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Observatoire de la CÔTE d'AZUR

Galactic and extra-galactic radio sources

Introduction to Radioastronomy

Third Part

January 2011

- Fundamentals of radio observations: first part
- Physical mechanisms responsible for emission at radio frequencies: second part
- **Galactic and extra-galactic radio sources: third part**

Lecture Outline

- Examples of galactic radio sources
  - Supernovae
  - Galactic continuum radiation and the inter stellar medium
- Examples of extra-galactic radio sources
  - Active Galactic Nuclei (AGN)
  - Galaxy clusters
  - Cosmic Microwave Background (CMB)
  - Epoch of Re-ionization (EoR)

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Supernova: a confusing name!

Super - 1: very large or powerful
2: exhibiting the characteristics of its type to an extreme degree

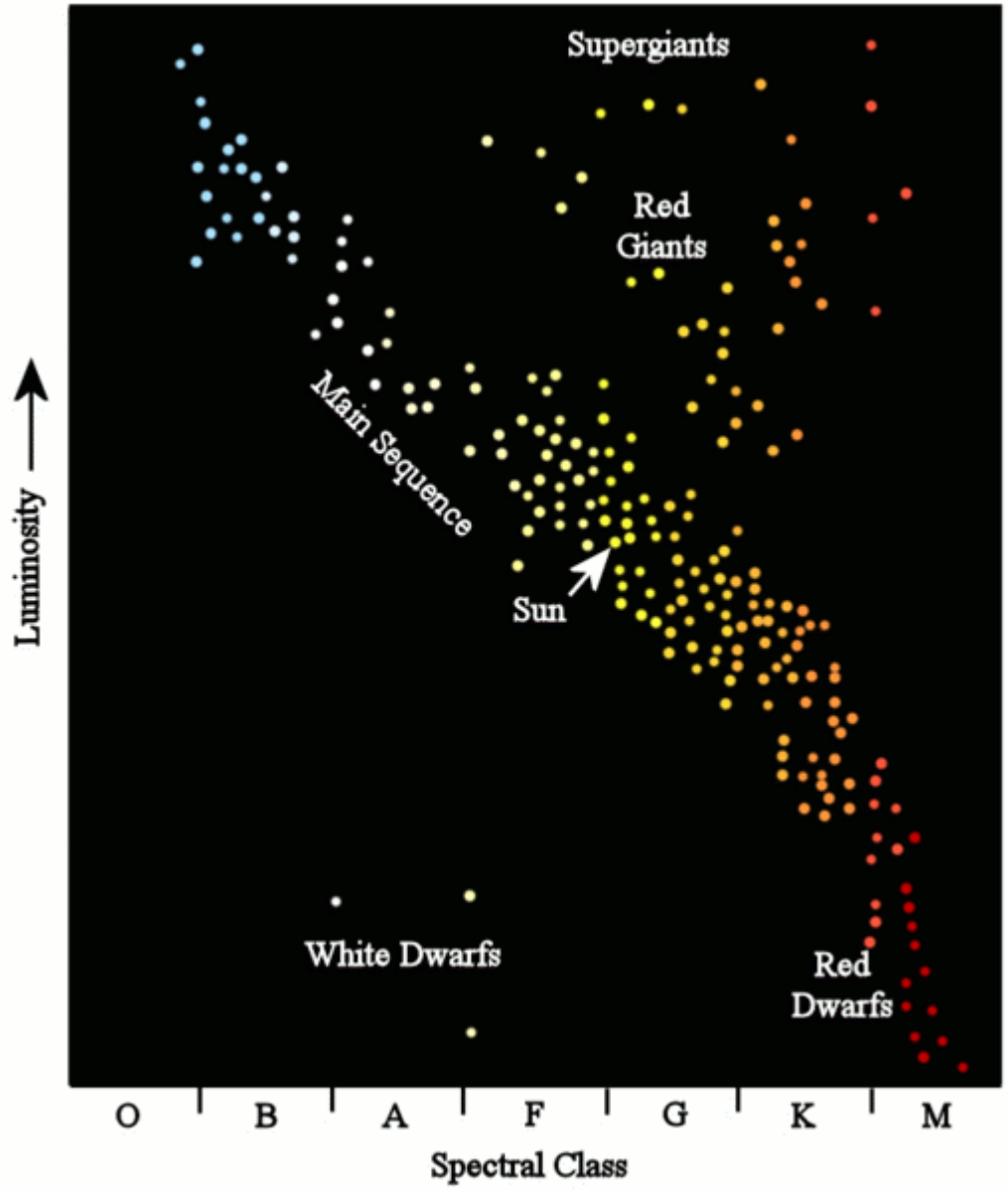
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Nova - a star that suddenly becomes thousands of times brighter and then gradually fades to its original intensity

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But in Latin, "nova" means "new", while a "nova" star is not new at all, and, ironically, supernovae are actually stars at the end of their life!!!

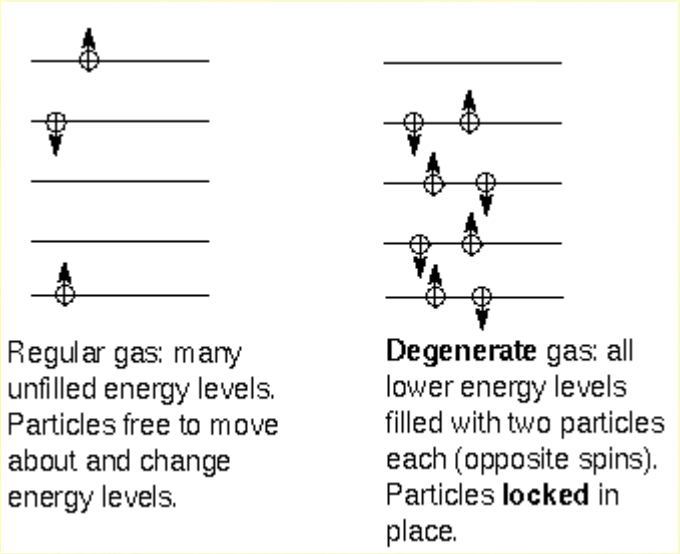
The main sequence of stars

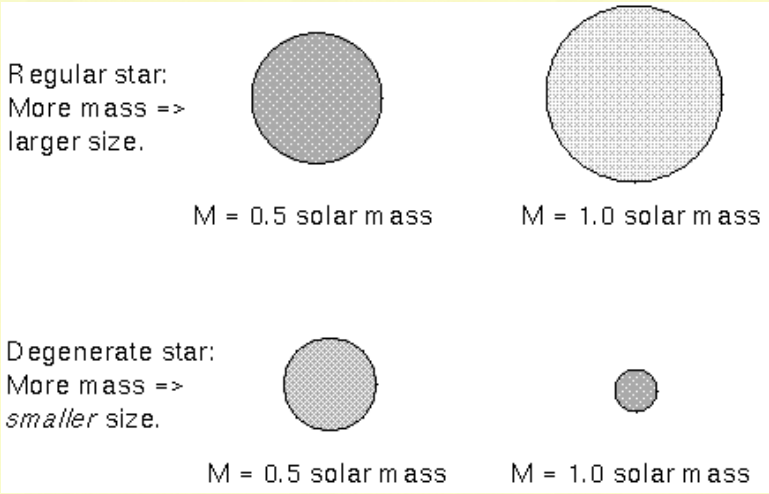


From the upper left to the lower right a prominent concentration of objects defines the main sequence. The main-sequence stars are at the early phases of their lives, and are powered by the fusing of hydrogen to helium in their centers. Masses of the main-sequence stars increase going toward the upper left of the diagram and decrease going to the lower right. Due to their higher central temperatures and pressures, the more massive stars are burning hydrogen more rapidly and are therefore brighter.

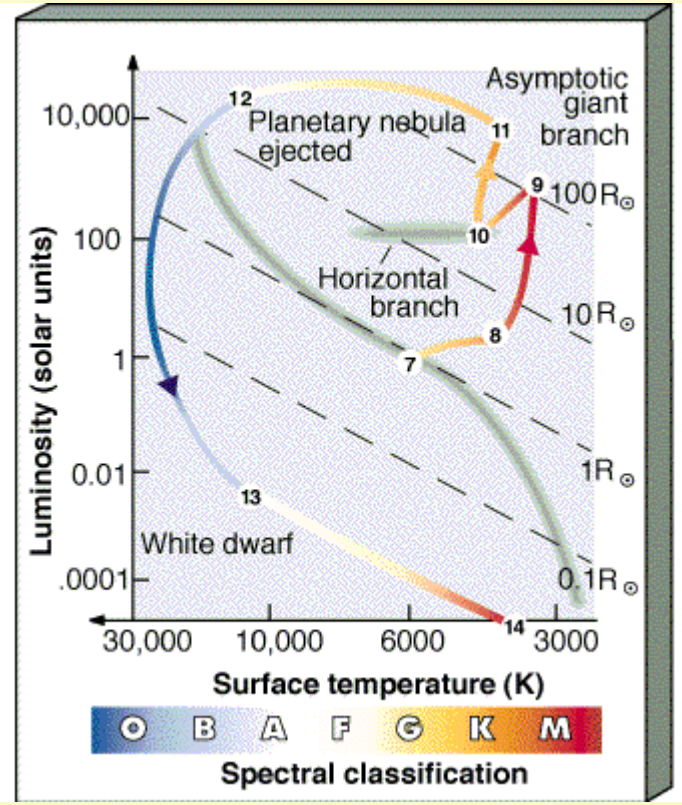
Degenerate gas

- **First rule:** only certain energies are permitted in a closely confined space. The particles are arranged in energy levels. In ordinary gas, most of the energy levels are unfilled and the particles are free to move about. But in a degenerate gas, all of the lower energy levels are filled.
- **Second rule:** only two particles can share the same energy level in a given volume at one time. We will see that for white dwarfs the degenerate particles are the electrons. For neutron stars the degenerate particles are neutrons.
- **Third rule:** how close particles can be spaced depends *inversely* on their masses. Electrons are spaced further apart in a degenerate electron gas than the neutrons in a degenerate neutron gas because electrons are much less massive than neutrons.
- **One consequence:** increasing the mass of the stellar core increases the compression of the core. The degenerate particles are forced closer together, but not much closer together because there is no room left. A more massive stellar core remnant will be *smaller* than a lighter core remnant. This is the opposite behavior of regular materials: usually adding mass to something makes it bigger!



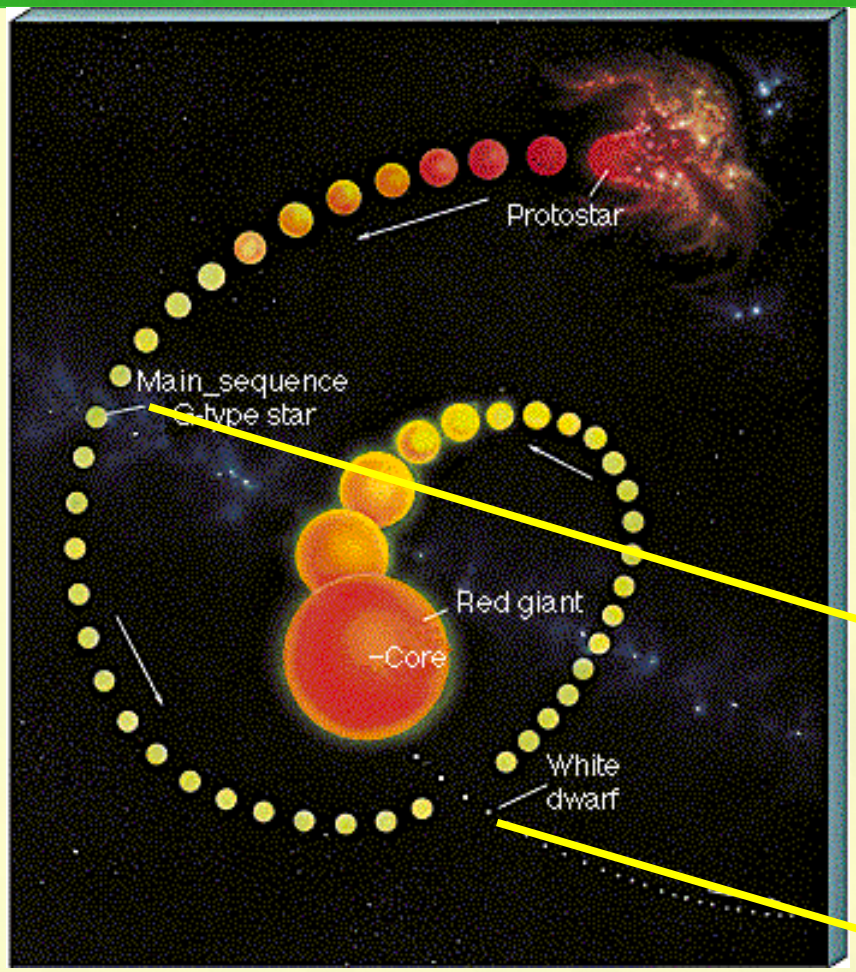


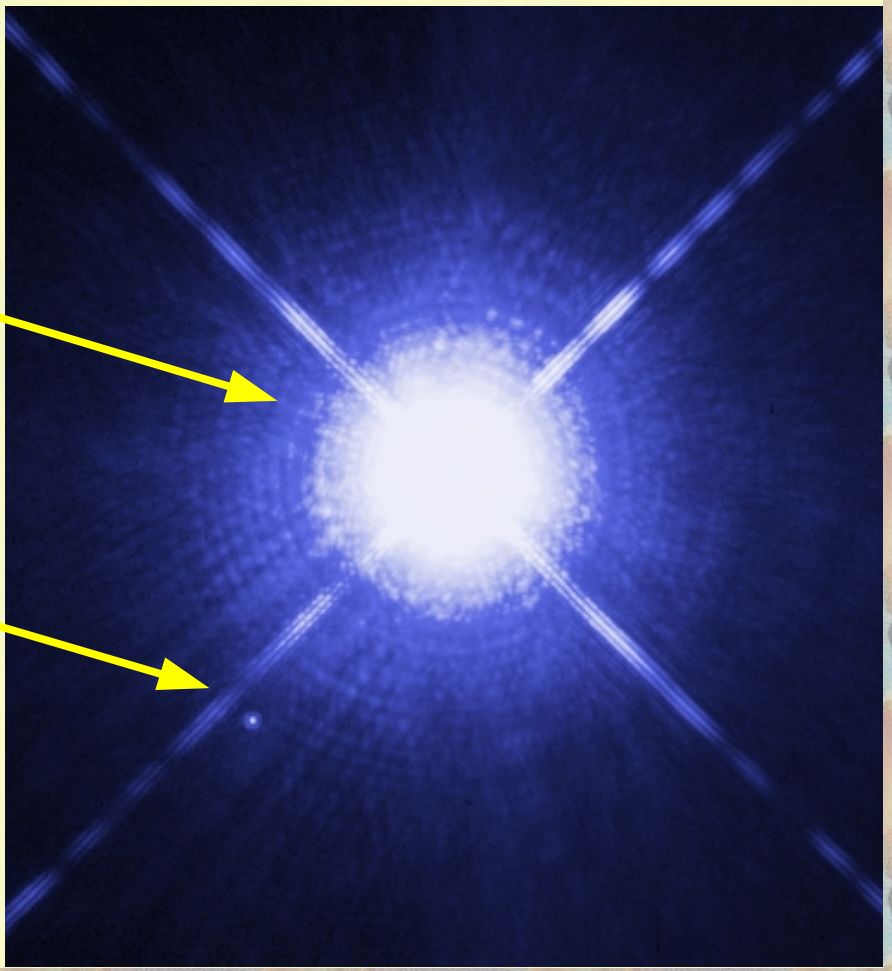
White dwarfs



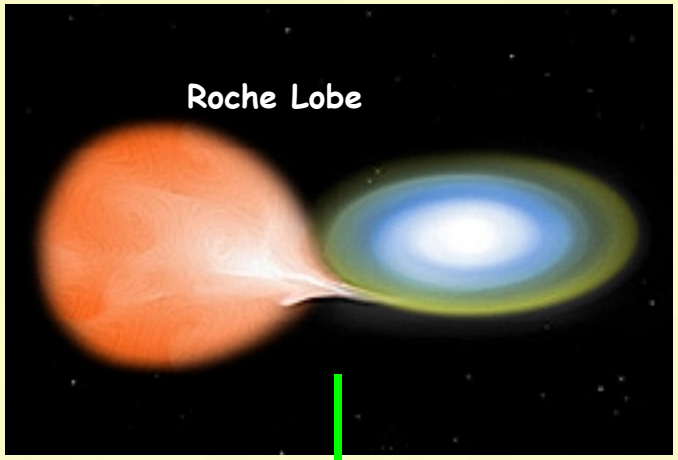
- **White dwarf** = kind of star which a main-sequence of low or medium mass will become in the last stage of its evolution
- Such a star firstly becomes a **red giant** during its helium-burning phase, in which helium is fused to carbon and oxygen
- It generally has insufficient mass to generate the core temperatures required to fuse carbon
- After shedding its outer layers to form a **planetary nebula**, it will leave behind an inert core, which forms the remnant **white dwarf**
- The material in a white dwarf no longer undergoes fusion reactions, so the star has no source of energy, nor is it supported against gravitational collapse by the heat generated by fusion
- It is supported only by **electron degeneracy pressure** (see Pauli exclusion principle) and is therefore extremely dense, with a typical mass on the order of the Sun's contained in a volume on the order of the Earth's
- Maximum mass for a non-rotating white dwarf = **Chandrasekhar limit**—approximately 1.4 M_{Sun}—beyond which it cannot be supported by degeneracy pressure
- A white dwarf is very hot when it is formed, but since it has no source of energy, it will gradually radiate away its energy and cool down.

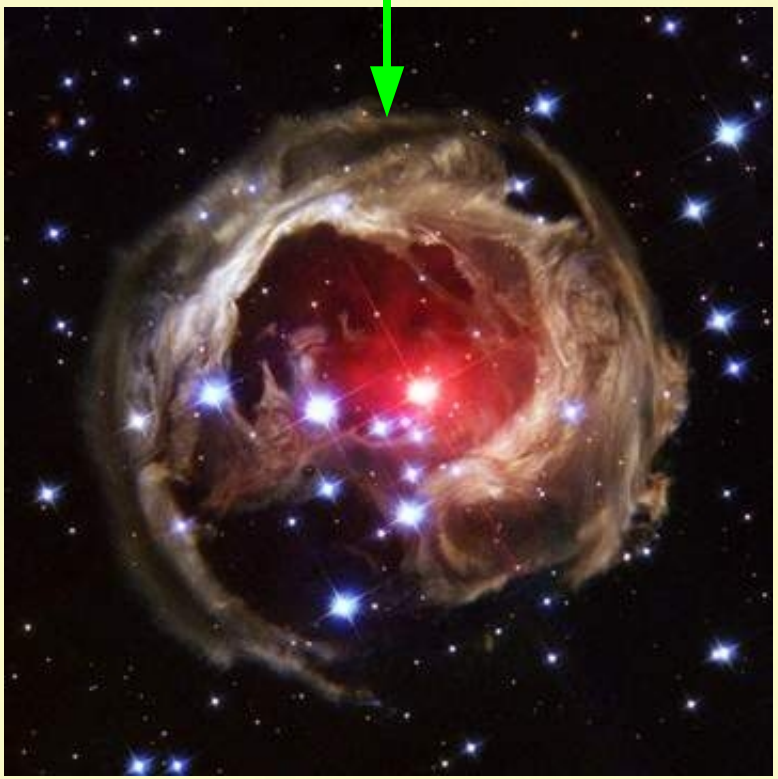
White dwarfs





Novae



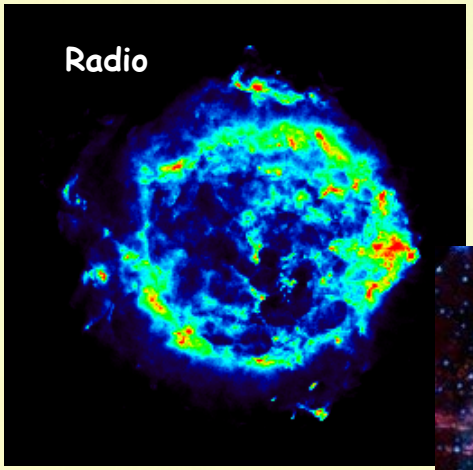


- Nova = white dwarf which is accreting material from a normal star companion in a close binary system
- Accretion brings a new supply of hydrogen to its surface, forming a degenerate and unstable layer
- A mass of about 10^{-3} M_{Sun} may accumulate before the layer ignites
- An increase in temperature in the degenerate hydrogen brings no increase in pressure
- The hydrogen layer therefore explodes rather than expand smoothly
- The whole layer blows outwards as an expanding shell with a velocity of hundreds or a few thousand km per second
- The optical emission lasts a few days
- The radio emission is from an outer shell which is ionized by intense UV light
- The radio emission grows and decays over a typical period of some years. It is thermal, free-free radiation

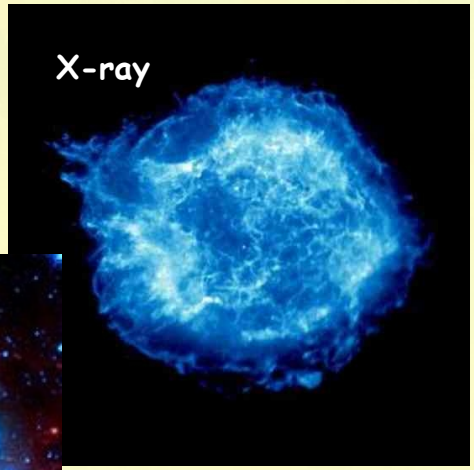
Supernovae (SNae)

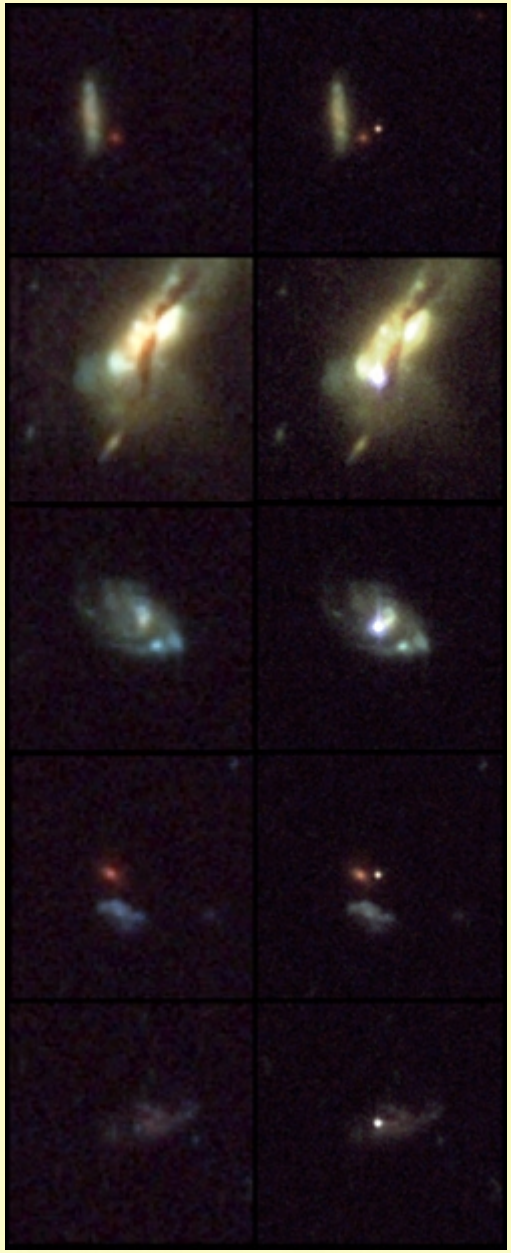
A **supernova** (SN) is the instantaneous release of ~10^{51} ergs of energy, the result of either the gravitational collapse of a massive star or the explosion and complete disruption of a white dwarf accreting mass from a companion star

Although only a small fraction of the energy is released in the form of visible light, this is enough to make it appear as if a new star has appeared in the sky. The effects of the SNae are profound and far-reaching, and it is possible to see the remains of SNae that occured many hundreds of years ago

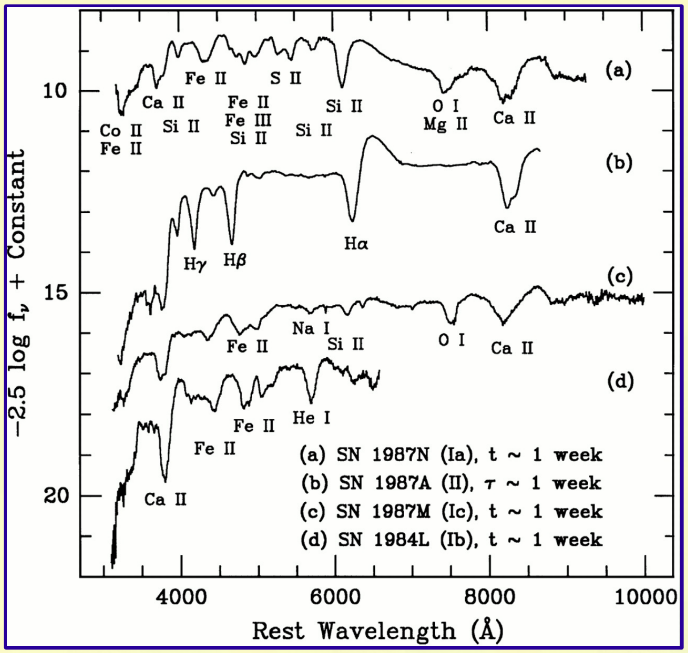






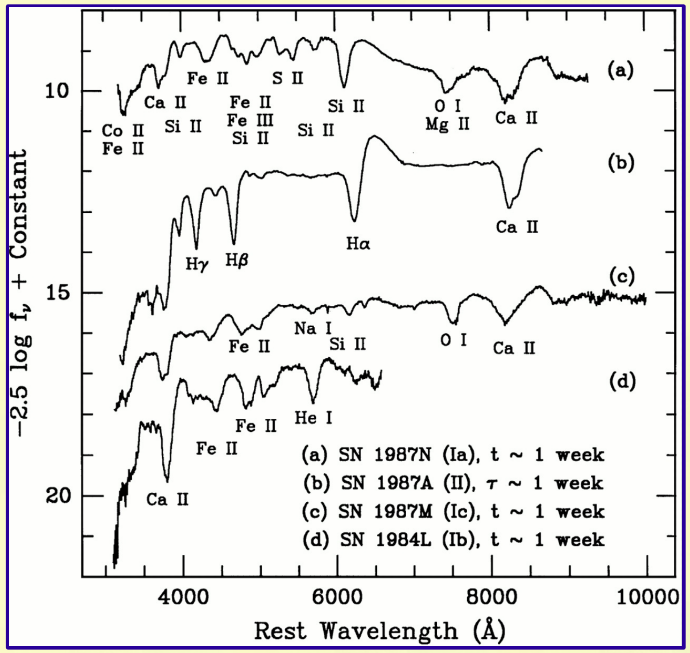


SNae: type I and II



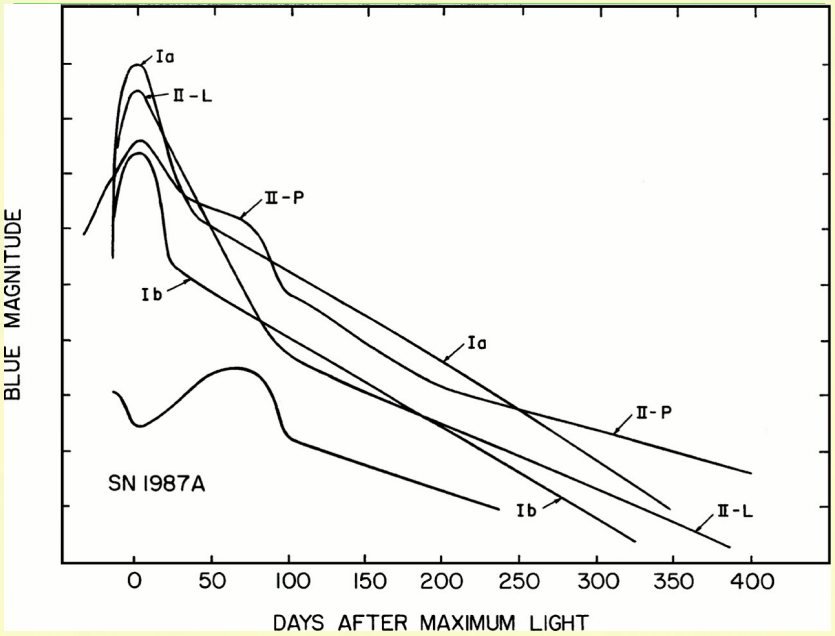
- **Type I(a):** SNae whose spectrum does not show hydrogen lines. They are located in all the different galaxy types
- **Type II:** SNae whose spectrum does show hydrogen lines. Their host galaxies are only spirals with quite open arms. Never in ellipticals or irregular galaxies

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- **Type I(a):** SNae with a very constant shape of the curve of light – rapid rise of the luminosity, which stays at the maximum value for about one week, then steep decrease of the luminosity during the next 25 days, and finally a flatter decrease over about 70 days
- **Type II:** SNae with less constant shape of the light curves, which always have lower maxima



Type II SNae

Gravitational collapse of a young, metal rich, massive stars



- At some point in a massive star's life, the center of the star has been converted to iron, and nuclear fusion in the core is no longer an exothermal process
- Nuclear fusion ceases and, without this source of thermal pressure, gravity, exerting its inexorable pull on the star, seems to be winning the battle
- The star continues its collapse. Then a strange reaction takes place during which electrons and protons are pushed so close together that they merge to become neutrons, releasing energy (remember that a bound system has a lower potential energy than its constituent parts)
- There is no available space between the neutrons: they are supported by neutron degenerate pressure
- This halts the gravitational collapse and the outer, more tenuous stellar material 'bounces' upon hitting the degenerate core, much like a wave hitting a sea wall bounces back on itself
- The conversion of the central core to neutrons releases 10^{51} ergs of neutron binding potential energy, and after the bounce, the outer layers of the star are violently ejected into the ISM

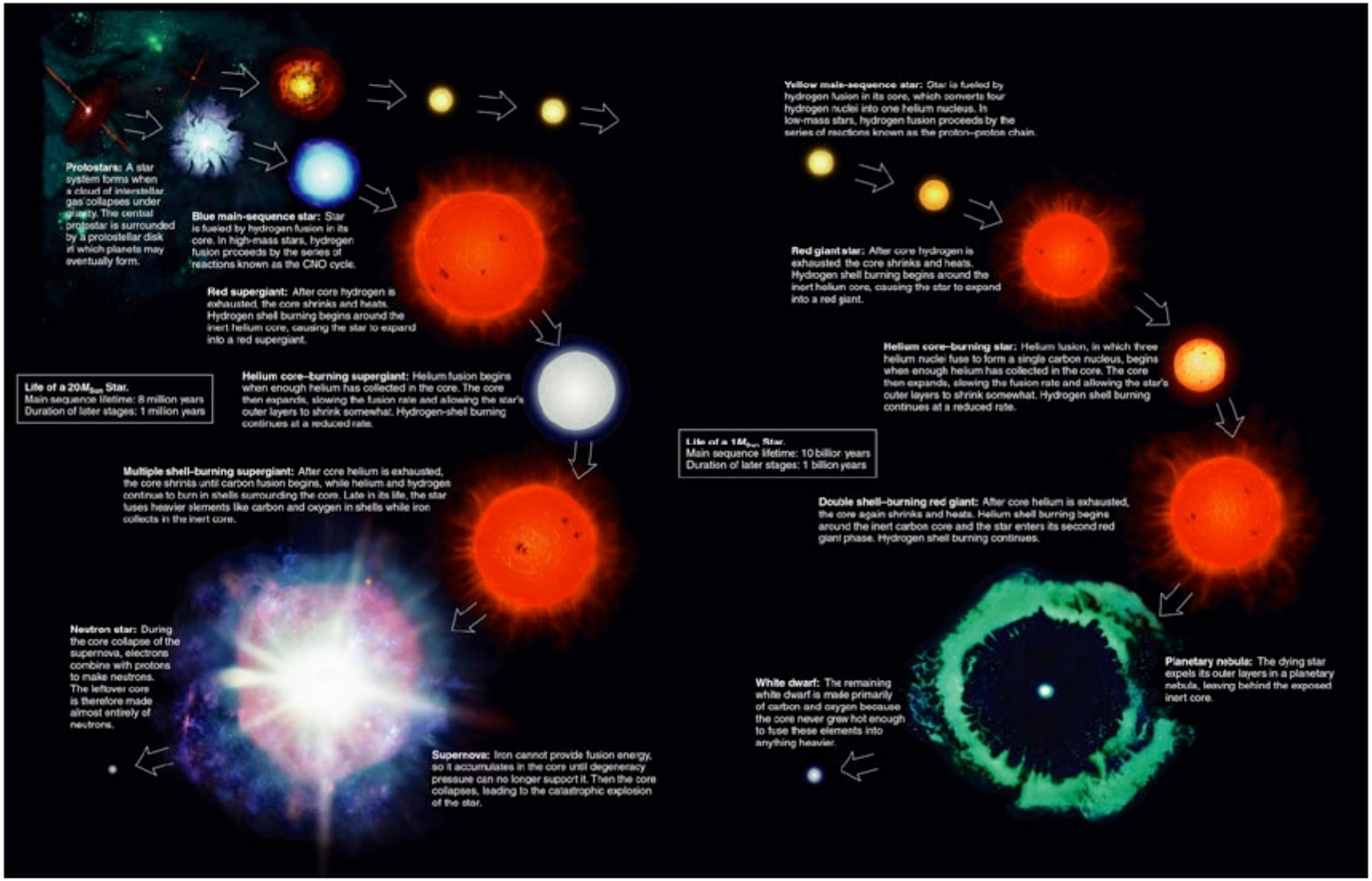
Type I SNae

Explosion of a white dwarf



- In the usual scheme of things, we expect low mass stars to settle down, slowly fizzle out and become white dwarfs
- Their masses are too low to bring about the collapse to a neutron star and the resulting spectacle of a supernova type II explosion
- They resist gravity's pull with electron degenerate pressure, where the electrons are squeezed until there is no more space between them. The gravitational pressure of the star is not enough to cause the conversion to neutrons and the star has reached a stable equilibrium
- However, if the white dwarf is in a binary system with a red giant, it is possible for the dwarf to accrete matter from its companion (like in Novae)
- Type I(a) SNae take place when the accreting material falling onto a white dwarf in a binary system takes it over the mass set by the Chandrasekhar limit - i.e. the maximum non-rotating mass which can be supported against gravitational collapse by electron degeneracy pressure
- The resulting instability triggers a runaway thermonuclear explosion that destroys the star and releases large amounts of radioactive and heavy elements into space
- SNae Ib and Ic: like supernovae of Type II, are probably massive stars running out of fuel at their centers; however, the progenitors of Types Ib and Ic have lost most of their outer (hydrogen) envelopes due to strong stellar winds or interactions with other stars

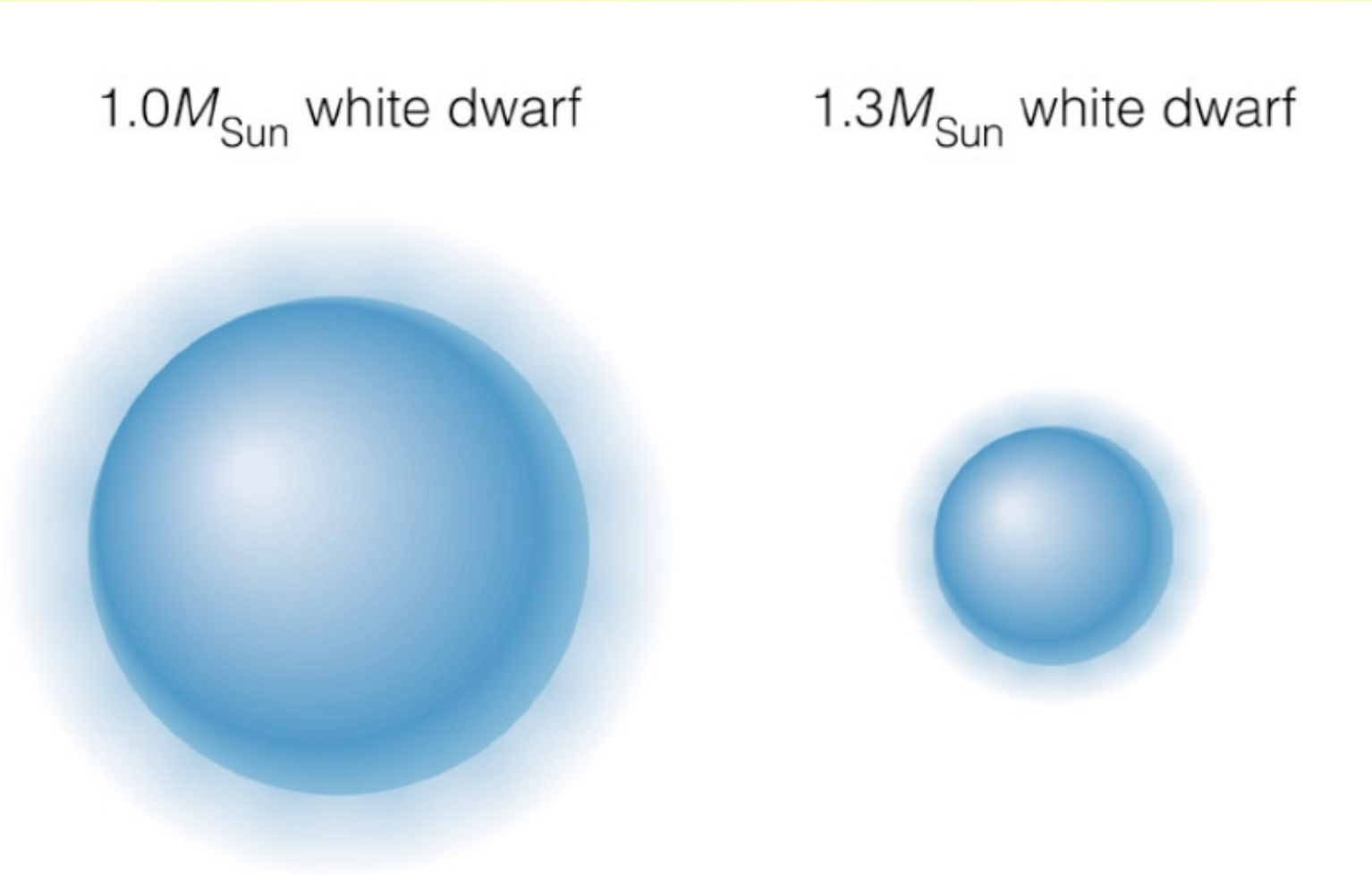
SNa type II or white dwarf?



Life of a $20M_{\text{Sun}}$ star

Life of a $1M_{\text{Sun}}$ star

SNa type I or Nova?



White dwarfs shrink when you add mass to them, because their gravity gets stronger.

Shrinkage of White Dwarfs

- Quantum mechanics says that electrons in the same place cannot be in the same state.
- Adding mass to a white dwarf increases its gravity, forcing electrons into a smaller space.
- In order to avoid being in the same state some of the electrons need to move faster.
- Is there a limit to how much you can shrink a white dwarf?

The White Dwarf Limit

Einstein's theory of relativity says that nothing can move faster than light.

When electron speeds in white dwarf approach speed of light, electron degeneracy pressure can no longer support it.

Chandrasekhar found (at age 20!) that this happens when a white dwarf's mass reaches **1.4** M_{Sun}.



S. Chandrasekhar

SNa type I or Nova?

http://ifa.hawaii.edu/users/iroussev/Lecture28_110f2006.pdf

- **Nova ($<10^5 L_{Sun}$):** H to He fusion of a layer; white dwarf left intact.

- **Supernova ($\sim 10^{10} L_{Sun}$):** complete explosion of white dwarf; nothing left behind.

Compact stellar objects: white dwarfs & neutron stars

Exhaustion of nuclear fuel: collapse of a normal star from its equilibrium state

White dwarfs

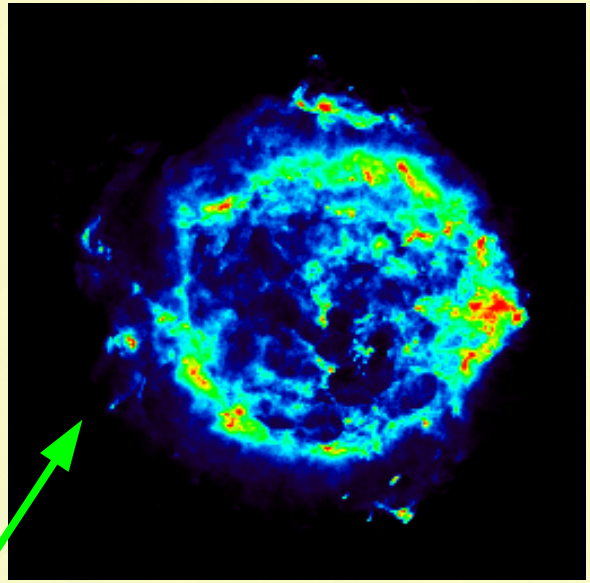
1) collapse under gravitation prevented by the pressure of degenerate electrons
2) 0.02-1.4 M_{Sun}
3) Larger mass --> SNae Ia
4) Properties determined solely by their mass
5) The temperature has no effects on density and size
6) The diameter decreases with increasing mass

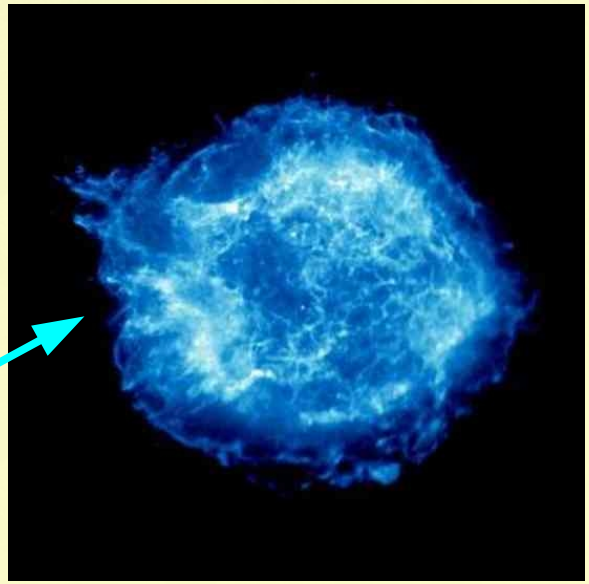
Neutron stars

1) collapse under gravitation prevented by the pressure of degenerate neutrons
2) 0.2-2.0 M_{Sun}
3) Larger mass --> BH (but remember SNae II --> neutron star)
4) Properties determined solely by their mass
5) The temperature has no effects on density and size
6) The diameter decreases with increasing mass

Supernova remnants (SNR)

- After the SN explosion a supernova remnant develops
- It is bounded by an expanding hydromagnetic shock wave
- It consists of ejected material expanding from the explosion, and the interstellar material it sweeps up and shocks along the way
- Initial expansion velocities of about 20000 km/s are observed
- SNR are radio sources – synchrotron emission due to the presence of relativistic electrons and magnetic fields in the shell
- Their radio emission is very well superimposed on the possible residual optical emission
- Many SNRs are also X-ray sources – thermal bremsstrahlung produced by the ionized gas of the expanding shell

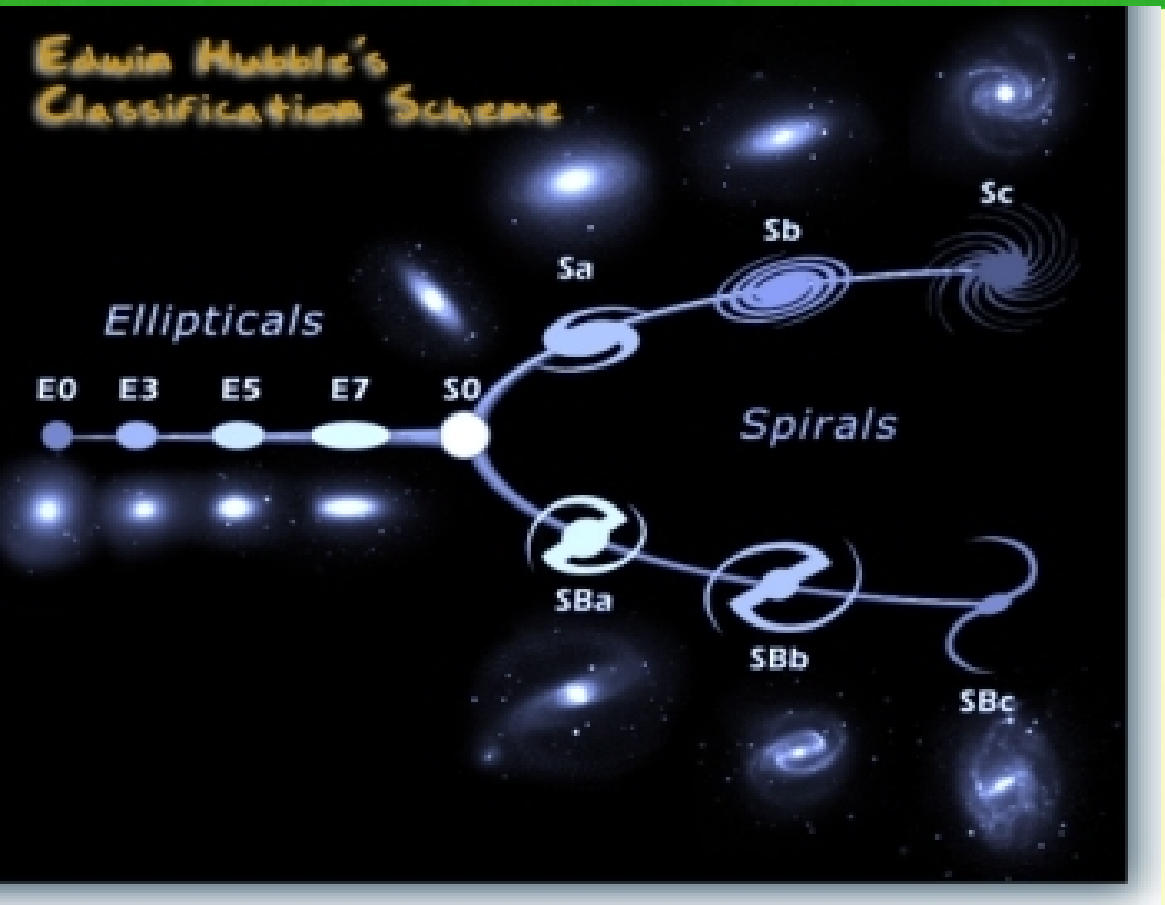




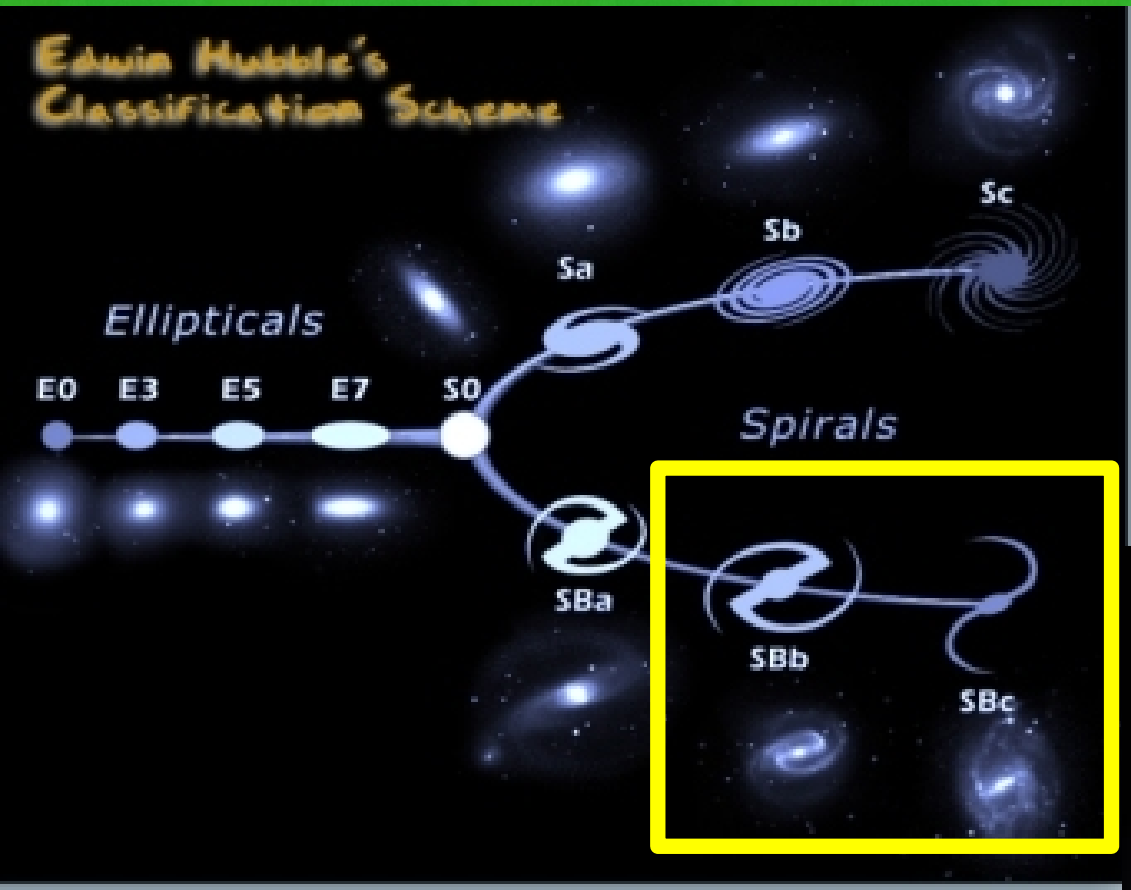
Lecture Outline

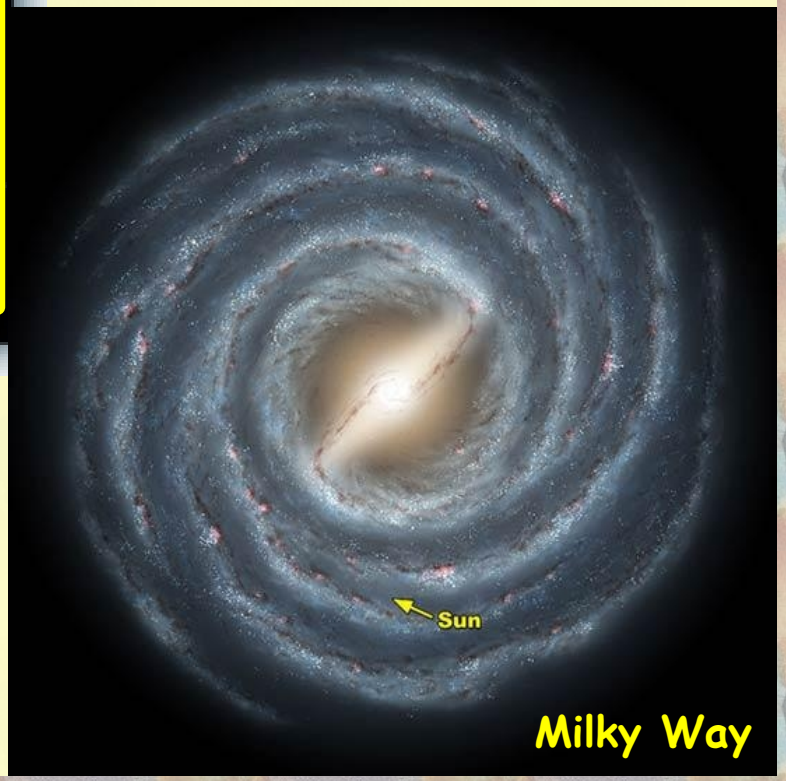
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The Milky Way: a spiral galaxy



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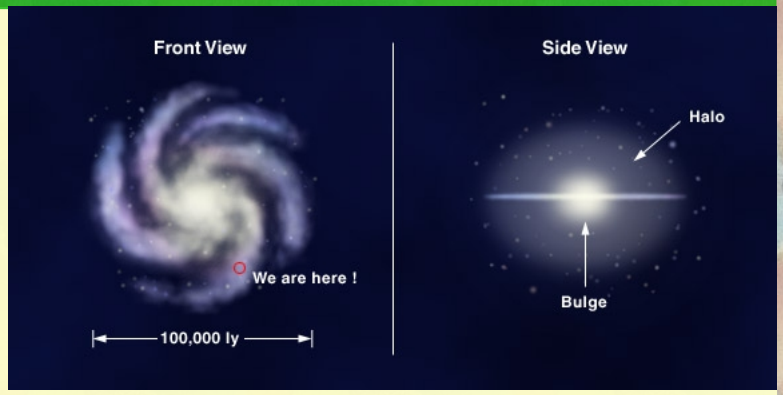
Galactic continuum radiation: optical

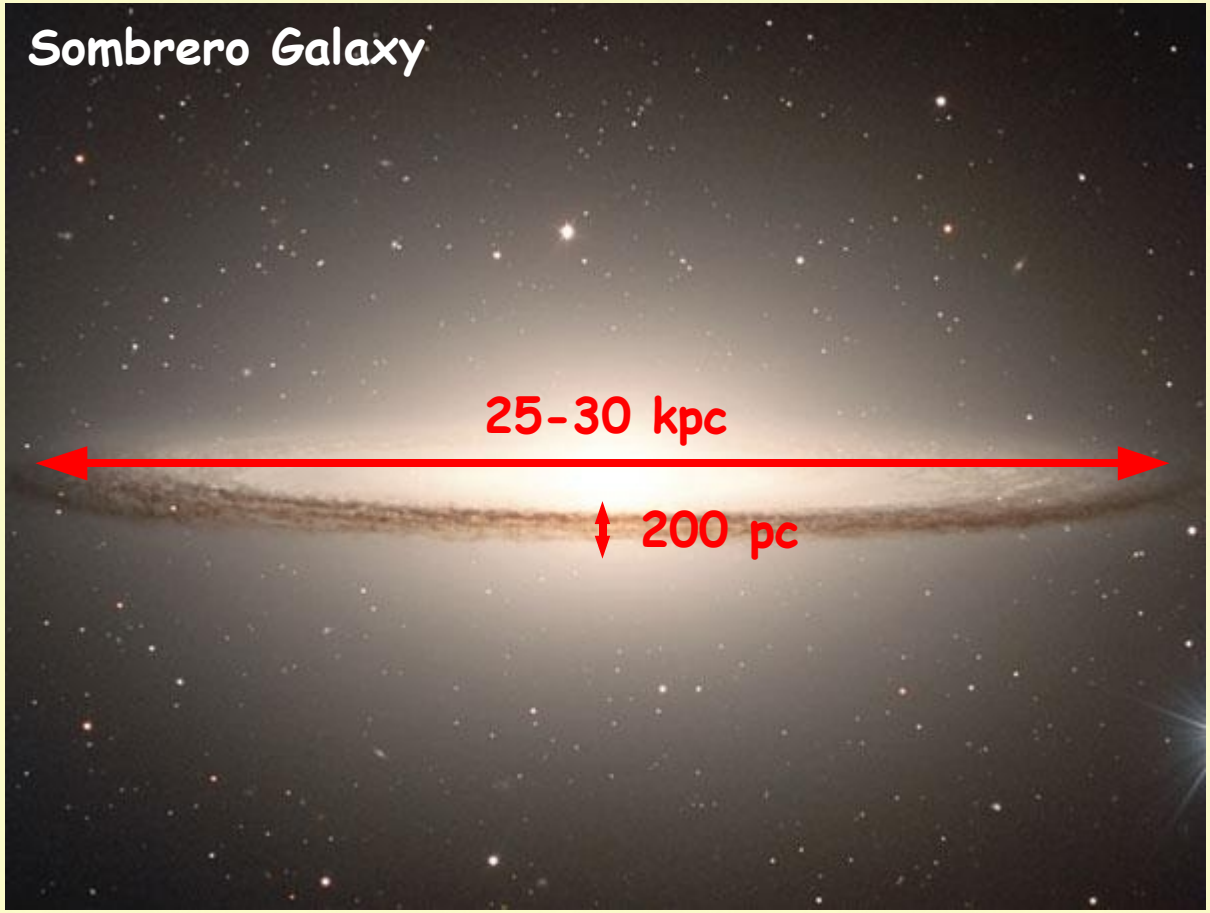
Two components:

a) a disc

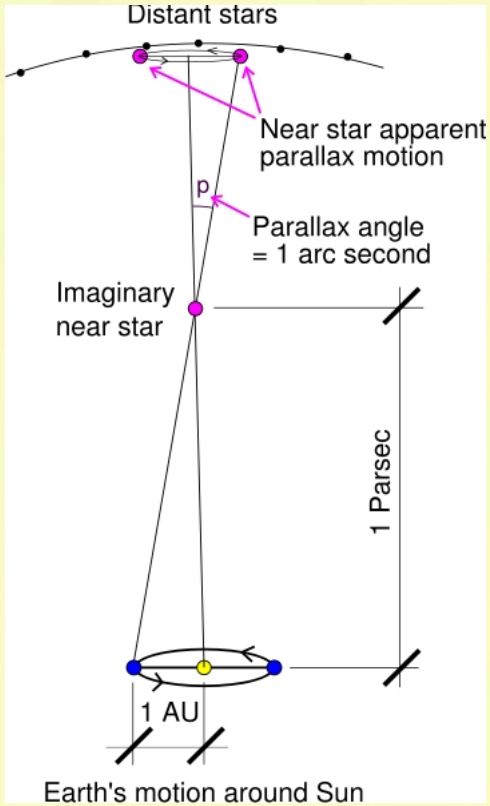
b) a spheroid

Different stellar populations, ISM, kinematics and dynamics





1 pc = 3.0857×10^{16} m



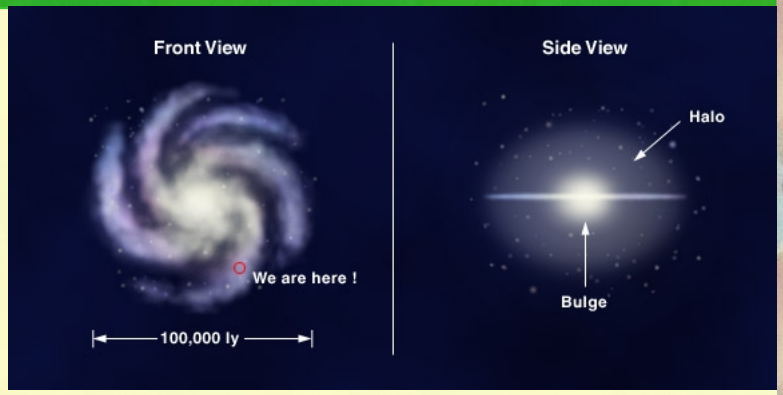
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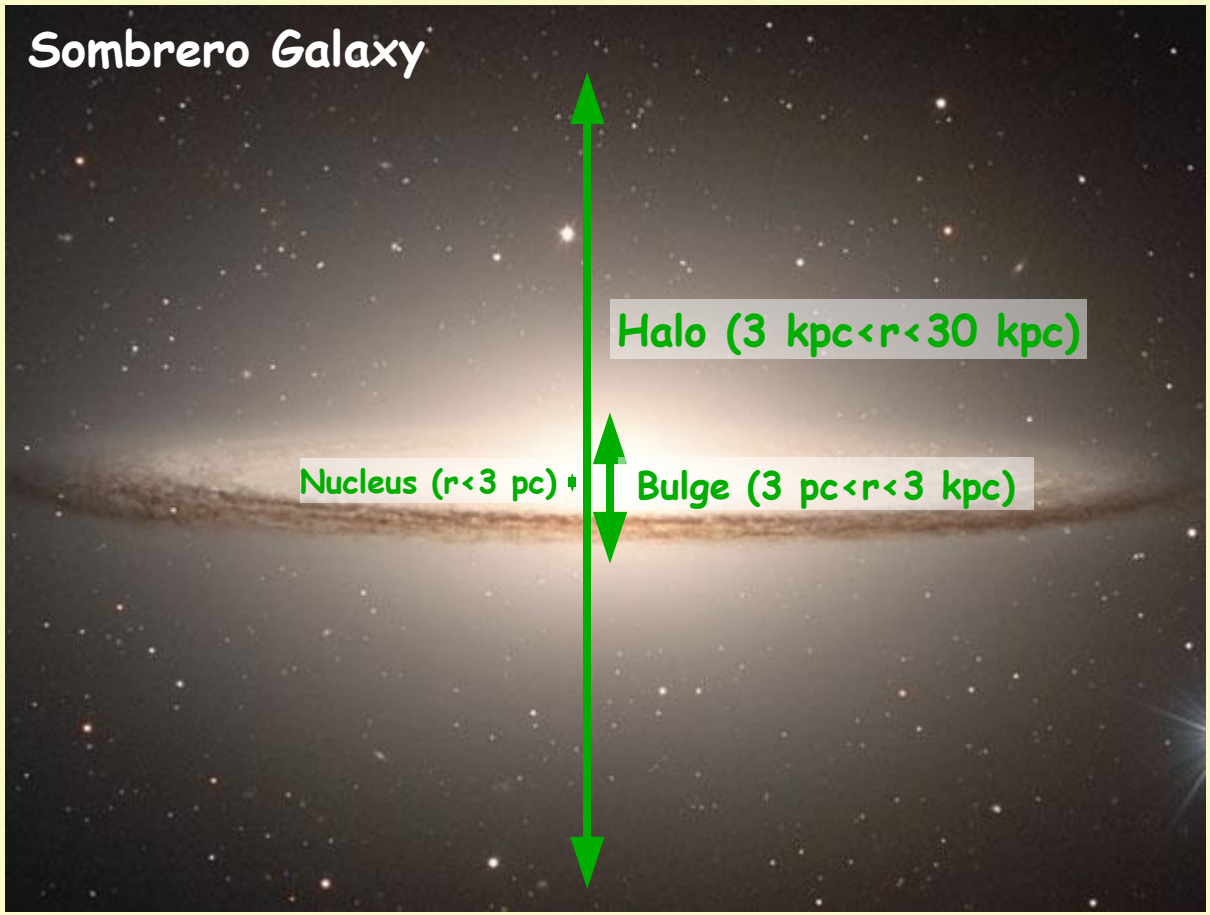
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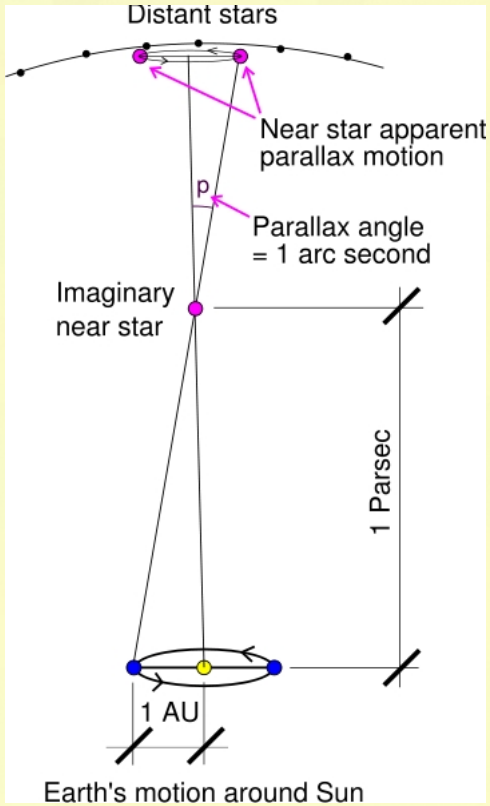
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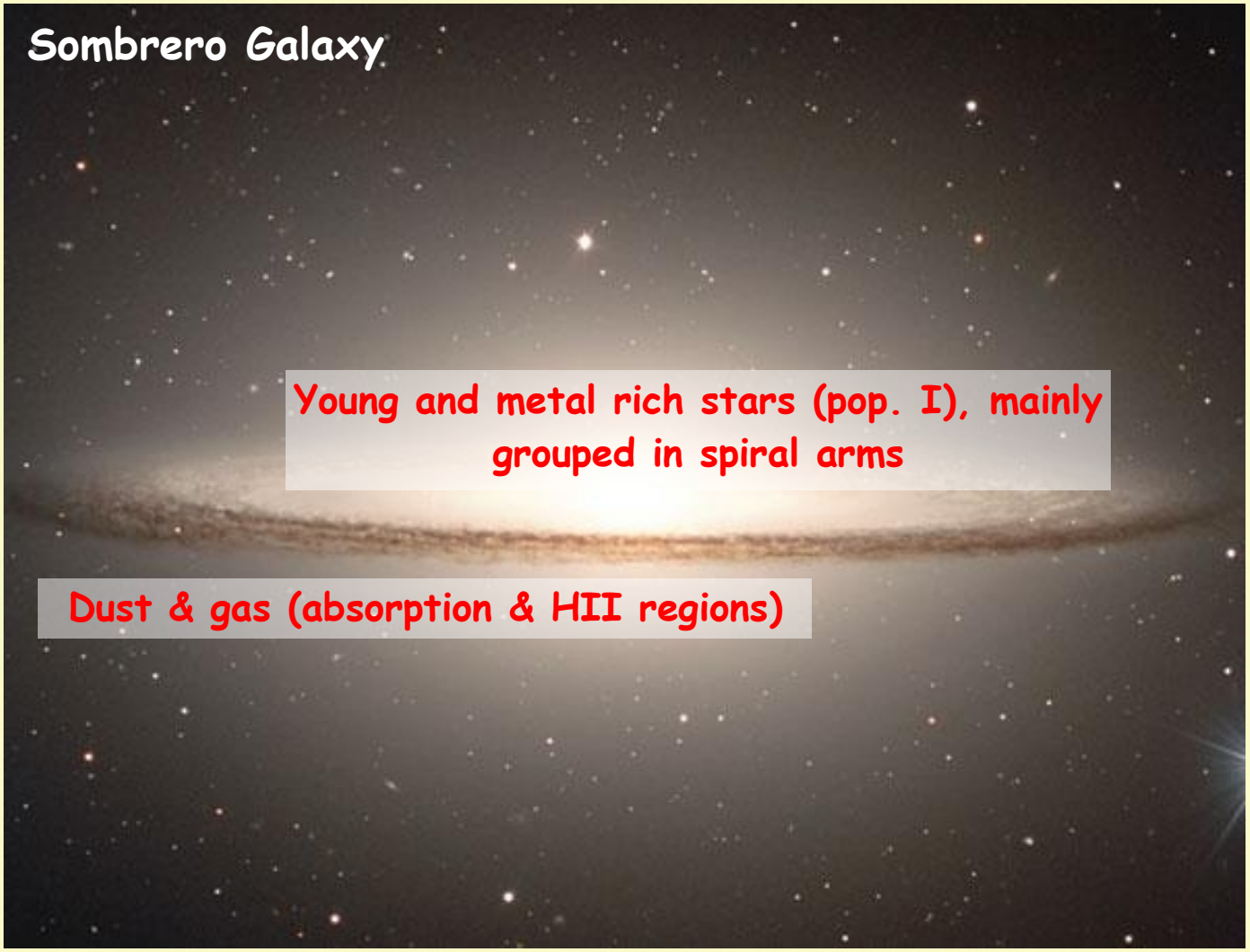


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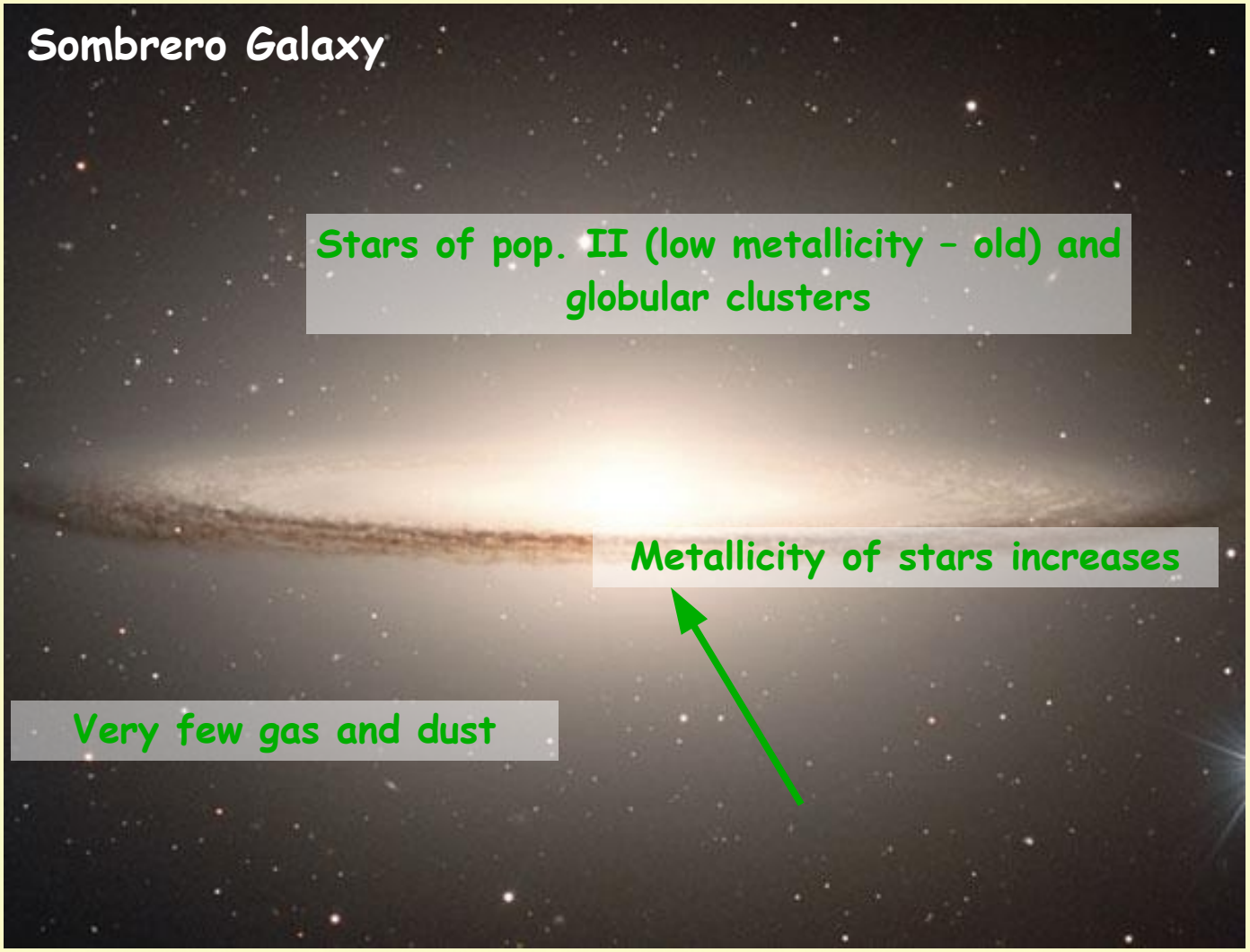


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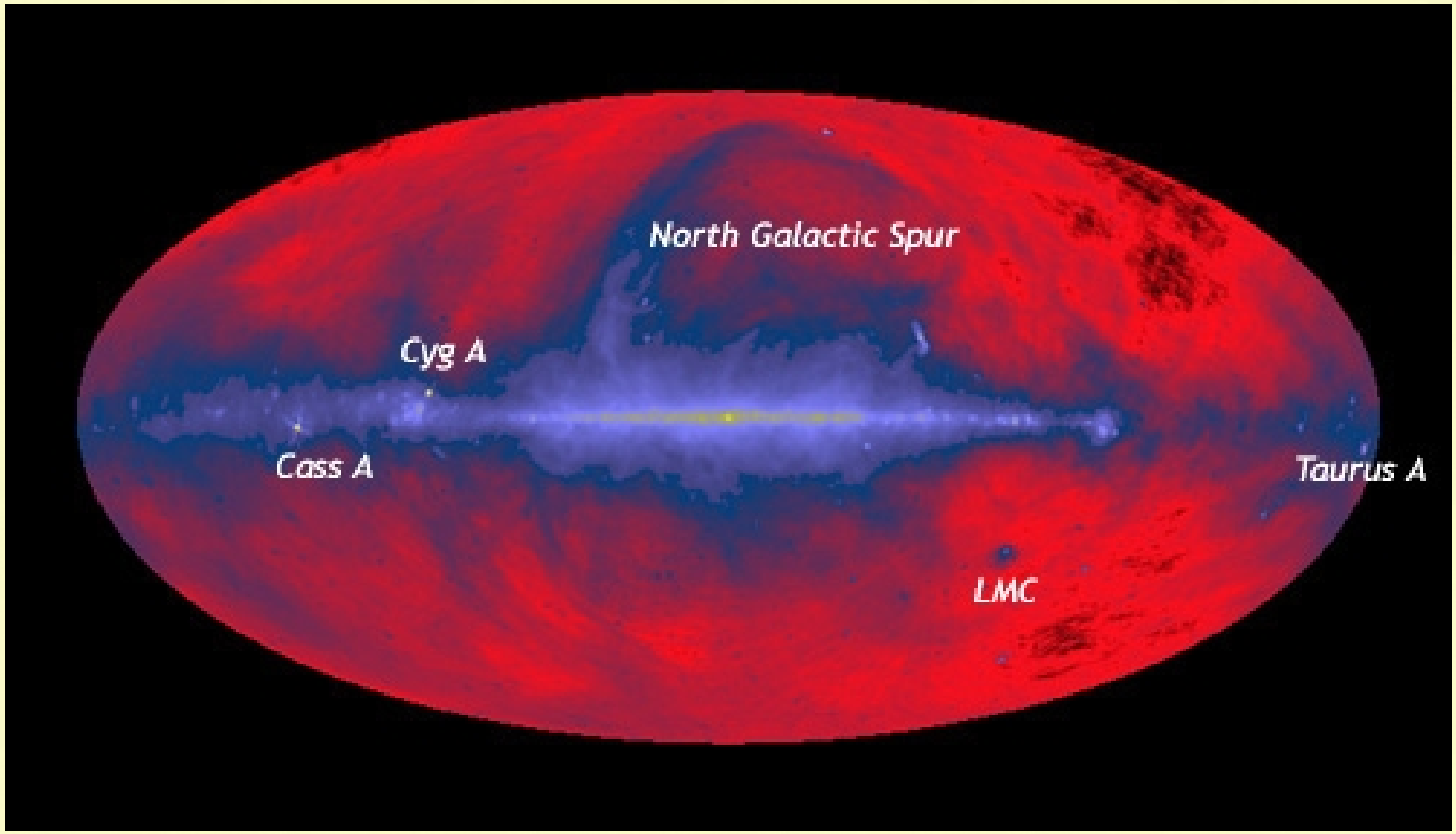


Galactic continuum radiation: radio

Two main components:

a) a disc, corresponding to the optical disc

b) a halo, more extended and with lower brightness

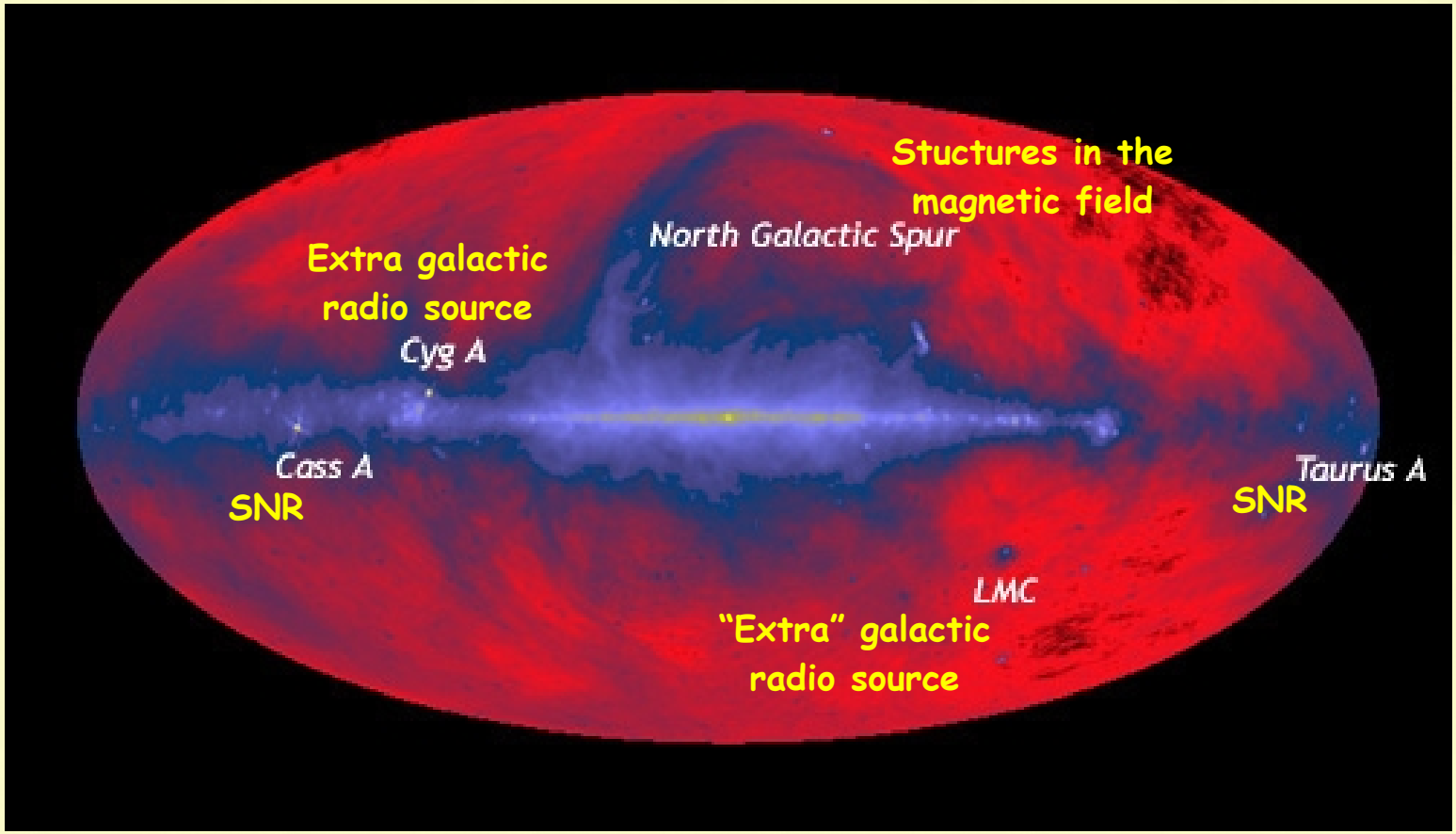


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ν = 115 GHz



→ The halo dominates over the disc at low frequencies – for ν > 1 GHz the halo disappears

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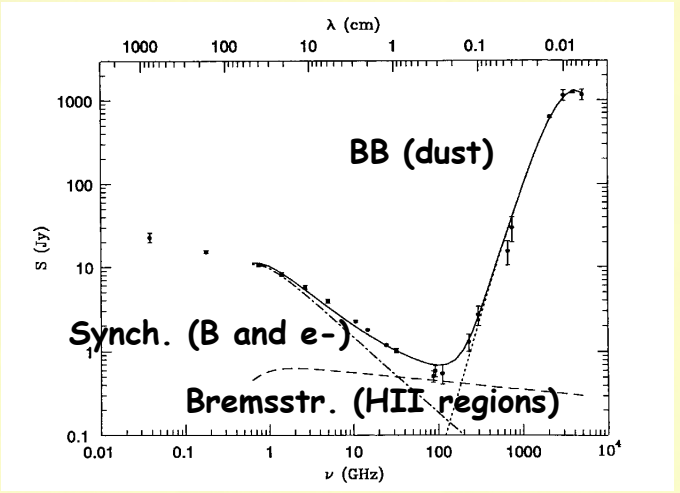


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Two main origins of continuum radio emission:

1) non-thermal (synchrotron) : relativistic electrons and magnetic field – **disc** + **halo**

2) thermal (BB + bremsstrahlung) : dust and ionized ISM – more fragmented - **disc**



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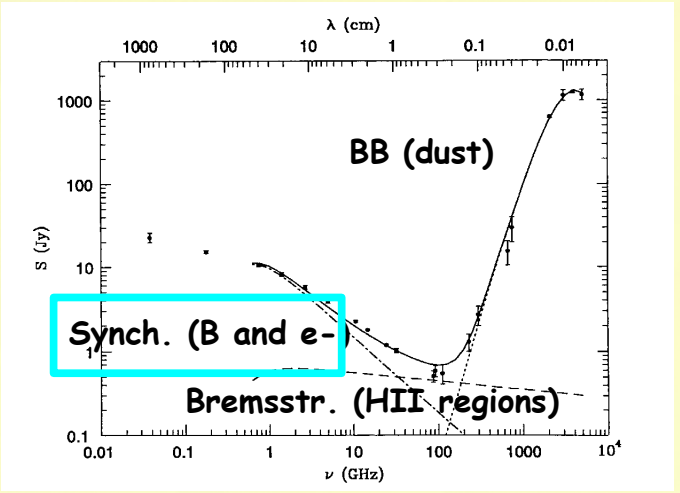


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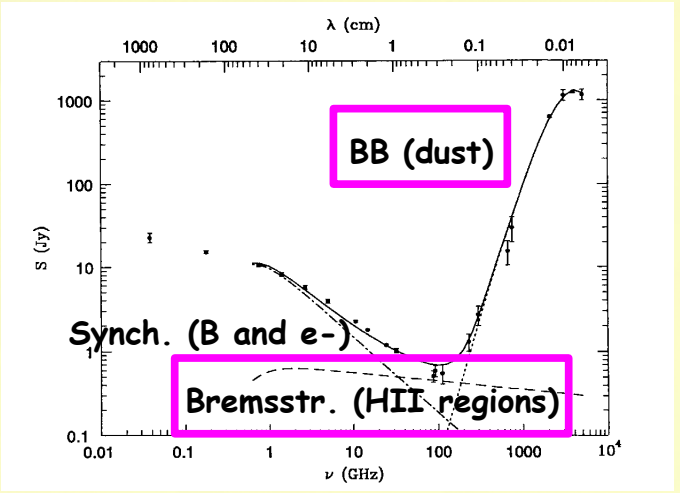


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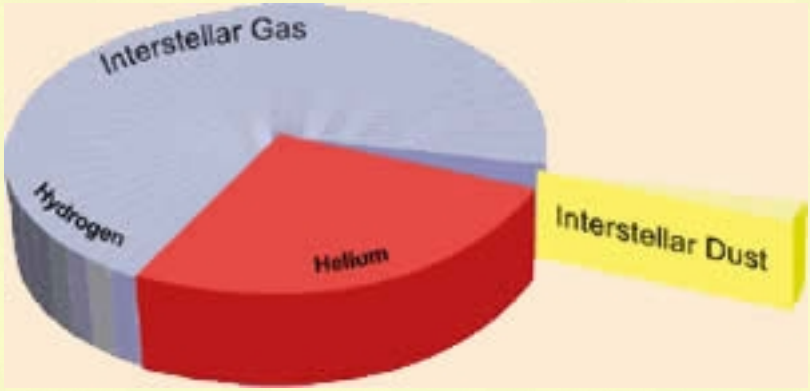
Inter-Stellar Medium (ISM)

5-10% M_{galaxy}: Inter-Stellar Medium (ISM)

(30% in the region of the Sun)

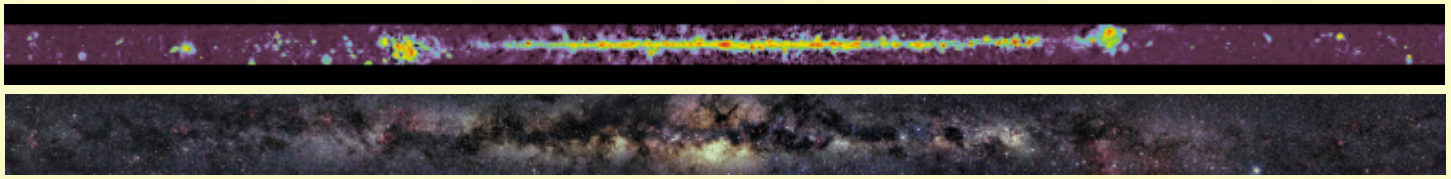
Gas
(atomic and molecular)

Dust



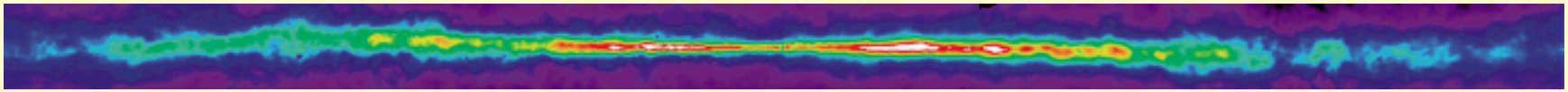
IR

Optical



Main component of ISM: neutral hydrogen - HI

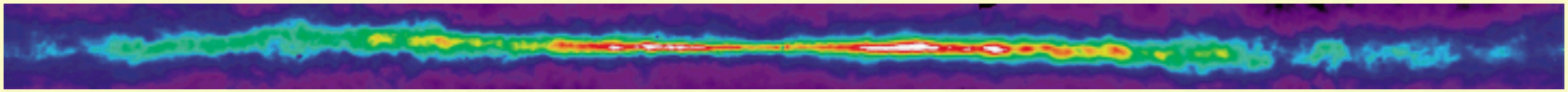
Milky way @ 21.1049 cm <--> 1.4204 GHz

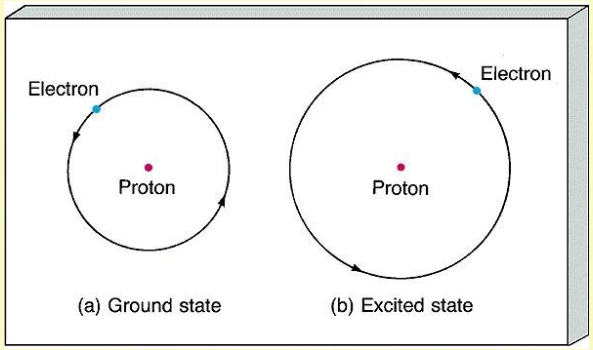


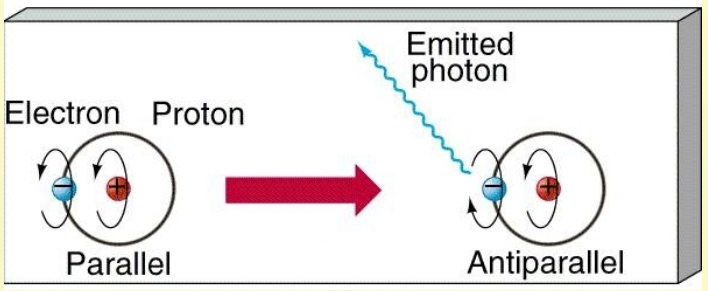
- **Brightness of the emission** → density and kinetic temperature of HI
- **Spectroscopic observations** → rotation curve of our Galaxy (i.e. how its material moves as a function of radius) → mass distribution of the Milky Way

Main component of ISM: neutral hydrogen - HI

Milky way @ 21.1049 cm <--> 1.4204 GHz





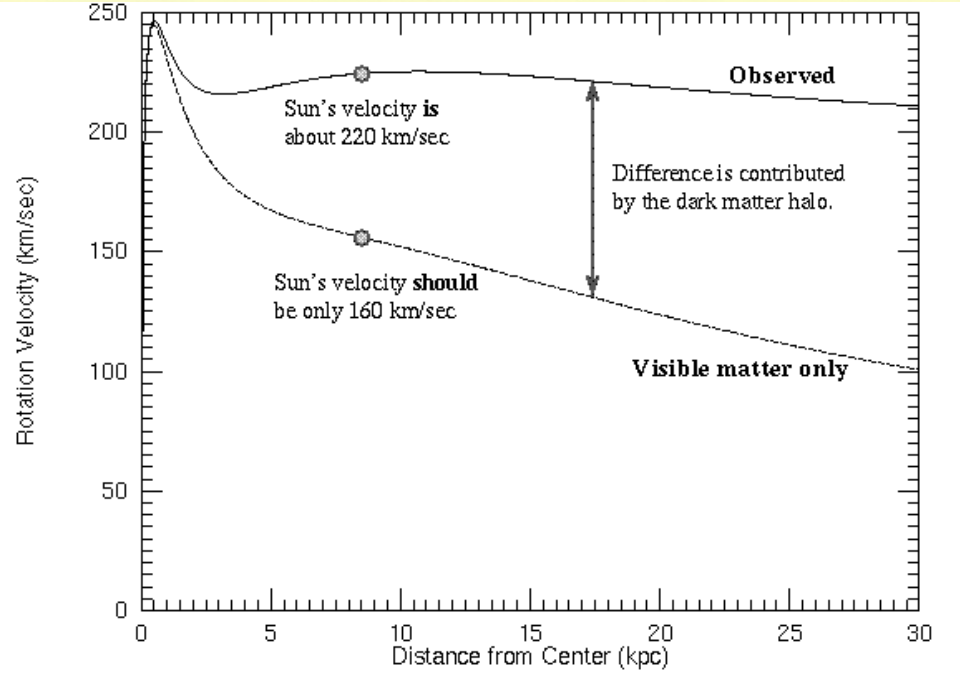


Doppler effect:

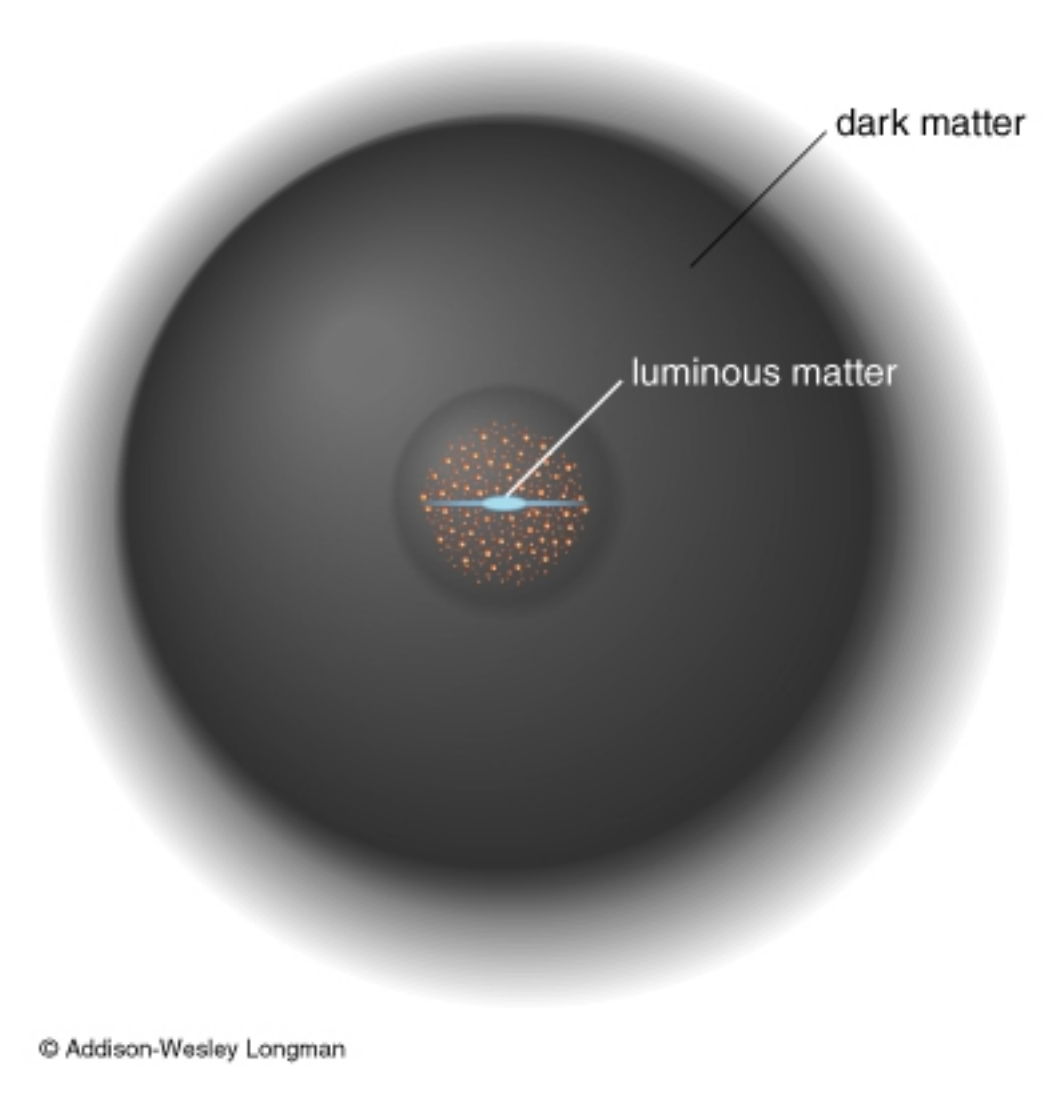
$$\nu_{HI,oss} = \nu_{HI,rest}\left(1 - \frac{v_r}{c}\right)$$

Gravitational force + centripetal acceleration

$$M(R) = \frac{v(R)^2 R}{G}$$

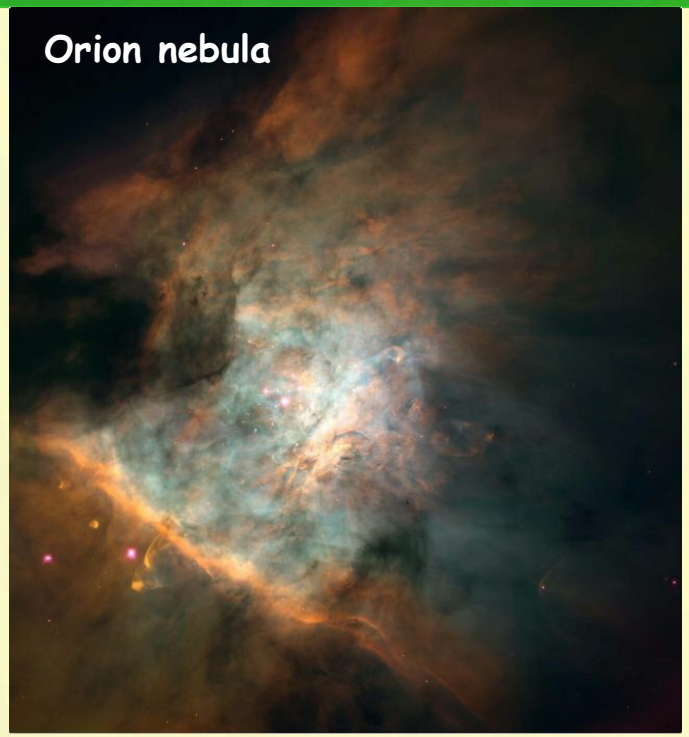


Main component of ISM: neutral hydrogen - HI



Ionized hydrogen: HII

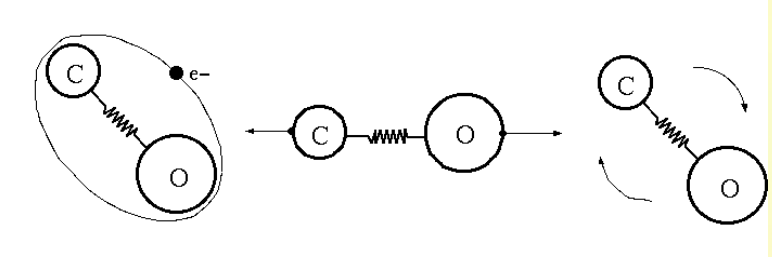
- HII regions are hot, thin hydrogen emission nebulae
- UV photons from hot ($T=10^5$ K), young stars (O-B types) ionize the surrounding hydrogen gas
- Two emission mechanisms:
  - Continuum emission – Bremsstrahlung: due to interactions between free electrons and protons resulting from ionization (radio emission)
  - Line emission: recombination of electrons and protons. Generally the recombination happens in at least two steps → two photons of lower energy (e.l.s in radio, in optical...)

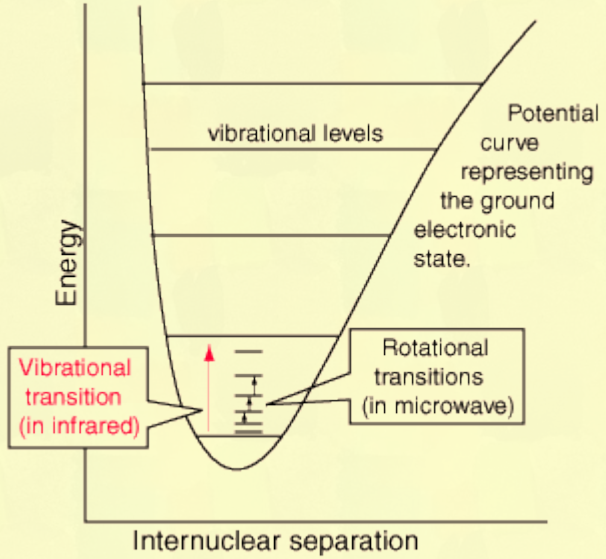




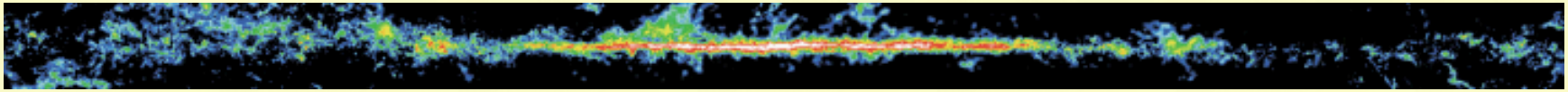
Molecular gas

- Electronic, vibrational and rotational transitions in molecules: they can absorb and emit photons
- Today we know more than 100 kind of molecules in the ISM (most observed at radio wavelengths, i.e. low frequency - energies)
- They trace the region of star-formation
- One of the main molecule that we can study in radio is *CO*, that also traces H_2 as *CO* molecules emit due to collisions with H_2 molecules
- H_2 and *CO* are the most common molecules in the ISM





Molecular gas (*CO*) in the Milky Way (115 GHz map)



Lecture Outline

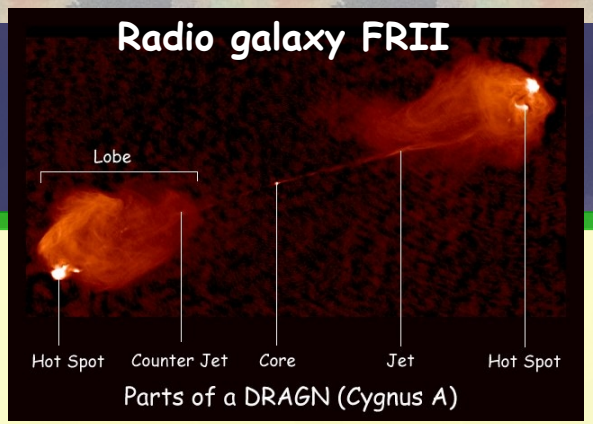
- Examples of galactic radio sources
  - Supernovae
  - Galactic continuum radiation and the inter stellar medium
- Examples of extra-galactic radio sources
  - **Active Galactic Nuclei (AGN)**
  - Galaxy clusters
  - Cosmic Microwave Background (CMB)
  - Epoch of Re-ionization (EoR)

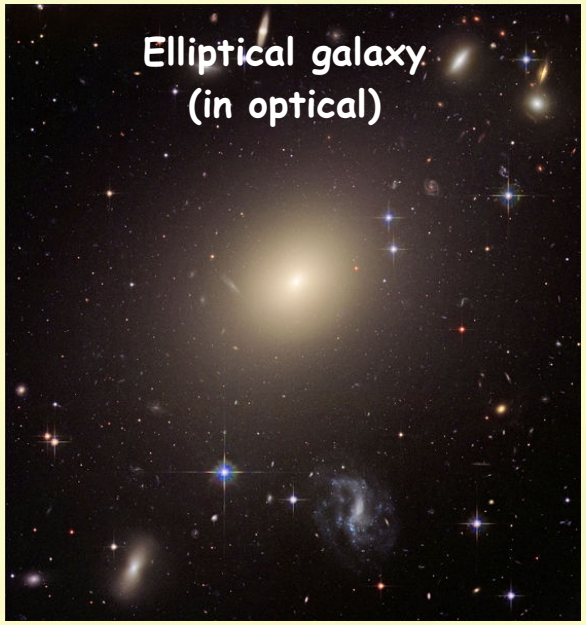
Active Galactic Nuclei

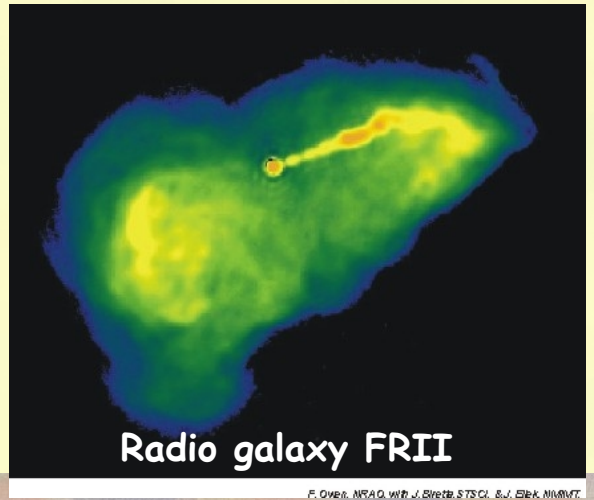
- **Active galactic nucleus (AGN)** = compact region at the center of a galaxy which has a much higher than normal luminosity over some or all of the e.m. spectrum
- **Active galaxy** = galaxy hosting an AGN. The radiation from AGN is believed to be a result of accretion on to the super-massive black hole at the center of the host galaxy
- **Black hole** = extremely dense object with a gravitational field so powerful that a region of space becomes cut off from the rest of the universe – no matter or radiation that has entered the region can ever escape: black holes are so massive that their escape velocity is faster than the speed of light. Since nothing can travel faster than light, nothing can escape the gravity of a black hole

Different class of active galaxies:

- **Radio galaxies**
- **Quasars**
- **Seyfert galaxies**
- **BL Lac & OVV**
- (LINERS, Nuclear HII regions, Star bursts, Strong IRAS galaxies...)



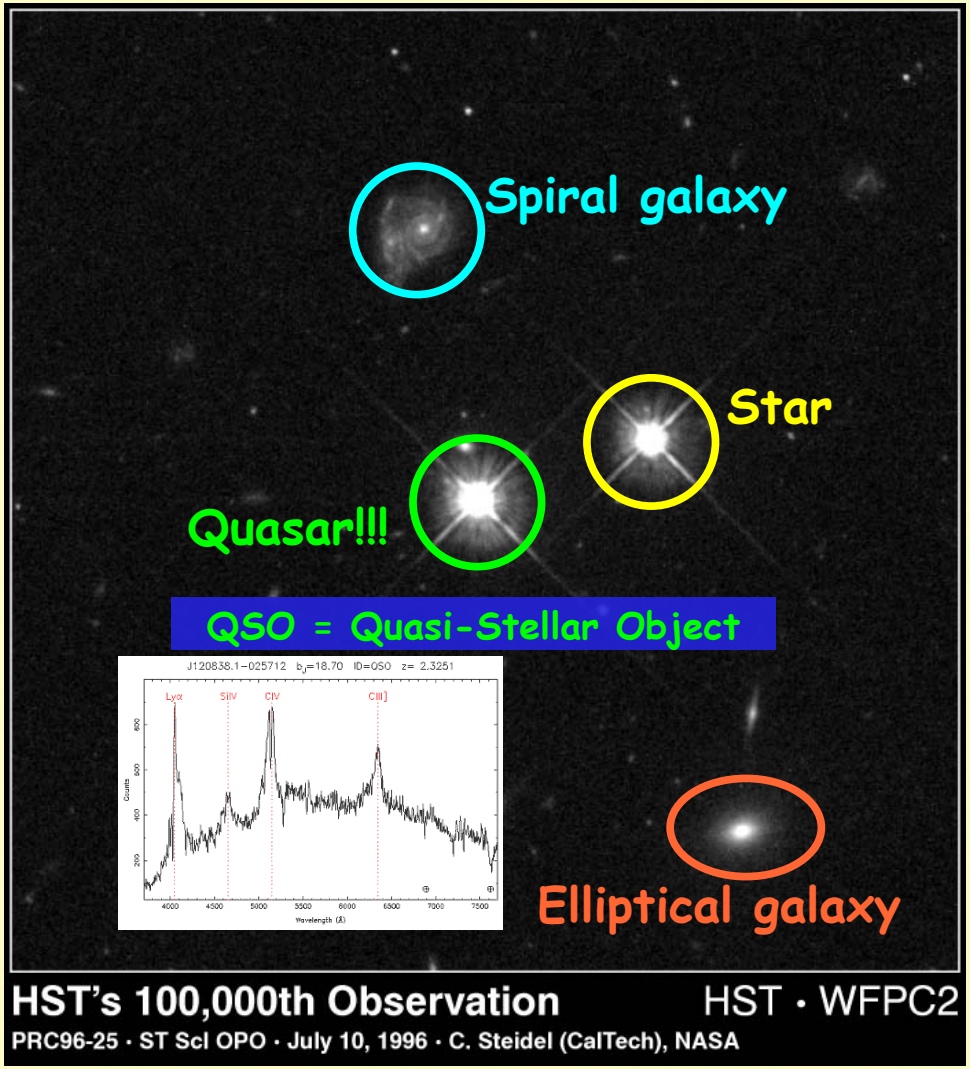




Radio galaxies

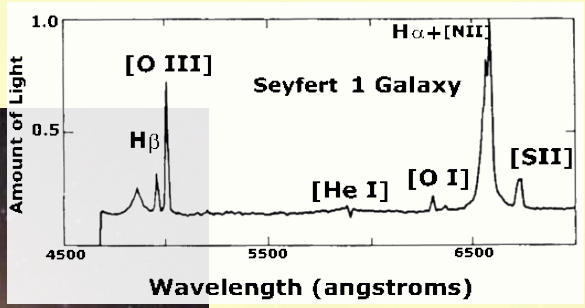
- Low power radio emission from most of the galaxies ($L_{radio} < 10^{22}$ W/Hz)
- Radio galaxies have much stronger radio emission
- They are associated to giant elliptical galaxies
- Based on their radio power/morphology they are classified as (FR stands for Fanaroff and Riley who introduced this classification):
  - **FRI** ($L_{radio} < 10^{24.5}$ W/Hz): jets are subsonic close to the nucleus, creating a diffuse structure with no obvious concentrations (hot-spots) at the extremes. The lobes are extended compared to the total size of the radio source, and not aligned with the nucleus
  - **FRII** ($L_{radio} > 10^{24.5}$ W/Hz): jets are supersonic, therefore faint and very well collimated. They give rise to two well separate lobes and give up their energy mainly in very bright hot-spots.

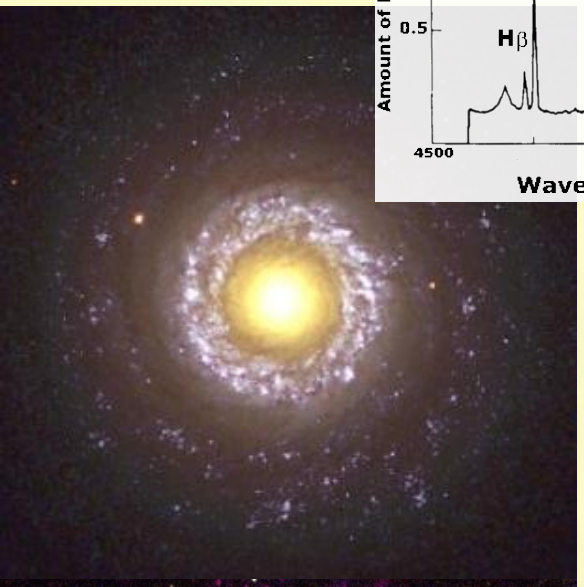
Quasars

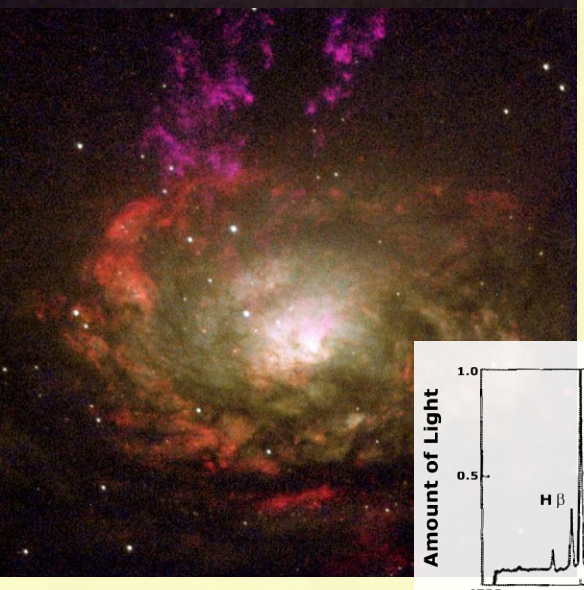


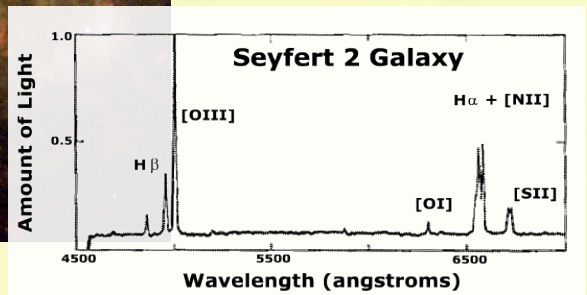
- They are the most powerful AGN
- Associated to both elliptical and spiral galaxies
- Mostly emitting in: IR, Optical, UV, X-ray
- Their optical emission is dominated by a non-resolved nucleus (<1"), often blue, very bright
- Very wide emission lines in their spectrum
- 10% are strong radio sources, with morphological features similar to the most extreme FRII
- Thus:
  - **Quasar radio quiet** (90%) - not really quiet... ($L_{radio} < 5 \times 10^{24}$ W/Hz)
  - **Quasar radio loud** (10%)

Seyfert galaxies



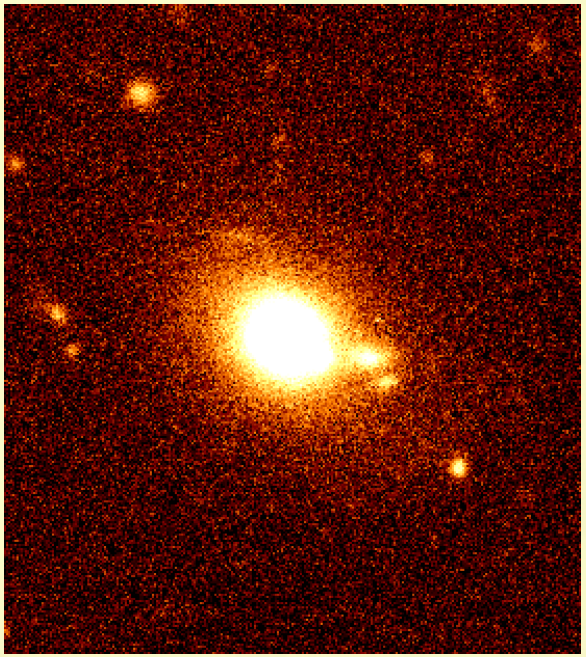


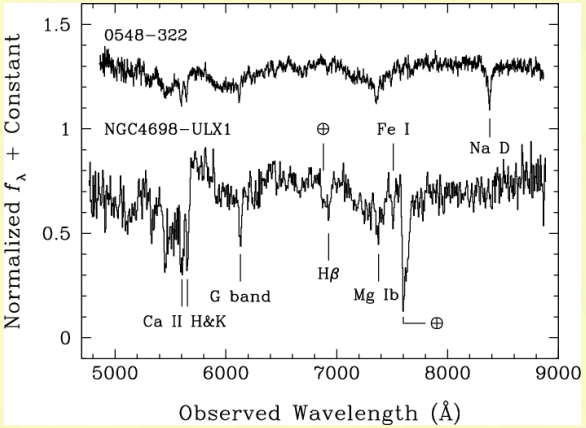




- Associated to bright spiral galaxies
- Like QSOs, bright sources in: IR, Optical, UV, X-ray
- Generally weak radio emission (L_{radio} ~ 10^{20}-10^{23} W/Hz)
- Their spectra are characterized by high excitation emission lines
- Classified as:
  - **Seyfert 1 (Sy1)**: broad allowed emission lines and narrow forbidden emission lines. The continuum emission of the quasi-stellar nucleus is non-thermal, as in QSOs
  - **Seyfert 2 (Sy2):** both allowed and forbidden emission lines are narrow
- The difference is related to the velocity at which the gas in the galaxy's central regions is moving:
  - **Sy1**: σ_v ~ 5 - 10 x 10^3 km/s
  - **Sy2**: σ_v ~ 5 x 10^2 km/s

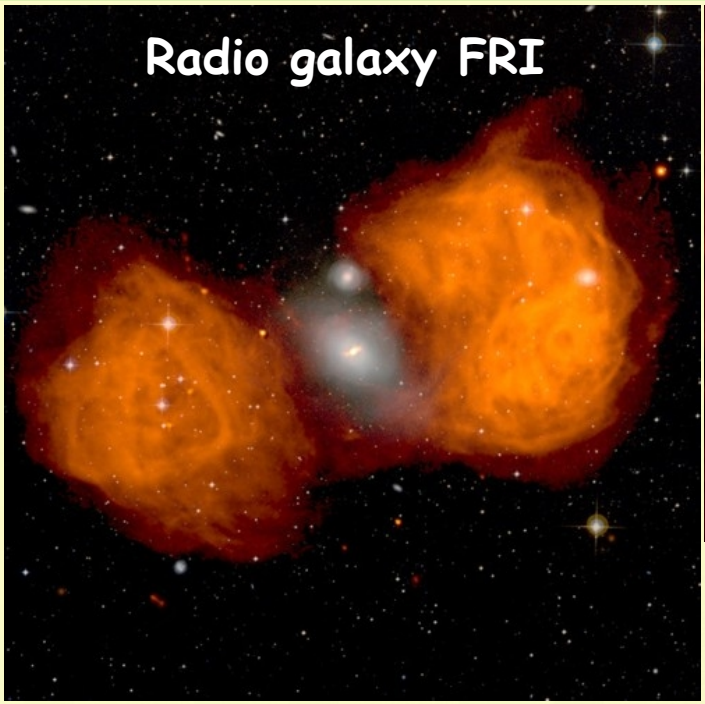
BL Lac

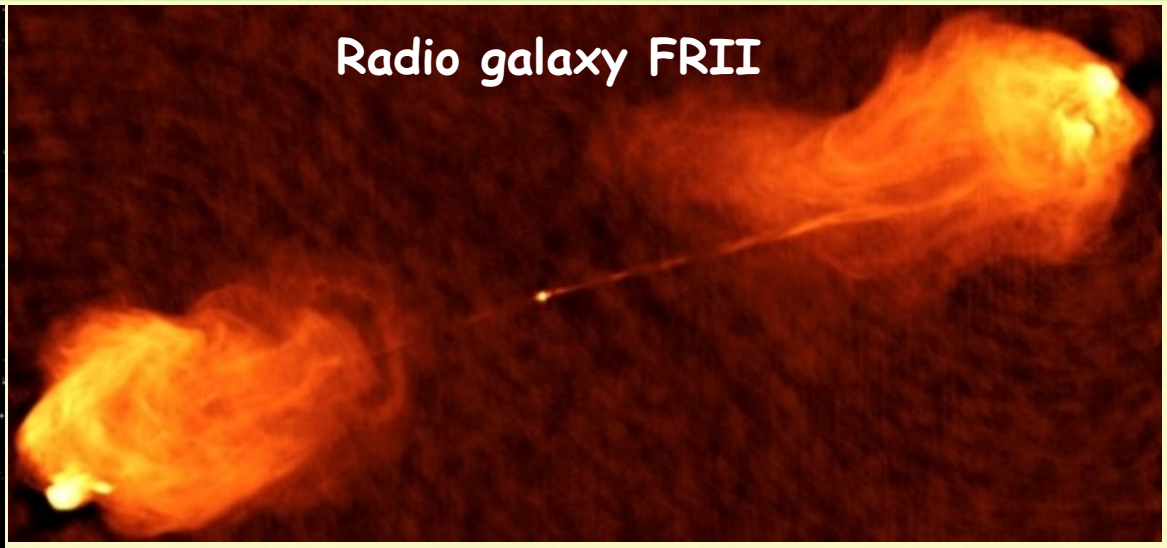


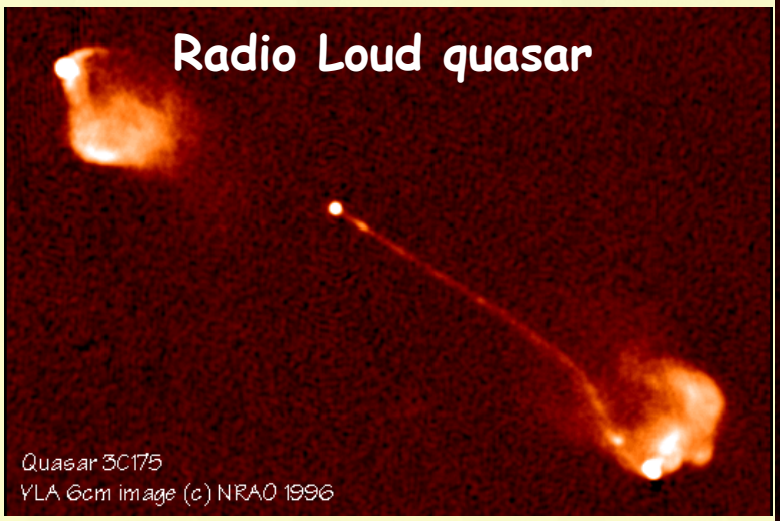


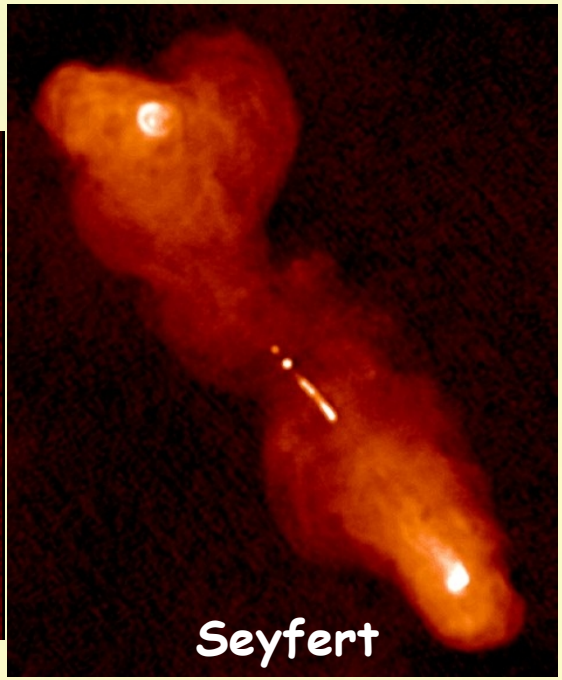
- Associated to bright elliptical galaxies
- Like QSOs, bright sources in: IR, Optical, UV, X-ray
- They are ALWAYS radio emitting
- Strongly polarized radio emission (synchrotron)
- Unlike the other AGN, BL Lac are characterized by rapid and large flux variability (their name derives from the prototype of this class of sources BL Lacertae, originally thought to be an irregular variable star in our Galaxy)
- Absence of emission lines in their spectra:
  - There is not gas enough to be ionized
  - The continuum is so strong that it "masks" the lines
- Optically Violently Variable (OVV) quasars: very similat to BL Lac, but with broad e.l. in their spectra
- OVV + BL Lac = Blazars... but: are we sure that they are the same kind of objects?! NO!!!

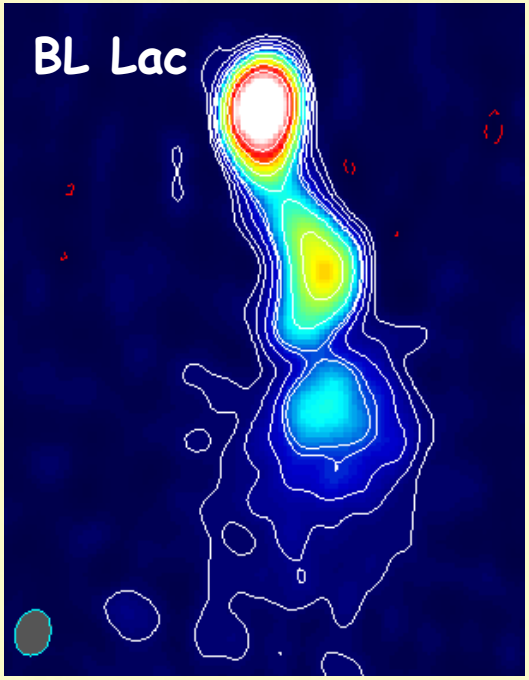
AGNs in the radio band





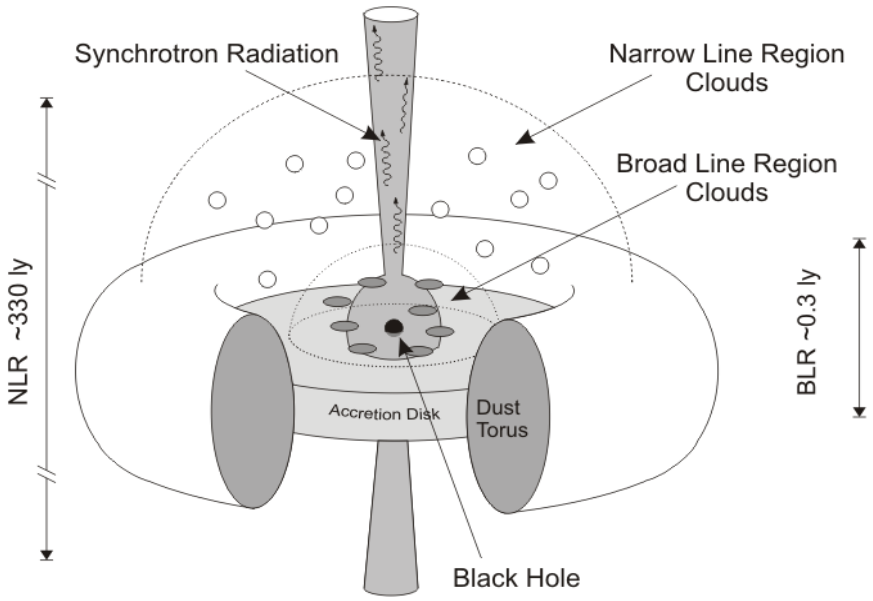






Unified model of active galaxies

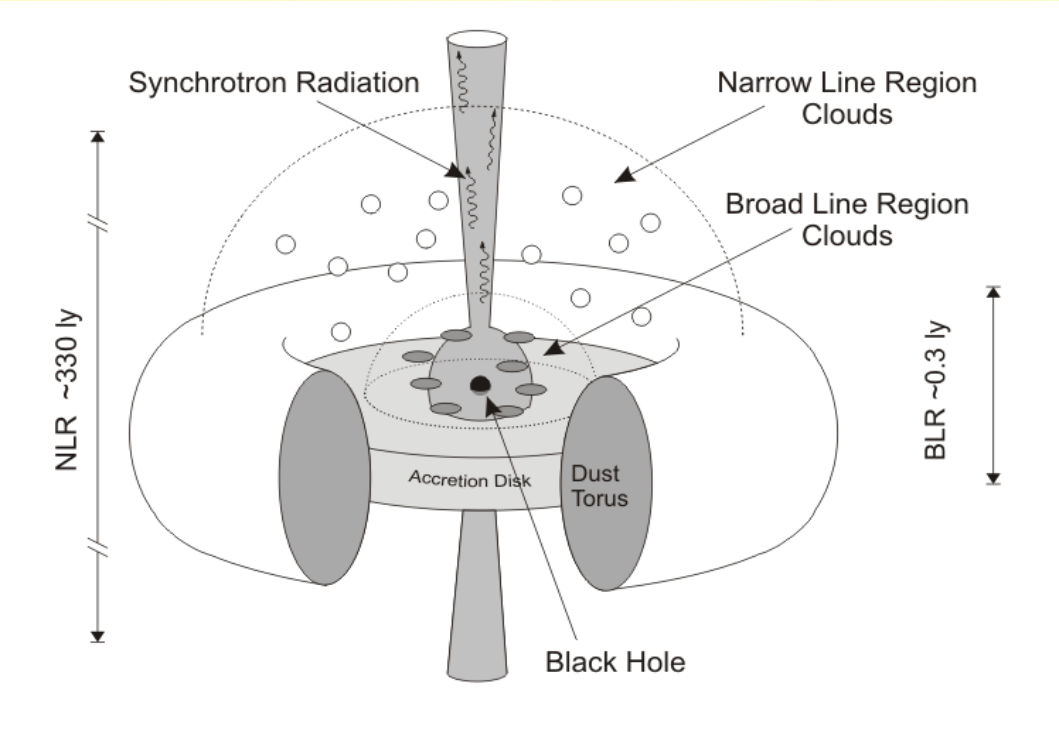
Probably oversimplified (as soon as observations reach closer to active nucleus), but good approximation for many of the phenomena



- **Active Galactic Nucleus (AGN):** central energy source (black hole)
- **Accretion disc:** concentration of material infalling onto the BH
- **Thick torus:** torus of accreting material, cooler and opaque to make the thin disc invisible from the side
- **Broad Line Region (BLR):** region of highly ionized gas at about 1 pc from the BH
- **Narrow Line Ragion (NLR):** region of less ionized gas at about 10-100 pc from the BH
- **Pair of jets:** energetic material ejected from the nucleus along the polar directions

→ Distinctions between active galaxies arise from:
- differences in the strength of these components
- above all, difference in the line of sight orientation

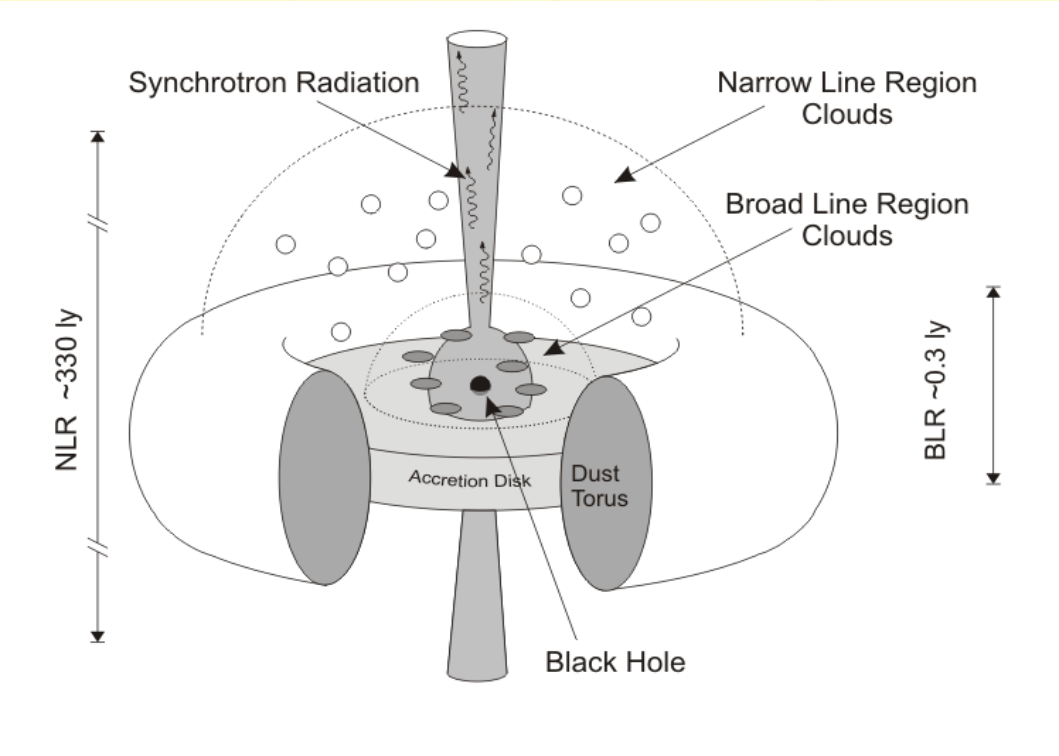
Unified model: the central black hole



Central black hole:

- 10^6-10^9 solar masses within 0.01 pc or even less (about our Solar System size)
- The energy of the AGN derives from the potential energy of the surrounding material, released as it falls into the BH
- Material = ISM + stars
- It emits synchrotron radiation over the whole spectrum, from radio to gamma rays

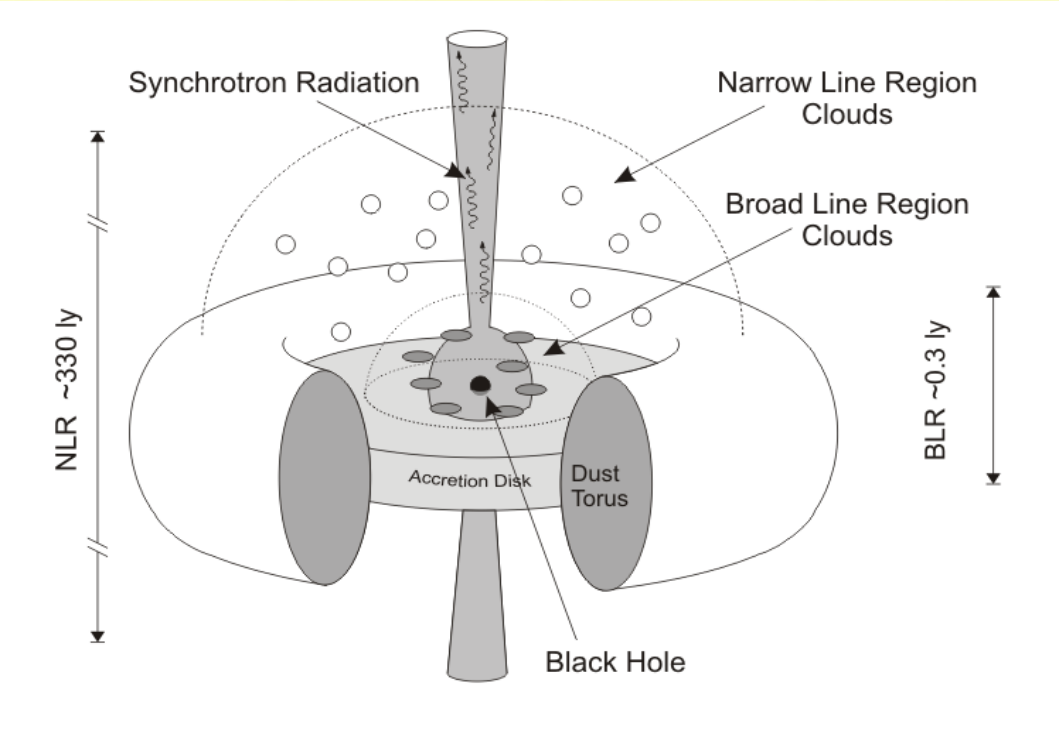
Unified model: the accretion disc



Accretion disc:

- Only few parsecs across: need of an incredibly high angular resolution
- Radiation from the disc is thermal: the continuum spectrum should provide the temperature
- But T far from uniform over the disc: the observed spectra are composites of thermal radiation over a range of T

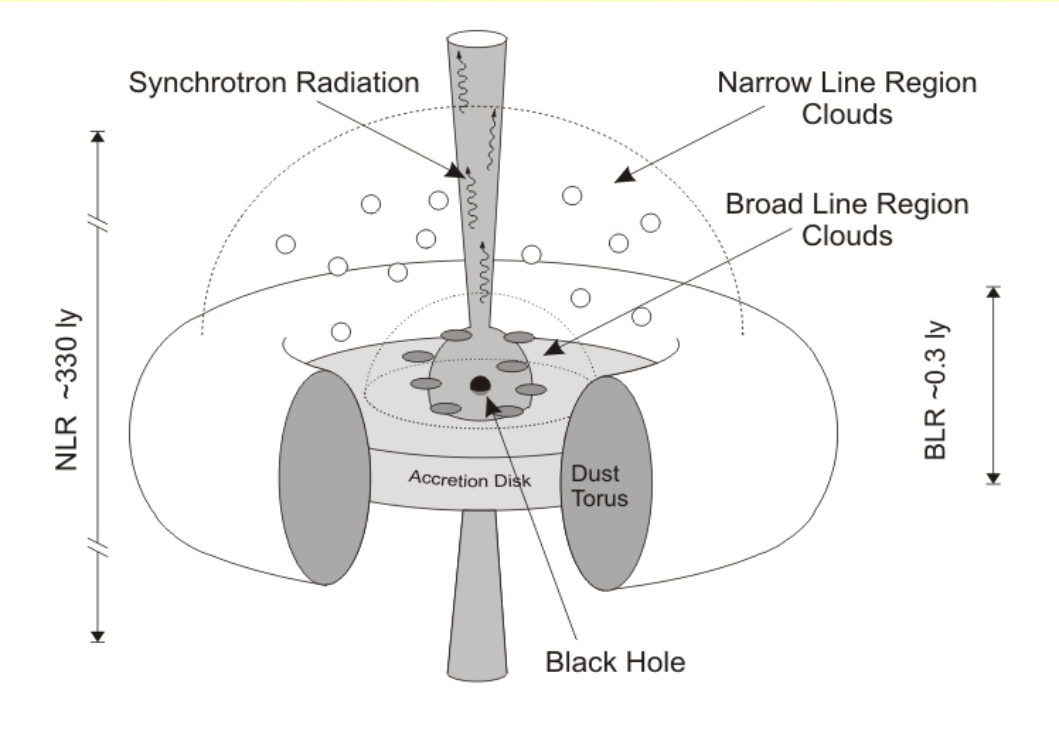
Unified model: the torus



Torus:

- Its existence is more a deduction from the observations outlined before than the result of direct observations
- There is however an excess of IR radiation from AGNs, which indicates the presence of a dust cloud
- The torus is probably made by cool molecular clouds

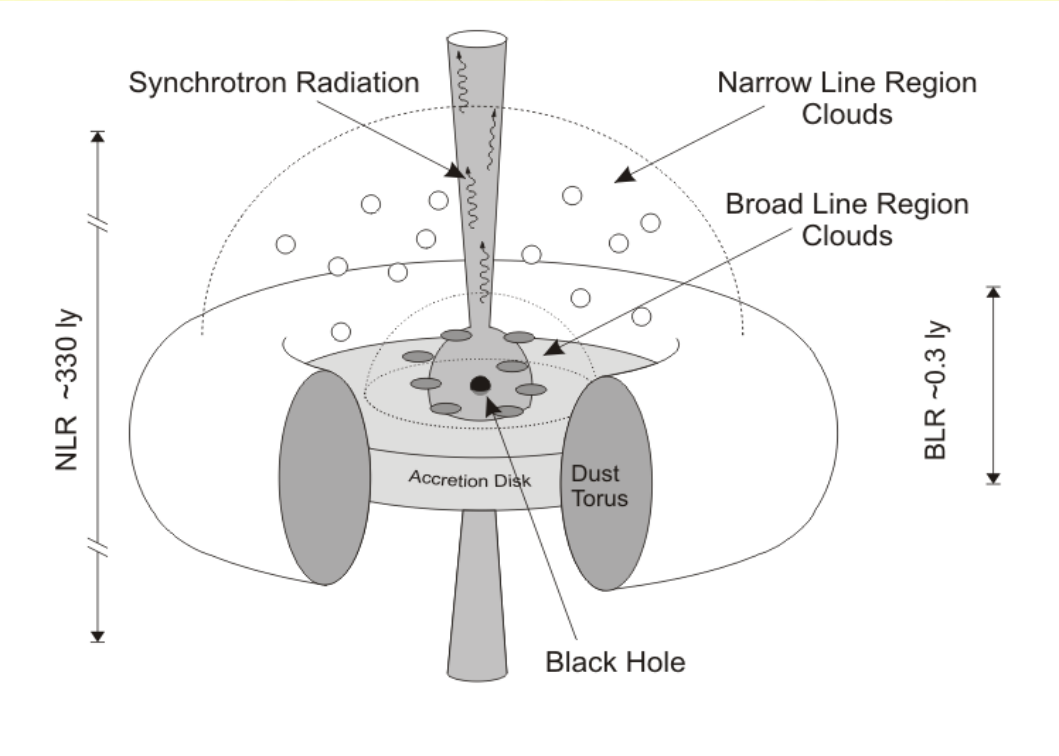
Unified model: BLR and NLR



BLR and NLR:

- Optical spectral lines are observed from AGNs (H, He, C, N, O, Mg, Ne, as seen in HII regions)
- Lines can be broad (velocities of about 10000 km/s) or narrow (<1000 km/s)
- It has been suggested that the BLR could be the accretion disc itself
- NLR is more extended and can be see even if the torus obscures the BLR

Unified model: the jets

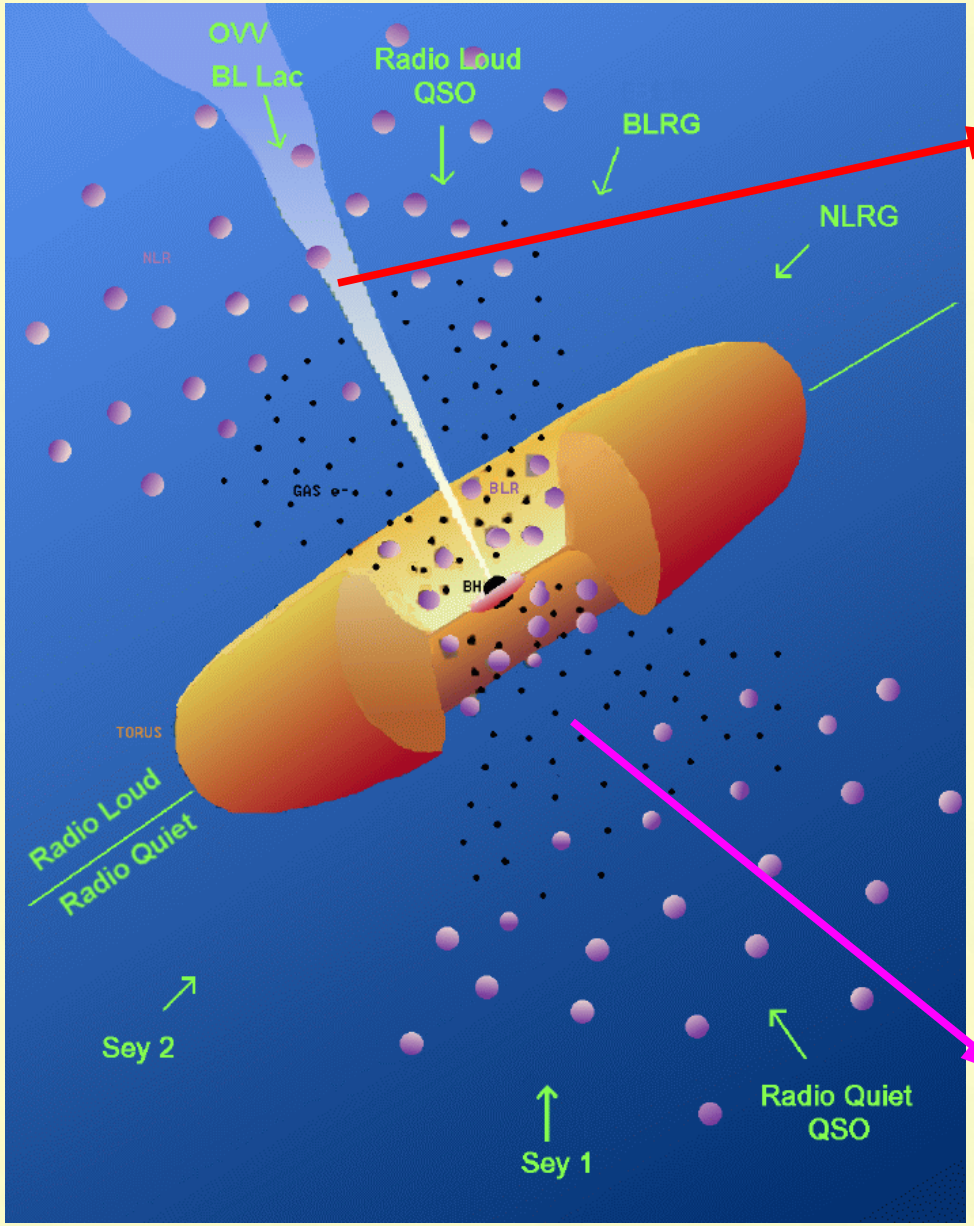


An effect, predicted by the special theory of relativity, that enhances the radiation from material that is moving toward the observer at nearly the speed of light, and hides material moving in the opposite direction at such speeds

Jets

- Energetic material ejected from the nucleus along the polar directions
- In 1977 Blandford added a vital ingredient to the model: the jet material is streaming out with high relativistic velocities
- Radiation from any source within the it will be beamed in the direction of the jet, with an increase in intensity because of the Doppler boosting
- A jet pointing away from the observer would be faint, or even unobservable

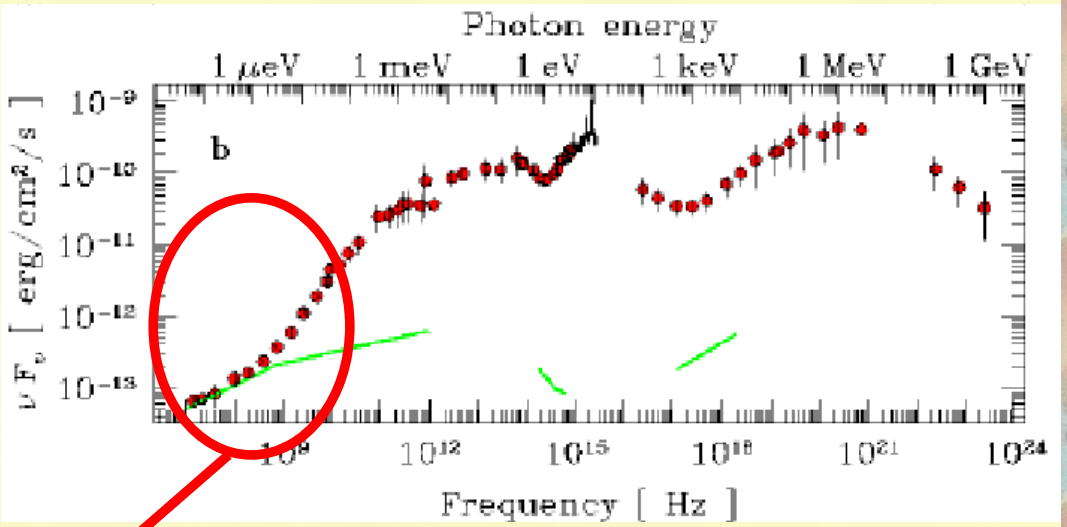
Active galaxies in the unified model



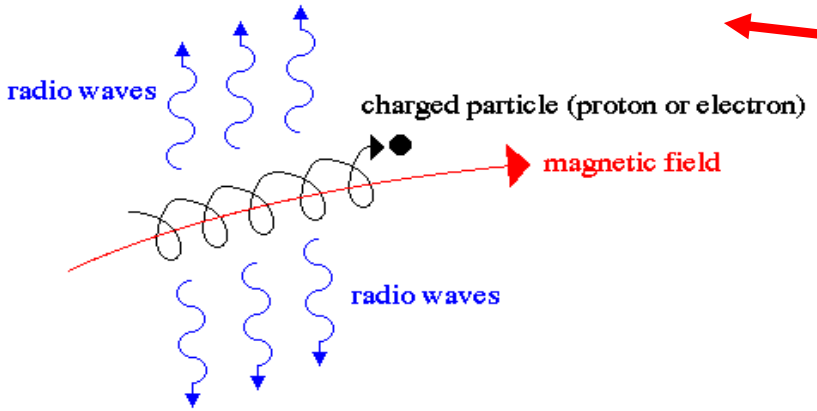
Radio galaxies, radio loud QSOs, BL Lac and OVV:
associated with elliptical galaxies and most massive BHs (10^8-10^{10} M_{Sun})

Seyfert galaxies, radio quiet (weak) QSOs:
associated with spiral bulges and less massive BHs (10^6-10^8 M_{Sun})

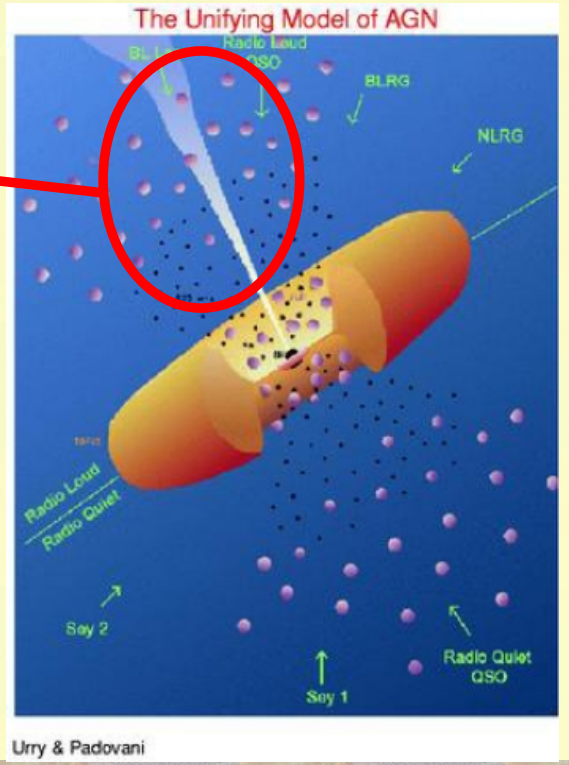
AGN spectrum



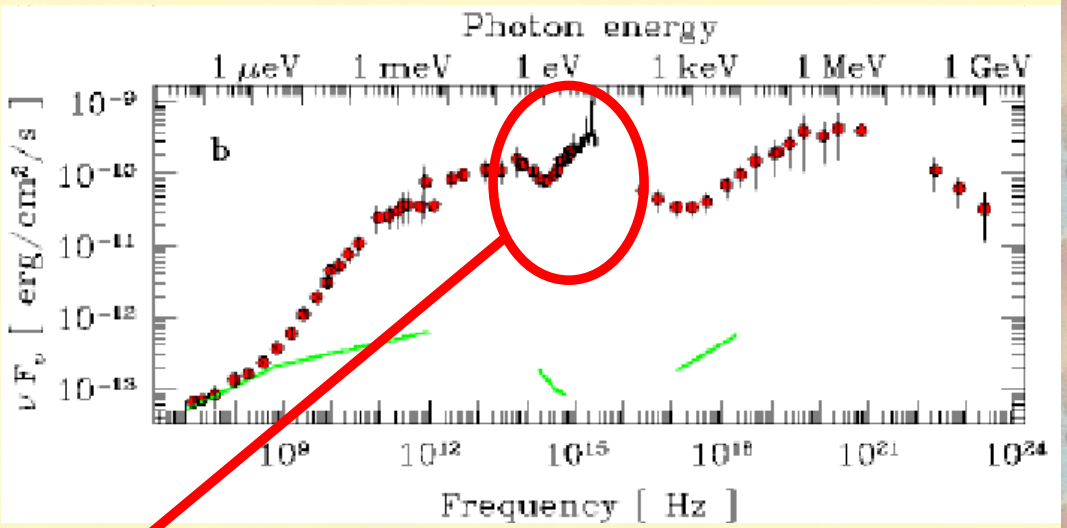
Synchrotron radiation



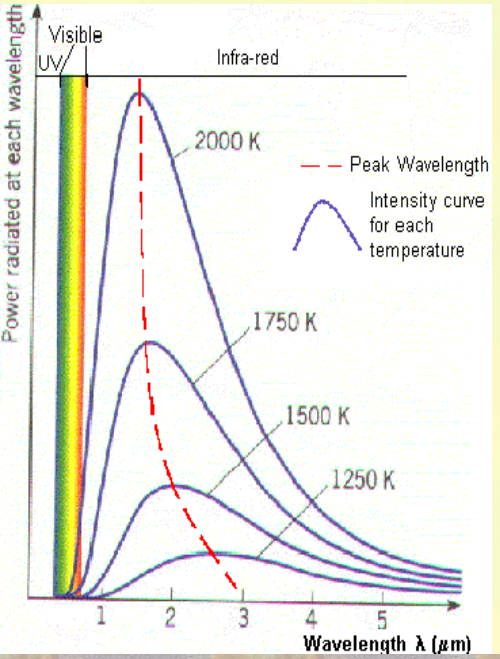
synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

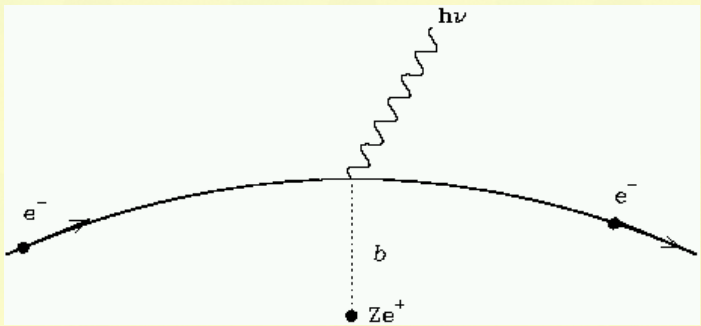


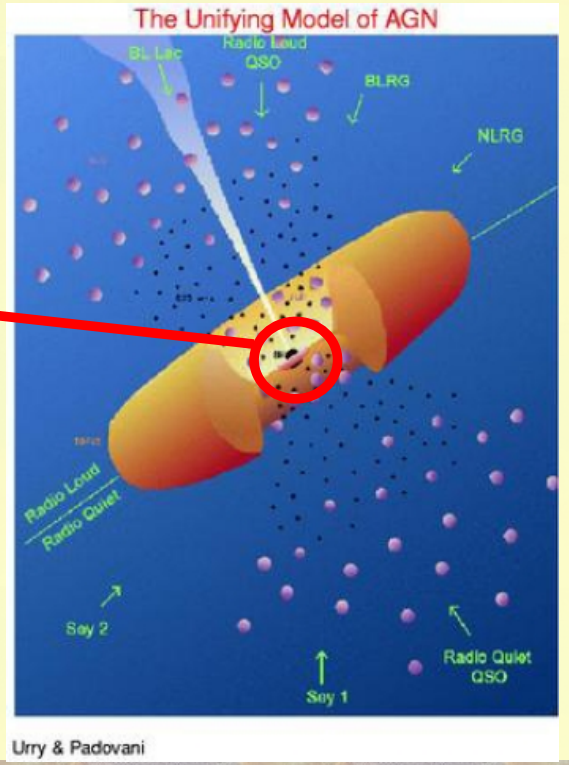
AGN spectrum



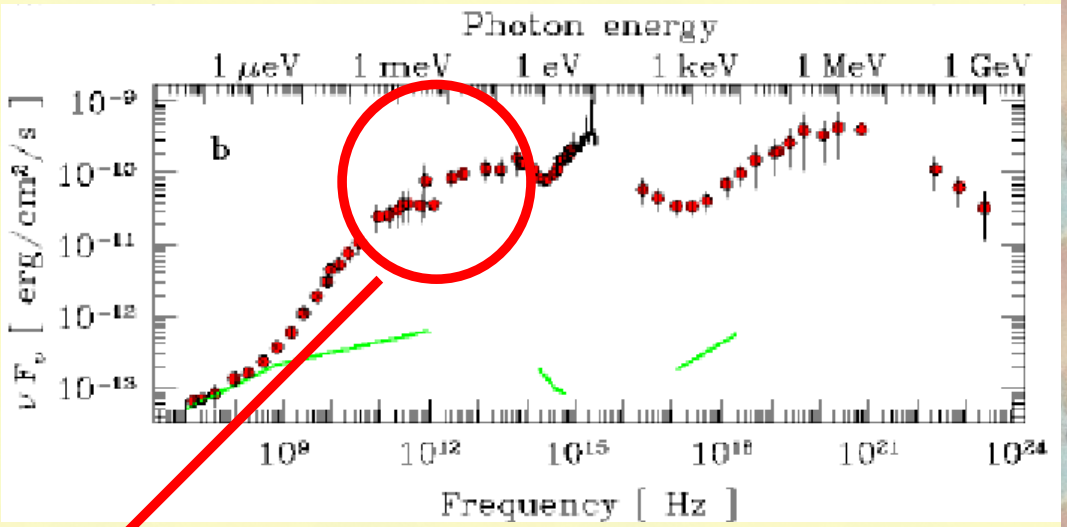
Material that falls into the BH



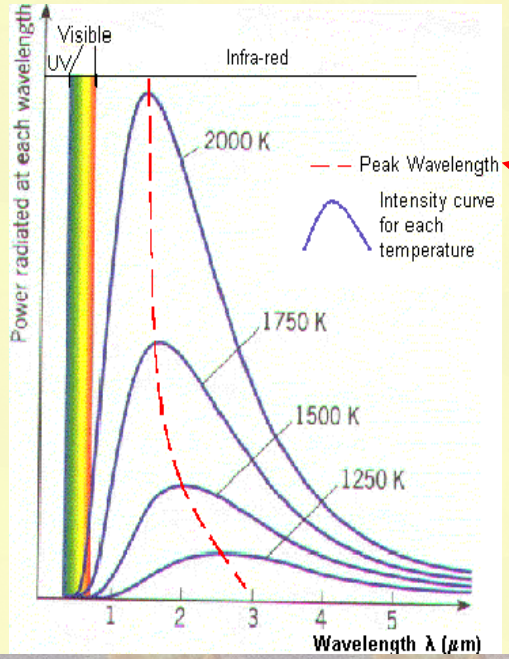


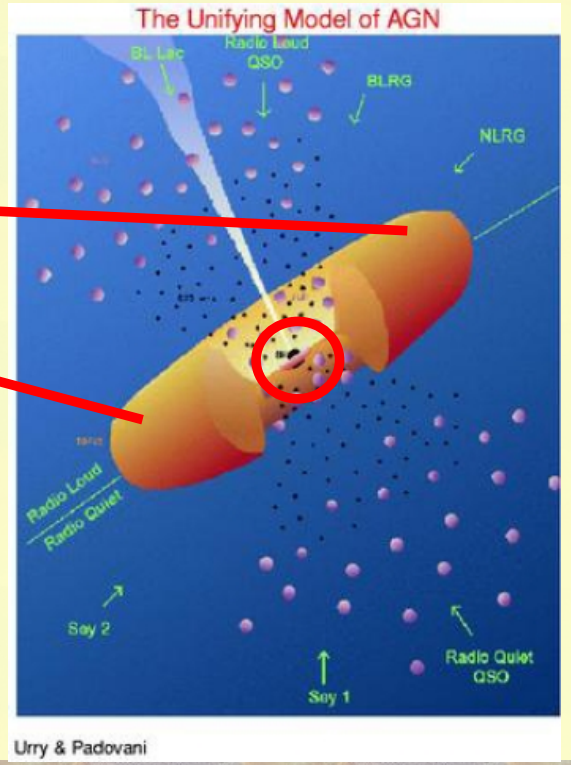


AGN spectrum

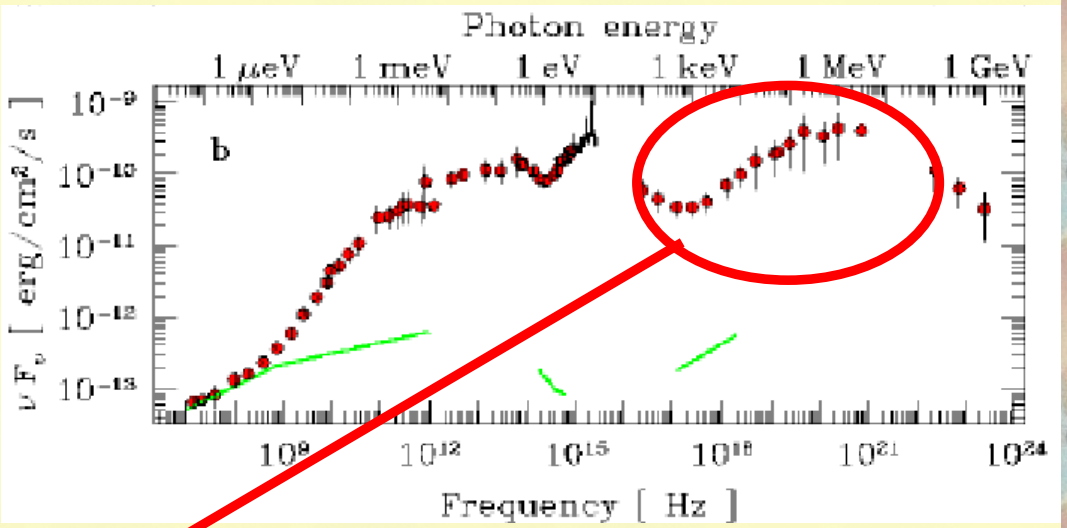


Dust in the thick disk absorb UV radiation from accretion disk. Re-emission in the IR

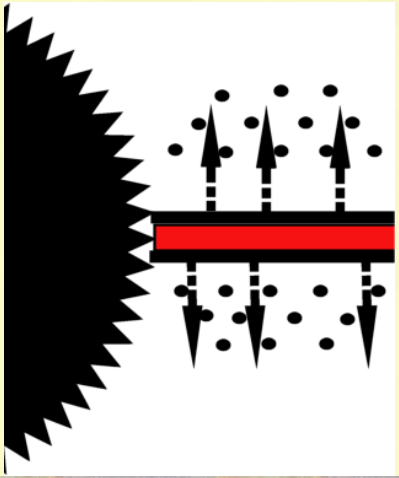


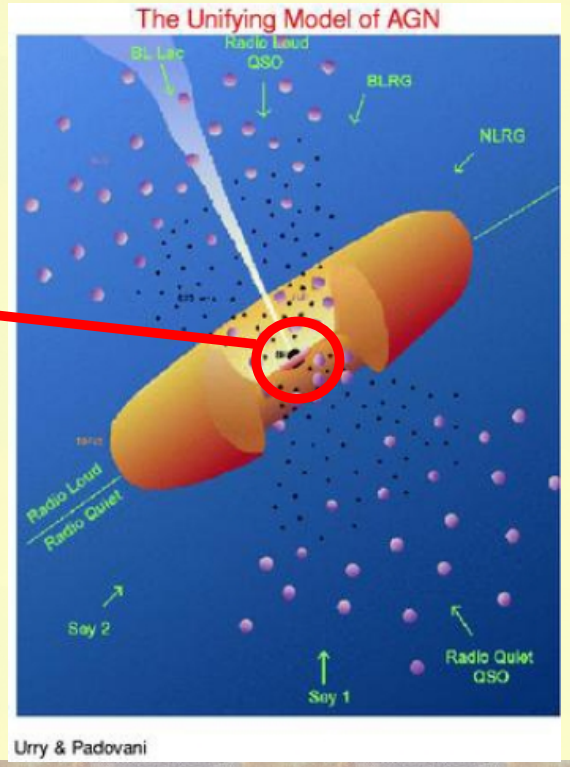


AGN spectrum



X-ray emission by Inverse Compton. Photons produced in the thin disk interact with hot electrons in the corona and are scattered at X-ray frequencies





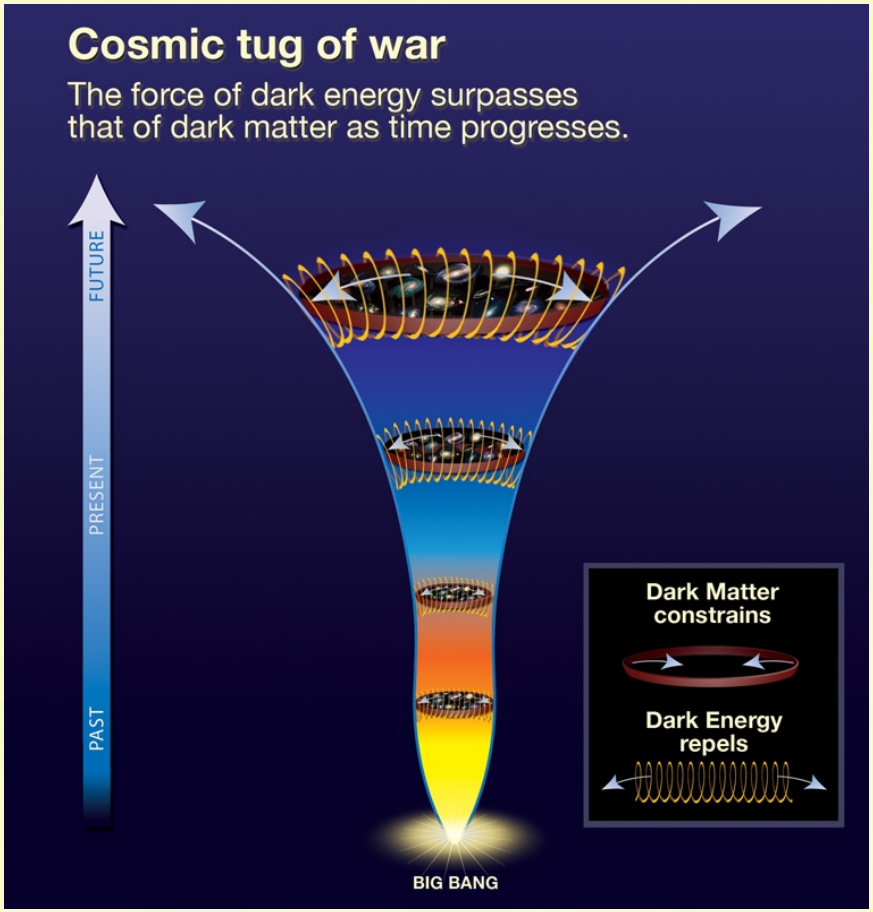
Lecture Outline

- Examples of galactic radio sources
  - Supernovae
  - Galactic continuum radiation and the inter stellar medium
- Examples of extra-galactic radio sources
  - Active Galactic Nuclei (AGN)
  - **Galaxy clusters**
  - Cosmic Microwave Background (CMB)
  - Epoch of Re-ionization (EoR)

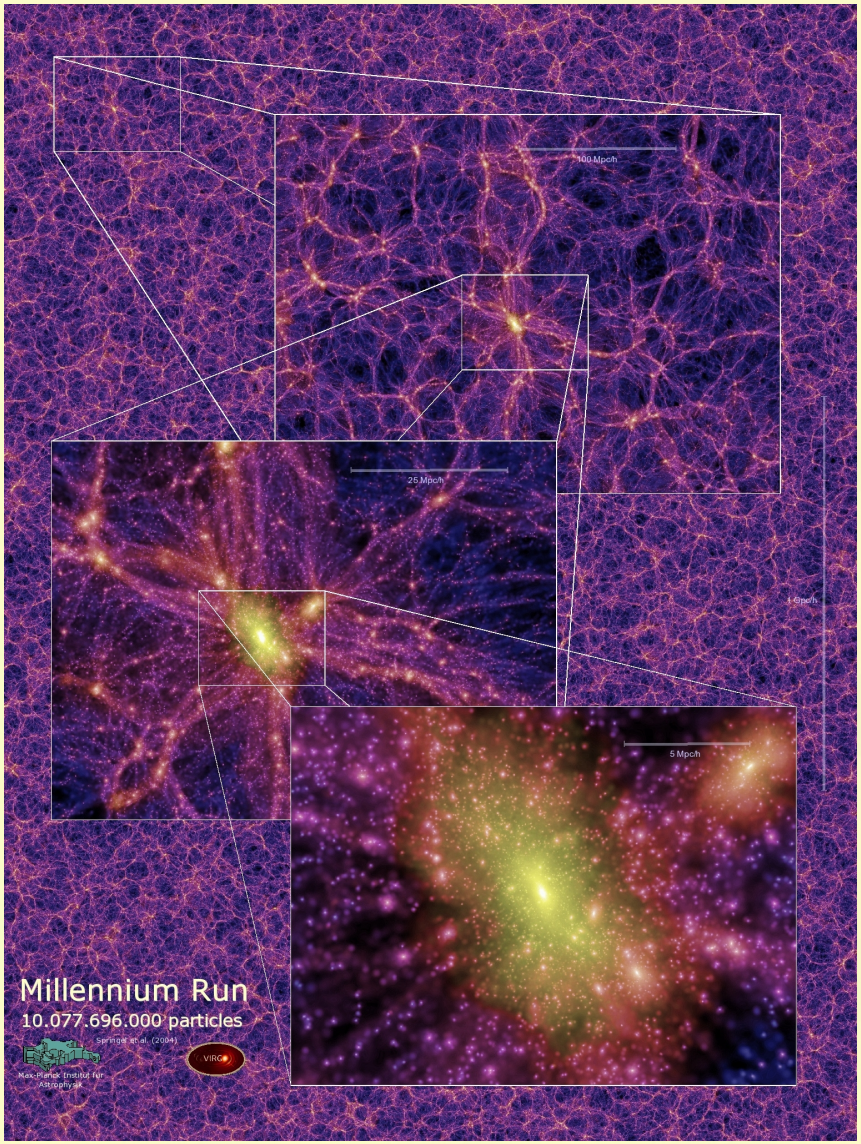
Concordant cosmological model: ΛCDM

Λ-Cold Dark Matter:

- It is the simplest known model that is in general **agreement** with **observed phenomena**
- The **Universe** is spatially **flat**, i.e. the rules of Euclidean geometry are valid on the largest scales
- **Λ** stands for the **cosmological constant** which is a **dark energy** term that allows for the current accelerating expansion of the universe
- Ω_Λ = fraction of the dark energy density of a flat Universe = 0.73
- **Cold dark matter** is the model where the particles making up this matter are slowly moving and hence are cold
- **Ωm** = fraction of the matter density of a flat Universe = 0.27

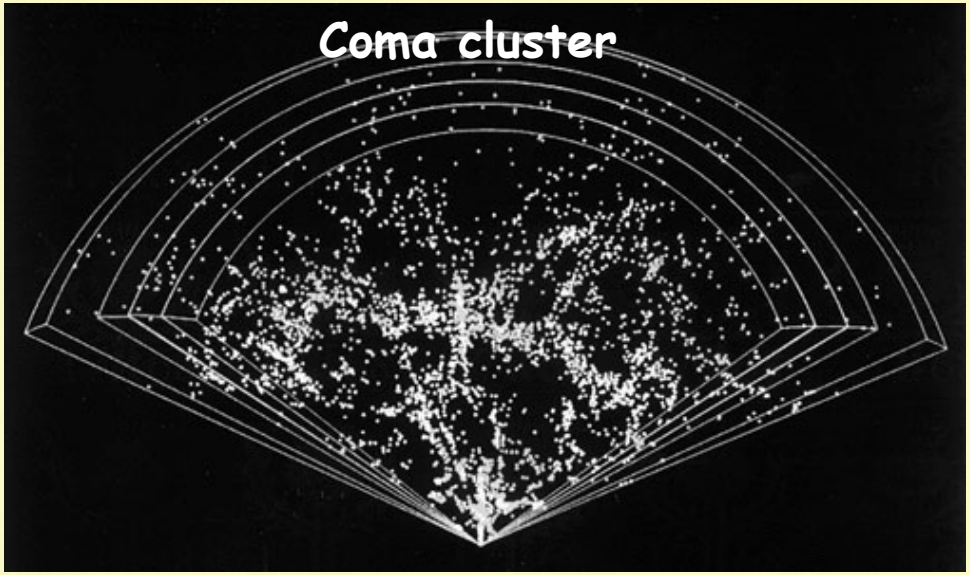


Galaxy clusters: tools for Cosmology



Hierarchical structure formation

from concordant cosmological scenario



Galaxy clusters

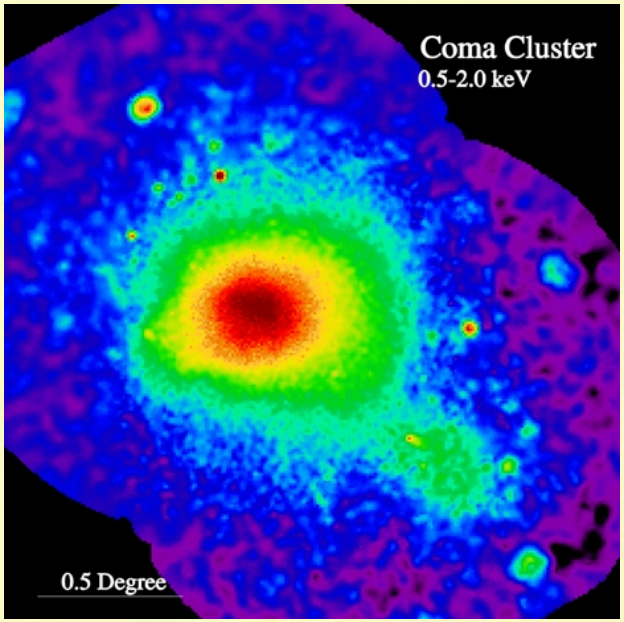
largest virialized structures of the present Universe

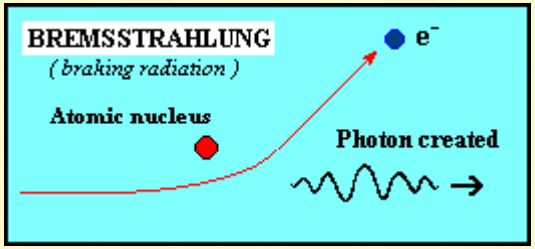
Galaxy clusters: complex astrophysical objects



Component	Mass	Em.mech.	Band
Galaxies	3%	Composite	Different (but discovered in optical)
Thermal gas	16%	Thermal Breemstrahlung	X-ray
Relativistic e^- and **B**	0%	Synchrotron	Radio
Dark Matter	81%	???	???

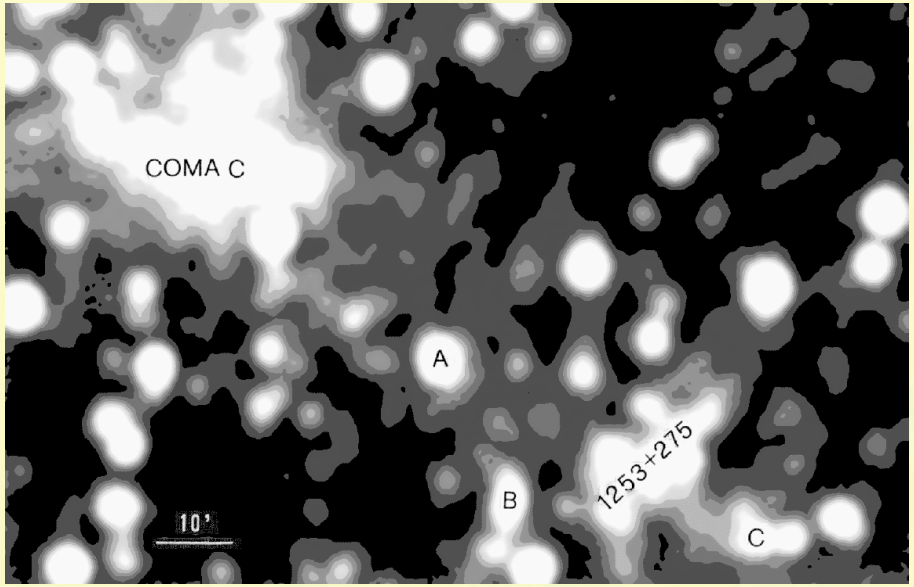
Galaxy clusters: complex astrophysical objects

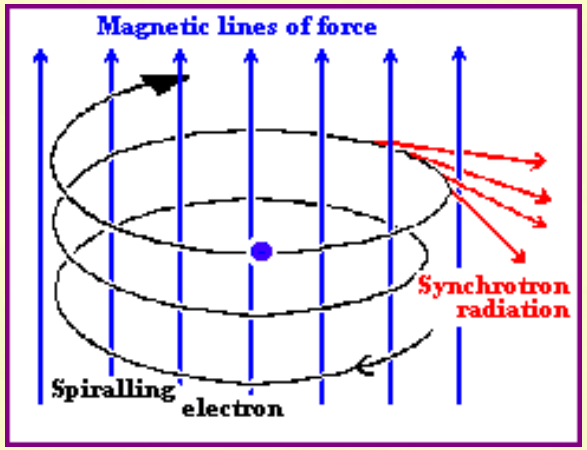




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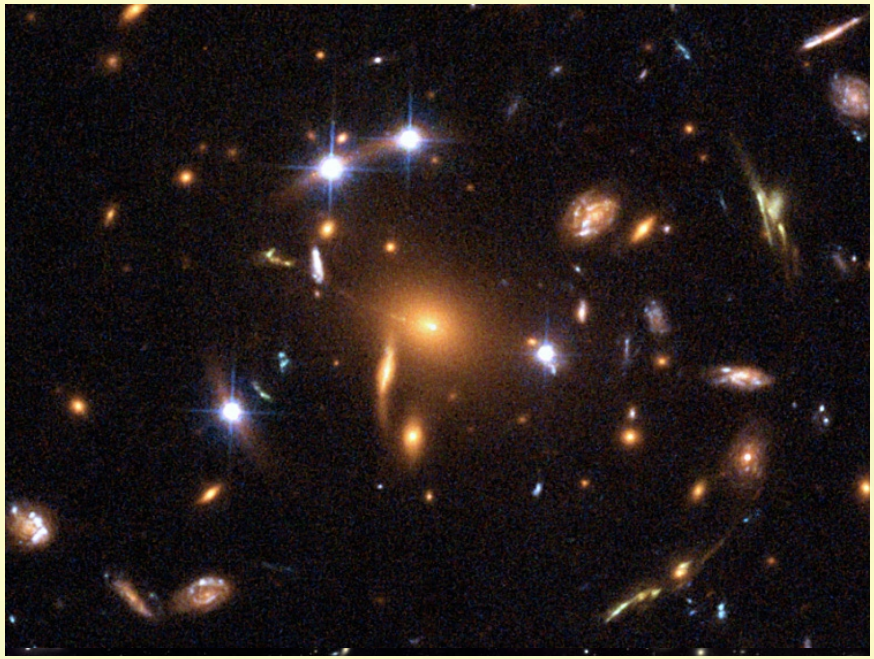
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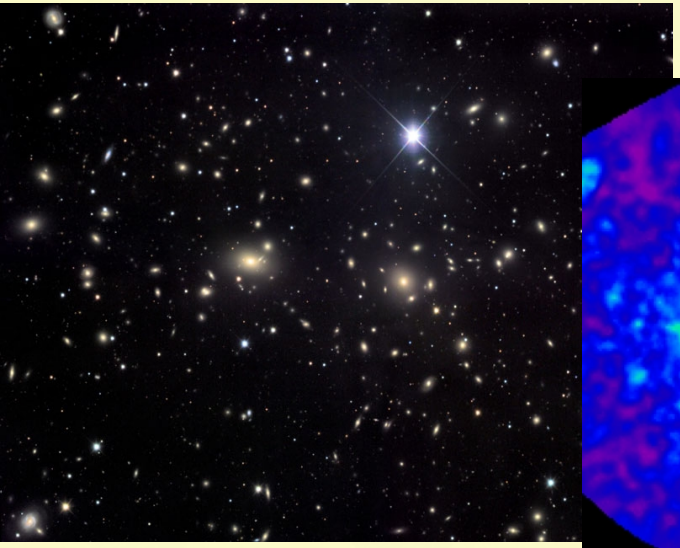
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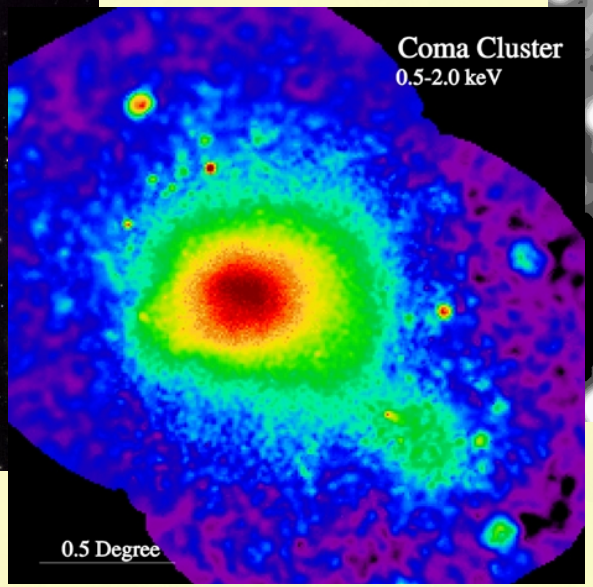
Galaxy clusters: complex astrophysical objects

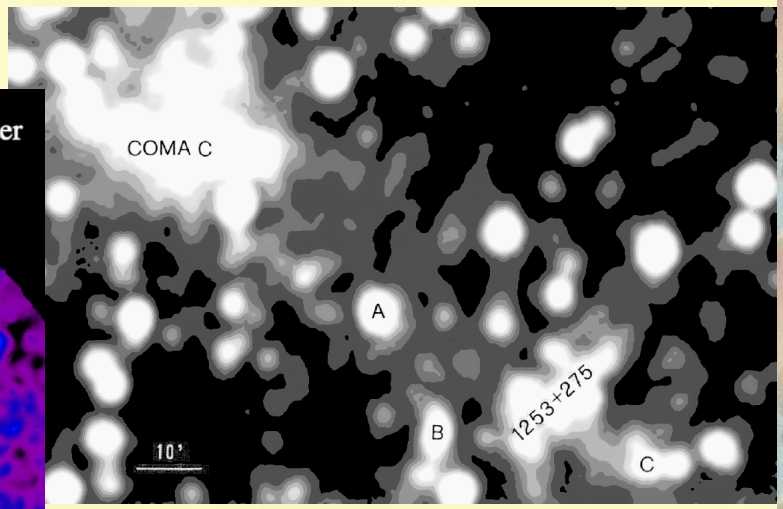


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Galaxy clusters: complex astrophysical objects

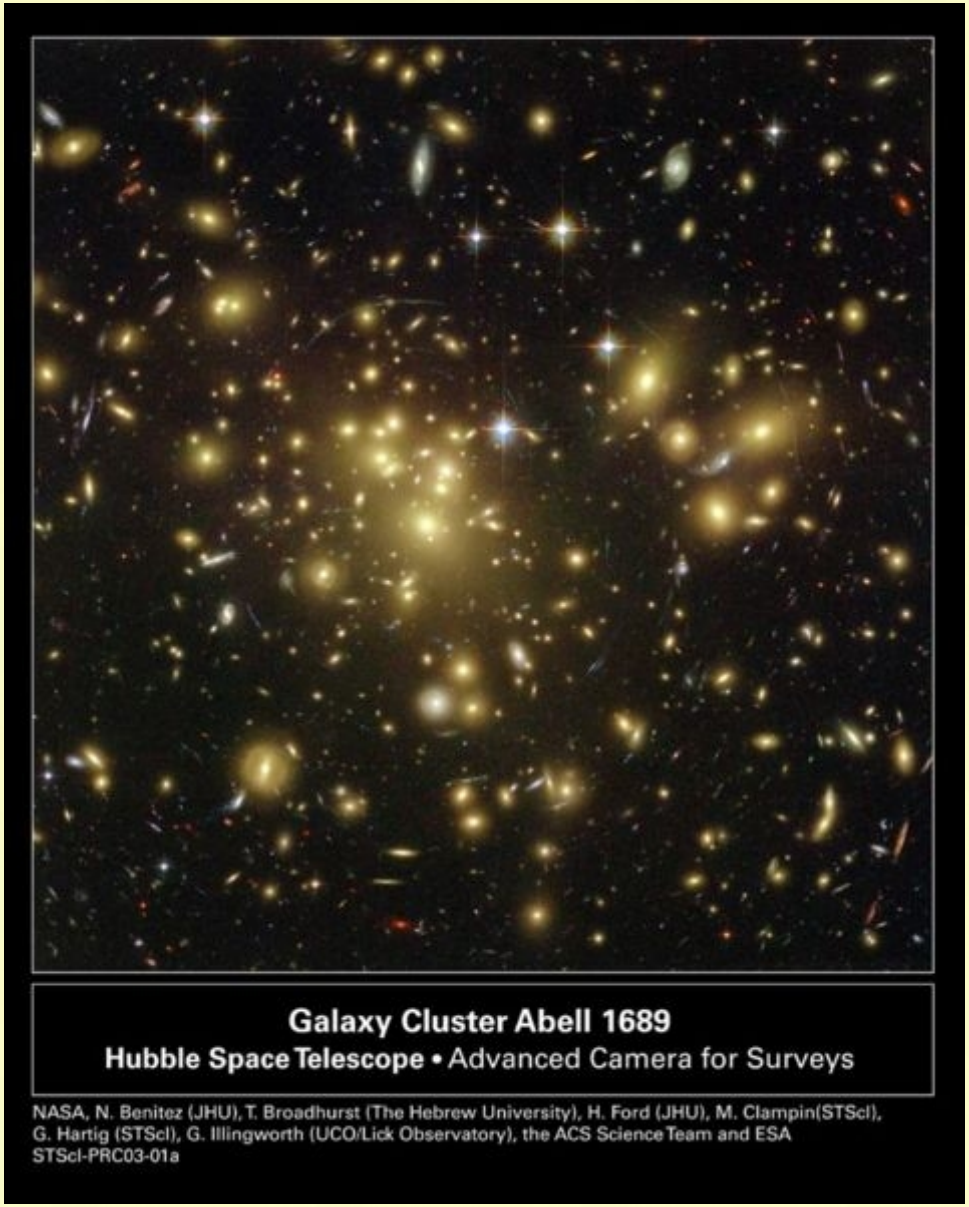






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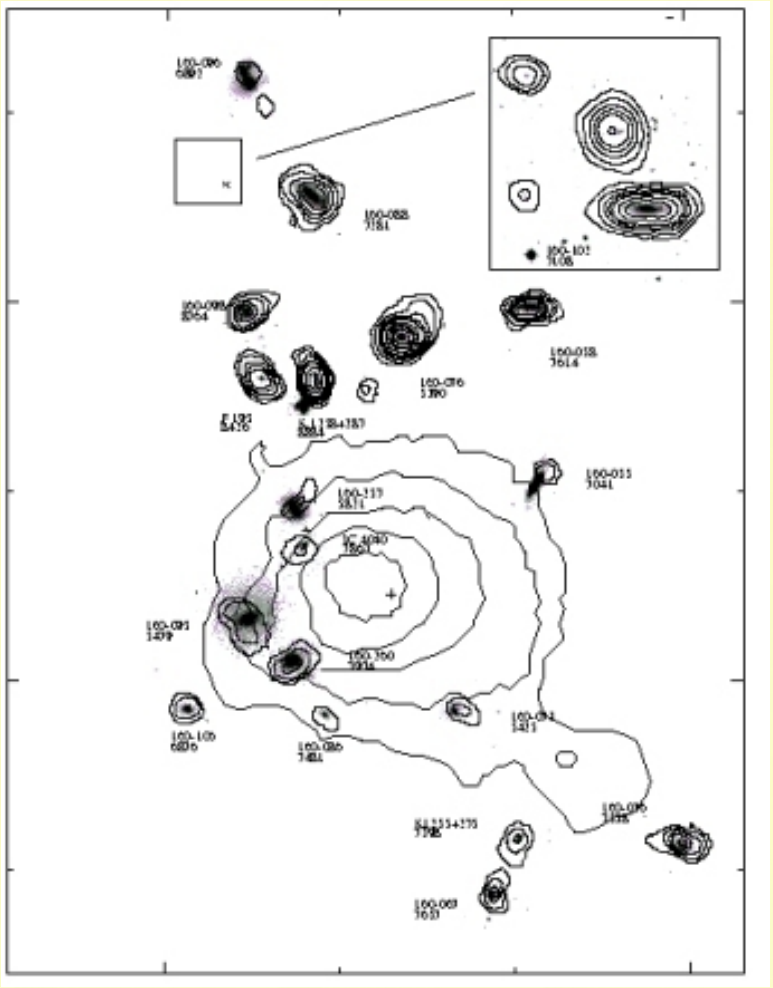
Galaxy clusters: complex astrophysical objects



Environmental effects on cluster galaxies: HI

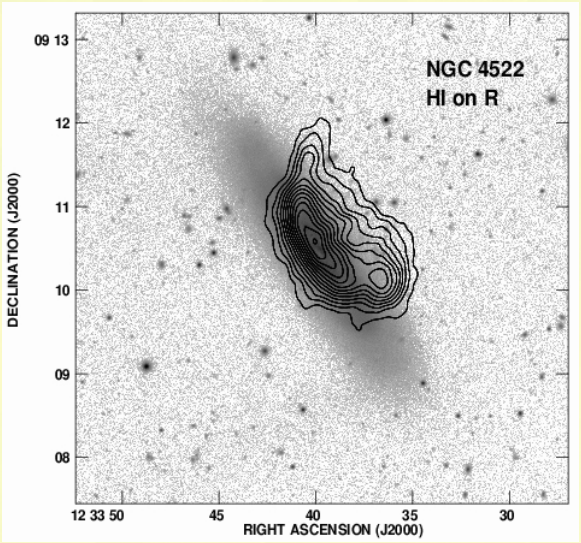


HI content



Ram pressure:

$$P_{ram} \propto \rho_{ICM} v_{rel}^{2}$$

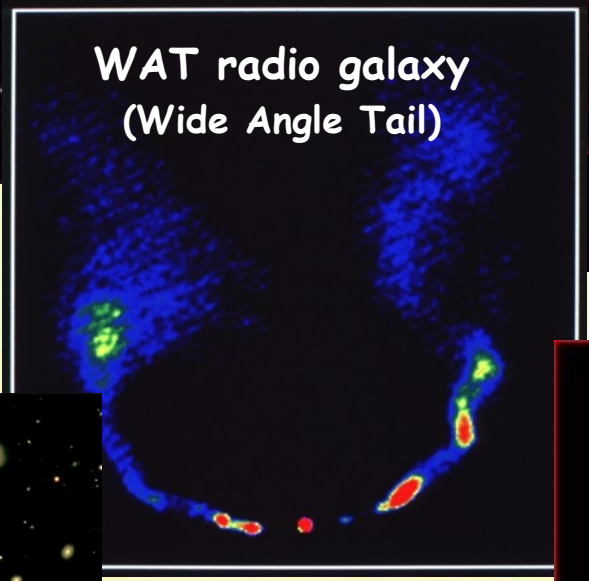


Environmental effects on cluster galaxies: AGN

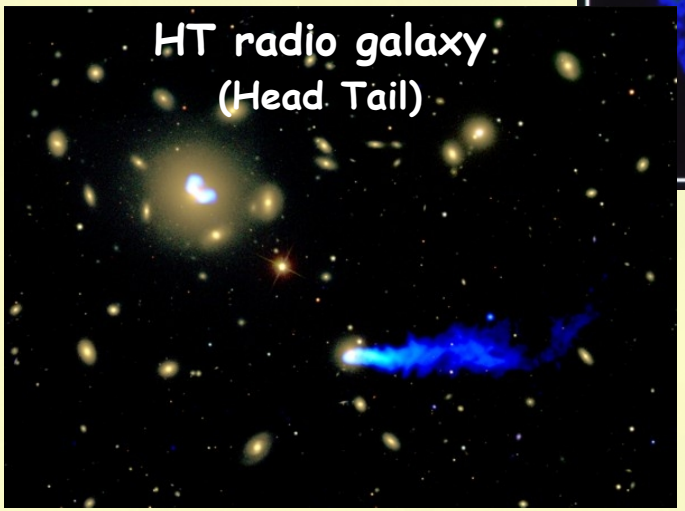


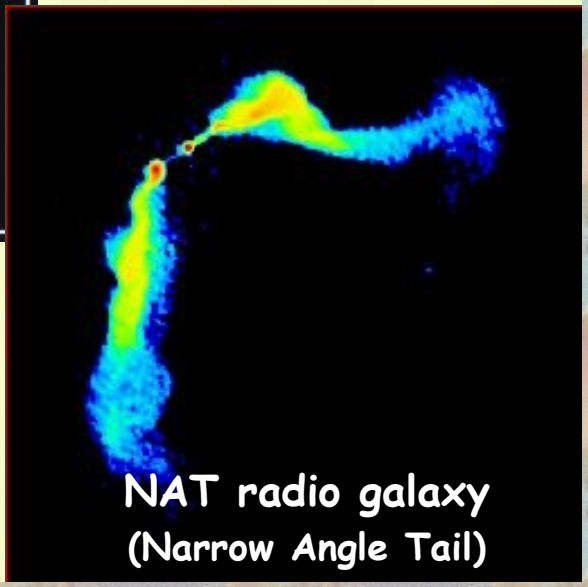
Ram pressure:

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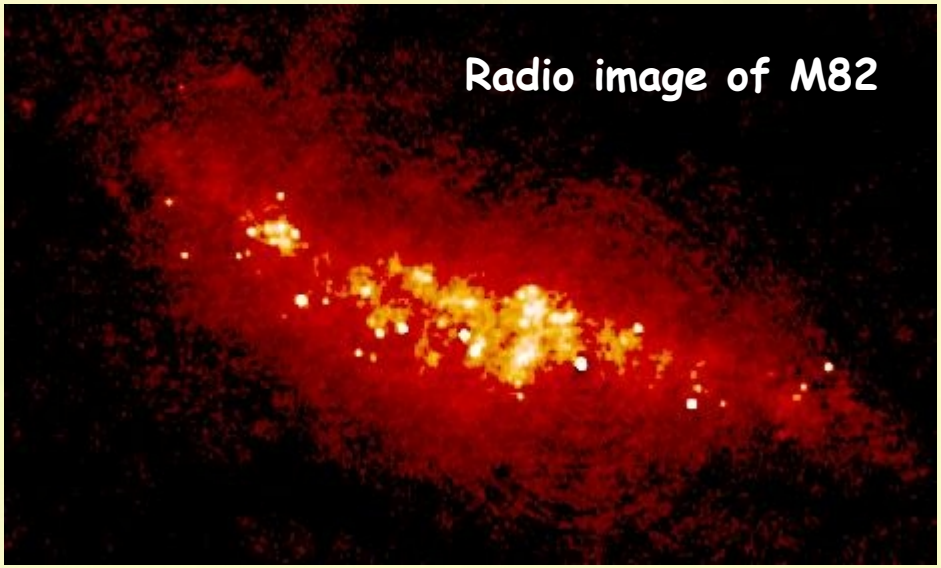


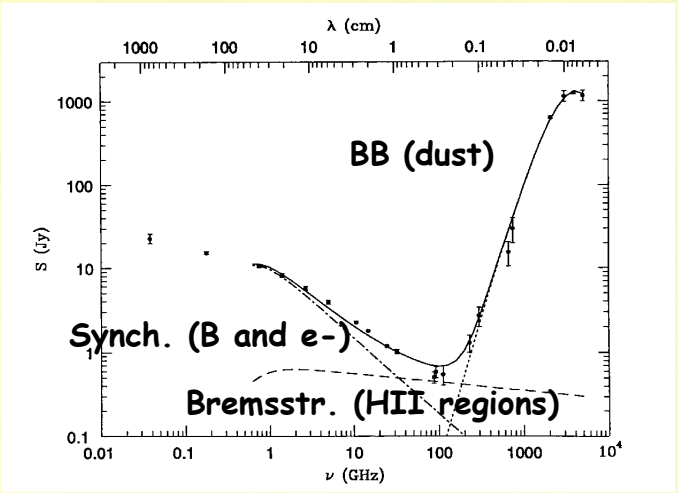


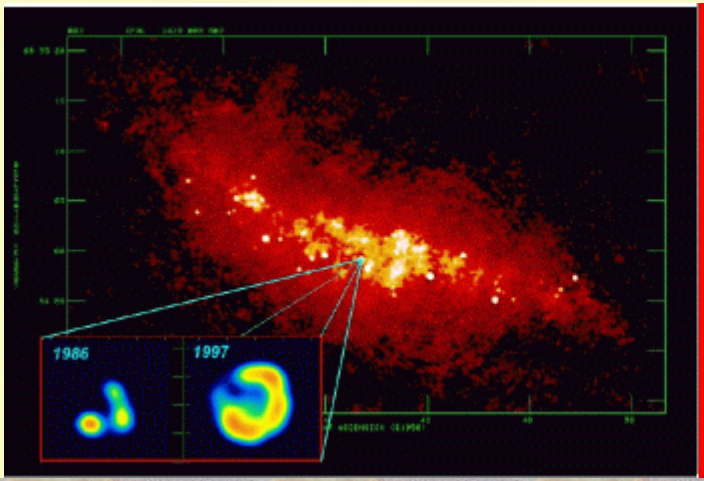
Radio emission from “normal” (cluster) galaxies

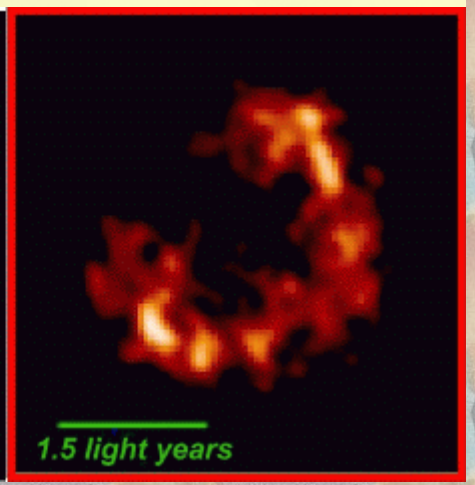


Star formation





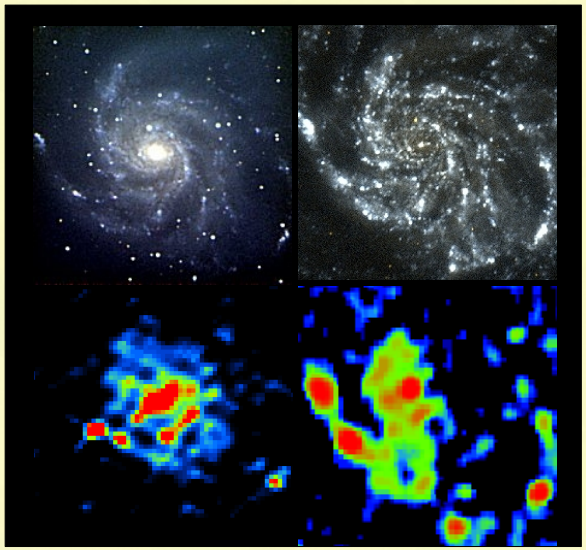


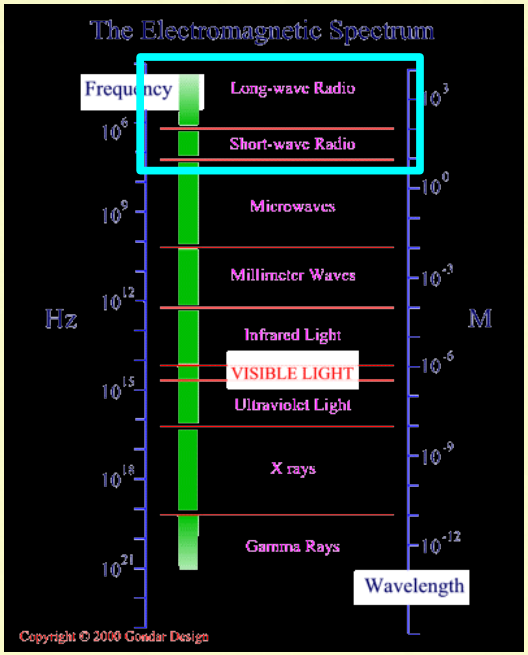


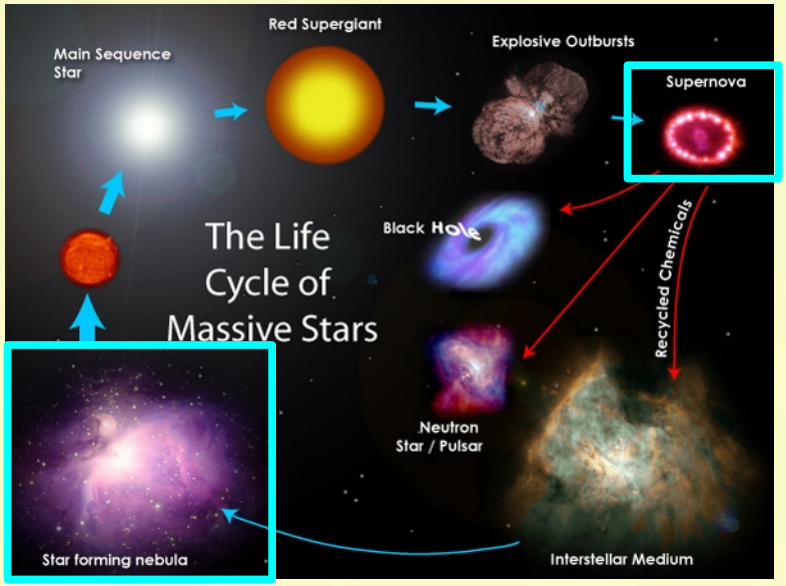
Radio emission from “normal” (cluster) galaxies



Star formation

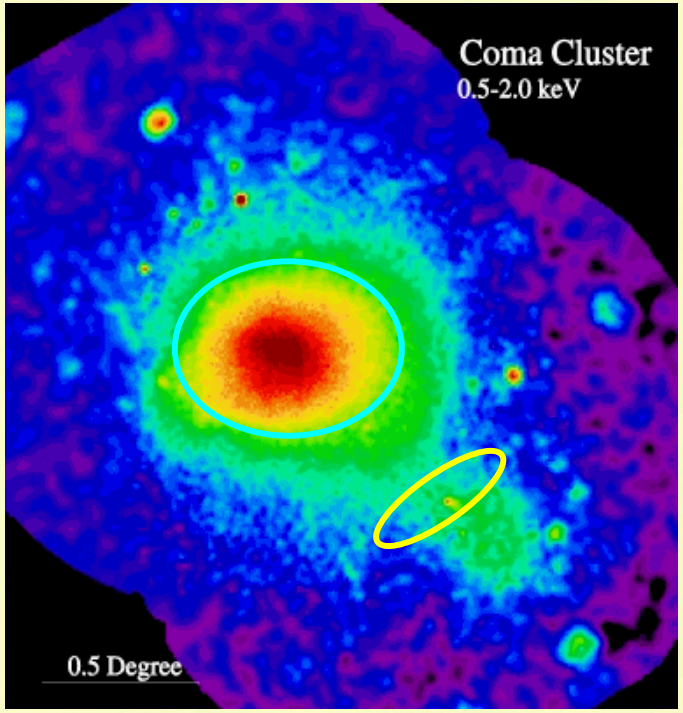




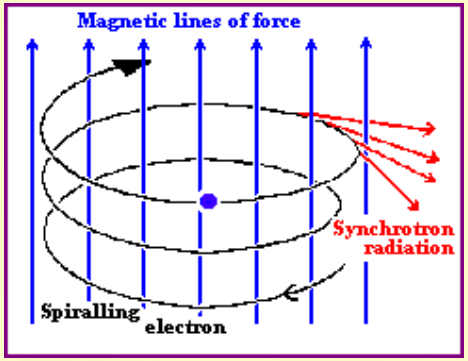


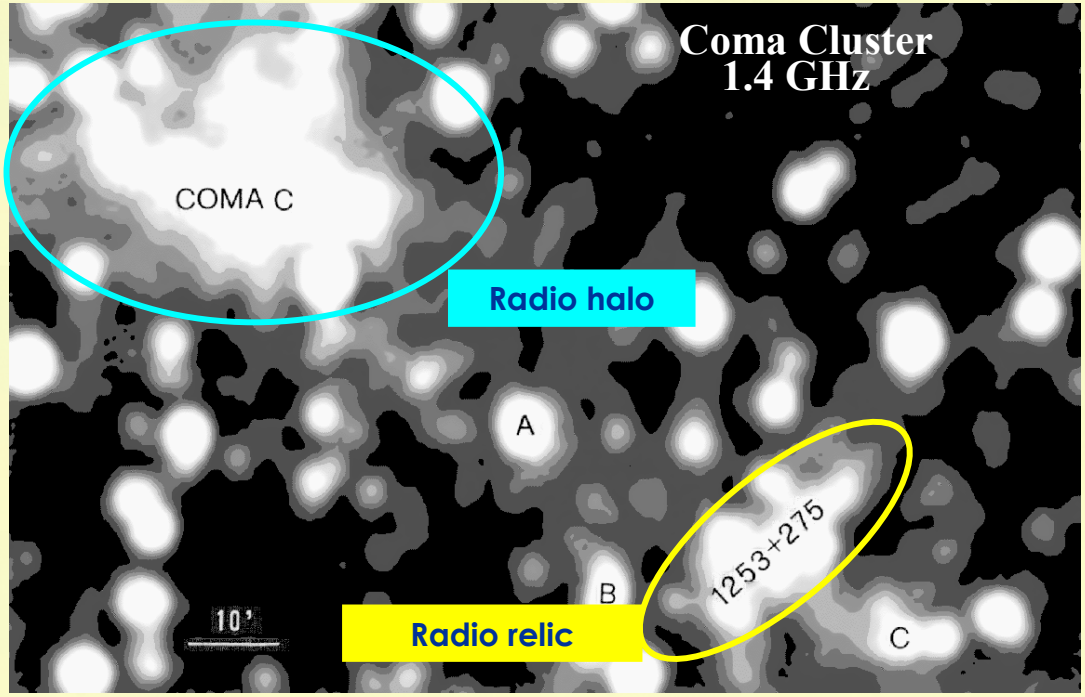
The most spectacular radio emission in clusters

Diffuse and extended radio sources: halos and relics



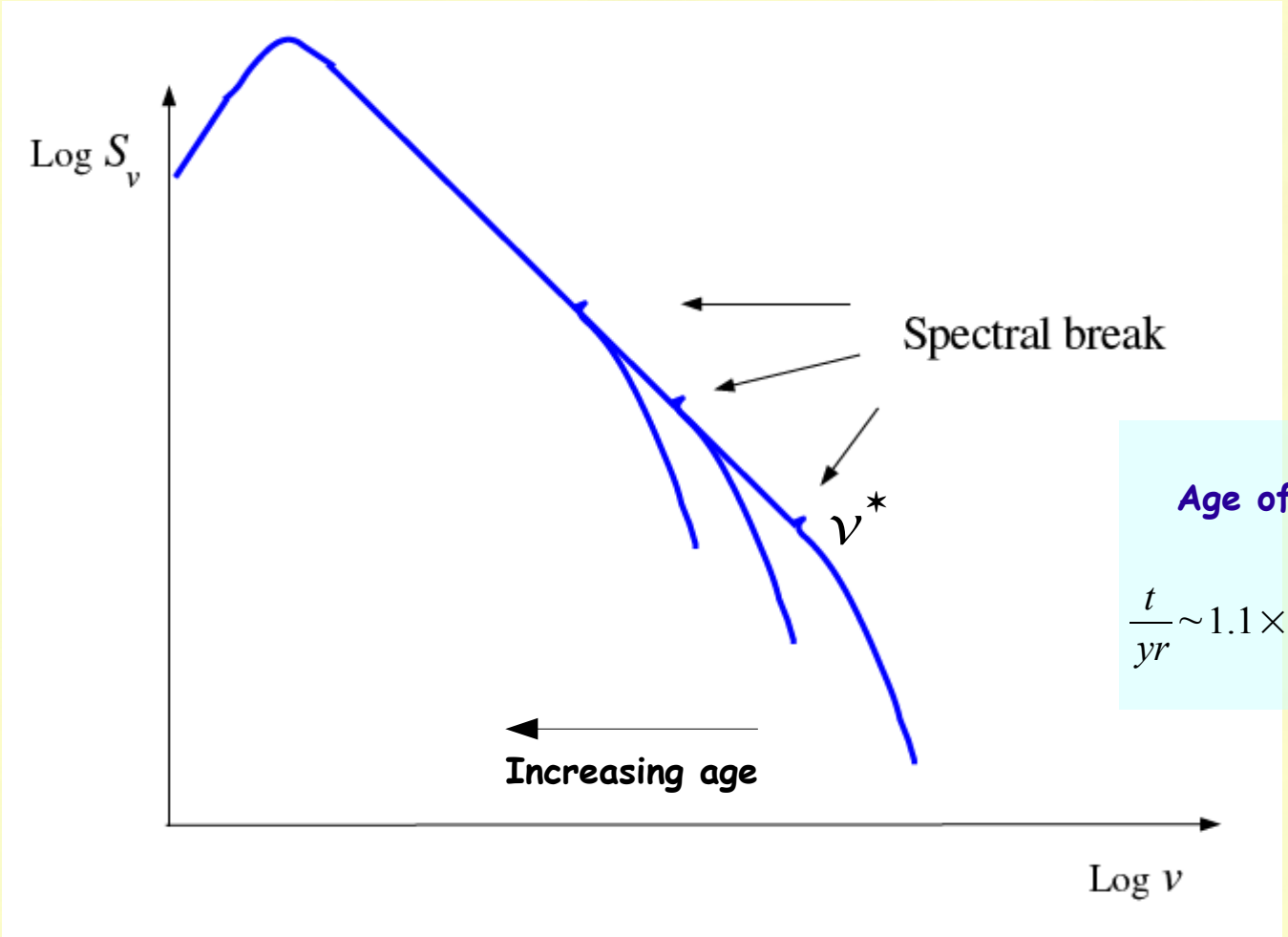
- Magnetic field (μGauss)
- Relativistic electrons (GeV)





Evolution of the synchrotron spectrum

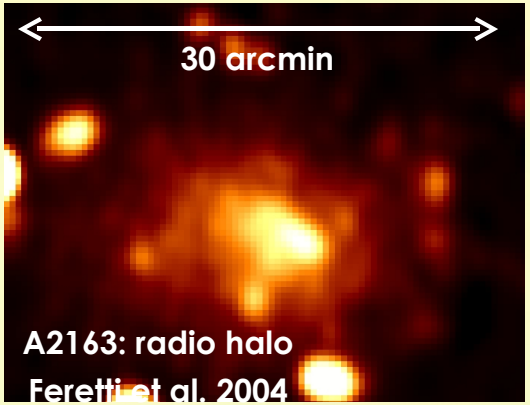
High energy (i.e. high frequency) particles have shorter radiative life time than low energy ones and the emission spectrum is modified accordingly due to the depletion of high energy particles from the energy distribution

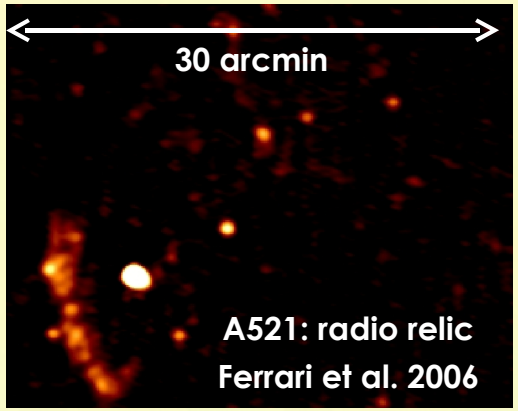


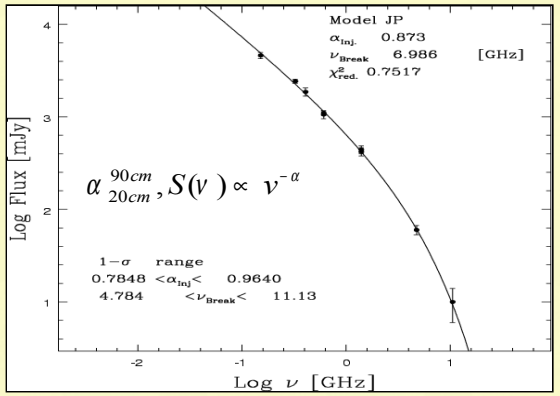
Age of the radio source

$$\frac{t}{yr} \sim 1.1 \times 10^9 \left(\frac{H}{\mu G}\right)^{-3/2} \left(\frac{\nu^*}{GHz}\right)^{-1/2}$$

Diffuse and extended radio emission in clusters







Dimensions: ~1 Mpc

Crossing time e^-: ~9.5 Gyr

Life time of e^-: ~0.1 Gyr

Electrons must be (re-)accelerated in situ!!!

Possible acceleration mechanisms:

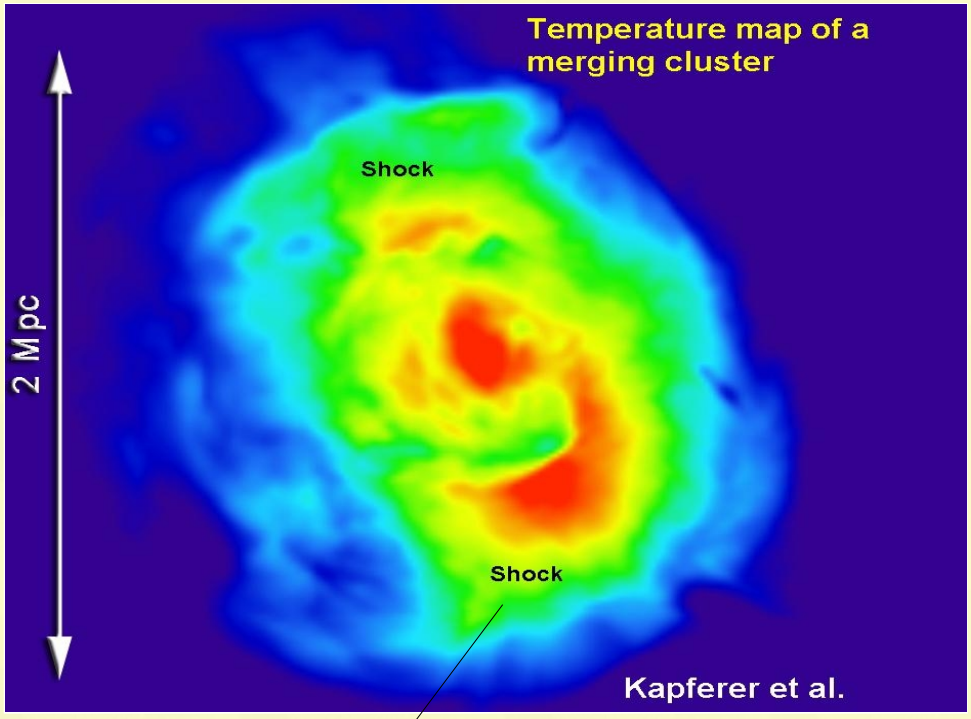
- Primary: (re-)acceleration due to shocks/turbulences
- Secondary: hadronic collisions of relativistic p^+ with the ICM

Primary models: electrons directly accelerated

Electrons can be (re-)accelerated by shocks and turbulences resulting from cluster-cluster mergers!!!

Merger shocks:

- Typical shock velocity: 200 km/s
- $E_{shock} \sim 3 \times 10^{63}$ ergs
- Main heating mechanism of intra-cluster gas
- Re-acceleration of electrons!



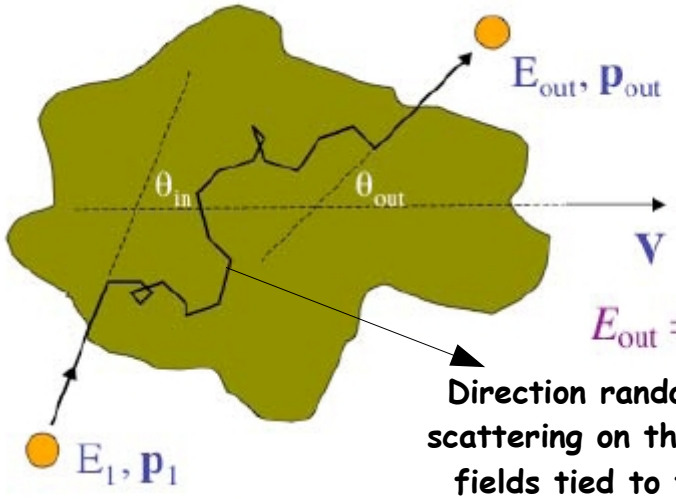
Supersonic wave propagating in the ICM. Density, pressure and temperature always increase along the direction of flow

Acceleration mechanisms: Fermi's mechanisms

- **Fermi's idea (50's):** stochastic Fermi acceleration (Fermi II – second order)
- **Following development (70's):** shock acceleration (Fermi I – first oder)

- ✔ When a particle is reflected off a magnetic mirror coming towards it, in a **head-on** collision, it **gains energy**
- ✔ When a particle is reflected off a magnetic mirror going away from it, in an **overtaking** collision, it **loses energy**
- ✔ Head-on collisions are **more frequent** than overtaking collisions

→ **Net energy gain, on average (stochastic process)**



$$\begin{cases} E'_{in} = \gamma E_{in}(1 - \beta\cos\theta_{in}) \\ E_{out} = \gamma E'_{out}(1 + \beta\cos\theta'_{out}) \end{cases}$$

→ Ref. frame of the cloud

→ Ref. frame of the obs.

$$E_{out} = \gamma^2 E_{in}(1 - \beta\cos\theta_{in})(1 + \beta\cos\theta'_{out})$$

Direction randomized by scattering on the magnetic fields tied to the cloud

$$\frac{\Delta E}{E} = \frac{\beta(\cos\theta'_{out} - \cos\theta_{in}) + \beta^2(1 - \cos\theta_{in}\cos\theta'_{out})}{1 - \beta^2}$$

Acceleration mechanisms: Fermi's mechanisms

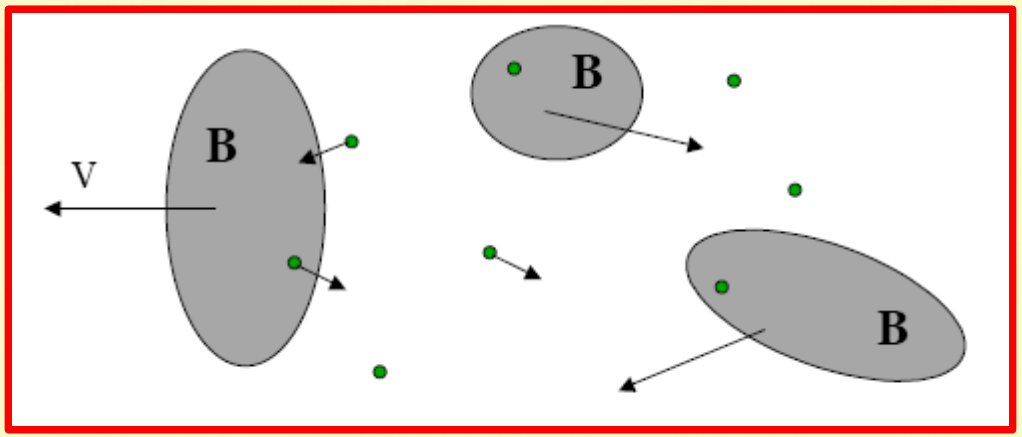
- **Fermi's idea (50's):** stochastic Fermi acceleration (Fermi II – second order)
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$$\frac{\Delta E}{E} = \frac{\beta(\cos\theta'_{out} - \cos\theta_{inp}) + \beta^2(1 - \cos\theta_{inp}\cos\theta'_{out})}{1-\beta^2}$$

On average: $\langle\cos\theta'_{out}\rangle = 0 \qquad \langle\cos\theta_{inp}\rangle = -\frac{1}{3}\beta$

$$\rightarrow \quad \left\langle\frac{\Delta E}{E}\right\rangle = \frac{4}{3}\frac{\beta^2}{1-\beta^2} \simeq \frac{4}{3}\beta^2$$

Second order, stochastic Fermi acceleration



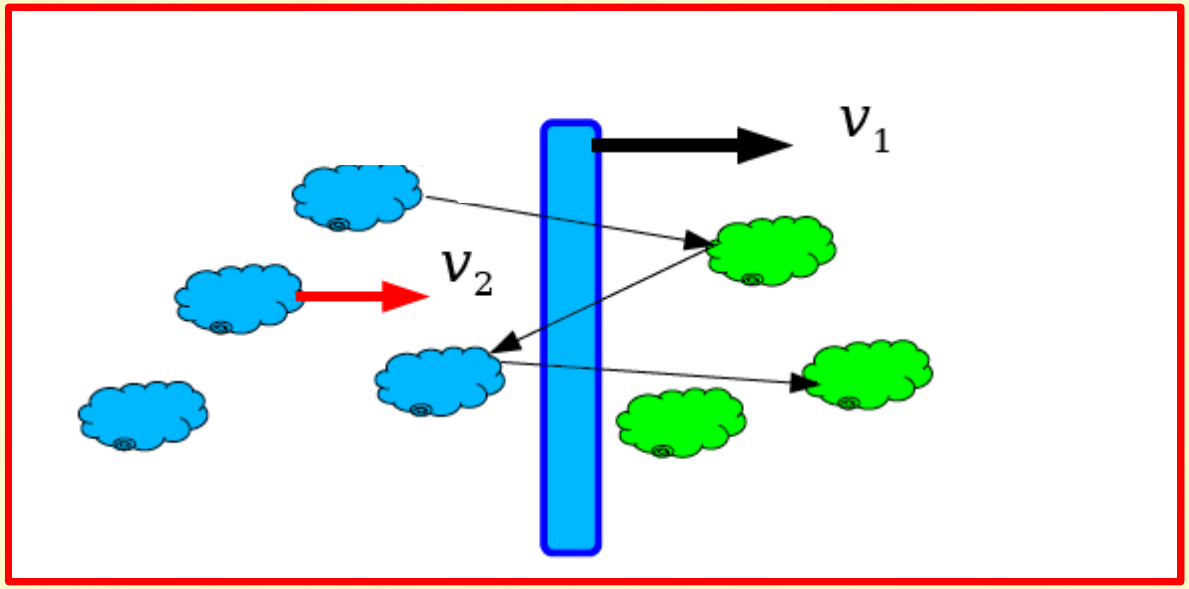
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$$\frac{\Delta E}{E}=\frac{E'-E}{E}=\frac{E+p_x V-E}{E}=\frac{p V\cos\theta}{p c}=\frac{3}{4}\frac{U\cos\theta}{c}=\frac{3}{4}\beta\cos\theta$$

$$\left\langle\frac{\Delta E}{E}\right\rangle\propto\beta$$

First order Fermi acceleration

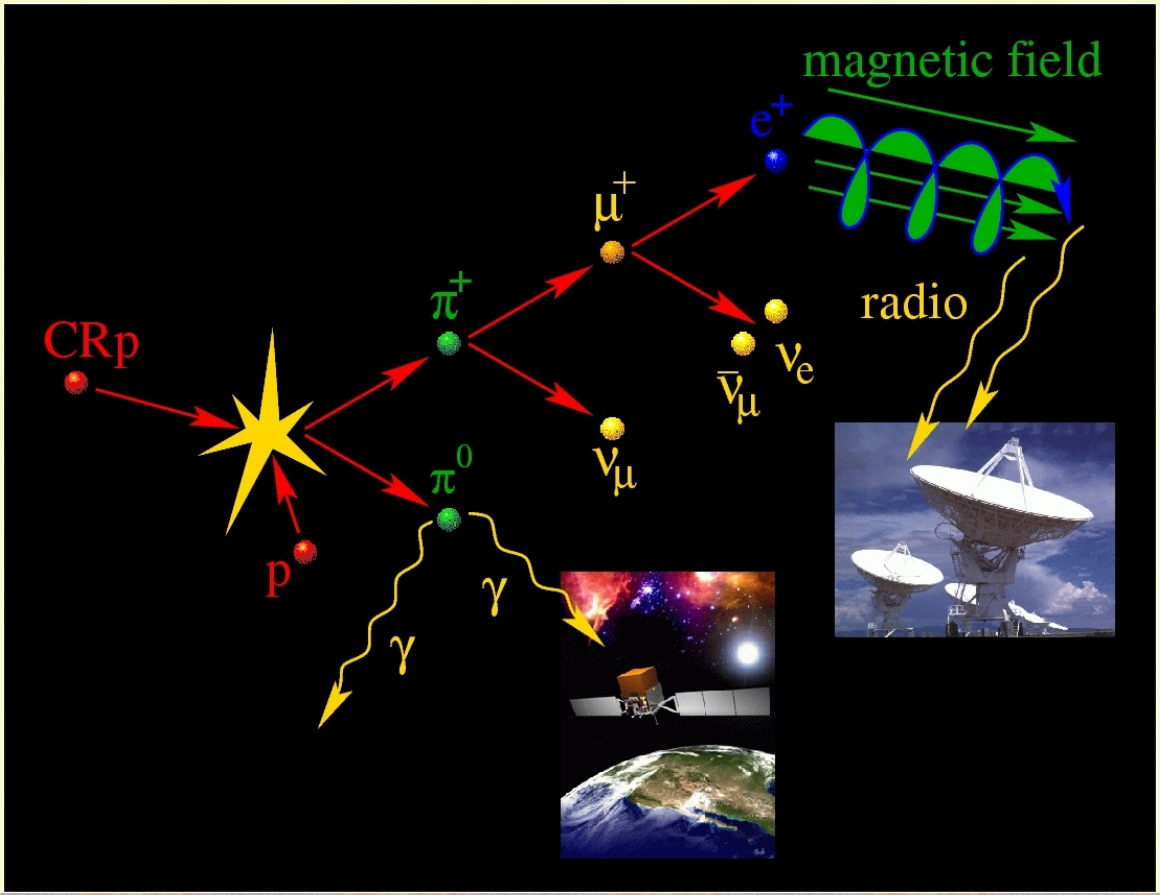


Primary models: acceleration mechanisms

- Fermi I: diffusive shock acceleration
- Fermi II: stochastic acceleration related to turbulences in the thermal intra-cluster medium
- Interaction between particles and magneto-hydro-dynamic waves:
  - ✔ Alfvén waves
  - ✔ Magneto-sonic waves

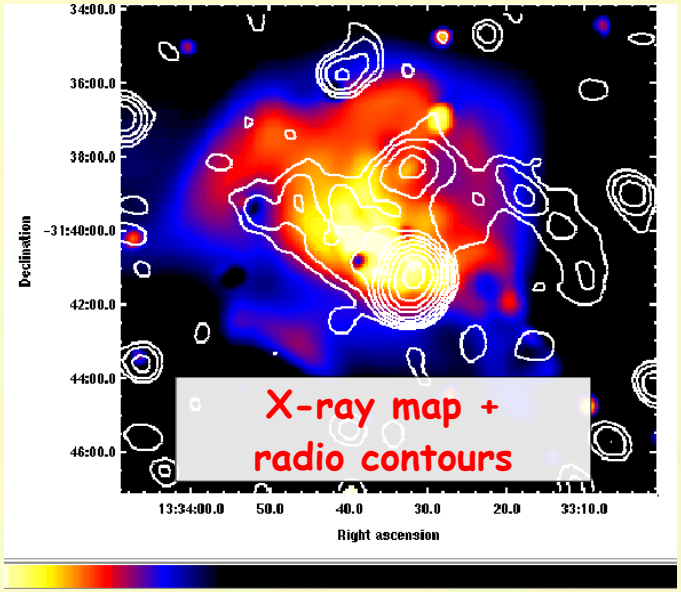
Secondary models: hadronic collisions

- As we have seen in Lecture 2, relativistic protons have a significantly lower synchrotron emissivity compared to electrons → relativistic protons have longer timescales (Gyr)
- Relativistic protons can collide with the thermal protons of the intra-cluster medium, making pions
- Pions decay, giving rise to relativistic electrons



Why primary models?

Based on secondary models:



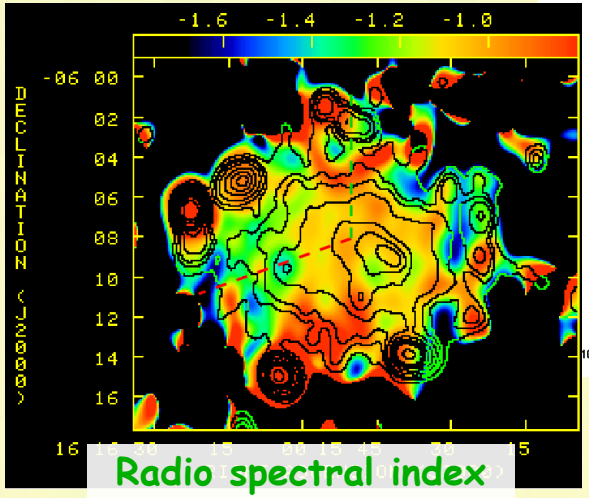
X-ray map + radio contours

Occurrence of radio halos and relics:

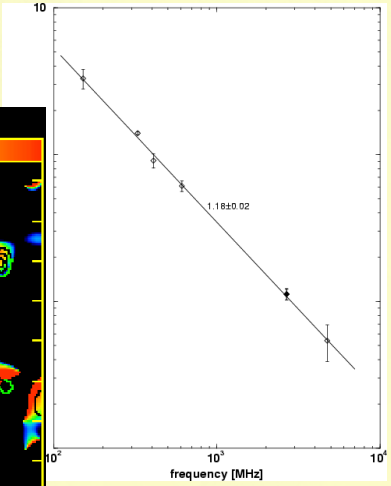
- clusters with similar physical properties (mass, luminosity, temperature, ...) should have similar radio properties
- while halos and relics have been detected only in merging galaxy clusters

Spectrum:

- The spectrum of the whole radio source should be a simple power-law
- While the observed spectral index maps of radio halos and relics show a patchy structure, correlated with cluster sub-structures

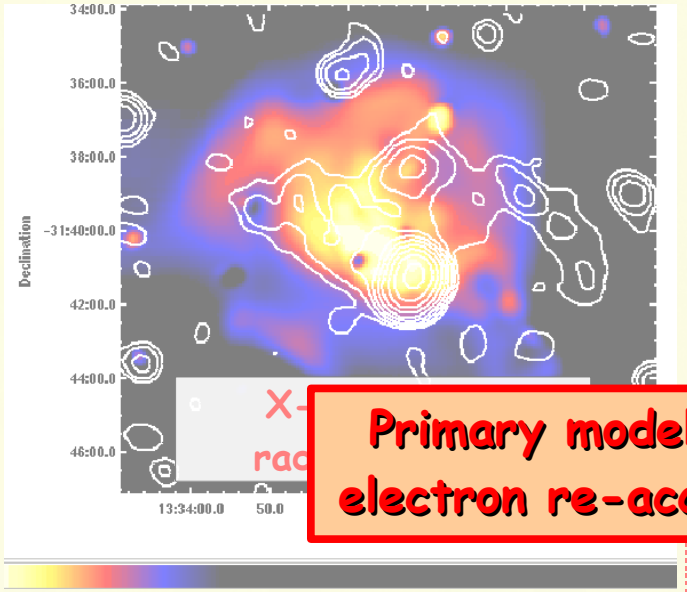


Radio spectral index map + radio contours



Why primary models?

Based on secondary models:



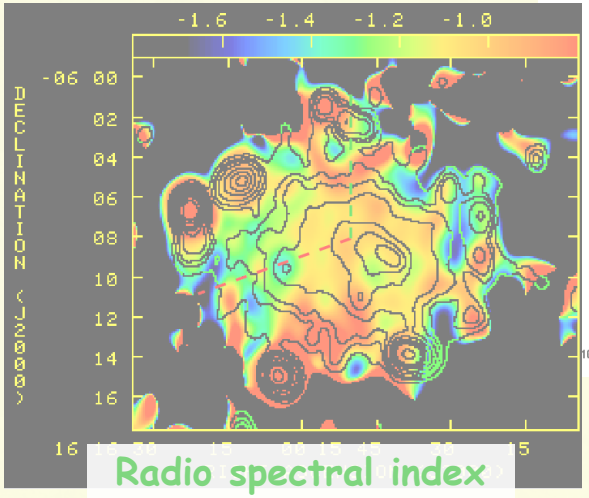
Occurrence of radio halos and relics:

- clusters with similar physical properties (mass, luminosity, temperature, ...) should have similar radio properties
- while halos and relics have been detected only in merging galaxy clusters

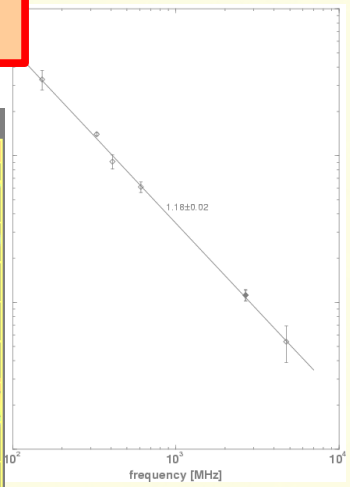
Primary models are most likely responsible for electron re-acceleration in radio halos and relics

Spectrum:

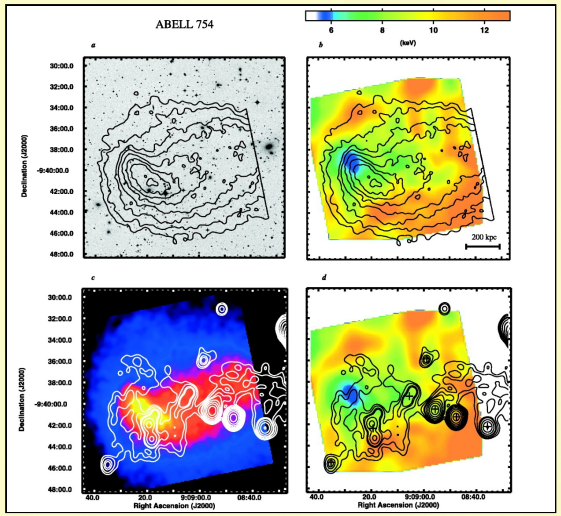
- The spectrum of the whole radio source should be a simple power-law
- While the observed spectral index maps of radio halos and relics show a patchy structure, correlated with cluster sub-structures

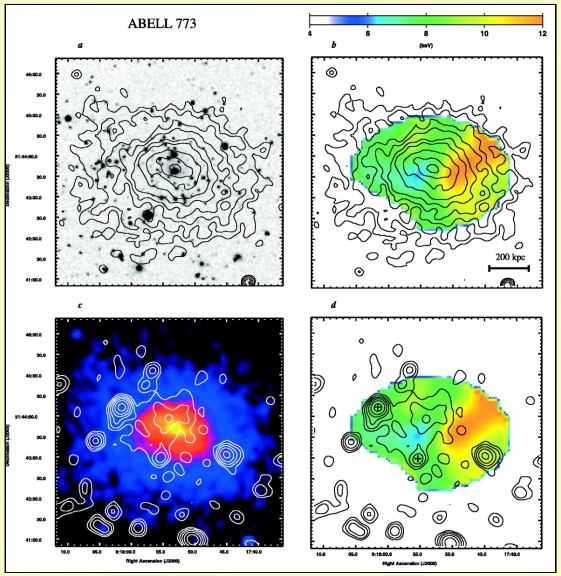


Radio spectral index map + radio contours

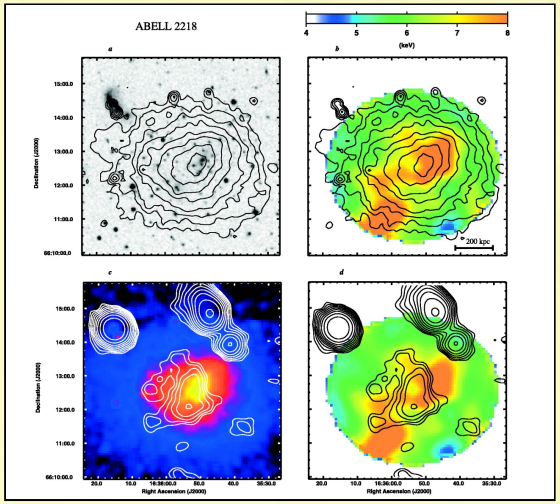


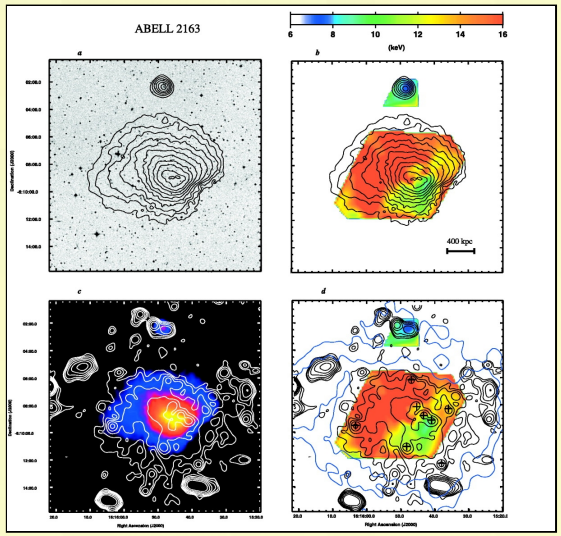
Radio halos





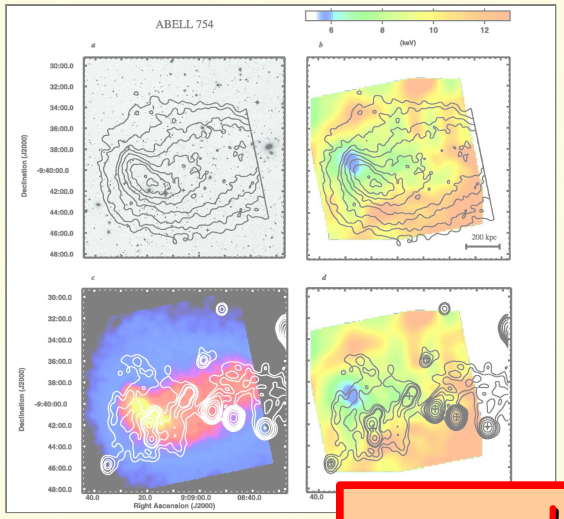
Optical + X-ray contours	T_{ICM} + X-ray contours
X-ray + radio contours	T_{ICM} + radio contours

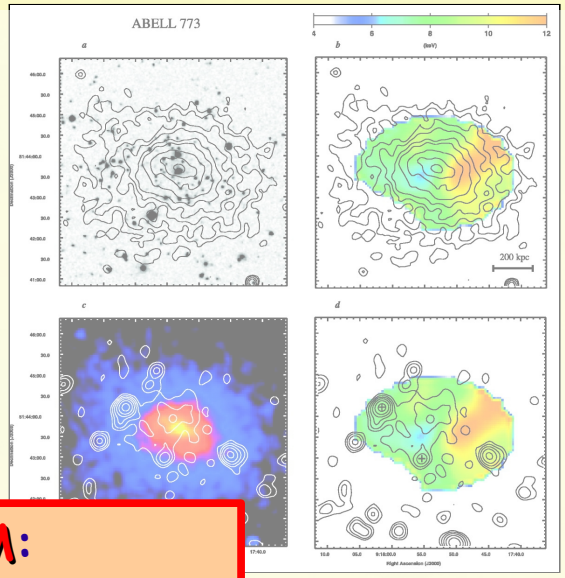




Govoni et al. 2004

Radio halos

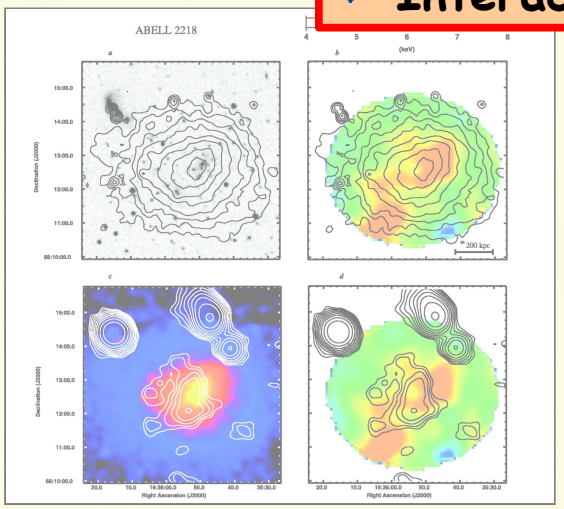


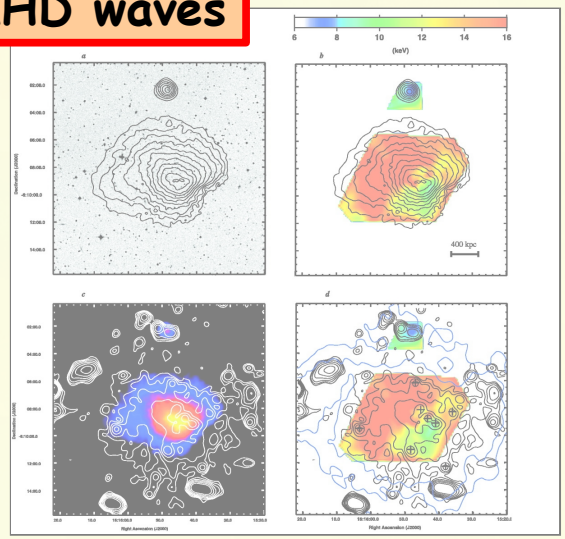


Optical + X-ray	T_{ICM} + X-ray
radio contours	radio contours

Halos ↔ Turbulences in the ICM:

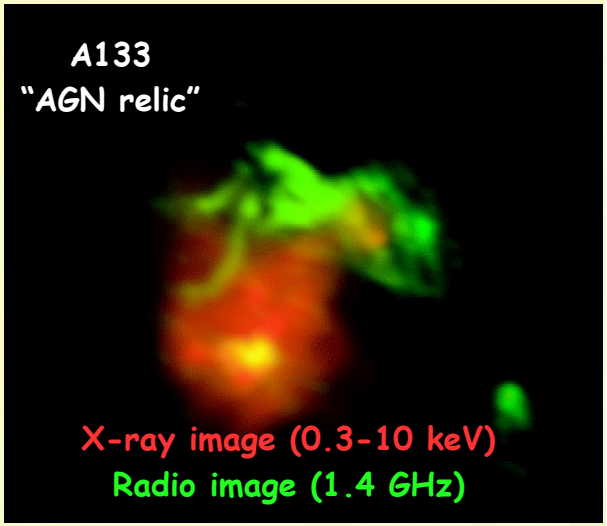
- Fermi II acceleration
- Interactions between particles and MHD waves



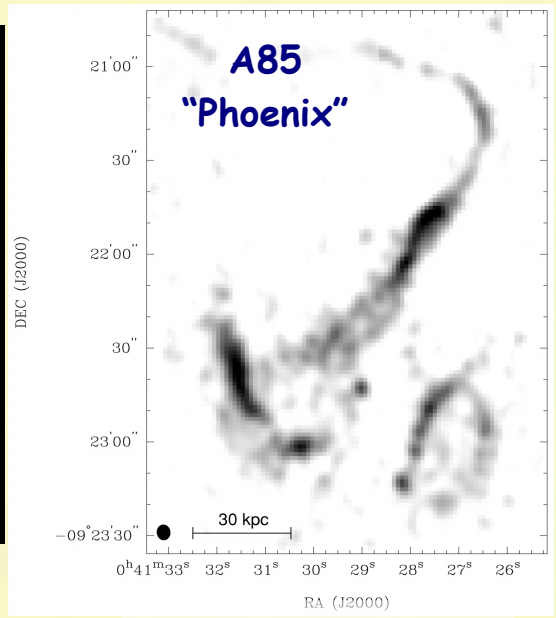


Govoni et al. 2004

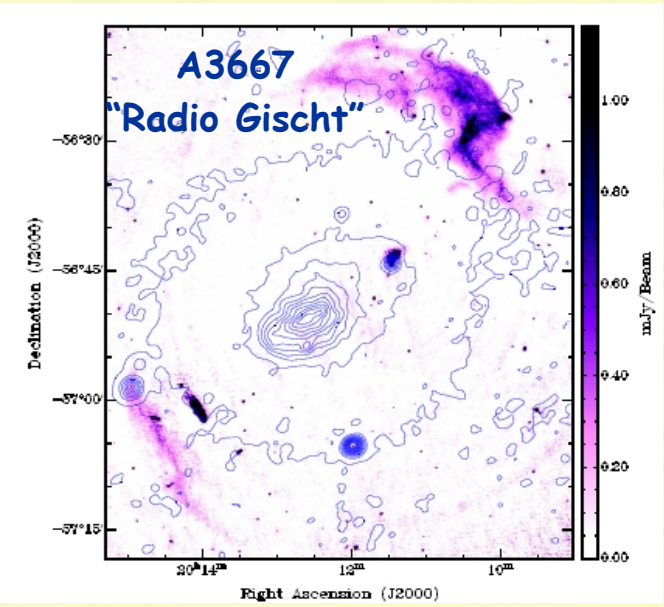
Radio relics: a bit of confusion about...



Slee et al. 2001; Fujita et al. 2002



Radio map (1.4 GHz)
Slee et al. 2001



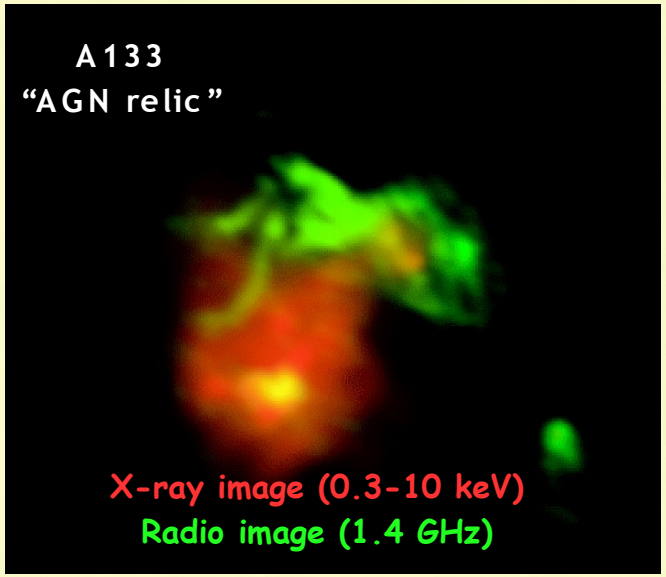
Radio map (1.4 GHz) + X-ray contours
Johnston-Hollitt et al. 2003

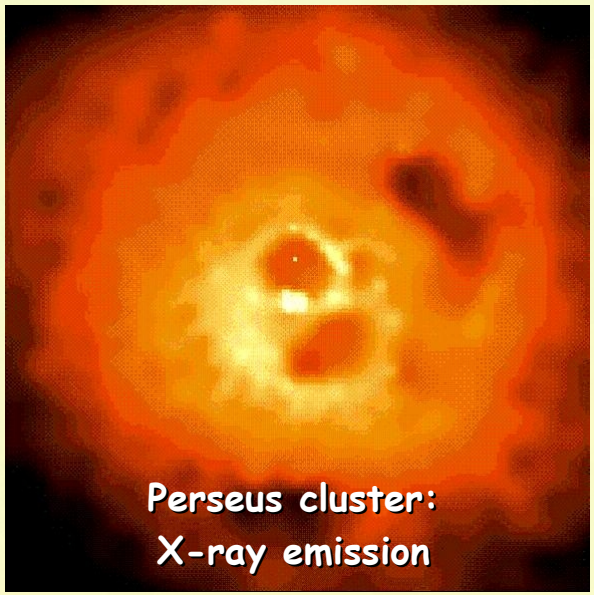
10 100 1000

Size (kpc)

Radio relics: a bit of confusion about...

- ✓Spectral index : $\alpha \leq -1.5$ ⟵ $(S(\nu) \propto \nu^{\alpha})$
- ✓Polarization: ≤ 20%
- ✓At cluster centre
- ✓Anti-correlation with the ICM(?)



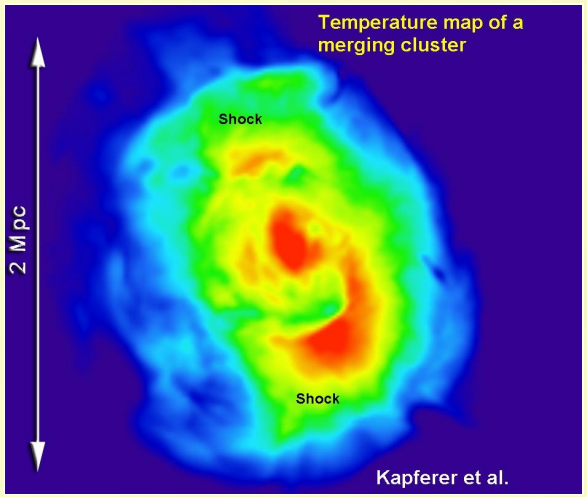


Slee et al. 2001; Fujita et al. 2002

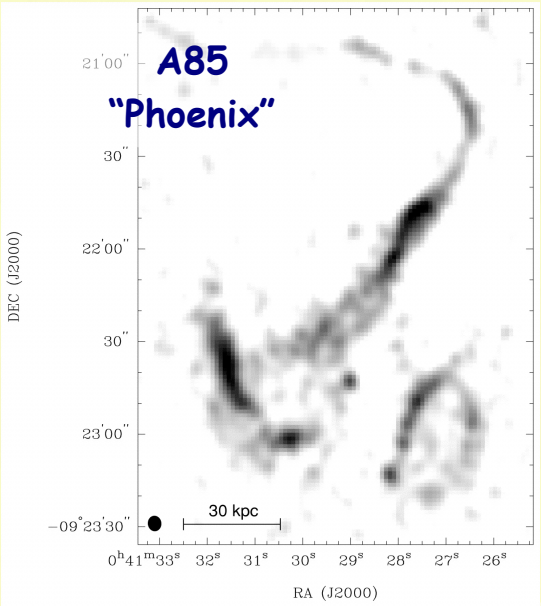
Radio relics: a bit of confusion about...

$(S(\nu) \propto \nu^{\alpha})$ ⟶

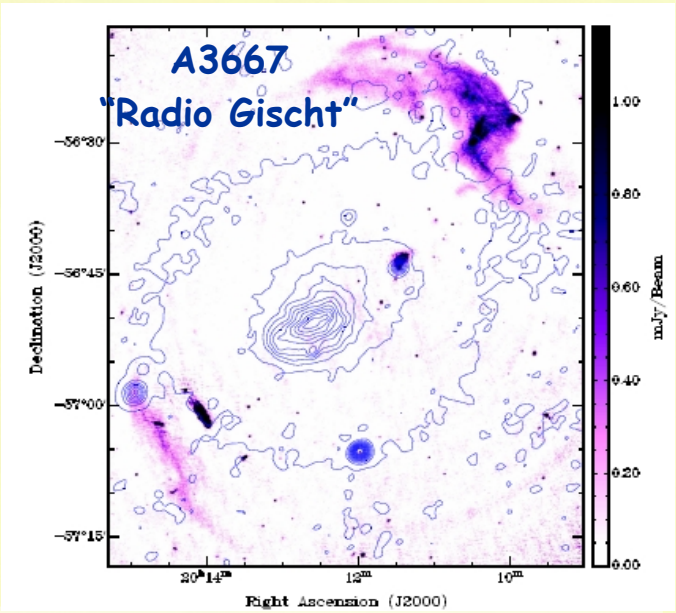
- ✓Spectral index: $\alpha \leq -1.5$
- ✓Polarization: 10-30%
- ✓In cluster outskirts
- ✓Correlated with ICM shocks



Numerical simulations of merging clusters



Radio map (1.4 GHz)
Slee et al. 2001



Radio map (1.4 GHz) + X-ray contours
Johnston-Hollitt et al. 2003

100 1000

Size (kpc)

Radio relics: a bit of confusion about...

✓Spectral index : $\alpha \leq -1.5$ ⟵ $(S(\nu) \propto \nu^{\alpha})$ ⟶ ✓Spectral index: $\alpha \leq -1.5$

✓Polarization: ≤ 20%

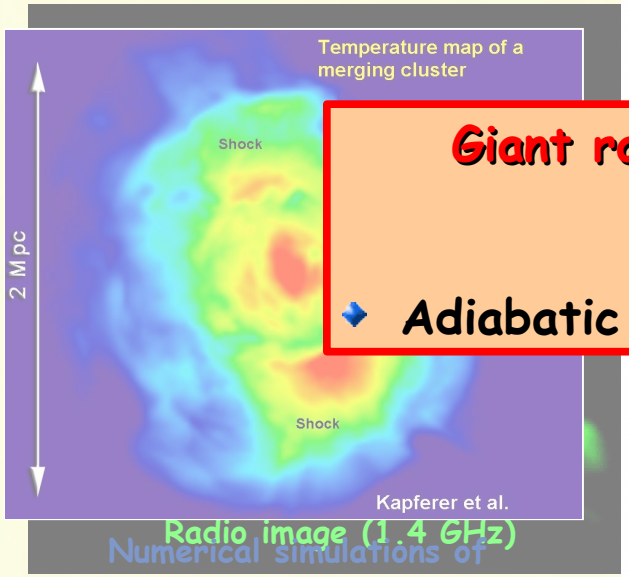
✓At cluster centre

✓Anti-correlation with the ICM(?)

✓Polarization: 10-30%

✓In cluster outskirts

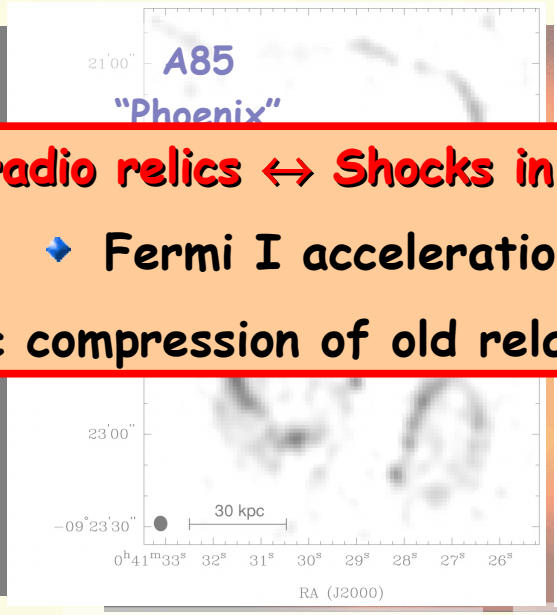
✓Correlated with ICM shocks



Radio image (1.4 GHz)

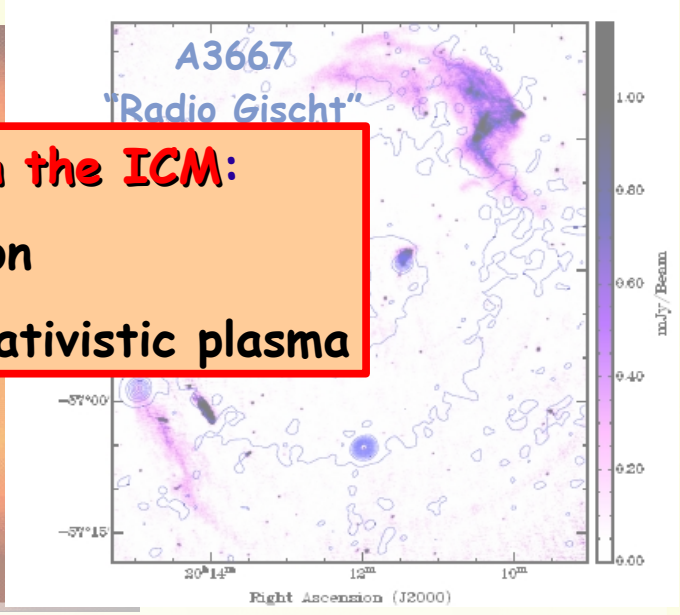
Numerical simulations of merging clusters

Slee et al. 2001; Fujita et al. 2002



Radio map (1.4 GHz)

Slee et al. 2001



Radio map (1.4 GHz) + X-ray contours

Johnston-Hollitt et al. 2003

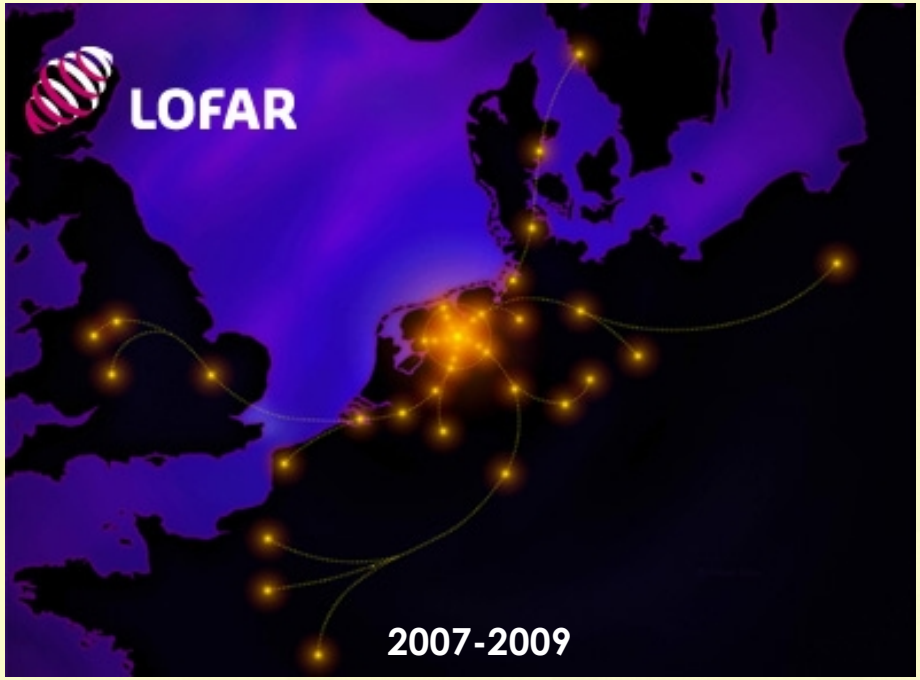
Giant radio relics ↔ Shocks in the ICM:

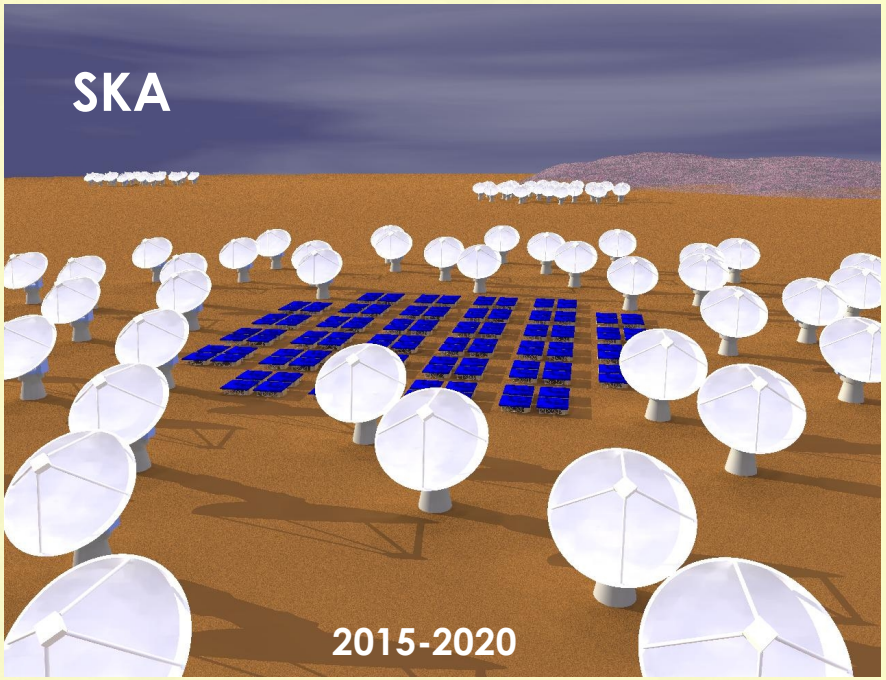
- Fermi I acceleration
- Adiabatic compression of old relativistic plasma

100 1000

Size (kpc)

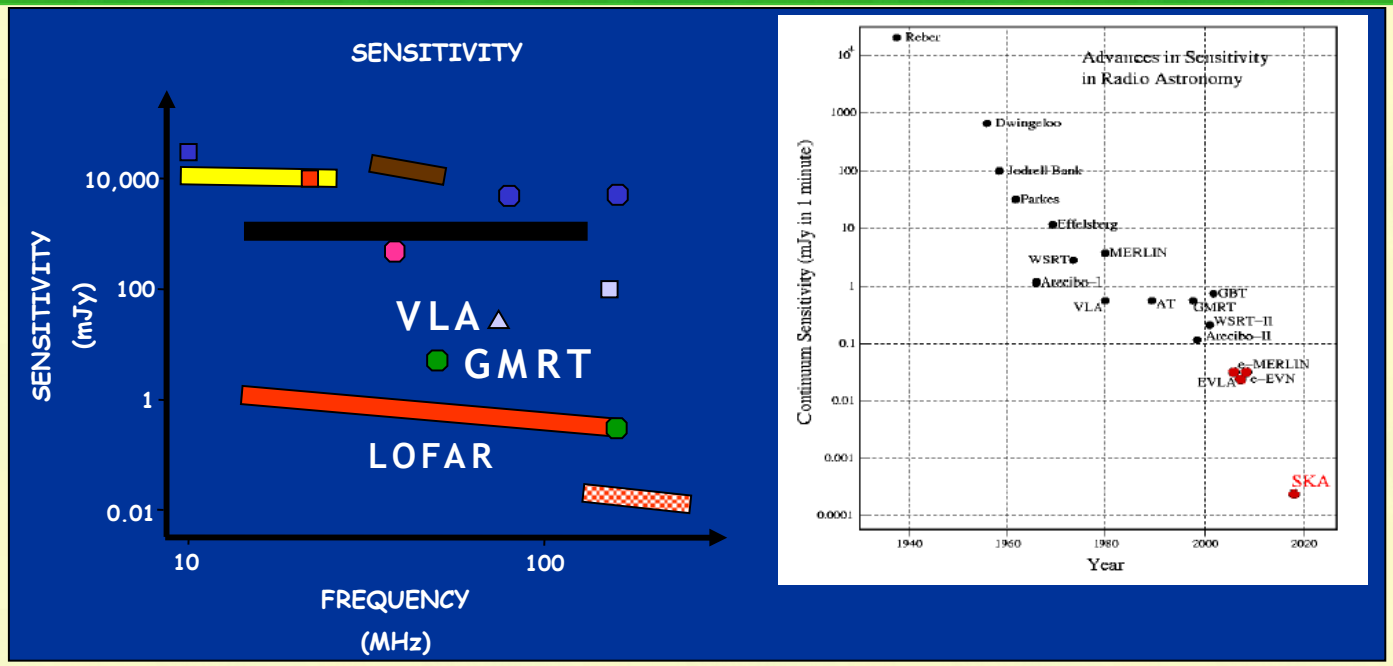
Perspectives: LOFAR and SKA

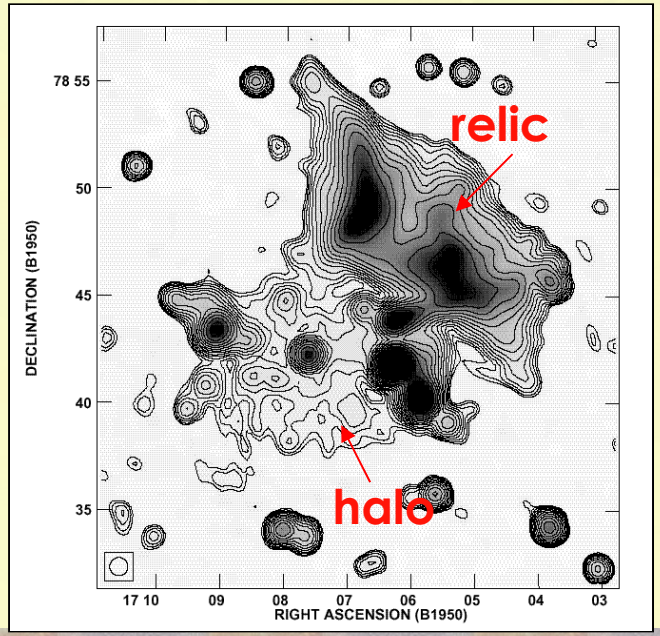


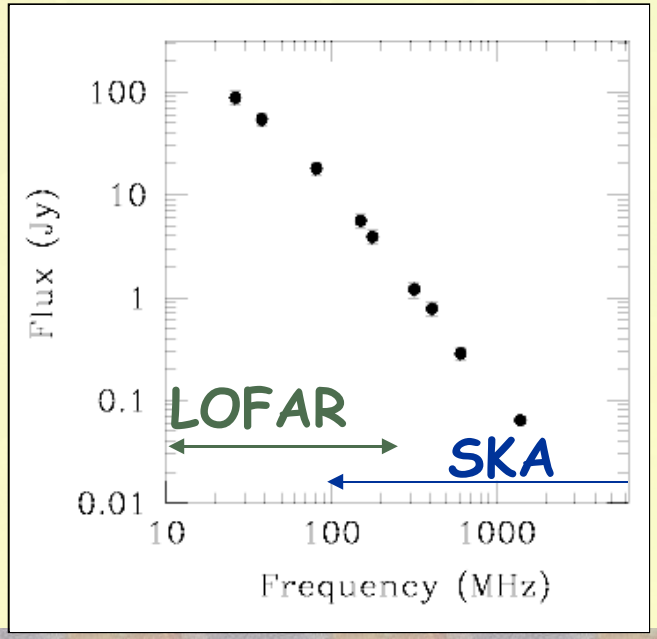


	Frequency Coverage	Sensitivity Improvement	Resolution Improvement	Polarization Purity
LOFAR	20-200 MHz	~100-1000	~100	≥30 dB
SKA	0.1-20 GHz	~100	~10	~40 dB

Perspectives: LOFAR and SKA



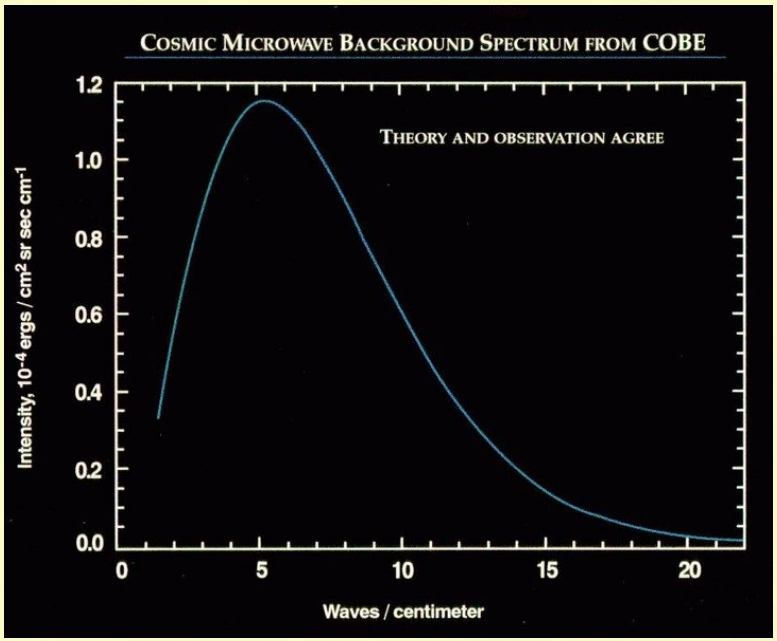




Lecture Outline

- Examples of galactic radio sources
  - Supernovae
  - Galactic continuum radiation and the inter stellar medium
- Examples of extra-galactic radio sources
  - Active Galactic Nuclei (AGN)
  - Galaxy clusters
  - **Cosmic Microwave Background (CMB)**
  - Epoch of Re-ionization (EoR)

Cosmic Microwave Background (CMB)



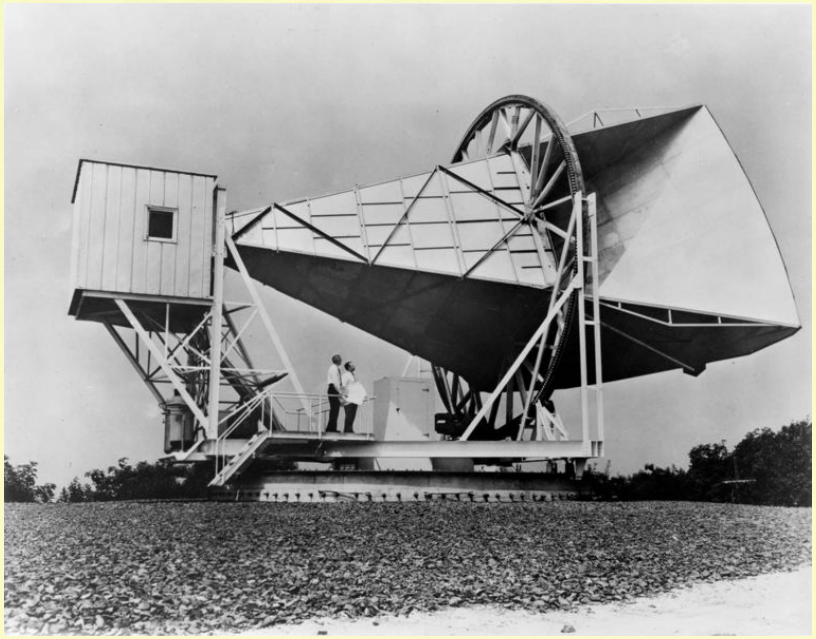
- Cosmic Microwave Background = e.m. radiation filling isotropically the entire Universe
- Thermal 2.725 K black body spectrum (the most precise ever measured in nature!)
- Peak in the microwaves (160.2 GHz <--> 1.9 mm)

- Bell telephones have been very important for astronomy!!!

(a) 1931 - Jansky's discovered radio emission from the Milky Way

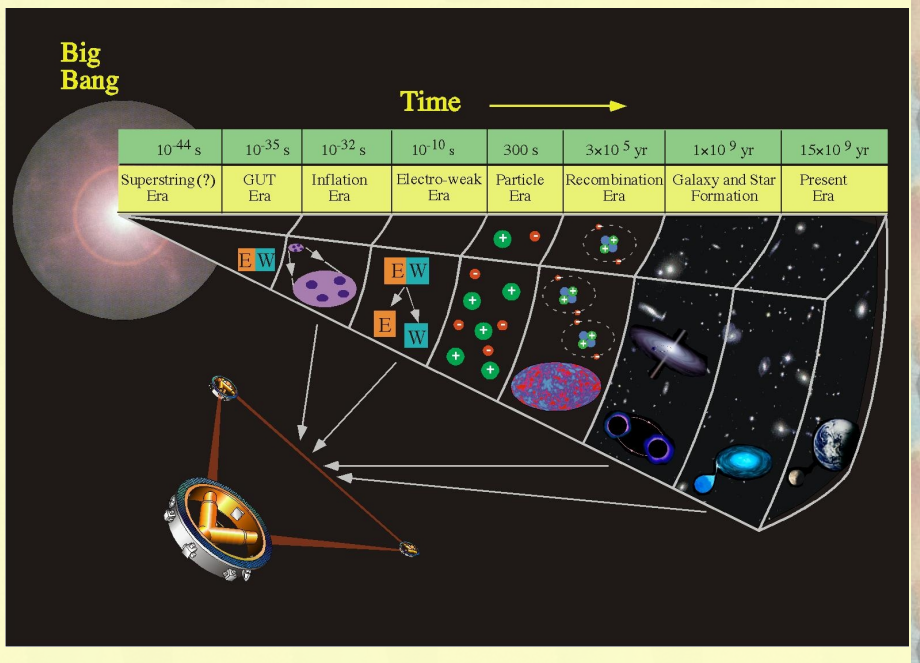
(b) 1965 – Penzias and Wilson discovered the CMB (even if they did not know at that time that it was the CMB!)

- At about the same time: theoretical prediction by Dicke and Peebles (following Gamow's first idea)
- 1978 - Penzias and Wilson got the Noble prize. Dicke and Peebles did not get a mention :-(

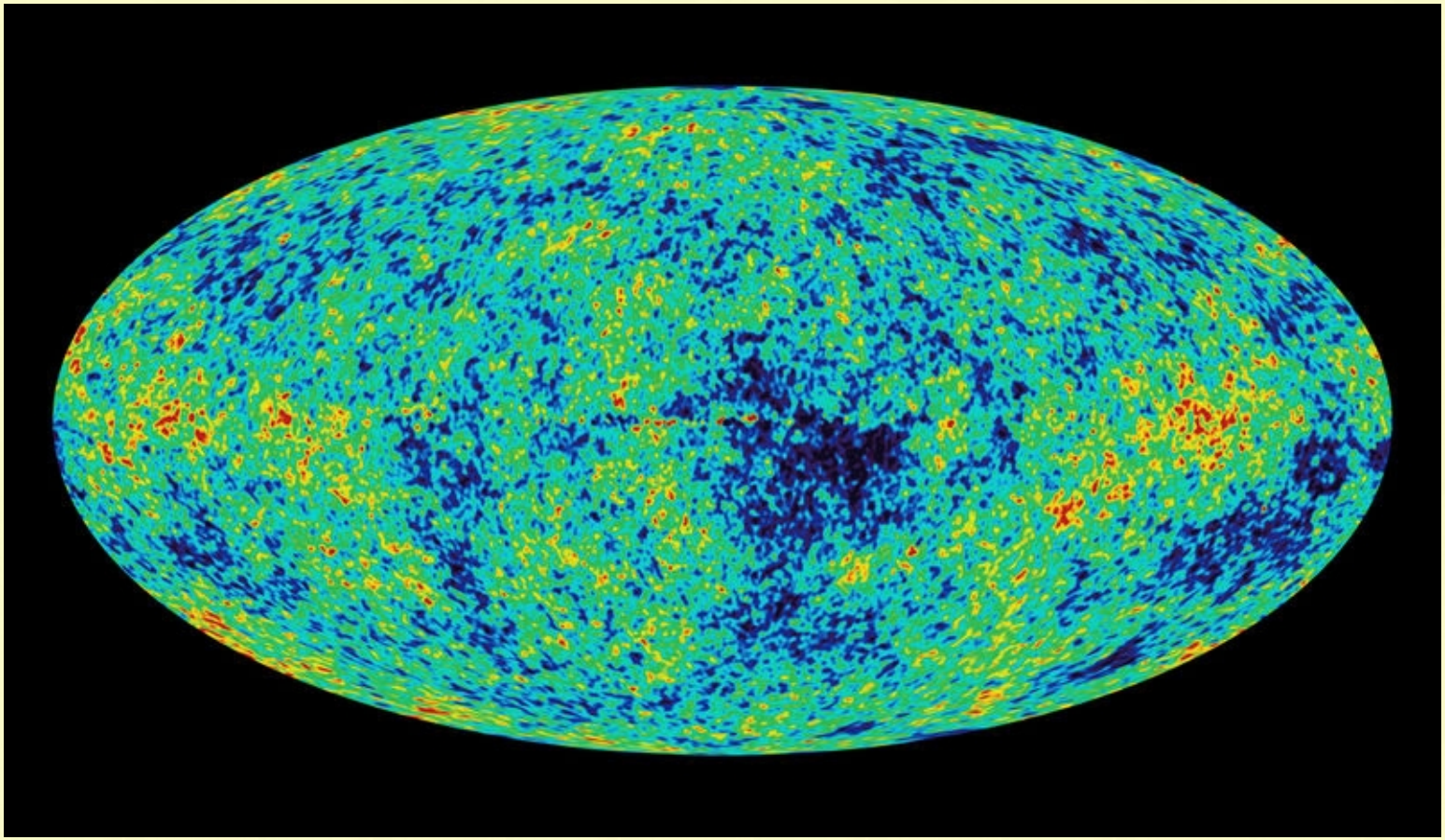


Why the CMB?

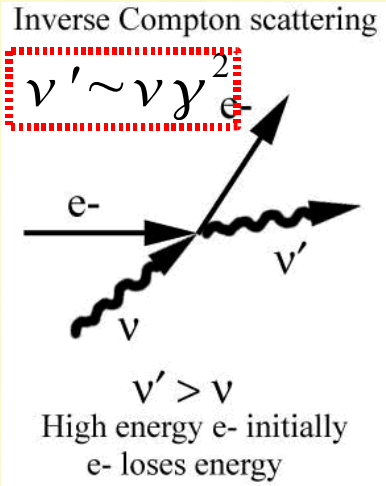
- CMB: prediction of Big Bang theory
- The early Universe was made up of a hot plasma of photons, electrons and baryons
- The photons were constantly interacting with the plasma through Thomson scattering
- As the Universe expanded, adiabatic cooling caused the plasma to cool until it became favorable for electrons to combine with protons and form hydrogen atoms
- This happened at around 3000 K or when the universe was approximately 380000 years old (z=1088)
- At this point, the photons did not scatter off of the now neutral atoms and began to travel freely through space: recombination or decoupling
- The photons have continued cooling ever since; they have now reached 2.725 K and their temperature
- The CMB comes from a spherical surface, called the surface of last scattering, from which the photons that decoupled from interaction with matter in the early universe, 13.7 billion years (13.7 G yr) ago



Cosmic Microwave Background (CMB)



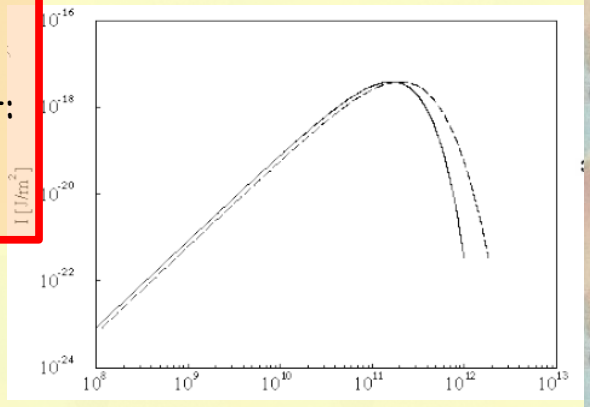
WMAP satellite reconstruction of the primordial fluctuations in the cosmic microwave background (CMB). The average temperature of the CMB radiation is 2.7 K, with some variation from place to place. The variations seen in the image are on the order of 10^{-5} K (that's 1/10000th of a degree!). These fluctuations are the seed of structures' formation.


Inverse Compton scattering
$\nu' \sim \nu \gamma_{e^-}^2$
e-
ν′
ν
$\nu' > \nu$
High energy e- initially
e- loses energy

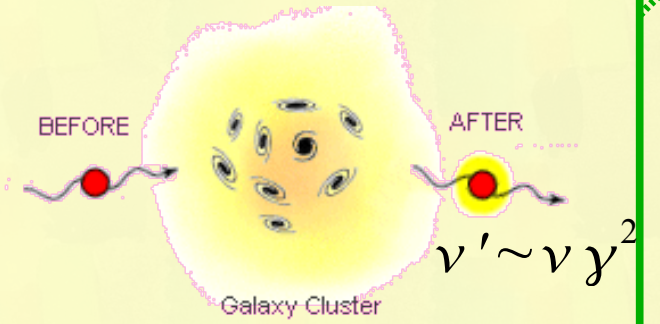
CMB and galaxy clusters

Thermal electrons:

- 150 MeV --> $\gamma \sim 300$
- Sunyaev-Zel'dovich effect: distortion of the CMB spectrum



IC scattering of the CMB photons due to the free (thermal and non-thermal) electrons of the ICM:

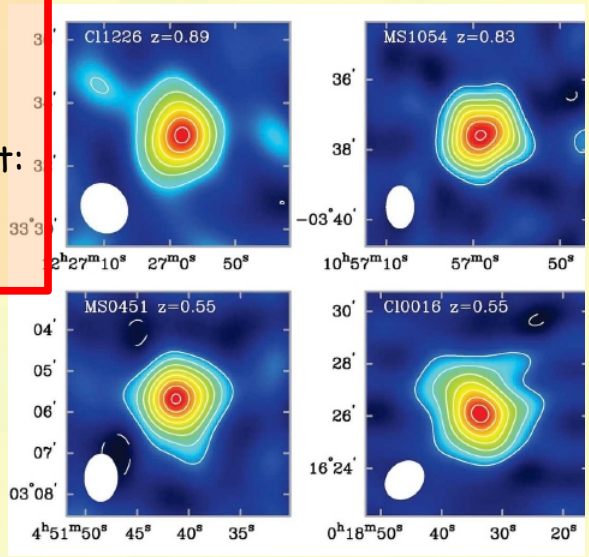


$$\nu' \sim \nu \gamma^2$$

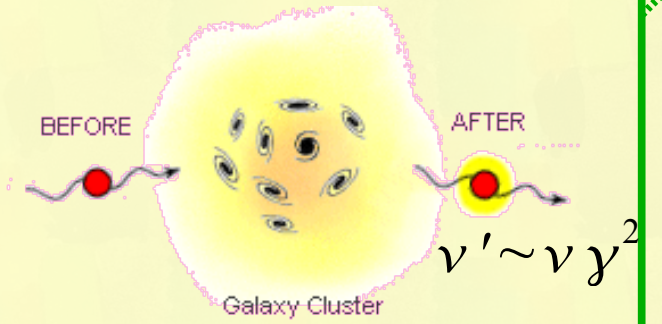
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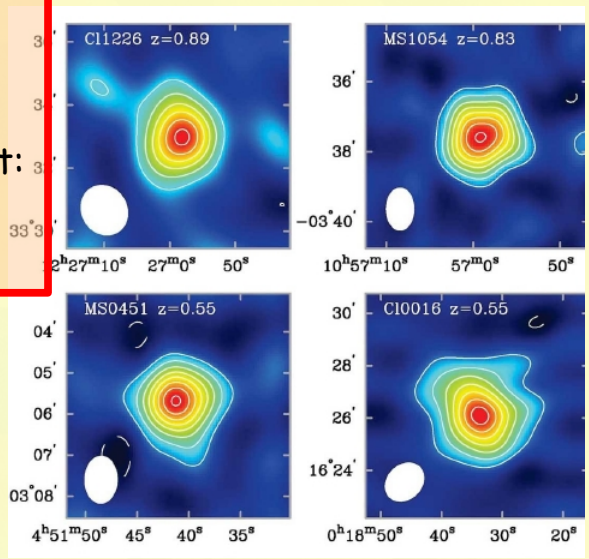
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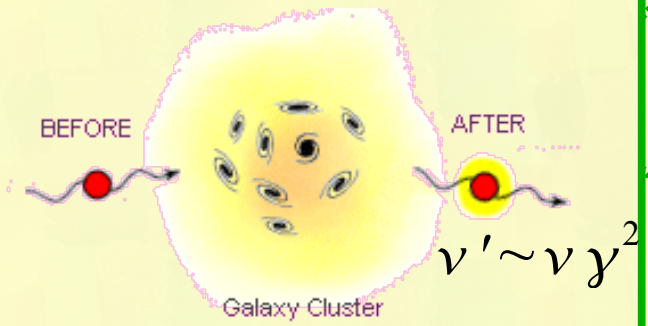
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Thermal electrons:

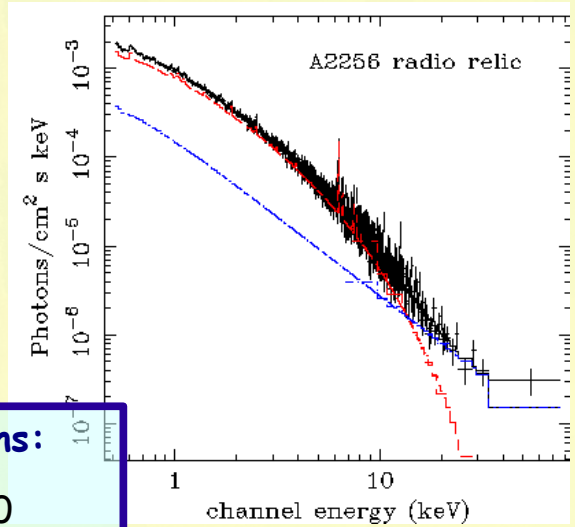
- 150 MeV --> $\gamma \sim 300$
- Sunyaev-Zel'dovich effect: distortion of the CMB spectrum



IC scattering of the CMB photons due to the free (thermal and non-thermal) electrons of the ICM:



$$\nu' \sim \nu \gamma^2$$



Non-thermal electrons:

- GeV --> $\gamma >>> 1000$
- microwaves --> hard X-ray

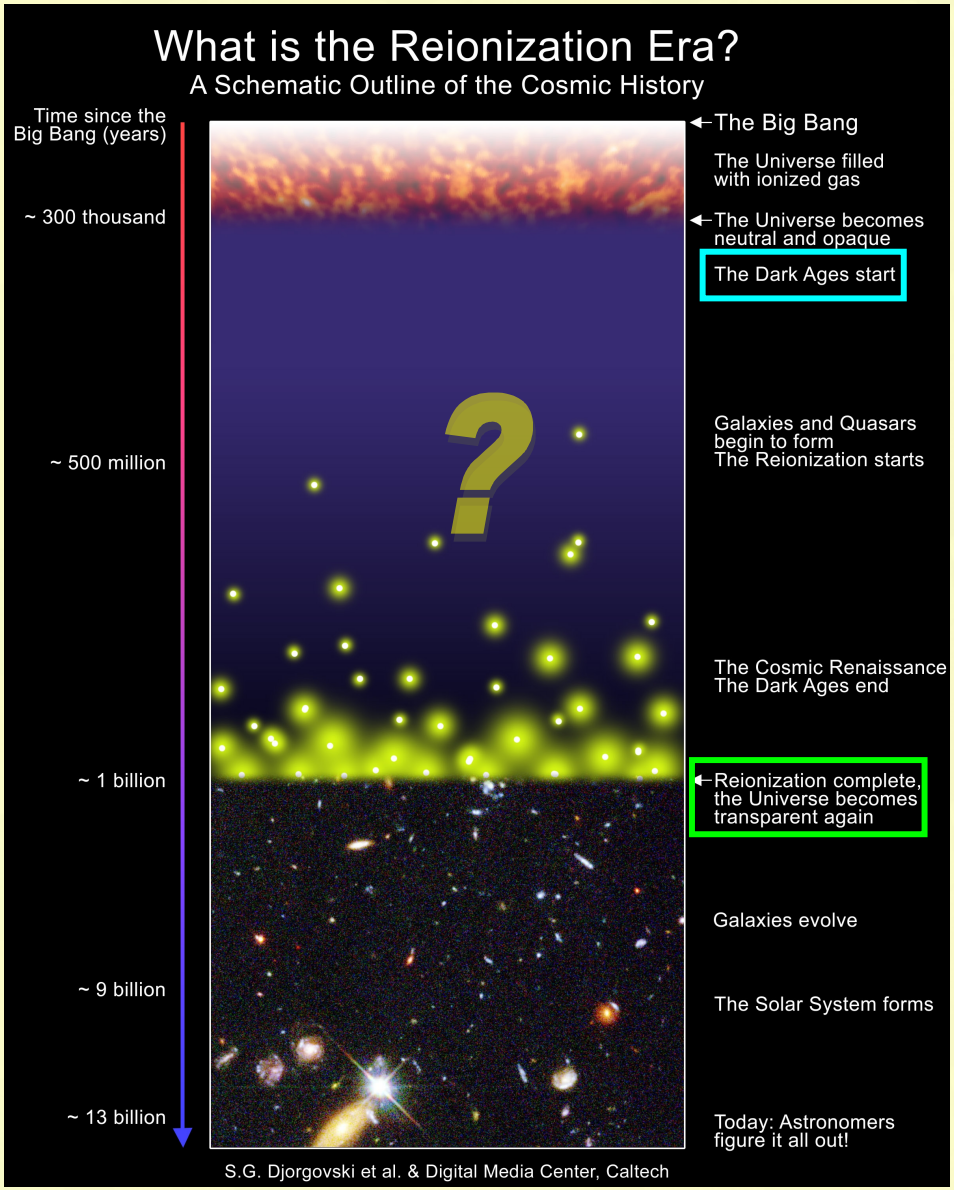
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  - **Epoch of Re-ionization (EoR)**

Epoch of Re-ionization (EoR)

z~1000

z~6



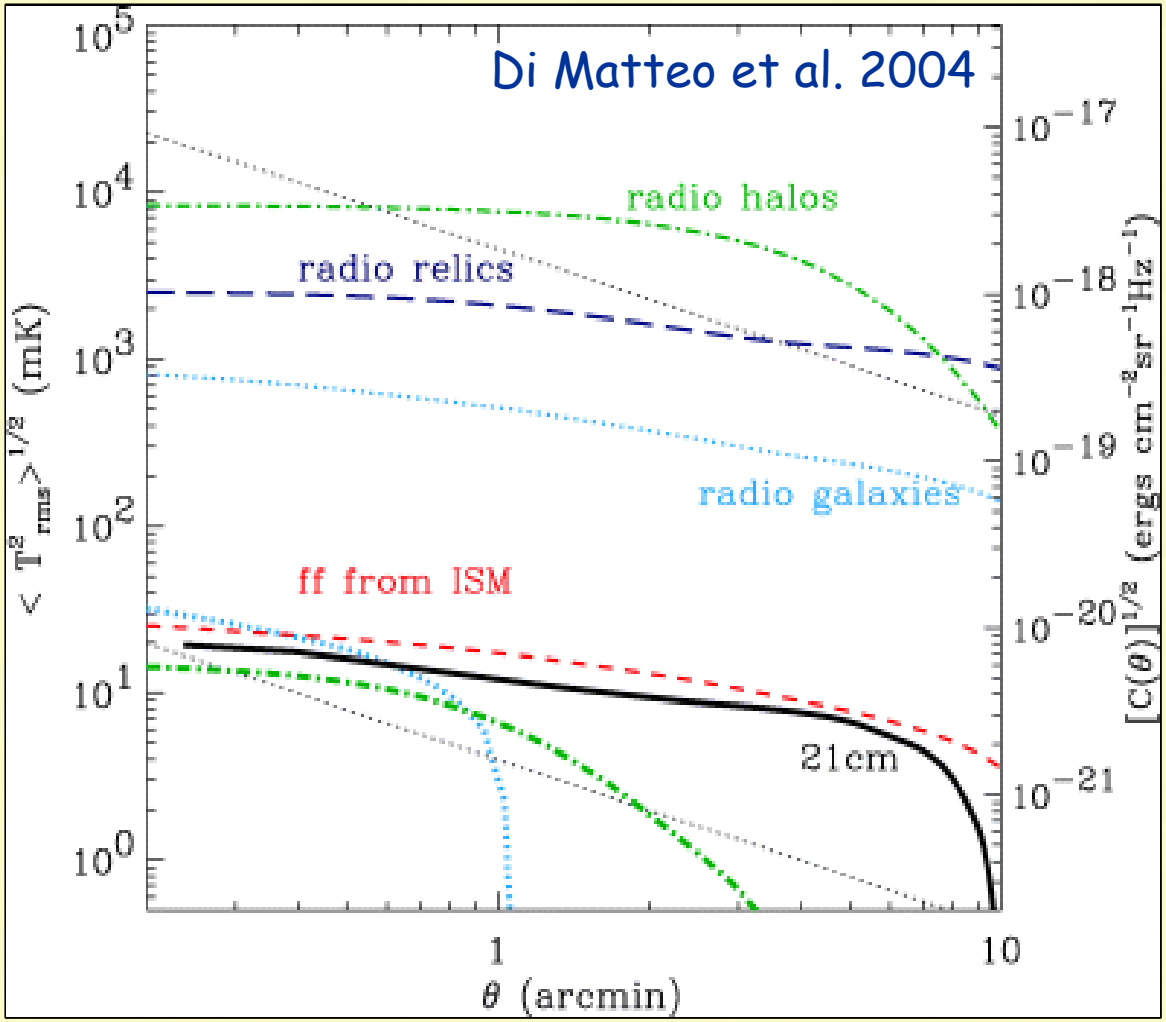
Reionization:

- Transition from neutral to ionized "intergalactic" medium (z~1000 à z~6)
- Second of two major phase changes of hydrogen gas in the Universe (first: recombination - CMB)
- 21cm transition of HI: it allows to trace the neutral gas before and after the reionization

z =1000 – 6

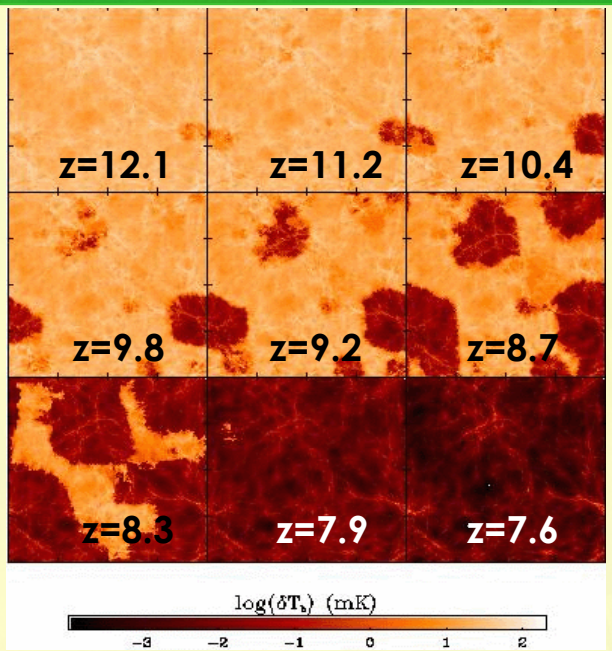
1.4 - 200 MHz

EoR: foreground contamination

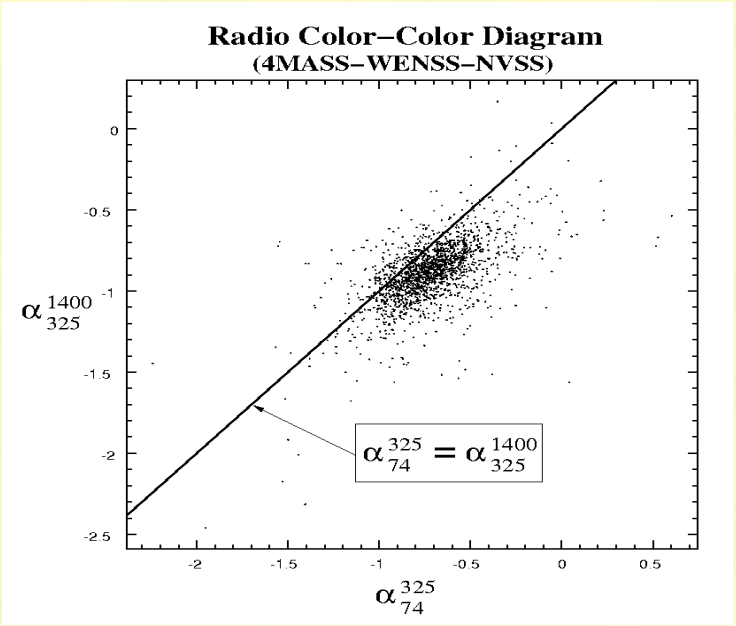


Signal owing to intensity fluctuations of the **redshifted 21 cm emission** and to the different **foreground sources**

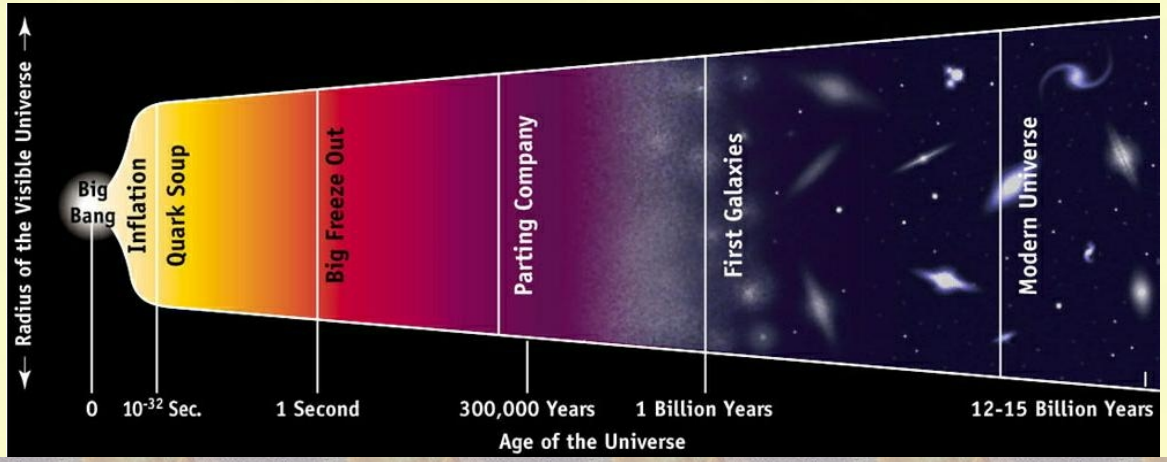
Could we remove the foreground contamination?



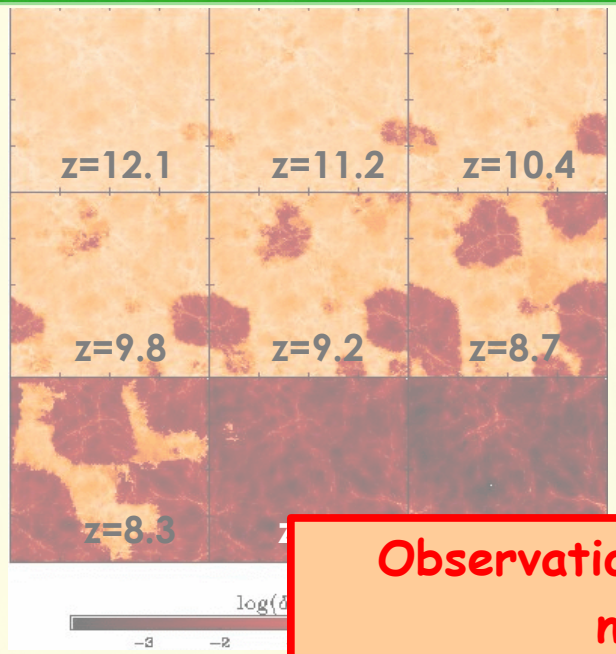
Transition at 21 cm:
simulations of the evolution of the brightness temperature ($\Delta\nu$~6 MHz)



Foreground:
Colour-colour diagram of radio halos and relics



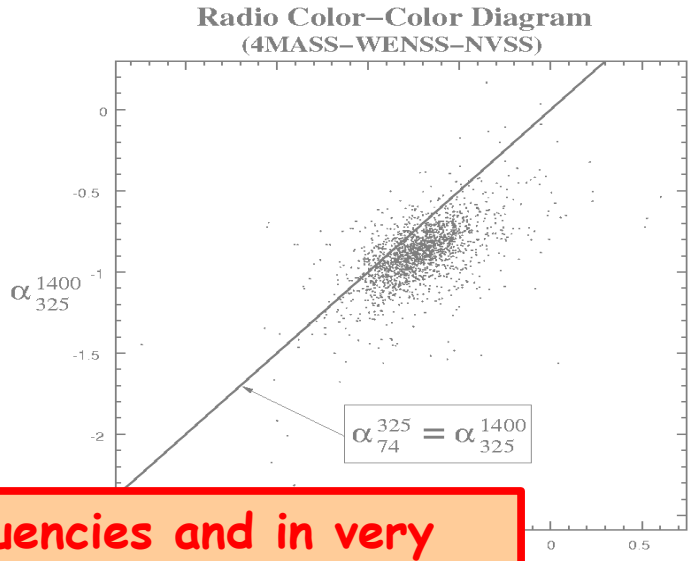
Could we remove the foreground contamination?



Transition

simulations of th

brightness temperature ($\Delta\nu$~6 MHz)



Observations at low frequencies and in very narrow frequency bands!!!

LOFAR & SKA

of radio halos and relics

