Time-Domain Astronomy

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Course Structure

All the population and its time, energy/luminosity/brightness range, coherent-incoherent emission

Pulsars, Millisecond Pulsars, Pulsar Search

Online quiz on topic covered so far (**5% evaluation**)

Pulsar Timing, Pulsar Emission properties, a tool for probing ISM, detecting GWs

Presentation + Report on Pulsar Astronomy (**15% evaluation**) - 7th April

RRATs in general, Magnetars in general

Online quiz on topic covered so far (**5% evaluation**)

Fast Radio Bursts (FRBs) in general, FRBs discovery, localisation and Cosmology

Online quiz on topic covered so far (**5% evaluation**)

Long Period Transients (LPTs)

Presentation + Report on FRBs and LPTs (**15% evaluation**) - 21st April

Other transients

Coding assignments on pulsars, FRBs (**10% evaluation**) - 28th April

Instrumentation developments for TDA: Single dish Vs Phased Array

Observational techniques for TDA

Coding assignments on instrumentation/techniques (**10% evaluation**) - 12th May

Online quiz on topic covered so far (**5% evaluation**)

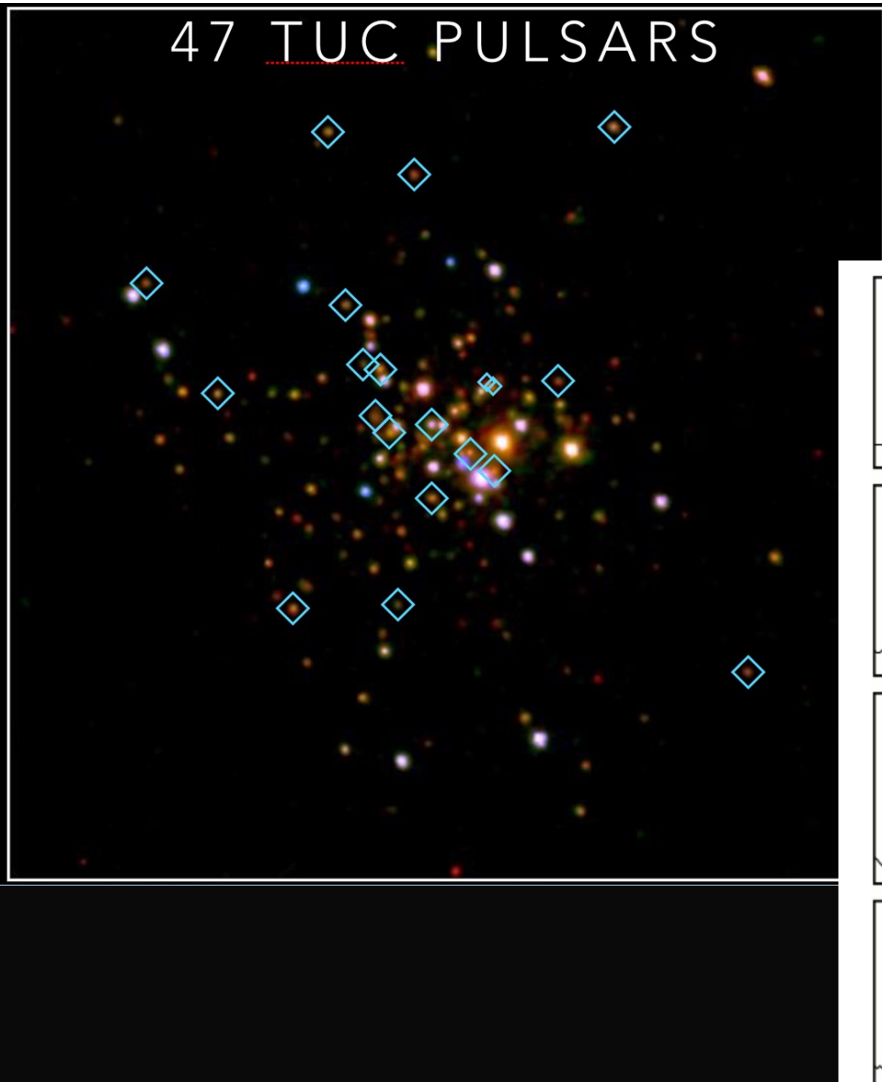
Multi-messenger TDA, Future of TDRA

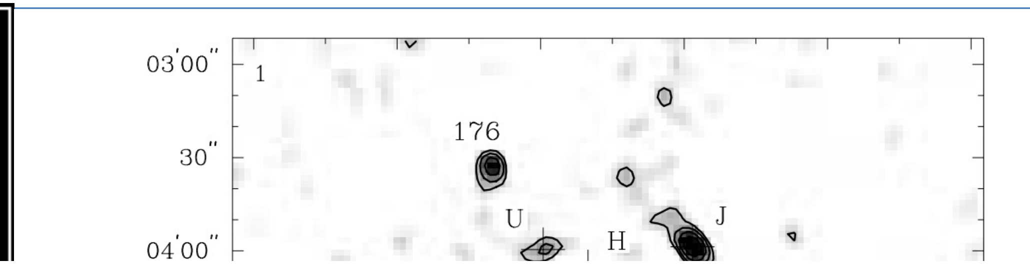
30% evaluation from class attendance and performance

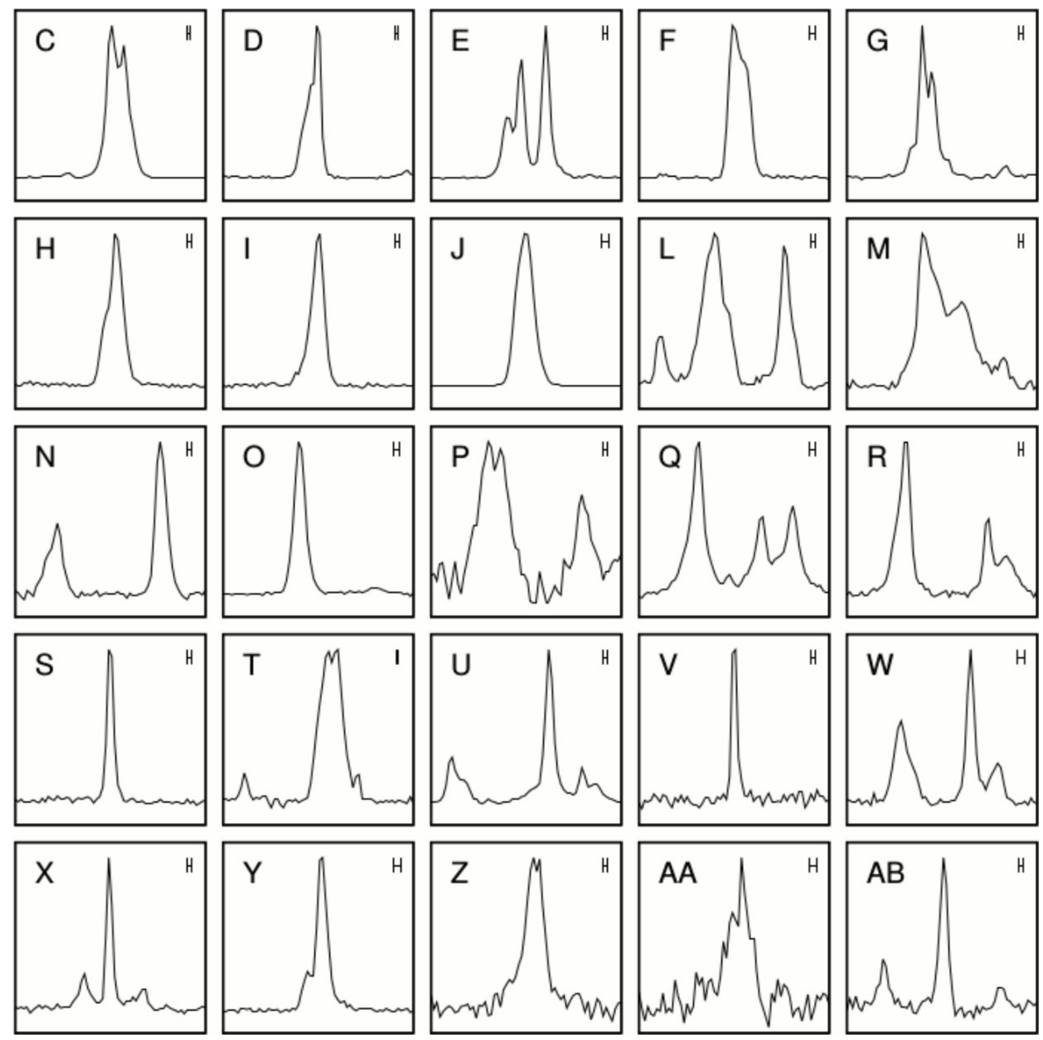
Reference Materials

Pulsar Astronomy by Andrew G. Lyne and Francis Graham-Smith
Handbook of Pulsar Astronomy by Duncan R. Lorimer and Michael Kramer
Pulsars by R. N. Manchester and J. H. Taylor
The Physics of Fast Radio Bursts by Bing Zhang
Long Period Transients (LPTs): a comprehensive review by Nanda Rea, Natasha Hurley-Walker and Manisha Caleb
Radio Millisecond Pulsars by Bhaswati Bhattacharyya and Jayanta Roy
The discovery and significance of fast radio bursts by Duncan R. Lorimer, Maura A. McLaughlin, Matthew Bailes
Multi-wavelength and Multi-messenger Counterparts of Fast Radio Bursts by Bing Zhang
The Astrophysics of Nanohertz Gravitational Waves by Sarah Burke-Spolaor et al.

Time-domain imprint of point sources







Time-domain astronomy

Study of astronomical phenomena that change with time

→ focuses on variability, transients, and dynamic events by monitoring how the brightness, spectrum, or other properties of sources evolve over time

Revealing dynamic processes in the universe

Variability type

→ Periodic: e.g. Pulsars

→ Transient: e.g. Fast Radio Bursts

→ Stochastic: Steller flares

Time-domain astronomy

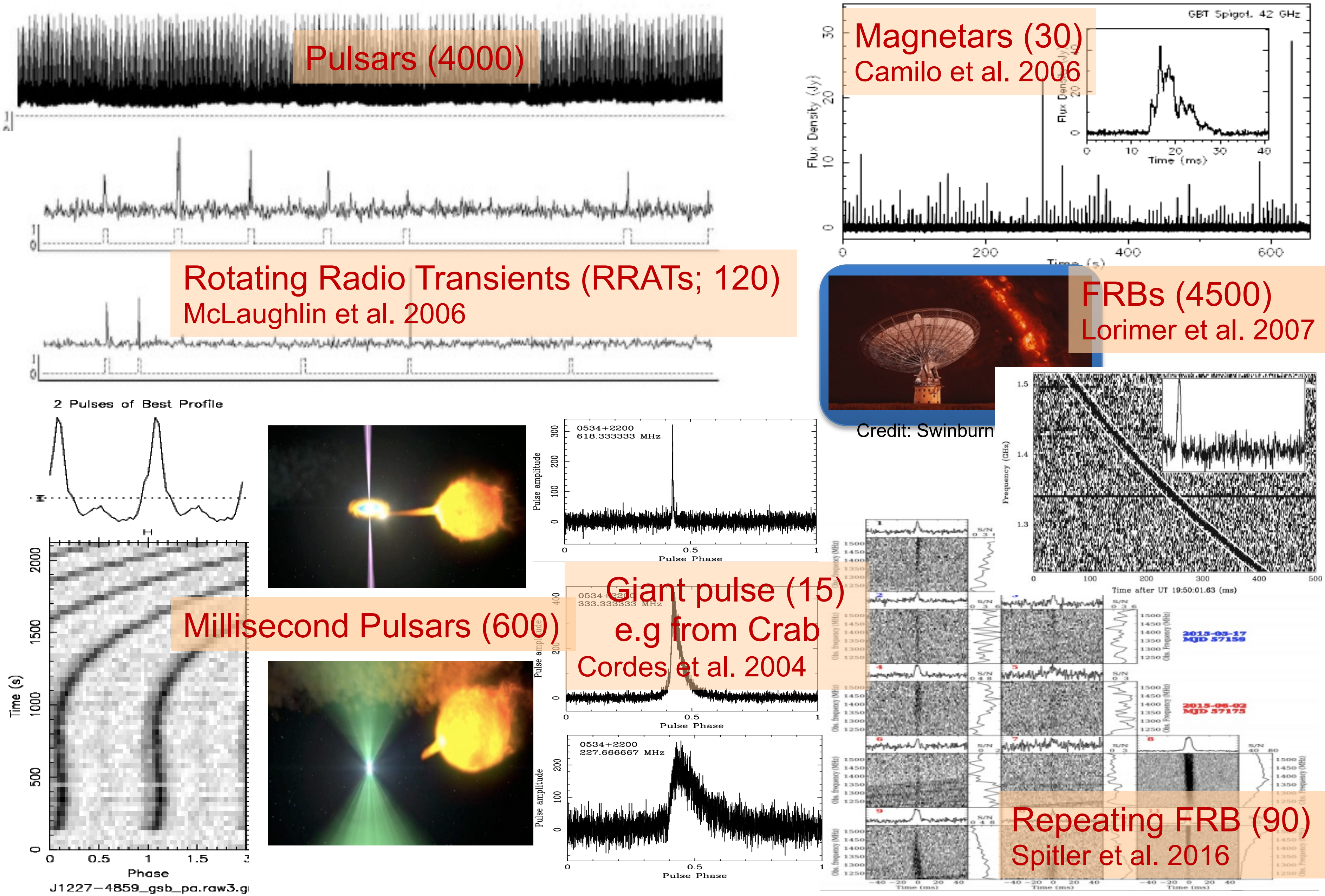
Timescale	**Sources**
nanoseconds	pulsar nanoshots
microseconds	giant pulses
milliseconds	FRBs
seconds	Magnetar bursts
hours–days	stellar flares
months–years	supernovae
decades	AGN variability

Time-domain astronomy

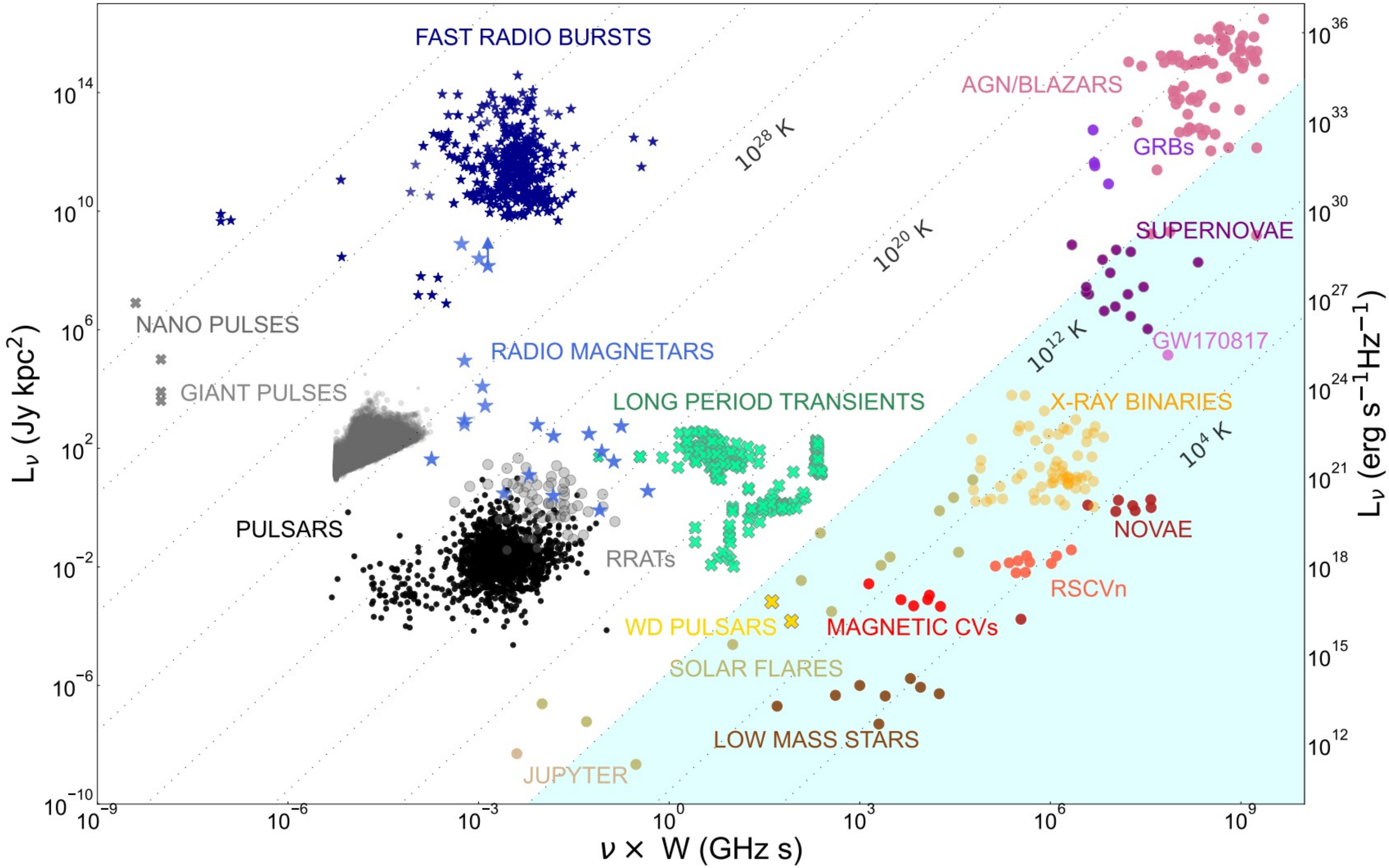
Wavelength	**Time-domain phenomena**
Radio	Pulsars, FRBs
Optical	Supernovae, variable stars
X-ray	Accreting binaries
Gamma-ray	GRBs

Entering a “golden era” because recent technological advances now allow to monitor large portions of the sky continuously with high sensitivity and rapid response

Fast Transients Population



Fast Transients Population



The x-axis represents the product of observing frequency and burst duration

The y-axis axis shows spectral radio luminosity

Luminosity, Flux density

Observing frequency ranges from 100s of MHz to couple of GHz

Burst duration ranges from μs to days/months/years

Radio luminosity

EM power in bandwidth δν from solid angle δΩ intercepted by surface δA is:

$$\delta W = I_\nu \delta\Omega \delta A \delta\nu$$

Defines surface brightness $\boldsymbol{I_\nu}$ (W m^{-2} Hz^{-1} sr^{-1})

Flux density $\boldsymbol{S_\nu}$ (W m^{-2} Hz^{-1}) – integrate brightness over solid angle of source

$$S_\nu = \int_{\Omega_s} I_\nu d\Omega$$

Convenient unit – the **Jansky** ➔ 1 Jy = 10^{-26} W m^{-2} Hz^{-1} = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}

Brightness temperature

Note: $S_\nu = L_\nu / 4\pi d^2$ ie. distance dependent

$\Omega \propto 1/d^2 \Rightarrow I_\nu \propto S_\nu / \Omega$ ie. distance independent

In general surface brightness is position dependent, ie. $I_\nu = I_\nu(\theta,\phi)$

$$I_\nu(\theta,\varphi) = \frac{2k\nu^2 T(\theta,\varphi)}{c^2}$$

(if I_ν described by a blackbody in the Rayleigh-Jeans limit; $h\nu/kT << 1$)

Back to flux:

$$S_\nu = \int_{\Omega_s} I_\nu(\theta,\varphi)d\Omega = \frac{2k\nu^2}{c^2}\int T(\theta,\varphi)d\Omega$$

In general, a radio telescope maps the *temperature distribution of the sky*

Brightness temperature

Brightness temperature (T_B) of a source is defined as the temperature of a blackbody with the same surface brightness at a given frequency:

$$I_\nu = \frac{2k\nu^2 T_B}{c^2}$$

This implies that the flux density

$$S_\nu = \int_{\Omega_s} I_\nu d\Omega = \frac{2k\nu^2}{c^2} \int T_B d\Omega$$

Spectral luminosity ~ 100 Jy kpc^2 ~ 10^{22} erg s^{-1} cm^{-2} Hz^{-1}

Brightness temperature

Source size D ~ c * W_{pulse}

$\Omega = (c * W_{pulse} / D)^2$

Brightness Temperature $T_B \propto L_\nu / (\nu W_{pulse})^2$

Constant Brightness Temperature is diagonal line in the transient phase-space plot

For Pulsars, $T_B \propto 10^{25}$ erg s^{-1} cm^{-2} Hz^{-1}/ (1 GHz * 0.01s) ~ 10^{25} K

For FRBs, $T_B \propto 10^{35}$ erg s^{-1} cm^{-2} Hz^{-1}/ (1 GHz * 0.01s) ~ 10^{35} K

$T_B \sim 10^{12}$ K is a approximate boundary between coherent and incoherent emission processes

For $T_B > 10^{12}$ K, in compact sources, effective temperature of the emitting electrons exceed the synchrotron limit by many orders of magnitude, which means their emission cannot be incoherent synchrotron radiation. Instead they must involve coherent emission processes, where many charges radiate in phase.

Incoherent to Coherent radio emission

Coherent emission processes for high luminosity, narrow pulse (i.e. compact emitting region)

Pulsars ~ millisecond time-scale

FRBs ~ millisecond time-scale

Giant Pulses ~ nano/micro-seconds time-scale

Steller flares ~ minutes/hours time-scale

Supernovae ~ weeks/years time-scale

Radio Telescope

EM power in bandwidth δν from solid angle δΩ intercepted by surface δA is:

$$\delta W = I_\nu \delta\Omega \delta A \delta\nu$$

Telescope of effective area A_e receives power P_{rec} per unit frequency from an unpolarised source but is only sensitive to one mode of polarisation:

$$P_{rec} = \frac{1}{2} I_\nu A_e \delta\Omega$$

Telescope is sensitive to radiation from more than one direction with *relative* sensitivity given by the normalized antenna pattern $P_N(\theta,\varphi)$:

$$P_{rec} = \frac{1}{2} A_e \int_{4\pi} I_\nu(\theta,\varphi) P_N(\theta,\varphi) d\Omega$$

Antenna Temperature

Power received by the antenna: $P_{rec} = kT_A$

$$P_{rec} = \frac{A_e}{2} \int_{4\pi} I_\nu(\theta,\varphi) P_N(\theta,\varphi)\, d\Omega$$

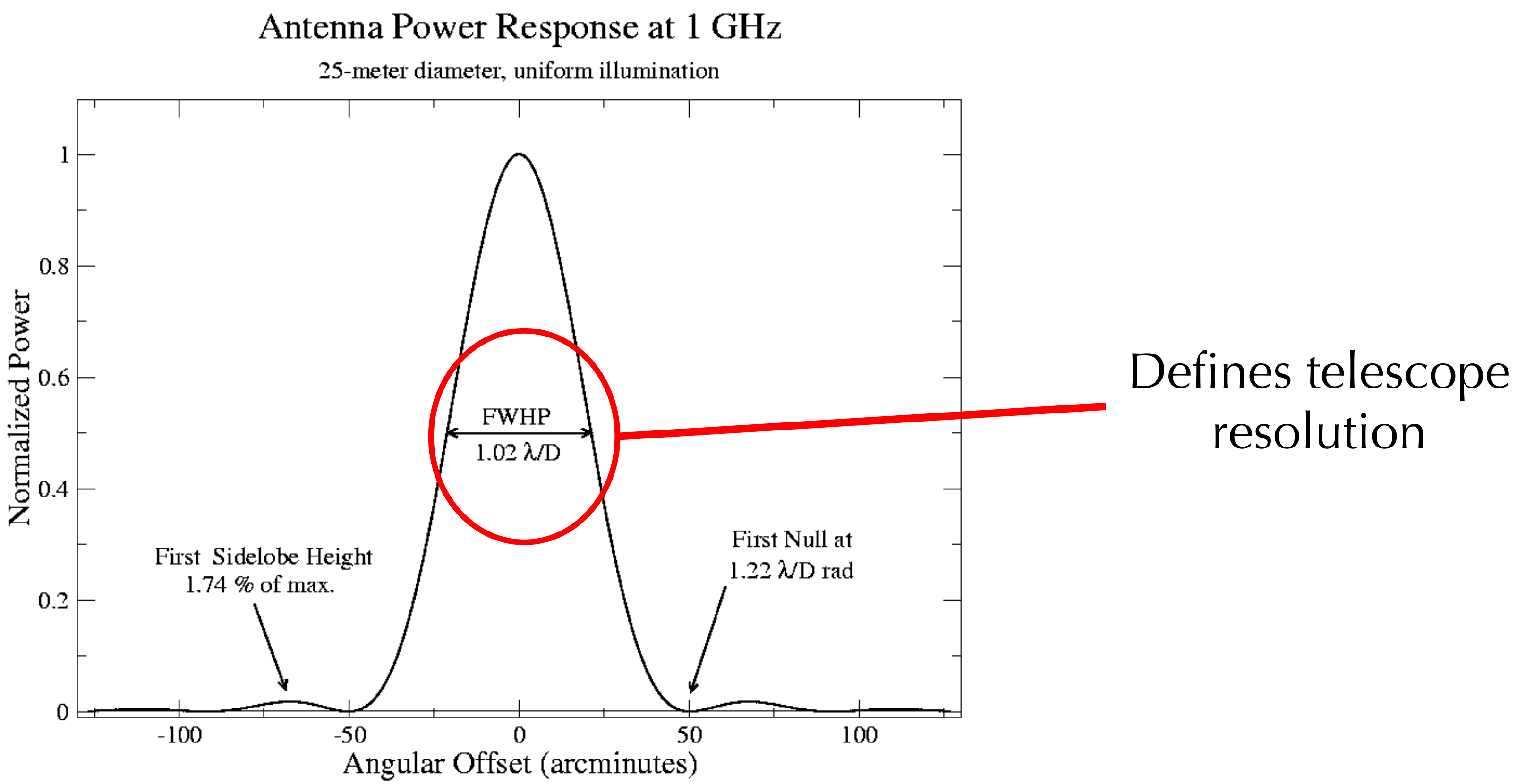
$$\therefore T_A = \frac{A_e}{2k} \int_{4\pi} I_\nu(\theta,\varphi) P_N(\theta,\varphi)\, d\Omega$$

Antenna temperature is what is observed by the radio telescope.

A “convolution” of sky brightness with the beam pattern

It is an inversion problem to determine the source temperature distribution.

Antenna Power Pattern



- In interferometry we measure the Fourier components of the sky, so we must perform an FFT to recover the sky image.
- In time-domain astronomy we directly measure the signal as a function of time, so temporal variability is already visible without any Fourier transform.

Sensitivity

Unfortunately, the telescope system itself contributes noise to the the signal detected by the telescope, i.e.,

$$P_{out} = P_A + P_{sys} \quad \Rightarrow \quad T_{out} = T_A + T_{sys}$$

The *system temperature*, T_{sys}, represents noise added by the system:

$$T_{sys} = T_{bg} + T_{sky} + T_{spill} + T_{loss} + T_{cal} + T_{rx}$$

T_{bg} = microwave and galactic background (3K, except below 1GHz)
T_{sky} = atmospheric emission (increases with frequency--dominant in mm)
T_{spill} = ground radiation (via sidelobes) (telescope design)
T_{loss} = losses in the feed and signal transmission system (design)
T_{cal} = injected calibrator signal (usually small)
T_{rx} = receiver system (often dominates at cm — a design challenge)

Note that T_{bg}, T_{sky}, and T_{spill} vary with sky position and T_{sky} is time variable

Sensitivity

Q: How can you detect T_A (signal) in the presence of T_{sys} (noise)?

A: The signal is correlated from one sample to the next but the noise is not

For bandwidth $\Delta\nu$, samples taken less than $\Delta\tau = 1/\Delta\nu$ are not independent

(Nyquist sampling theorem!)

Time τ contains $N = \tau / \Delta\tau = \tau\,\Delta\nu$ independent samples

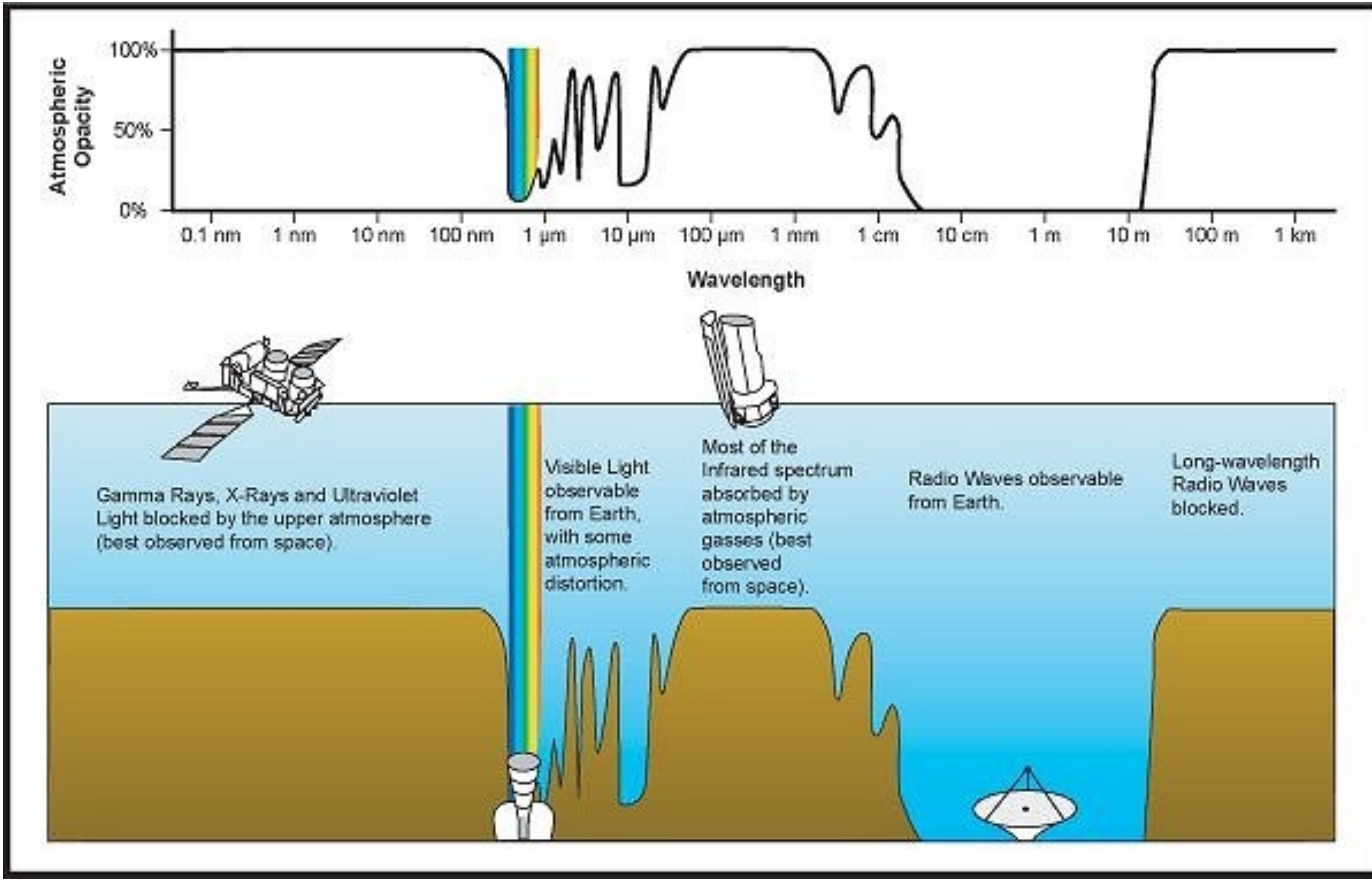
For Gaussian noise, total error for N samples is $1/\sqrt{N}$ that of single sample

$$\therefore \quad \frac{\Delta T_A}{T_{sys}} = \frac{1}{\sqrt{\tau\,\Delta\nu}}$$

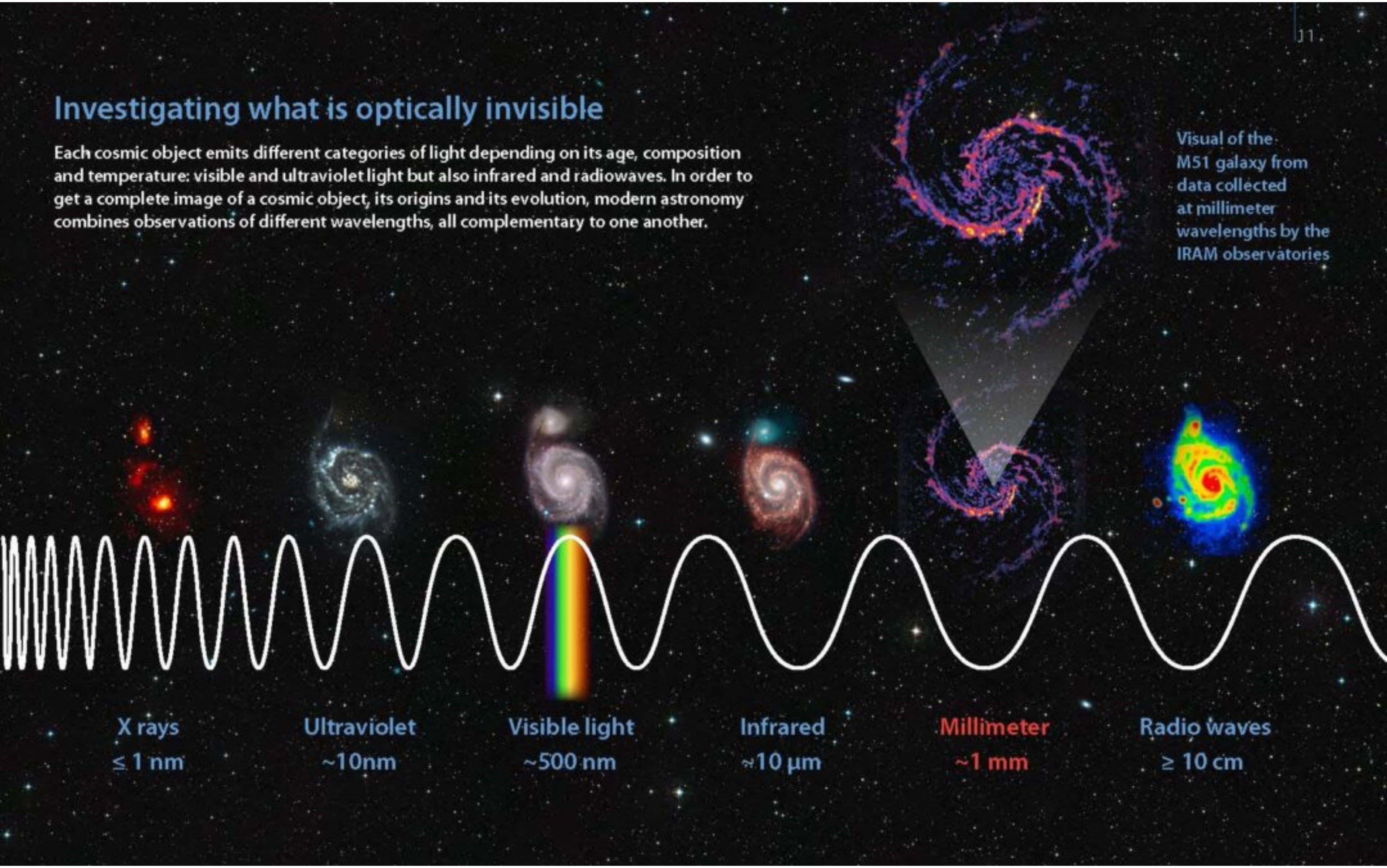
Radiometer equation

$$SNR = \frac{T_A}{\Delta T_A} = \frac{T_A}{T_{sys}}\sqrt{\tau\,\Delta\nu}$$

Radio Astronomy



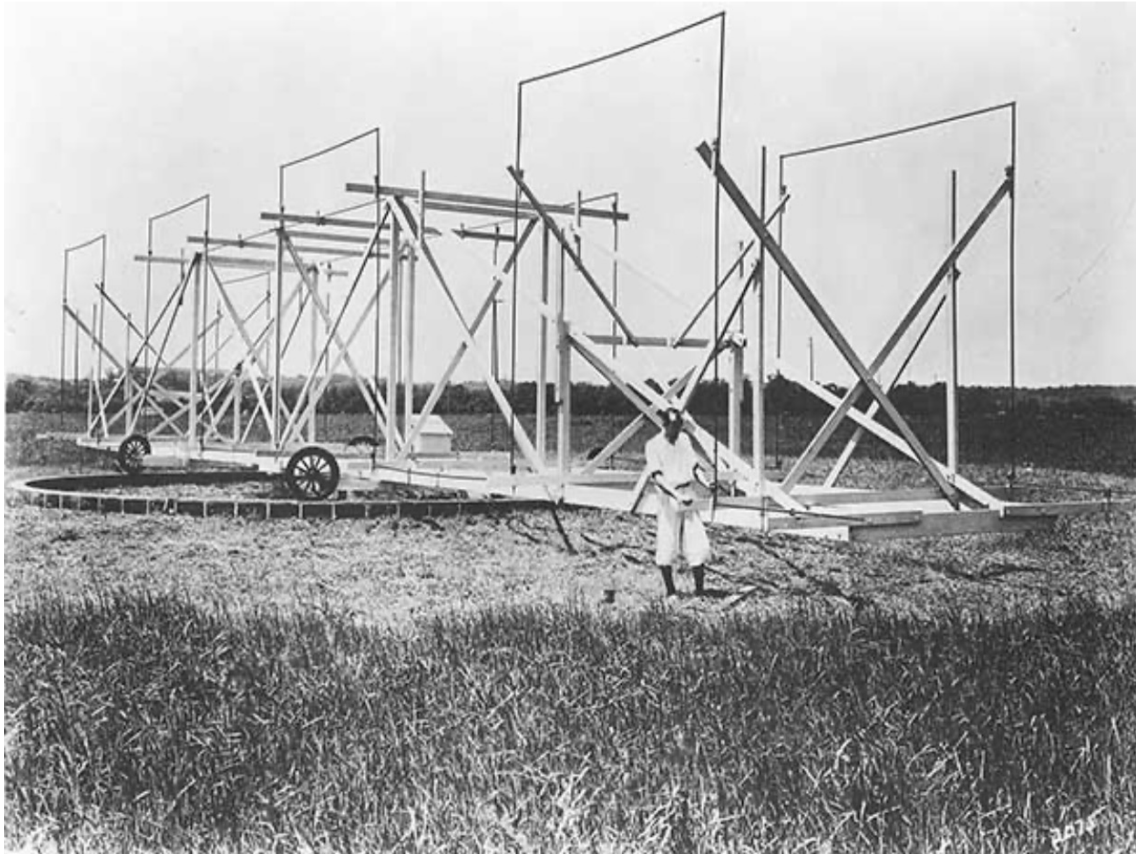
Radio Astronomy



Radio Astronomy processes

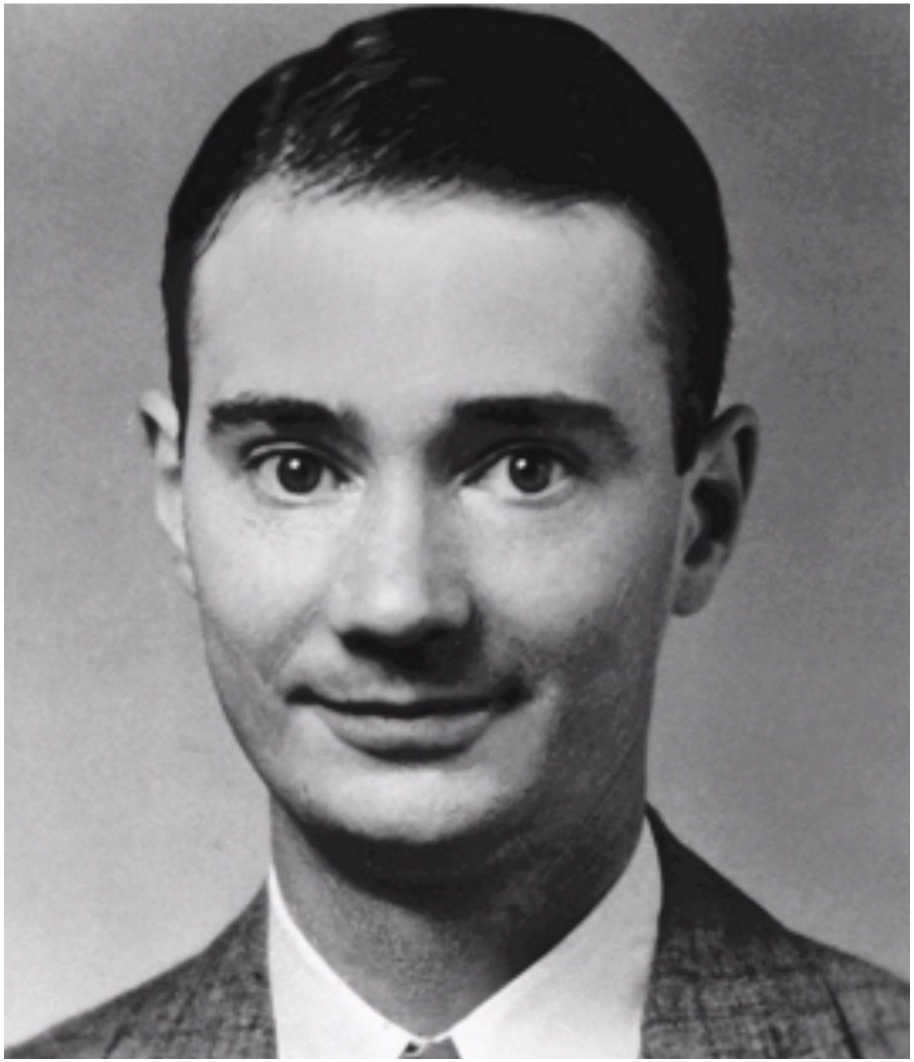
Frequency Range	Main Processes	Typical Sources
10 MHz – 3 GHz	Pulsar emission, neutral hydrogen 21-cm line, Synchrotron radiation from relativistic electrons	Pulsars, galaxies, interstellar medium, Supernova remnants, radio galaxies
1 – 30 GHz	Free–free emission, synchrotron + thermal emission	HII regions, star-forming galaxies
30 – 300 GHz	Cold dust emission, molecular lines	Molecular clouds, protoplanetary disks
~100 GHz peak	Cosmic Microwave Background (CMB)	Early Universe relic radiation

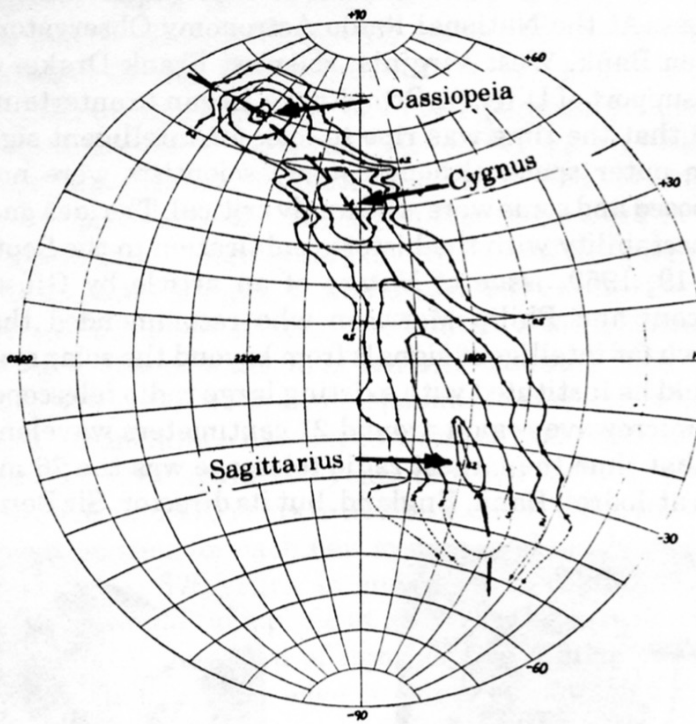
The beginning – Karl Jansky 1933



Discovered radio emission from the centre of the Milky Way

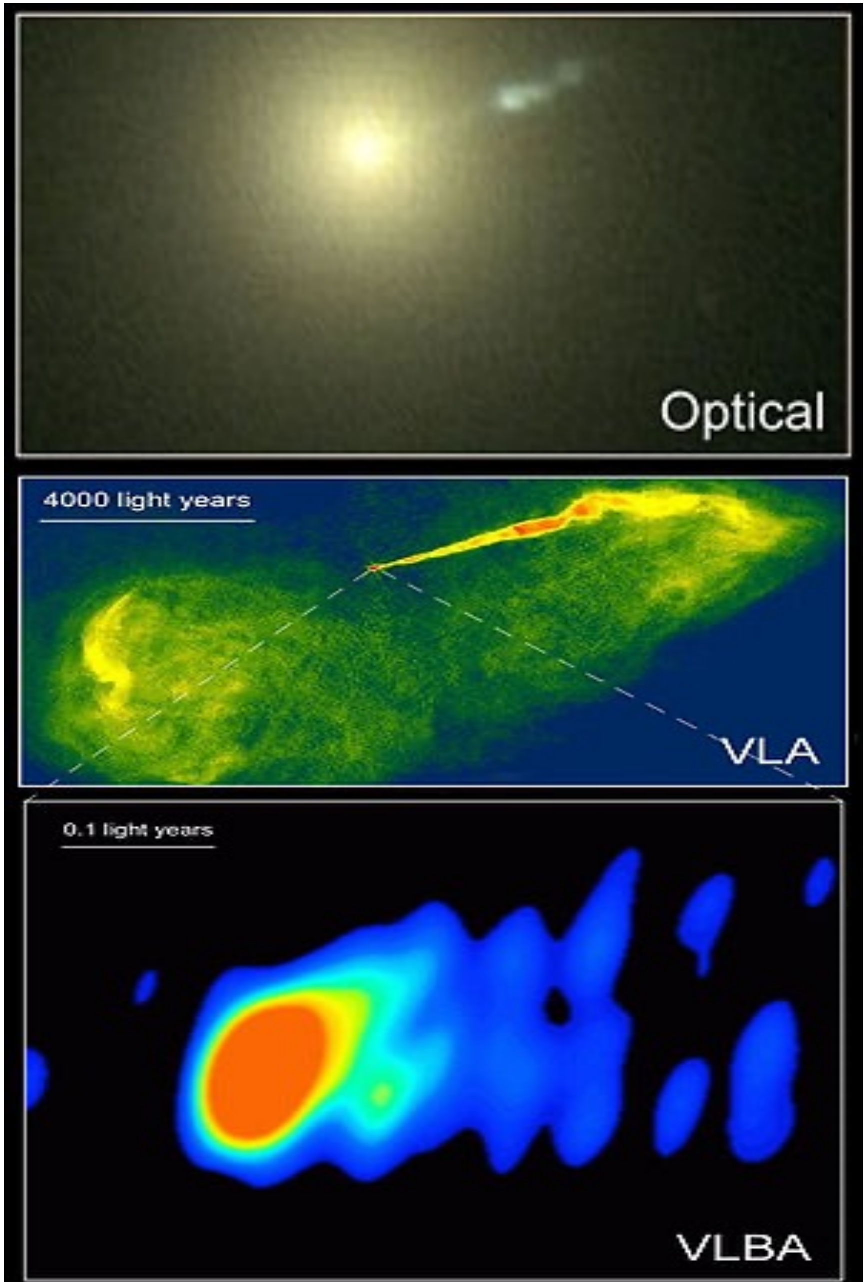
First radio map of the sky – Grote Reber 1941





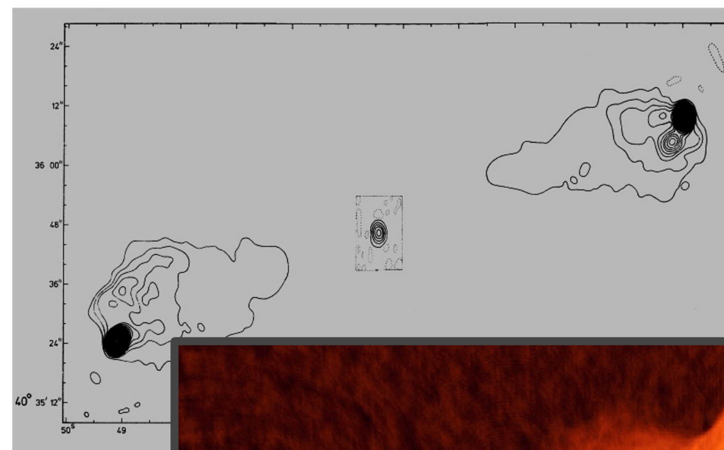
First map of the radio sky as produced by Grote Reber showing strong sources of radiation in Cassiopeia, in Cygnus and in Sagittarius, the center of the galaxy, the region from which Karl Jansky had detected radio emission.

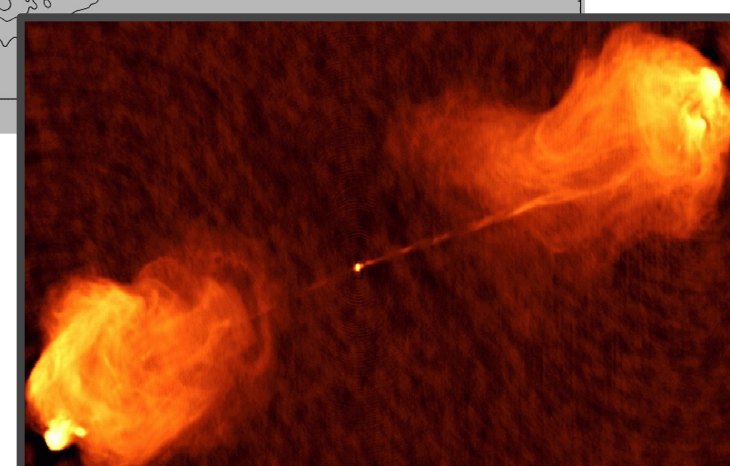
Optical Vs Radio



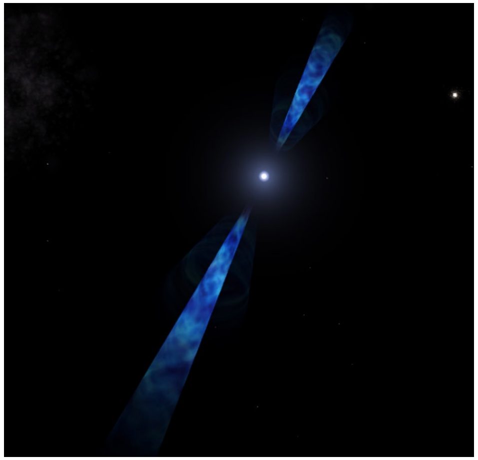
An optical image of the galaxy M87 (HST), a radio image of same galaxy using Interferometry (Very Large Array-VLA), and an image of the center section (VLBA) using a Very Long Baseline Array (Global VLBI) consisting of antennas in the US, Germany, Italy, Finland, Sweden and Spain.

Power of Array Telescopes



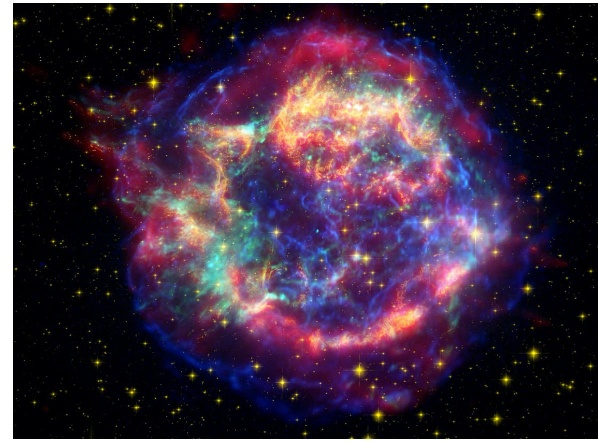


Exploring radio sky



Pulsars: strong magnetic fields

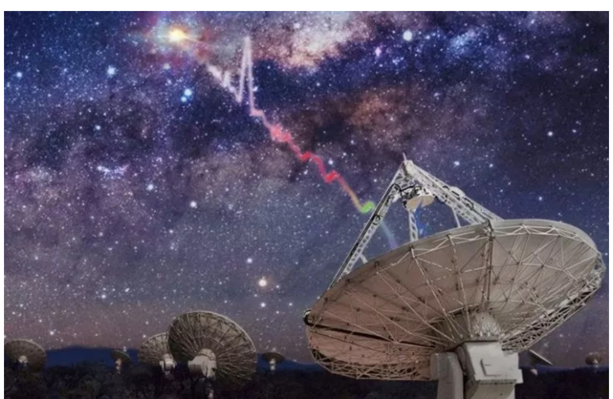
Luminous stars – star-forming regions

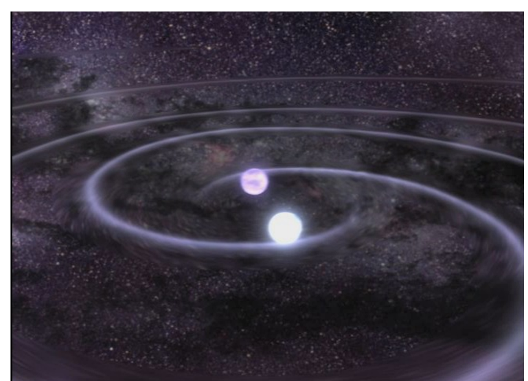


Supernovae remnants Cassiopeia A

Supermassive black holes - quasars, blazars

Fast transients: Fast Radio Bursts





Gravitational waves, theory of gravity

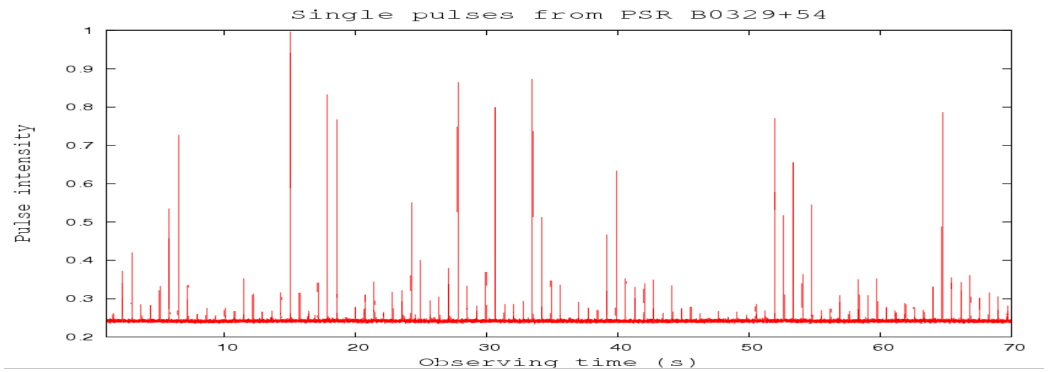
Radio Astronomy processes

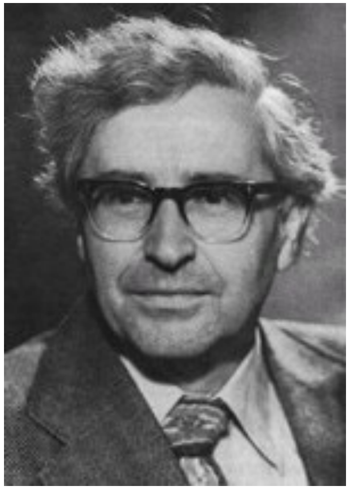
Frequency Range	Time-domain sources
100–300 MHz	Low-frequency pulsars, coherent emission, some FRBs, LPTs
300 MHz – 1.5 GHz	Pulsars, RRATs, magnetars, FRBs, LPTs
1 – 3 GHz	FRBs, pulsars, millisecond pulsar timing for Pulsar Timing Arrays
3 – 5 GHz	High-frequency pulsars, magnetars, scattering studies

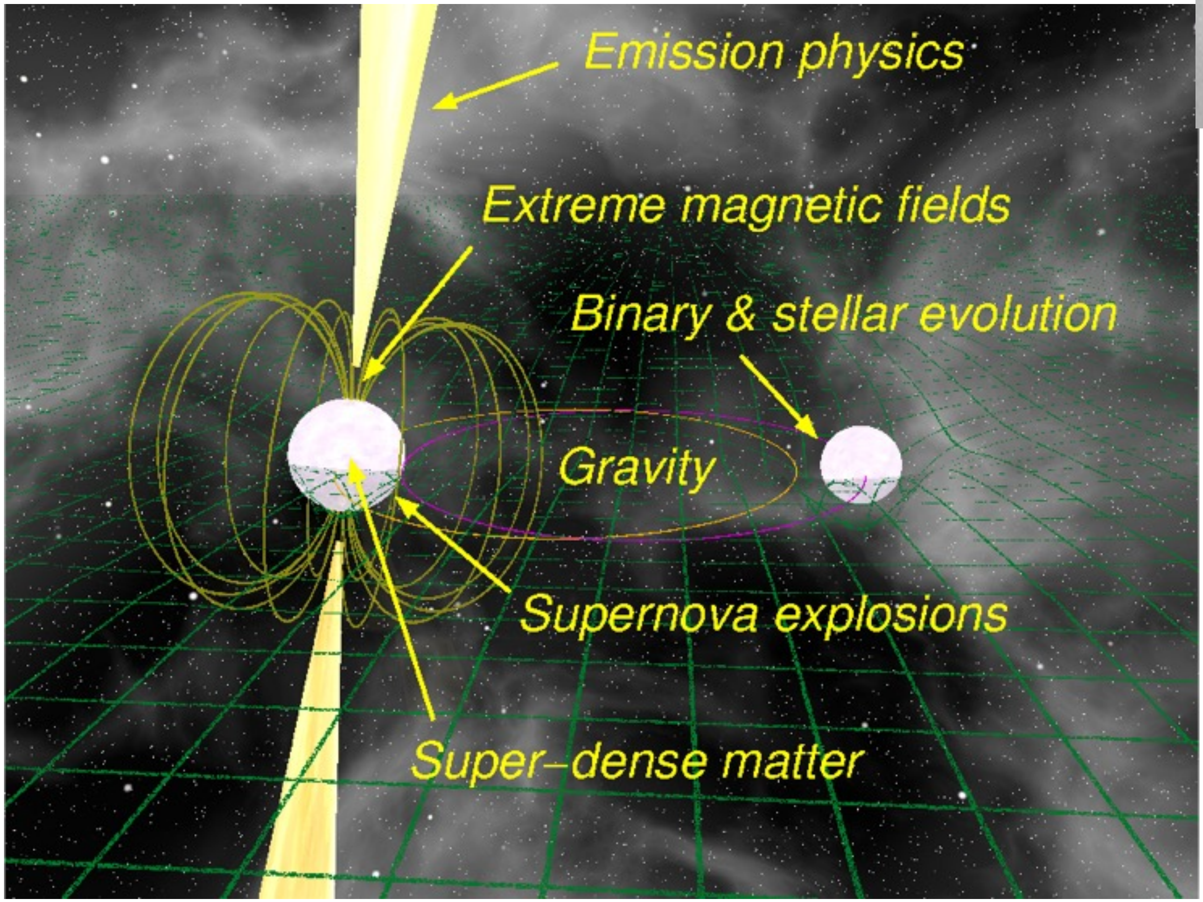
Time-domain radio astronomy sources

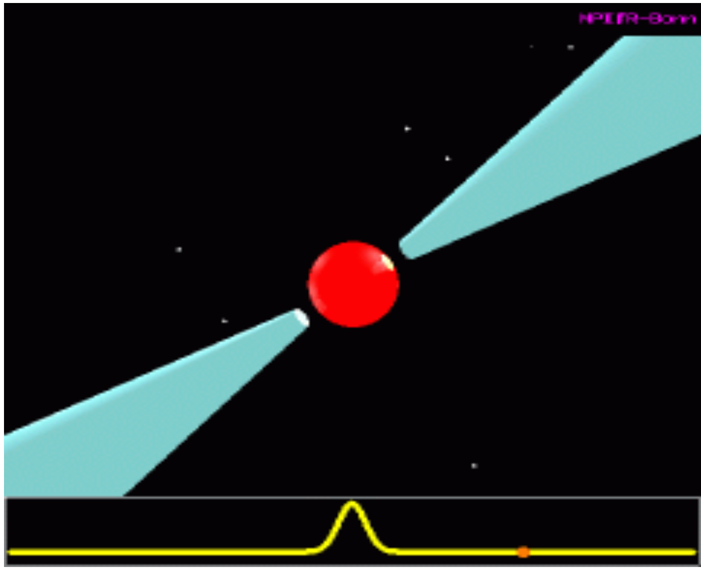
Class	Timescale	Examples
Fast transients	microseconds–seconds	Pulsars, FRBs
Intermediate	seconds–minutes	Magnetars, RRATs
Long-period	minutes–hours	Long-period transients
Slow transients	days–years	Supernovae, AGN flares

Pulsars


Single pulses from PSR B0329+54
Pulse intensity
Observing time (s)



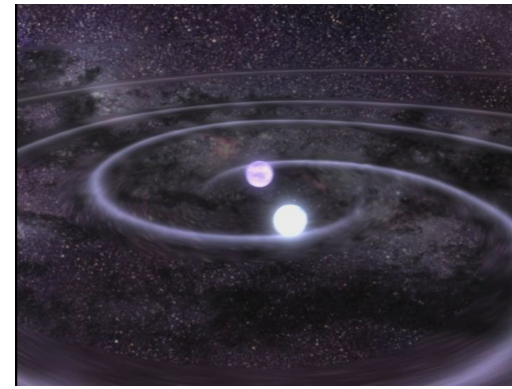

Emission physics
Extreme magnetic fields
Binary & stellar evolution
Gravity
Supernova explosions
Super–dense matter



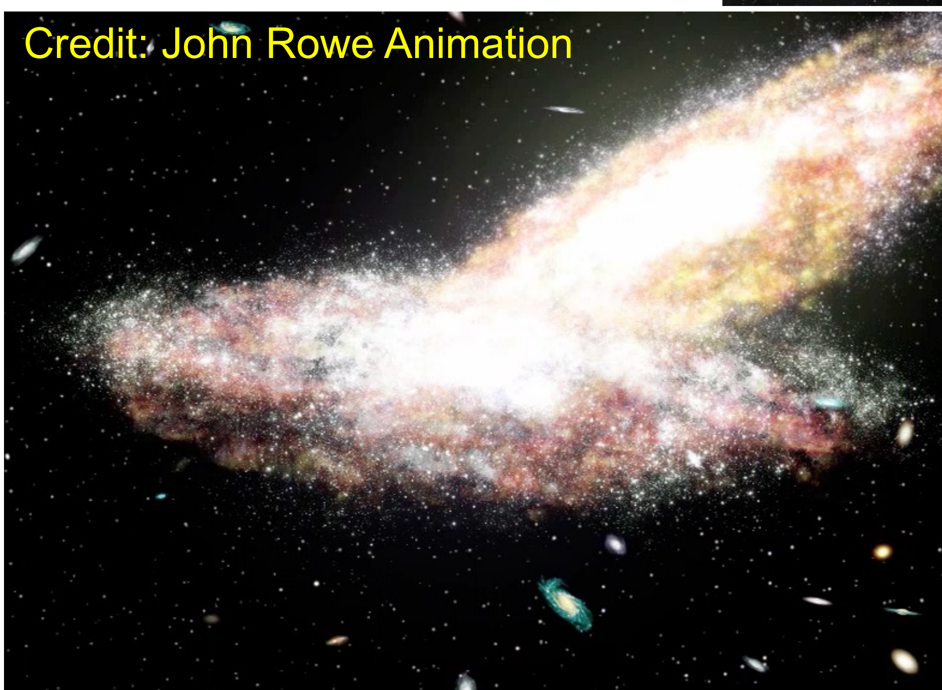
Pulsars to detect GWs

Pulsar rotation period as 0.00306184403674401 +/- 0.00000000000000005 s predict the arrival times of all incoming pulses for the next 10 million years!

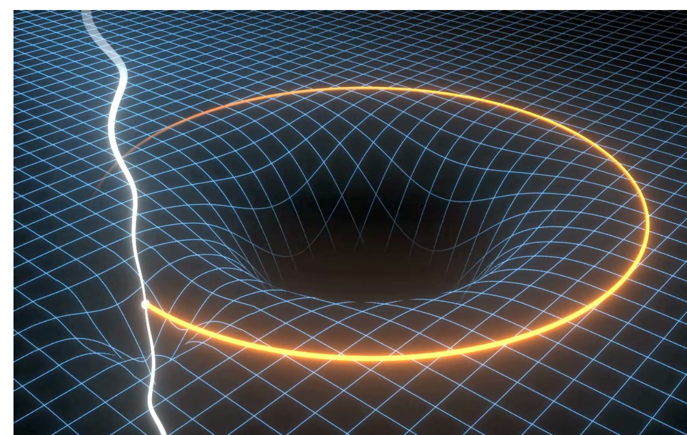
GW source: Orbital period shrinking
→ merging of Neutron stars



GW170817: detected with LIG



GW source: Pulsars orbiting a Black Hole



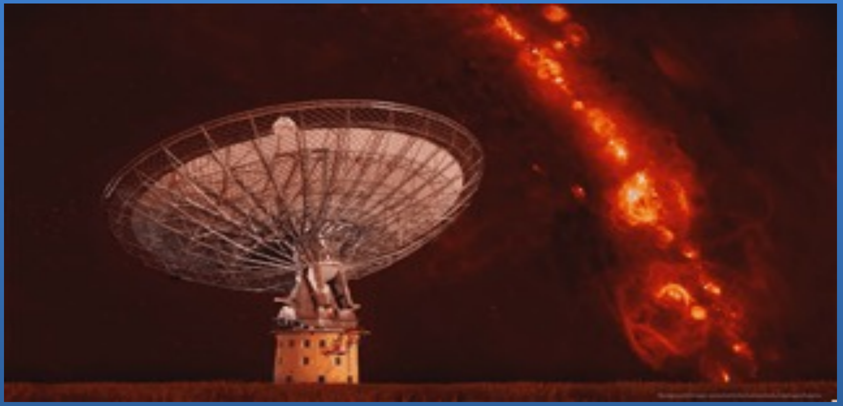
Credit: John Rowe's Animations

Fast Transients: Fast Radio Bursts

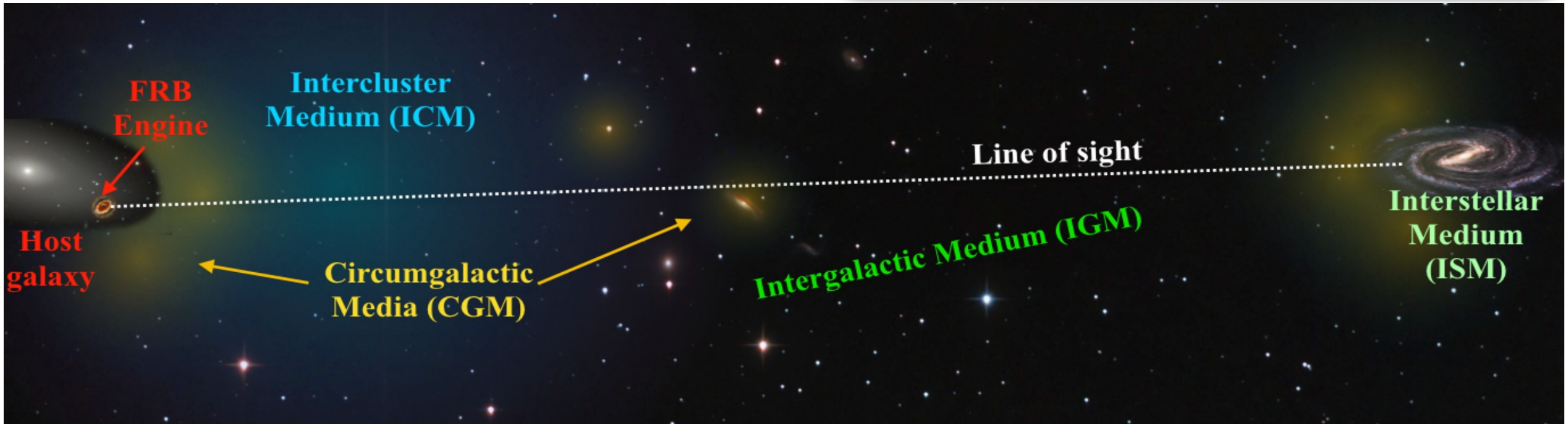
Millisecond duration radio bursts with likely extragalactic origin

Only ~ 4500 discovered so far

Millisecond duration cosmic flashlights having energy equal to the total energy emitted by Sun in 80 years!



Credit: Swinburne Astronomy Productions

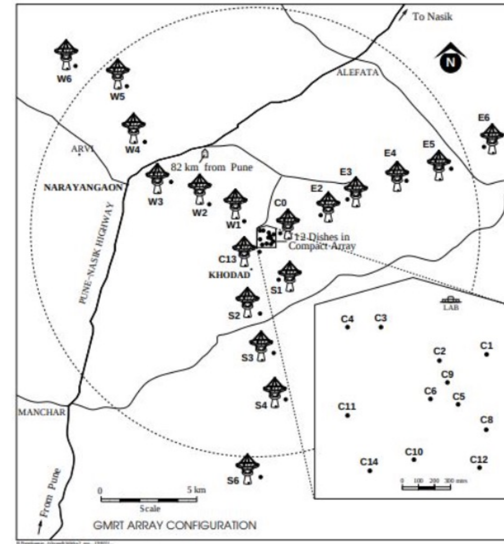


Father of Indian Radio Astronomy

Prof. Govind Swarup

"GMRT is a marriage of the world's two big radio telescopes, the Very Large Array in New Mexico, and Arecibo in Puerto Rico, with the advantages of both".

The upgraded GMRT



A radio interferometer
with fully steerable dishes of 45 metres diameter, operating over 120-1460 MHz bands

One of the most sensitive instrument in the world at its frequencies of operation

Array located at 80 km north to Pune consisting of 30 antennas over 25 km maximum baseline

With Instantaneous bandwidth of 200/400 MHz GMRT is an excellent instrument for time-domain studies of Pulsars/FRBs: Pulsar Search (surveys like GHRSS, GCGPS), Timing, Eclipse studies of spider MSPs, Single pulse studies, repeating FRBs