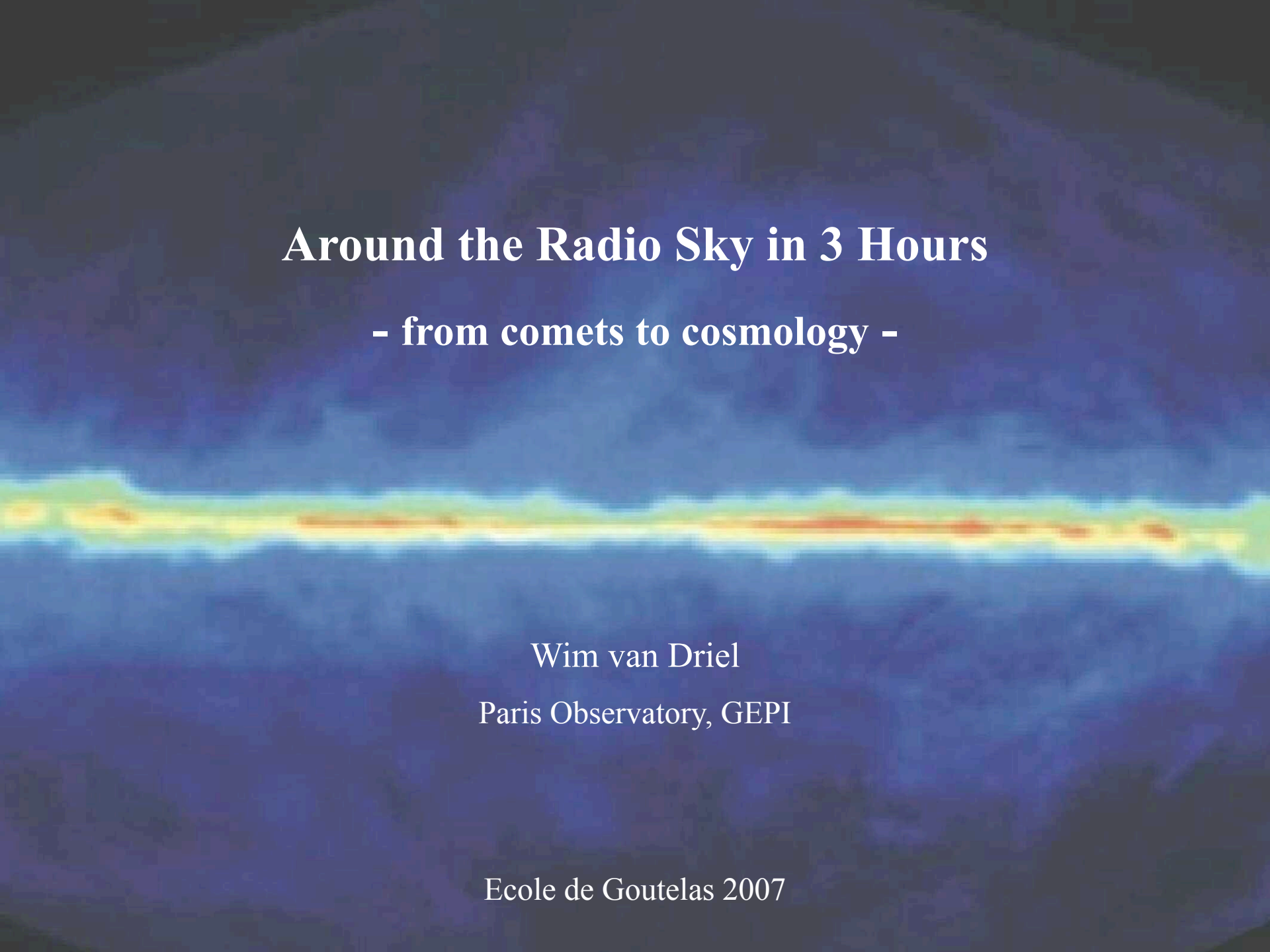


Around the Radio Sky in 3 Hours

- from comets to cosmology -

Wim van Driel

Paris Observatory, GEPI

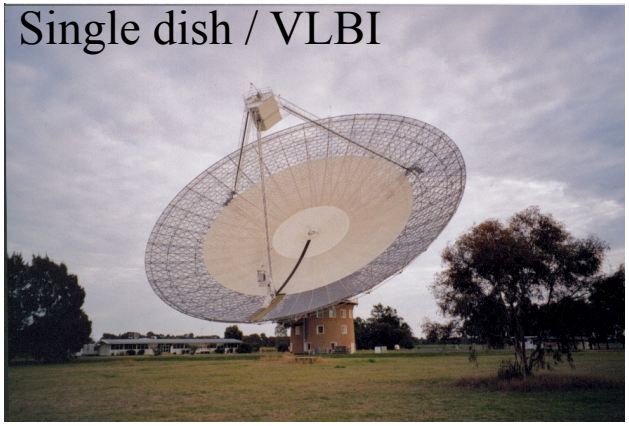
Ecole de Goutelas 2007

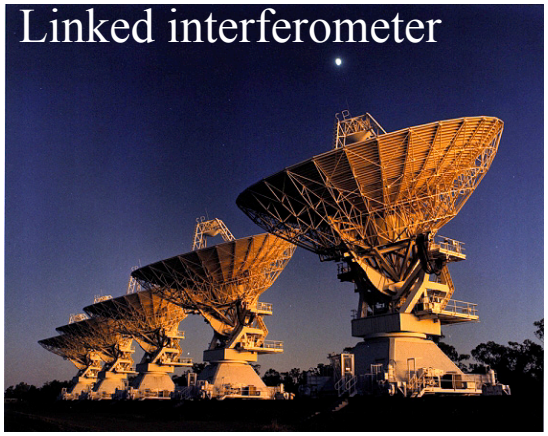
What poore Astronomers are They

But such as will run mad with will,
I cannot clear their sight,
but leave them to their study still,
to look where is no light.
'Till them too late we make them try,
they study false astronomy!

John Dowland, The Third Booke of Songs (1603)

Radio telescopes – tools of the trade





Spatial resolution at 1.4 GHz, or λ 21 cm:

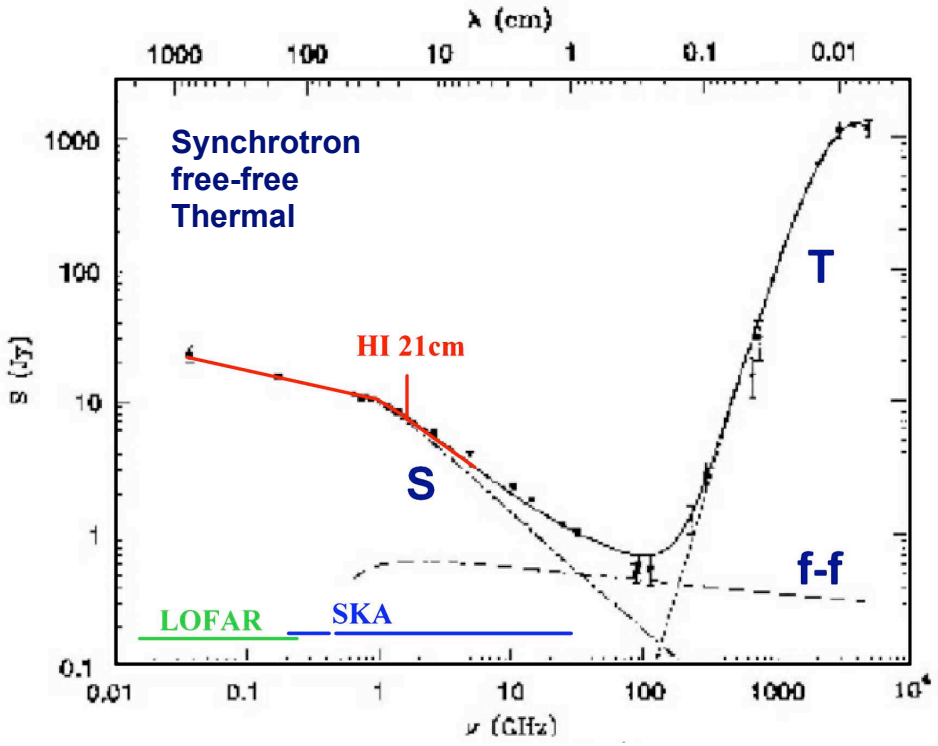
- single dish: 9 arcmin for a 100m, 3.5 arcmin for a 300m
- linked interferometer – VLA 27 × 25m: 1 arcmin to 3 arcsec
- VLBI: down to milliarcsec

  … but missing short baselines: not sensitive to large structures

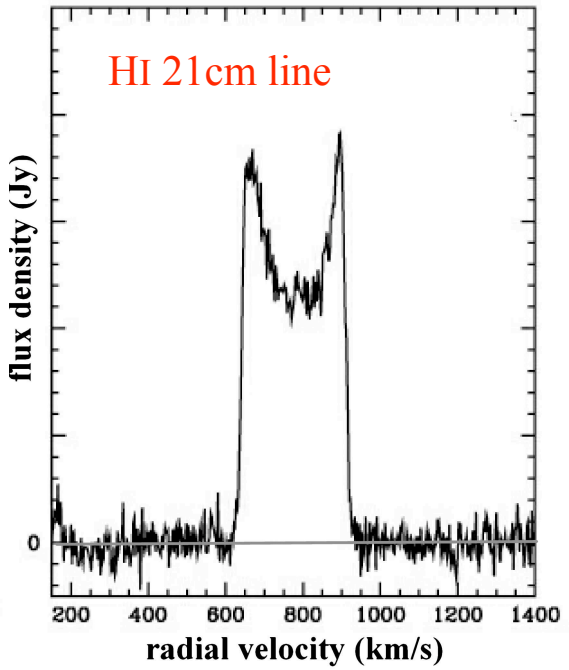
Spectral resolution: 8096 channels is standard

HI galaxy search: 2 pols, 2.5 km/s resolution → 10,000 km/s bandwidth

Continuum and spectral lines – smooth and spiky



Galaxy spectra



Radio **continuum** spectrum at low frequencies: non-thermal (in ionized gas)

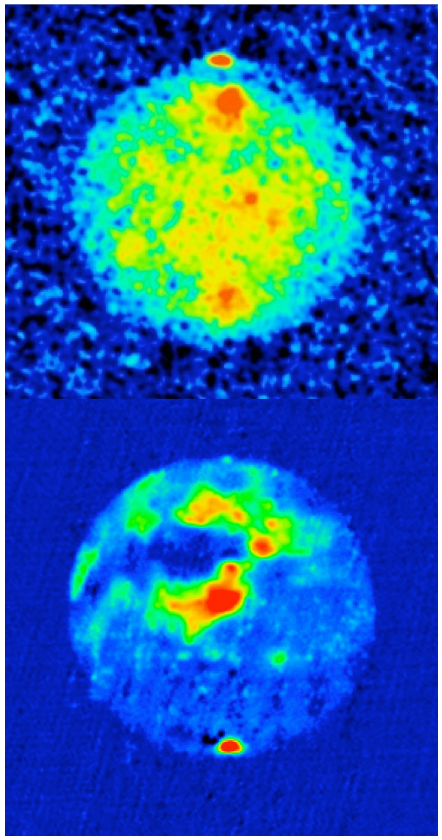
- synchrotron: fast electrons + magnetic field
- free-free (Bremsstrahlung): fast electrons fly-by

to improve telescope sensitivity: broader bandwidth

Radio **line** spectrum: 21cm line of neutral hydrogen (not-ionized)

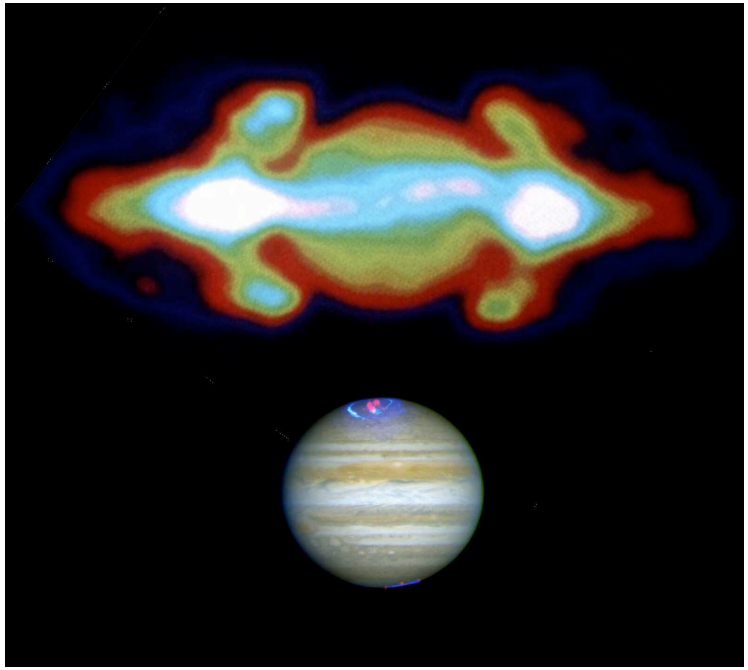
to improve telescope sensitivity: cannot increase bandwidth

Planets – radio from next door



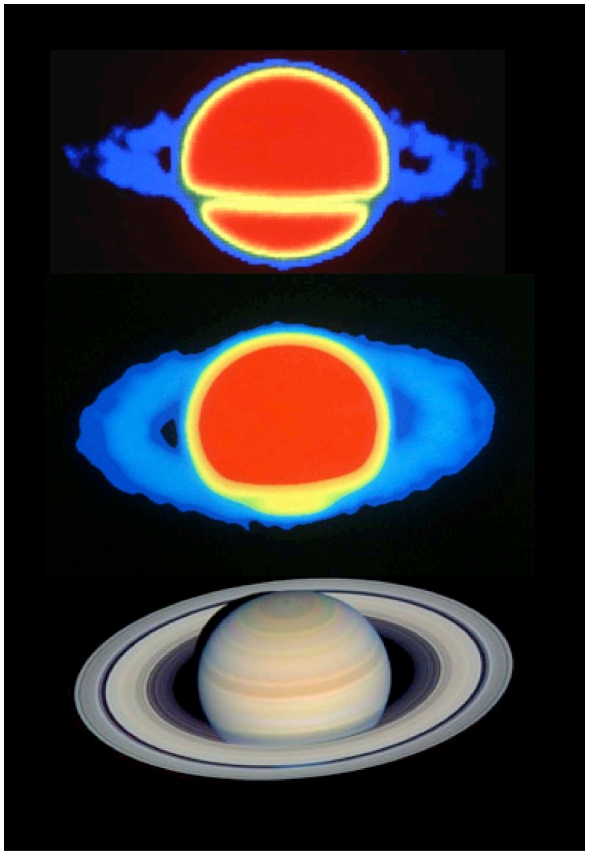
Mercury, Mars

radar images



Jupiter

radiation belts



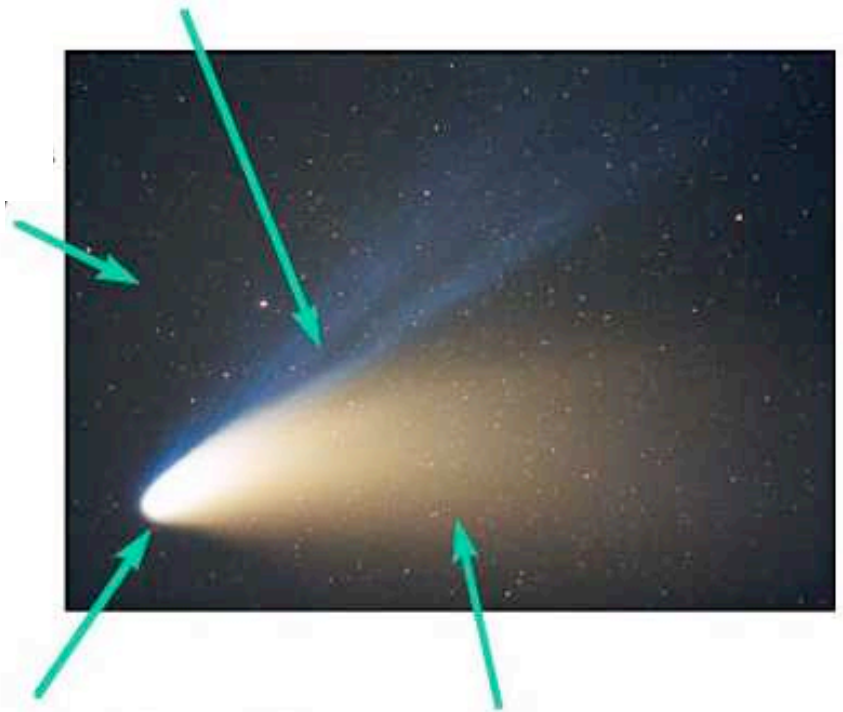
Saturn

thermal emission

Comets – primordial visitors

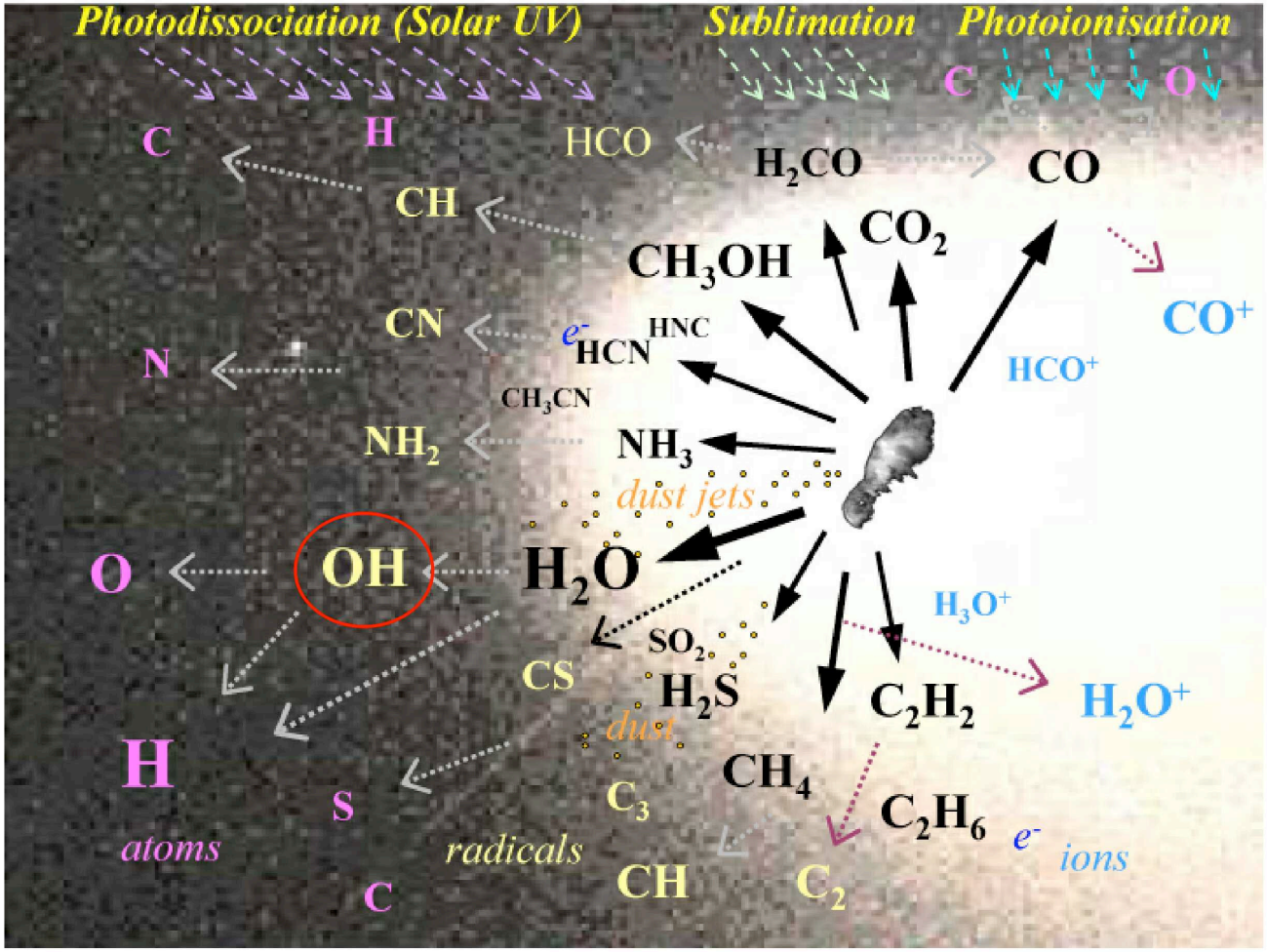
primordial stuff :

blocks of dirty ice getting
a terminal sun-burn

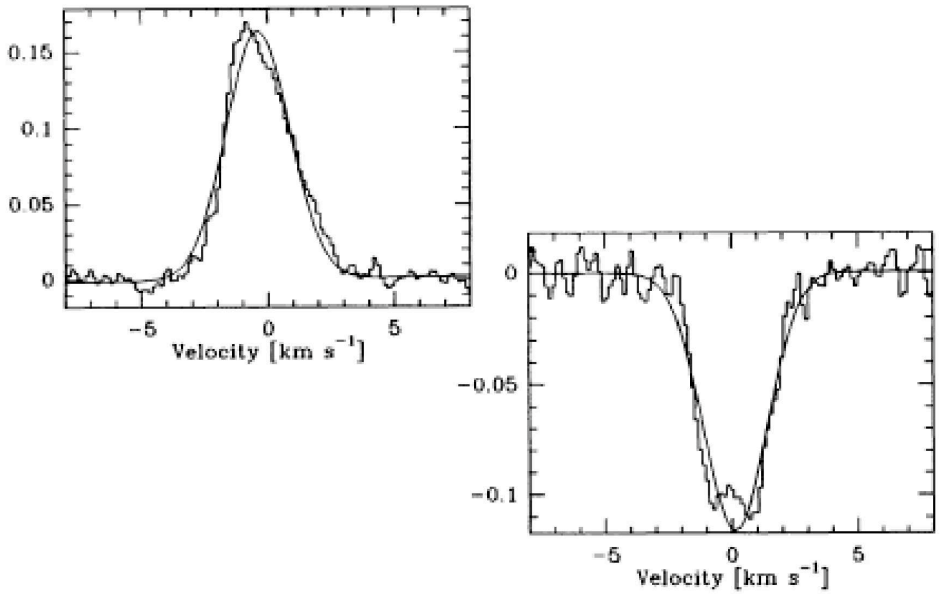


Comets – a witch's kitchen

Chemistry in Motion



Comets – OH gas works



Outgassing:

OH line

(1612 MHz, λ 18 cm)

in emission or in absorption

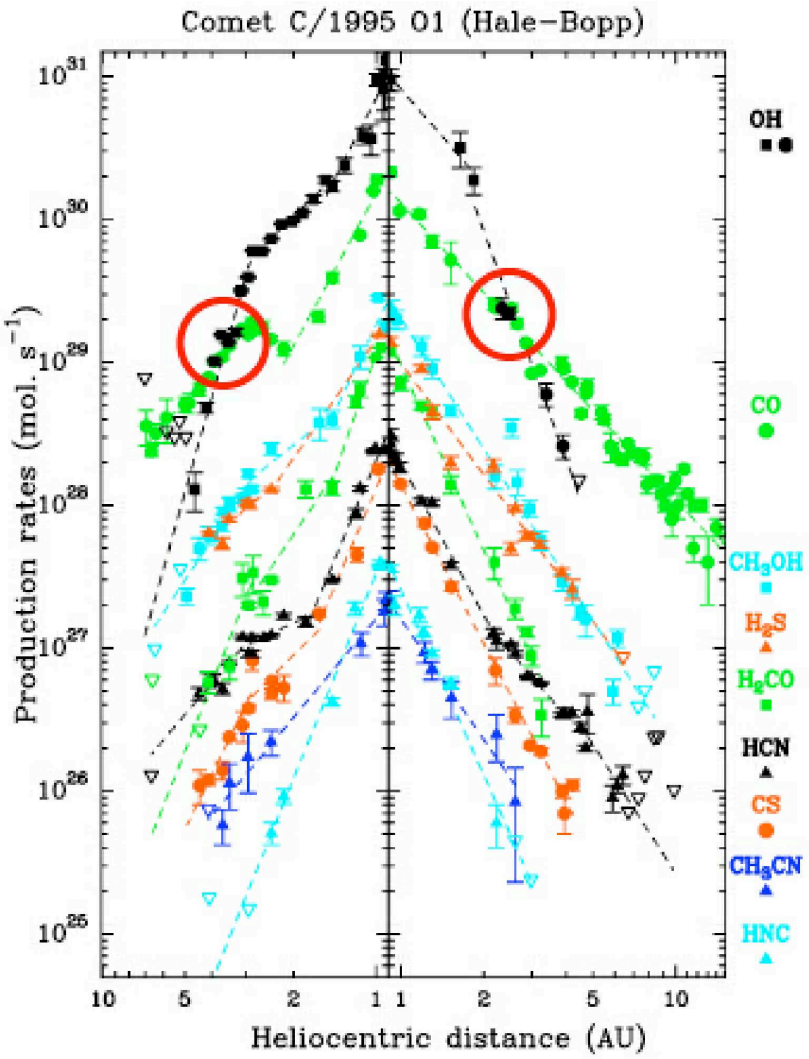
centre velocity → radial velocity

profile integral → amount of OH → rate of outgassing (tons/min)

asymmetry → solar radiation/wind

Zeeman effect → local magnetic field strength

Comets – slowly losing it

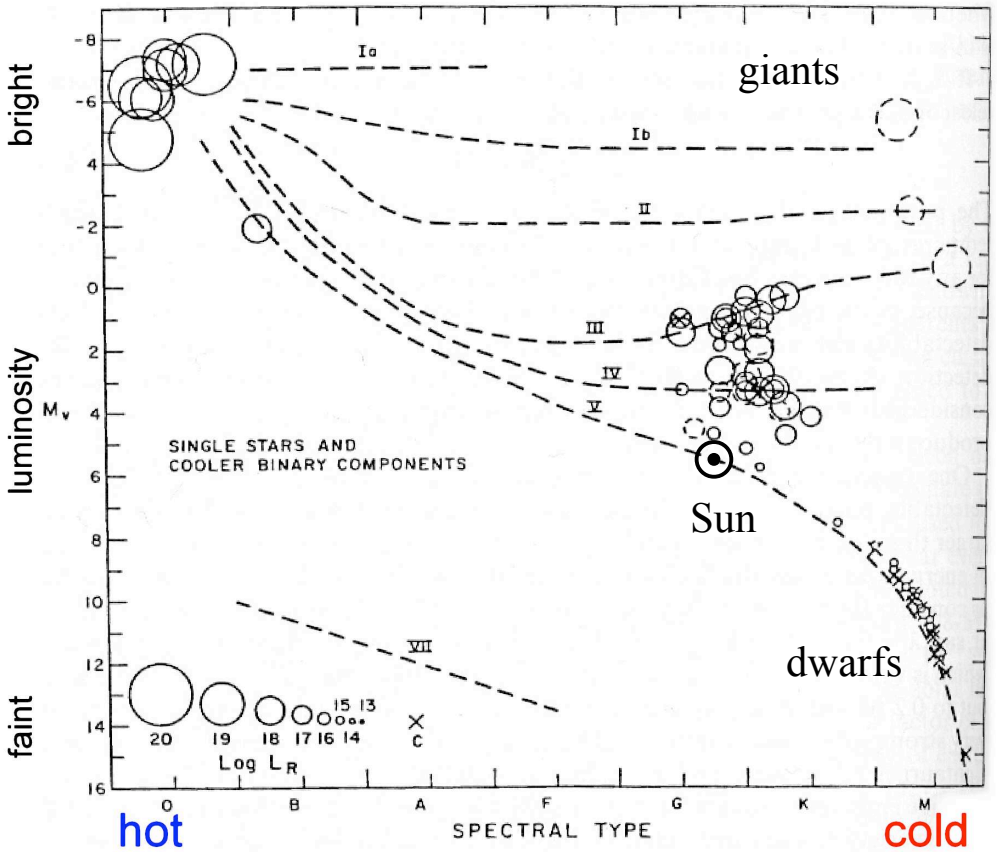


production rates of
different molecules
as function of
distance to the Sun

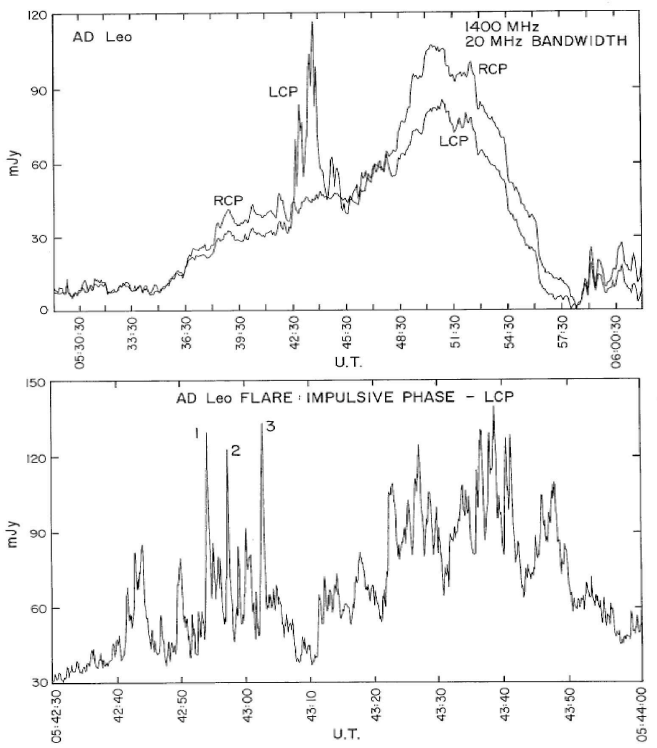
- cross-over between OH and CO

Stars – shining faintly in radio

Hertzsprung-Russel Diagram: absolute magnitude vs. surface temperature



flare star

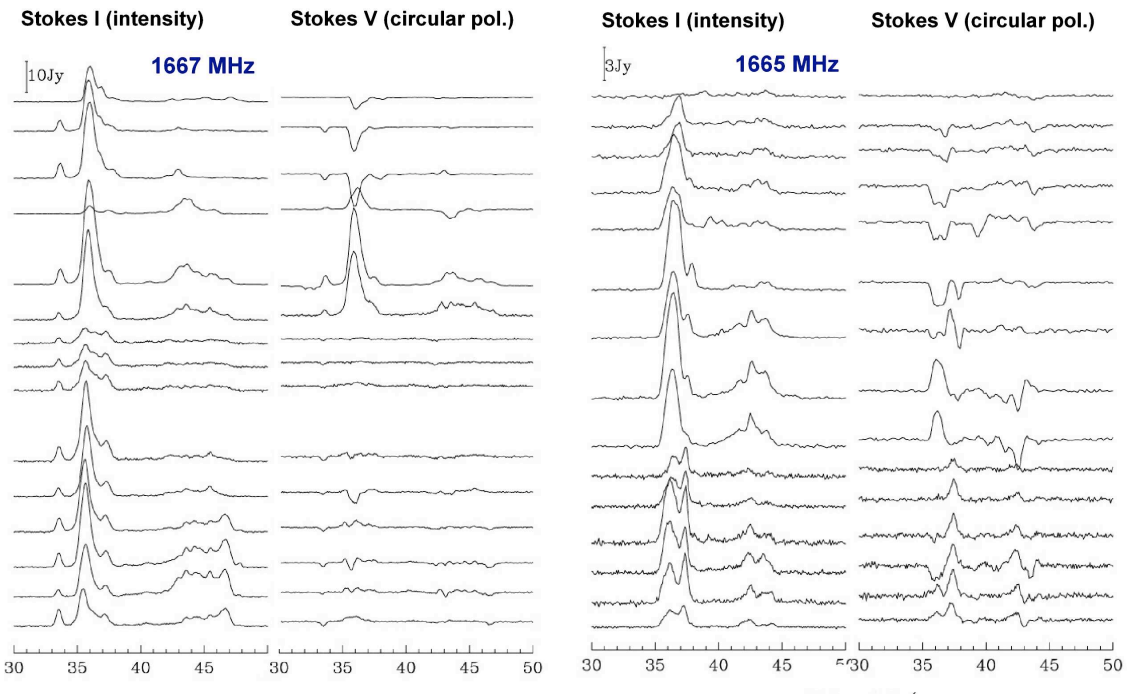


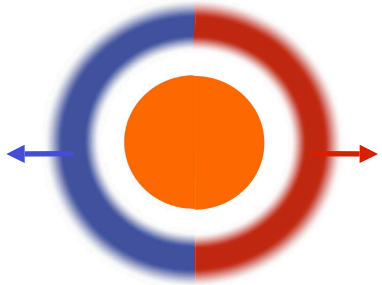
non-thermal radio radiation (free-free); × means maser

Sun: strongest radio emission from flares

Stars – circumstellar shell shock

Circumstellar shells around Long Period Variable stars:
amplified maser line emission (OH; 1612, 1665, 1667, 1720 MHz)





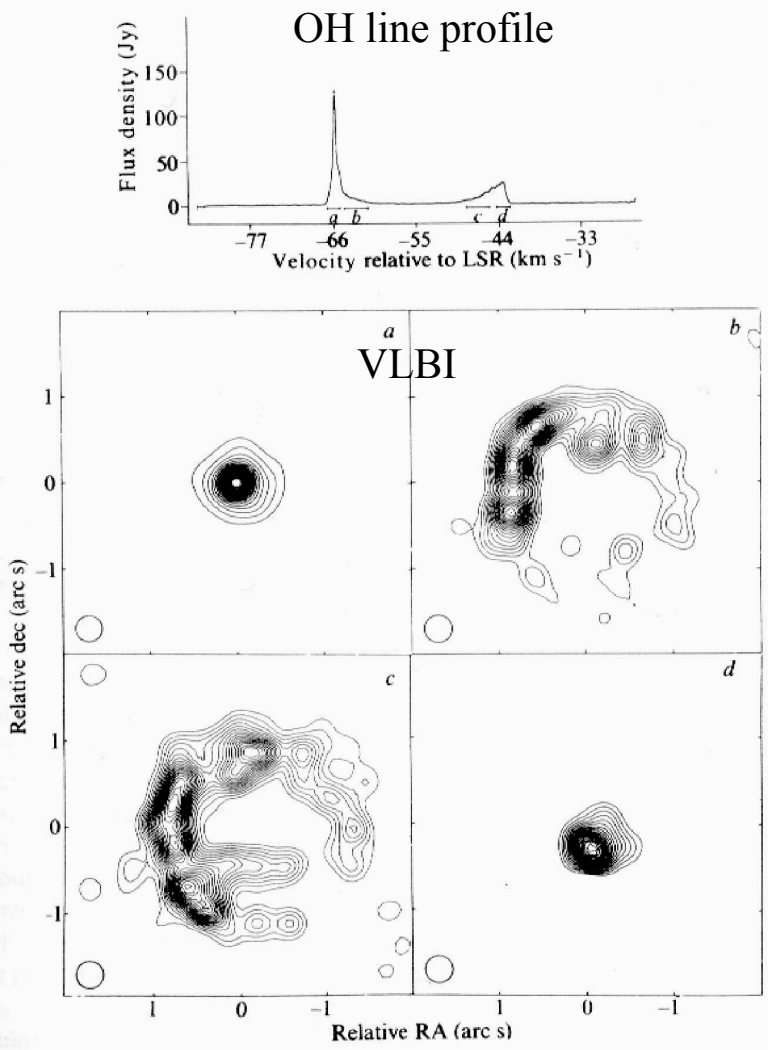
Line profile variations
over a 15 year period

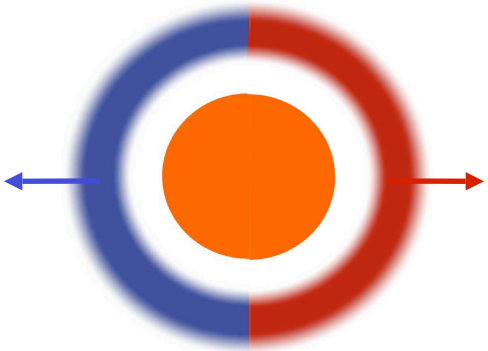
Giant stars in late evolution stages → mass loss, variability
→ circumstellar gas/dust shells

Line profile variations over a 15 year period

Stars – circumstellar masers

Circumstellar shells around evolved stars: maser line emission



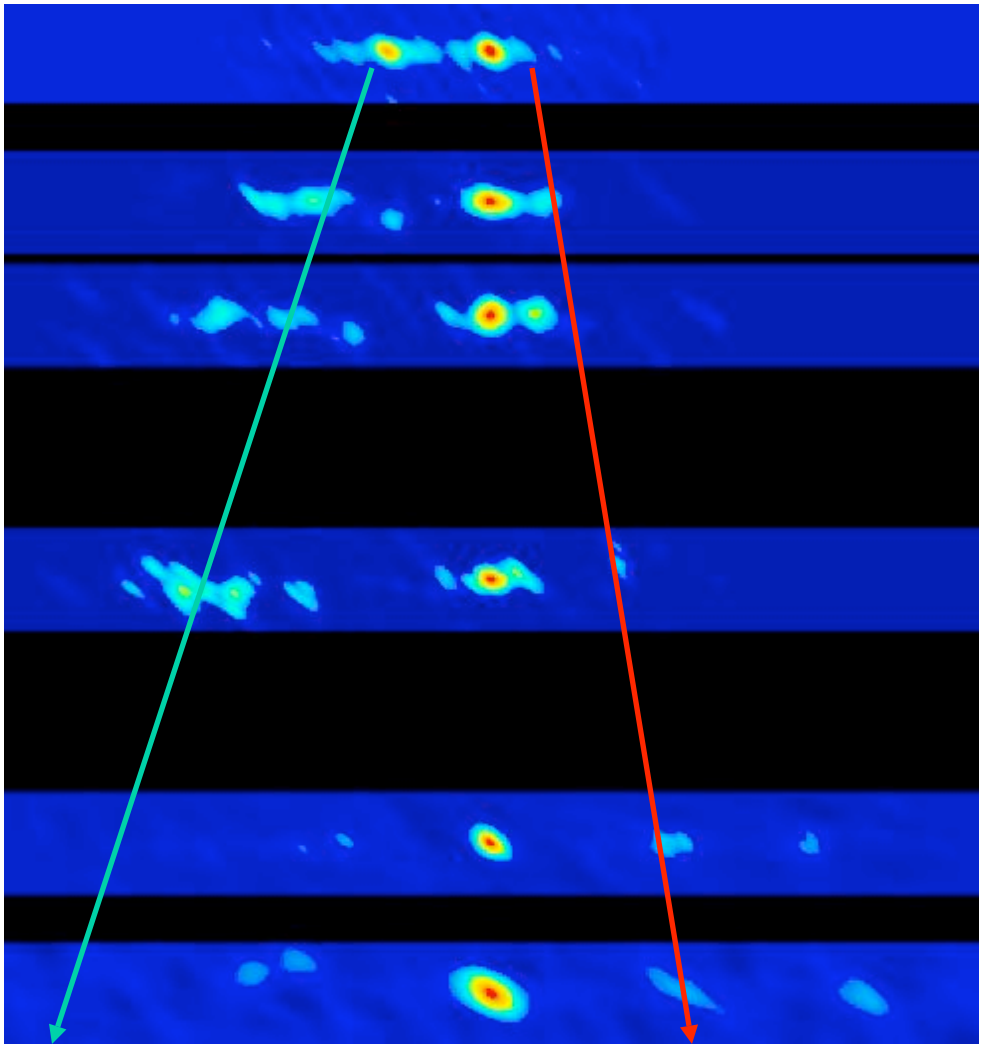


VLBI OH line imaging:
expanding shell structure

Maser pumping mechanism:
infared radiation of warm dust?

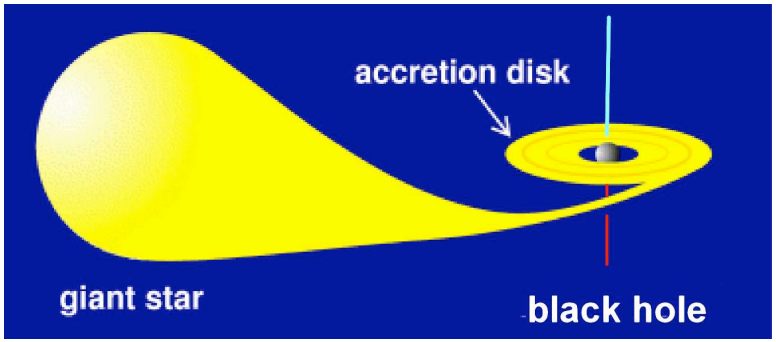
Stars – Black Holes let it fly

Star / black hole double system: ejection of material at almost the light speed



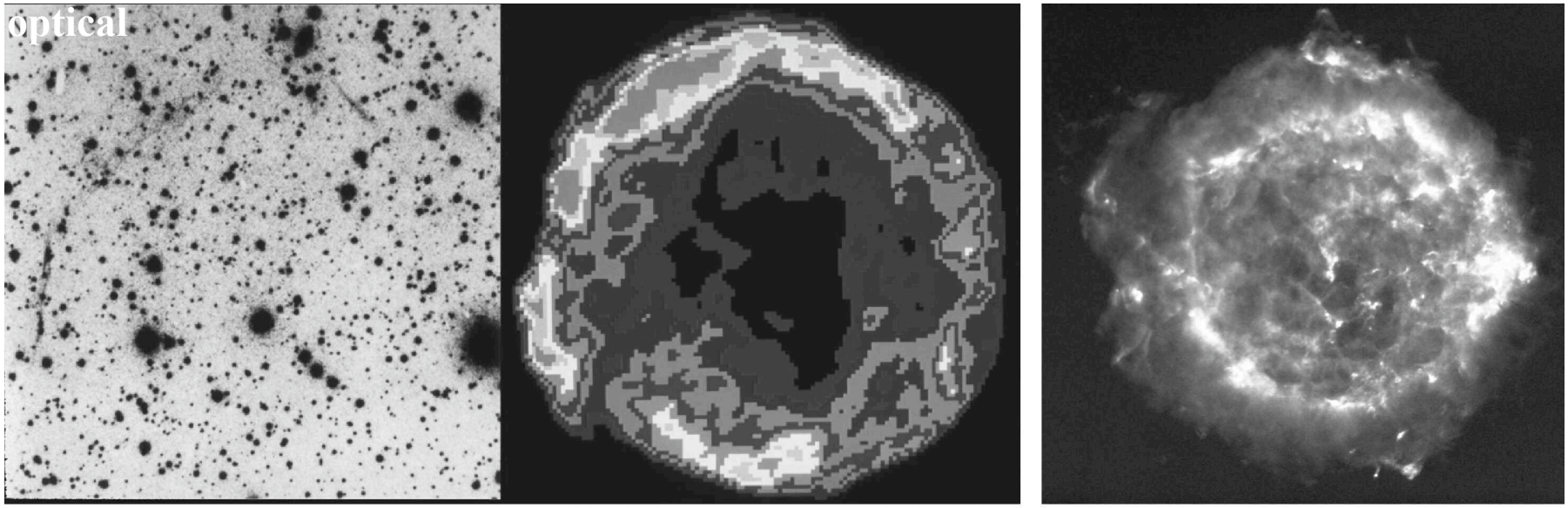
Radio continuum VLBI:

- milli-arcsec esolution
- asymmetry in speed of ejecta: relativistic projection effect



Stars – the Afterlife

Supernova remnants (SNRs)

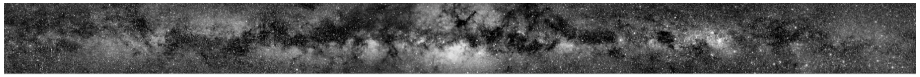


expanding shells, outer layers of exploded massive stars: synchrotron emission

- expansion phases: free/adiabatic/radiative/dissipative
- expansion velocity (need to know distance): optical lines, radio images

Milky Way Galaxy – spilt milk

Milky Way – “our” galaxy



seen from the inside

Spiral galaxies

seen from the outside:

- flat disc:

young stars, gas, dust

in rotation

- central bulge:

old stars; no rotation

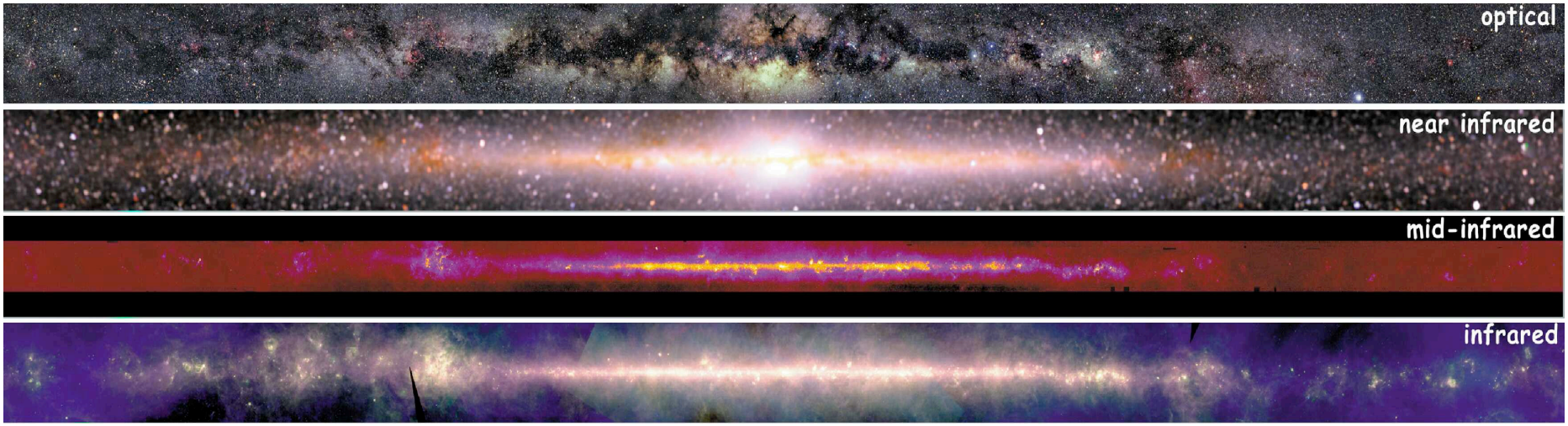
Unraveling the Milky Way Galaxy: a parisian perspective

Milky Way Galaxy – rotation: round and round…

Comparing a bird-eye view of cars moving around the Place de l'étoile, with the view from inside a car driving on it in dense mist:

Seen from above,
all is in orderly rotation;
Seen from inside,
it seems rather confusing …

Milky Way Galaxy – stars and dust



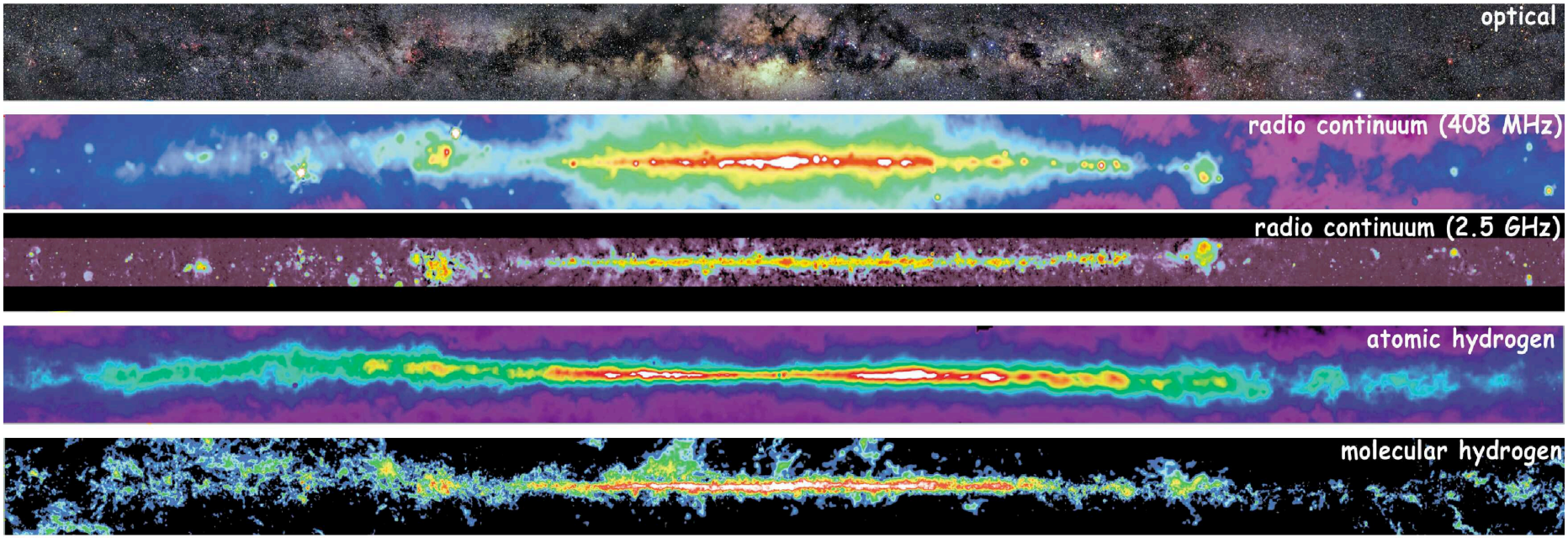
Getting a clear picture of the Milky Way:

optical (0.3-0.8 μm): stars; dust obscures

near infrared (few μm): better dust transparency

far-infrared (X0 μm): dust emits

Milky Way Galaxy – stars and gas



Getting a clear picture of the Milky Way:

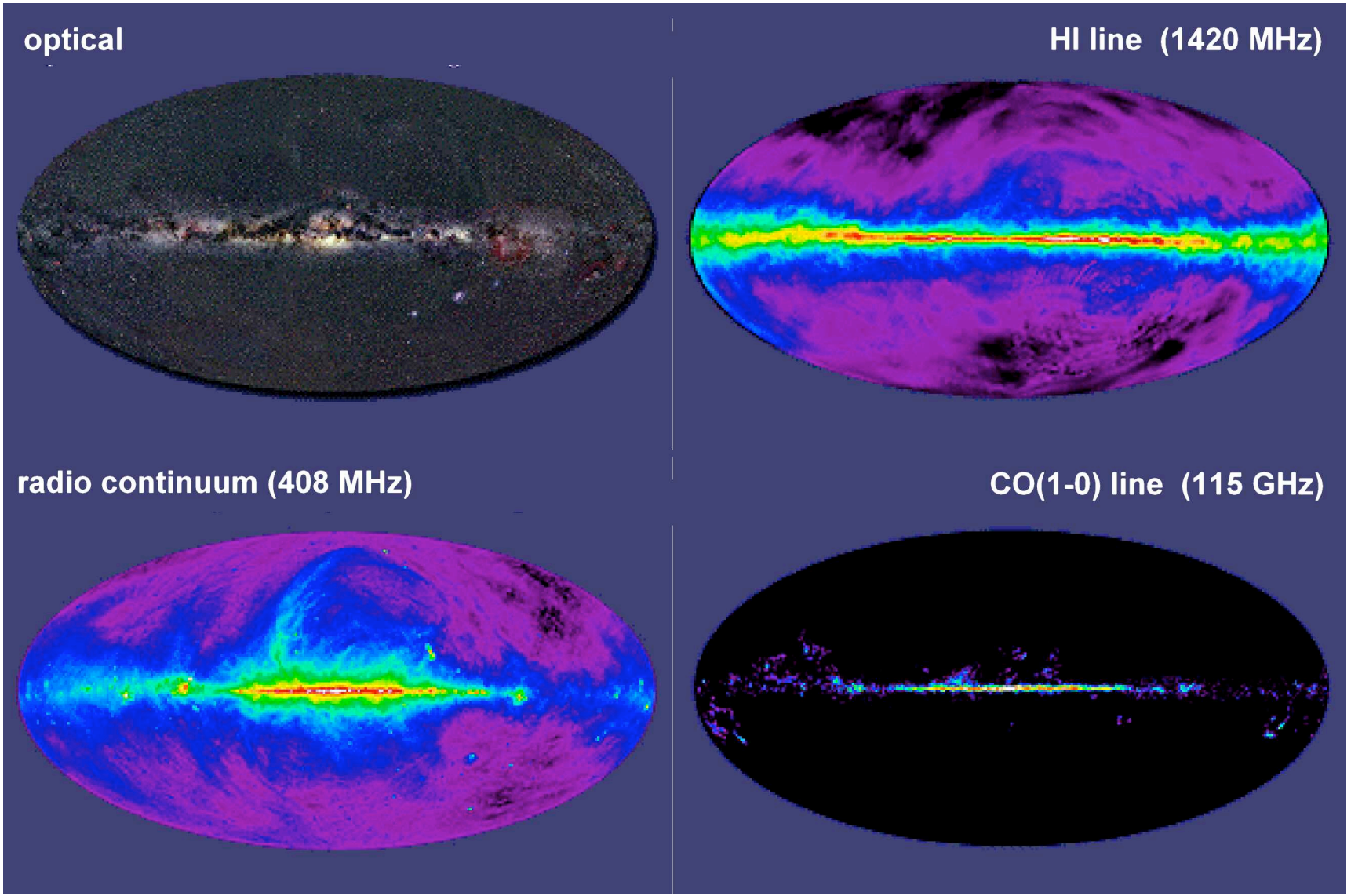
radio continuum: synchrotron radiation

radio lines: transparency and kinematics

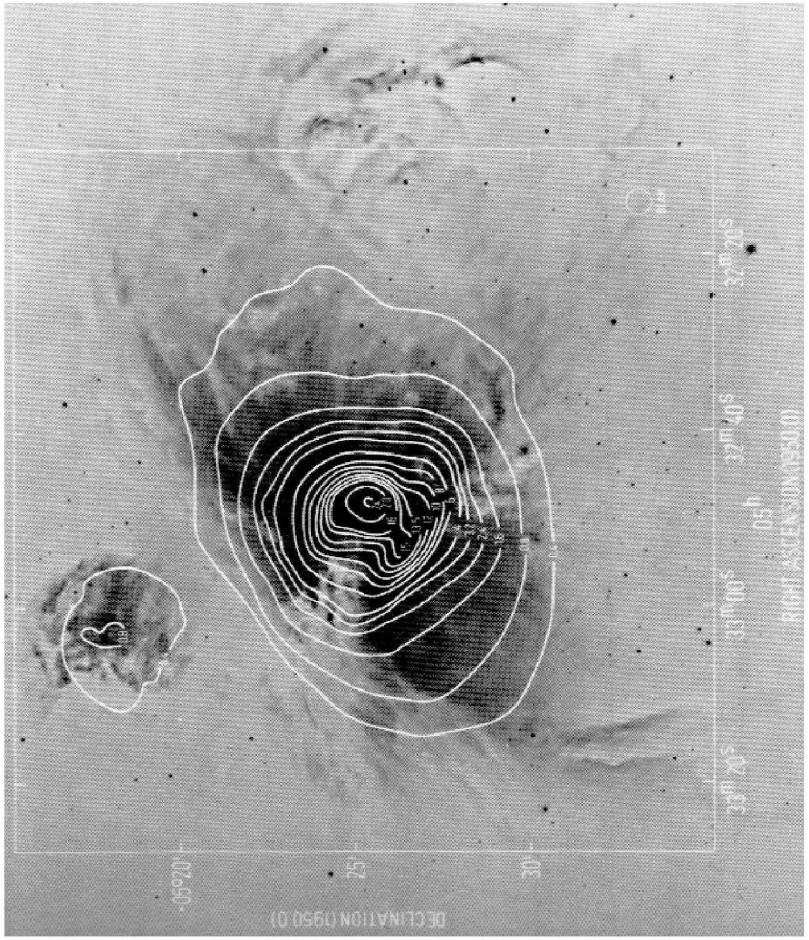
HI 21cm: general interstellar medium

CO 2.6mm: star forming regions

Milky Way Galaxy – multi-wavelength views



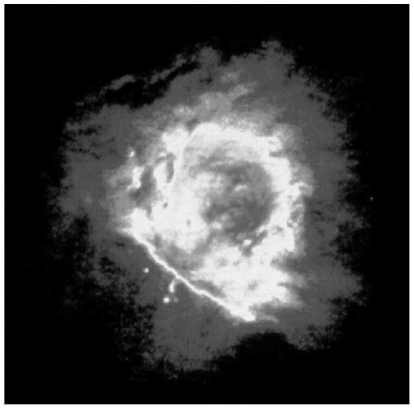
Milky Way Galaxy – the true shape of things



Star forming regions:

radio emission not obscured by dust

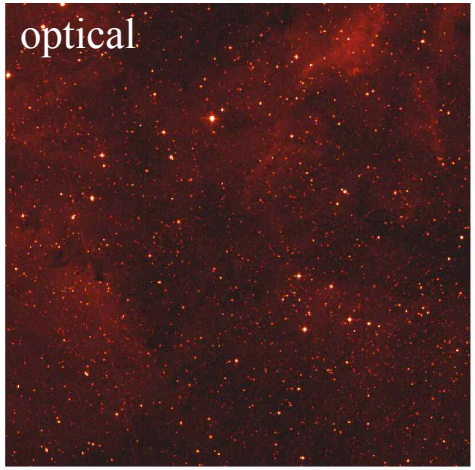
but mainly non-thermal

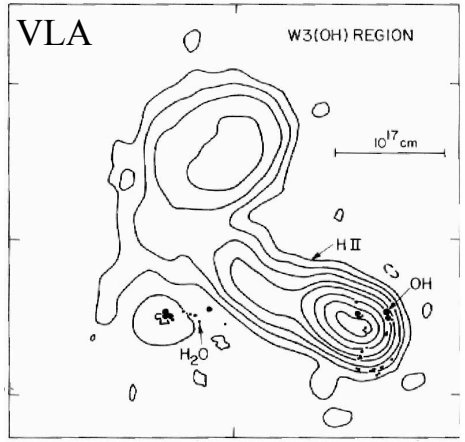


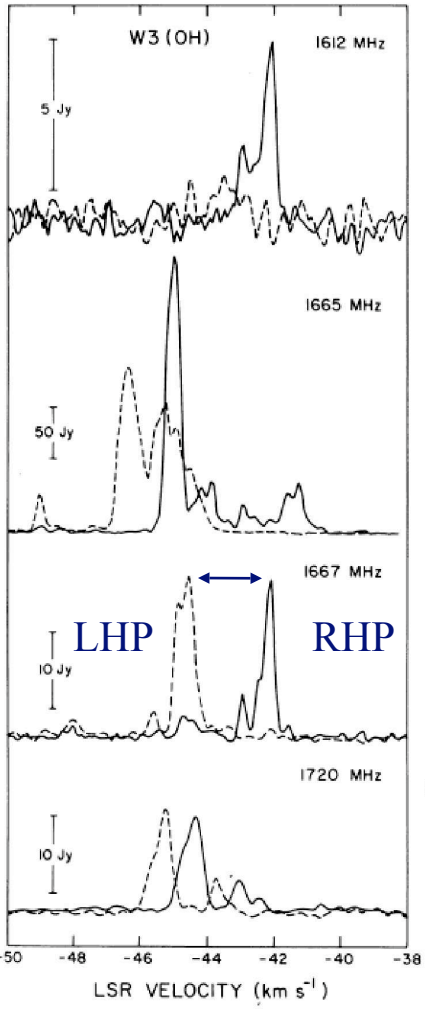
Orion nebula (M42): optical + radio continuum

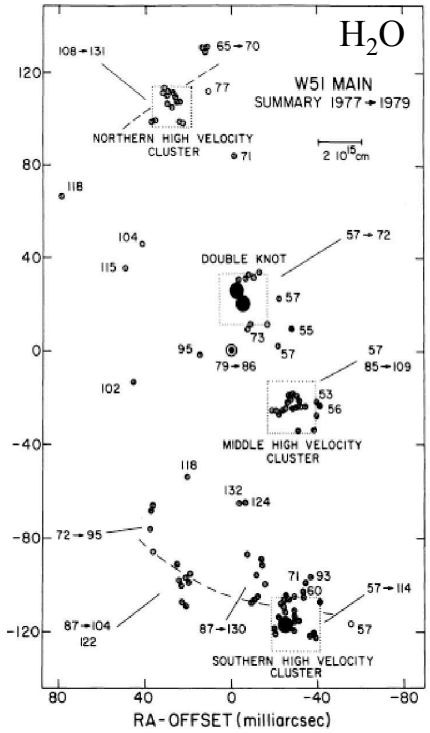
Star forming regions – stimulated emission

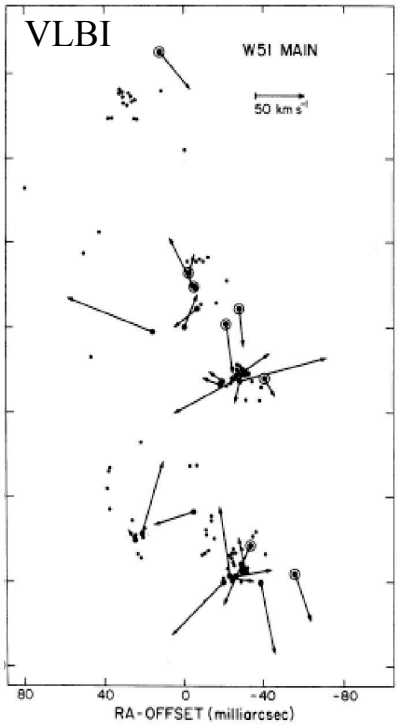
maser line emission (OH; 1612, 1665, 1667, 1720 MHz), H_20, …

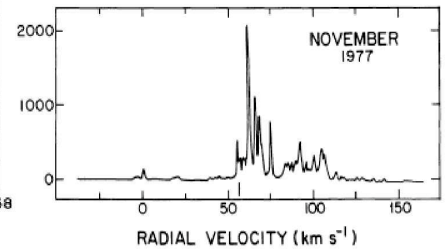








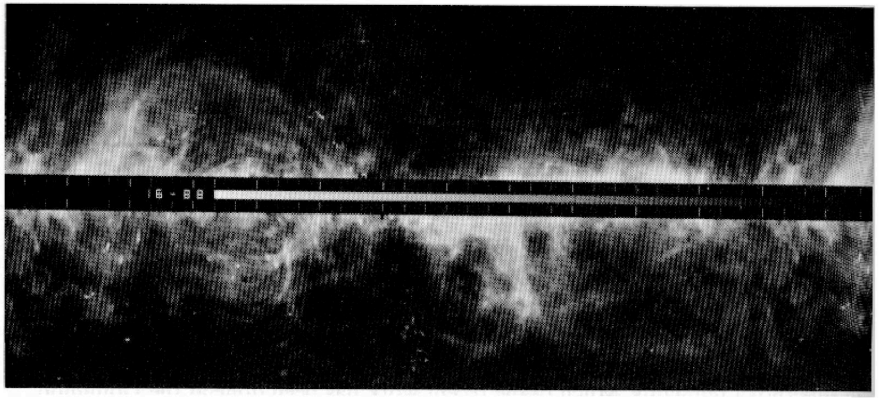


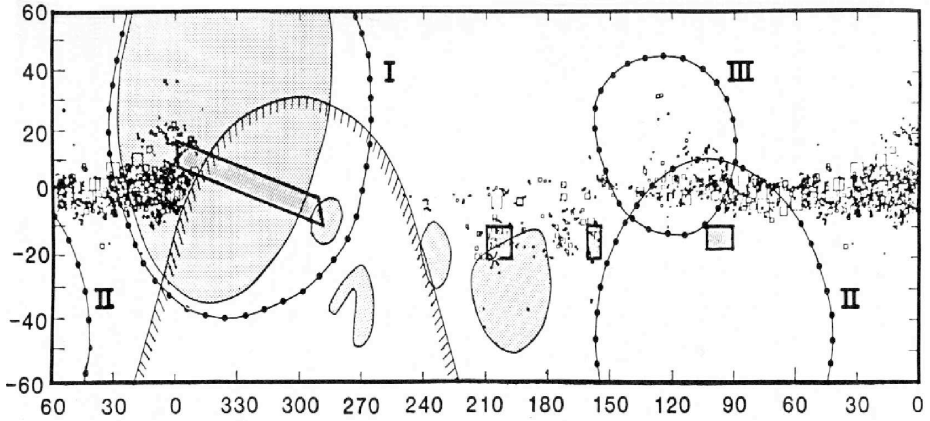


Zeeman splitting → magnetic field strength variability & proper motions

Milky Way Galaxy – as seen in HI

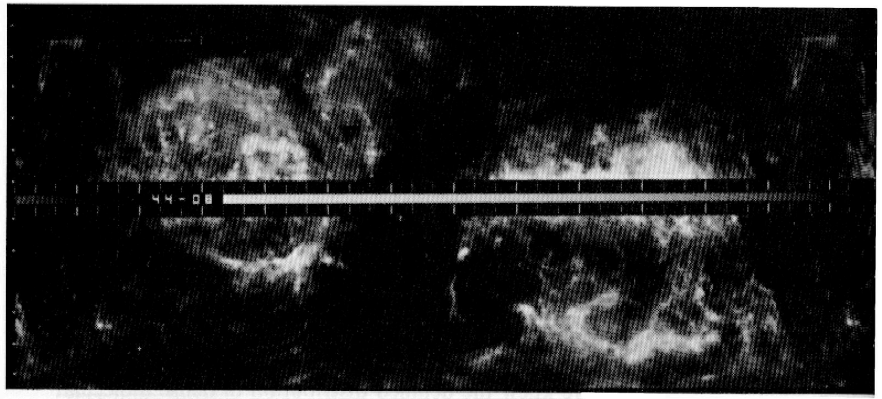
HI column density

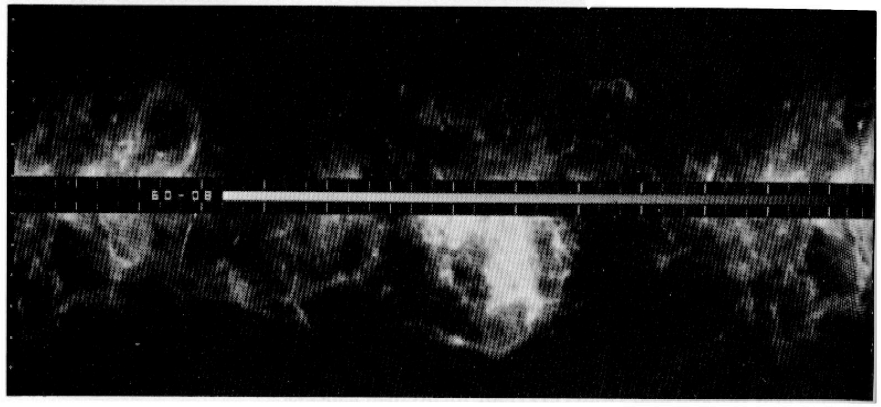




Optical / radio continuum features

V= +8 km/s





HI line features

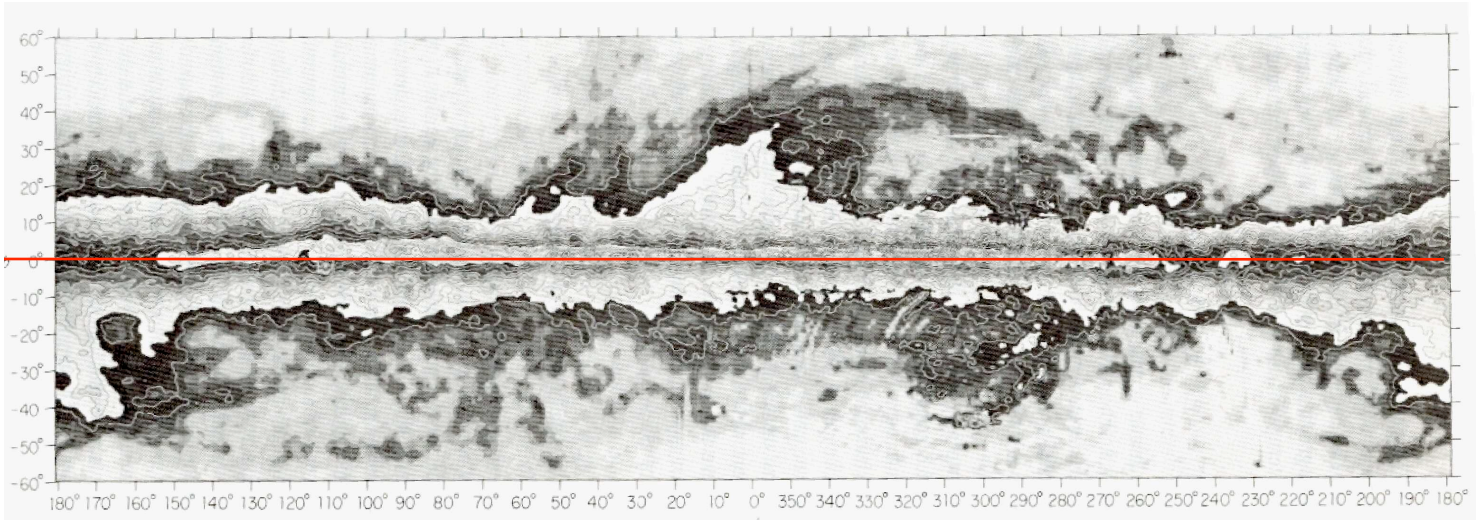
V= -8 km/s

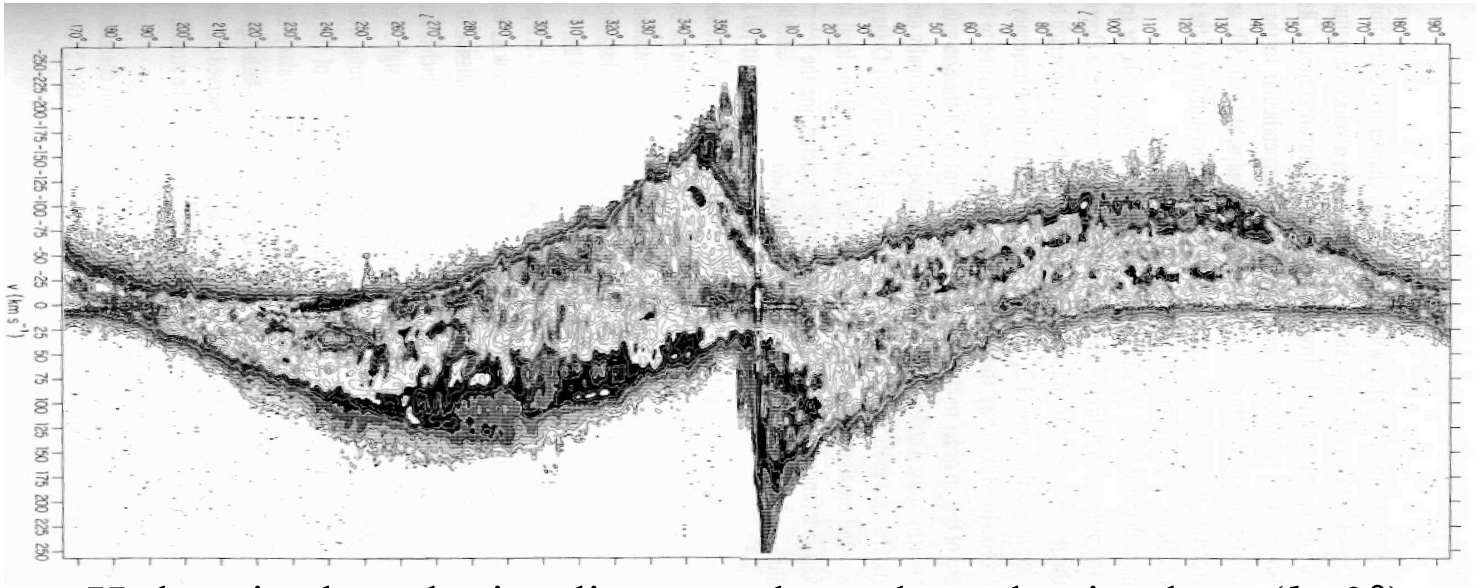
different features at –8 and +8 km/s

Milky Way Galaxy – as seen in HI

HI column density distribution

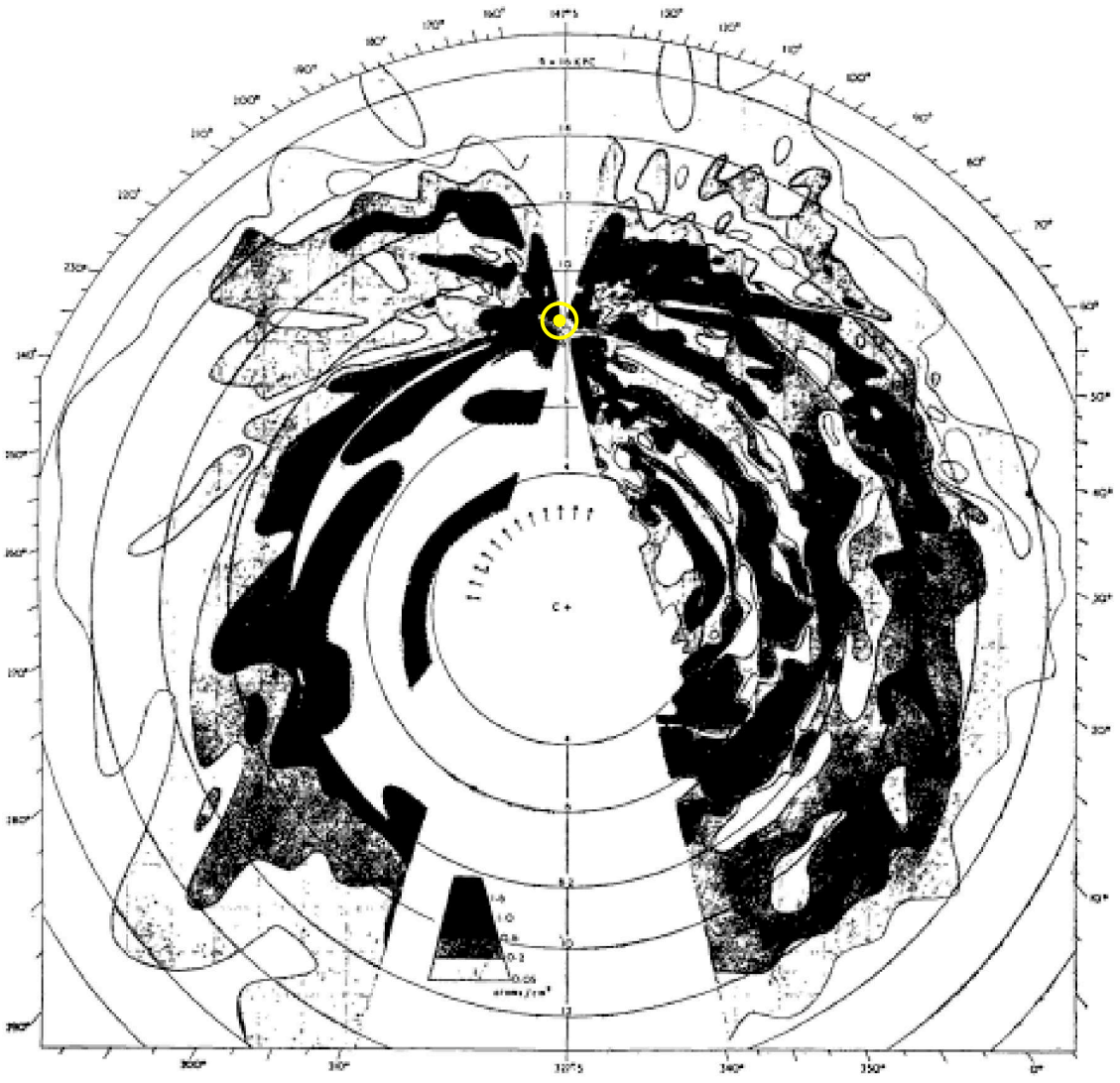
b=0°





HI longitude-velocity diagram along the galactic plane (b=0°)

Milky Way Galaxy – HI disc structure finally revealed

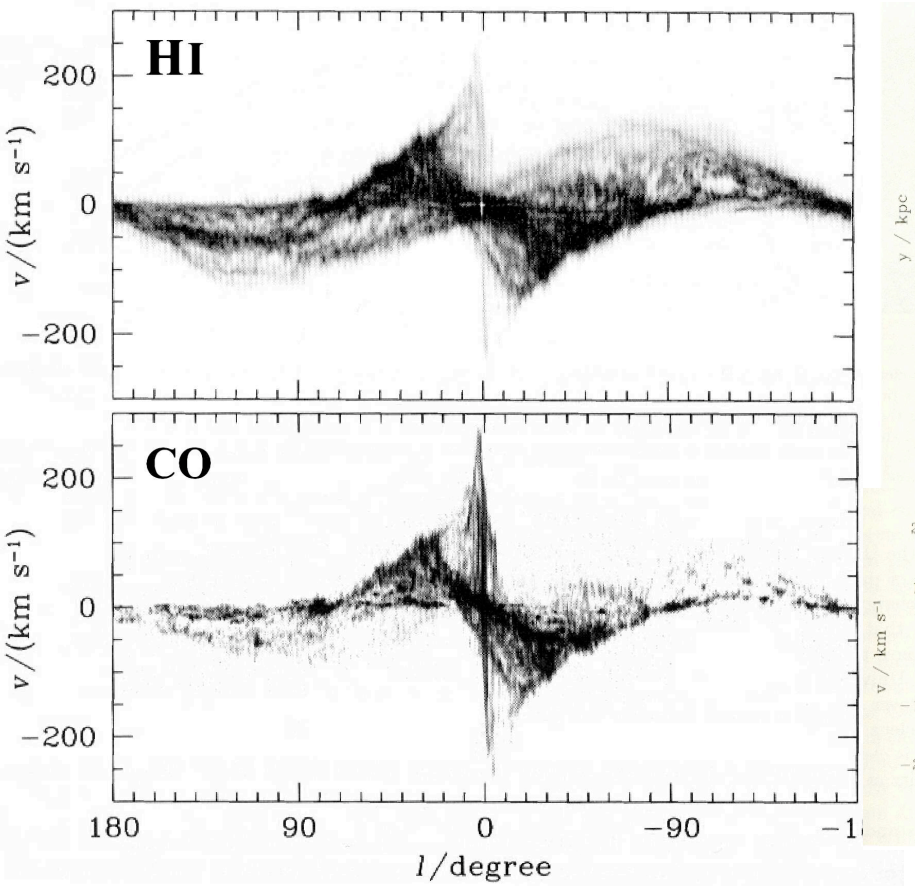


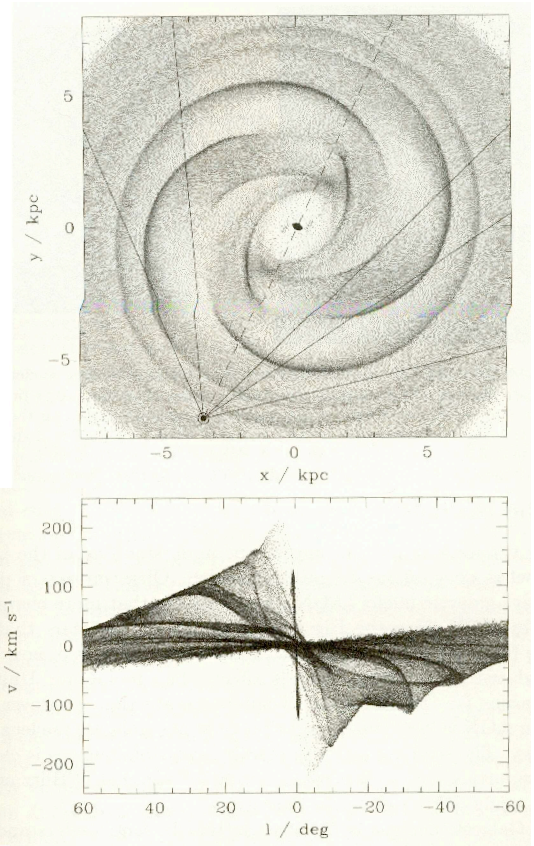
MW seen from above
in 21 cm HI line;
circular rotation assumed

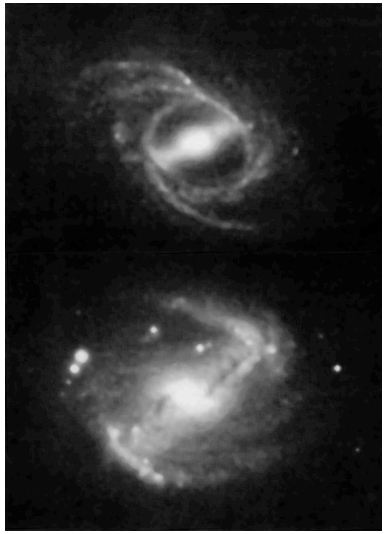
first view (early 60's)
of global spiral structure
and disc kinematics

Milky Way Galaxy - modelling

HI and CO line longitude-velocity diagram



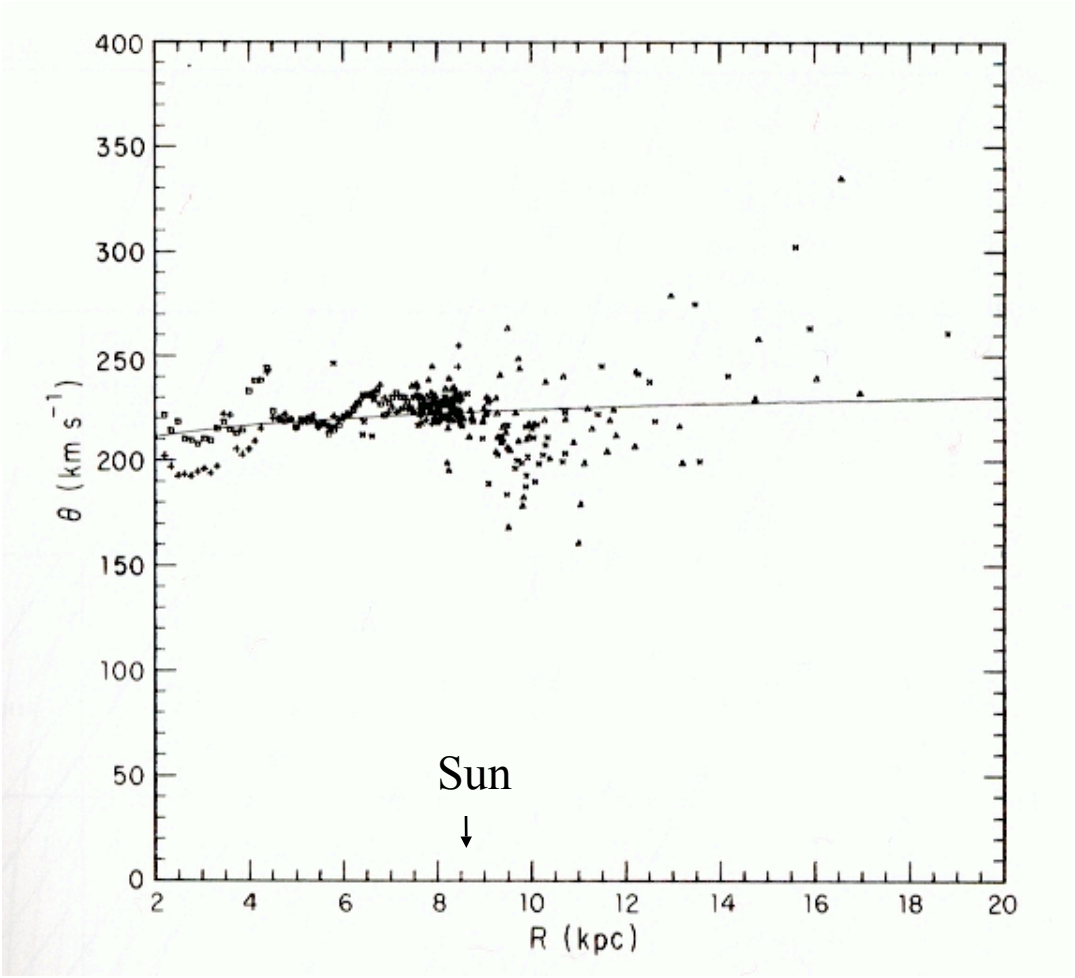




Hydrodynamical model, matching structures in longitude-velocity diagrams: spiral arms; peculiar motions near Galactic Centre → bar structure

Milky Way Galaxy – spin control

HI rotation curve



HI kinematics:

determination of rotation curve

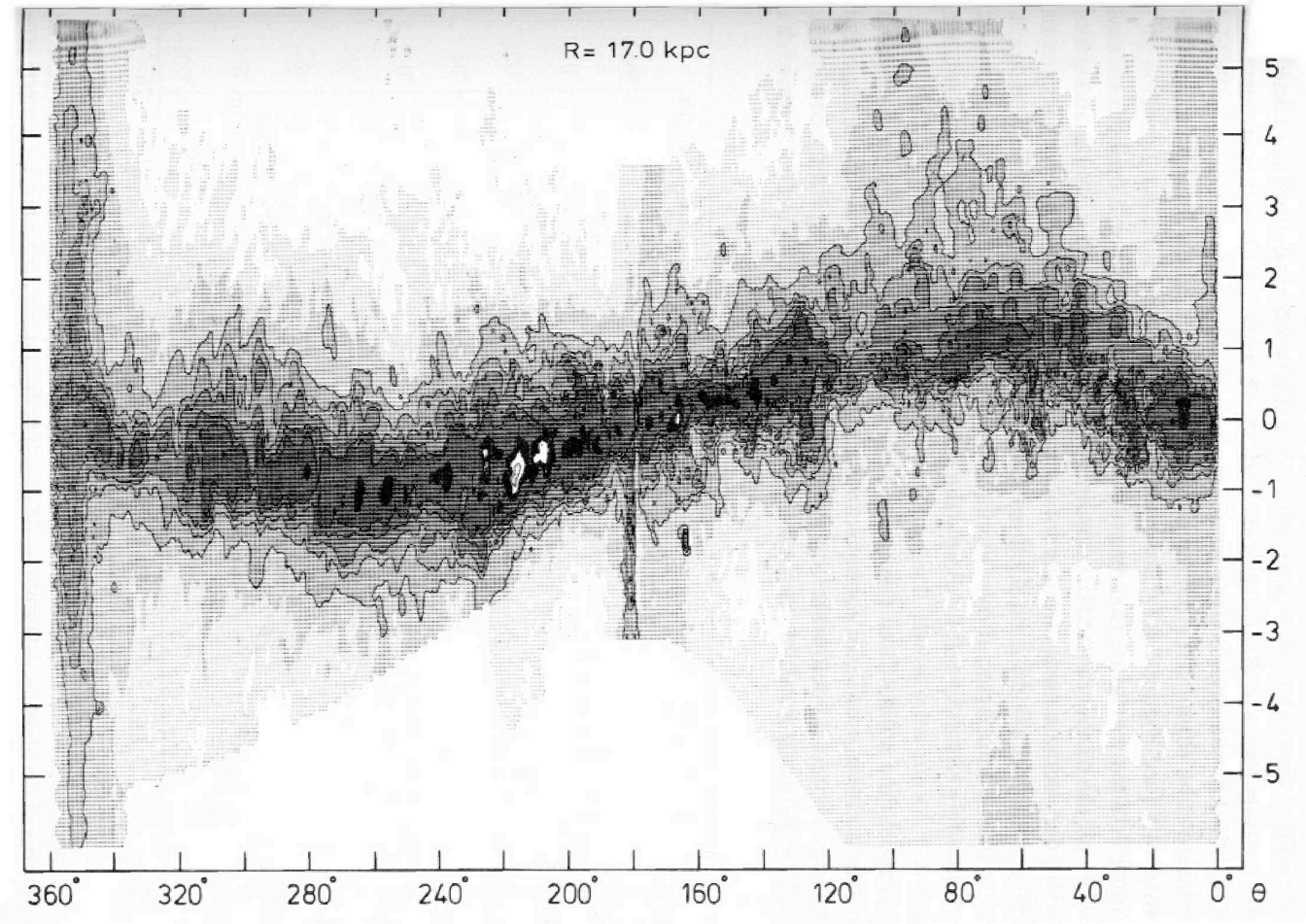
estimate of total MW mass,

compare to mass of components:

Dark Matter needed

Milky Way Galaxy – flat out?

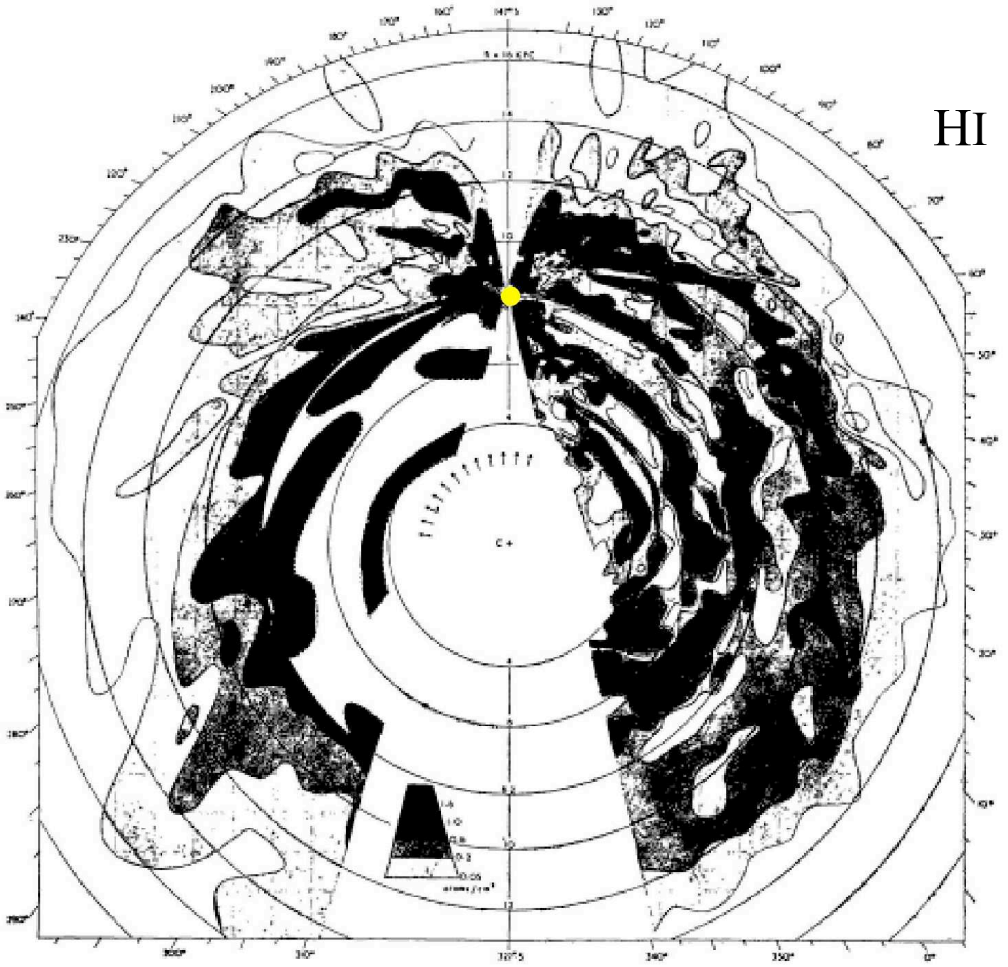
Outer HI disc: height above disc plane at 17 kpc radius



HI disc not flat: warped in outer regions

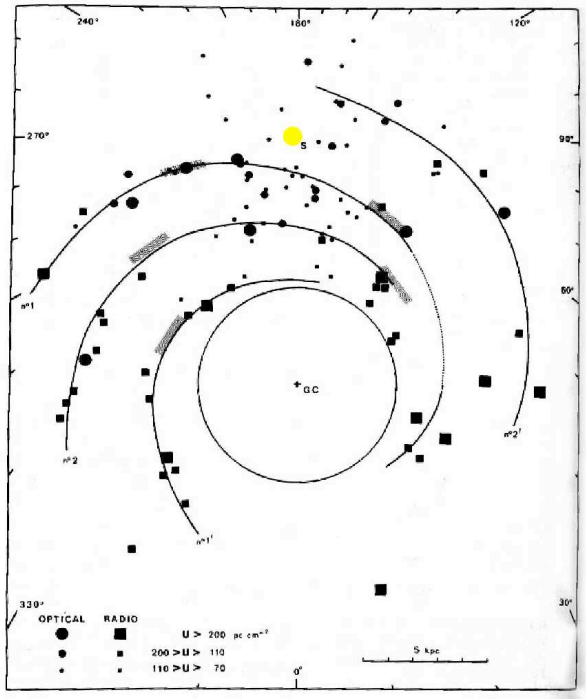
Milky Way Galaxy – recombination lines

Galactic structure: radio recombination lines in star forming regions
line transitions between very high n levels possible in space vacuum



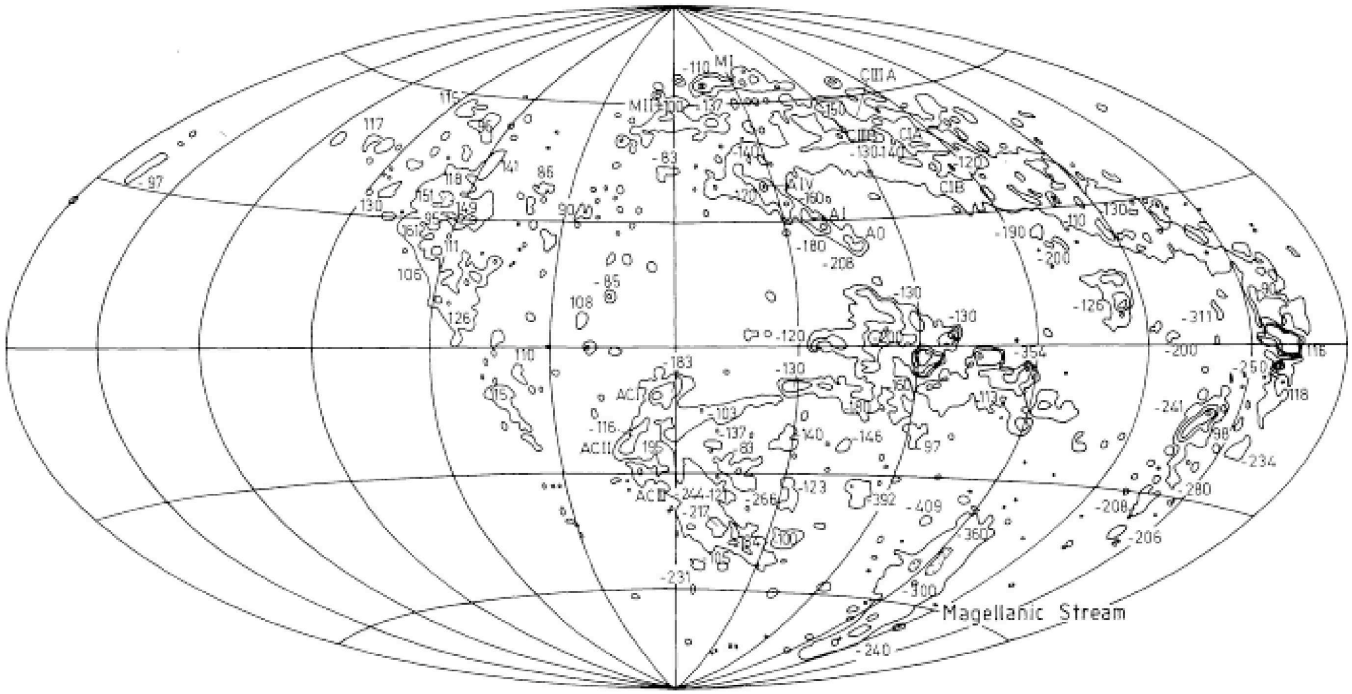
HI

n: 166→165 H166α



Milky Way Galaxy – step on the gas

High Velocity Clouds (HVCs): radial velocities exceed MW rotation



N hemisphere
HI with
$|V_{LSR}| > 100$ km/s

HI masses: $10^5 - 10^6\ M_\odot$ (Milky Way: $10^9\ M_\odot$)

Distances very hard to determine (ISM absorption lines): few kpc, in MW halo

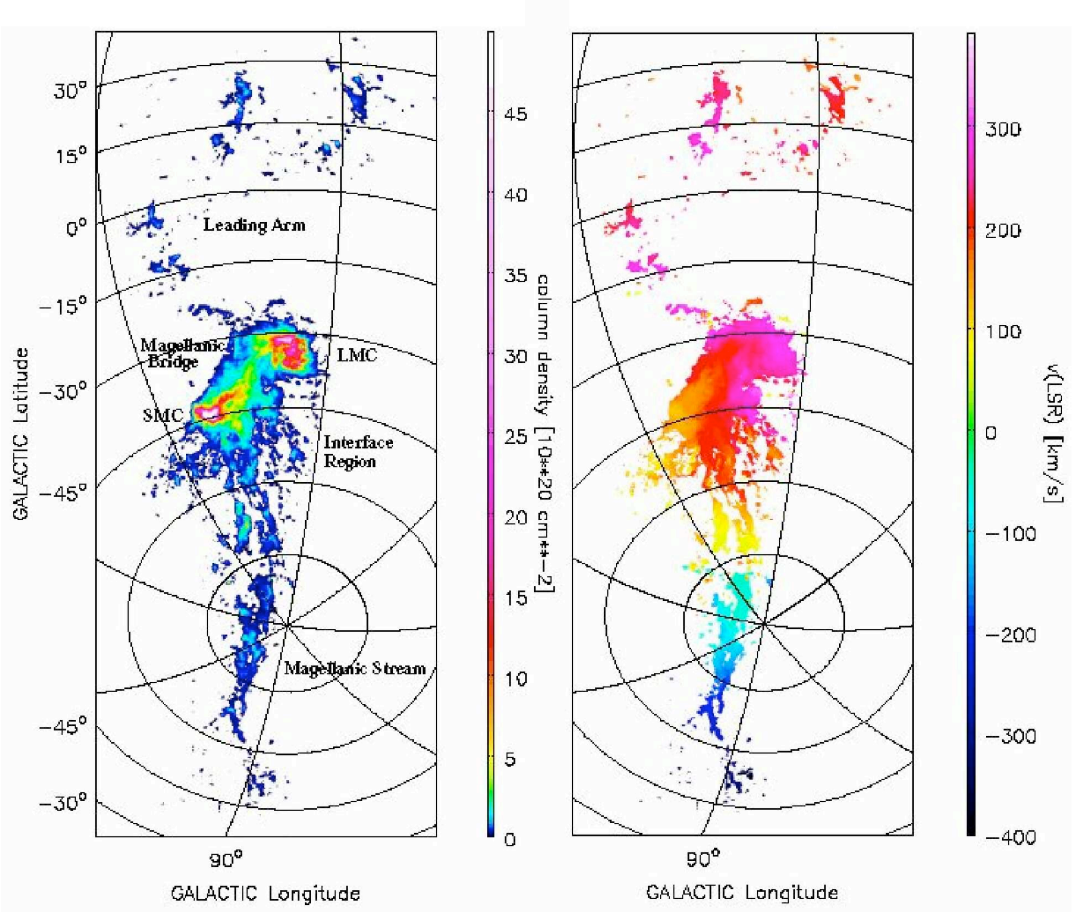
Metallicities: 0.1 – 0.25 solar – not primordial, but recycled material

Milky Way Galaxy – we are not alone

Magellanic Stream in HI: interaction with 2 dwarf companion galaxies

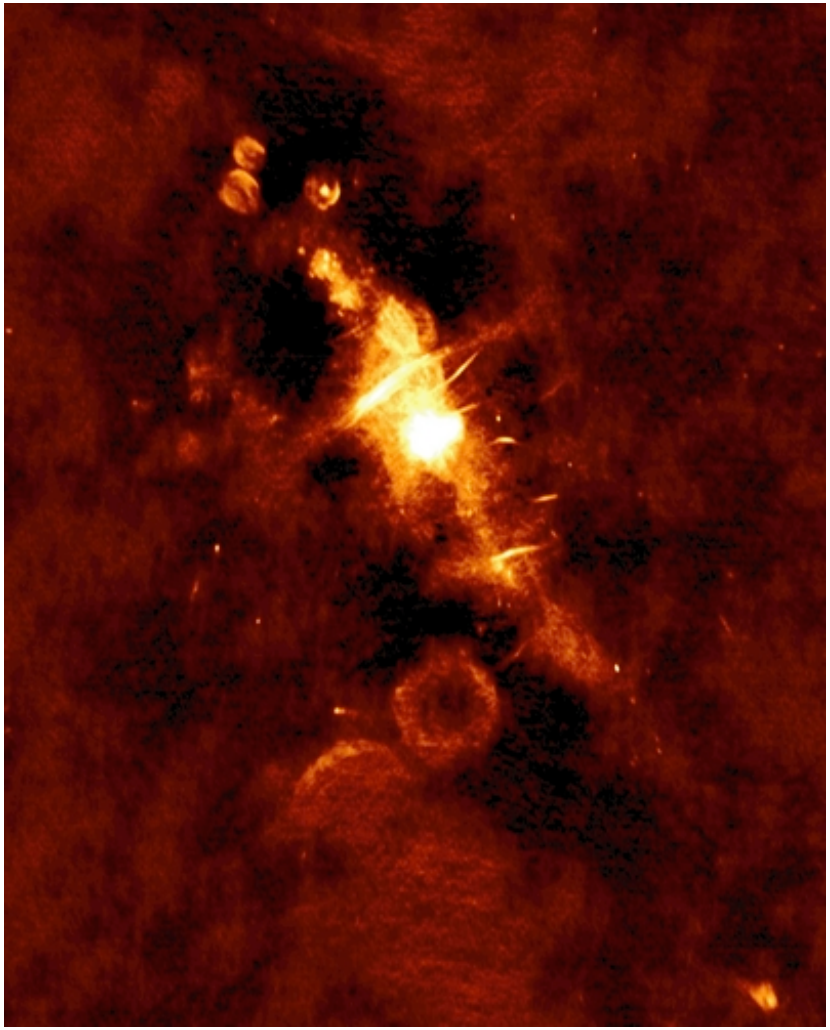
Small & Large
Magellanic Clouds

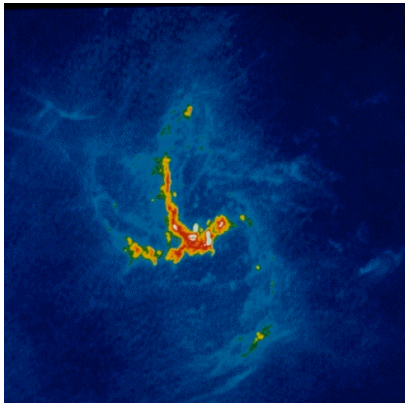
stretches out over
180 degrees on the S sky

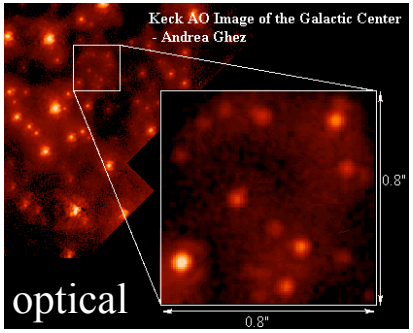


Milky Way Galaxy – right in the middle of it

Galactic Centre region – radio continuum





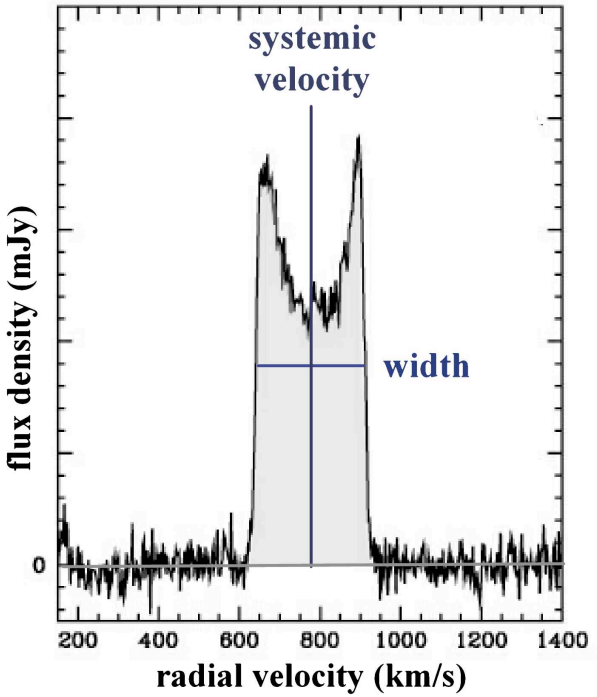


Unique place in the MW,

Funny structures:

Black Hole
mini radio spiral
radio arcs

Spiral galaxies - basics



flat, rotating disc

21cm HI line profile:

redshift, HI gas mass

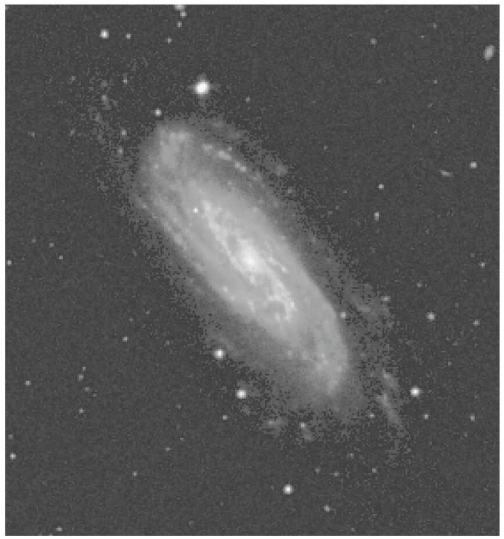
line width → total mass

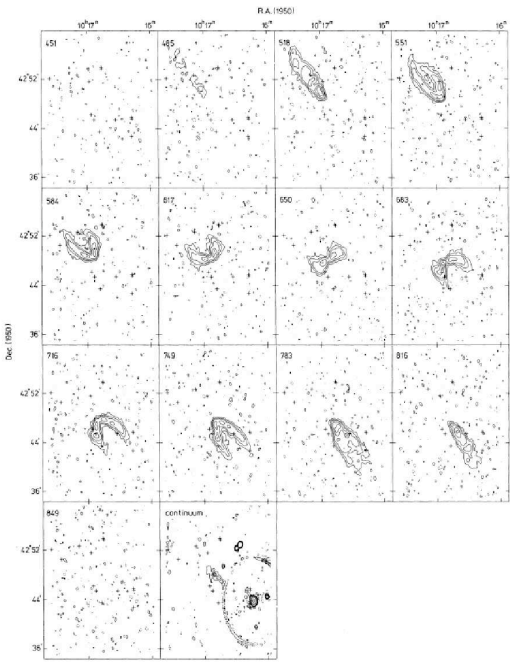
Galaxies – gas and light

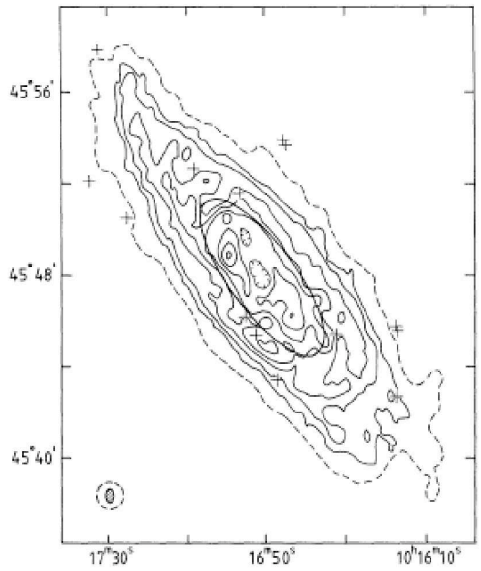
optical

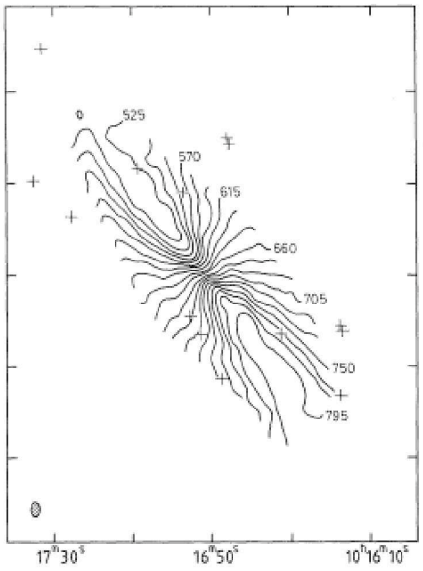
HI

Galaxies – HI line imaging data cube









HI interferometry:

channel maps

continuum subtraction

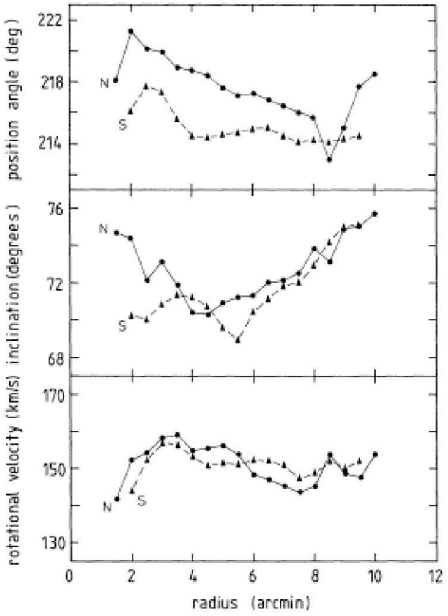
CLEANing

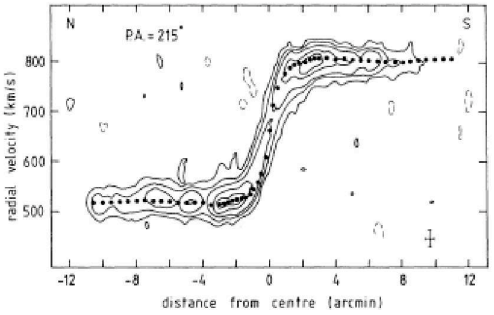
Spatial filtering

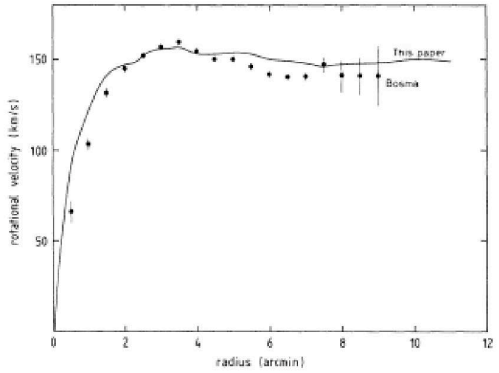
HI column density map

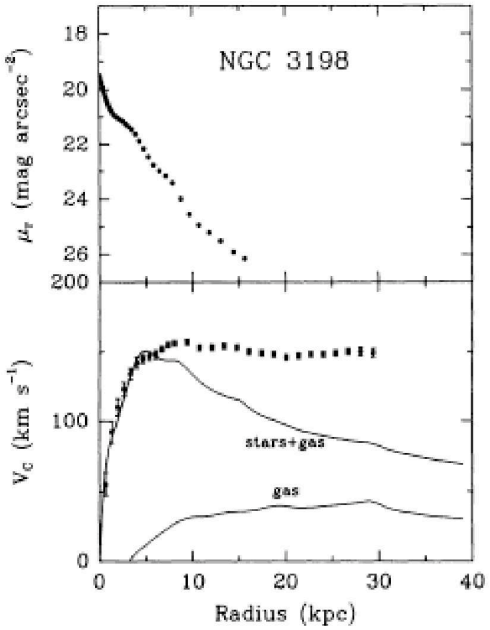
HI velocity field
(intensity-weighted,
gauss fits)

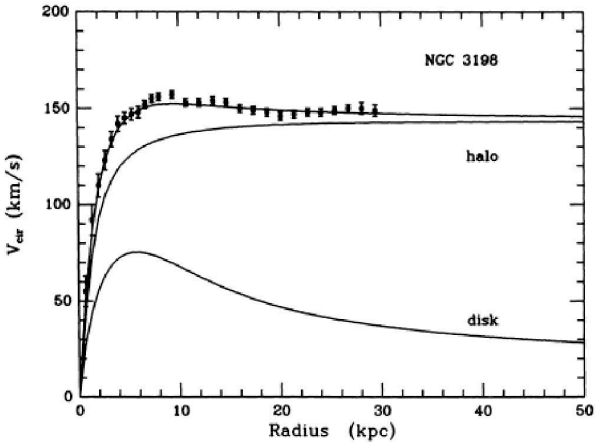
Galaxies – HI line imaging data cube











position-velocity diagram

fitting tilted-ring model

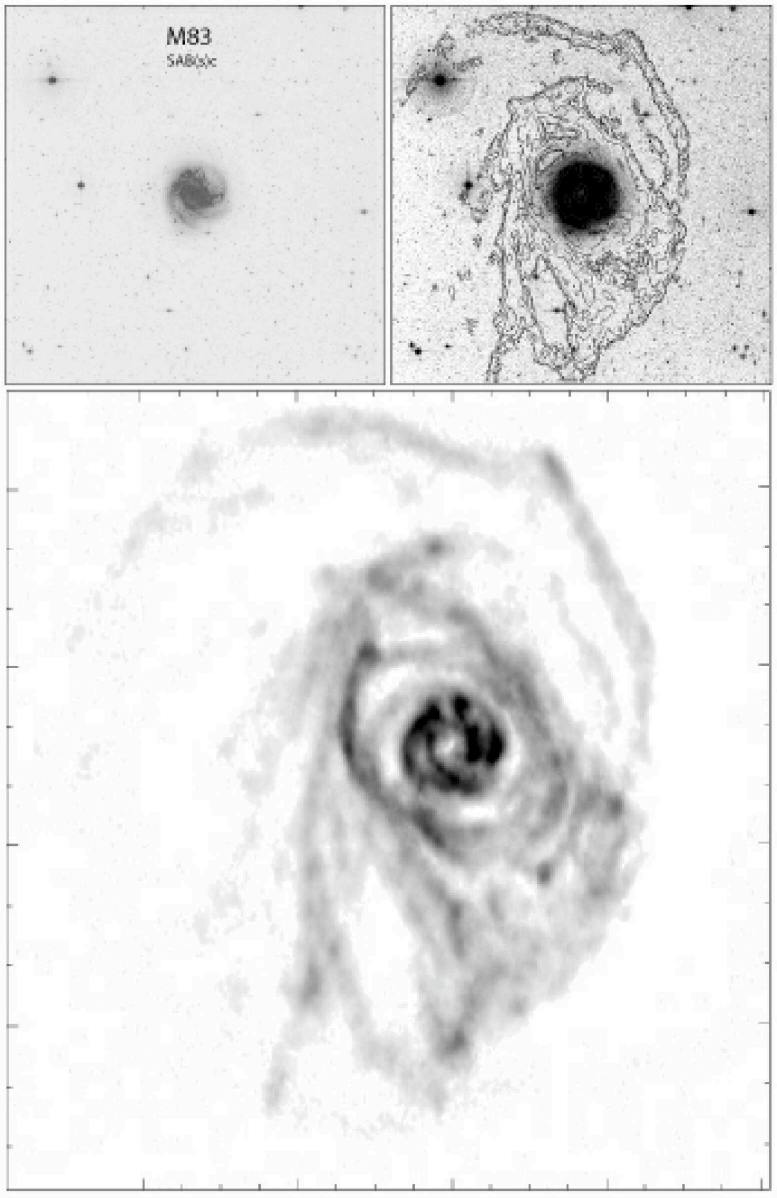
- position angle
- inclination
- rotation velocity

rotation curve

fit with mass components:

Dark Matter dominates

Galaxies – larger in HI



HI discs (much) larger than optical

important for DM studies,

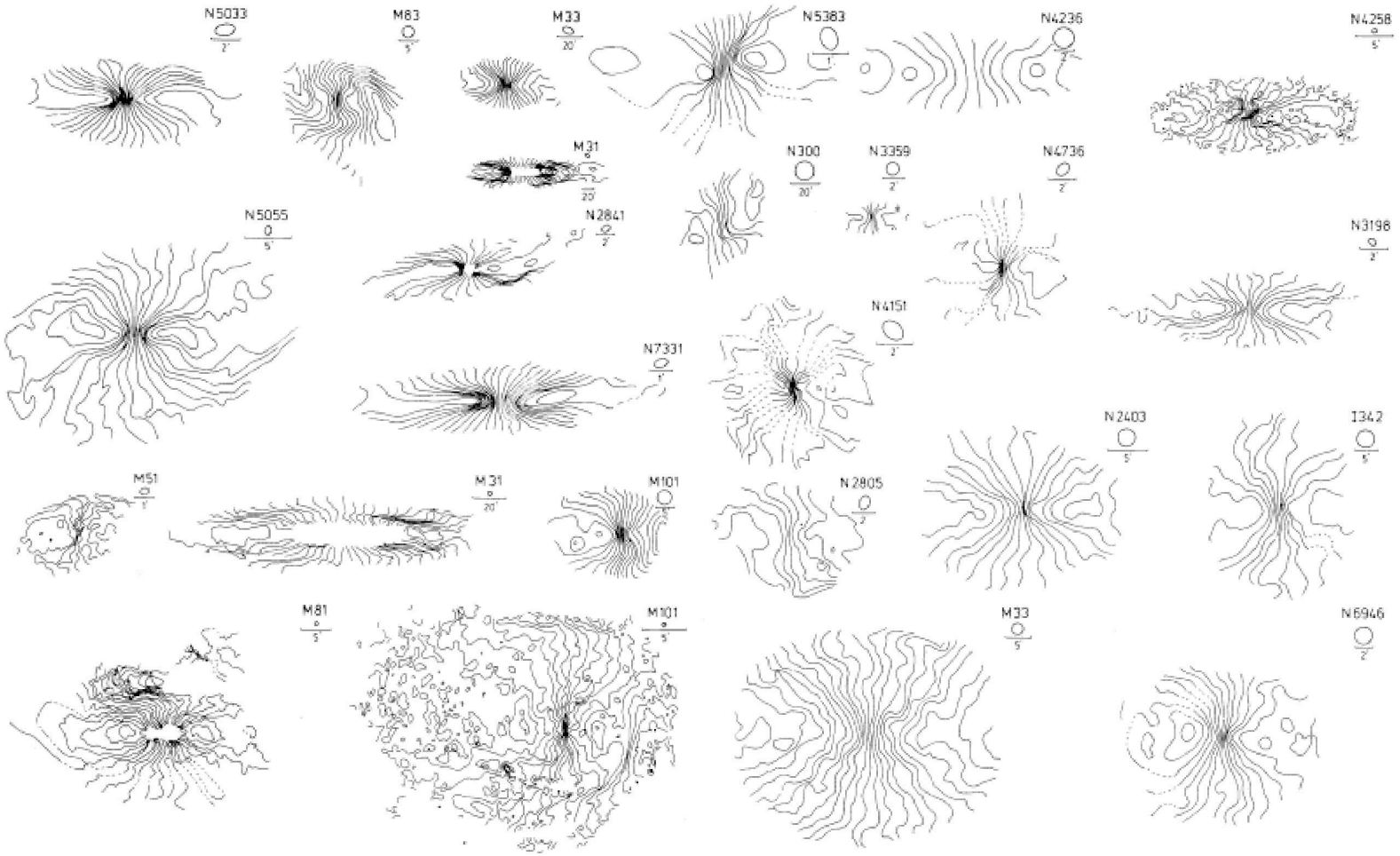
outer rotation curves show DM

Complete view of velocity field,

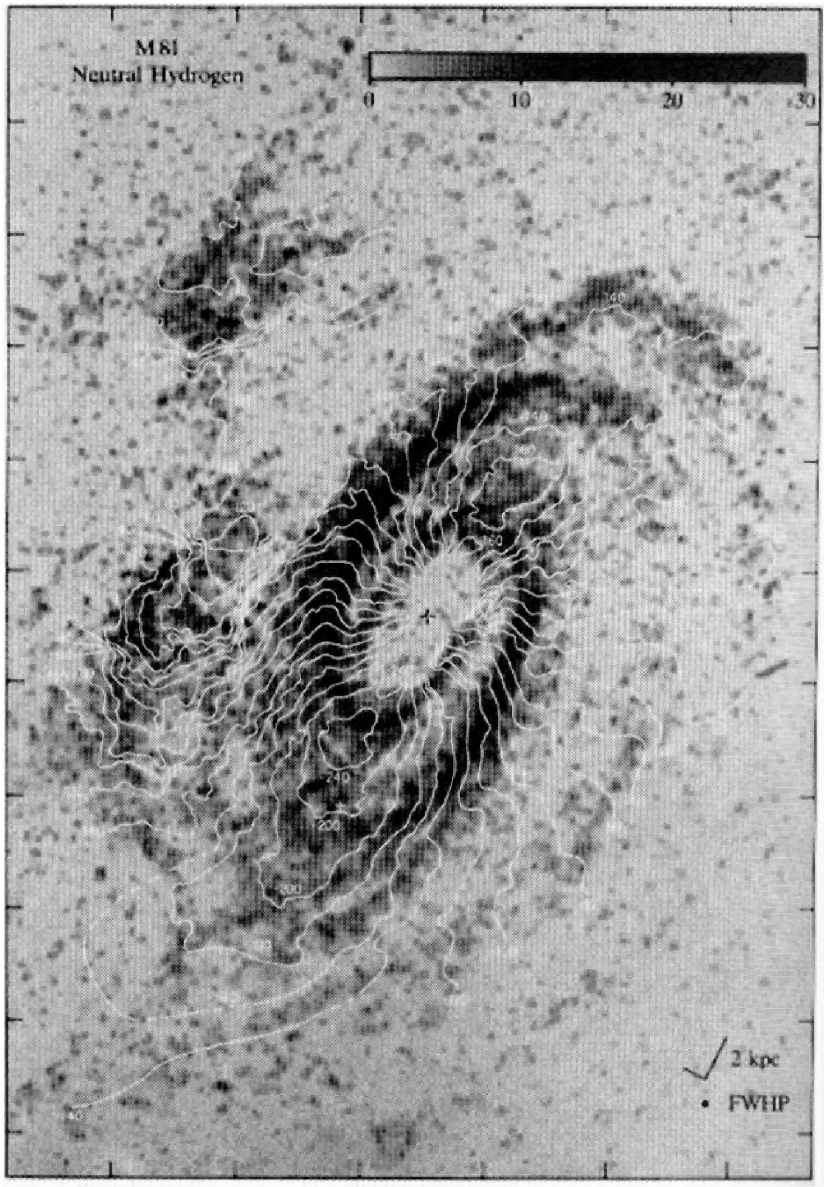
better than optical long-slit spectra

Galaxies – spider diagrams

Velocity fields: isovelocity contours – deviations from symmetry



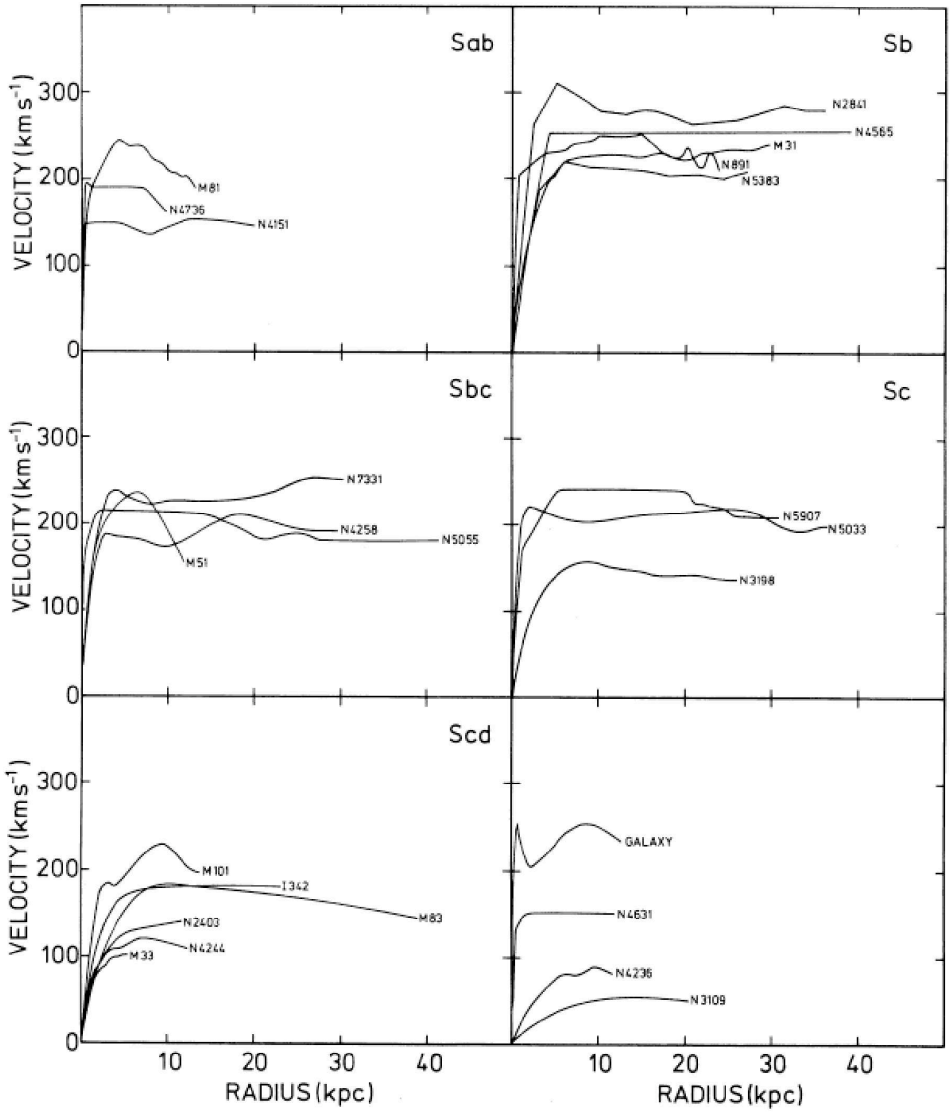
Galaxies – making waves



spiral arm density waves

seen in detailed velocity fields

Galaxies – speed limits

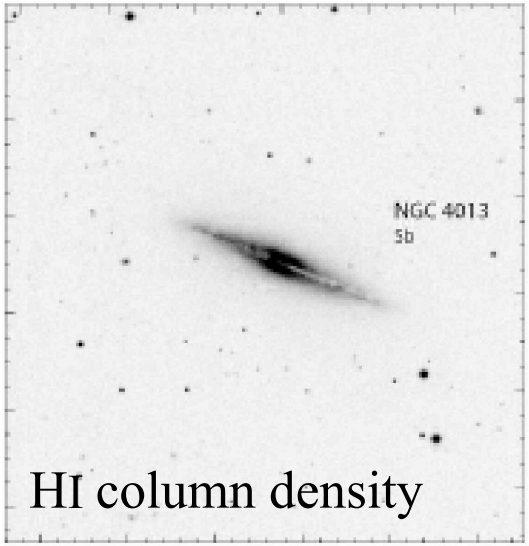


Looking for systematics in rotation curves:

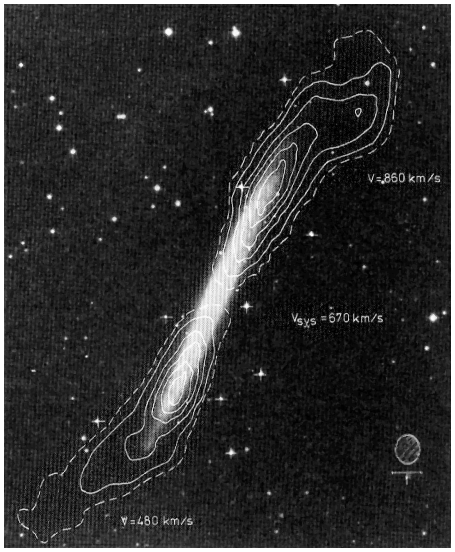
total mass, …

Galaxies – the warp zone

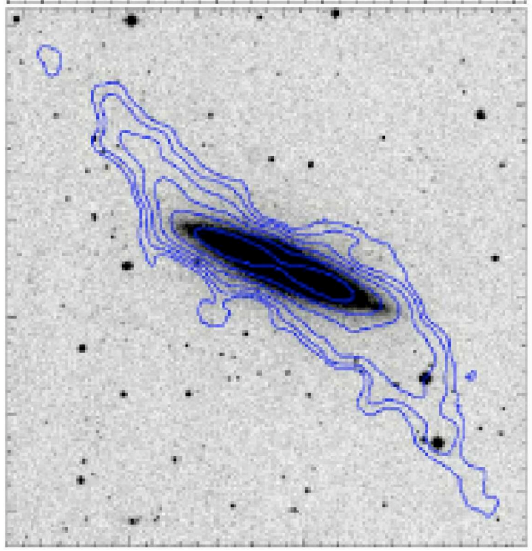
Warped outer discs

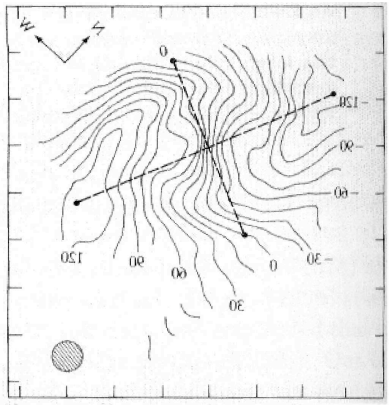


HI column density

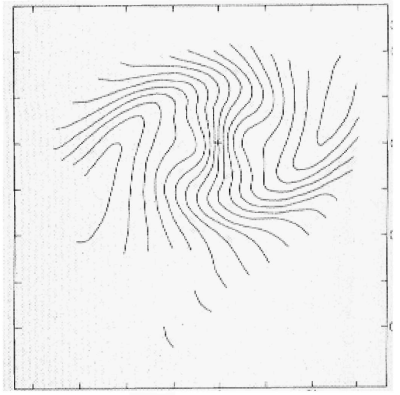


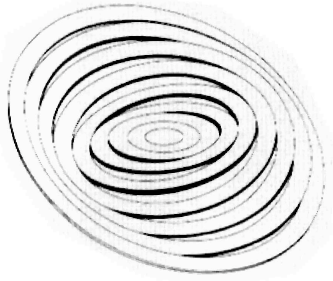
Channel maps at extreme velocities





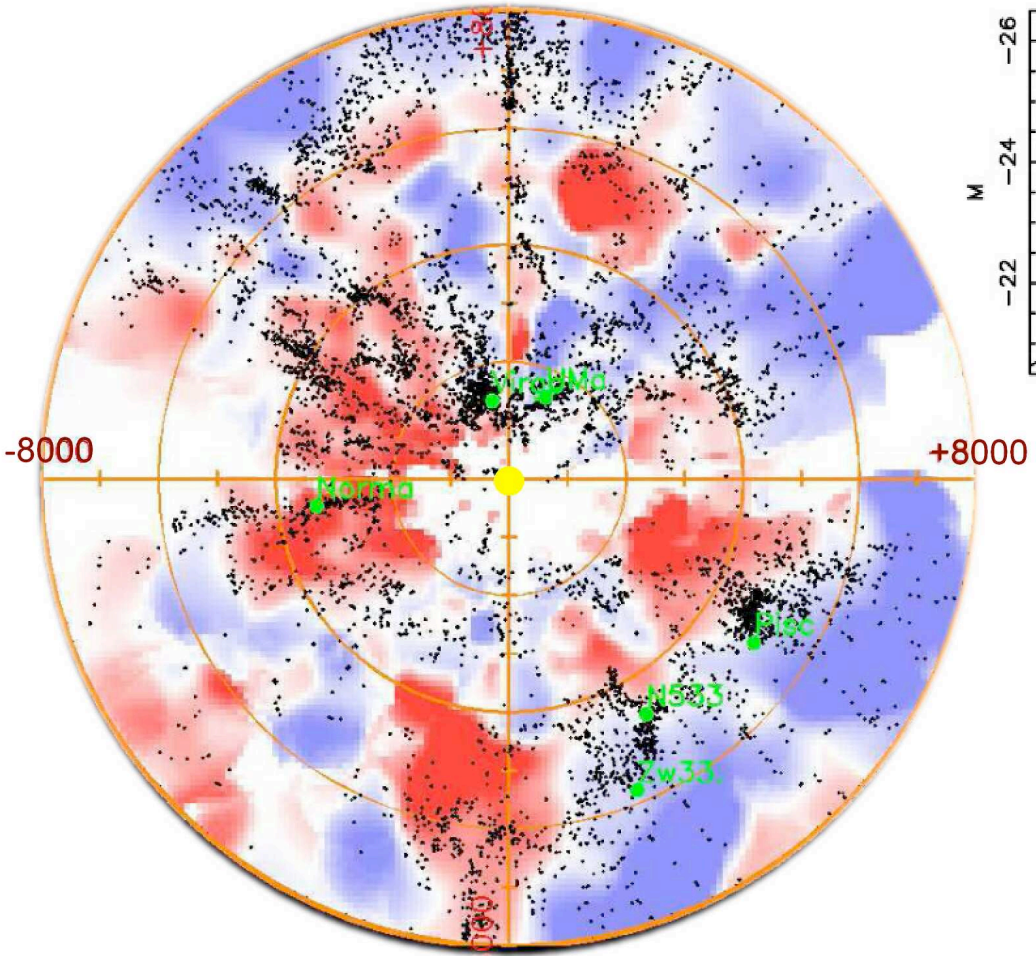
Tilted disc model



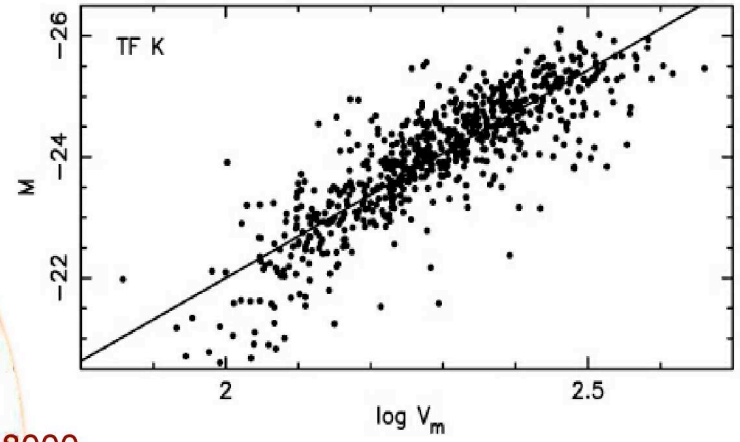


Galaxies – (not) going with the flow

Tully-Fisher relation: rotation velocity vs. absolute magnitude



Peculiar galaxy velocities in local Universe



HI profile → galaxy line width

+ inclination → rotation velocity

Compare with TF relation

→ absolute magnitude

+ apparent magnitude → **distance**

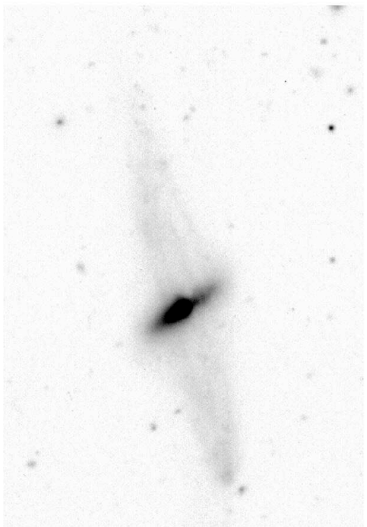
Compare with Hubble flow

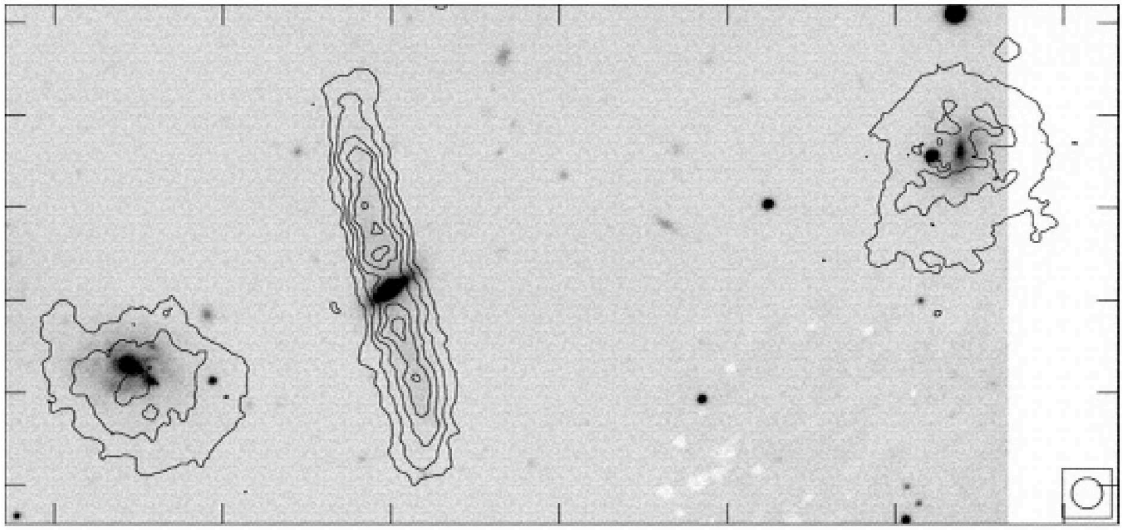
→ peculiar velocities

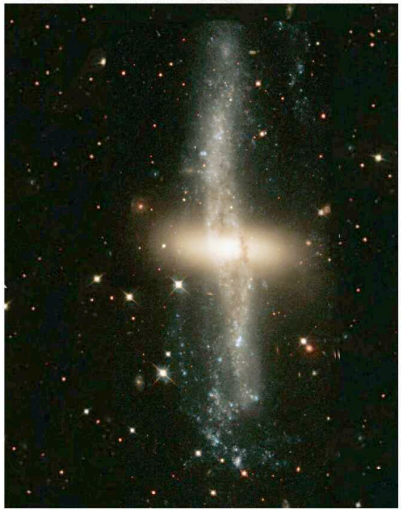
→ Dark Matter in galaxy clusters

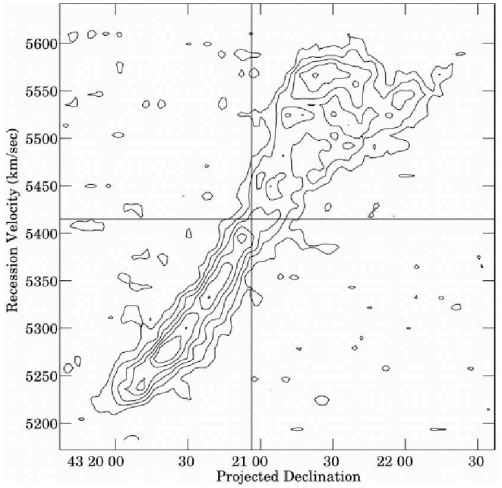
Galaxies – cosmic traffic accidents

Polar Ring Galaxies









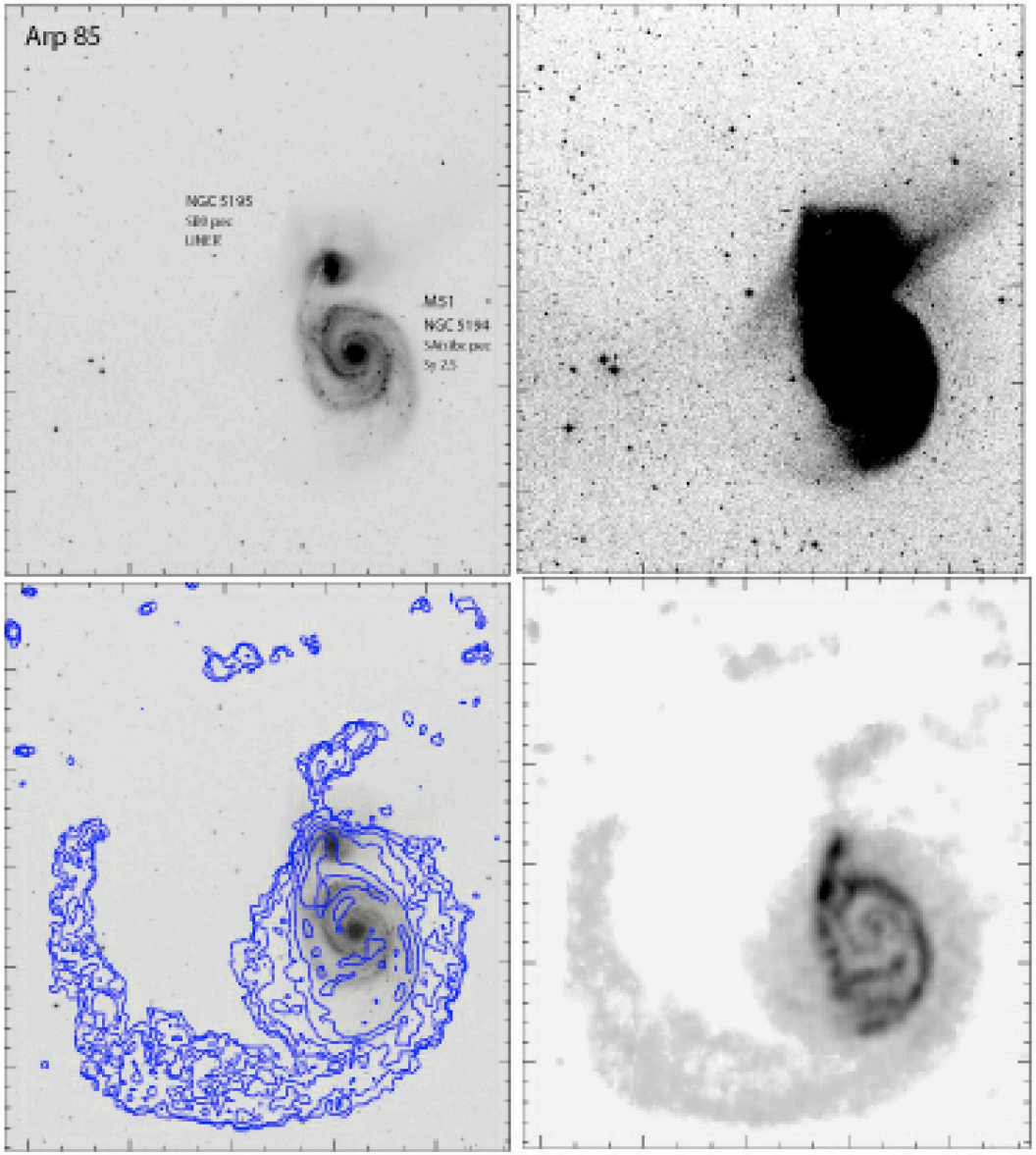
Cosmic traffic accidents

disc + polar ring

can study kinematics in two orthogonal planes

3D Dark Matter distribution

Galaxies – fender-benders

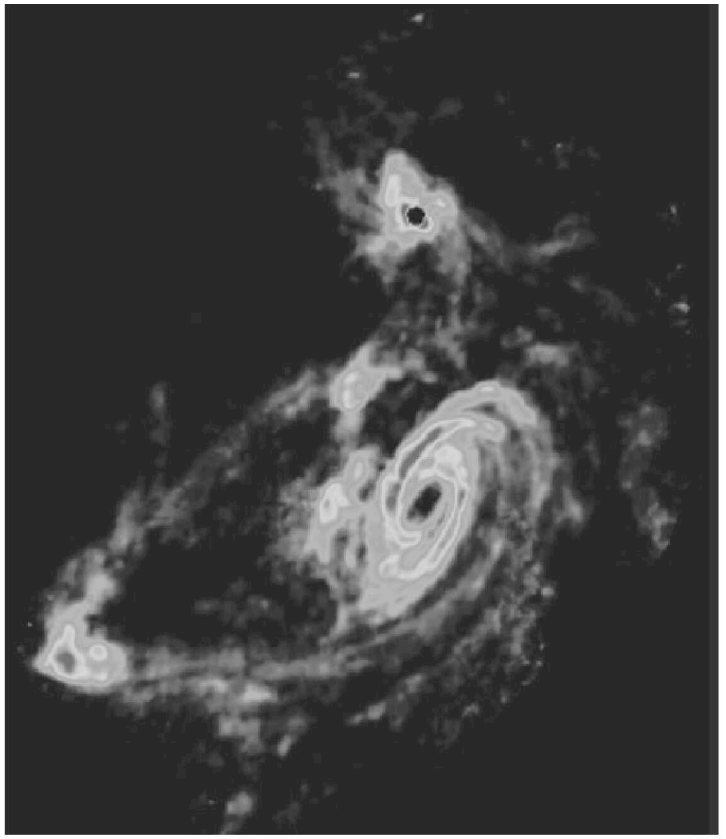


HI gas much more susceptible to gravitational interactions than stars:

shows accretion, stripping, minor mergers, …

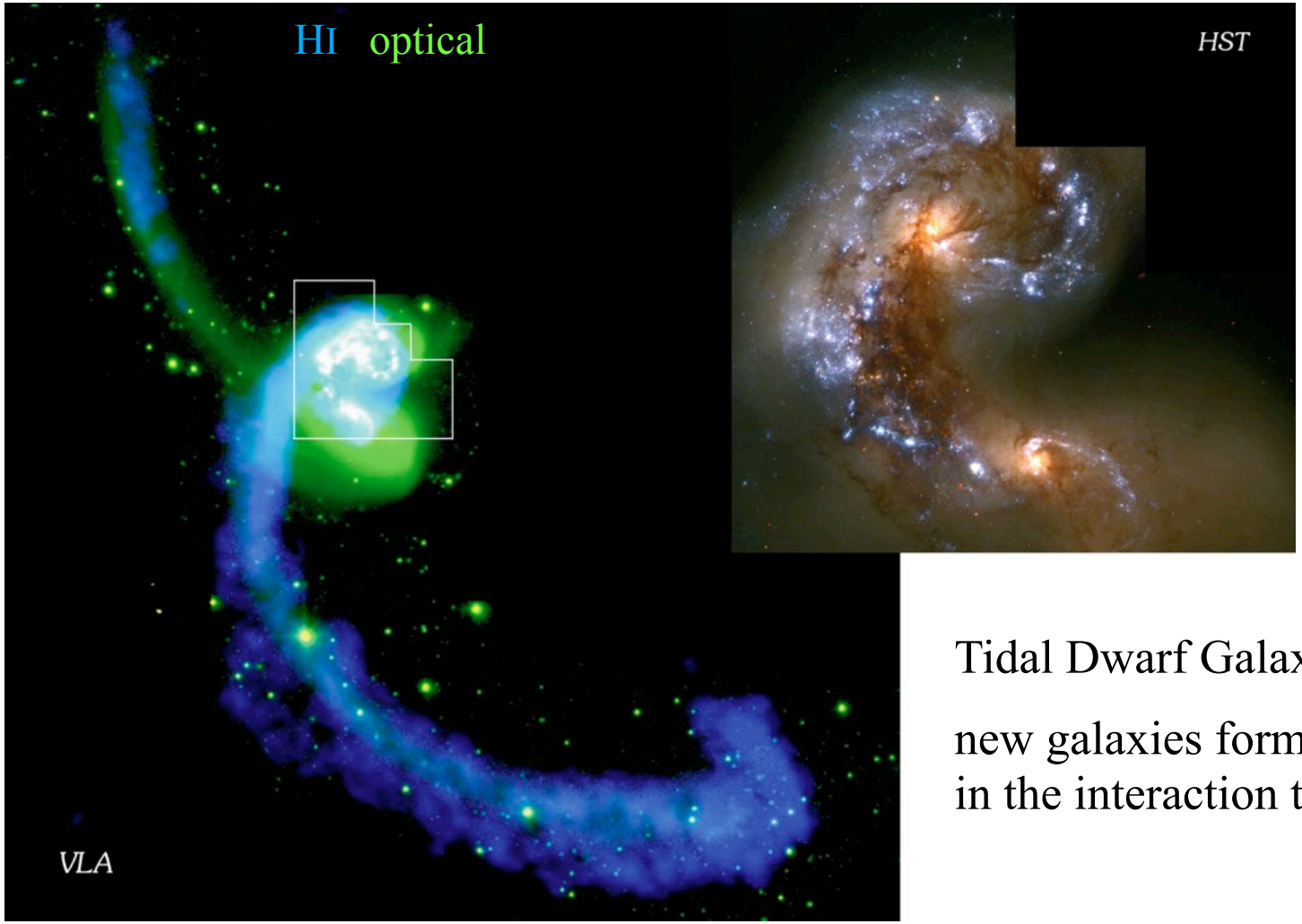
Galaxies - stripping

Spectacular evidence of galaxy interactions in HI



M81 group of galaxies optical HI

Galaxies - collissions

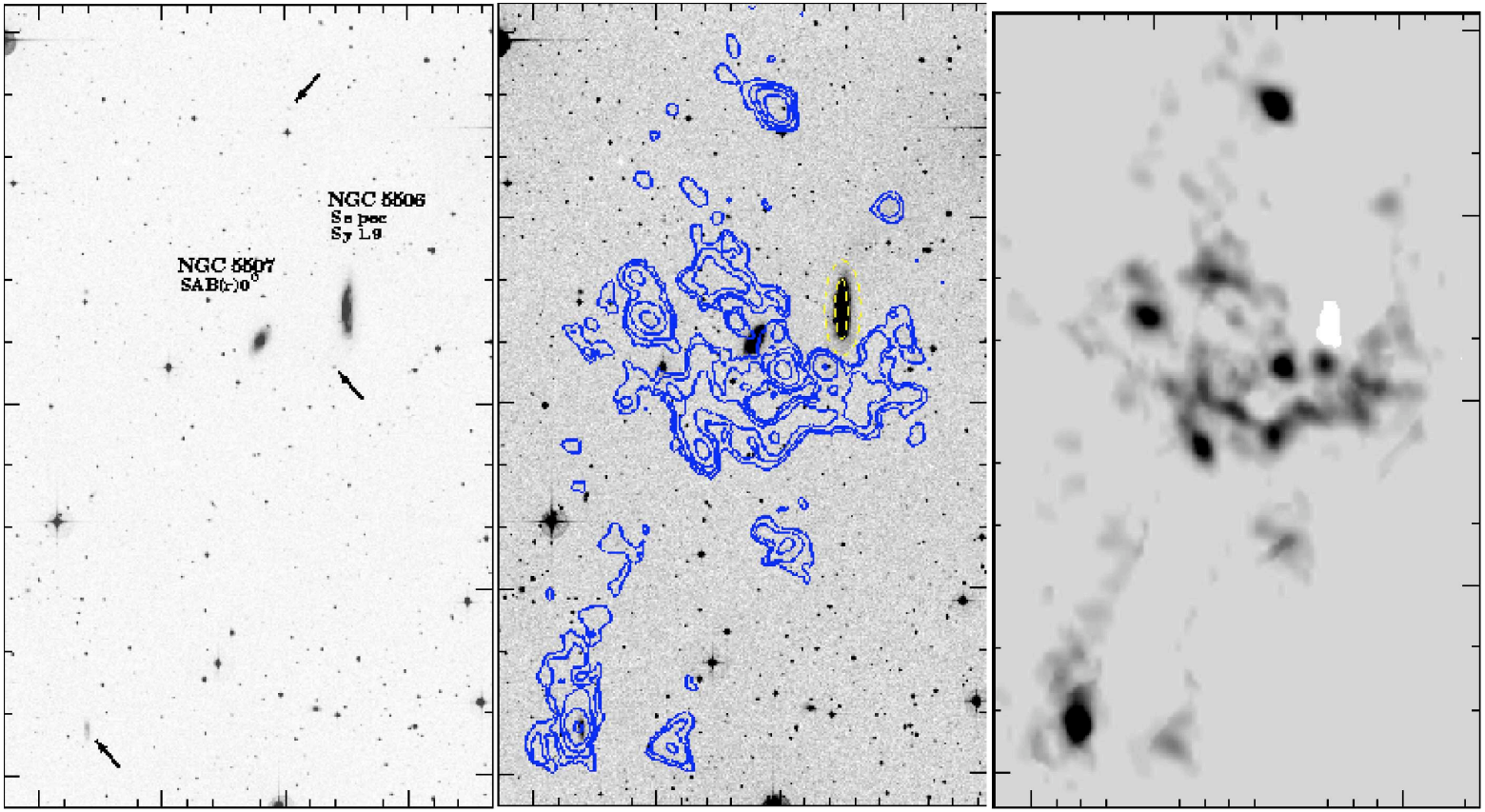


Tidal Dwarf Galaxies:

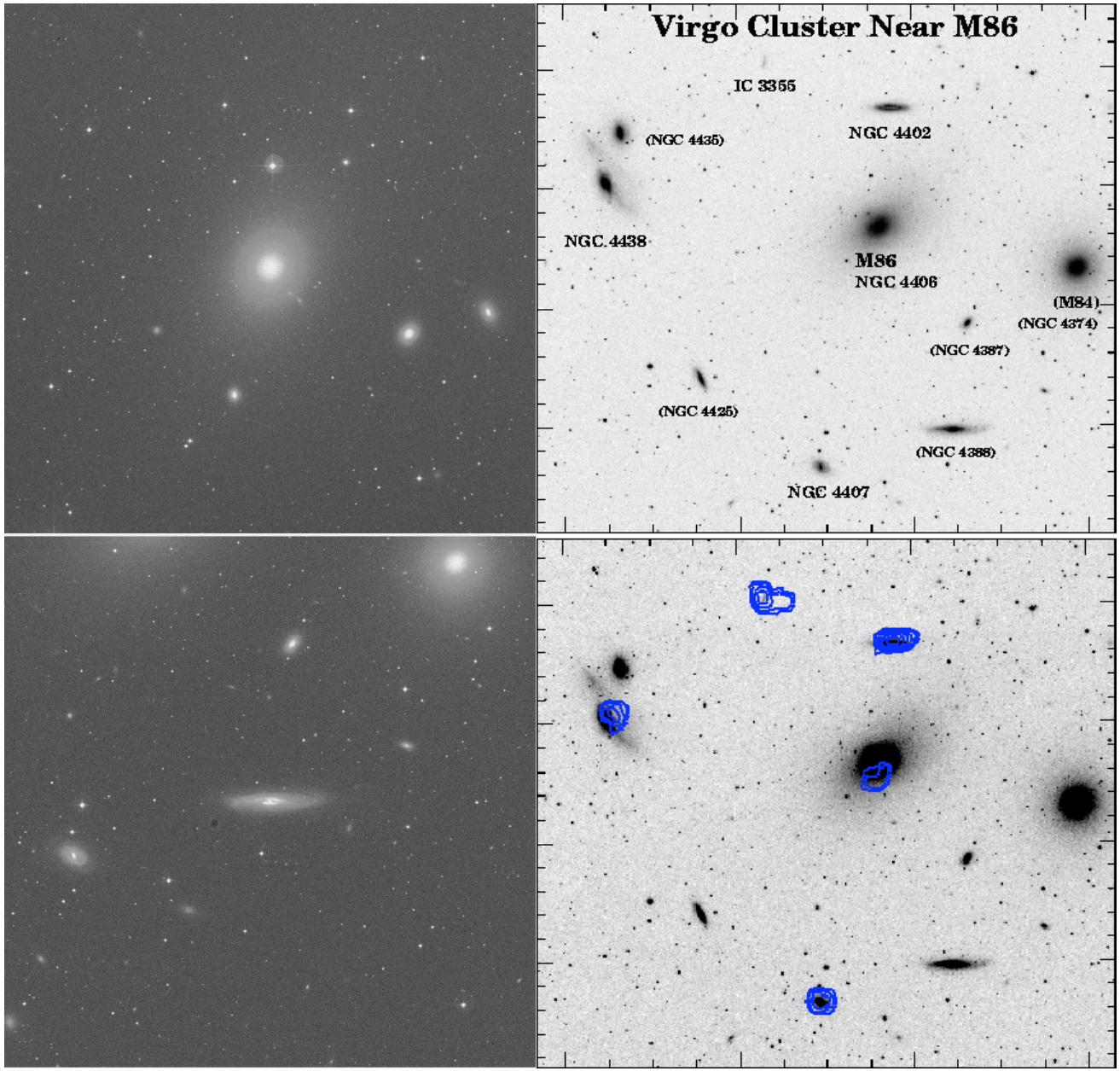
new galaxies formed in the interaction tails

Galaxies - groups

Interactions in groups of galaxies: HI all over the place



Galaxy clusters – environmental hazards

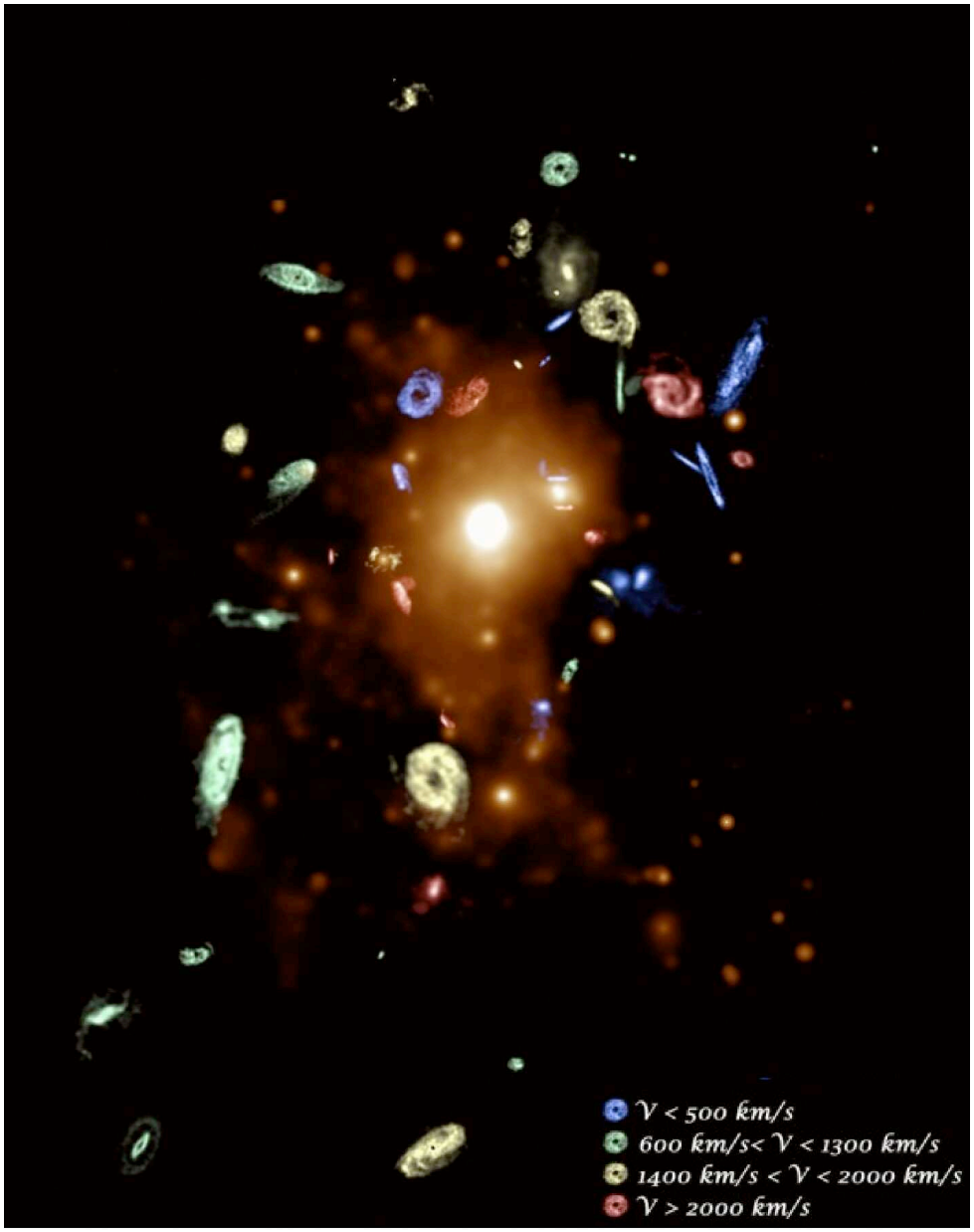


Interactions:

Between galaxies:
giant ellipticals,
stripping;
anemic spirals

With hot gas
between galaxies:
ram-pressure
stripping

Galaxy clusters – it's a gas



Virgo cluster in

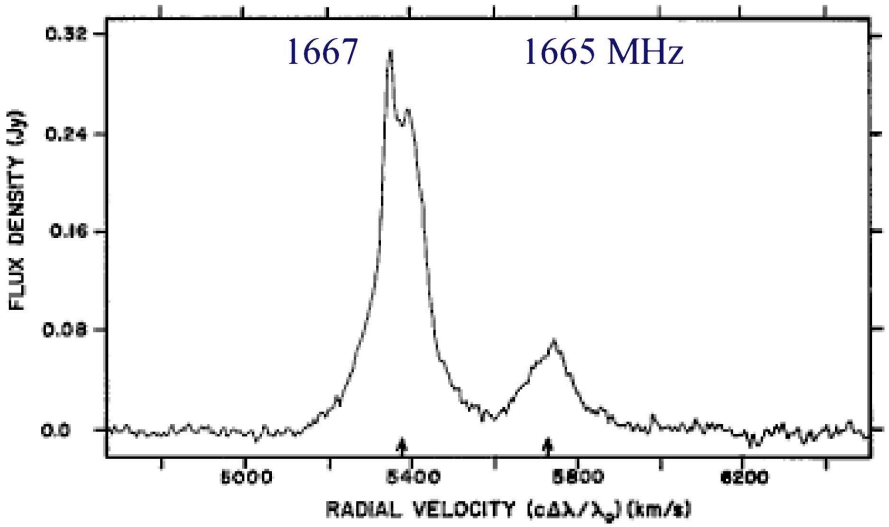
X-rays (hot gas)

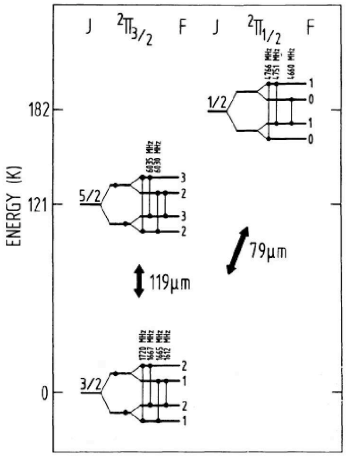
HI (cold gas)

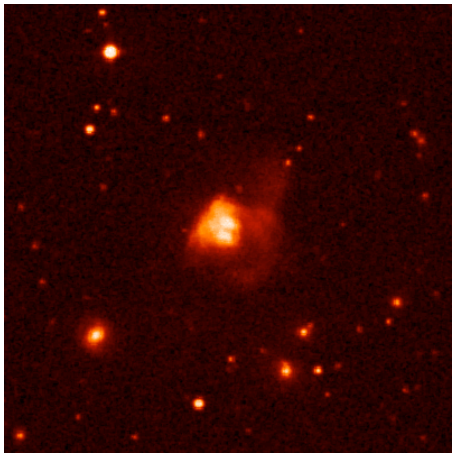
effects of ram-pressure stripping of galaxies moving through the hot cluster gas

Galaxies – masering mega monsters

OH megamasers



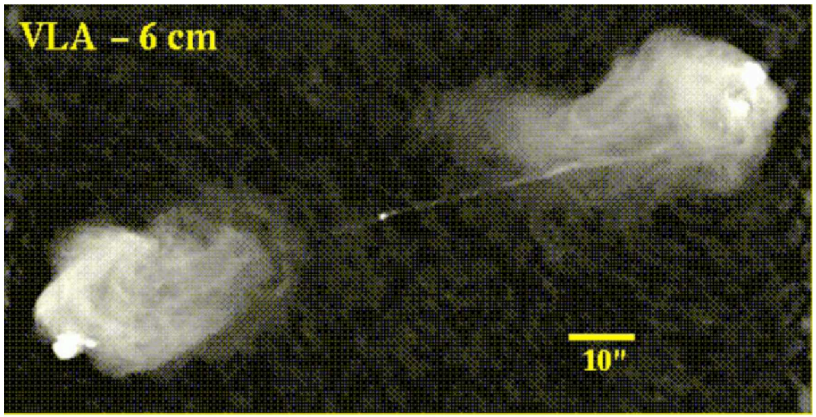


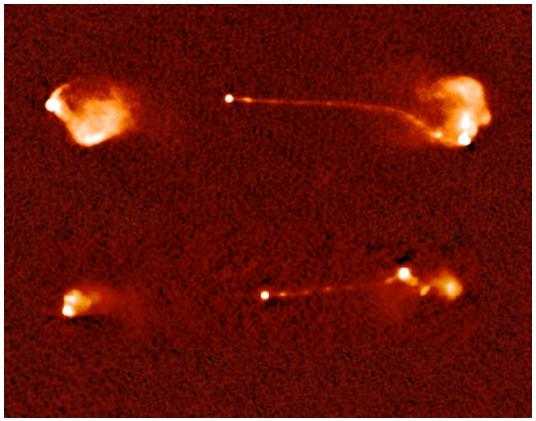


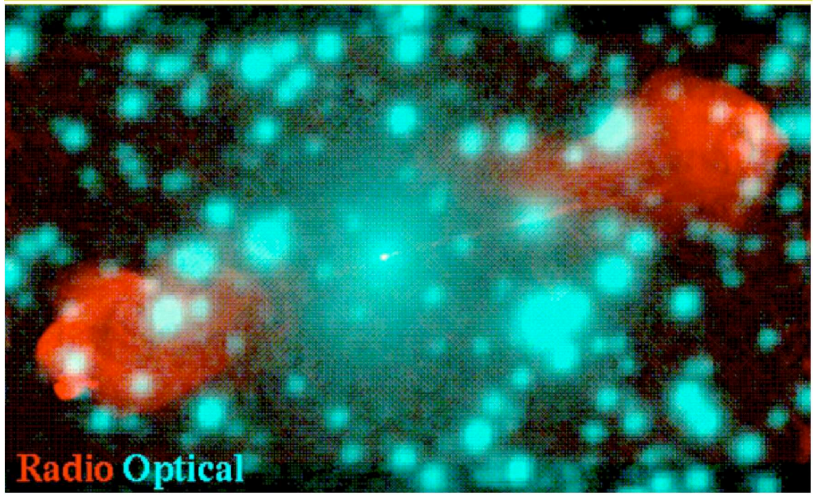
Galaxies with nuclear starburst: powerful energy source and lots of dust provides a pumping mechanism to stimulate maser line emission

Ultra-luminous galaxies, detectable at cosmological distances in OH

Radio galaxies – cosmic beacons







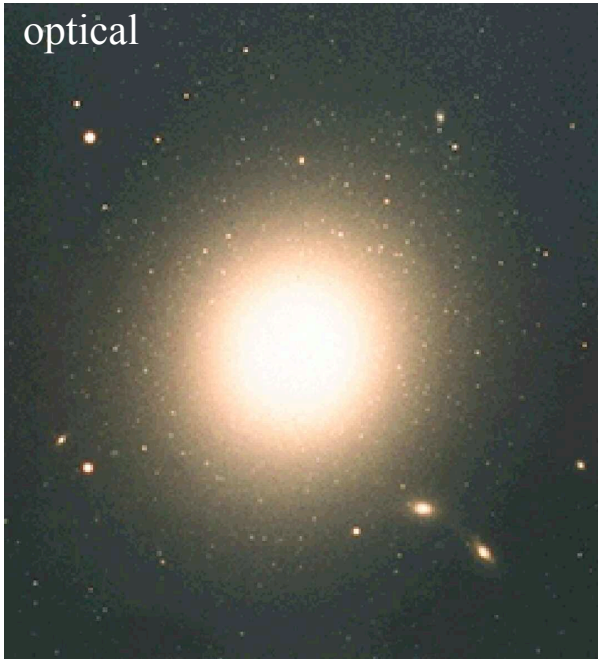
central spinning black hole

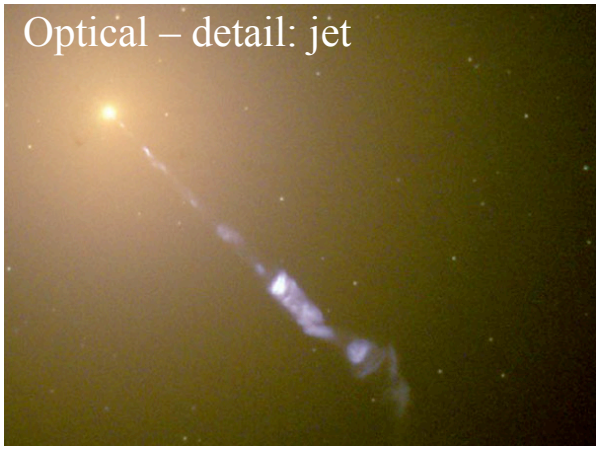
two relativistic jets

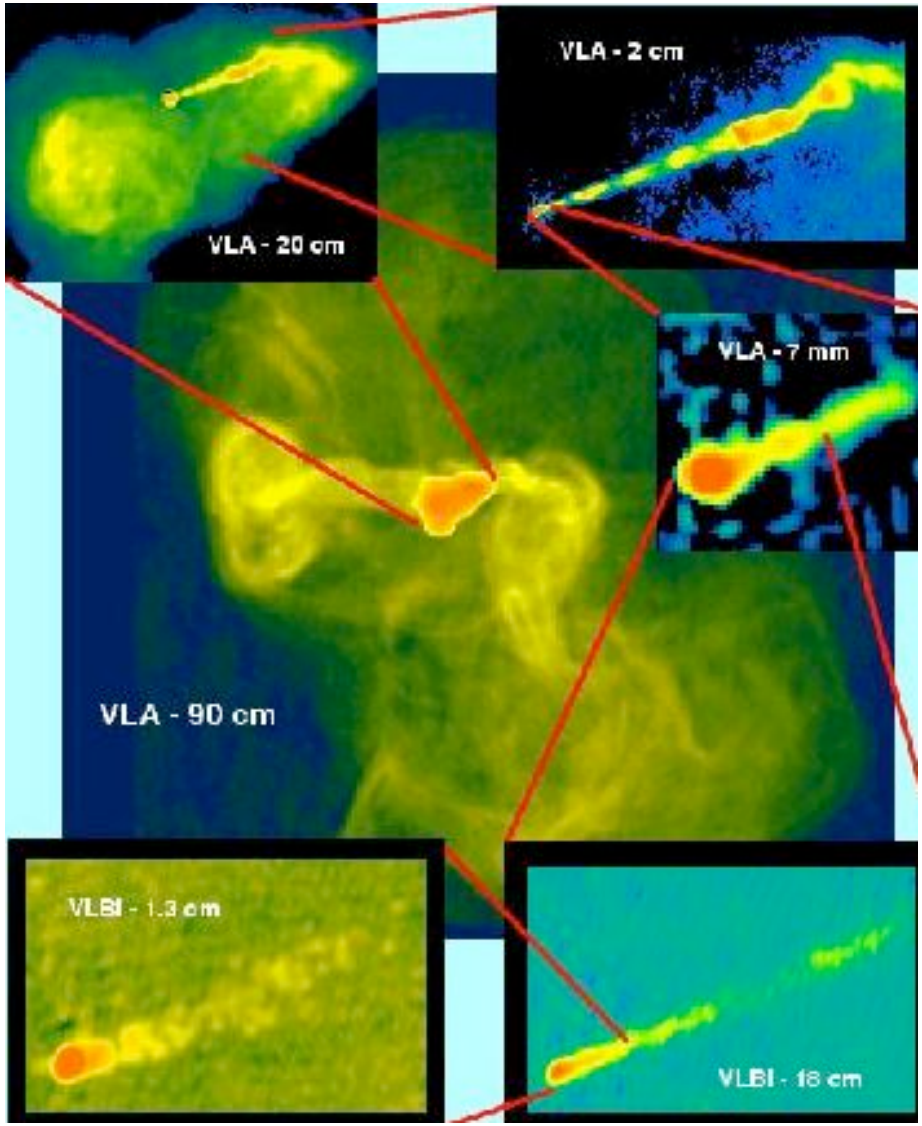
expanding into lobes outside the confines of the host galaxy

Radio galaxies – straight jet set

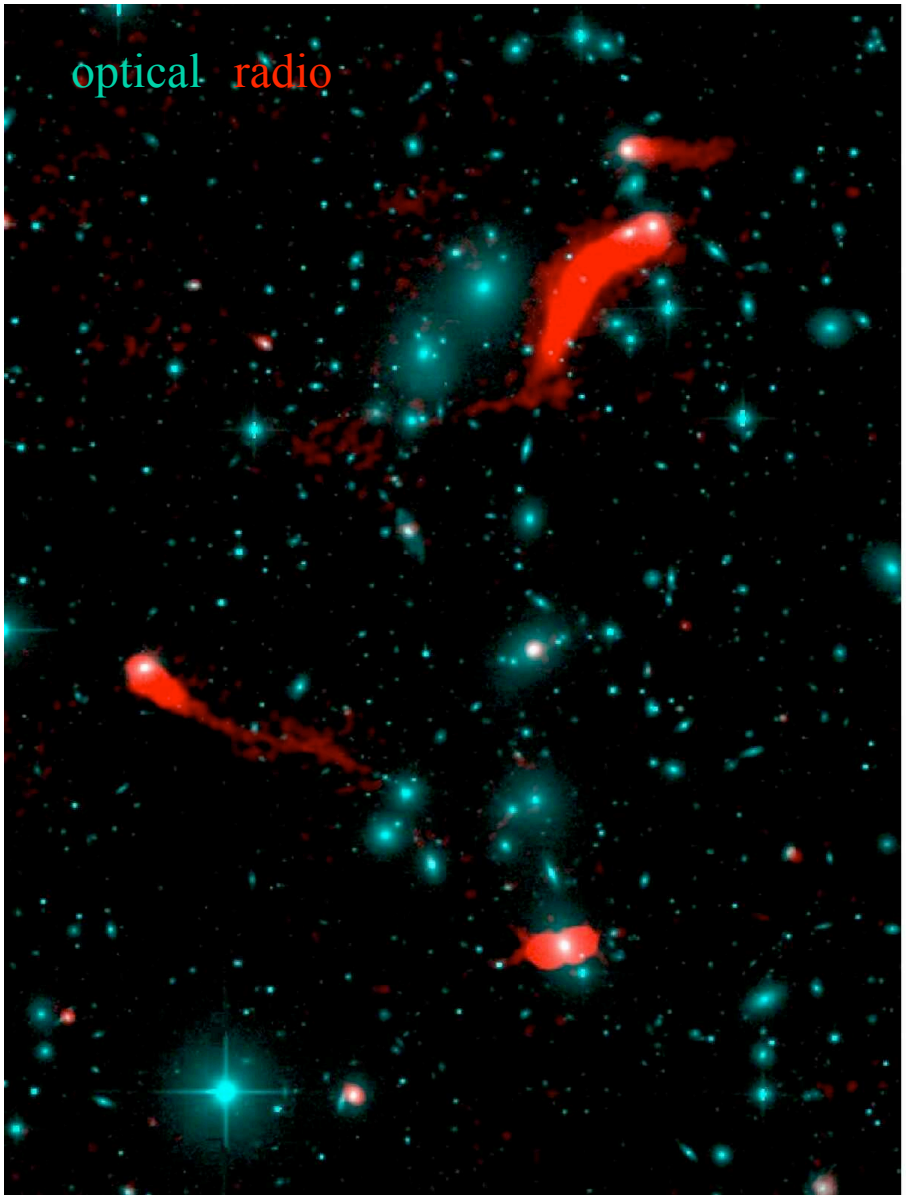
M87: giant elliptical in Virgo Cluster: optical and radio images of jet

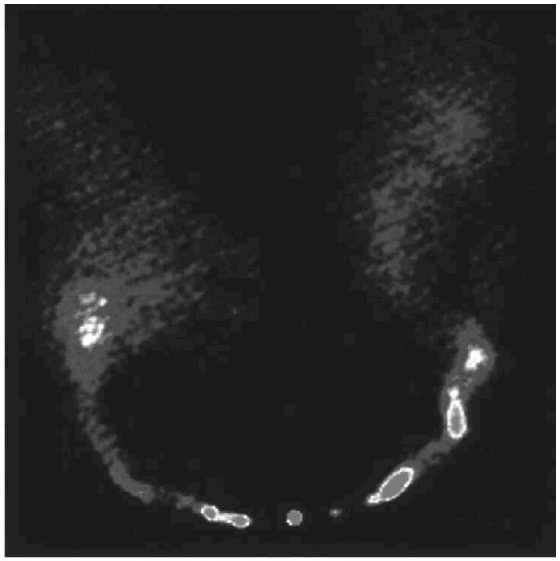






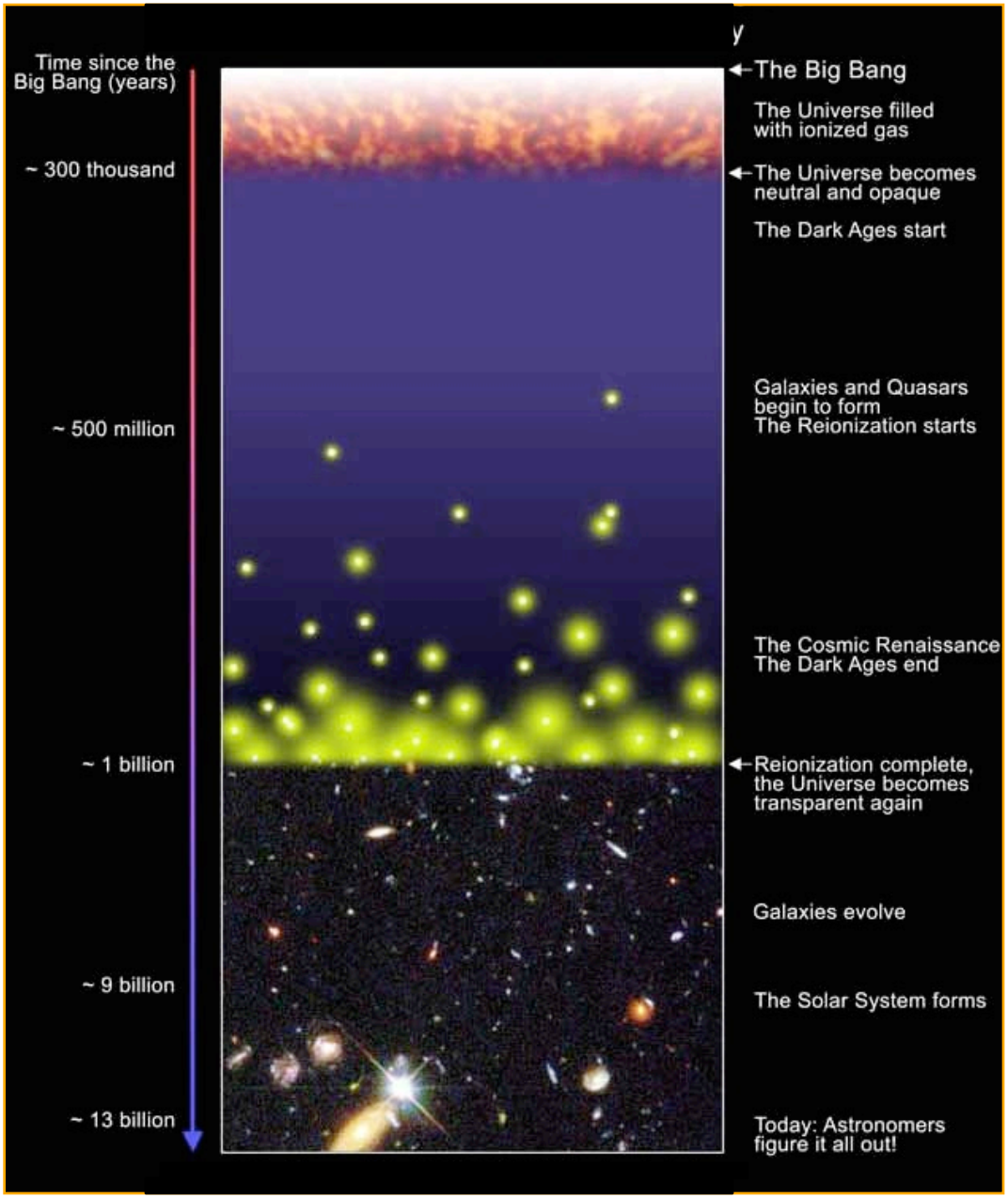
Radio galaxies – gone with the wind





Outside the host galaxy radio jets interact with the hot gas between galaxies and get pulled, twisted, …

Look back in radio

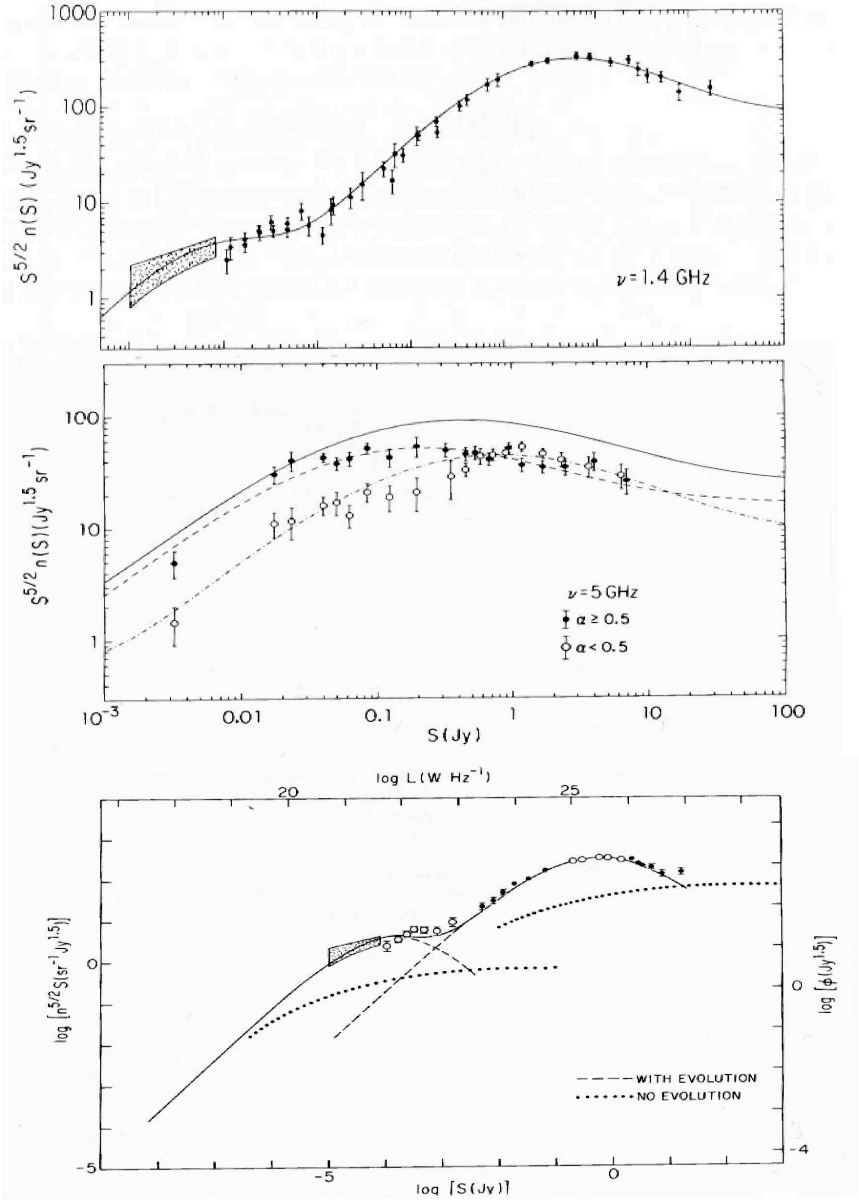


History of the Universe in a nutshell:

Big Bang, Dark Ages, Illumination, Stuff forms

Optical and radio views very different, complementary

Distant galaxies – looking for universal stuff



Radio galaxies – world model choice:

apparent vs. true properties:

- source counts
- size distributions

Looking for universal candles/rods;

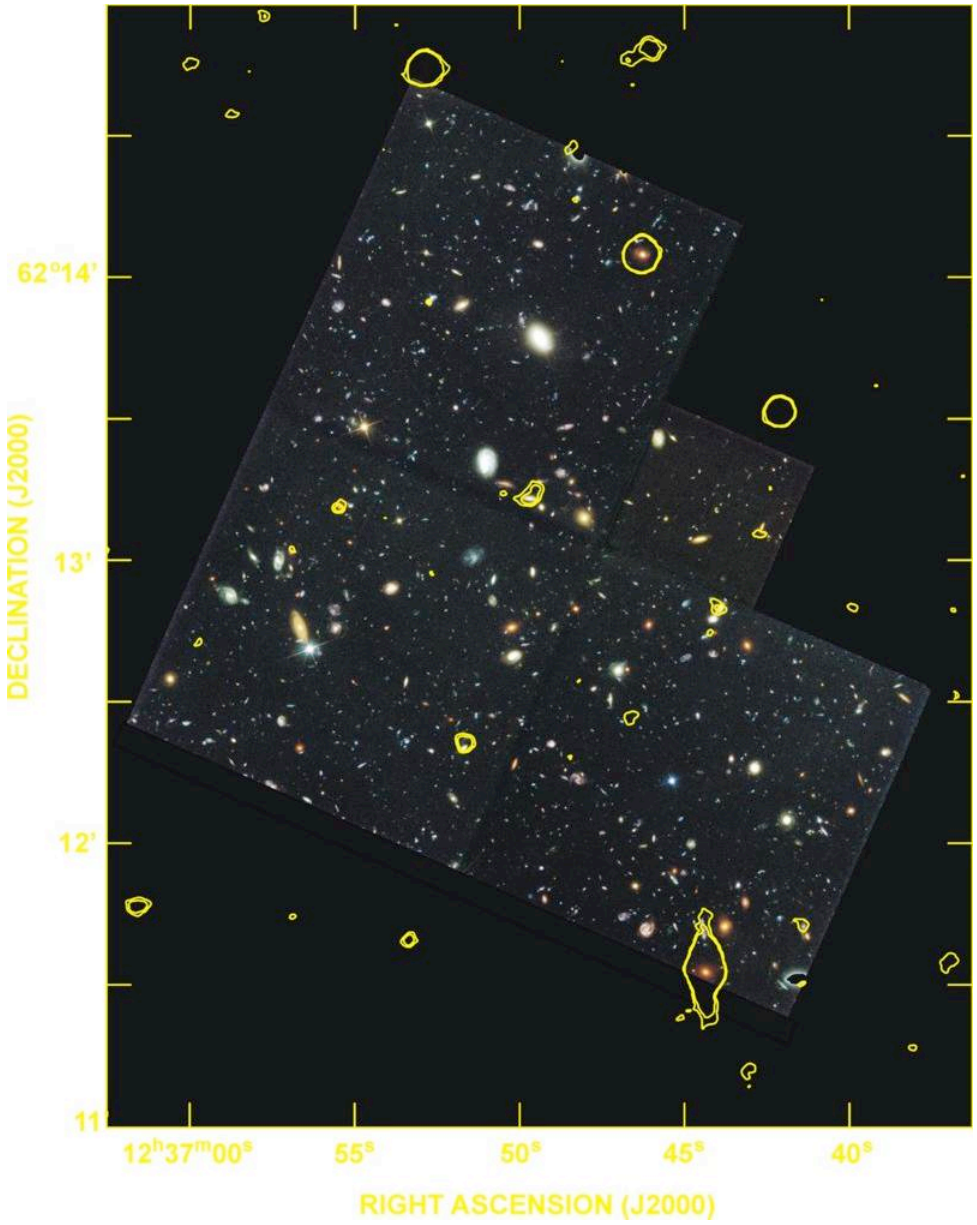
But too much variation

Radio source populations:

- evidence for evolution

Long before found in optical

Distant galaxies – how deep is my field?



Hubble Deep Field:

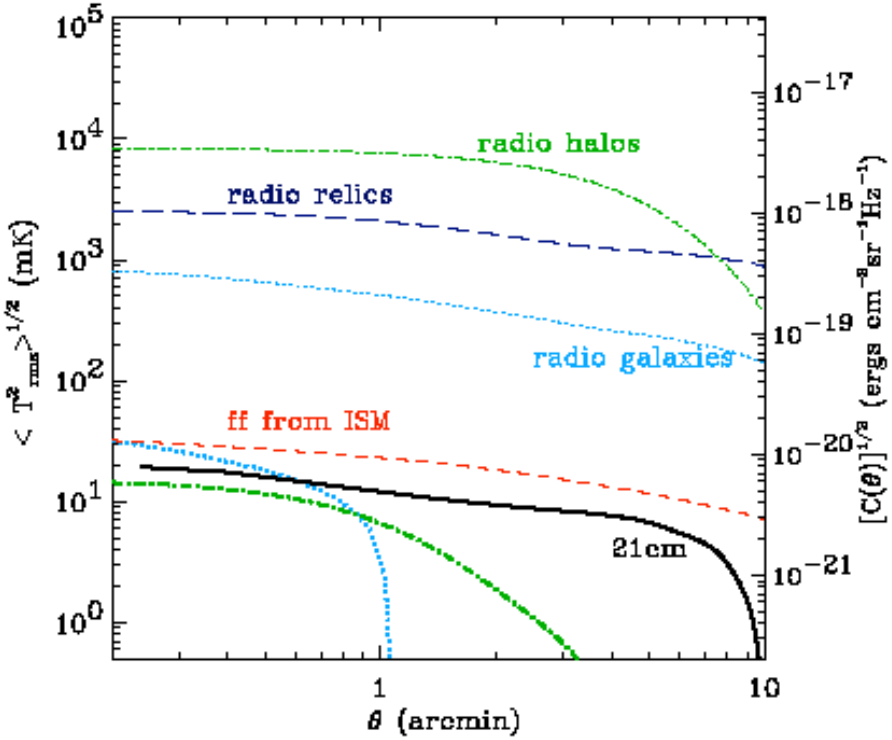
Optical / radio continuum

thousands of HST detections

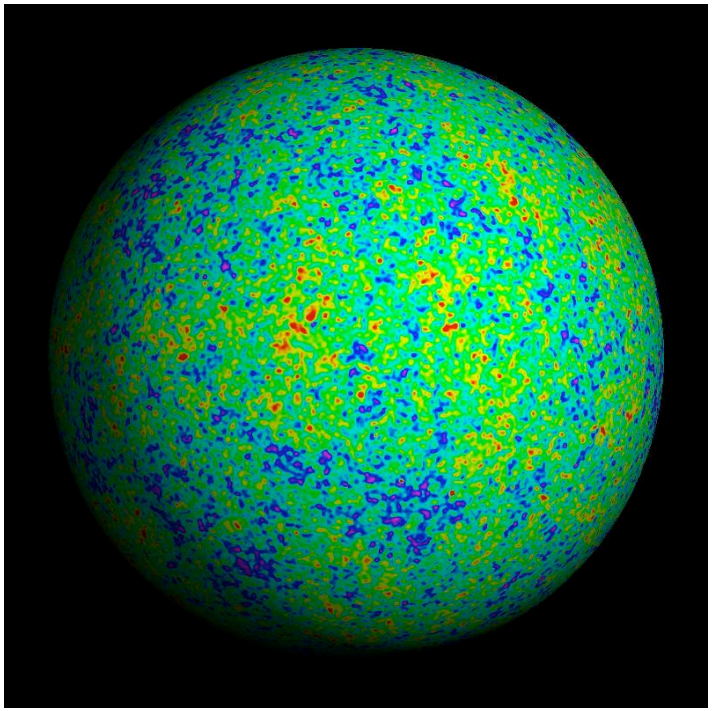
handful of radio detections

… need the SKA

Epoch of Reionisation / Cosmic Background Radiation

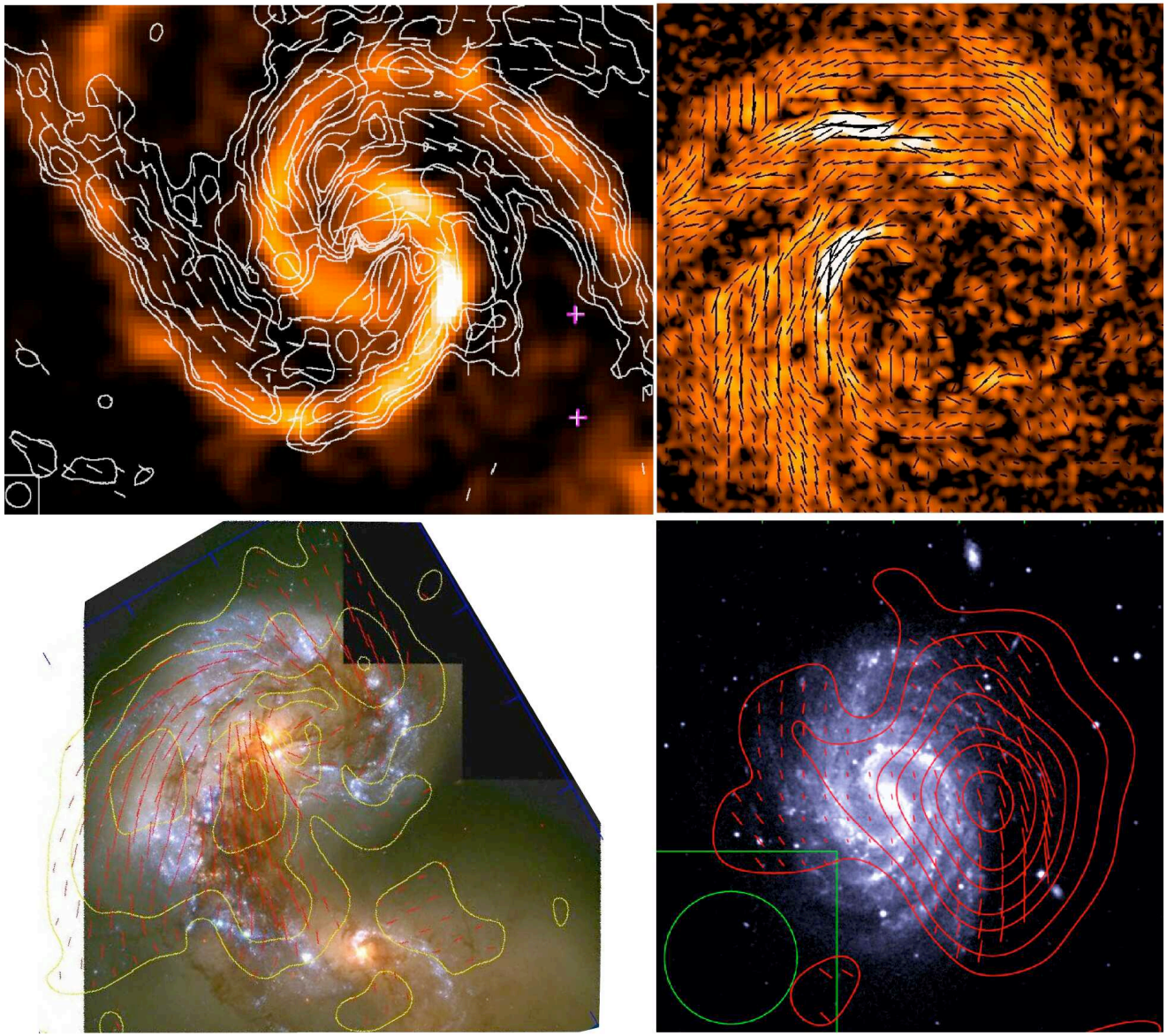


EoR: HI needle in a radio haystack



CMB: statistical oscillations

Cosmic Magnetism – unique radio subject



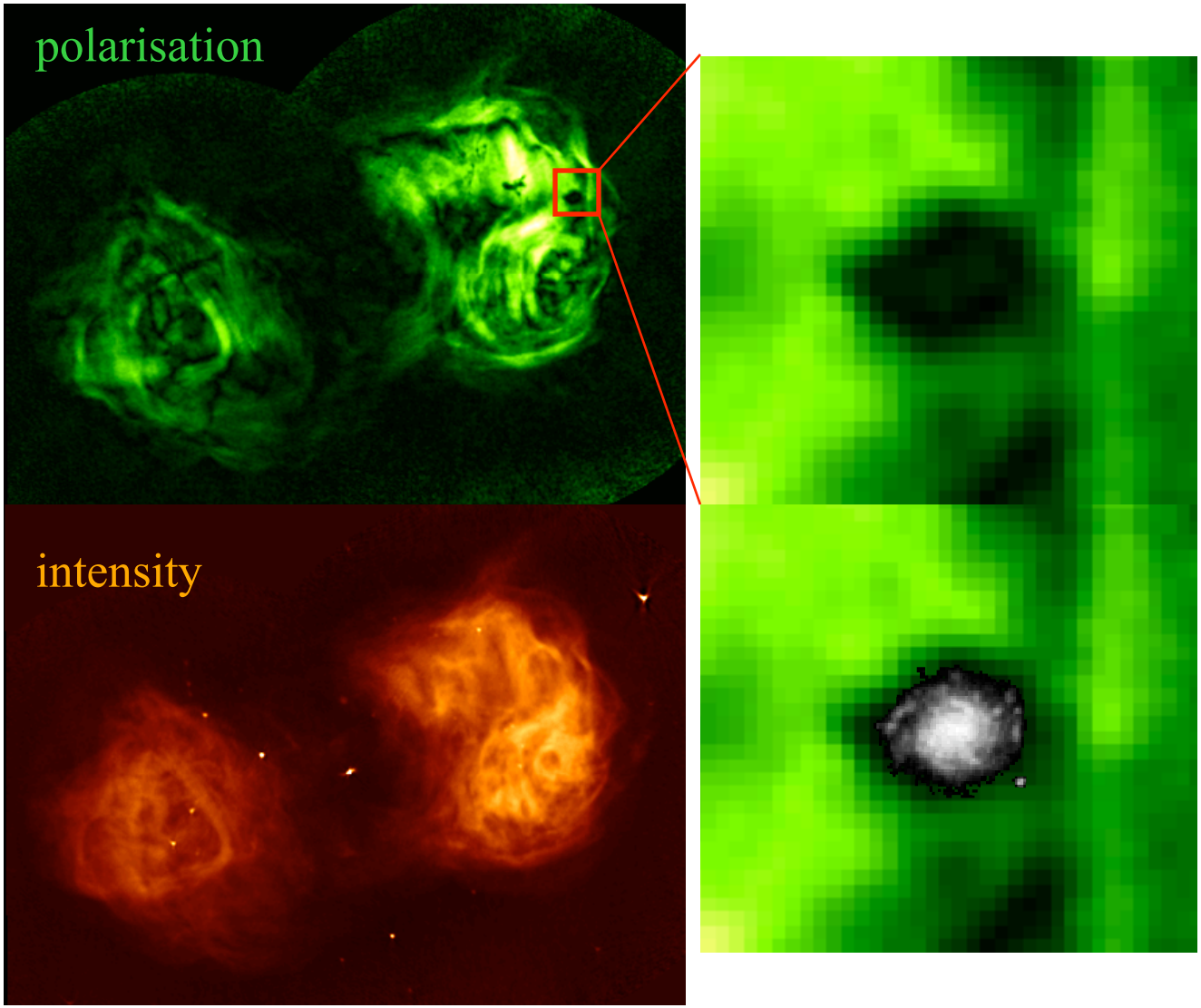
Fundamental force, but unknown

In radio:

- Faraday rotation
- Zeeman splitting

Lines:
length = % pol
direction of pol.

Cosmic Magnetism – polaroid pictures



Nearby galaxy seen against radio galaxy lobes:

Faraday depolarisation

Douglas Adams, The Restaurant at the End of the Universe (1981)

There is a theory which states that if anyone discovers just exactly what the universe is for and why we are here, that it will instantly disappear and be replaced by something even more bizarre and inexplicable.

Then there is a theory which states that this has already happened…