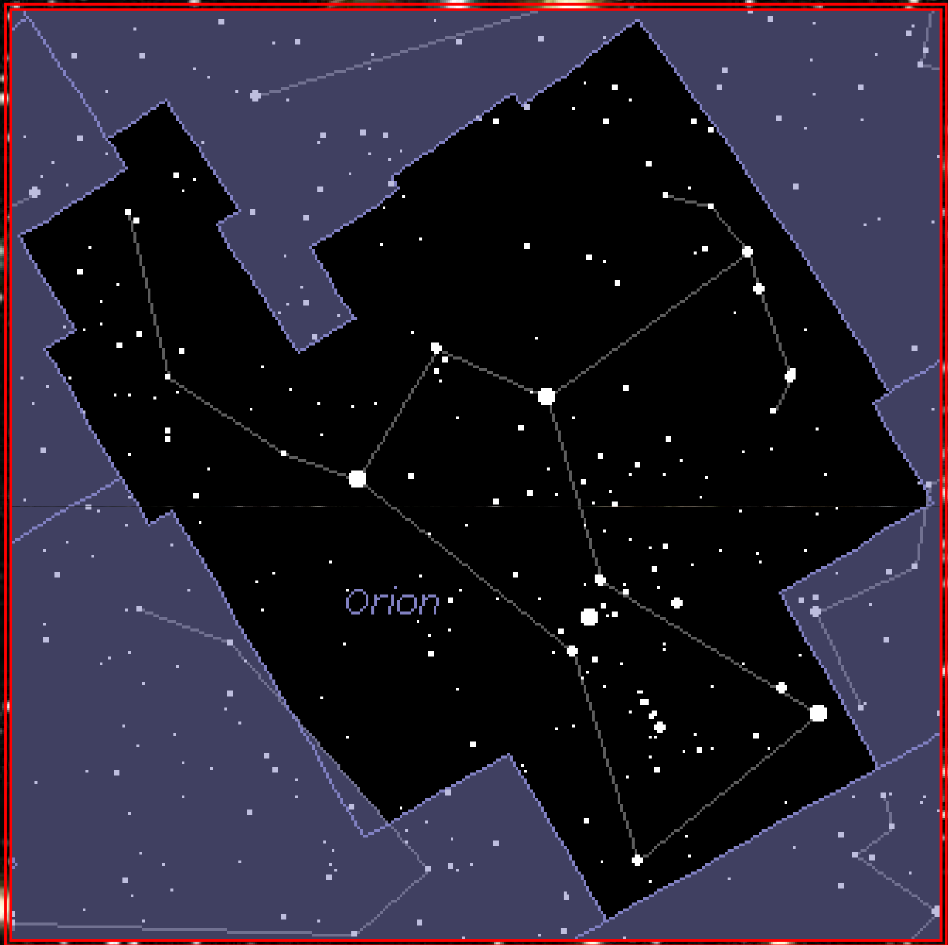
Les nouveaux regards sur l'Univers

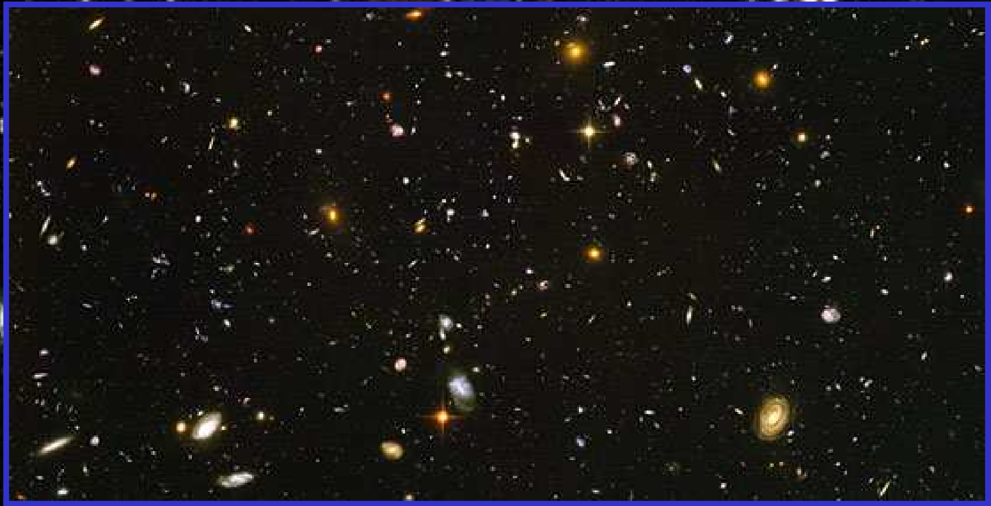
Comment étudier l’Univers

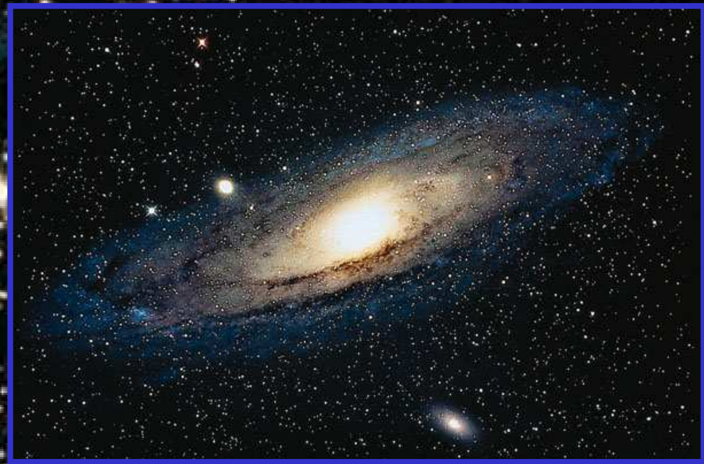
Univers “visible”

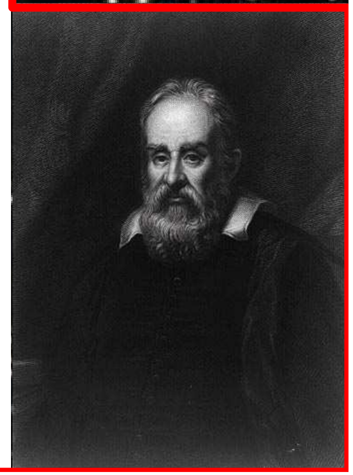
sans télescope



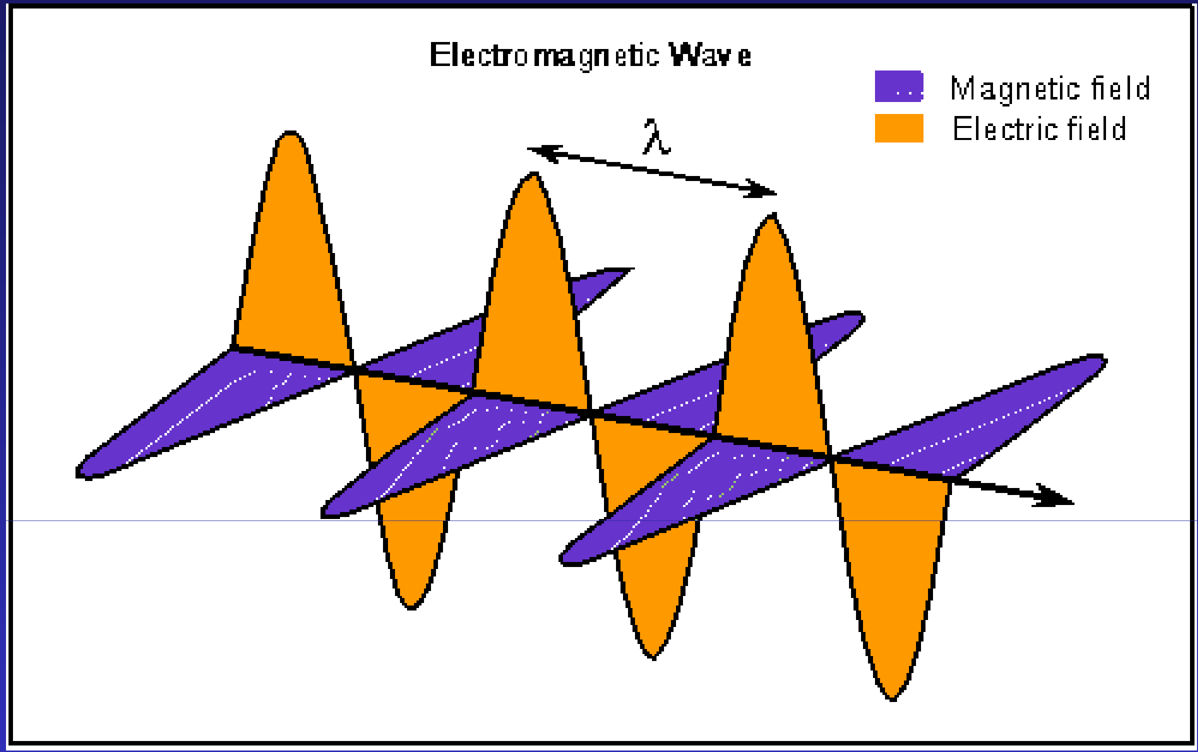
avec télescope







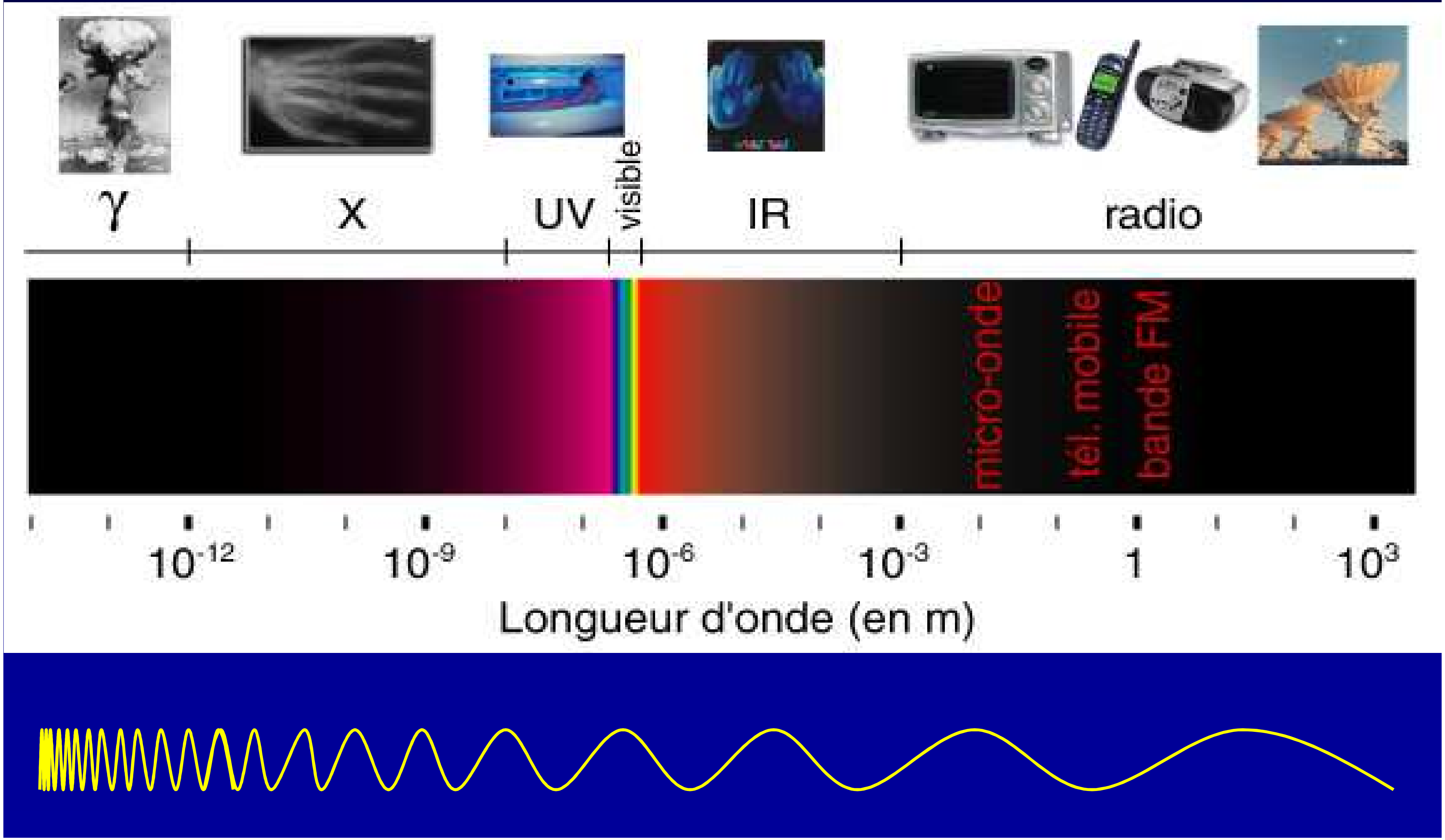
Lumière = Onde Electro-magnétique



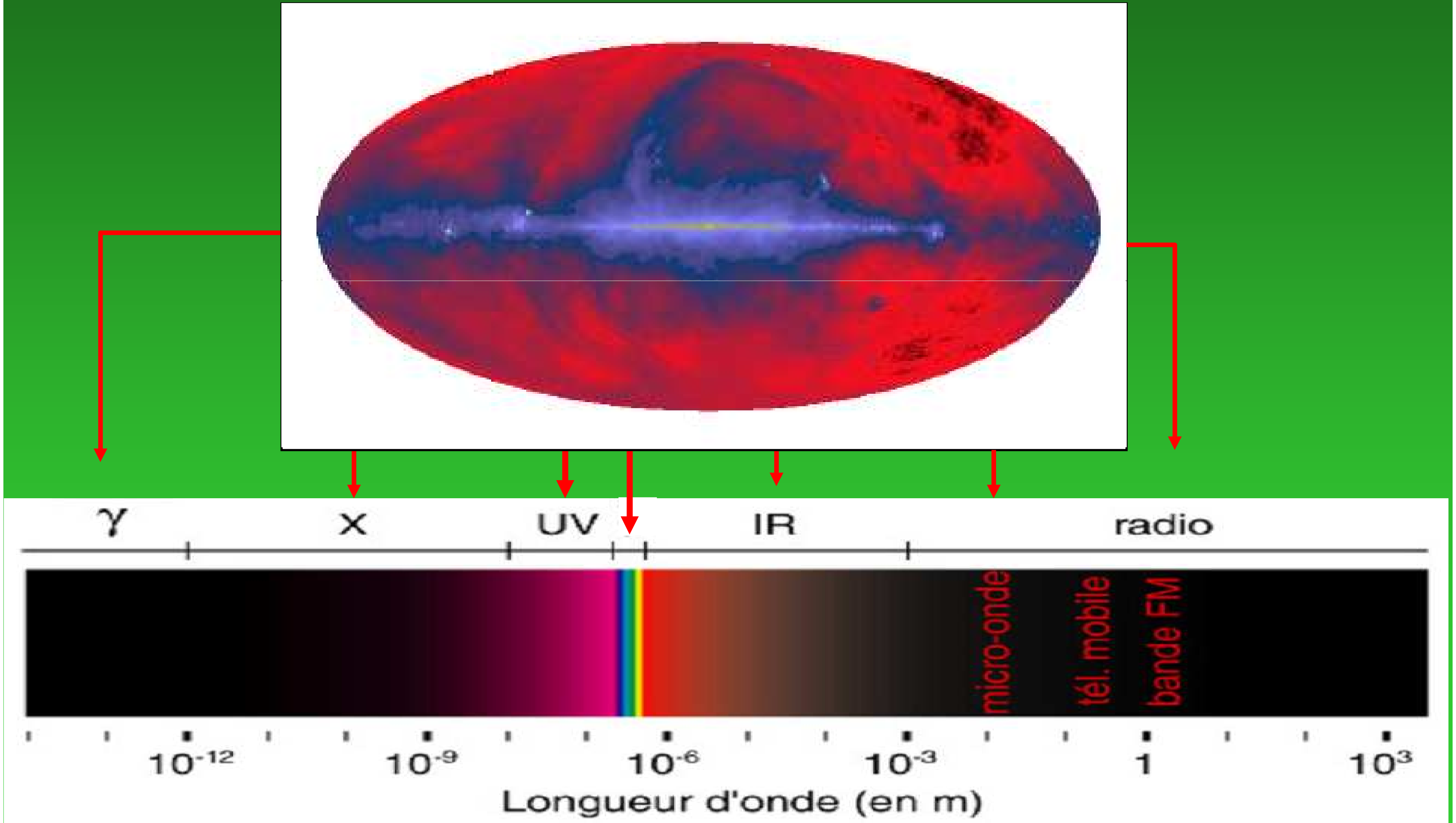
- Longueur d'onde: $\lambda = c/\nu$
- Fréquence: ν (Hz)
- Energie : $E = h\nu$ (photon = grain de lumière)

(Mécanique quantique)

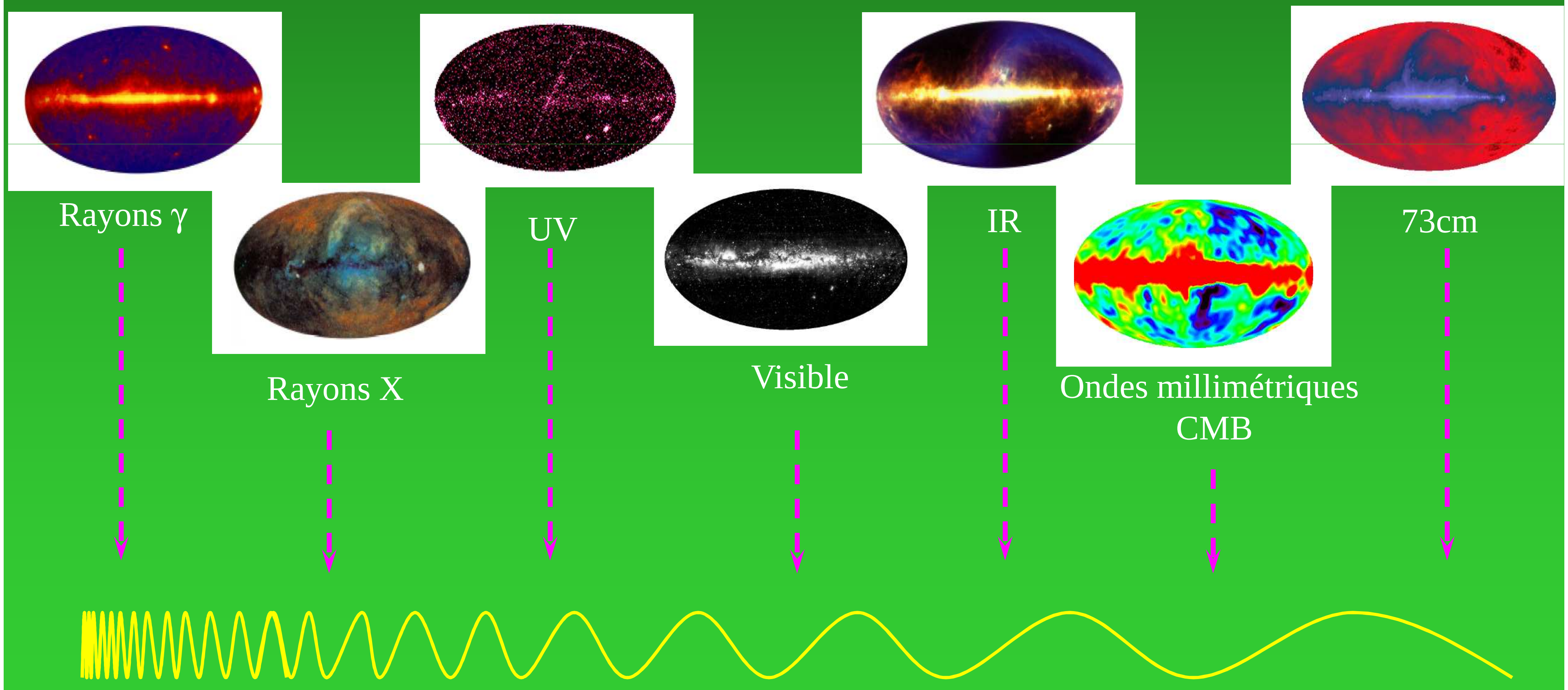
L'Univers à travers les ondes EM



Multiples fenêtres Électromagnétiques ouvertes à l'Univers



Multiples fenêtres Électromagnétiques ouvertes à l'Univers




Les nouvelles fenêtres
Les nouvelles fenêtres
ouvertes à l'Univers


Astronomie neutrino

Les constituants élémentaires de la matière

Charge:

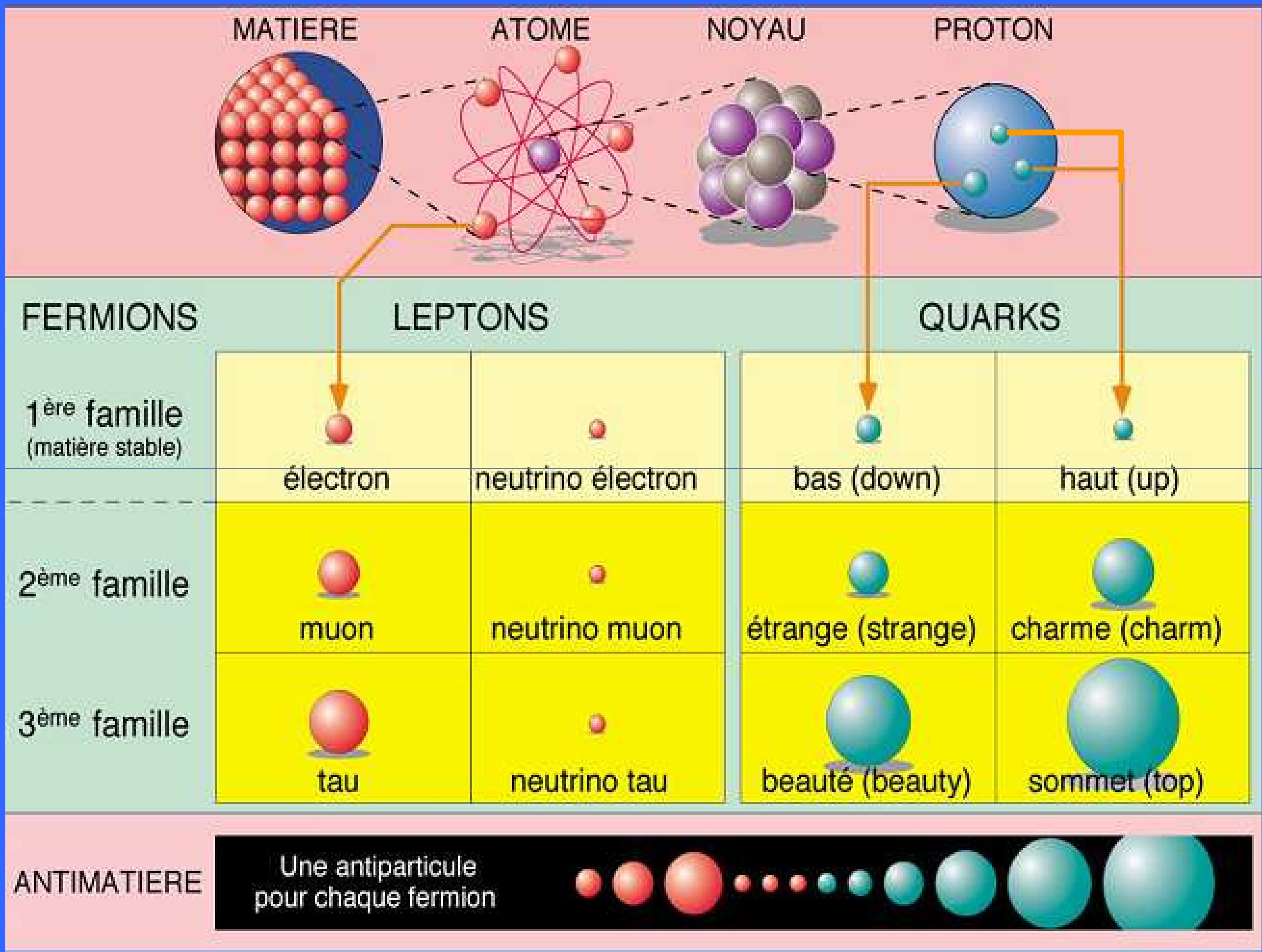
$q_\nu = 0$

Seule particule élémentaire neutre

Masse :

$m_\nu \sim 0$

$\frac{m_e}{m_\nu} > 500000$



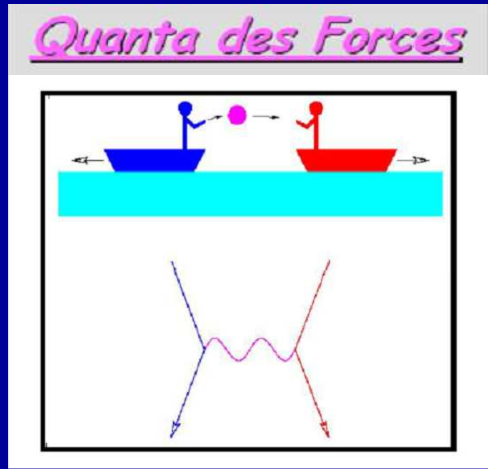
3 neutrinos ν_e, ν_μ, ν_τ

Le Modèle Standard

MATIERE

QUARKS

u	d
s	c
b	t



LEPTONS

e	ν_e
μ	ν_μ
τ	ν_τ

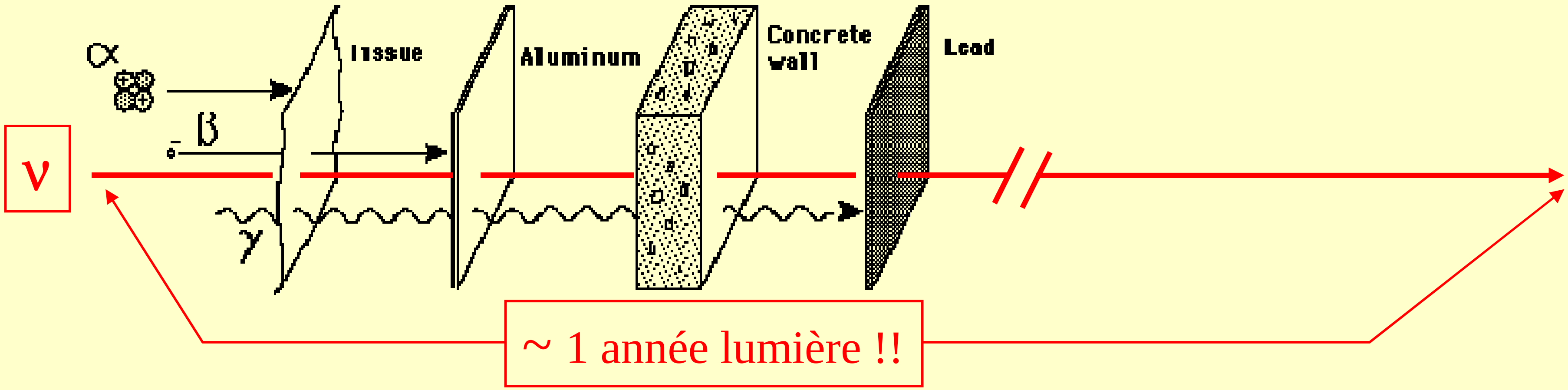
FORCES

Le neutrino ne "sent" que l'interaction faible !

Portée :	infinie	infinie	10^{-18} cm	10^{-13} cm
Intensité :	10^{-38}	10^{-2}	10^{-7}	1

$m_\nu \sim 0$
$Q_\nu = 0$
Interaction faible

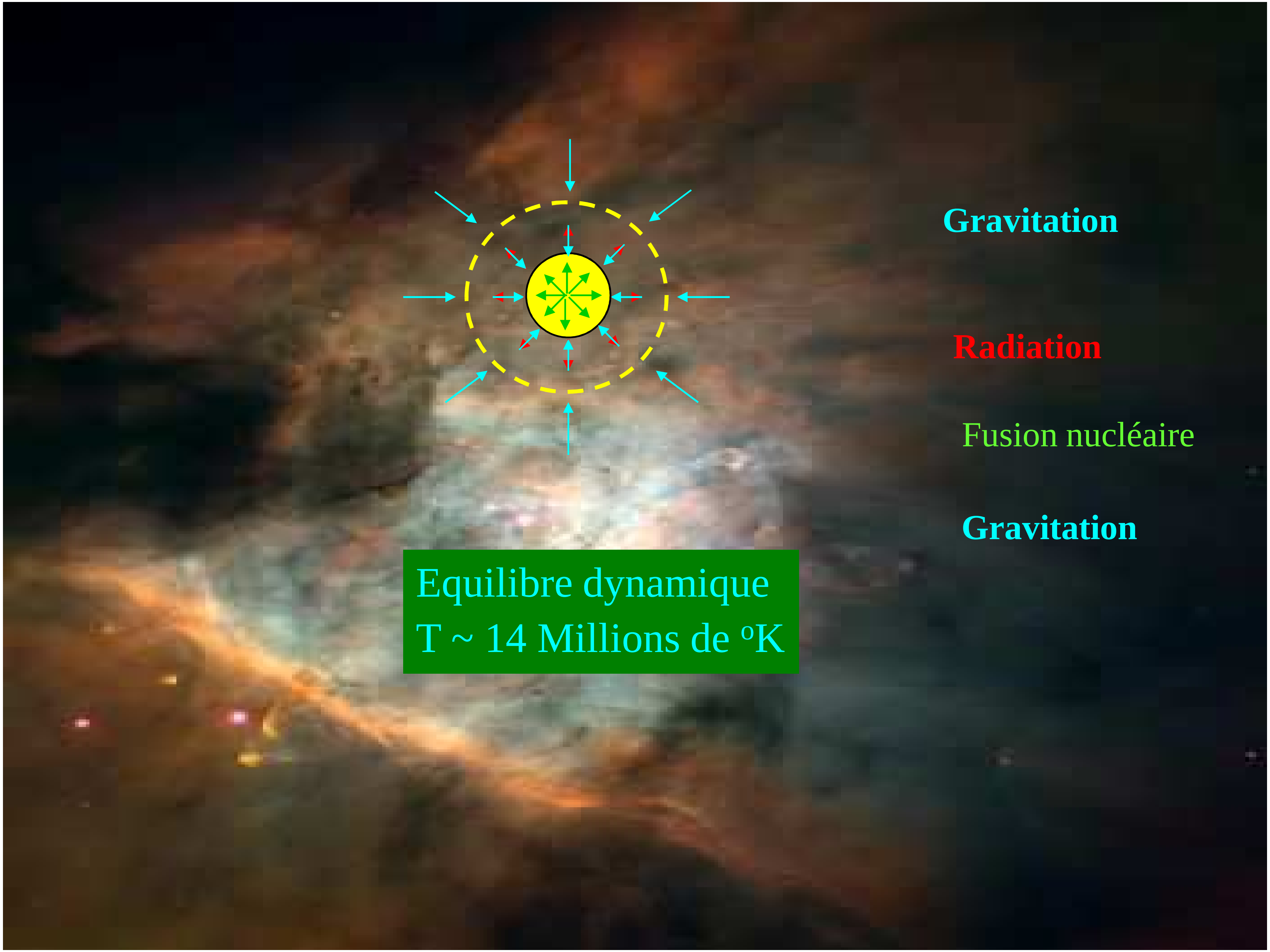
Le neutrino, particule passe-muraille



- Le neutrino peut sonder les régions les plus reculées de l'Univers
- Le neutrino peut sonder les régions le plus intimes des objets cosmiques


Les Neutrinos dans l'Univers

Les neutrinos des étoiles
Le Soleil


Gravitation
Radiation
Fusion nucléaire
Gravitation
Equilibre dynamique
T ~ 14 Millions de ºK

Comment cela marche ?

$p + p \rightarrow d + e^+ + \nu_e$

(ν_e - pp)

$d + p \rightarrow {}^3He + \gamma$

85 %

$^3He + {}^3He \rightarrow {}^4He + 2p$

pp I

15 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.87 %

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

(ν_e - ^{7}Be)

$^7Li + p \rightarrow 2\ {}^4He$

pp II

0.13 %

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

(ν_e - ^{8}B)

$^8Be^* \rightarrow 2\ {}^4He$

pp III

Fusion H → He

$$4p + 2e^- \longrightarrow He + 2\nu_e + 26.731\ MeV$$

Dont 46 milliards /cm² / s sur la Terre

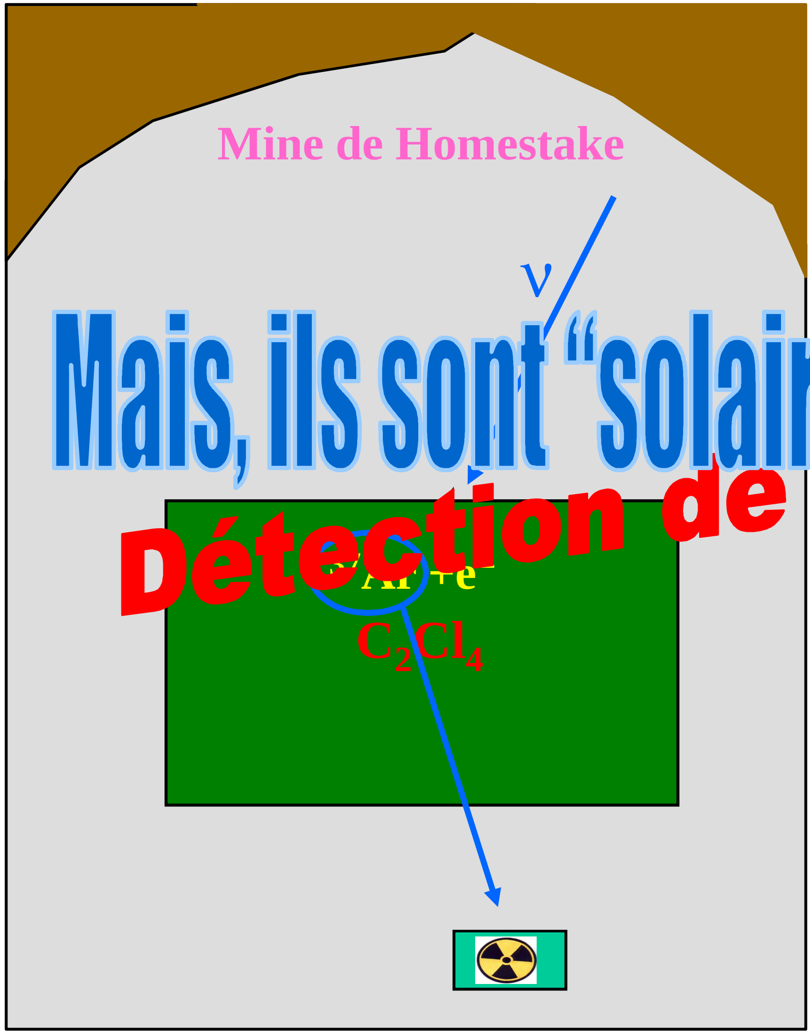
$N\nu \sim 2 \cdot 10^{38}\ s^{-1}$

1964 Ray Davis propose de detecter les ν du soleil

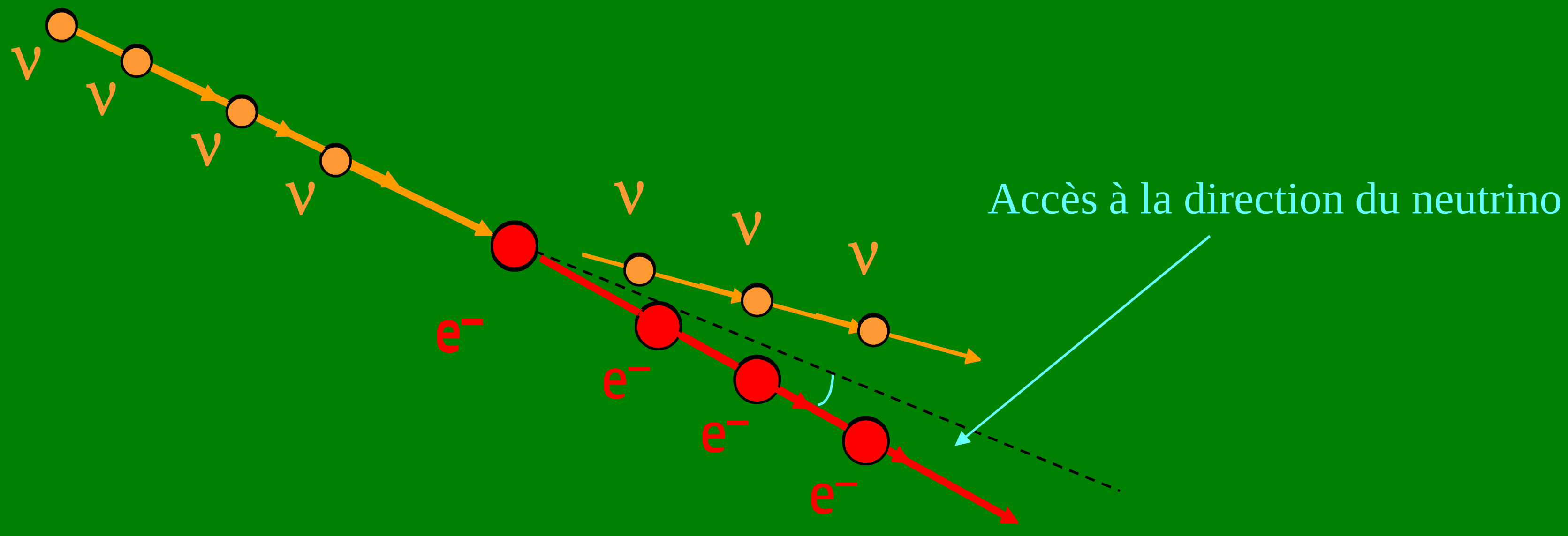
$$^{37}Cl + \nu_e^{\odot} \longrightarrow {}^{37}Ar + e^-$$

Mais, ils sont "solaires" ces neutrinos ?

Détection de neu



Détection directe des neutrinos



$$\nu + e^- \longrightarrow \nu + e^-$$

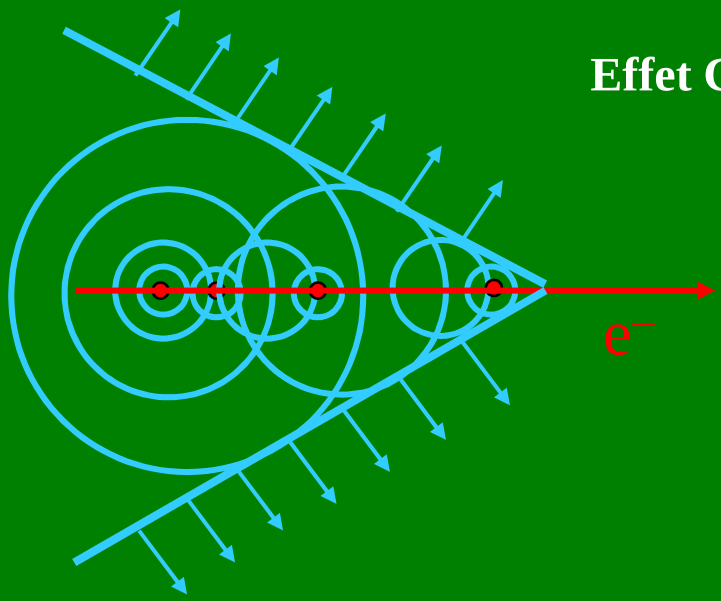
(Diffusion élastique)

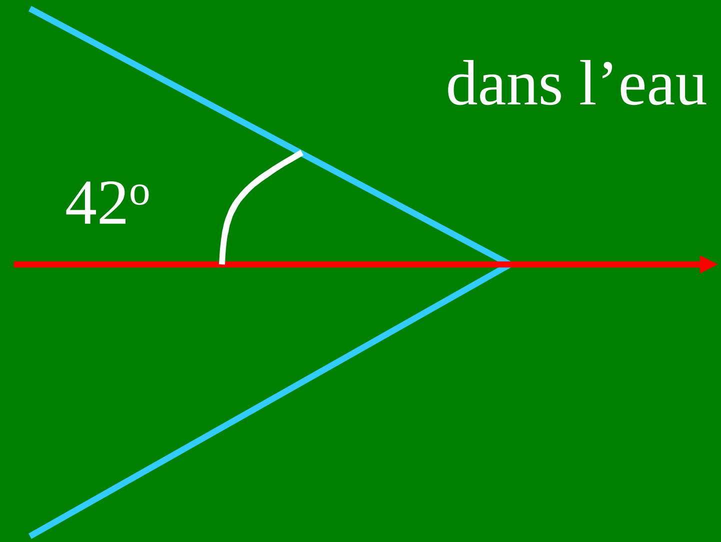
Détection directe des neutrinos

Déplacement d'une particule chargée dans un milieu transparent

Effet Cherenkov

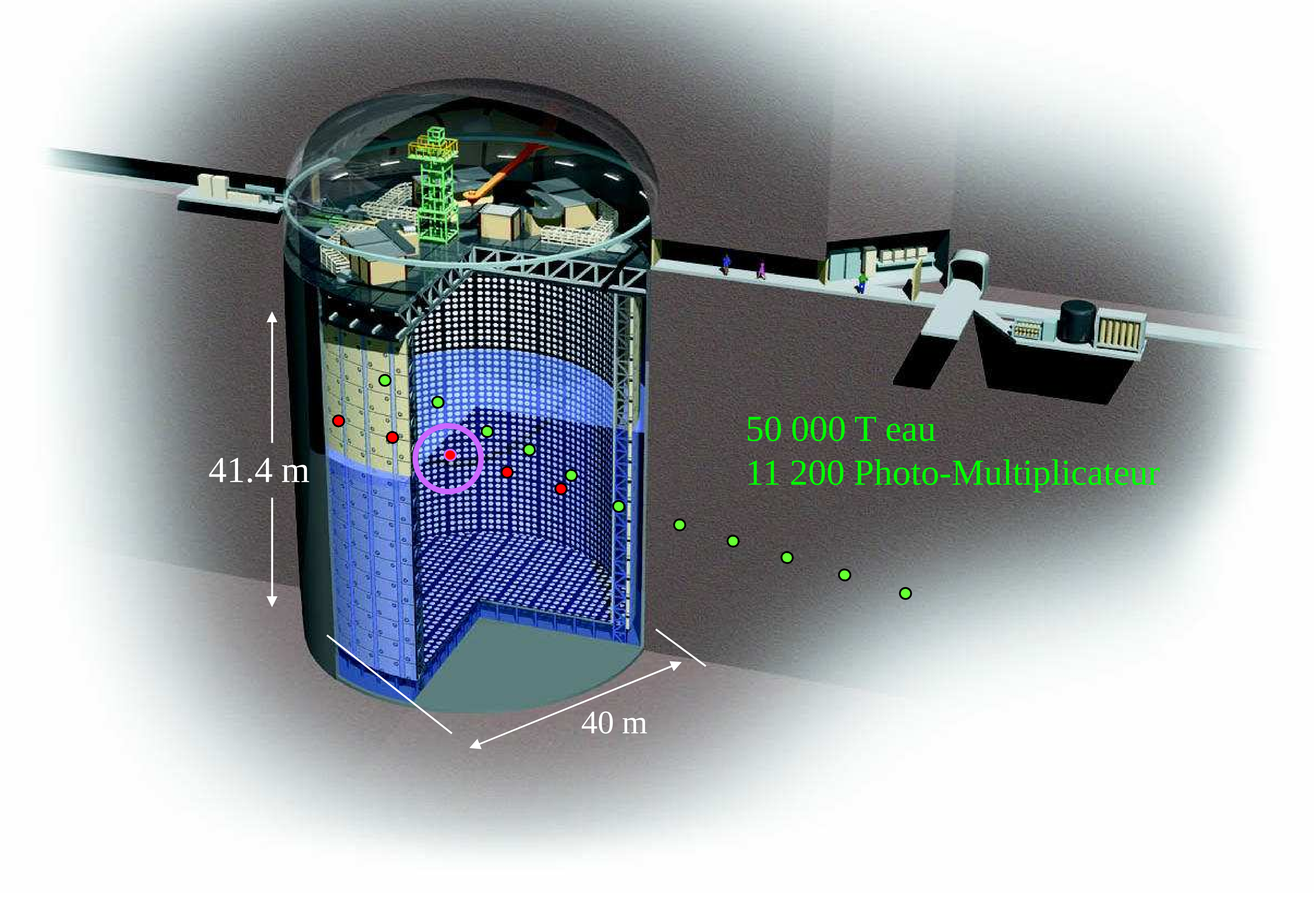
V_e⁻ > V_lumiere (dans le milieu)

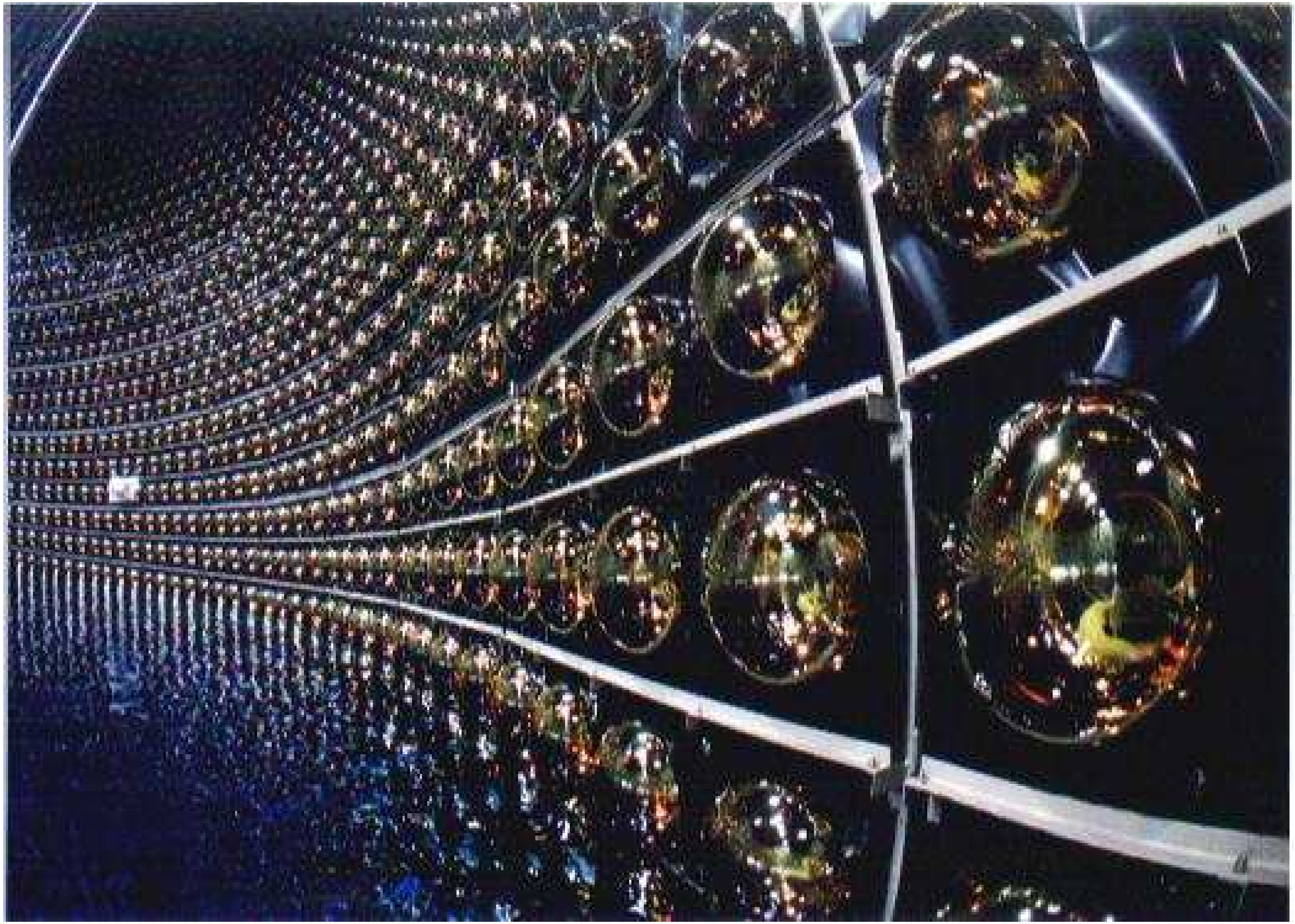


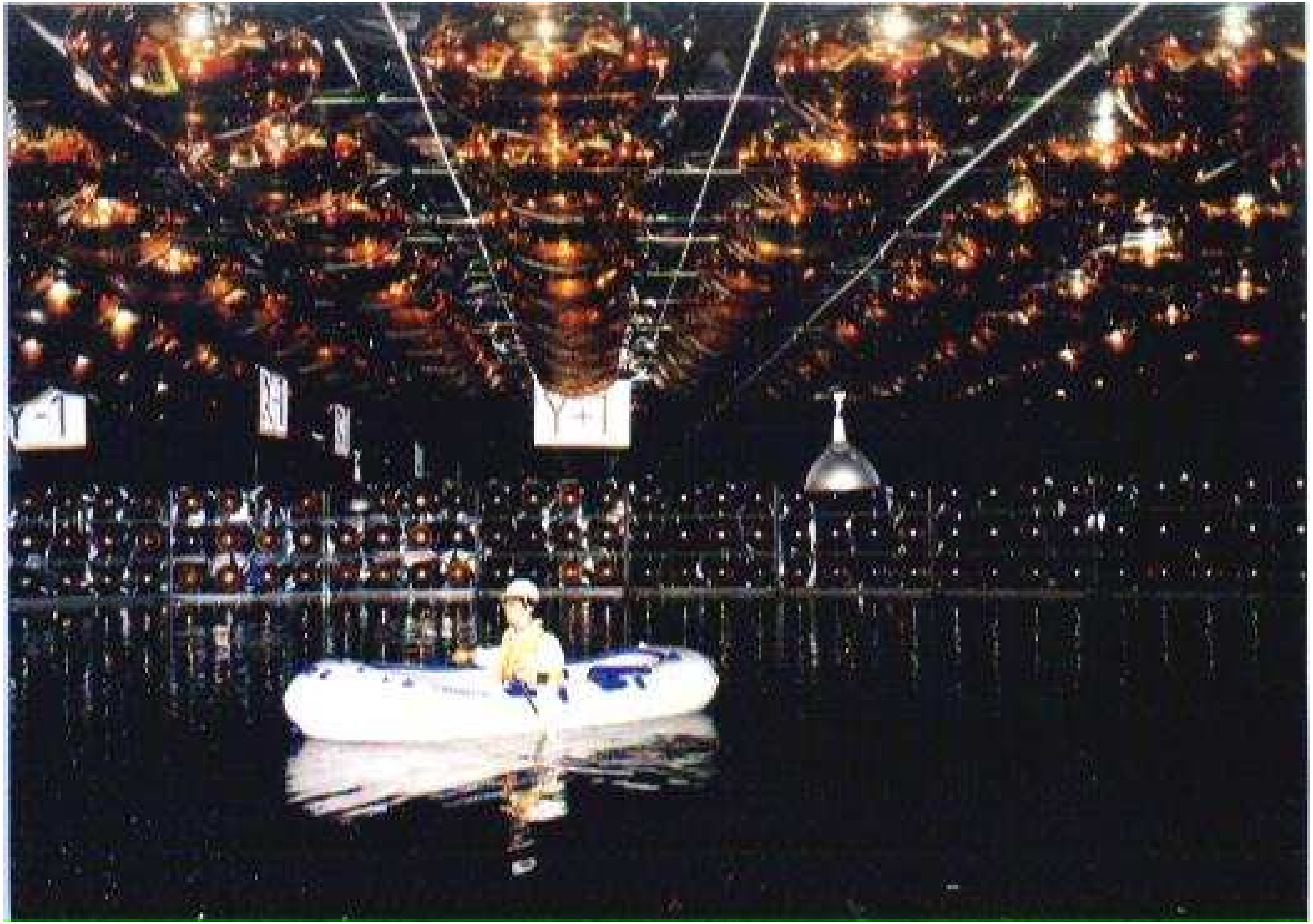


Direction de l'électron

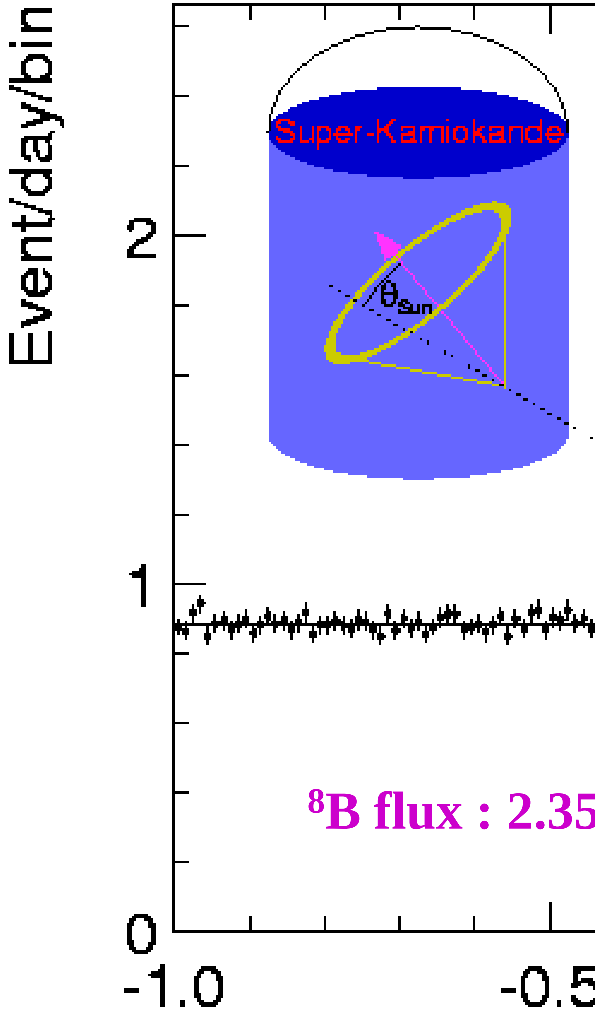
Super Kamiokande

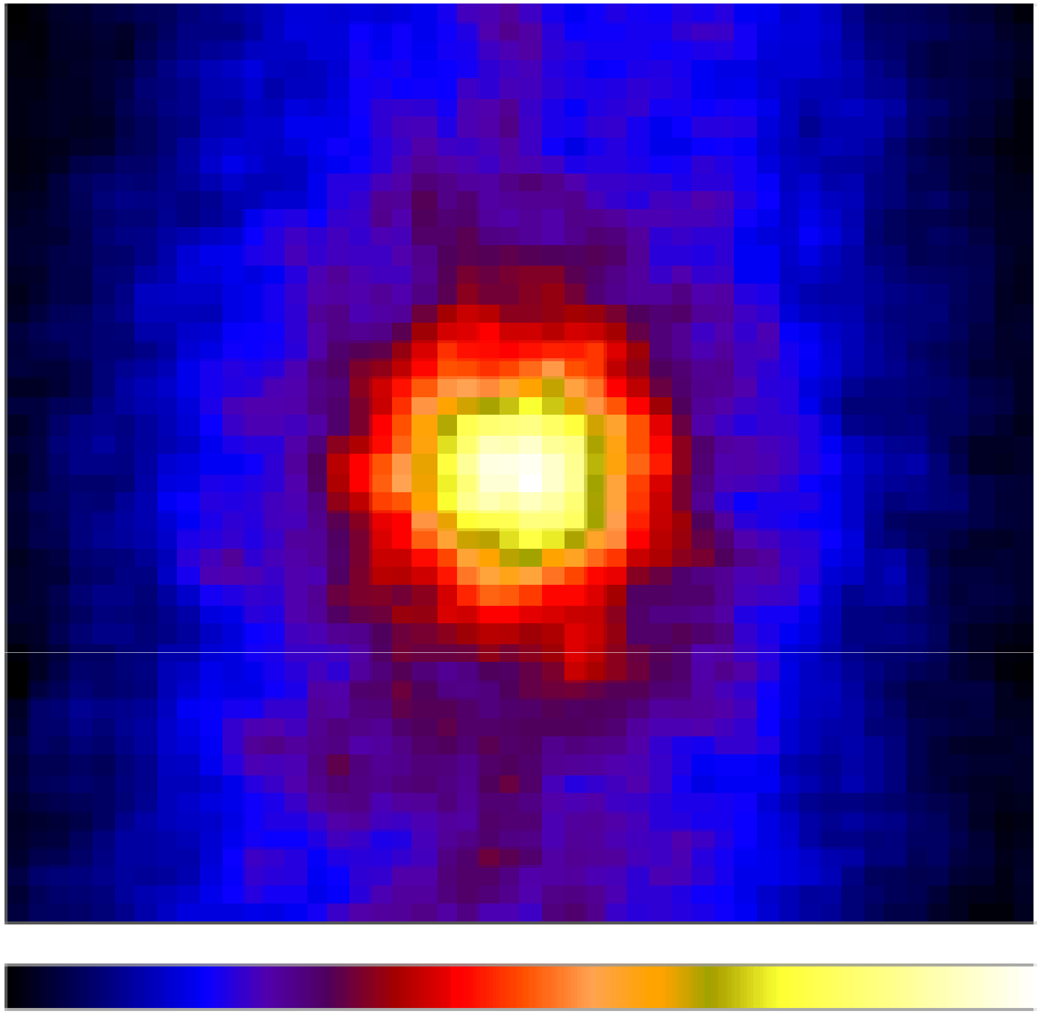




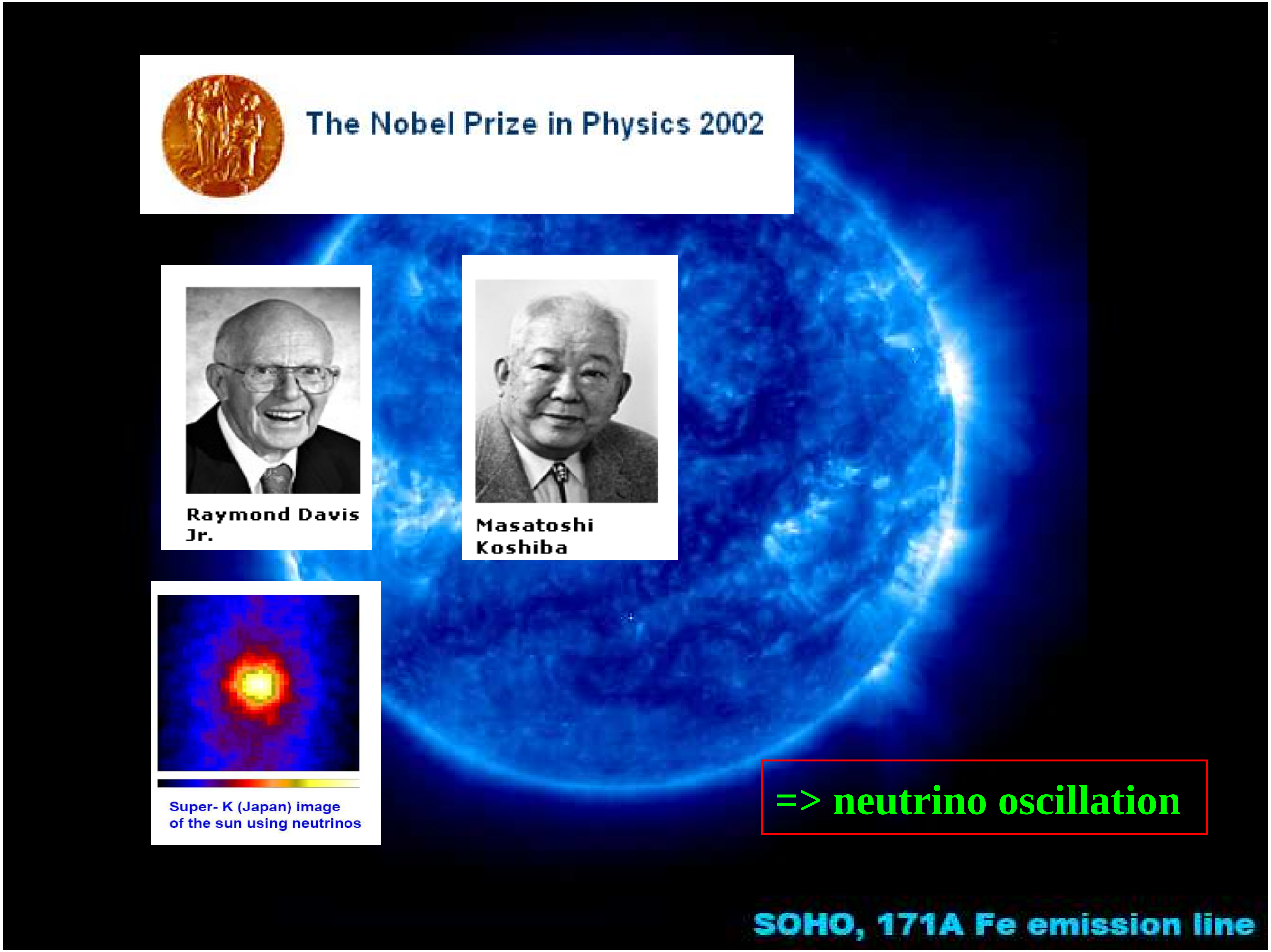

Y-1
Y+1

Resultat 31/



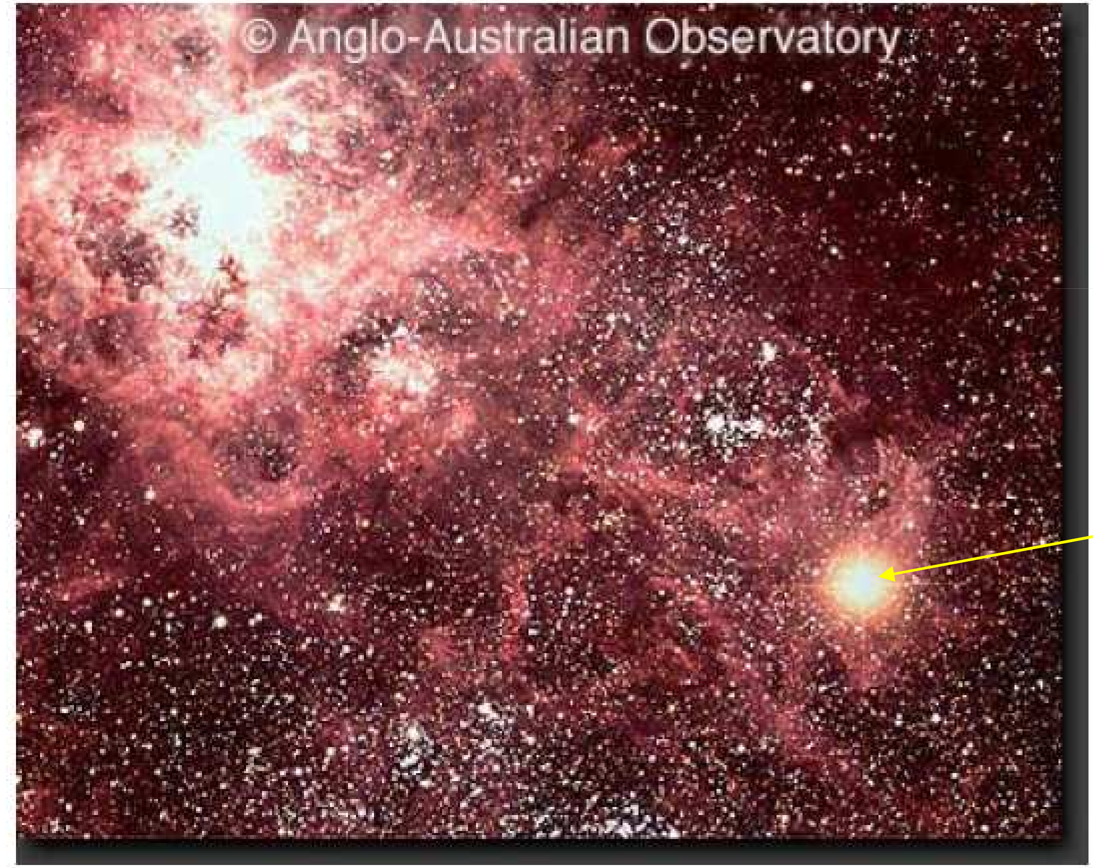


Super- K (Japan) image
of the sun using neutrinos


The Nobel Prize in Physics 2002
Raymond Davis Jr.
Masatoshi Koshiba
Super- K (Japan) image of the sun using neutrinos
=> neutrino oscillation
SOHO, 171A Fe emission line

Astronomie neutrino au delà du soleil

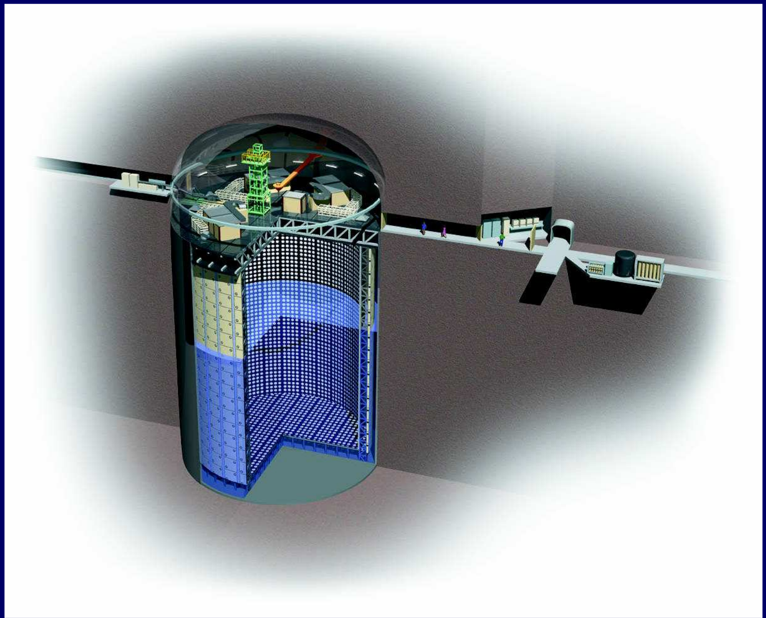
23 fevrier 1987, Grand Nuage de Magellan (150000 a.l.)

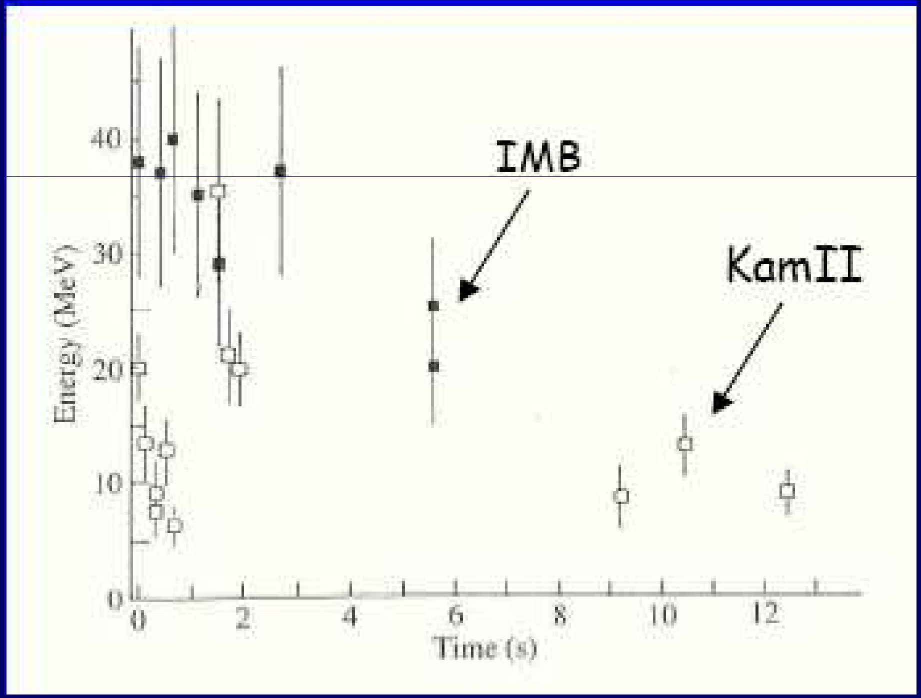


Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~180000 ly

Supernovae 1987A

On a vu les neutrinos de la SN !





Les supernovae "historiques"

an

185
369
1006 — Chinois

1054

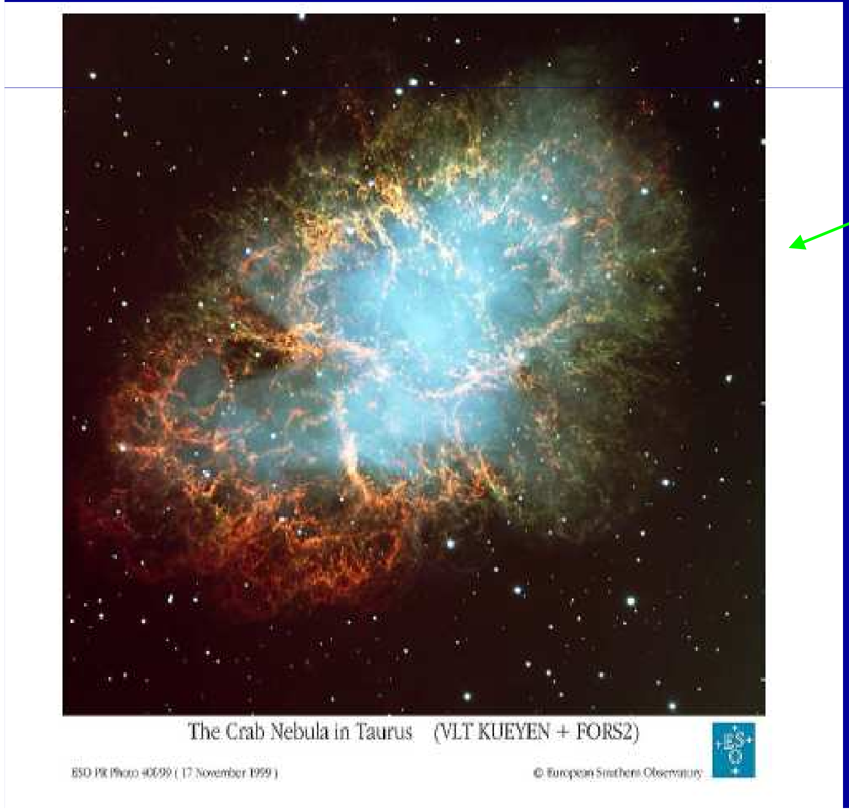
1181

1572 Tycho Brahe

1604 Kepler

1987A → Première (et seule) observée en ν

Nebuleuse du Crabe

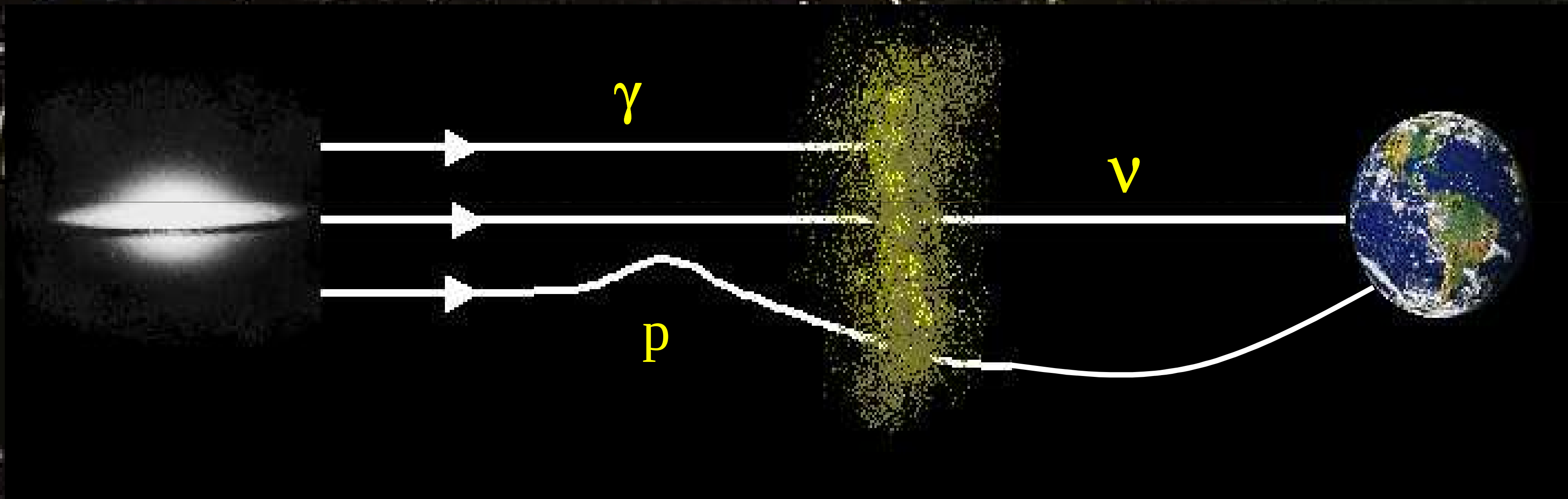


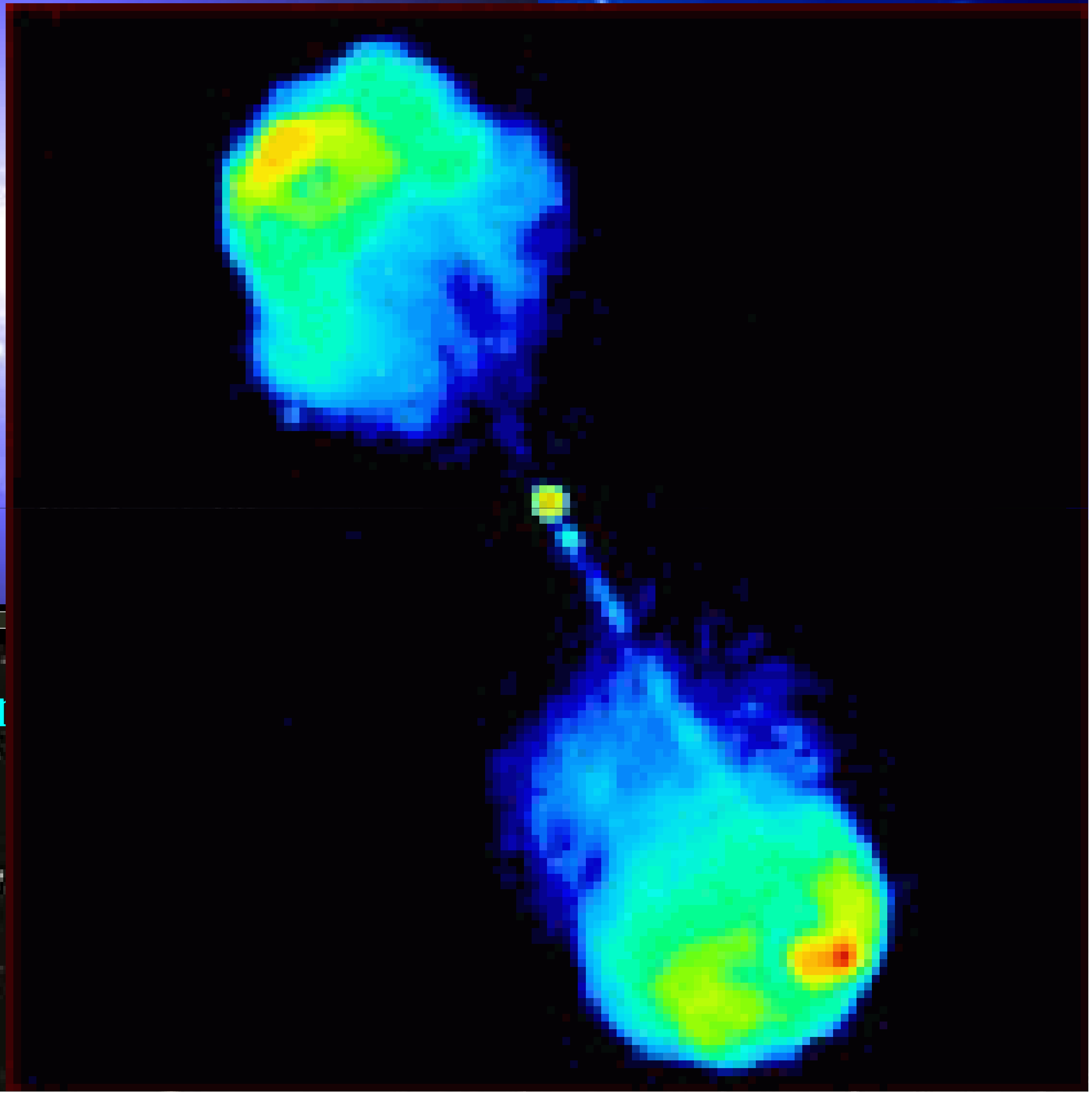
et “prochainement”

Astronomie de l'extrême

Astronomie Haute énergie

Messagers : γ, p, ν

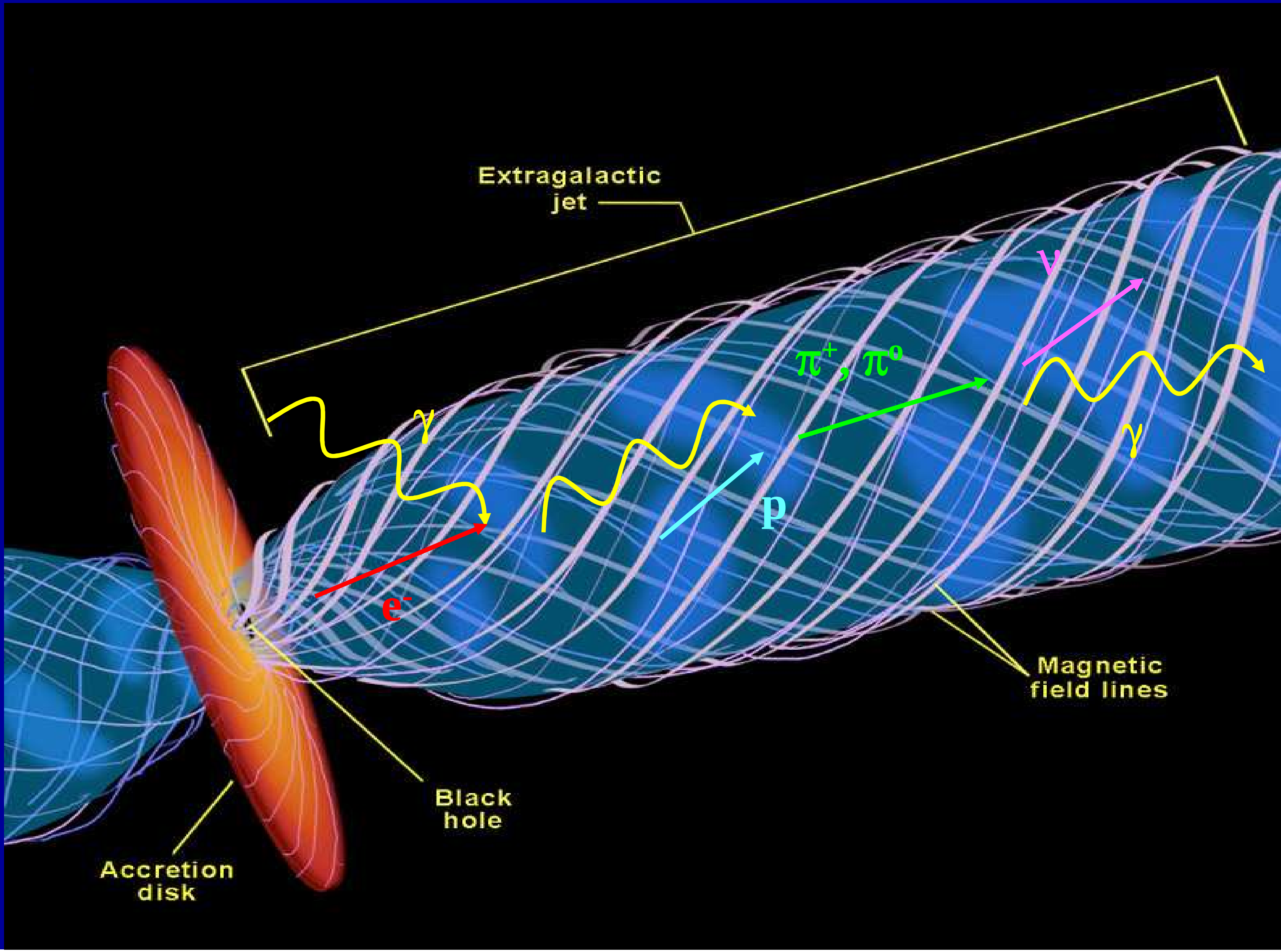




– Sources Extr

- AGN
- GRBs

Accélérateurs cosmiques



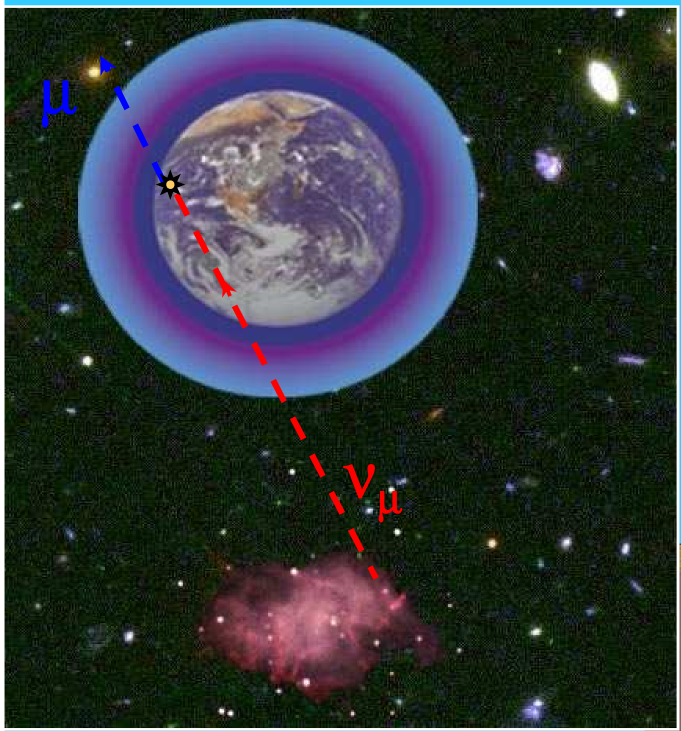
Comment détecter les ν haute énergie

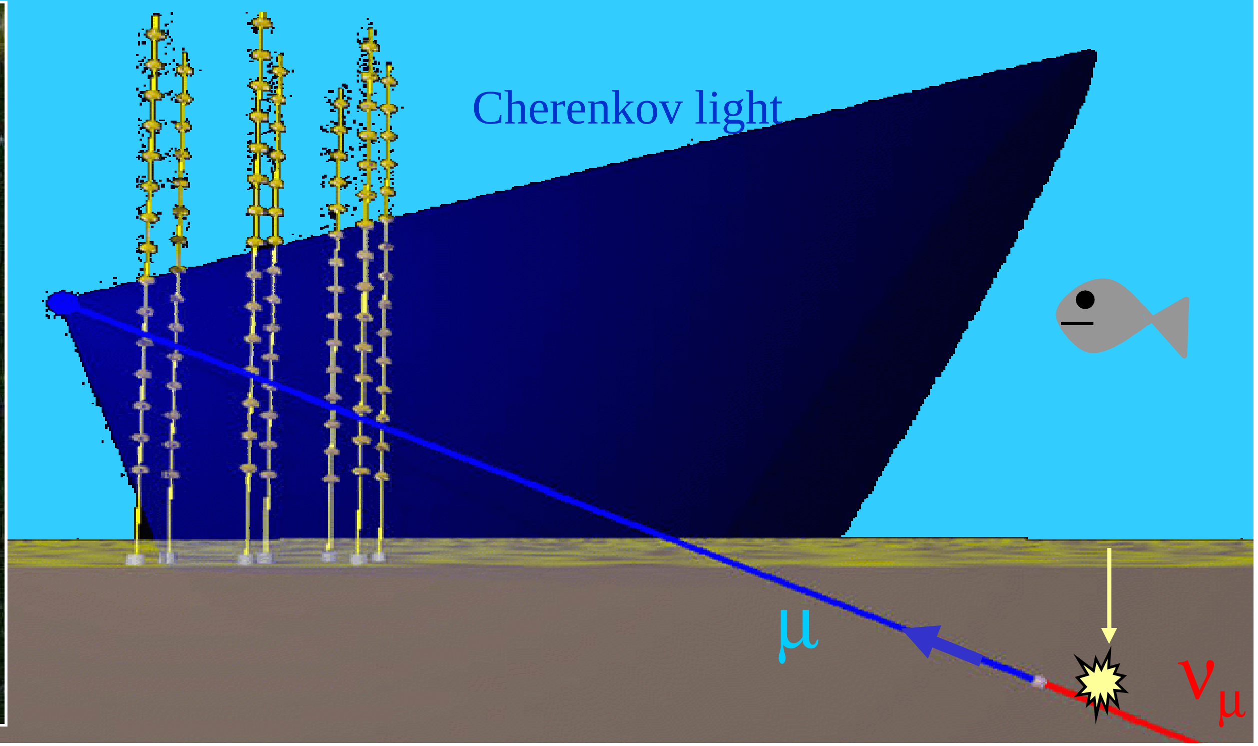
Très faibles flux => très grand détecteurs => Détecteur "naturel"

→ **Lumière Cherenkov dans l'eau de mer ou la glace**

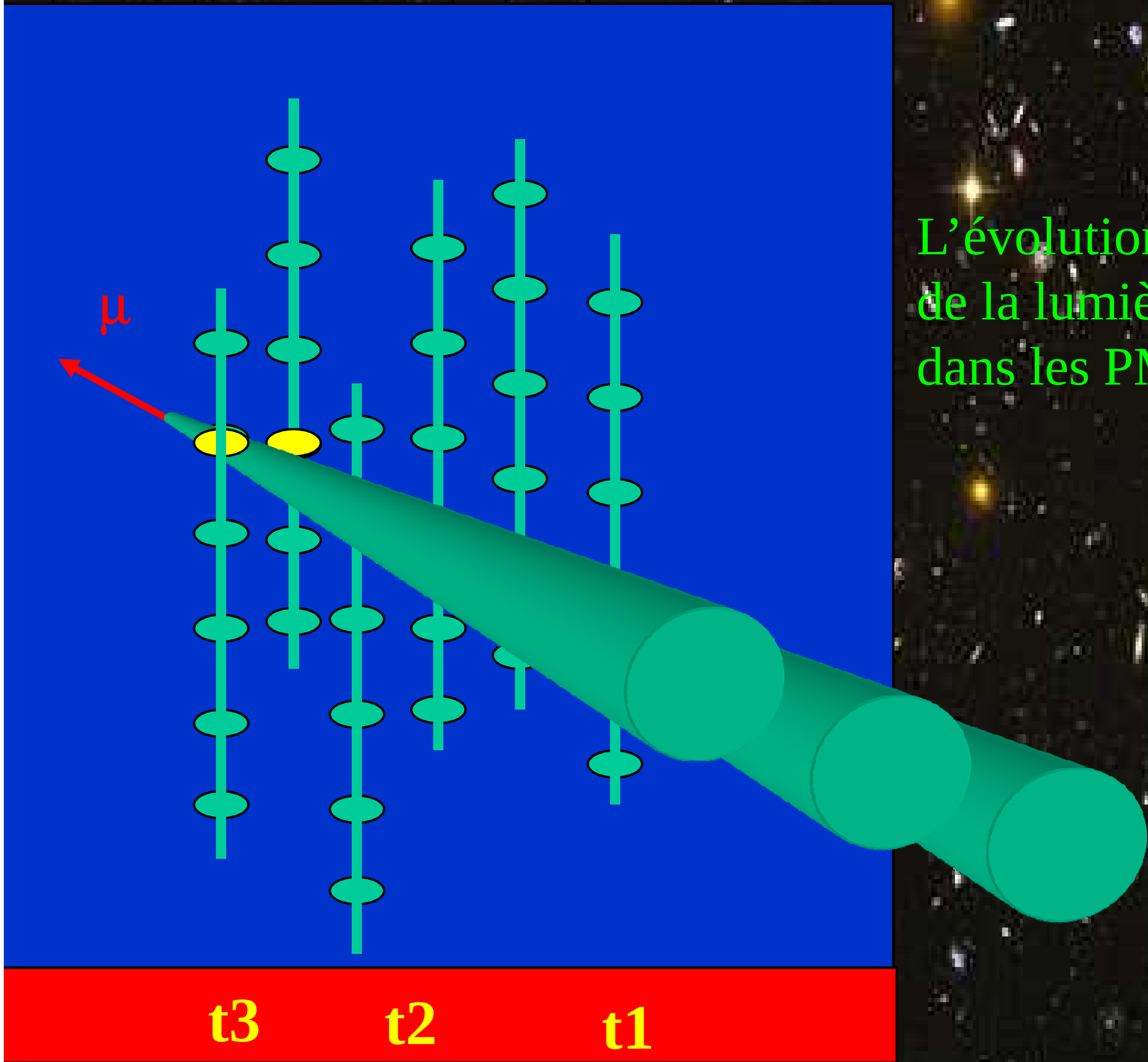
→ **Produite par les muons issus des neutrinos muoniques**

$$(\nu_\mu + M \longrightarrow M' + \mu)$$



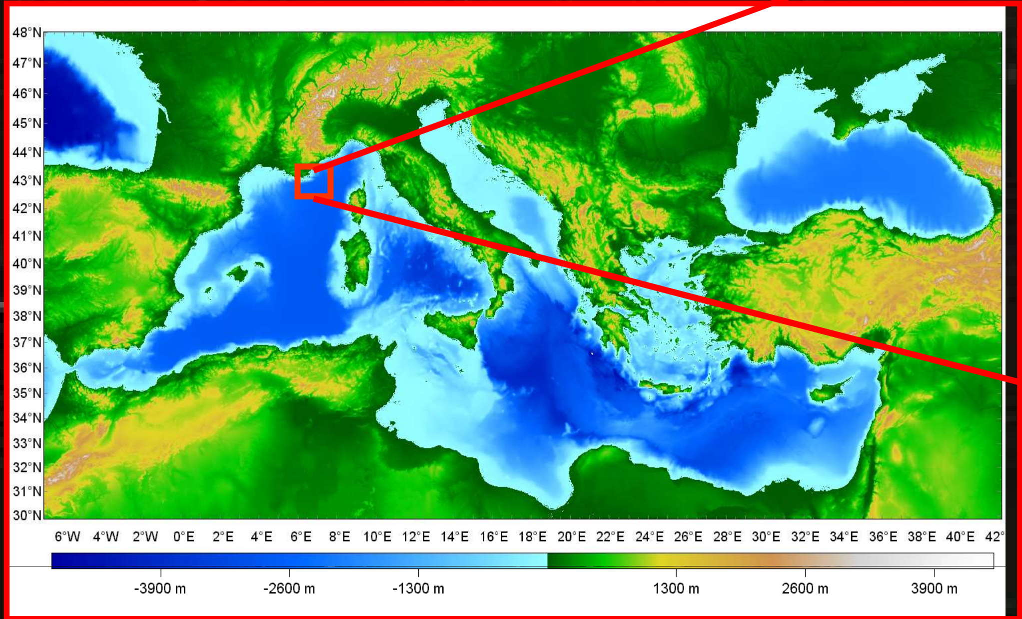


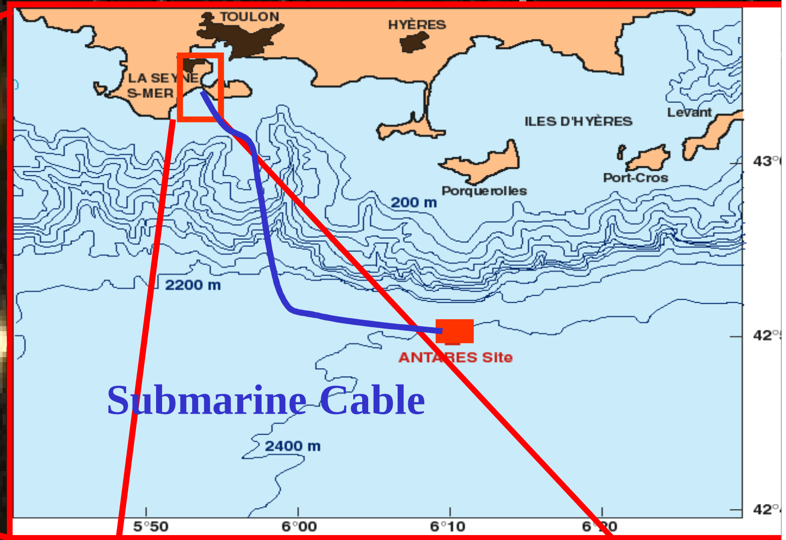
Reconstruction de la trajectoire



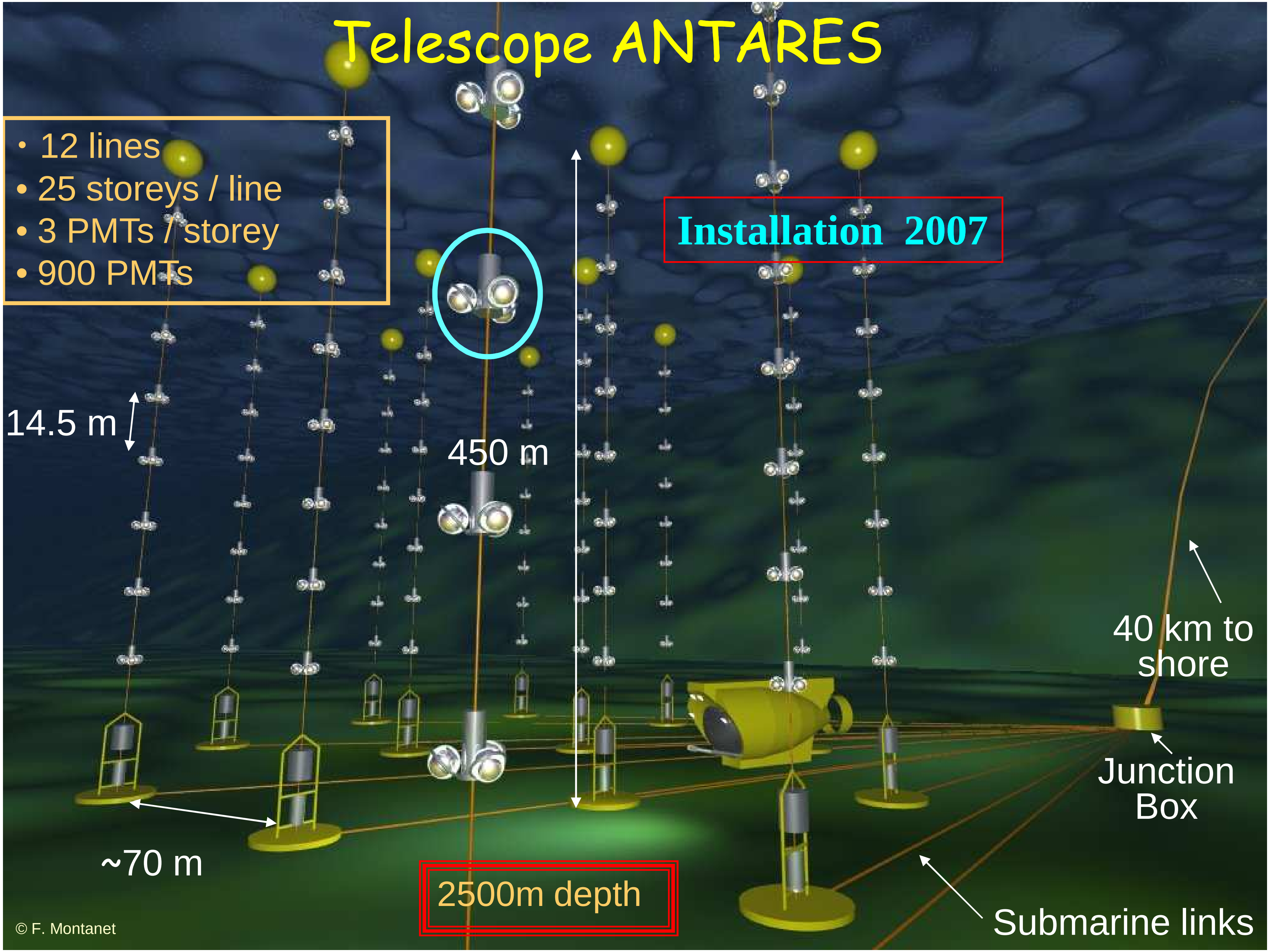
L'évolution en temps
de la lumière Cherenkov
dans les PM donne la direction

ANTARES

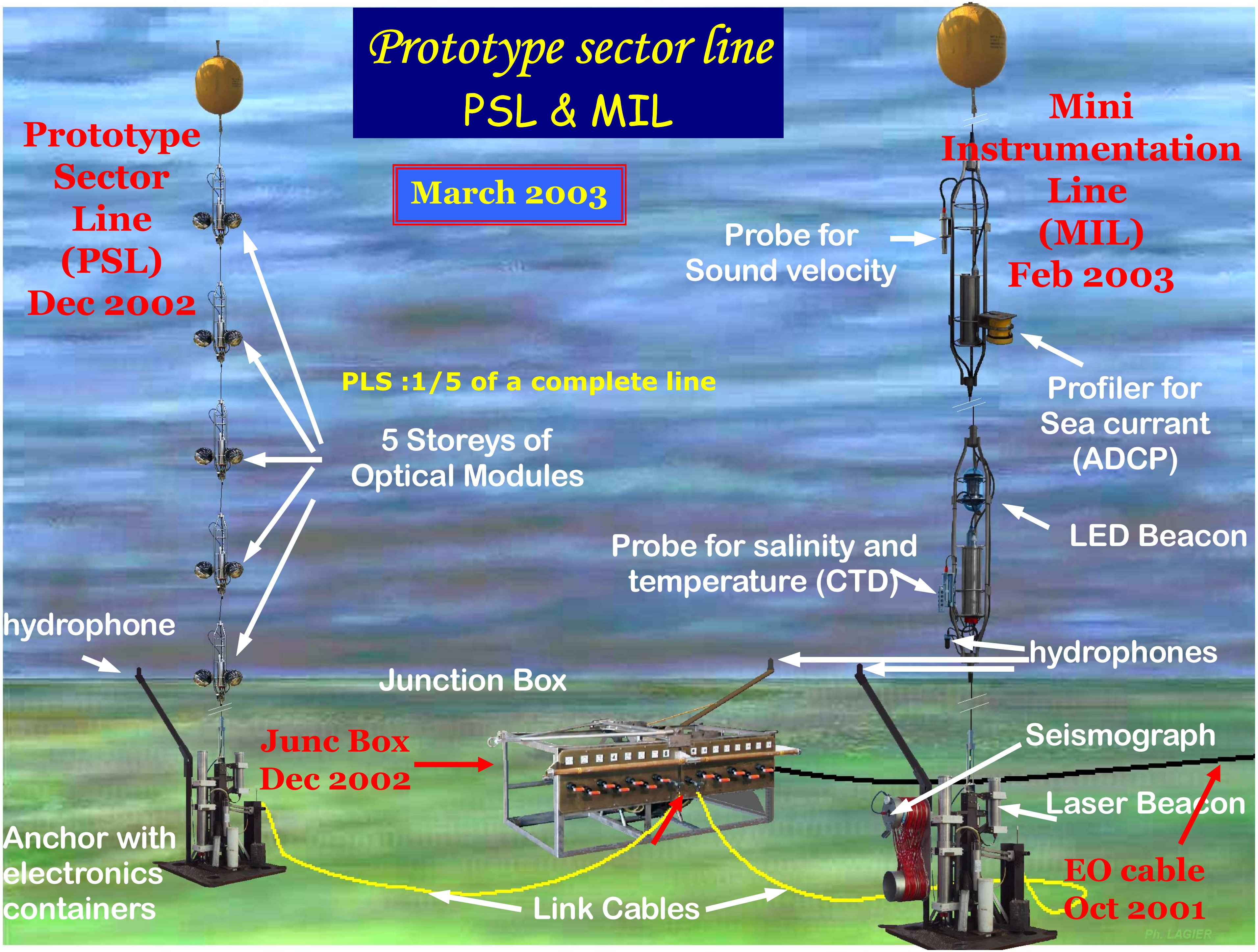


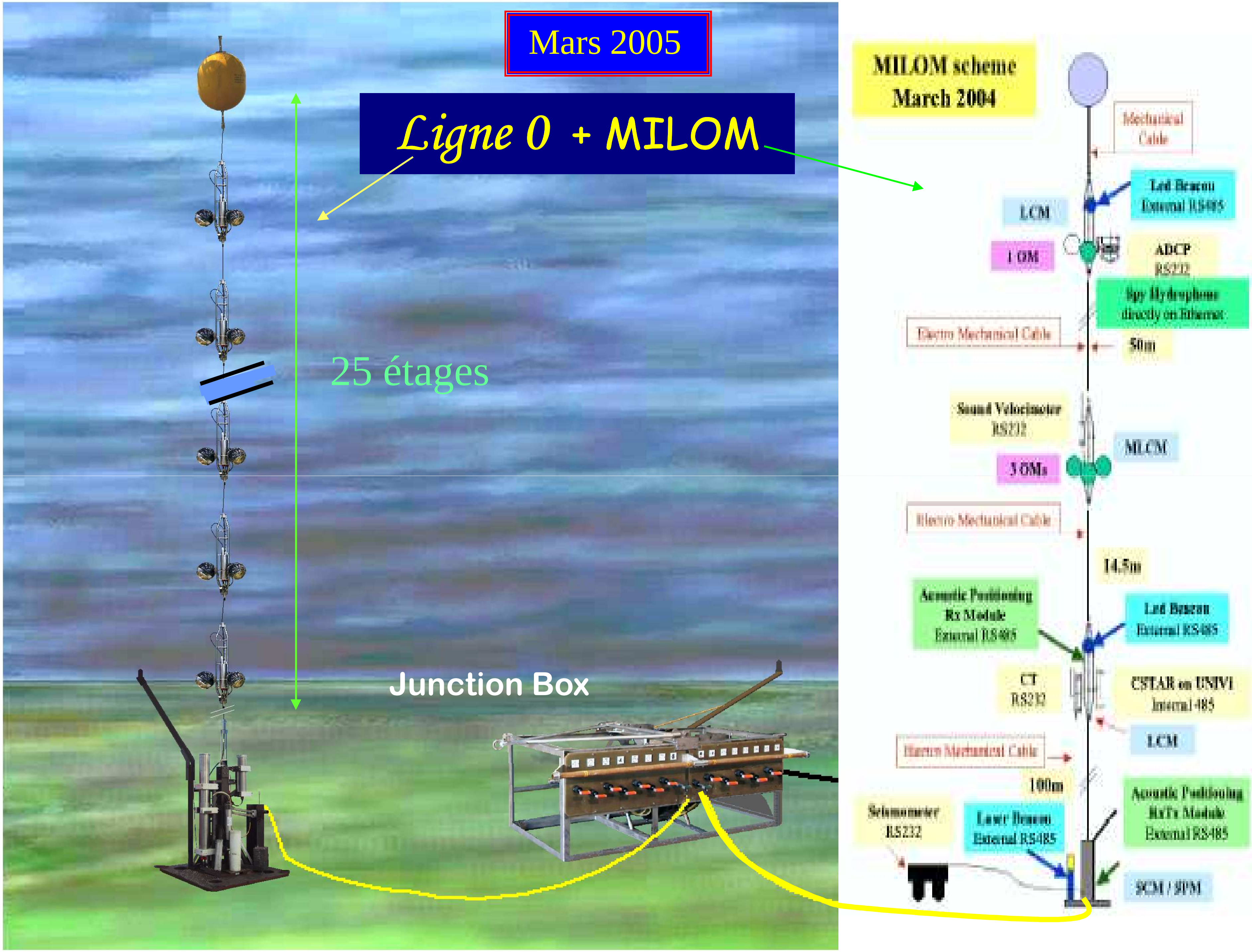


Shore Station


Telescope ANTARES
• 12 lines
• 25 storeys / line
• 3 PMTs / storey
• 900 PMTs
Installation 2007
14.5 m
450 m
40 km to shore
Junction Box
~70 m
2500m depth
Submarine links
© F. Montanet


1000


Prototype sector line
PSL & MIL
March 2003
Prototype Sector Line (PSL) Dec 2002
Mini Instrumentation Line (MIL) Feb 2003
Probe for Sound velocity
PLS :1/5 of a complete line
5 Storeys of Optical Modules
Profiler for Sea currant (ADCP)
LED Beacon
Probe for salinity and temperature (CTD)
hydrophone
hydrophones
Junction Box
Junc Box Dec 2002
Seismograph
Laser Beacon
Anchor with electronics containers
Link Cables
EO cable Oct 2001
Ph. LAGIER

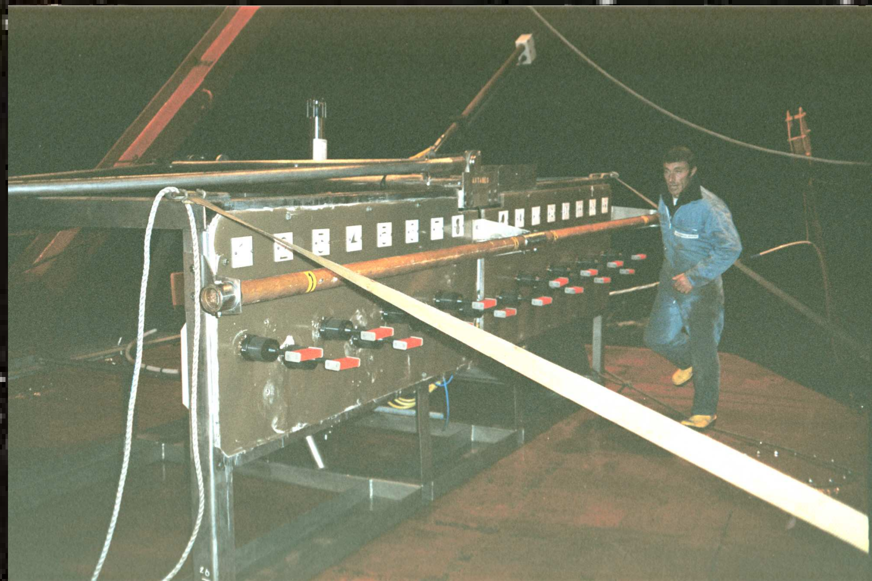

Mars 2005
Ligne 0 + MILOM
25 étages
Junction Box
MILOM scheme
March 2004
Mechanical Cable
Led Beacon External RS485
LCM
1 OM
ADCP RS232
Spy Hydrophone directly on Ethernet
Electro Mechanical Cable
50m
Sound Velocimeter RS232
MLCM
3 OMs
Electro Mechanical Cable
14.5m
Acoustic Positioning Rx Module External RS485
Led Beacon External RS485
CT RS232
CSTAR on UNIVI Internal 485
LCM
Electro Mechanical Cable
100m
Seismometer RS232
Laser Beacon External RS485
Acoustic Positioning RxTx Module External RS485
SCM / SPM

- Surveillance du site

- Approximately 1 big object per ha
- All objects around detector location measured

- Déploiement du câble électro-optique

- Déploiement de la boite de jonction

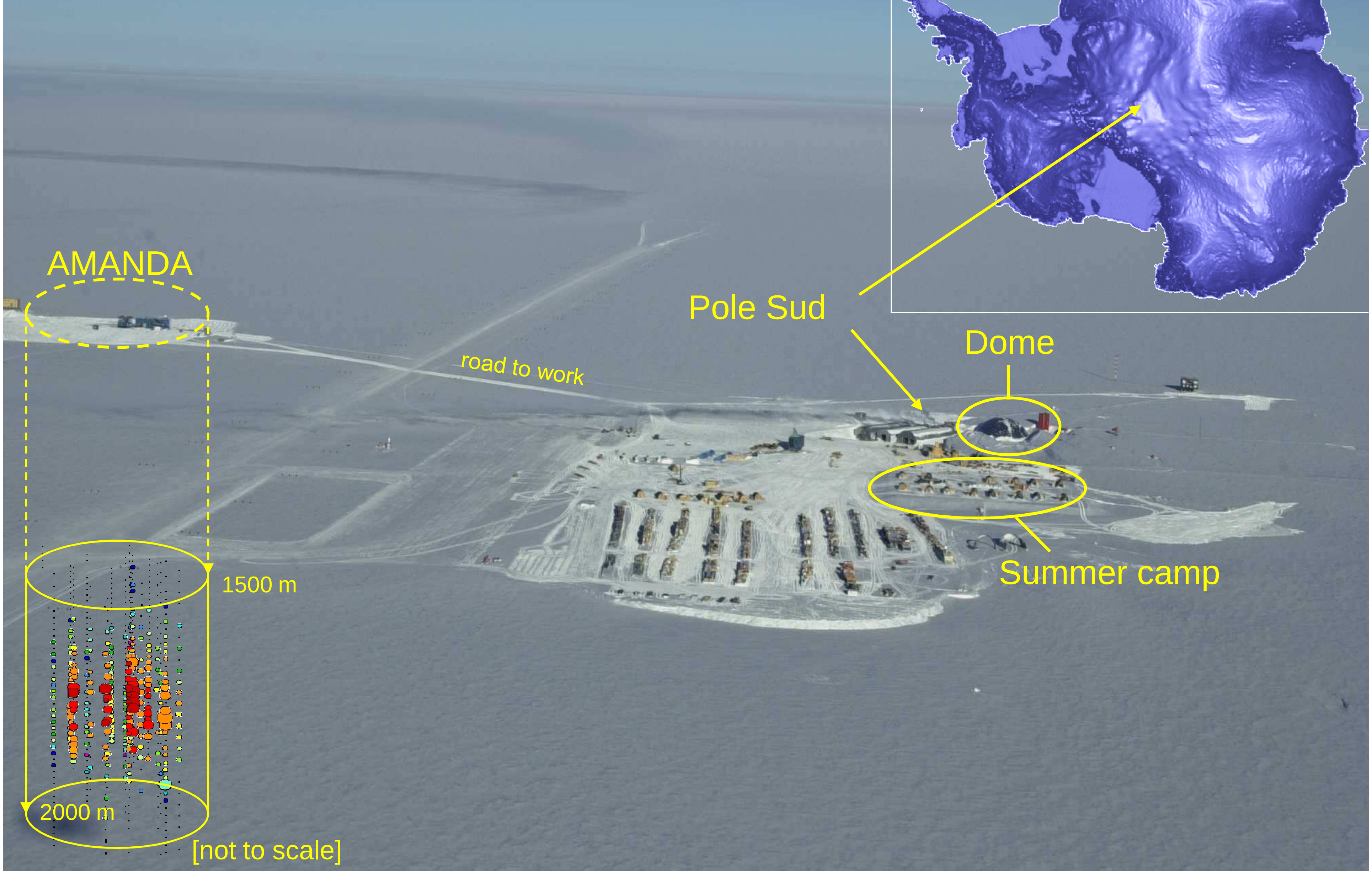


Detailed knowledge of large objects on site

PSL deployment and connection

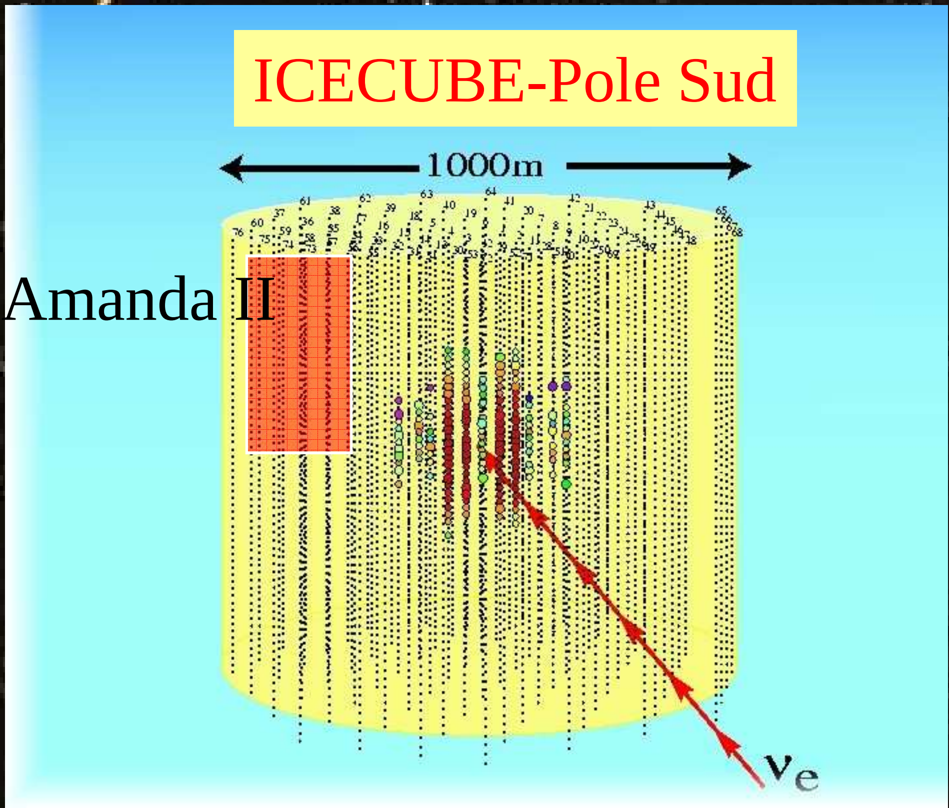
Astronomie neutrino au pole sud

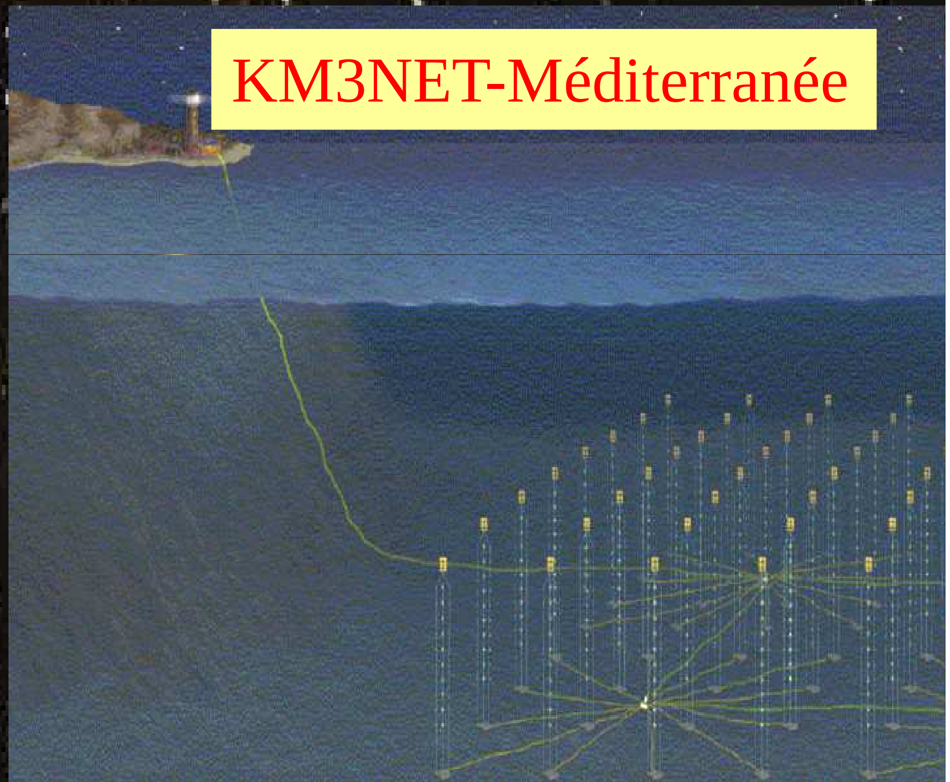
AMANDA



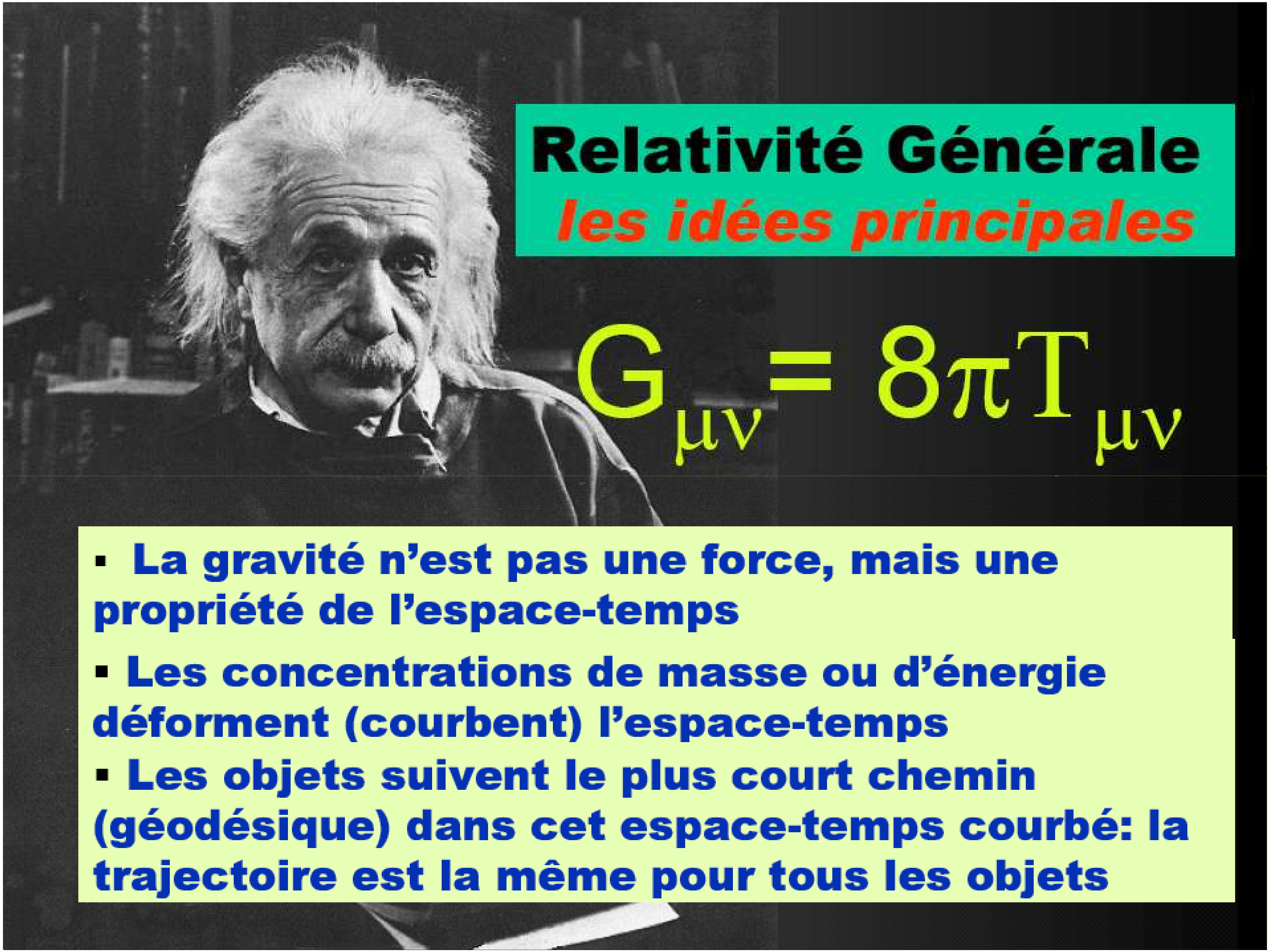
Prochaine Génération: KM3

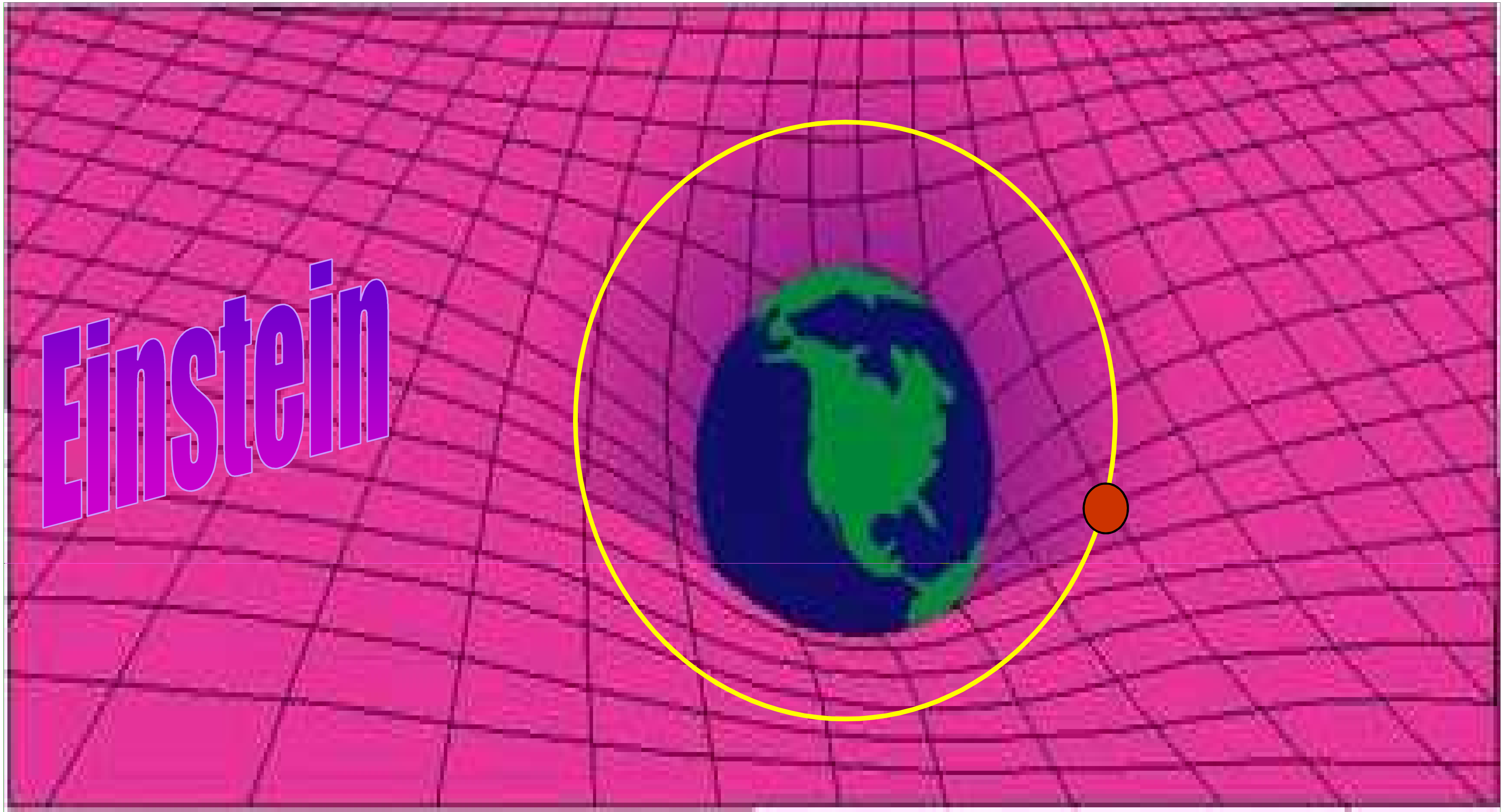
Vers les plus grandes statistiques






Ondes Gravitationnelles


Relativité Générale
les idées principales
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$
▪ La gravité n'est pas une force, mais une propriété de l'espace-temps
▪ Les concentrations de masse ou d'énergie déforment (courbent) l'espace-temps
▪ Les objets suivent le plus court chemin (géodésique) dans cet espace-temps courbé: la trajectoire est la même pour tous les objets



Equation d'Einstein:

La matière indique comment l'espace se courbe.

La géométrie indique comment la matière se déplace.

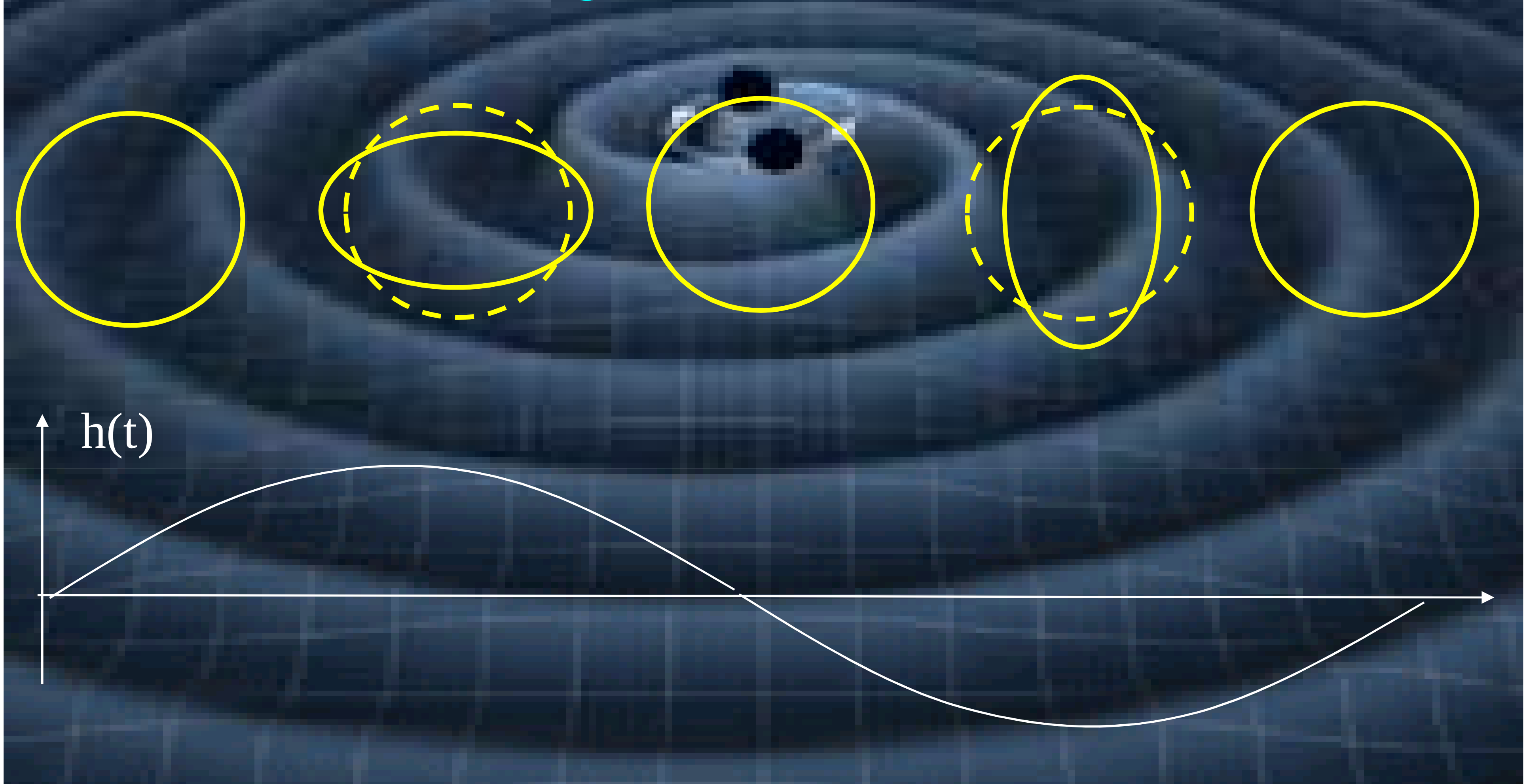
Ondes gravitationnelles

- *Masses en mouvement => variation de courbure*

- *Propagation comme une onde à la surface de l’eau*

Une onde gravitationnelle propage une perturbation locale de coubure de l’espace-temps

Effet d'une onde gravitationnelle sur un cercle test



La déformation relative ΔL/L est égale à leur amplitude h

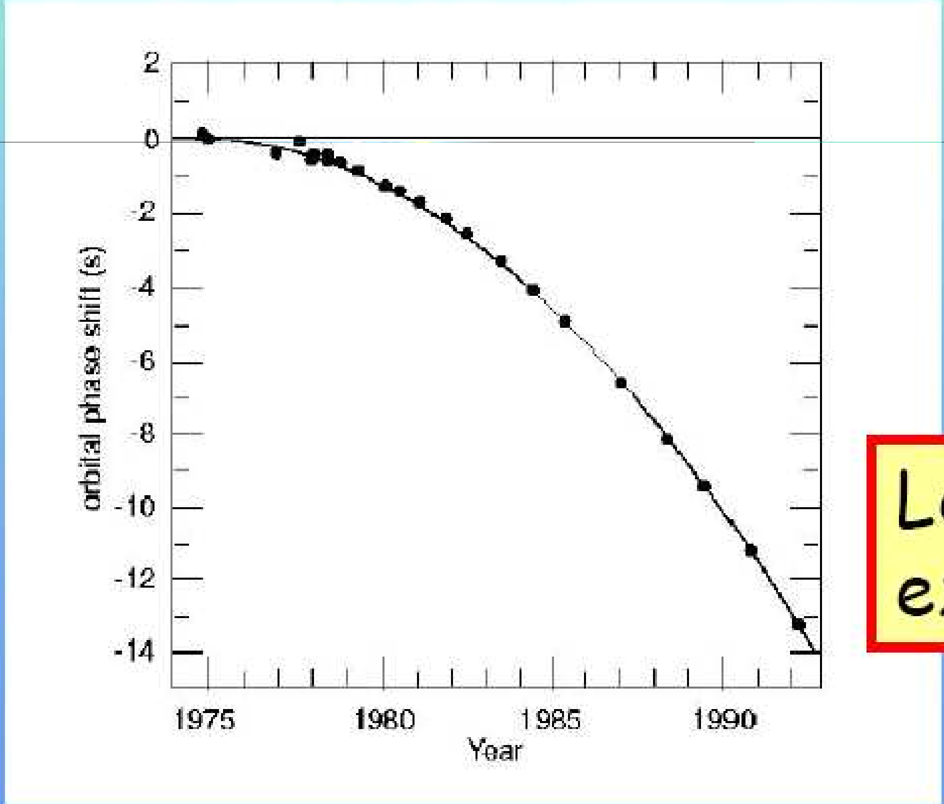
Prédictions: h ≈ 10^{-21} pour une source astrophysique à 10 Mpc.

Une preuve indirecte : PSR 1913+16

(Hulse & Taylor, Nobel'93)

PSR 1913+16 : pulsar binaire (couple de 2 étoiles à neutrons)
⇒ tests de la gravitation en champ fort et en régime dynamique

Perte d'énergie par émission d'OG : la période orbitale diminue

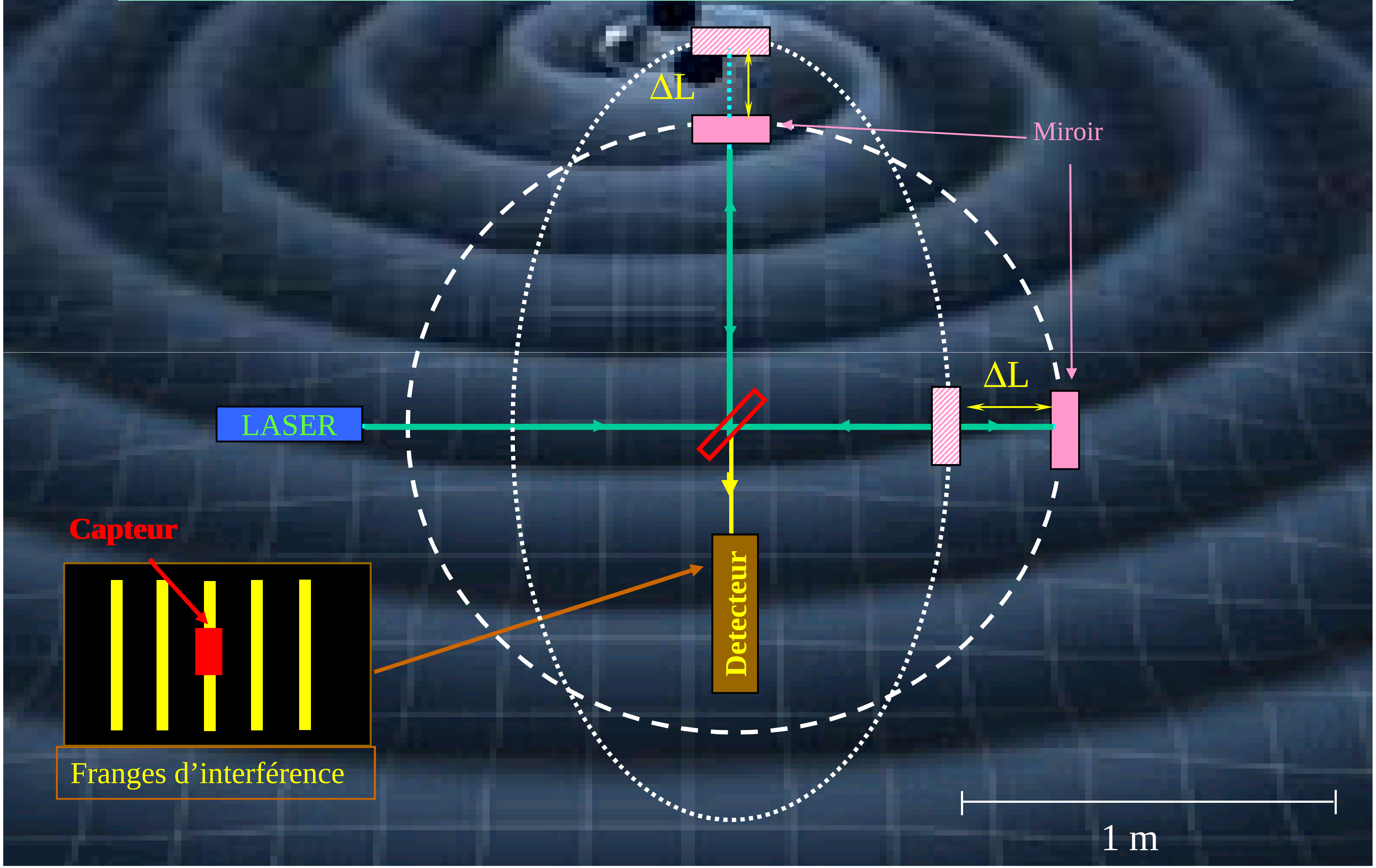


(Damour-Deruelle)

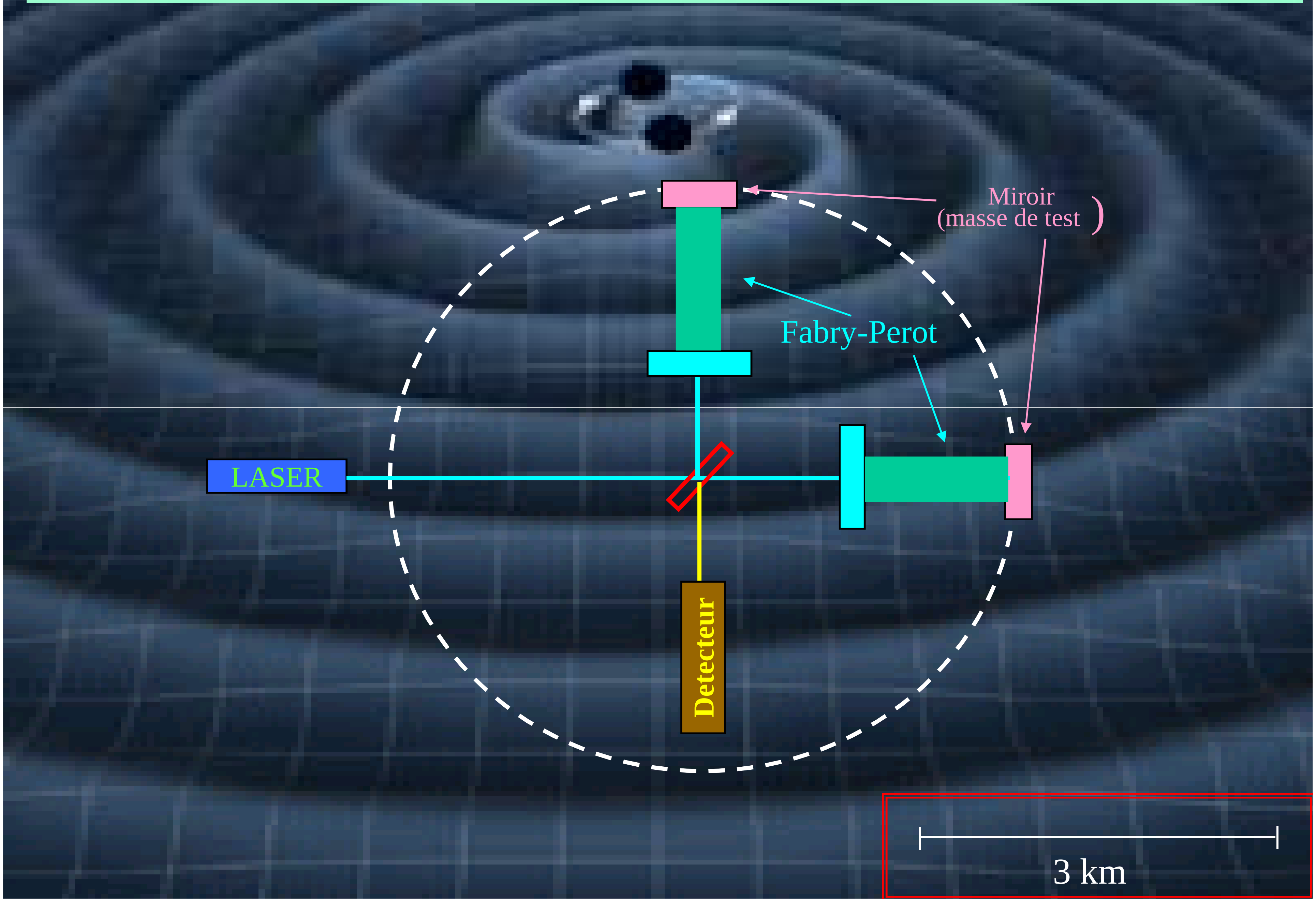
- séparation ~10^6 km
- diminution de 3mm/orbite de 8h
- observation pendant 20 ans

Les ondes gravitationnelles existent !

Interféromètre de Michelson bien adapté au problème



Amélioration du principe de base

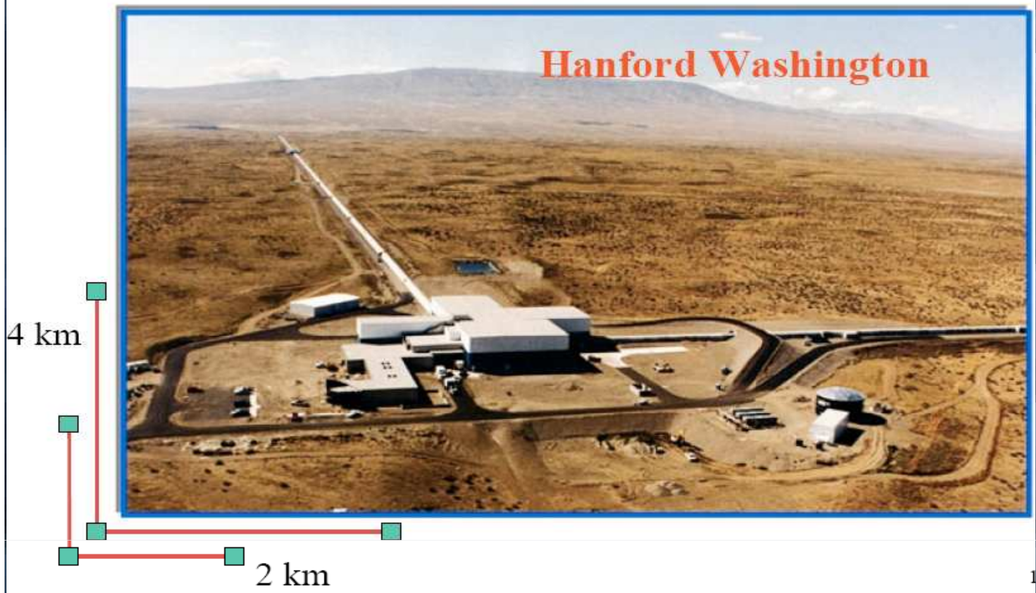


VIRGO

Site : Cascina - près de Pise

Sensibilité visée : $\tilde{h} \approx 10^{-21} / \sqrt{\mathrm{Hz}}$ @ 10Hz et $\tilde{h} \approx 3 \times 10^{-23} / \sqrt{\mathrm{Hz}}$ @ 1kHz

LIGO
(USA)



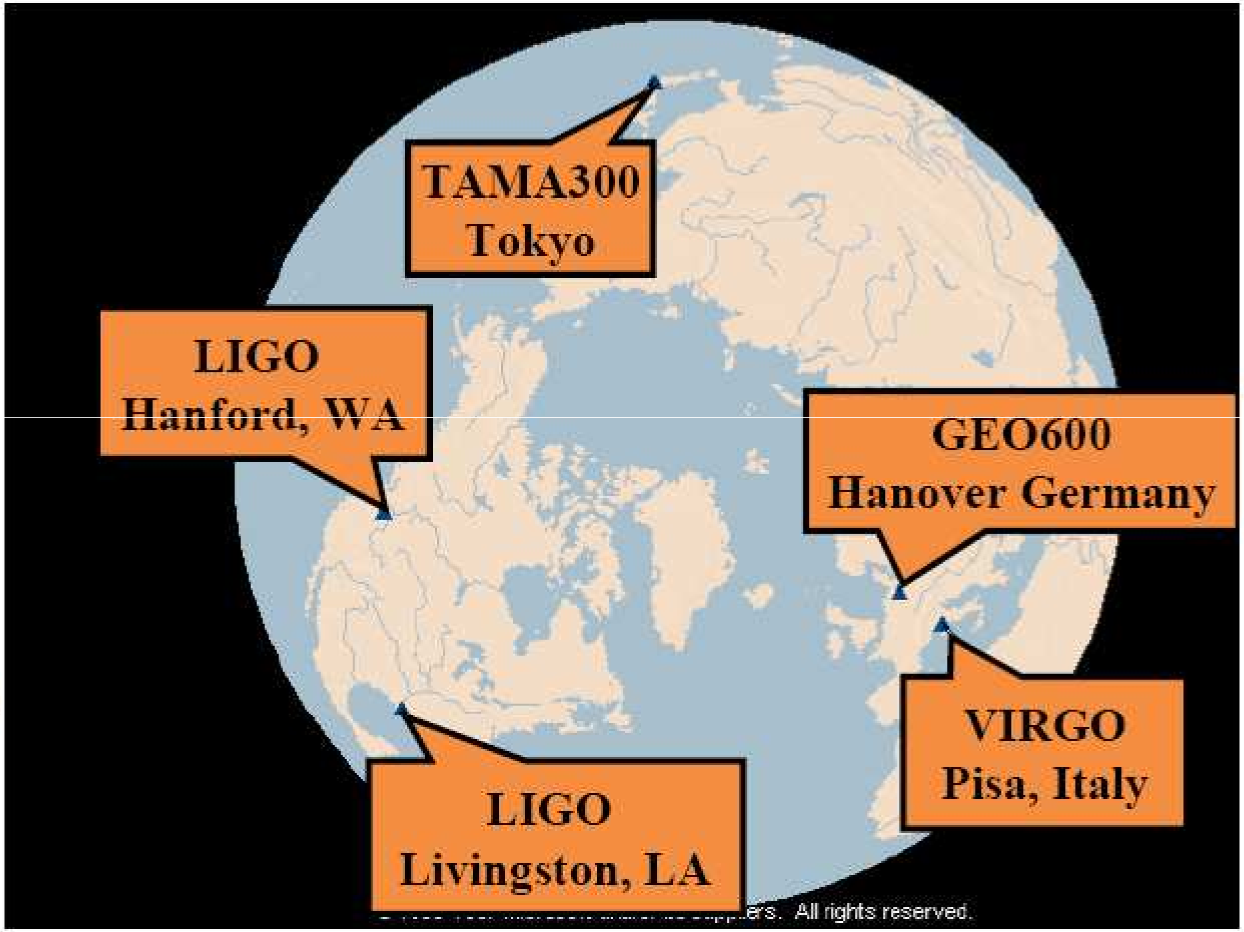
GEO600, Hanover Germany [UK, Germany]

TAMA300, Tokyo [Japan]

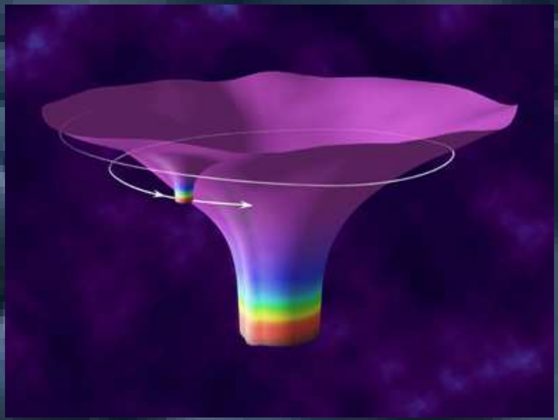
Collaboration international

- Confirmation des signaux

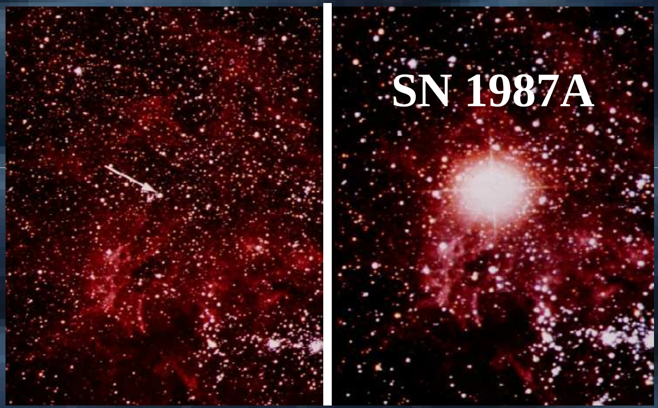
- Direction : triangulation



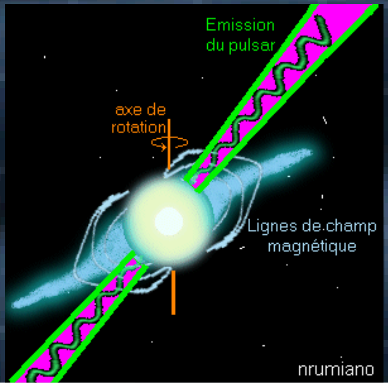
Sources



• Coalescences binaires

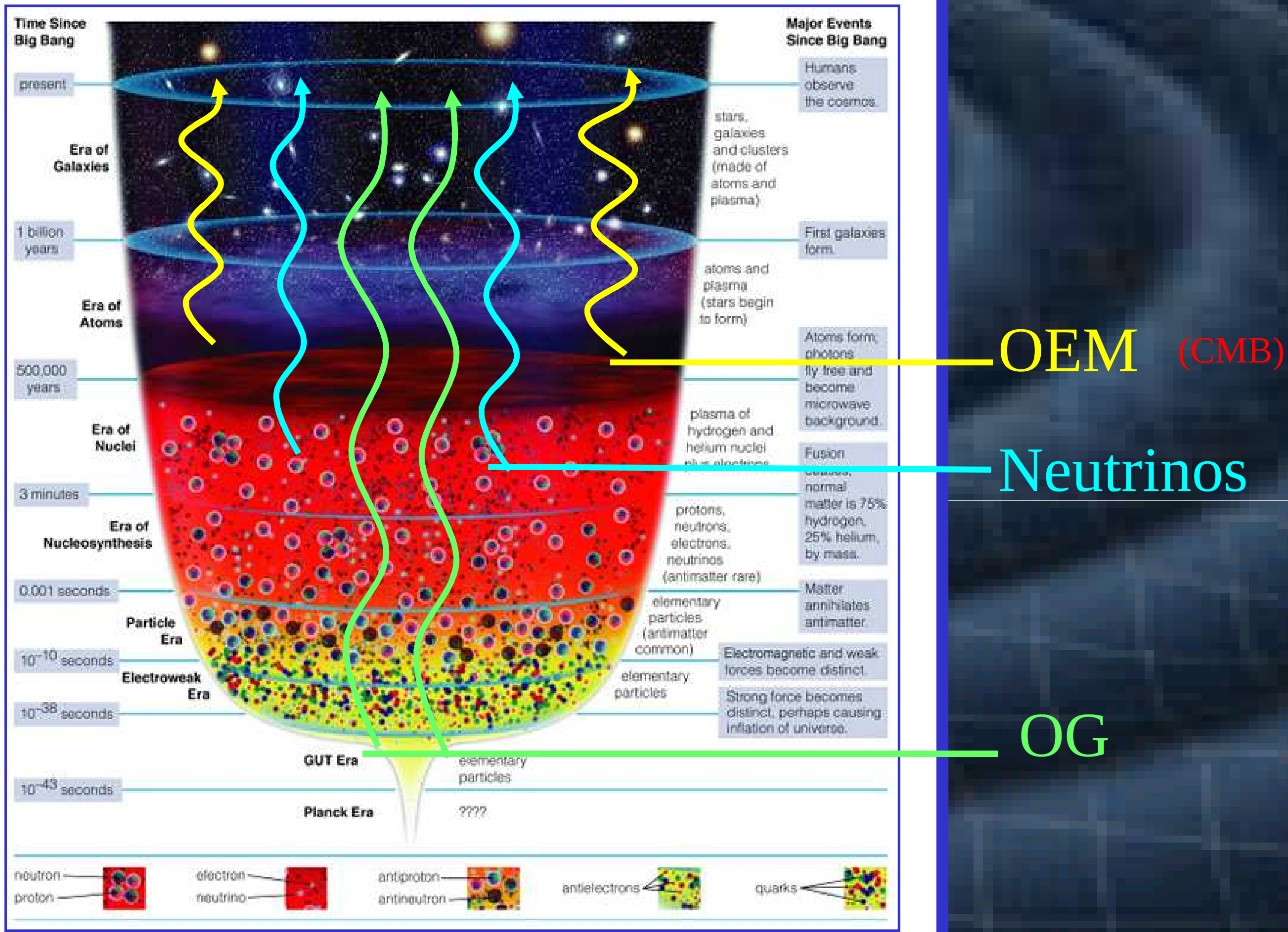


• Supernovae

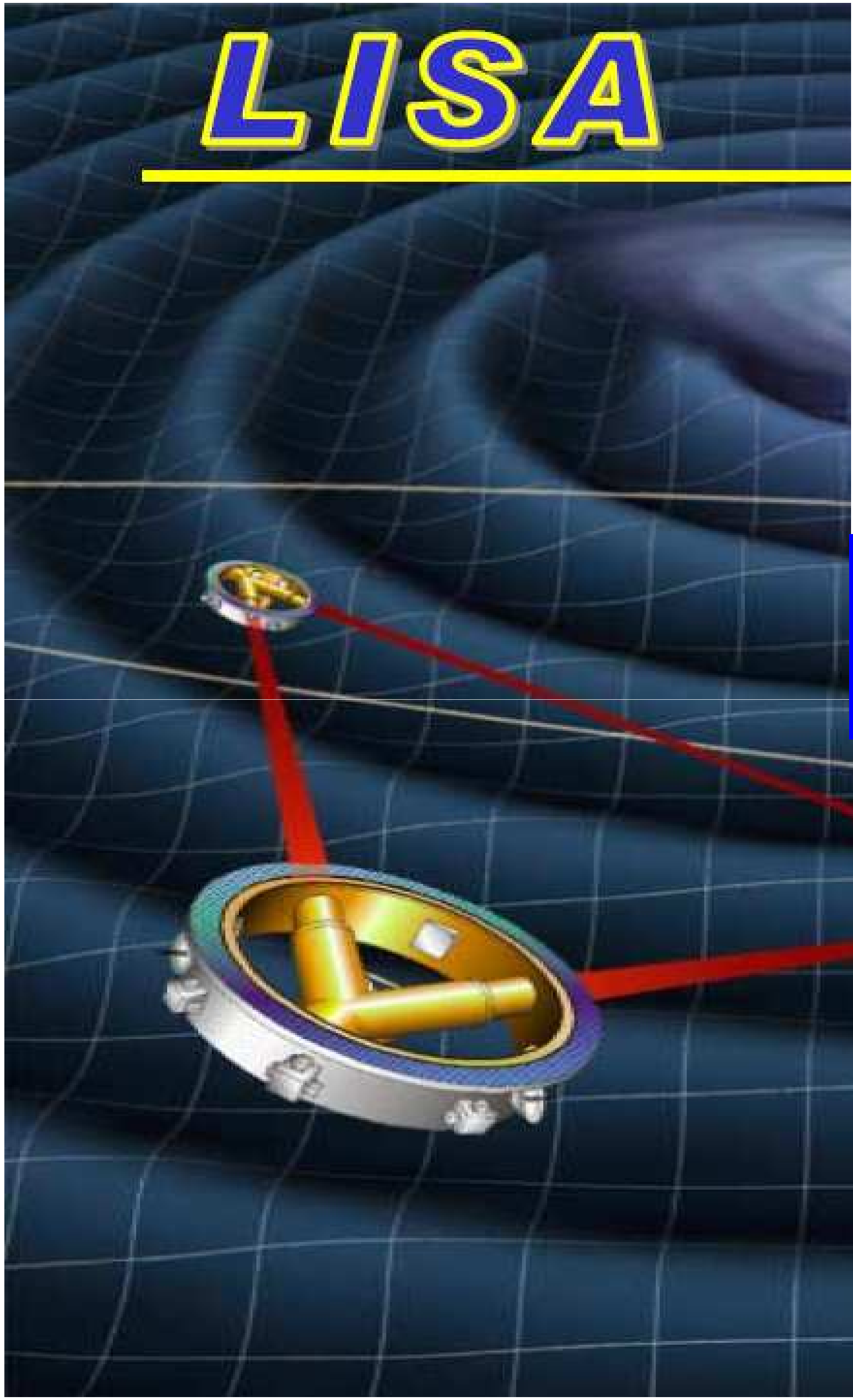


• Pulsars asymétriques

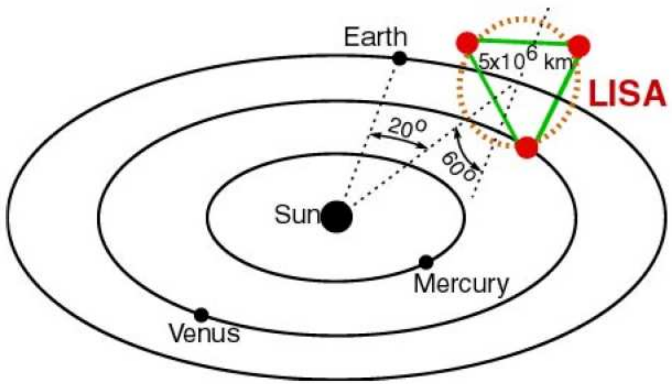
• Fond Stochastique



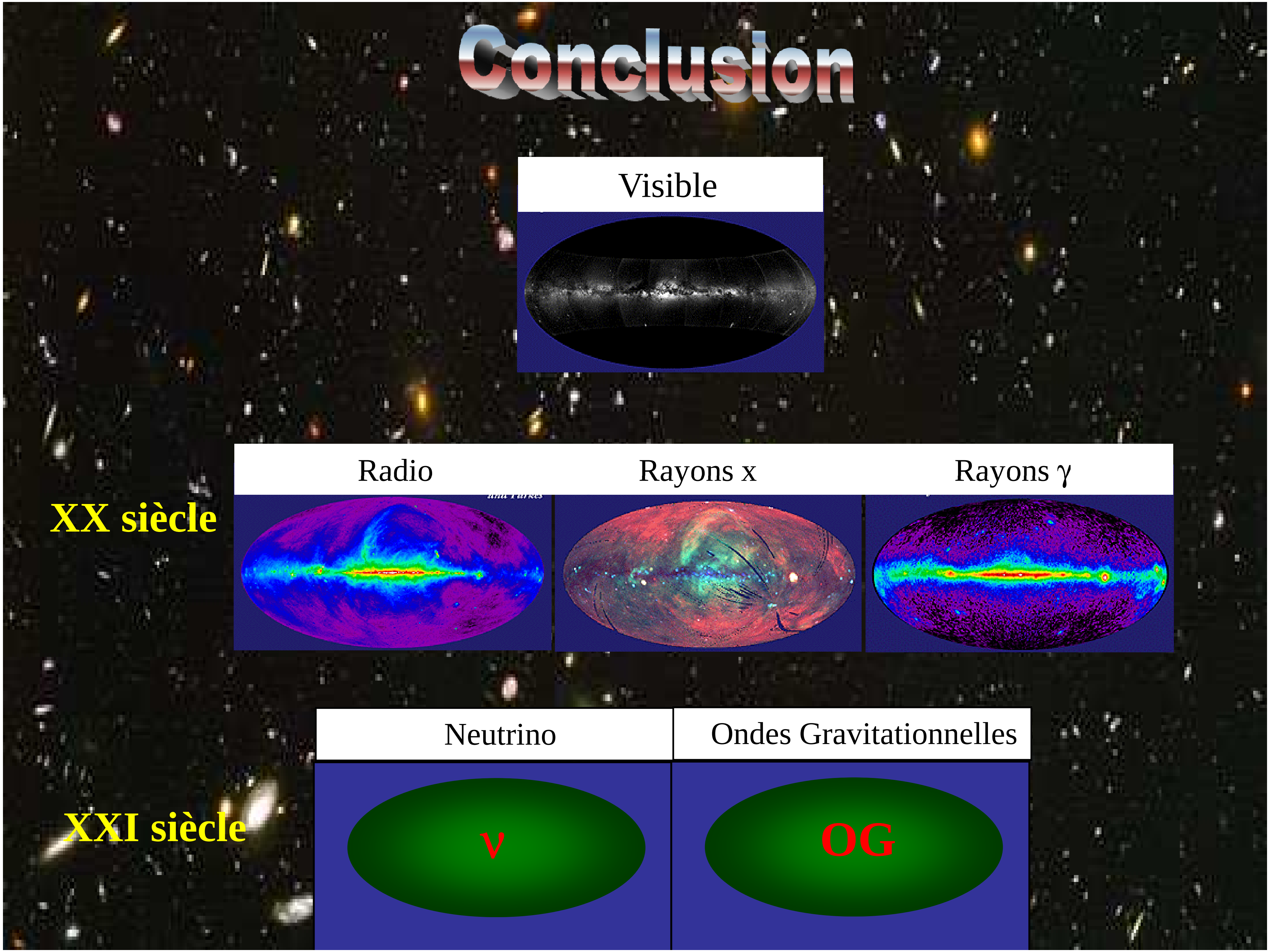
Le Big Bang



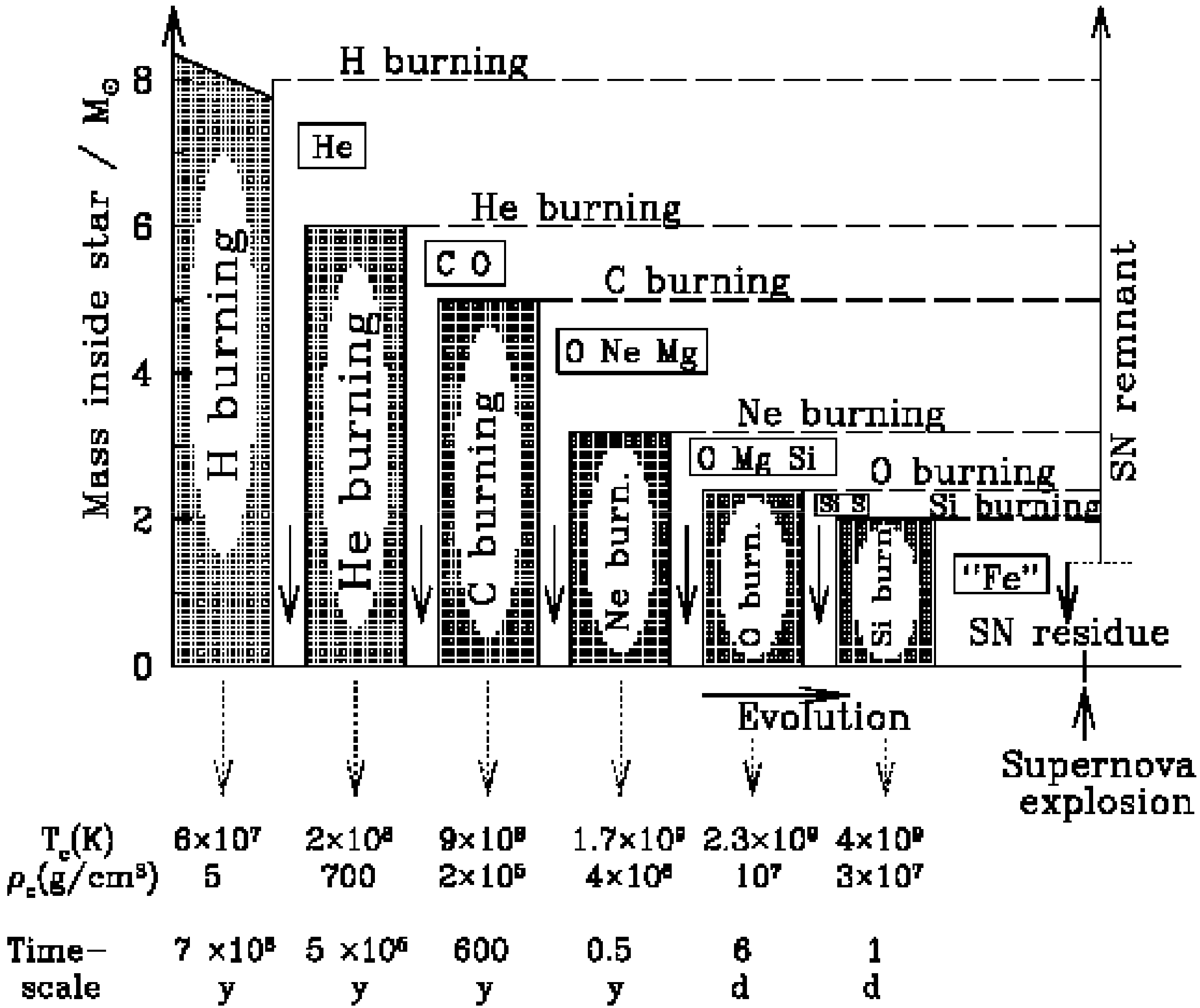
LISA Configuration



- **Longueur des bras : 5 millions de km**
- **Précision position : 10^{-9} cm**

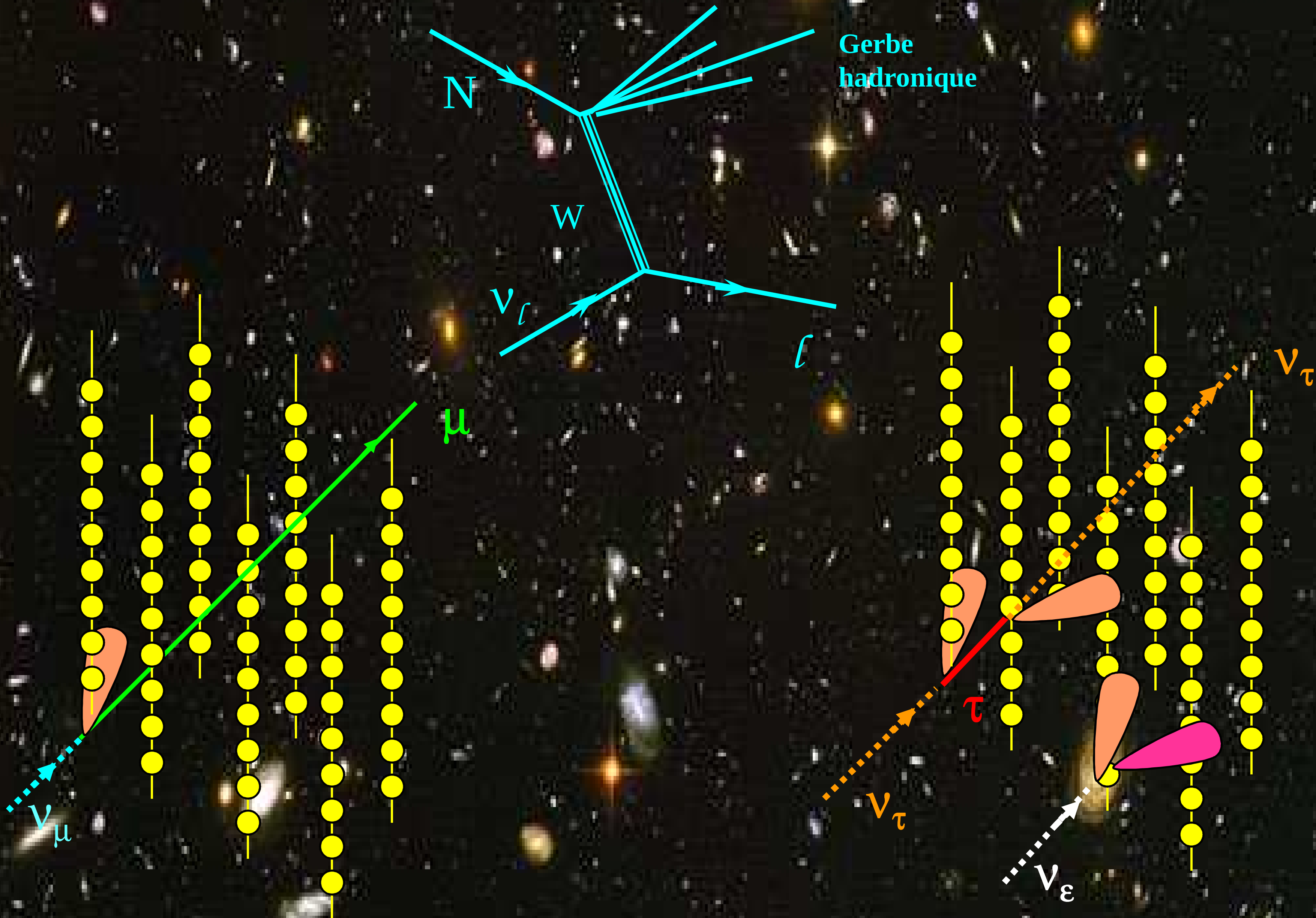


Conclusion
Visible
Radio
Rayons x
Rayons γ
XX siècle
Neutrino
Ondes Gravitationnelles
XXI siècle
ν
OG

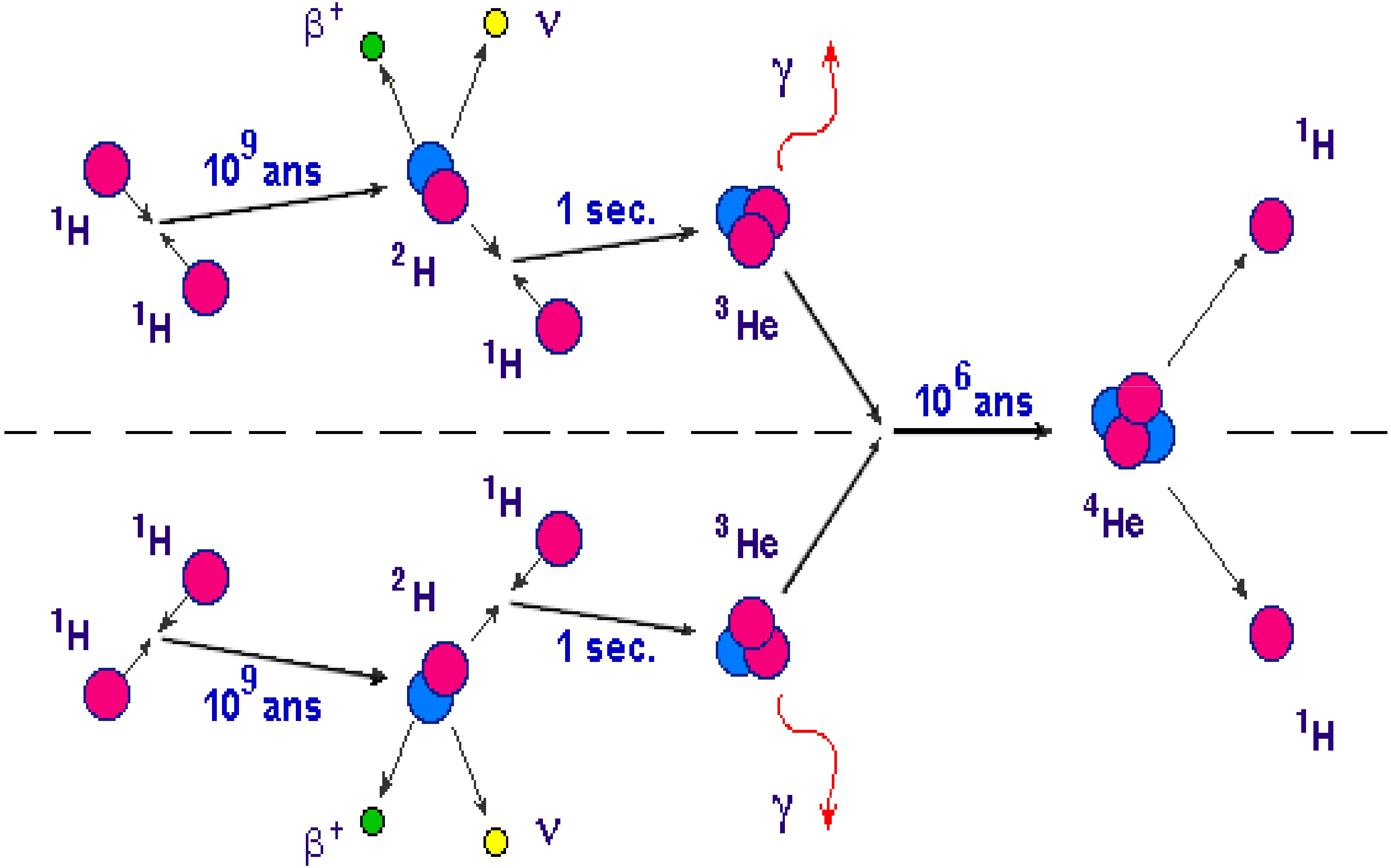


Mass inside star / $M_\odot$
0
2
4
6
8
H burning
He
H burning
He burning
C O
He burning
C burning
O Ne Mg
C burning
Ne burning
O Mg Si
Ne burn.
O burning
Si S
Si burning
O burn.
Si burn.
"Fe"
SN residue
SN remnant
Evolution
Supernova explosion
T_c(K) 6×10^7 2×10^8 9×10^8 1.7×10^9 2.3×10^9 4×10^9
ρ_c(g/cm^3) 5 700 2×10^5 4×10^6 10^7 3×10^7
Time-scale 7×10^6 y 5×10^5 y 600 y 0.5 y 6 d 1 d

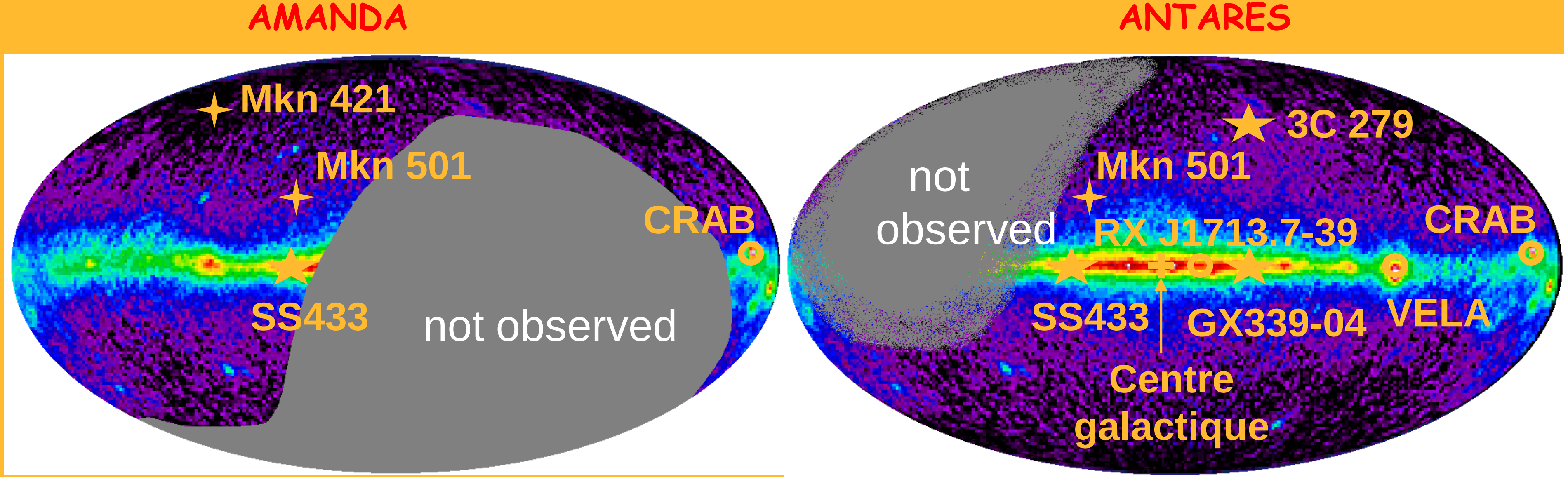
Différents type d'événements



Dépendance en temps



Most promising sources



EGRET Source Type	number of sources	seen by Antares	seen by Amanda
All	271	89%	43%
AGN	94	86%	52%
Pulsars	5	100%	40%
Unidentified Gal. Plane	55	93%	36%
Unidentified off Gal. Plane	116	90%	40%

Microquasars:

SS433 →

GX339 →

Source		Signal	atm. nu's
SS433	Antares 1 year	4.3	0.3
SS433	Amanda 1 year (*)	2.0	4.4
SS433	Amanda observed (*)	0	2.4
GX339	Antares 1 year	6.5	0.3
GX339	Amanda	invisible	—

Predictions. Galactic sources

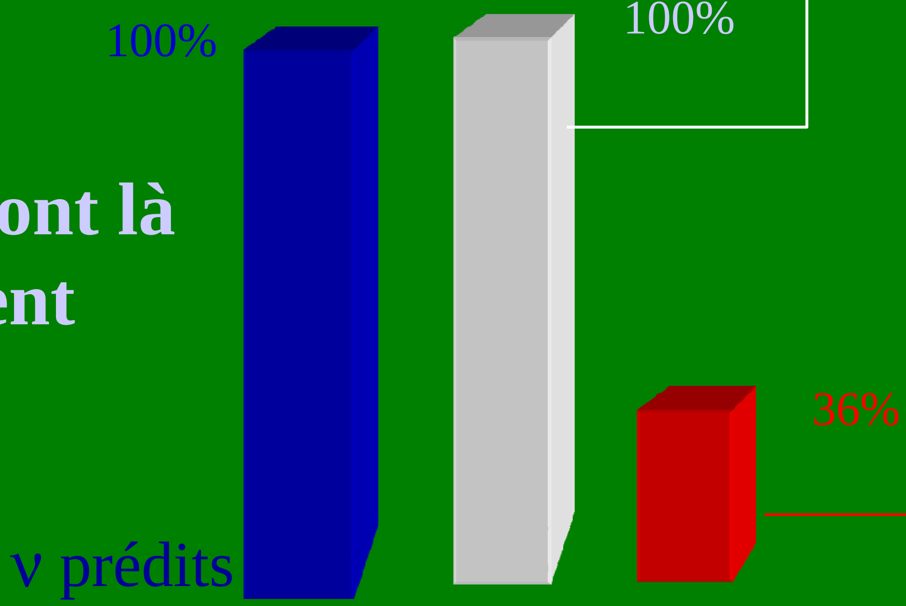
Source Type	Distance (kpc)	E_ν (GeV)	$N_{\nu\mu}$ ($km^{-2}\ yr^{-1}$)	Ref.
Supernovae Shocks pulsars	10	$<\sim 10^3$ $\sim 10^2 - 10^6$ $\sim 10^5 - 10^8$ $\sim 10 - 10^8$	~ 100 $50 - 1000$ $\sim 100 - 1000$ $<\sim 1000$	Waxman & Loeb 2001 Protheroe et al. 1998 Beall & Bednarek 2002 Nagataki 2004
Plerions Crab	0.5 – 4.4 2	$< 10^3 - 10^5$ $\sim 10^3 - 5 \cdot 10^5$ $\sim 10^3 - 5 \cdot 10^5$ $\sim 10^3 - 5 \cdot 10^5$ $10 - 10^6$	$\sim 1 - 12$ $<\sim 1$ a few ~ 1 $\sim 4 - 14$	Guetta & Amatto 2003 Bednarek 2003 Bednarek & Protheroe 1997 Bednarek 2003 Amato et al. 2003
Shell SNRs SNR RX J1713.7-3946 Sgr A East	6 8	$<\sim 10^4$ $<\sim 10^5$	~ 40 ~ 140	Alvarez-Muñiz & Halzen 2002
Pulsars + Clouds Galactic Centre Cygnus OB2	8 1.7	$10^4 - 10^7$ $>\sim 10^3$ $10^4 - 10^7$ $<\sim 10^6$	$\sim 2 - 30$ a few ~ 0.5 ~ 4	Bednarek 2002 Torres et al. 2004 Bednarek 2003 Anchordoqui et al. 2003
Binary systems **A0535+26**	2.6	$3 \cdot 10^2 - 10^3$	a few	Anchordoqui et al. 2003
Microquasars	1 – 10	$10^3 - 10^5$	$1 - 300$	Distefano et al. 2002
Magnetars	3 – 16	$<\sim 10^5$	$1.7\ (0.1/\Delta\Omega)\ (5/d^2)$	Zhang et al. 2003

La détection de neutrinos dans SNO

SNO : H_2O –> D_2O

$\nu + d$ ––––> $p + p + e^-$ **Sensible aux ν_e**

$\nu_x + p + n$ Sensible à tous les ν_x



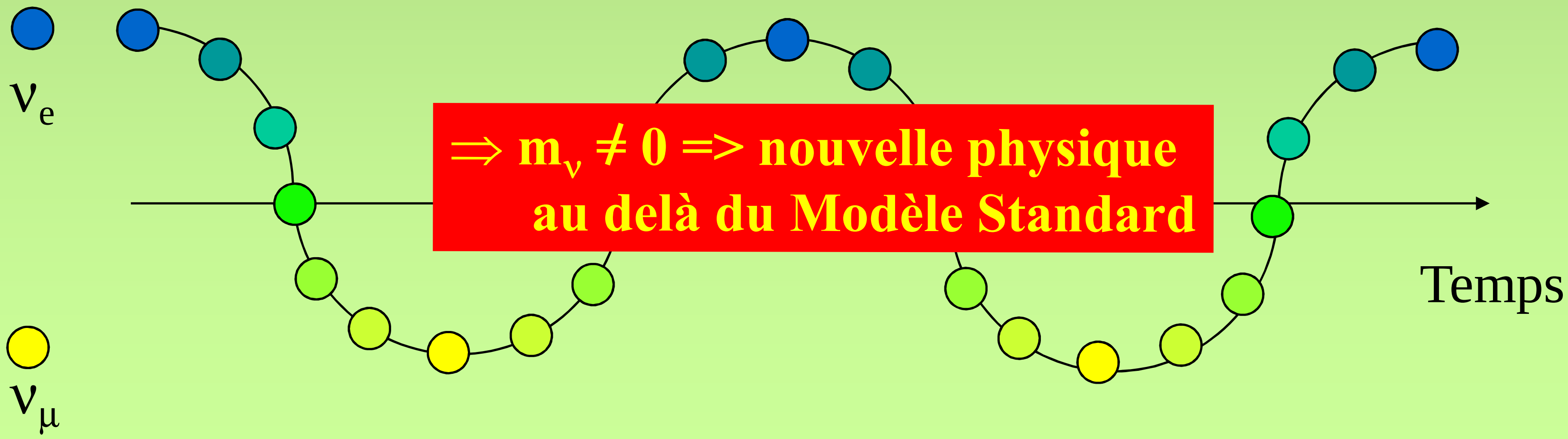
Tous le neutrinos sont là mais les ν_e manquent

Où sont passes les neutrinos ?

Oscillations des neutrinos

Si le neutrino possède une masse il peut changer de saveur dans le temps

Exemple très chromatique de l'oscillation de neutrinos entre deux saveurs



$\Rightarrow$ $m_\nu \neq 0$ => nouvelle physique au delà du Modèle Standard

La période dépend de l'énergie

Encore plus sur les etoiles

Etoile : 75% H et 25% He

Fusion “lente” de l’hydrogene

$4H + 2e^{-} \rightarrow {}^{4}He + 2\nu_e$ 26.731 MeV

$3\ {}^{4}He \rightarrow {}^{12}C$ + 7.656 MeV : Geante Rouge --> Naine Blanche

Si plus de 8 masse solaire

$2\ {}^{12}C \rightarrow {}^{20}Ne + \alpha$ + 4.62 MeV

$2\ {}^{20}Ne \rightarrow {}^{16}O + {}^{24}Mg$ + 4.59 MeV

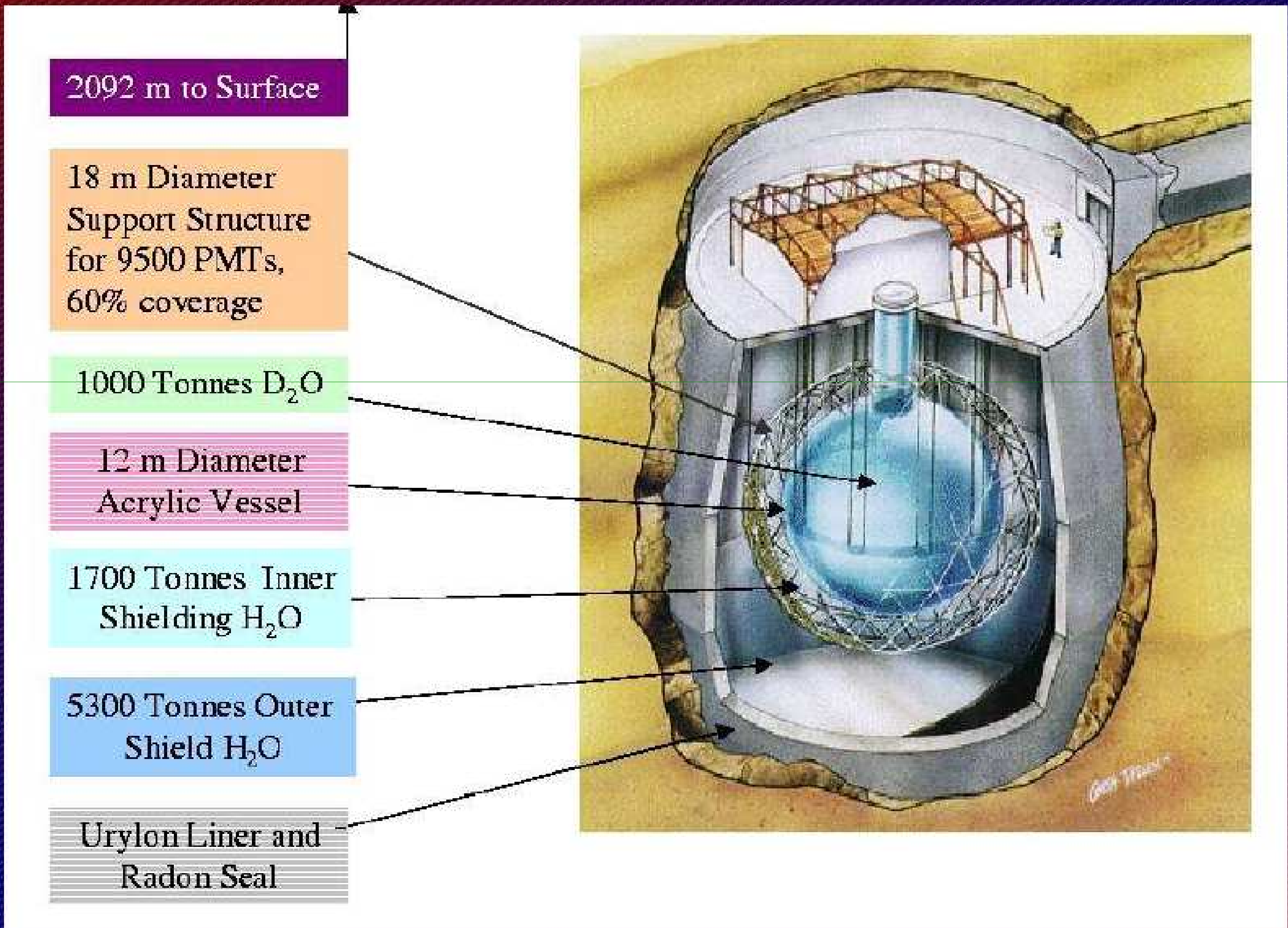
$2\ {}^{16}O \rightarrow {}^{28}Si + \alpha$ + 9.59 MeV

$2\ {}^{28}Si \rightarrow {}^{56}Ni \rightarrow \ldots \rightarrow {}^{56}Fe$

Au delà, réactions endothermiques => fin du combustible

Une expérience dans une météorite

Détecteur SNO



Départ 1999

Oser ICHEP 2002

Origine des neutrinos haute énergie

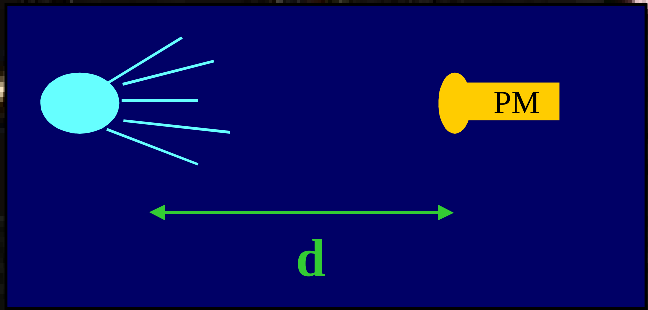
$$p + A \longrightarrow \pi^{+-} + \ \ldots$$

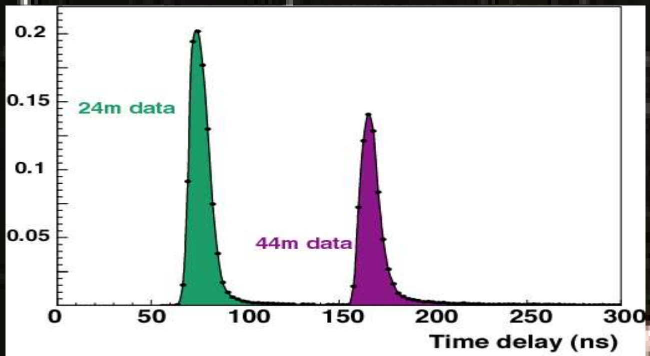
$$\pi^{+-} \longrightarrow \bar{\nu}_{\mu} + \mu$$

$$\mu \longrightarrow \nu_{\mu} + \nu_{e} + e$$

Evaluation du site

Transparence de l'eau



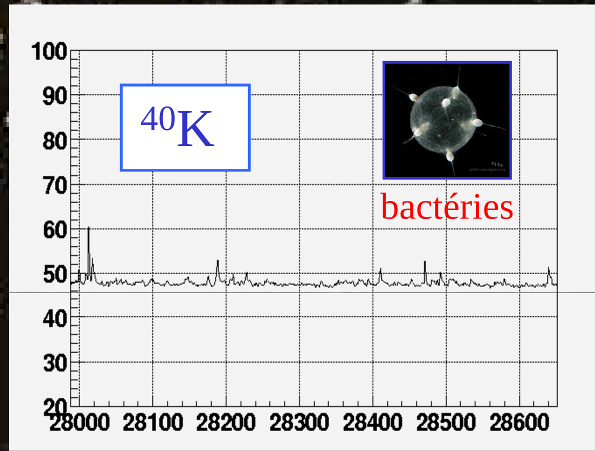


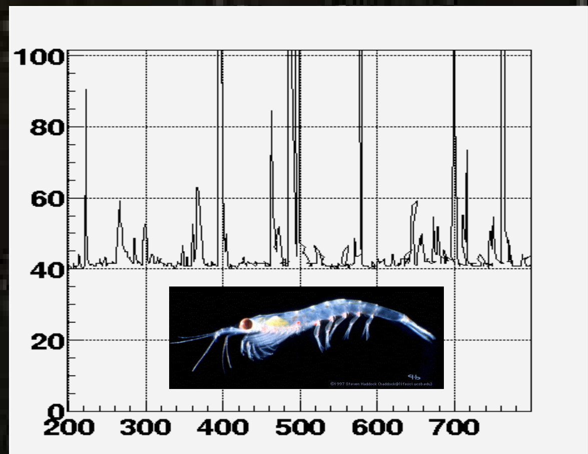
- Lumière bleu (470 nm)

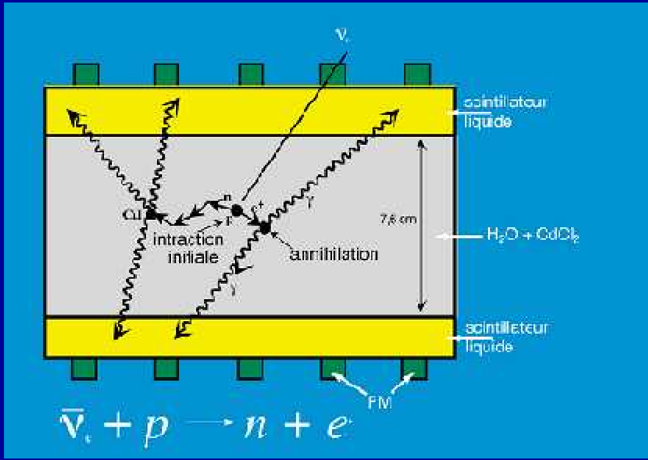
$\lambda_{abs} \sim 60 \pm 8$ m

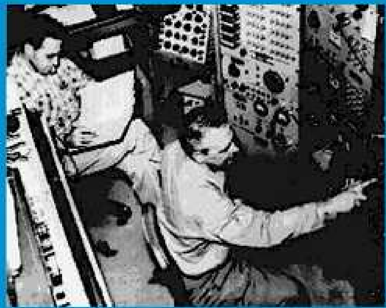
$\lambda_{scat\ eff} \sim 260$ m

Bioluminescence



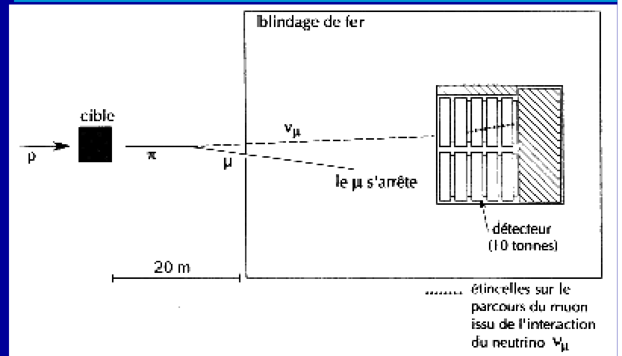






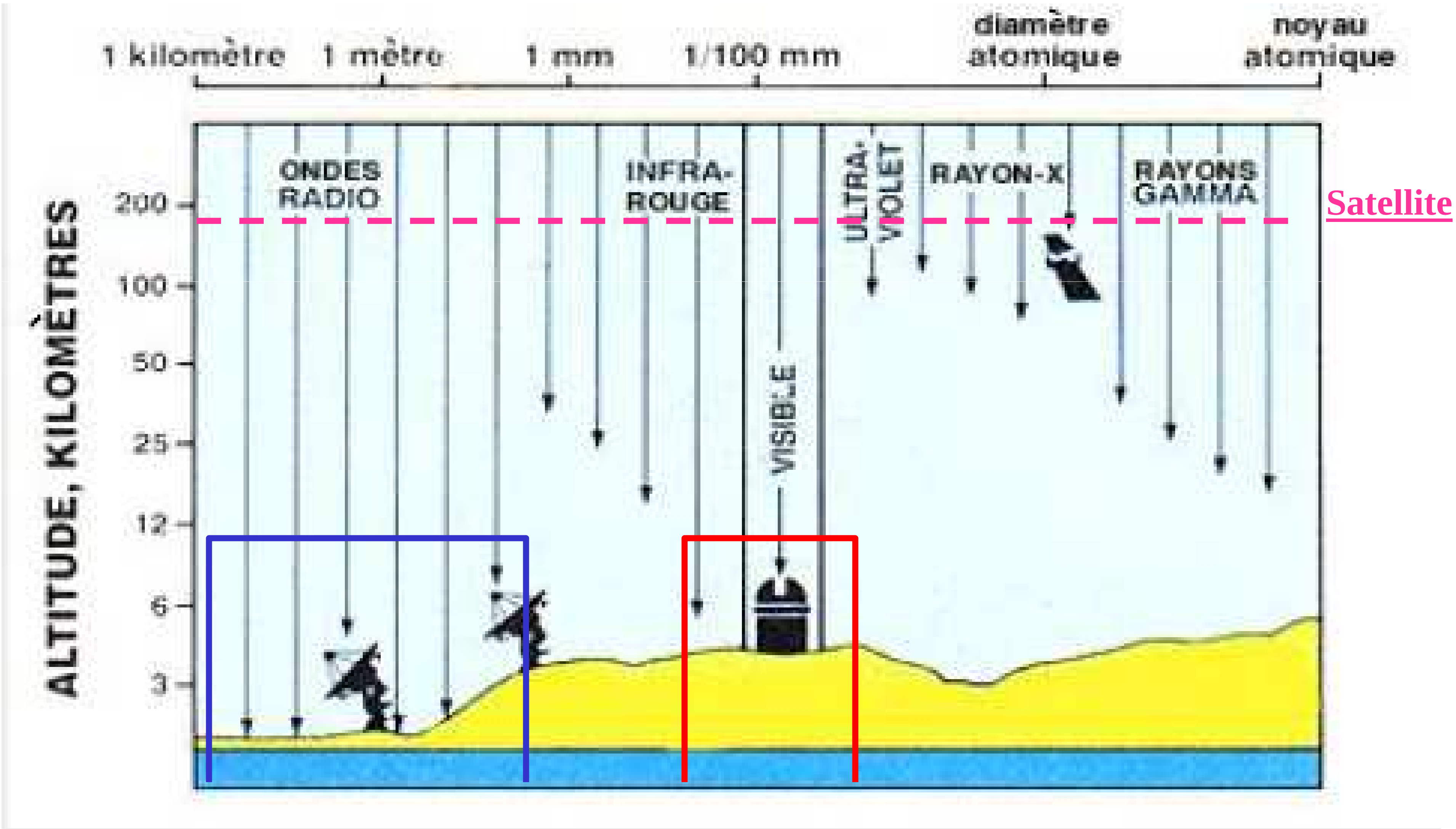
1957 : découverte du neutrino électronique

1963 : découverte du <u>neutrino muonique</u>



2000: découverte du <u>neutrino de Tau</u>
Fermi Lab.

Le filtre atmosphérique



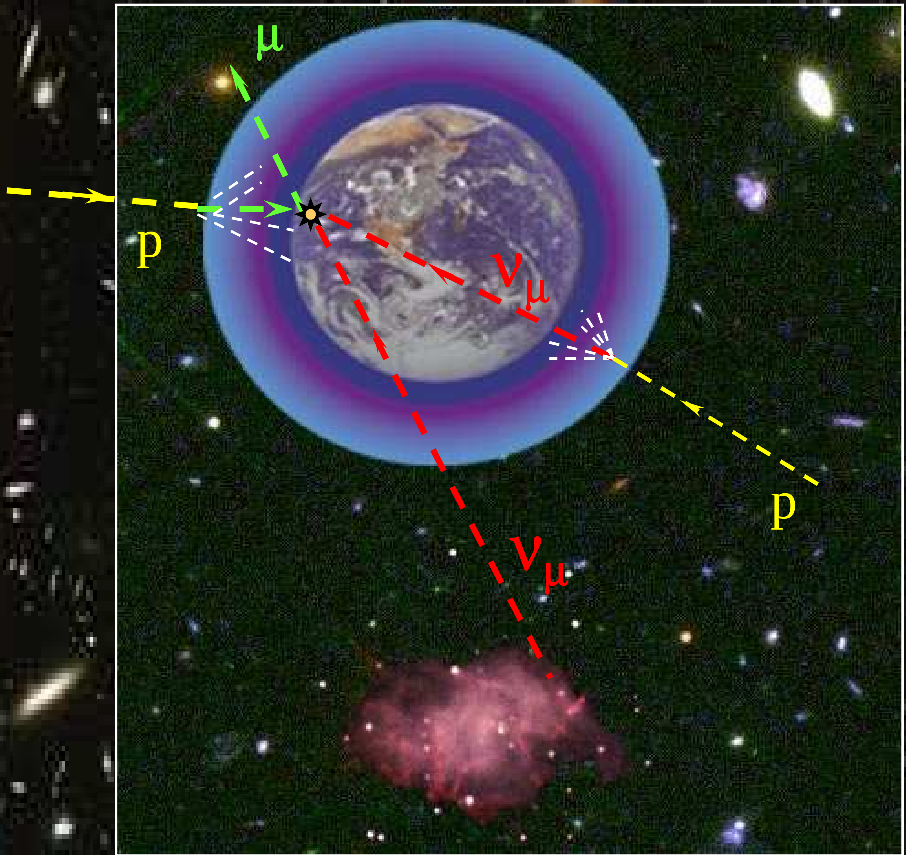
Bruit de fond physique

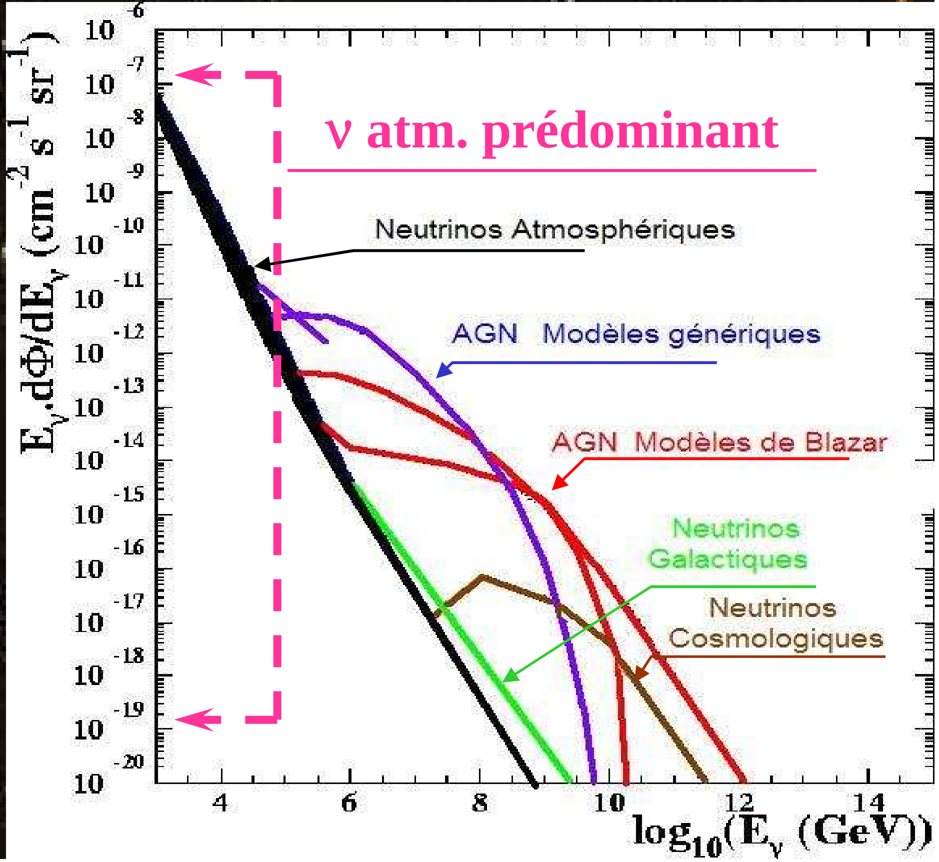
Le bruit de fond physique provient de l'interaction dur rayonnement cosmique avec l'atmosphère.

$$p + Air \rightarrow \pi^{+}(+K^{+}...) \rightarrow \mu^{+} + \nu_{\mu}$$

$$\bar{\nu}_{\mu} + \nu_{e}$$

"Il faut regarder vers le bas et à haute énergie"

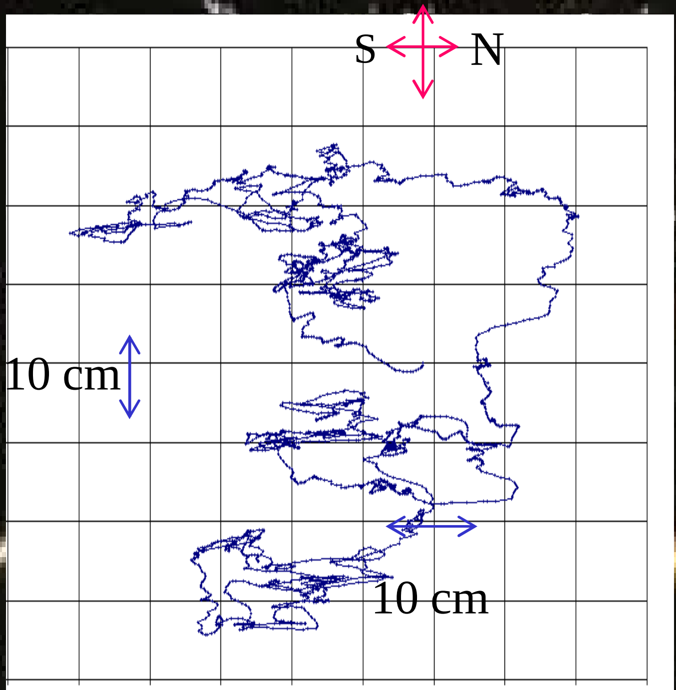


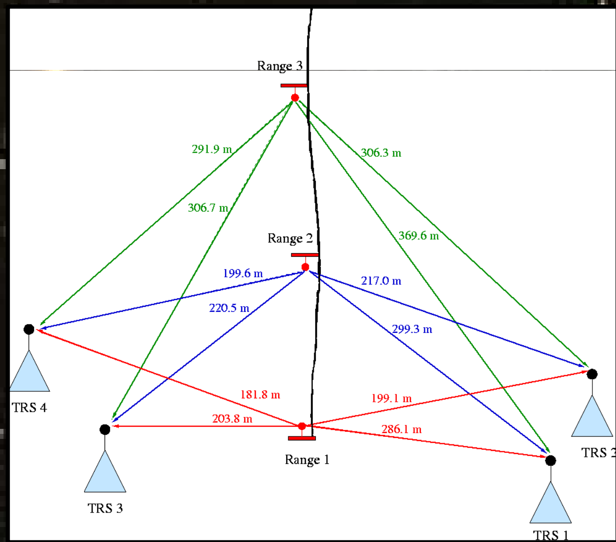


Positionnement de la ligne

Triangulation avec balise acoustique et hydrophones

Précision ~5 cm

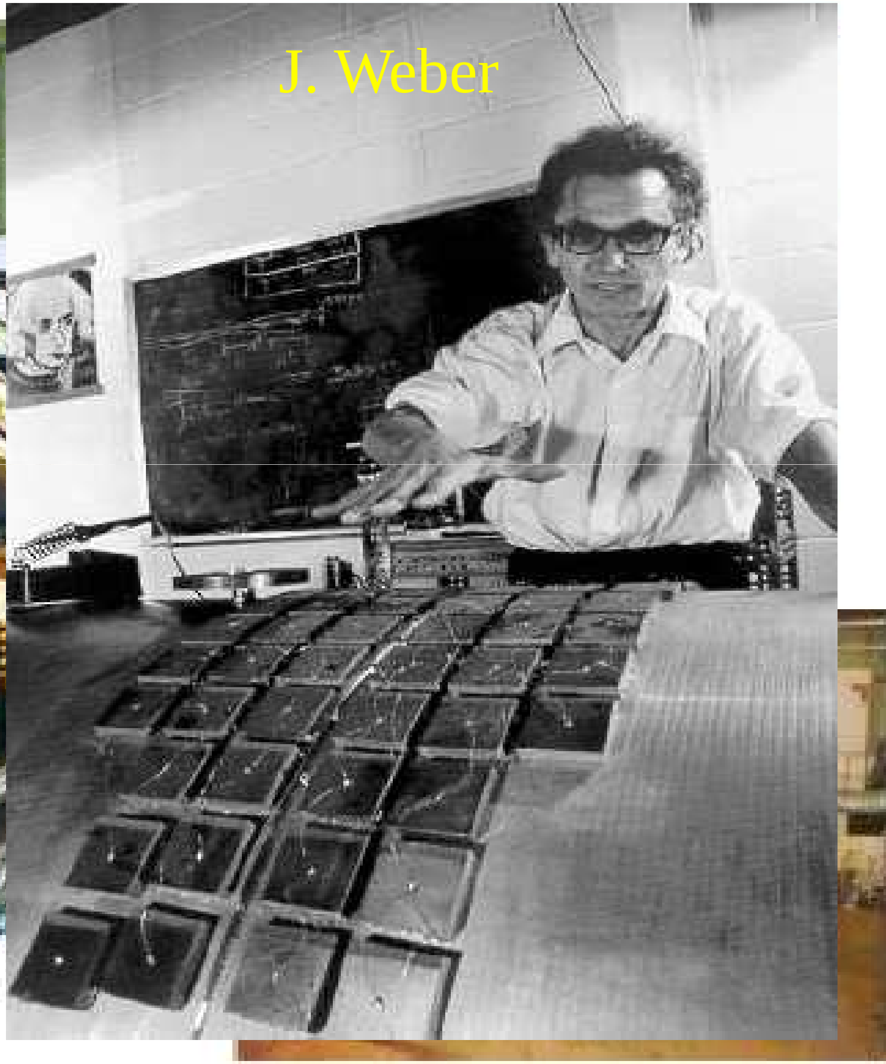




International Network of Bar Detectors

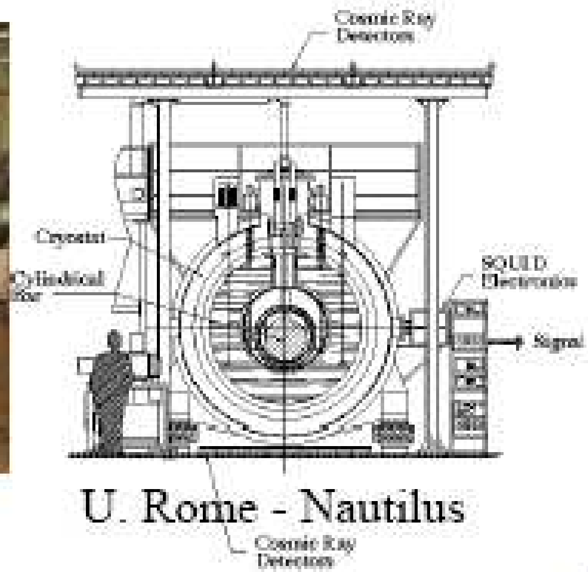
Now in Operation [~1000 Hz]

Louisiana State U.

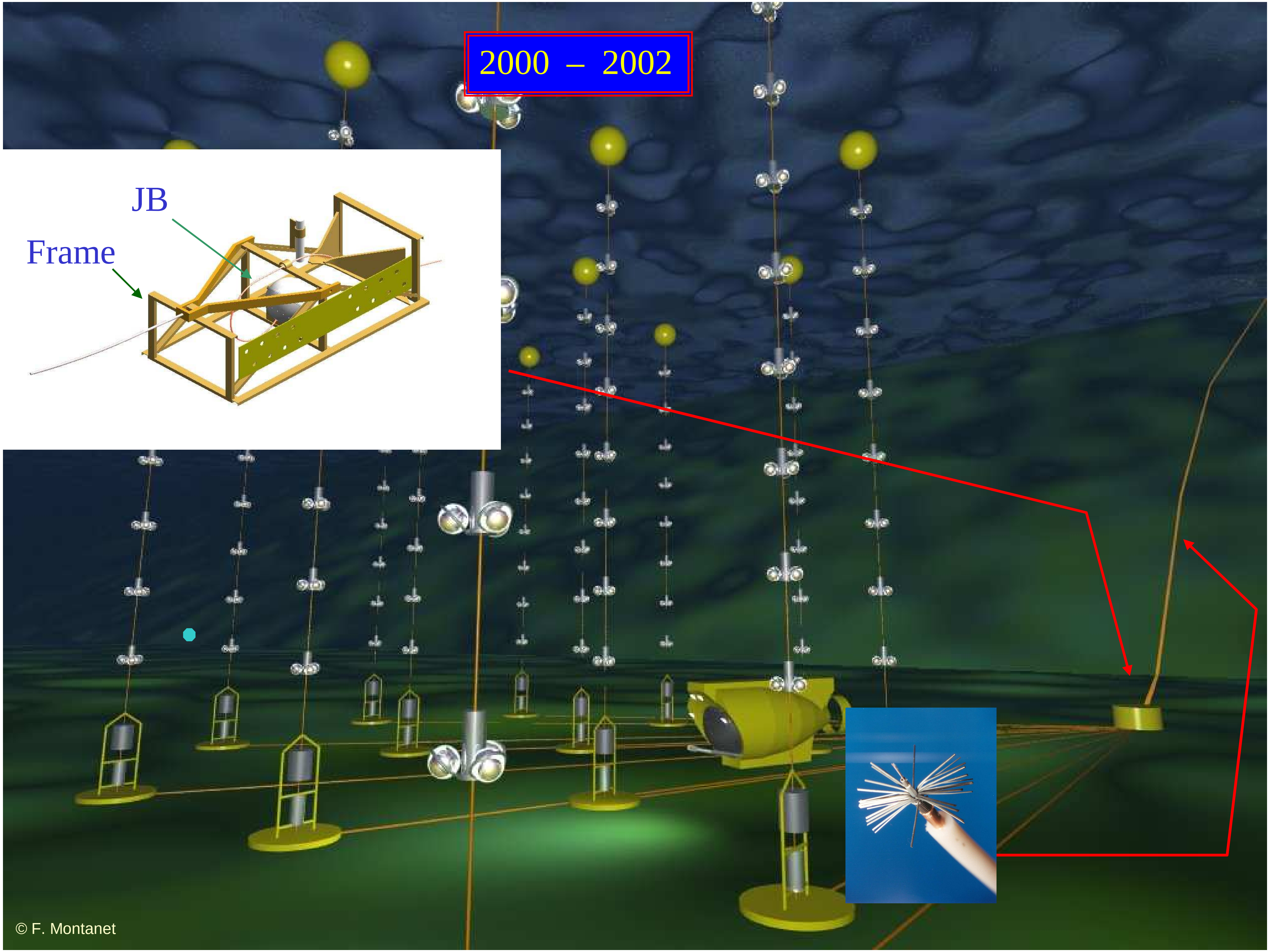


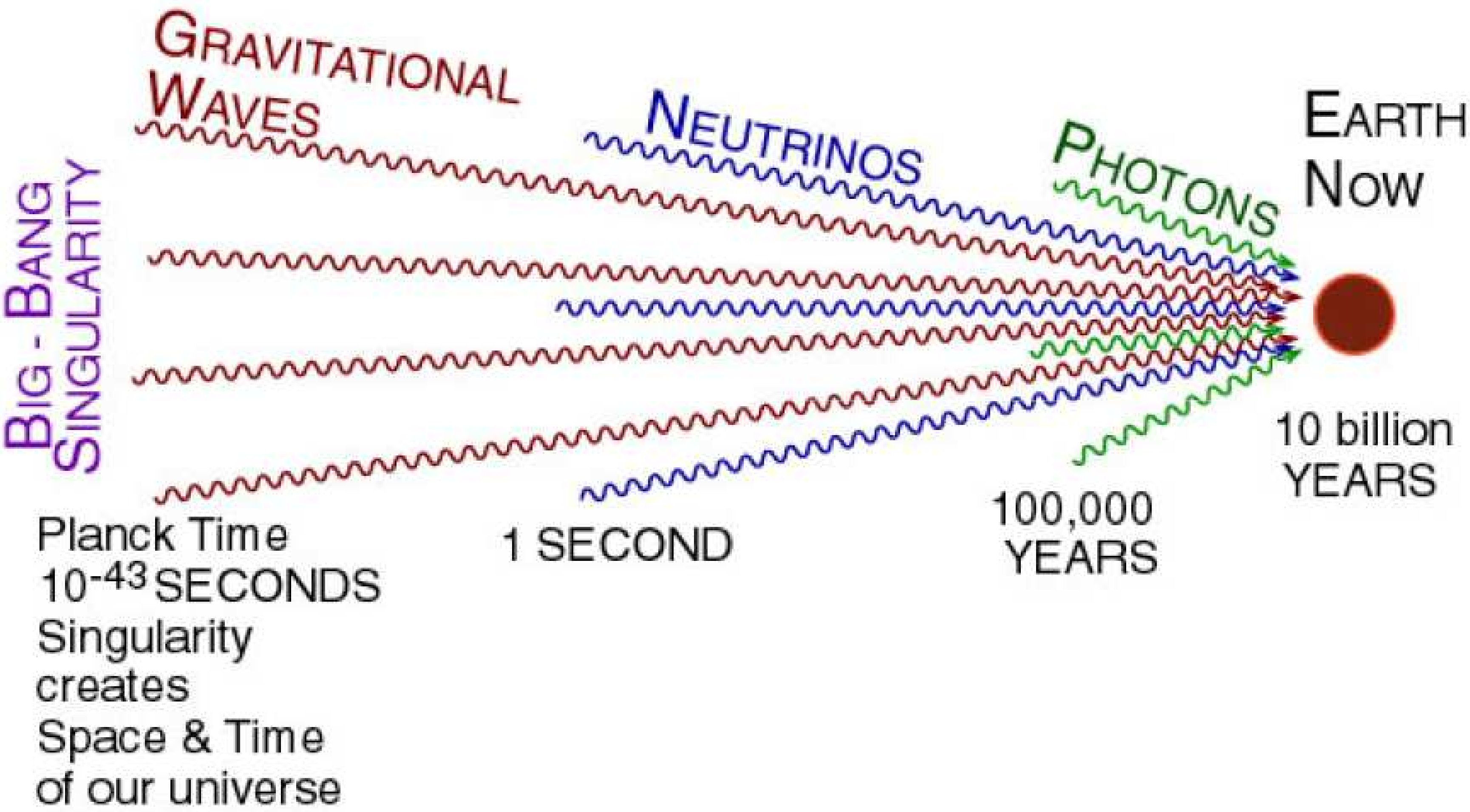
CERN - Explorer

U. Padova - Auriga



U. Rome - Nautilus

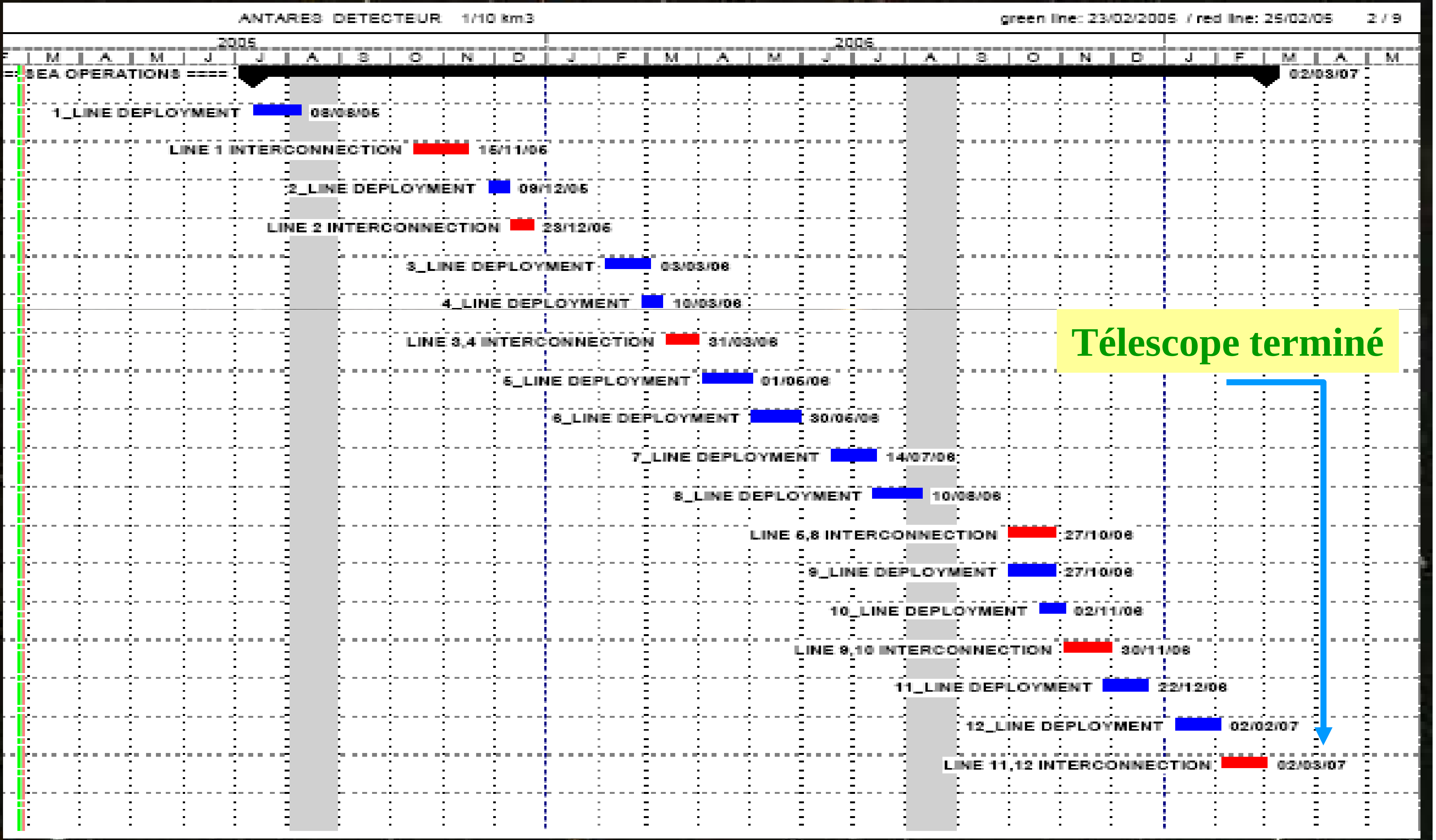

2000 – 2002
JB
Frame
© F. Montanet

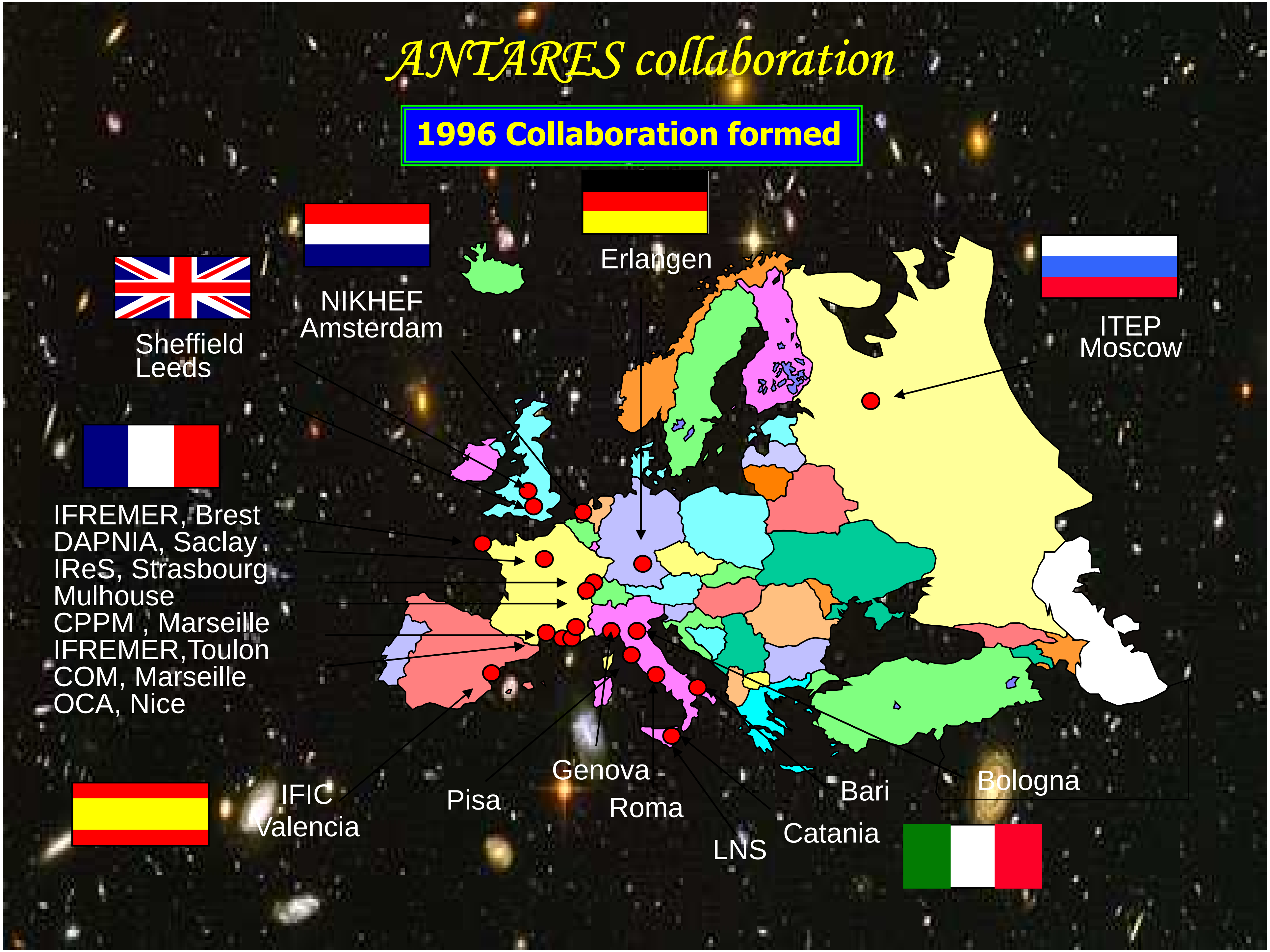


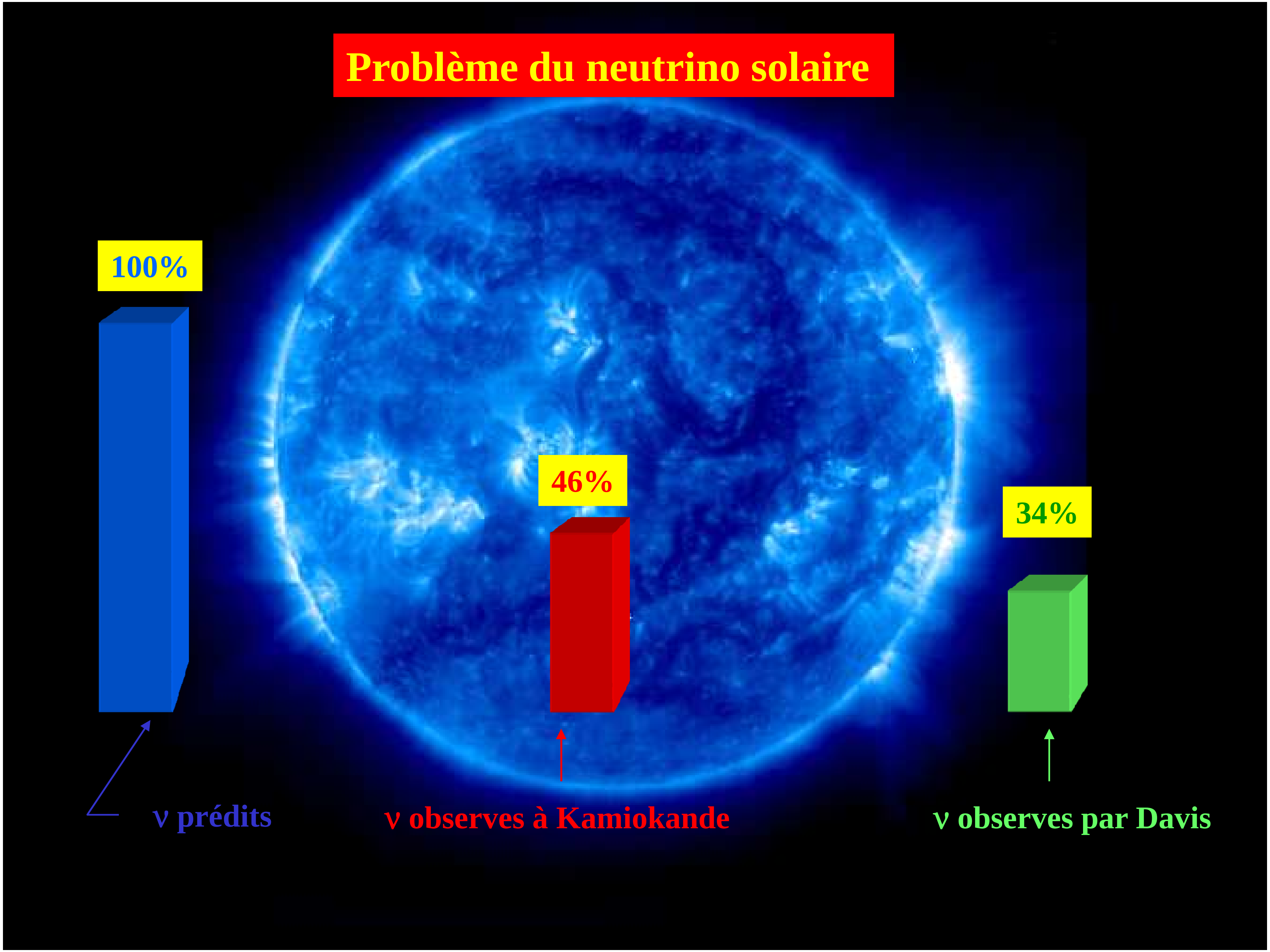
GRAVITATIONAL WAVES
NEUTRINOS
PHOTONS
EARTH
NOW
BIG - BANG
SINGULARITY
10 billion YEARS
100,000 YEARS
1 SECOND
Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe

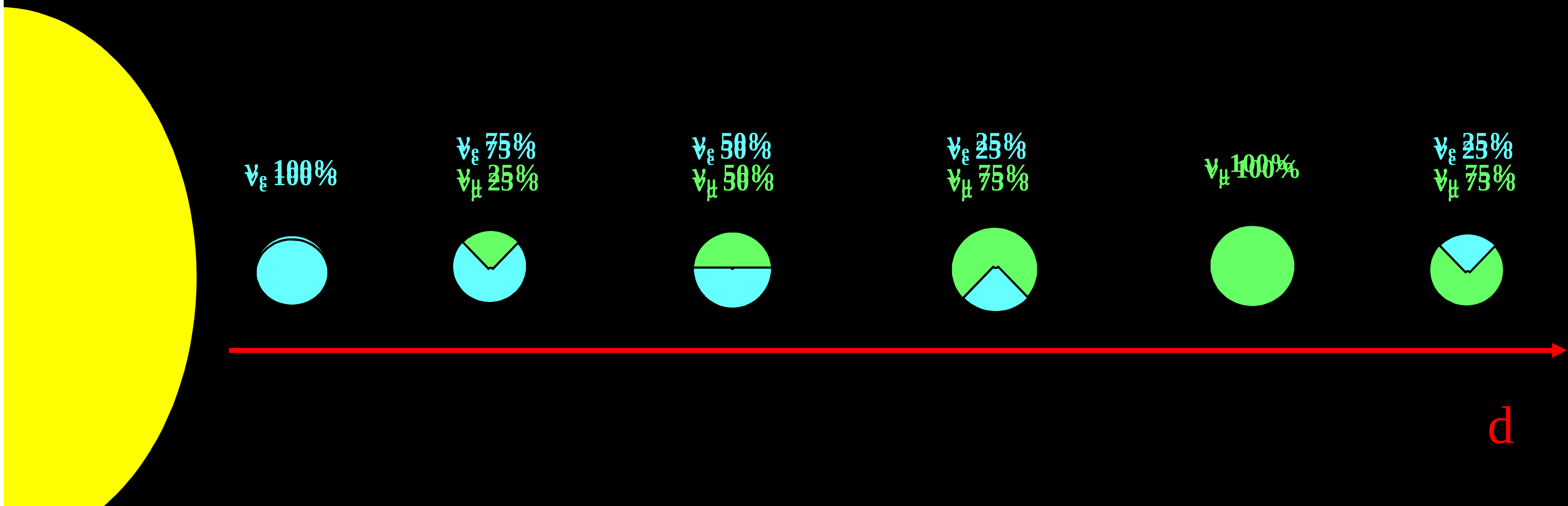
Avenir pour ANTARES

Juillet 2005 - 2007




ANTARES collaboration
1996 Collaboration formed
Sheffield
Leeds
NIKHEF
Amsterdam
Erlangen
ITEP
Moscow
IFREMER, Brest
DAPNIA, Saclay
IReS, Strasbourg
Mulhouse
CPPM , Marseille
IFREMER,Toulon
COM, Marseille
OCA, Nice
IFIC
Valencia
Pisa
Genova
Roma
LNS
Catania
Bari
Bologna


Problème du neutrino solaire
100%
46%
34%
ν prédits
ν observes à Kamiokande
ν observes par Davis



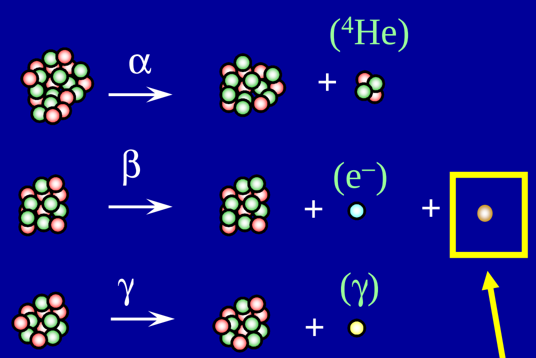
Oscillations de neutrinos => $m_\nu \neq 0$

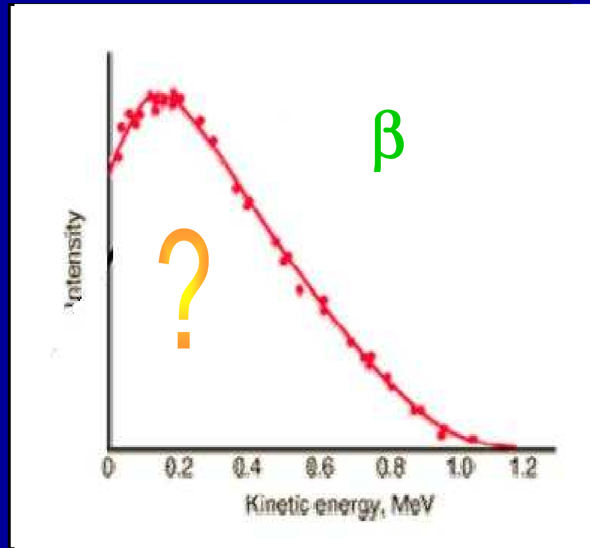
Nouvelle Physique !

Le neutrino

1896 **Découverte de la radioactivité**

3 processus d'instabilité de la matière : α, β, γ

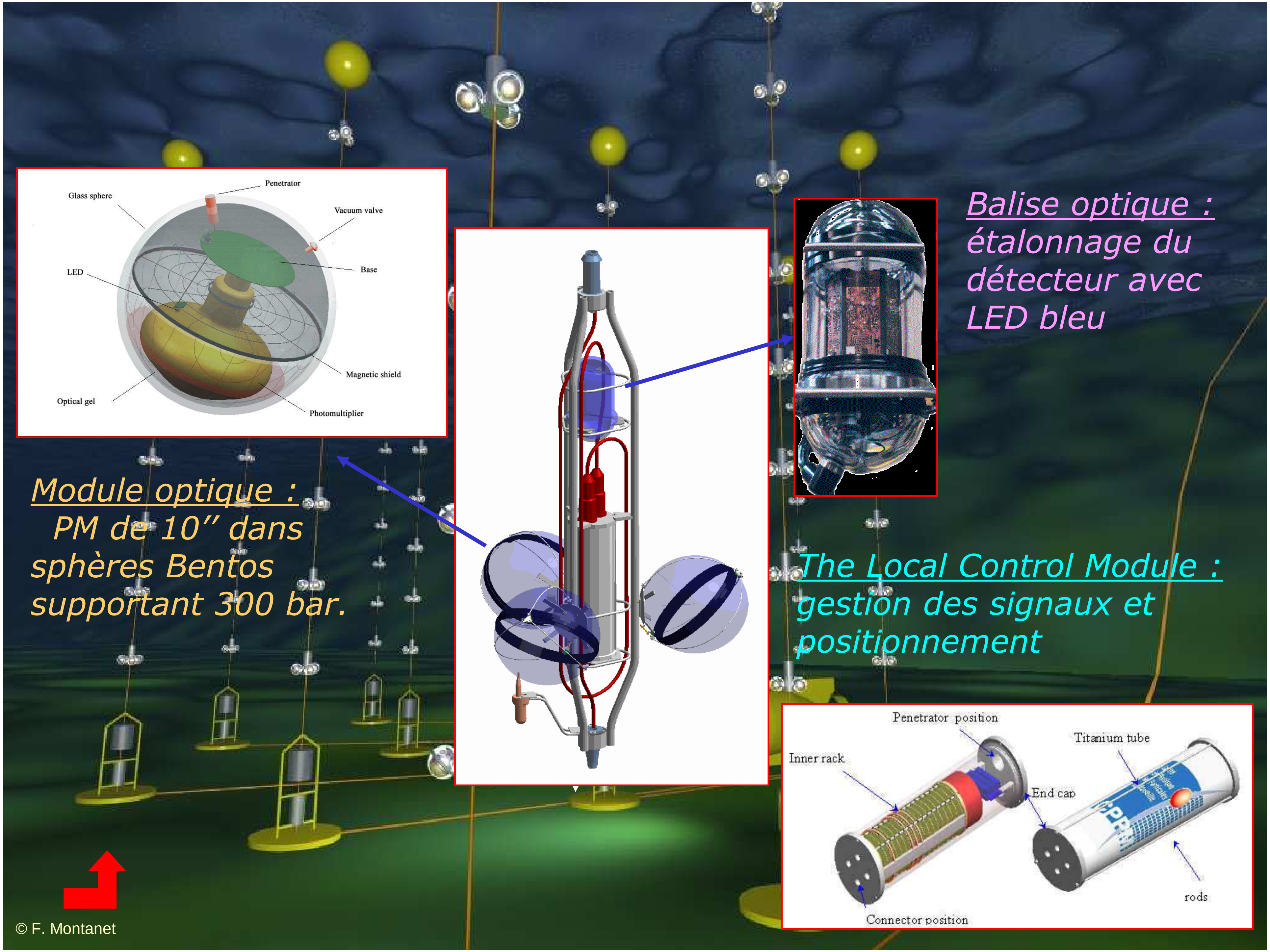




La solution "désespérée" : **neutrino**

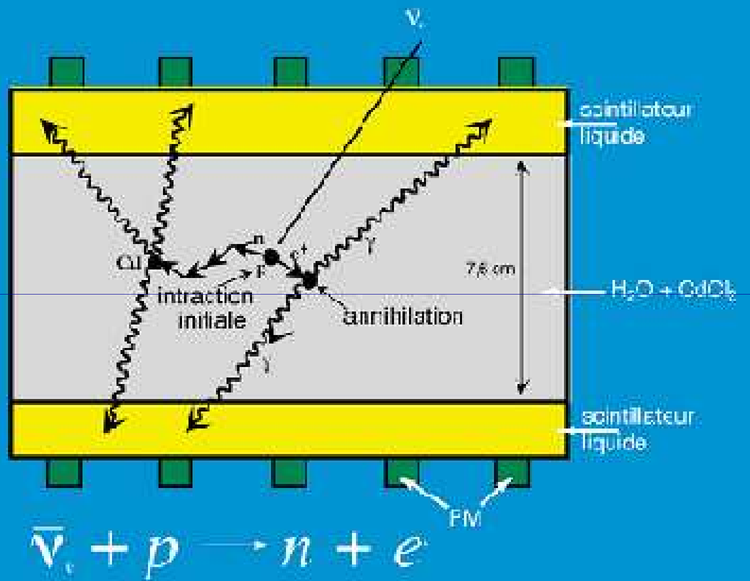
(Lettre de Pauli du 4 Decembre 1930)

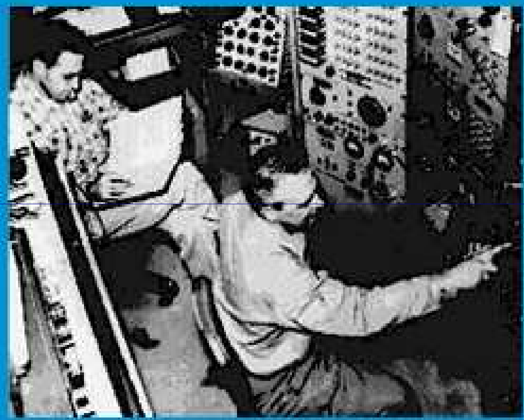
Jamais observée => pas de masse, pas de charge, …


Glass sphere
Penetrator
Vacuum valve
LED
Base
Magnetic shield
Optical gel
Photomultiplier
Balise optique :
étalonnage du détecteur avec LED bleu
Module optique :
PM de 10'' dans sphères Bentos supportant 300 bar.
The Local Control Module :
gestion des signaux et positionnement
Penetrator position
Titanium tube
Inner rack
End cap
rods
Connector position
© F. Montanet

La découverte

1957 : découverte du neutrino électronique





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