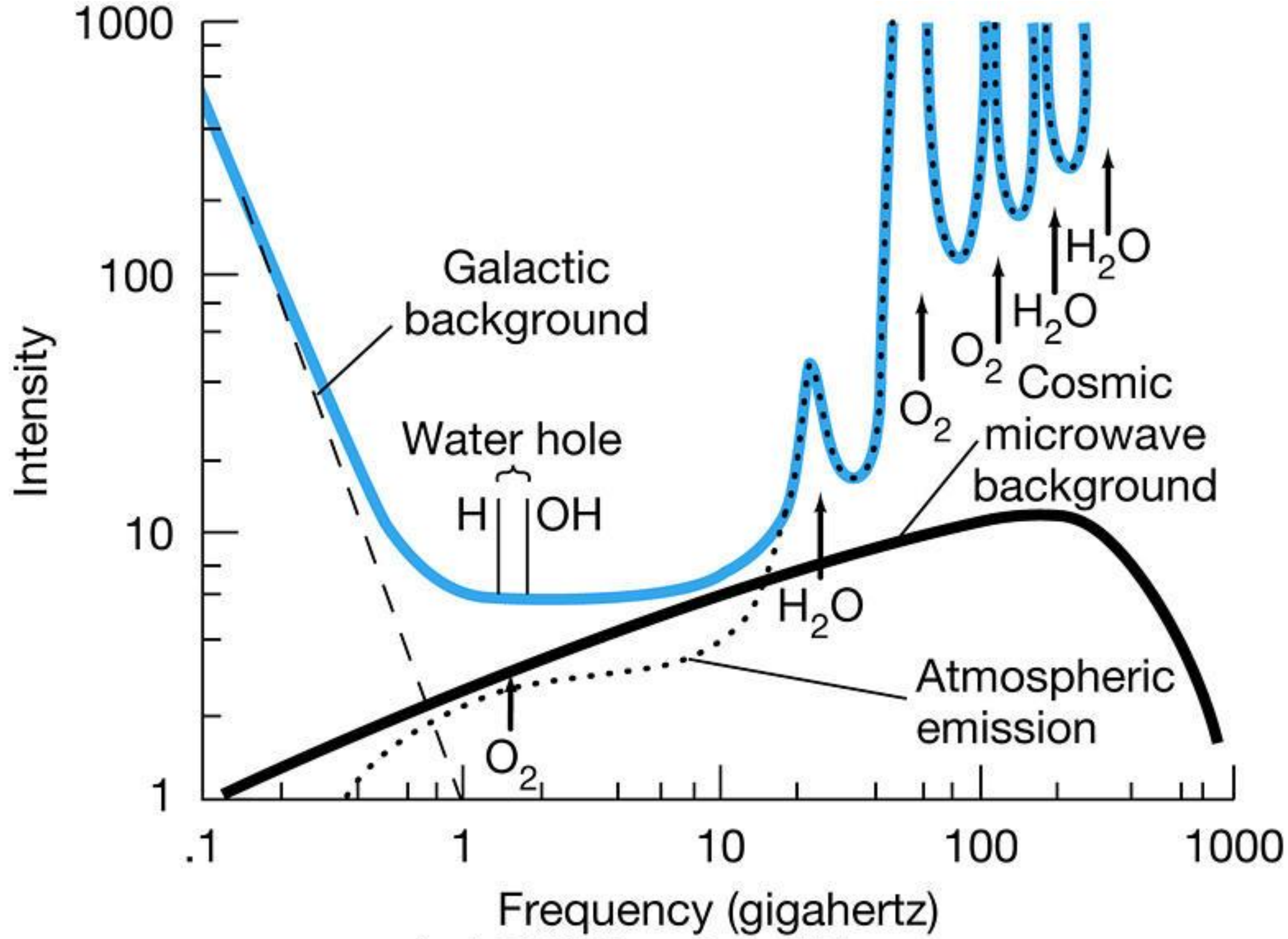
Giant exoplanets around magnetic stars may be detectable with LOFAR



SETI

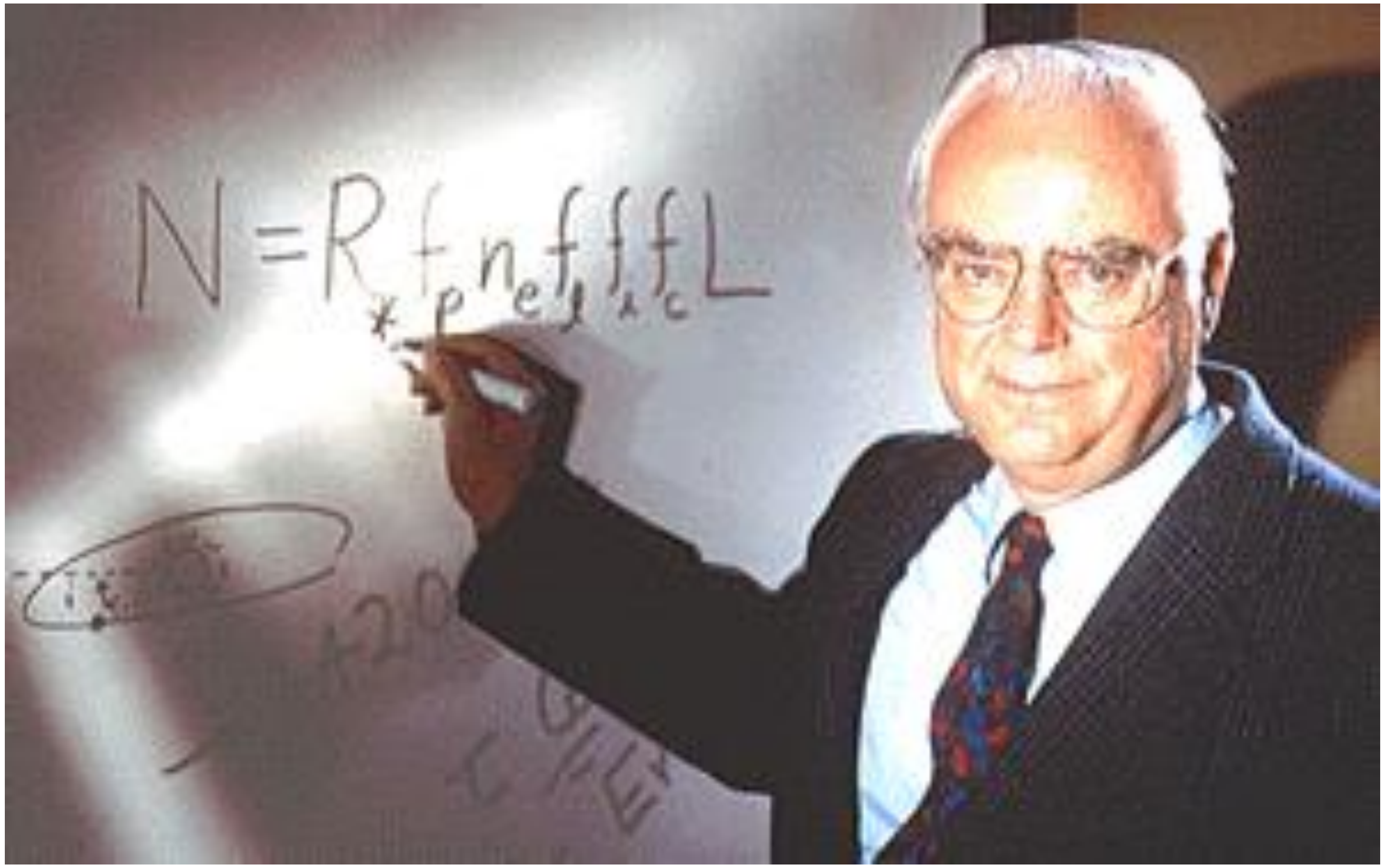
Intelligent life probably easiest to detect in radio

Naturally occurring radiation defines least “noisy” frequencies



SETI

This led Frank Drake to his equation for the number of planets we could communicate with



SETI

Example:

Suppose there are $\approx 10^{11}$ stars in Milky Way, but only 10% in "habitable zone": leaves 10^{10}

Suppose 10% have planets: leaves 10^9

If 1% are like Earth, then 10^7 are left

Suppose 1% develop life: leaves 10^5

But if only 1% of life is intelligent: leaves 10^3

Suppose 10% develop communication: 100

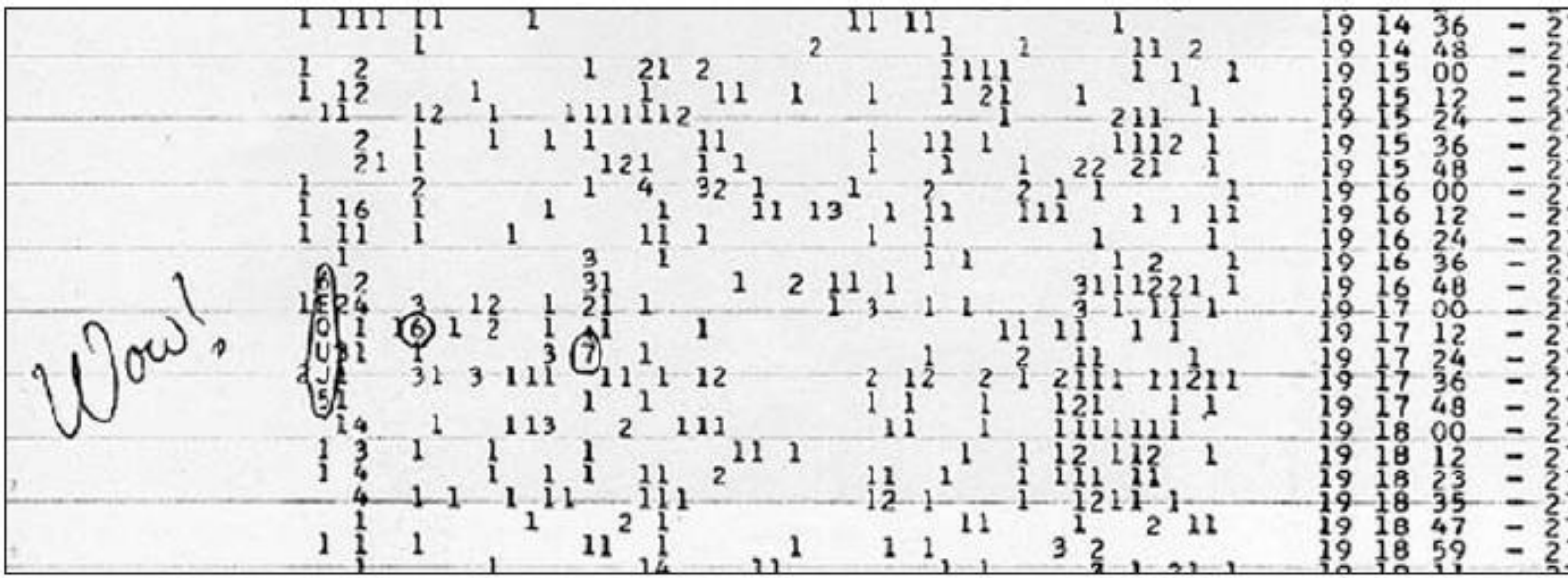
If communication lasts 1% of lifetime: 1 left

SETI

Searches with Ohio, Arecibo, Nançay, *LOFAR*

Much overlap with pulsar searching

Some analysis done with SETI@home software



SETI

Dedicated search telescope: *The Allen Telescope Array*

Questions?