Astroparticle physics

Pierre Binétruy
APC, Paris

CERN Summer Student Lecture Programme 2010

What is particle astrophysics?

What is physics?

What is physics?

Oxford dictionary :

Physics, *plural noun* [treated as singular] :
the branch of science concerned with the nature and properties of matter and energy.

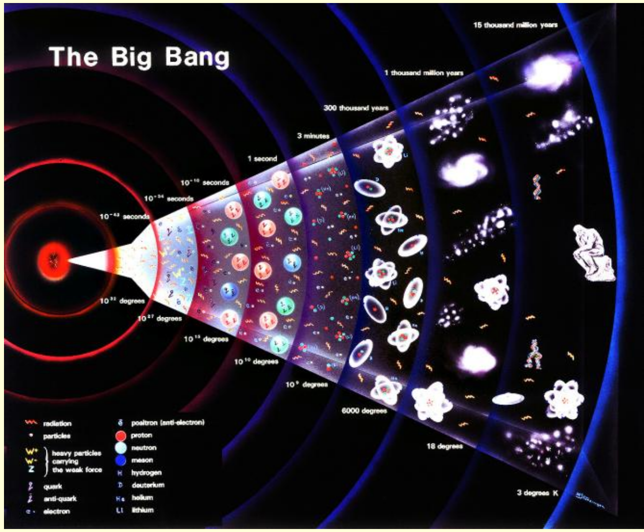
What is particle astrophysics?

Particle astrophysics :
the branch of science concerned with the nature and fundamental properties of matter and energy in the Universe.

Many different aspects:

- The early Universe a a particle physics laboratory

In the big bang theory, the early Universe is hot and dense



- The matter and energy content of the present Universe: dark and luminous matter, neutrinos, radiation, dark energy…

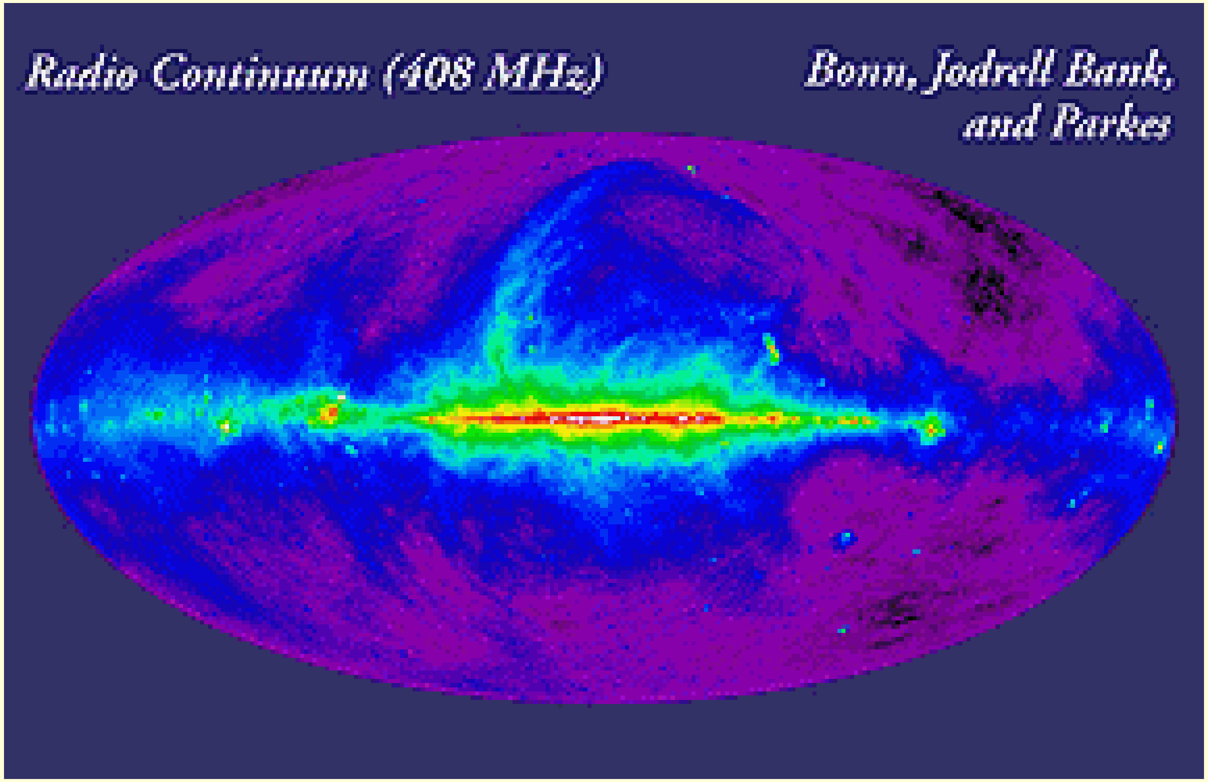
- Study of violent phenomena in the Universe : particles ejected provide a complementary signal to visible (or electromagnetic) observations

Astrophysics at the end of XXst century :

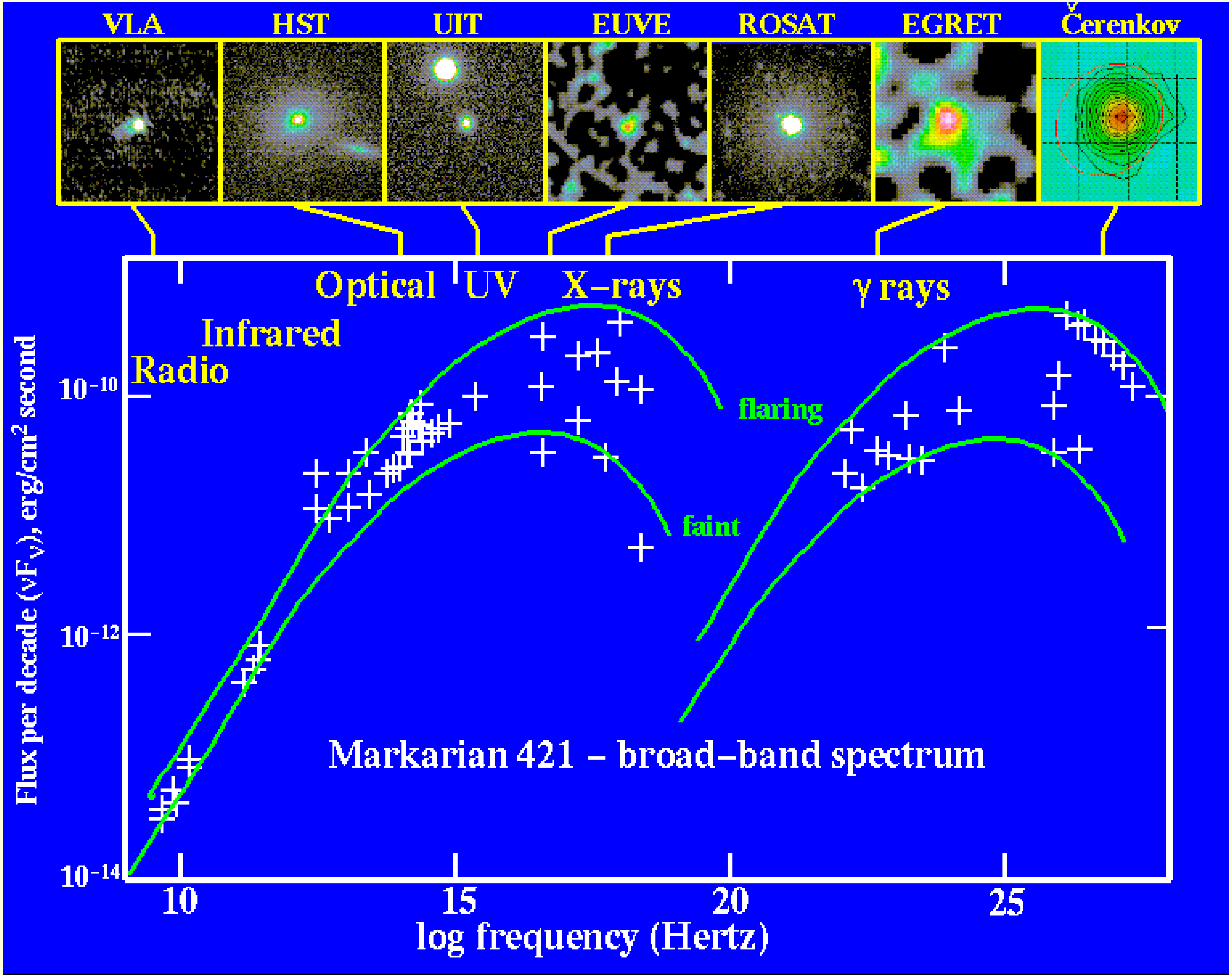
http://adc.gsfc.nasa.gov/mw

The milky way

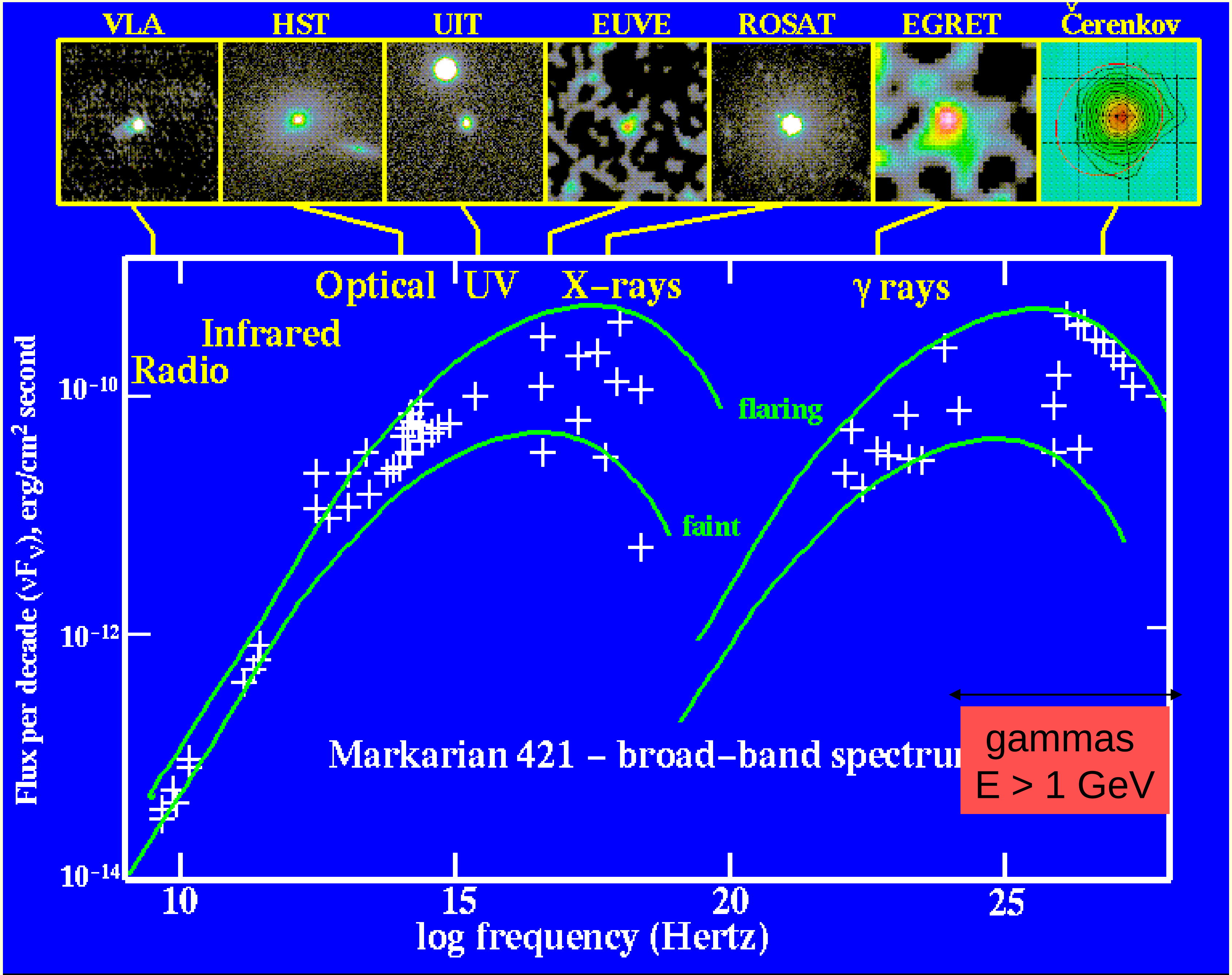
Astrophysics: a multi-wavelength strategy



A multi-wavelength strategy : the Ma 421 source



A multi-wavelength strategy : the Ma 421 source



gammas
E > 1 GeV

A multi-messenger strategy

Ideally, one would like to study the same source by detecting the photons, protons, neutrinos and gravitational waves emitted :

- high energy photons trace populations of accelerated particules, as well as dark matter annihilation
- protons provide information on the cosmic accelerators that have produced them
- neutrinos give information on the deepest zones, opaque to photons (e.g. on the origin --hadronic or electromagnetic-- of γ).
- gravitational waves give information on the bulk motion of matter in energetic processes

Outline of these lectures:

Chapter I The tools of the trade

Chapter II The violent universe

Chapter III The Universe at large

Astroparticle physics

I - The tools of the trade

Pierre Binétruy
APC, Paris

CERN Summer Student Lecture Programme 2010

Outline

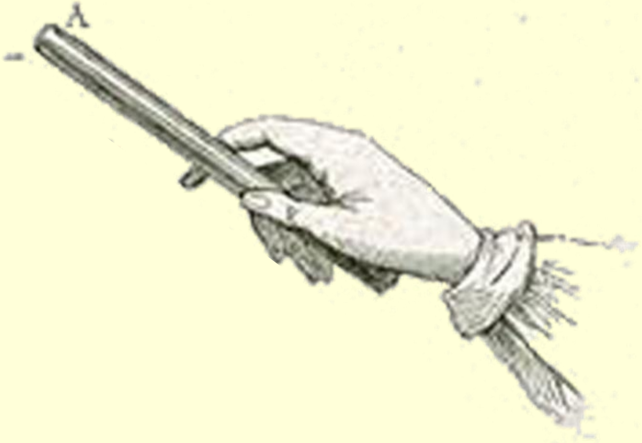
1. An extraterrestrial radiation
2. The light of particles
3. Detector Earth
4. Particle detectors in space
5. Underground: neutrinos and dark matter
6. Ripples of spacetime

1. An extraterrestrial radiation

1785

Coulomb

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.



1785 Coulomb

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

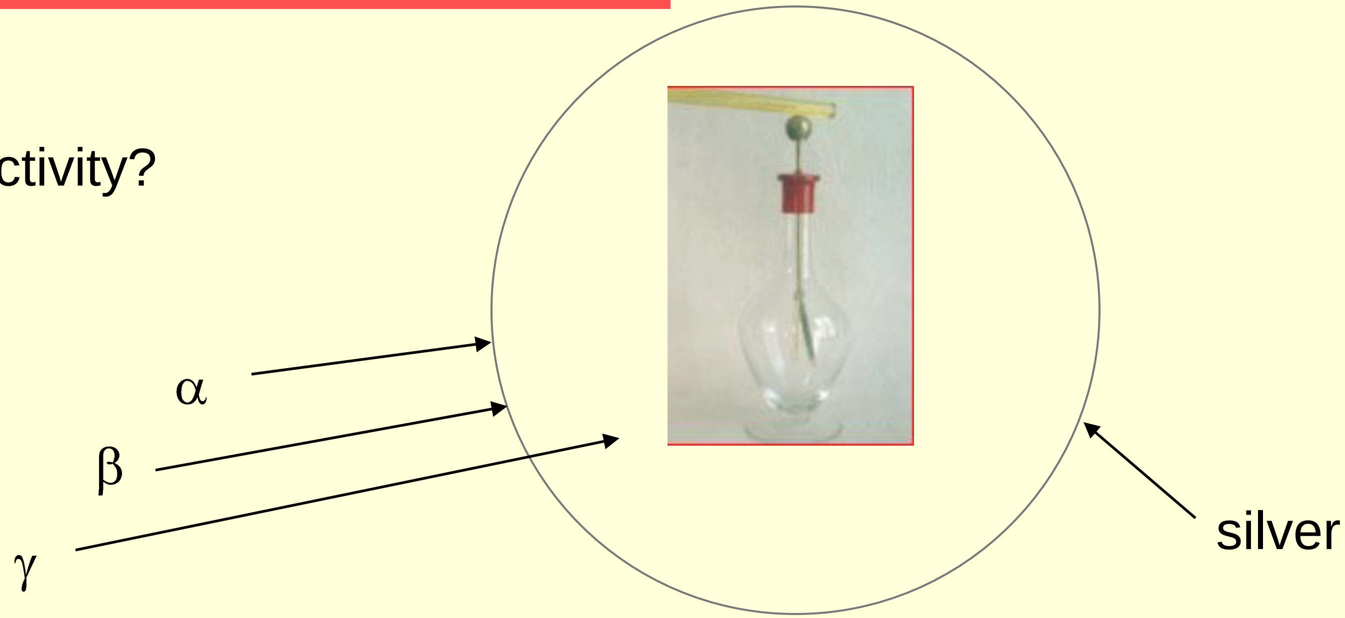
The electrometer discharges with time. Why?

Faraday : the air is a conductor because of ionisation

Molecules of air $\xrightarrow{\text{unknown radiation}}$ Ions

What is the nature of this radiation?

Radioactivity?

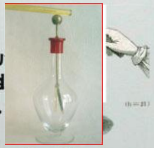


The cosmic adventure begins

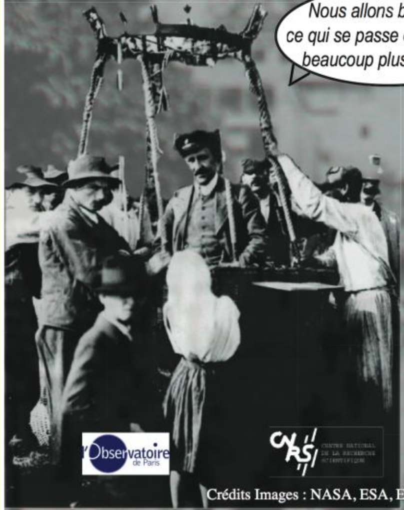
1[illegible]

In 1909, Theodore Wurtz who had developed an ultra-sensitive electroscope sets it up at the top of the Eiffel Tower…

Dans les laboratoires des physiciens au début du siècle, les électroscopes se déchargeaient de manière incompréhensible pendant la nuit..



En 1909, un jésuite allemand, le Père WULF (1[illegible]-1[illegible]), qui avait développé un électroscope ultra stable, l'installa en haut de la Tour Eiffel. Il constata alors que la diminution du taux de décharge de son électroscope était moindre que prévu si tout l'effet ionisant était dû à un rayonnement uniquement d'origine terrestre.



In 1912, Victor Hess climbs to an altitude of 4200 m to prove that the ionising radiation decreases with altitude: it has a cosmic origin

chute emp atu aute altitude .

Crédits Images : NASA, ESA, ESO, CNES, CEA, CNRS, OBSPM, APC, Droits réservés.

Millikan calls this radiation cosmic rays

Cosmic rays are neutral (gamma rays). This is why they are so penetrating

Cosmic rays are charged. This why they are so energetic. They can be accelerated by cosmic magnetic fields

QuickTime™ et un décompresseur sont requis pour visionner cette image.

QuickTime™ et un décompresseur sont requis pour visionner cette image.

1868-1953

Millikan - Compton controversy

Millikan calls this radiation cosmic rays

Cosmic rays are neutral (gamma rays). This is why they are so penetrating

Cosmic rays are charged. This why they are so energetic. They can be accelerated by cosmic magnetic fields

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

1868-1953

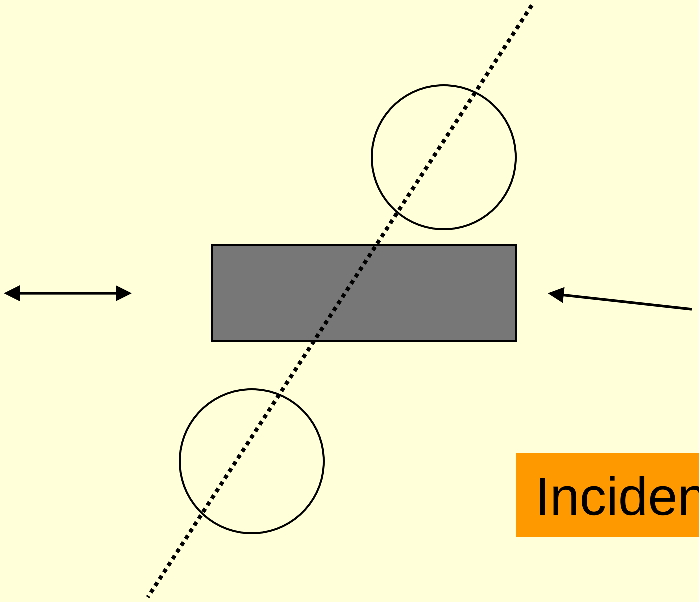
Millikan - Compton controversy

Solved by Jacob Clay on a trip from Genova to Java

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

Cosmic rays
are charged!

Geiger counter developped in 1912-1928 proved to be very useful for studying cosmic rays

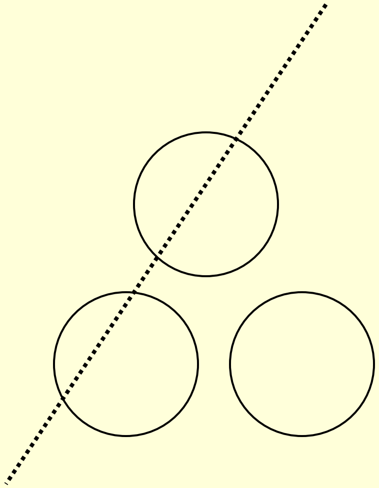


coincidence method

absorber makes no difference

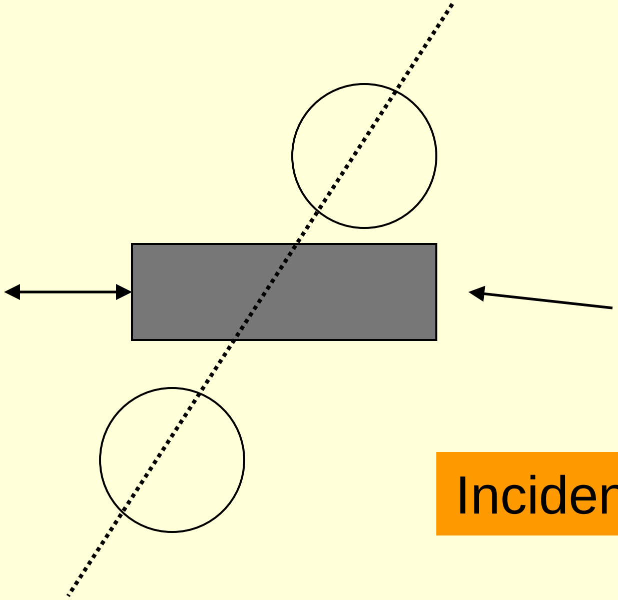
Incident particles come preferentially from the zenith

1933 Rossi



No single particle can hit
the three detectors

Geiger counter developped in 1912-1928 proved to be very useful for studying cosmic rays

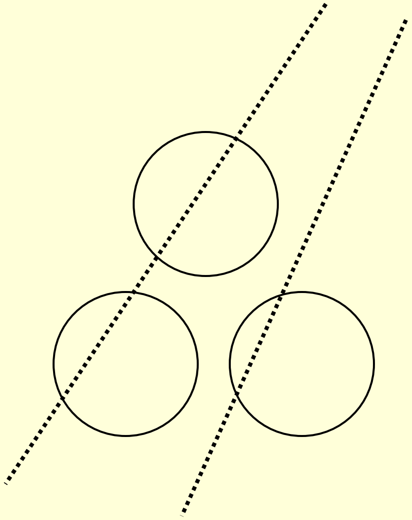


coincidence method

absorber makes no difference

Incident particles come preferentially from the zenith

1933 Rossi



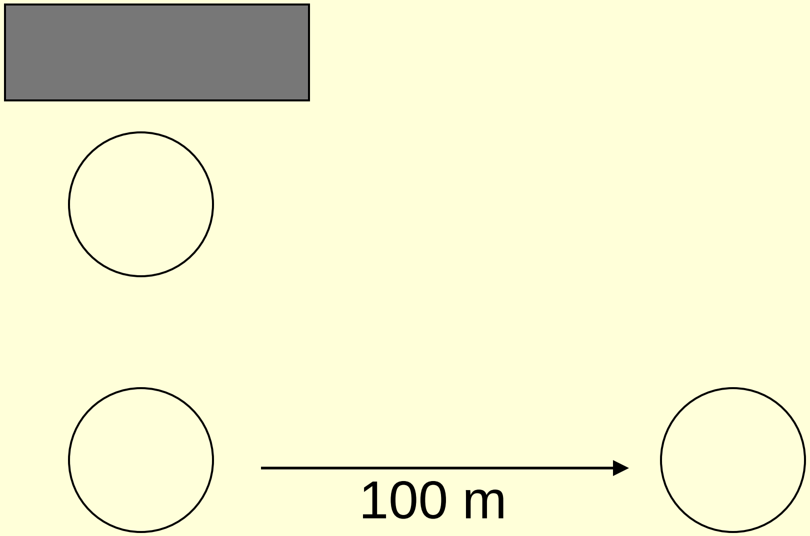
No single particle can hit
the three detectors

Triple coincidences are observed!

Several particles arrive in coincidence:
cosmic ray showers

In lates ‘30s, Pierre Auger and collaborators study these showers

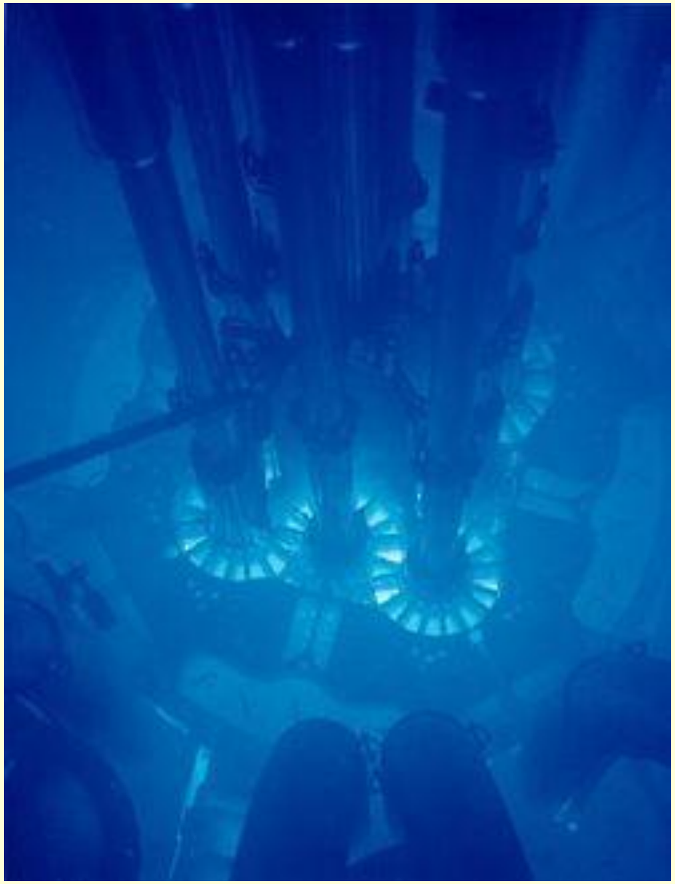
Jungfraujoch (alt. 3500m)



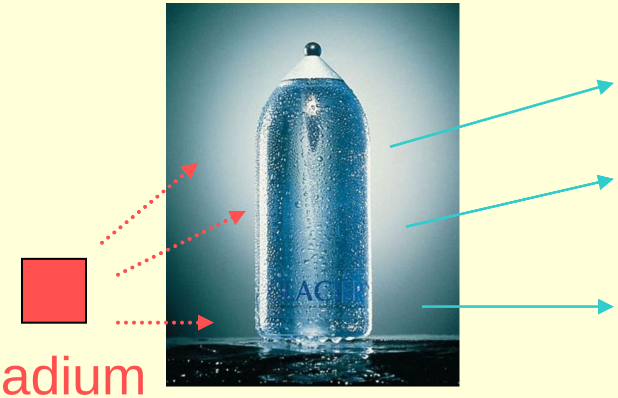
Energy of the primary particle can reach 10^{15} eV (1000 TeV)!

What is the source of such particles?

2. The light of particles



Early ‘30s, young Ph.D. student Pavel Cherenkov is asked to study this blue light



blue light

radium

Is this fluorescence?

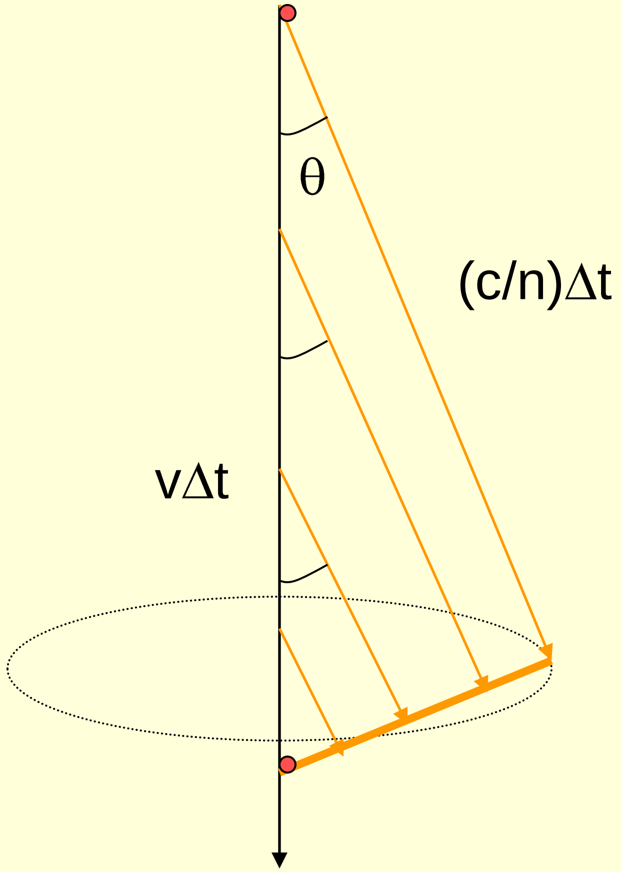
Fluorescence is associated with the emission of a photon by an excited molecule returning to its fundamental state.

Cherenkov: no, because the phenomenon does not depend on the type of liquid

1937, Frank and Tamm: a (light) shock wave due to the fact that the energetic particles travel at a velocity larger than the speed of light.

In a medium of index n, light travels at a speed c/n

Hence, particles can travel at velocity v > c/n

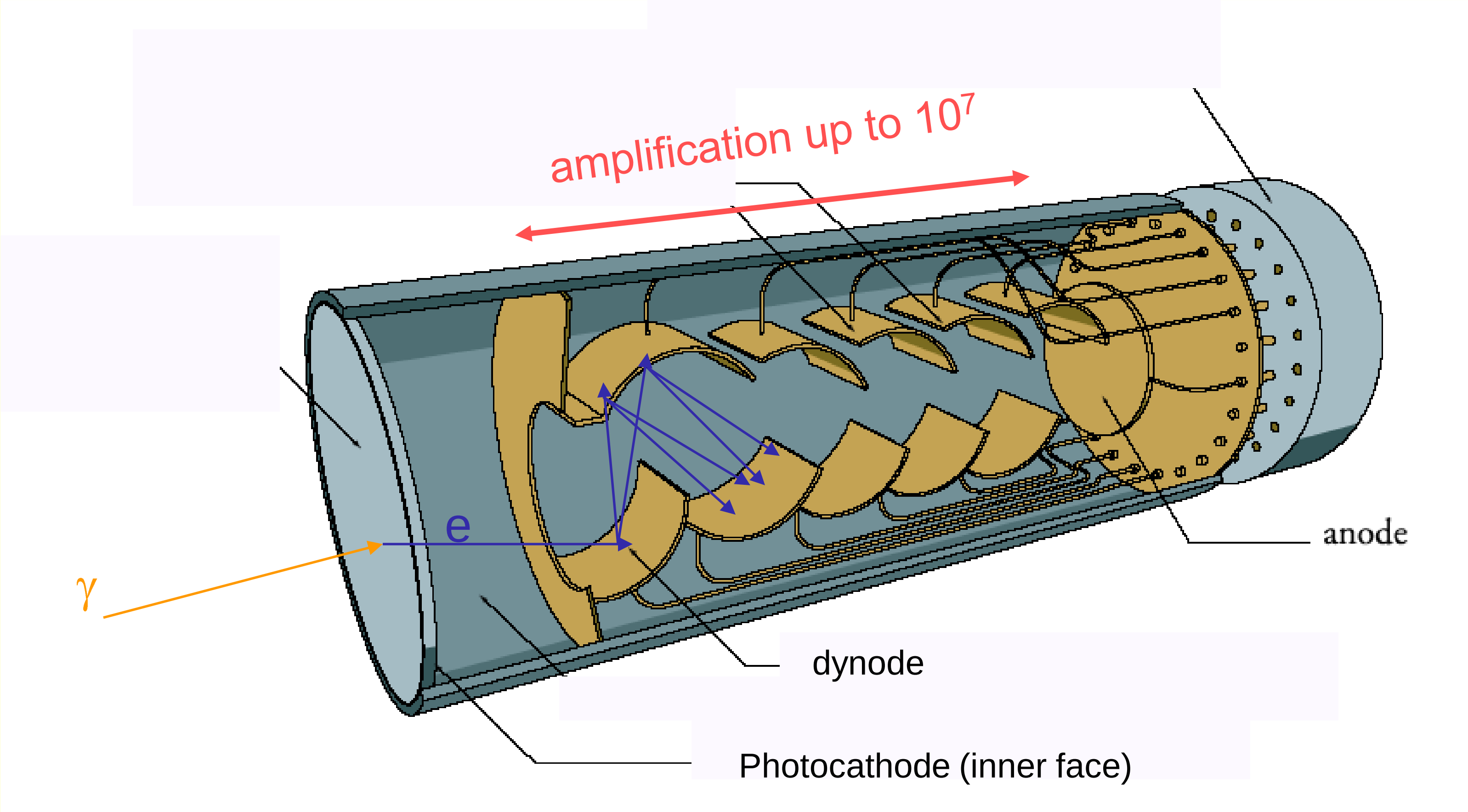


In direction θ, all light waves emitted successively by the particle interfere constructively :

$$\cos\theta = \frac{(c/n)}{v}$$

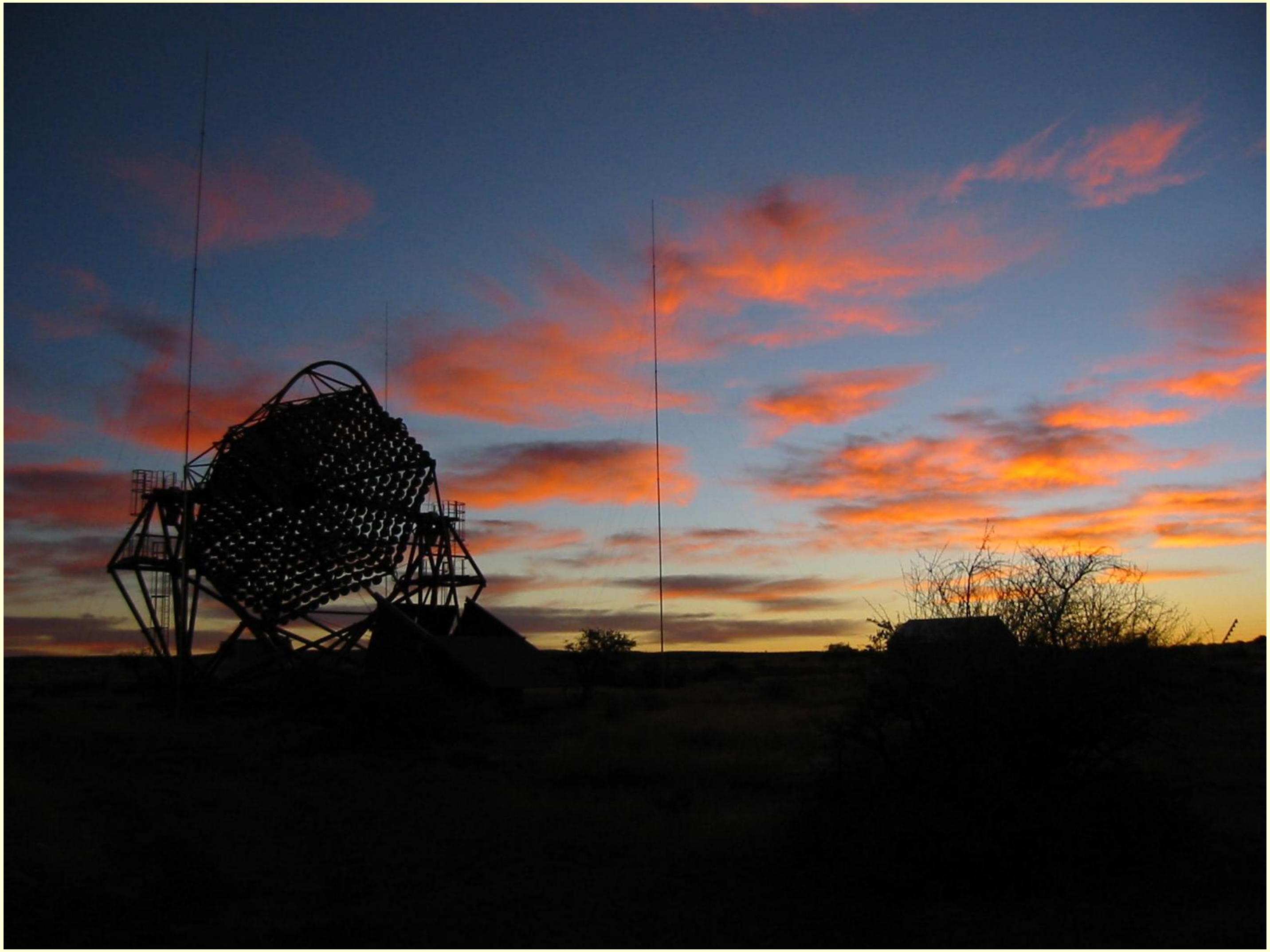
θ= 1° in air
42° in water

How to collect this light? Photomultipliers

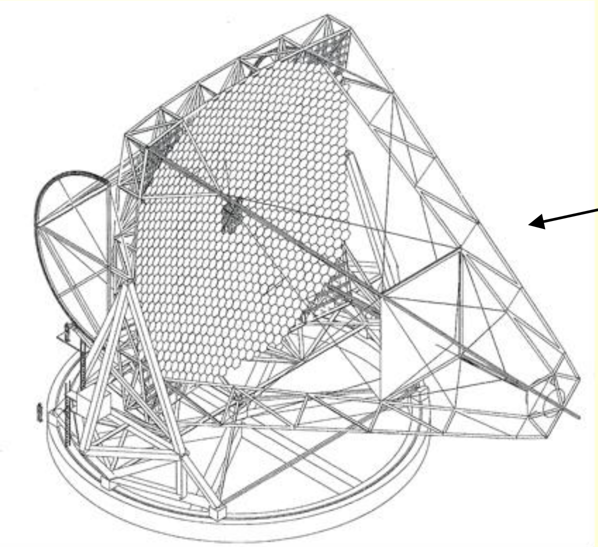


Examples of photomultipliers

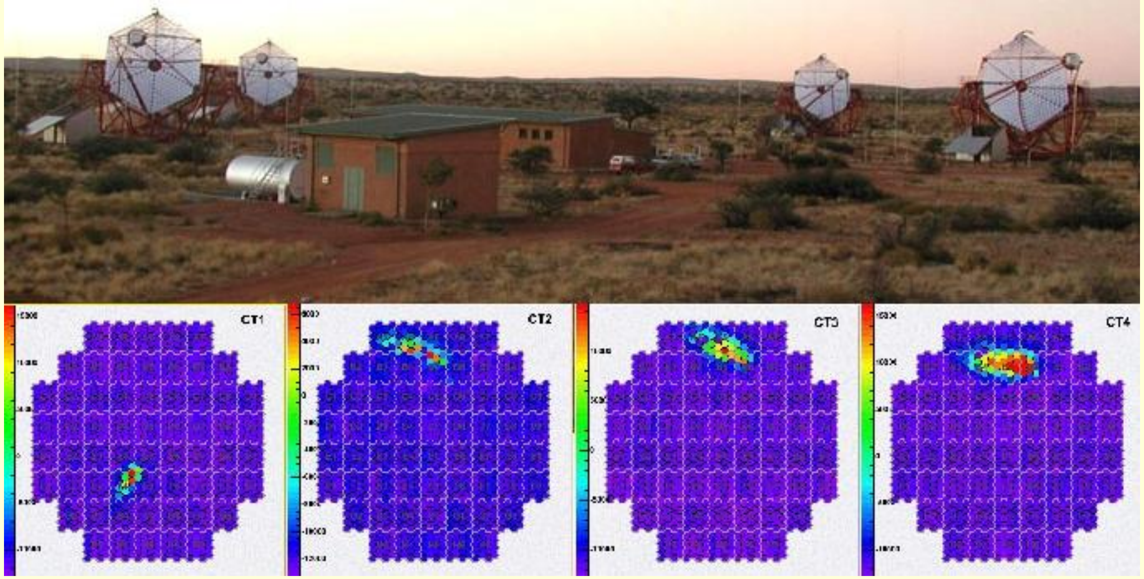
Detecting high energy gammas through their Cherenkov light:
the Cherenkov telescopes of the HESS experiment in Namibia



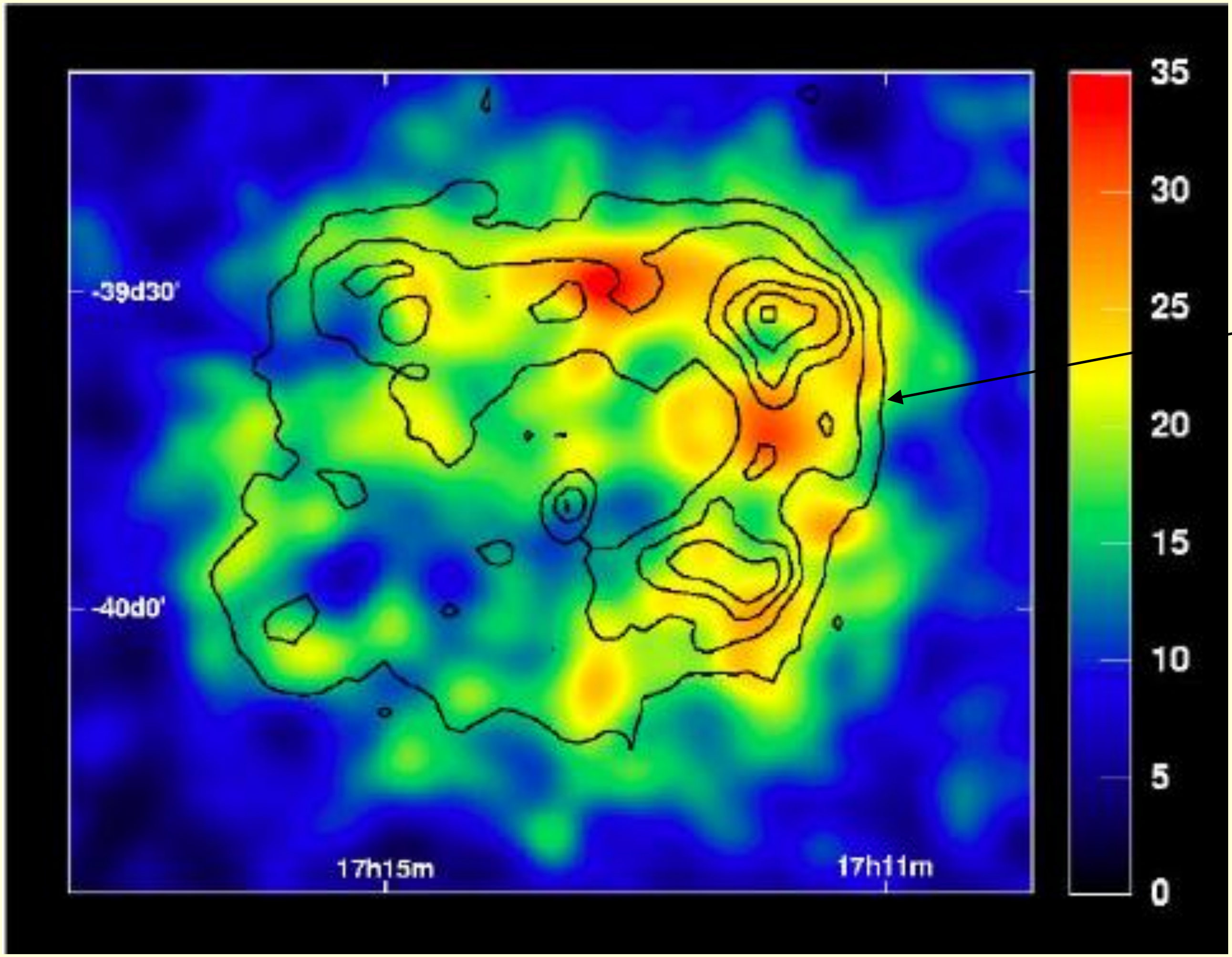
Detection of gamma rays in the 100 GeV to 10 TeV range



one HESS telescope



stereoscopic view

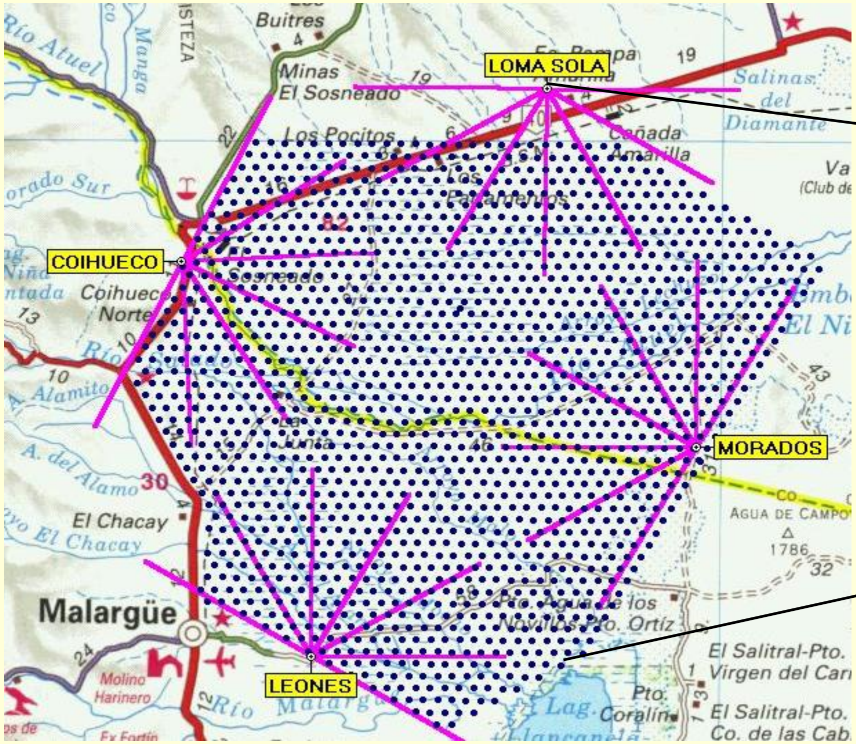


X ray

Detection of the shell structure of a supernova remnant

The Pierre Auger observatory

To study the cosmic ray showers of the highest energy, one needs to instrument a very large area



QuickTime™ et un décompresseur sont requis pour visionner cette image.

fluorescence detectors

Cherenkov detectors

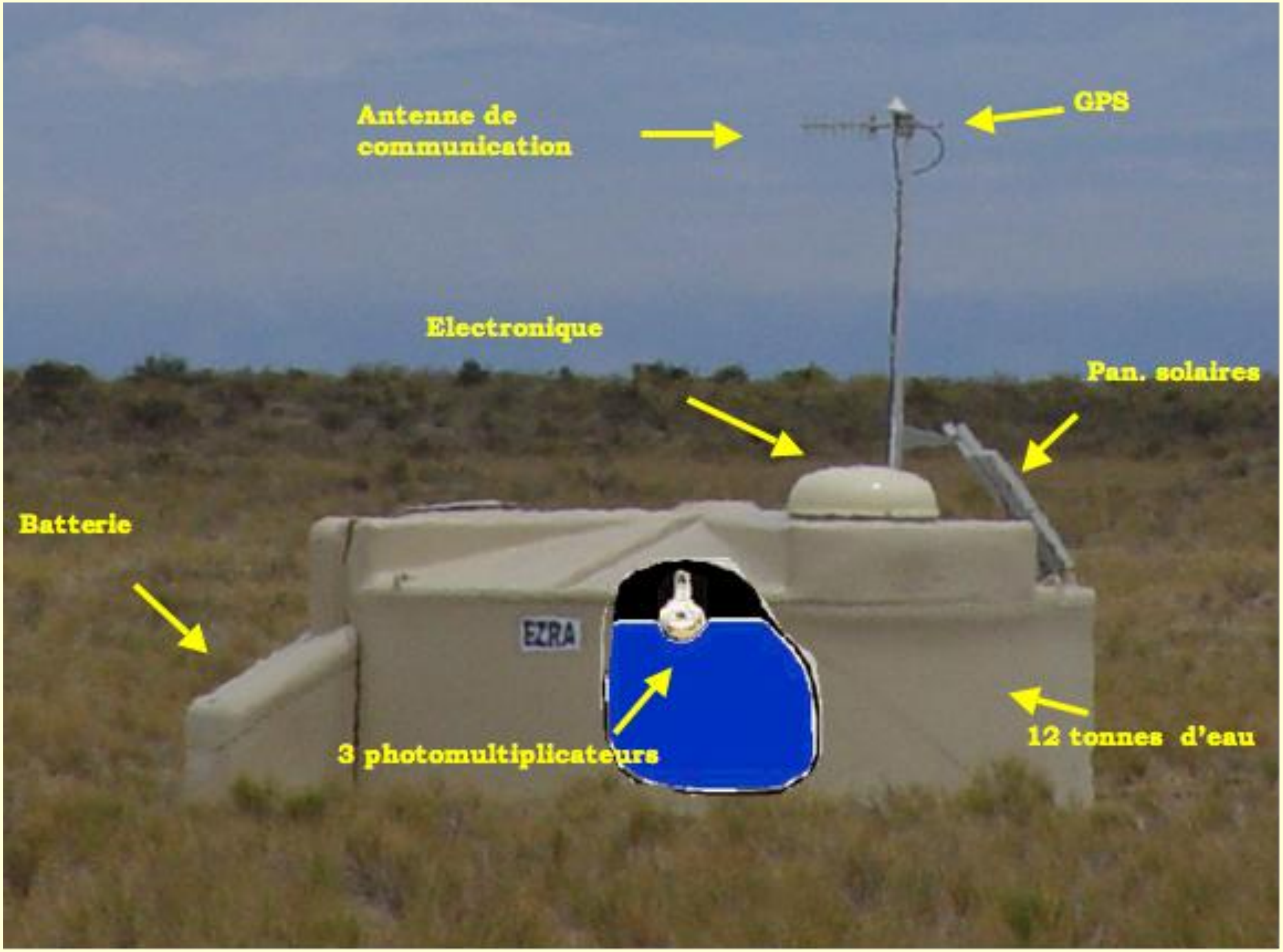
In Argentina, the Pierre Auger Observatory uses an array of 1600 detectors to cover an area of 3000 km^2

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

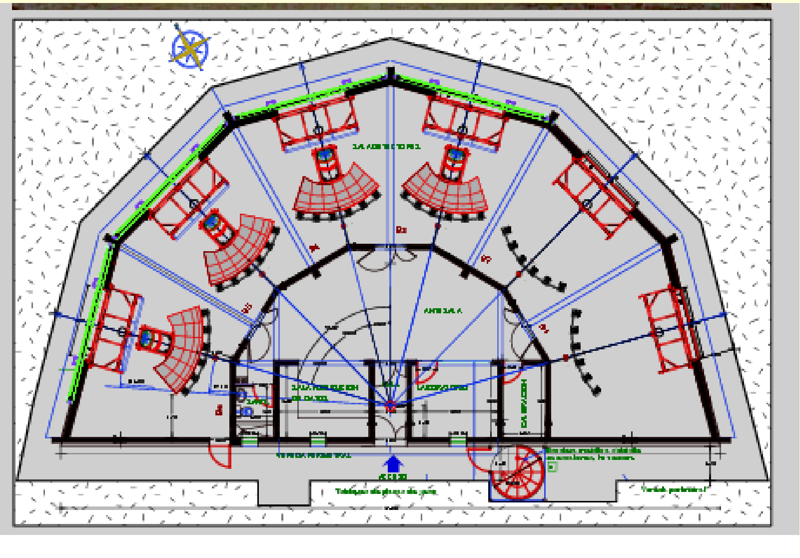
telescopes for detecting fluorescence light produced by shower

tanks filled with water fpr Cherenkov light detection

One tank of Auger (Cherenkov light)

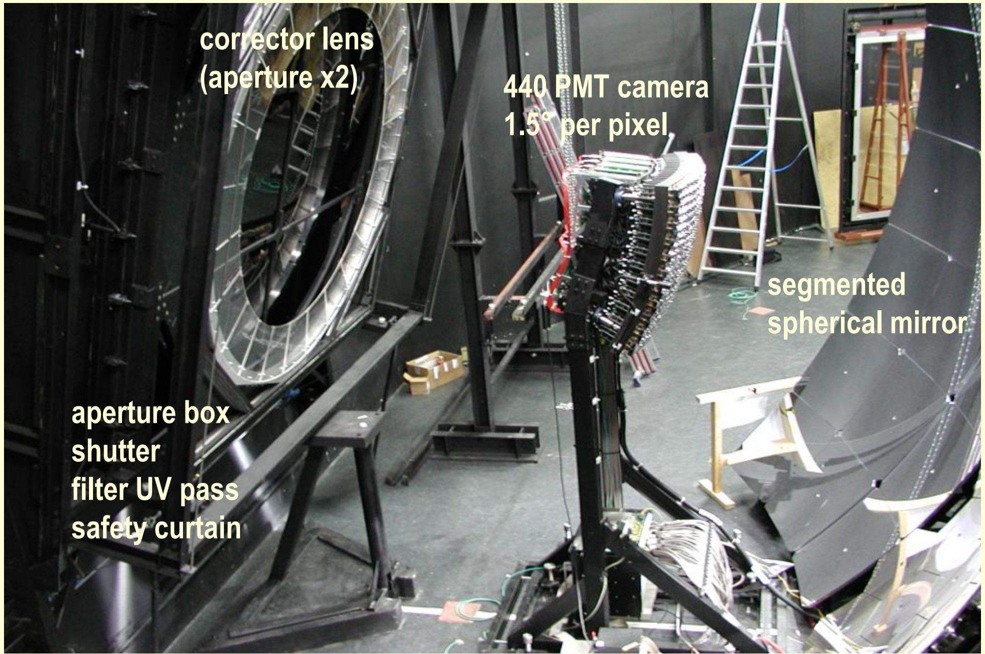


Fluorescence detectors

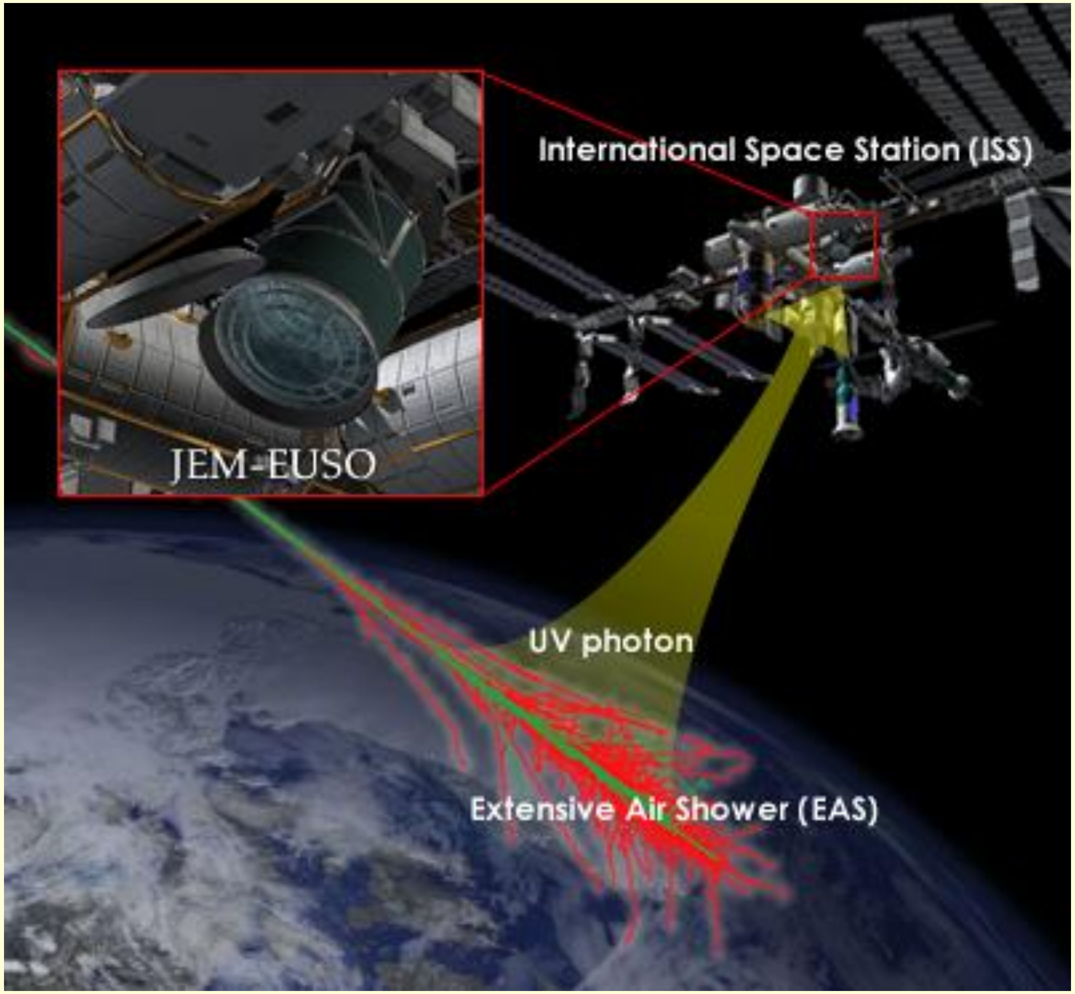


Internal lay out

optical system

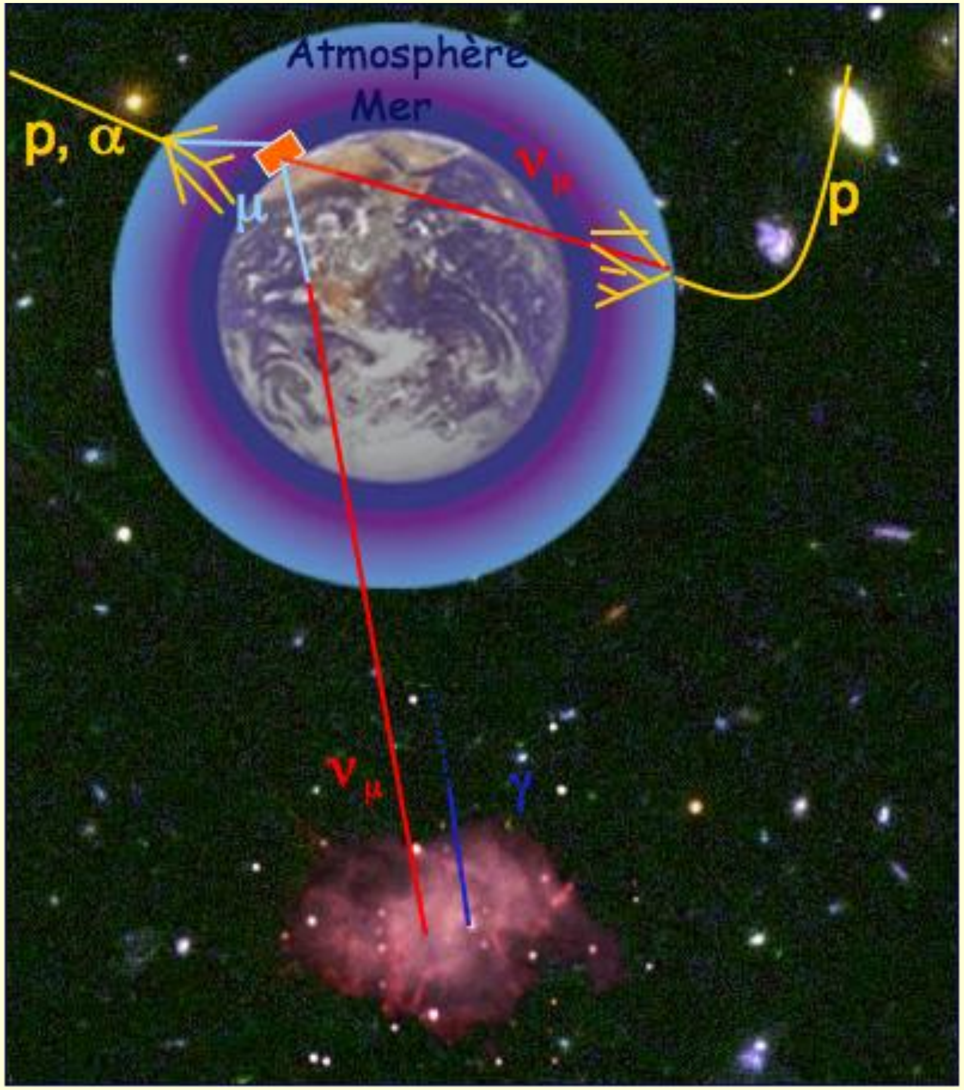


Using fluorescence to observe these showers from space: JEM-EUSO on the ISS



QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

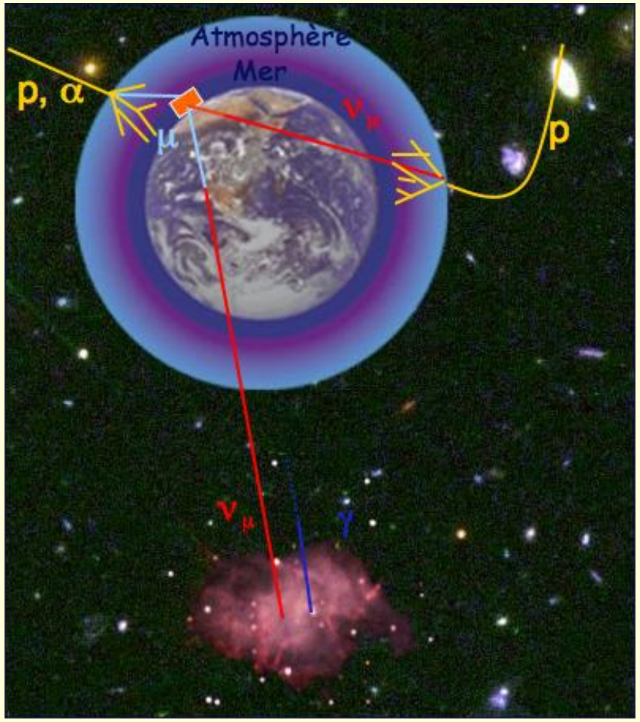
3. Detector Earth



Neutrinos are very difficult to detect because of their small cross section

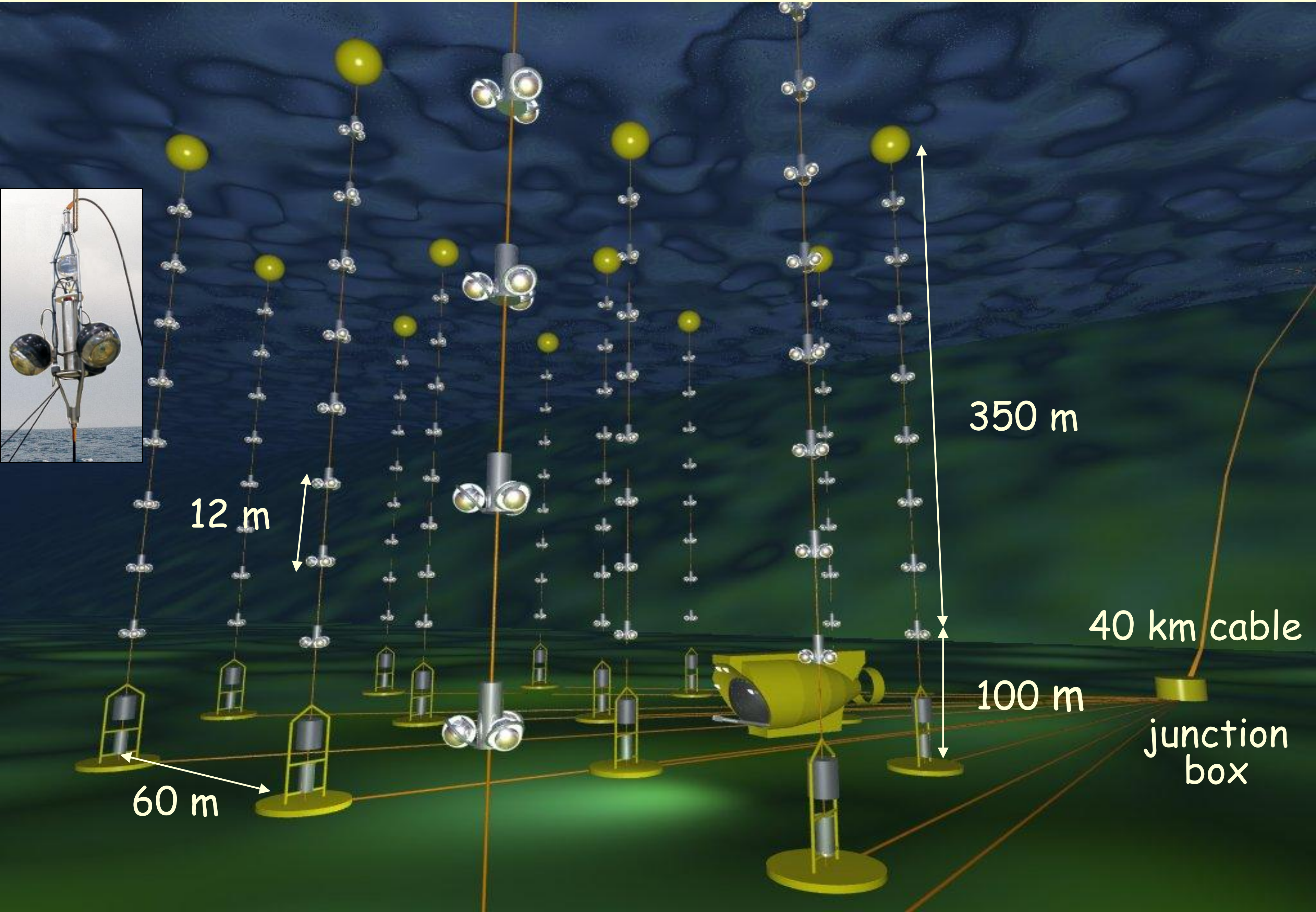
e.g. neutrinos produced in the Sun reach the Earth with a flux of 60 billion/cm^2,
only 1 in 10^{12} are stopped

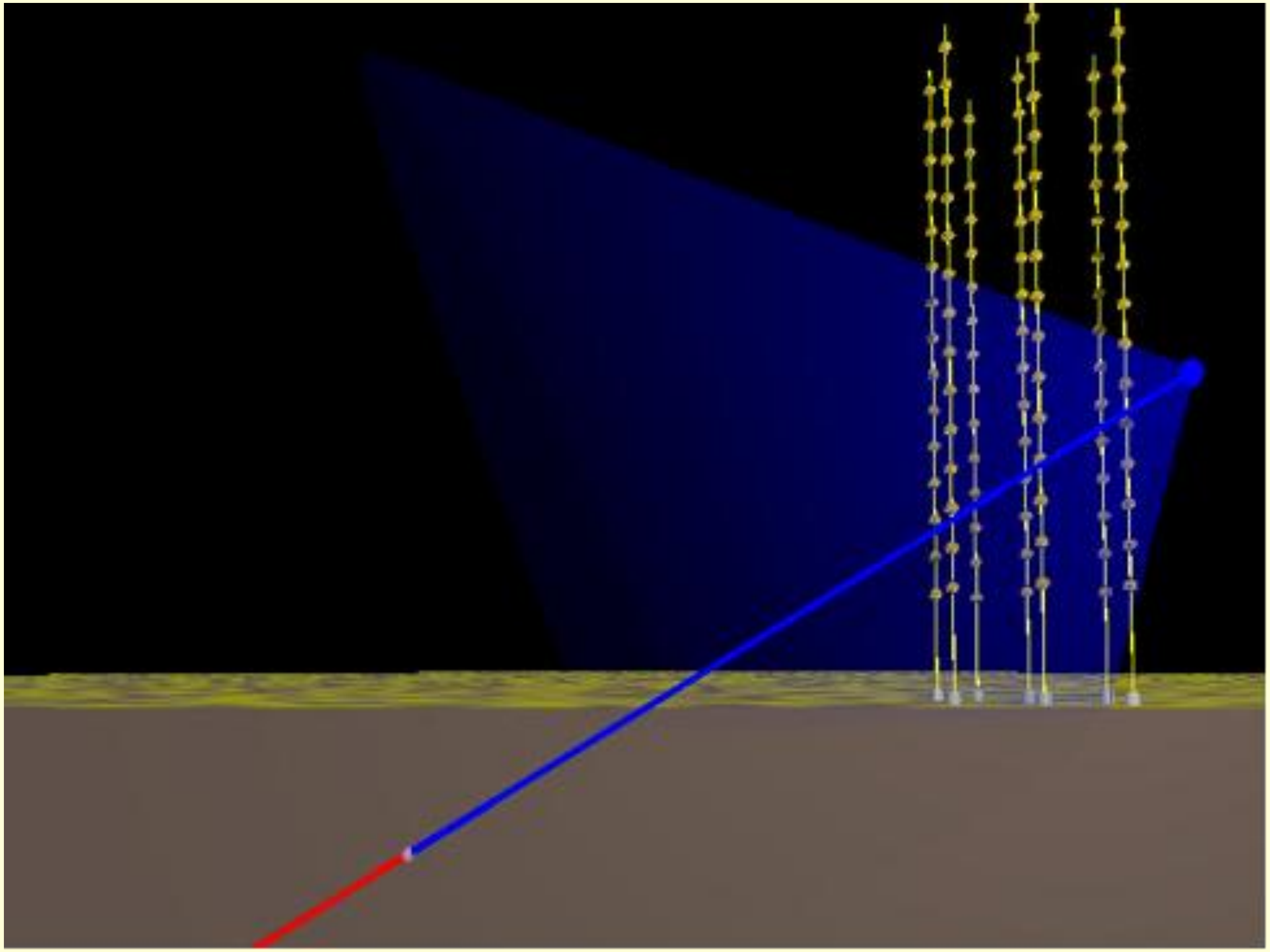
Positive side: cosmic neutrinos arrive on Earth unperturbed
they trace the sources



To track the elusive neutrinos, one uses the Earth as detector.

Example of ANTARES in the Mediterranean

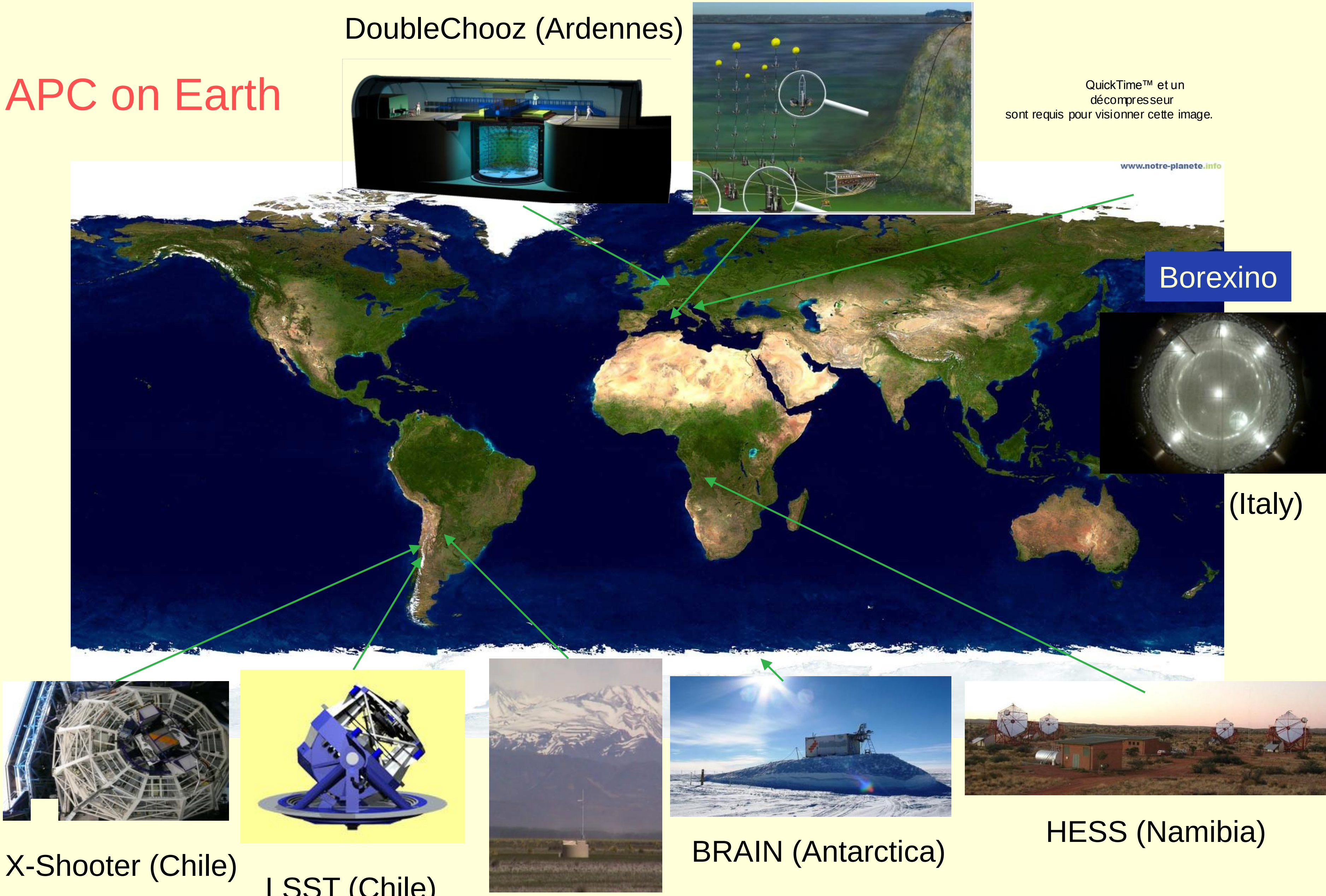




QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

QuickTime™ et un
décompresseur codec YUV420
sont requis pour visionner cette image.

APC on Earth



ANTARES (Mediterranean)

VIRGO (Italy)

DoubleChooz (Ardennes)

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

Borexino

(Italy)

X-Shooter (Chile)

LSST (Chile)

Auger (Argentina)

BRAIN (Antarctica)

HESS (Namibia)

Outline

1. An extraterrestrial radiation
2. The light of particles
3. Detector Earth
4. Particle detectors in space
5. Underground: neutrinos and dark matter
6. Ripples of spacetime

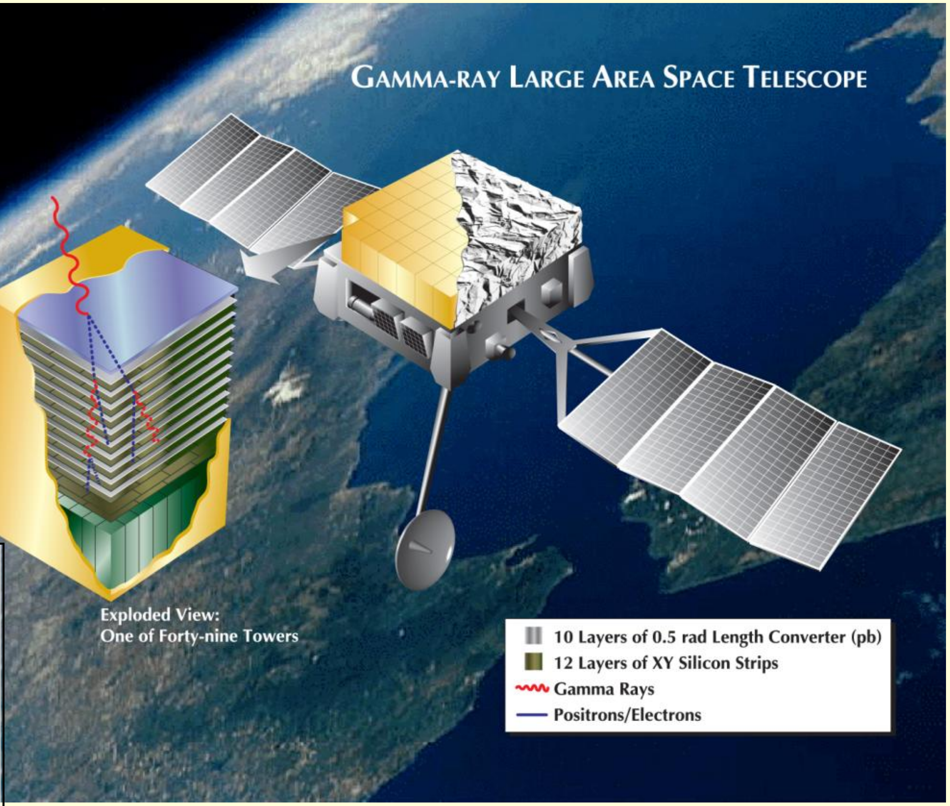
4. Particle detectors in space

Why go into space?

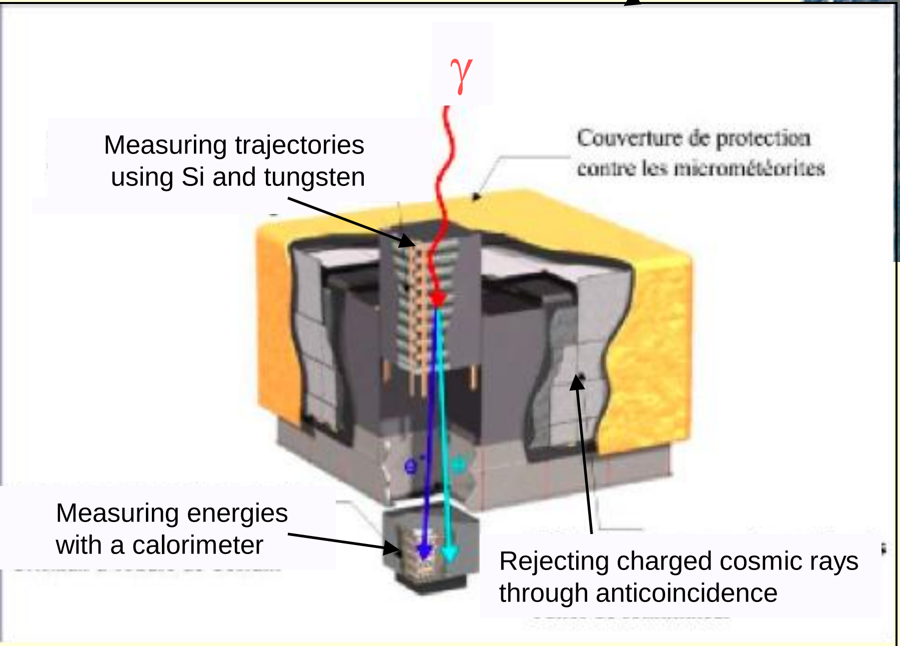
Catch the primary cosmic particles before they hit the atmosphere and form cosmic ray showers.

Launch in 2008

γ from 10 keV to 300 GeV



Large Area Telescope (20 to 300 MeV)



γ

Measuring trajectories
using Si and tungsten

Measuring energies
with a calorimeter

Rejecting charged cosmic rays
through anticoincidence

Detecting the primary particles responsible for cosmic rays: AMS on the ISS

(launch planned in 2010)

permanent
magnet
(charged particles)

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

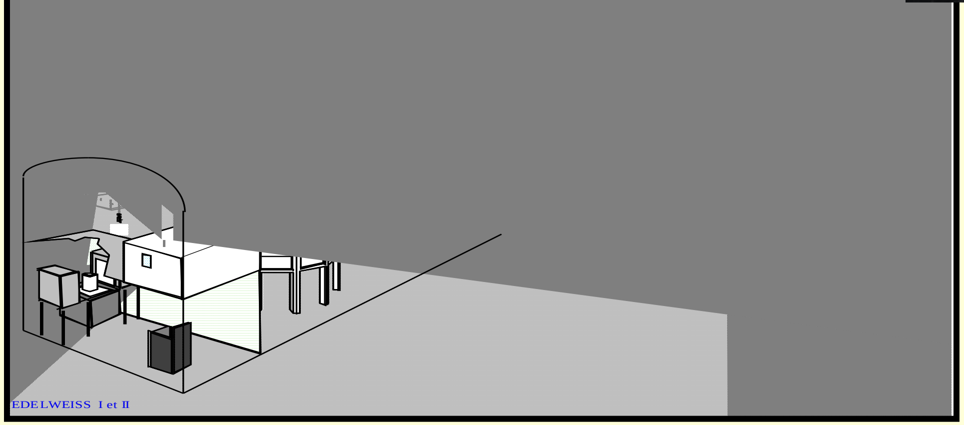
launched in 2006

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

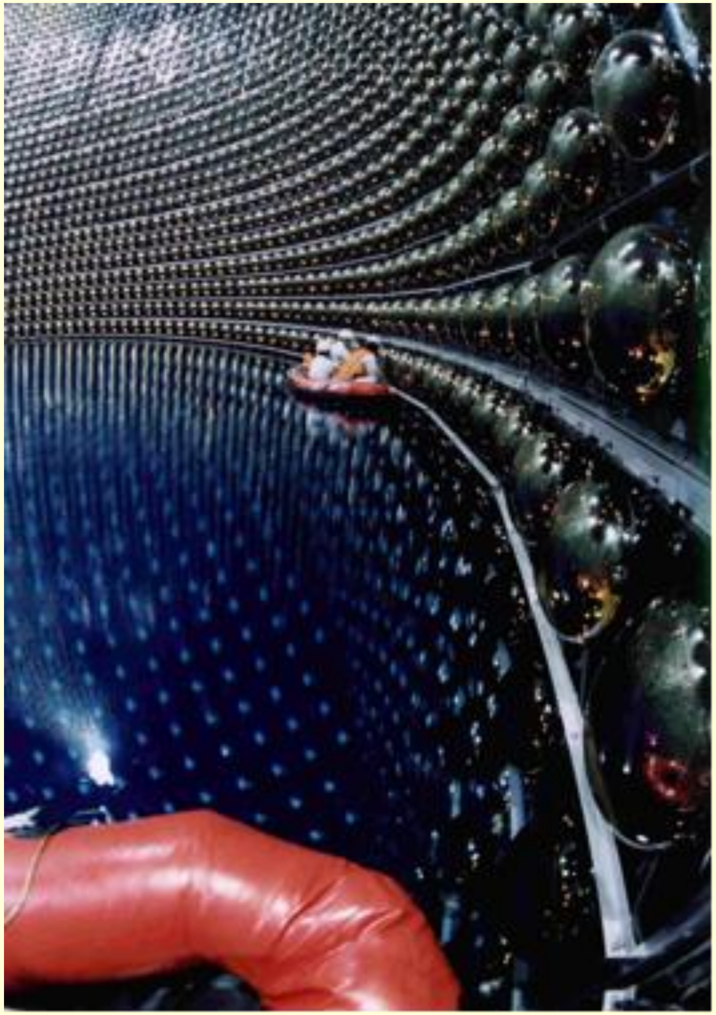
5. Underground

The detection of elusive particles such as neutrinos or dark matter particles
Require very low background environments

→ underground laboratories



Neutrino (solar and atmospheric) detectors



SuperKamiokande (in Japan) during the filling of the tank

Edelweiss-II experiment to detect dark matter

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

Astroparticle physics :

II - The violent Universe

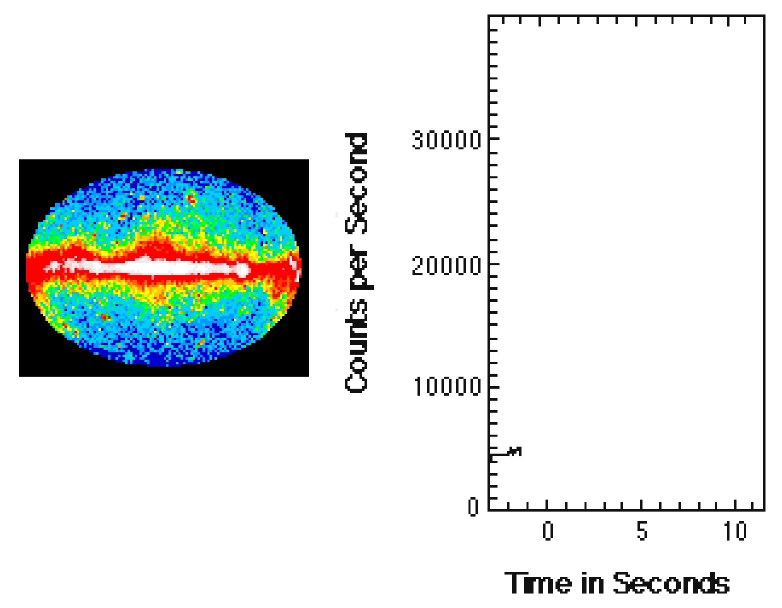
Pierre Binétruy
APC, Paris

CERN Summer Student Lecture Programme 2010

Outline

1. The example of gamma ray bursts
2. The end of a star
3. The story of black holes ← Ripples in spacetime: gravitational waves
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. $M_{\odot}c^2$

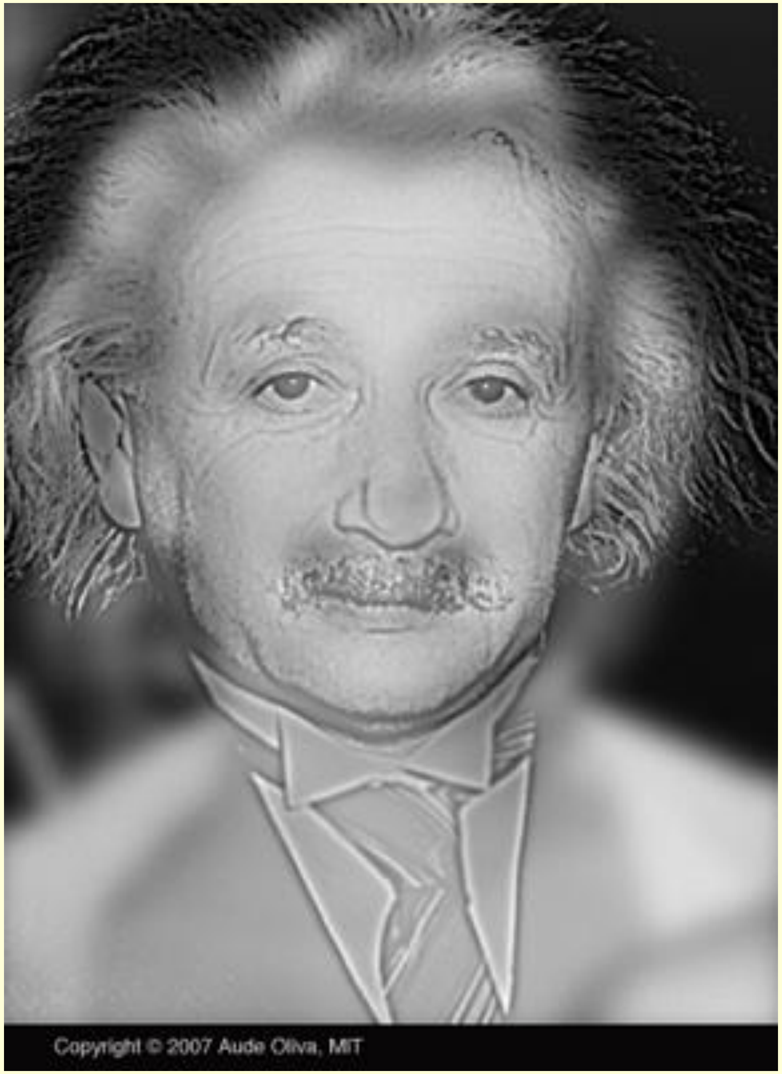
Distance that light travels in 5 seconds: 1 500 000 km i.e. 0.01 au

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

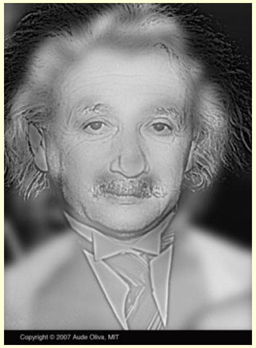
→ compact objects

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

2. The end of a star

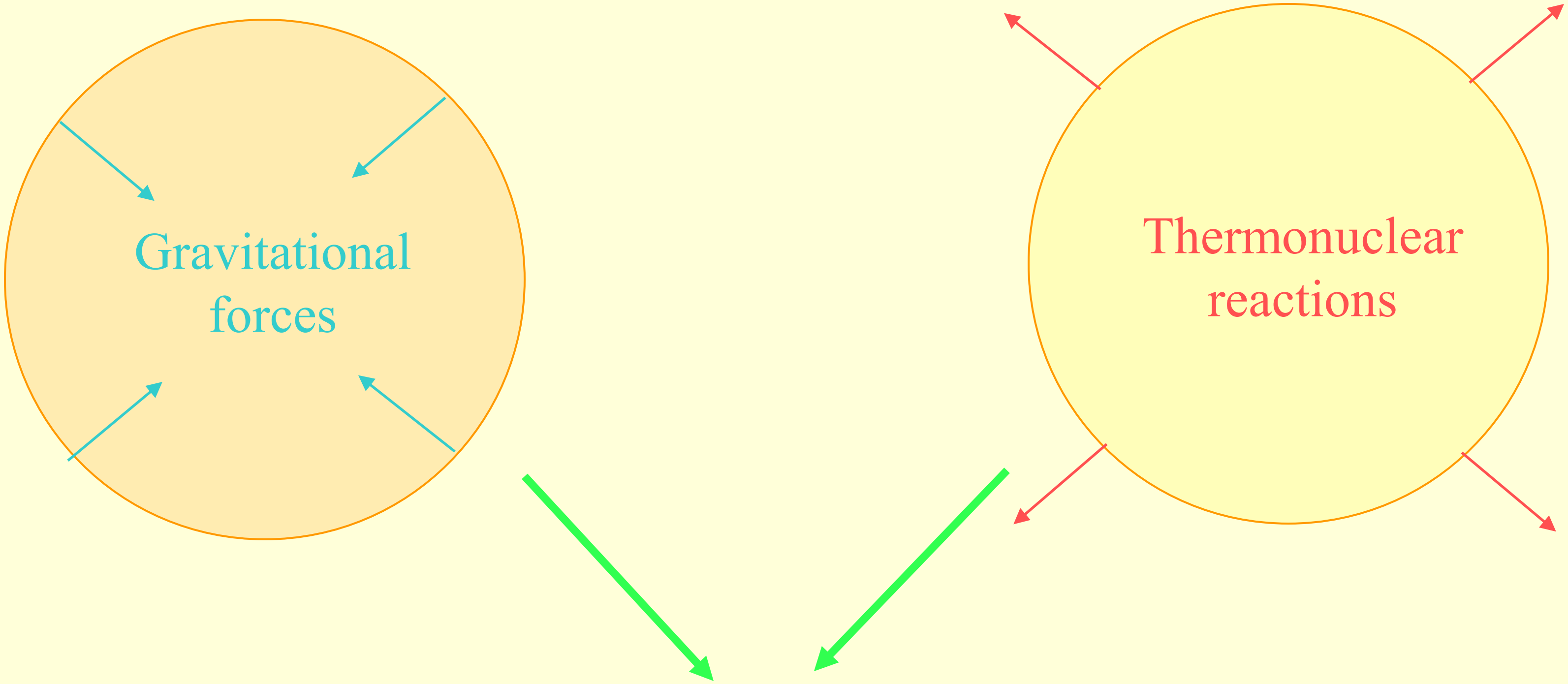


Copyright © 2007 Aude Oliva, MIT



Copyright © 2007 Aude Oliva, MIT

Some notions about star evolution (such as our Sun)



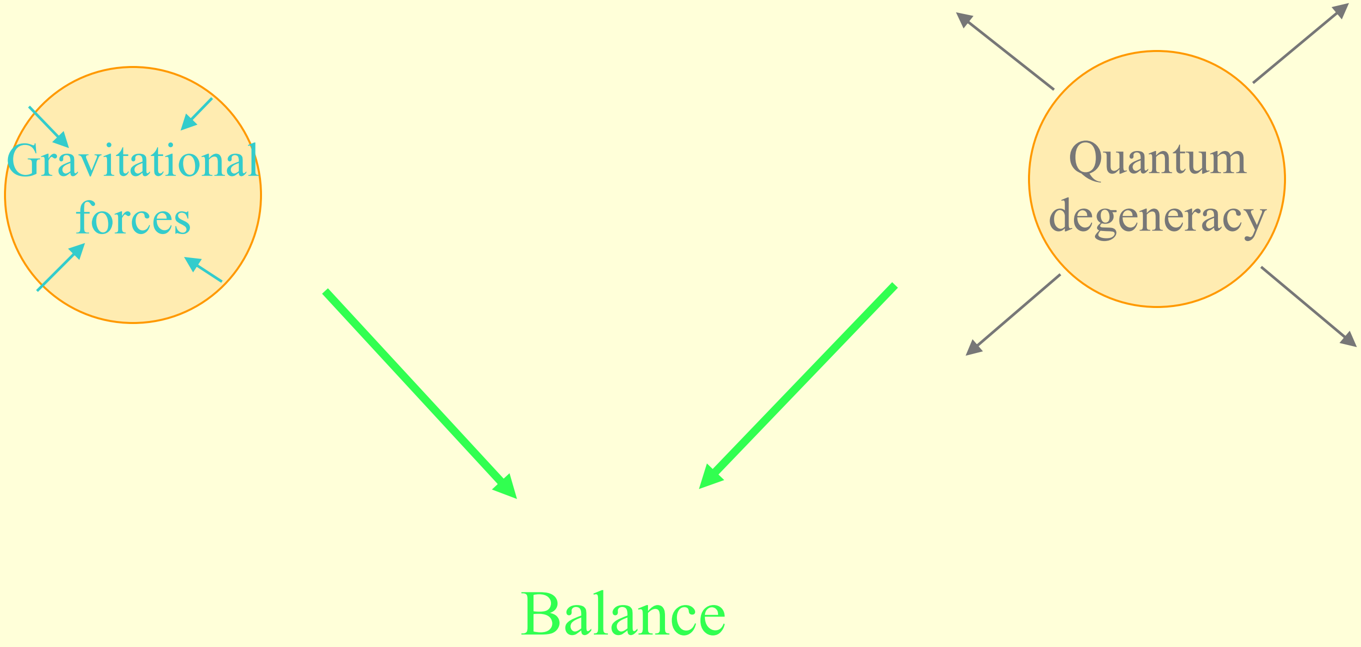
Gravitational forces

Thermonuclear reactions

Balance

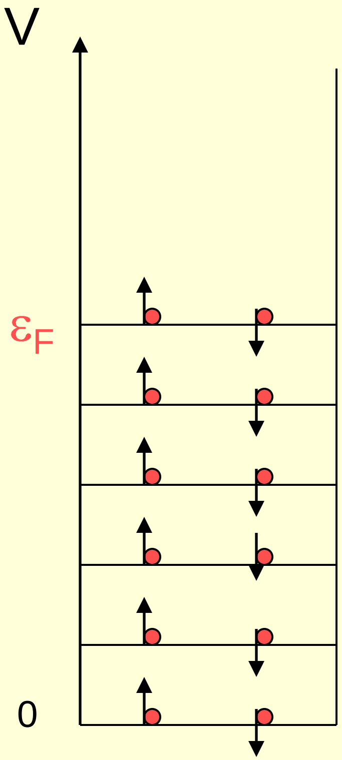
But when the nuclear fuel is exhausted, there is collapse under the effect of gravity → FORMATION OF A COMPACT OBJECT

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



Fermi level → « incompressible » energy

ground 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 collape is first stopped by the quantum degeneracy of electrons :

Chandrasekhar limit

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

WHITE DWARFS

number of nucleons
per electron, typ. 2

If density becomes larger, then

$$e + p \to n + \nu$$

and gravitational collapse is stopped by the quantum degeneracy of neutrons

Oppenheimer-Volkoff bound

NEUTRON STARS

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

If the mass is larger, 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

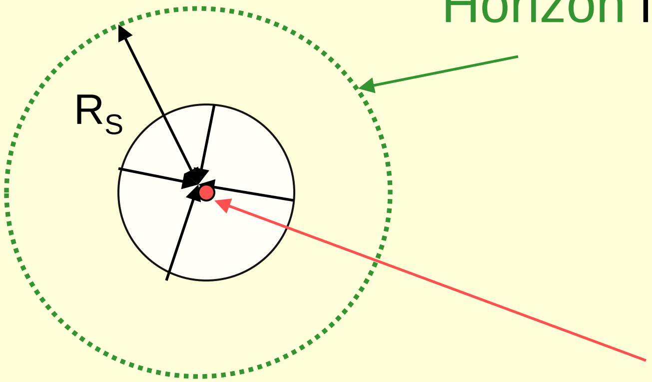
What is then the meaning of the Schwarschild radius?

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 :

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

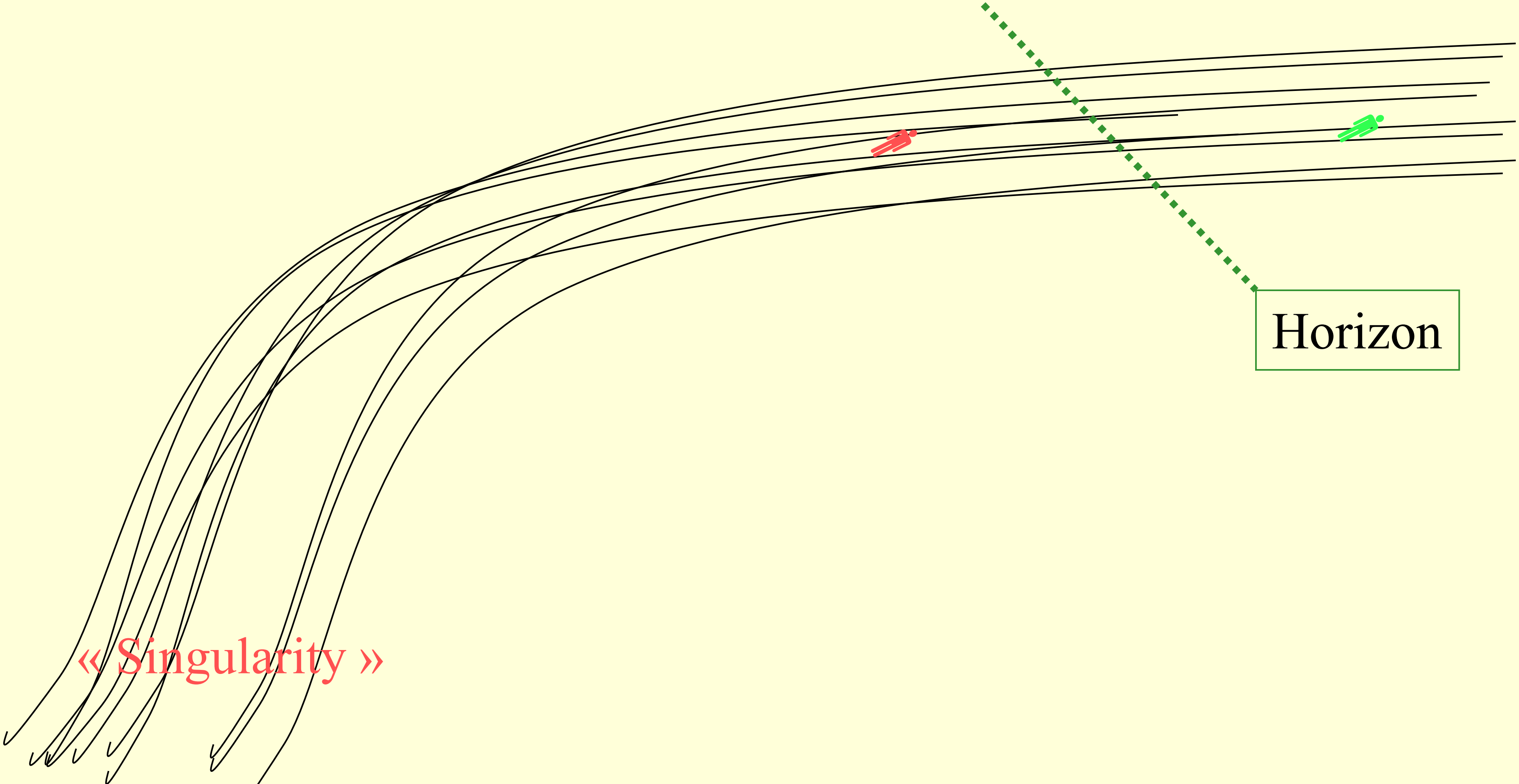
Hence even light (v=c) cannot escape if $R < 2\, G_N M/c^2 = R_S$



Horizon is protecting the singularity

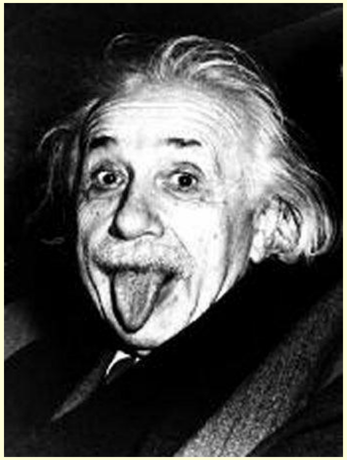
singularity

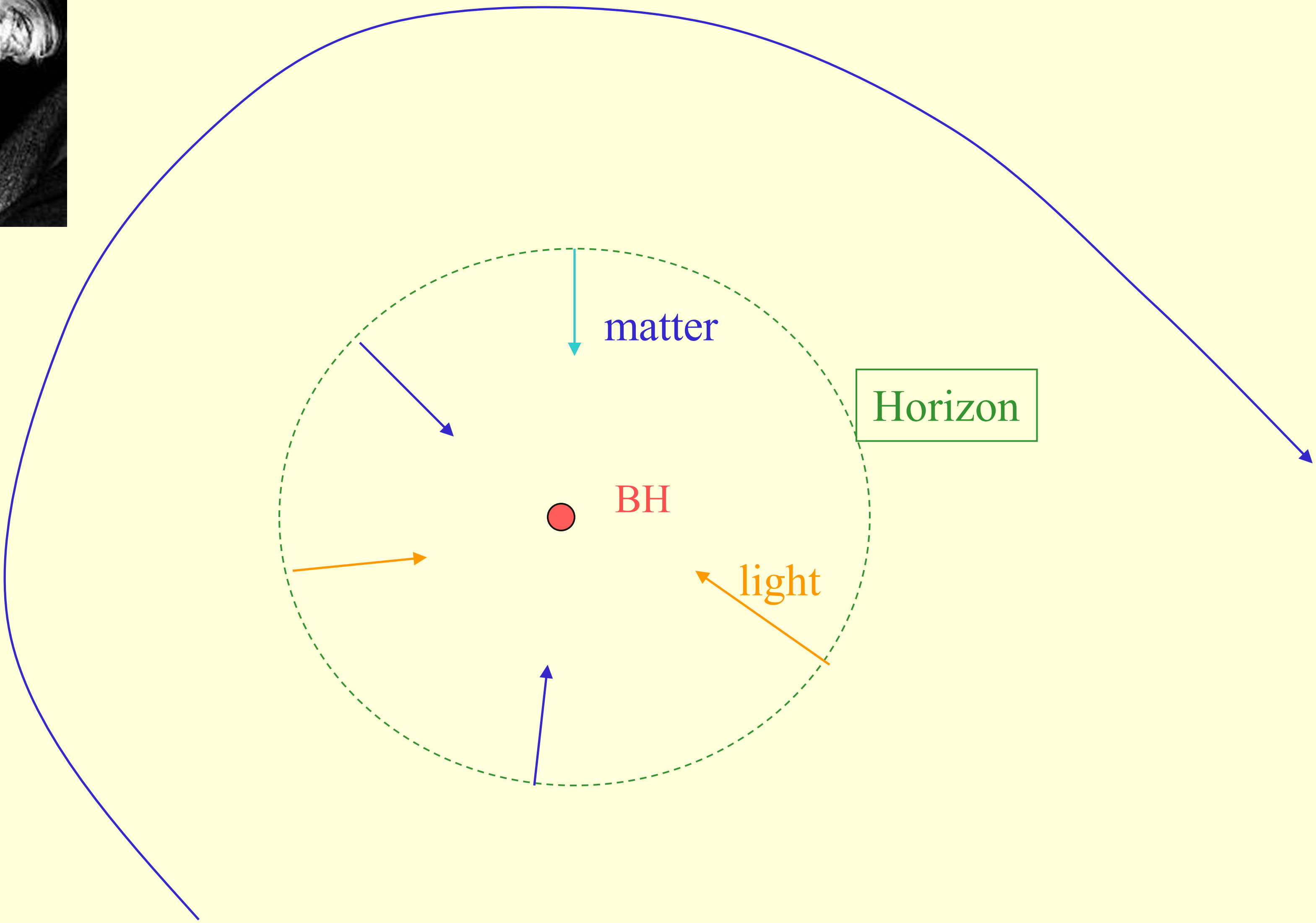
A comparison to understand the notion of (Schwarschild) horizon : the waterfall.



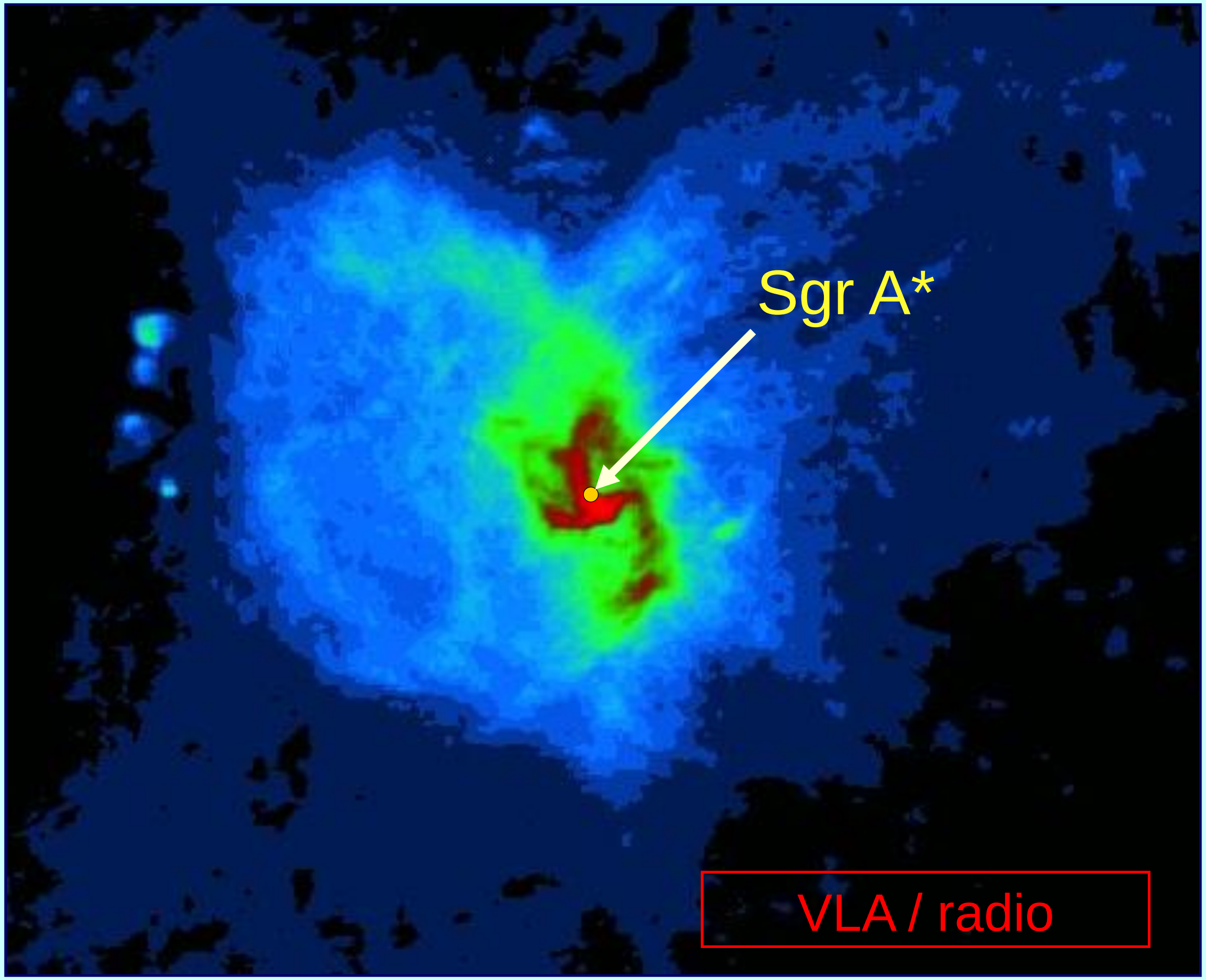
Horizon

« Singularity »




matter
Horizon
BH
light

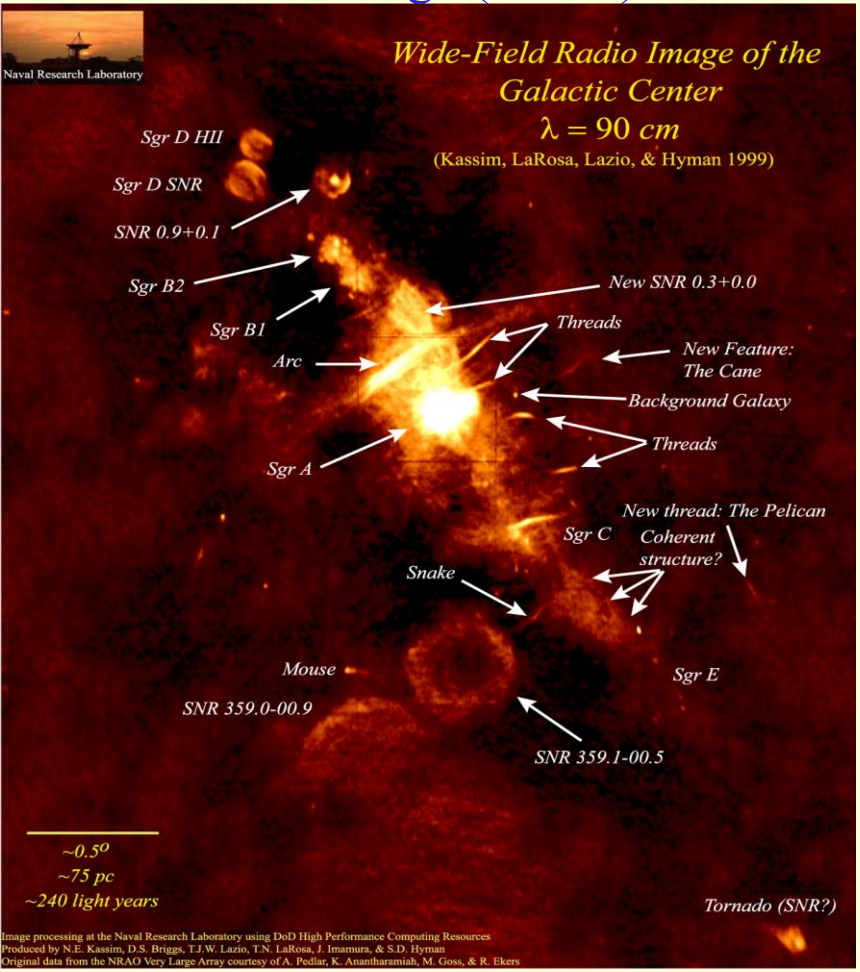
From « black holes » to black holes…



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

Let us come closer!

Radio image (90 cm)



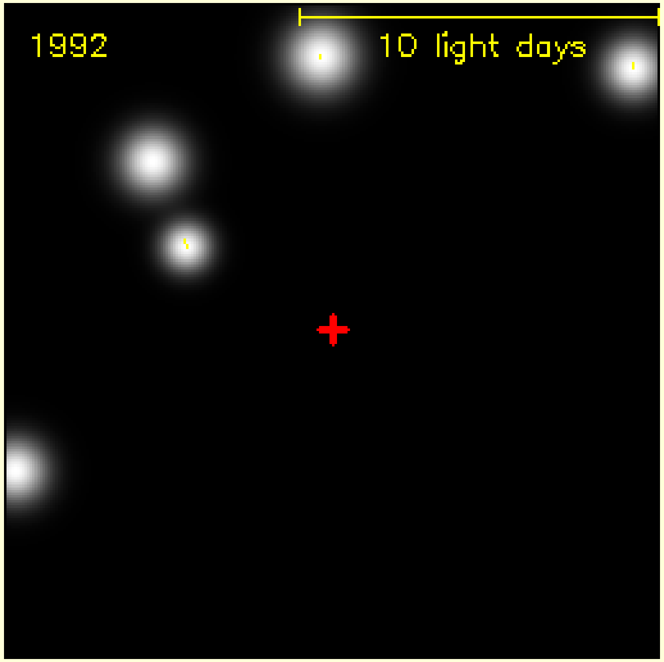
Wide-Field Radio Image of the Galactic Center

$\lambda = 90$ cm

(Kassim, LaRosa, Lazio, & Hyman 1999)

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

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

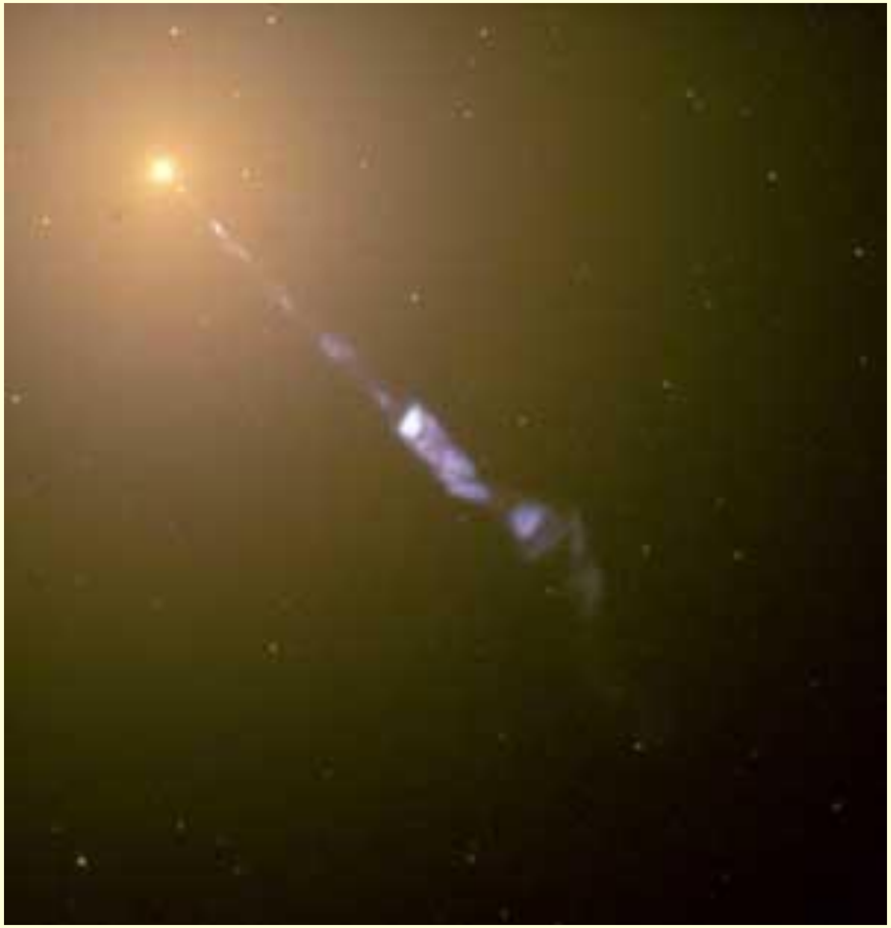


Black hole of mass of the order of 3 million solar masses

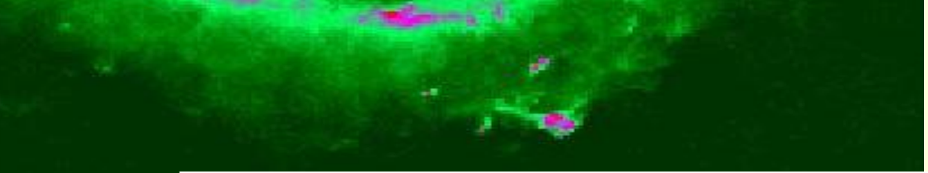
Why is the central black hole associated with the emission of energetic particles?

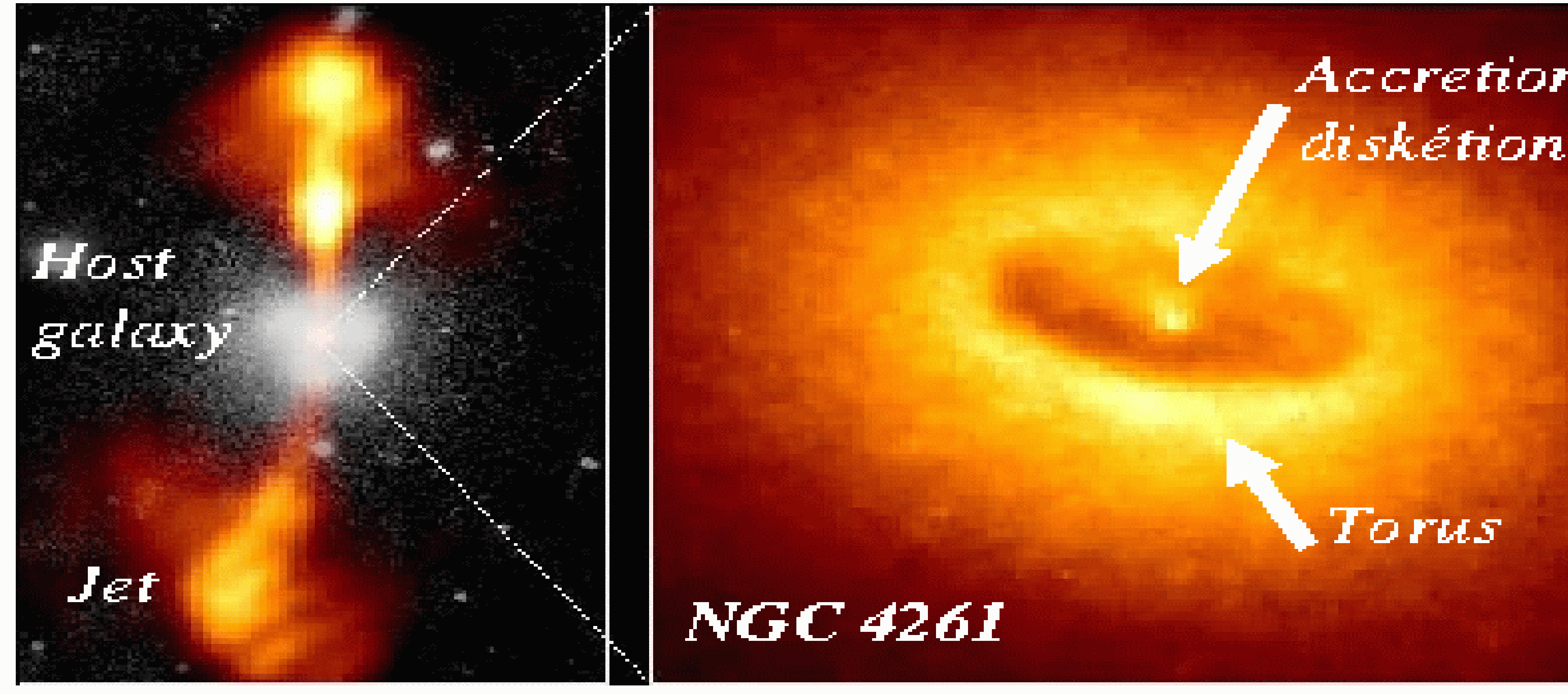
Because matter falling into the black hole is undergoing a very intense activity.

Torus of dust surrounding a black hole



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



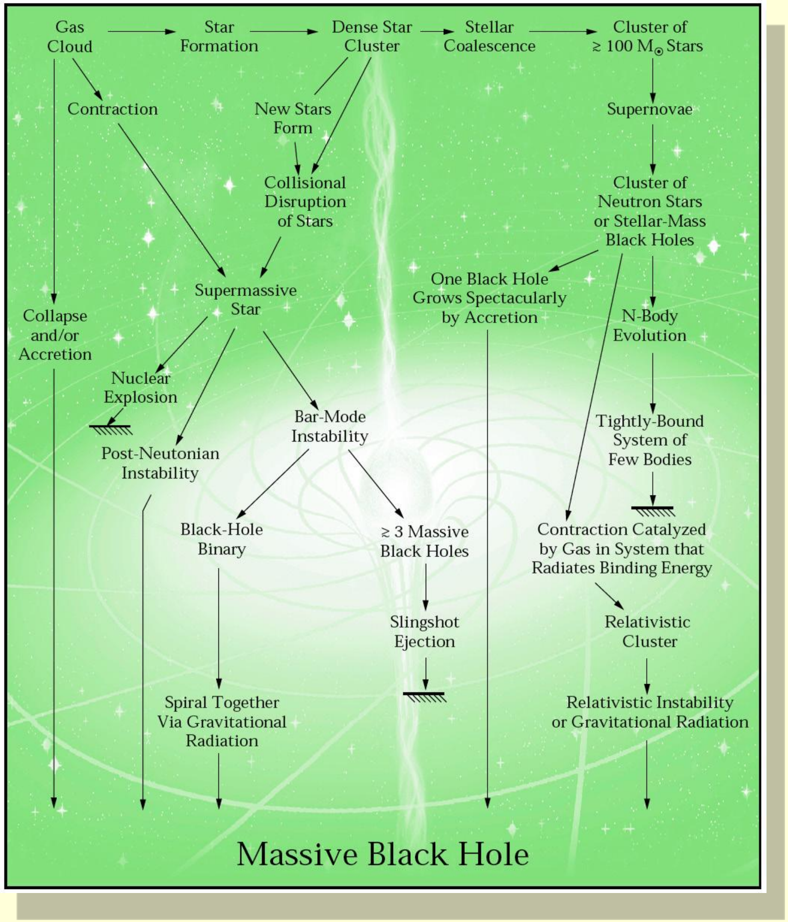

Host galaxy
Jet
Accretio
diskétion
Torus
NGC 4261

QuickTime™ et un
décompresseur codec YUV420
sont requis pour visionner cette image.

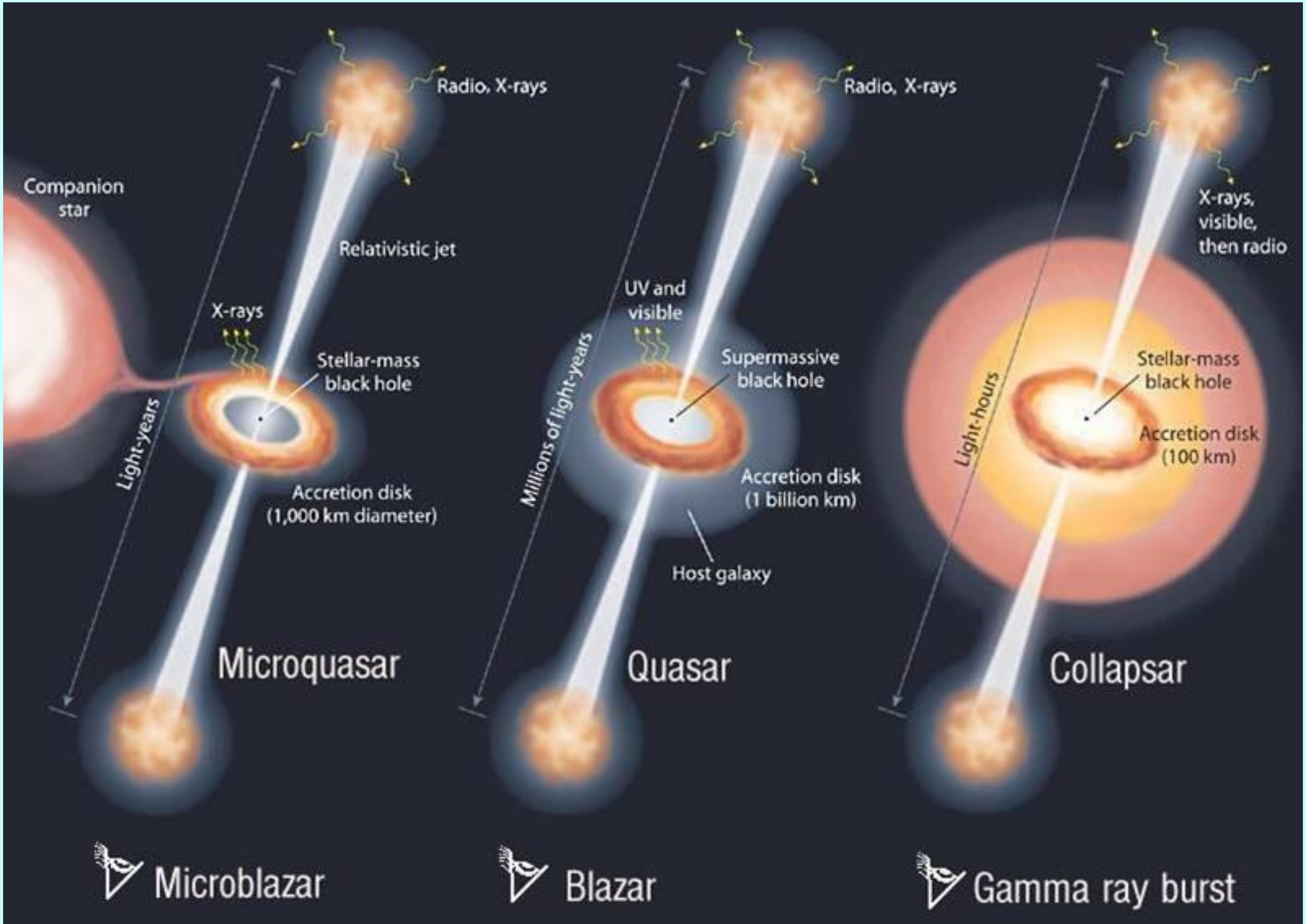
One finds such supermassive black holes at the centre of most, if not all galaxies.

How did they form?

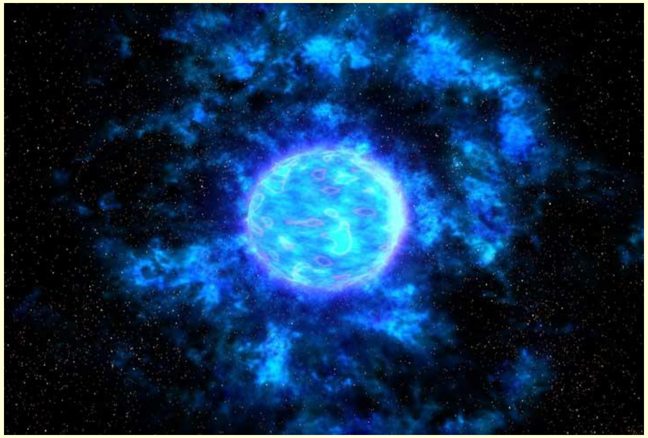
Strongly connected with galaxy formation.



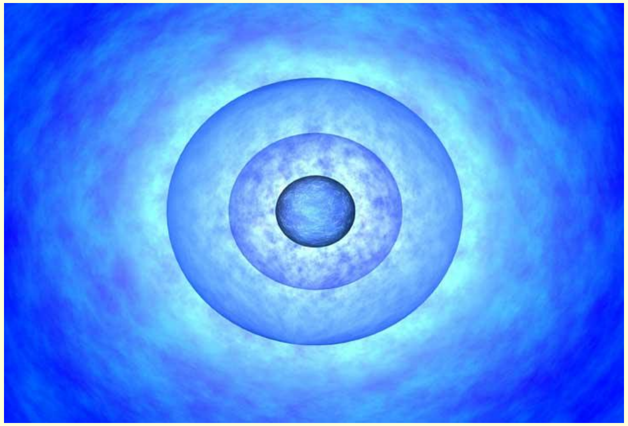
One finds black holes as the building blocks of many astronomical systems where violent phenomena take place



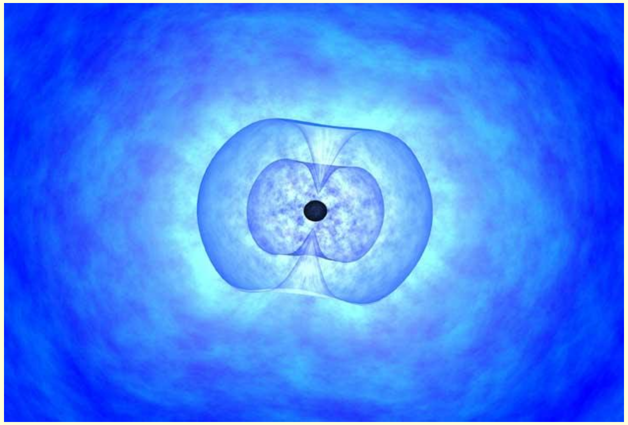
A model for (long) gamma ray bursts



A massive star ends its existence
with an explosion



Its inner core collapses
into a black hole

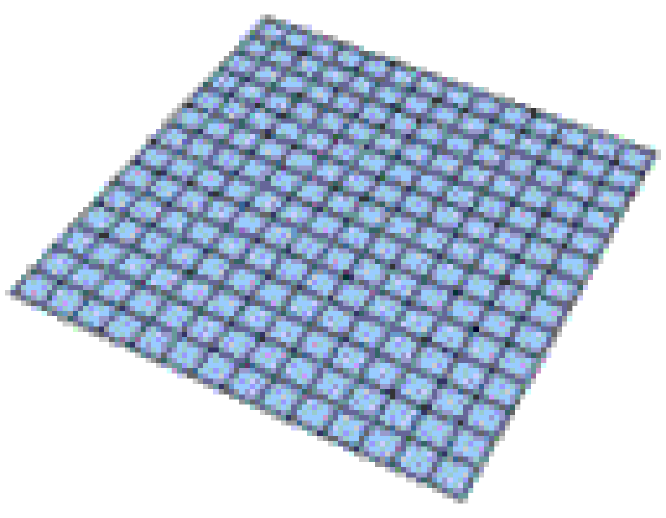


Collapse is not uniform.
There is creation of a jet of particles

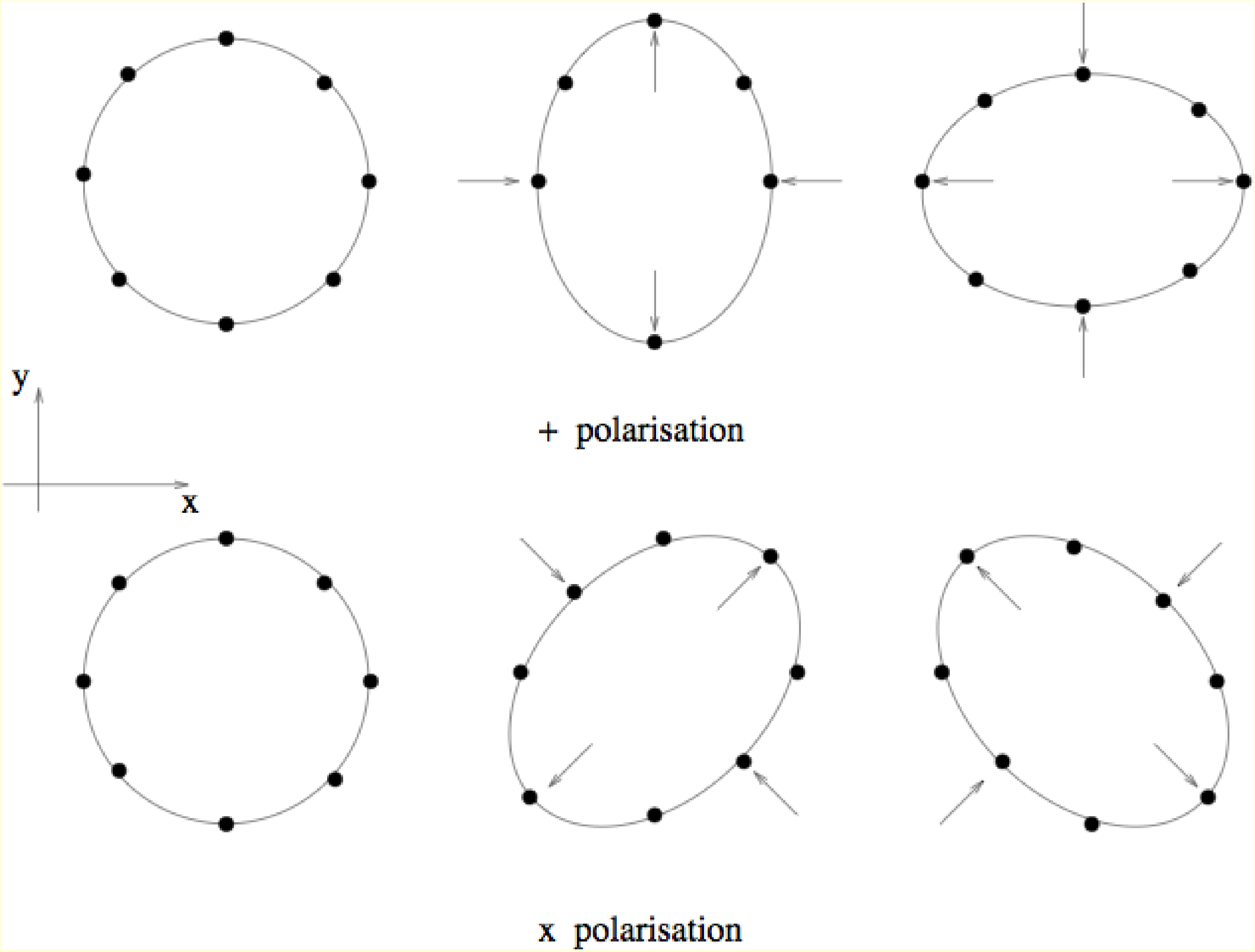
This jet interacts with the outer layers of
the star, which accelerates the particles.

6. Ripples of space-time

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

total length

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

ΔL

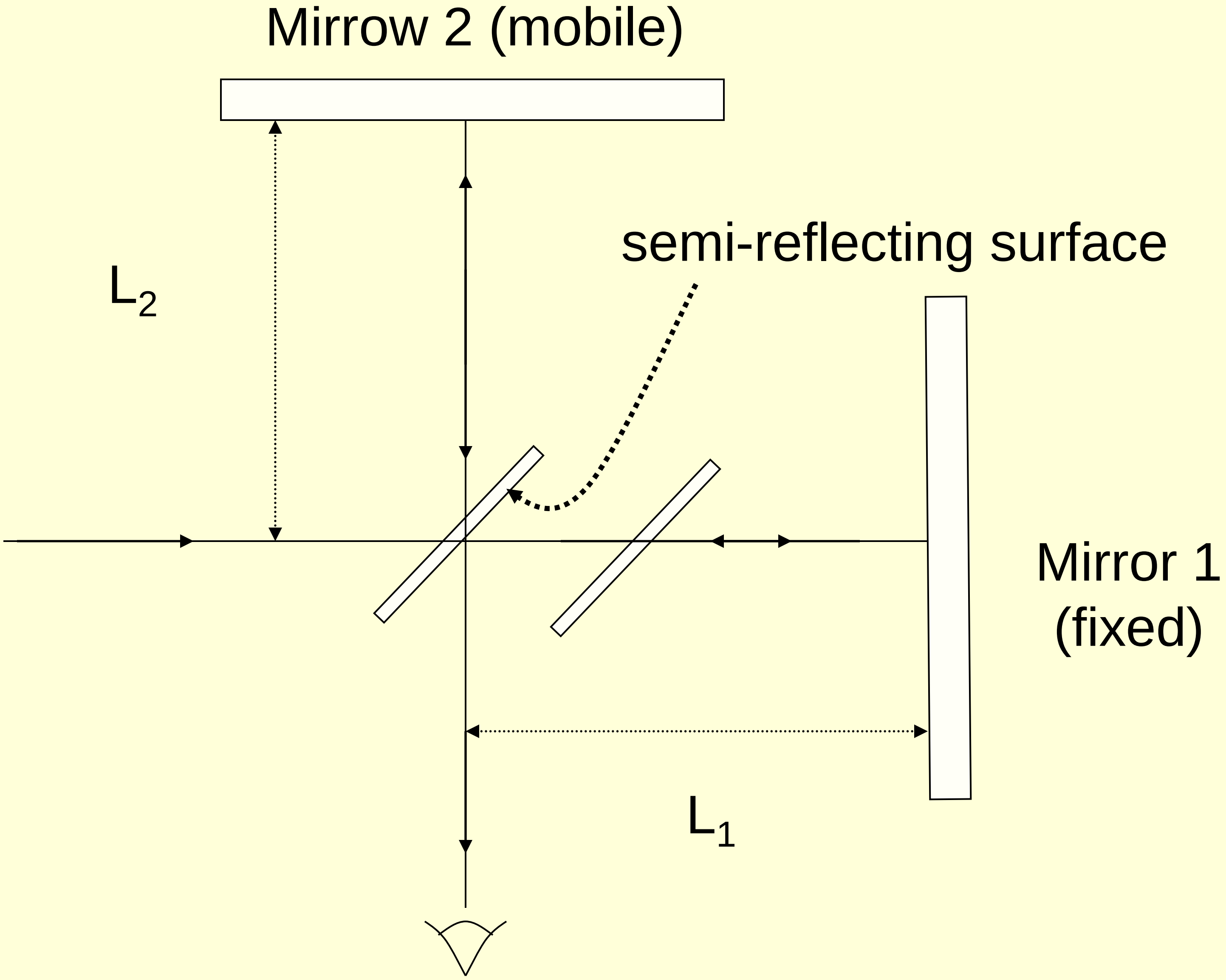
Examples:

- 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

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

Only known solution : interferometry



Mirrow 2 (mobile)

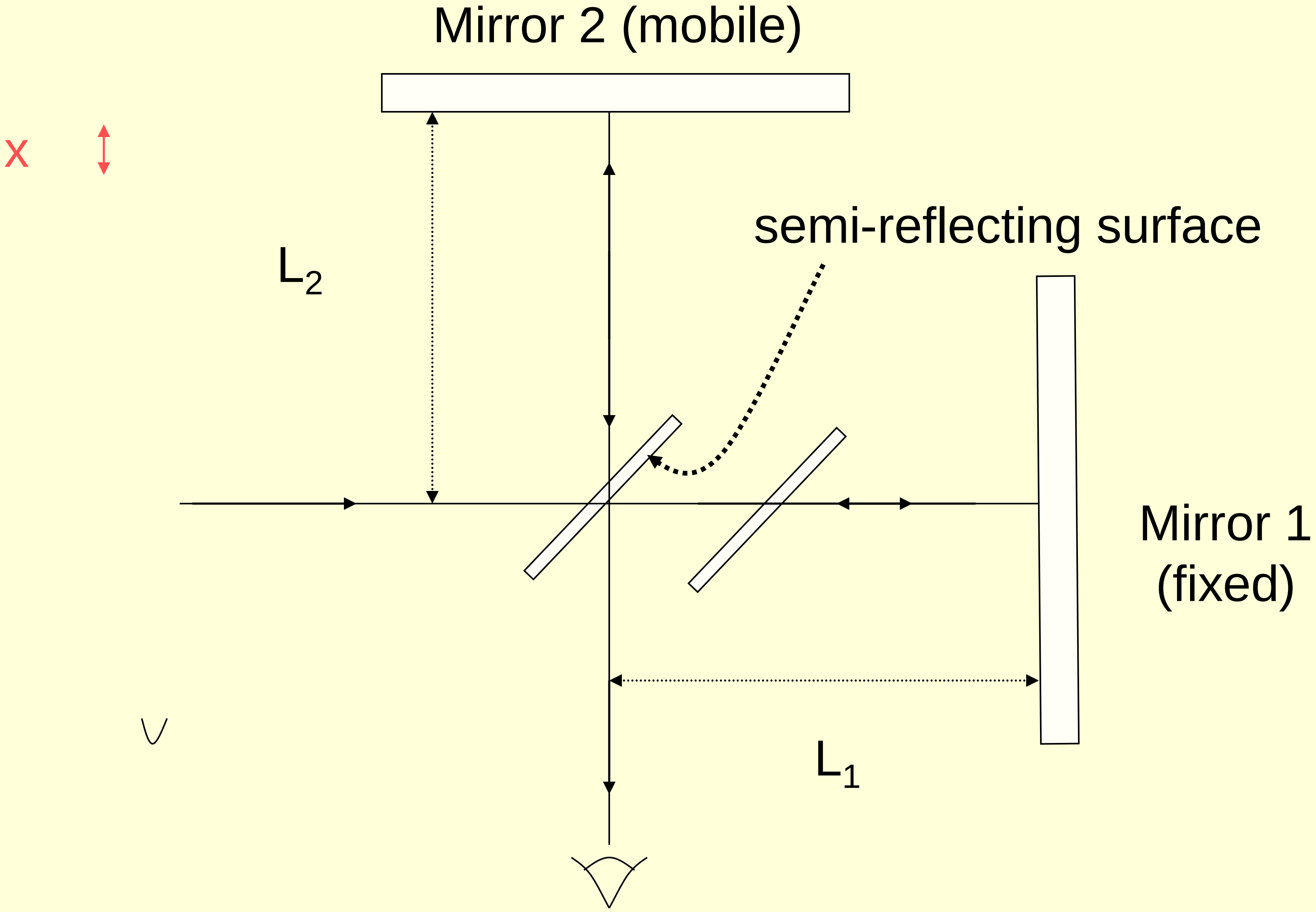
semi-reflecting surface

L_2

Mirror 1 (fixed)

L_1

Michelson interferometer



Mirror 2 (mobile)

x

L_2

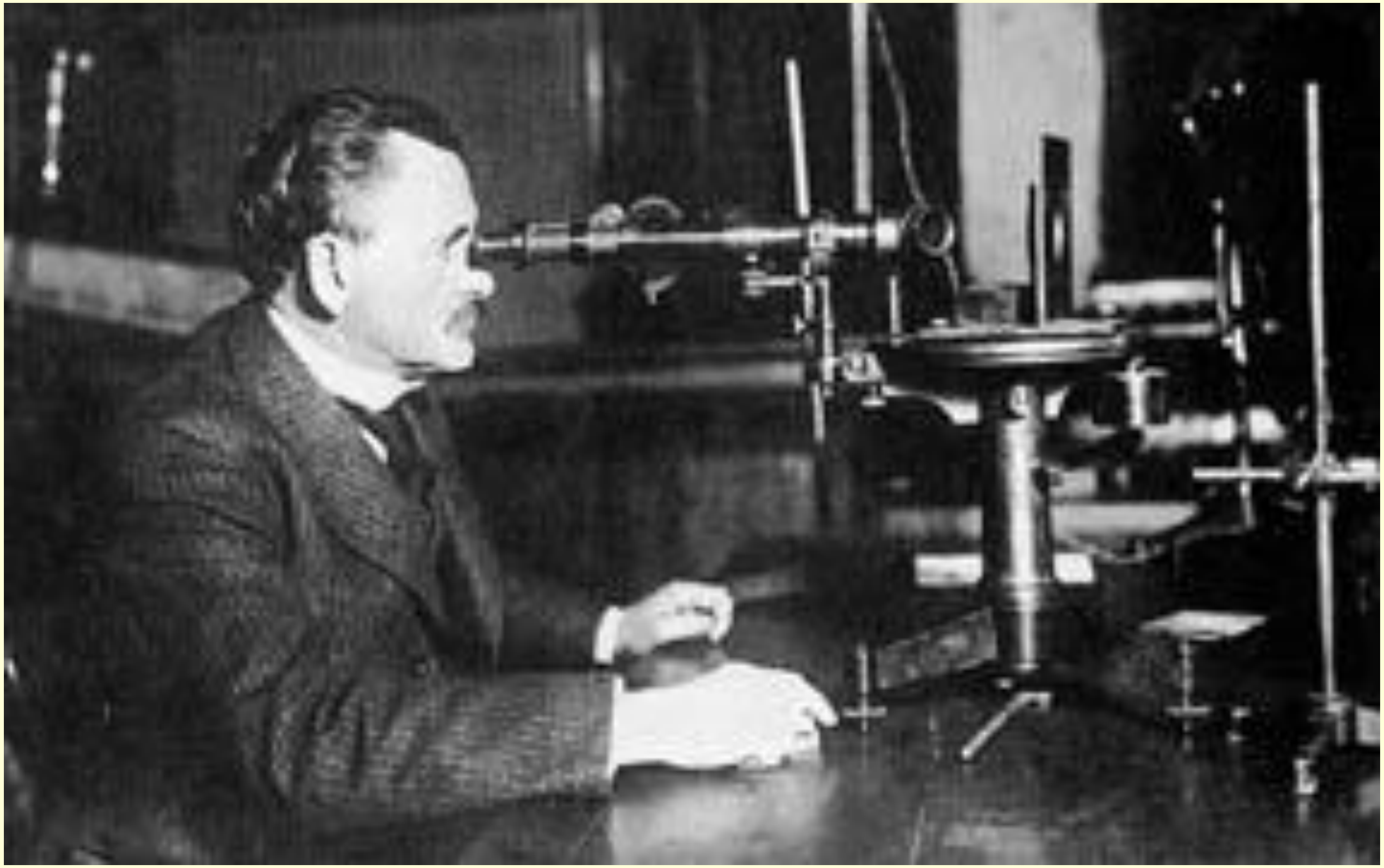
semi-reflecting surface

Mirror 1 (fixed)

L_1

$$x = m \lambda / 2$$

Albert Michelson counting interference fringes



Sensitivity in 1887: ΔL= 6.10^{-10} m!

Which size for an interferometer detecting grviational 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 ($M \sim 1{,}4M_\odot$) : $f \sim 100$ Hz

$\Rightarrow$ size ~ 3000 km

Ground Interferometers?

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

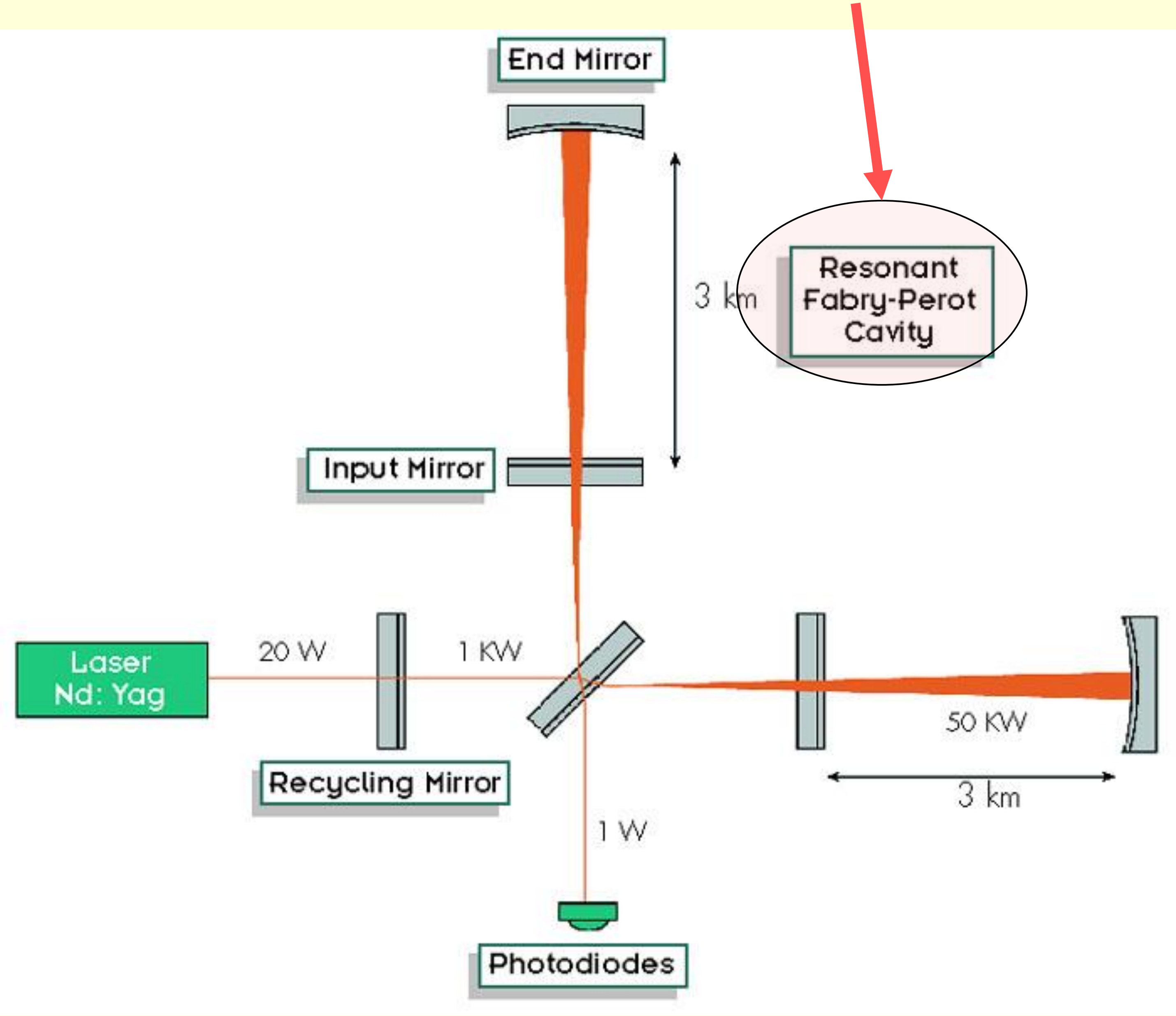
$\Rightarrow$ size ~ 30 million km

LISA

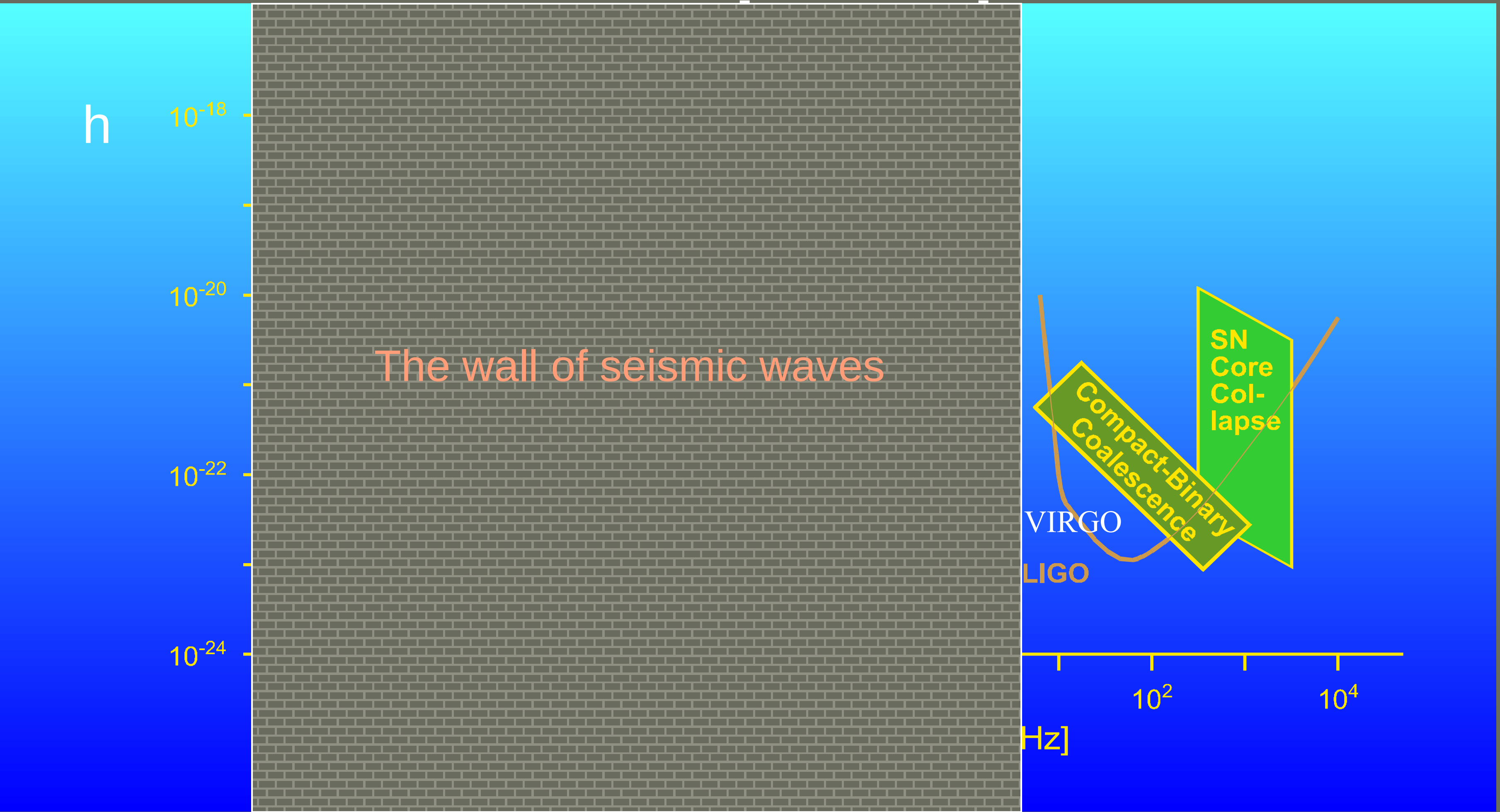
Virgo interferometer near Pisa

Size = 3 km

How to obtain the 3000 km necessary?



Sensitivity of ground detectors

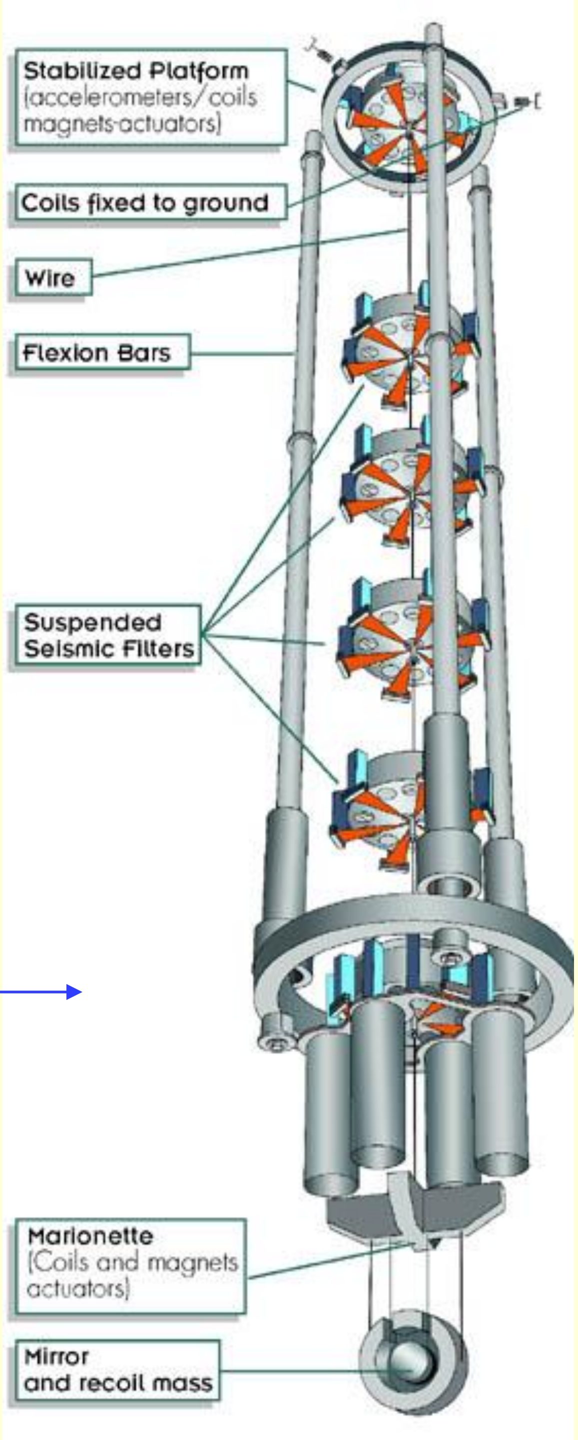


How to ecape as much as possible seismic waves?

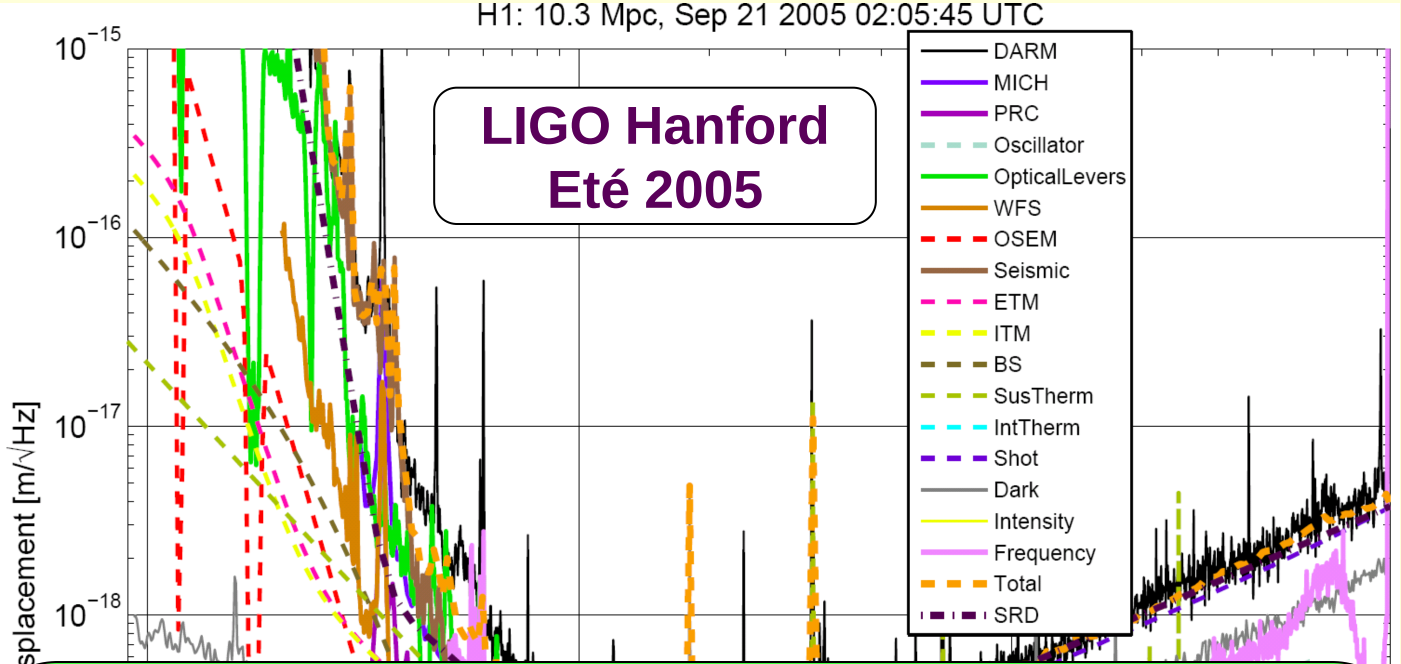
Suspend the interferometer

Virgo suspensions →

(ou put it underground)



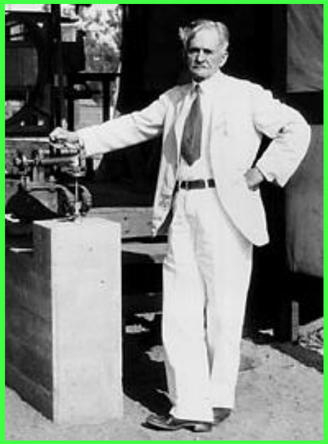
Sensitivity to displacement of ground interférometers



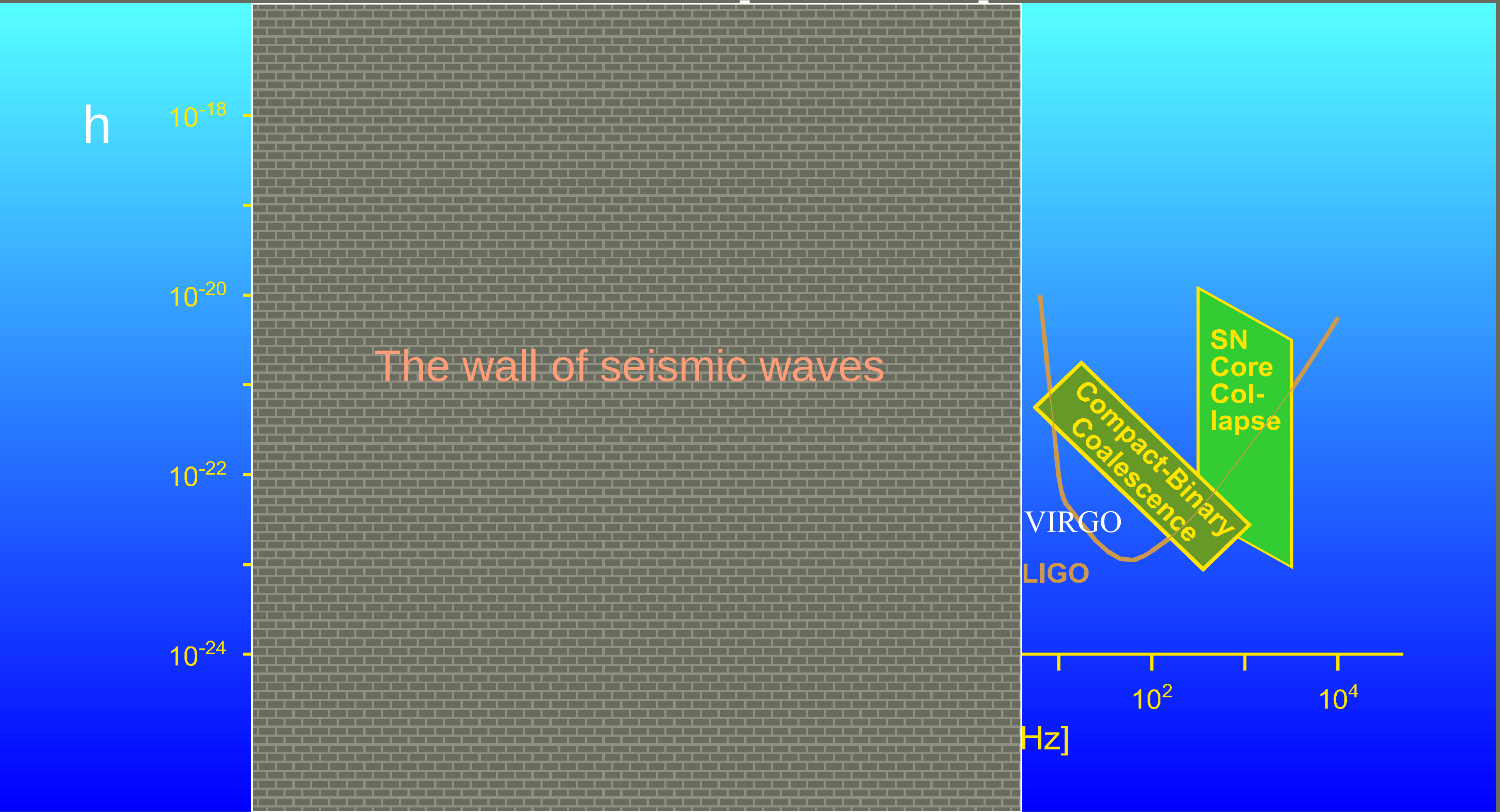
LIGO Hanford
Eté 2005

1×10^{-19} m/√Hz!

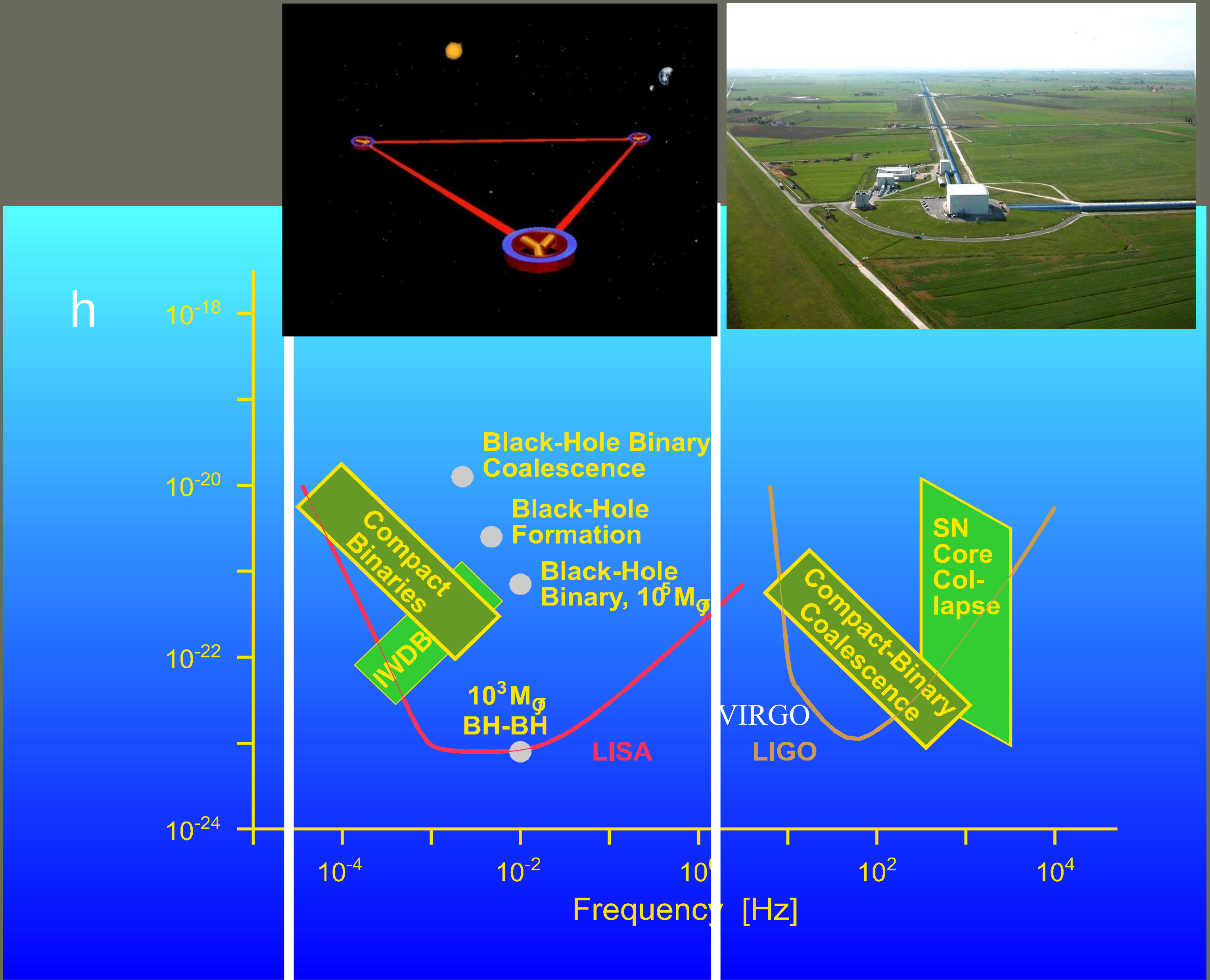
6×10^{9} times better than Michelson/Morley 1887!

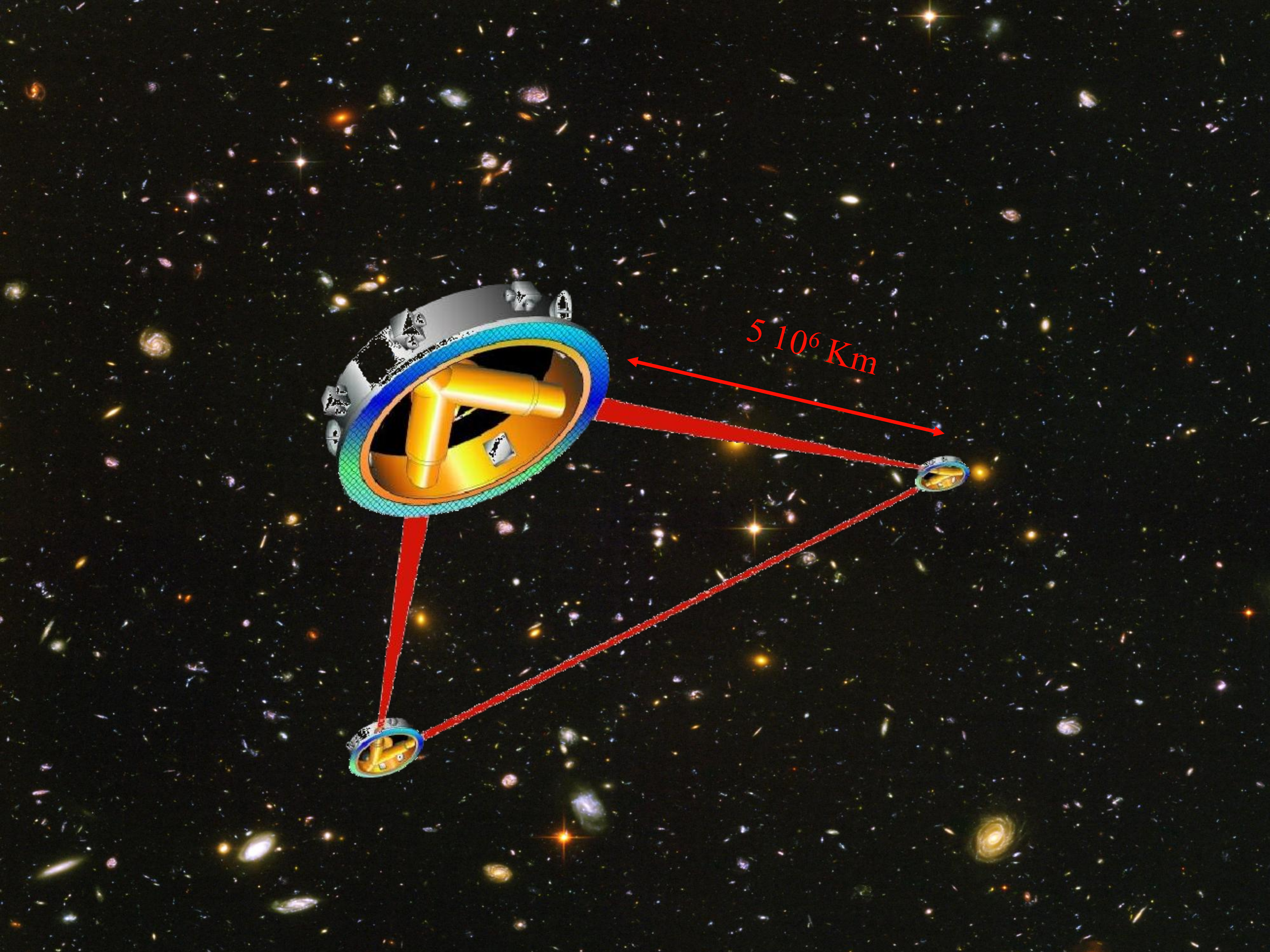


How to completely get away with the seismic wall?



Go into space : LISA interferometer





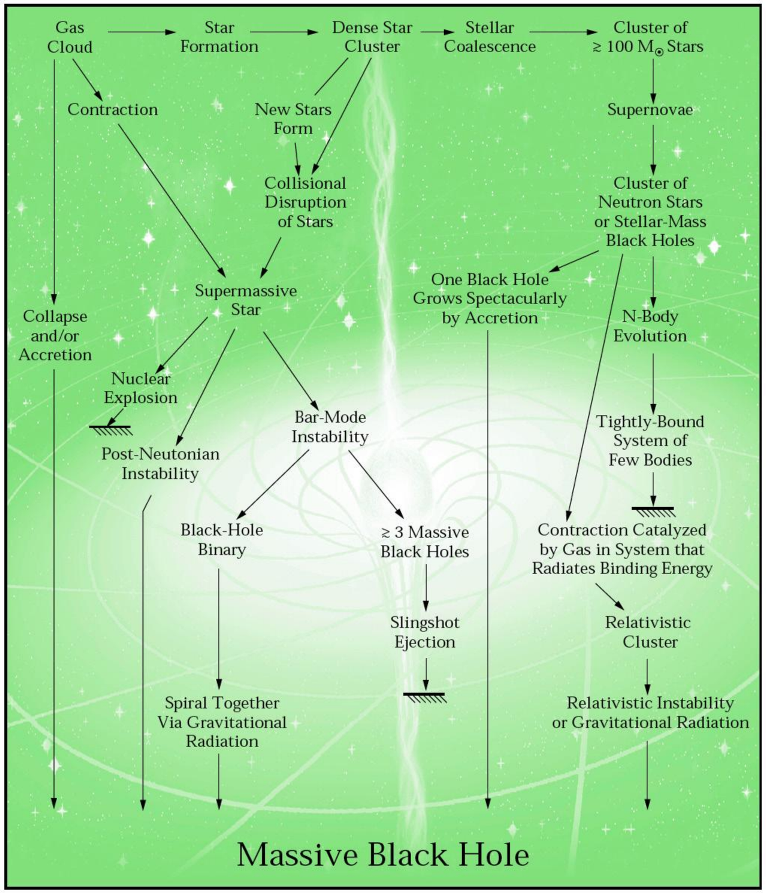
$5\ 10^6$ Km

QuickTime™ et un
décompresseur Cinepak
sont requis pour visionner cette image.

One finds such supermassive black holes at the centre of most, if not all galaxies.

How did they form?

Strongly connected with galaxy formation.



4. Supernova explosions

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

Classification of supernovae according to spectroscopy:

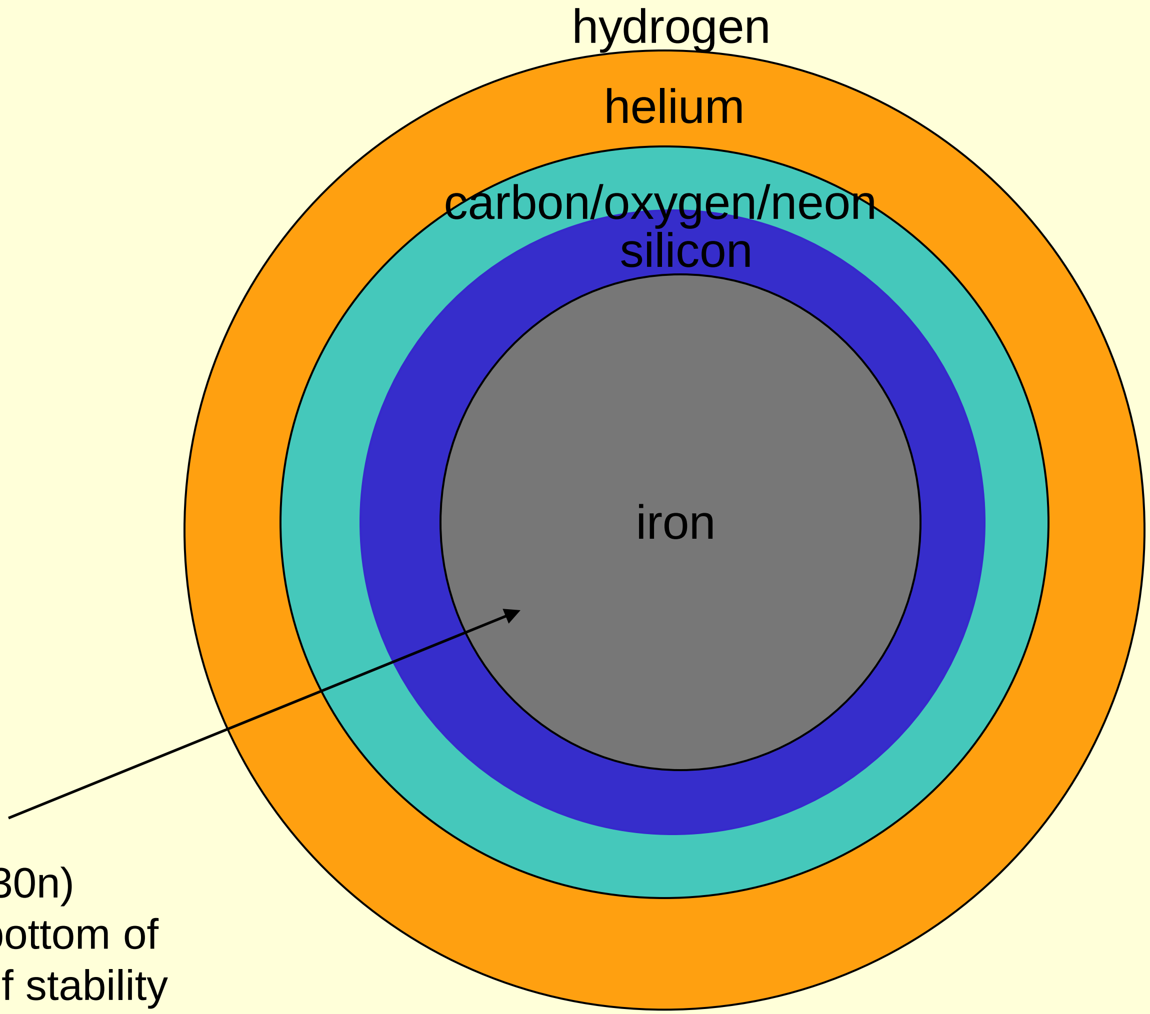
I : Hydrogen lines are absent

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

II : Hydrogen lines are present

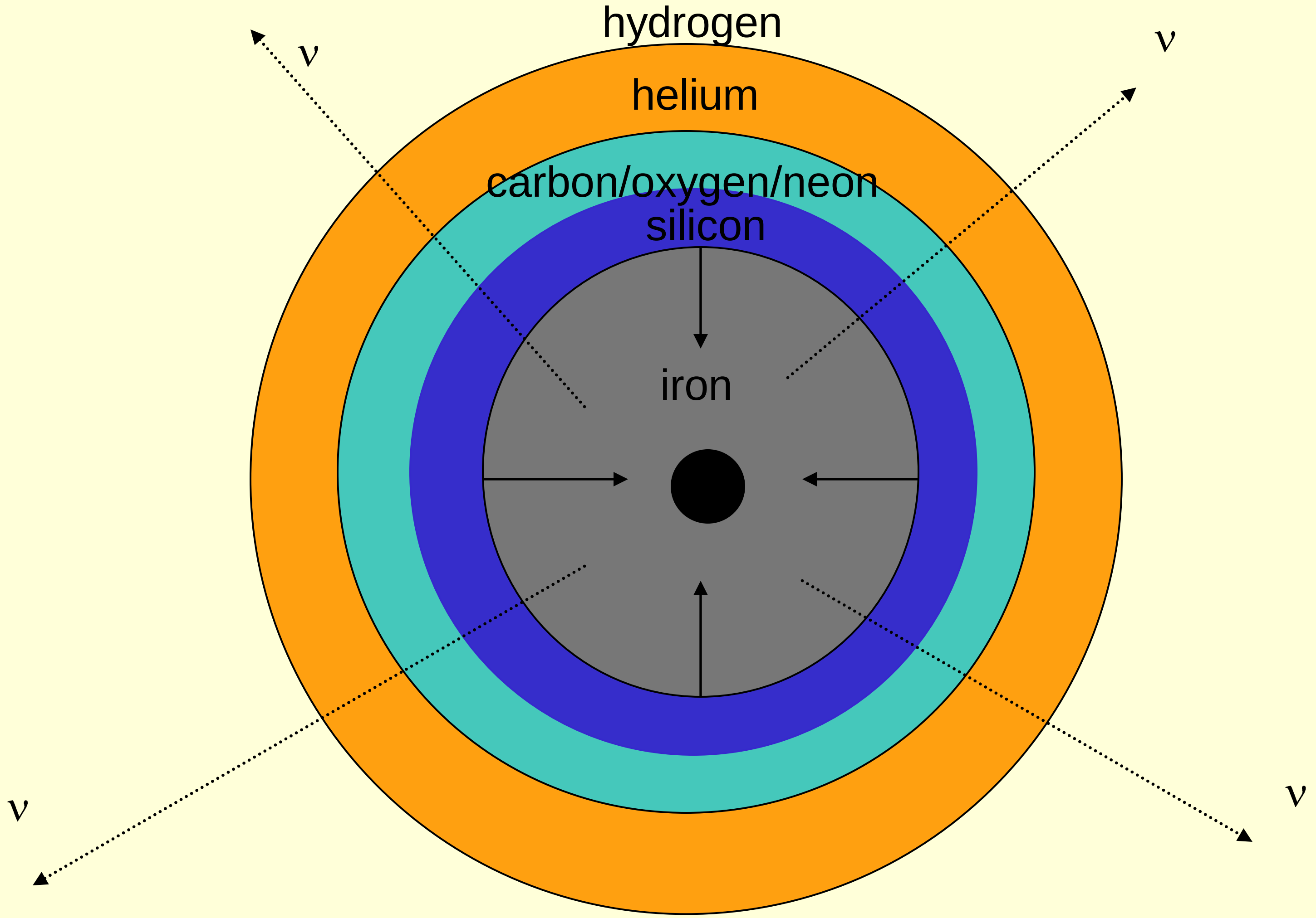
Supernovae of type II

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

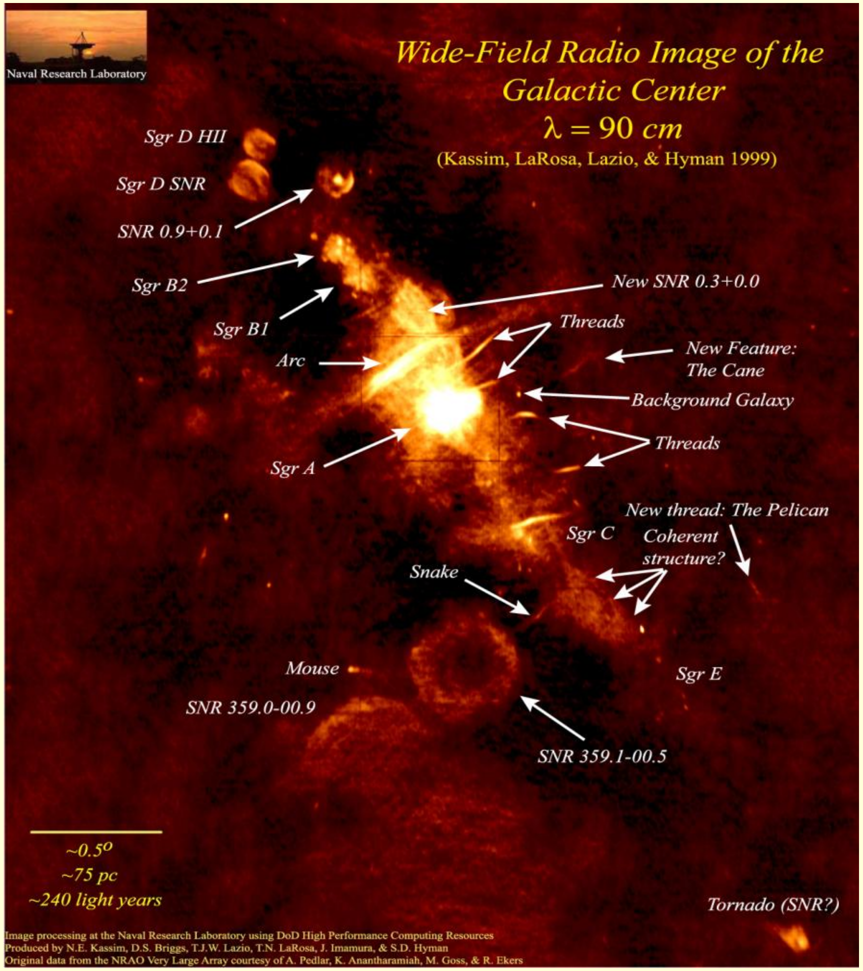


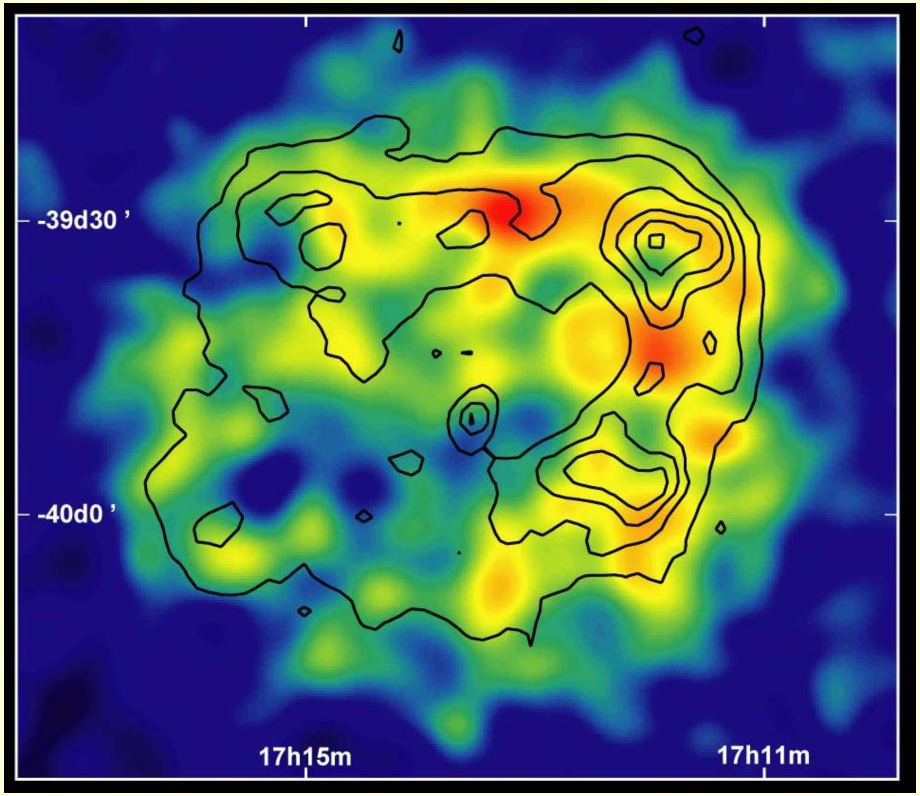
^{56}Fe (26p+30n)
lies at the bottom of
the valley of stability

As Si is burned, the mass of the Fe core increases. The density increase turns the electrons relativistic and favours e+p → n+ν. 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. Anantharamaiah, M. Goss, & R. Ekers

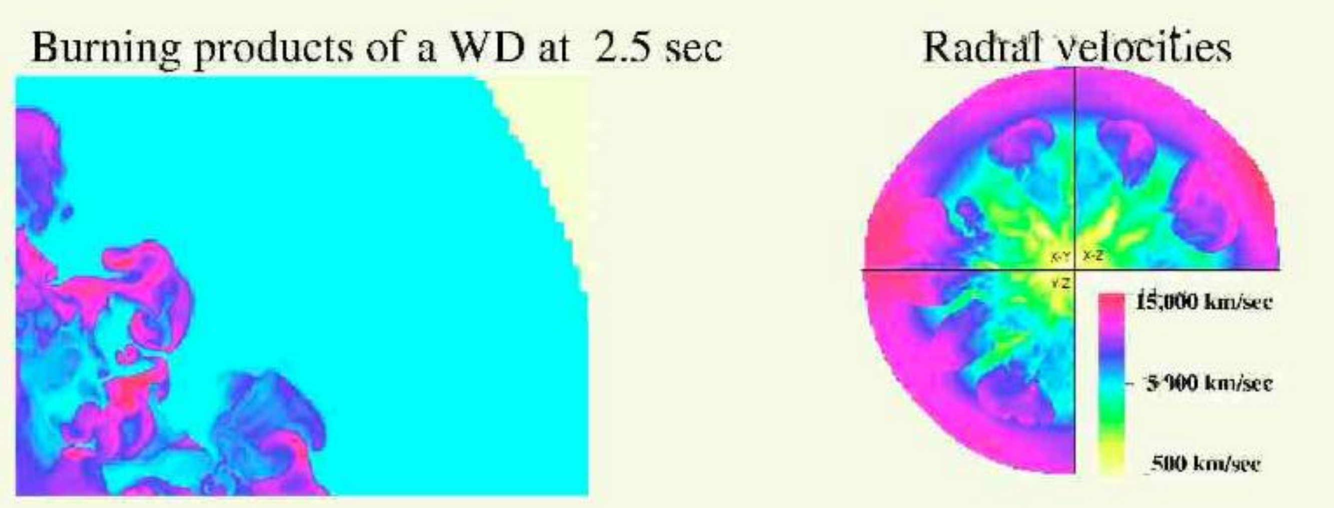

-39d30 ’
-40d0 ’
17h15m
17h11m

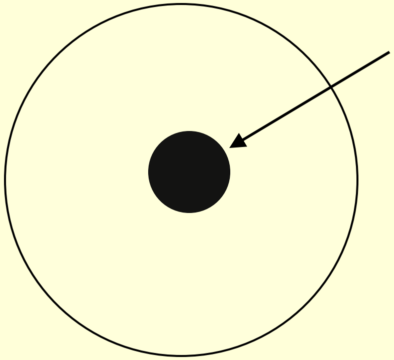
HESS

Supernovae of type Ia

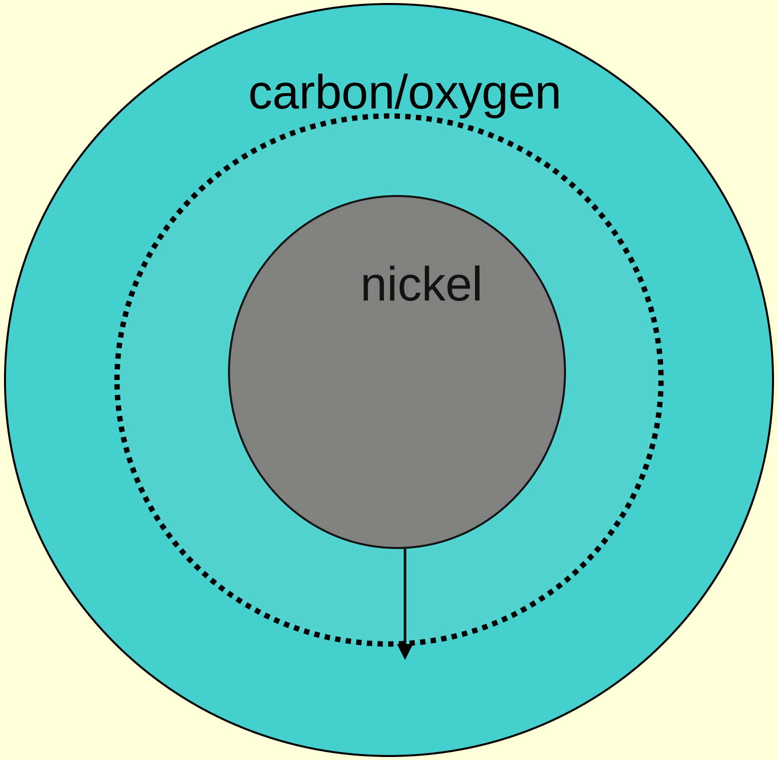
Thermonuclear explosion of white dwarfs:

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



carbon/oxygen

nickel

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

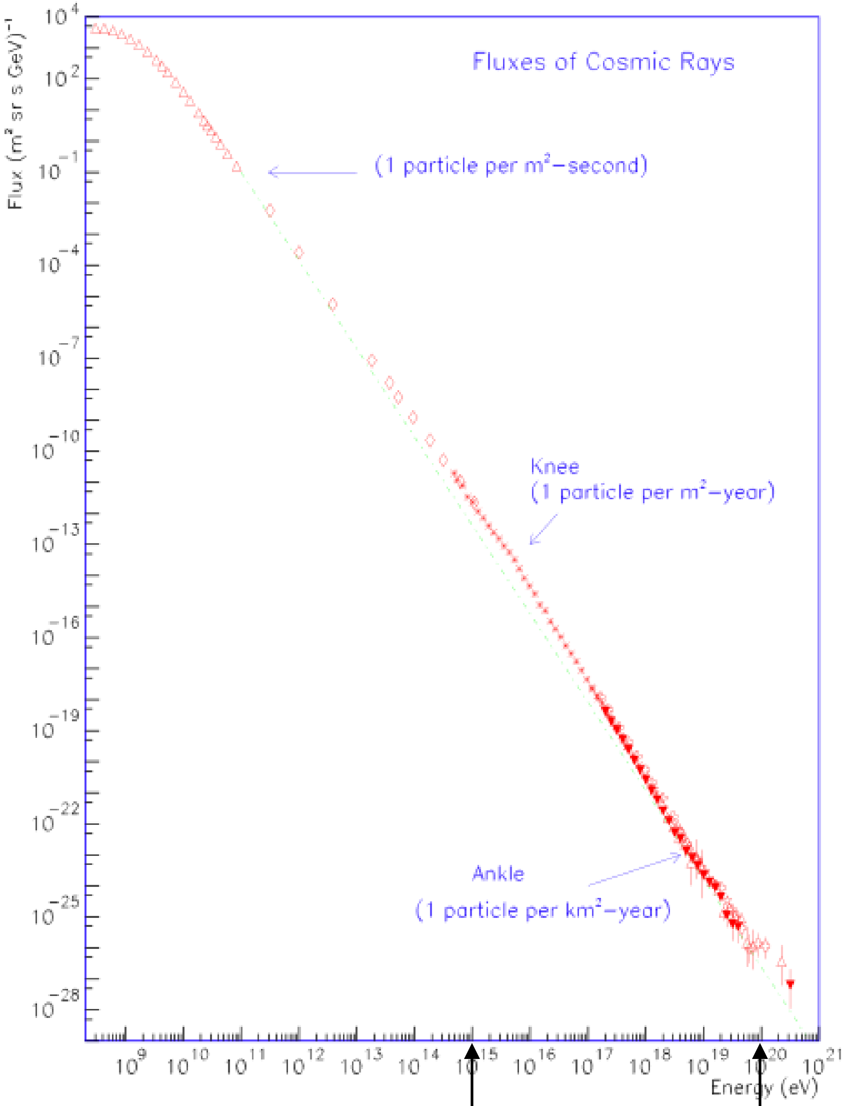
→ ^{56}Co and ^{56}Fe

(weak interactions)

5. Cosmic rays and cosmic acceleration

Flux of cosmic rays vs energy

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



Flux ∝ E^{-3}

Single origin for the acceleration?

QuickTime™ et un décompresseur sont requis pour visionner cette image.

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: $$n = \frac{\ln(E/E_0)}{\ln(1+\xi)}$$

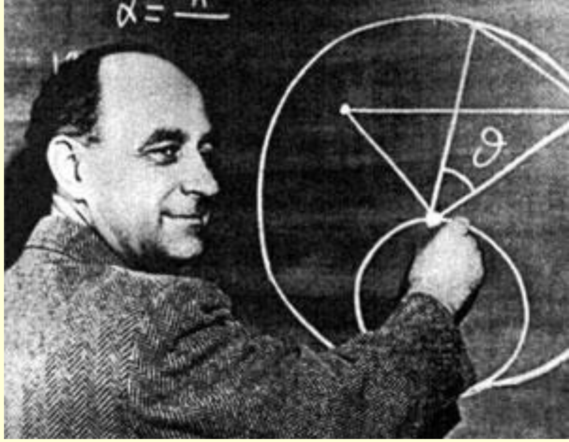
Define P_{esc} as the probability to escape the acceleration region per encounter, $(1-P_{esc})^k$ is the probability of remaining in the region after k encounters and the number of particles accelerated beyond energy E is

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

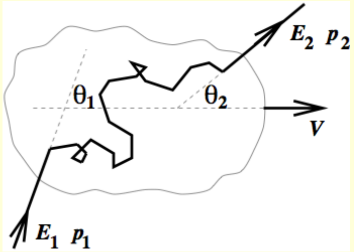
$$\boxed{N(>E) \propto \frac{1}{P_{esc}}\left(\frac{E}{E_0}\right)^{\alpha}}$$

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

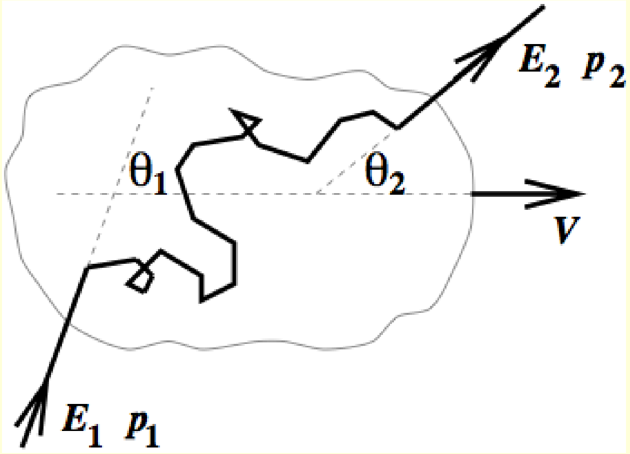
Fermi mechanism



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

$$\beta = V/c$$

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

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

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

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

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

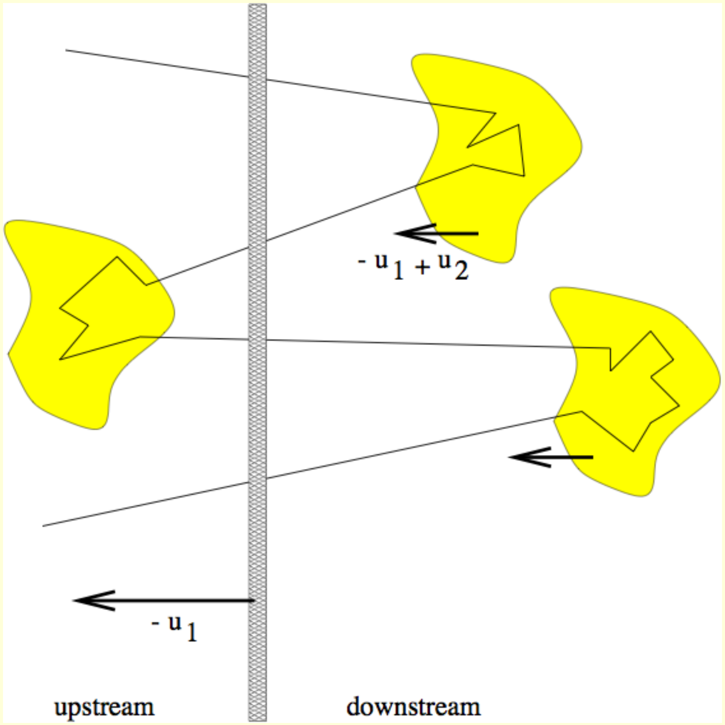
Since $$\frac{dP}{d\cos\theta_1} = \frac{c - V\cos\theta_1}{2c} \qquad < \cos\theta_1 > = - \beta/3$$

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

$$\frac{dP}{d\cos\theta'_2} = \text{cst} \qquad < \cos\theta'_2 > = 0$$

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.



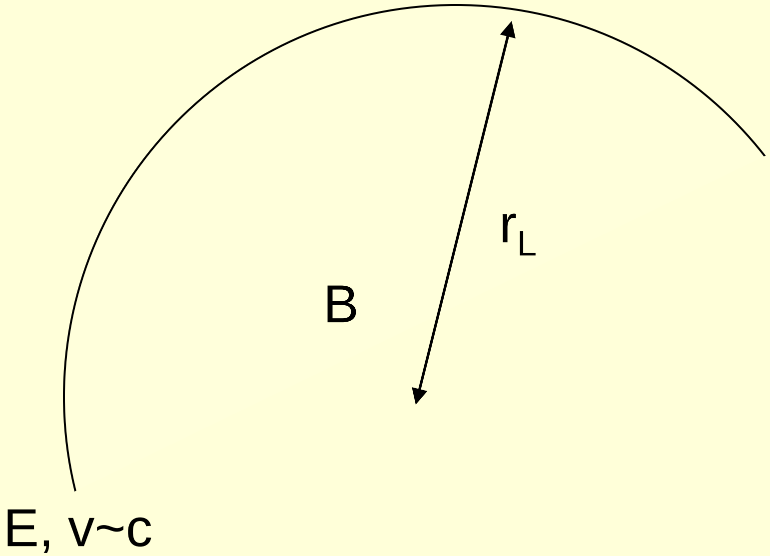
$\xi \sim 4\beta/3$

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:

$r_L = E/(qBc)$

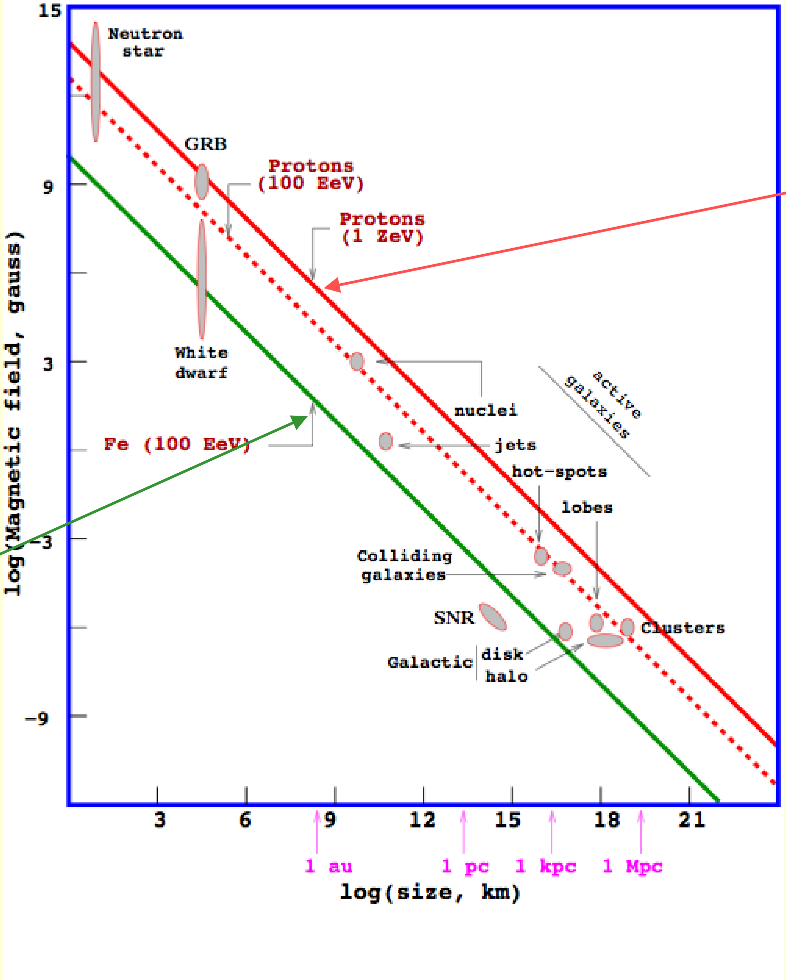
When the energy E increases, r_L may become larger than the size R of the accelerating site.

$$\boxed{E < E_{max} = qBcR = Z \frac{B}{1\mu G} \frac{R}{1Mpc} 9.3x10^{20}eV}$$

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).

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

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

→ Possibility with more statistics to identify the sources

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

Astroparticle physics

III - The Universe at large

Pierre Binétruy
APC, Paris

CERN Summer Student Lecture Programme 2010

Outline

1. Indirect detection of dark matter

2. Looking for standard candles to study dark energy

1. Indirect detection of dark matter

Weakly interacting massive particles remain the best candidate for dark matter (see L. Verde's lectures).

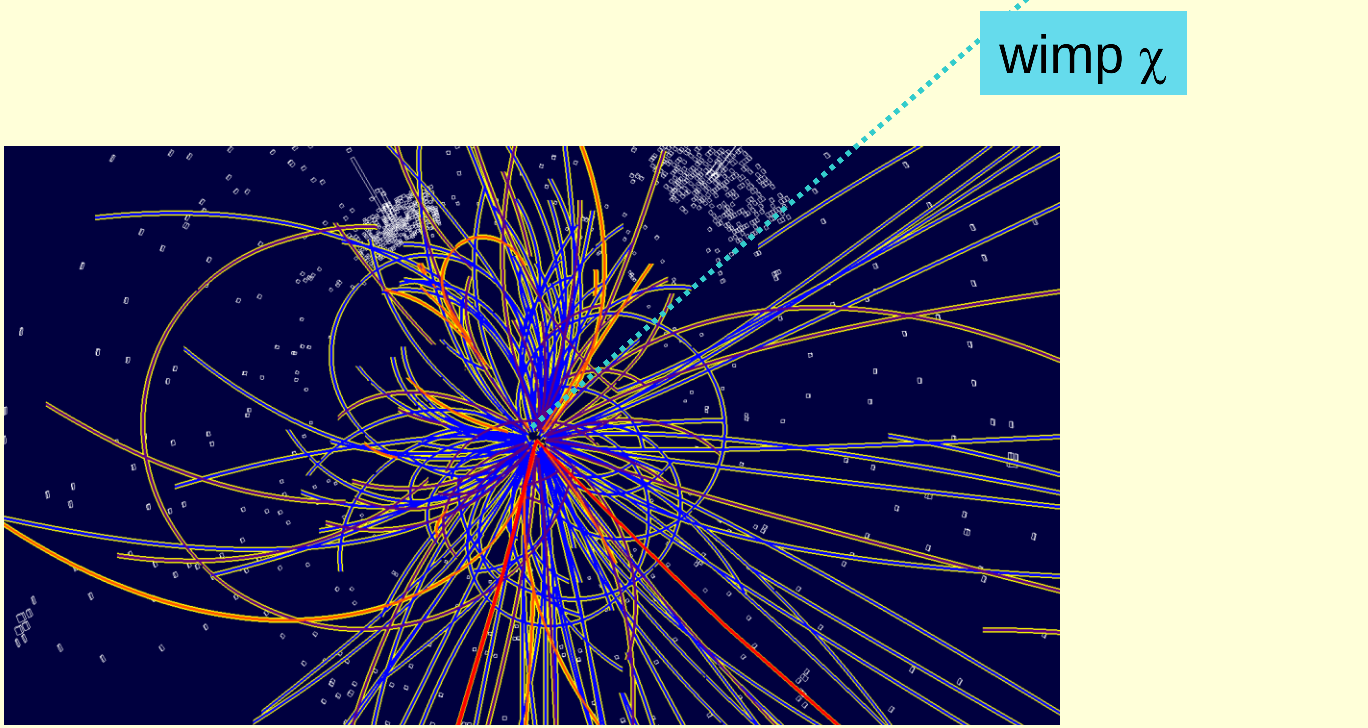
Typically particles with mass around 100 GeV and interactions of the type of the weak interactions of the Standard Model

Appear naturally in many extensions of the Standard Model (in particular Supersymmetry)

They will be searched for at LHC…

These particles are stable and leave the detector unseen while taking away some of the energy :

Signature : missing energy



Simulated event in CMS detector

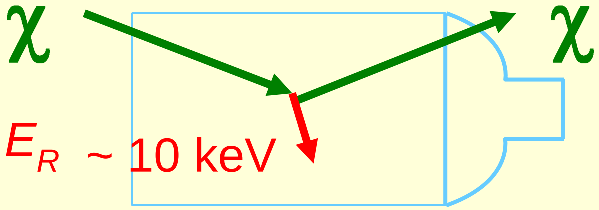
If one discovers at LHC one or several weakly interacting massive stable particles, will this be dark matter?

Not necessarily :

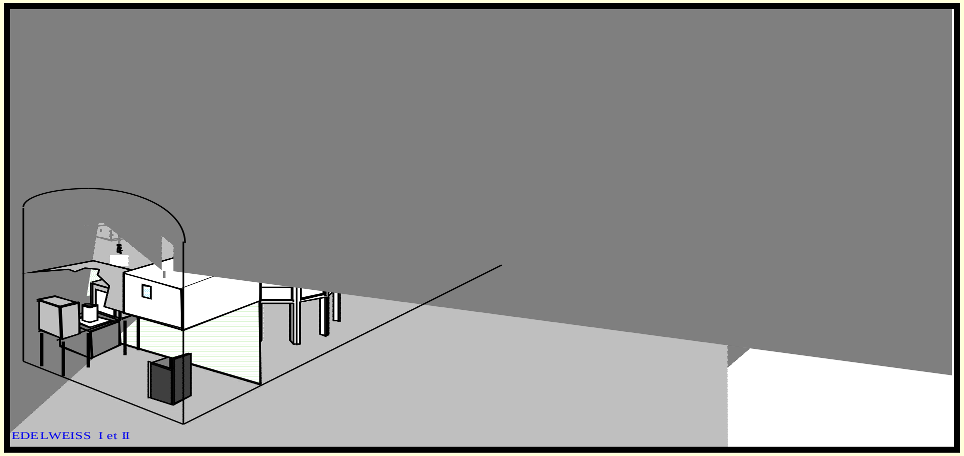
- numerous tests to make to identify their properties: mass, coupling to other particles

- necessary to show that these particles exist in our environment

- direct detection

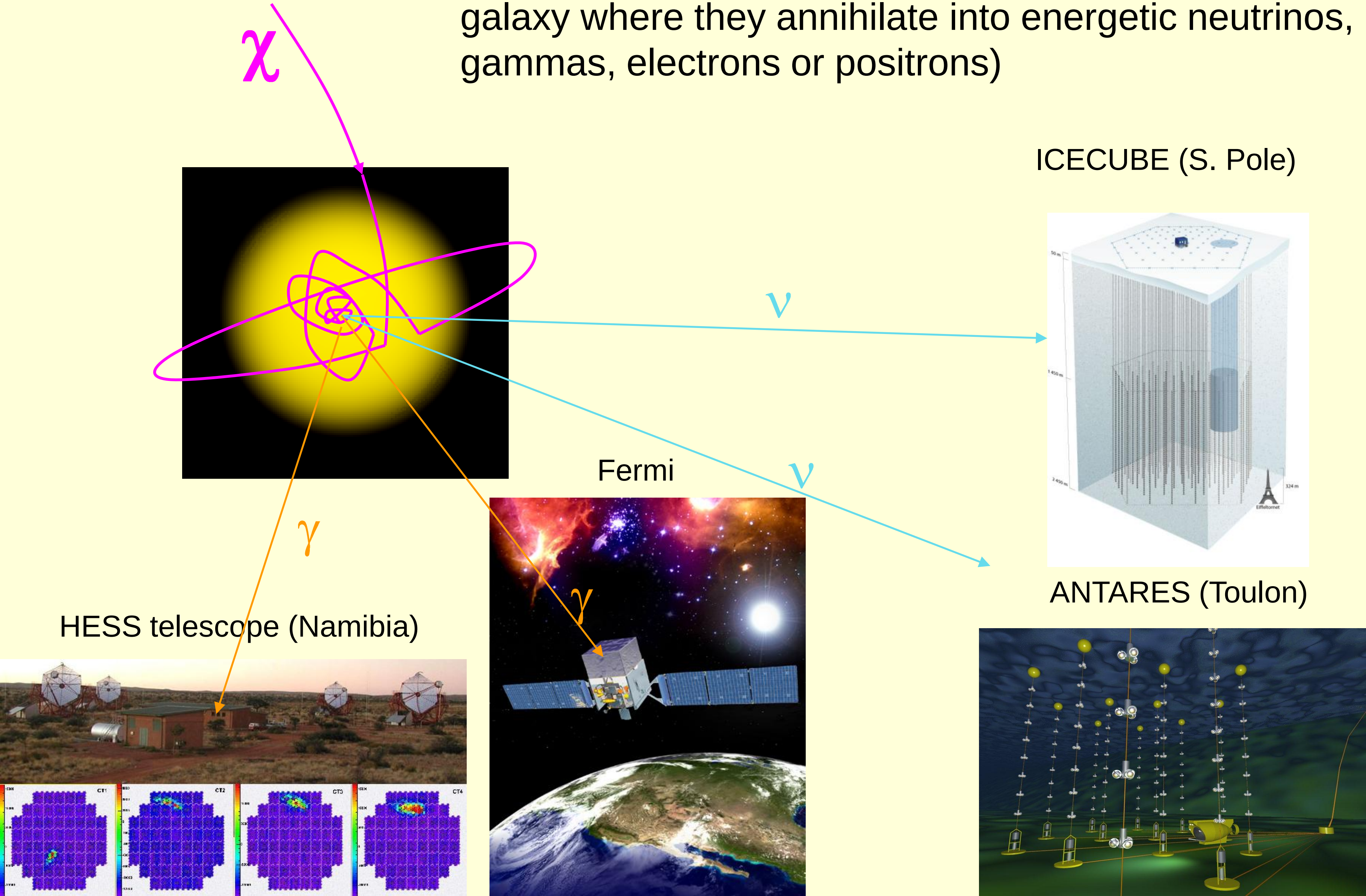


Underground sites
(mines, tunnels…)



Modane lab

- indirect detection (wimps accumulate at the centre of the Sun or of the galaxy where they annihilate into energetic neutrinos, gammas, electrons or positrons)



ICECUBE (S. Pole)

Fermi

ANTARES (Toulon)

HESS telescope (Namibia)

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

A few surprises!

From PAMELA which detects antiprotons and positrons

antiproton flux

No excess in antiprotons

QuickTime™ et un décompresseur sont requis pour visionner cette image.

Excess in positrons

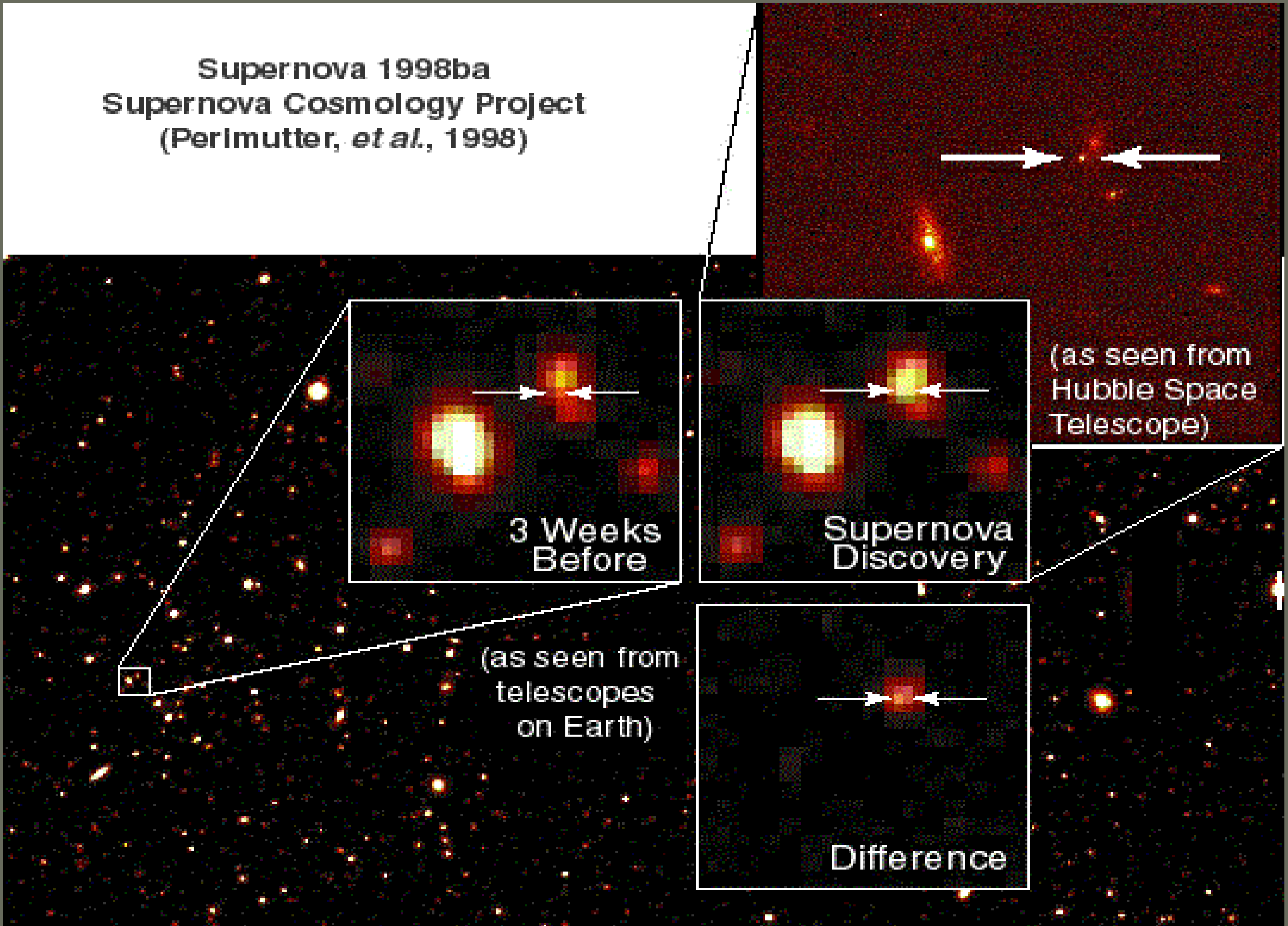
If it is dark matter, it is non-standard because it couples preferentially to leptons.

Astrophysical source?

QuickTime™ et un
décompresseur
sont requis pour visionner cette image.

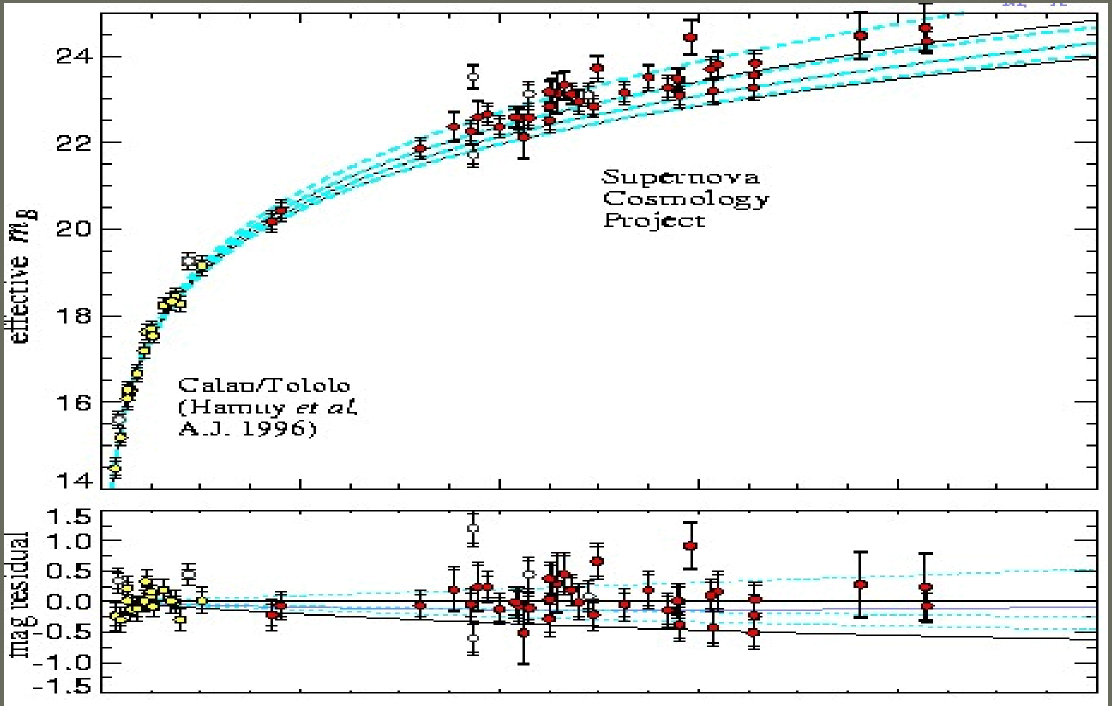
2. Looking for standard candles

Supernovae of type Ia may be used as standard candles to test the geometry of spacetime


Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)

Distant supernovae appear less bright than in an expanding universe

⇒ accelerated expansion



$$\boxed{m_B = 5 \log(H_0 d_L) + M - 5 \log H_0 + 25}$$

luminosity distance $d_L = l_{H0}\, z \left(1 + \frac{1-q_0}{2} z + \ldots \right)$

q_0 deceleration parameter

Why do supernova explosion of type Ia provide standard candles?

Origin: white dwarf where gravitational force is counterbalanced by electron degeneracy pressure (hence independent of the details of the chemical composition)

The star is completely disrupted and all the energy of the explosion goes into the expansion of the products.

But the luminosity depends on the amount of Ni synthesized;
for instance, less Ni means lower luminosity, but also lower temperature
In the gas and thus less opacity and more rapide energy escape:
dimmer supernovae are quicker.

QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

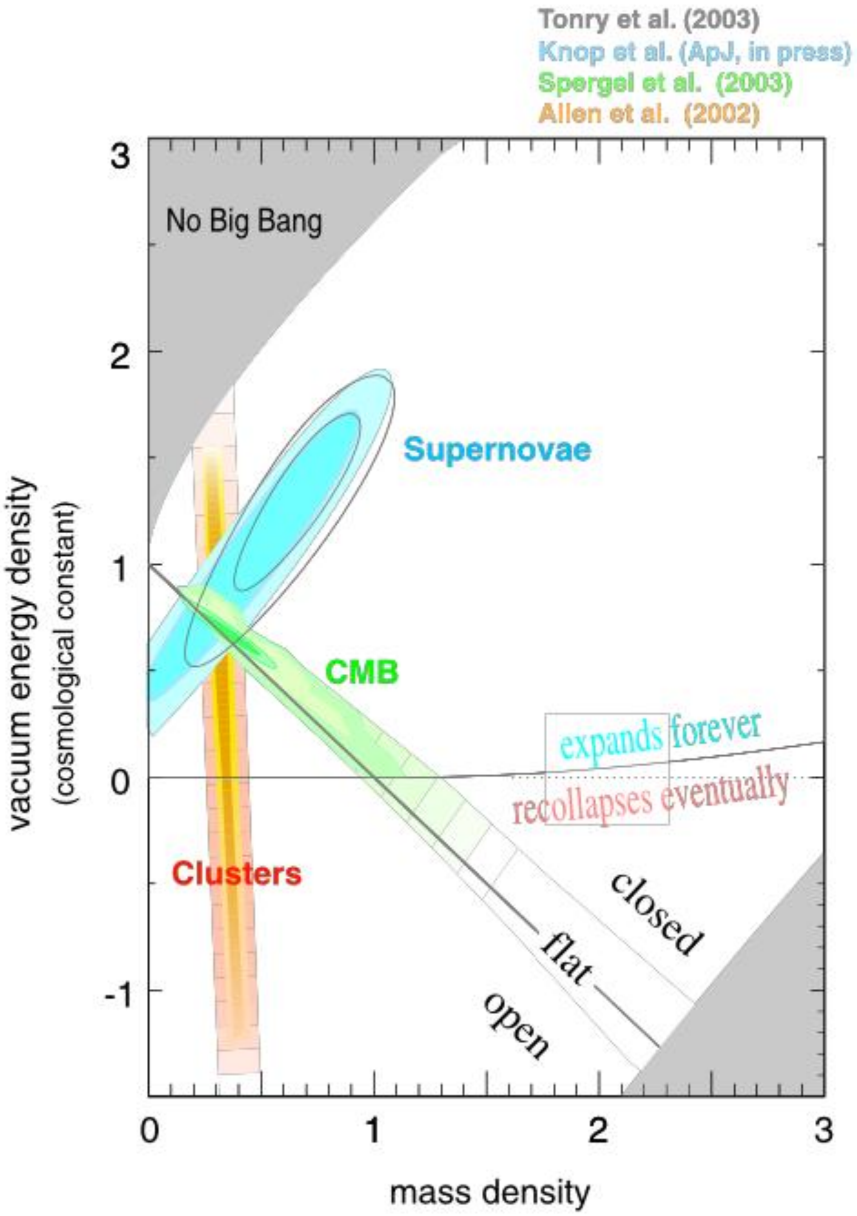
Could this be explained by a cosmological constant ?

Plot $(\Omega_\Lambda , \Omega_M)$:

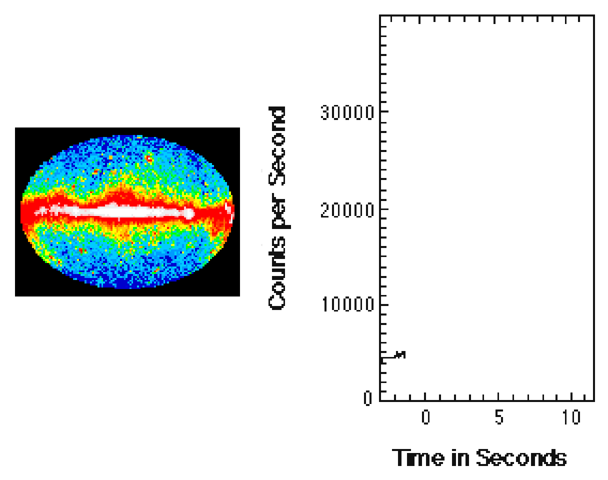
$$\Omega_\Lambda = \rho_\Lambda/\rho_c , \ \Omega_M = \rho_M/\rho_c$$

Concordance model

Note: if this is so, the vacuum energy takes the value expected in the context of gravity.
Associated energy scale :
$\Lambda \sim 10^{-3}$ eV

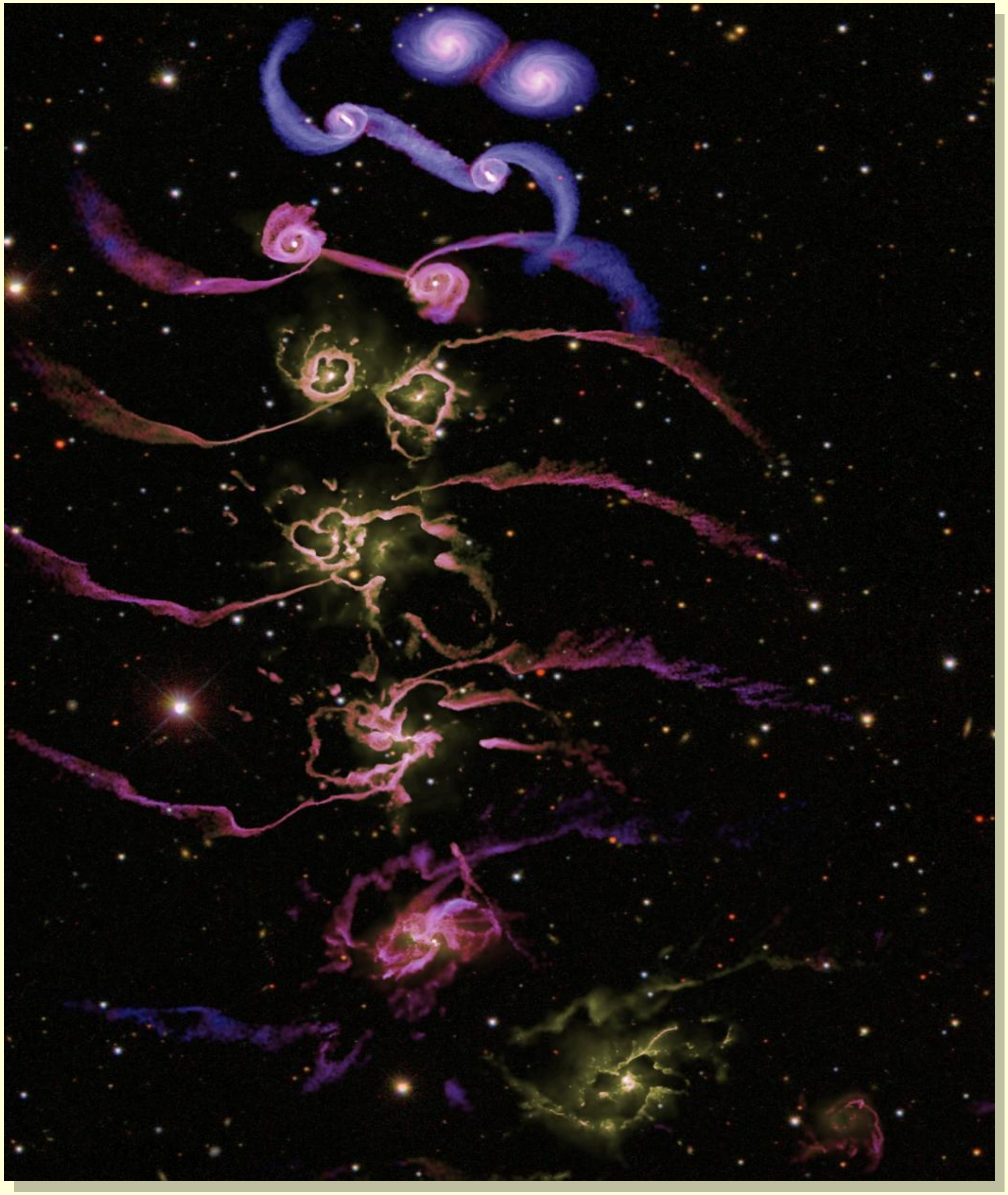


✓ Gamma ray bursts



Determine the luminosity through a relation between the collimation corrected energy E_γ and the peak energy

- ✓ Coalescence of supermassive black holes



Inspiral phase

Key parameter : chirp mass

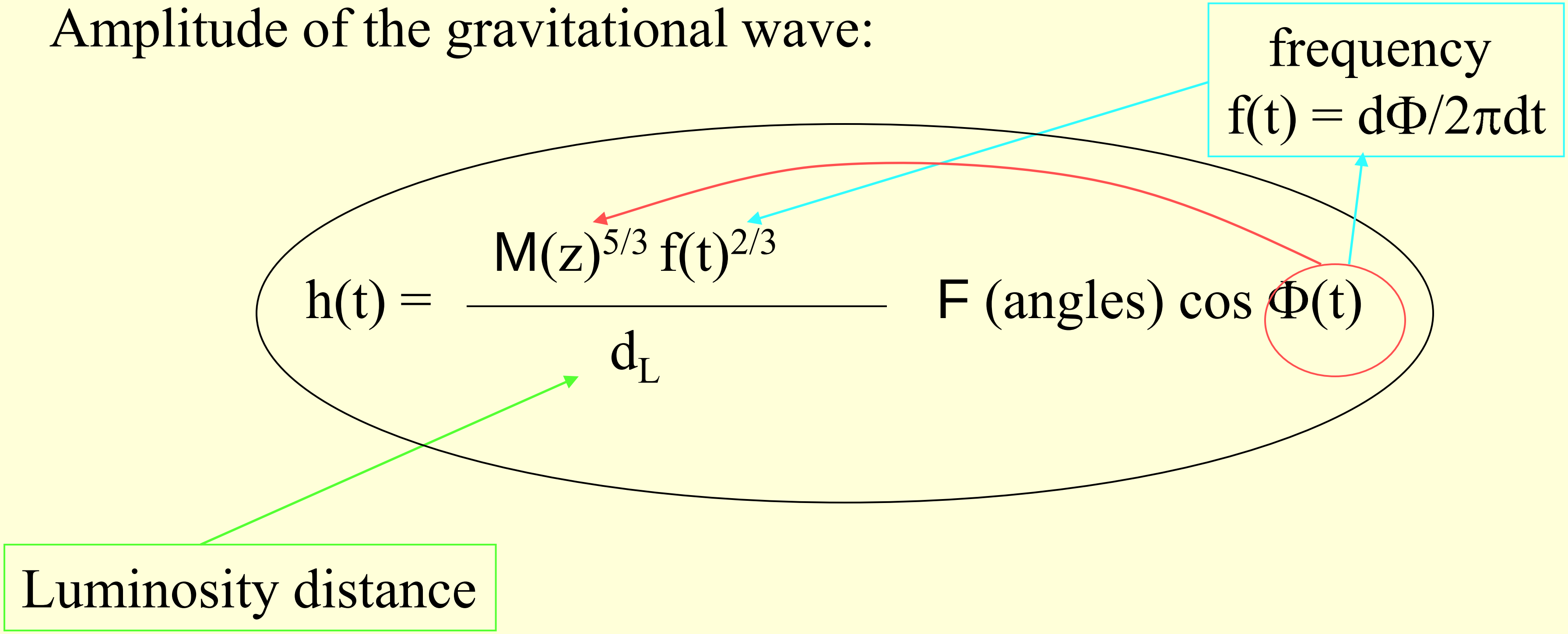
$$\boxed{M_{(z)} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} (1+z)}$$

Inspiral phase

Key parameter : chirp mass

$$\mathrm{M}_{(z)} = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \; (1+z)$$

Amplitude of the gravitational wave:



$$h(t) = \frac{\mathrm{M}(z)^{5/3}\, f(t)^{2/3}}{d_L} \; \mathrm{F}\,(\text{angles}) \cos \Phi(t)$$

frequency

$f(t) = d\Phi/2\pi dt$

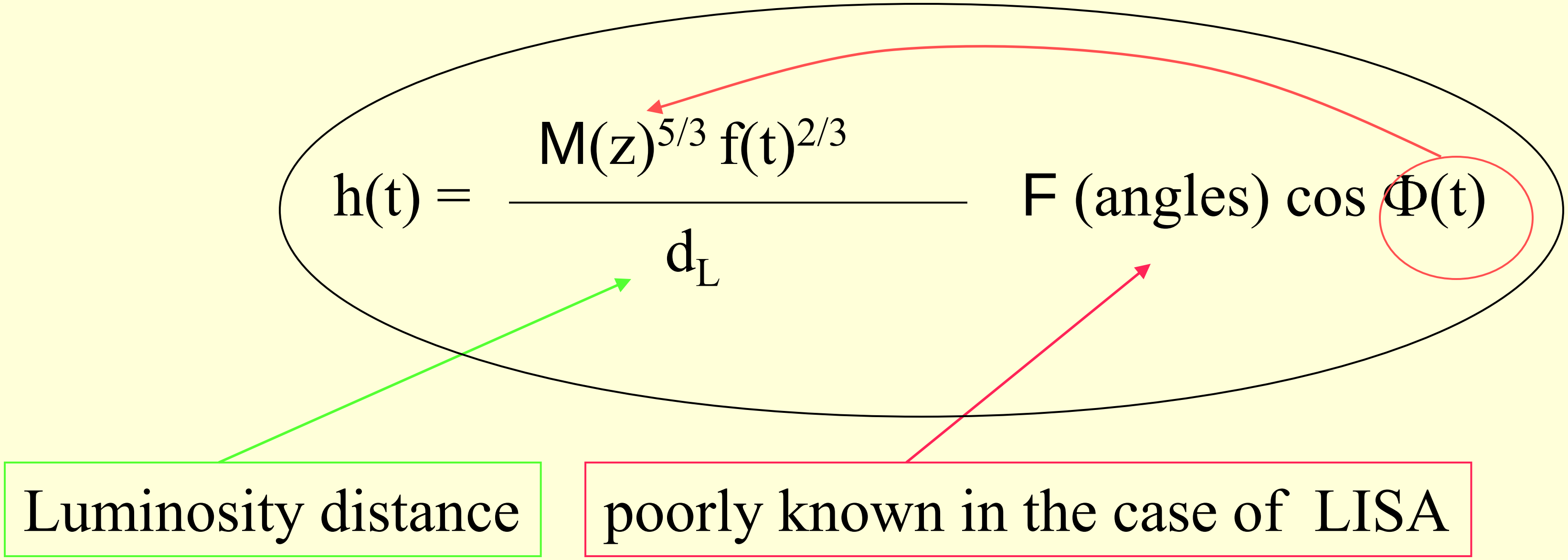
Luminosity distance

Inspiral phase

Key parameter : chirp mass

$$M_{(z)} = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}\;(1+z)$$

Amplitude of the gravitational wave:



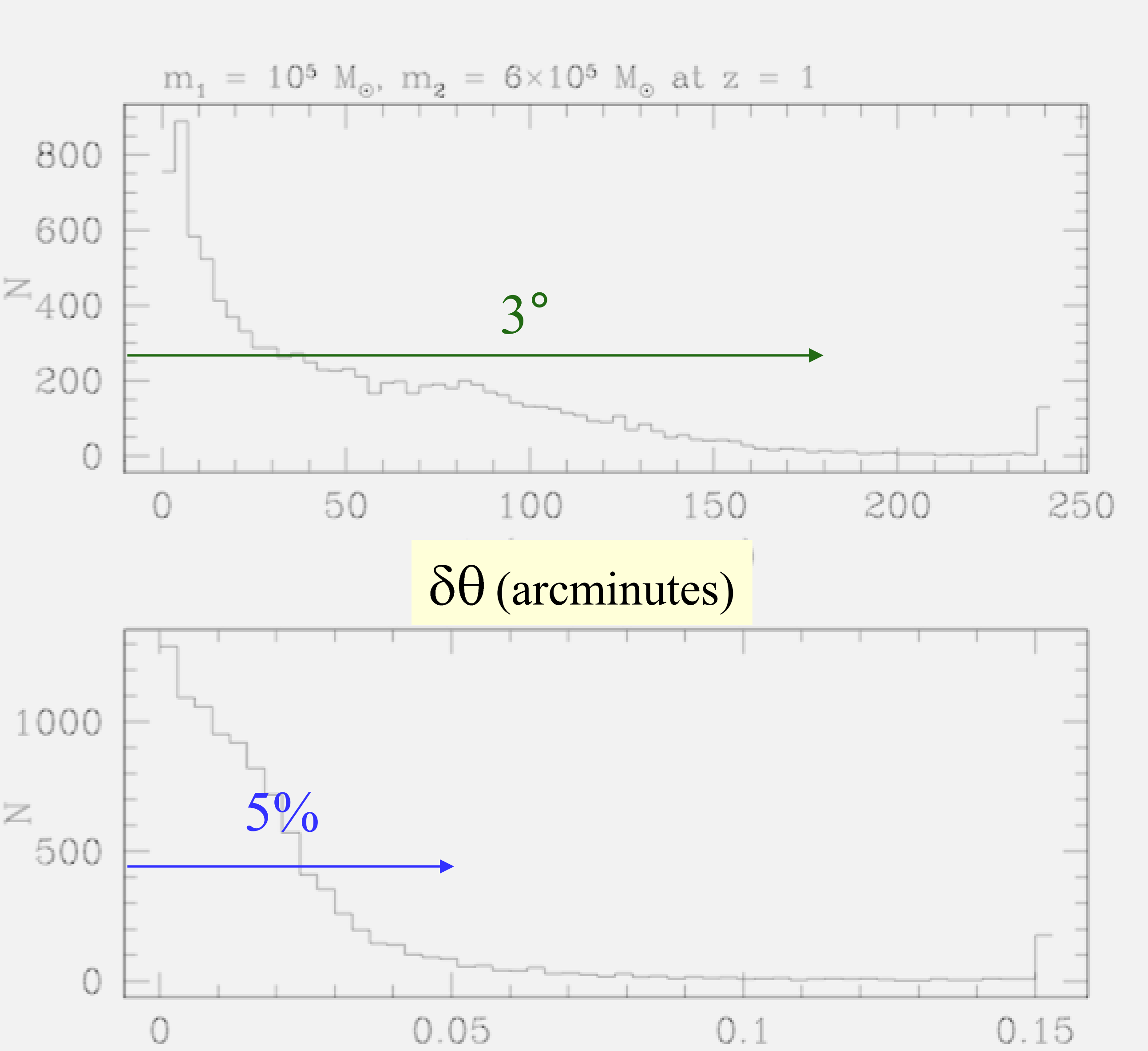
$$h(t) = \frac{M(z)^{5/3}\, f(t)^{2/3}}{d_L}\; F\,(\text{angles})\, \cos \Phi(t)$$

Luminosity distance

poorly known in the case of LISA

$$\Delta\theta \sim \frac{10\ \text{arcmin}}{\text{SNR}}\; \frac{1\ \text{Hz}}{f_{GW}}$$

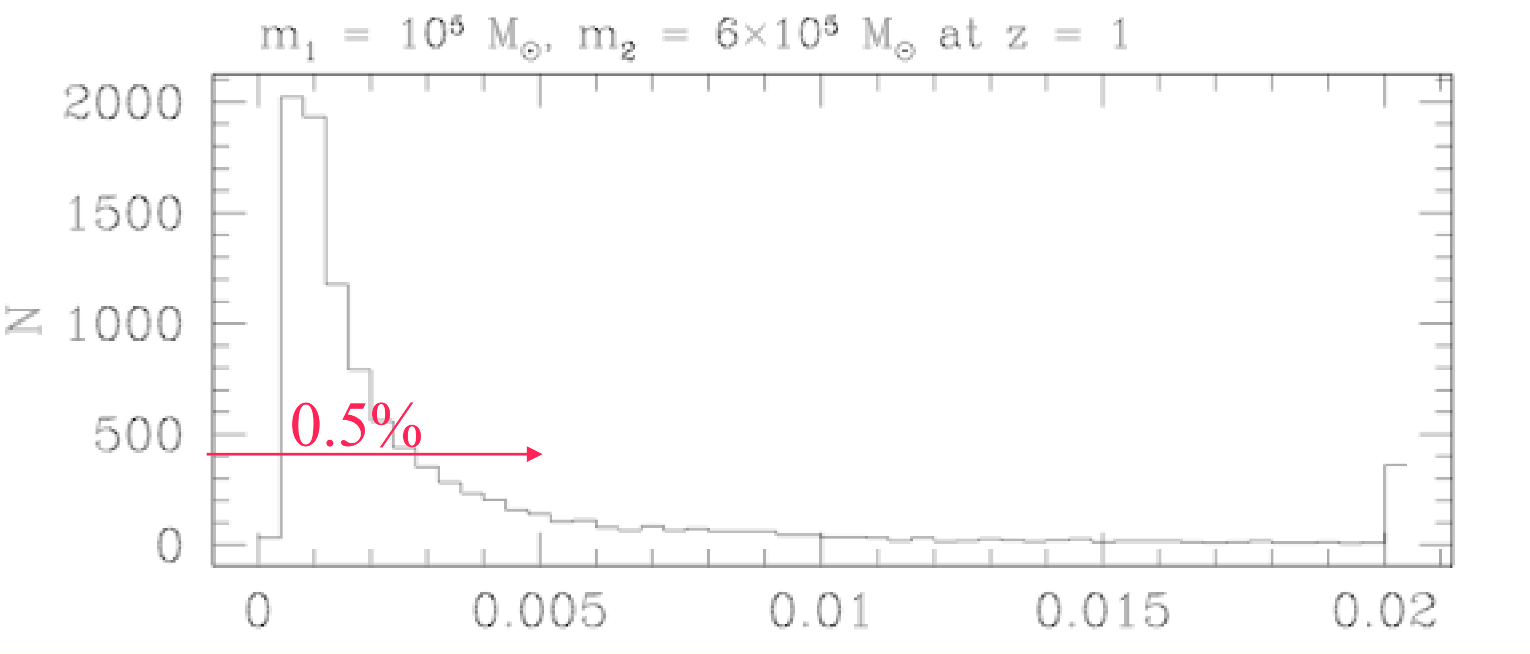
$z = 1$, $m_1 = 10^5\,M_\odot$, $m_2 = 6.10^5\,M_\odot$



Holz & Hughes

Using the electromagnetic counterpart

Allows both a measure of the direction and of the redshift

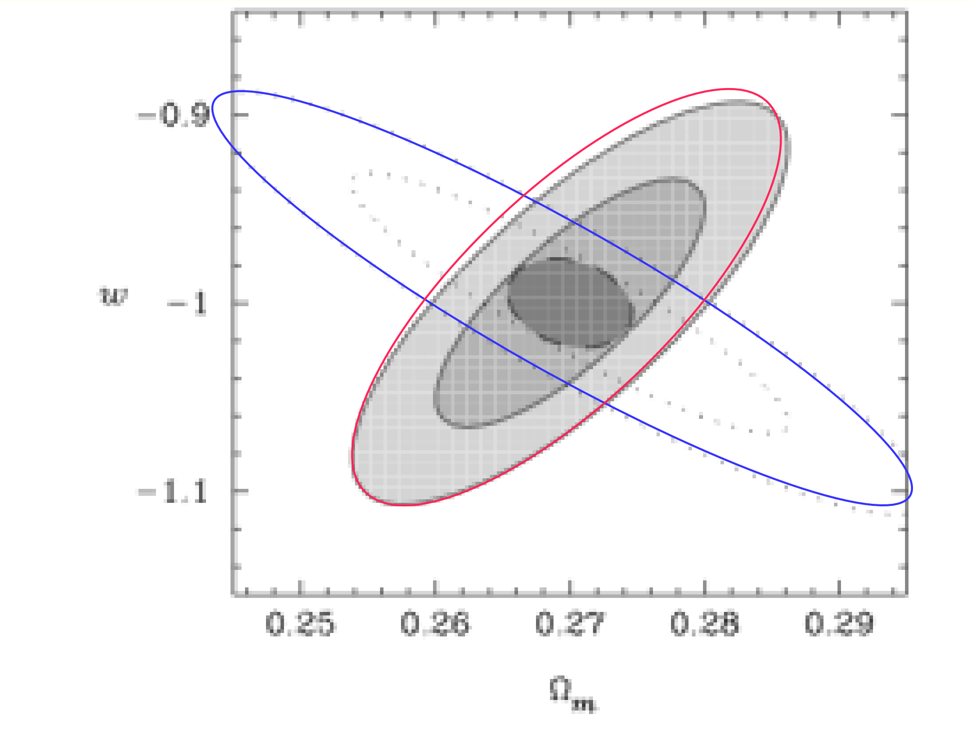


0.5%

$\delta d_L/d_L$

Holz and Hughes

Determining the equation of state of dark matter



3000 supernovae

100 SMBH sources

Dalal et al. astro-ph/0603275

Conclusion

A new window is being opened towards the Universe using the knowledge accumulated over more than 50 years of high energy physics.

Back to where the field started, but this time not to understand the infinitely small, but to grasp the infinitely large.