Cosmology and gravitation: the grand scheme for high energy physics
Part 2

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Plan

A brief history of cosmology

The days where cosmology became a quantitative science: Cosmic Microwave Background

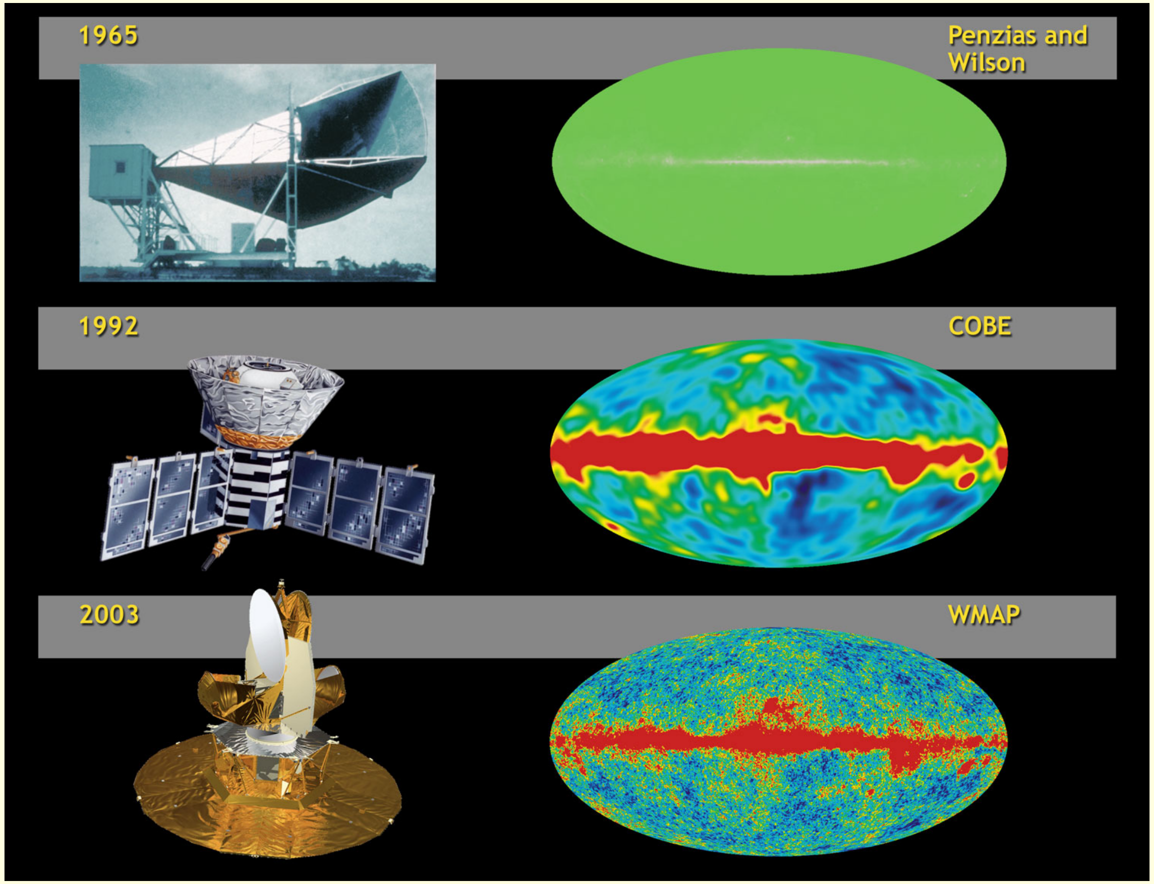
Light does not say it all (1): the violent Universe

Light does not say it all (2): dark matter

Light does not say it all (3) : dark energy

The beginning and the end

The days where cosmology became a quantitative science:
Cosmic Microwave Background



Cosmological distances

Recall that photons follow geodesics defined by $ds^2=0$ i.e.

$$c^2dt^2 = a^2(t)\frac{dr^2}{1-kr^2}$$

One defines the proper distance as

$$d(t) \equiv a(t)\int_0^r \frac{dr}{\sqrt{1-kr^2}} = a(t)\int_t^{t_0}\frac{cdt'}{a(t')}$$

If a photon source of luminosity L is placed at a distance r from the observer, the energy flux received by the observer is

$$\phi = \frac{L}{4\pi a_0^2 r^2 \underline{(1+z)^2}} \equiv \frac{L}{4\pi d_L^2}$$

2 powers of (1+z):
- photon energy redshift
- time dilatation between emission and observation

$d_L = a_0 r(1+z)$ is called the luminosity distance

If D is the diameter of a source, δ its observed angular diameter, $d_A \equiv D/\delta$ is called the angular distance:

$$d_A = \frac{d_L}{(1+z)^2}$$

An important distance scale is the particle horizon.

A photon emitted at the big bang (t=0) would have travelled a finite distance at time t.

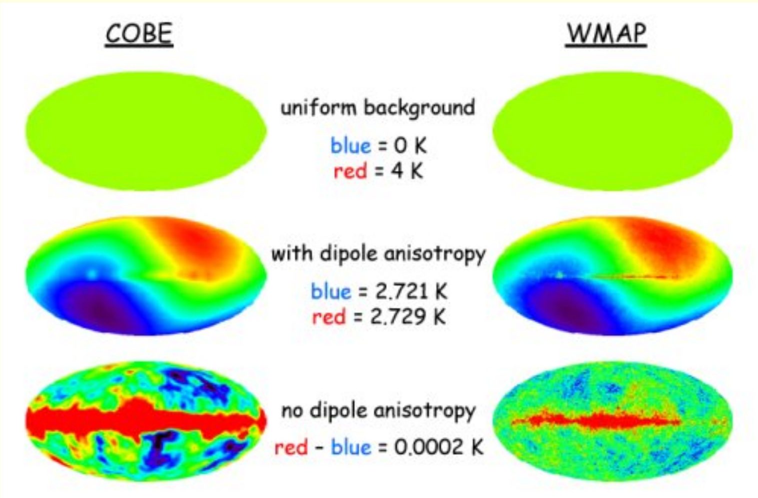
proper distance
$$d_h(t) = a(t)\int_0^t \frac{c\,dt'}{a(t')}$$

$$= \frac{\ell_{H_0}}{1+z}\int_z^\infty \frac{dz}{\left[\Omega_M(1+z)^3 + \Omega_R(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]^{1/2}}$$

$\ell_{H0} \equiv c\,H_0^{-1}$

This horizon scale measures the maximal distance at which causal effects can propagate.

Cosmic Microwave Background



The early Universe is an ionized plasma : photons interact strongly with the plasma and are absorbed before propagating: the Universe is dark.

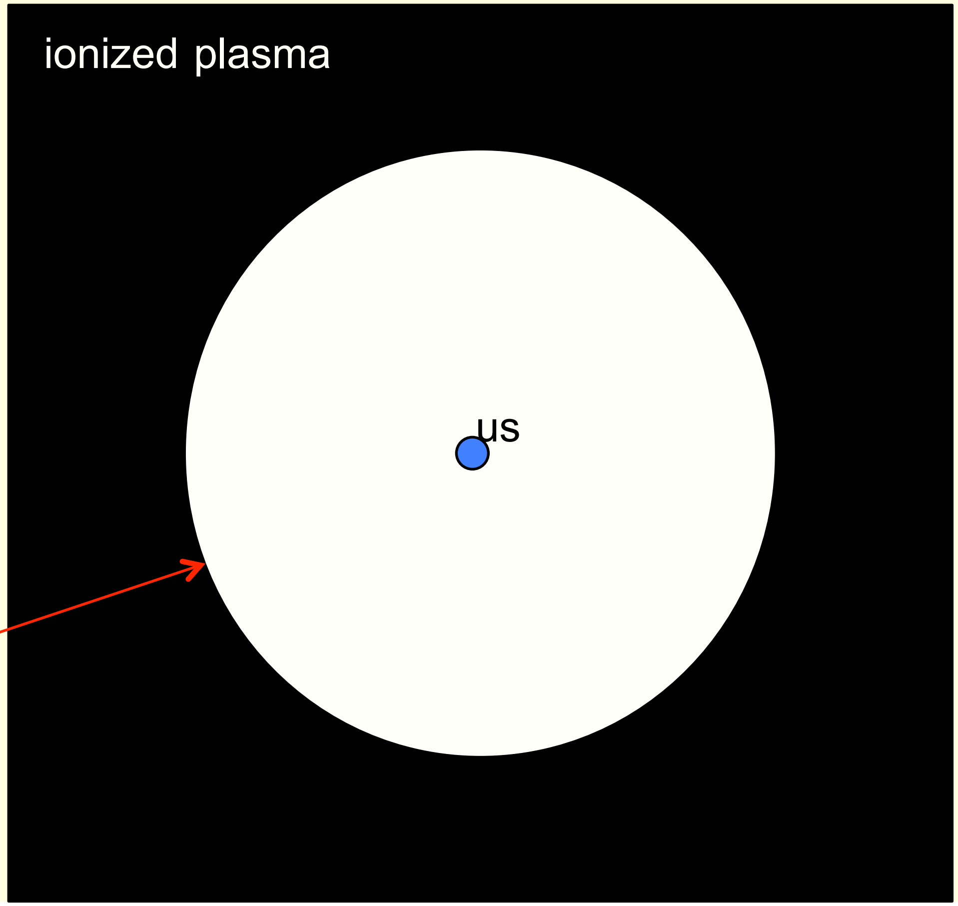
At $t \sim 400\,000$ yrs i.e. $kT \sim 0.26$ eV i.e. $z \sim 1100$, electrons combine with protons to form neutral hydrogen: photons can travel large distances. The universe becomes transparent to light.

Which light?

The early Universe is an ionized plasma : photons interact strongly with the plasma and are absorbed before propagating: the Universe is dark.

At t ~ 400 000 yrs i.e. kT ~ 0.26 eV i.e. z ~ 1100, electrons combine with protons to form neutral hydrogen: photons can travel large distances. The universe becomes transparent to light.

Which light?



last scattering surface

Which light?

The light emitted by a black body at temperature kT = 0.26 eV observed at the redshifted temperature T_γ = 2.725 K

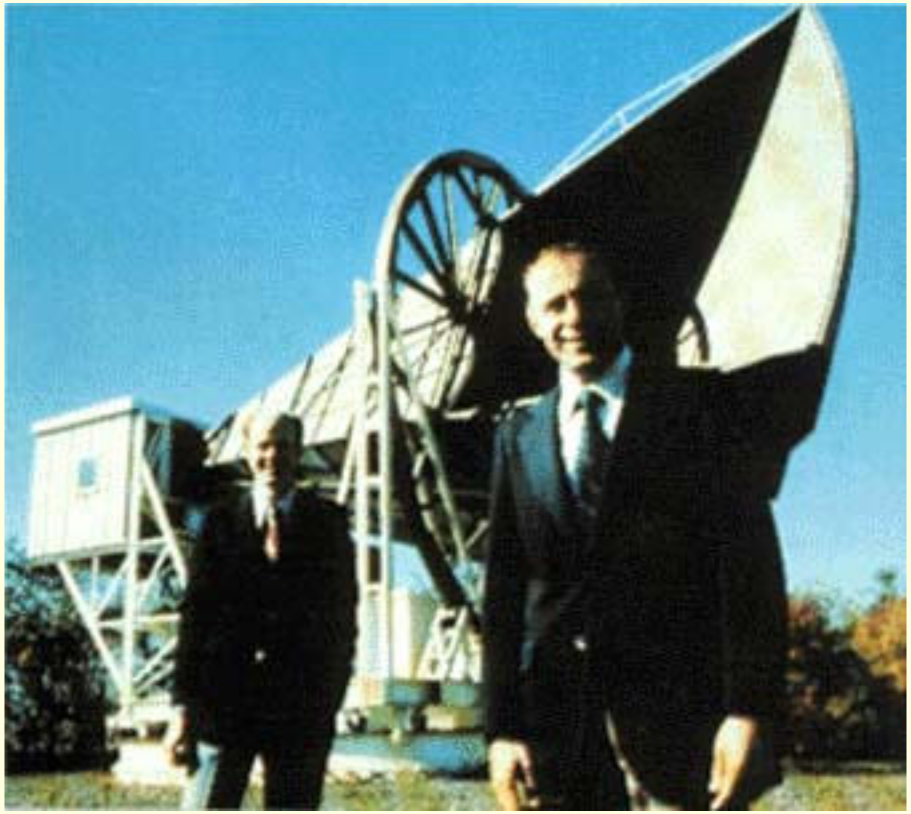
$$d\rho_\gamma = 2hf \frac{1}{e^{hf/kT_\gamma} - 1} \frac{4\pi f^2 df}{c^3}$$

$$\frac{d\rho_\gamma}{d\ln f} = 3.8 \times 10^{-15} \mathrm{J/m^3} \left(\frac{f}{f_\gamma}\right)^4 \frac{e-1}{e^{f/f_\gamma} - 1} ,$$

$f_\gamma = kT_\gamma/h = 5.7\ 10^{10}$ Hz

microwave range

Accidentally observed by Penzias and Wilson in 1965



$n_\gamma \sim 411$ photons cm^{-3}

Isotropic and homogeneous radiation throughout the sky $\Longrightarrow$ cosmic origin

<u>A problem with causality</u>

At recombination, $z_{rec} \sim 1100$, the Universe is matter dominated. Hence the particle horizon d_h is:

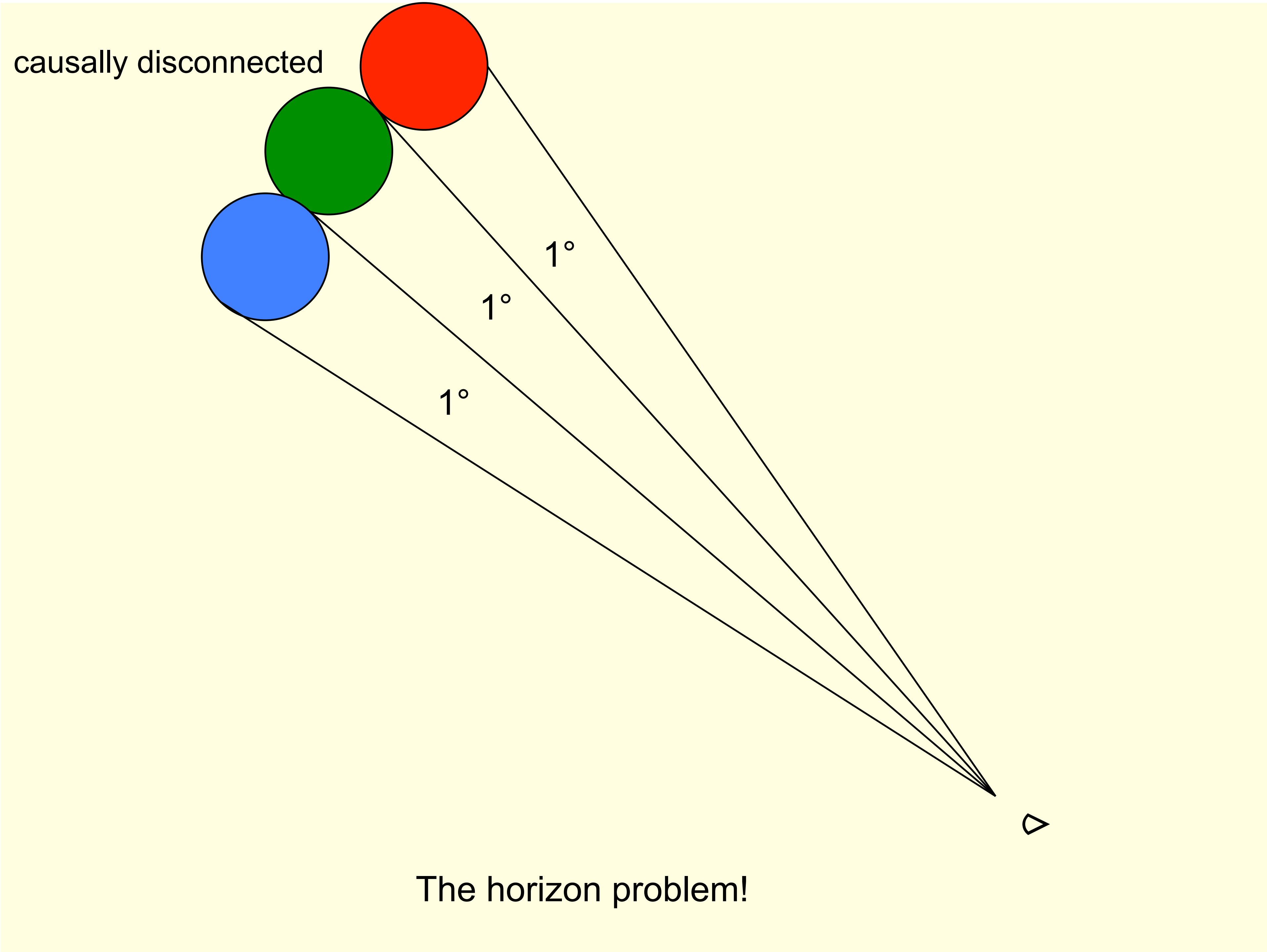
$R_H(t_{rec}) = H^{-1}(z_{rec})$
Hubble radius at recombination

$$d_h(t_{rec}) \sim \frac{2\,\ell_{H0}}{\Omega_M^{1/2}\, z_{rec}^{3/2}} \sim 2\, R_H(t_{rec}) \sim 0.3 \text{ Mpc}$$

This radius is seen by an observer at present time under an angle

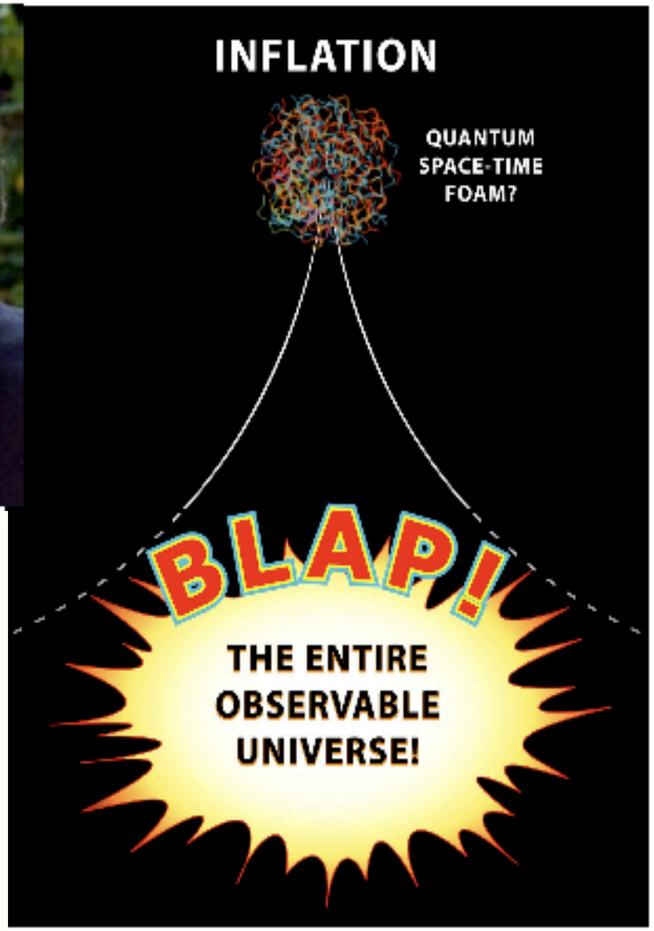
$$\theta_H(t_{rec}) = R_H(t_{rec})/d_A(t_{rec}) \quad \text{with} \quad d_A(t_{rec}) \sim \frac{2\,\ell_{H0}}{\Omega_M\, z_{rec}}$$

Hence $\theta_H(t_{rec}) = \Omega_M^{1/2}/(2 z_{rec}^{1/2}) \sim 1°\ \Omega_M^{1/2}$


causally disconnected
1°
1°
1°
The horizon problem!

A. Linde

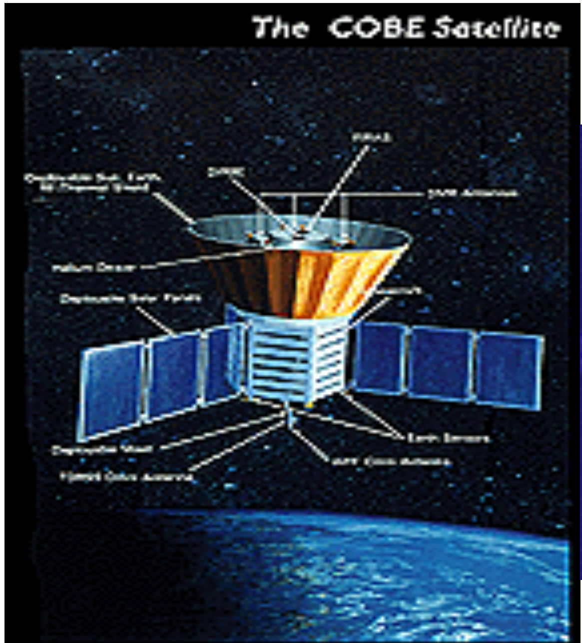
A. Guth

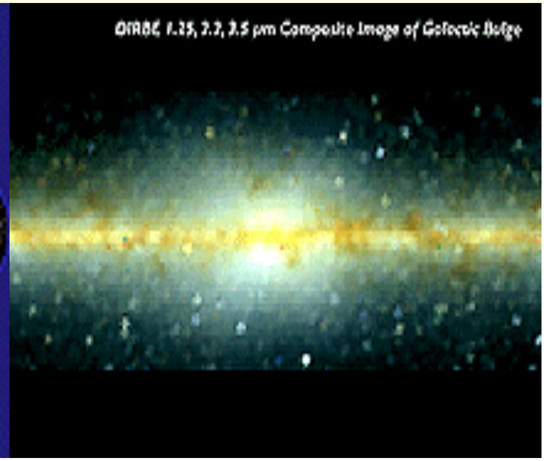


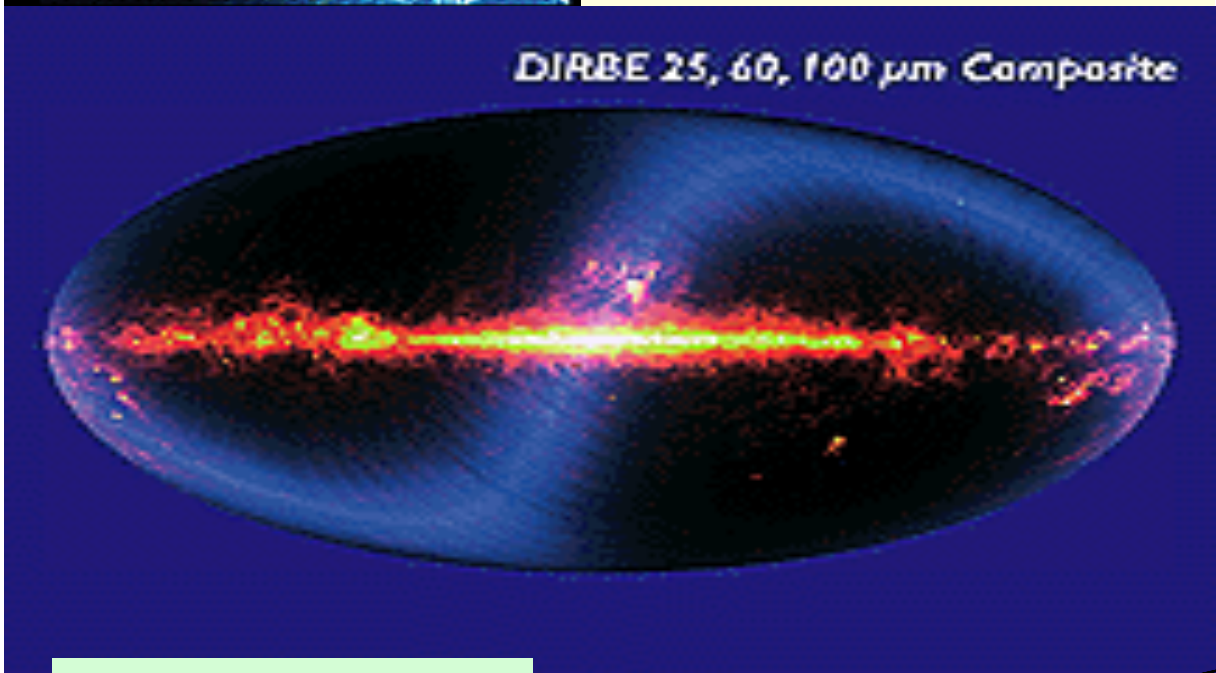
But there are some traces of the inflationary period, in particular the quantum fluctuations of the scalar field leave imprints in the cosmic microwave background (CMB).

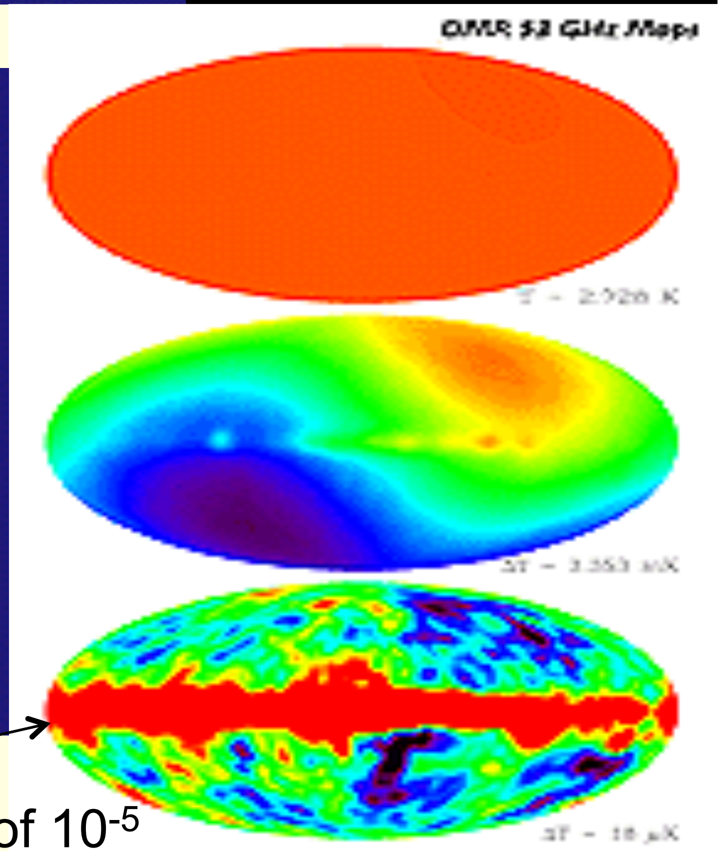
Hence, one was expecting some level of anisotropy in the CMB even if its very isotropy was explained by inflation.

COBE







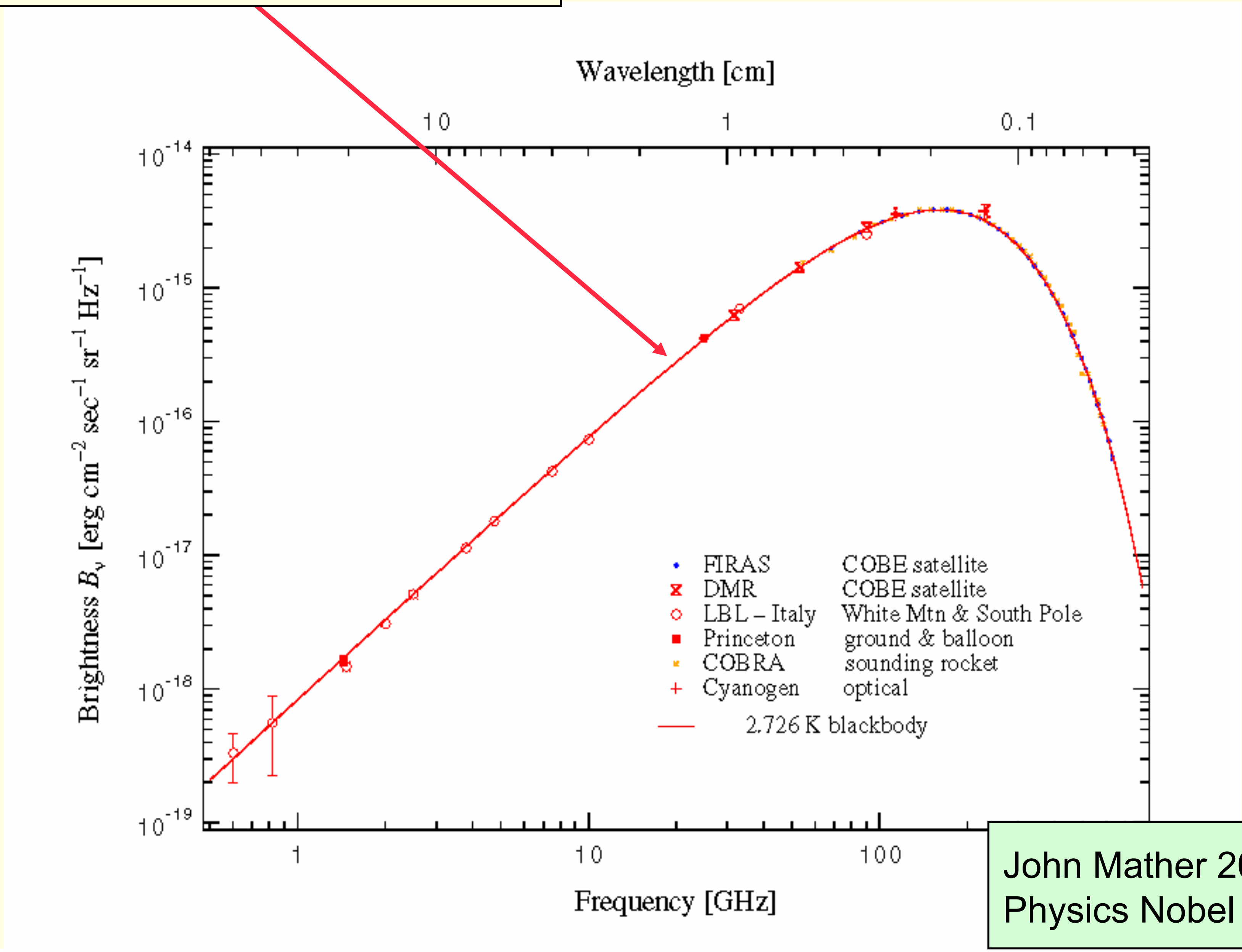


George Smoot 2006
Physics Nobel Prize

Anisotropies at the level of 10^{-5}

Planck black body distribution at 2.7 K

$T(z) = T_o (1+z)$



John Mather 2006
Physics Nobel Prize

Before recombination, photons and baryons are tightly coupled through Thomson scattering.

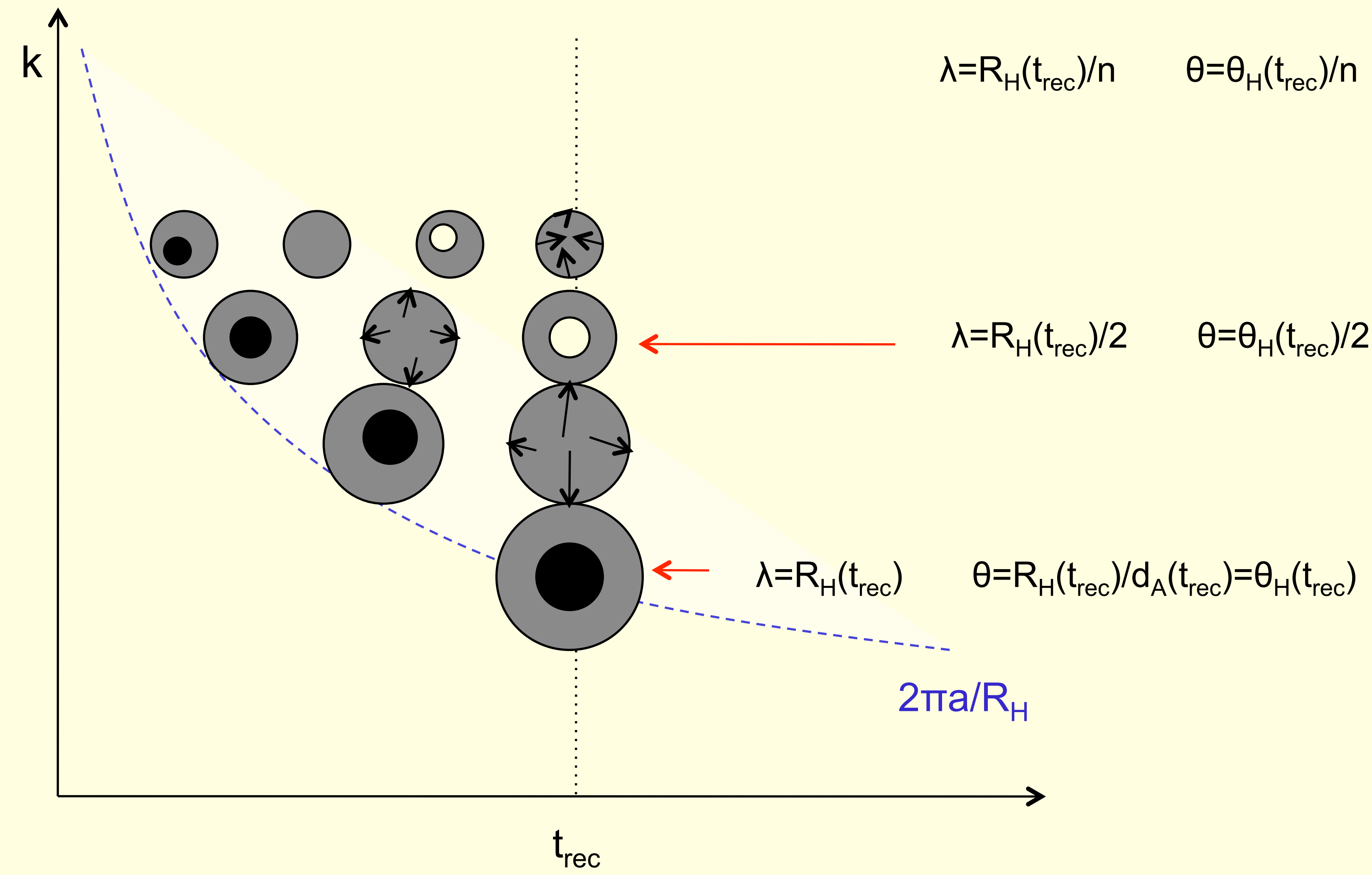
Two competing effects in the « box » of radius $R_H(t)$:
- gravitational attraction (due to baryons) $\rightarrow \leftarrow$
- radiation pressure (due to photons) $\leftarrow \rightarrow$

result in the creation of acoustic oscillations.

These oscillations can only proceed if their wave length is smaller than the horizon scale or Hubble radius $R_H(t)$:

$$\lambda = 2\pi a(t)/k < R_H(t)$$

$$\text{or} \quad k > 2\pi a(t)/R_H(t) \sim t^{-1/3}$$

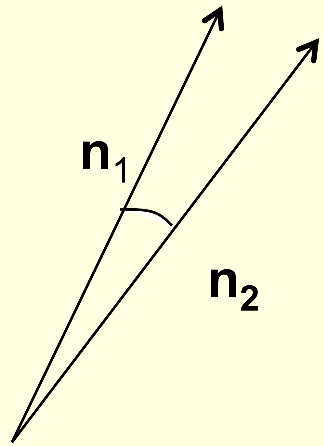


Hence the first compression peak is expected at $\theta_H(t_{rec})$ ~ $1°\ \Omega_T$

(we restore a cosmological cst)

Experiments measure the temperature difference of photons received by two antennas separated by an angle θ:

$$C(\theta) = \left\langle \frac{\Delta T}{T_0}(\mathbf{n}_1) \frac{\Delta T}{T_0}(\mathbf{n}_2) \right\rangle$$



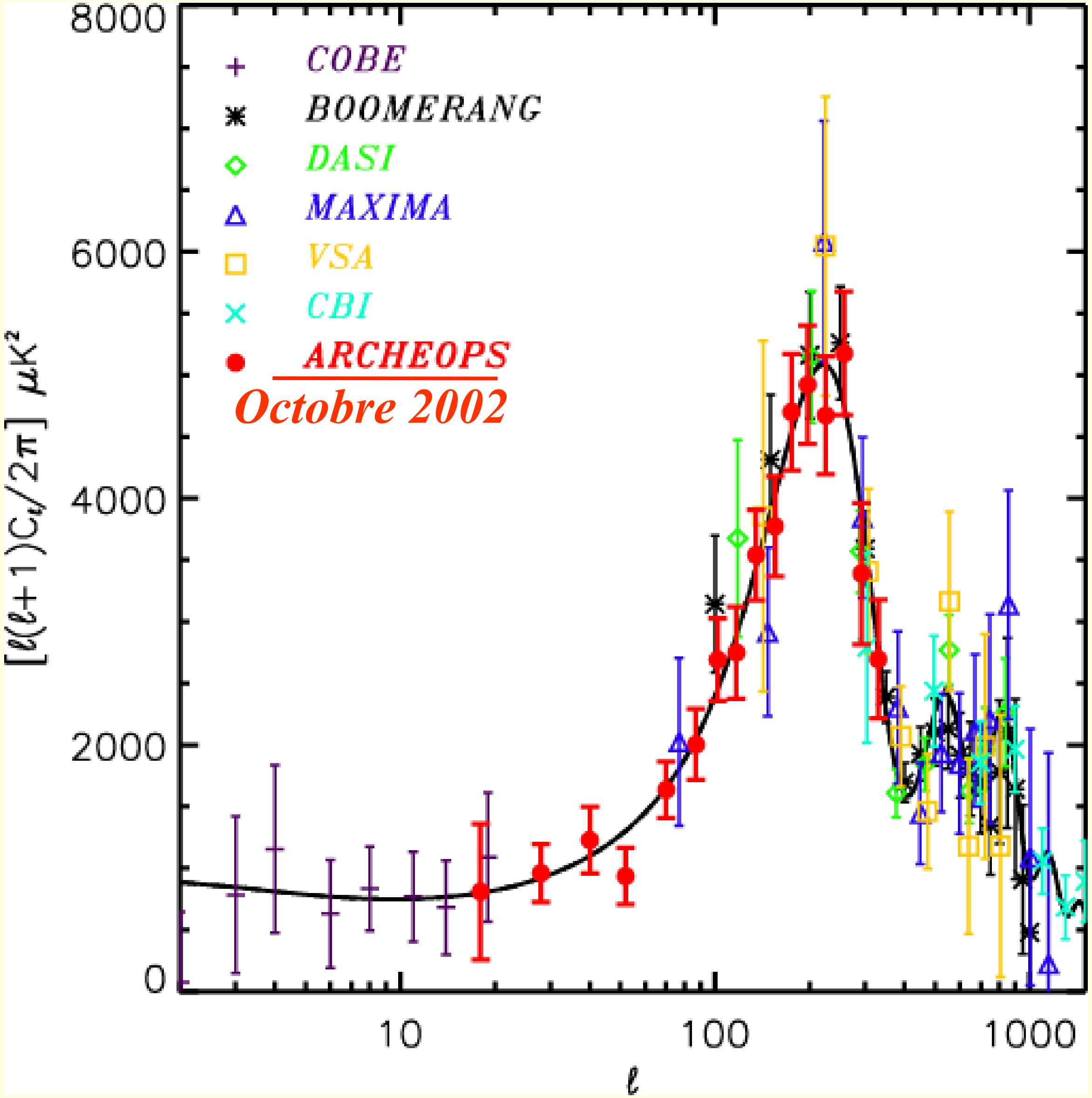
One decomposes C(θ) over Legendre polynomials

$$C(\theta) = \frac{1}{4\pi} \sum_{l}^{\infty} (2l+1) C_l P_l(\cos\theta) \ .$$

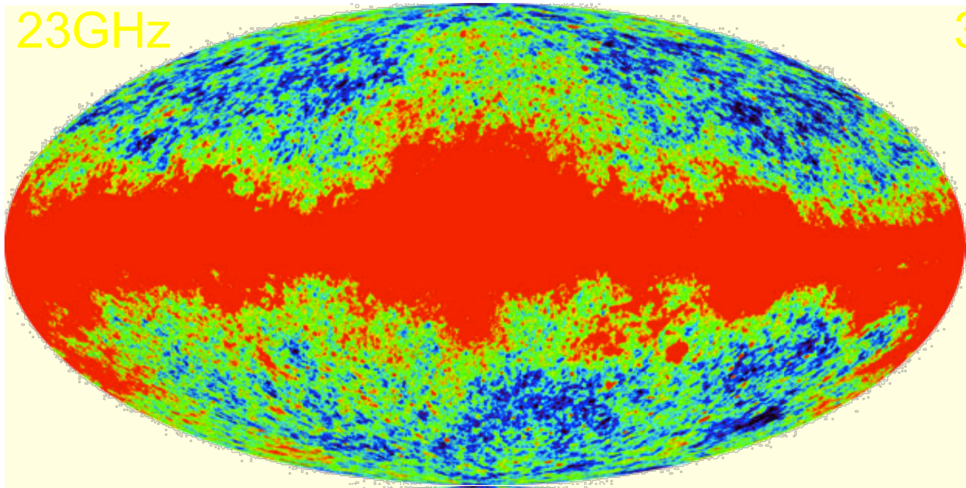
Basically, C_ℓ corresponds to $\theta \sim 200°/\ell$

Thus expect first peak at $\ell \sim 200\ \Omega_T^{-1/2}$

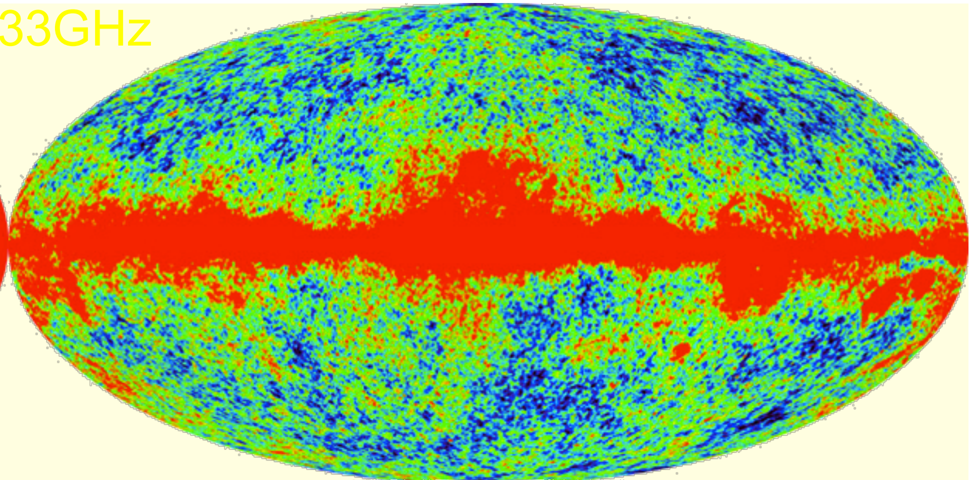
Balloon experiments 2002 Status



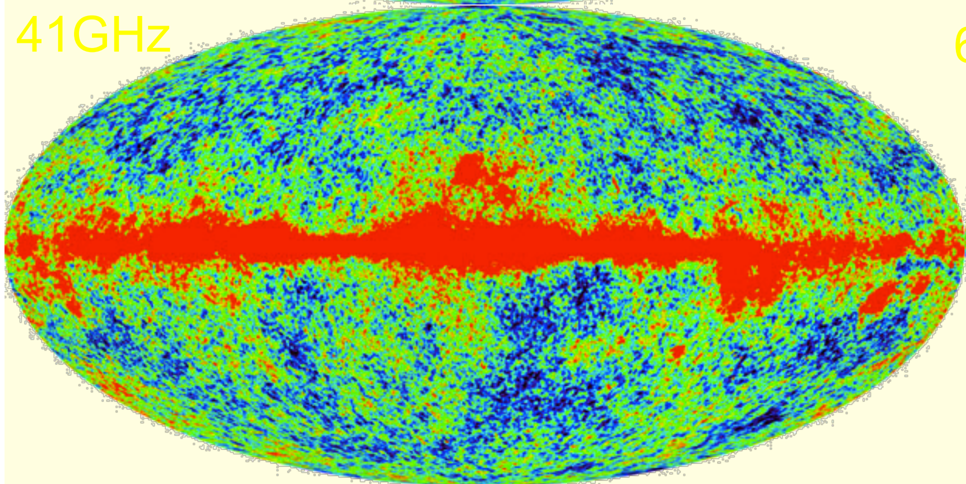
23GHz



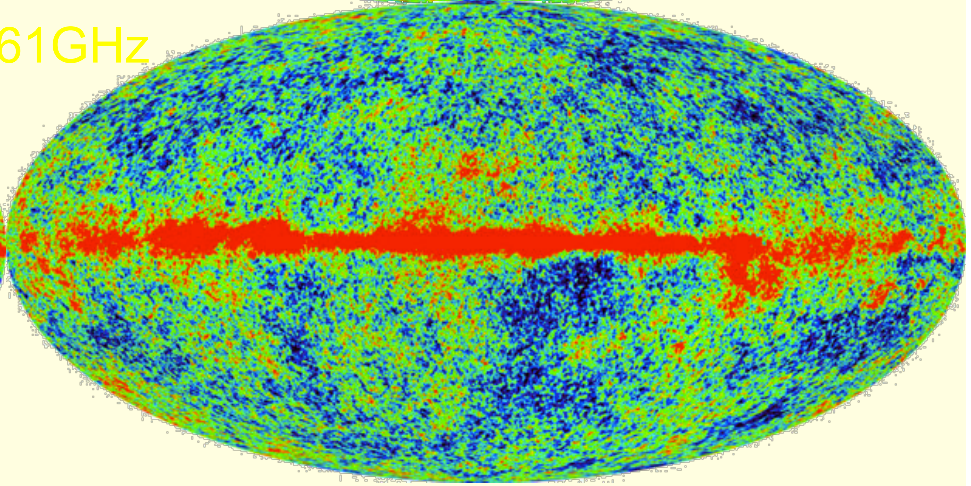
33GHz



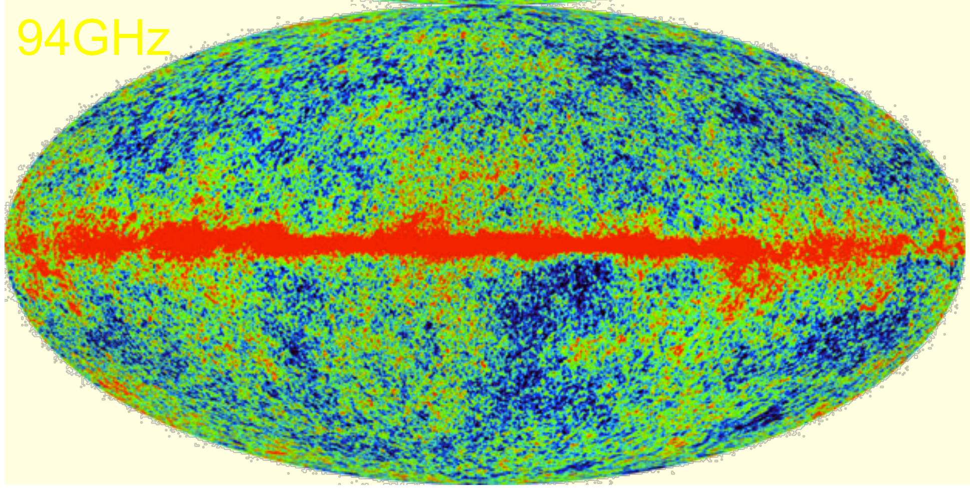
41GHz

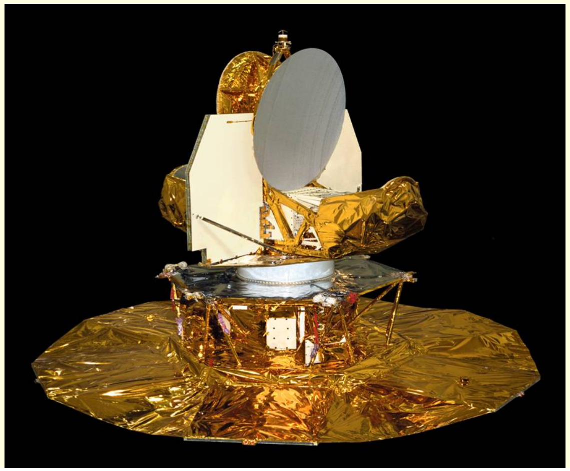


61GHz



94GHz

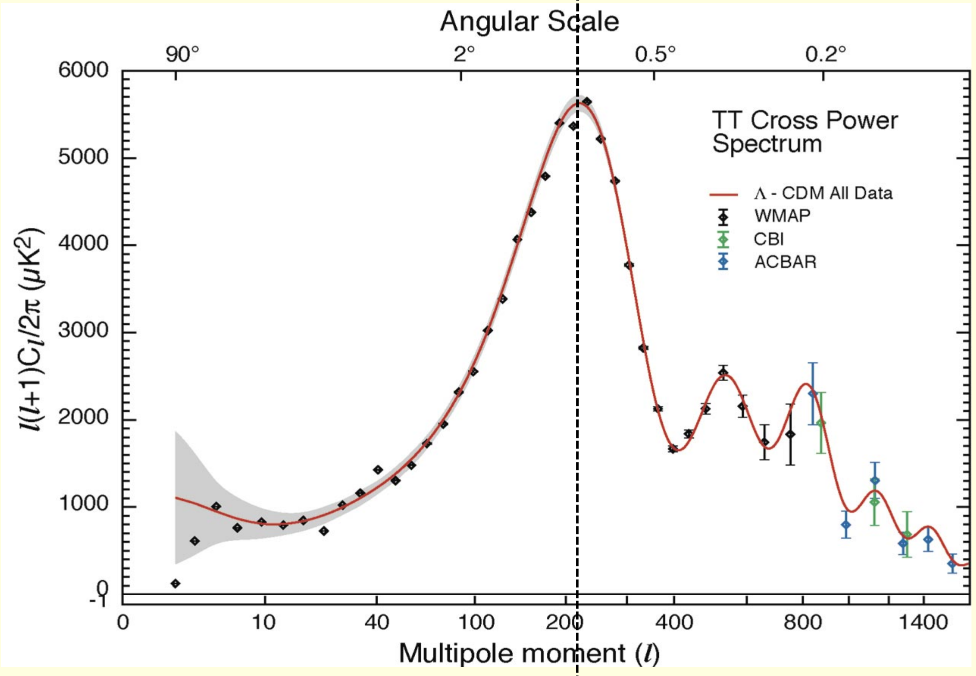




WMAP

launched in 2001

θ=1°



$\ell = 200$

$\Rightarrow \quad \Omega_T \sim 1$ Space is flat

PARAMETER SUMMARY

$\boxed{\Omega_{tot} = 1.02^{+0.02}_{-0.02}}$

$w < -0.78$ (95% CL)

$\boxed{\Omega_{\Lambda} = 0.73^{+0.04}_{-0.04}}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\boxed{\Omega_m h^2 = 0.135^{+0.008}_{-0.009}}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_{\nu} h^2 < 0.0076$ (95%CL)

$m_{\nu} < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_{\gamma} = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$\boxed{n_s = 0.93^{+0.03}_{-0.03}}$

$dn_s/d \ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

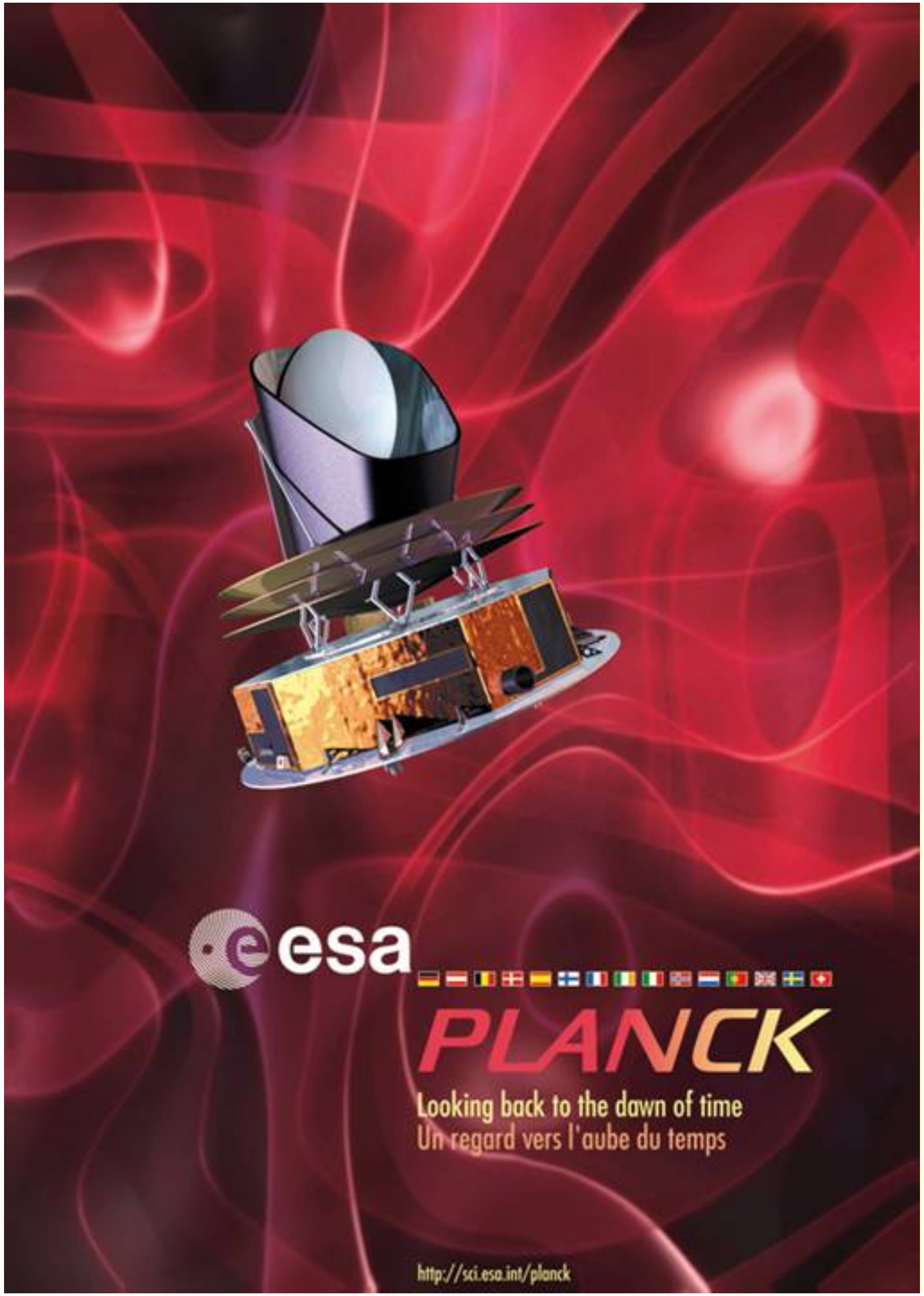
$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0^{\circ}.598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

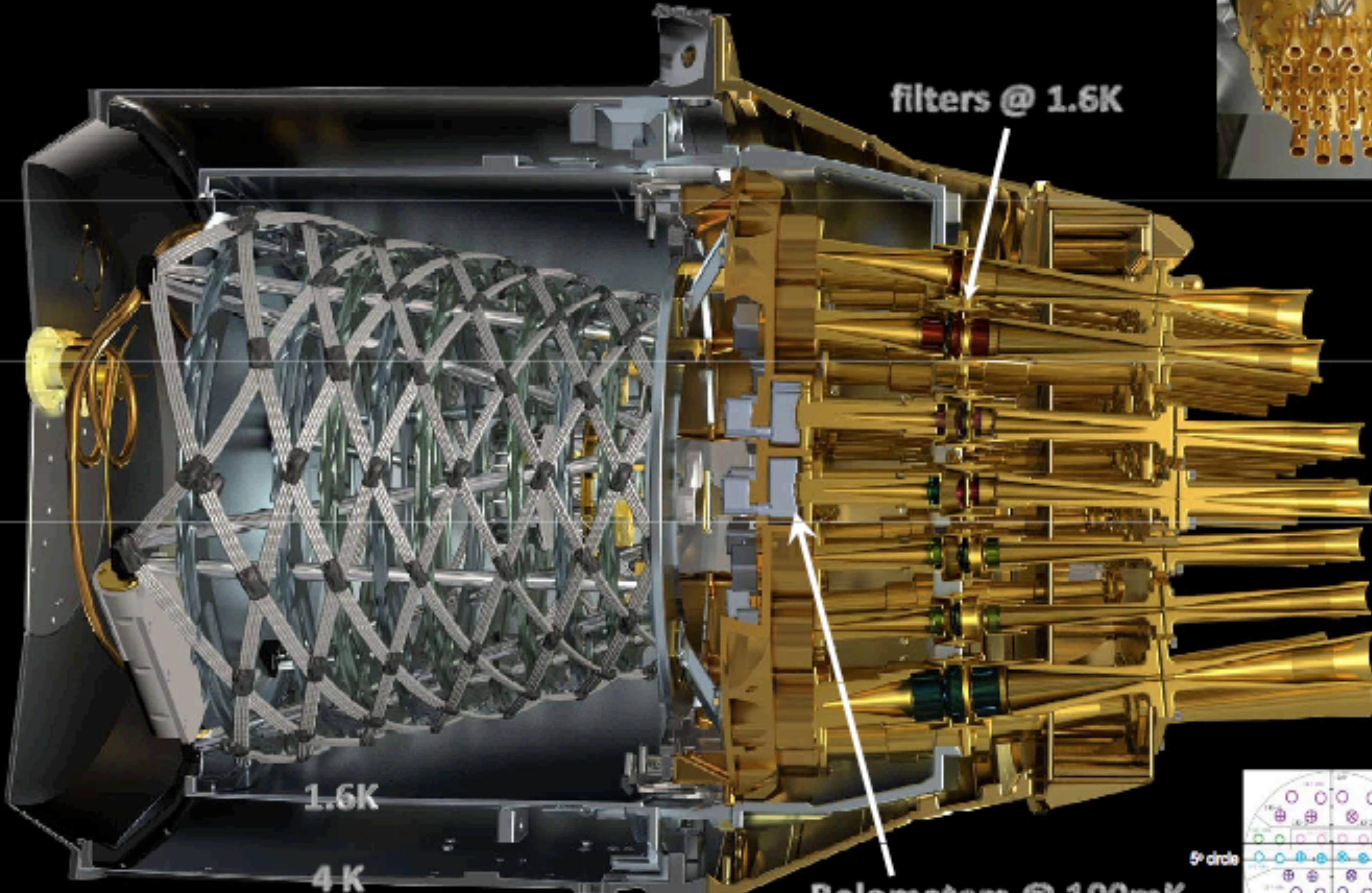
$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc

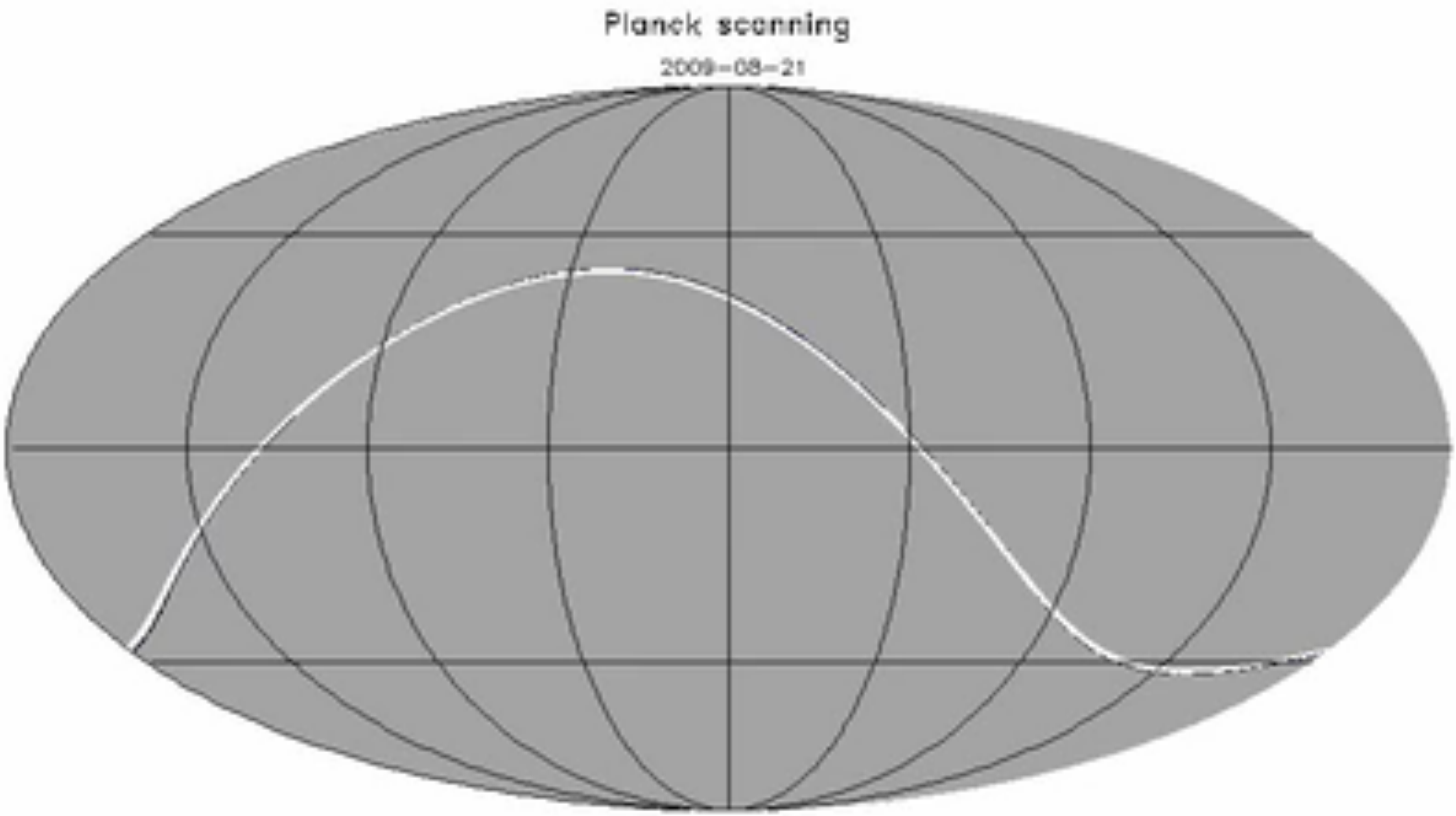


Planck satellite
launched in 2009

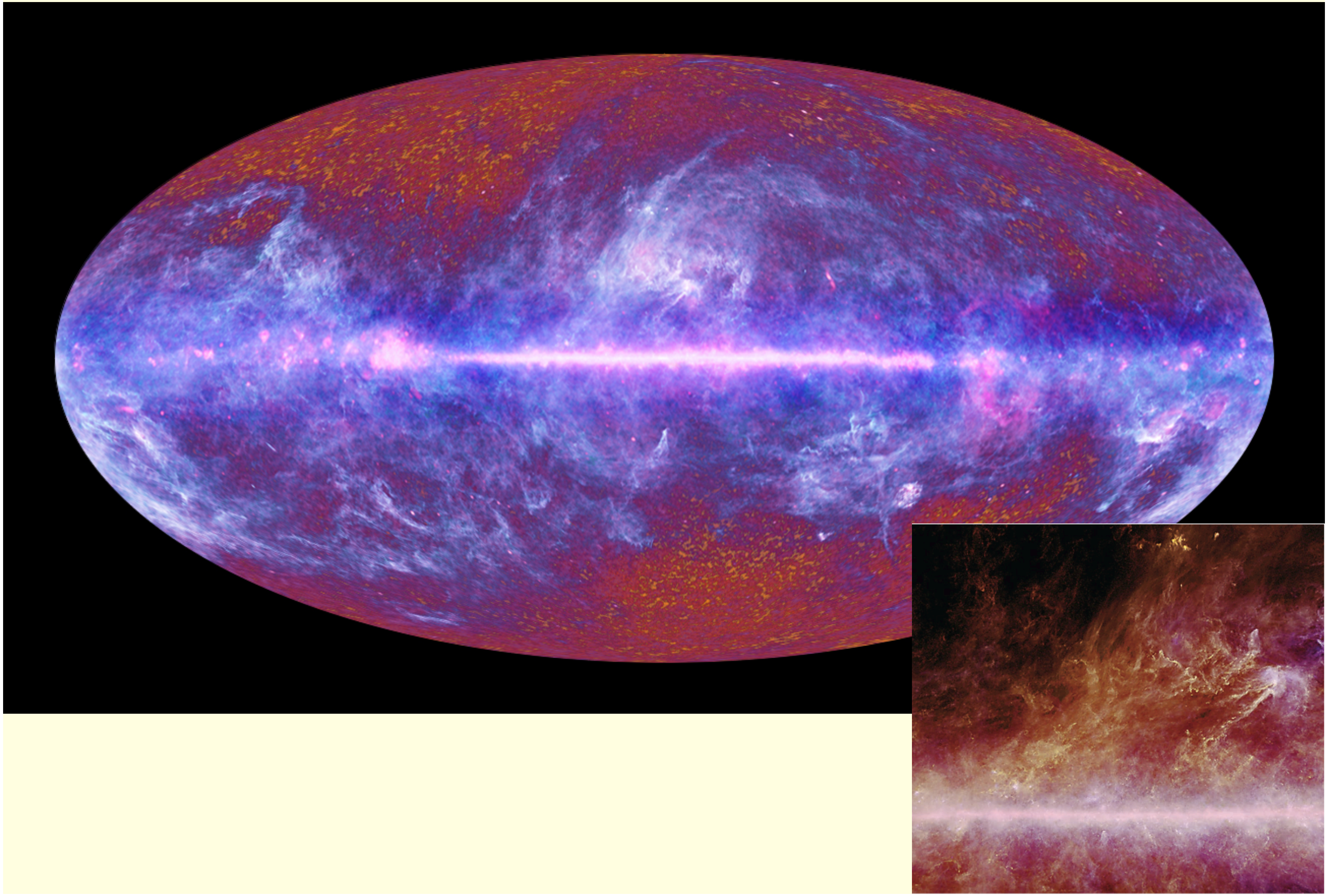
HFI cut-away



5° circle


Planck scanning
2009-08-21

Necessity to subtract the galactic foregrounds before extracting cosmological observation



Quantum fluctuations of the scalar fields during de Sitter phase induce scalar fluctuations of the metric

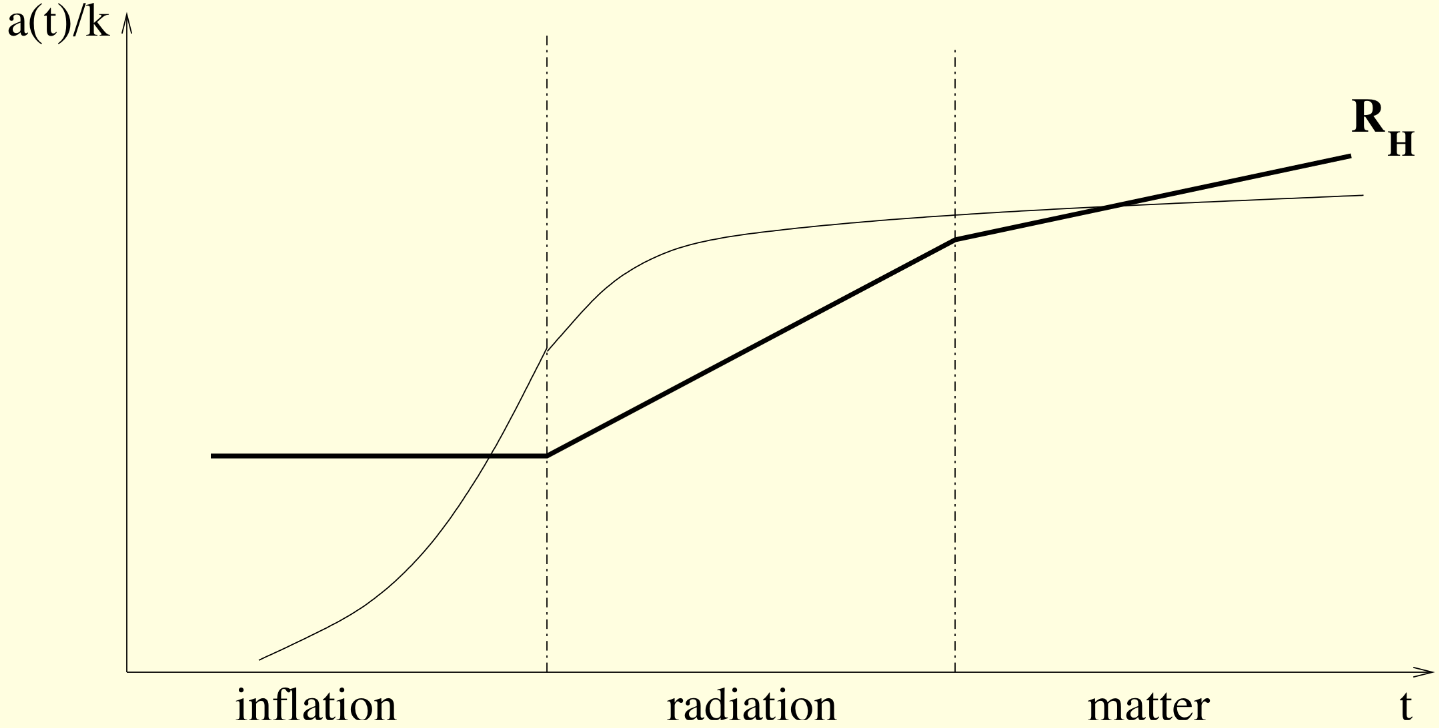
$$ds^2 = a^2\left[(1+2\Phi)d\eta^2 - (1-2\Phi)\delta_{ij}dx^i dx^j\right]$$

Correlation function in Fourier space: $\langle \Phi_{\mathbf{k}} \Phi^*_{\mathbf{k}'} \rangle = 2\pi^2 k^{-3} \mathcal{P}_S(k) \delta^3(\mathbf{k} - \mathbf{k}')$.

$$\mathcal{P}_S(k) = \left[\left(\frac{H^2}{\dot{\phi}^2}\right)\left(\frac{H}{2\pi}\right)^2\right]_{k=aH} = \frac{1}{12\pi^2 m_p^6}\left(\frac{V^3}{V'^2}\right)_{k=aH}$$

Spectral index:

$$n_S(k) - 1 \equiv \frac{d\ln \mathcal{P}_S(k)}{d\ln k} = -6\epsilon + 2\eta \ .$$



a(t)/k
R_H
inflation
radiation
matter
t

Besides scalar fluctuations, inflation produces fluctuations which have a tensor structure i.e. gravitons, or more precisely gravitational waves:

$$ds^2 = a^2 \left[\eta_{\mu\nu} + h_{\mu\nu}^{TT}\right] ,$$

Similarly, one defines the tensor spectrum

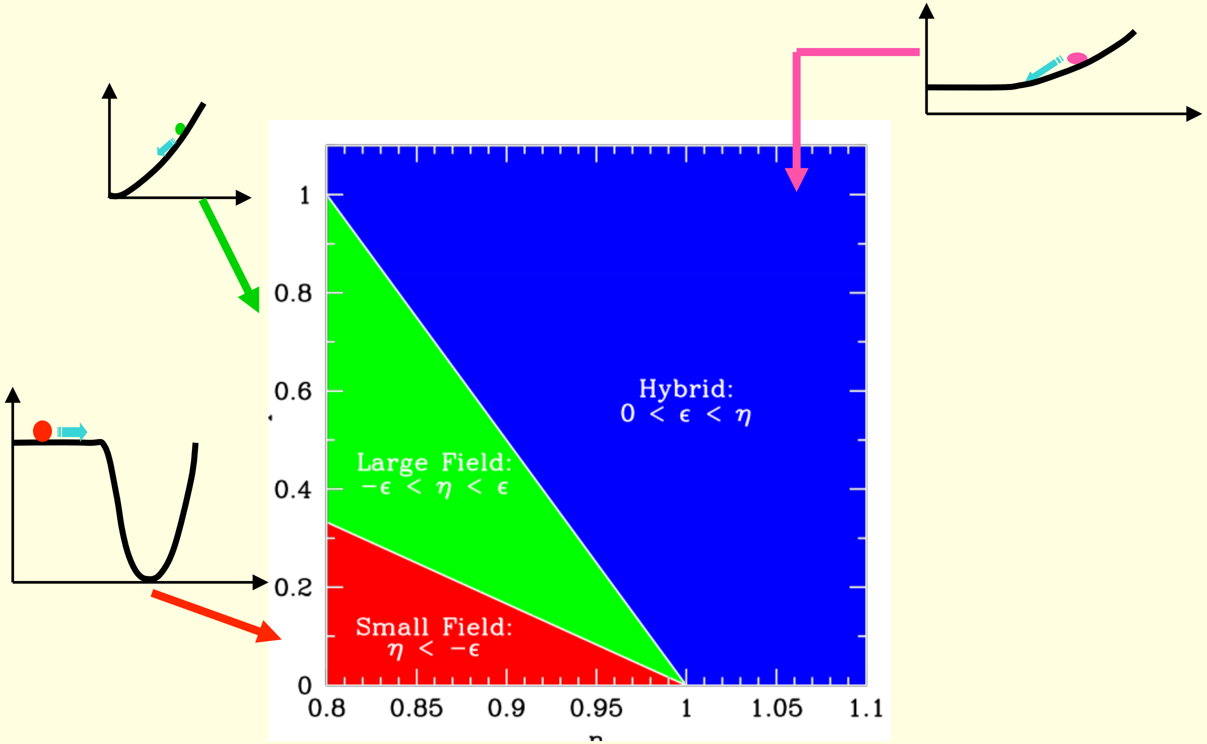
$$\mathcal{P}_T(k) = \frac{8}{m_P^2}\left(\frac{H}{2\pi}\right)^2 ,$$

And the corresponding index

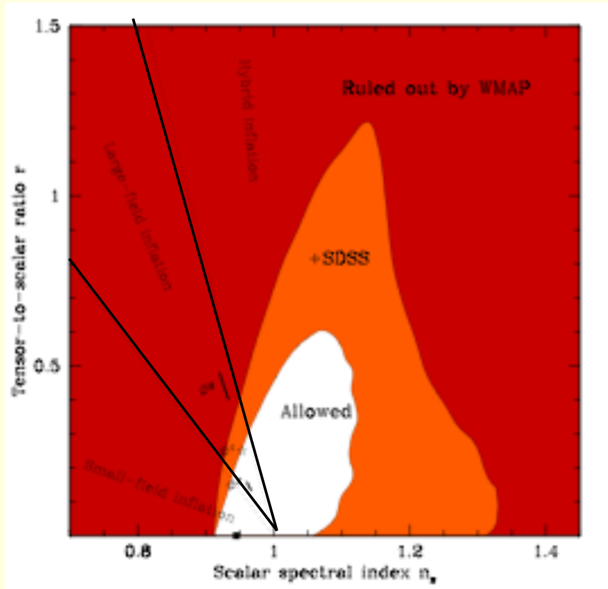
$$n_T(k) \equiv \frac{d\ln\mathcal{P}_T(k)}{d\ln k} = -2\epsilon .$$

• Testing inflation models :

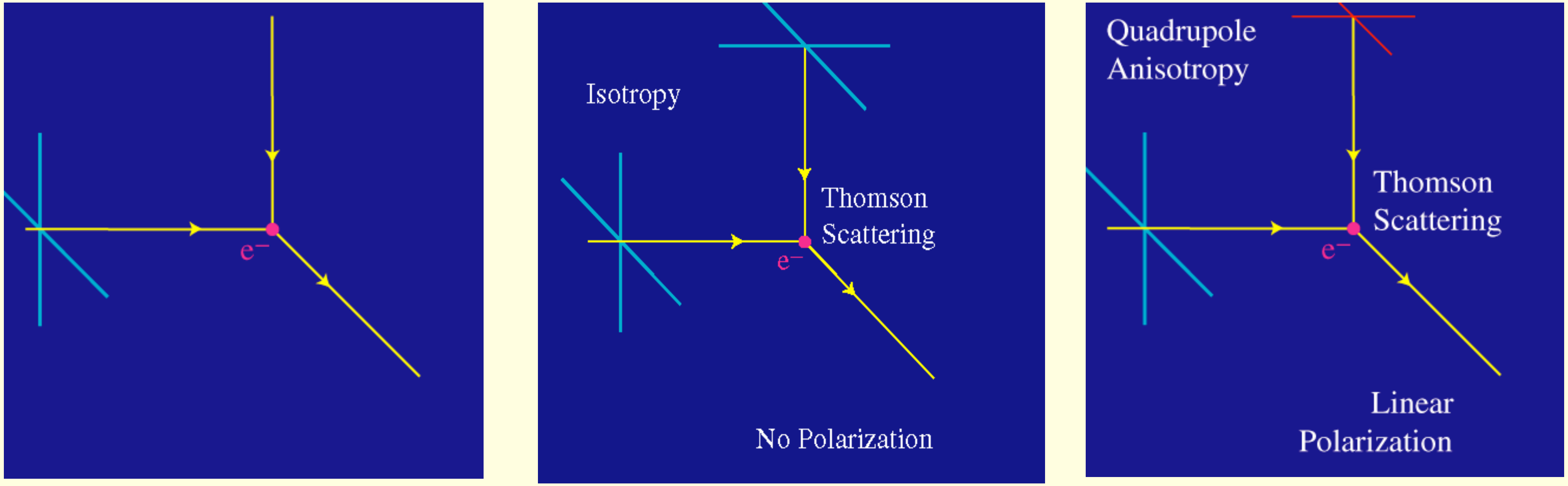
tensor/scalar ratio r

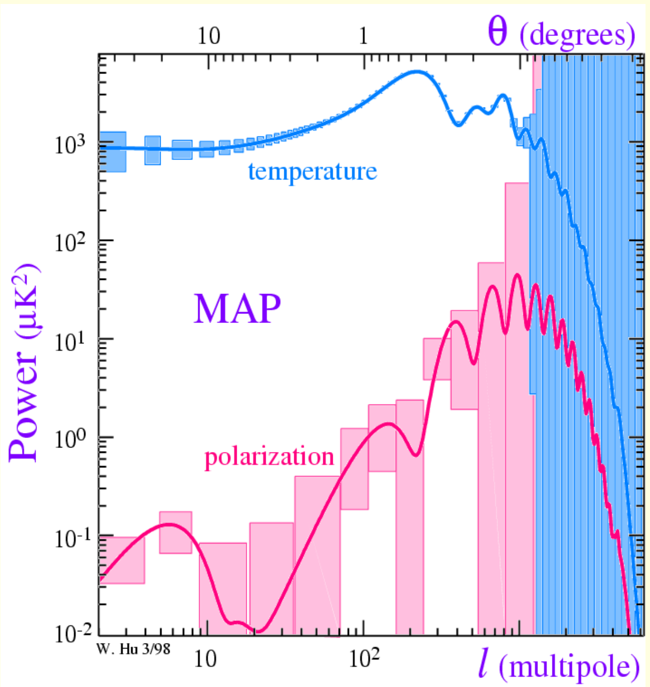


spectral index n_s

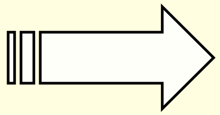


Thomson scattering leads to polarization of the CMB

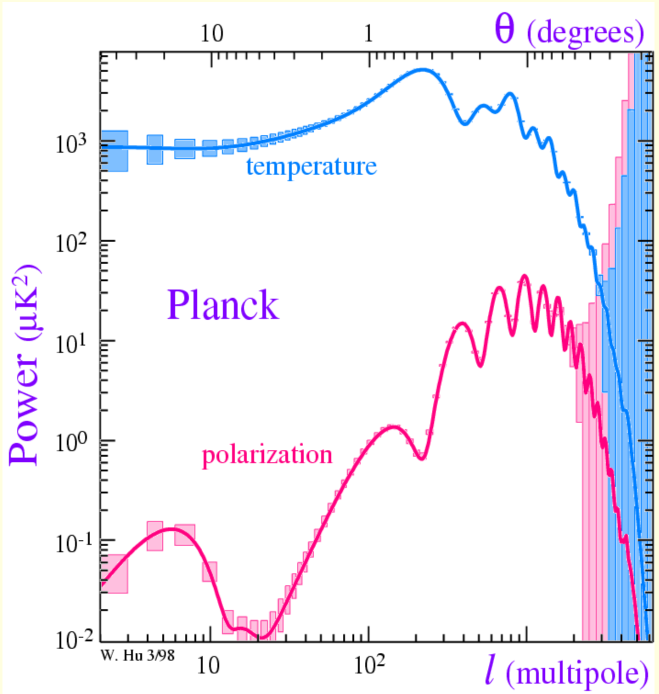




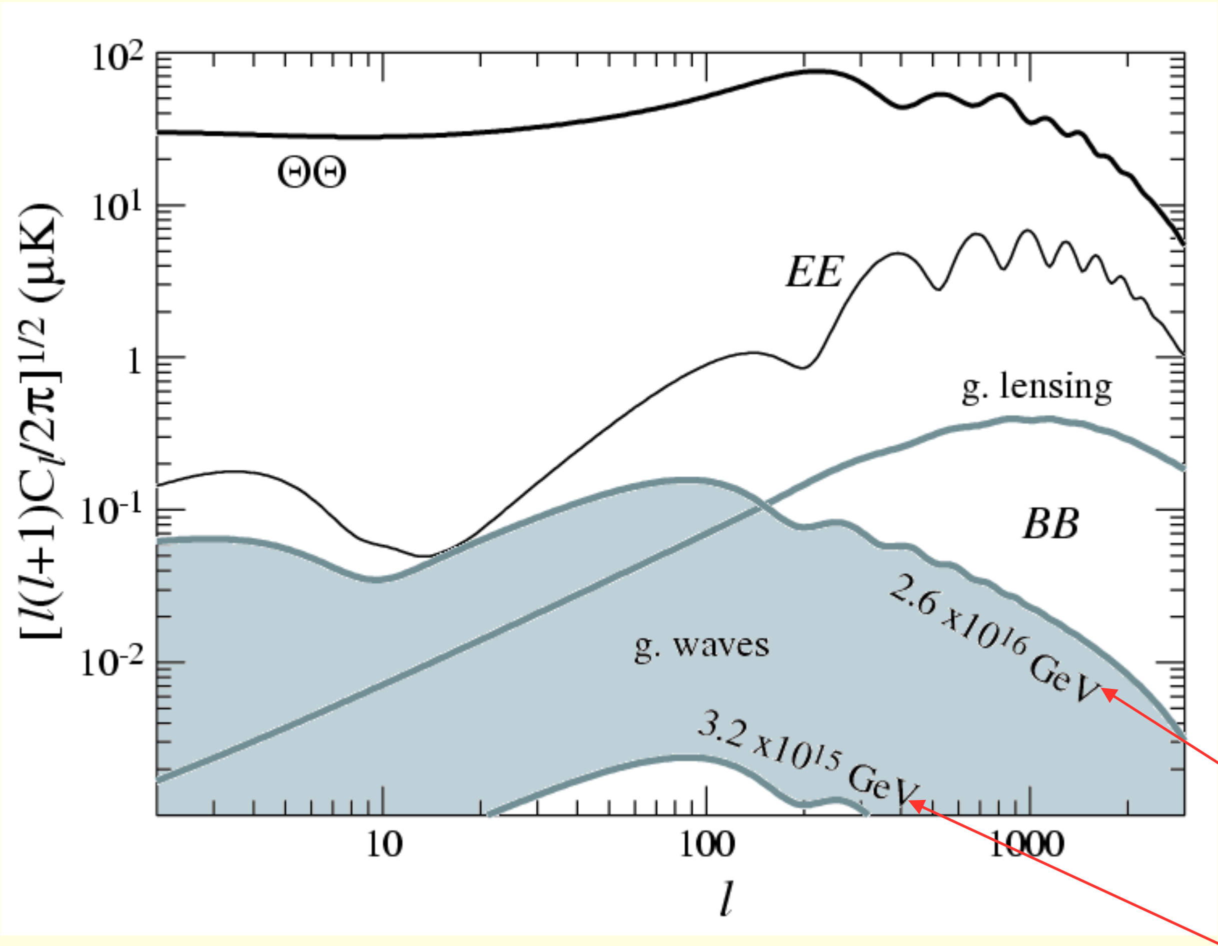
2003



2009



Inflation potential $V_0 = \varepsilon^{1/4}\ 6.7\ 10^{16}$ GeV

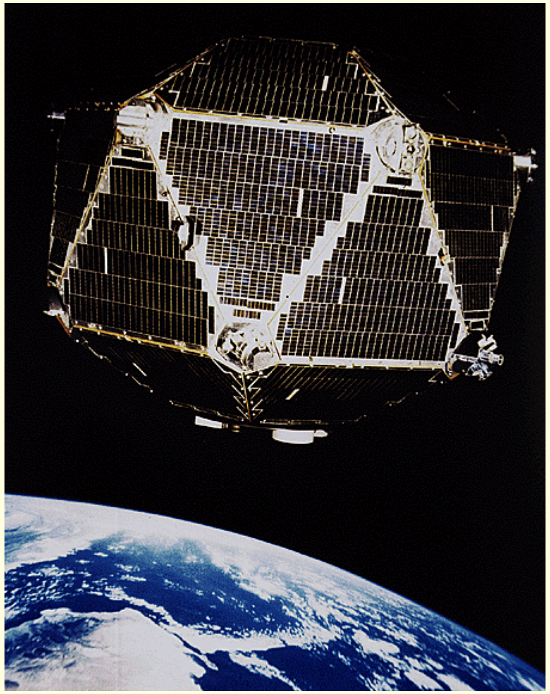


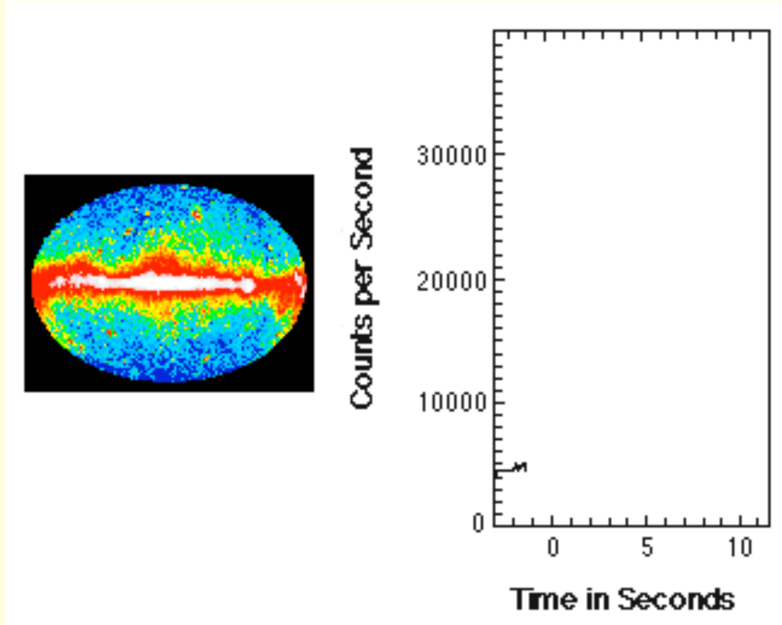
ε slowroll parameter :
$2\varepsilon = (M_P V'/V)^2 \ll 1$

Scale of inflation

Light does not say it all (1): the violent Universe

Some very energetic events in the Universe:
the example of Gamma Ray Bursts (GRB)





Vela, US military satellite looking for gamma emission from Soviet nuclear explosions

Some orders of magnitude

Energy released by the GRB : approximately 10^{44} to 10^{47} J i.e. $M_{\odot}c^2$

Distance that light travels in 5 seconds: 1 500 000 km i.e. 0.01 au

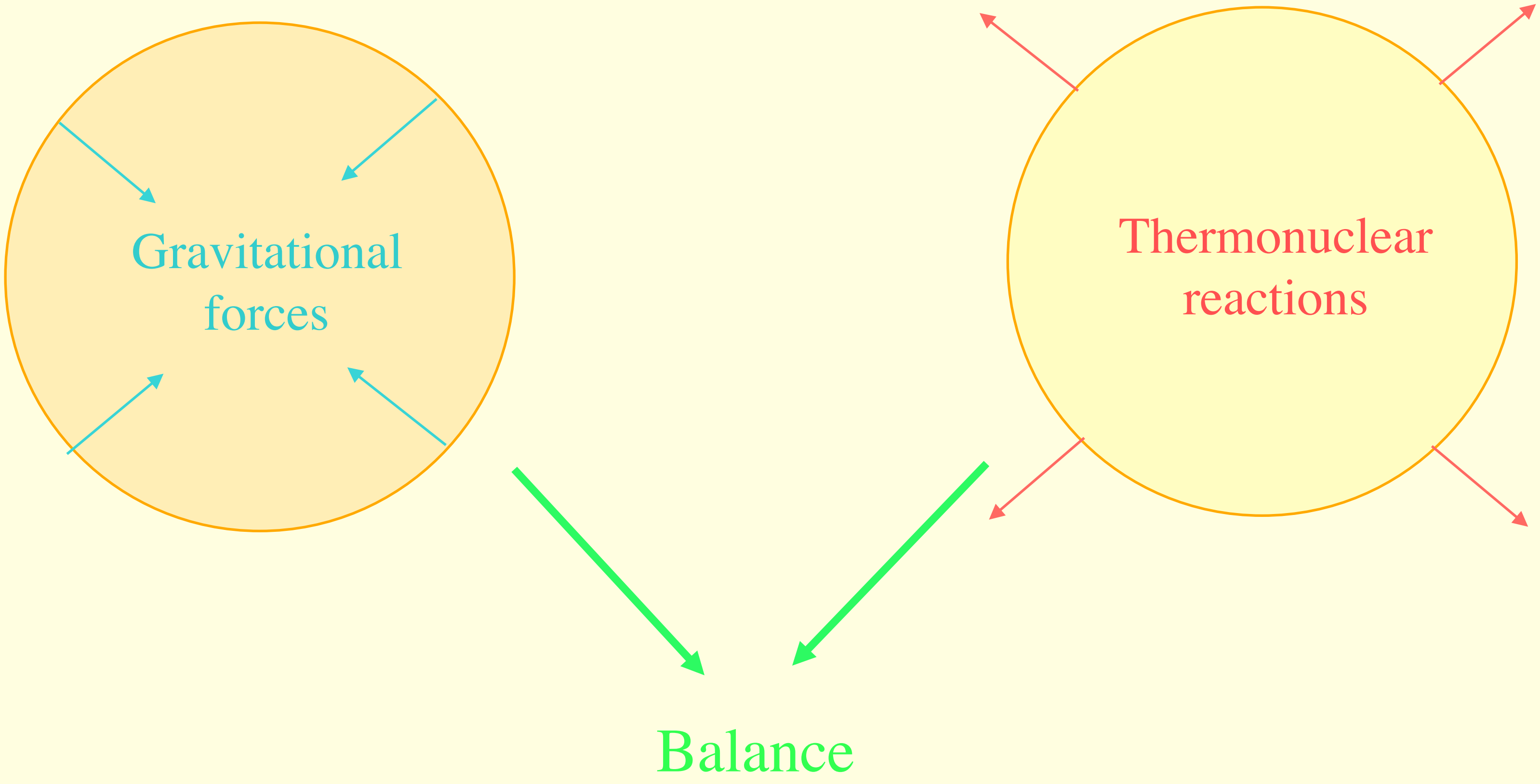
Hence the energy released occupies a very small volume on the scale of the Universe

$\rightarrow$ compact objects

e.g. black holes, neutron stars, white dwarfs

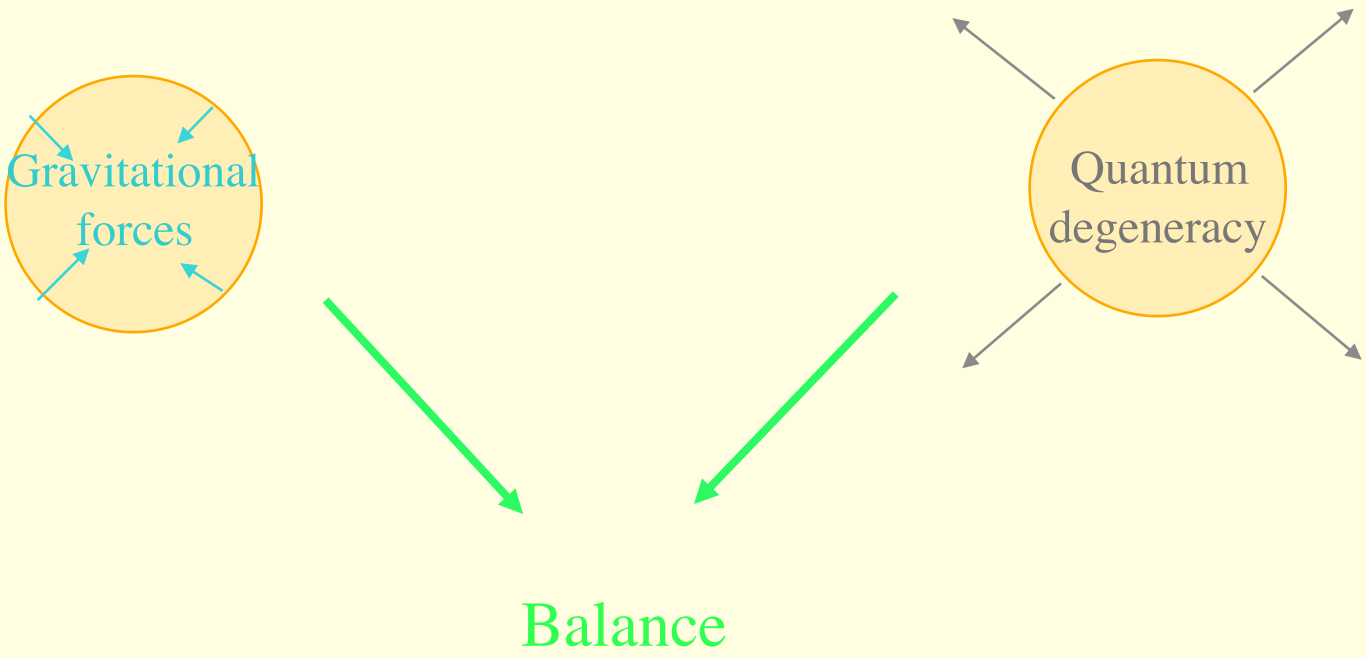
The end of a star

Some notions about star evolution (such as our Sun)



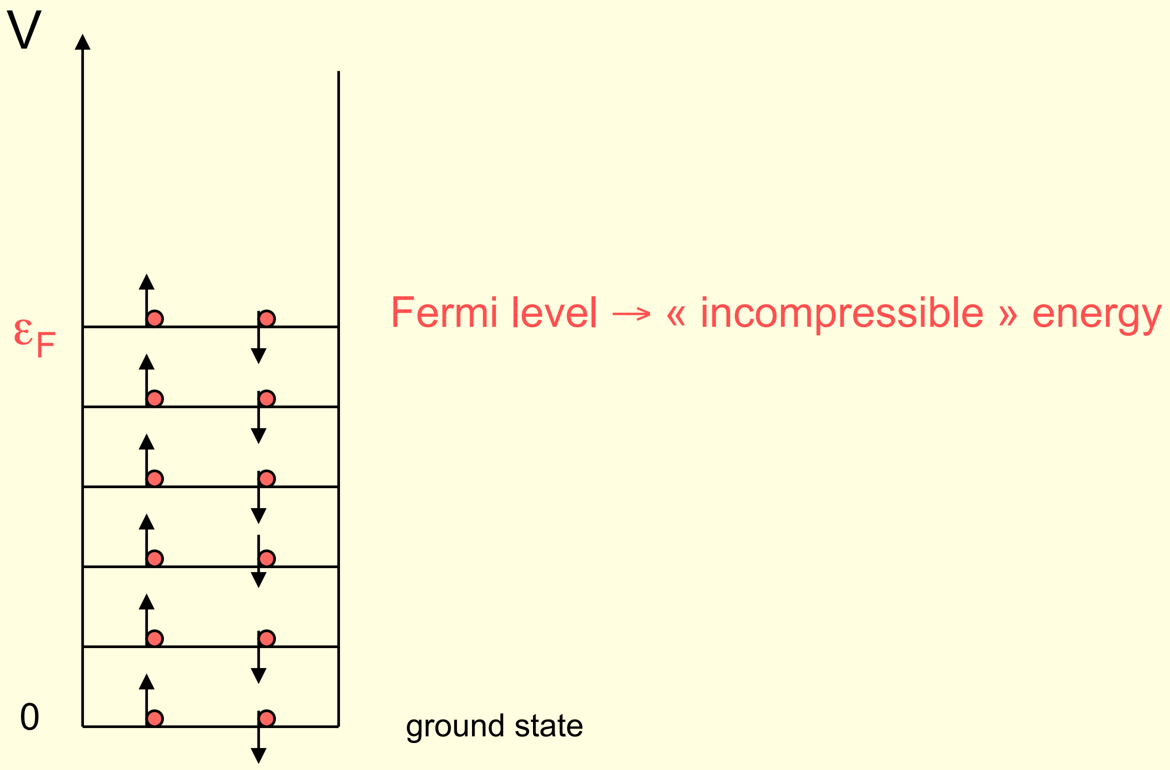
But when the nuclear fuel is exhausted, there is collapse under the effect of gravity → FORMATION OF A COMPACT OBJECT

But when nuclear fuel becomes exhausted, quantum degeneracy comes to the rescue…



What is quantum degeneracy pressure?

Pauli principle: two fermions cannot be in the same state



A technical transparency

$$N = 2\int_0^{p_F} V \frac{4\pi p^2 dp}{(2\pi\hbar)^3} = \frac{p_F^3\, V}{3\pi^2\hbar^3}$$

$$\varepsilon_F = \frac{p_F^2}{2m} \sim h^2 \frac{(N/V)^{2/3}}{m}$$

Hence the Fermi energy is larger for electrons than for neutrons.

When the nuclear fuel is exhausted, gravitational collapse is first stopped by the quantum degeneracy of electrons :

Chandrasekhar limit

WHITE DWARFS

$$M_{WD} < 6\ M_{\odot}/\nu^2$$

number of nucleons per electron, typ. 2

If density becomes larger i.e. for more massive stars, then

$$e + p \rightarrow n + \nu$$

and gravitational collapse is stopped by the quantum degeneracy of neutrons

Oppenheimer-Volkoff bound

NEUTRON STARS

$$M_{NS} < 0.7\ M_{\odot}$$

If the density is larger i.e. for even more massive stars, then the gravitational collapse leads to

BLACK HOLES

The story of black holes

Recall the Schwarzschild solution of Einstein's equations

$$ds^2 = \left(1 - \frac{2G_N M}{r}\right) dt^2 - \left(1 - \frac{2G_N M}{r}\right)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

It describes the exterior of a static star of mass M and radius R if

$$R > 2G_N M/c^2 \equiv R_S \text{ Schwarzschild radius}$$

For the Sun, $R_S = 2.9\text{km}$

If $R < R_S$, the star undergoes gravitational collapse: it falls in a finite time Into a state of infinite energy density.

Oppenheimer and Snyder, 1939

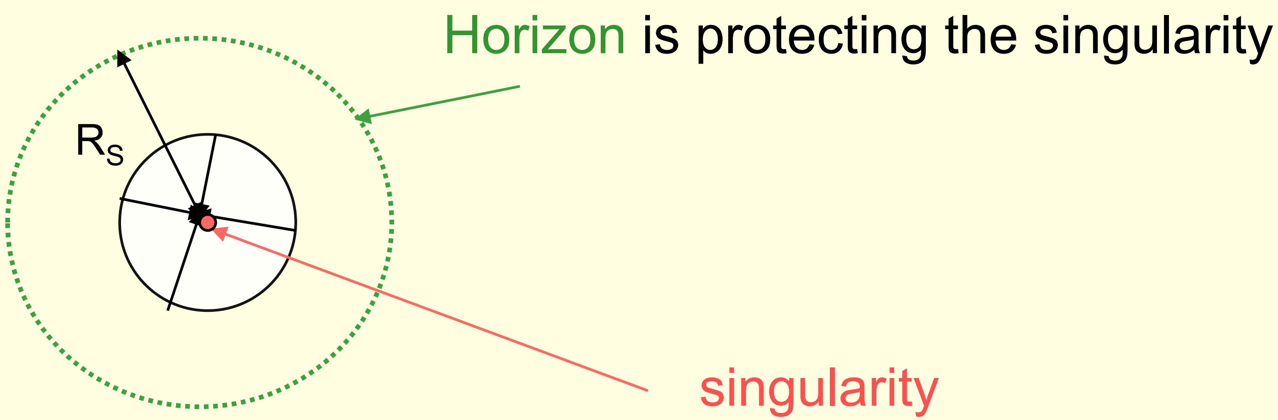
What is then the meaning of the Schwarschild radius?

Mitchell (1784) Laplace (1795)

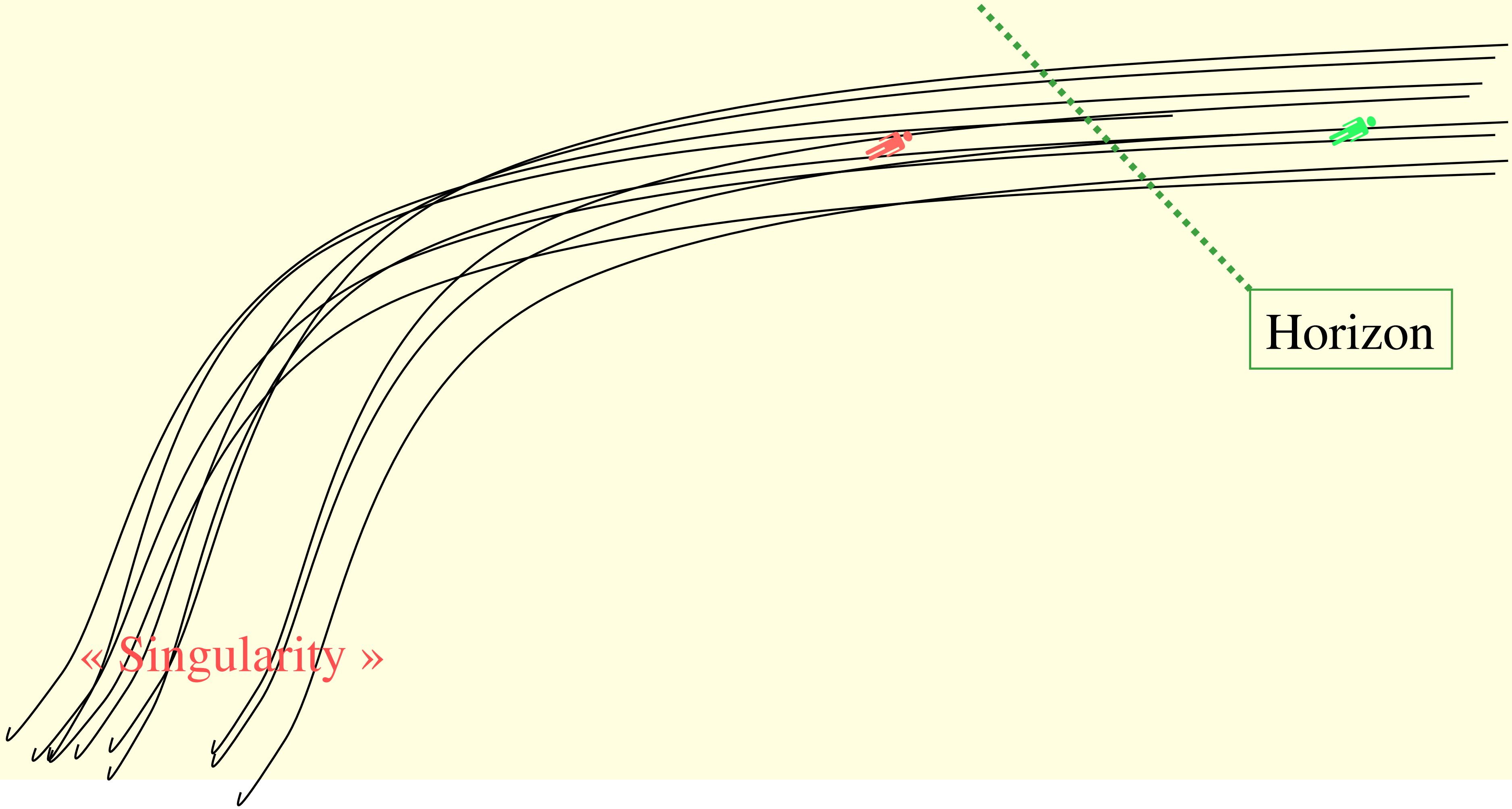
Classical condition for a body of mass m and velocity v to escape from a spherical star of mass M and radius R :

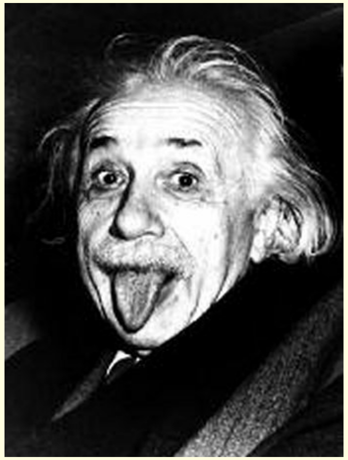
$$\frac{1}{2} mv^2 > \frac{G_N Mm}{R}$$

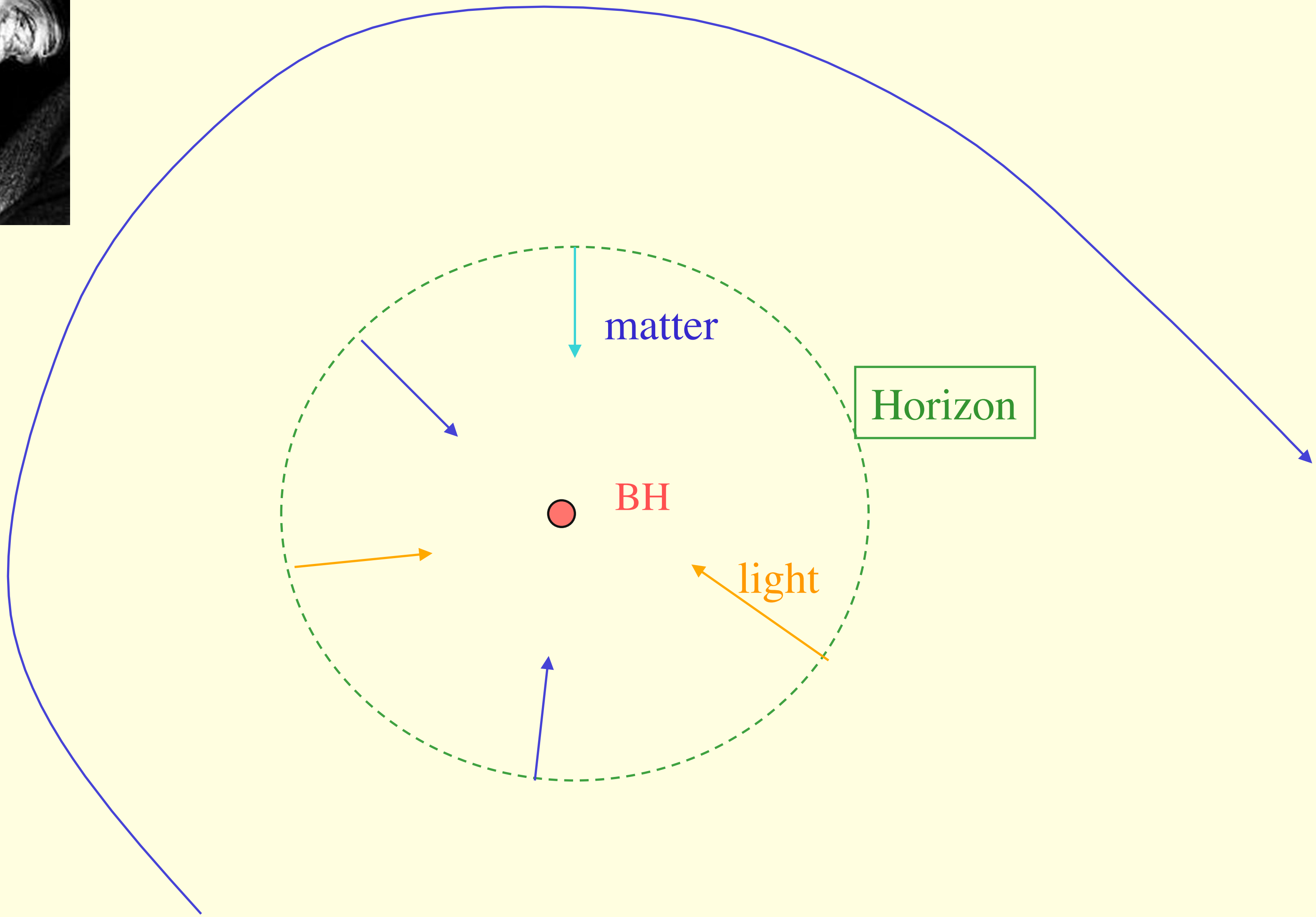
Hence even light (v=c) cannot escape if $R < 2\, G_N M/c^2 = R_S$



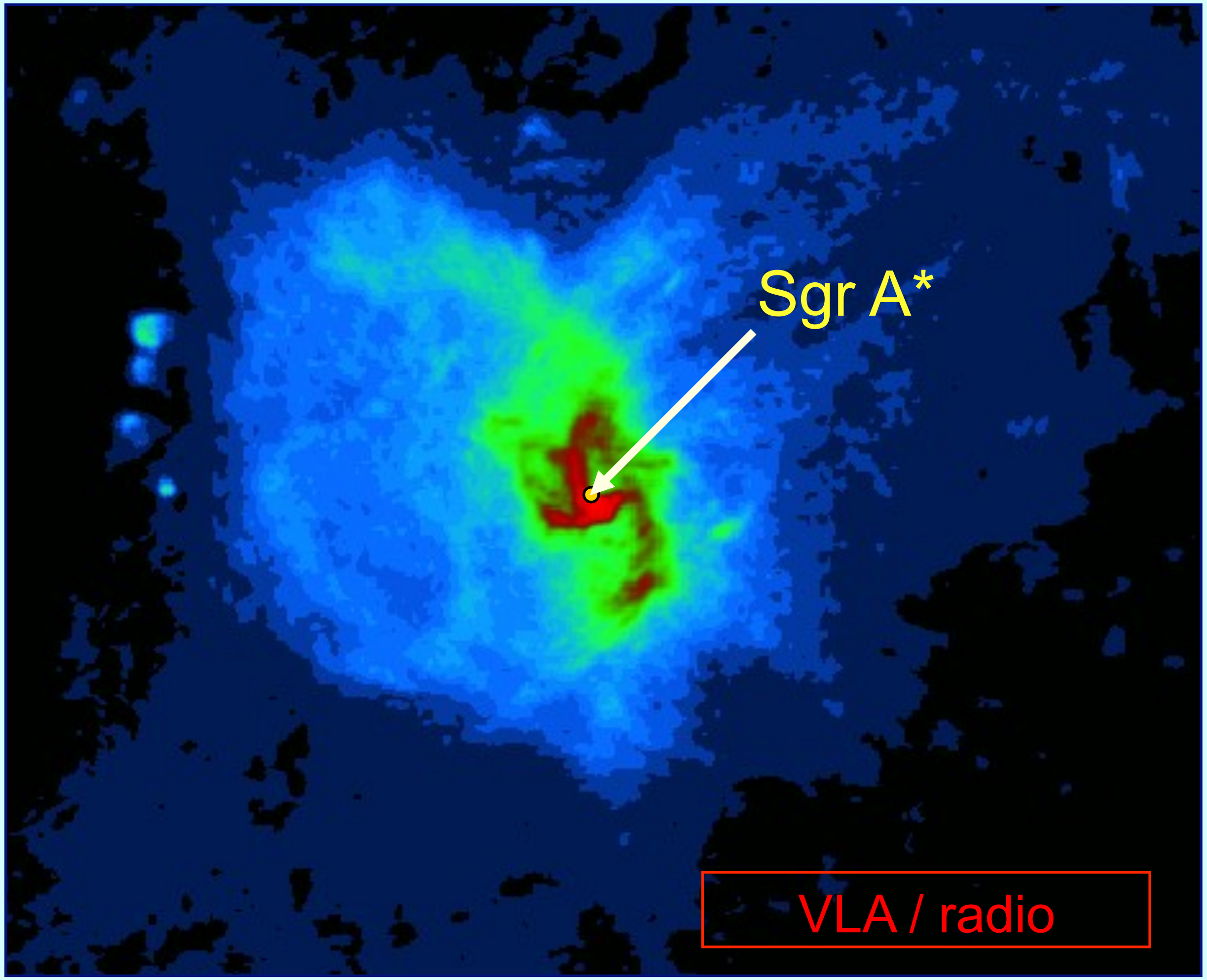
A comparison to understand the notion of (Schwarschild) horizon : the waterfall.






matter
Horizon
BH
light

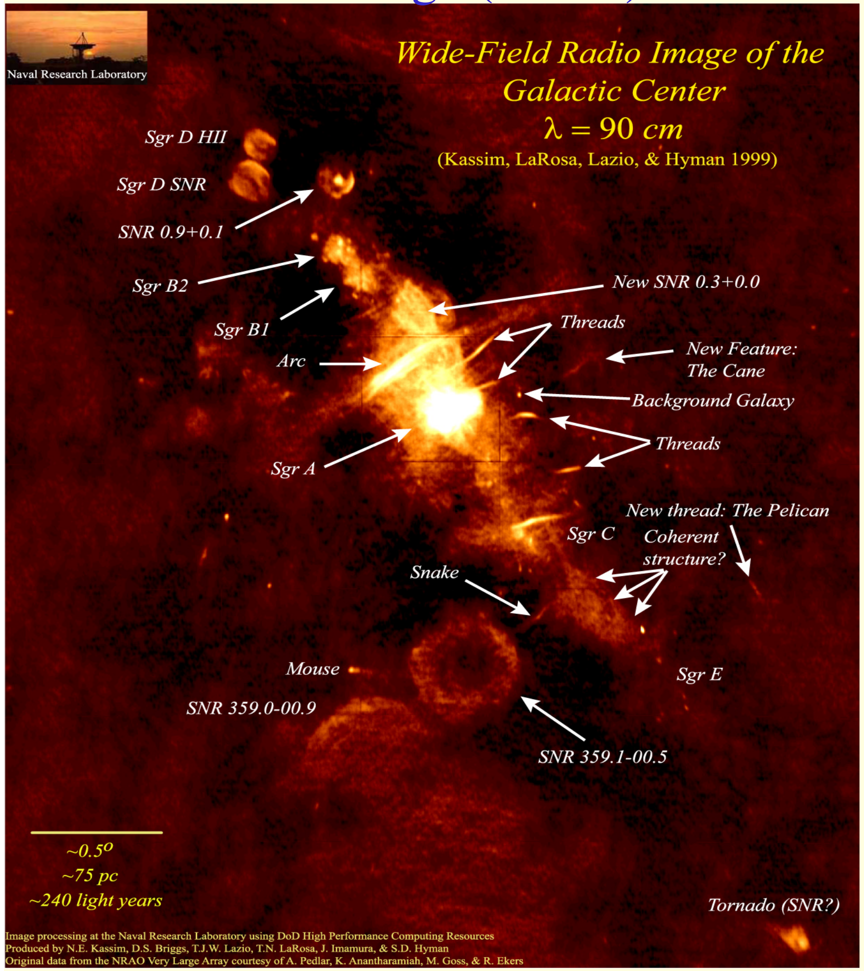
From « black holes » to black holes…



At the centre of our own galaxy, a source emits very energetic particles

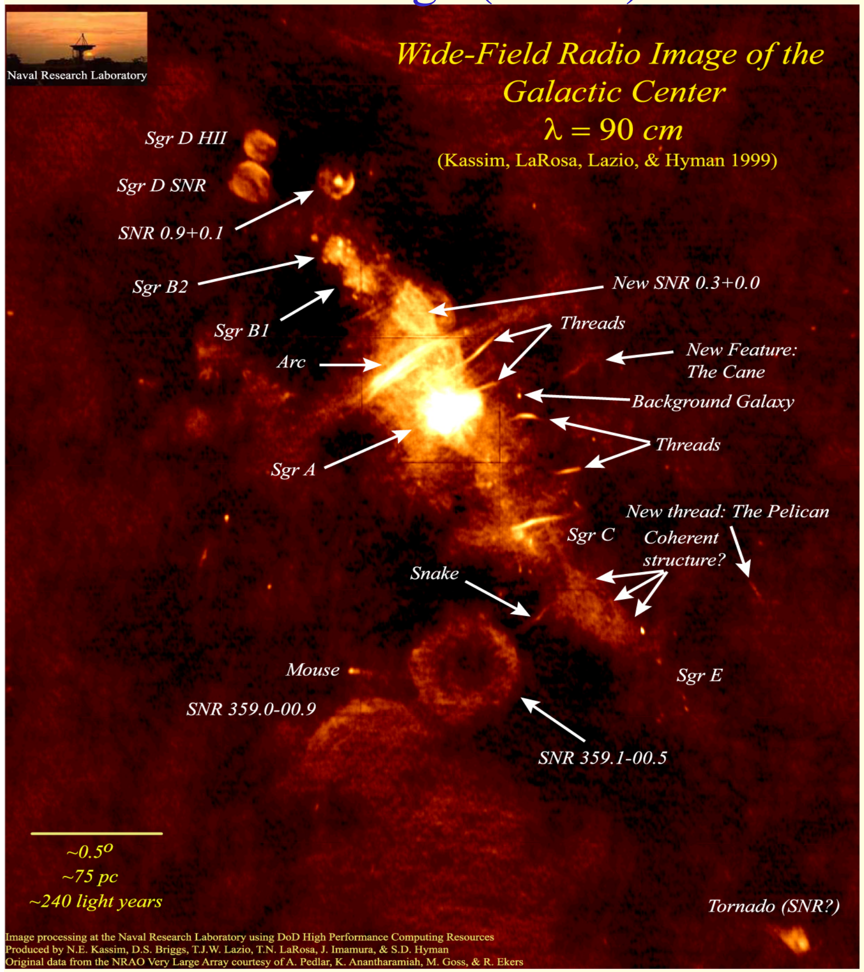
Let us come closer!

Radio image (90 cm)

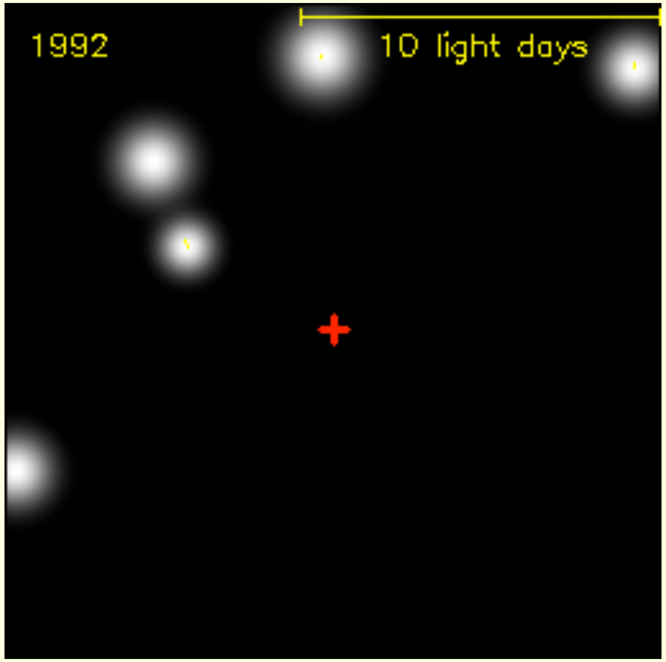


Let us come closer!

Radio image (90 cm)

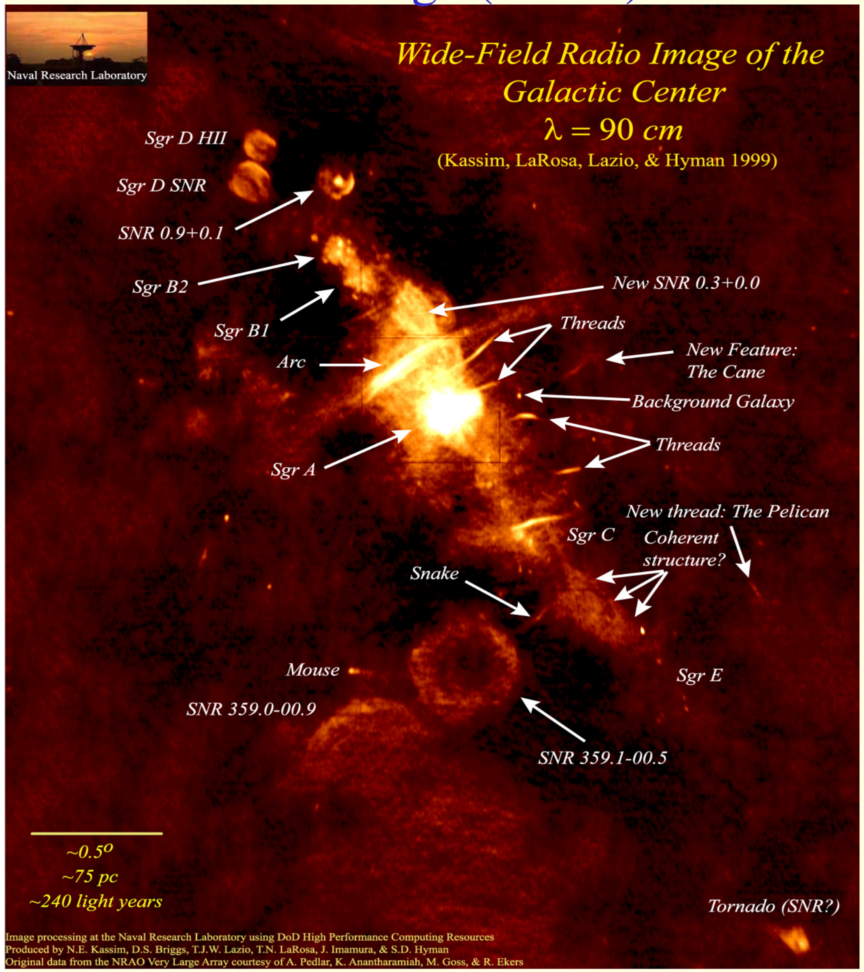


Infrared (1.6 µm <λ <3.5µm)
NAOS/CONICA



Let us come closer!

Radio image (90 cm)



Infrared (1.6 μm <λ <3.5μm)
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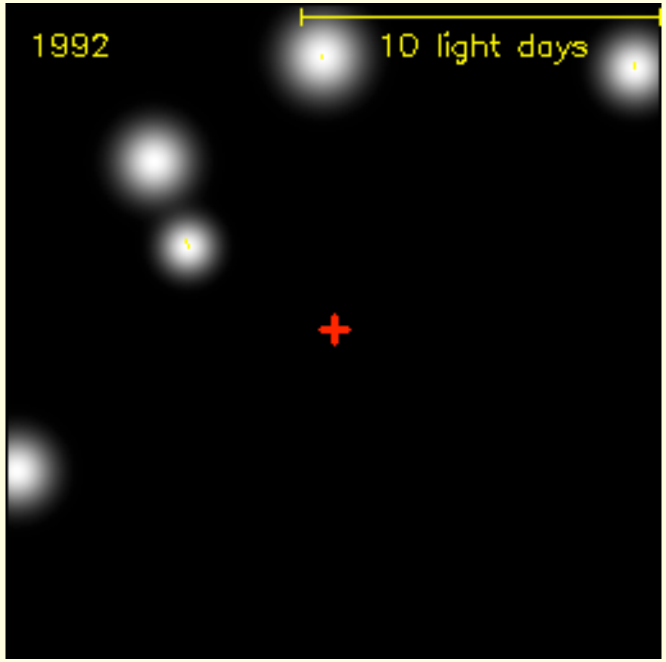


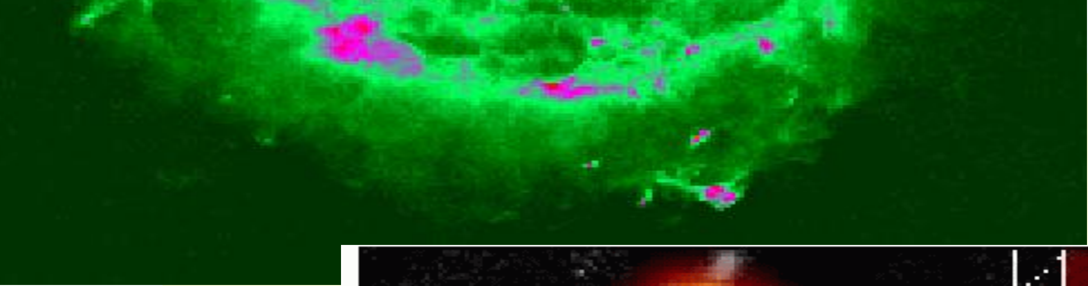
Black hole of mass of the order of 3 million solar masses

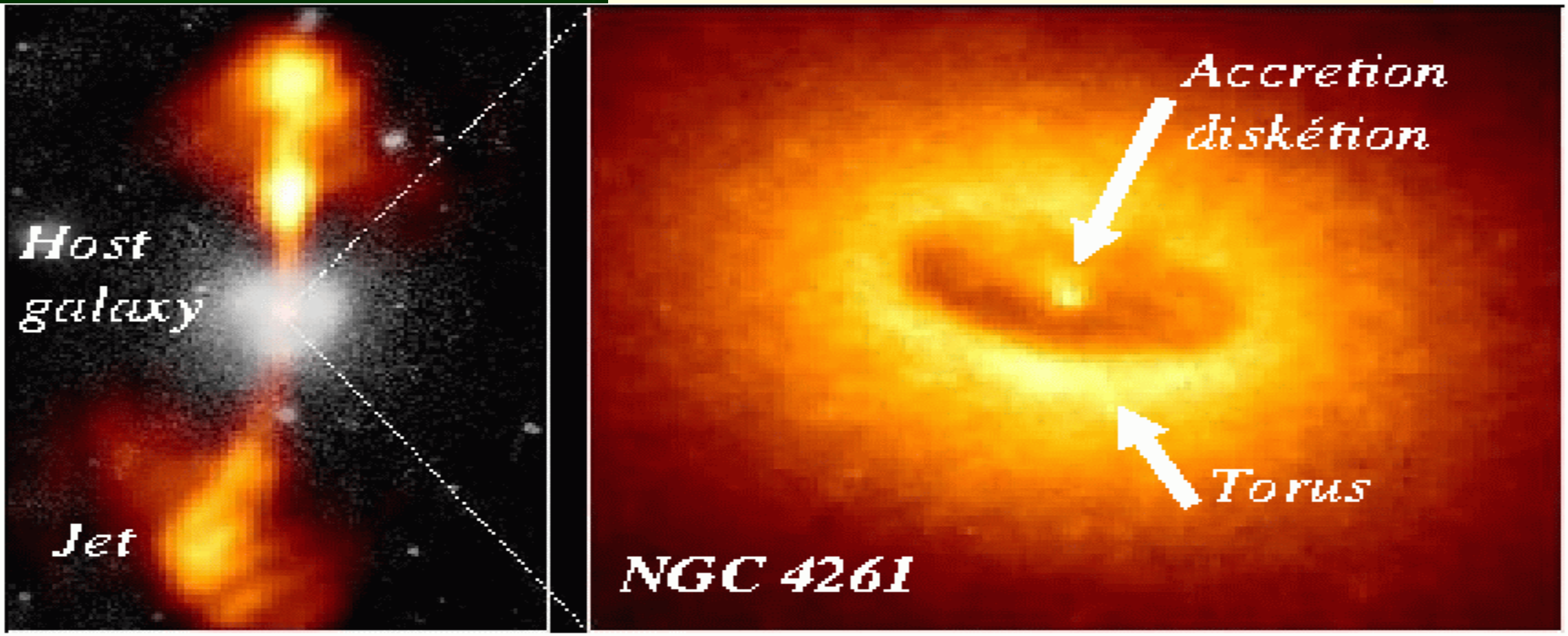
Why is the central black hole associated with the emission of energetic particles?

Because matter falling into the black hole is undergoing a very intense activity.

Torus of dust surrounding a black hole

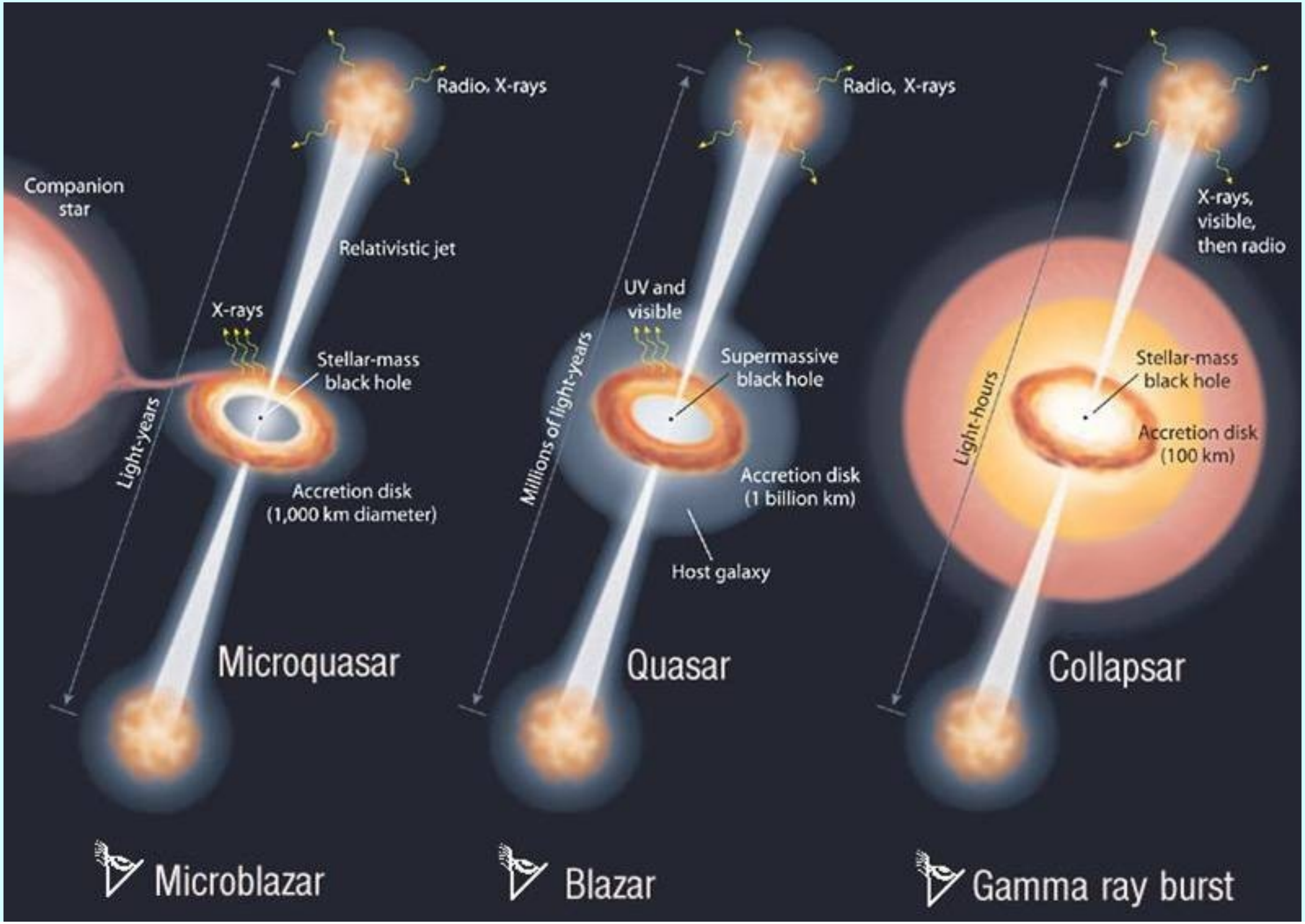
A jet of particles associated with a black hole of M87 galaxy



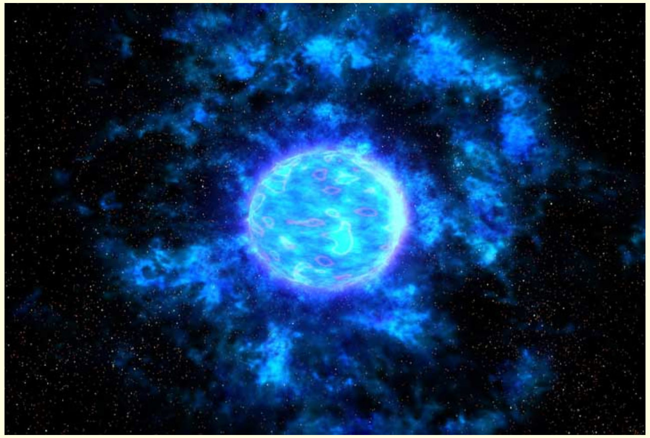

Host
galaxy
Jet
Accretion
diskétion
Torus
NGC 4261

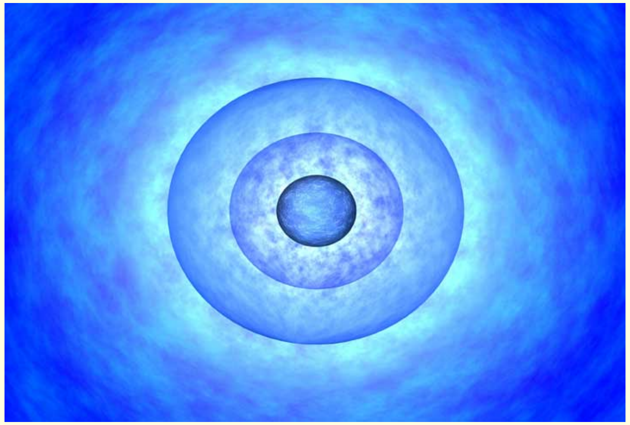
We still have to understand fully the accretion (disk, torus) and ejection phenomena present around a black hole.

One finds black holes as the building blocks of many astronomical systems where violent phenomena take place



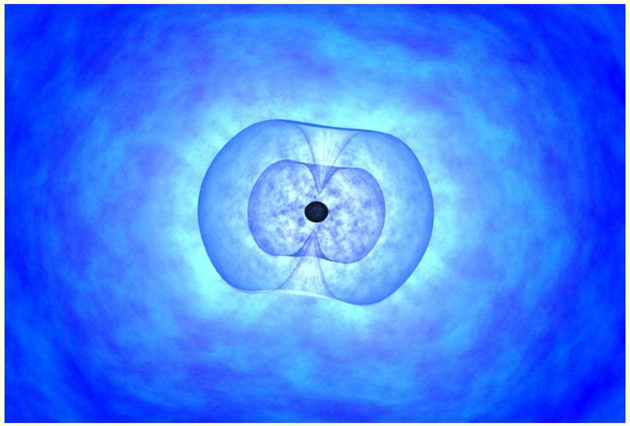
A model for (long) gamma ray bursts





A massive star ends its existence with an explosion

Its inner core collapses into a black hole



Collapse is not uniform.
There is creation of a jet of particles

This jet interacts with the outer layers of the star, which accelerates the particles.

Supernova explosions

Modern theory of supernovae was initiated by Zwicky and Baade in the 30s

Classification of supernovae according to spectroscopy:

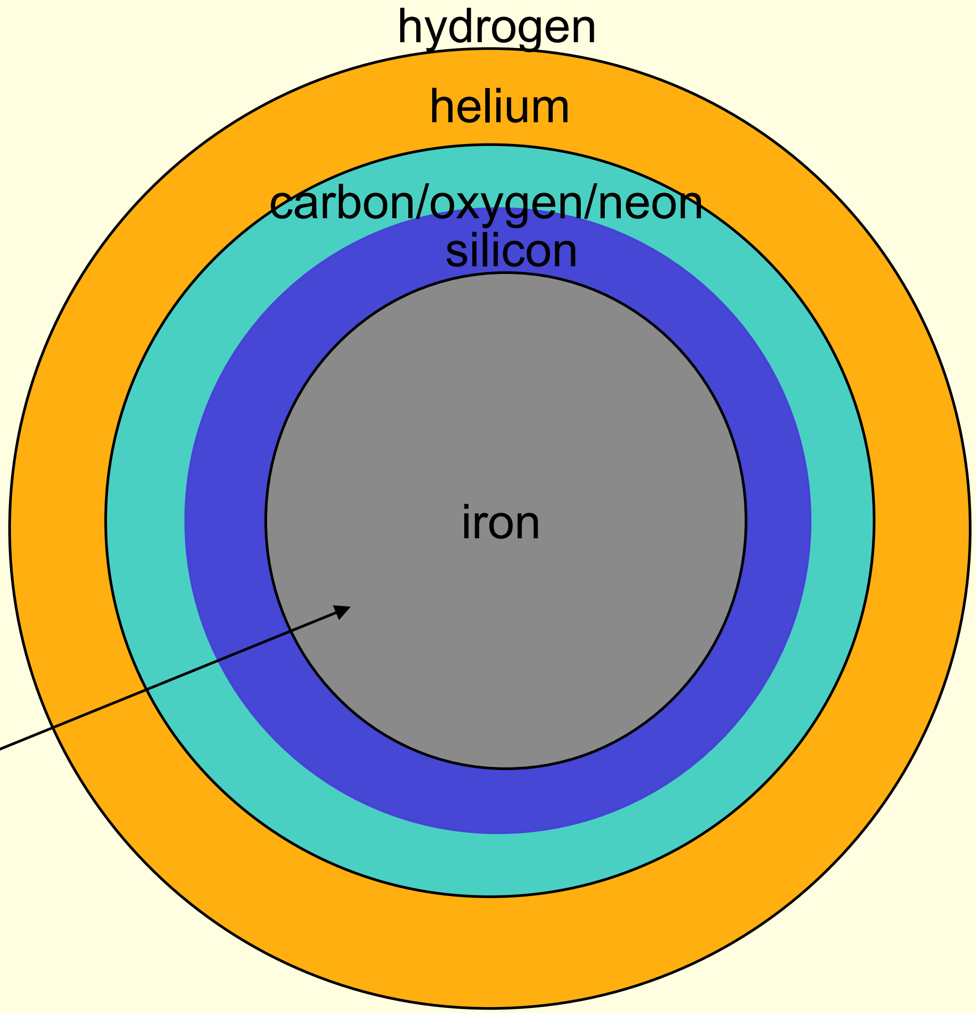
I : Hydrogen lines are absent

- Ia: intermediate mass elements
- Ib: Helium line present
- Ic: Helium lines weak or absent

II : Hydrogen lines are present

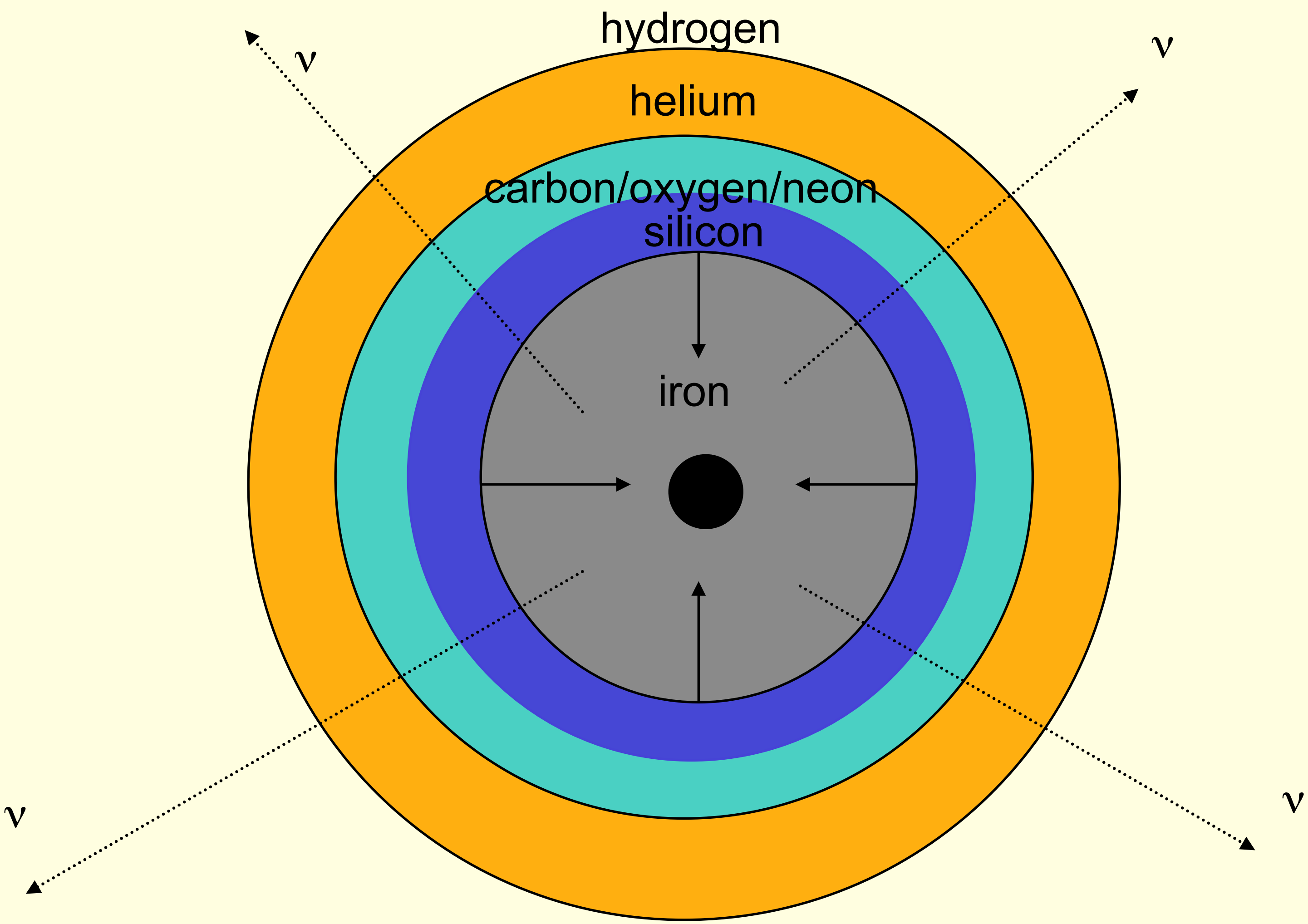
Supernovae of type II

Pre-supernova stars ($M>8M_{\odot}$) have an onion-like structure

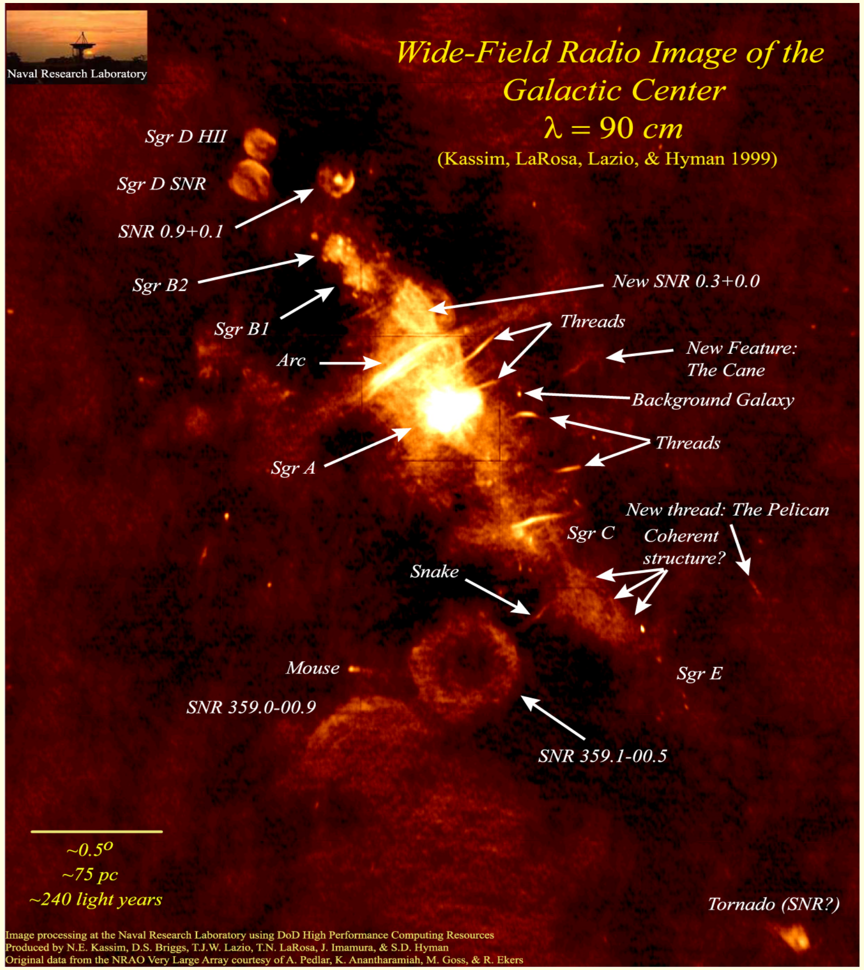


^{56}Fe (26p+30n)
lies at the bottom of
the valley of stability

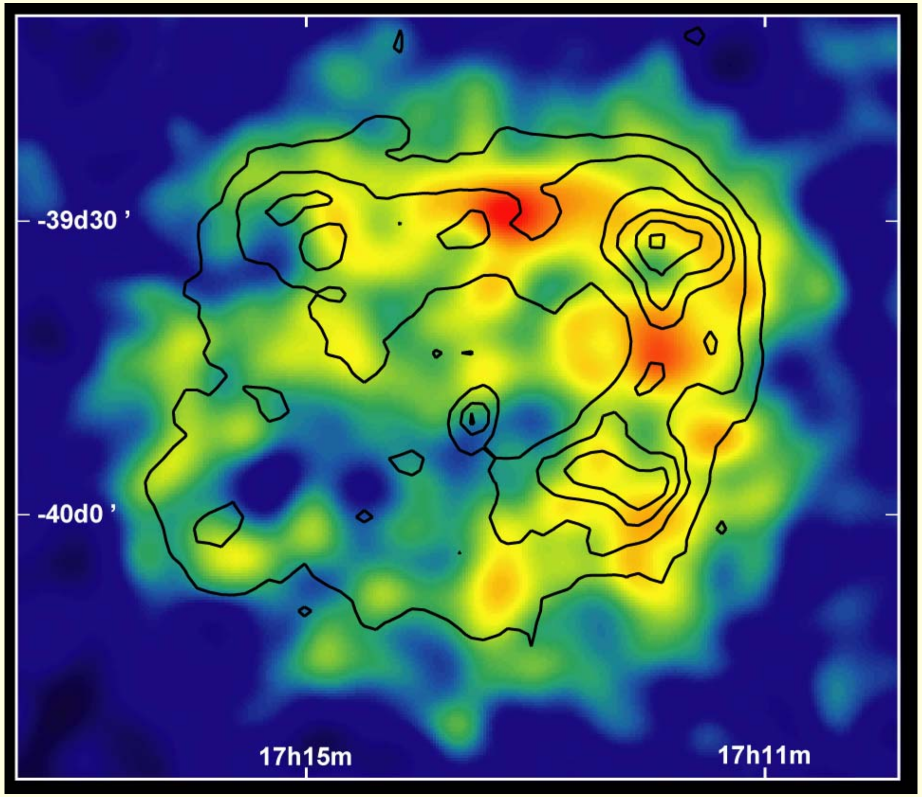
As Si is burned, the mass of the Fe core increases. The density increase turns the electrons relativistic and favours $e+p \rightarrow n+\nu$. This diminishes the electron degeneracy pressure and leads to a collapse of the core.



Radio



Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
Arc
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers



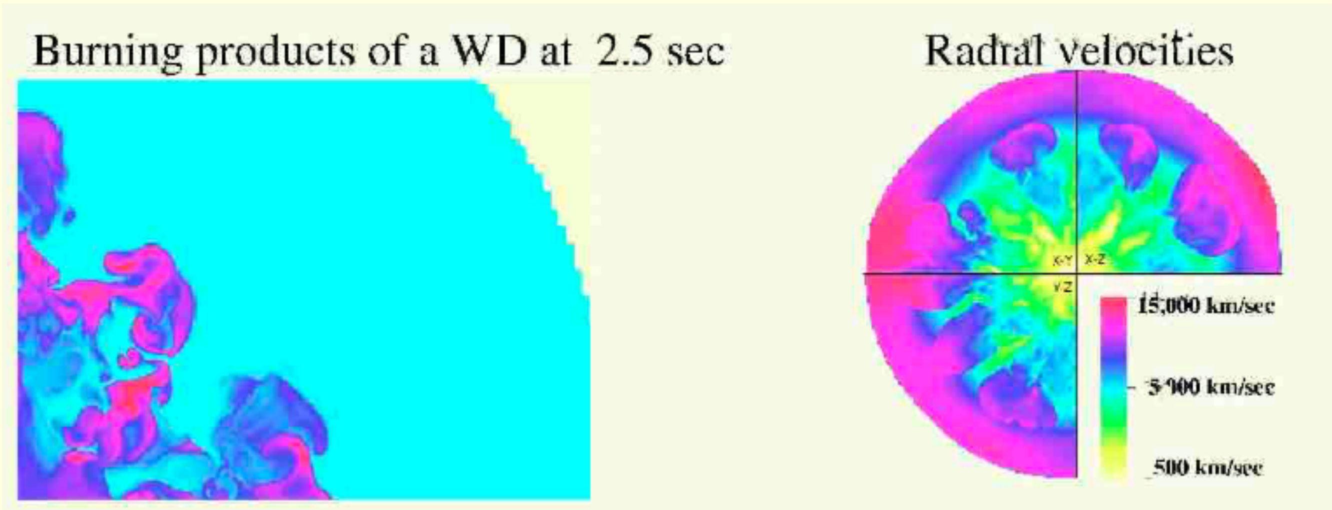
-39d30 '
-40d0 '
17h15m
17h11m

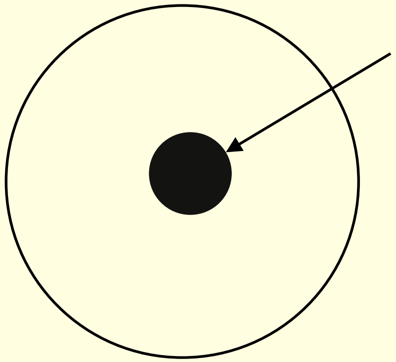
HESS

Supernovae of type Ia

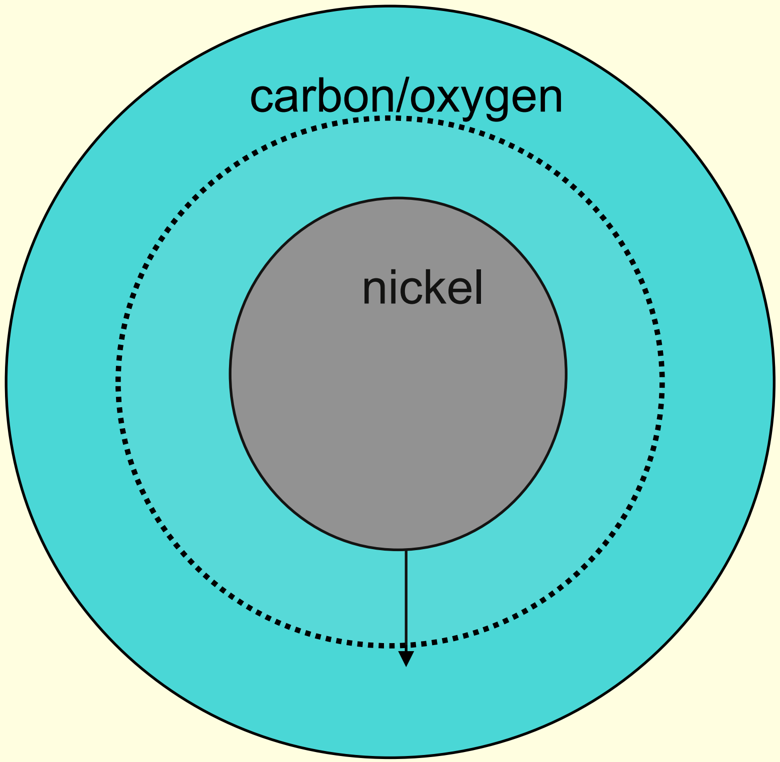
Thermonuclear explosion of white dwarfs:

A carbon-oxygen white dwarf accretes matter (from a companion star) which causes its mass to reach the Chandrasekhar limit: the central core collapses making the carbon burn and causing a wave of combustion that completely disrupts the star.





carbon ignites



^{56}Ni (28p+28n)

$\rightarrow$ ^{56}Co and ^{56}Fe

(weak interactions)