Astroparticle physics :

II - The violent Universe

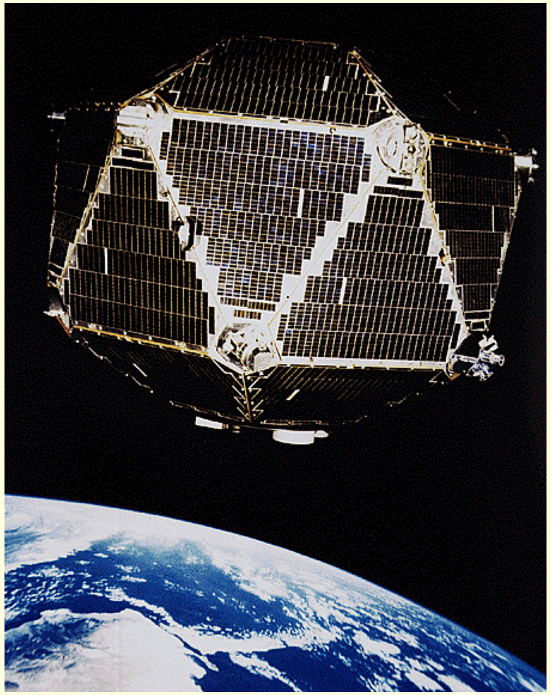
Pierre Binétruy
APC, Paris

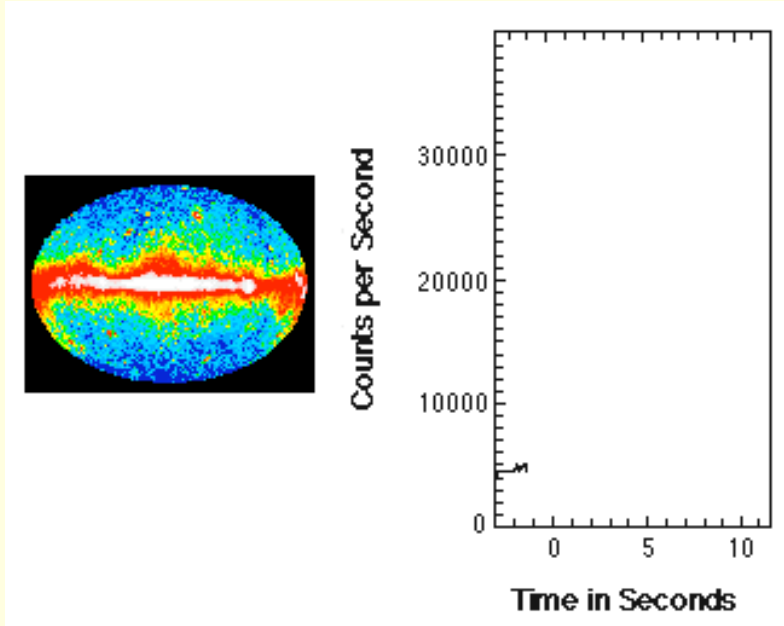
CERN Summer Student Lecture Programme 2011

Outline

1. The example of gamma ray bursts
2. The end of a star
3. The story of black holes
4. Supernovae explosions
5. Cosmic rays and cosmic accelerators

1. 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. $M_{\odot}c^2$

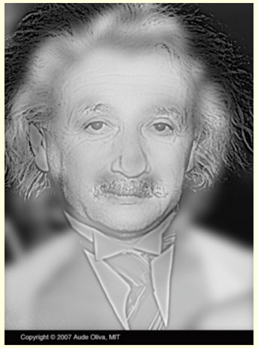
Distance that light travels in 5 seconds: 1 500 000 km i.e. 0.01 au

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

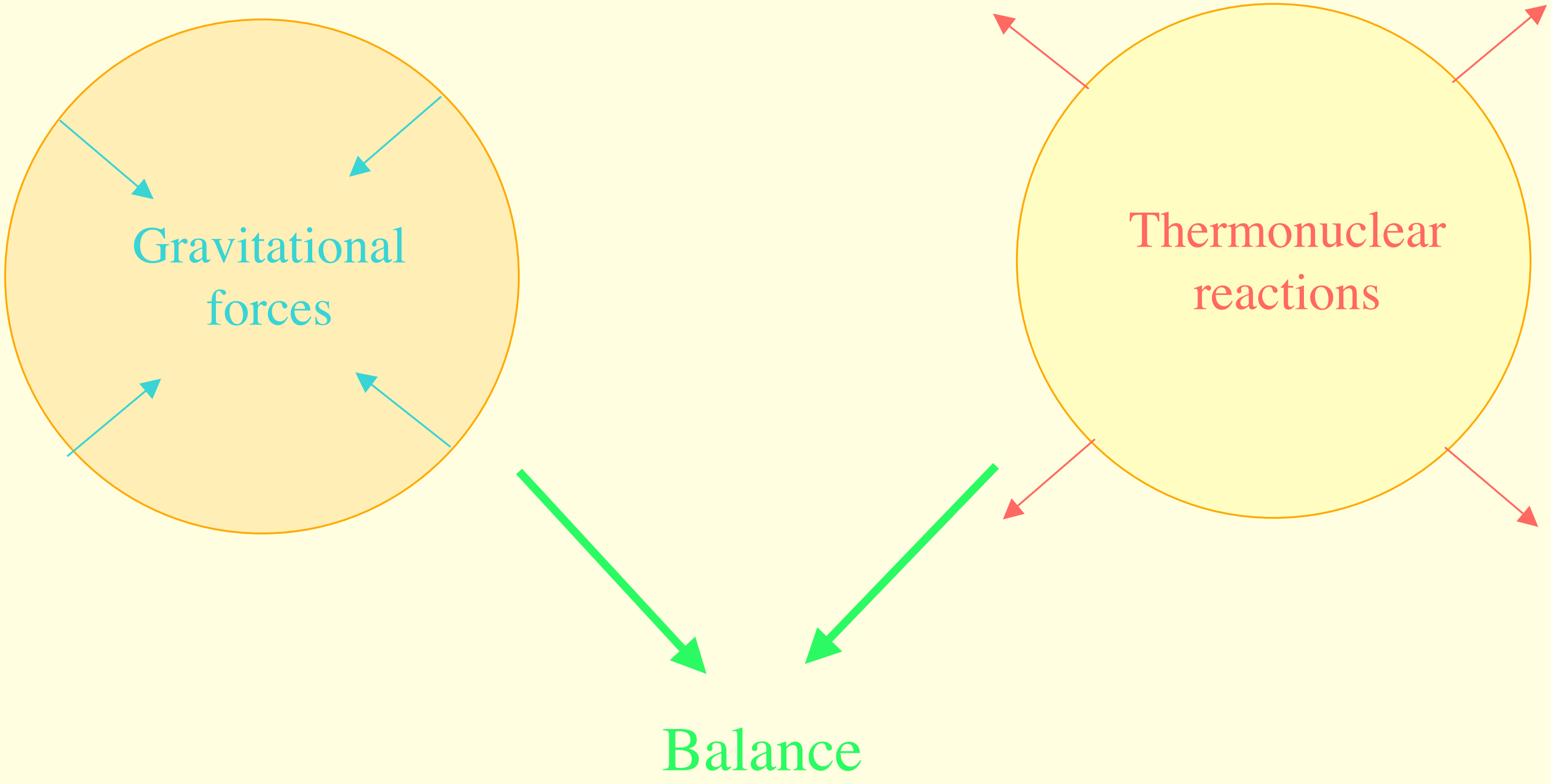
→ compact objects

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

2. The end of a star

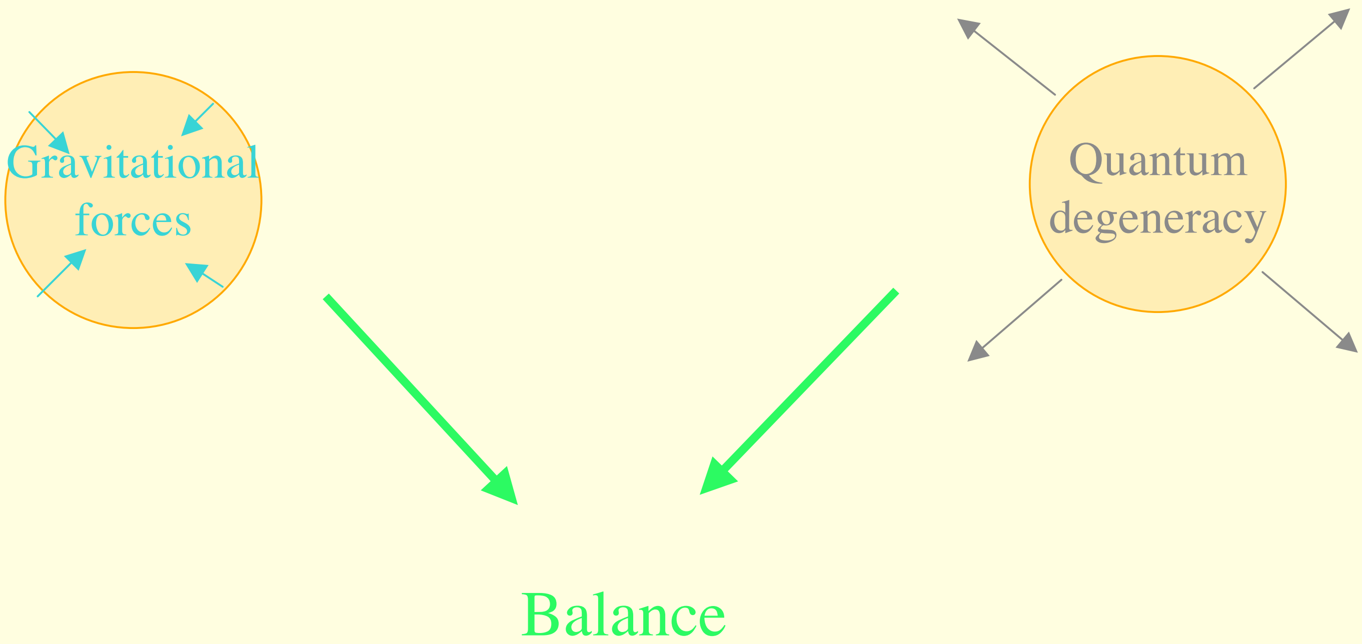


Some notions about star evolution (such as our Sun)



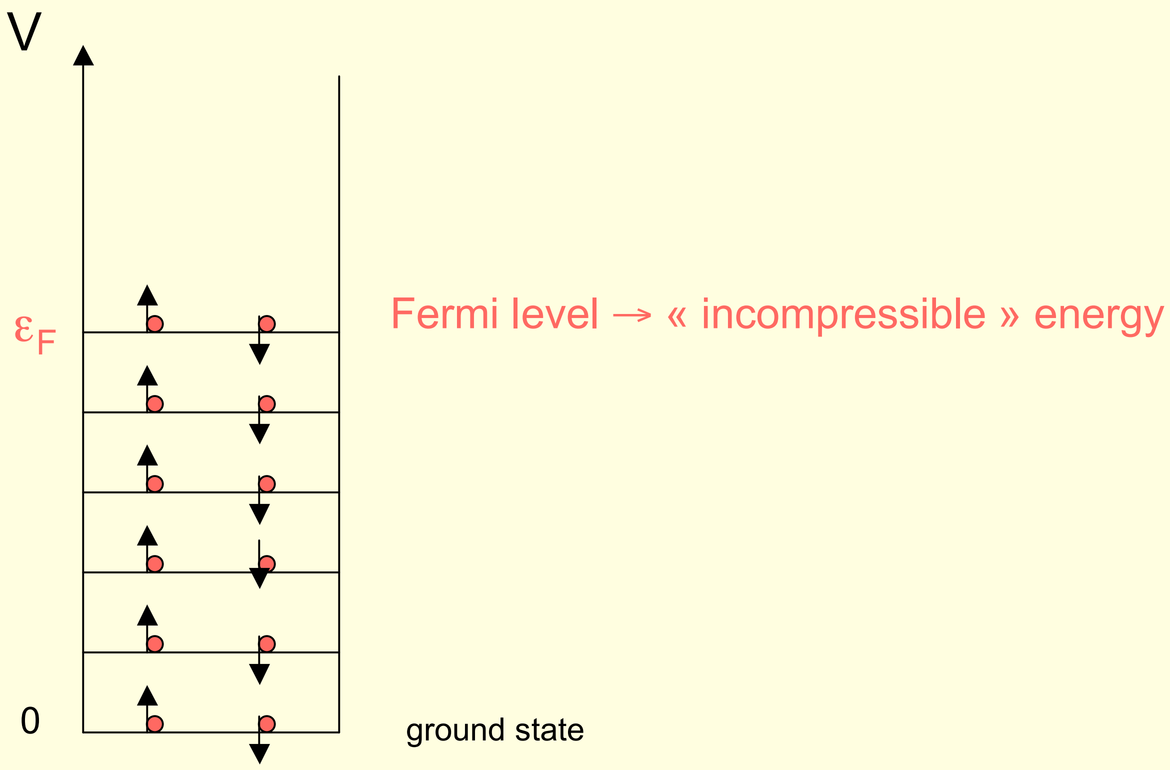
But when the nuclear fuel is exhausted, there is collapse under the effect of gravity → FORMATION OF A COMPACT OBJECT

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

3. The story of black holes

A technical transparency

One month after the publication of Einstein's theory, Schwarzschild found an isotropic 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, $R_S = 2.9$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

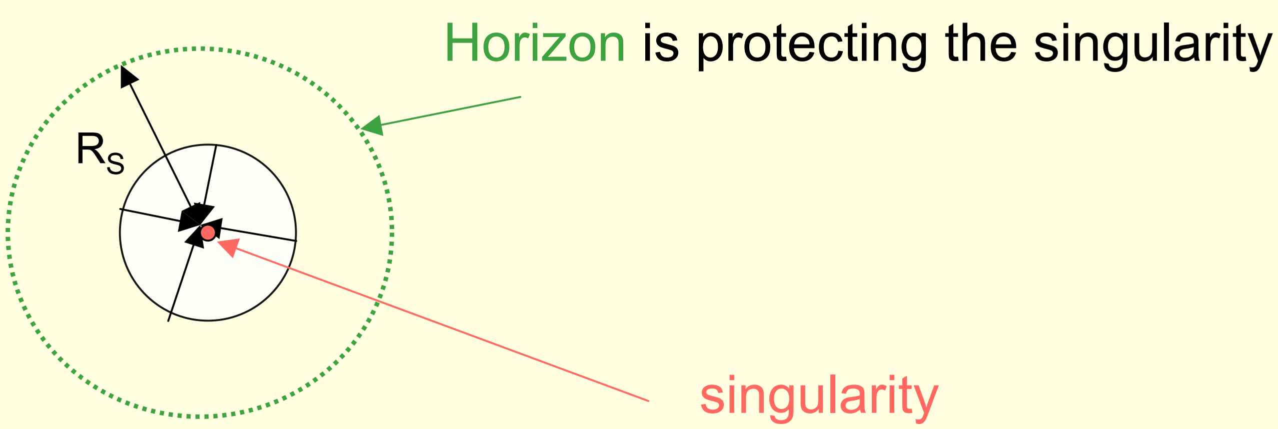
What is then the meaning of the Schwarschild radius?

Mitchell (1784) Laplace (1795)

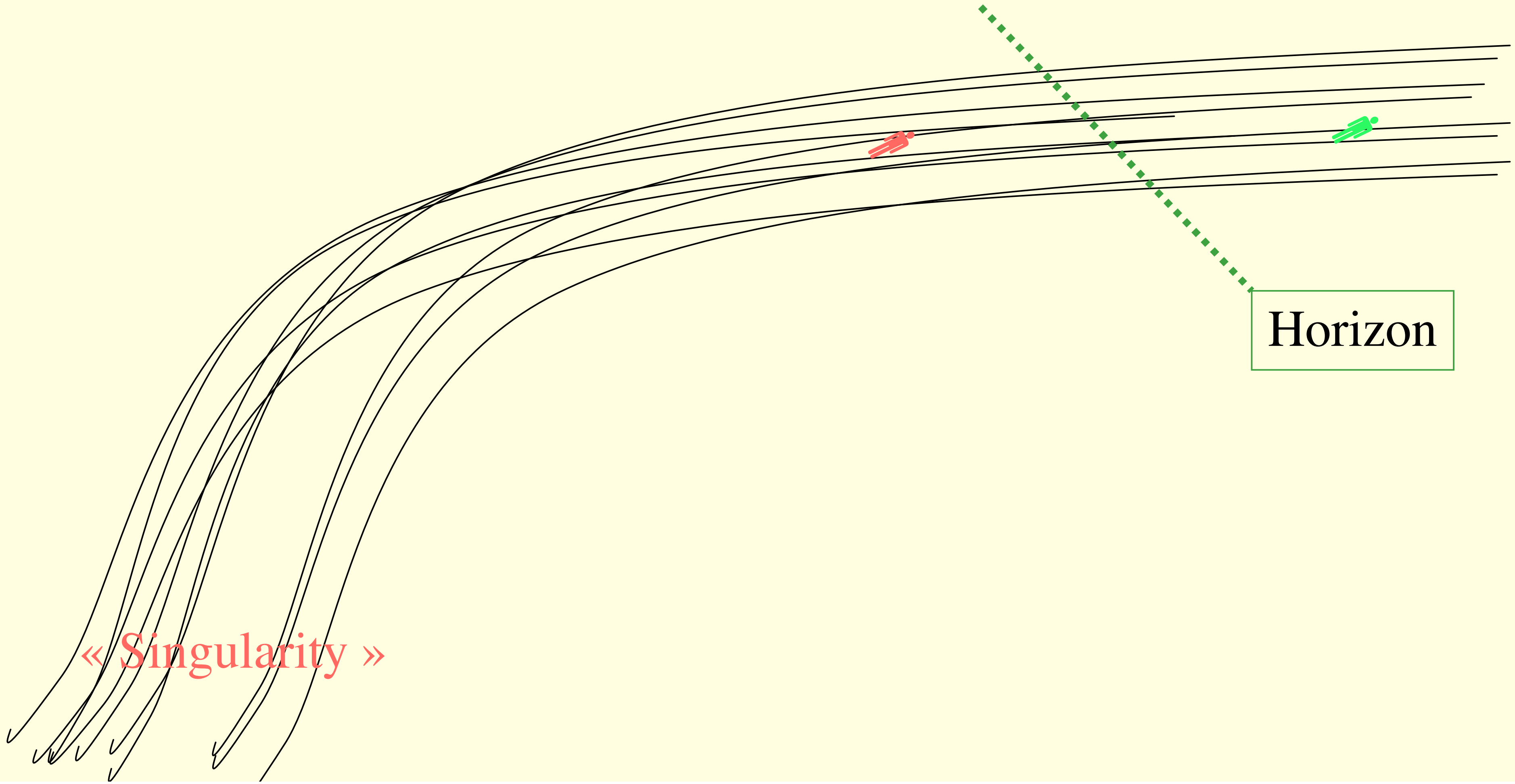
Classical condition for a body of mass m and velocity v to escape from a spherical star of mass M and radius R :

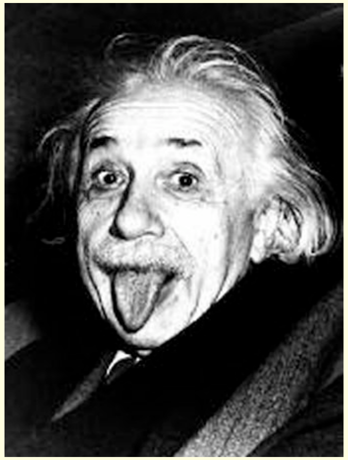
$$\frac{1}{2} m v^2 > \frac{G_N M m}{R}$$

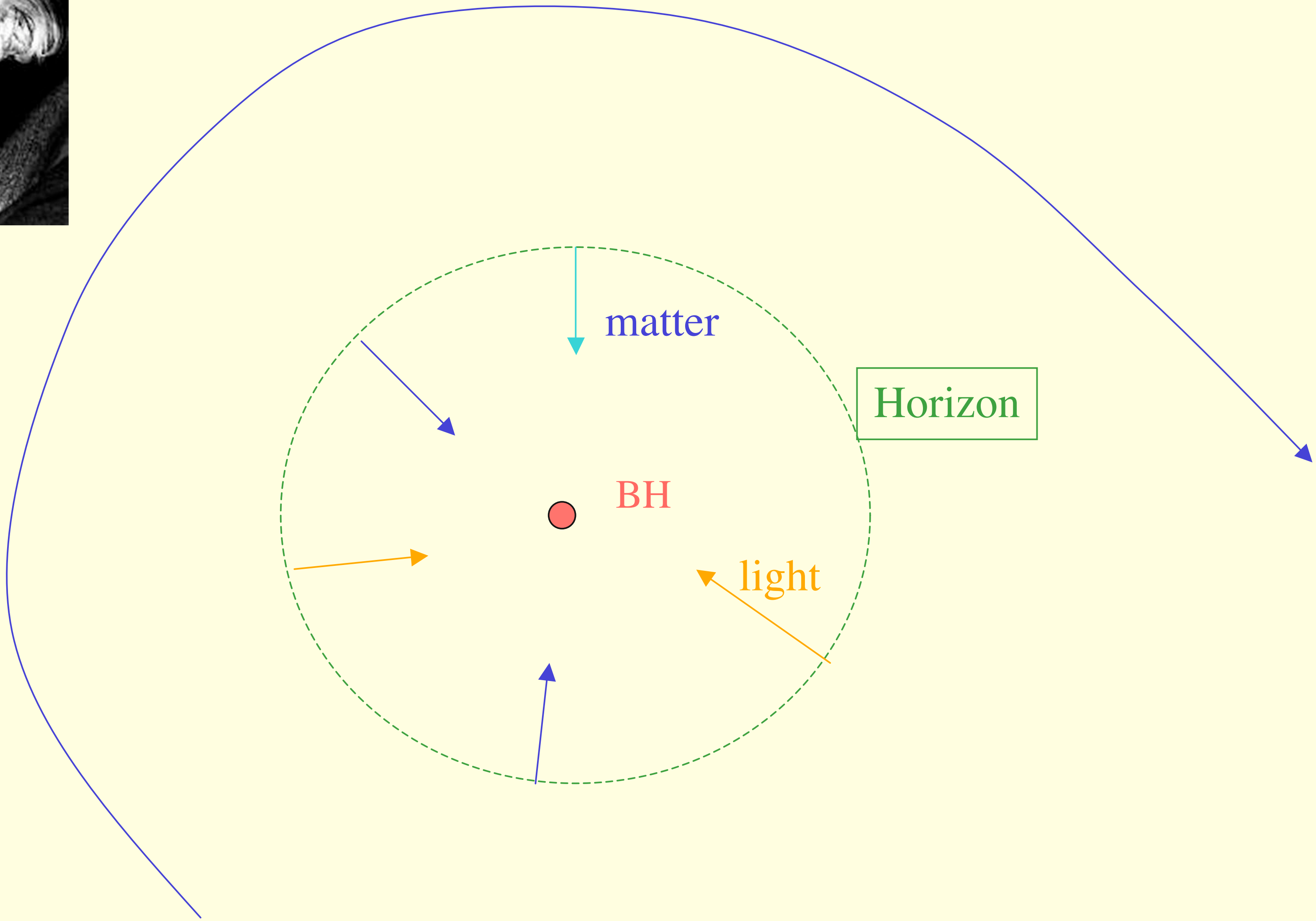
Hence even light (v=c) cannot escape if $R < 2\, G_N M/c^2 = R_S$



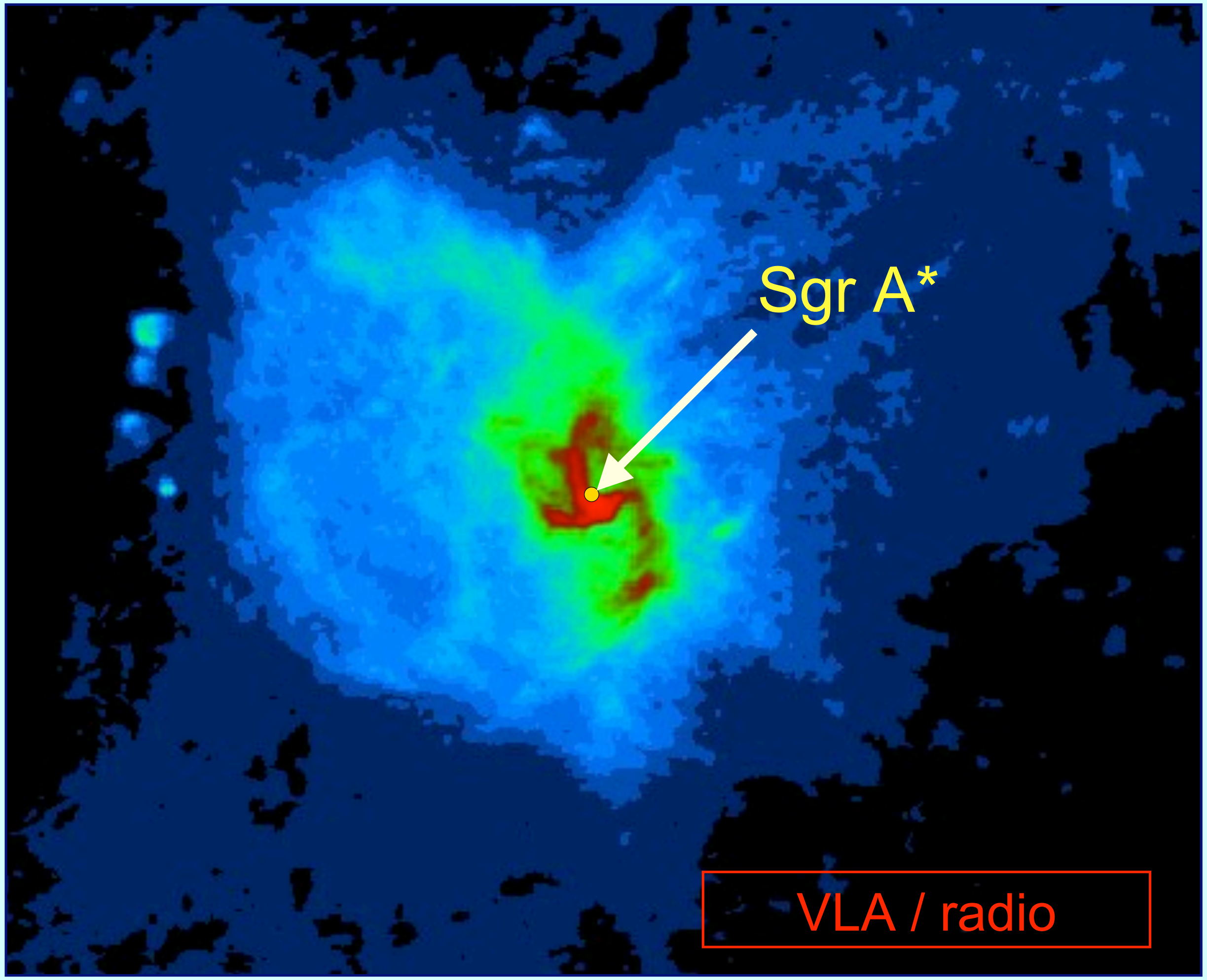
A comparison to understand the notion of (Schwarschild) horizon : the waterfall.






matter
Horizon
BH
light

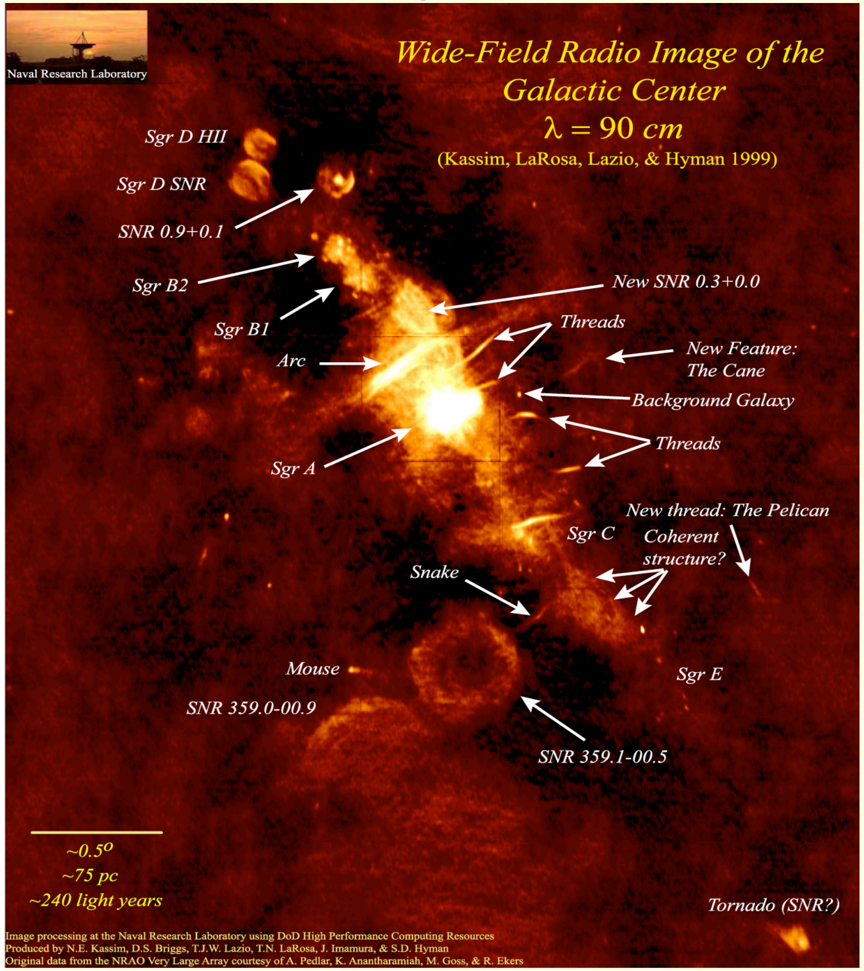
From « black holes » to black holes…



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

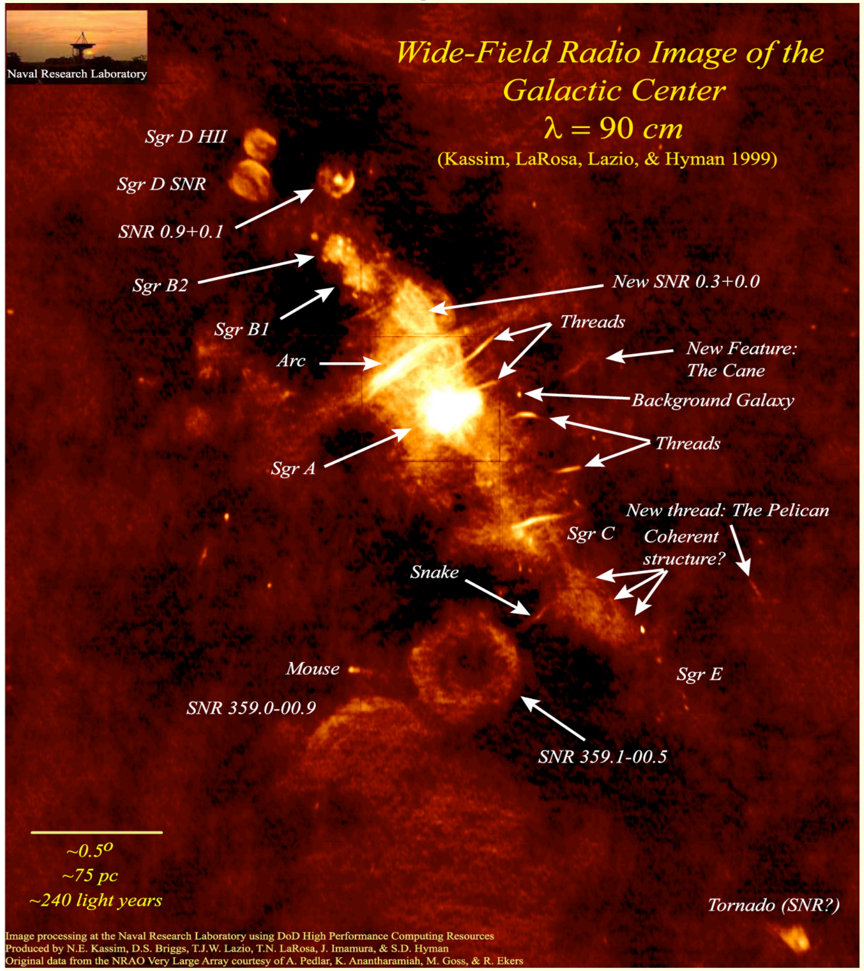
Let us come closer!

Radio image (90 cm)

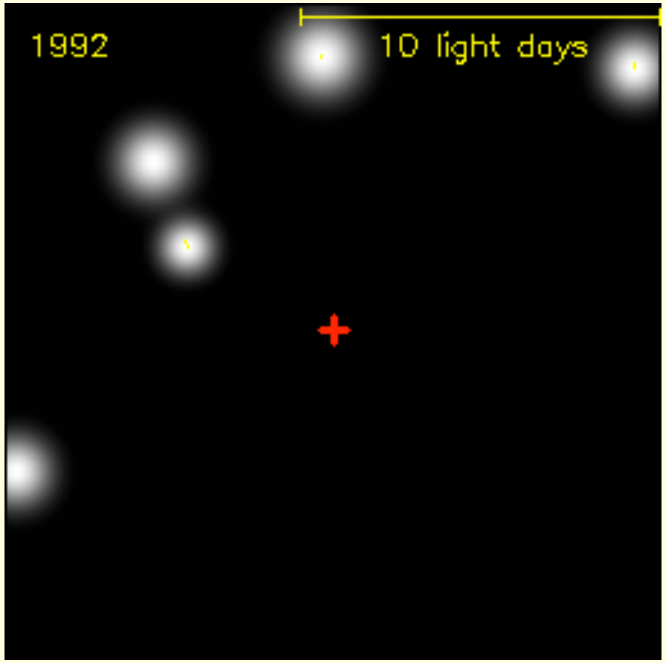


Let us come closer!

Radio image (90 cm)

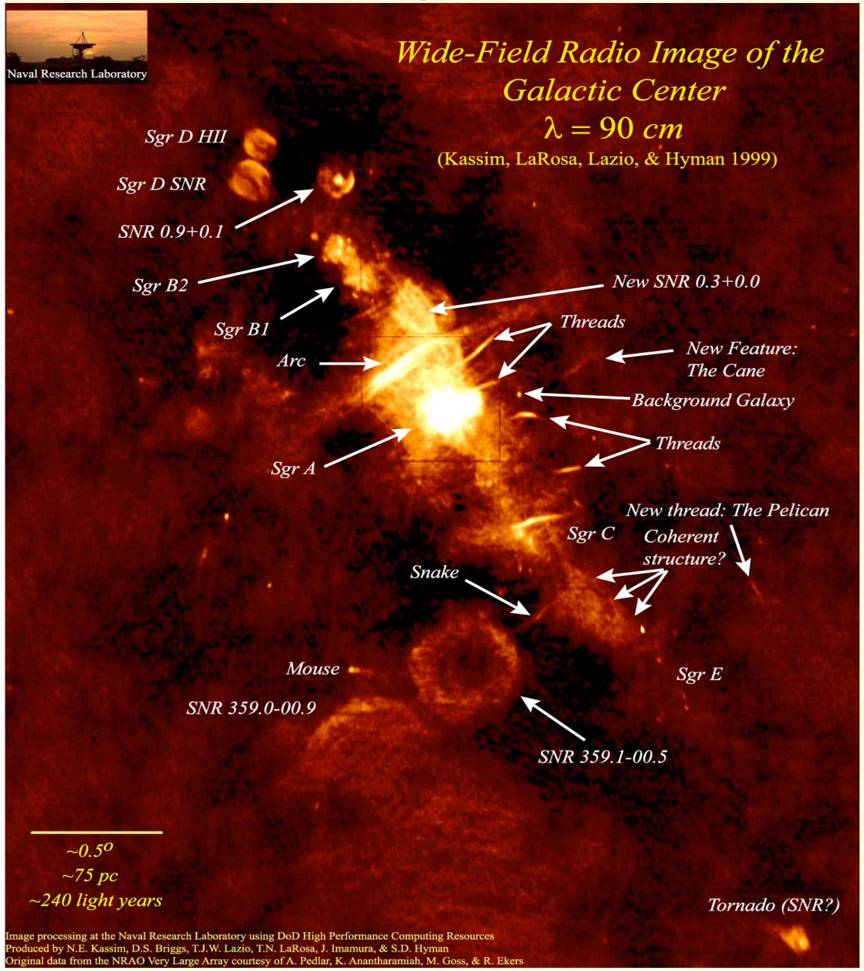


Infrared (1.6 μm <λ <3.5μm)
NAOS/CONICA

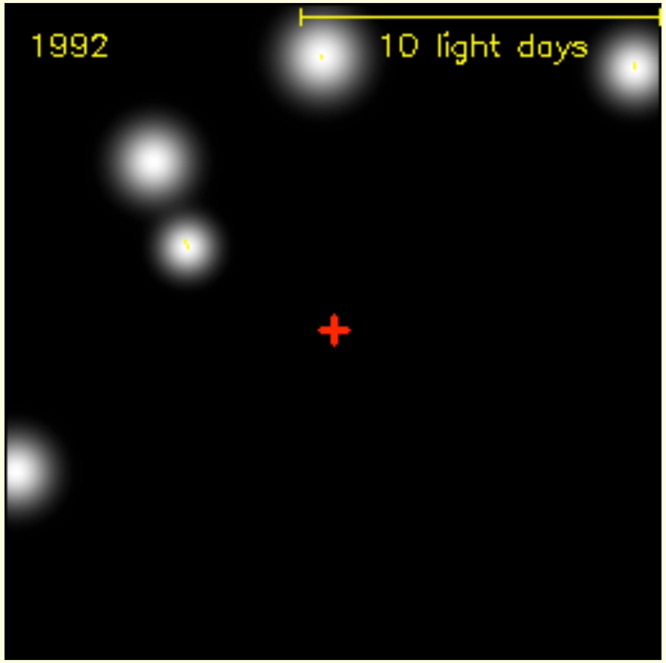


Let us come closer!

Radio image (90 cm)



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

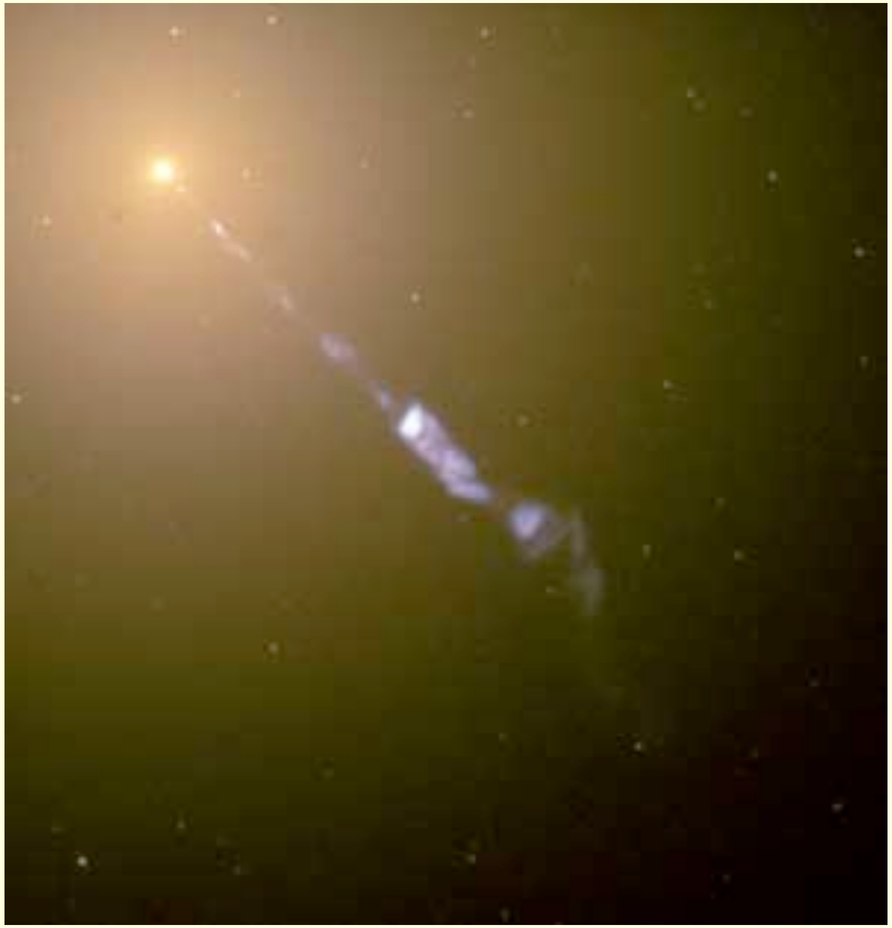


Black hole of mass of the order of 3 million solar masses

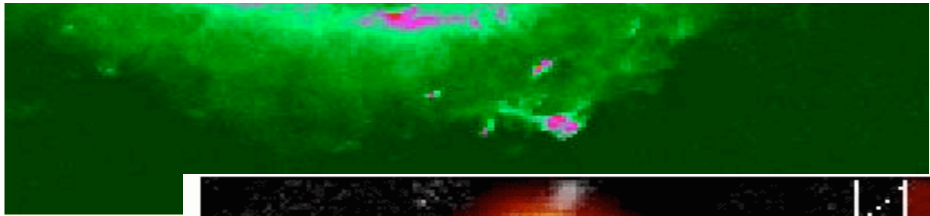
Why is the central black hole associated with the emission of energetic particles?

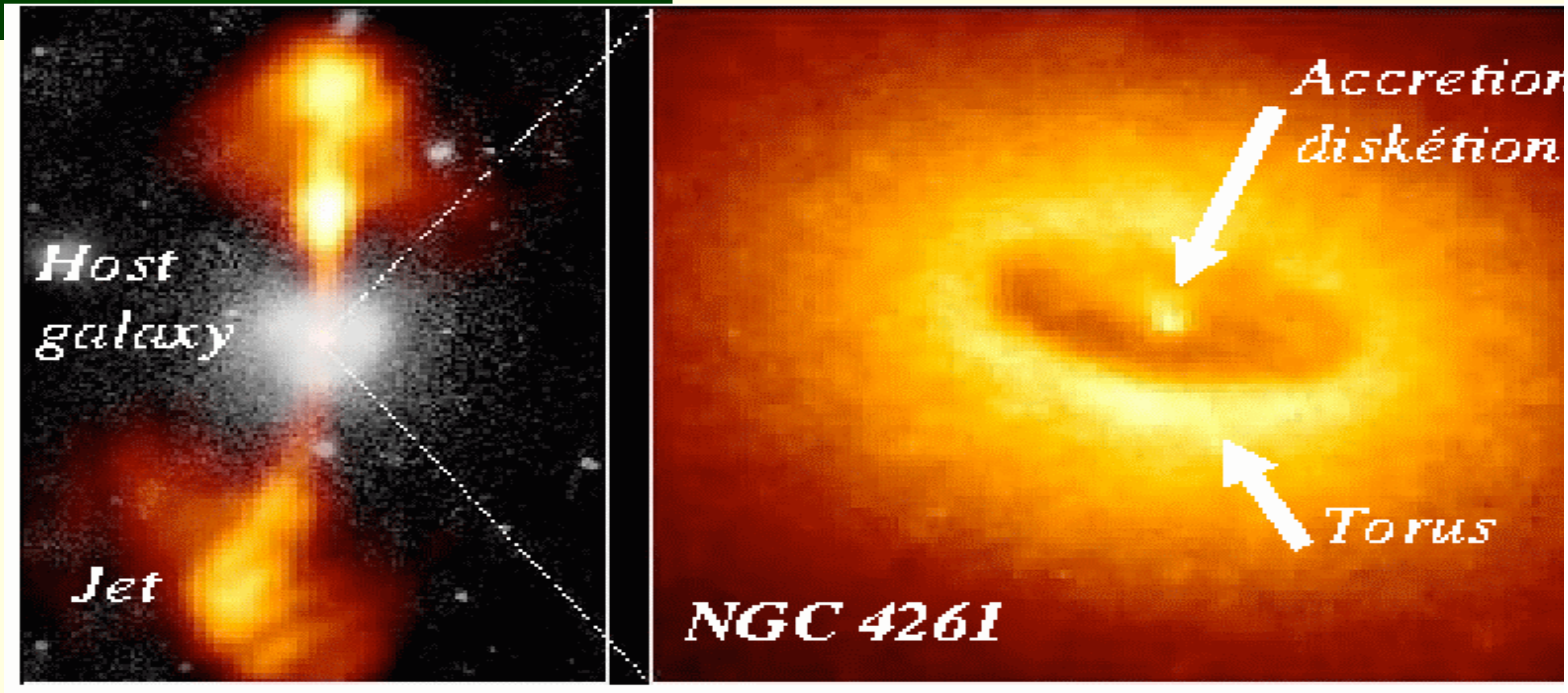
Because matter falling into the black hole is undergoing a very intense activity.

Torus of dust surrounding a black hole



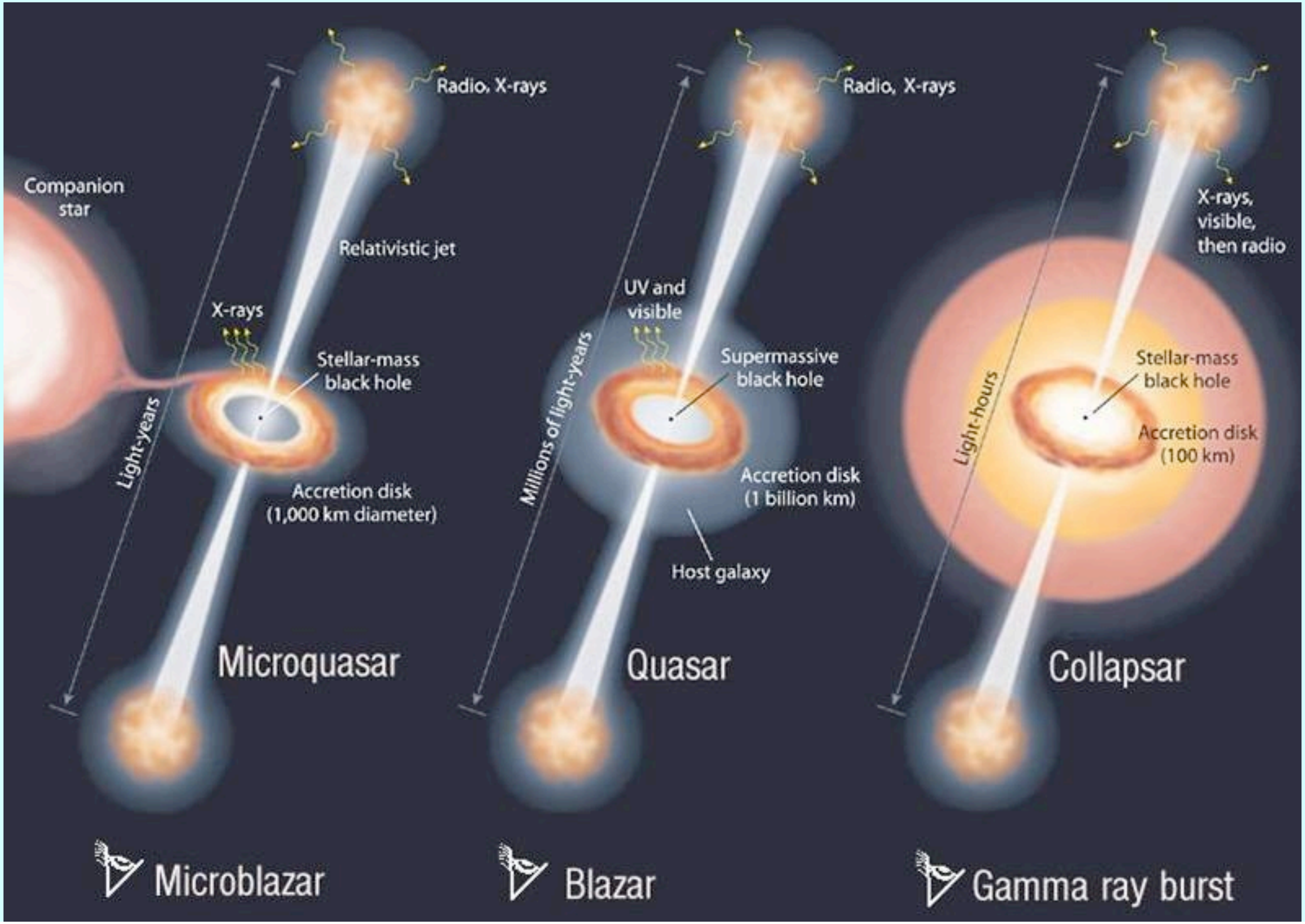
A jet of particles associated with a black hole of M87 galaxy



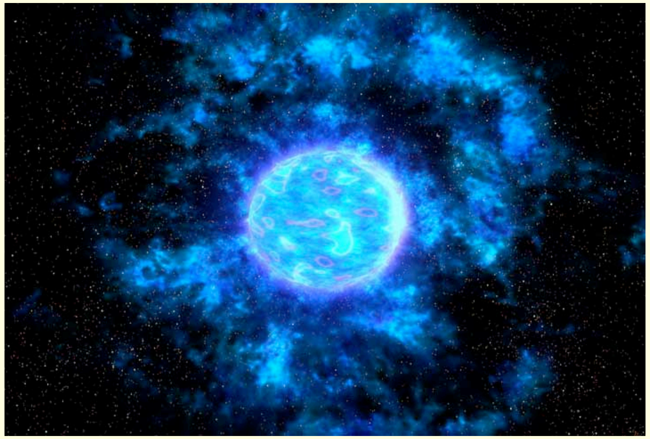

Host galaxy
Jet
Accretion
diskétion
Torus
NGC 4261

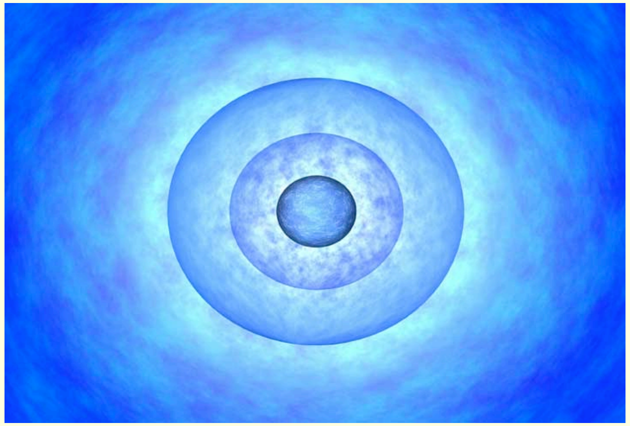
We still have to understand fully the accretion (disk, torus) and ejection phenomena present around a black hole.

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



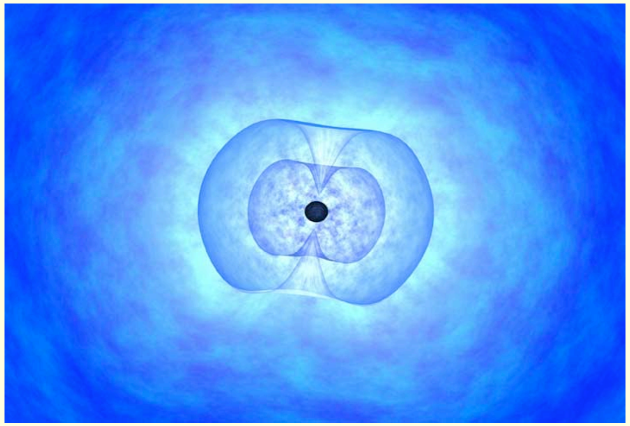
A model for (long) gamma ray bursts





A massive star ends its existence with an explosion

Its inner core collapses into a black hole

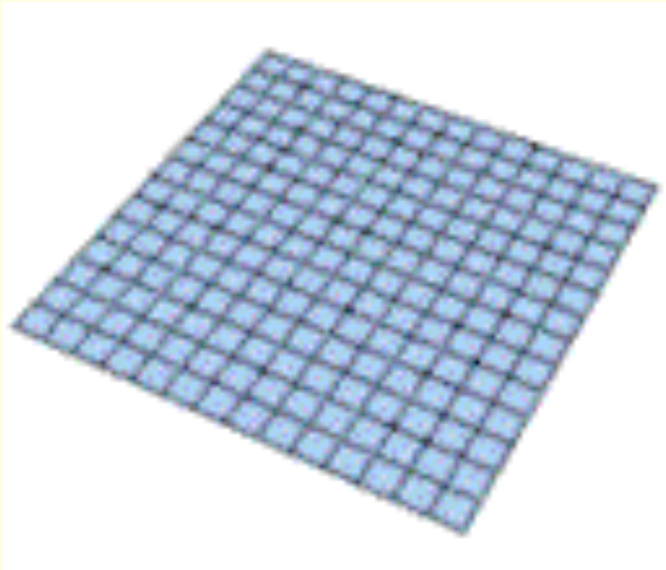


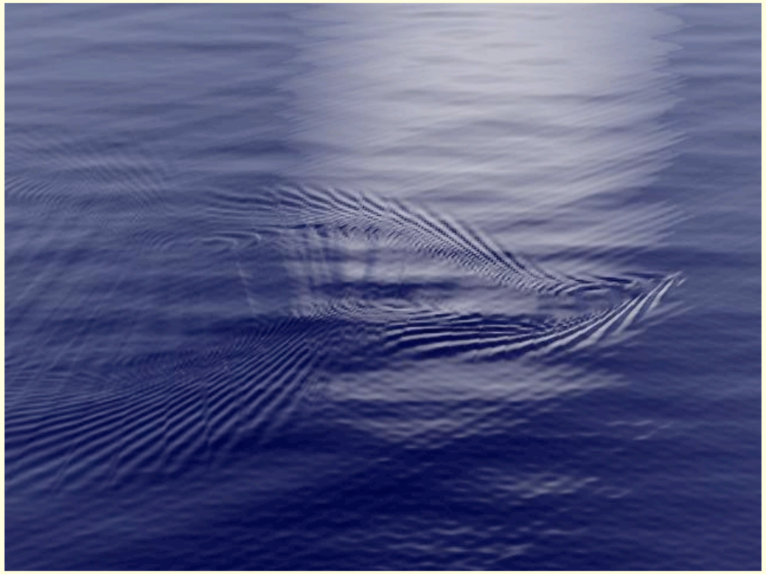
Collapse is not uniform.
There is creation of a jet of particles

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

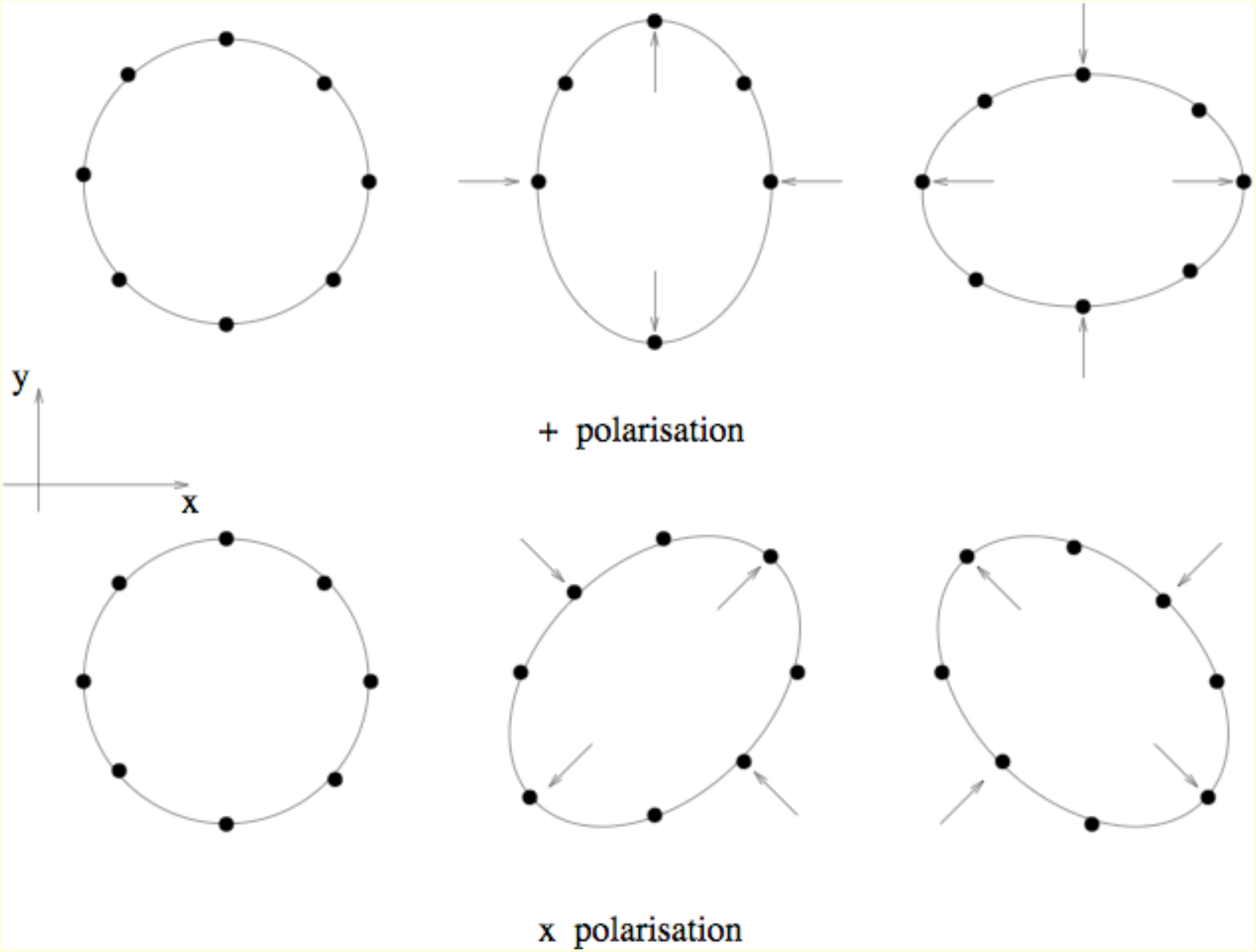
3a. Black holes and gravitational waves

Space-time (4D) is « elastic ».
Any mass or localized form of energy perturbs it and curves it.
Just as when you drop a stone in a pond …





… violent phenomena (sudden motion of bulk of matter) may lead to waves of deformaton of spacetime that will propagate in the Universe.



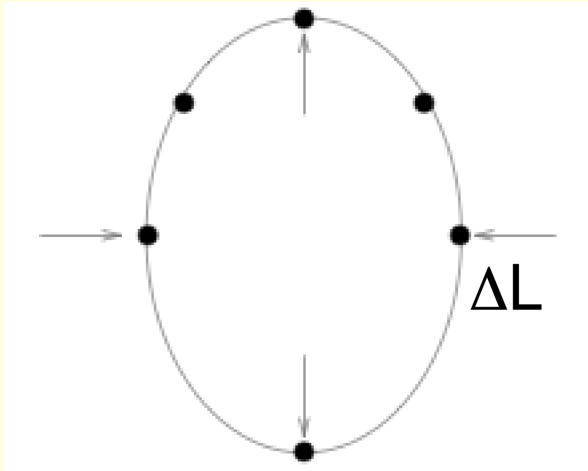
Two types of polarisation for gravitational waves

One introduces the amplitude of the gravitational wave:

$$h = \frac{\Delta L}{L}$$

variation of length due to the gravitational wave (ΔL)

total length (L)



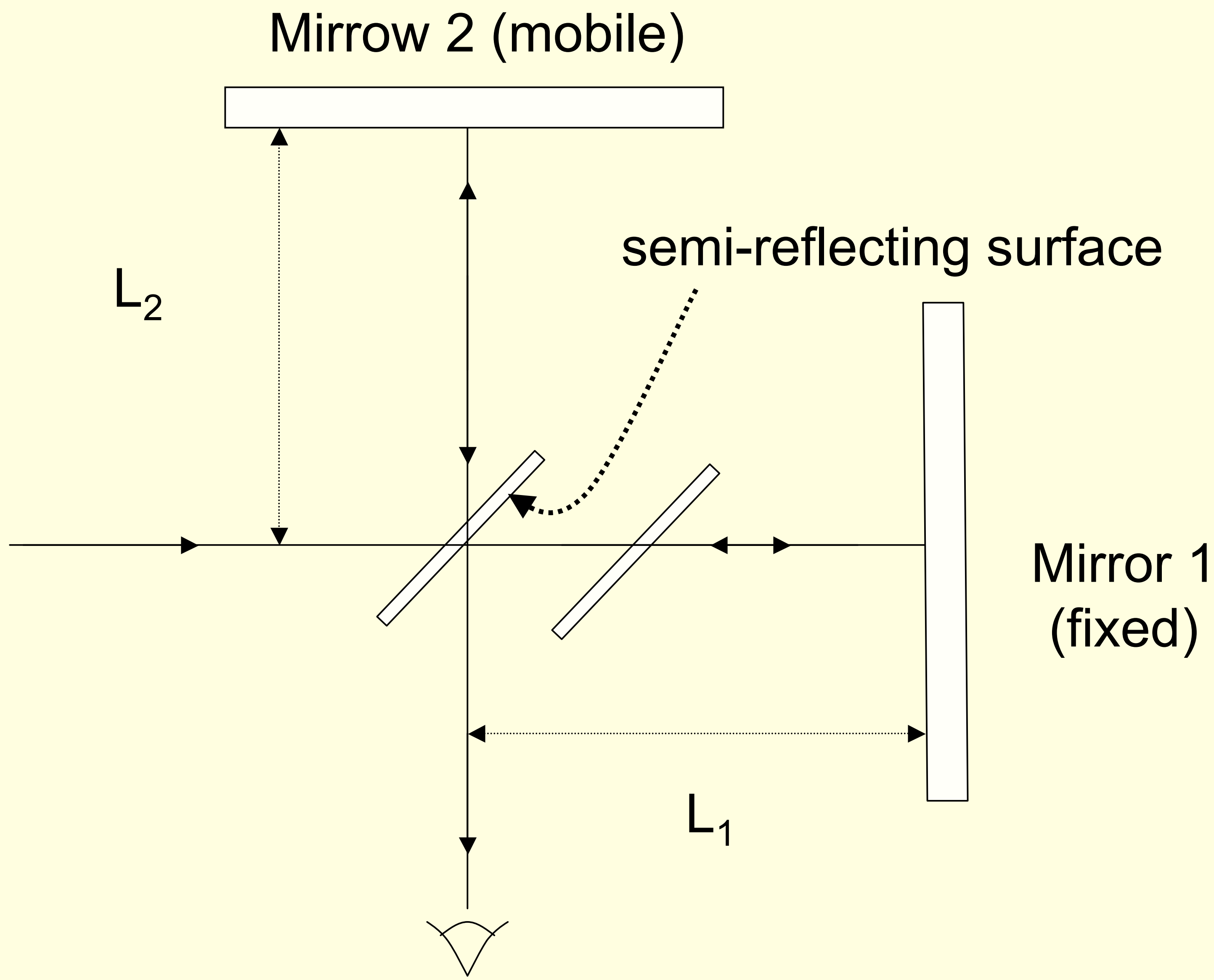
Examples:

- explosion of a supernova in the Virgo cluster (15Mpc): $h=10^{-21}$ à 10^{-24}
- binary system of 2 black holes ($M=1,4M_{\odot}$) at 10 Mpc: $h=10^{-22}$ à 10^{-23}

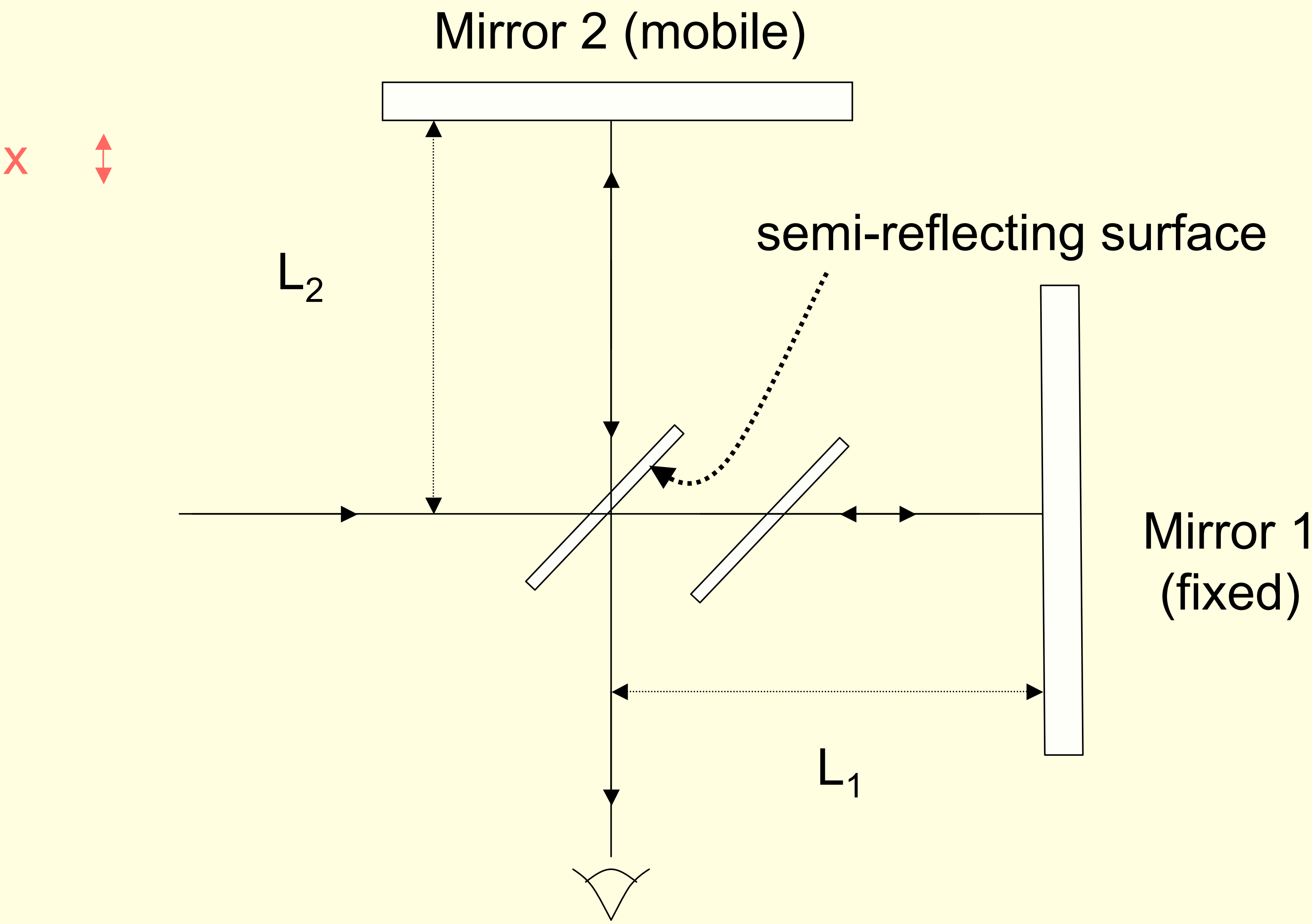
For masses localized at a distance of one kilometer

$$\Delta L = h\,L \sim 10^{-22} \,.\, 10^{3} = 10^{-19}\ \text{m !}$$

Only known solution : interferometry

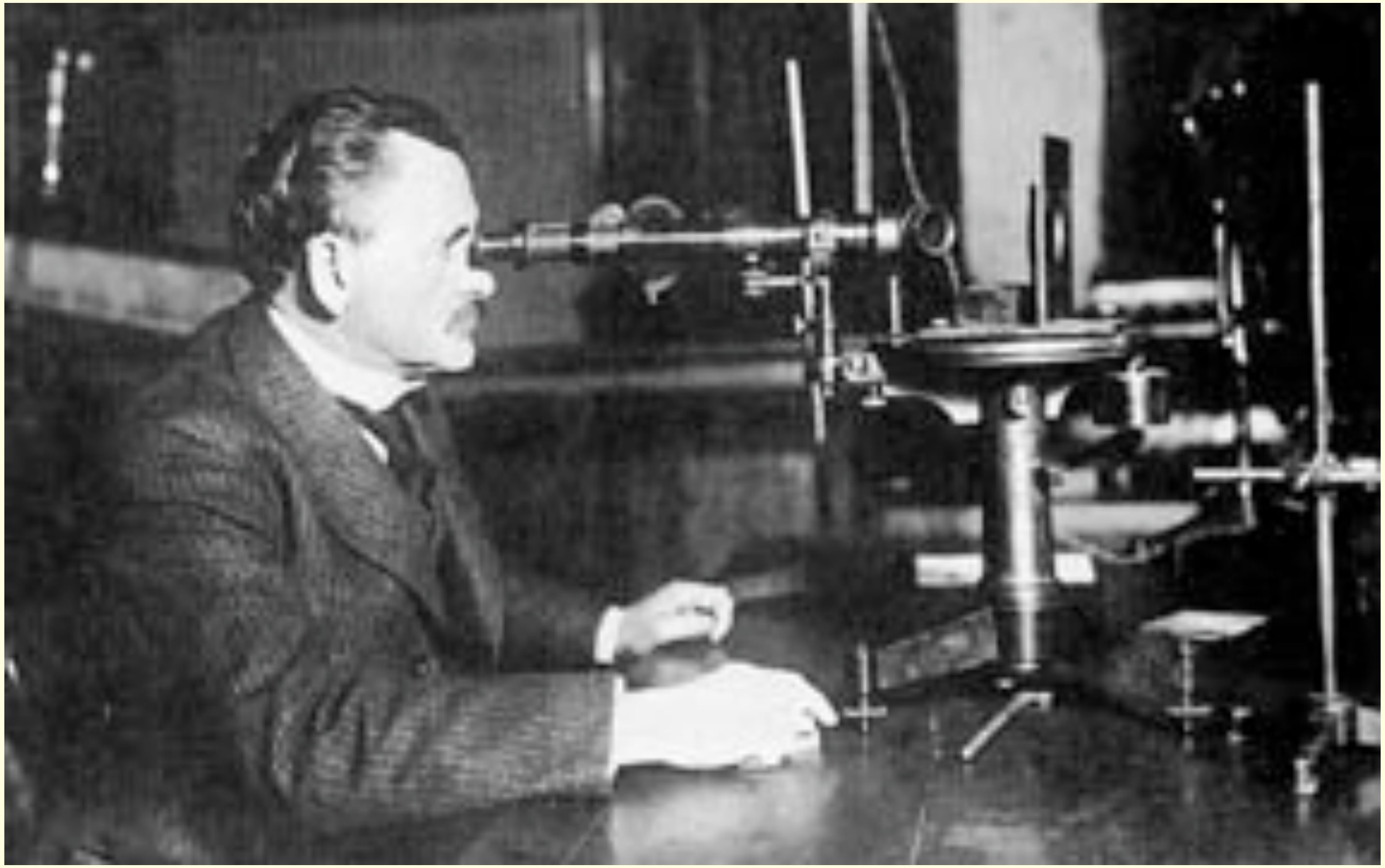


Michelson interferometer


Mirror 2 (mobile)
x
L_2
semi-reflecting surface
Mirror 1
(fixed)
L_1

$x = m \lambda / 2$

Albert Michelson counting interference fringes



Sensitivity in 1887: $\Delta L = 6.10^{-10}$ m!

Which size for an interferometer detecting gravitational waves?

Size ~ Wavelength of the gravitational wave

~ c / f

Frequency f of gravitational waves $\sim\sqrt{M/R^3}$

(Kepler law for binary systems)

Neutron stars ($M \sim 1{,}4 M_{\odot}$) : $f \sim 100$ Hz

$\Rightarrow$ size ~ 3000 km

Ground Interferometers?

Supermassive black holes ($M \sim 10^6\, M_{\odot}$) : $f \sim 10^{-4}$ à 10^{-2} Hz

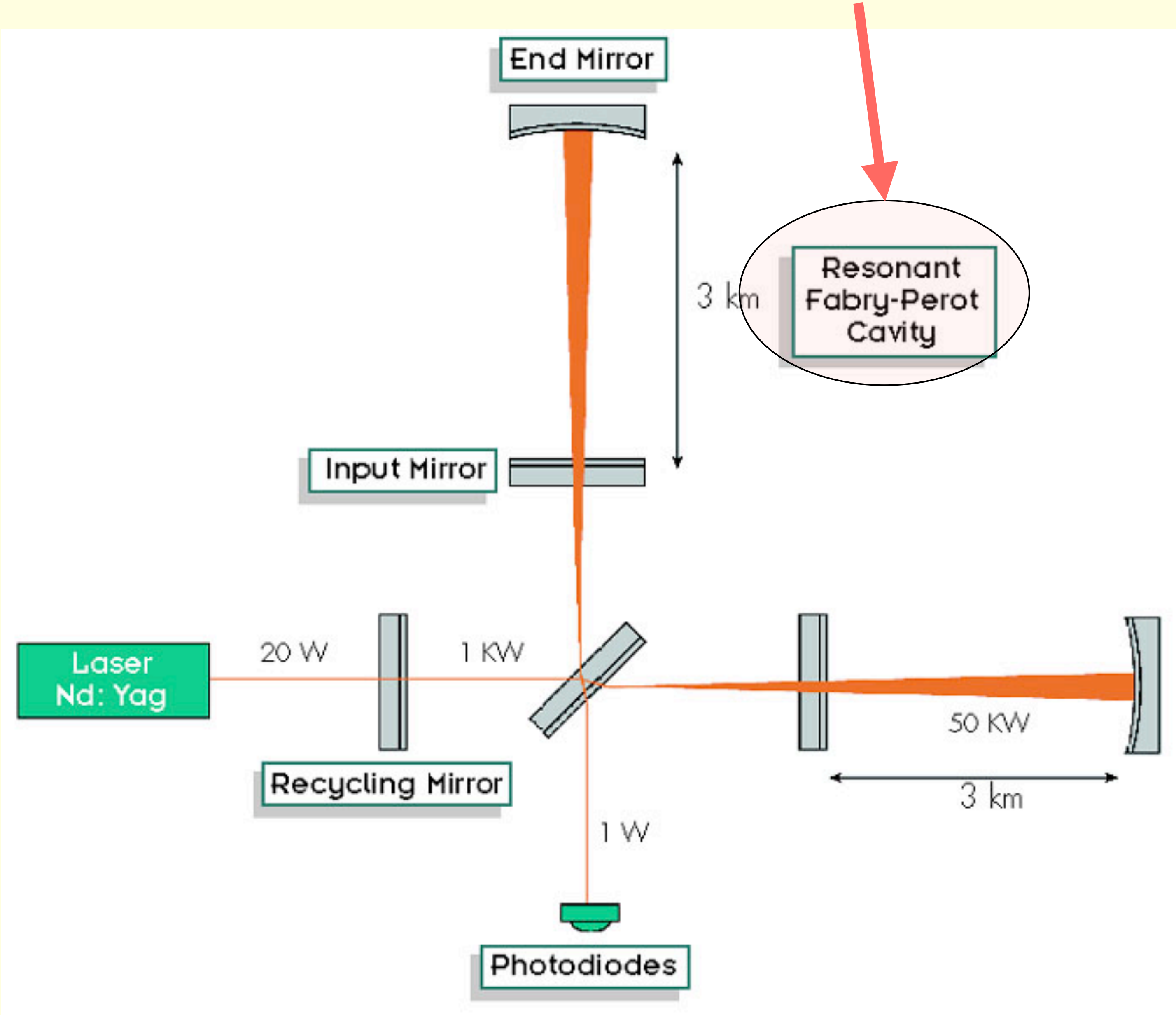
$\Rightarrow$ size ~ 30 million km

LISA

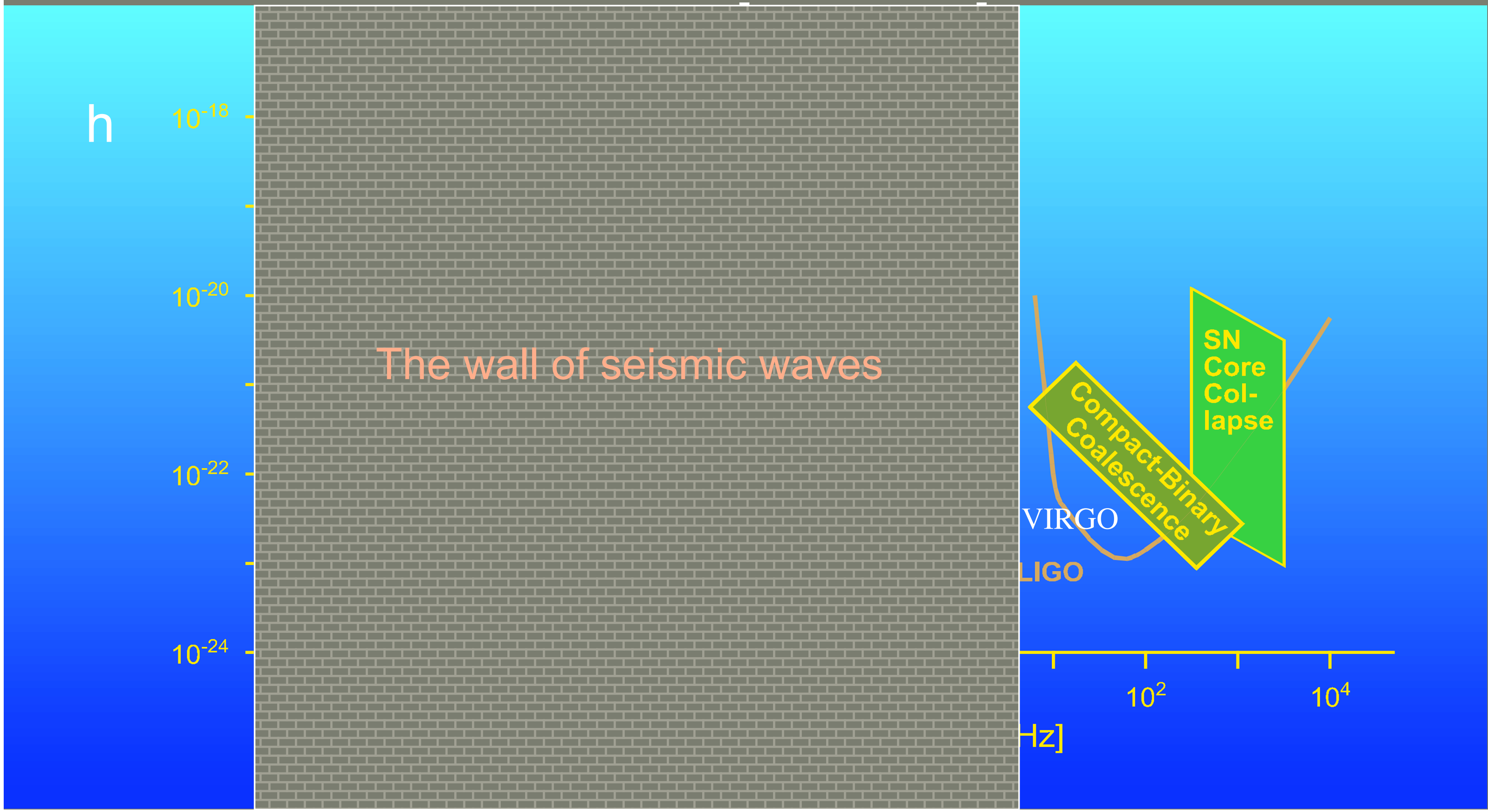
Virgo interferometer near Pisa

Size = 3 km

How to obtain the 3000 km necessary?



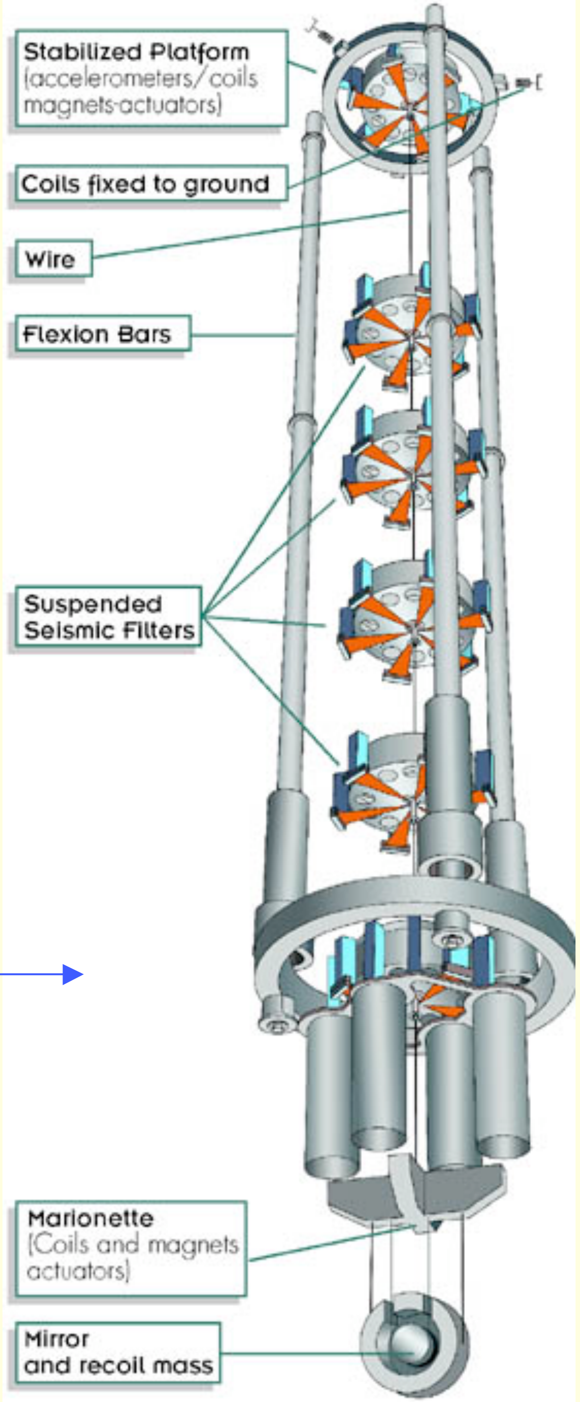
Sensitivity of ground detectors



How to escape as much as possible seismic waves?

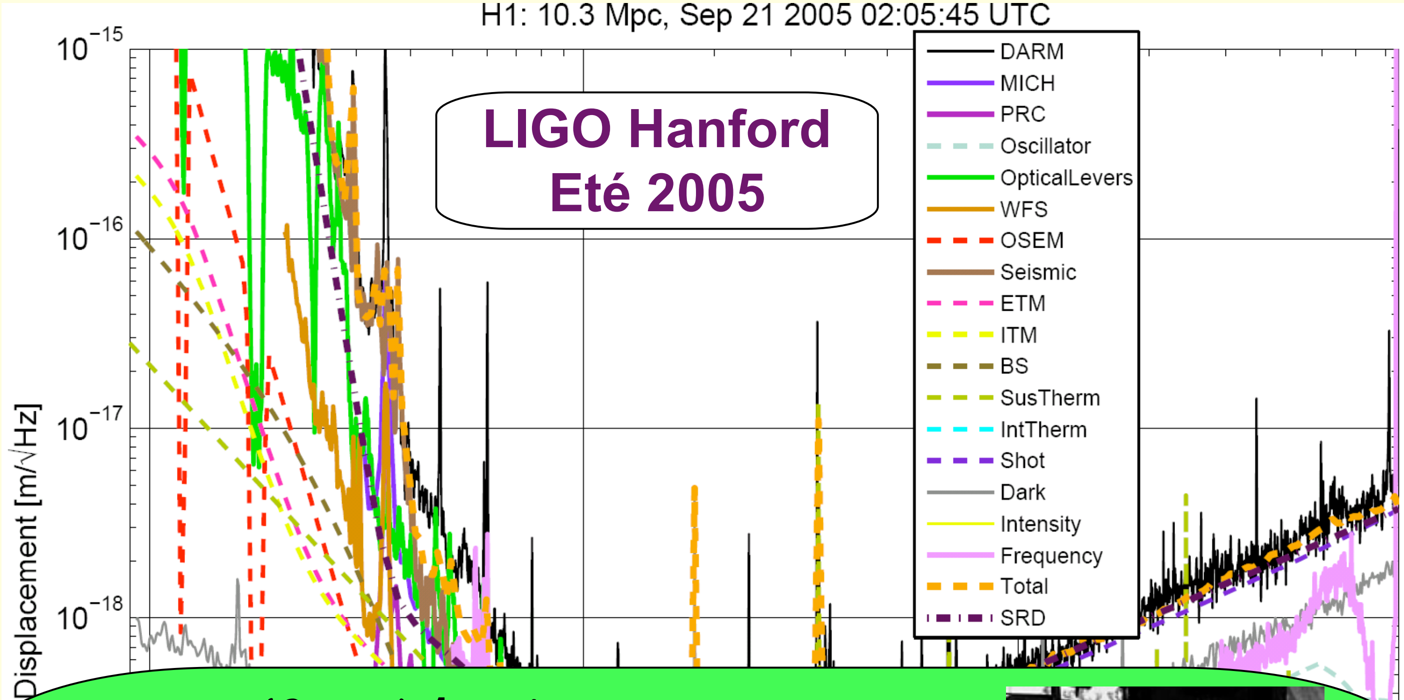
Suspend the interferometer

Virgo suspensions →



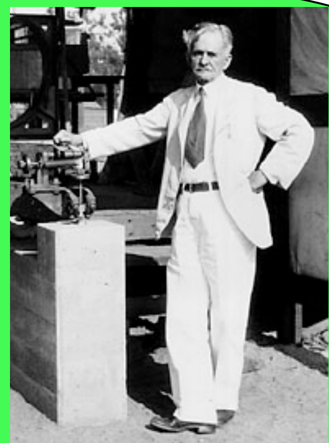
(ou put it underground)

Sensitivity to displacement of ground interférometers

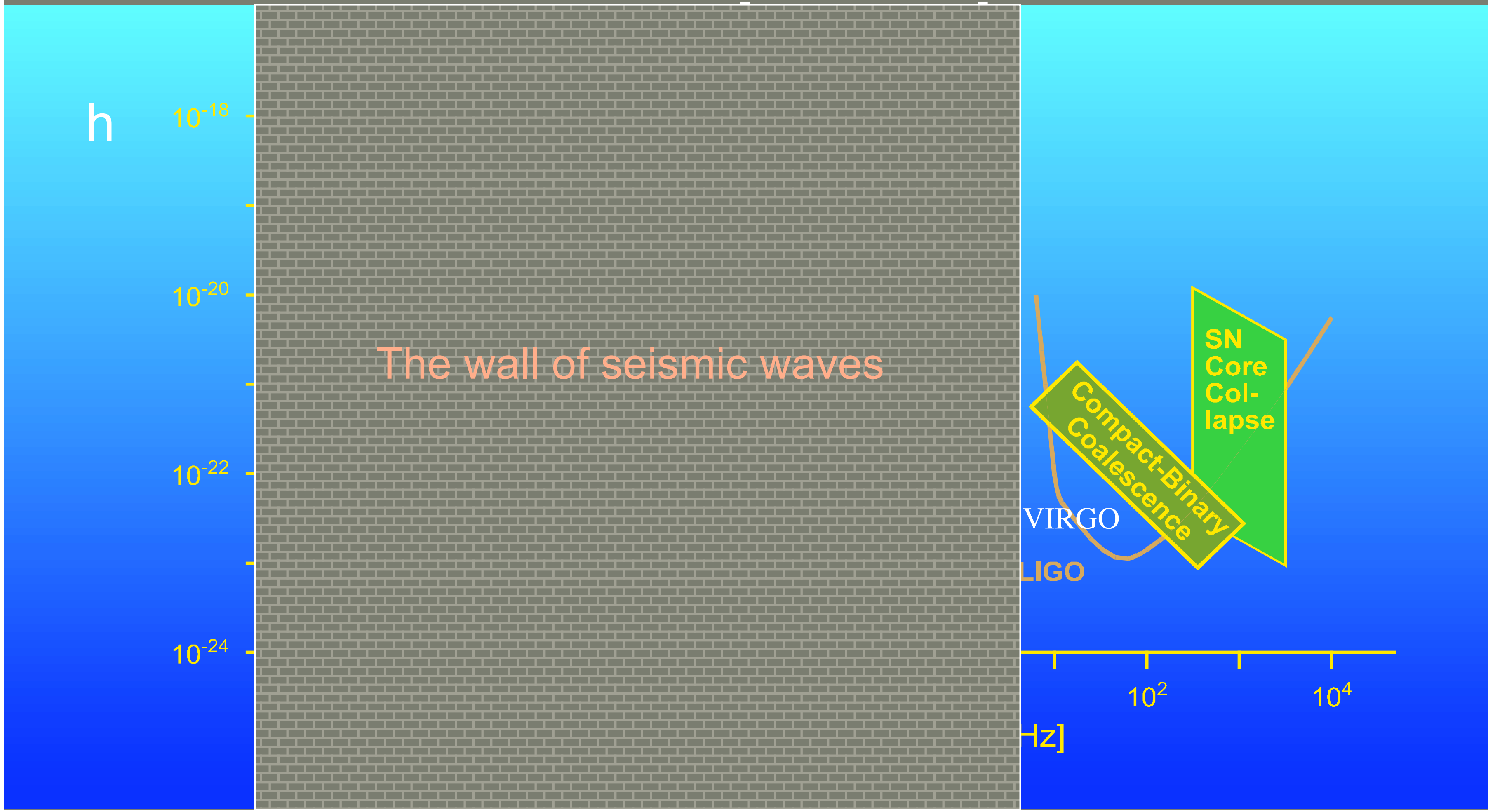


1 x 10 $^{-19}$ m/√Hz!

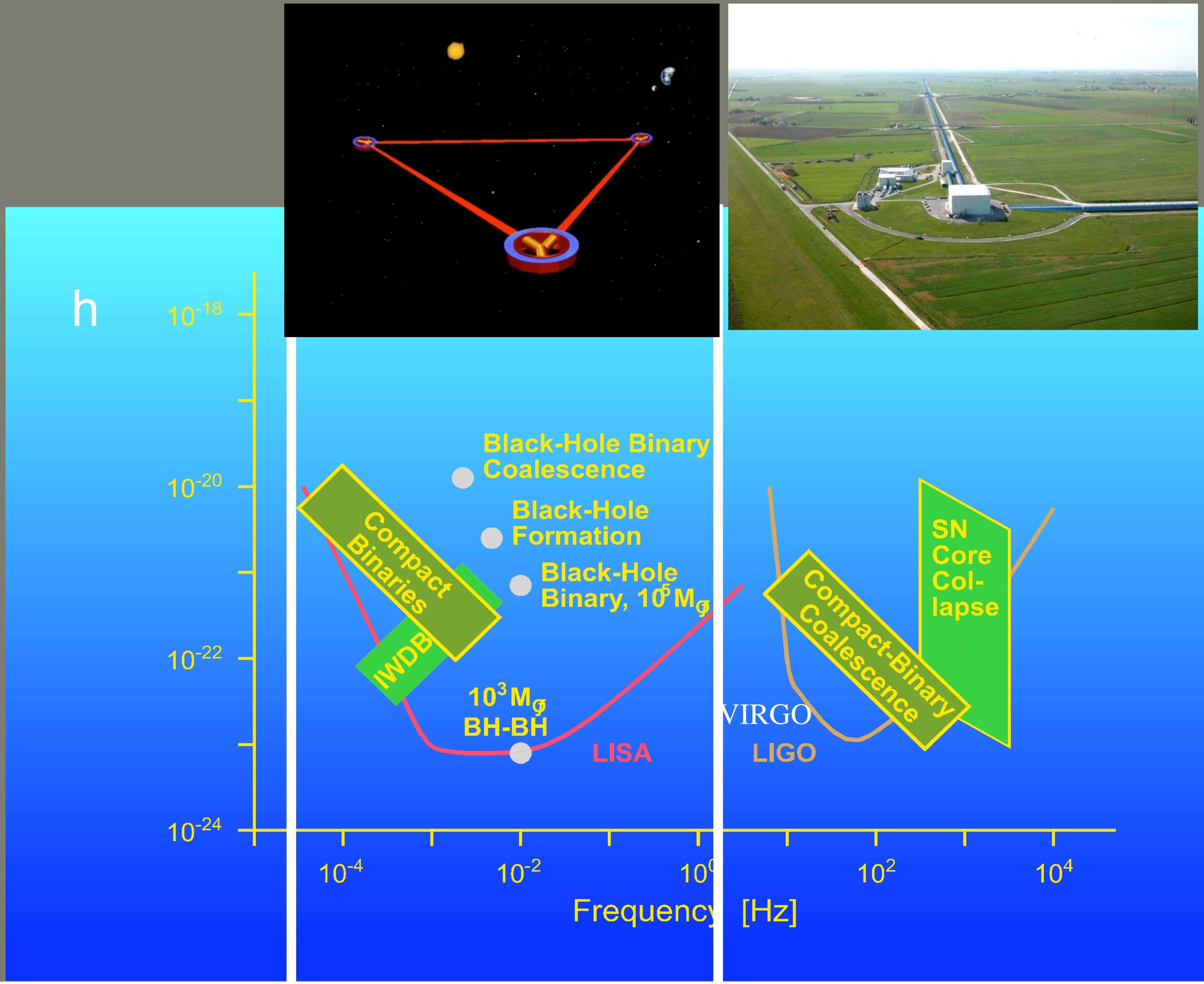
6 x 10^{9} times better than Michelson/Morley 1887!

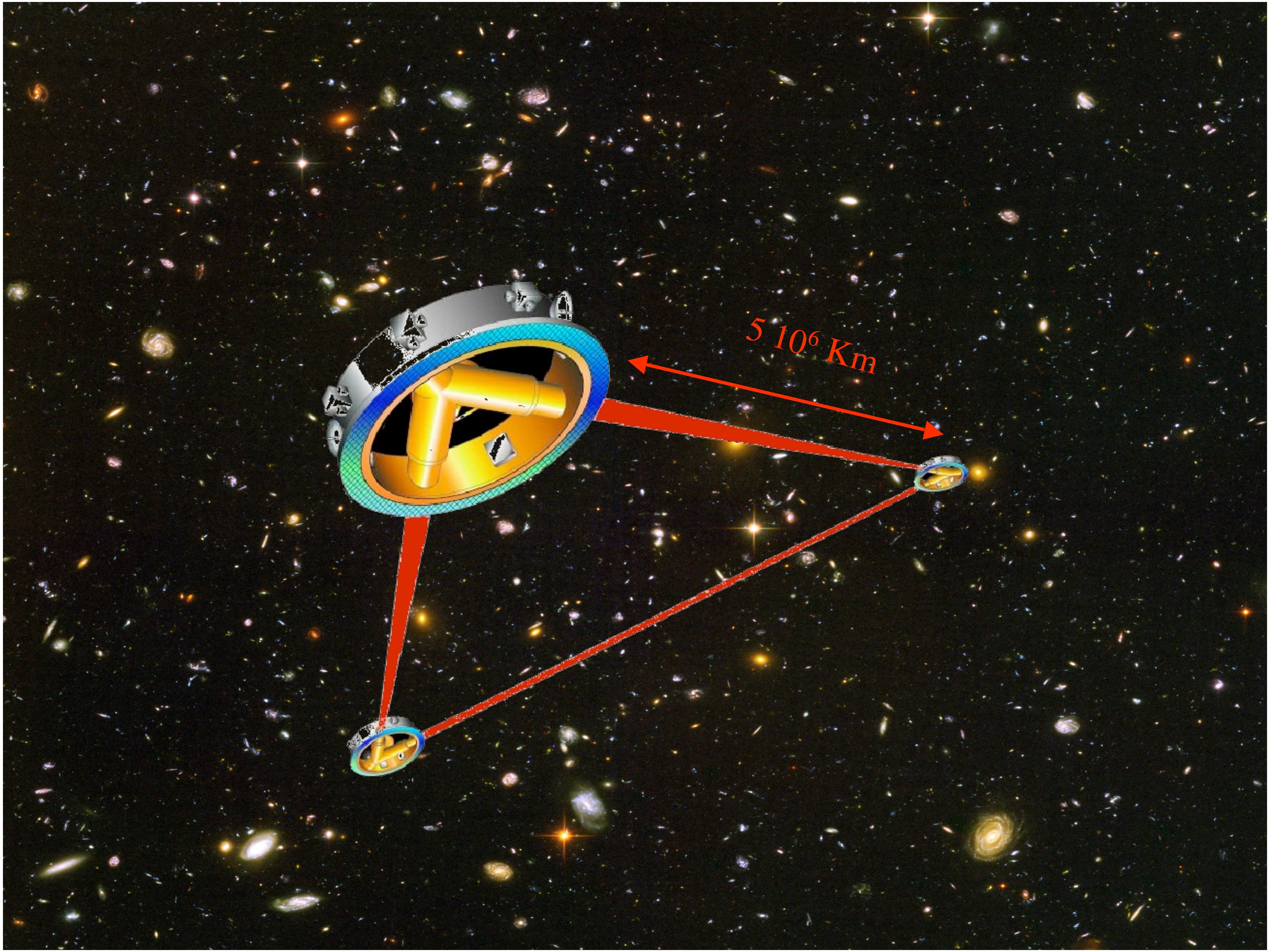


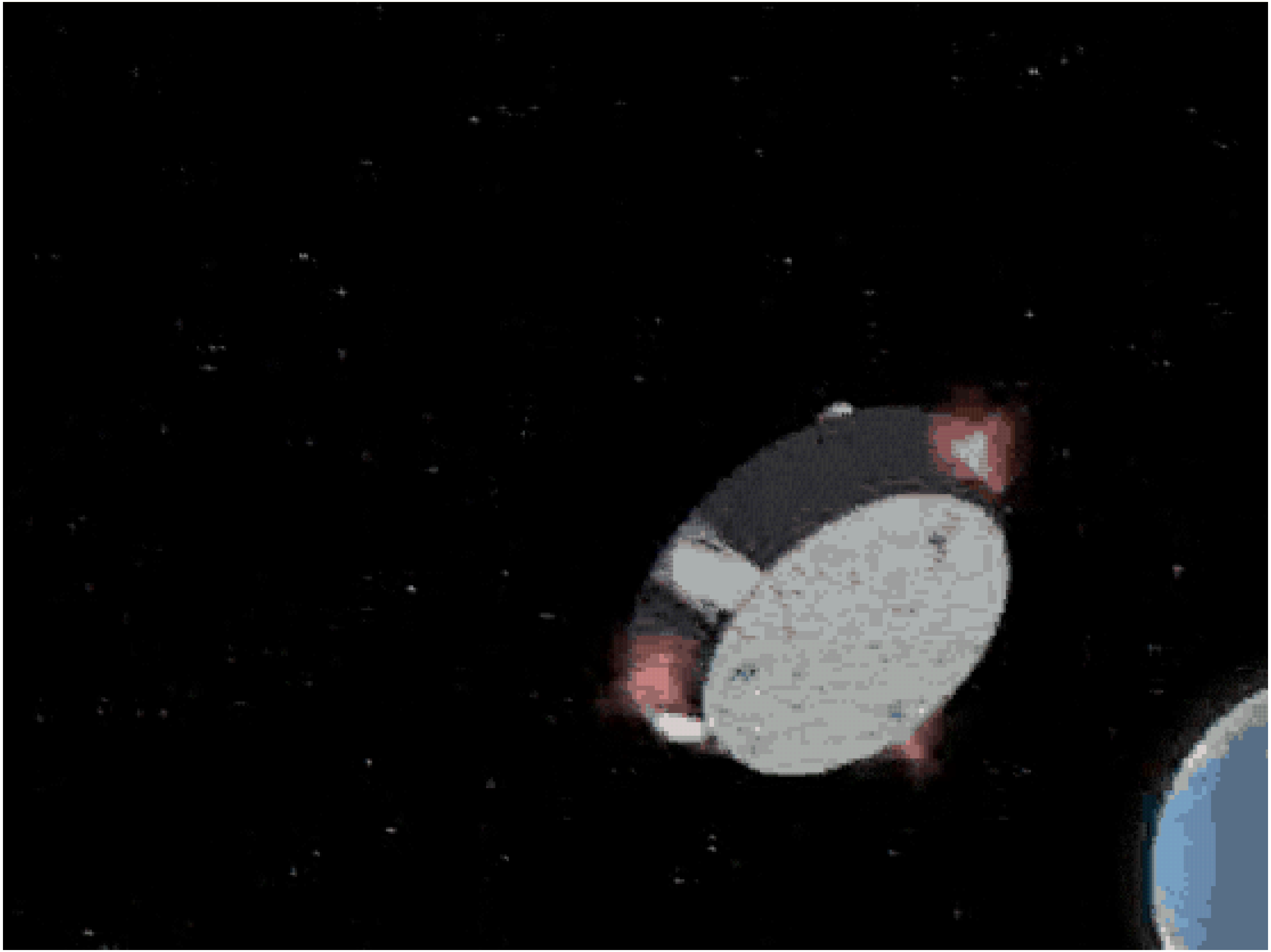
How to completely get away with the seismic wall?



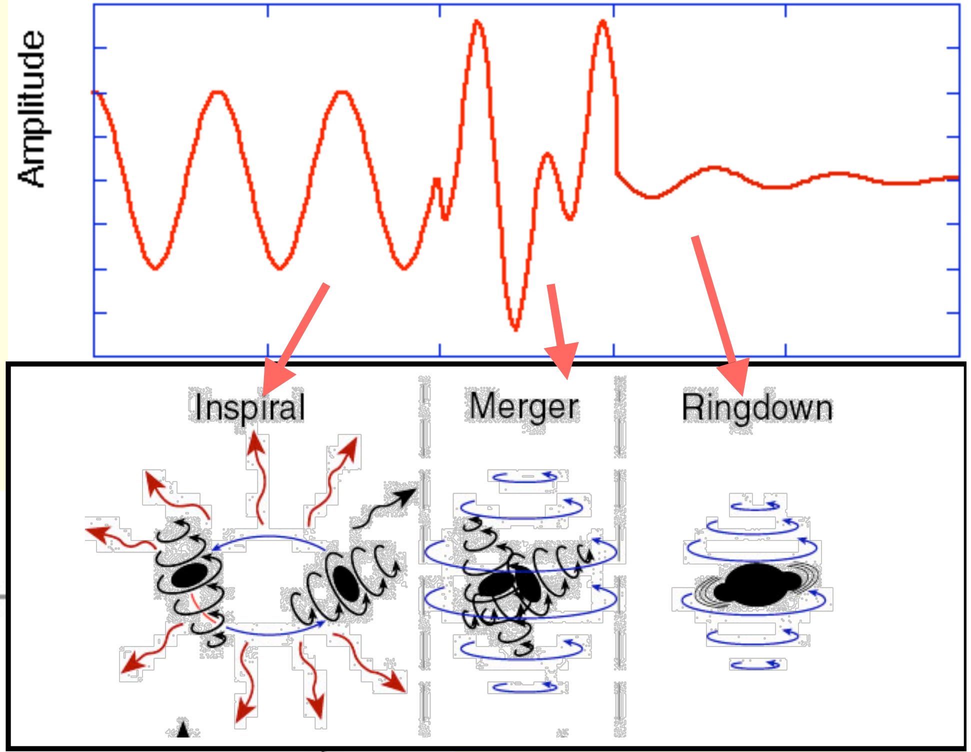
Go into space : LISA interferometer

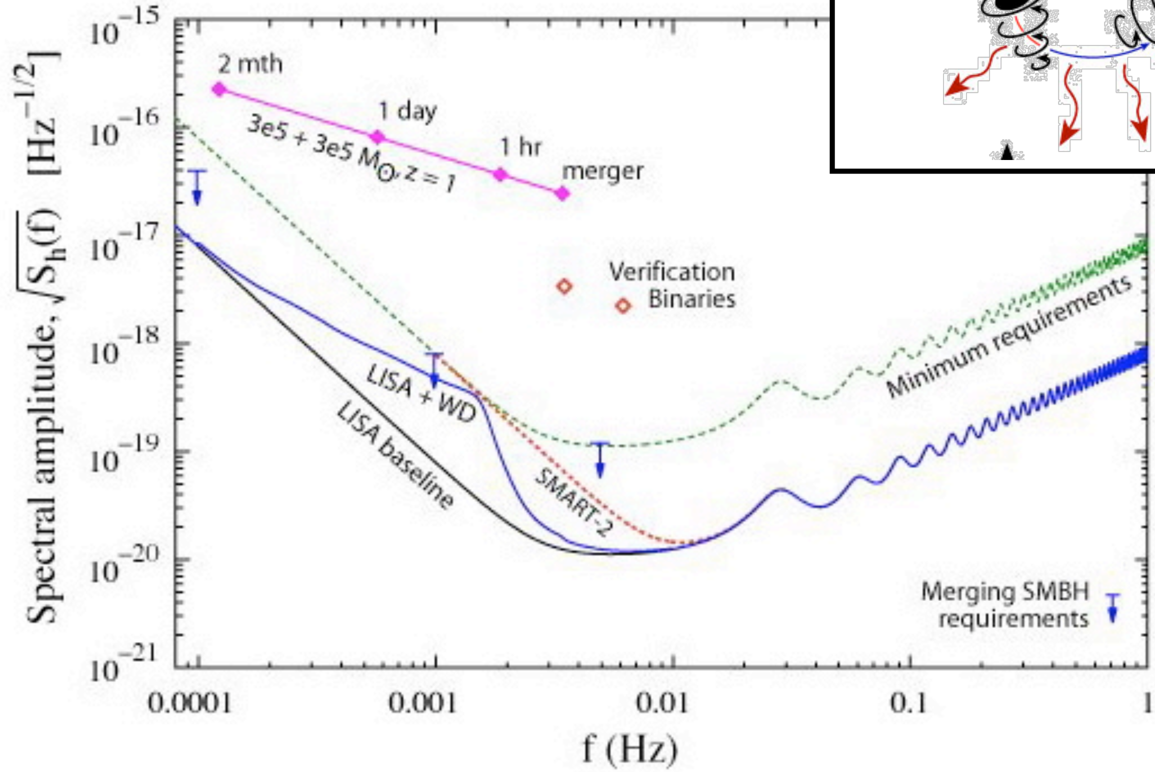



5 10^6 Km



Among the science open to LISA, one of the most remarkable events is the merger of two supermassive black holes during the collision of two galaxies.


Amplitude
Inspiral
Merger
Ringdown


Spectral amplitude, $\sqrt{S_h(f)}$ [$Hz^{-1/2}$]
f (Hz)
2 mth
1 day
1 hr
merger
3e5 + 3e5 $M_\odot$, z = 1
Verification
Binaries
Minimum requirements
LISA + WD
LISA baseline
SMART-2
Merging SMBH
requirements

4. Supernova explosions

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

Classification of supernovae according to spectroscopy:

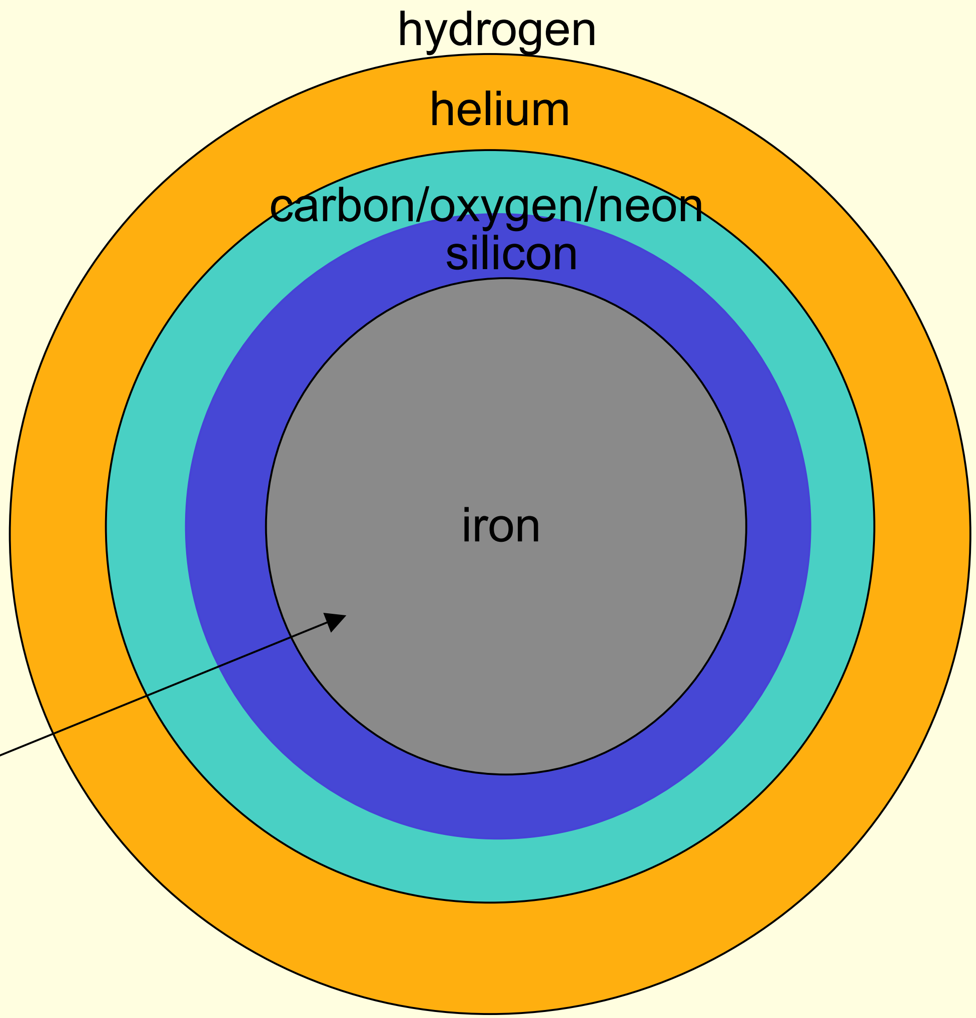
I : Hydrogen lines are absent

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

II : Hydrogen lines are present

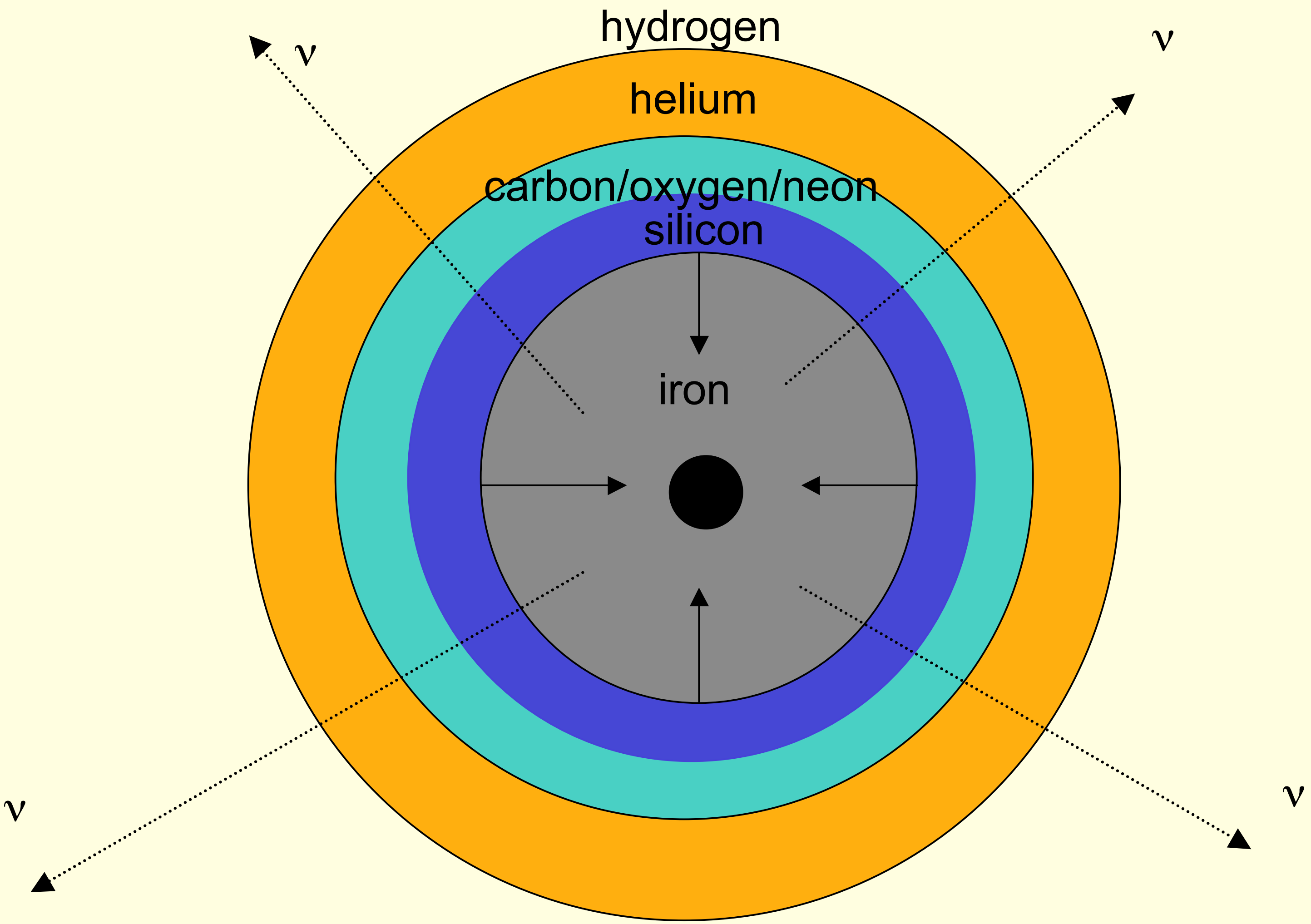
Supernovae of type II

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



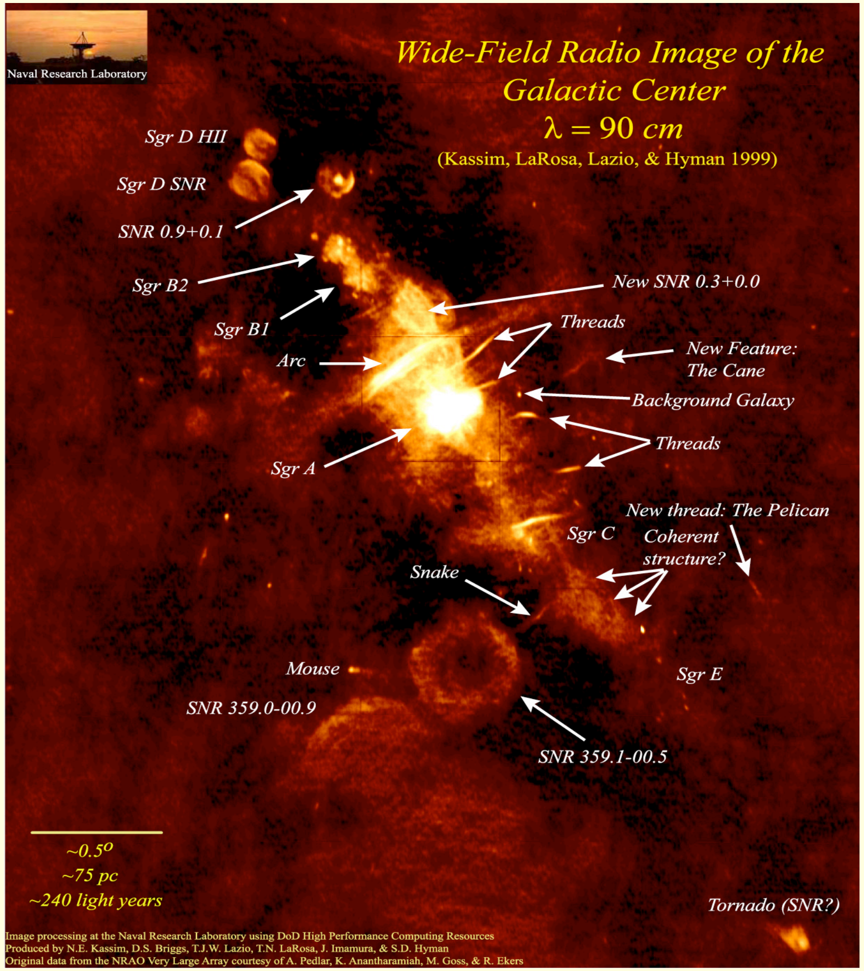
^{56}Fe (26p+30n)
lies at the bottom of
the valley of stability

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.

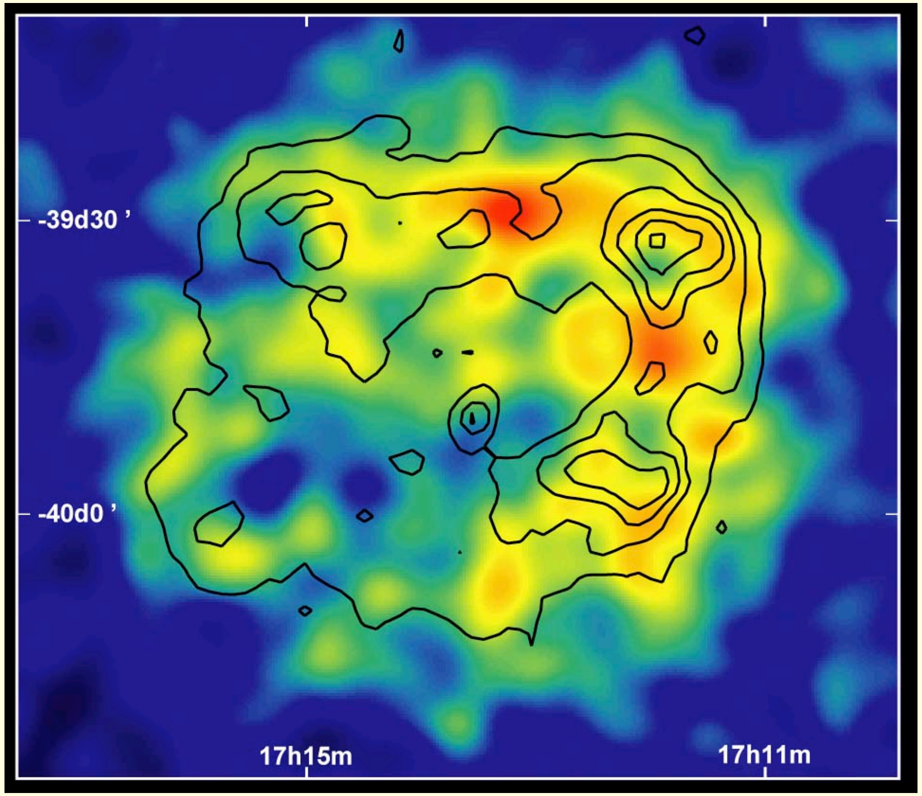


[redacted]

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
Sgr A
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
SNR 359.0-00.9
Sgr E
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



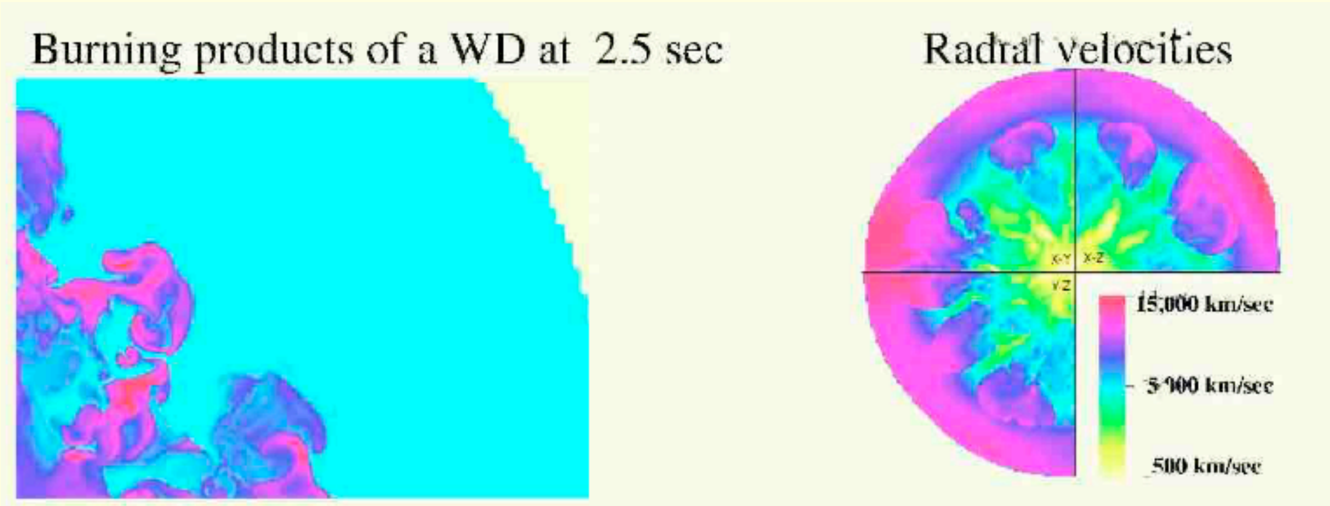
-39d30 '
-40d0 '
17h15m
17h11m

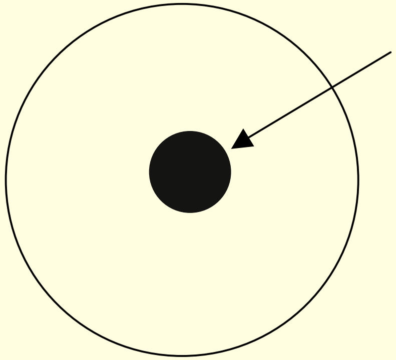
HESS

Supernovae of type Ia

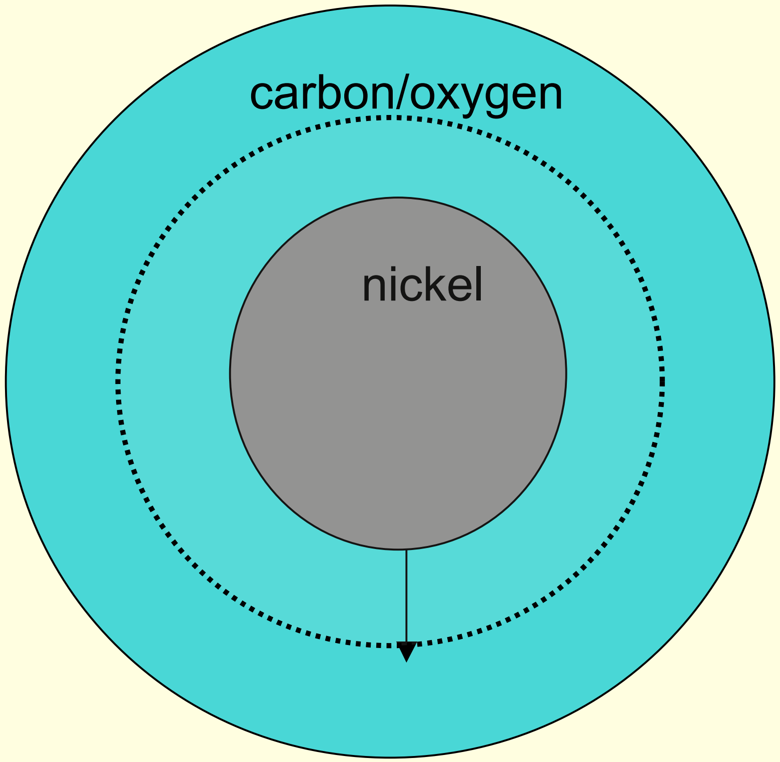
Thermonuclear explosion of white dwarfs:

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)

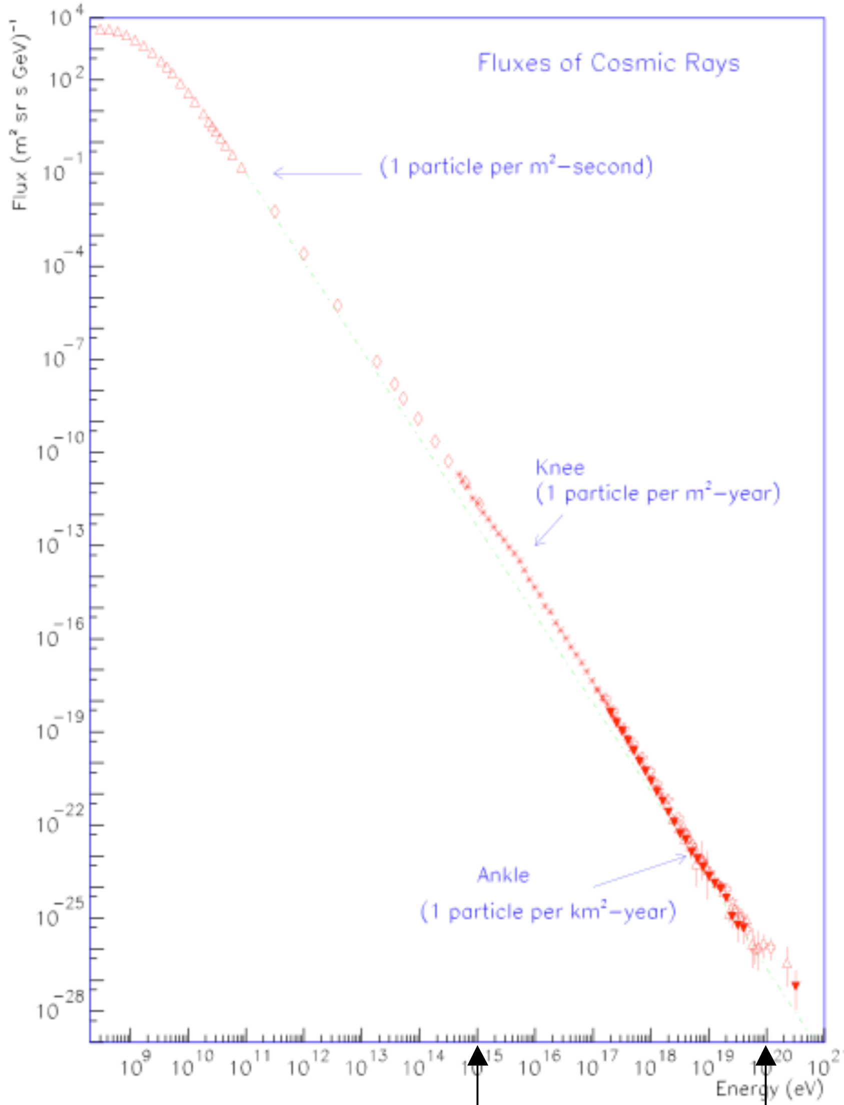
5. Cosmic rays and cosmic acceleration

Flux of cosmic rays vs energy

($m^{-2}s^{-1}sr^{-1}GeV^{-1}$) (eV)

Flux $\propto E^{-3}$

Single origin for the acceleration?



One easily obtain a power law spectrum $E^{-\gamma}$ if the particles have many encounters where they increase their energy.

A technical transparency

One easily obtain a power law spectrum $E^{-\gamma}$ if the particle have many encounters where they increase their energy.

Proof If a test particle of energy E_0 acquires a fraction ξ of its energy at each encounter, then after n encounters:

$$E_n = E_0(1+ \xi)^n$$

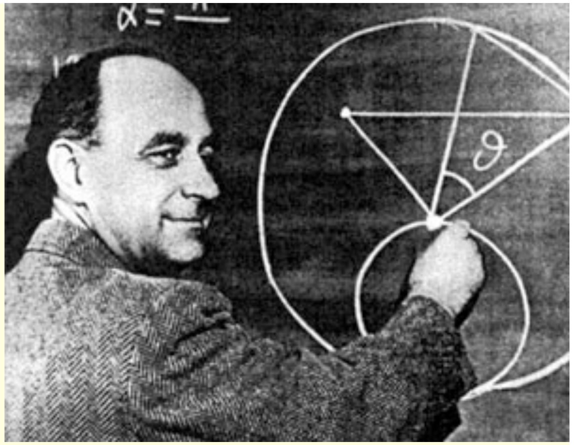
i.e. n encounters necessary to accelerate the particle to energy E: $n = \dfrac{\ln(E/E_0)}{\ln(1+ \xi)}$

Define $\mathcal{P}_{esc}$ as the probability to escape the acceleration region per encounter, $(1- \mathcal{P}_{esc})^k$ is the probability of remaining in the region after k encounters and the number of particles accelerated beyond energy E is

$$N(>E) \propto \sum_{k=n}^{\infty} (1- \mathcal{P}_{esc})^k = (1- \mathcal{P}_{esc})^n / \mathcal{P}_{esc}$$

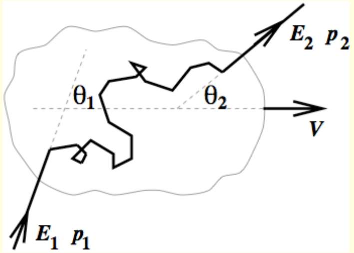
$$N(>E) \propto \frac{1}{\mathcal{P}_{esc}} \left(\frac{E}{E_0} \right)^{\alpha}$$

$$\alpha \equiv - \frac{\ln(1- \mathcal{P}_{esc})}{\ln(1+ \xi)} \sim \frac{\mathcal{P}_{esc}}{\xi}$$

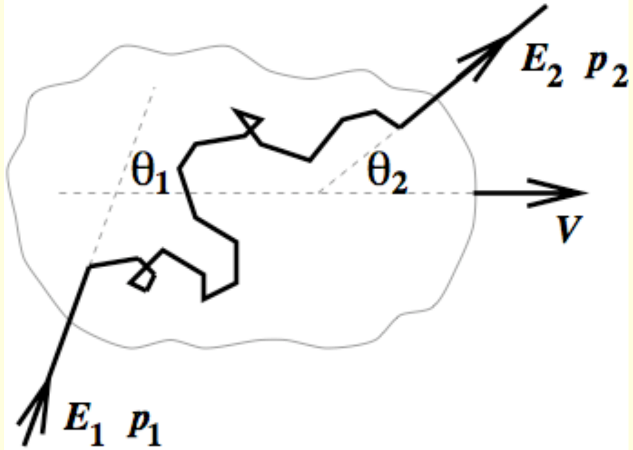


Fermi mechanism

Fermi (1949) proposes that cosmic rays are accelerated by scattering off magnetized clouds



A technical transparency



Consider in the lab frame an ultra-relativistic cosmic ray of energy E_1 and momentum $p_1 = E_1/c$

In the cloud frame

$$E'_1 = \gamma E_1 (1 - \beta \cos\theta_1)$$

$$\beta = V/c$$

$$\gamma = 1/\sqrt{1-\beta^2}$$

Because scattering is collisionless in the cloud, the final energy E'_2 is equal to E'_1

Back to the lab frame $\quad E_2 = \gamma E'_2 (1 + \beta \cos\theta'_2)$

Then $\quad \xi = \dfrac{\Delta E}{E} \equiv \dfrac{E_2 - E_1}{E_1} = \dfrac{1 - \beta\cos\theta_1 + \beta\cos\theta'_2 - \beta^2 \cos\theta_1 \, \beta\cos\theta'_2}{1 - \beta^2} - 1$

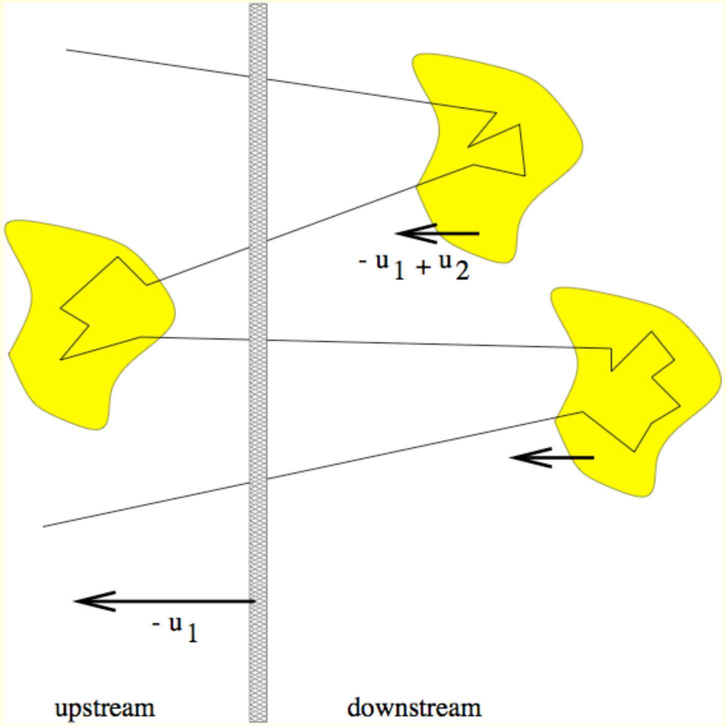
Since $\quad \dfrac{d\mathcal{P}}{d\cos\theta_1} = \dfrac{c - V\cos\theta_1}{2c} \qquad \langle \cos\theta_1 \rangle = -\beta/3$

$$\frac{d\mathcal{P}}{d\cos\theta'_2} = \text{cst} \qquad \langle \cos\theta'_2 \rangle = 0$$

$\xi \sim \beta^2/3$

2nd order Fermi mechanism

Because the second order is too small, alternate model where the particle multiply crosses a shock front such as induced by supernova explosions.



$\xi \sim 4\beta/3$

1st order Fermi mechanism

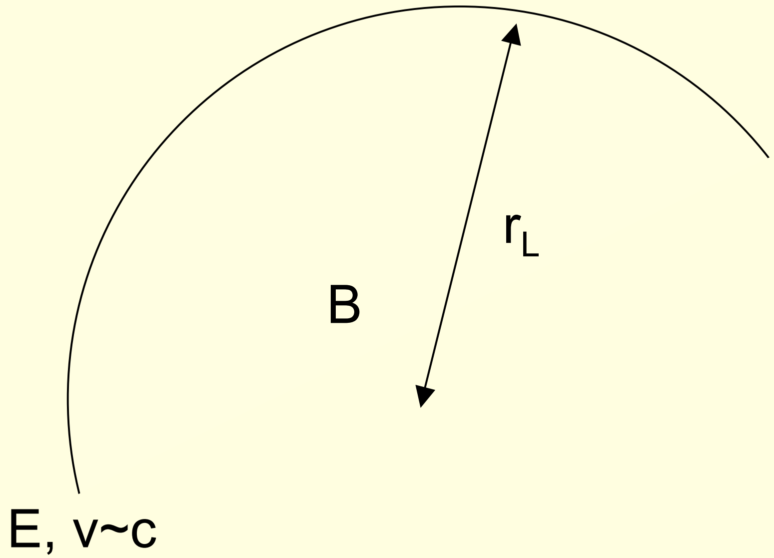
A complementary view of acceleration sites: Hillas diagram

A particle may not stay for ever in an acceleration site

e.g. in a large magnetic field

Larmor radius:

$r_L = E/(qBc)$



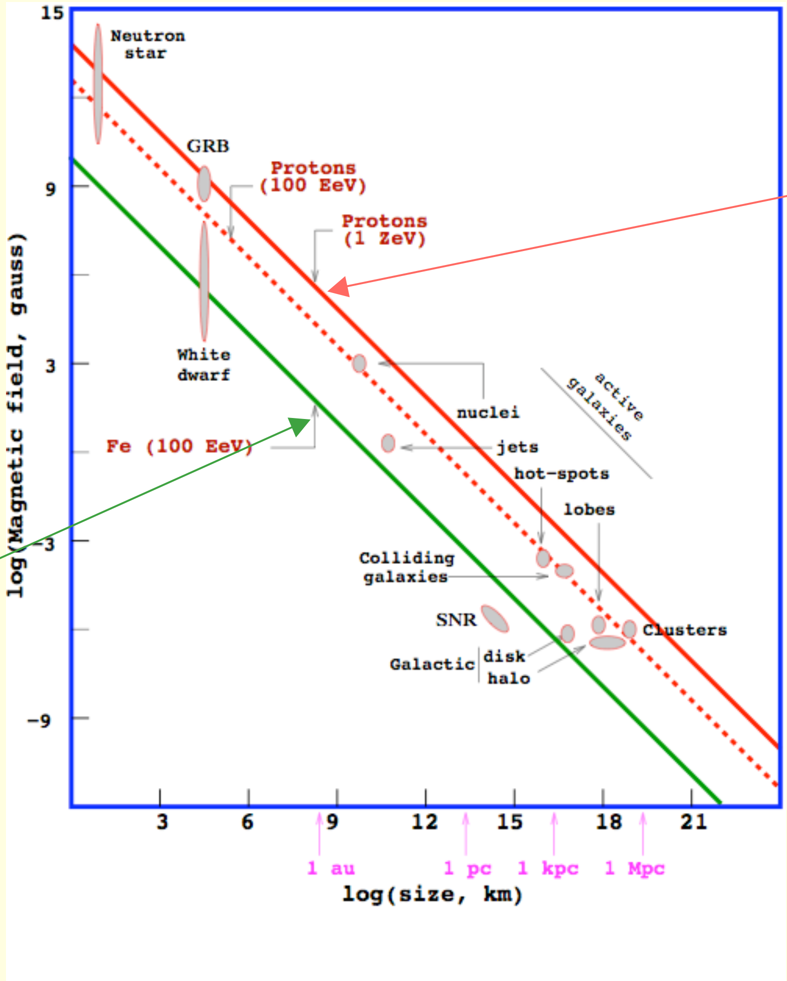
When the energy E increases, r_L may become larger than the size R of the accelerating site.

$$E < E_{max} = qBcR = Z \frac{B}{1\mu G} \frac{R}{1Mpc} 9.3\times10^{20}eV$$

q=Ze

Hillas diagram

log(B/1Gauss)



p accelerated to $E_{max} = 10^{21}$eV

Fe accelerated to $E_{max} = 10^{20}$eV

log(R/1km)

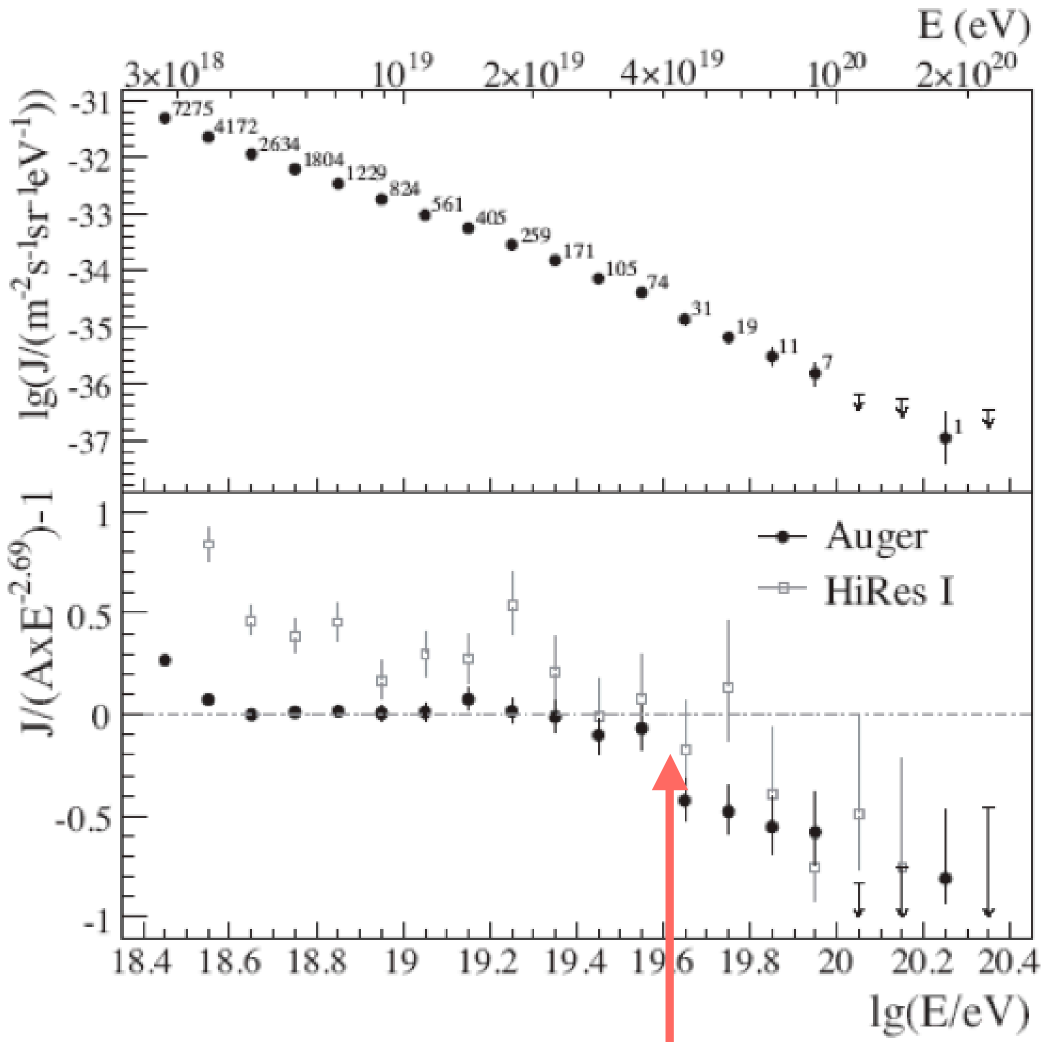
The Greisen-Zatsepin-Kuzmin (GZK) effect

Protons of the highest energy (around 10^{20} eV) interact with the photons of CMB

$$p\gamma \rightarrow pe^+e^-$$
$$p\gamma \rightarrow \pi N$$

The Universe is opaque to such protons.

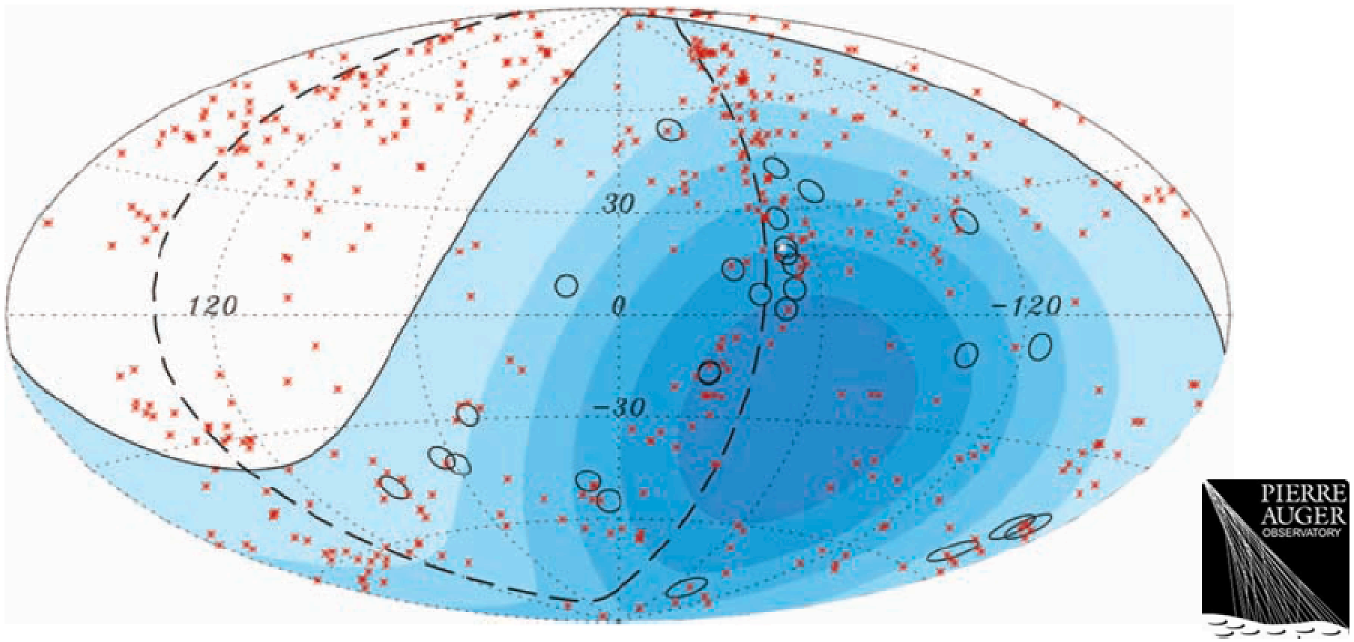
Protons of the highest energy observed on Earth can only come from its vicinity (sources not further than 100 Mpc).



[PRL 101 (2008) 061101,arXiv:0806.4302]

Observation by Auger of anisotropies for the cosmic rays of the highest energy?

→ Necessary to have more statistics to identify the sources



[Science 318 (2007) 939-943, arXiv:0711.2256]