A brief introduction to the RADIO Universe

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Incorporating Slides From: Garrett, Kramer, Lazio, Wilkinson

Provides Unique Information on the Universe

Explores fundamental physics using:

- the first photons set free in the universe after the "Big Bang"
- the basic element, hydrogen – the 21cm line
- magnetic fields -- polarisation imaging
- the most accurate clocks in the universe – millisecond pulsars

"Window" on matter in different phases

- synchrotron radiation
- maser emission
- bremsstrahlung/free-free emission from thermal gas
- thermal emission from cold dust

Penetrates dust/gas:

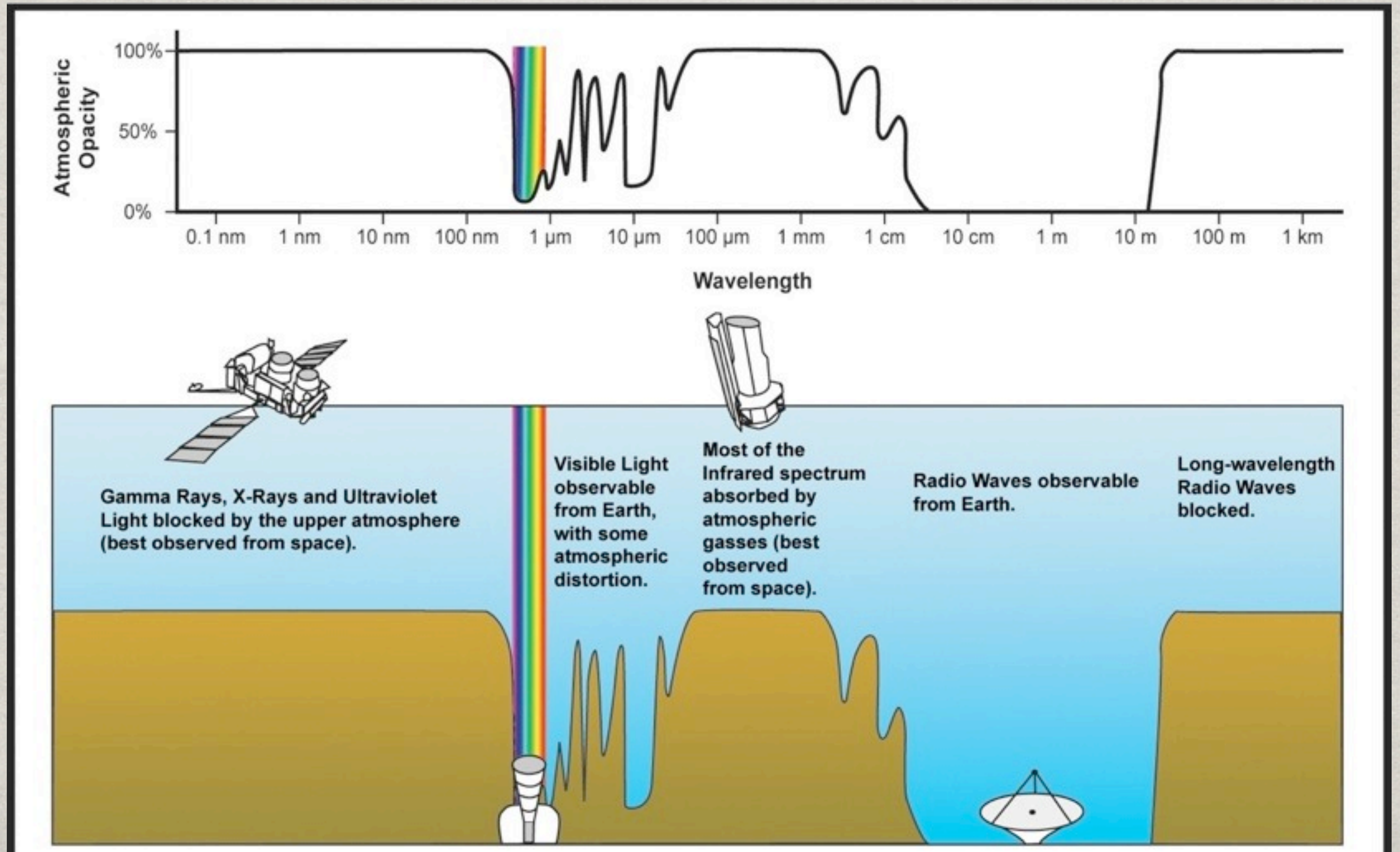
- absorbs & scatters radiation in most other wavebands – can see into molecular clouds

Provides highest resolution images at any λ: Very Long Baseline Interferometry

The Radio Window

From the ground the "radio" window is defined by:

- atmospheric transparency
- lower boundary: ~10 MHz i.e. ~30 metres set by the ionosphere (solar activity)
- upper boundary: ~1 THz (10^{12} Hz) i.e. ~0.3 mm set by absorption by quantized molecular vibrations or rotations (at longer wavelengths) (limitations imposed by quantum noise in amplifiers/detectors at the high frequency end)



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

Where to Observe From?

Band	Characteristic wavelength	Frequency	Best to observe from
optical	500 nm	6×10^{14} Hz (600 THz)	mountains space
sub-mm wave	100 microns	3×10^{12} Hz (3 THz)	aircraft, balloons, space
mm wave	1 mm	3×10^{11} Hz (300 GHz)	mountains, balloons, space
radio	1 cm	3×10^{10} Hz (30 GHz)	mountains, surface in good weather
radio	1 m	3×10^{8} Hz (300 MHz)	ground
radio	10 m	3×10^{7} Hz (30 MHz)	ground

History Summary (pre 1980)

Prehistory:

1870's: James Clerk Maxwell predicts existence of electromagnetic radiation with any wavelength!
1888: Heinrich Hertz demonstrates transmission and reception of radio waves

Early pioneers:

1932: Karl Jansky discovers cosmic radio waves from the galactic centre (USA)
1937-1944: Grote Reber's First Surveys of the Radio Sky (USA)
1942: Sun discovered to be a radio source by J.S. Hey (UK)
1936-1945: Development of radar before and during world war II e.g. Sir Bernard Lovell
1944: Prediction by Henk van der Hulst and Oort (NL) of neutral Hydrogen spectral line emission at 1.4GHz.
1951: Detection of neutral Hydrogen Ewen & Purcell (USA) and van der Hulst & Oort (NL)

Major discoveries:

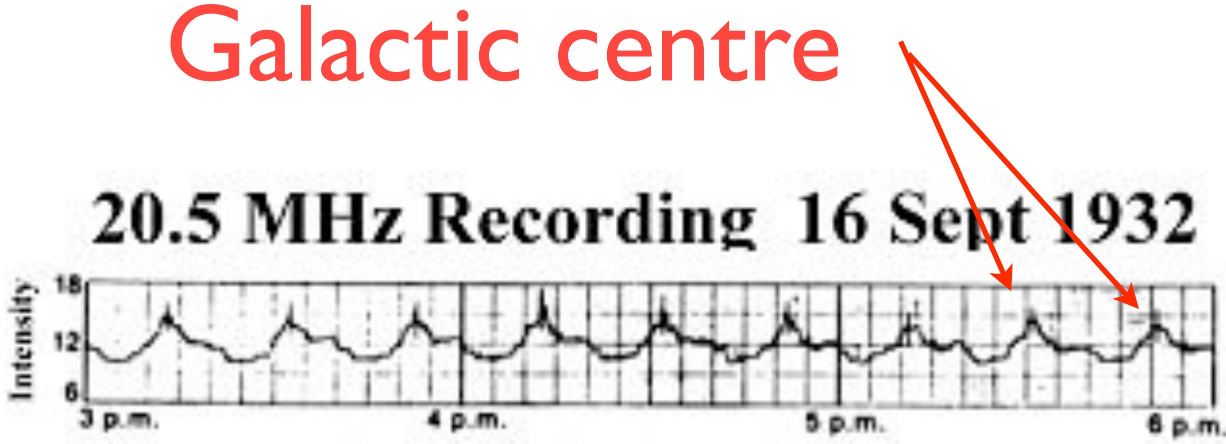
1960-63: Radio sources identified with blue quasi-stellar objects with huge recession velocities
1960s: First radio interferometers constructed; Aperture Synthesis developed (Ryle, UK) - Noble Prize
1965: Cosmic Microwave Background (CMB) detected (Penzias & Wilson, USA) - Noble Prize
1967: Pulsars (rotating neutron stars) discovered by Jocelyn Bell & Tony Hewish (UK) - Noble Prize

Large scale radio telescope facilities:

1956/7: Construction of the first large steerable telescopes (Dwingeloo-NL, Jodrell Bank-UK...)
1967: First successful transatlantic Very Long Baseline Interferometery observations.
1970: Westerbork Synthesis Array telescope starts operations (NL)
1976: Very Large Array (VLA) becomes operational (USA) etc. etc.

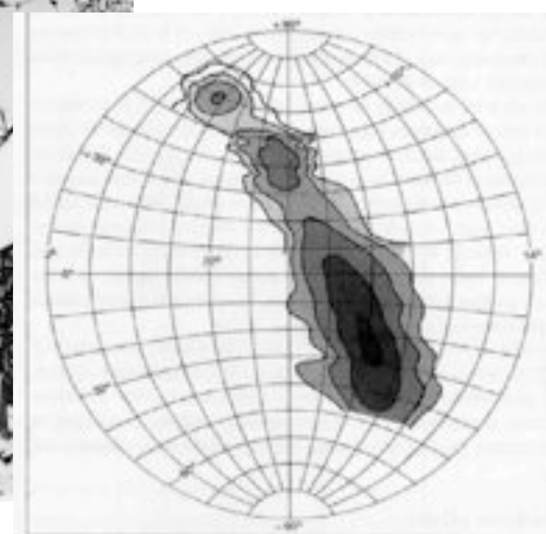
Early History

1932 Discovery of cosmic radio waves (Karl Jansky):



Early History

Grote Reber (1911-2002)- the first radio astronomer



Built the first parabolic radio telescope:

- "Good" angular resolution

- Good visibility of the sky

- Detected Milky Way, Sun, Cas-A, Cyg-A, Cyg-X @ 160 & 480 MHz (ca. 1939-1947).

- Published his results in ApJ

- Multi-frequency observations

- Ground-breaking work (1937-1947):
- discovered that most radio emission was "non-thermal"

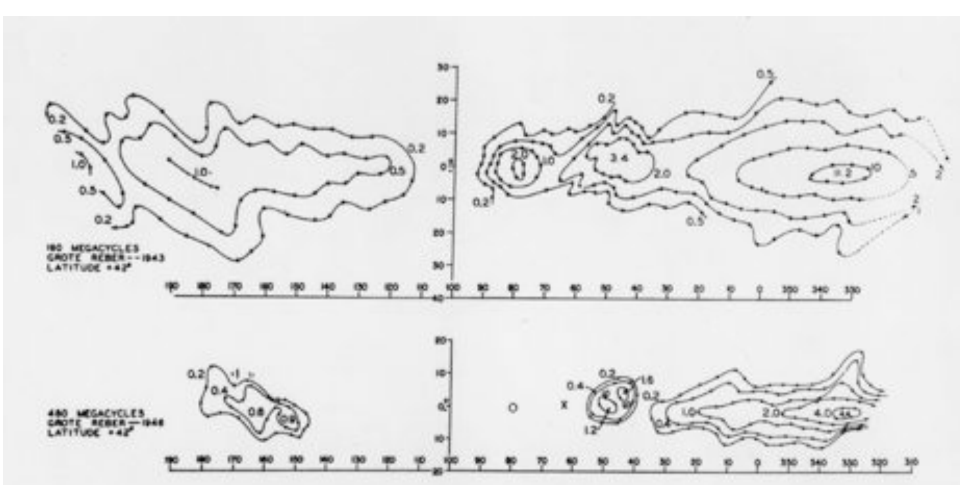
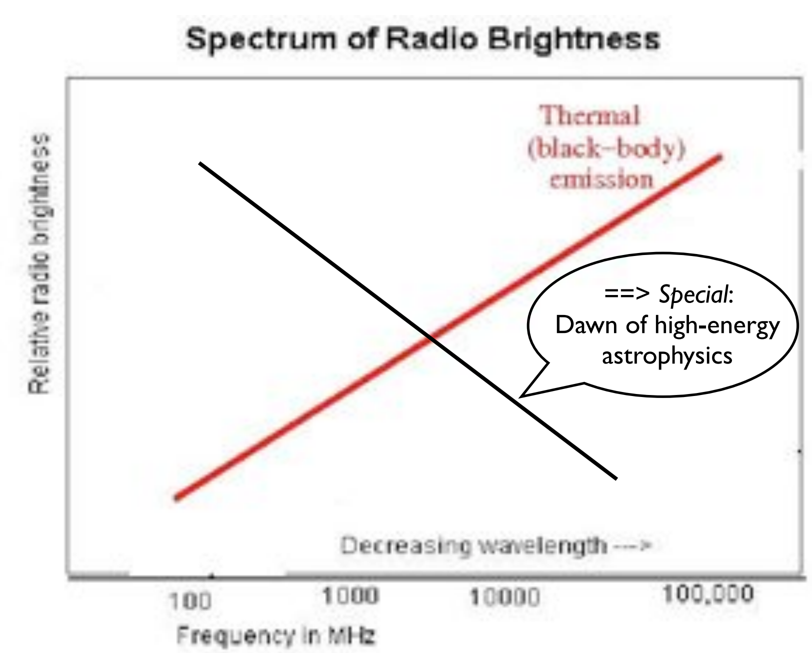


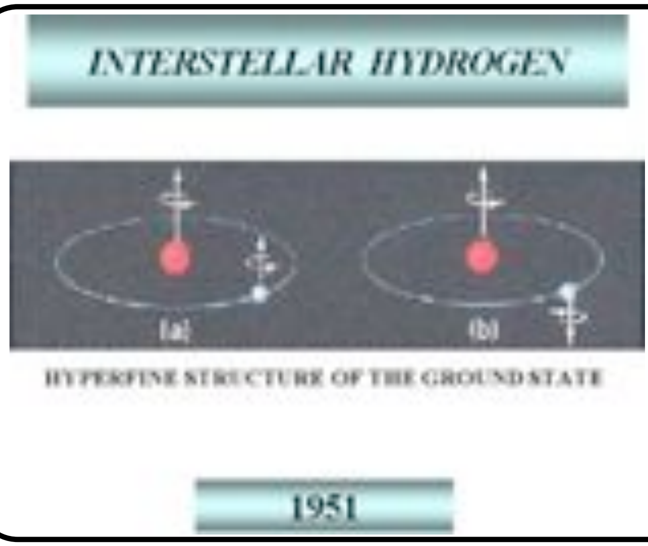
Fig. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Reber's multi-frequency observations revealed the non-thermal nature of radio emission (UNEXPECTED!)

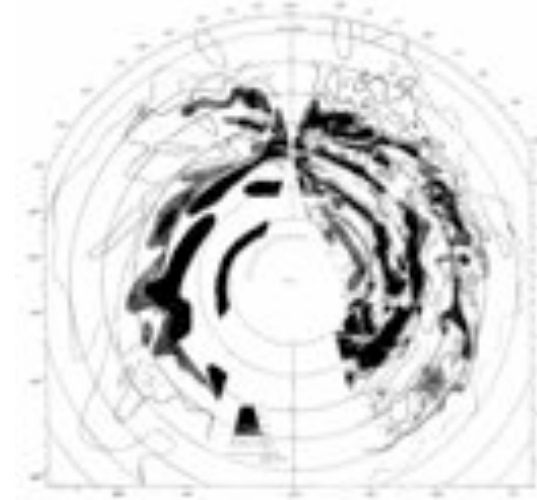


Radio Spectral Lines - neutral hydrogen

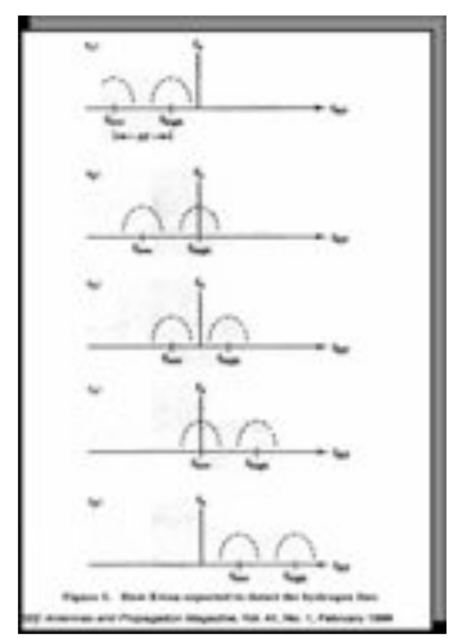
1944: van der Hulst predicts discrete 1420 MHz (21 cm) emission from neutral Hydrogen (HI).




Wurzburg "Riese" Radar Antenna, 7.5 m diameter

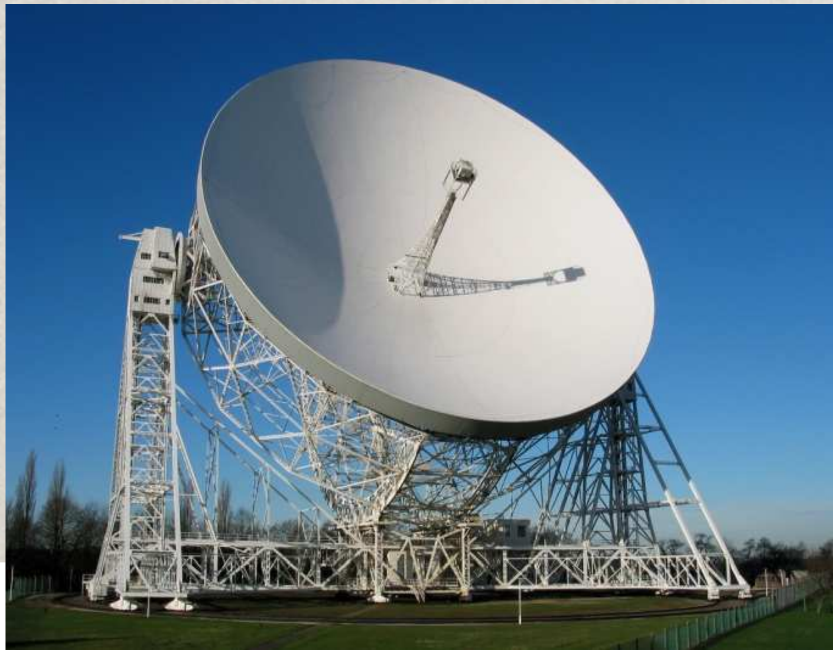


1951: HI detected by Ewen & Purcell and Oort & Muller.

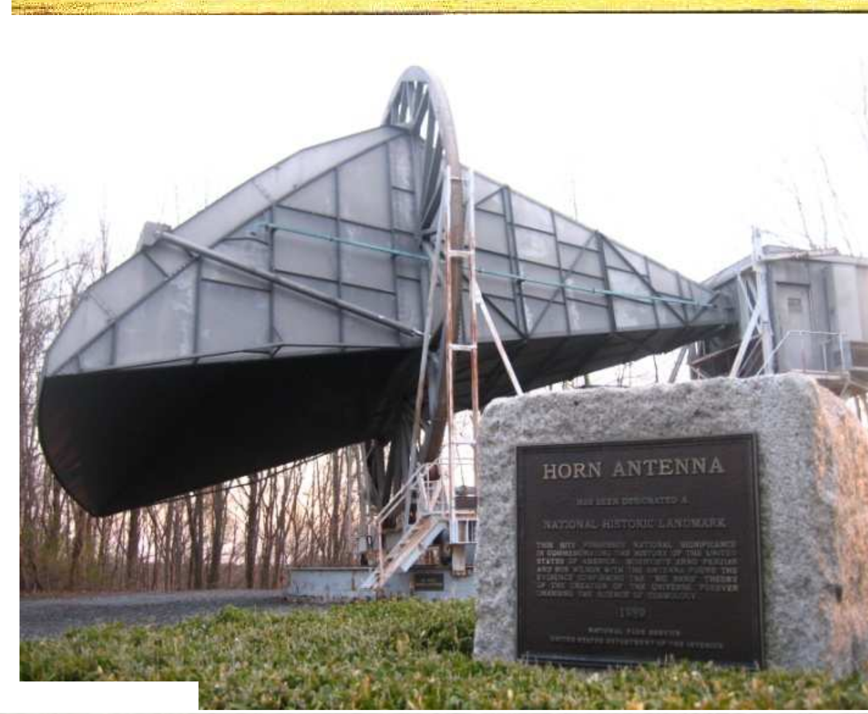


Special: Radio astronomy traces the FIRST and most ABUNDANT element in the Universe.

Large radio telescopes in 1950s and 60s : many different designs





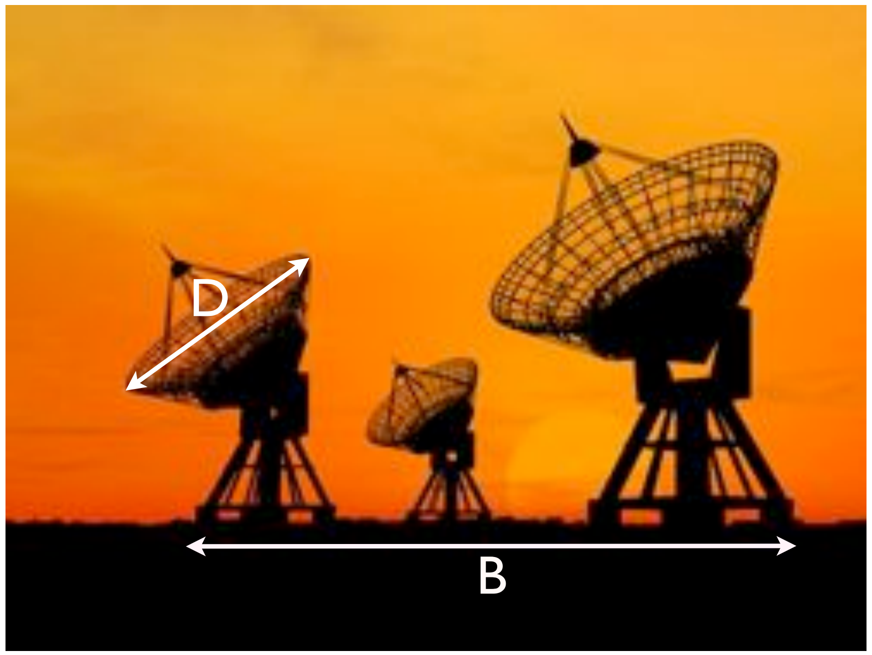



Many still doing cutting edge science!

Single dishes versus Interferometers

The quest for resolution drove radio astronomers towards interferometric techniques.

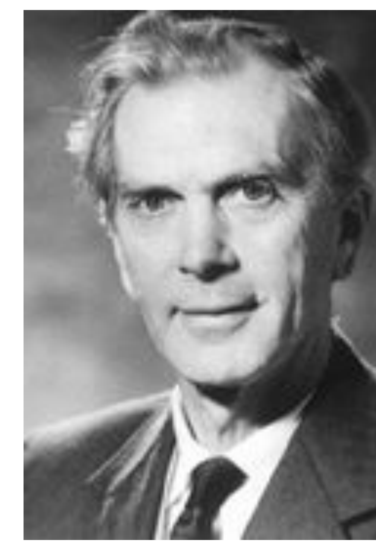
For a single dish the resolution is λ/D where D is the diameter of the telescope.



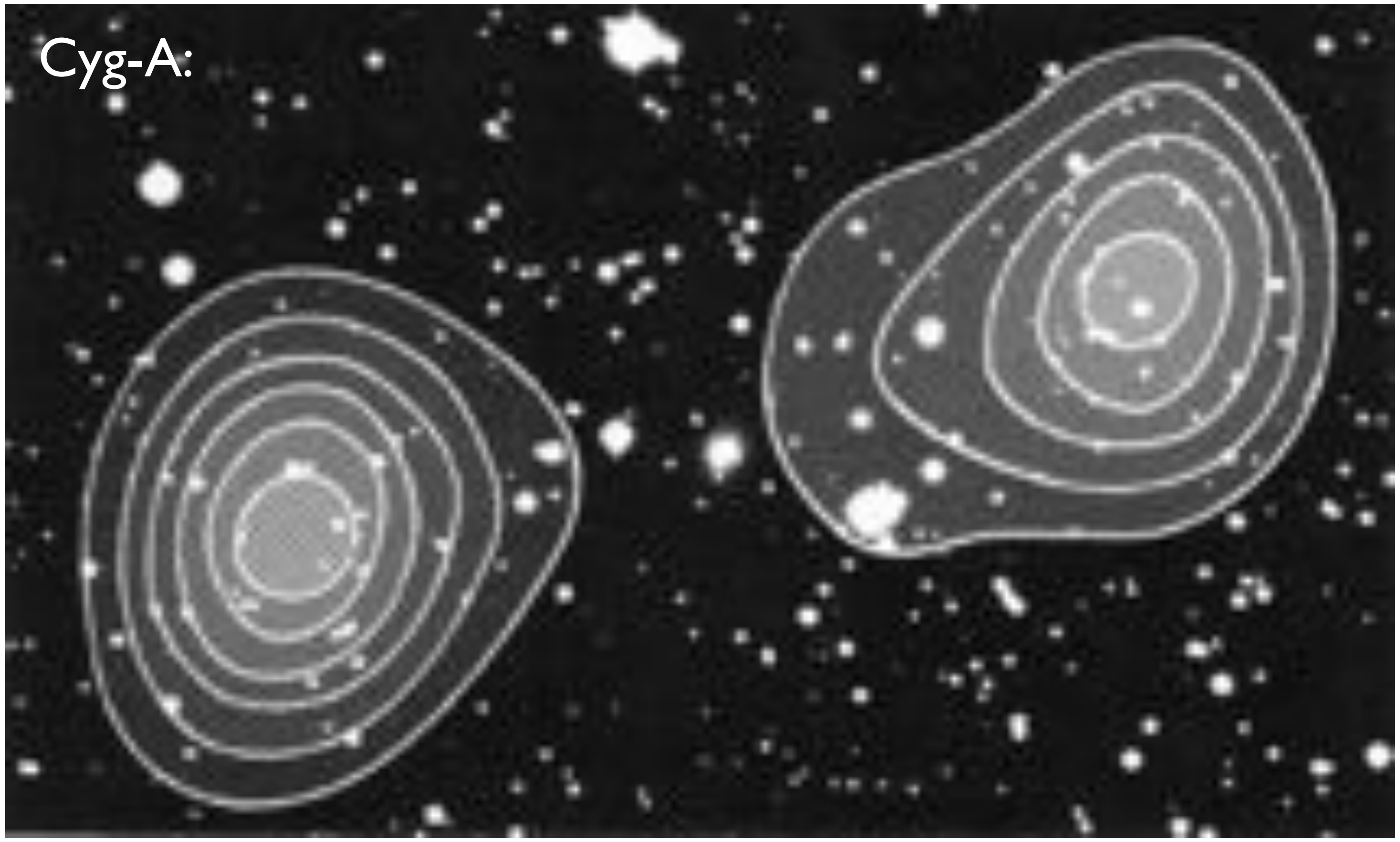
But for an interferometer array the resolution is λ/B where B is the maximum baseline.

Radio interferometers

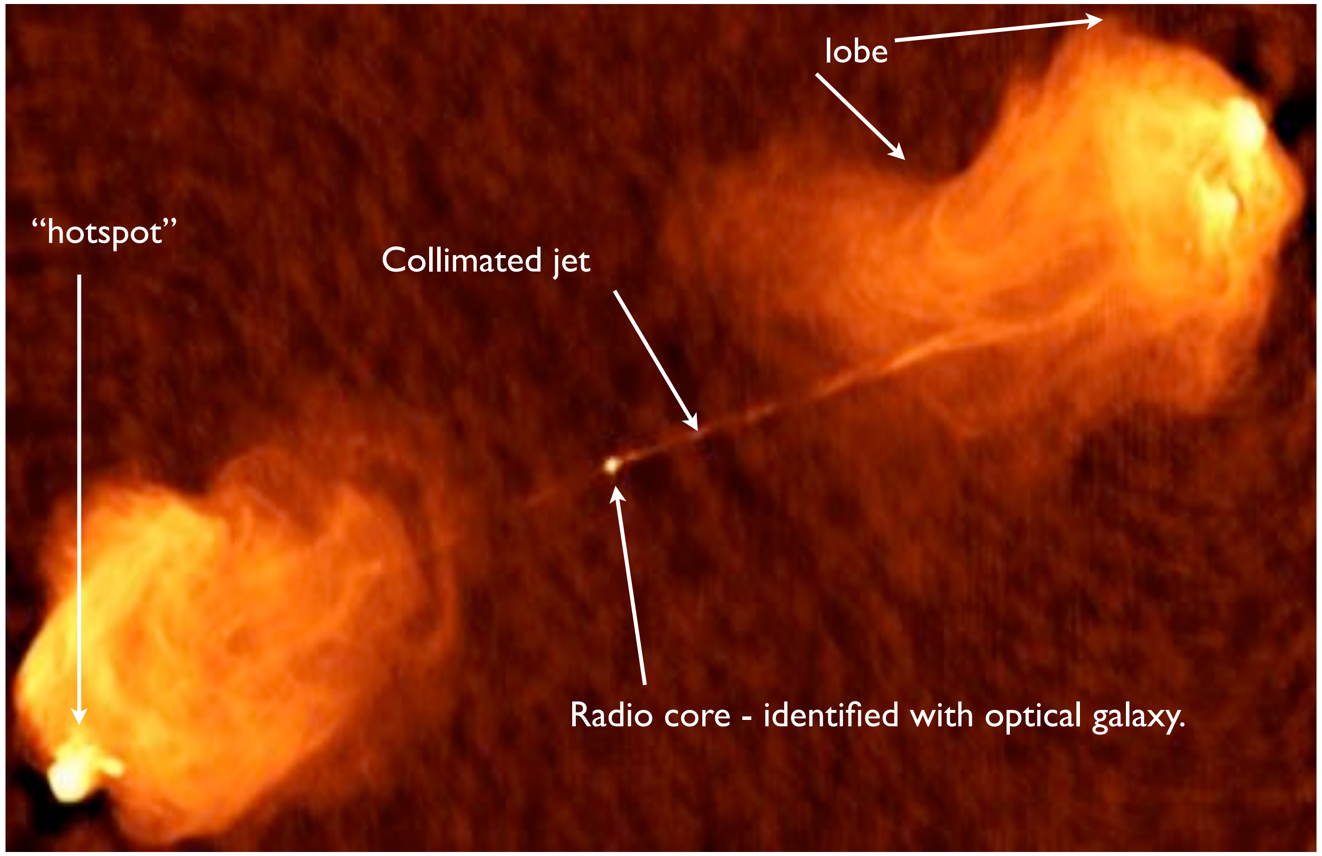
In the 1950's the first radio arrays (interferometers) were constructed. People like Martin Ryle (pictured) pioneered the the interferometry technique, receiving the Noble Prize in 1974 for developing the concept of aperture synthesis (see lecture 4).



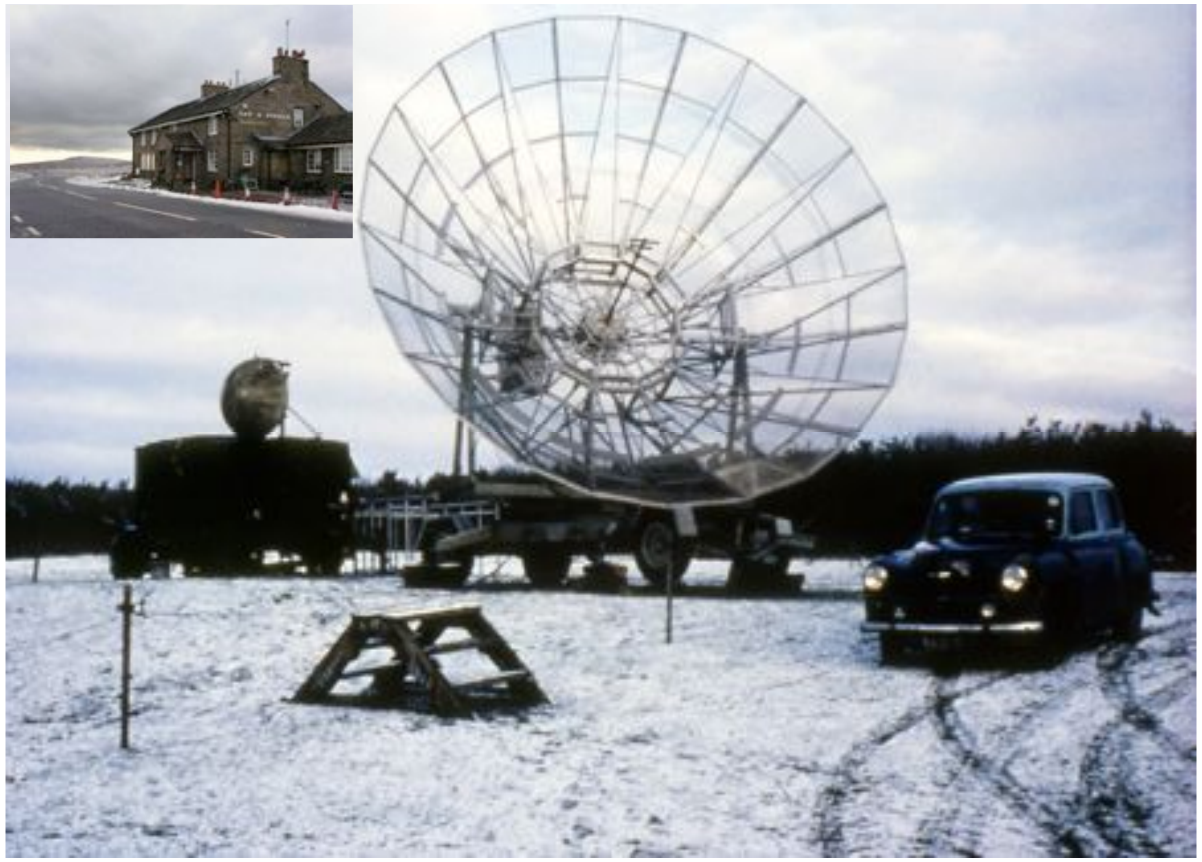
In 1954 interferometer measurements showed that the radio emission from one of the brightest sources in the sky, Cyg-A came from bright regions on either side of a host galaxy.



As interferometers began to survey hundreds of bright radio sources, many of them exhibited this "classical double-structure".

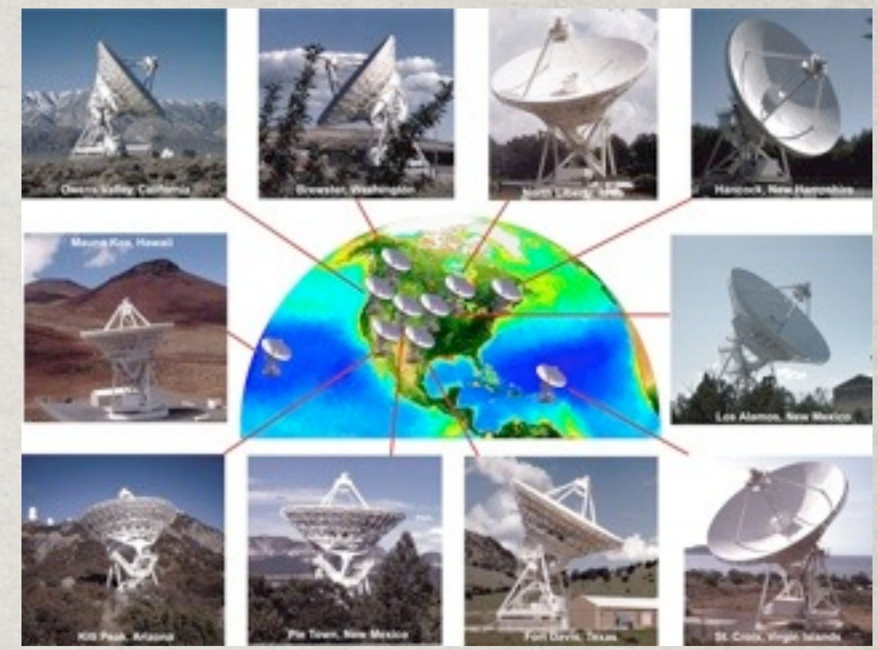


"Modern" (1990!) VLA image of the radio galaxy Cyg-A



The need for sub-arcsecond resolution led to the technique of VLBI (Very Long Baseline Interferometry). First over distances of ~ 50 km via remote transportable antennas (Jodrell Bank, UK).

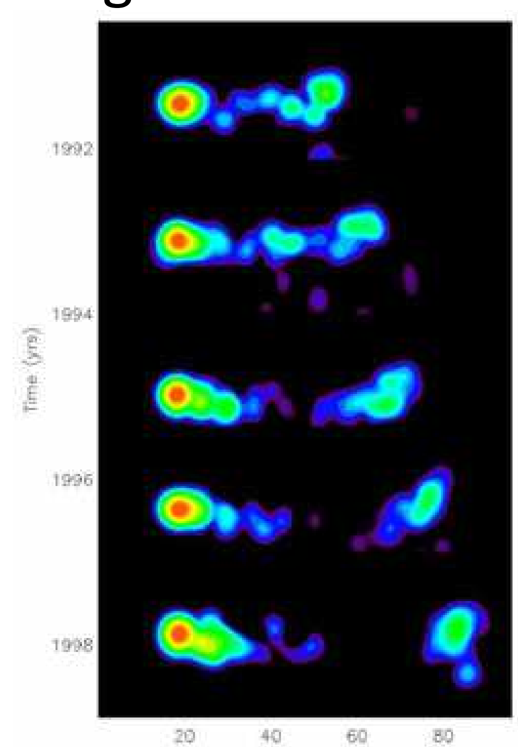
VLBA



(e) Merlin

Very Long Baseline Interferometry (VLBI)

Baseline comparable to D_{Earth}
Highest resolution in astronomy



Apparent faster-than-light expansion from the core of a quasar

Not a violation of SR but an indication of expansion speeds at 0.98-0.99c in a plasma jet aligned close to the line of sight

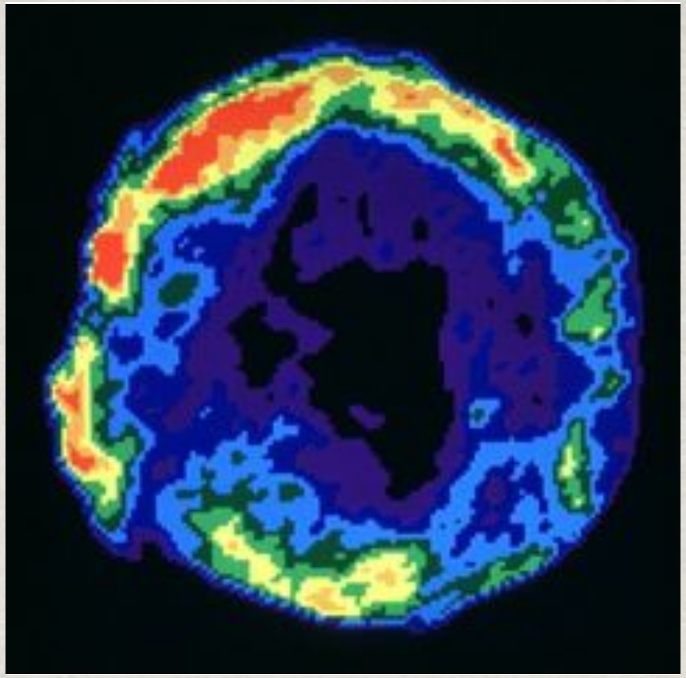
http://www.cv.nrao.edu/course/astr534/images/3C279.jpg

By the early 1960's it was becoming clear that many types of cosmic objects were unexpectedly detected as strong sources of radio emission:

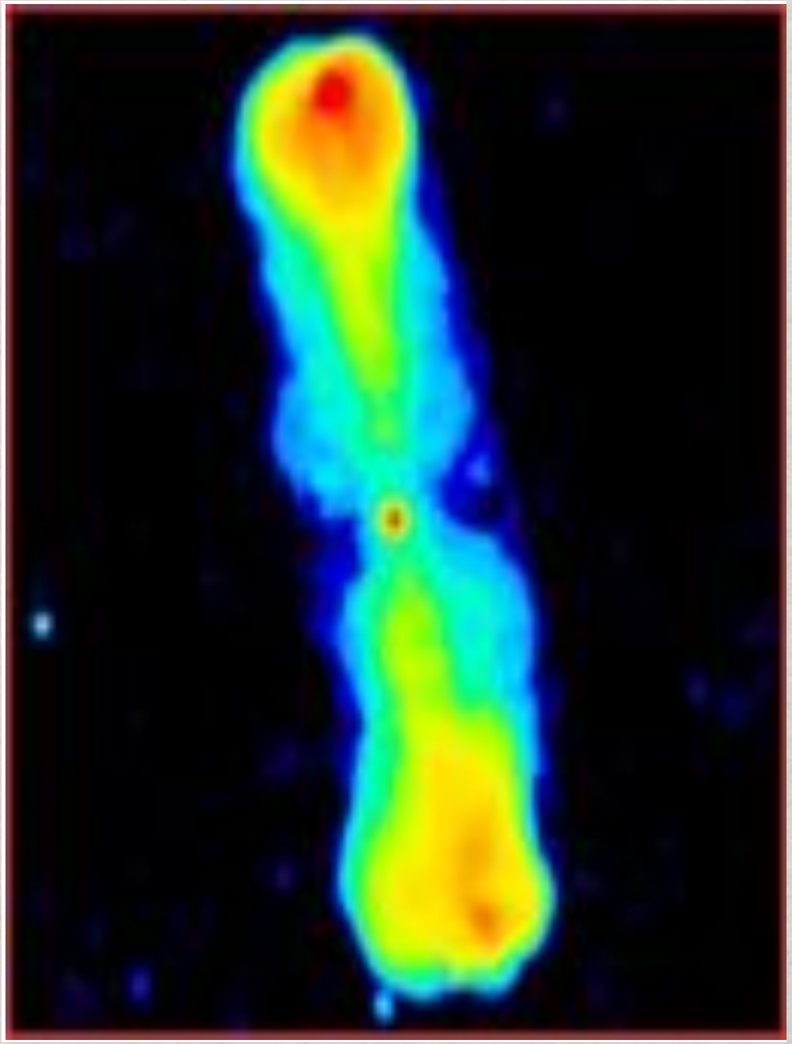
- in the solar system the Sun and Jupiter,

- in the Milky Way stellar explosions (supernovae) and interstellar gas clouds

- but most common of all were the ubiquitous double sources associated with active galaxies at *cosmological distances,* with the radio emission *appearing far beyond the optical extent* of the galaxy (see Cen-A - extreme right). The luminosity of these sources could not be explained by an conventional sources of energy e.g. nuclear fusion.....



Above: Bright ring-like radio source was identified at the position of Tycho's 1572 nova.



Cosmic Microwave Background.

As well as all these discrete sources what remained was an excess temperature that Penzias & Wilson measured.
Penzias happened to have a conversation with Bernie Burke (MIT) who knew that a physicist Robert Dickie at Princeton was predicting a background signal associated with the cooling of radiation from the big bang.
When Dickie heard of Penzias & Wilson's detection he told his students (top right):"Boys we've been scooped"!

http://www.phy.davidson.edu/FacHome/thg/230s07_files/penzias-wilson.jpg

Discovery by Penzias and Wilson 1965

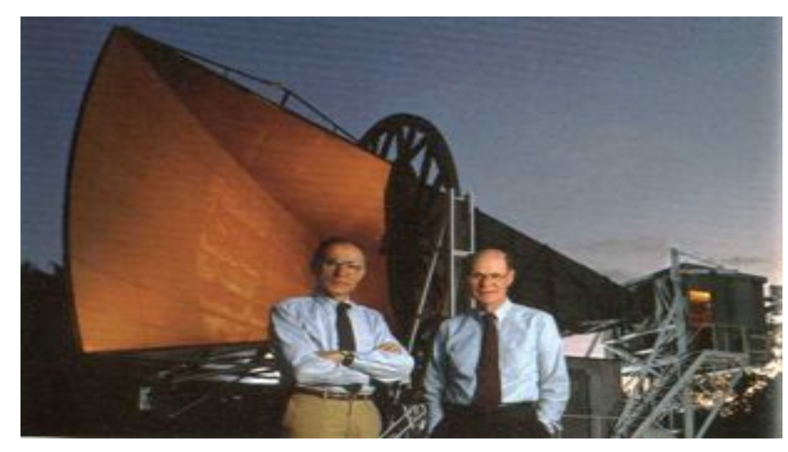
Black-body radiation from the early Universe

T = 2.75K

Very hard to measure in the face of lots of other sources of "noise"

Penzias & Wilson and Dicke et al. published their results side-by-side in Nature. P&W did not say much about the CMB - they were still a little sceptical that this was really the source of the background radiation!

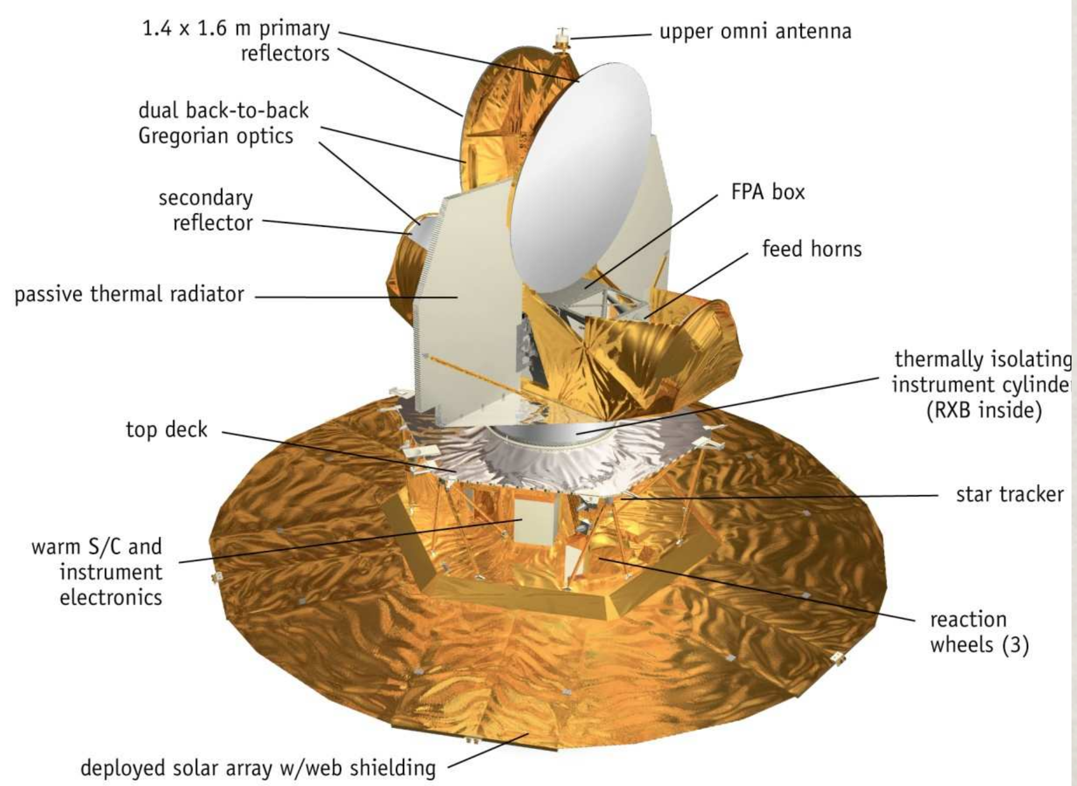
In 1978 they *alone* received the Noble Prize for the CMB detection.



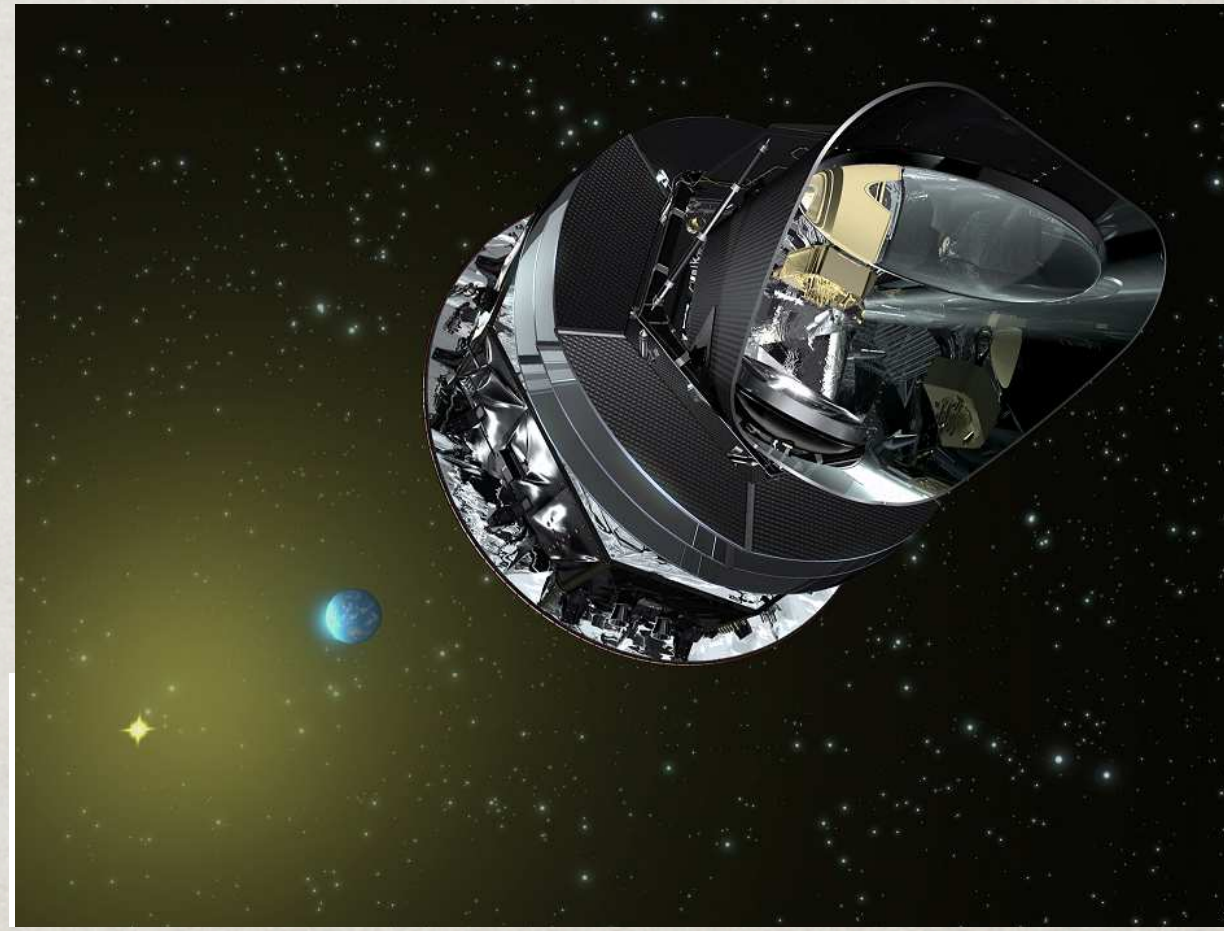
Modern Experiments

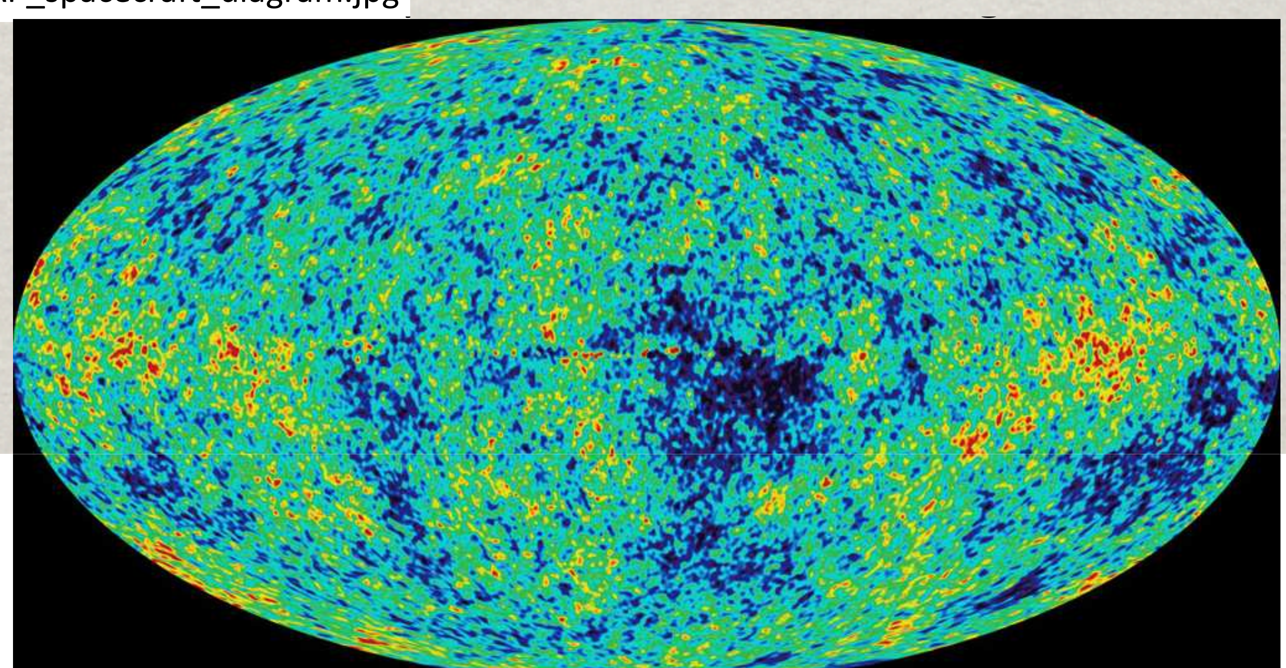
WMAP

Planck



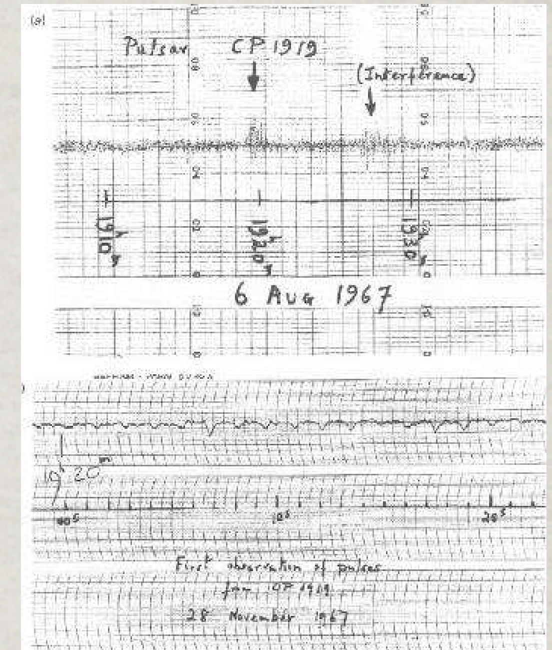
http://en.wikivisual.com/images/b/be/WMAP_spacecraft_diagram.jpg





http://map.gsfc.nasa.gov/media/101080/101080_7yrFullSky_WMAP_1600W.png

Pulsars



Pulsars discovered by Jocelyn Belll-Burnell (PhD student) and Anthony Hewish, as a by-product of Interplanetary Scintilation Studies (ISS) in Cambridge.

The signal was recorded on chart paper - telescope produced about 30 metres per day!

Jocelyn carefully waded through the paper (and interference), and started to notice an unusual source that appear to be periodic (T ~ 2 secs) she called this "scruff ".

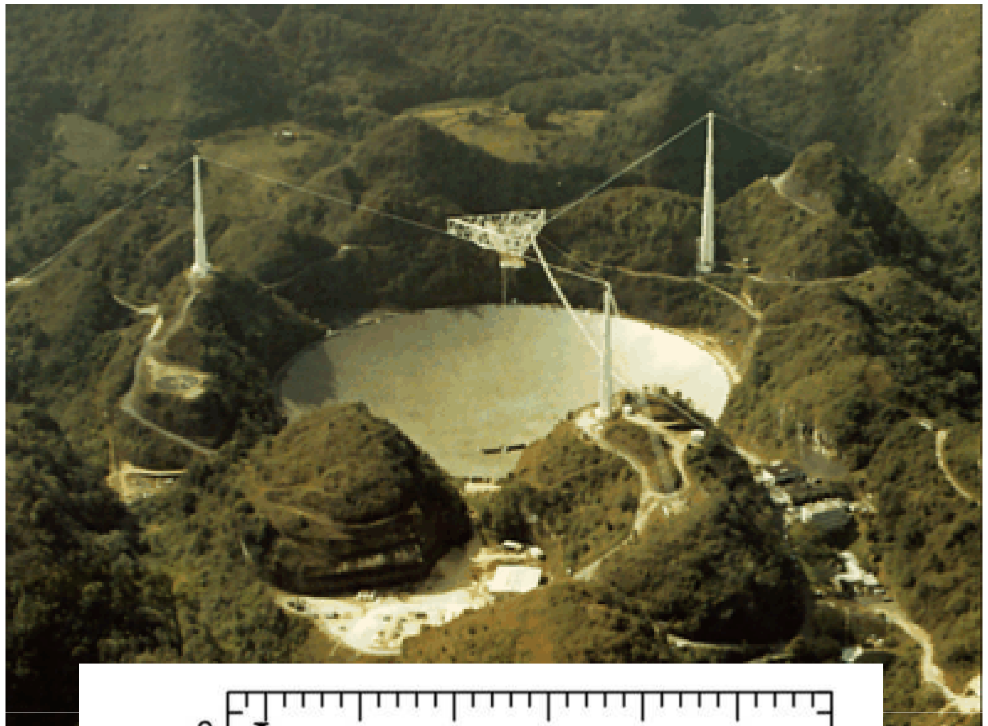
By 1968, four periodic sources had been discovered.

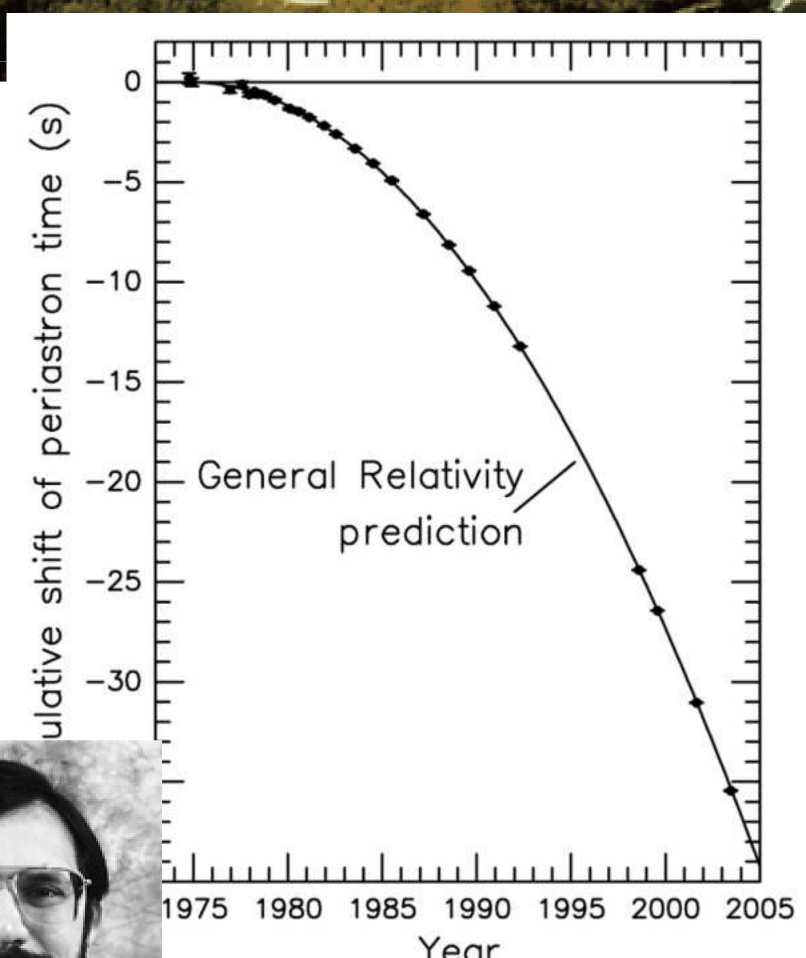
After instrumental causes were ruled out, other physical explanations were considered - including that the signal were being beamed to us by other intelligent life-forms in the galaxy.

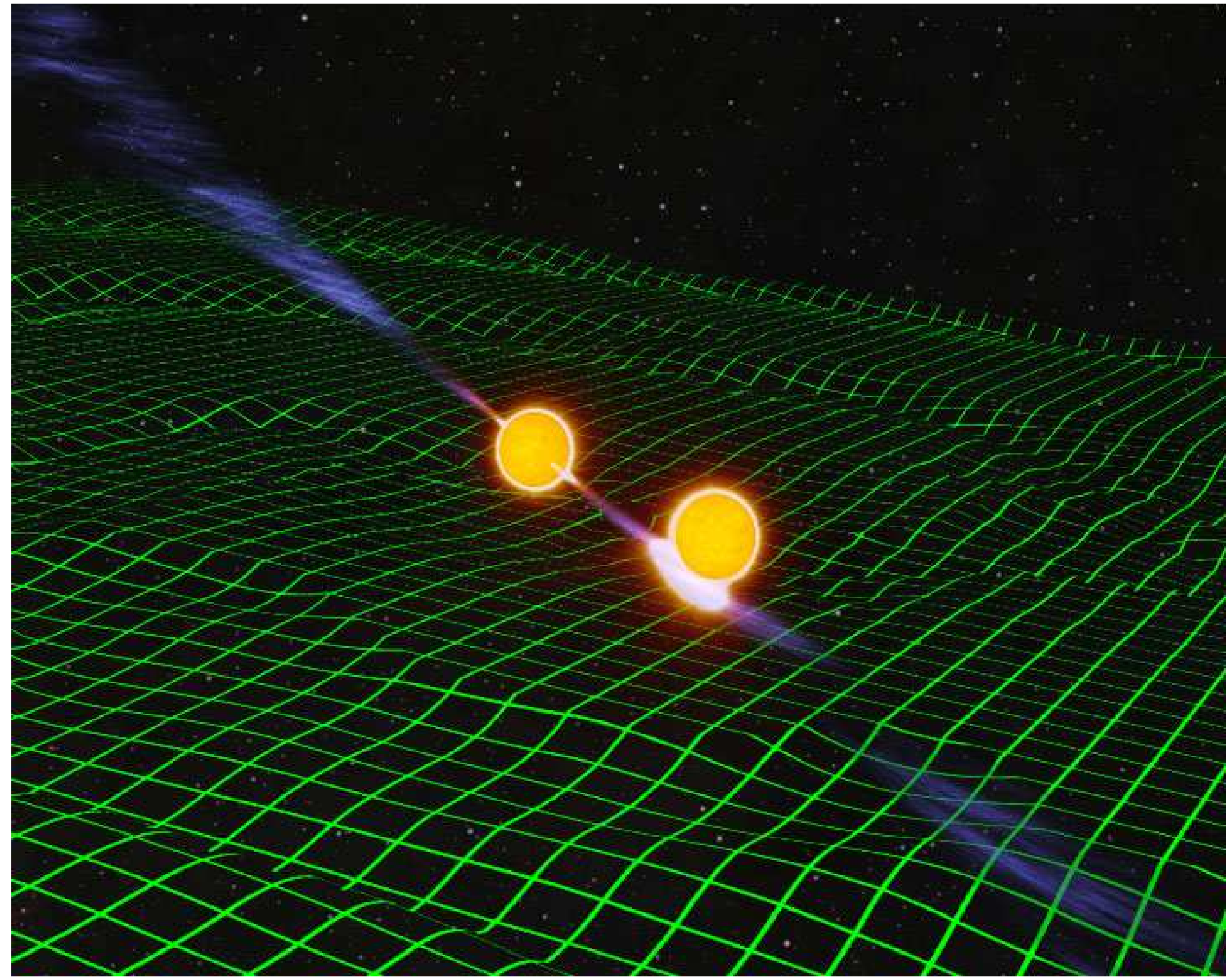
Ultimately recognised that they were rapidly rotating highly magnetised neutron stars.

Hewish received a Nobel prize for this discovery and contributions to radio astronomy (with Ryle).

Discovery of Gravitational Waves







Courtesy M. Kramer

Latest observations providing sternest tests of General Relativity

Hulse and Taylor awarded Nobel Prize in 1993

Radio emission mechanisms

Electromagnetic radiation is emitted by charged particles – mainly electrons - when they are accelerated

In general, electromagnetic radiation is emitted by one of two means, either **thermal** or **non-thermal mechanisms**.

Thermal emission, which depends only on the temperature of the emitting object, includes **blackbody radiation**, **free-free emission** from an ionized gas, and **spectral line emission**.

Non-thermal emission, which does not depend on the temperature of the emitting object, includes **synchrotron** radiation, gyrosynchrotron emission from pulsars, and amplified emission from **masers** in space.

Radio emission mechanisms

- Black-body radiation (thermal)
  - all terrestrial objects; planetary surfaces ; dust in interstellar space

- Bremsstrahlung or free-free emission (thermal)
  - from ionised plasmas – in experimental fusion reactors (tokamaks); gas in interstellar space ionised by uv radiation from stars

- Atomic and Molecular Lines (thermal)
  - from many species in tenuous gas in interstellar space and giant molecular clouds

- Synchrotron radiation (non-thermal)
  - relativistic electrons spiralling around magnetic fields in interstellar space; supernova remnants ; active galaxies
  - related emission from pulsars

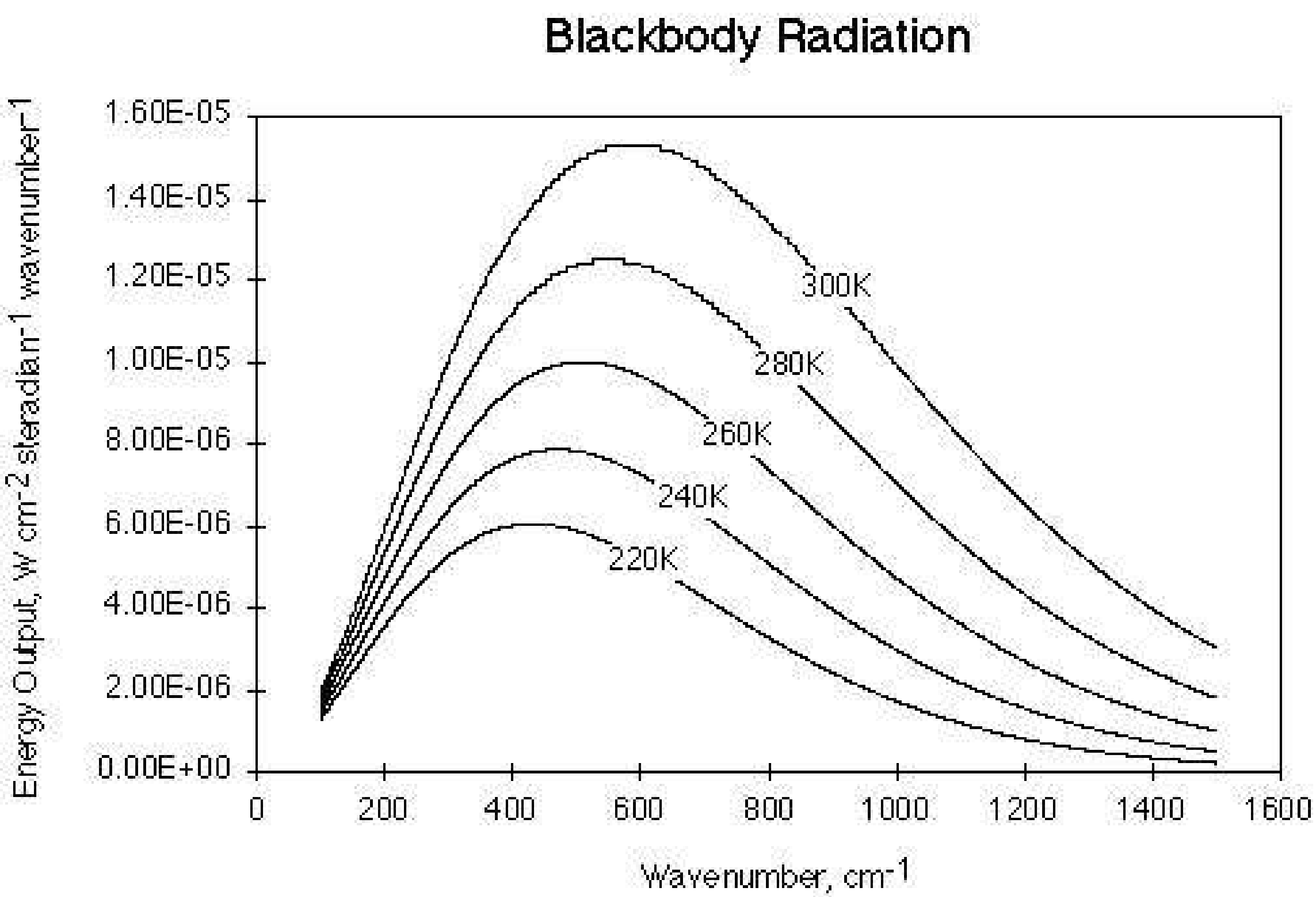
- Maser emission from specific molecular species (non-thermal)
  - from around stars – pumping by infra-red radiation

Black-body Radiation

For perfectly radiating (or perfectly absorbing) surfaces- ideal "black-bodies" - the emitted power output is given by the Planck radiation formula *which depends only on the physical temperature T.*

The peak of the emission is at a wavelength l_{max} (metres) = $2.9 \times 10^{-3} / T$ i.e. the higher the temperature the shorter the wavelength. (Wien's Law)

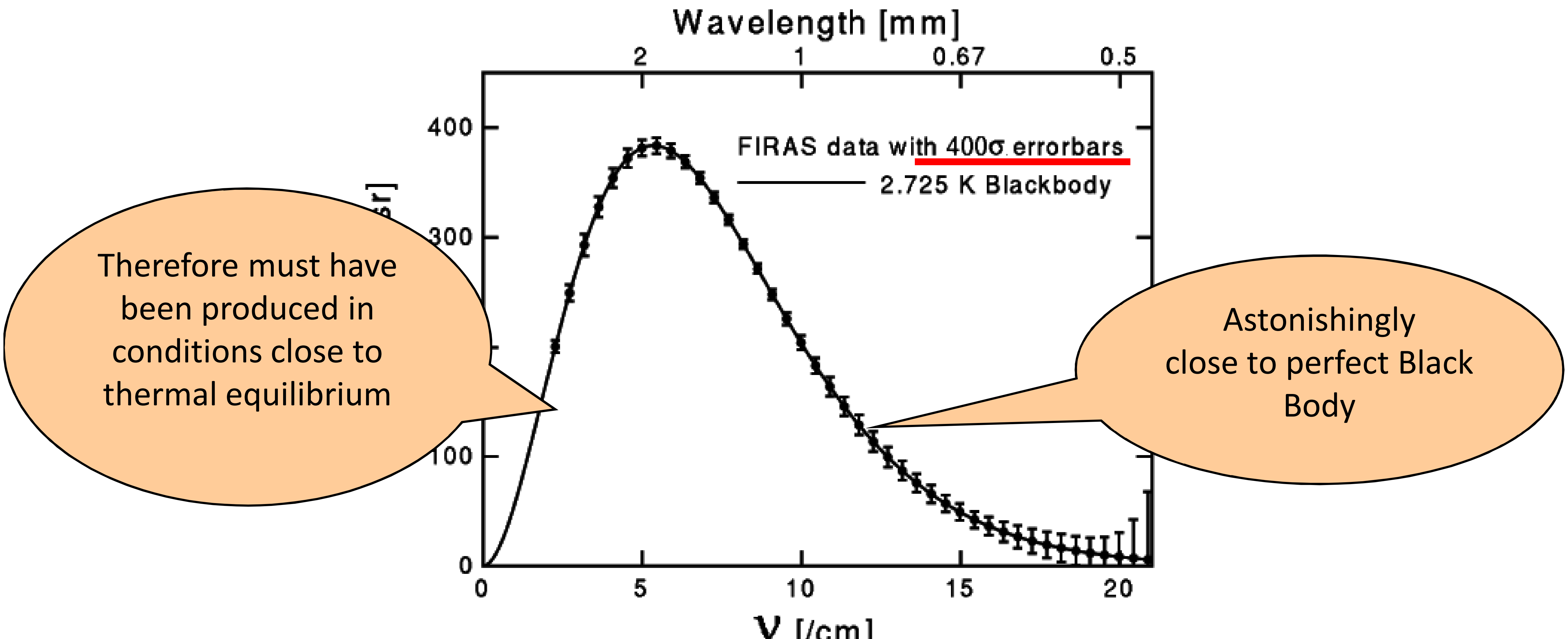
The total energy radiated per unit area per unit time is $5.7 \times 10^{-8}\ T^4$ Watts (Stefan's Law)



Black body curves for a range of terrestrial temperatures. The units in this diagram are the number of wavelengths per cm; thus 500 cm^{-1} corresponds to a wavelength of 2×10^{-5} m, in the infra-red region of the spectrum. The mm-wave regime corresponds to a few cm^{-1} i.e. well below the peak to the left; mm-wave receivers are, however, sensitive enough to detect this radiation – and hence can be used for many terrestrial applications.

http://www.thermal-survey.co.uk/thermal_images/planckcv.jpg

The CMB spectrum – taken from the COBE spacecraft in early 1990s



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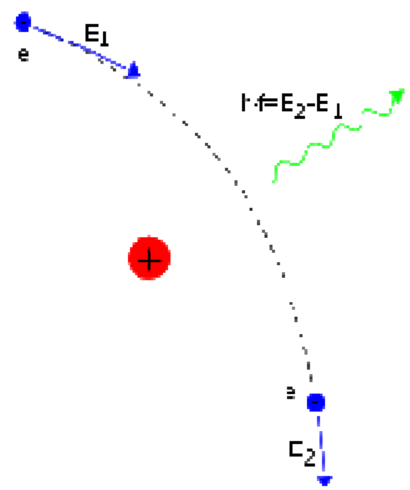
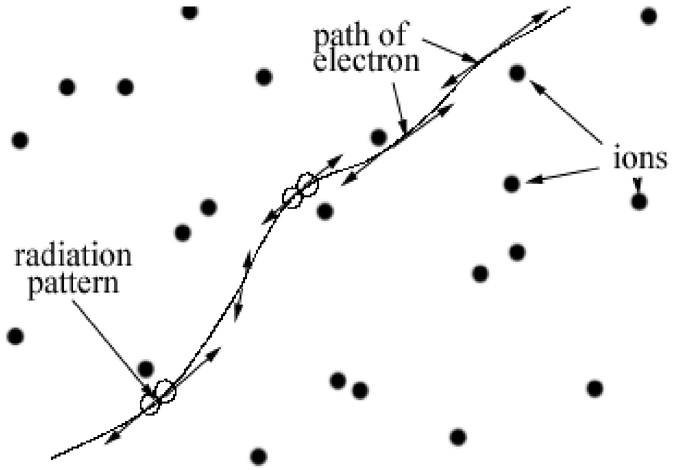
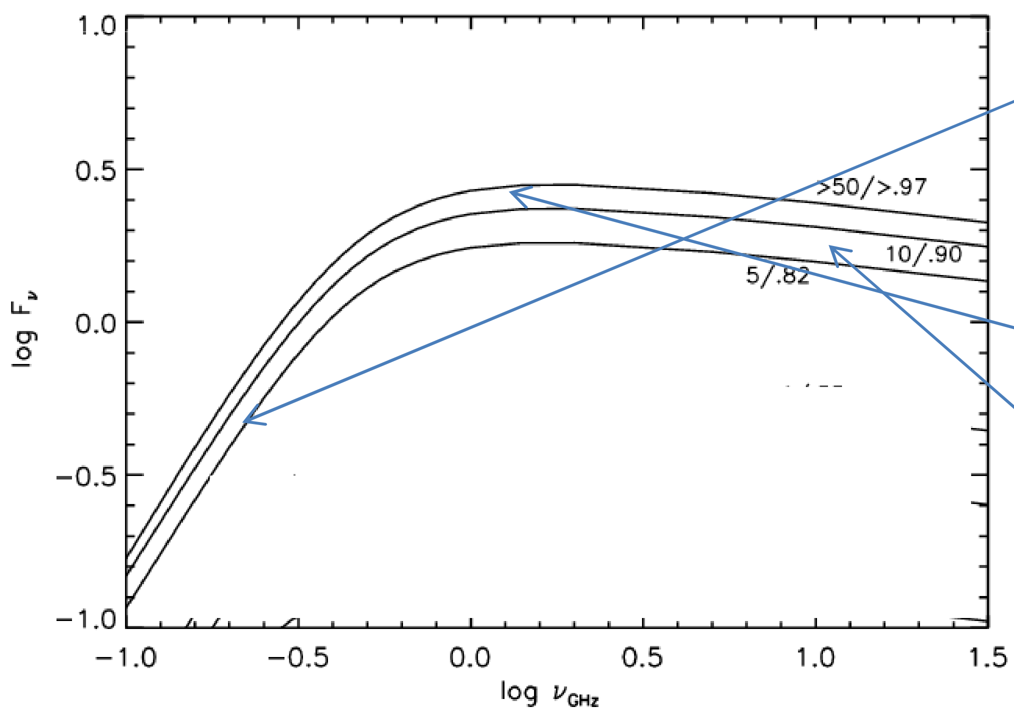
The Cosmic Microwave Background Radiation (T = 2.75 K) from the Big Bang has an almost perfect black body spectrum. All other objects emit less than that of a black body by a factor ε, the dimensionless emissivity - a function of emitted wavelength. The spectrum from real objects (“grey bodies”) does not follow the smooth curves given by the Planck Formula.

Bremsstrahlung or free-free emission





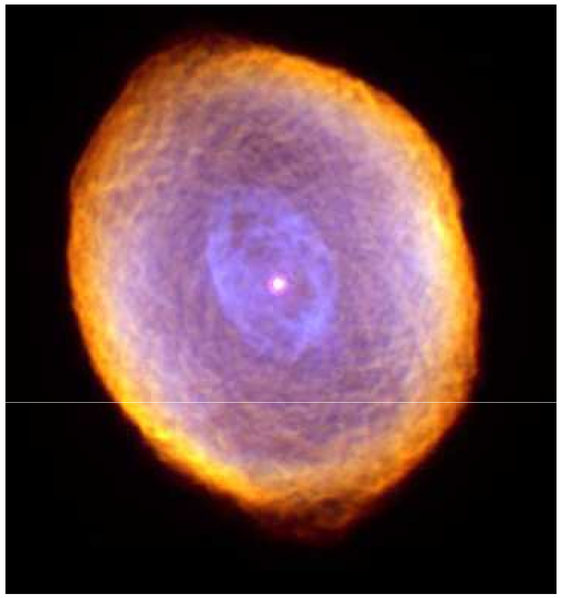
An electron moving through relatively immobile ions experiences many small accelerations, each one producing a radiation pattern along its direction of motion (perpendicular to its acceleration).



Representative radio spectra of free-free emitting plasmas. At low frequencies the plasma becomes opaque to its own emission and acts like a black body – the spectral slope is ~2 (see later for more details).

At some frequency the optical depth τ ~1 – and the cloud is partially transparent

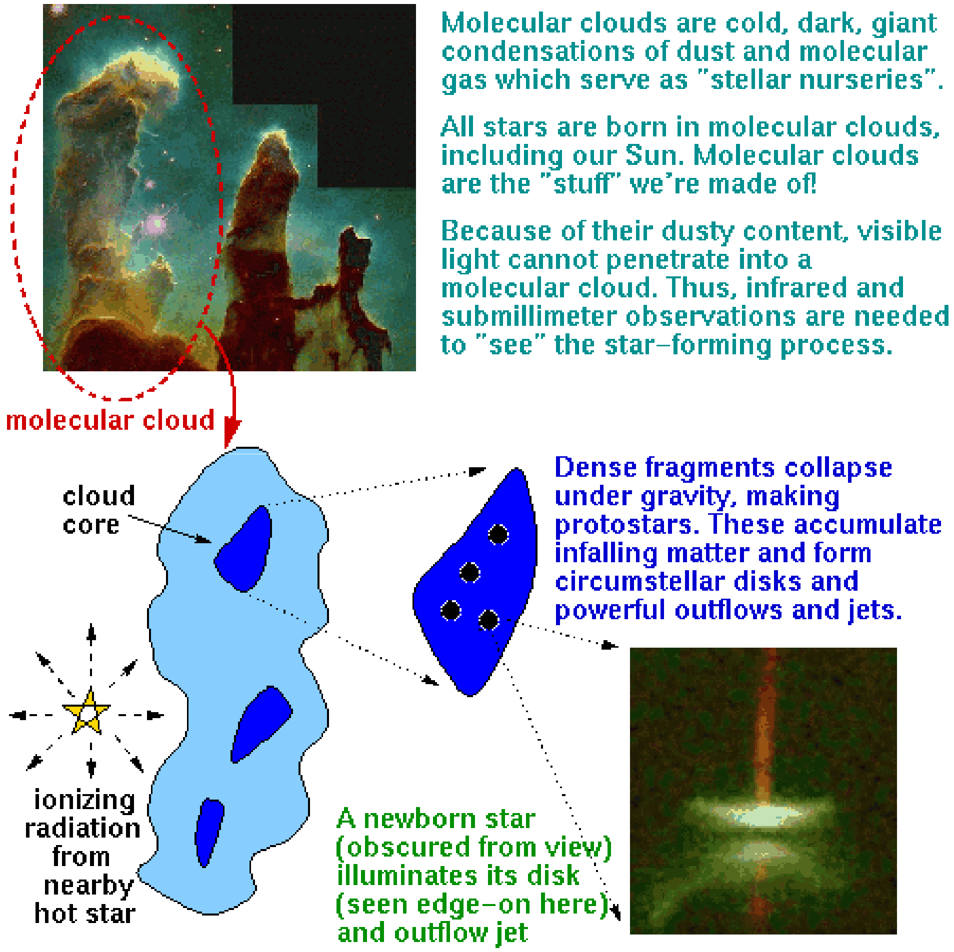
At much higher frequencies the cloud is transparent to its own emission the spectral slope becomes ~ 0.1. The brightness at low frequencies depends only on the electron temperature.



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

"Planetary nebulae" – hot (up to 15,000K) ionised plasma shells surrounding stars in the late stages of their evolution - are sources of free-free radio emission.

Spectral line radiation



Quantized *rotational transitions* from molecules with *dipole moments* give rise to spectral lines in the radio band

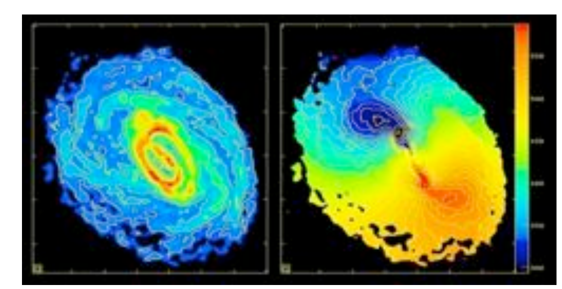
Nearly 150 molecular species have now been identified including the simplest amino acid glycine

Their study has become new subject

ASTROCHEMISTRY

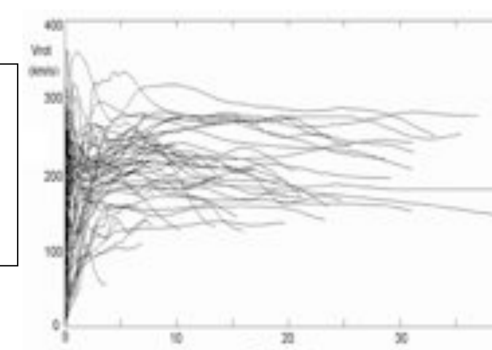
Significance of HI today...

The scale & structure of the Milky Way... free of dust obscuration



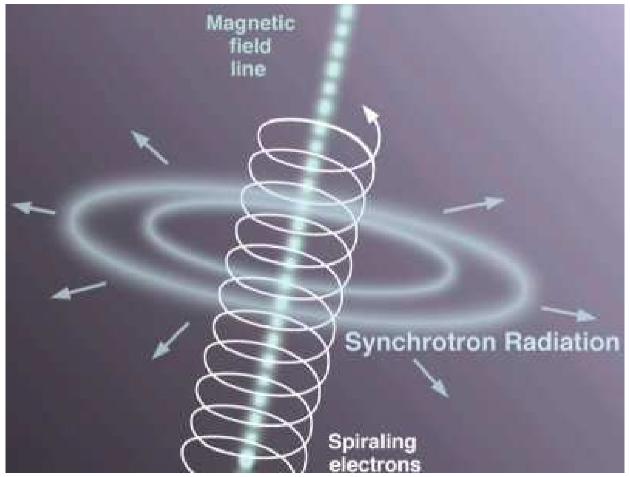
The scale, and *dynamics* of external galaxies

Tracing dark matter in galaxies well beyonf the optical extent of a galaxy

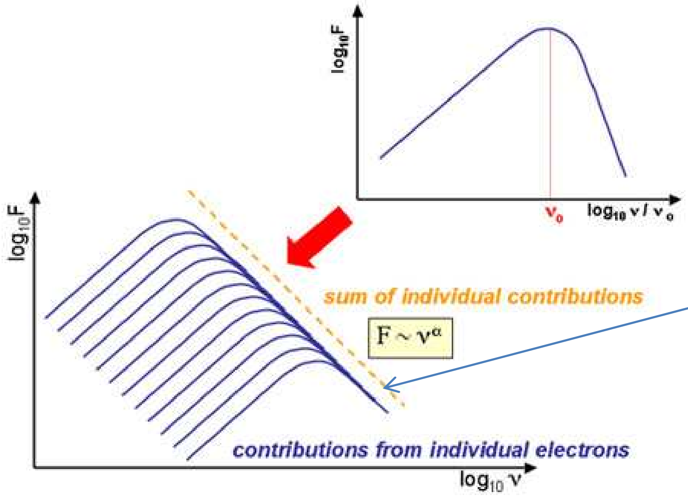


Non-thermal synchrotron radiation

http://astronomyonline.org/Stars/Images/ChrisFlynn/SynchrotronRadiation.jpg



Relativistic electrons *spiral* around magnetic field lines

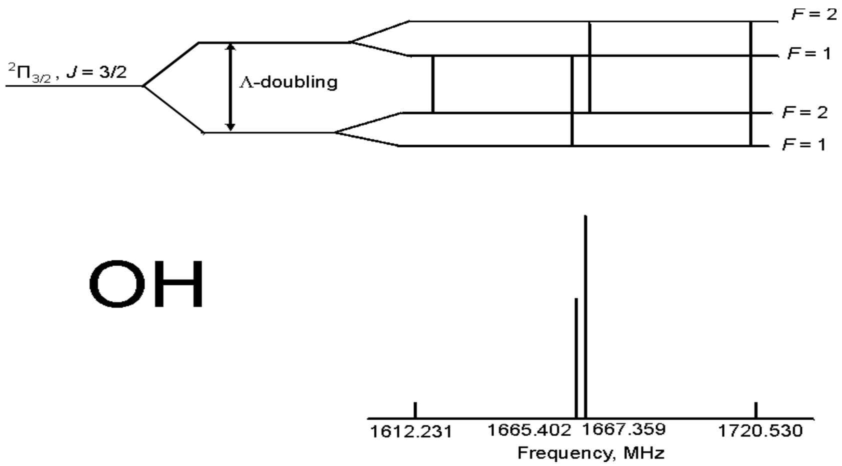


Electrons with different energies spiral with different radii and hence radiate at a different characteristic frequencies

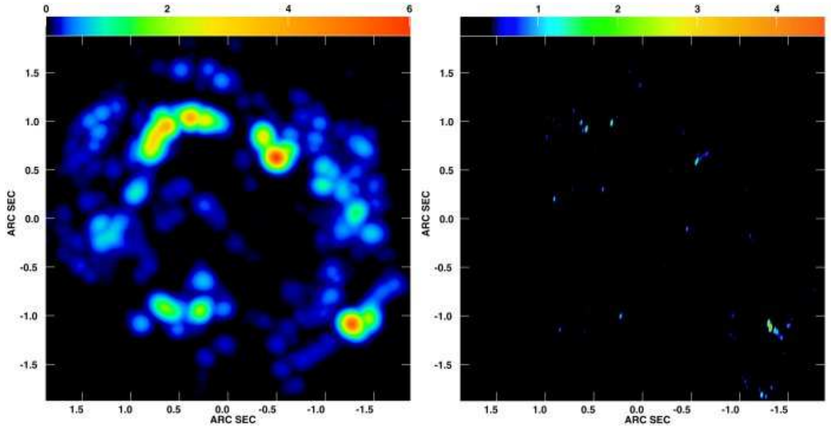
The final spectrum is a sum of all the individual contributions - typically it produces a power law spectrum

and the radiation is linearly polarised

Maser emission



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

“Cold” Radio Sources

- Temperatures of a few K to tens of K in deep space
- Energies kT ~ 1 milli eV

much lower than electronic energy levels -> correspond to vibrations and rotations of molecules

- The black-body (thermal) spectrum of matter at temperature T (K) peaks at a wavelength

$\lambda_{max}=2.9x10^{-3}/T$ metrw -> in mm range

Cosmic Microwave Background / Atomic hydrogen / Molecular clouds and molecular lines

“Warm” Radio Sources

Bremsstrahung or free-free emission – also thermally induced Temperatures 5,000 – 15,000 K

for astrophysical plasmas in higher-energy environments, free particles can dominate the radio emission mechanisms.

stellar photospheres / tenuous atmospheres around stars (stellar winds) / planetary nebulae / gaseous nebulae ionised by hot stars

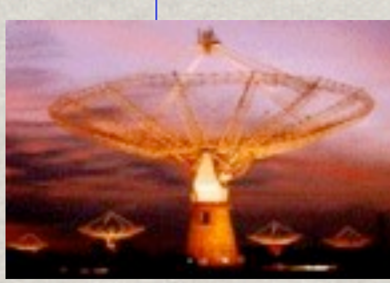
“Hot” Radio Sources

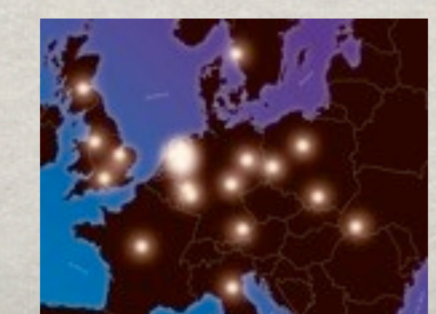
- Non-thermal radiation e.g. synchrotron radiation
- Typically more intense at lower frequencies
- “Effective” temperatures can be enormously higher e.g. 10^8- 10^{12} K
- Not subject to the laws of thermal radiation - comes instead from relativistic electrons associated with extreme environments

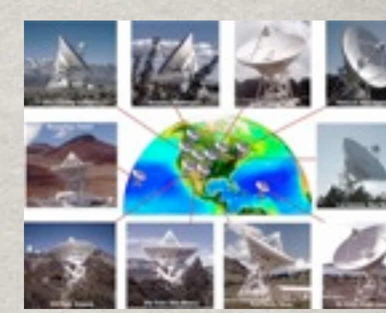
Supernovae / Pulsars / Gamma-ray bursters / Black holes and Active Galactic Nuclei (quasars)

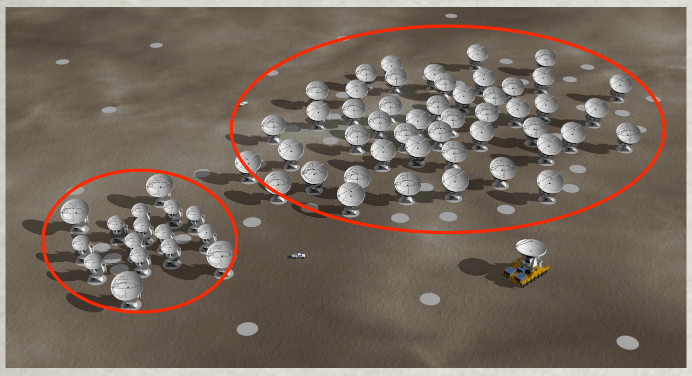
Many new/improved radio facilities coming online.

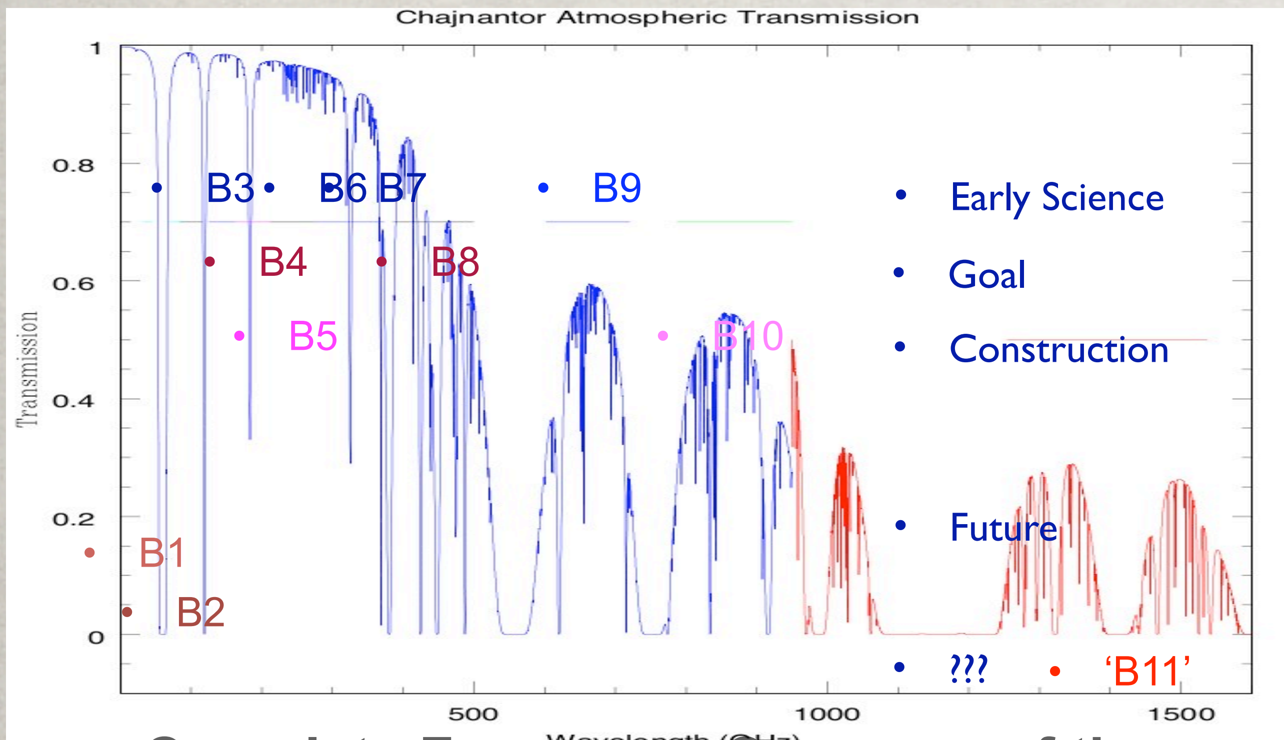
- SKA is ultimate goal, though long-term program
- Precursors and many pathfinders in existence or under construction
- ASKAP and MeerKAT being built on proposed sites
- ➢ Data challenges before SKA comes on-line
- ➢ Scalability could be an issue











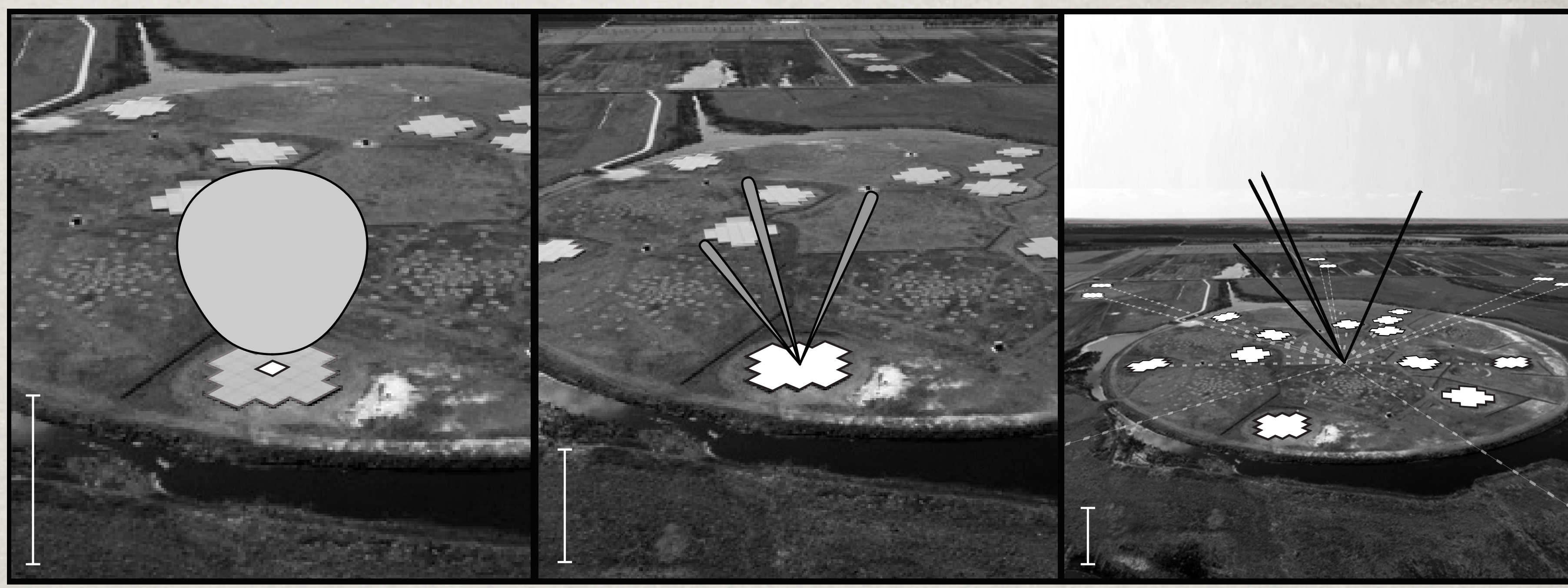
	ALMA ES	ALMA full
Antennas	16	66
Freq range	100, 230, 345, 650	+ 150, 450, 800
collecting area	> 1350	6500
max resolution	0.15″	0.01″
Tsys (freq)	30 K, 70 K, 430 K (100) (230) (650)	

Start of CSV - beginning of 2010
Call for Early Science - spring/first half of 2011
Start of Early Science - fall/second half of 2011
Inauguration - late 2012
End of construction - 2013

Joint US, EU and Japanese project located on high plateau in Chile

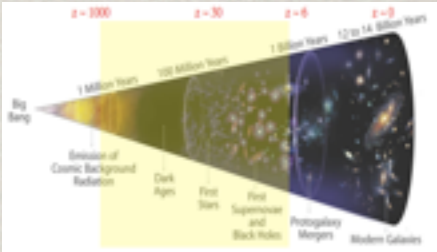
LOFAR: LOw Frequency ARray

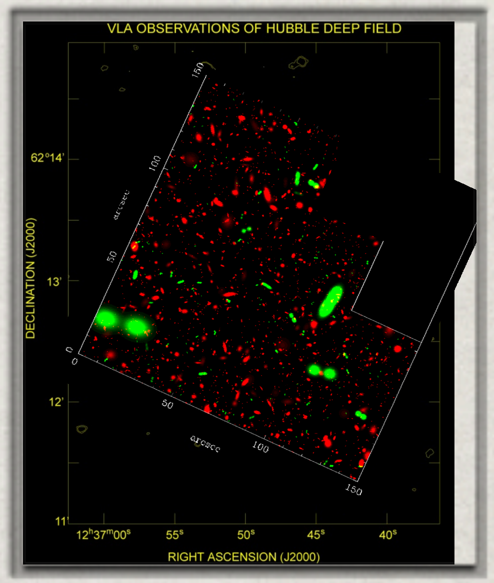
- Distributed in NL & EU
- 30 - 240 MHz
- LBA & HBA
- > 30000 dipoles
- 20 Core/18 NL/>10 EU
- 2.5km/100km/1000km



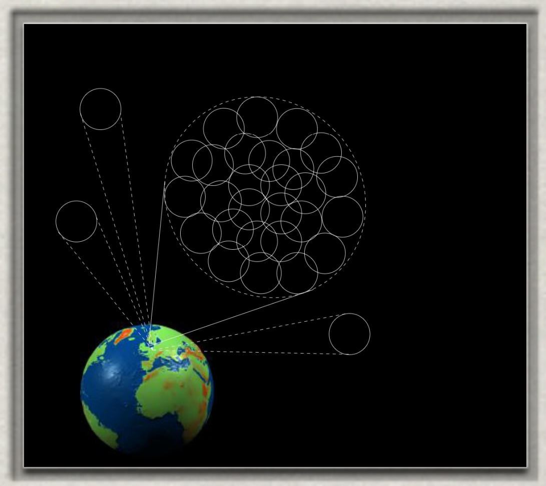
LOFAR Key Science Programs

- Epoch of Reionisation - de Bruyn

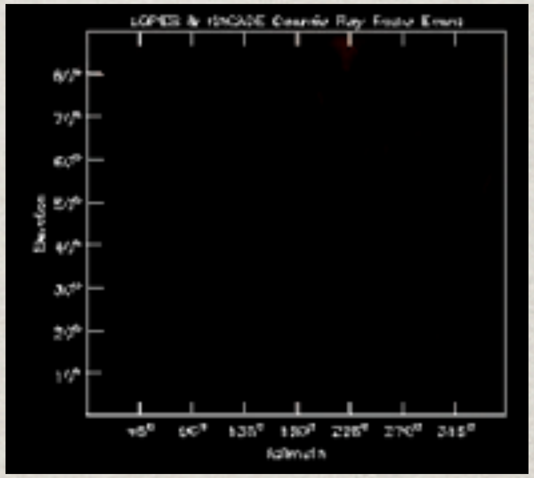




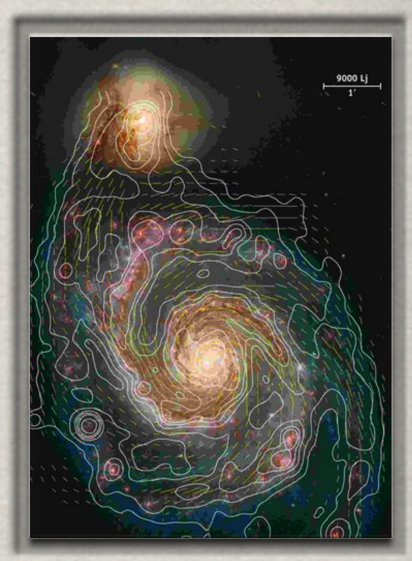
- Galaxy Surveys - Rottgering



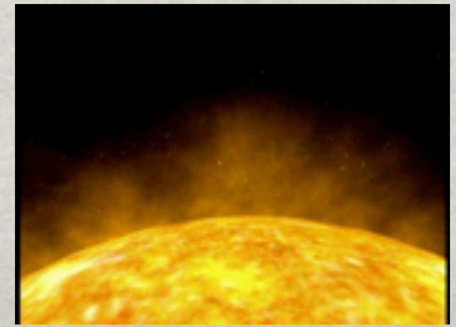
- Transients/Pulsars - Fender/Stappers/Wijers



- Astroparticle Physics - Falcke



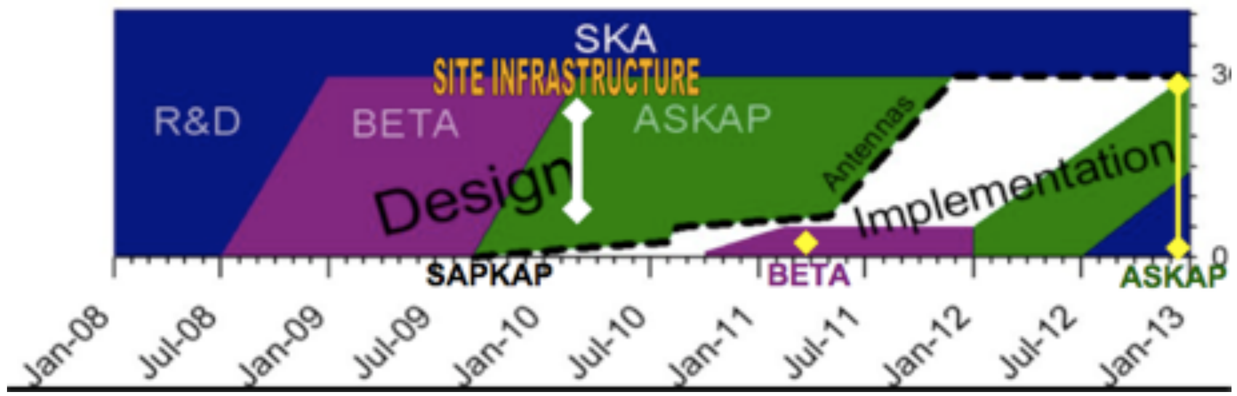
- Cosmic Magnetism - Beck



- Solar & solar-terrestrial physics - Mann

ASKAP

- Number of dishes 36 (3-axis)
- Dish diameter 12 m
- Max baseline 6km - Resolution 30″
- Sensitivity 65 m^2/K
- Speed 1.3×10^5 $m^4/K^2.deg^2$
- Observing frequency 700 – 1800 MHz
- Field of View 30 deg^2
- Processed Bandwidth 300 MHz
- Focal Plane Phased Array 188 elements



Evolutionary Map of the Universe (EMU)
Principal Investigator: Ray Norris (CSIRO)

Widefield ASKAP L-Band Legacy All-Sky Blind Survey (WALLABY)
Principal Investigators: Baerbel Koribalski (CSIRO) and Lister Staveley-Smith (ICRAR/University of Western Australia)

The First Large Absorption Survey in HI (FLASH)
Principal Investigator: Elaine Sadler (University of Sydney)

An ASKAP Survey for Variables and Slow Transients (VAST)
Principal Investigators: Tara Murphy (University of Sydney) and Shami Chatterjee (Cornell University)
The Galactic ASKAP Spectral Line Survey (GASKAP)

Polarization Sky Survey of the Universe's Magnetism (POSSUM)
Principal Investigators: Bryan Gaensler (University of Sydney), RussTaylor (University of Calgary) and Tom Landecker (Dominion Radio Astrophysical Observatory)

The Commensal Real-time ASKAP Fast Transients survey (CRAFT)
Principal Investigator: Peter Hall (ICRAR/Curtin University of Technology)

Deep Investigations of Neutral Gas Origins (DINGO)
Principal Investigator: Martin Meyer (ICRAR/University of Western Australia)

The High Resolution Components of ASKAP: Meeting the Long Baseline Specifications for the SKA (VLBI)
Principal Investigator: Steven Tingay (ICRAR/Curtin University of Technology)

Compact Objects with ASKAP: Surveys and Timing (COAST)
Principal Investigator: Ingrid Stairs (University of British Columbia)

de Boer/SKA 2010

MeerKAT

	KAT-7 2010	Phase 1 2013	Phase 2 2014	Phase 3 2015	Phase 4 2016
Number of dishes	7	80	80	87	87
Low freq. range (GHz)	1.2–1.95	0.9–1.75	0.9–1.75	0.9–1.75	0.58–2.5
High freq. range (GHz)	—	—	8–14.5	8–14.5	8–14.5
Maximum processed bandwidth (GHz)	0.256	0.850	2	2	4
Min. baseline (m)	20	20	20	20	20
Max. baseline (km)	0.2	8	8	60	60

12 m dishes and wide band single pixel feeds

Testing Einstein's theory of gravity and gravitational radiation - Investigating the physics of enigmatic neutron stars through observations of pulsars.
Professor Matthew Bailes, Swinburne Centre for Astrophysics and Supercomputing, Australia

LADUMA (Looking at the Distant Universe with the MeerKAT Array) - An ultra-deep survey of neutral hydrogen gas in the early universe.
Dr Sarah Blyth, University of Cape Town in South Africa; Dr Benne Holwerda, ESA, The Netherlands; Dr Andrew Baker, Rutgers University, United States

MESMER (MeerKAT Search for Molecules in the Epoch of Re-ionisation) - Searching for CO at high red-shift (z>7) to investigate the role of molecular hydrogen in the early universe. - Dr Ian Heywood, Oxford University, UK

MeerKAT Absorption Line Survey for atomic hydrogen and OH lines in absorption against distant continuum sources (OH line ratios may give clues about changes in the fundamental constants in the early universe). - Dr Neeraj Gupta, ASTRON, The Netherlands; Dr Raghunathan Srianand, IUCA, India

MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters) - Investigations of different types of galaxies; dark matter and the cosmic web. - Professor Erwin de Blok, University of Cape Town, South Africa

TRAPUM (Transients and Pulsars with MeerKAT) - Searching for, and investigating new and exotic pulsars.- Dr Benjamin Stappers, JBCA, UK; Professor Michael Kramer, Max Planck Institute for Radio Astronomy, Germany

A MeerKAT HI Survey of the Fornax Cluster (Galaxy formation and evolution in the cluster environment). - Dr Paolo Serra, ASTRON, The Netherlands

MeerGAL (MeerKAT High Frequency Galactic Plane Survey) - Galactic structure and dynamics, distribution of ionised gas, recombination lines, interstellar molecular gas and masers. - Dr Mark Thompson, University of Hertfordshire, UK; Dr Sharmilla Goedhart, South African SKA Project

MIGHTEE (MeerKAT International GigaHertz Tiered Extragalactic Exploration Survey) - Deep continuum observations of the earliest radio galaxies
Dr Kurt van der Heyden, University of Cape Town; & Matt Jarvis, University of the Western Cape, South Africa and the University of Hertfordshire, UK

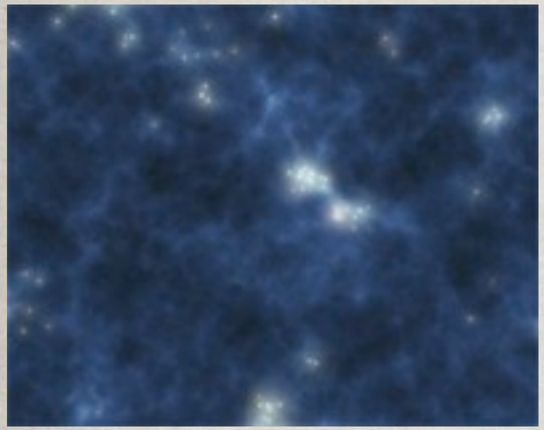
ThunderKAT (The Hunt for Dynamic and Explosive Radio Transients with MeerKAT) - eg gamma ray bursts, novae and supernovae, plus new types of transient radio sources. Professor Patrick Woudt, University of Cape Town, South Africa; & Professor Rob Fender, University of Southampton, UK

Jonas SKA2010

SKA Key Science: 21st Century Astrophysics

20th Century: We discovered our place in the Universe.

21st Century: We understand the Universe we inhabit.

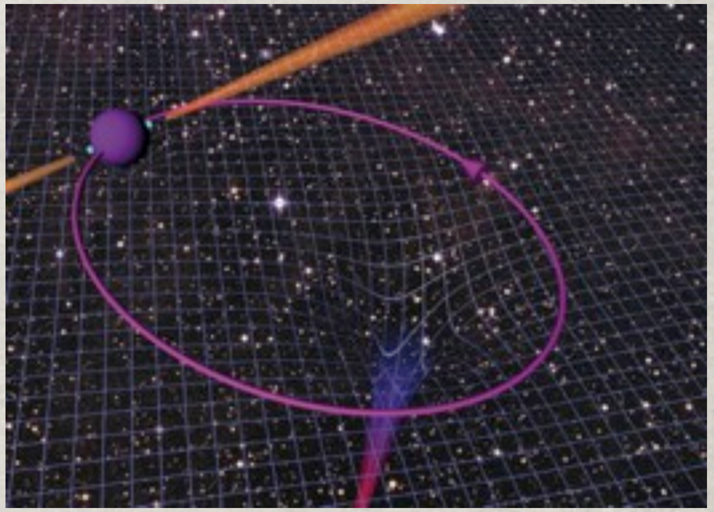


Dark ages

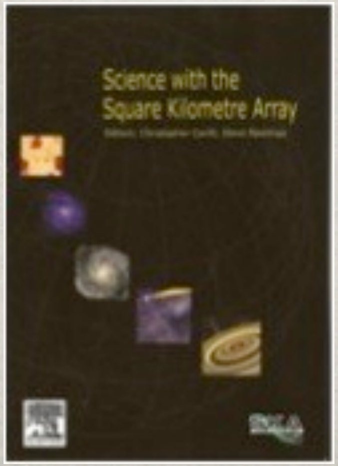
Cosmic Evolution

Cosmic Magnetism

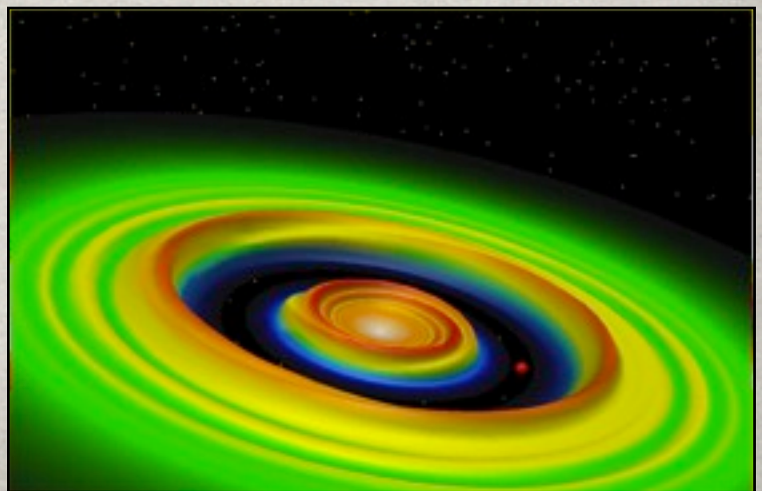
Gravitational Physics



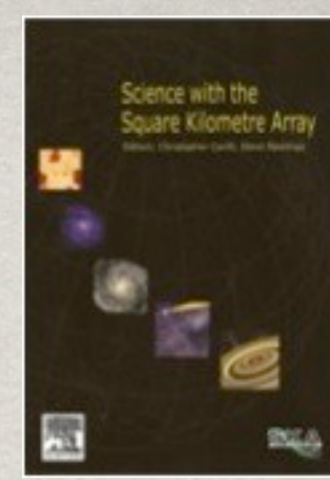
Five internationally selected Key Science Projects and lots of other good sciene: Carilli & Rawlings (eds), 2004:



Origins of Life



SKA Key Science: 21st Century Astrophysics



20th Century: We discovered our place in the Universe.

21st Century: We understand the Universe we inhabit.

Cosmology & Fundamental Physics

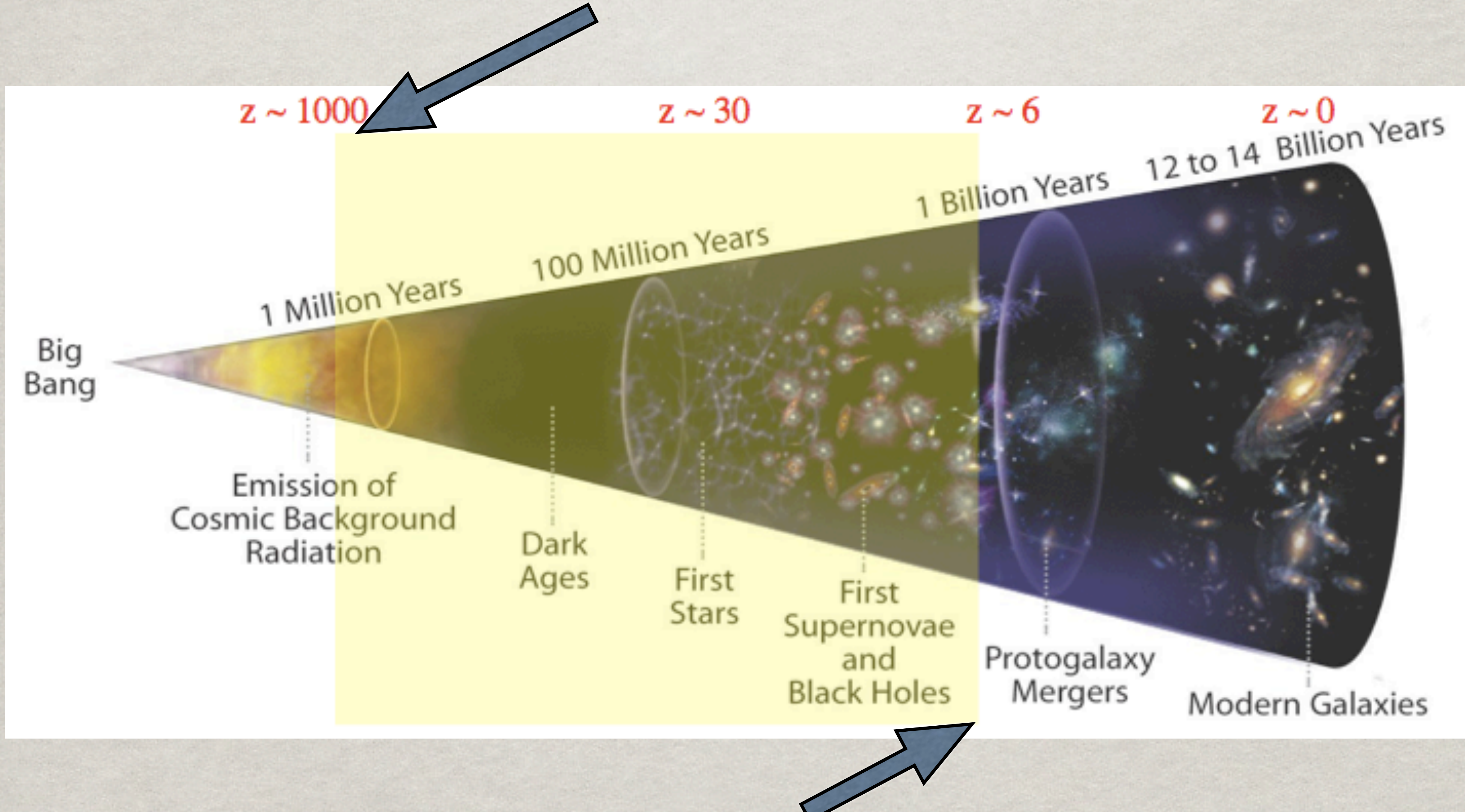
- Gravity
  - Is GR our last word in understanding gravity?
  - Can we observe strong gravity in action?
  - What are the properties of black holes and gravitational waves?
  - What is dark matter and dark energy?

Galaxies Across Cosmic Time, The Galactic Neighborhood, Stellar and Planetary Formation

- Galaxies and the Universe
  - How did the Universe emerge from its Dark Ages?
  - How did the structure of the cosmic web evolve?
  - Where are most of the metals throughout cosmic time?
  - How were galaxies assembled?
- Stars, Planets, and Life
  - How do planetary systems form and evolve?
  - What is the life-cycle of the interstellar medium and stars? (biomolecules)
  - Is there evidence for life on exoplanets? (SETI)

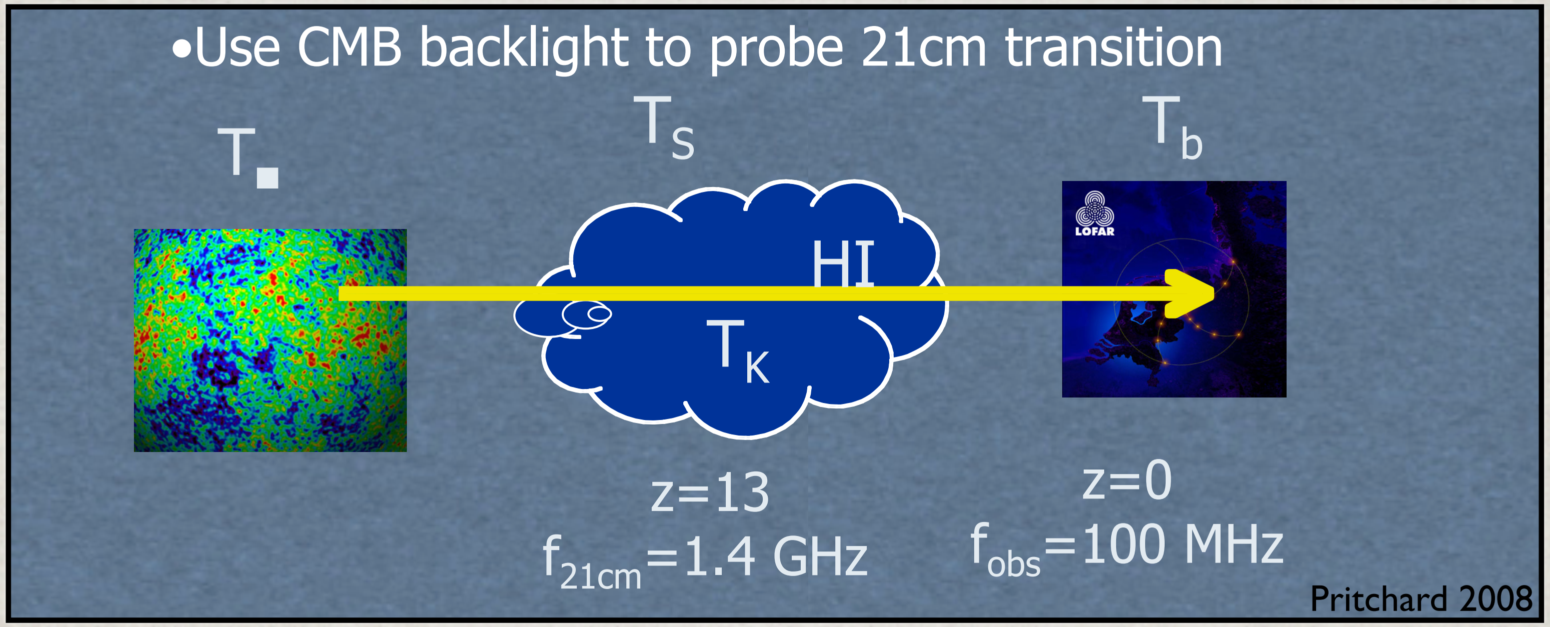
Epoch of Reionisation

EPOCH OF RECOMBINATION: Protons and electrons could form HI (neutral hydrogen)
- Marked the start of the "dark ages" as universe became opaque.



EPOCH OF REIONISATION: Once objects started to form and radiate they "reionise" the HI
- Marked the time when the universe became largely transparent again.

Redshifted HI



Brightness Temperature of 21cm

$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2} \text{mK}$$

Spin Temperature of 21cm

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

T_γ - CMB photons T_α - Collisional T_K - Kinetic gas temperature

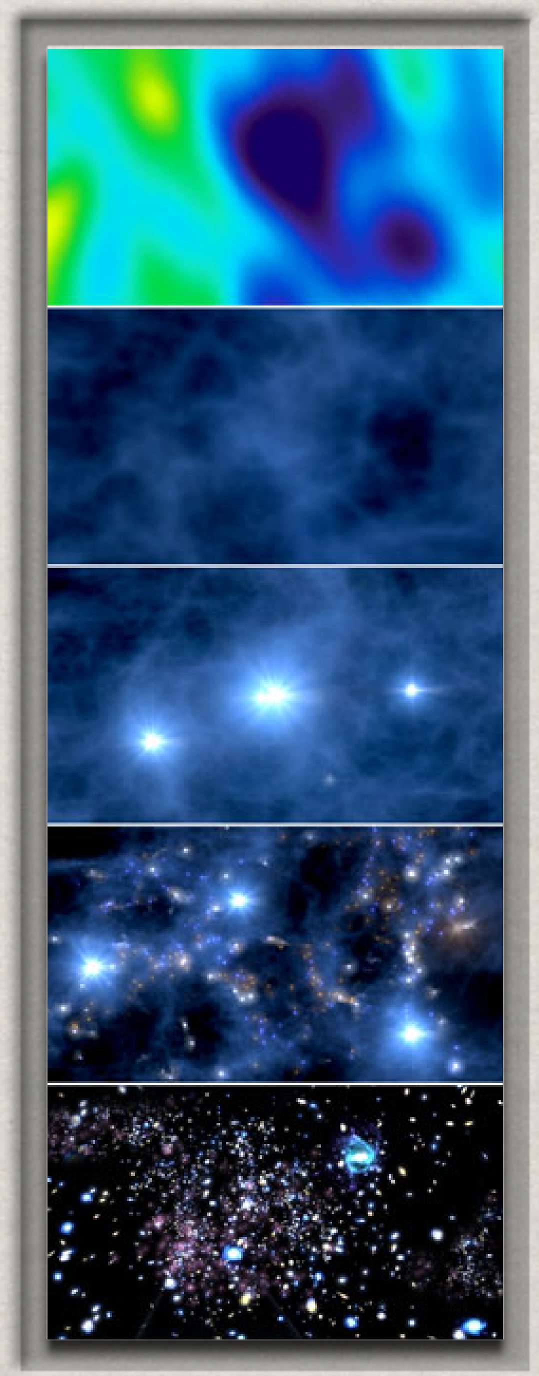
$T_\gamma = T_s$ - No signal $T_\gamma > T_s$ - Absorption $T_s > T_\gamma$ - emission

We measure the differential brightness distribution

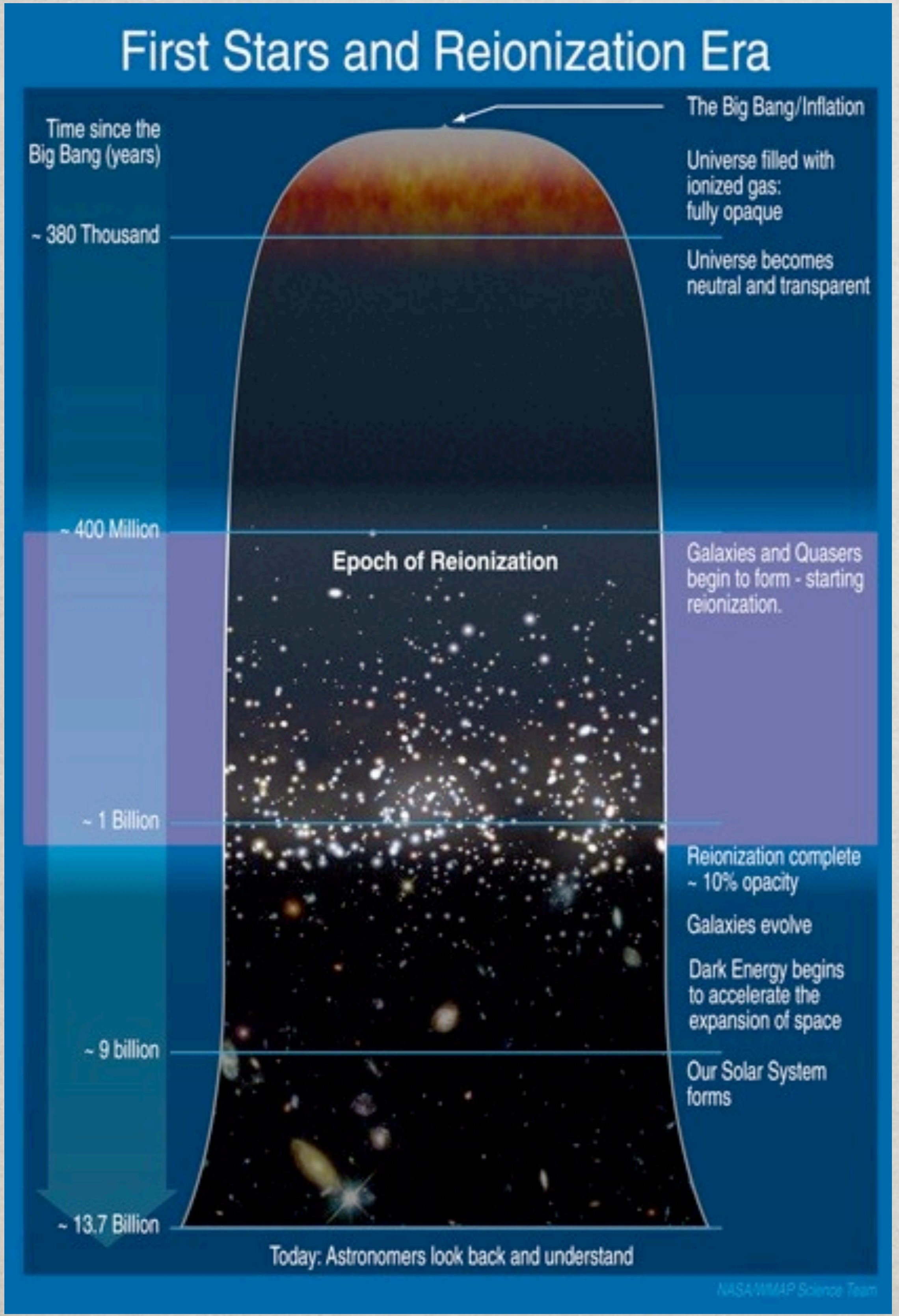
$$\delta T_b \sim 28\text{mK}(1+\delta)x_{\rm HI}\frac{T_s - T_\gamma}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{1/2}$$

Epoch of Reionisation

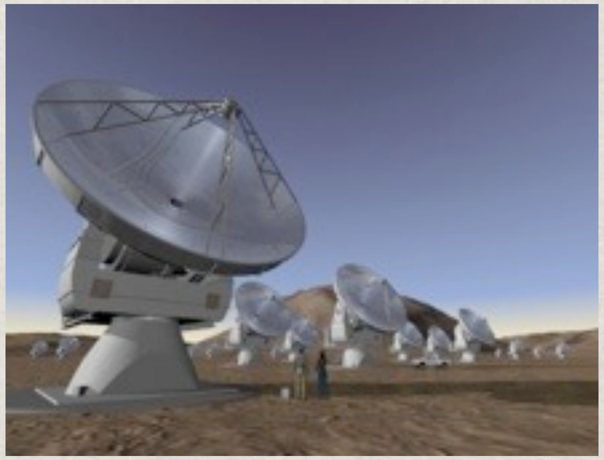
- Determine Epoch/Era of Ionisation
  - 115 MHz/z=14
  - WMAP 5 z=10.8±1.4
- Measure power spectrum of fluctuations as a fn. of redshift
  - angular scales 1' - 1°
  - frequency scales 0.1 - 10 MHz



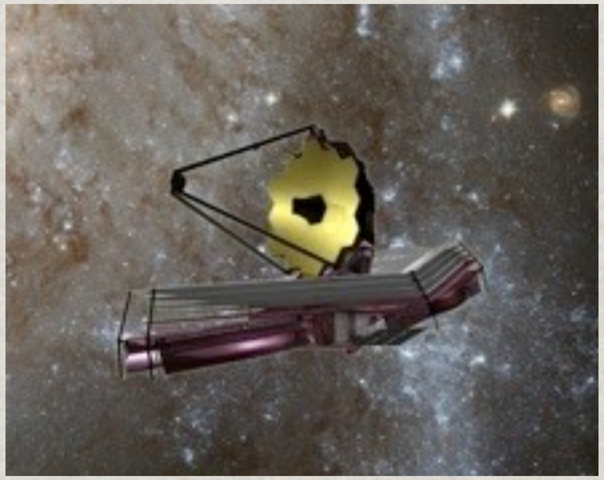
History of the Universe: Synergies



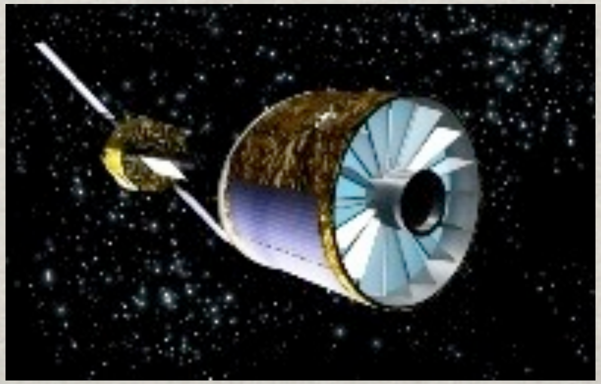
SKA: IGM and First Galaxies



ALMA: First Galaxies



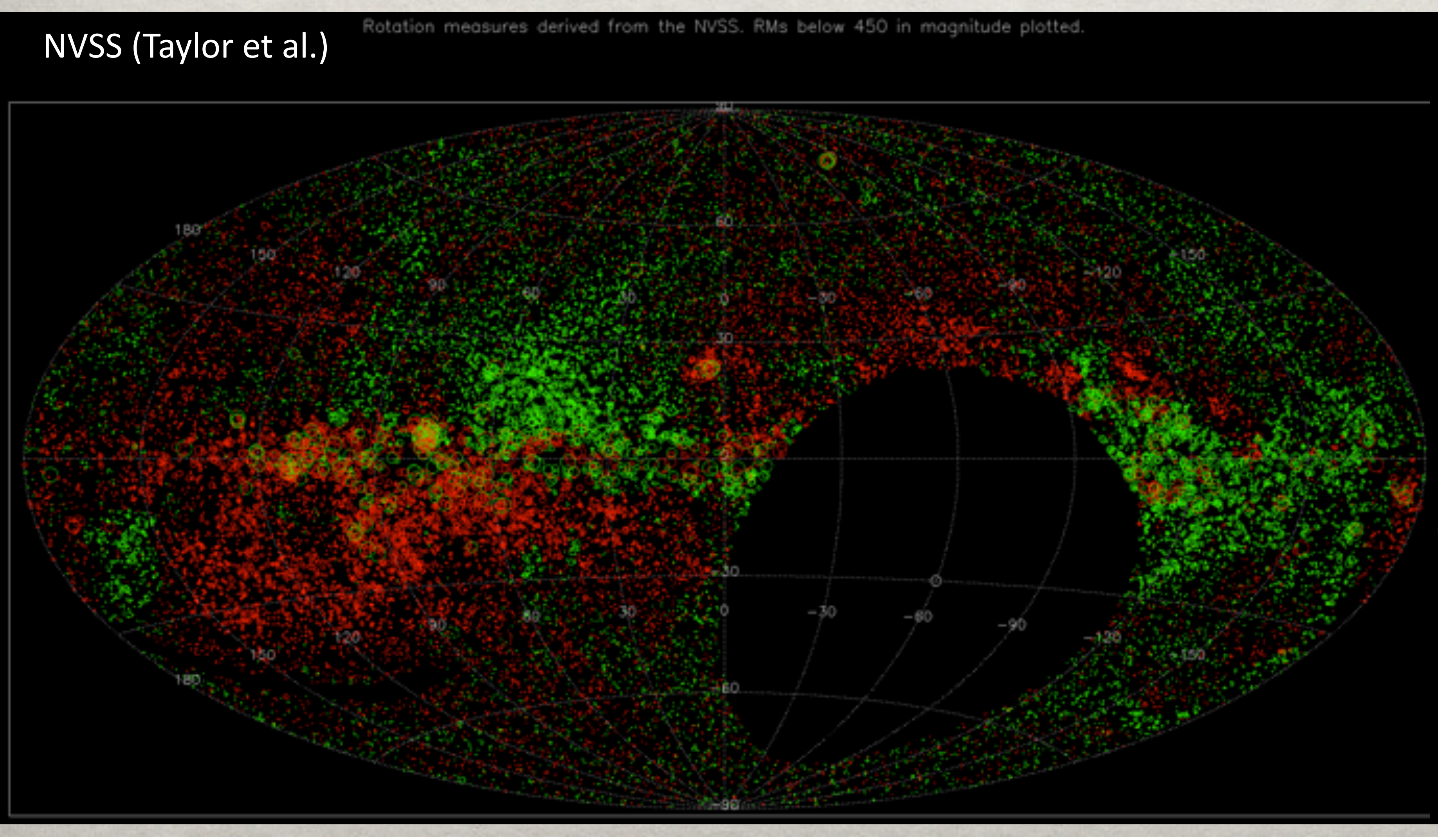
JWST: First Stars and Galaxies



X-rays: First Black Holes

Origin & Evolution of Cosmic Magnetism

- Magnetic fields are fundamental, but poorly constrained and their origin little understood
  - Affects galaxy, cluster evolution?
  - Affects propagation of cosmic rays in ISM and IGM
- All-sky rotation measure surveys provide **B** fields along lines of sight
- Continuum in I, Q, and U!



NVSS (Taylor et al.)


Effelsberg/VLA (Beck et al.)

Magnetic Fields: Cosmic

Are ultra-high energy cosmic rays (UHECRs) produced in nearby AGN?

- Galactic magnetic field influences cosmic ray propagation
- Different models of Galactic field imply different arrival directions

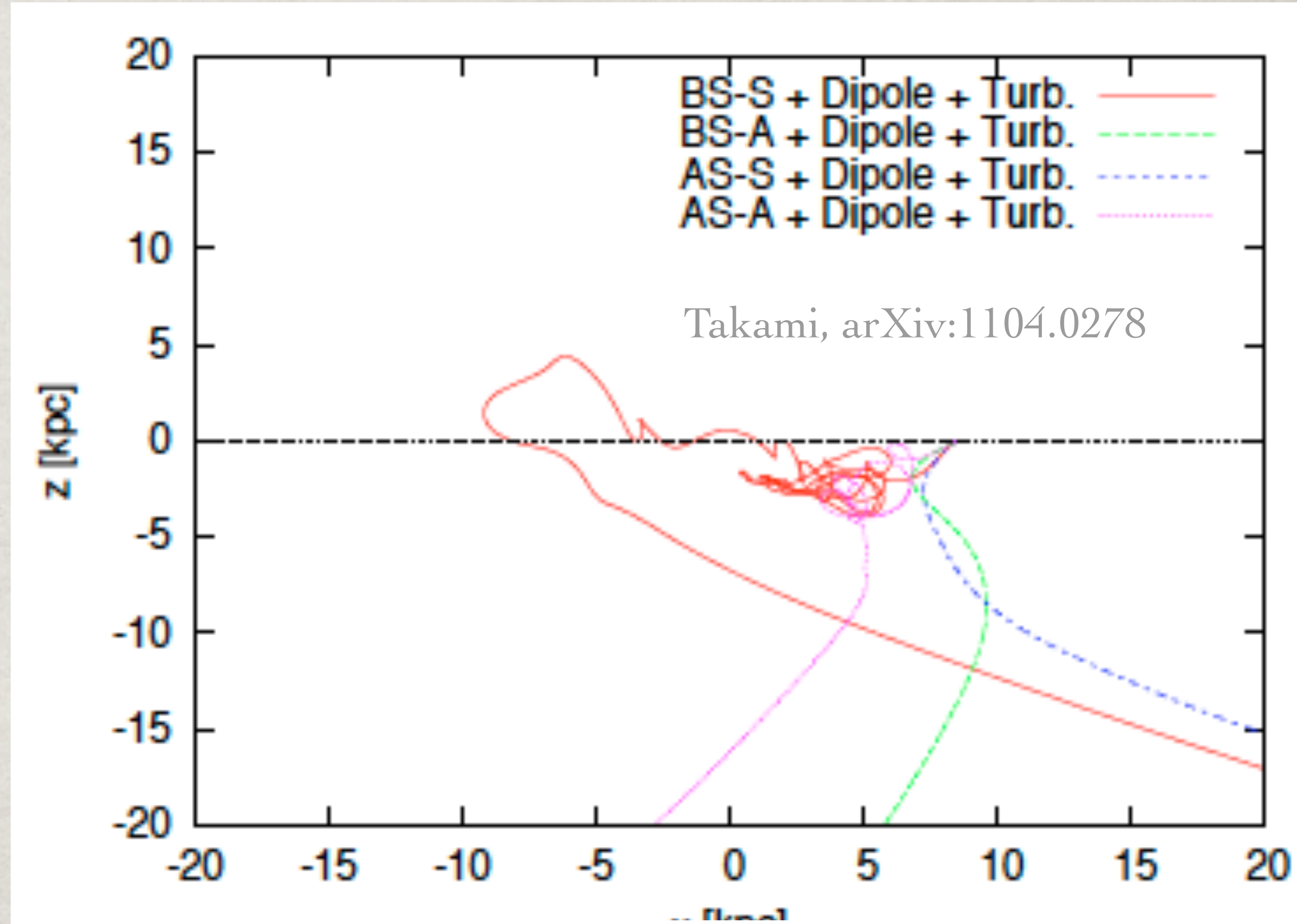
Rotation Measure (RM) measurements of millions of sources:

Axis-symmetric vs. bi-symmetric field directions above and below the Galactic plane? Effect of turbulence? …?

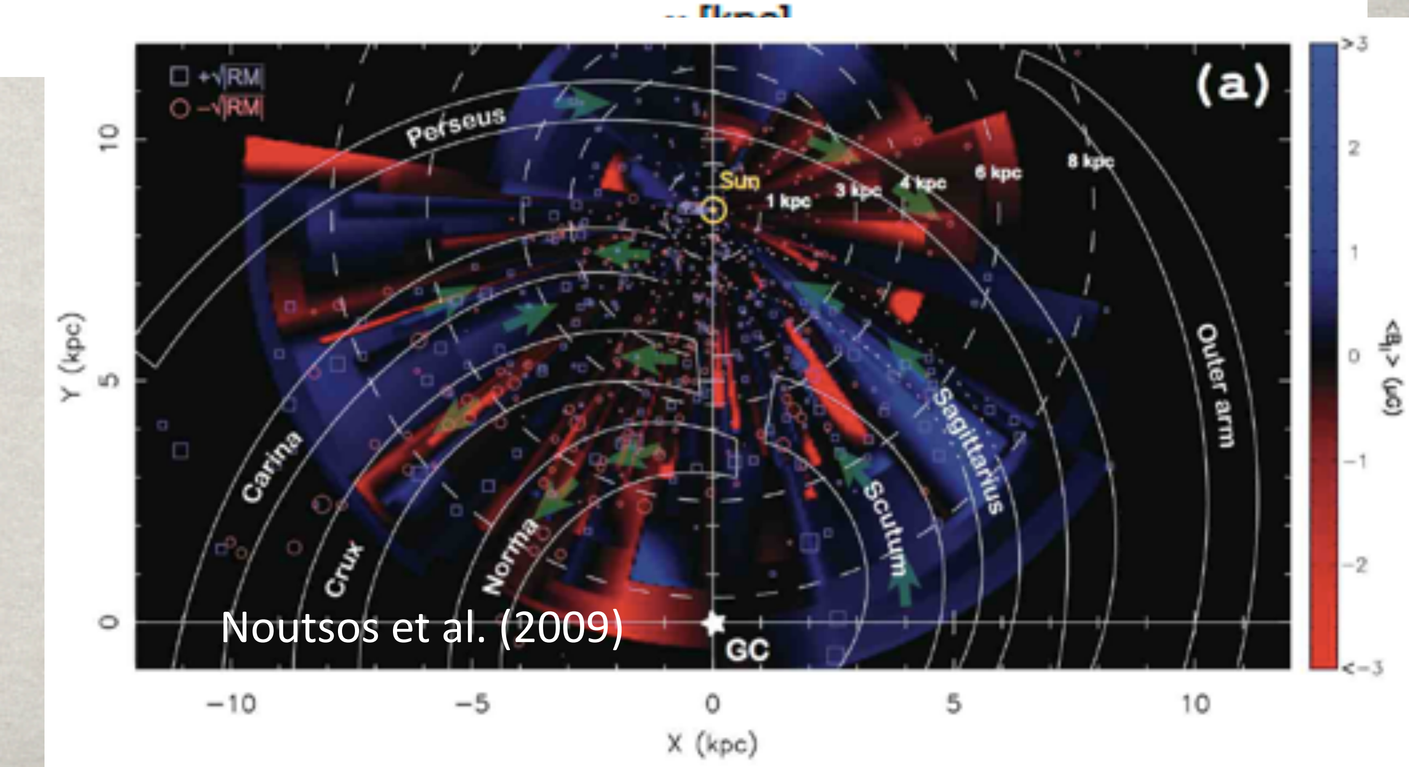
~500 RMs per sq. deg (one every 2’-3’)

Study B in IGM with 3D information (z from HI)

Essential if we are REALLY to understand physics of galaxy formation!



Takami, arXiv:1104.0278

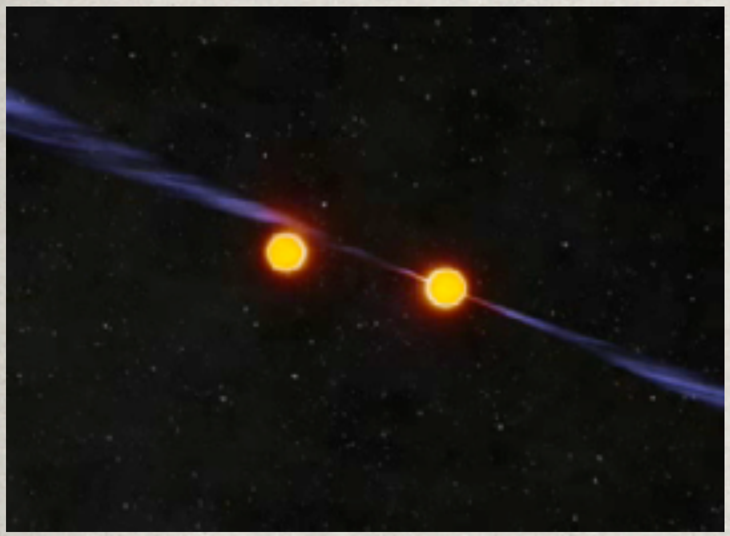


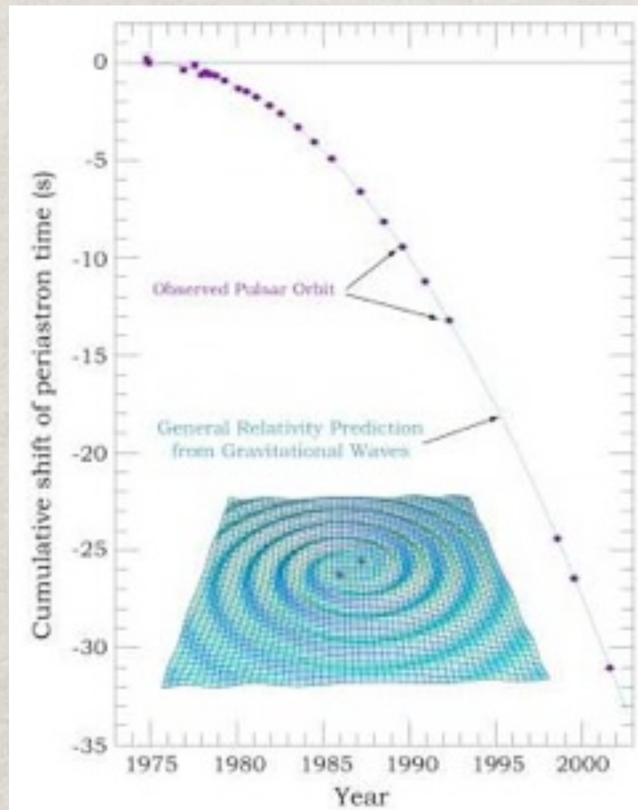
Noutsos et al. (2009)

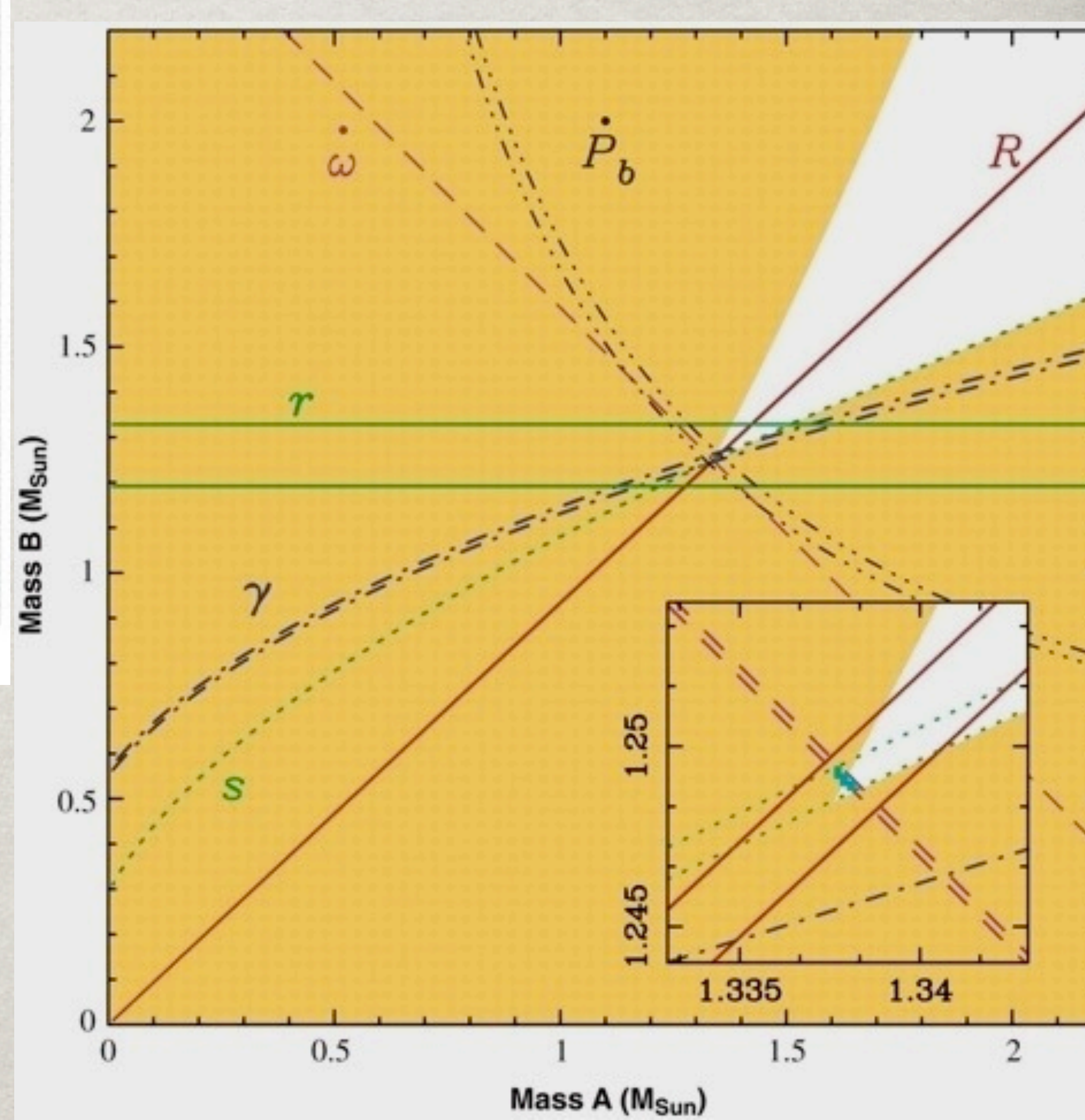
Did Einstein Have the Last Word on Gravity?

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$

PSR J0737–3039







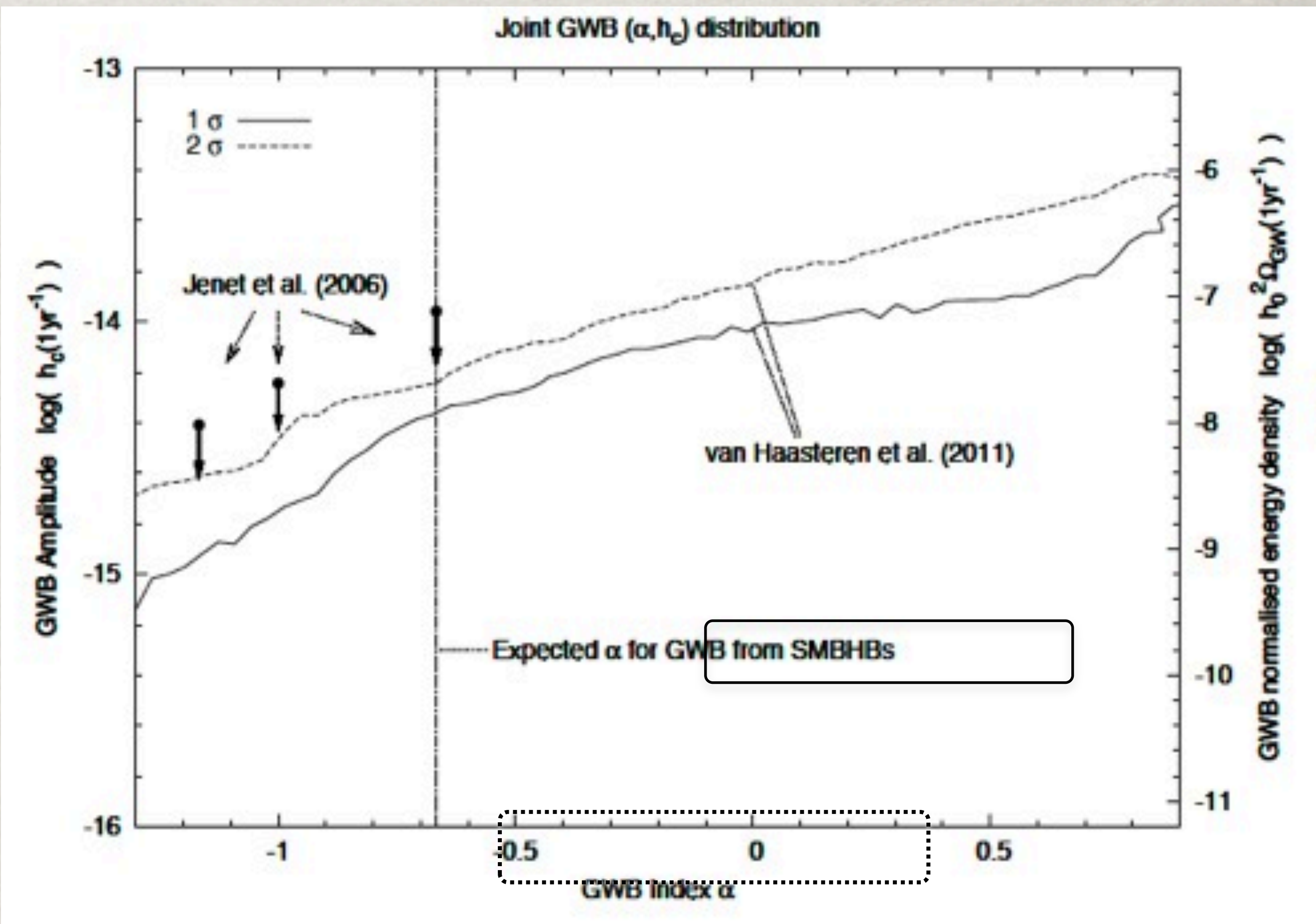
Kramer et al.

Relativistic binaries probe

- Equivalence principle
- Strong-field tests of gravity

- Neutron star-neutron star and neutron star-white dwarf binaries known

SKA: Gravitational Wave Detector



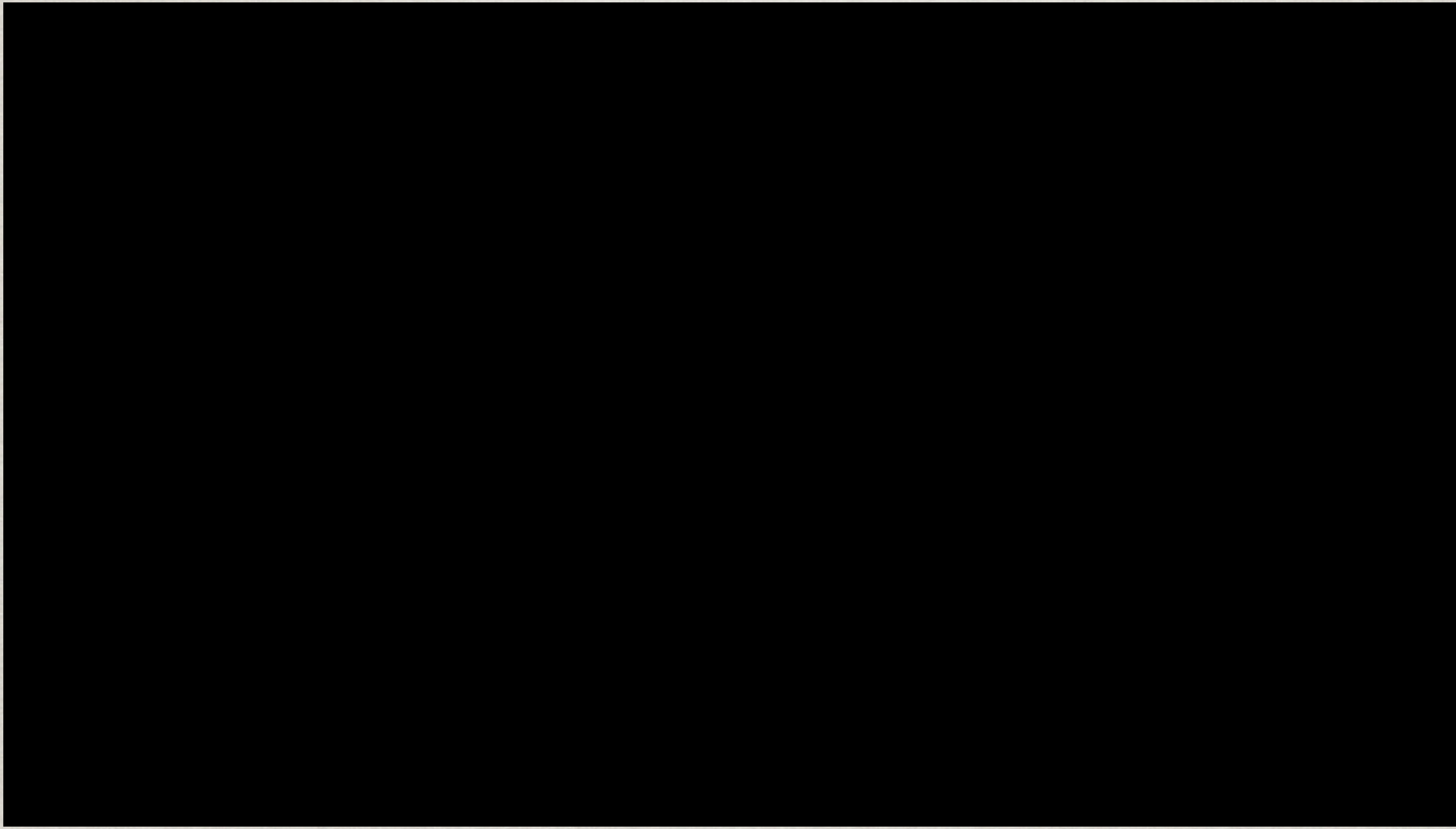
Test masses on lever arm

- Pulsar Timing Array = freely-falling millisecond pulsars
- LIGO = suspended mirrors
- LISA = freely-falling masses in spacecraft

Pulsar timing arrays starting to provide results from ensemble of pulsars

- EPTA (van Haastern et al., *above*)
- PPTA (Yardley et al.)
- *NANOGrav (Demorest et al.)*

The Telescope



Conclusions

- Radio Astronomy provides us with an excellent tool with which to study emission processes which are not possible at other wavelengths
- However the most gain is made by combining it with observations across the entire electromagnetic spectrum
- Hopefully in the near future also with non-photonic windows like gravitational waves and cosmic rays.
- Radio Astronomy is entering a new golden age
- New and improved facilities being developed all around the world
- ALMA online now/soon and the SKA on the horizon will provide high quality instruments for many years to come.