

DARA Training Unit 1 2017

Radio astronomy

Lecture 1

Introduction & Radio Sources

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Jodrell Bank Centre for Astrophysics

Why is astronomy in the radio band important?



Why is astronomy in the radio band important?

Penetrates dust/gas obscuring other wavelengths

Access to the fundamental element: hydrogen

Access to the most accurate clocks in the universe

Access to cosmic magnetic fields

Provides highest resolution images in all astronomy

- Unique information about the Universe
- Long record of fundamental discoveries
- Nobel Prizes on 4 occasions

A rich history of discovery

- Over the past 50 years
 - Pulsars
 - Microwave Background
 - Universe is evolving
 - Dark Matter in galaxies
 - Quasars
 - Jets + Superluminal motion
 - Gravitational Radiation
 - Aperture Synthesis

Nobel Prizes

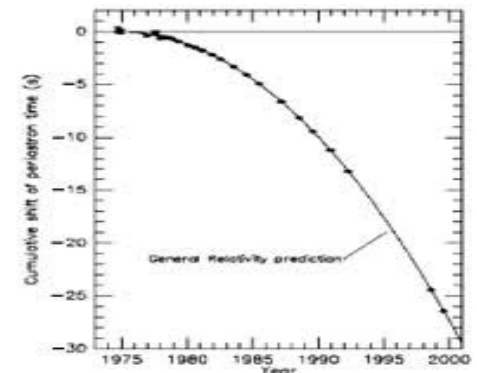
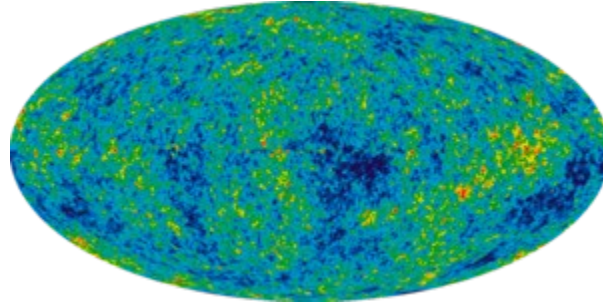
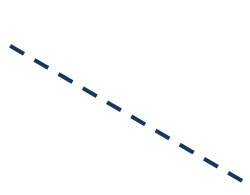
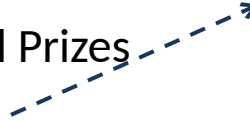
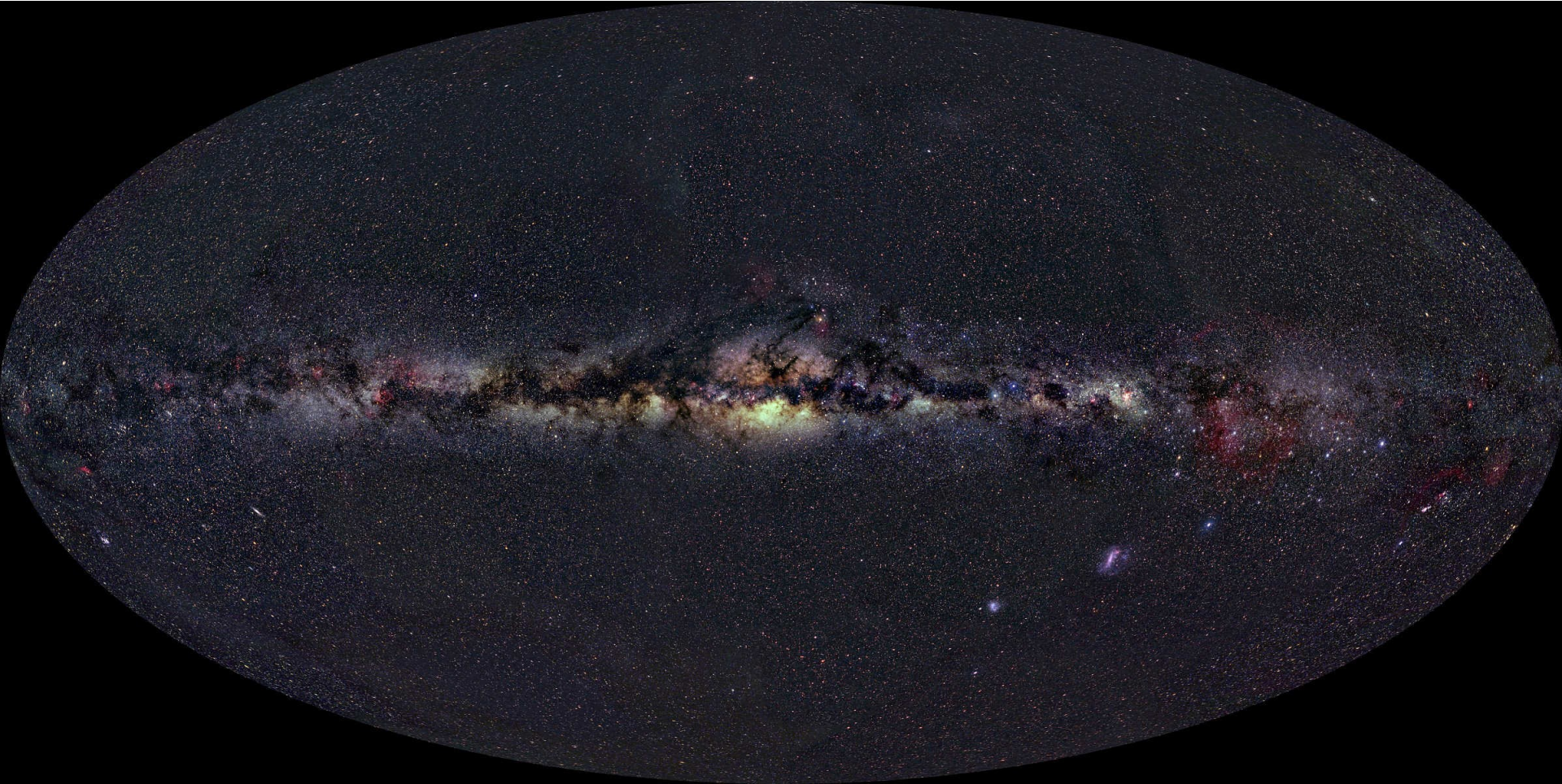


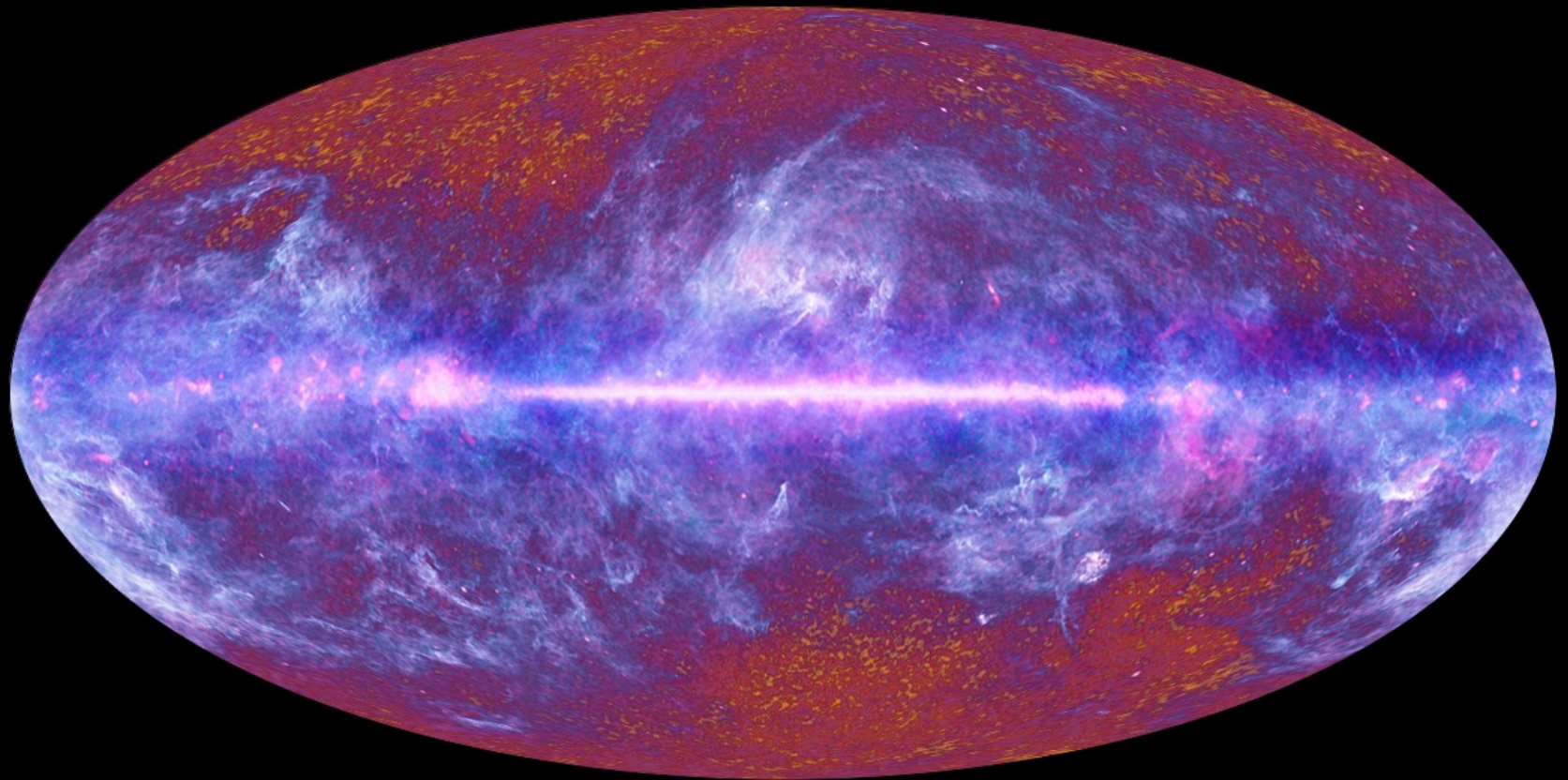
Figure 2. The evidence for gravitational wave emission from Taylor and Weisberg.

And many more ! It has set large part of the astrophysical agenda in second half of c20th

A Universe of stars and dust



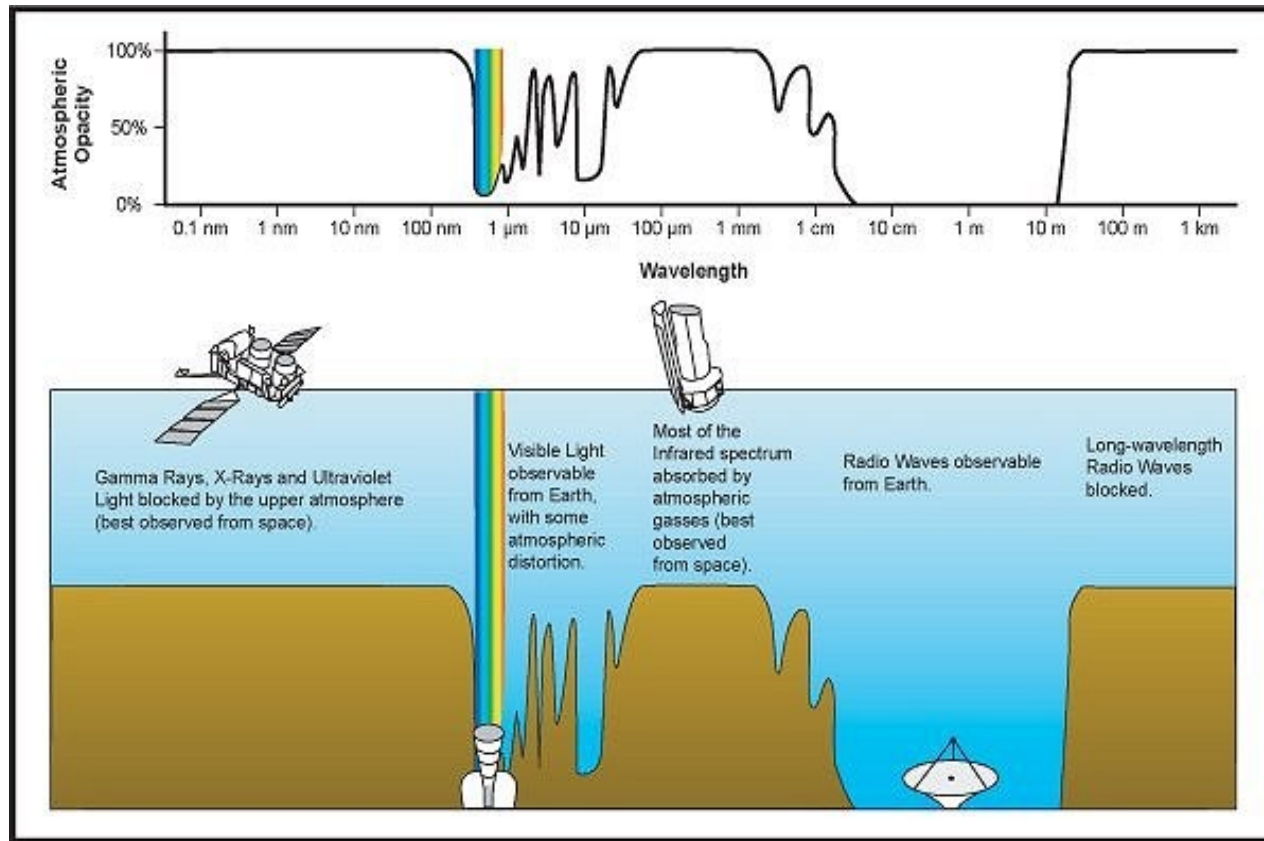
A Universe of gas, dust and radio radiation



MOST OF THE EM SPECTRUM DOES NOT PROPAGATE THROUGH THE ATMOSPHERE

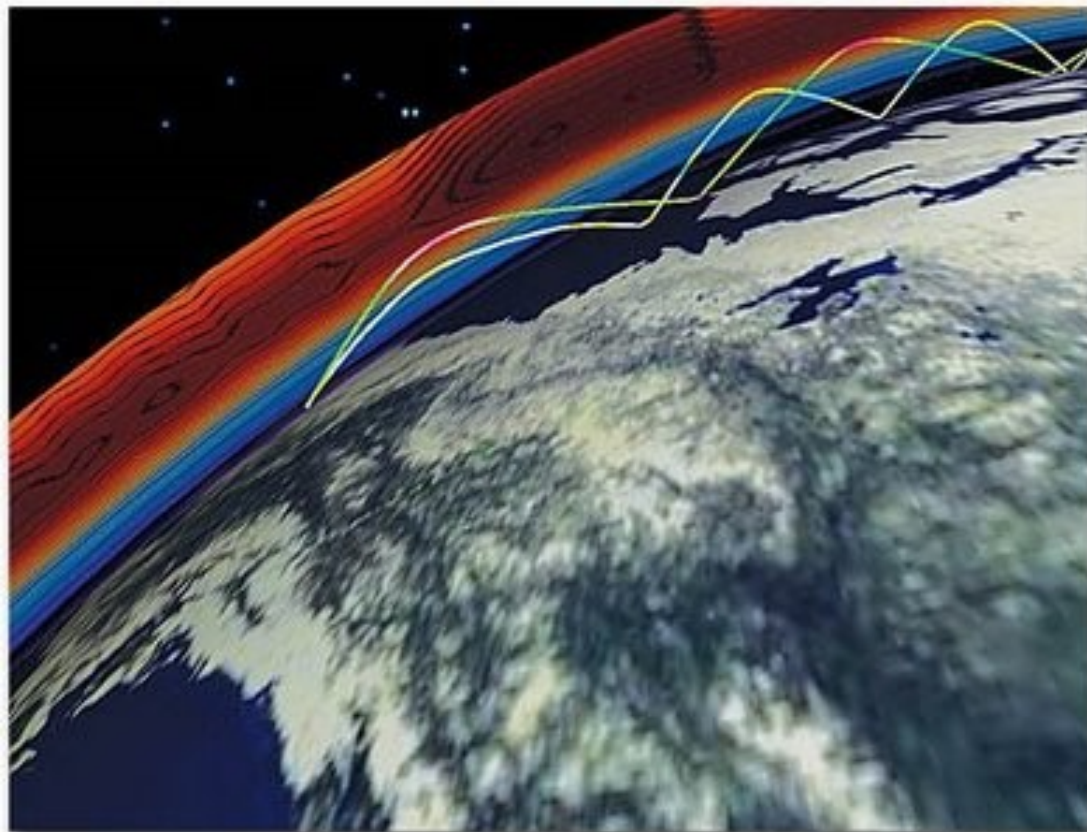
The **RADIO WINDOW**: from the ground defined by:

- lower boundary: <30 MHz i.e. wavelength $\lambda > 10$ metres : set by the ionosphere
- upper boundary: ~ 1 THz (10^{12} Hz) i.e. $\lambda \sim 0.3$ mm : set by absorption by quantized molecular rotations



Region covered in next slide

http://upload.wikimedia.org/wikipedia/commons/8/83/Atmospheric_electromagnetic_transmittance_or_opacity.jpg



At low frequencies the band is limited by absorption or reflection by the ionised plasma in the ionosphere - in different layers a few hundred km above the surface - the neutral atmosphere is ionised by the solar radiation

The plasma frequency $f_p \sim 9 \sqrt{N_e}$ Hz

N_e = the electron number density

A typical N_e in the ionosphere is $10^{12} \text{ m}^{-3} \rightarrow f_p \sim 9 \text{ MHz}$

<http://www.arsc.edu/science/images/ionosphere1.jpg>

EM waves cannot propagate at frequencies below the plasma frequency - so emissions from ground at frequencies below ~ 9 MHz are reflected back down (as in the picture). Emissions from space are reflected back into space and hence very low frequency radio astronomy is not possible from the Earth.

N.B. the plasma frequency changes over 24h: at night $\rightarrow N_e$ is lower and hence f_p is lower.

Cosmic radio sources are very weak!

Cassiopeia A “Cass A” is the strongest radio source in the sky (apart from the Sun)

Flux density ($10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$... see later) $S_\nu \sim 2000 \text{ Jy}$ at $\nu = 1.4 \text{ GHz}$

What would be the energy collected by the Lovell Telescope (LT) over its lifetime if it was fixed on Cass A?



Physical area ($\pi D^2/4$) = 4536 m^2 (diameter $D=76\text{m}$)

Effective area = $4536 \times 0.6 \sim 2700 \text{ m}^2$

(assuming $\sim 60\%$ “aperture efficiency” – see next lecture)

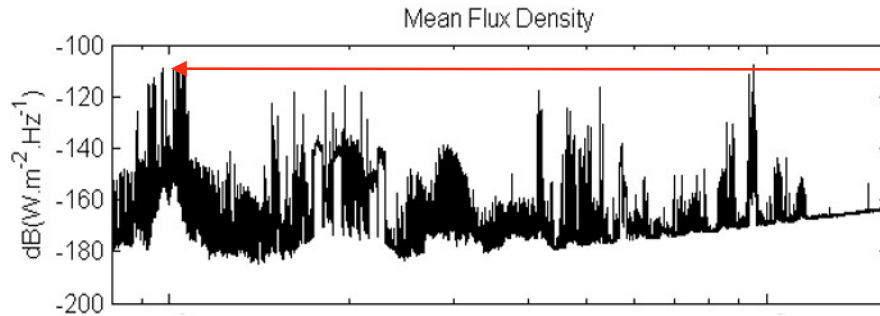
Assume receiver bandwidth $d\nu = 20 \text{ MHz}$

(arbitrary – but representative over its lifetime)

- Power collected = $(2000 \times 10^{-26}) \times (2700) \times (20 \times 10^6) \sim 10^{-12} \text{ Watt}$
- Time since the LT was commissioned in 1957: $\Delta t = 1.7 \times 10^9 \text{ s}$
- Total energy collected = $(10^{-12})(1.7 \times 10^9) \sim 1.7 \times 10^{-3} \text{ Joules}$

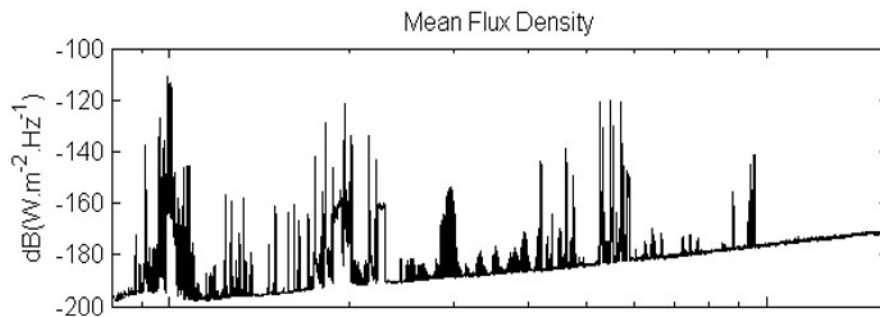
Same as that required to power a torch bulb (3V; 0.5A) for ~ 1 millisecond !!

Man-made signals are a challenge !

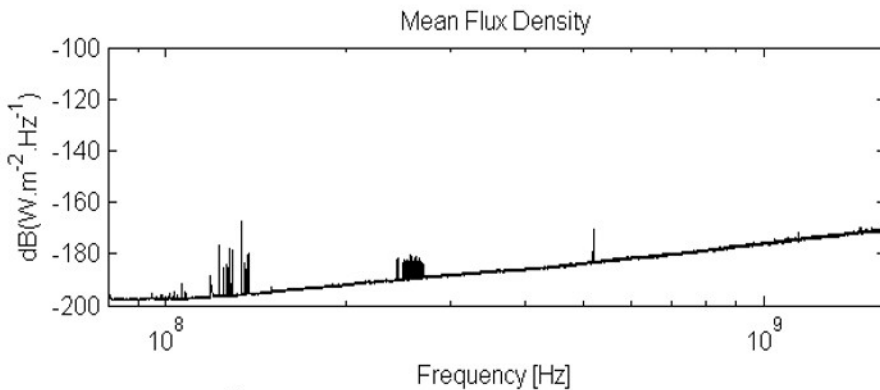


10¹² x Cass A

City



Town



Desert

Part of the radio sky imaged at low resolution showing compact radio sources - not the diffuse emission from our Galaxy (as in slide 6)



The resolution is ~ 3 arcmin - about twice that of the Planck image in slide 6 - however, the method of observation for this image subtracts out the diffuse emission. Most of the discrete sources are *extragalactic* radio galaxies and quasars radiating via the synchrotron mechanism - typically they are very compact < 1 arcmin and in some cases $\ll 1$ arcsec in size.

LOFAR Radio Image

A LOFAR radio image showing a dense field of stars against a dark blue background. The stars appear as numerous small, bright white and yellowish points of light scattered across the field. The overall appearance is that of a star cluster or a field of distant stars.

Active galaxies and active galactic nuclei (AGN)

- These kinds of galaxies have **active nuclei**:
 - **Quasars: in elliptical galaxies**
 - **Radio galaxies: in elliptical galaxies**
 - Both discovered originally by radio astronomers. Thousands of each are now known.
 - **Seyfert galaxies: spirals with weak central AGN activity**
 - **“Blazars”**: radio galaxies and quasar jets pointing at us
 - Both discovered originally by visible-light astronomers. Hundreds of each also now known.
- We know thousands of them, but active galaxies are rare (~1% powerful to 10% weak) → they are greatly outnumbered by normal galaxies.

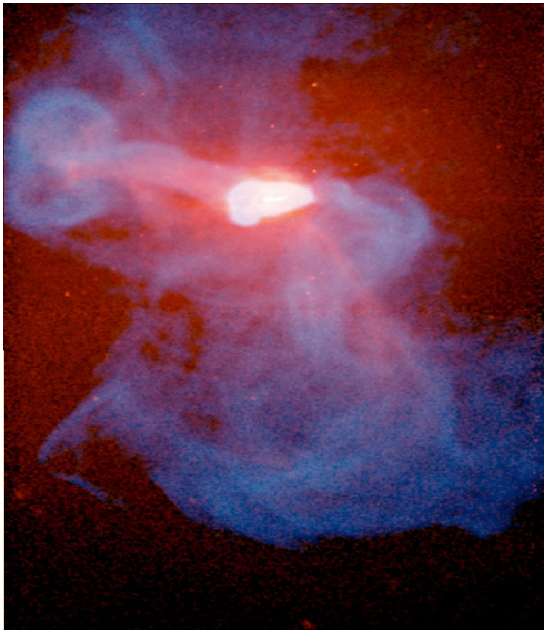
What makes AGN Special?

- Very large luminosities are possible (up to 10,000 times a typical galaxy)
- The emission spans a huge range of photon energy (radio to gamma-rays)
- The source of energy generation is very compact (< size of the solar system)
- In some cases, there is significant energy transported in relativistic jets → radio loud AGN

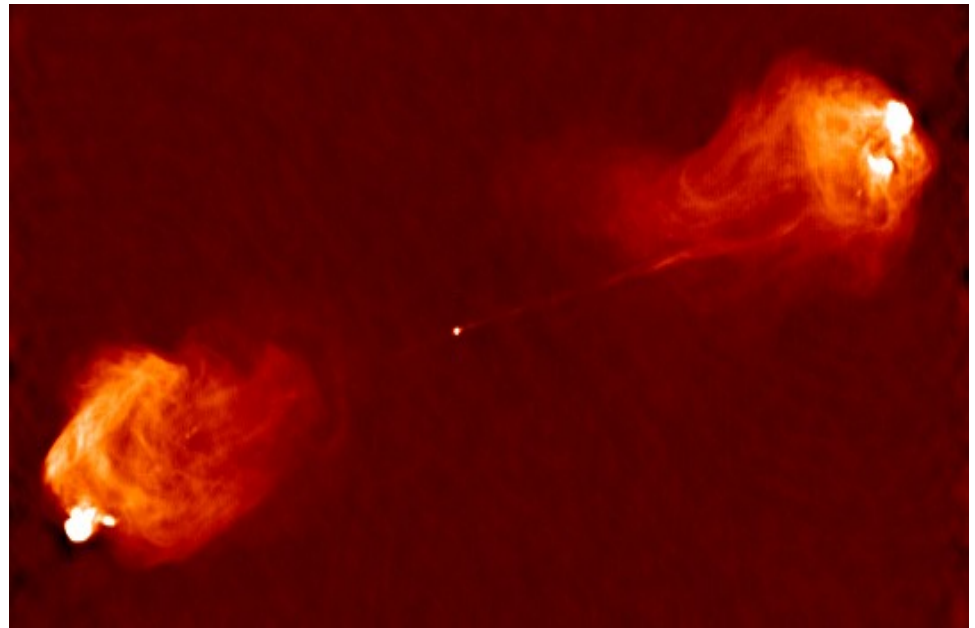
Attribution for AGN Slides 15-26 :
were taken from combination of:

- www3.nd.edu/~wzech/lecture20_21_agn.ppt
- www.kusastro.kyoto-u.ac.jp/~iwamuro/LECTURE/AGN/AGN.ppt
- physics.gmu.edu/~hgeller/astr113/ch27.ppt
- astro.psu.edu/users/niel/astro130/powerpoint/watson/watson-Lect_17.ppt
- wwwmpa.mpa-garching.mpg.de/~magpop/TALKS/.../Heckman.ppt

Luminosity & Radio Galaxies

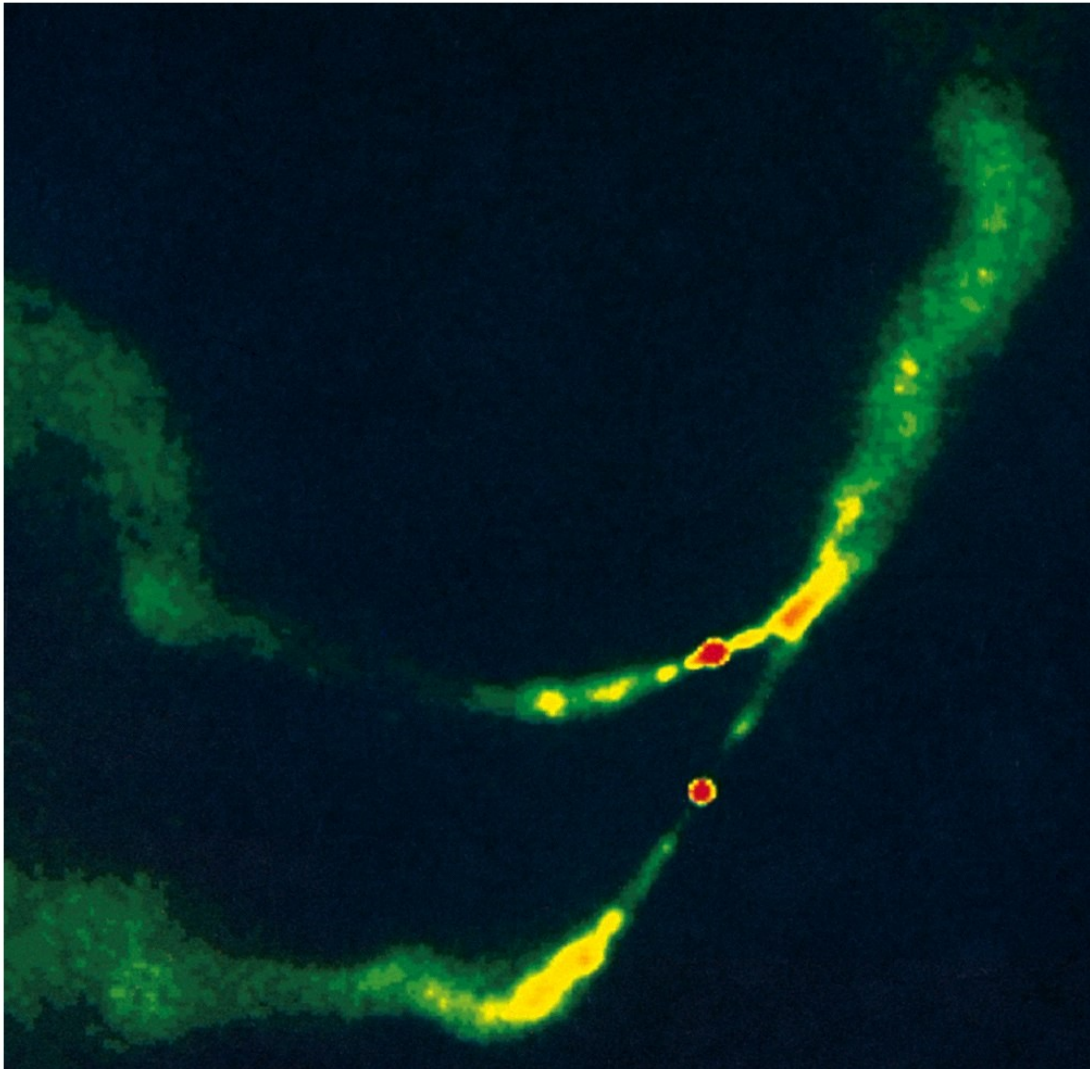


Lower power jets: maximum brightness nearest the nucleus. KE dissipated gradually (“FR I”)



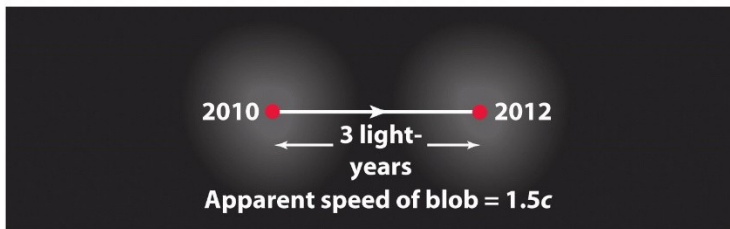
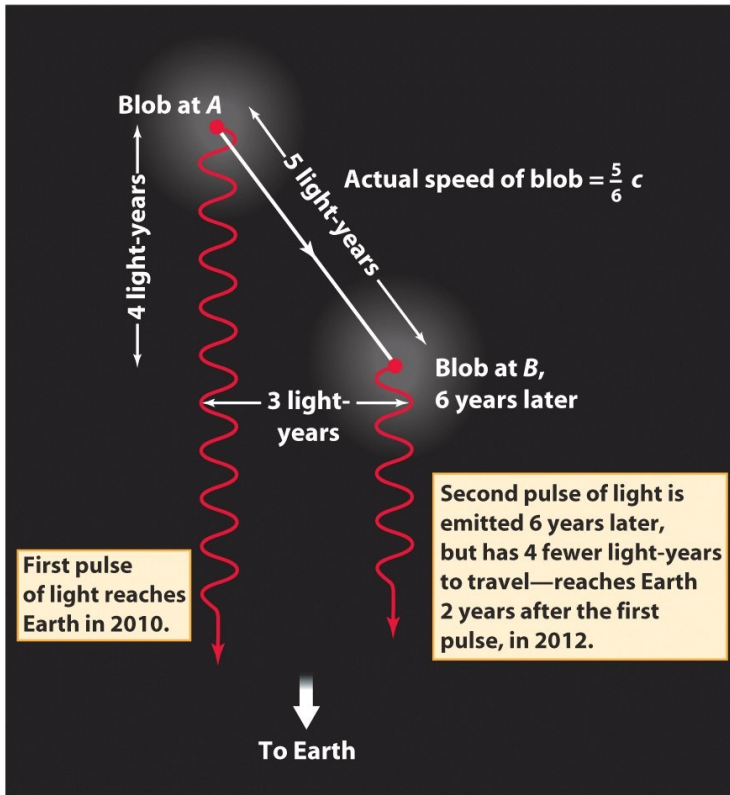
Very powerful jets: maximum brightness at termination point of jet (“FR II”)

Luminosity & Radio Galaxies

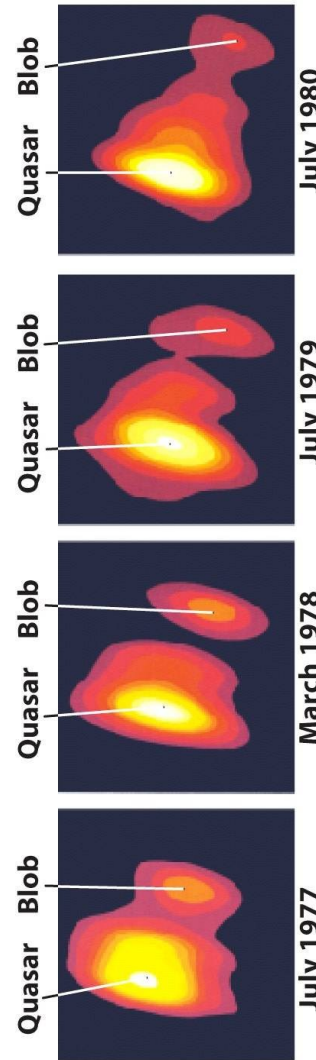


Lower power jets: maximum brightness nearest the nucleus. KE dissipated gradually (“FR I”)

Jets bend backwards by the ram pressure of the inter Galactic medium as the Galaxy (in this case 2) Moves through it.



View from Earth



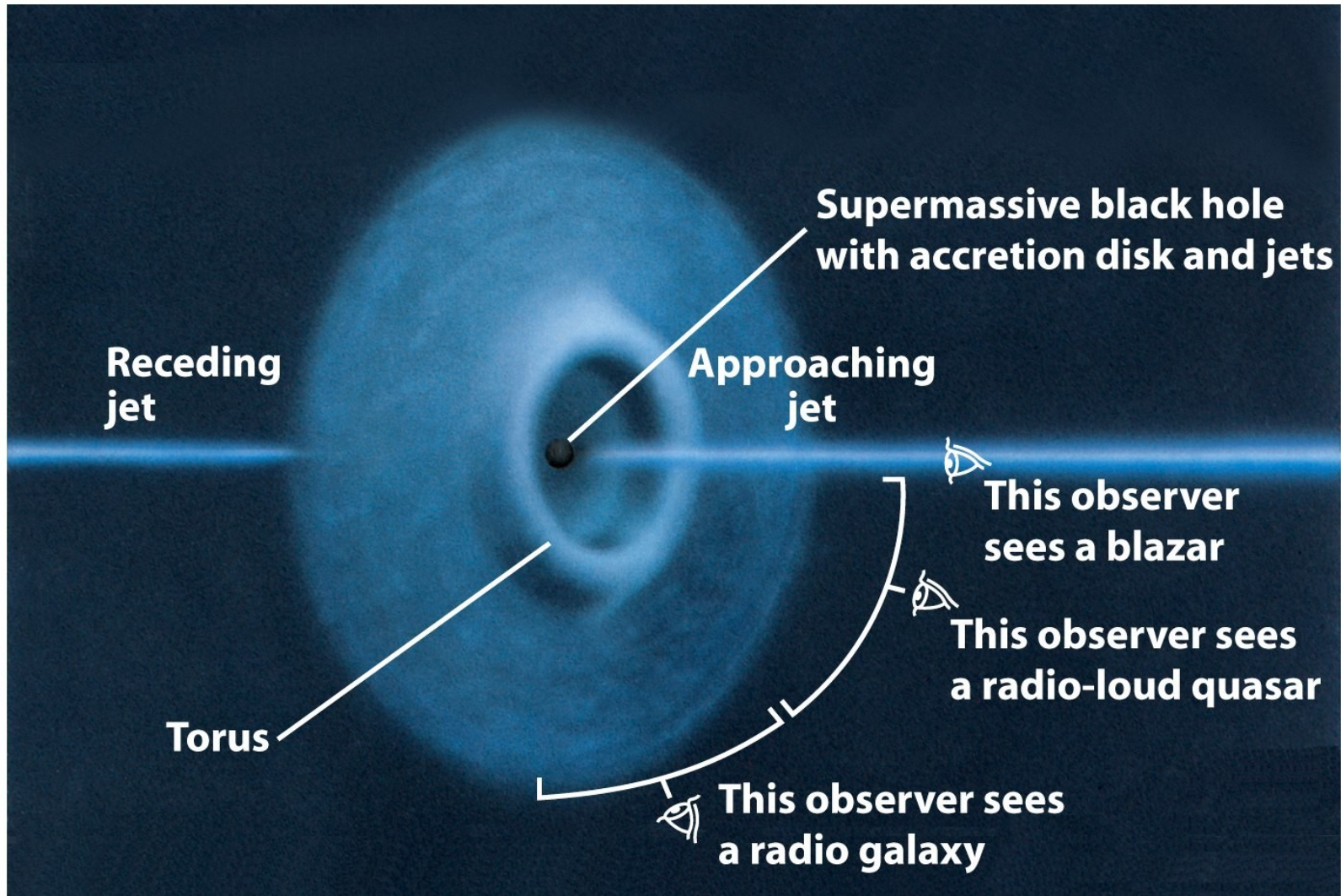
S
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More typical speeds $0.98-0.99c \rightarrow$ Lorentz Factor $\gamma = 5-7$ sometimes higher

Quasars, blazars, and radio galaxies are the same kind of object seen from different angles

Relativistic “Doppler boosting” is a $\sim \gamma^3$ effect!



“Starburst Galaxies”



M82



ARP 220

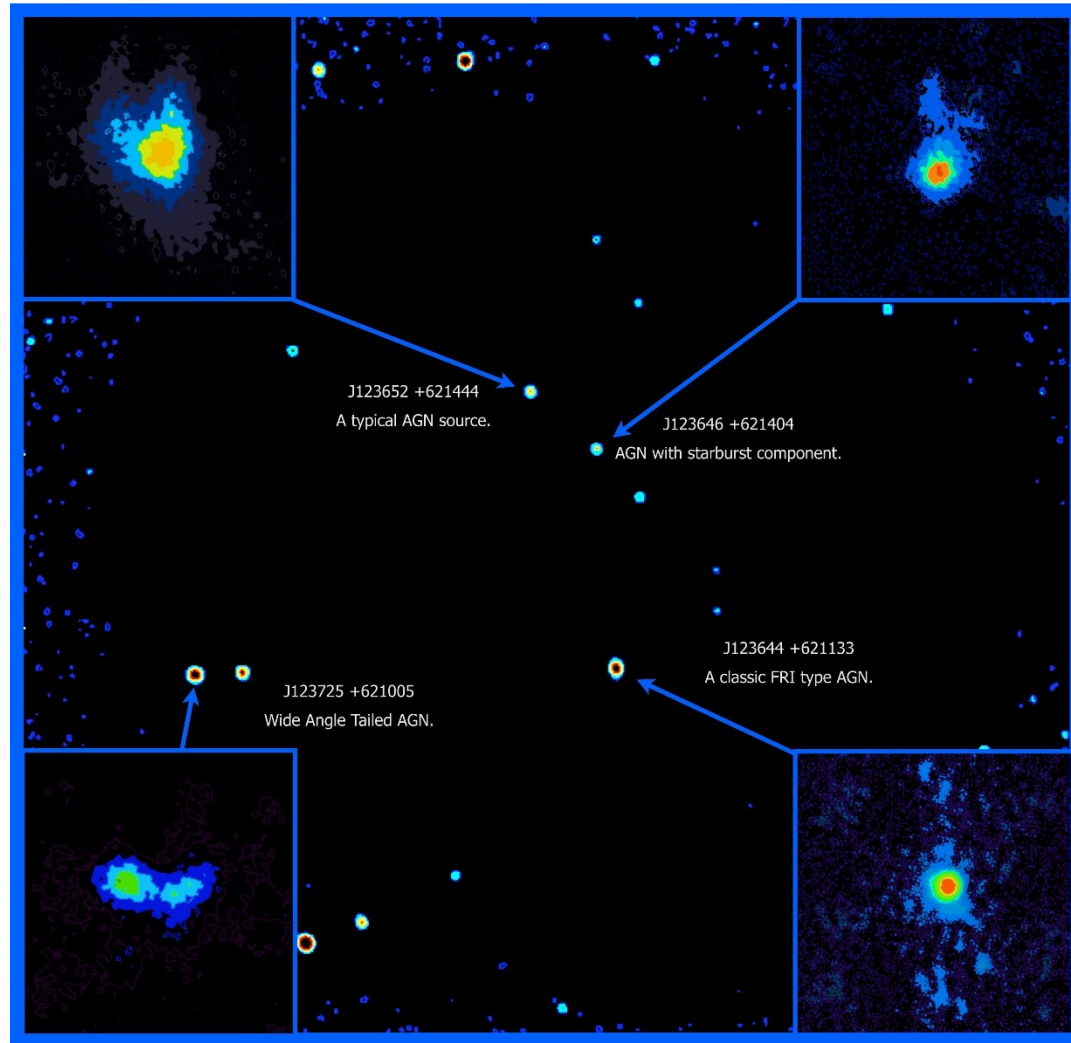
Arp220 supernova rate (several per year) is 10-100x Milky Way → its radio emission is the sum of many supernova remnants - invariably associated with galaxy/galaxy interactions or mergers

Hubble Deep Field in optical band : ~3000 galaxies detected

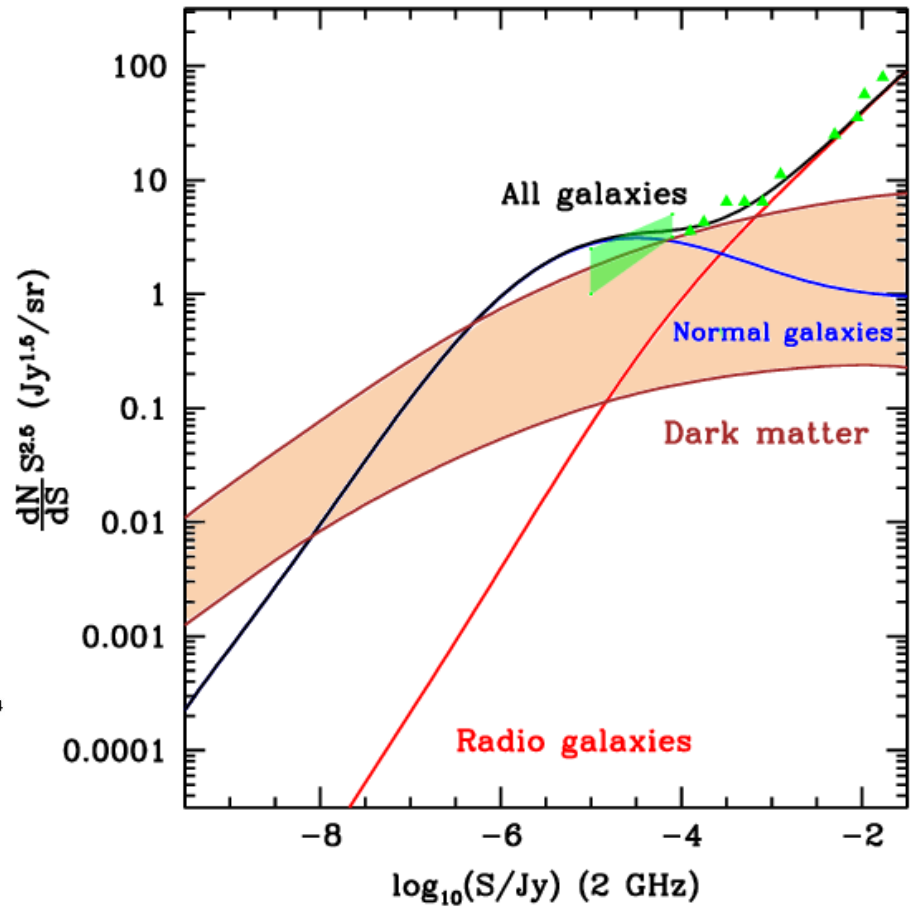
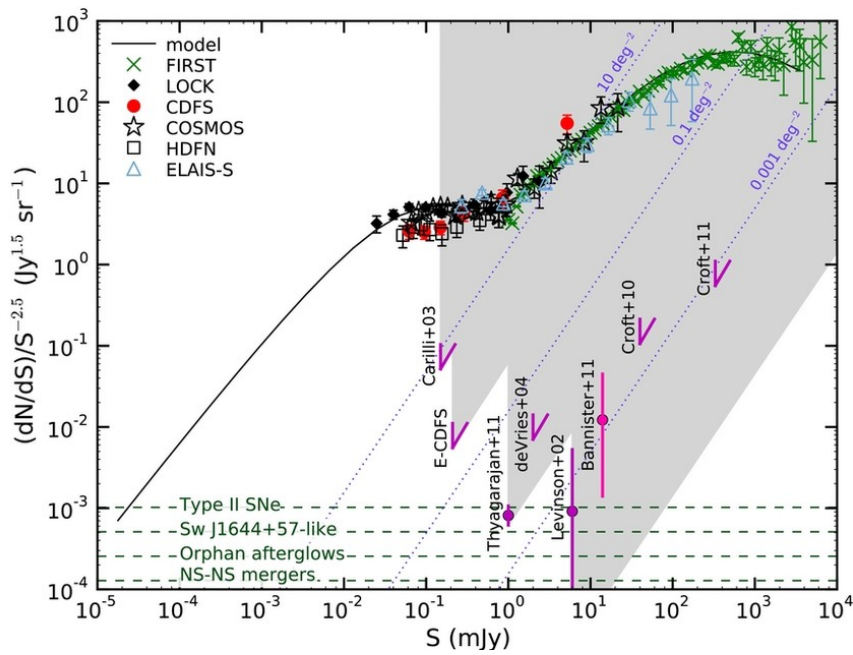


Hubble Deep Field in radio: Most galaxies not detected

Detected ones are mixtures of AGN & Starbursts



Radio Source Counts

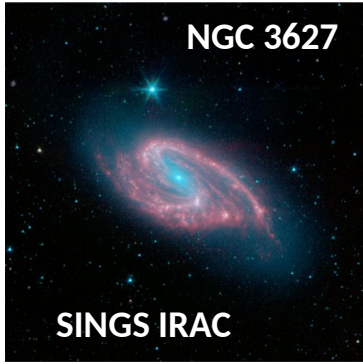


Nearby “normal” galaxies:

attribution: slides 31-37 from presentation by

Adam Leroy (MPIA Heidelberg)

Christof Buchbender (IRAM Granada)



NGC 3627

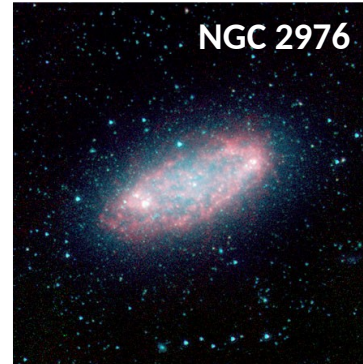
SINGS IRAC



NGC 3351



NGC 7793



NGC 2976

(IMAGE TEAM)



GALEX view of M81



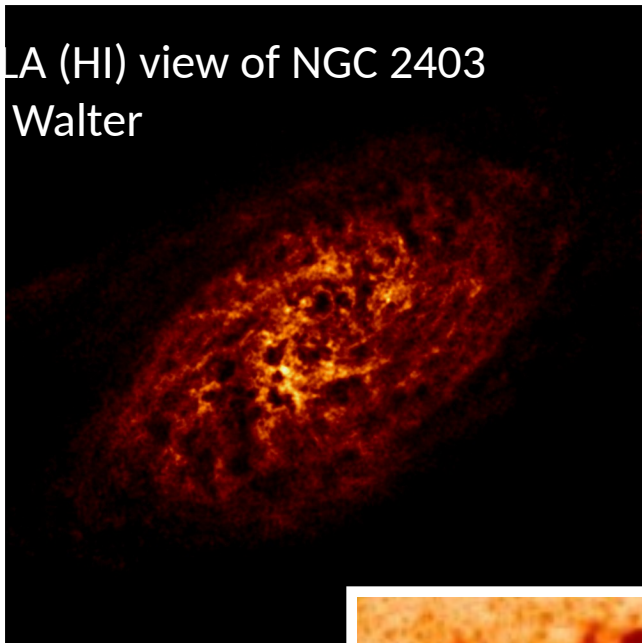
HST view of M64



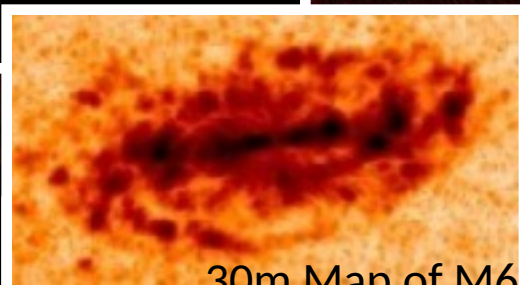
HST view of M51

swiped from A.P.o.D. & NASA heritage website

LA (HI) view of NGC 2403
Walter

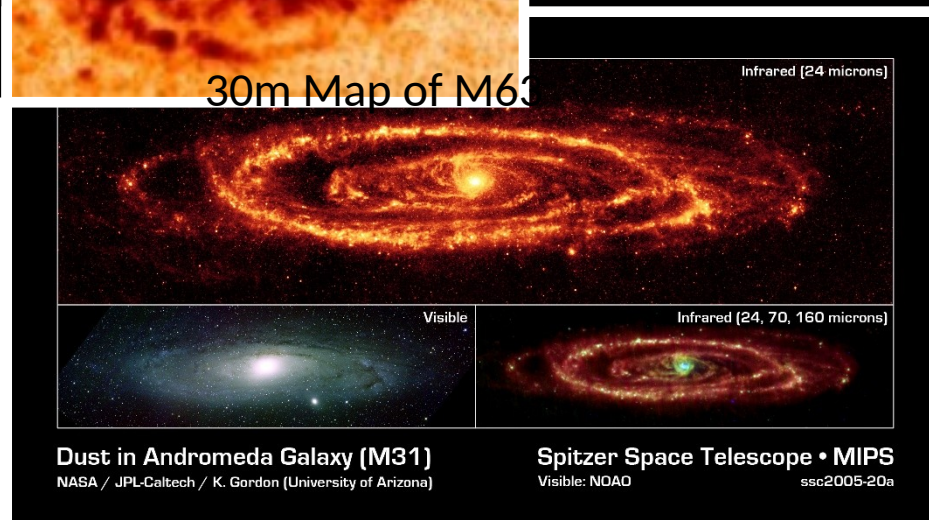


Spitzer view of the SM
K. Gordon et al.



30m Map of M63

QuickTime™ and a decompressor are needed to see this picture.

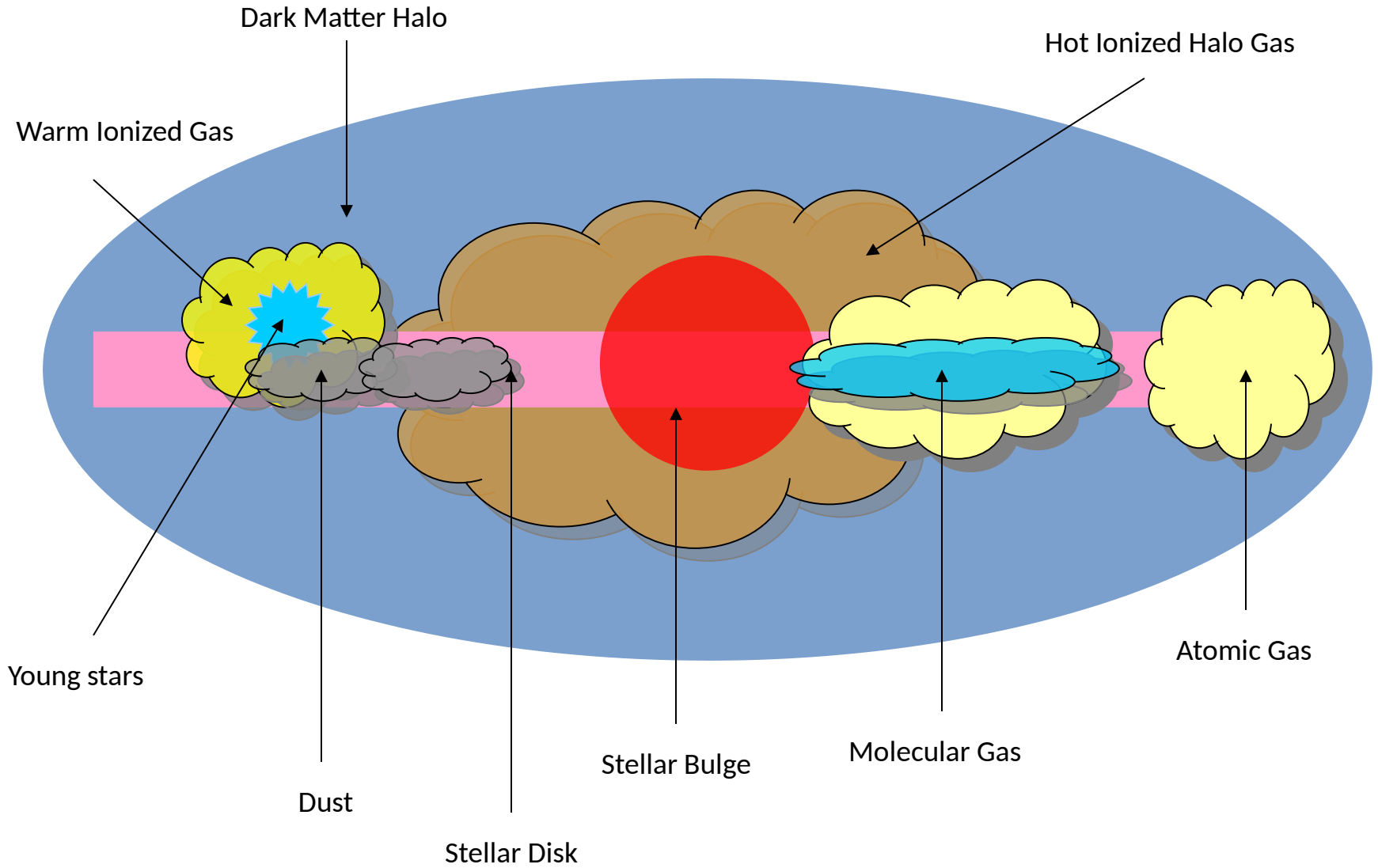


Dust in Andromeda Galaxy (M31)
NASA / JPL-Caltech / K. Gordon (University of Arizona)

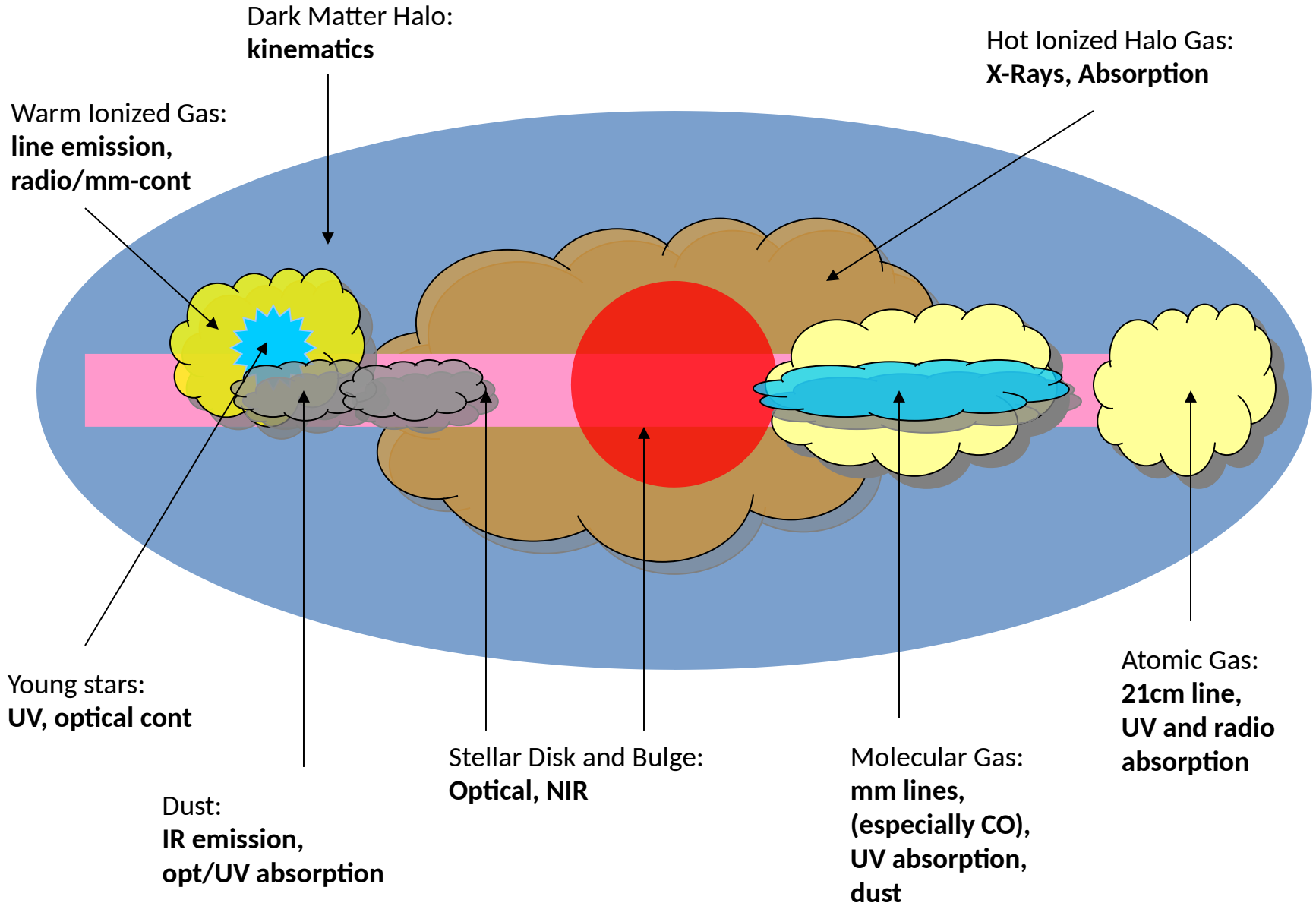
Spitzer Space Telescope • MIPS
Visible: NOAO ssc2005-20a

30m Map of M51
K. Schuster et al.

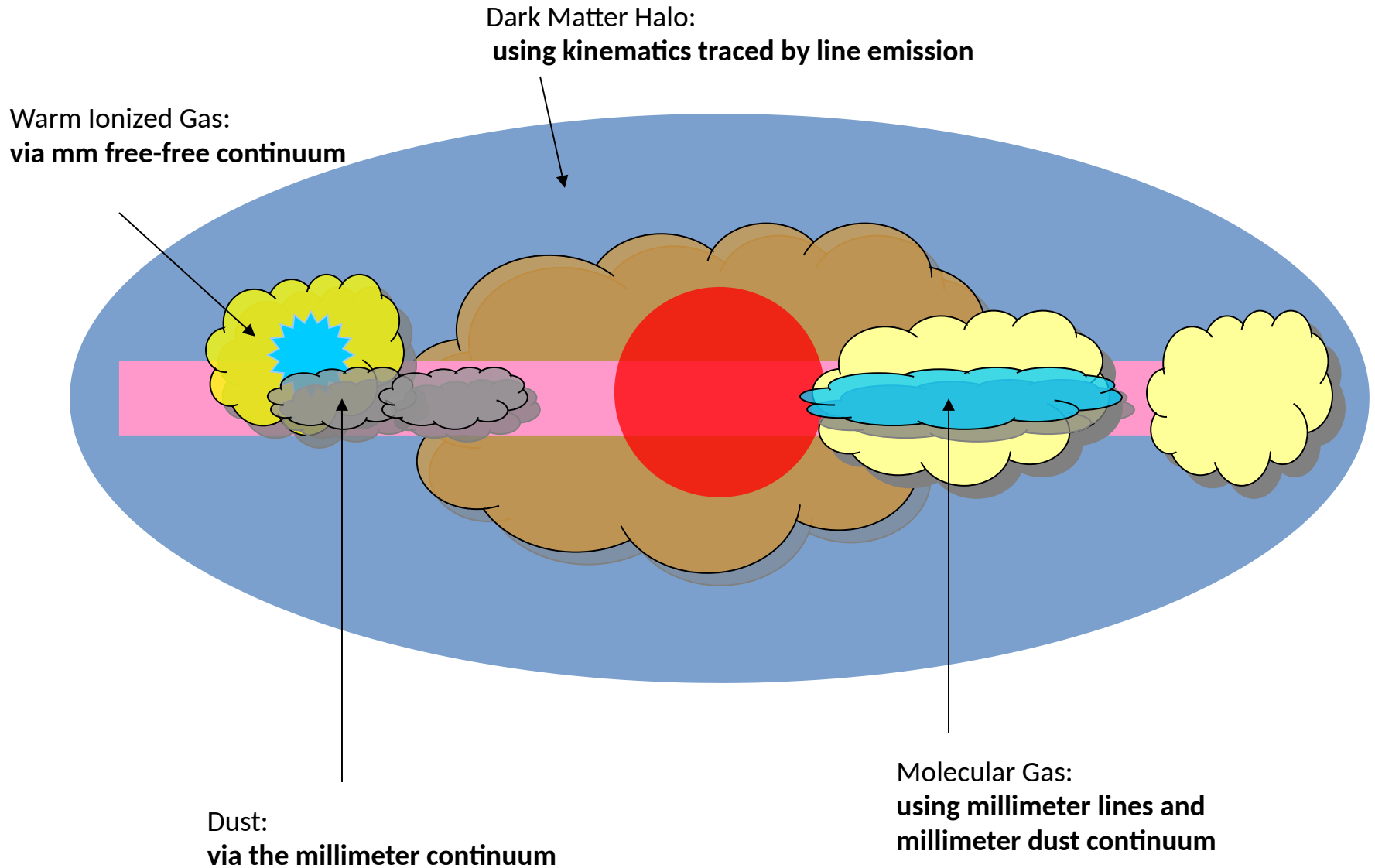
Cartoon Anatomy of A Galaxy



How To Study the Cartoon Anatomy



Galaxy Components Observable with the 30m



Cartoon Breakdown of the ISM

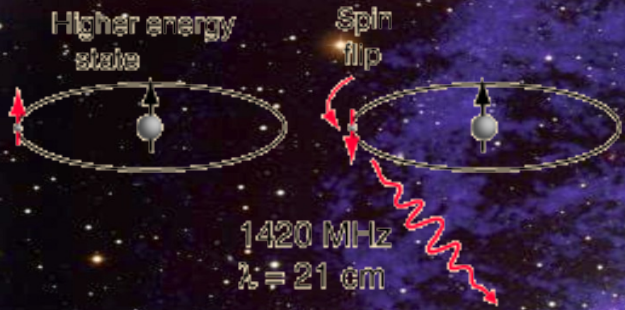
Phase	H State	Density	Temp.	Emission Diagnostics*
hot	ionized	10^{-2} cm^{-3}	10^6 K	X-ray
warm (H II)	Ionized (HII)	1 cm^{-3}	10^4 K	optical emission lines
warm neutral cold neutral	neutral Atomic (HI)	0.5 cm^{-3} 50 cm^{-3}	10^4 K 10^2 K	21cm line IR cooling lines
molecular	molecular (H ₂)	$100+ \text{ cm}^{-3}$	20 K	Molecular lines (CO, HCN, HCO+, CS, etc.) Dust, H ₂ rotational lines

* In addition to these diagnostics, absorption against background sources from the UV to the radio is an incredibly powerful diagnostic of physical conditions in the ISM.

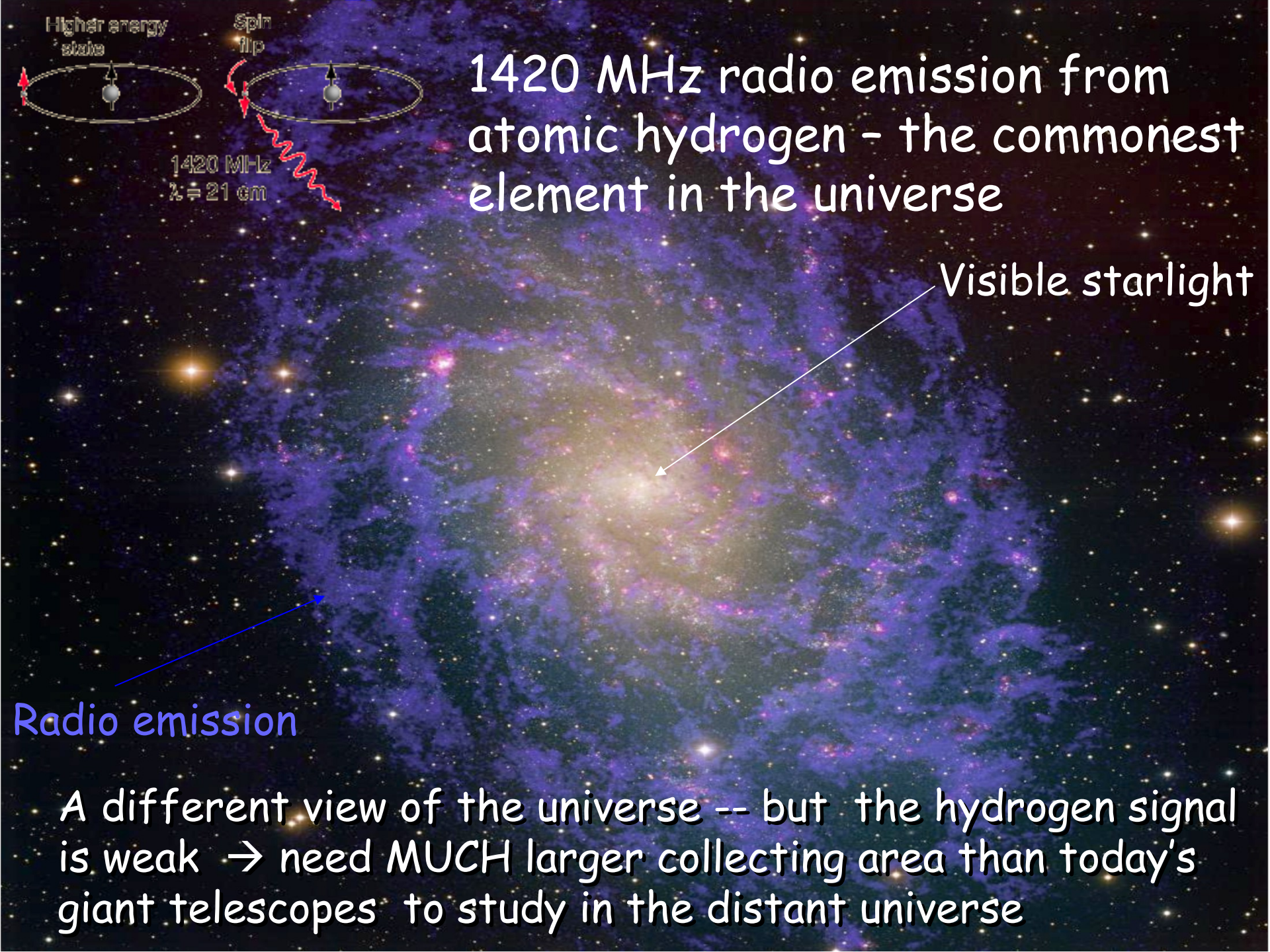
Cartoon Breakdown of the ISM

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warm (H II)	Ionized (HII)	1 cm^{-3}	10^4 K	optical emission lines, mm continuum
warm neutral cold neutral	neutral Atomic (HI)	0.5 cm^{-3} 50 cm^{-3}	10^4 K 10^2 K	21cm line IR cooling lines
molecular	molecular (H₂)	$100+ \text{ cm}^{-3}$	20 K	Molecular lines (CO, HCN, HCO⁺, CS, etc.) Dust, H₂ rotational lines

* In addition to these diagnostics, absorption against background sources from the UV to the radio is an incredibly powerful diagnostic of physical conditions in the ISM.



1420 MHz radio emission from atomic hydrogen - the commonest element in the universe

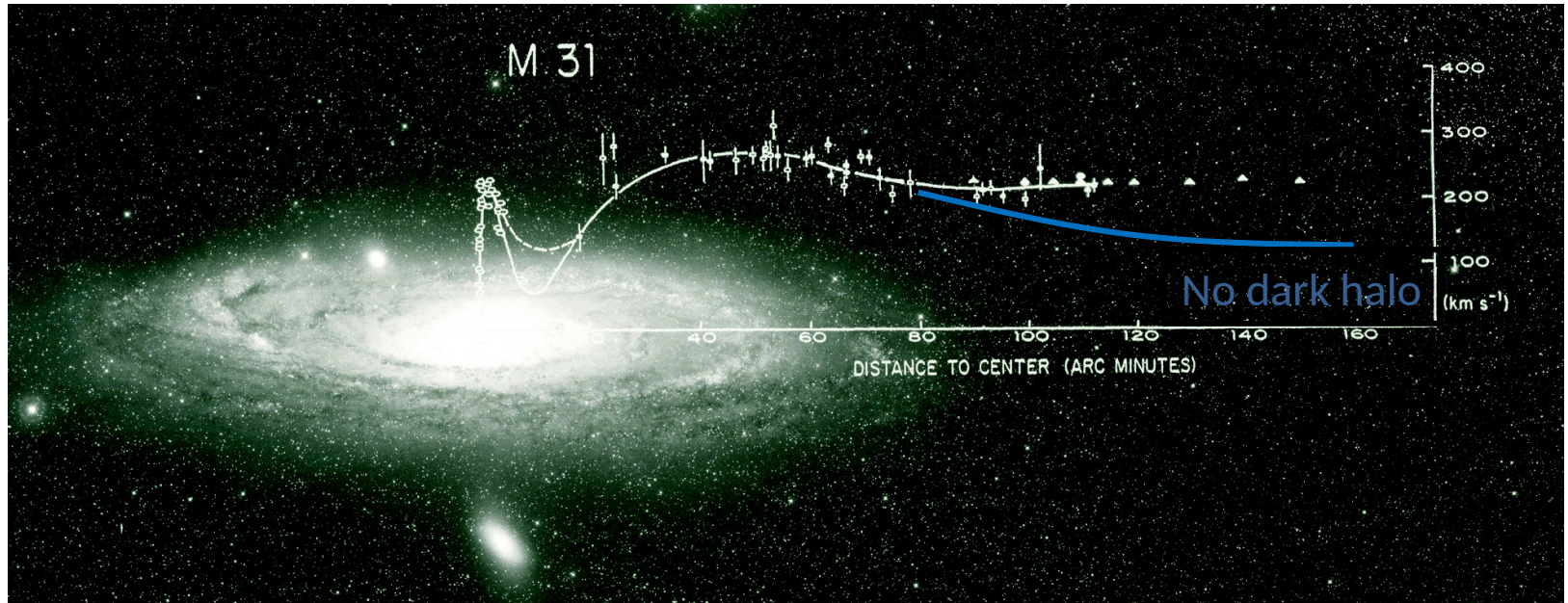


Visible starlight

Radio emission

A different view of the universe -- but the hydrogen signal is weak → need MUCH larger collecting area than today's giant telescopes to study in the distant universe

Galaxy mass distributions and dynamics



Atomic hydrogen in nearby galaxies – using Doppler shift to study galactic kinematics → dynamics

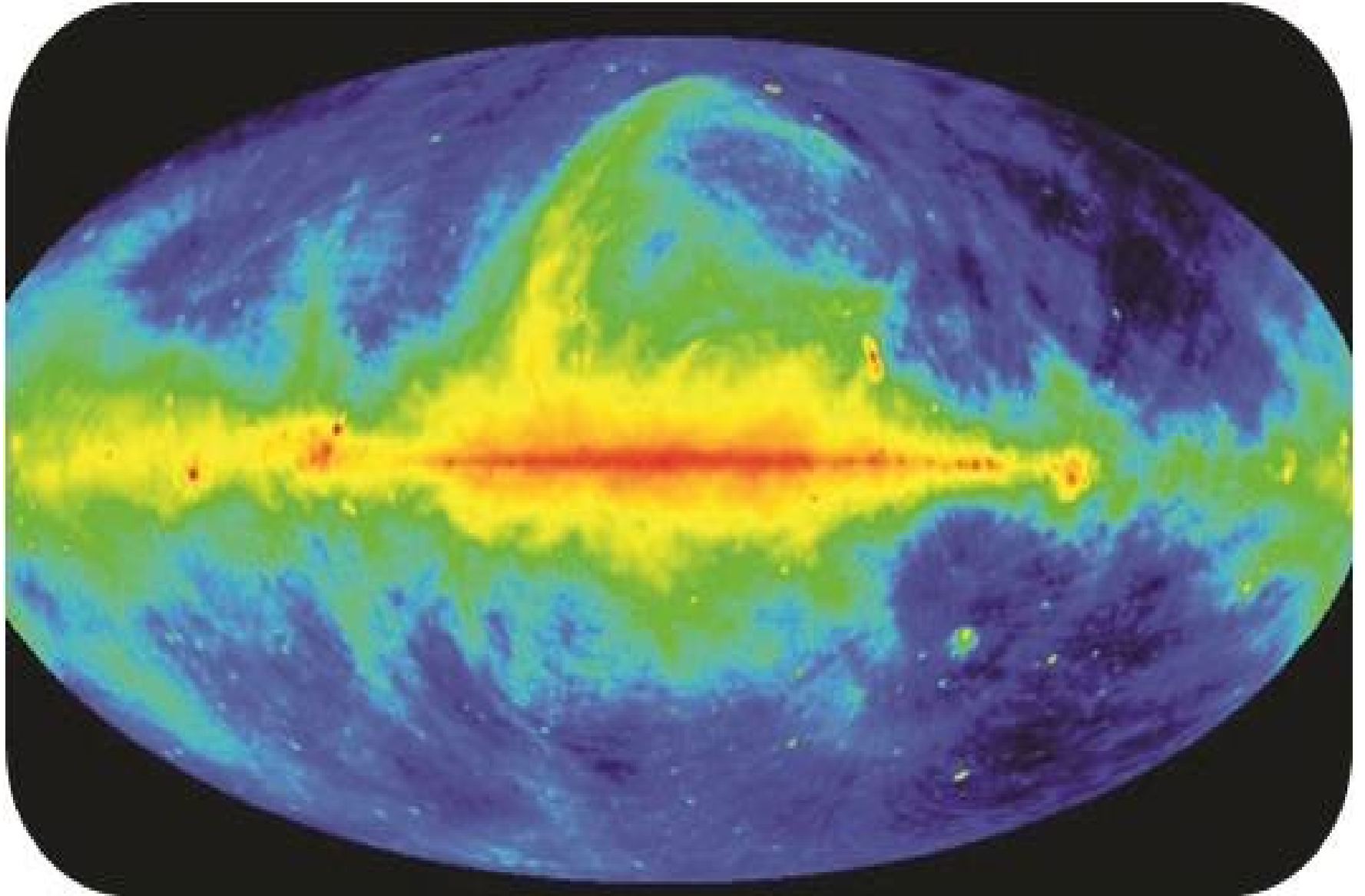
In the case above the speed of rotation of the gas is constant far beyond the optical image.

→ the stars must be embedded in a huge **dark matter halo**.

Synchrotron emission

- In between stars was missed out of slides 31-37 which concentrate on observations at millimetre—infrared—optical wavelengths with addition of 21cm hydrogen line in radio.
- See next slide....

Milky Way at 408 MHz (all synchrotron radiation)



Milky Way emission from different regions

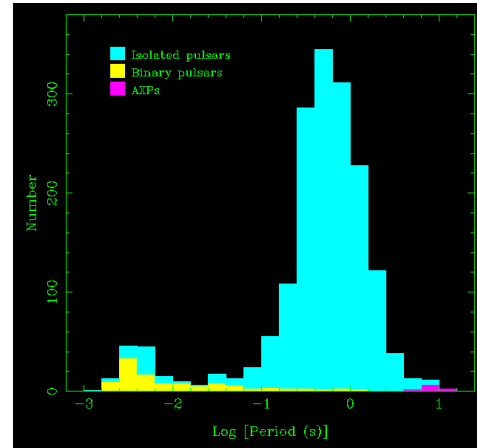
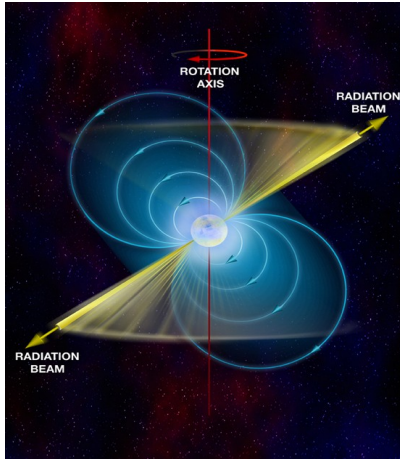


The emission from the Milky Way is displayed in different colours: red: thermal dust; yellow: carbon monoxide (CO) gas; green: free-free emission ; blue synchrotron emission. The Planck sky maps show a combination of **thermal emission from the CMB** plus Galactic emission from a combination of mechanisms: electrons in hot interstellar ionized gas (**free-free**); cold interstellar dust (**black body**) which extends over most of the sky; spinning dust; relativistic electrons and magnetic fields (**synchrotron**). Some maps are also sensitive to the **spectral line emission of carbon monoxide (CO) gas** in dense molecular clouds. Using the multi-frequency data the emission from each these different mechanisms can be dissected out.

Pulsars

Rotating neutron stars – the aftermath of supernova explosions

Mass $\sim 1.4 M_{\text{sun}}$ Radius ~ 15 km \rightarrow Density $\sim >$ atomic nucleus !!



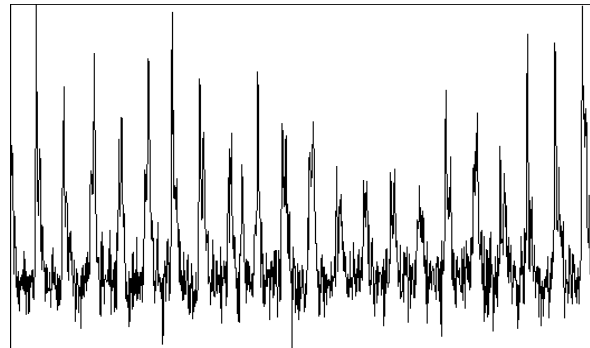
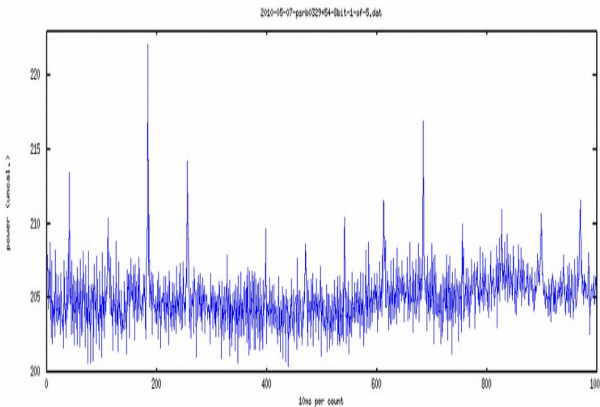
Number known: ~ 2000

Periods: 1.5 msec \rightarrow 8 seconds

Most in the range 0.2-2 sec

<http://www.nrao.edu/pr/2007/pulsarcollab/pulsargraphic.jpg>;

<http://www.atnf.csiro.au/research/pulsar/psrcat>



They are *weak radio sources* when integrated over a period \rightarrow need big telescopes to study them (pulse widths range from 0.1 -10% of period.)

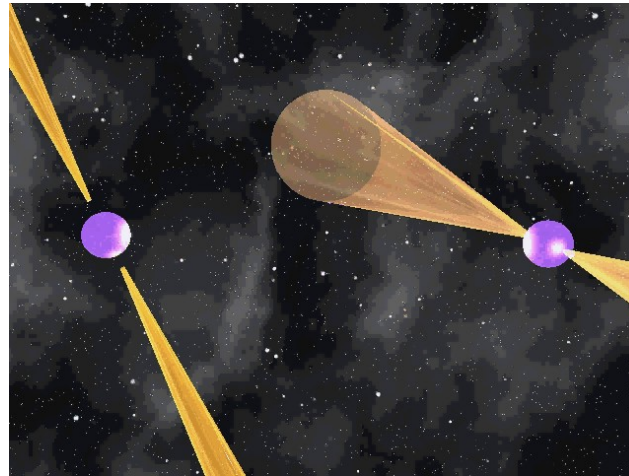
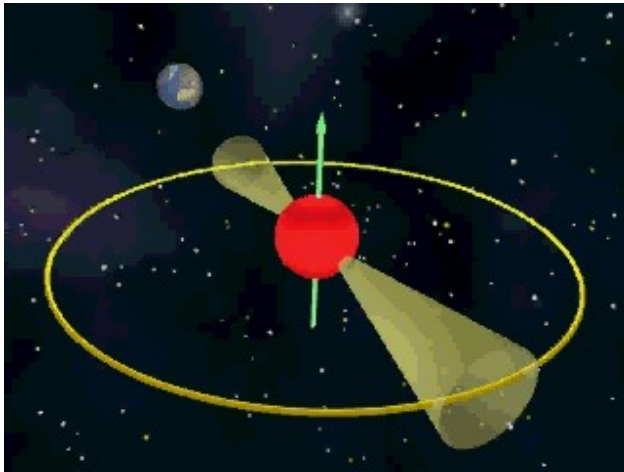
<http://setiquest.org/forum/topic/baudline-analysis-psr-b032954>

http://outreach.atnf.csiro.au/education/pulseatparkes/images2/pulsar_pulses.gif

Pulsars as Clocks

Because of their large mass and small radius, the spin rates - and hence pulsar periods - are incredibly stable in particular the millisecond pulsars.

Slower (~ 1 sec) pulsars are also very stable but their periods are not constant. Pulsars lose energy and slow down. Typical slowdown rates are less than $1 \mu\text{sec yr}^{-1}$



Both pictures courtesy
M. Kramer

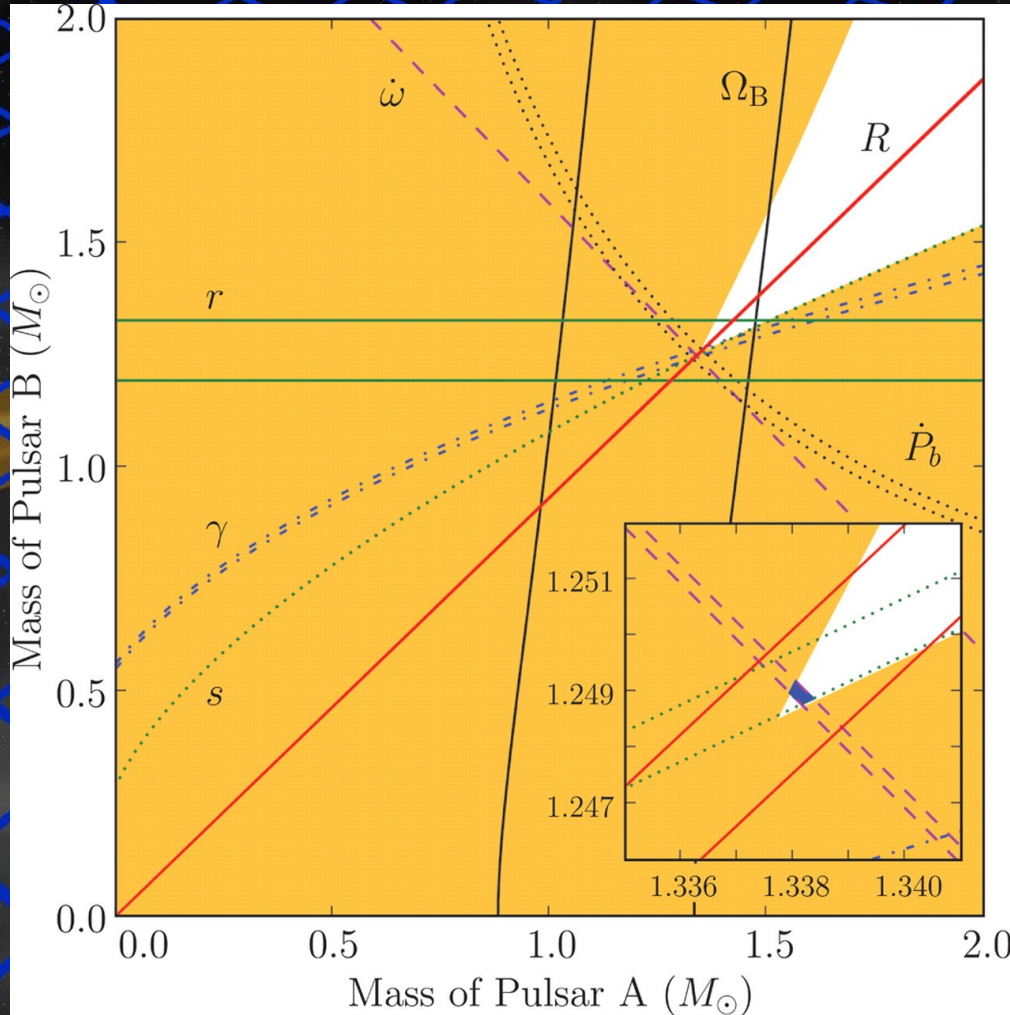
Many research directions:

- Physics of neutron stars & radio emission mechanisms (complicated !)
- Tests of General Relativity in binary systems (right hand cartoon of the “double pulsar”) - watch behaviour of clocks in varying a **gravitational potential**
- Exploring the properties of the interstellar medium - electron density and magnetic field

The Double Pulsar



Double pulsar



- GR effects orbit, depending on the masses of the stars.
- Different GR parameters agree at 99.95% level.



A radio source located in our galaxy - Cassiopeia A a supernova remnant - imaged at high resolution

http://images.nrao.edu/images/cas_a_vla_lo.jpg



Montage of radio image (in blue) superimposed on picture of part of the "Very Large Array" radio telescope with which the image, having a resolution of ~ 1 second of arc, was formed.

The apparent size of Cass A is very *greatly* exaggerated – in reality it is only 0.1 degrees across i.e 1/5th the size of the Moon just visible in the top right

At metre and cm-wavelengths Cass A is the strongest radio source in the sky apart from the Sun. *It radiates via the synchrotron mechanism.*

The star blew up in the 17th century

Sources of “free-free” emission

http://www.uv.es/jrtorres/index6_archivos/image003.png



Free-free is the dominant continuum emission in thermal plasmas

e.g. “planetary nebulae” – hot (up to 15,000K) ionised plasma shells surrounding hot stars in the *late stages of their evolution*

.



E.g. “HII regions” – interstellar gas also ionised by hot stars but in this case ones recently formed from the gas cloud. (this one is the Orion Nebula in Orion’s Belt)

Molecular line radiation



Molecular clouds are cold, dark, giant condensations of dust and molecular gas which serve as "stellar nurseries".

All stars are born in molecular clouds, including our Sun. Molecular clouds are the "stuff" we're made of!

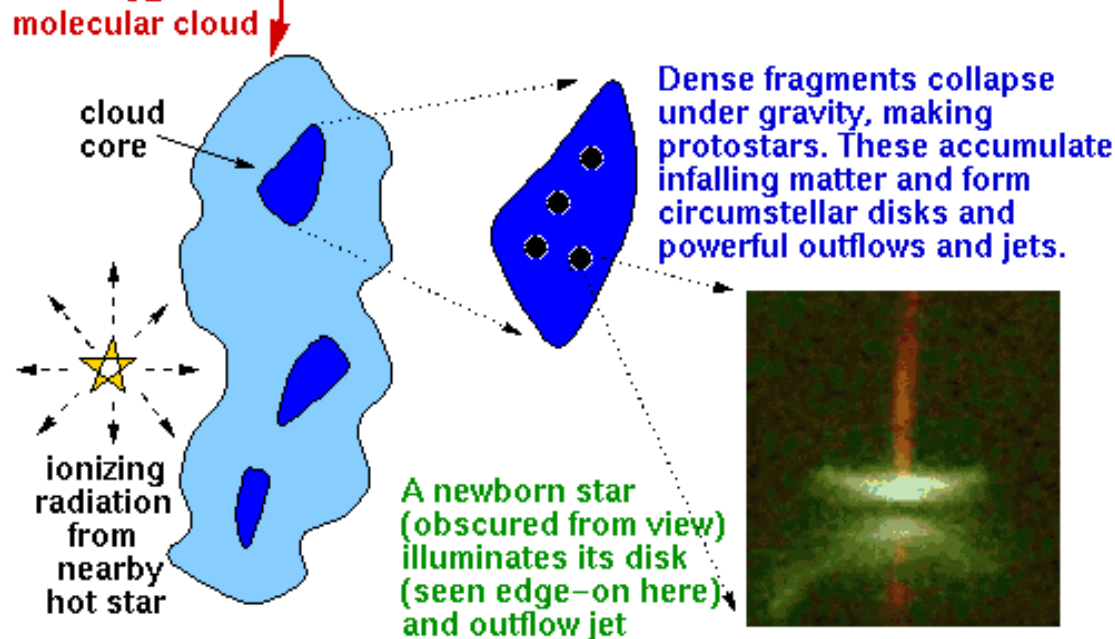
Because of their dusty content, visible light cannot penetrate into a molecular cloud. Thus, infrared and submillimeter observations are needed to "see" the star-forming process.

Quantized rotational transitions from molecules with dipole moments give rise to spectral lines in the radio band (see additional notes "B")

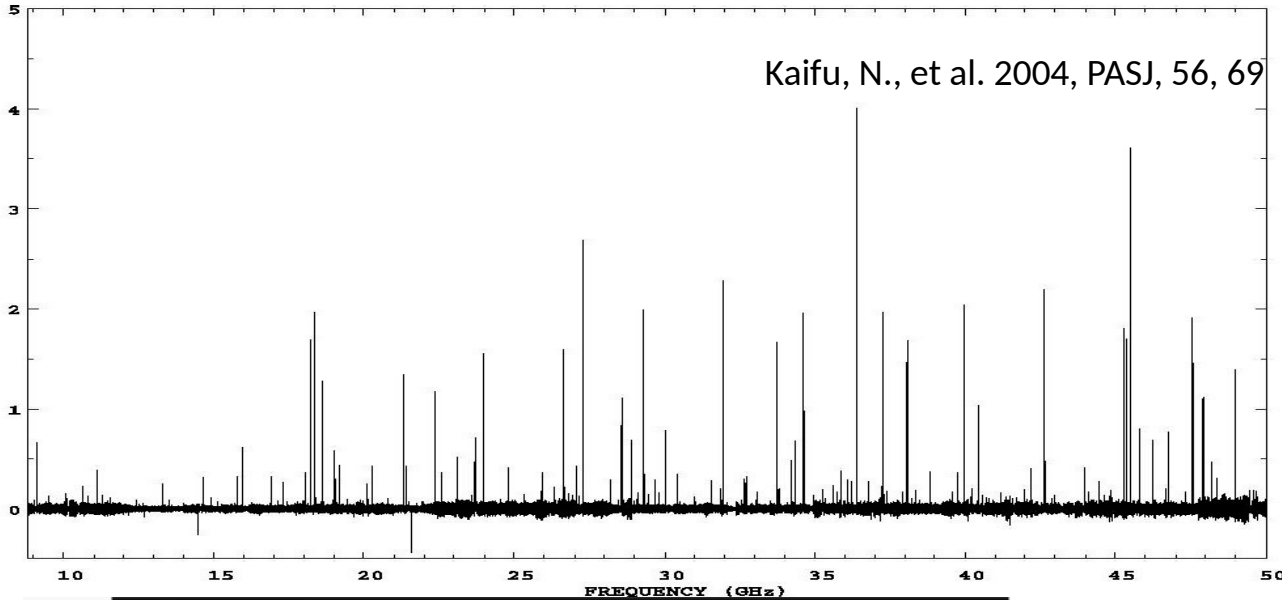
Nearly 150 molecular species have now been identified including the simplest amino acid glycine

Their study has become new subject

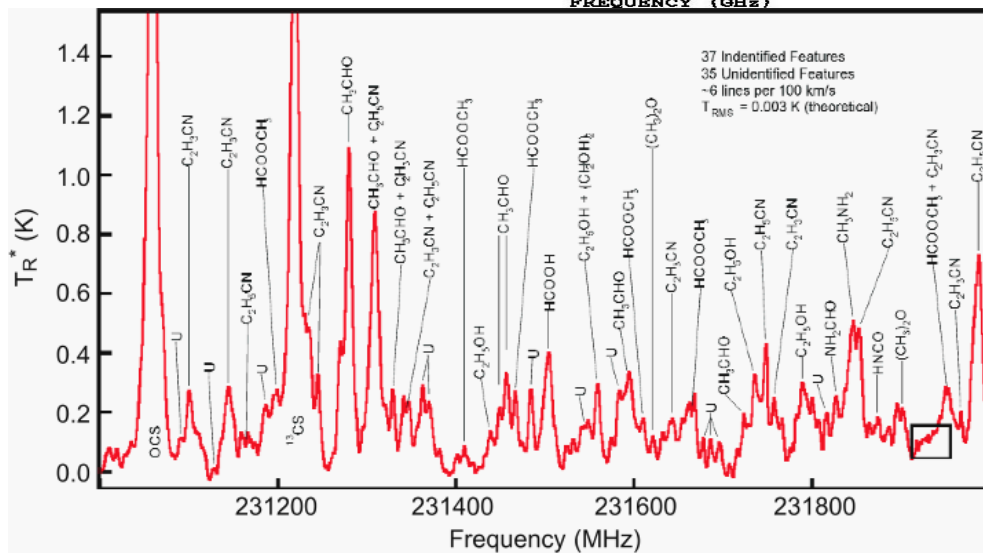
ASTROCHEMISTRY



There are many radio spectral lines !



8 to 50 GHz spectrum of a dark molecular cloud TMC-1 containing 414 lines from 38 species - but 117 lines remain unidentified.

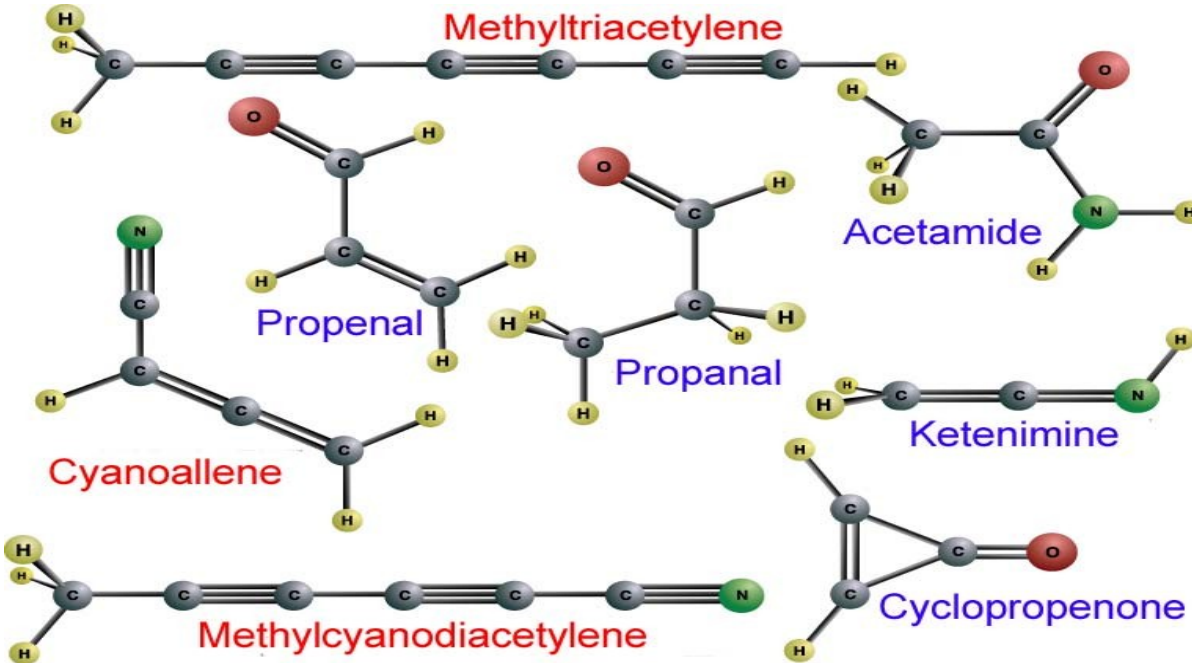


A 231 GHz spectrum of the molecular cloud SgrB2(N) near the Galactic center is completely dominated by molecular lines from known and unknown (U) species (Ziurys et al. 2006, NRAO Newsletter, 109, 11).

<http://www.cv.nrao.edu/course/astr534/MolecularSpectra.html>

Thermal line radiation

Nearly 190 molecules detected in interstellar space.



http://www.space.com/scienceastronomy/060808_st_life_molecules.html

- Many of these are “organic.”
 - Illustrates importance of carbon in chemistry of life.
 - Are there biological molecules not yet detected? (Amino acids?)
- Connection to protoplanetary disk chemistry?

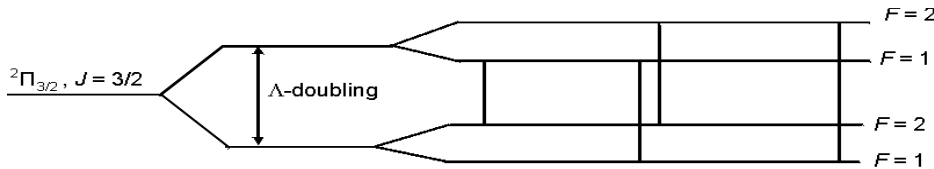
http://en.wikipedia.org/wiki/List_of_molecules_in_interstellar_space

<https://www.astro.uni-koeln.de/cdms/molecules>

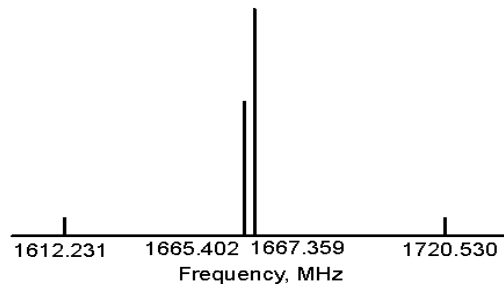
Masers

- A combination of dense molecular gas and either
 - strong IR radiation field
 - or collisions in outflows
- Leads to pumping of excited levels and a population inversion in certain molecules such as OH, H₂O, CH₃OH
- This leads to maser emission

Maser emission

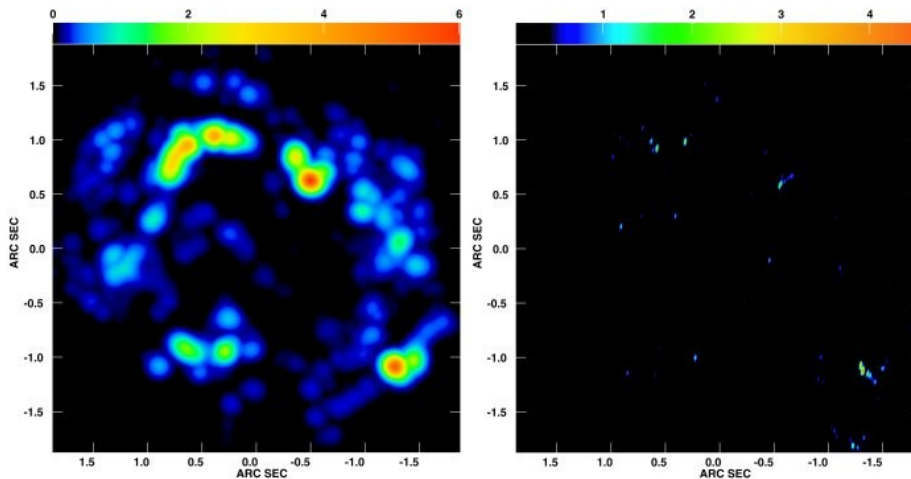


OH



the emission from a maser is stimulated and monochromatic, having the frequency corresponding to the energy difference between two quantum-mechanical energy levels of the species in the gain medium which have been pumped into a *non-thermal population distribution*.

arise in molecular clouds
comets, planetary
atmospheres, stellar
atmospheres and
circumstellar rings, or from
various conditions in
interstellar space.



A circumstellar ring of masers
whose diameter is far too small
to resolve with optical telescopes

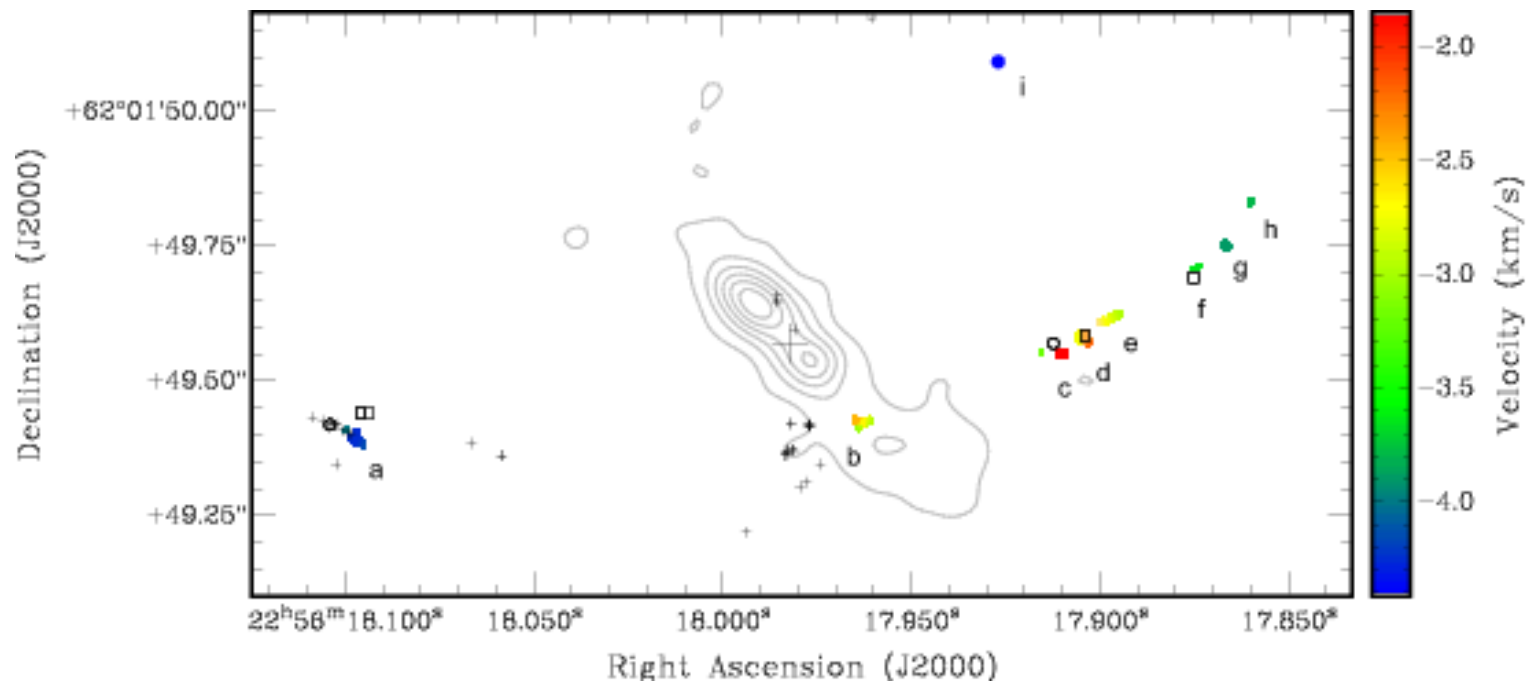
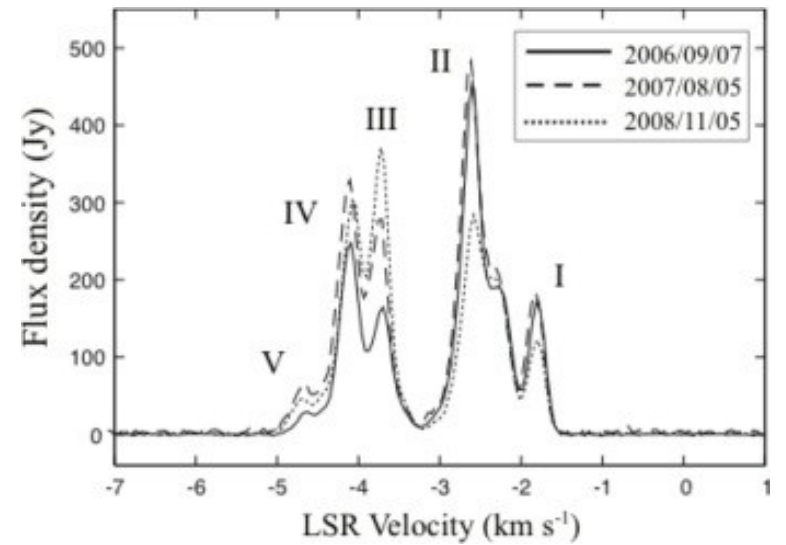
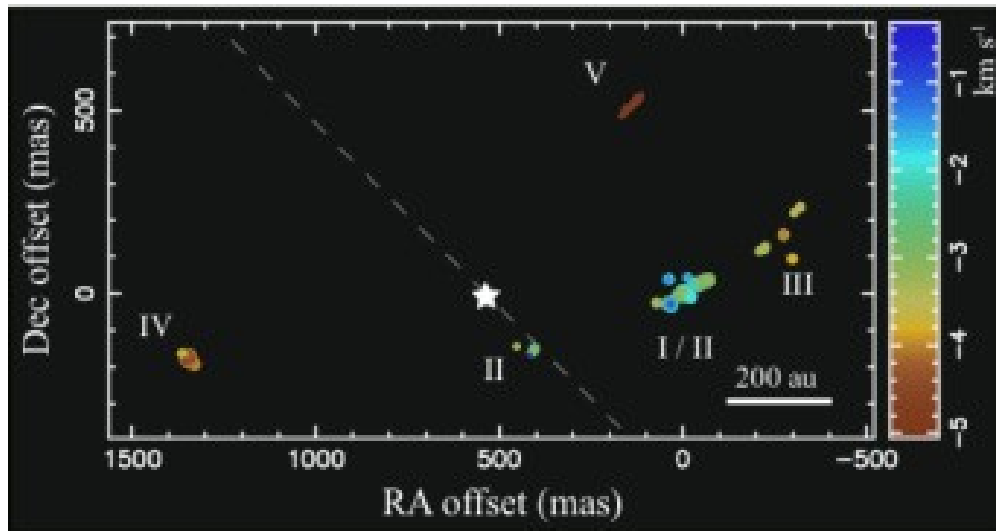
Stimulated Emission

- passing photon with same frequency as the maser transition can stimulate a radiative de-excitation
- emitted photon has same direction as stimulating photon

→beaming

Amplification

- photons can stimulate other molecules
→ cascade as in a laser
- can also view phenomena as a negative optical depth:
 - instead of attenuation $I_l \propto e^{-\tau}$
 - you get amplification $I_l \propto e^{\tau}$
- intense spots of maser emission



Masers can be found at different stage of stellar evolution

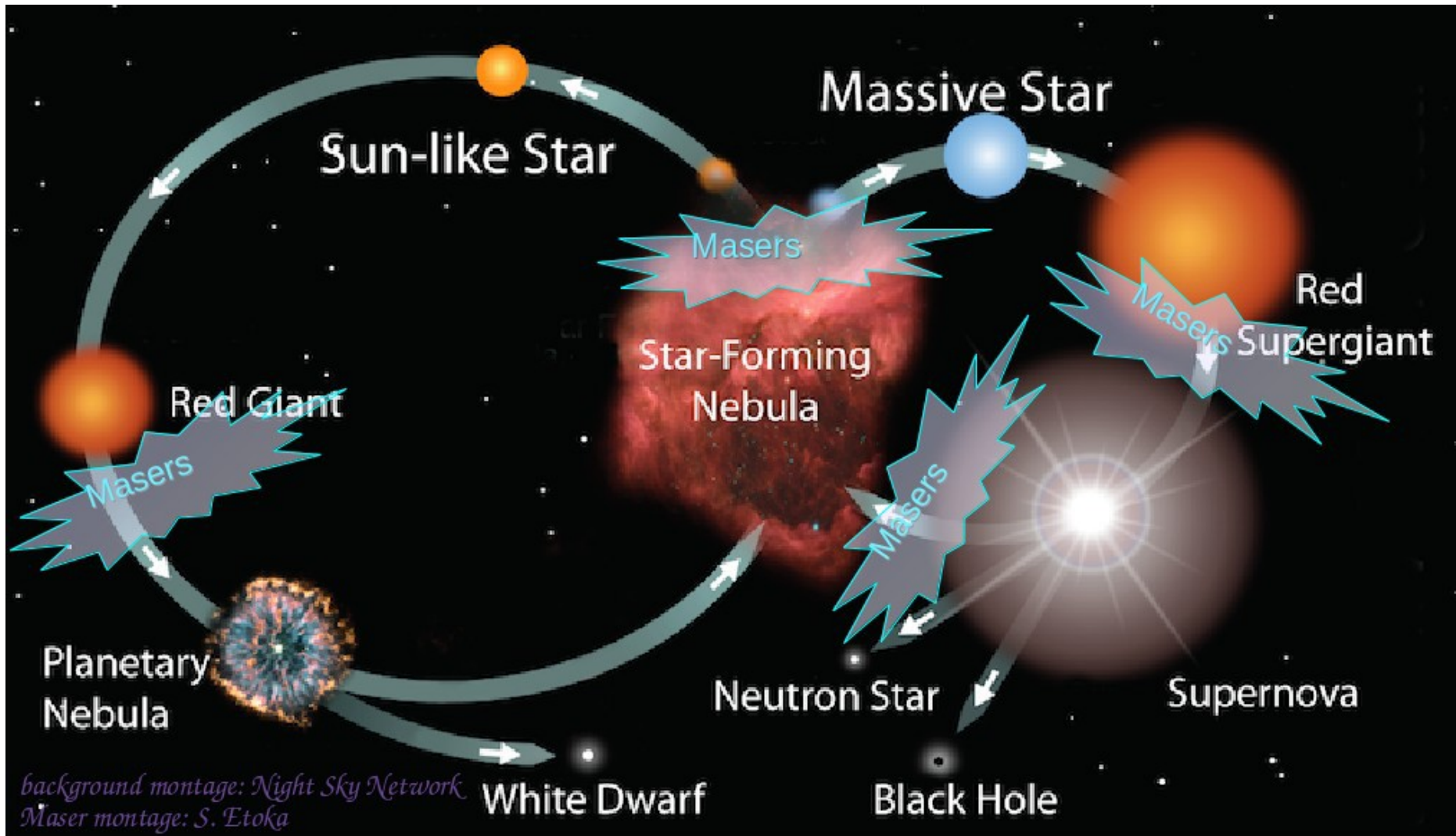


Image courtesy: Sandra Etoka

Masers are a powerful tool to study 2 crucial periods in the life of a star:

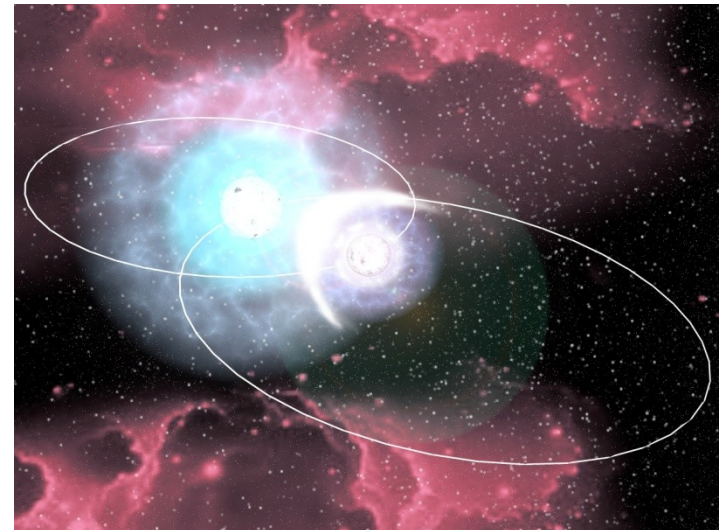
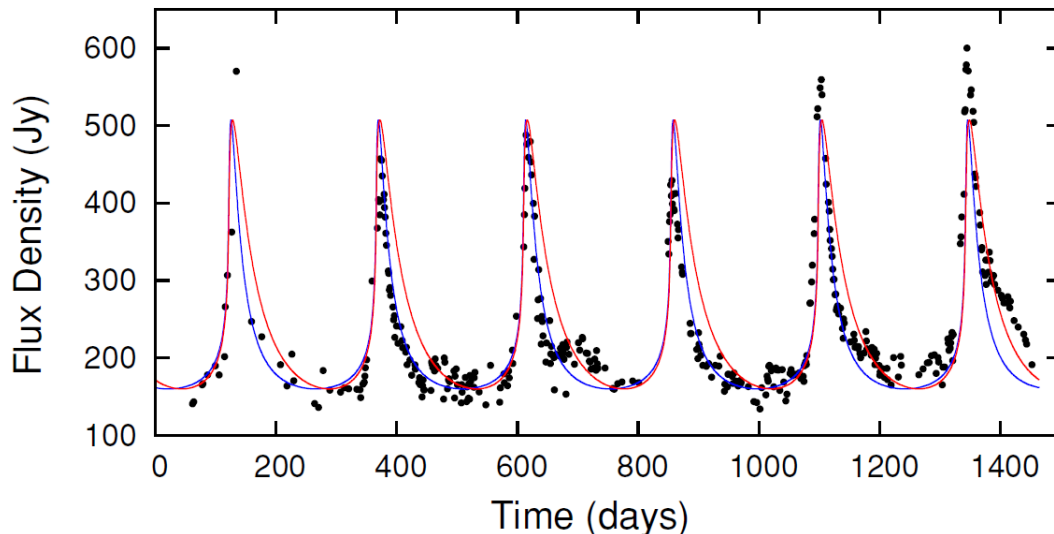
- During the formation process
*most common species: H_2O ,
 CH_3OH and OH*

*(also detected: SiO , NH_3 , H_2CO ,
 CH_3CHO)*

- In the late stages of evolution
in AGB - PPN& RSG: SiO , H_2O

Periodic Methanol Masers

- Some methanol masers exhibit periodic flaring of the intensity of some components
- May be caused by colliding winds in an eccentric massive young binary system



What has been missed out?

- Continuum radio emission from the Sun
 - a whole field in it own right
 - different types of bursts
 - relation to “Solar Weather”
- Radio emission from Stars
 - weak at standard radio wavelengths
so still a relatively niche research area
 - SKA will have a big impact

End of Lecture 1