

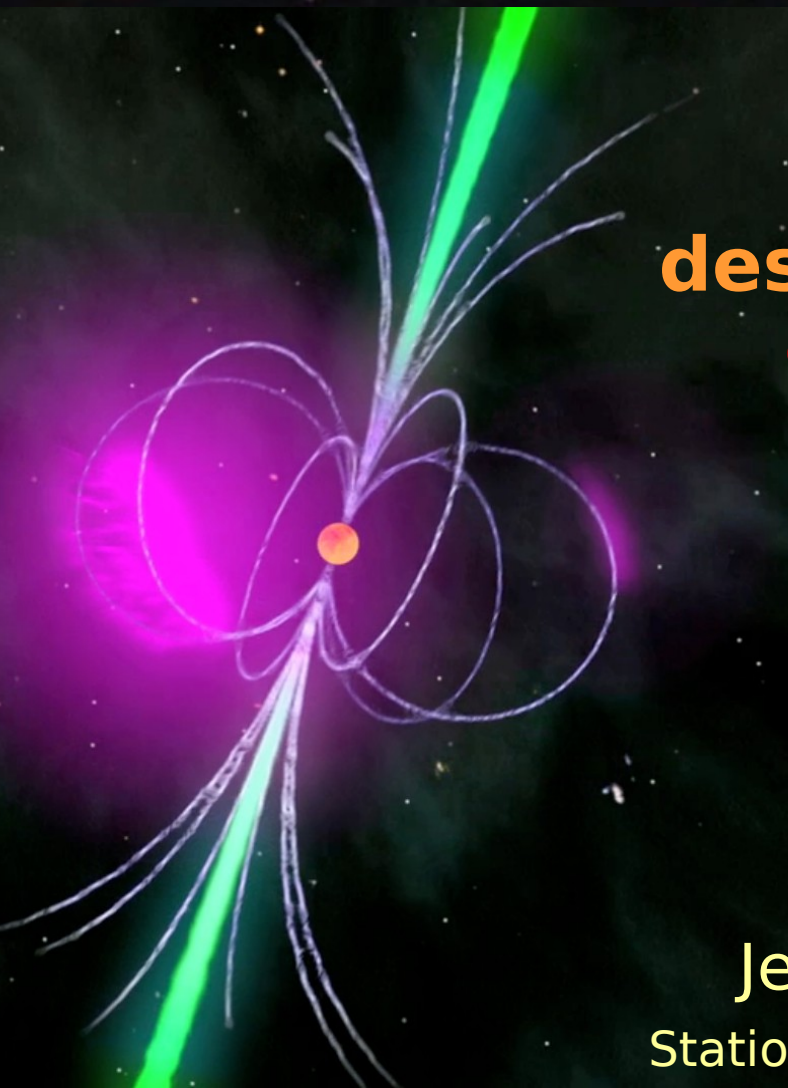
Les pulsars : des horloges astronomiques multi-fonction



Jean-Mathias Griessmeier

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Les pulsars : des horloges astronomiques extrêmement précises



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Mesure de temps et astronomie

1 an



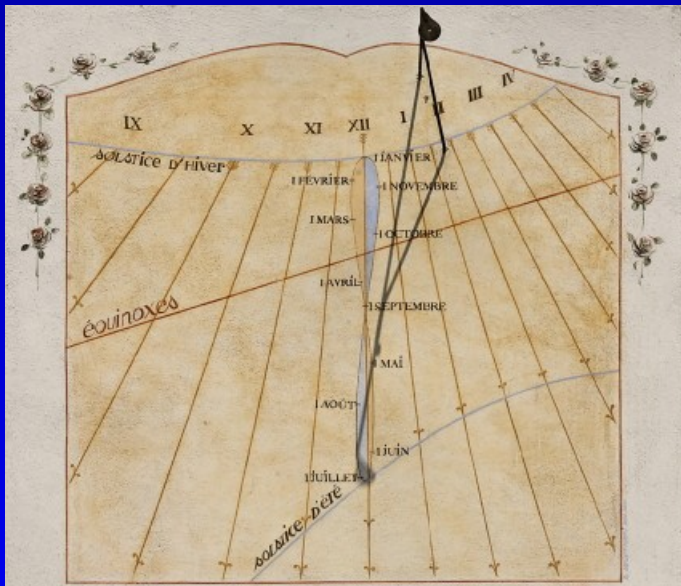
1 mois



1 jour



Horloges en astronomie: 1 an

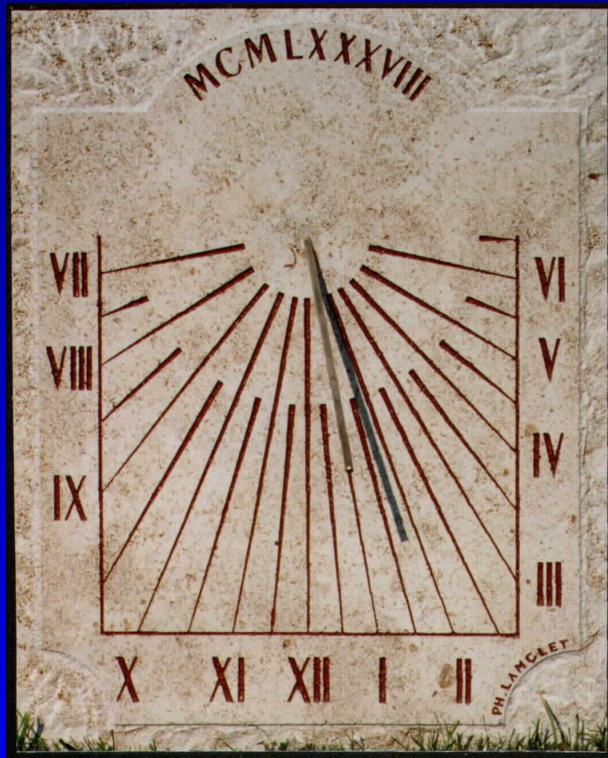


1er juillet

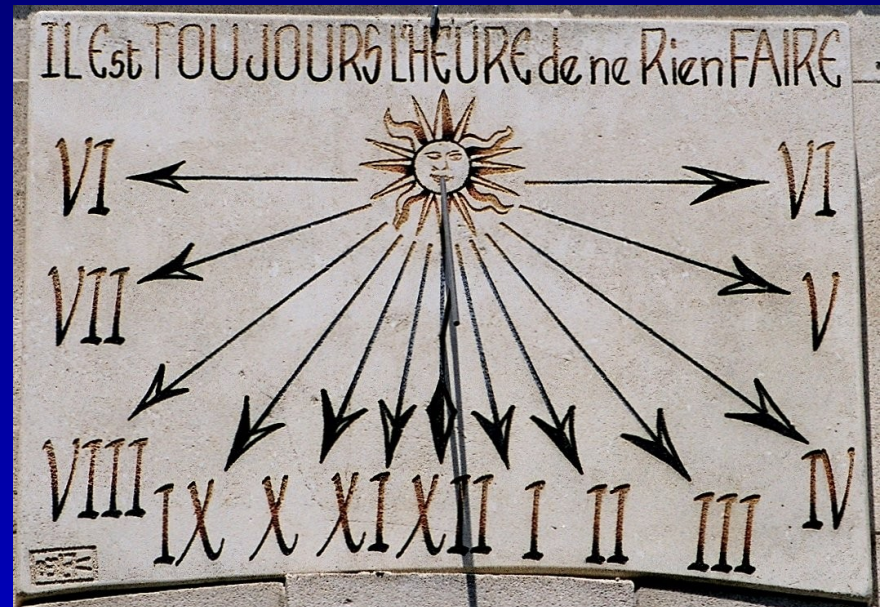


début février

Horloges en astronomie: 1 jour



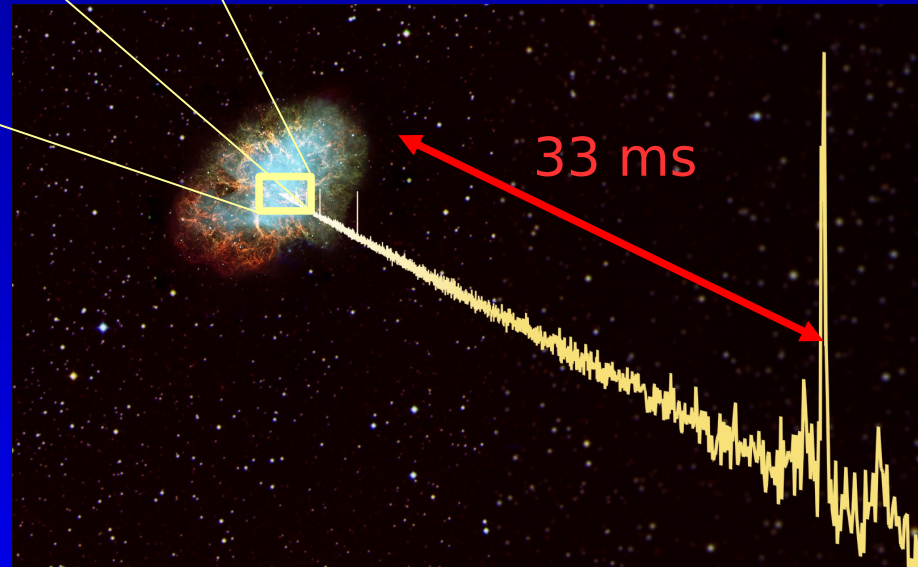
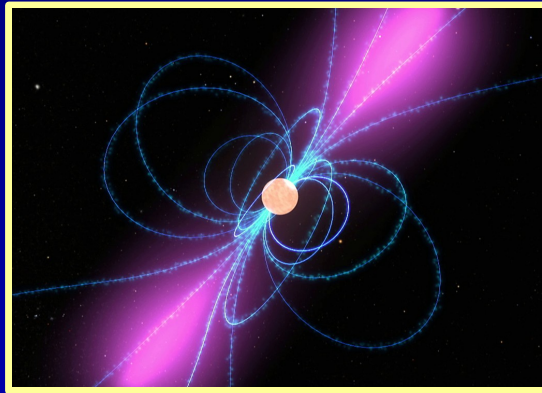
13h45



l'heure de ne rien faire

Horloges en astronomie: 1 seconde

PSR B0531+21



nebuleuse du crabe

Mesure de temps et astronomie

- Horloges astronomiques
- Les pulsars
- Les pulsars : horloges astronomiques
- Utiliser ces horloges
- Les radiotélescopes
- Une observation

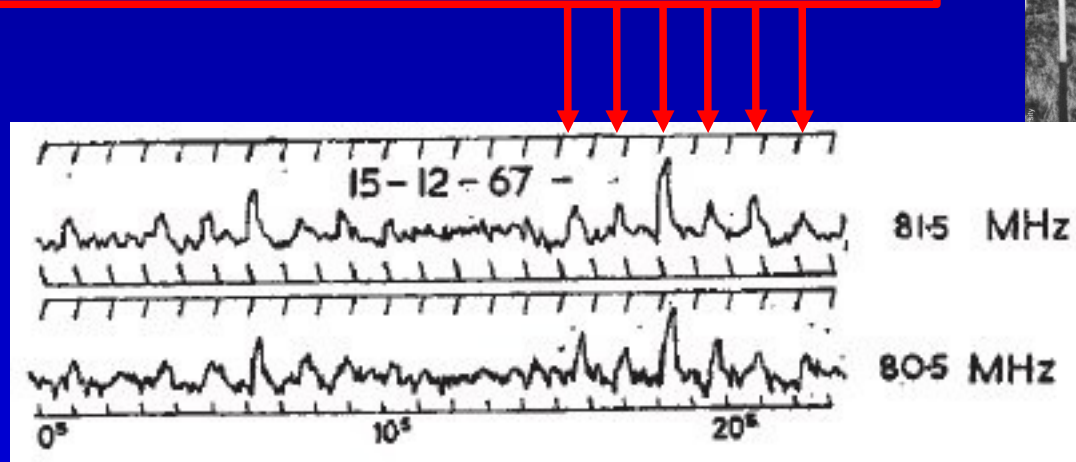
1967 : La detection des pulsars

observation radio (~ 81.5 MHz)

RA: 19h19m

DEC: $+21^{\circ}47'$

impulsion tout les 1,337301192269 s!

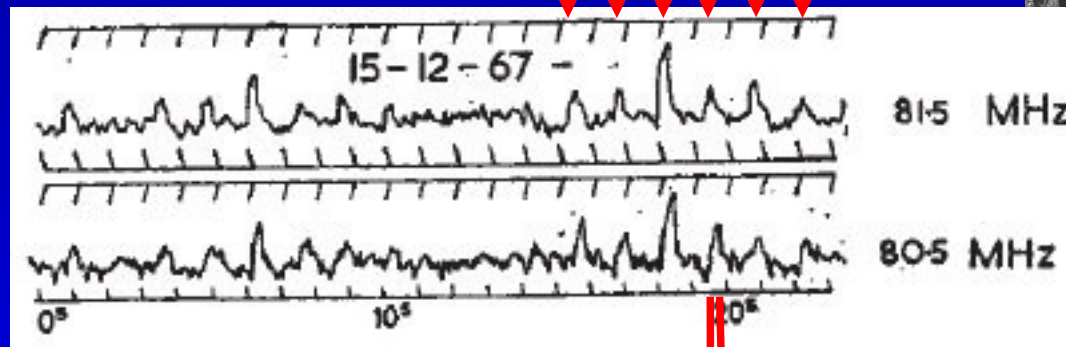


[Hewish et al. 1968]

1967 : La detection des pulsars

observation radio (~ 81.5 MHz)
RA: 19h19m → source
DEC: $+21^\circ 47'$ astronomique

impulsion tout les 1,337301192269 s!



80.5 et 81.5 MHz : 0.2 s decalage

[Hewish et al. 1968]

S. Jocelyn Bell Burnell was born in northern Ireland in 1943. After receiving a B.S. degree in physics from Glasgow University, Scotland, she went to Cambridge University, England, where she earned her doctorate in radio astronomy in 1969. Since then she has done research in the newest branches of astronomy involving gamma-rays and x-rays. In 1978 she received the American Tentative Society Award for her pulsar research. Currently she is a research scientist at the Mullard Space Science Laboratory of the University College London.



Burnell



Comment désigner cet objet ?

“LGM-1”? (“Little Green Men”)

“CP 1919”? (“Cambridge Pulsar”)

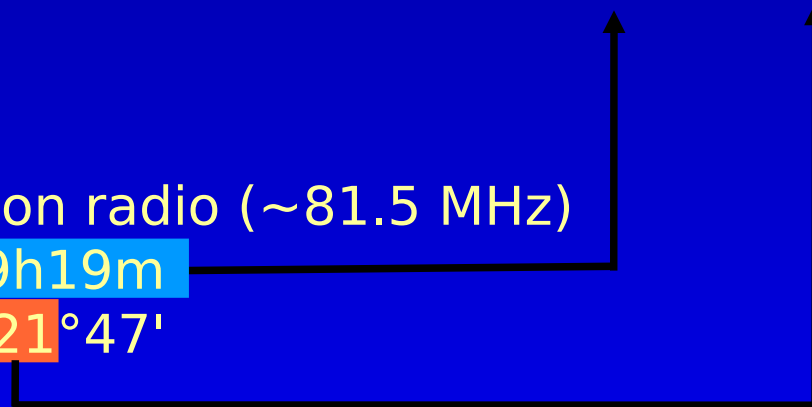
“pulsating star” → “pulsar” (PSR)



observation radio (~81.5 MHz)

RA: 19h19m

DEC: +21°47'



Comment désigner cet objet ?

“LGM-1”? (“Little Green Men”)

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PSR B1919+21

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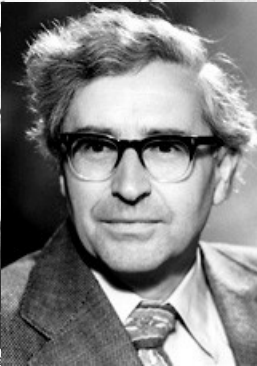
DEC: +21°47'

La detection des pulsars

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Burnell



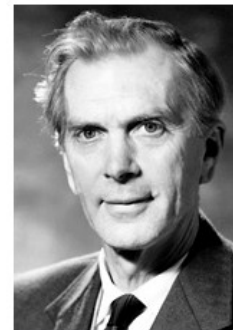
"We put up over a thousand posts and strung

1967: Detection de PSR B1919+21
1974: Prix nobel !



The Nobel Prize in Physics 1974

"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"



Sir Martin Ryle

🕒 1/2 of the prize

United Kingdom

University of Cambridge
Cambridge, United Kingdom

b. 1918
d. 1984



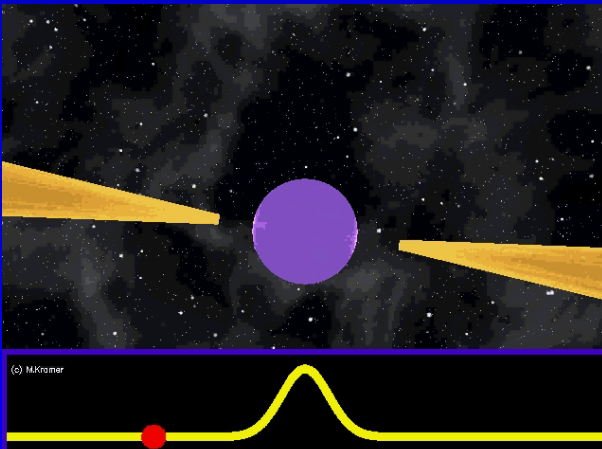
Antony Hewish

🕒 1/2 of the prize

United Kingdom

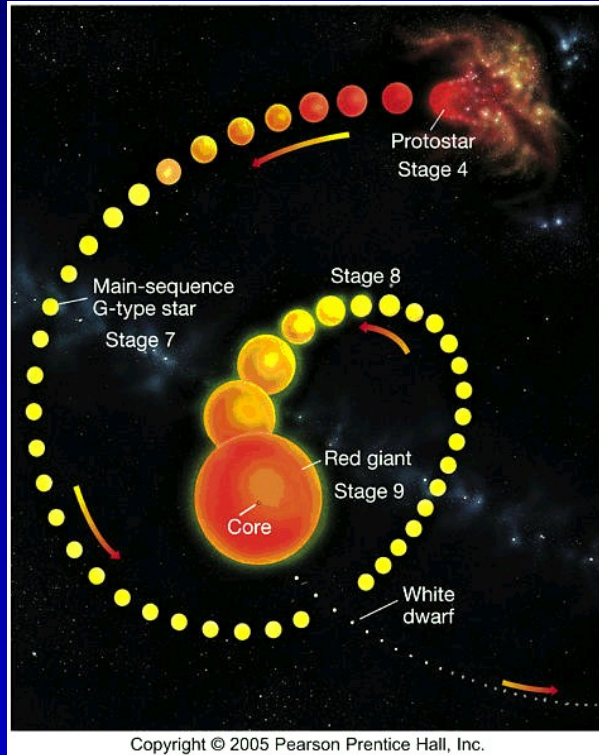
University of Cambridge
Cambridge, United Kingdom

b. 1924



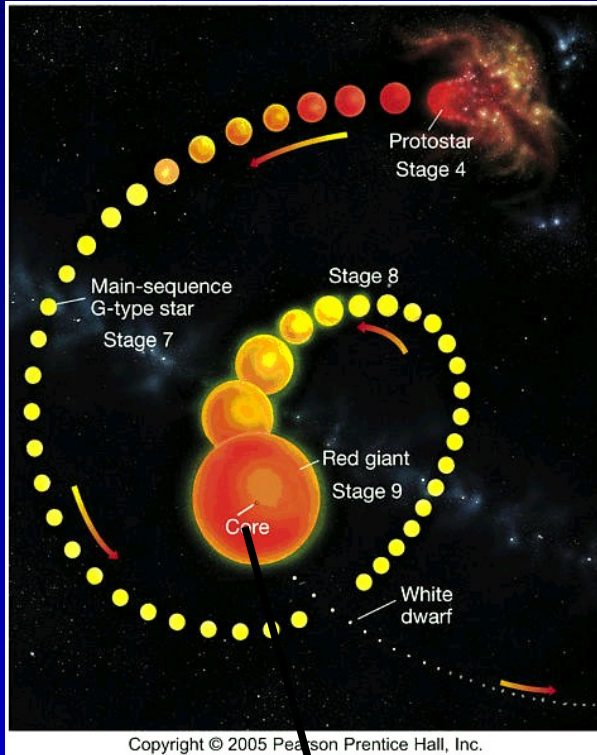
(c) MKromer

Mort d'une étoile



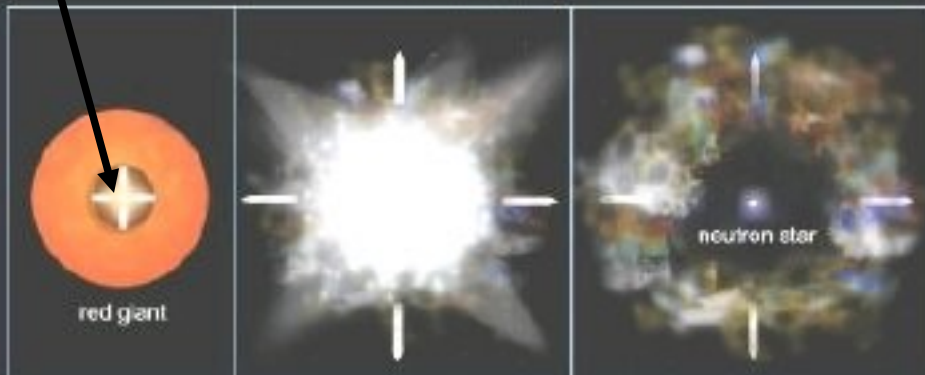
$$M < 10 M_{\text{soleil}}$$

Naissance d'un pulsar



$$M < 10 M_{\text{soleil}}$$

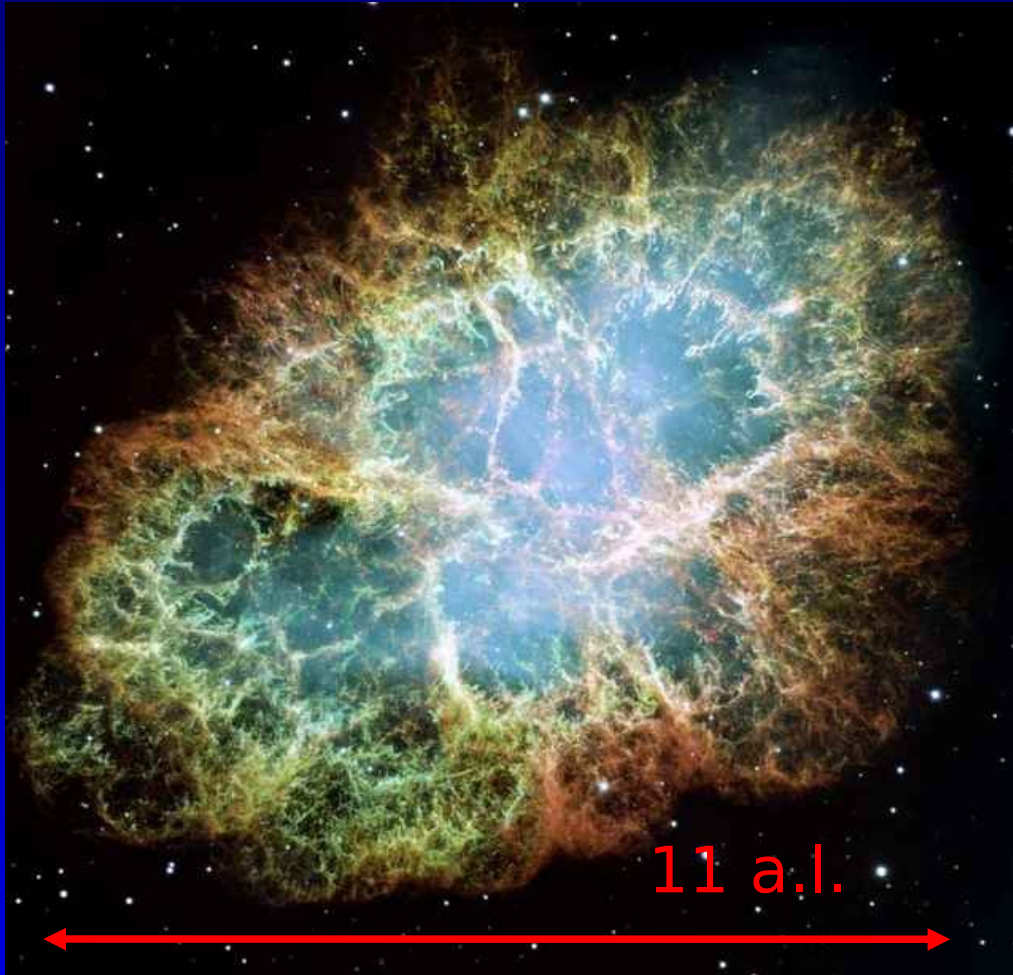
Birth of a Neutron Star and Supernova Remnant (not to scale)



Core Implosion → Supernova Explosion → Supernova Remnant

$$M > 10 M_{\text{soleil}}$$

Les pulsars



“Le Crabe”

Supernovae observée
en 1054

Source d'énergie de
la nébuleuse

$d=2 \text{ kpc}, v_{\text{exp}}=1500 \text{ km/s}$

Une étoile à neutrons

- 1932 : découverte du neutron par James Chadwick
- 1934 : F. Zwicky et W. Baade proposent l'existence d'étoiles à neutrons comme le résultat de l'effondrement gravitationnel d'étoiles massives
- 1967 : J. Bell et A. Hewish découvrent un signal périodique radio (PSR 1919+21, $P = 1.339\text{s}$)
- Seule une étoile très petite peut effectuer un tour en moins d'une seconde. La cohésion est assurée tant que le champ gravitationnel $G \cdot M/R^2$ est supérieur au champ centrifuge $R \cdot (2\pi/T)^2$
- Une étoile à neutrons est observable sous forme de pulsar

Propriétés des pulsars

Pulsars are Extreme Objects



$$R = 12 \text{ km}$$



$$M = 1.4 M_{\text{Sun}}$$



$$B = 10^{12} - 10^{15} \text{ G}$$



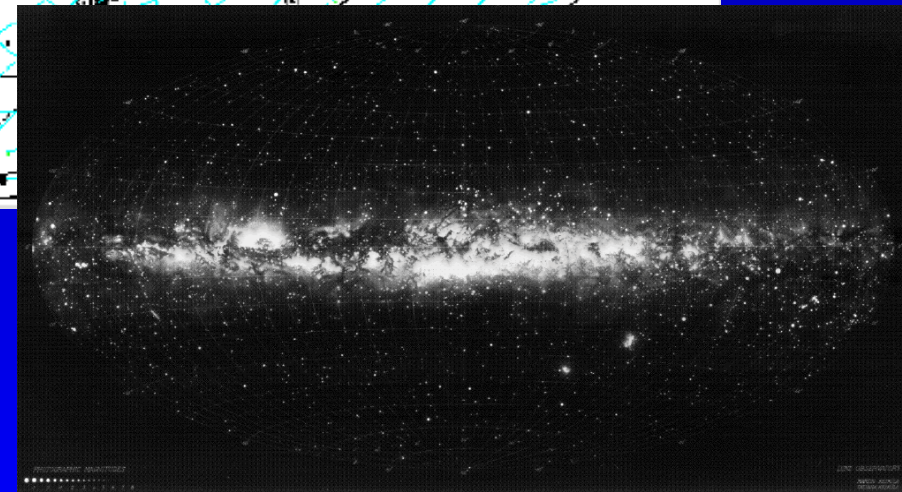
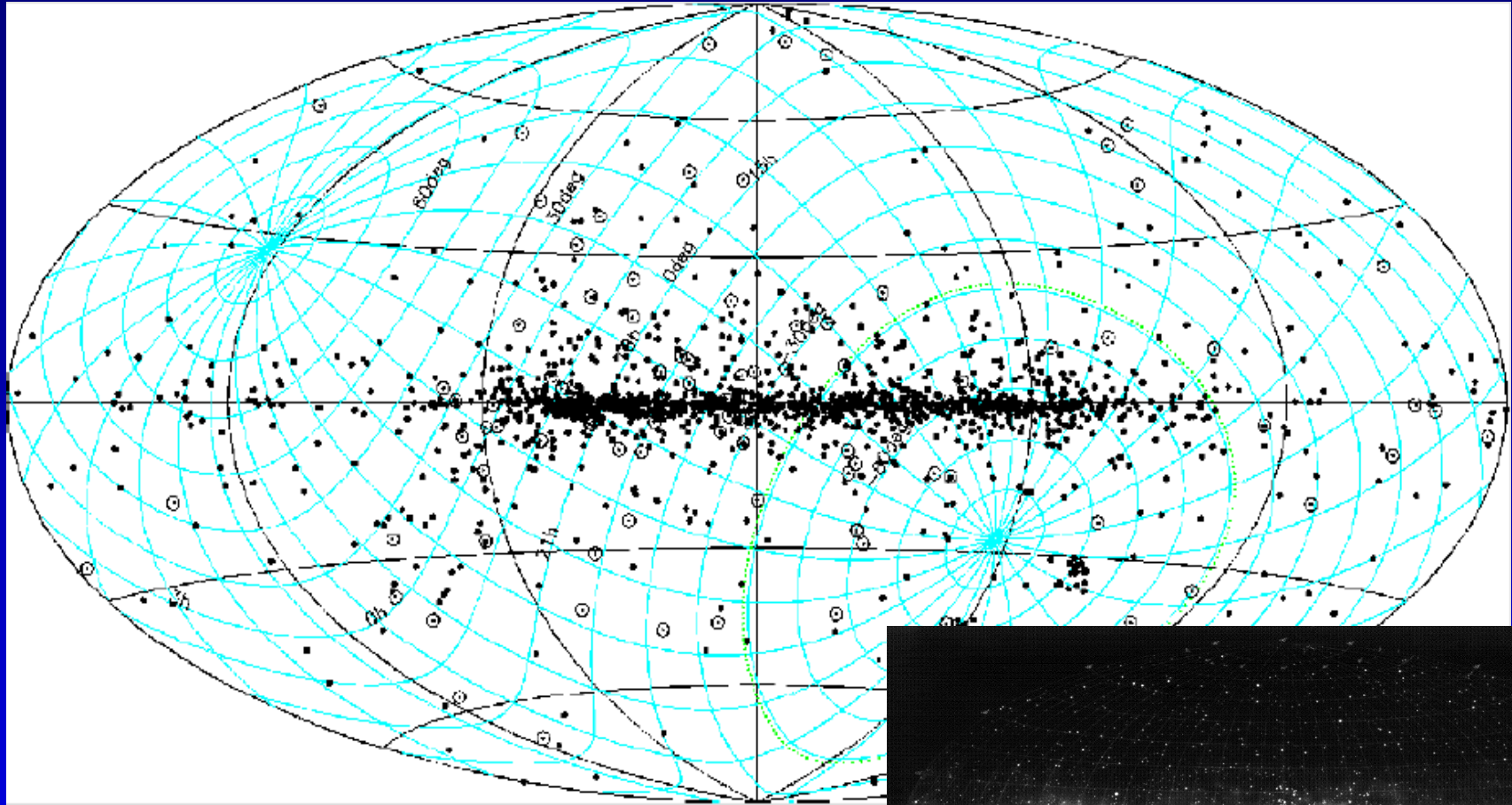
$$\nu_{\text{spin}} > 716 \text{ Hz}$$

$$v_t = 0.2 c$$



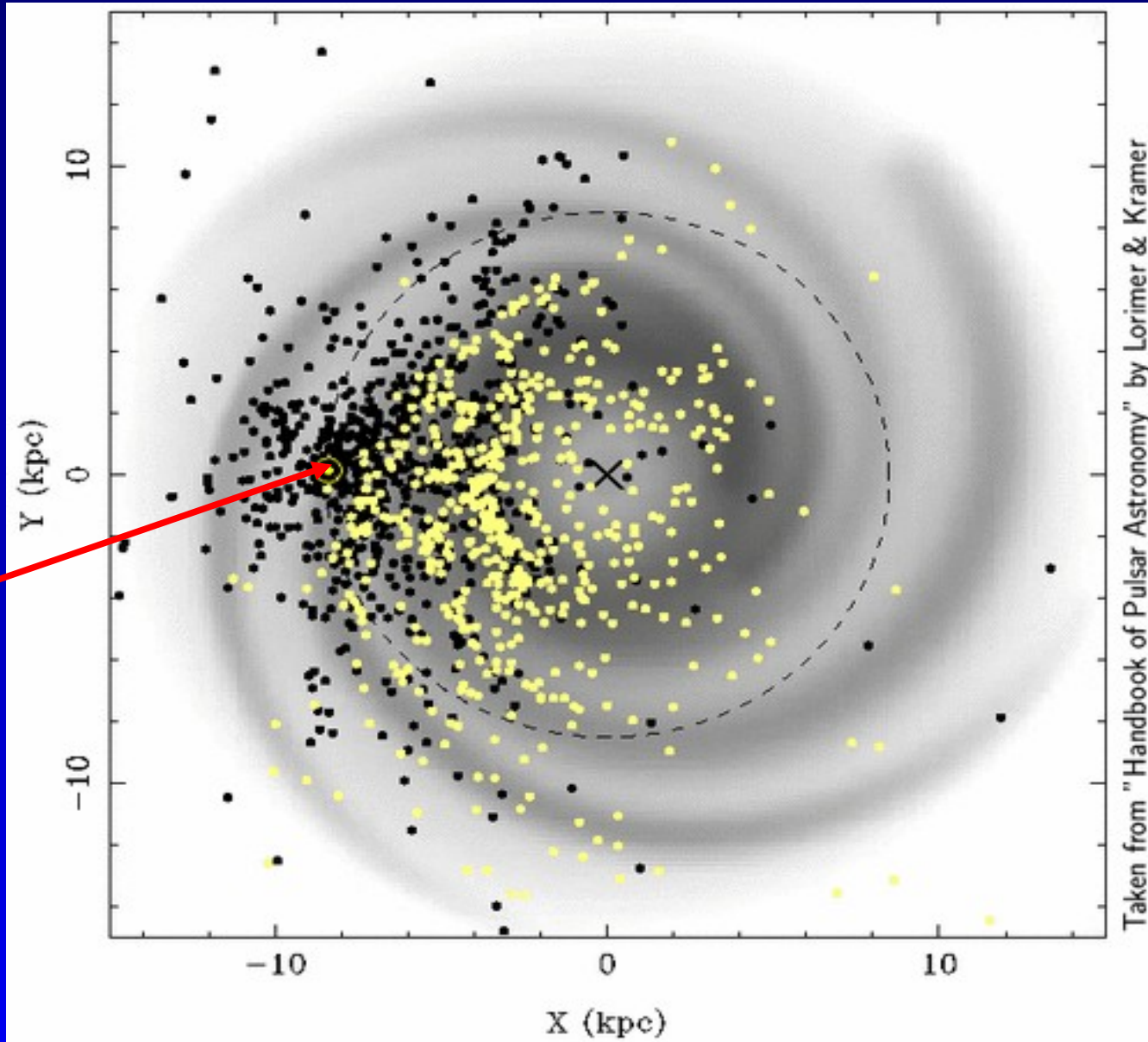
They are fascinating physical laboratories

2000 pulsars : Distribution spatiale

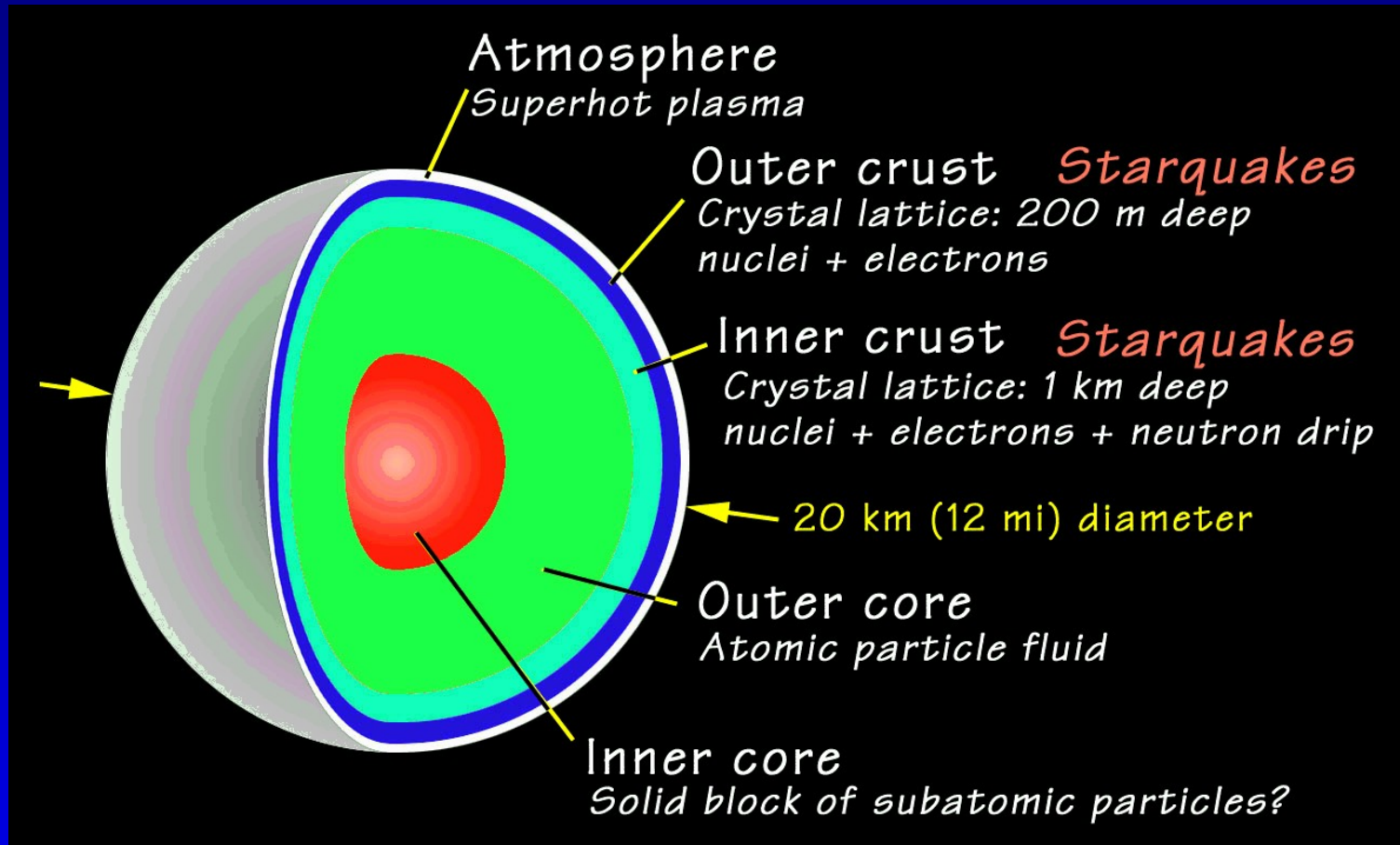


2000 pulsars : Distribution spatiale

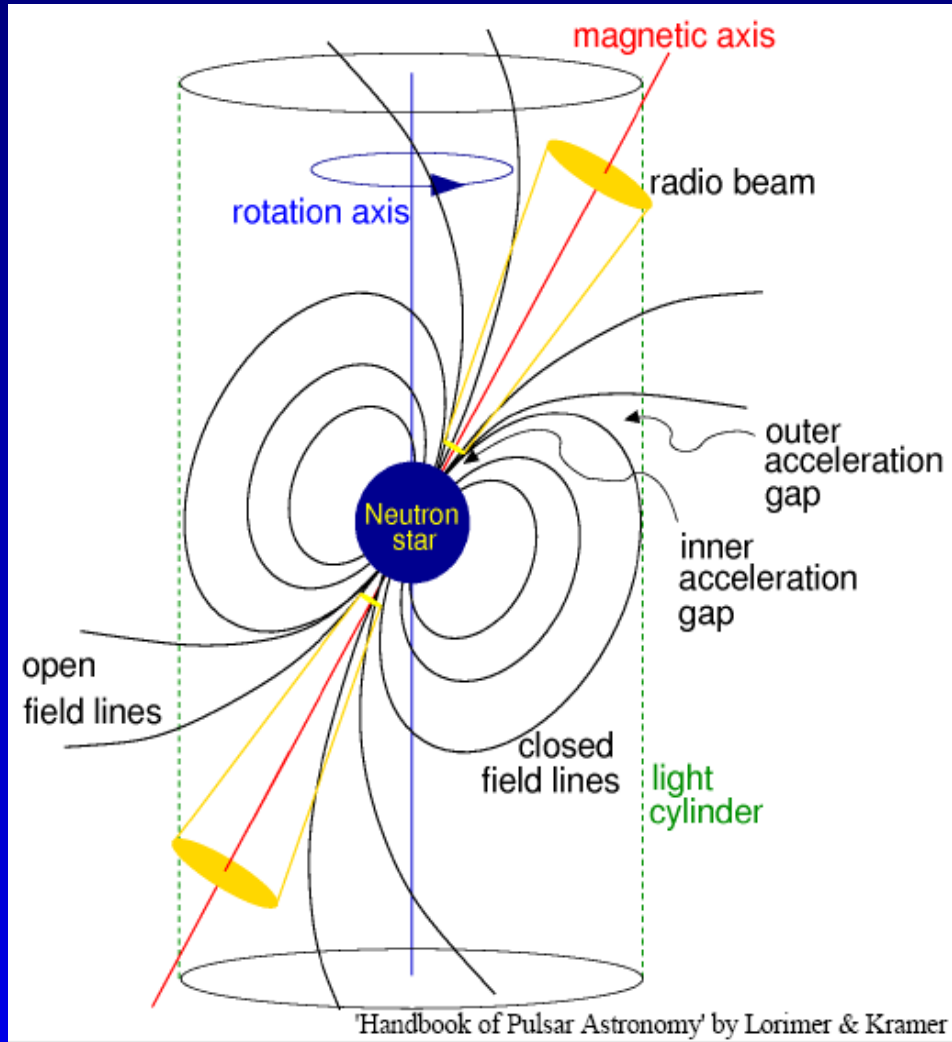
soleil



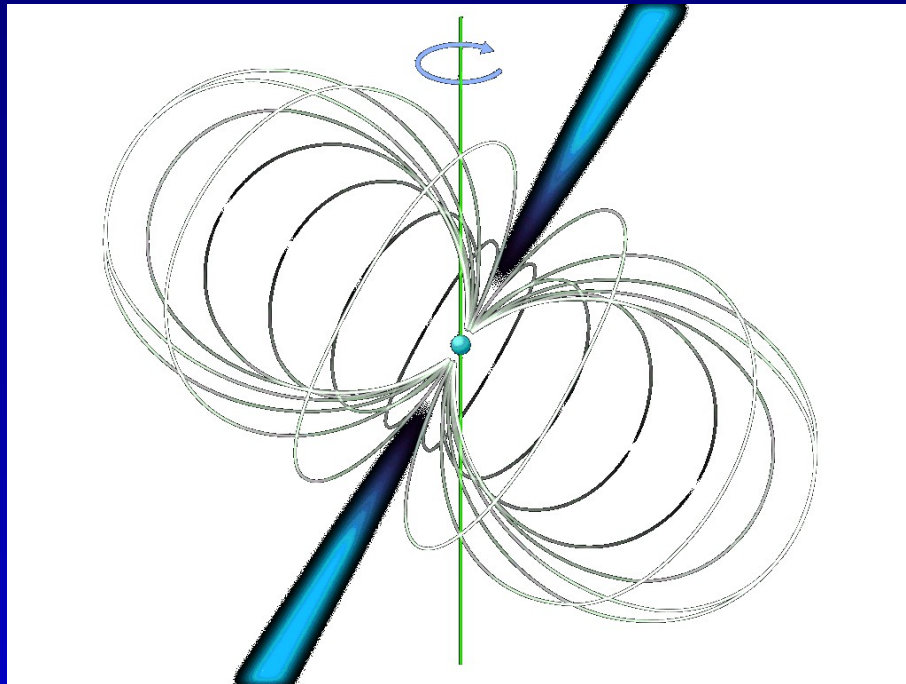
Structure interne



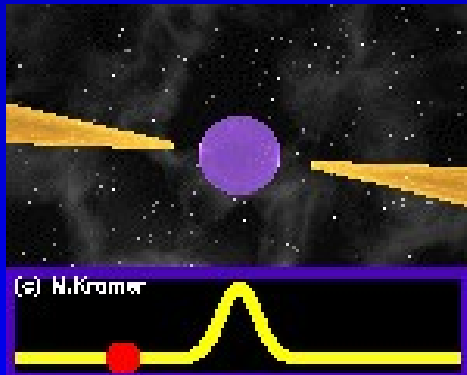
Structure externe



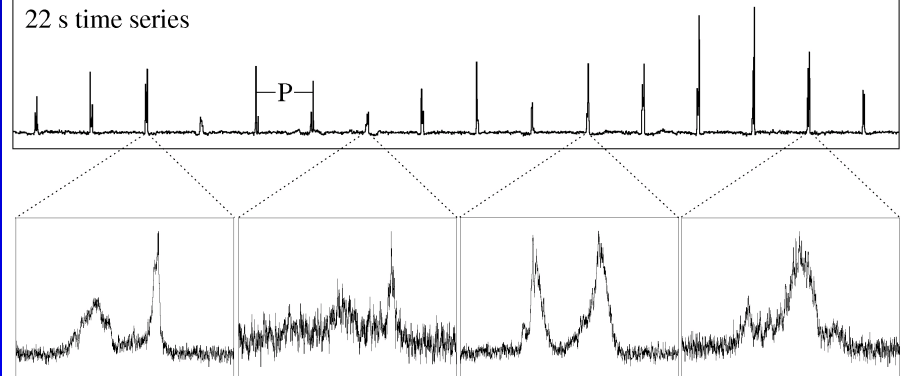
Le pulsar : un phare radio



Comme un phare au bord de la mer, les faisceaux radio interceptent le radiotélescope à chaque tour, produisant des impulsions régulières

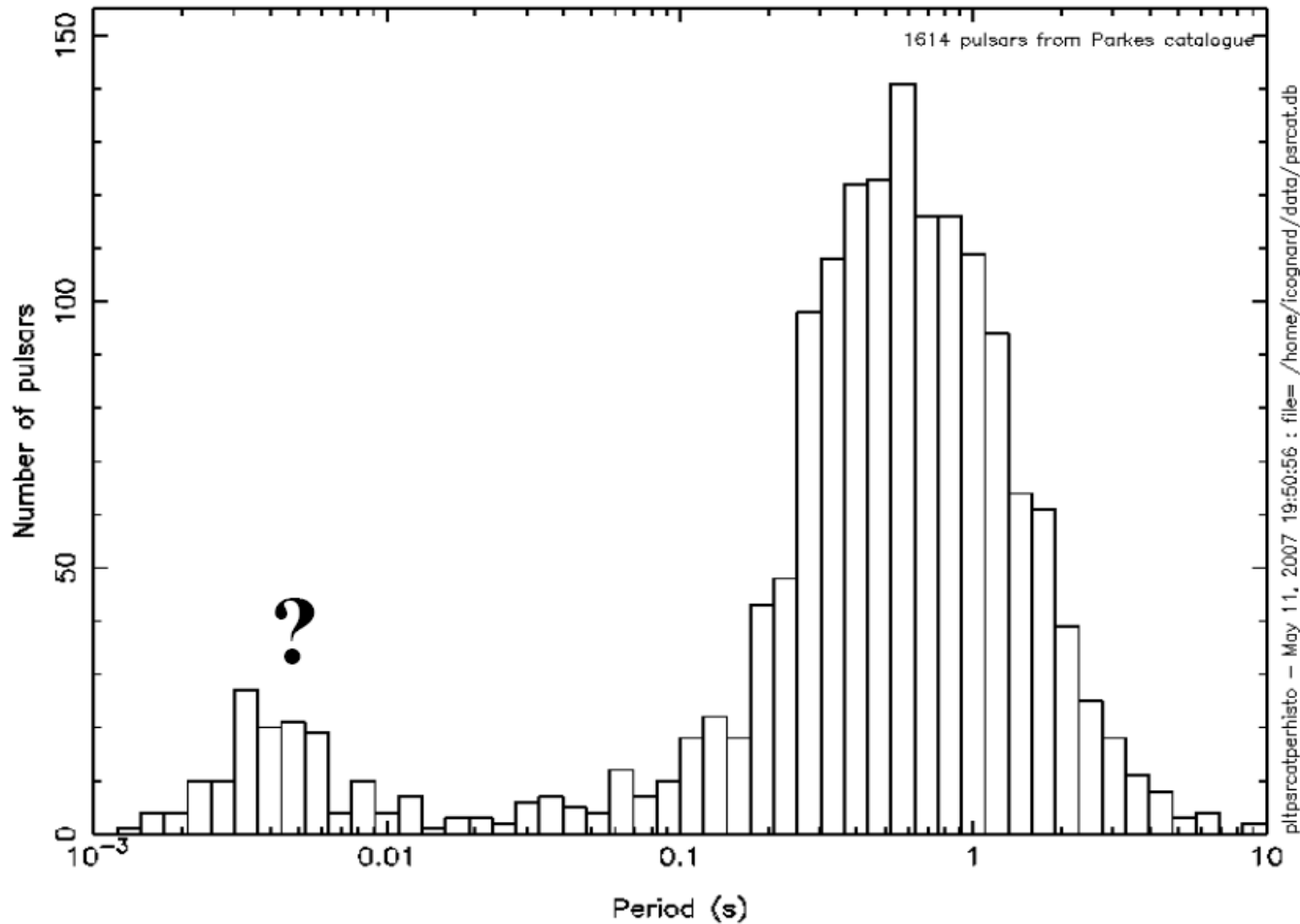


22 s time series

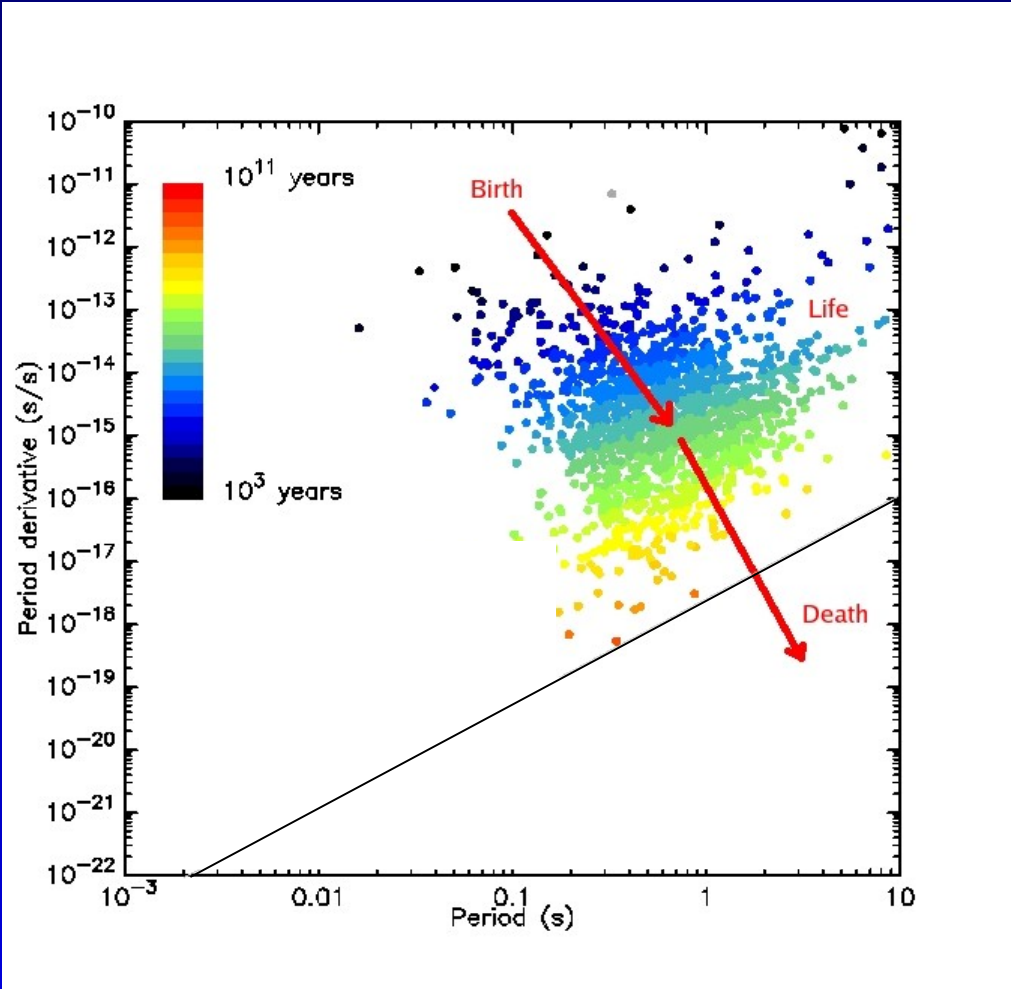


140 ms zoom in on individual pulses

Distribution des périodes



Les deux vies des pulsars

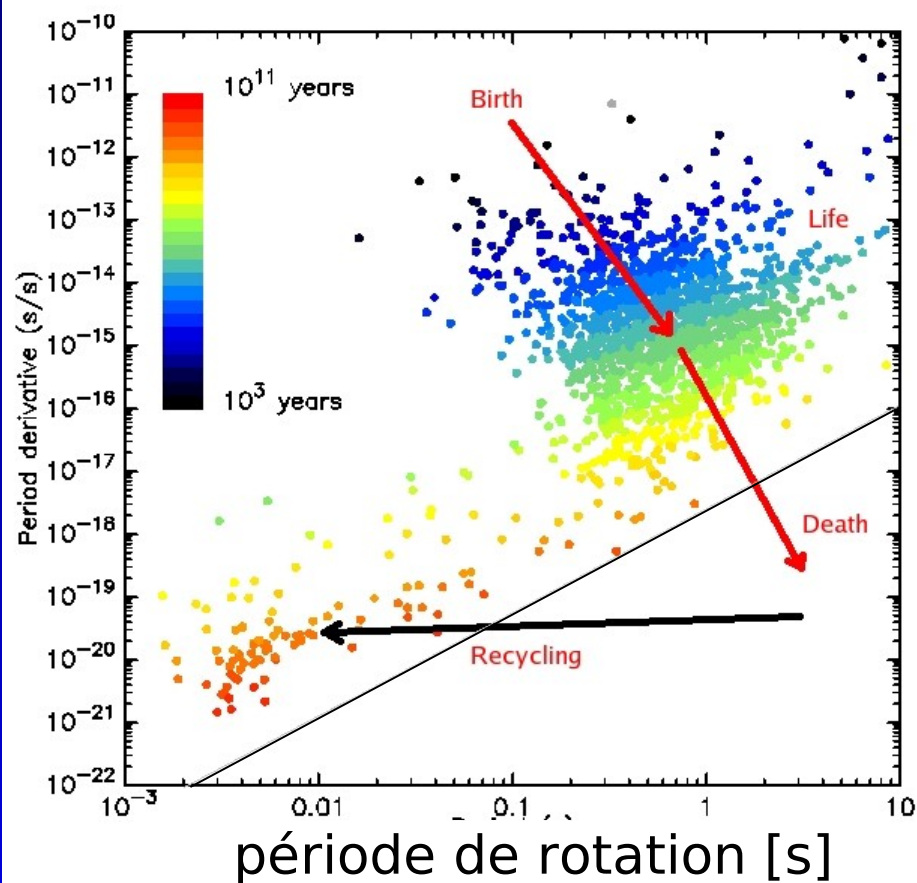


Période ($t=0$) : conservation du moment angulaire

Une première vie très courte...

Après une naissance à ~ 30 ms, le pulsar ralentit fortement et cesse d'émettre en quelques dizaines de millions d'années.

Les deux vies des pulsars



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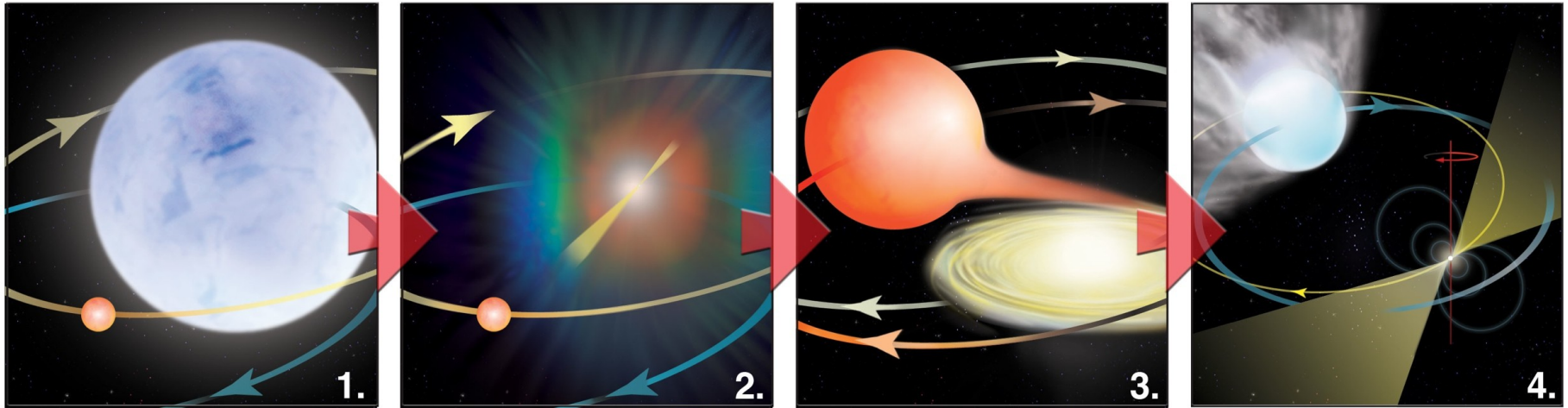
... puis l'éternité !

Ceux encore présents dans un système binaire se font ré-accélérer, et émettent à nouveau en radio, ce sont

les pulsars millisecondes recyclés à la stabilité de rotation exceptionnelle !

Alpar et al., Nature 300, 728 (1982)

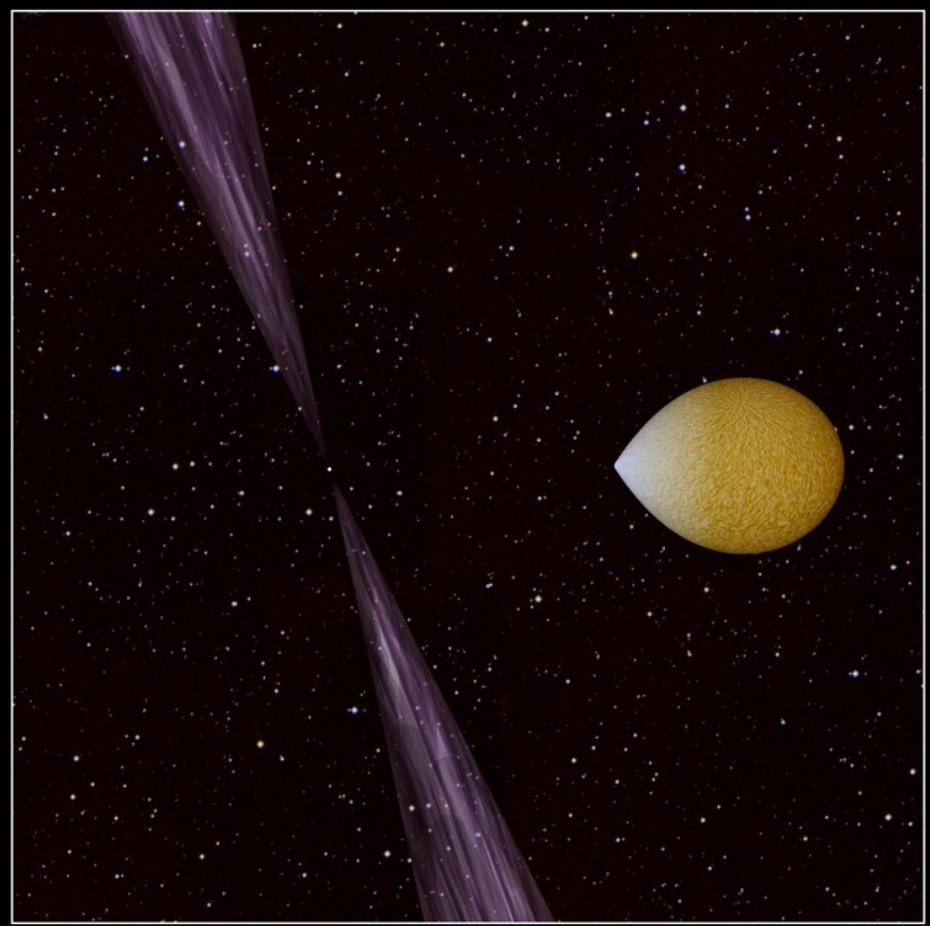
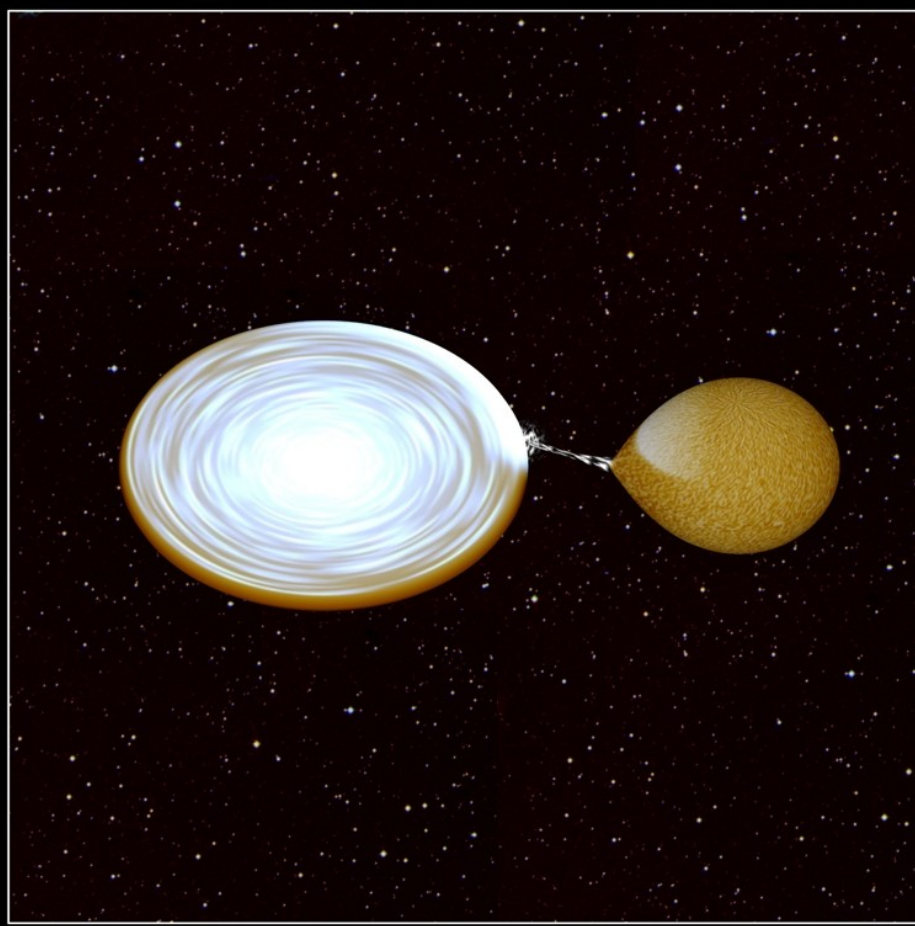
Du recyclage



Saxton, NRAO

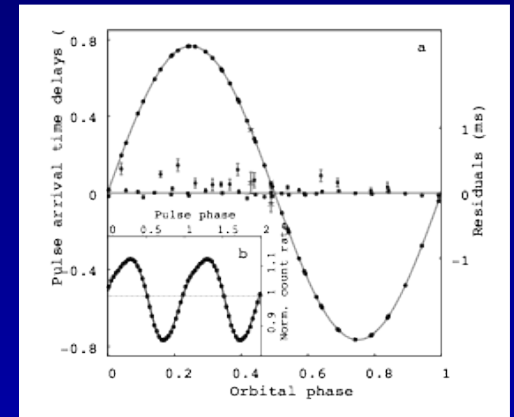
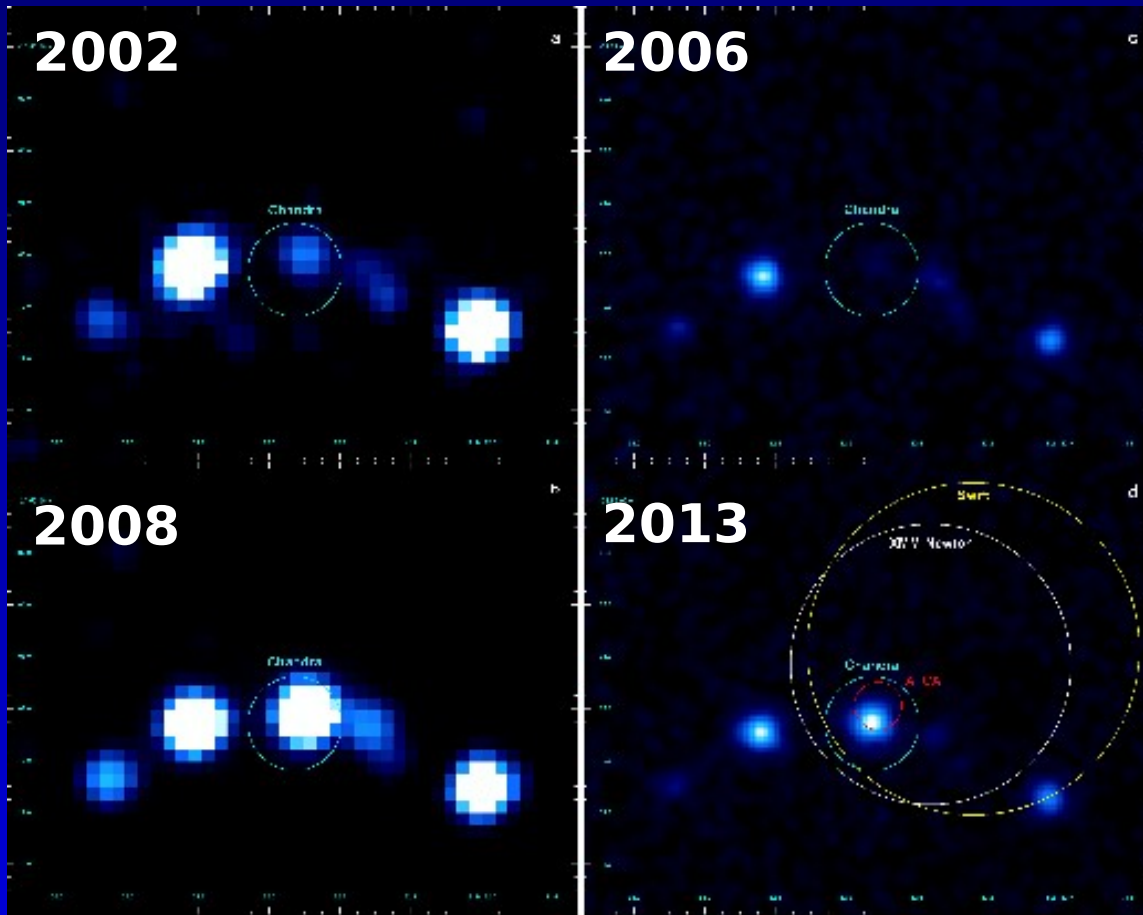
[Alpar et al. 1982; Rhadakrishnan et al. 1984]

Du recyclage



IGR J18245-2452 = PSR M28I

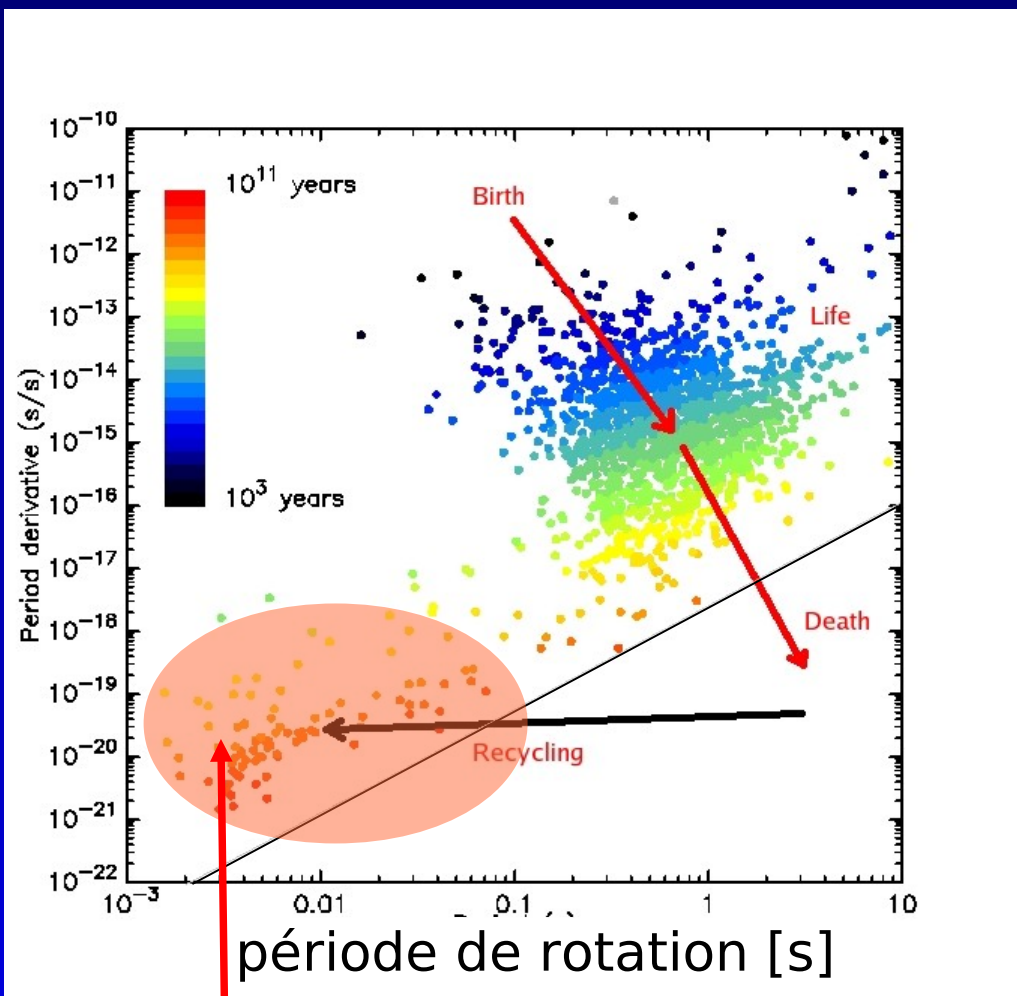
Du recyclage observé



[Papitto et al. 2013
in press]

IGR J18245-2452 = PSR M281

Les deux vies des pulsars



Période ($t=0$) : conservation du moment angulaire

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PSR J1909-3744

le 12 mars 1013, 20h30

période = 2.947108068107624(2) ms

augmentation: 0.0000000000000001 en 2 mins

Mesure de temps et astronomie

Horloges astronomiques

Les pulsars

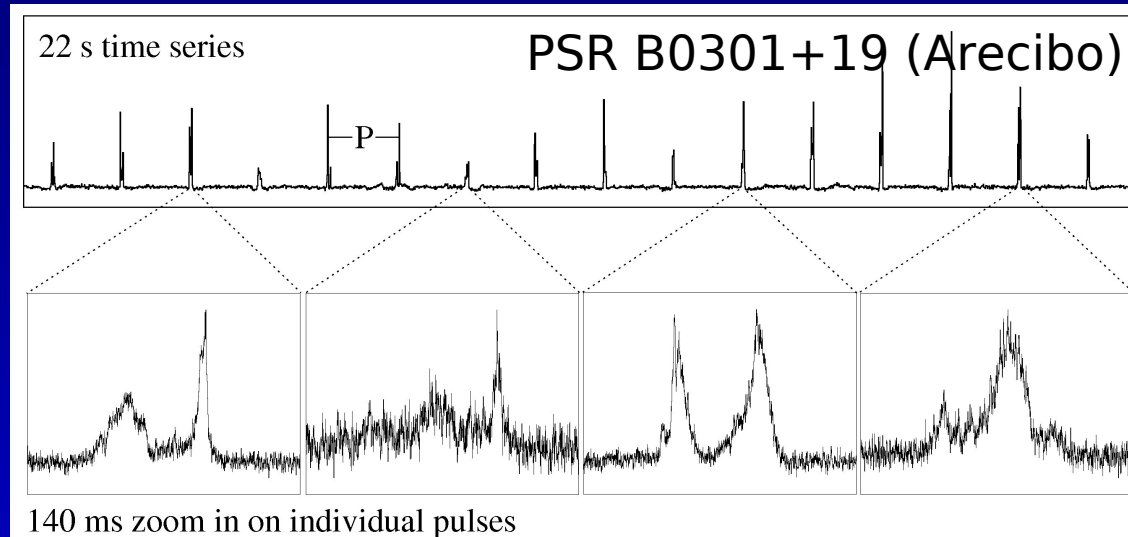
Les pulsars : horloges astronomiques

Utiliser ces horloges

Les radiotélescopes

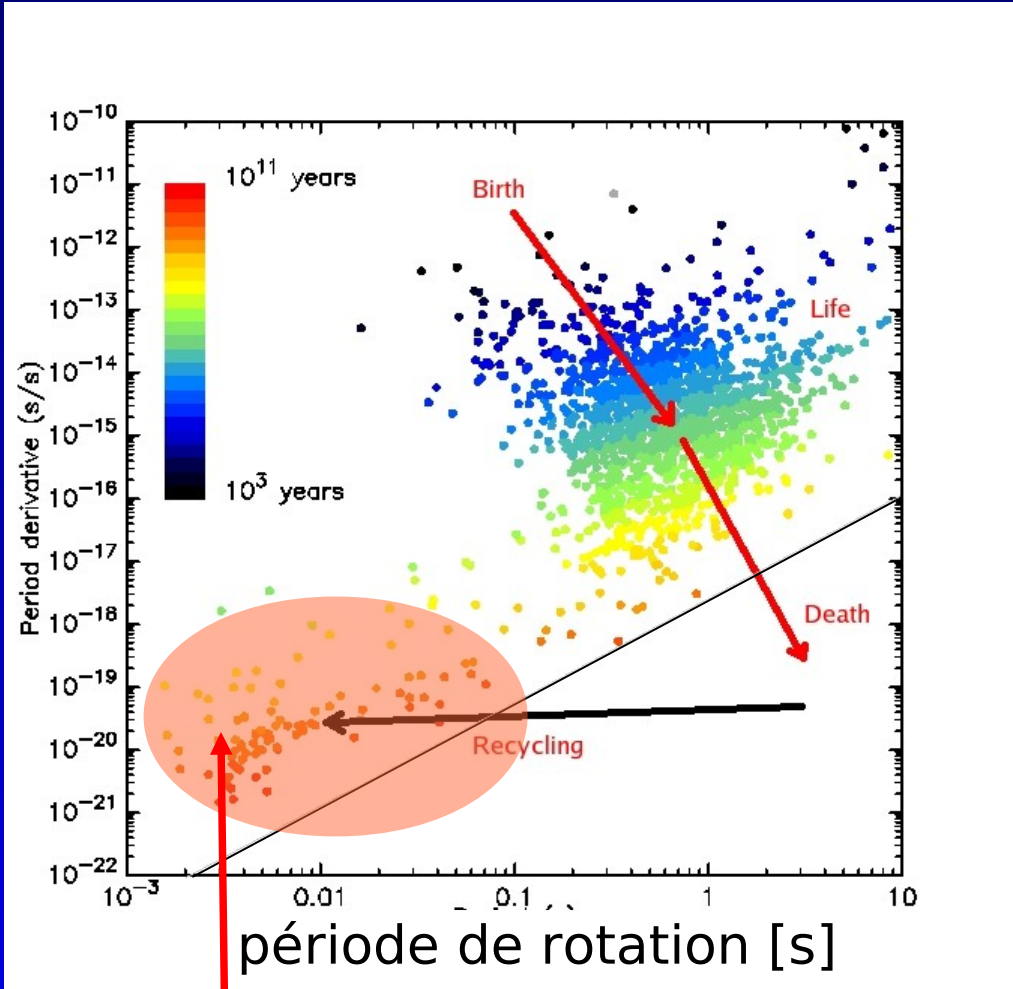
Une observation

Emission régulière et irrégulière



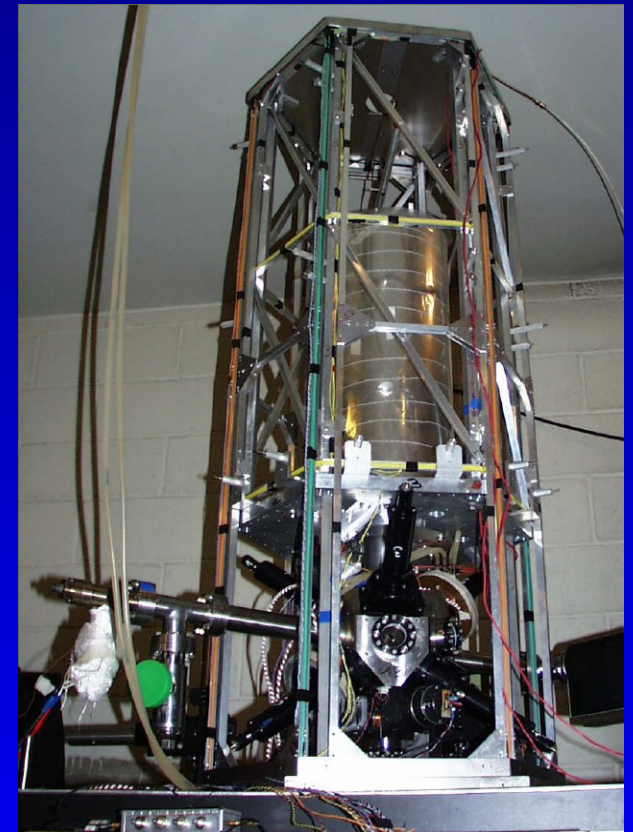
- la forme des pulses radio est variable
- le temps d'arrivé reste periodique !

Une stabilité exceptionnelle



Une stabilité hors du commun

qui rivalise avec celle
des meilleures horloges atomiques
que l'on construit sur Terre



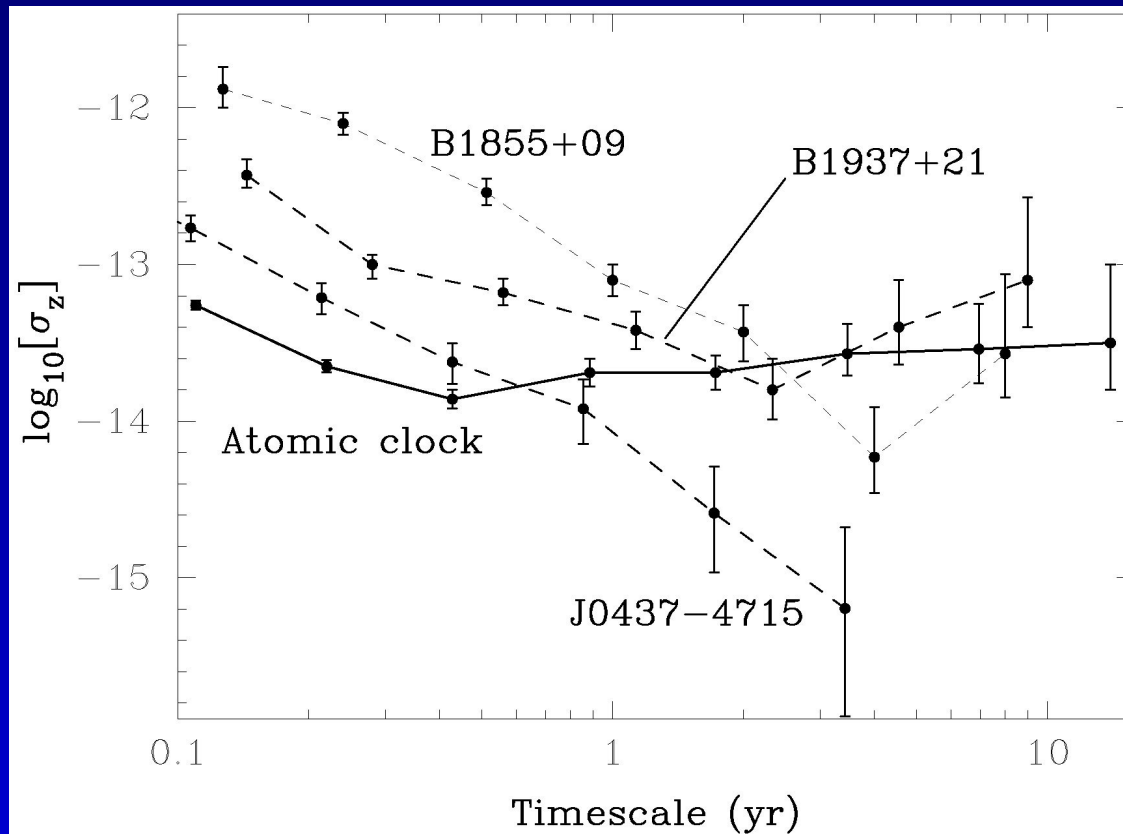
PSR J1909-3744

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La stabilité à long terme

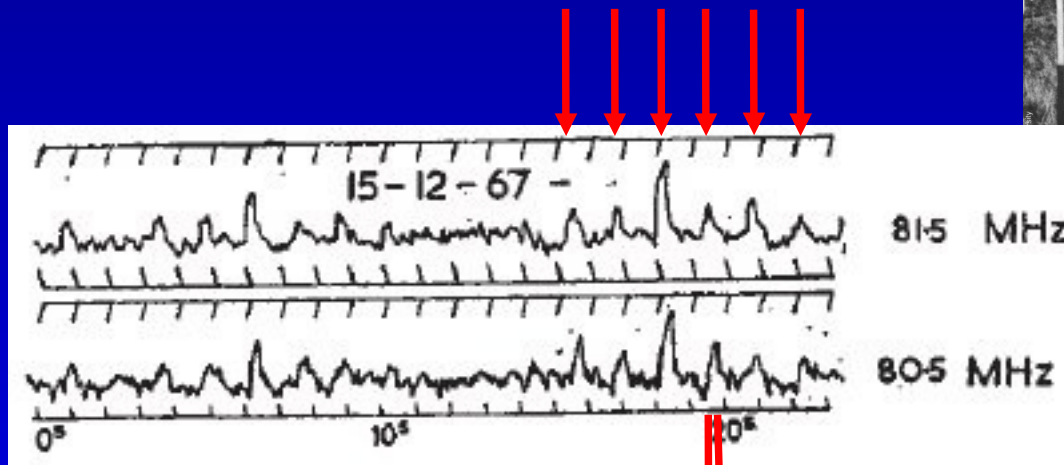


Les pulsars recyclés millisecondes les plus stables
sont probablement plus stables que les meilleures horloges sur Terre
et peuvent être utilisés pour piloter à long terme les échelles de temps terrestres

mais il faut d'abord corriger des effets de propagation !

La dispersion

impulsion tout les 1,337301192269 s!



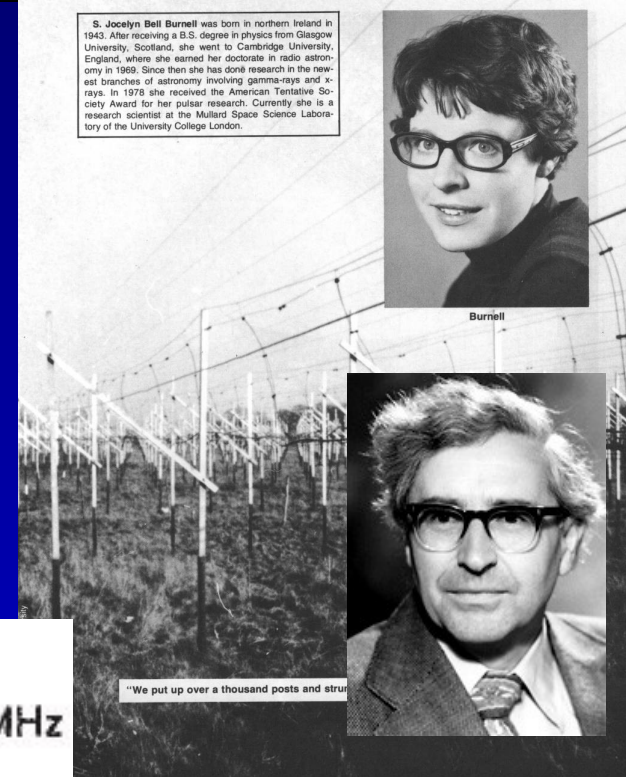
80.5 et 81.5 MHz : 0.2 s decalage

[Hewish et al. 1968]

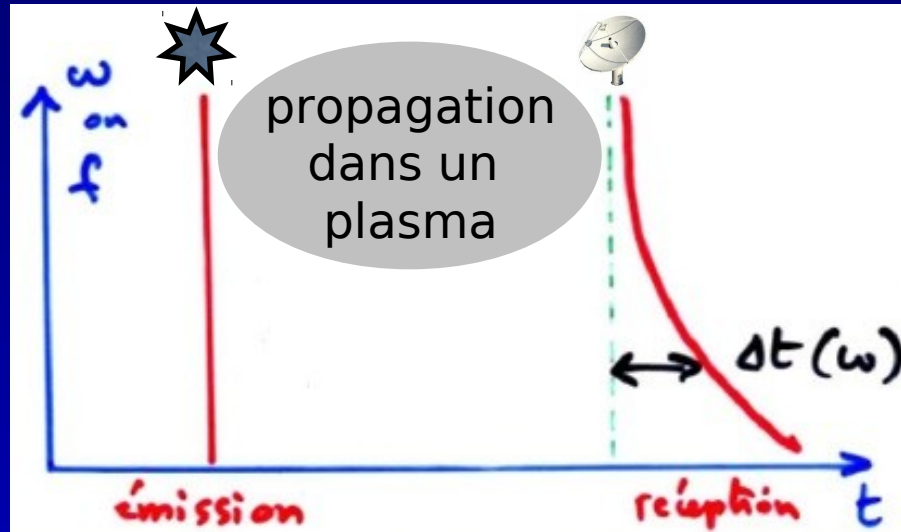
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Burnell



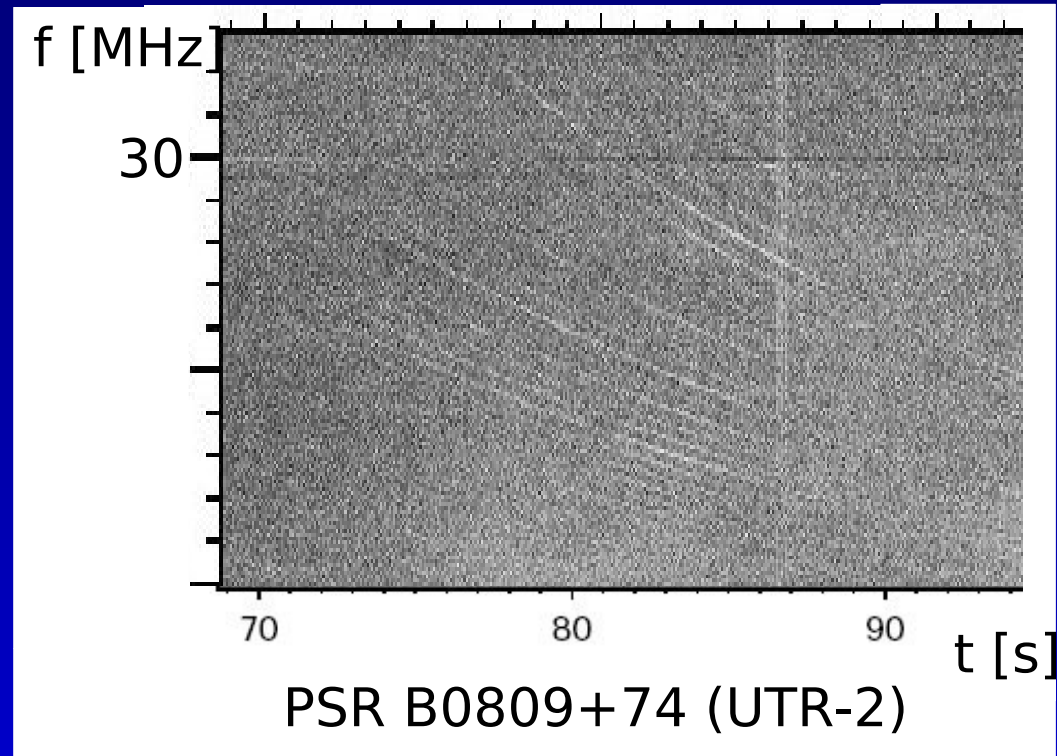
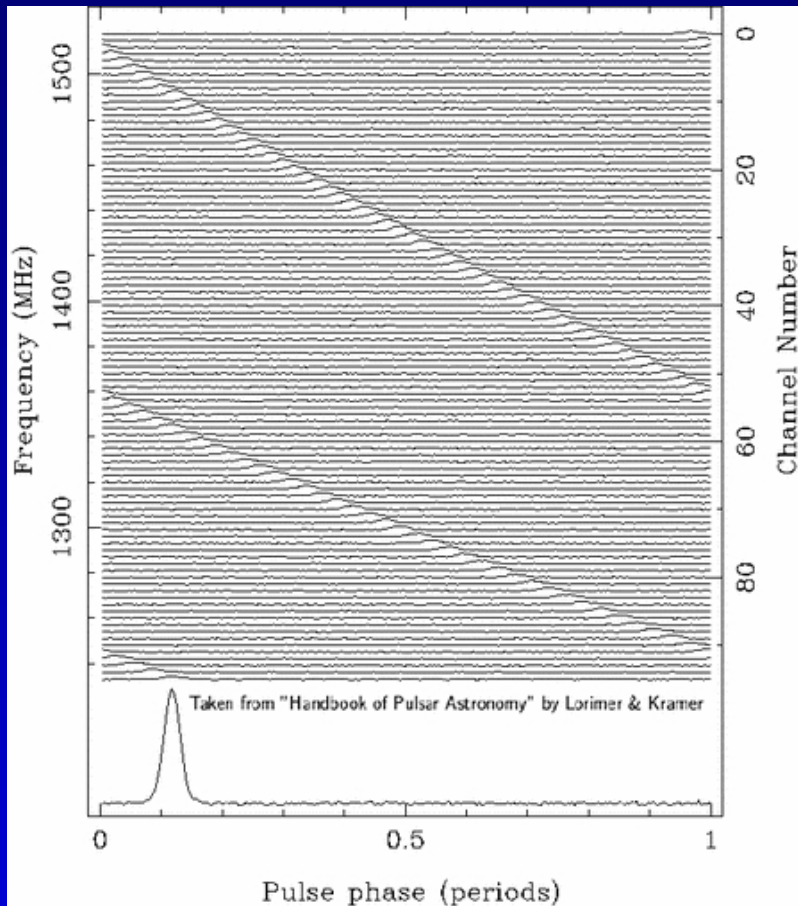
La dispersion



- refractive index of interstellar medium: $n(\nu)$
- lower frequencies are “delayed”

$$t(\nu_2) - t(\nu_1) = \frac{DM}{\alpha} \left(\frac{1}{\nu_2^2} - \frac{1}{\nu_1^2} \right)$$

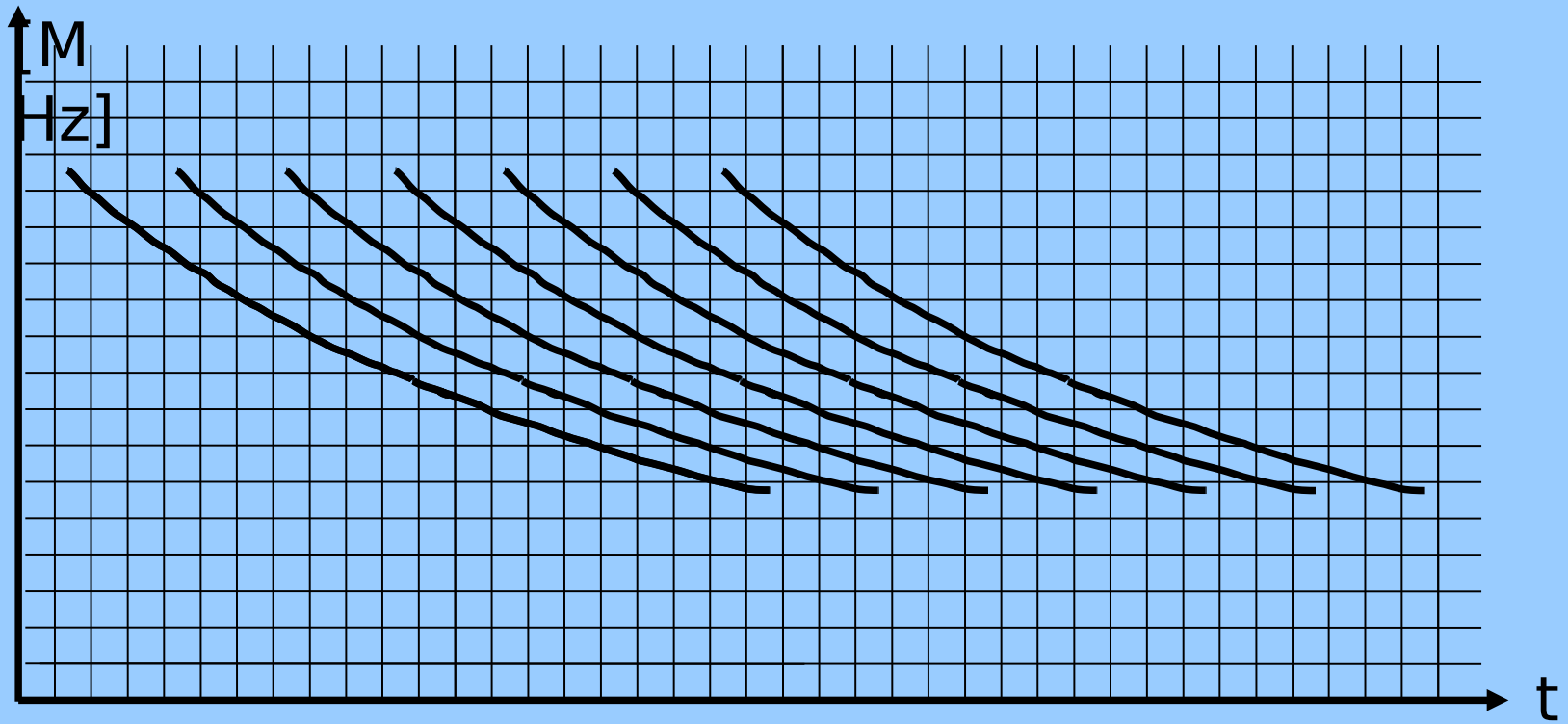
Dispersion : PSR B0809+74



between 1410 & 1400 MHz (DM=10): 0.3 ms
between 150 & 140 MHz (DM=10): 0.3 s
between 24 & 14 MHz (DM=10): 140 s

Dispersion : PSR B0809+74

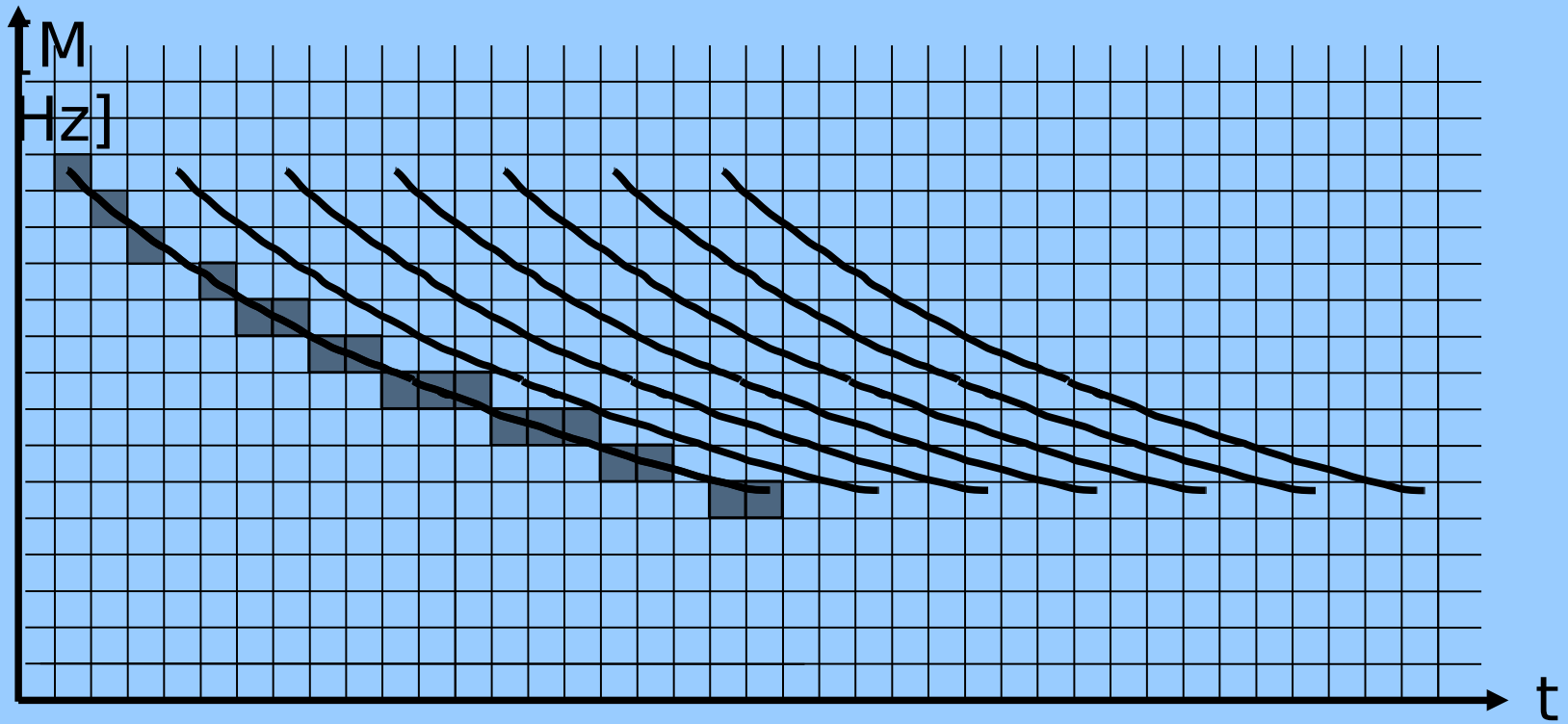
f



[
s
]

Dispersion : PSR B0809+74

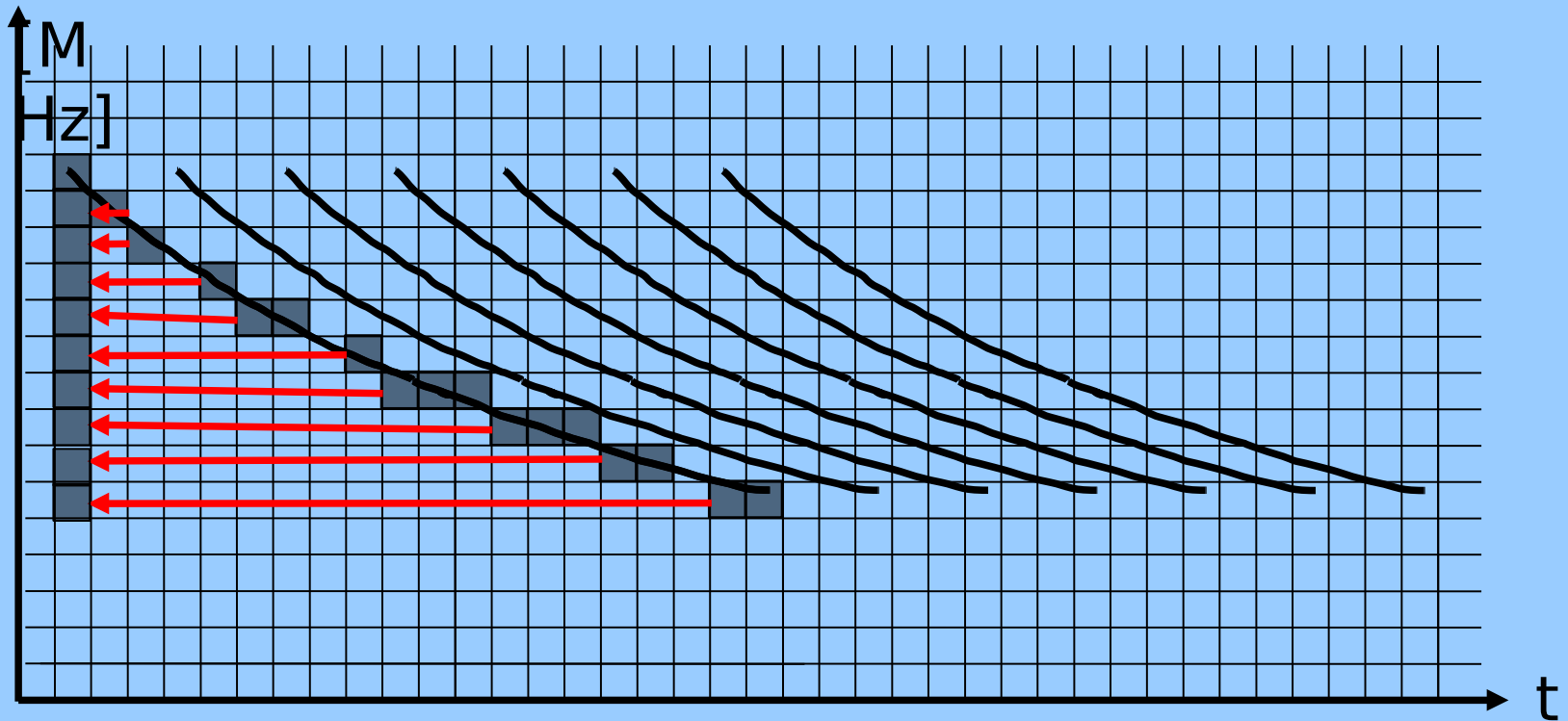
f



[
s
]

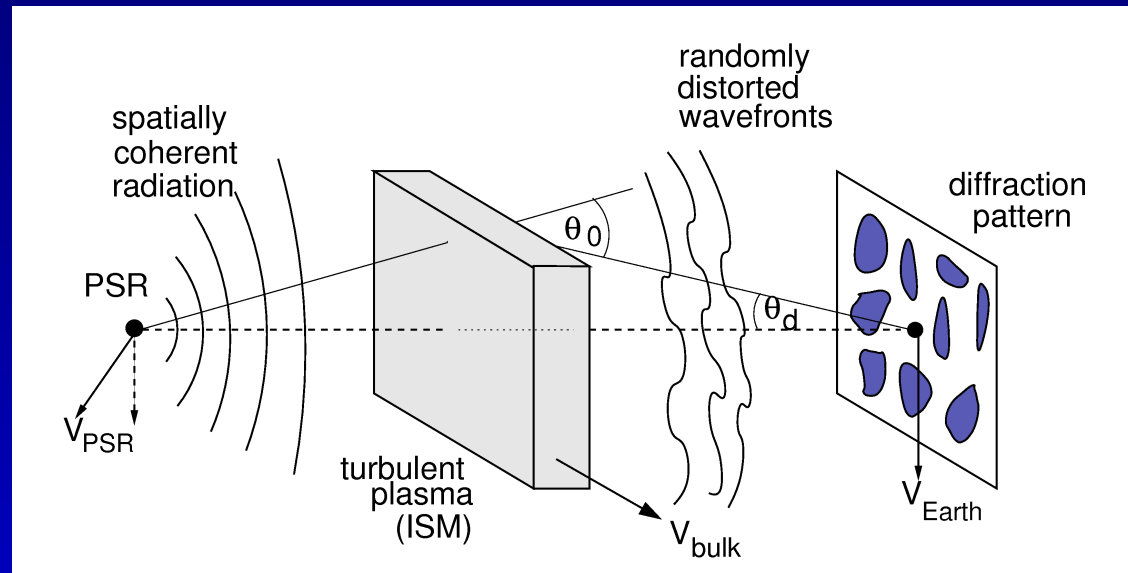
Dispersion : PSR B0809+74

f

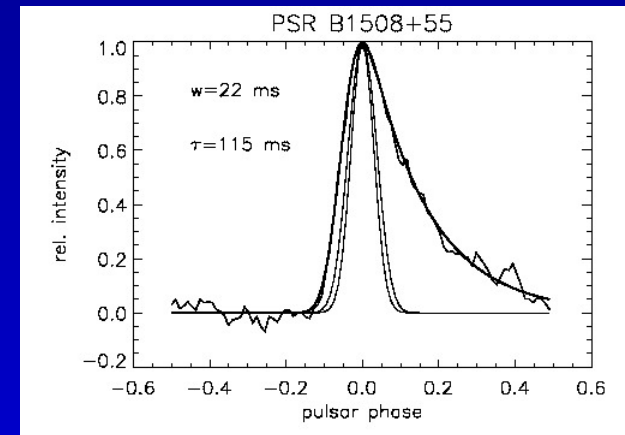
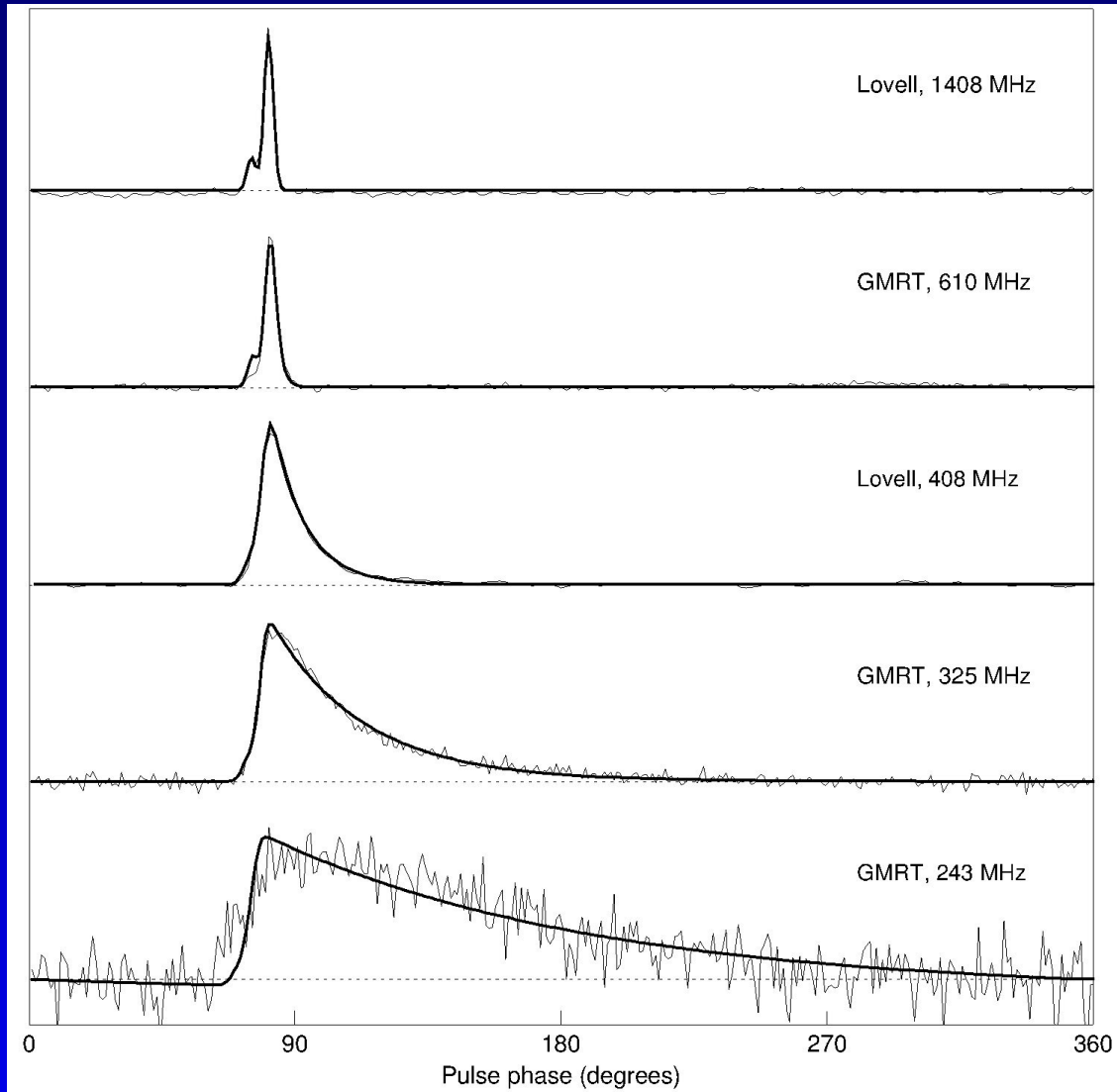


[S]

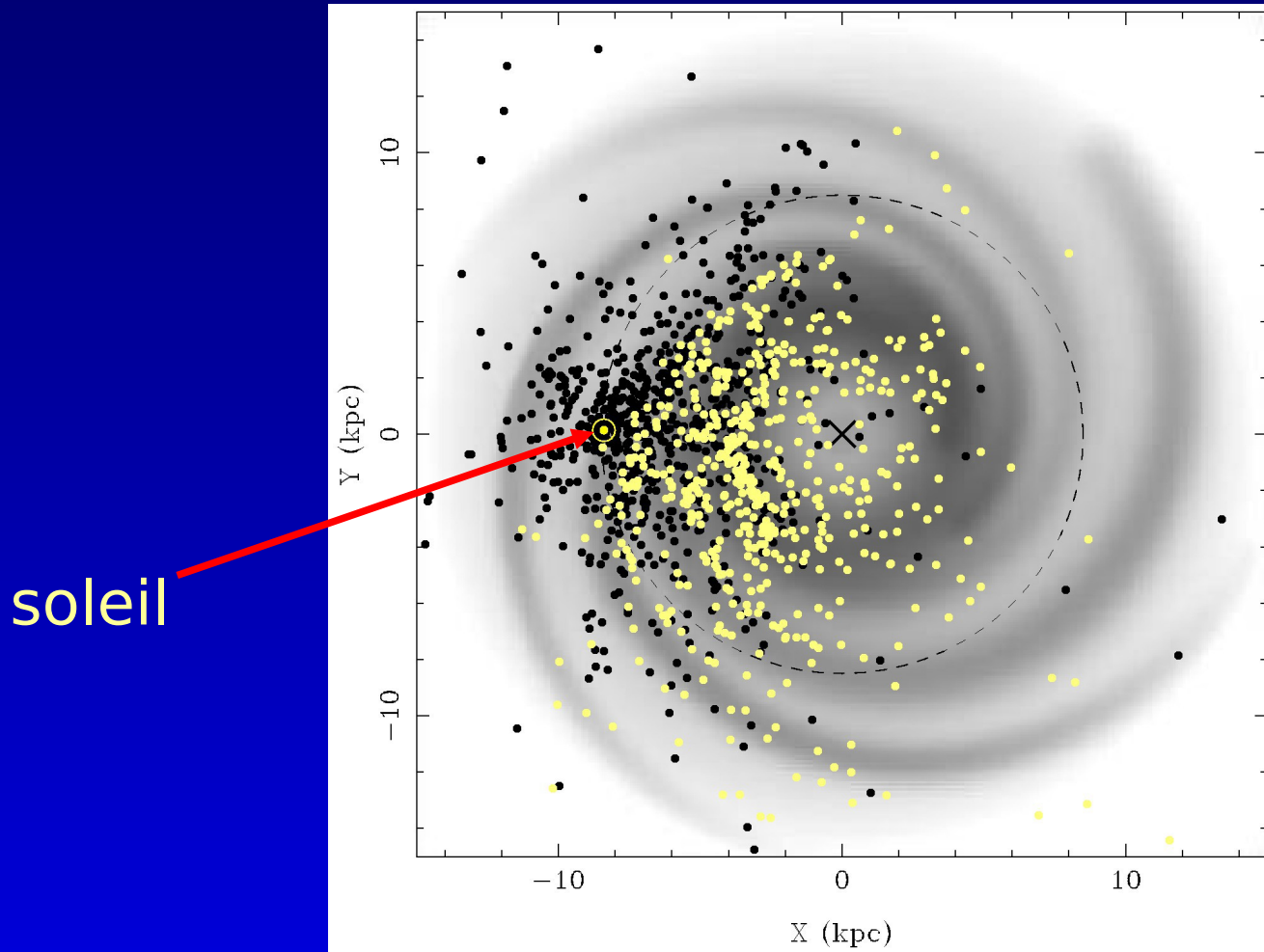
Propagation et turbulence



La detection des pulsars



La detection des pulsars

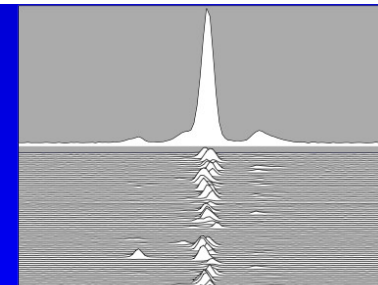
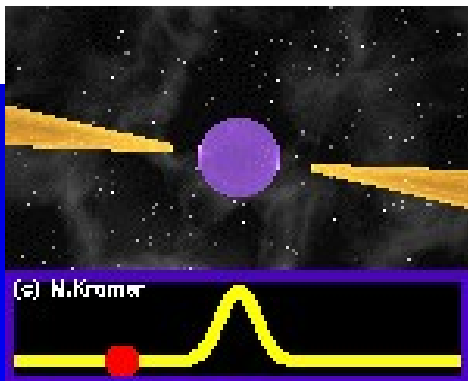
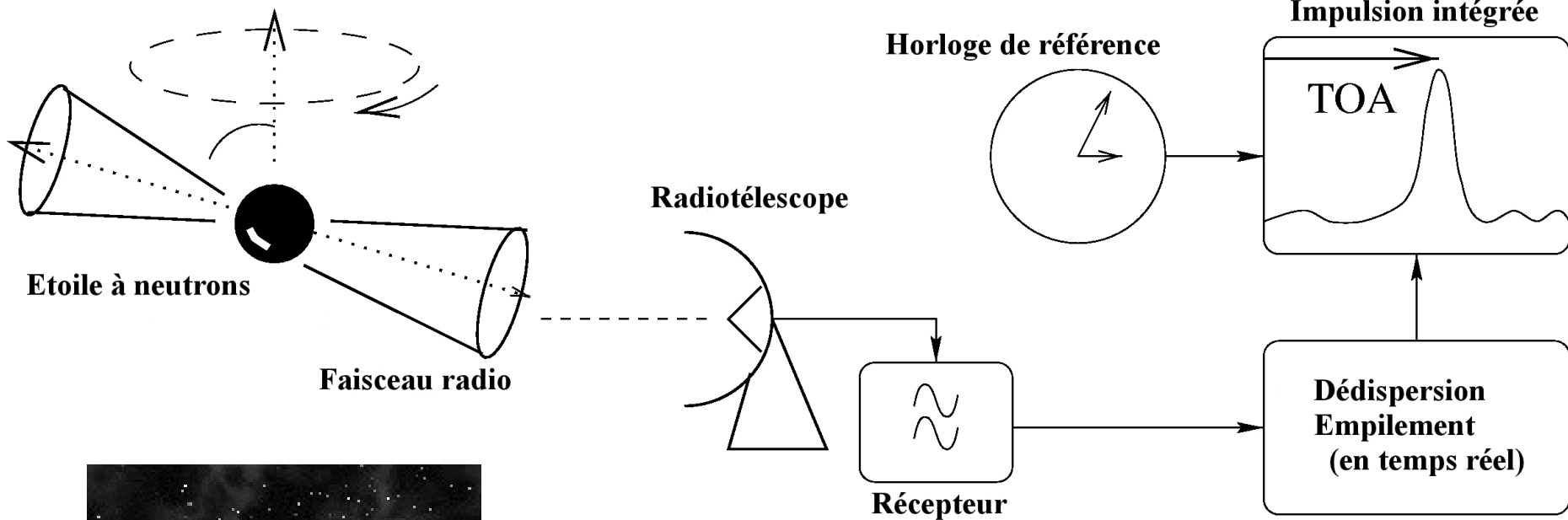
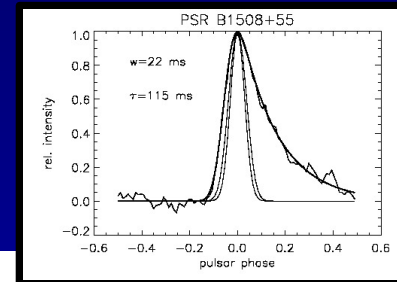


soleil

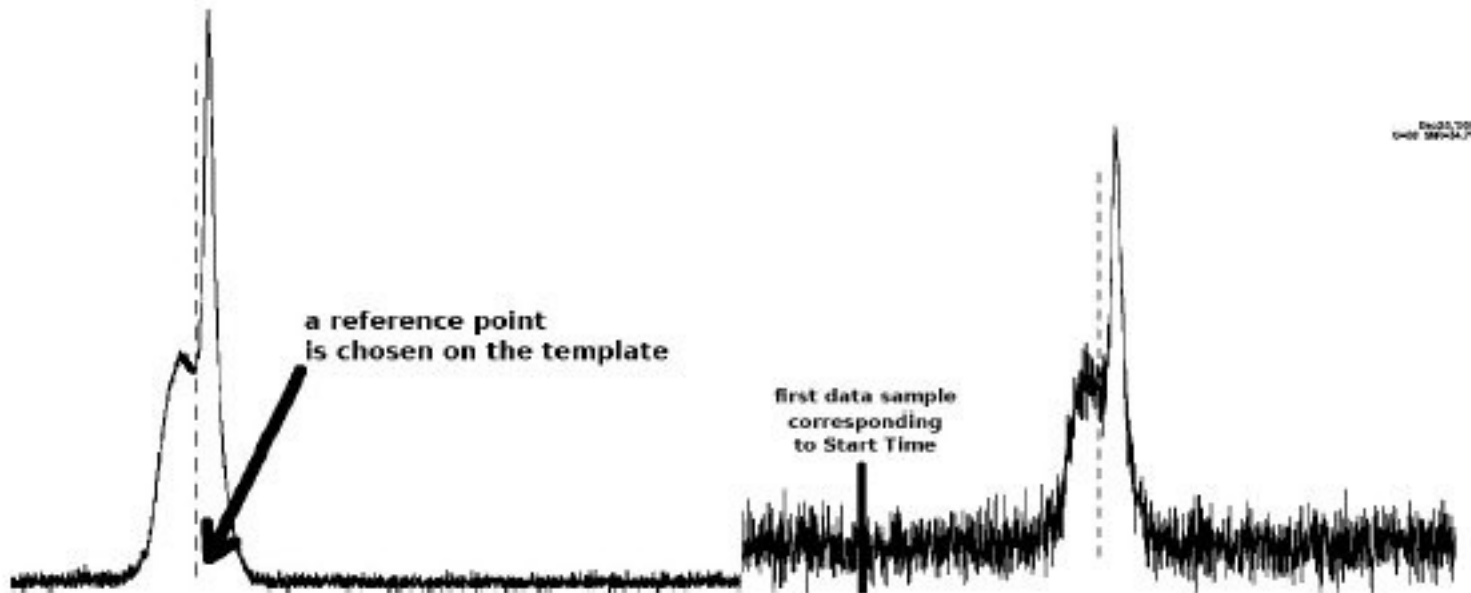
Répartition des pulsars dans la Galaxie (noirs=découverts à basse fréquence)
et modèle de la densité électronique

⇒ étude du milieu interstellaire

Les TOAs ("time of arrival")



Les TOAs (“time of arrival”)



Un 'modèle' (ou template) est construit comme :

- une version lissée d'une observation donnée, ou
- une somme de fonctions d'une base orthogonale, ou
- l'intégration cohérente d'un grand nombre d'observations

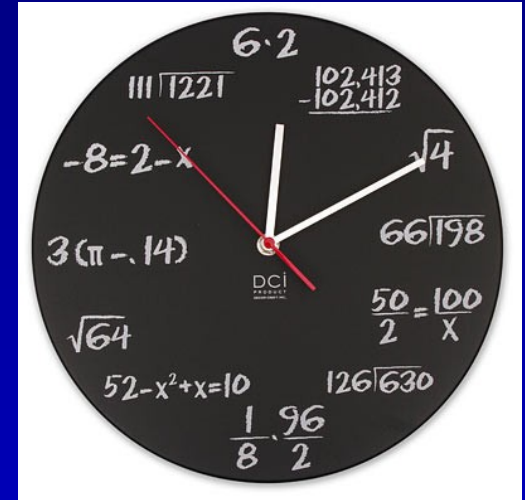
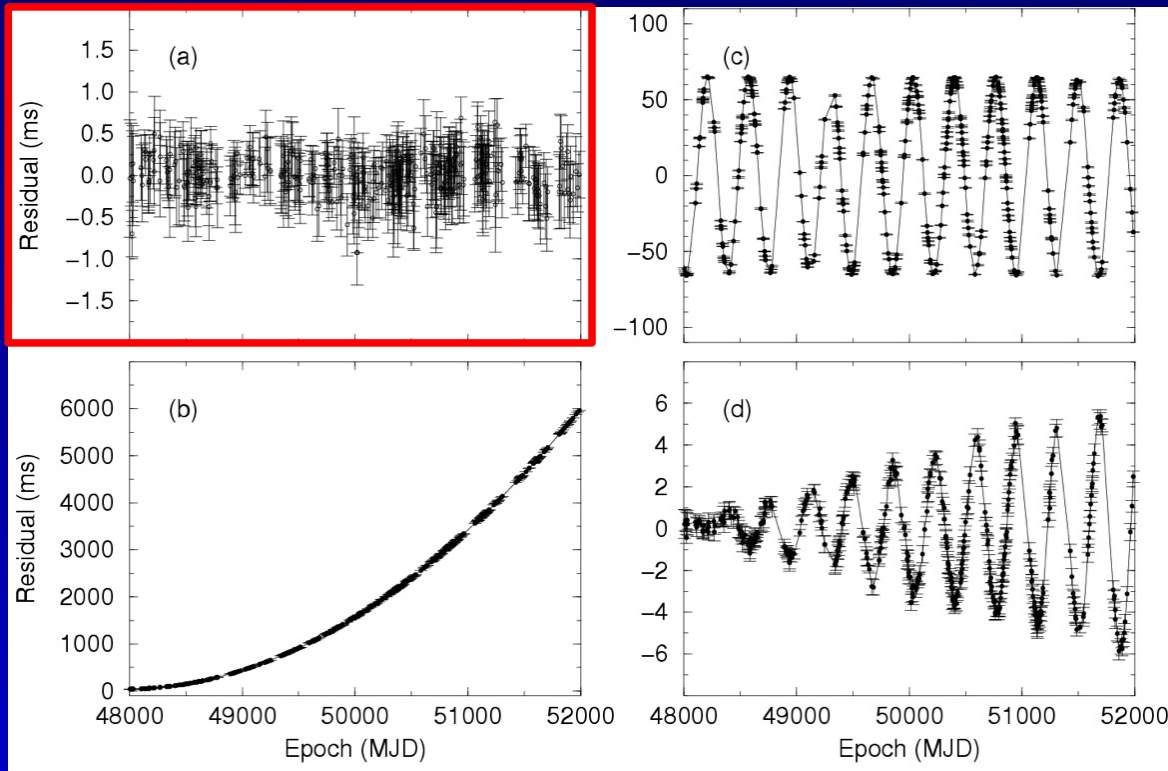
Une cross-corrélation du modèle avec chacune des observations produit un décalage converti en temps d'arrivée

La stabilité à long terme

Temps d'arrivée du pulsar J1600-3053

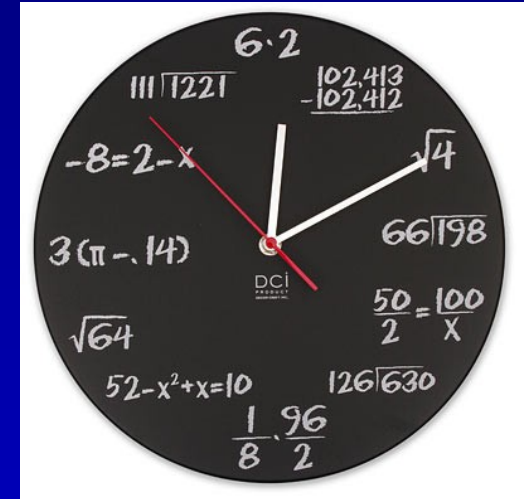
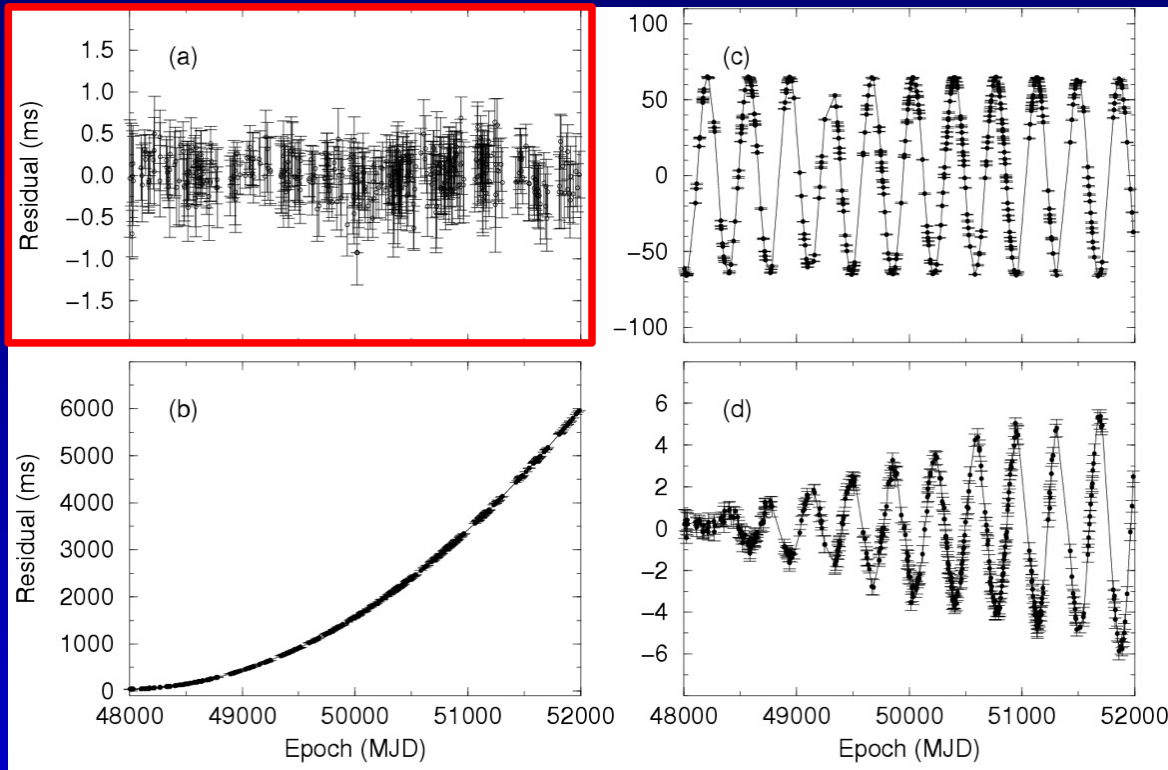
Observatory Code	'1'	Pulsar Name	Freq [MHz]	TOA [MJD]	Uncert [μ s]
f	1	1600-30	1368.000	54033.5511921591647	0.48
f	1	1600-30	1368.000	54036.5385764225914	0.54
f	1	1600-30	1368.000	54048.5021991052575	0.59
f	1	1600-30	1368.000	54051.5056597667359	0.50
f	1	1600-30	1368.000	54054.4968287444377	0.46
f	1	1600-30	1368.000	54056.4913888998682	0.48
f	1	1600-30	1368.000	54057.4889815273292	0.52
f	1	1600-30	1368.000	54060.4810301095328	0.51
f	1	1600-30	1368.000	54065.4600579101507	0.60
f	1	1600-30	1368.000	54071.4479745723167	0.57
f	1	1600-30	1368.000	54072.4445486474761	0.53
f	1	1600-30	1368.000	54079.4312384526258	0.50

La stabilité à long terme



Coherent timing: TOAs \Rightarrow count every rotation over years

La stabilité à long terme



Coherent timing: TOAs \Rightarrow count every rotation over years

- \Rightarrow Precise astrometry (sub-arcsecond)
- \Rightarrow Proper motion
- \Rightarrow Glitches in rotation
- \Rightarrow Precise orbital parameters
- \Rightarrow Tests of gravitational theories (PK parameters)

Mesure de temps et astronomie

Horloges astronomiques

Les pulsars

Les pulsars : horloges astronomiques

Utiliser ces horloges

Les radiotélescopes

Une observation

Les applications

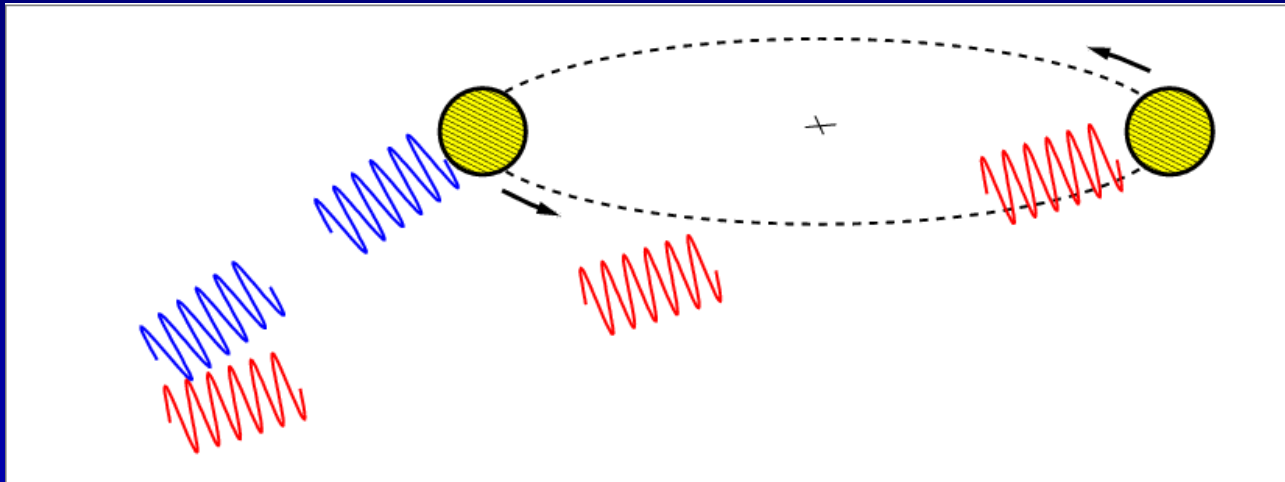
Une stabilité et une précision hors du commun

Alliée à la stabilité de rotation exceptionnelle des pulsars les plus rapides, l'excellence des instrumentations à dédispersion cohérente permet des mesures de temps d'arrivée des impulsions (ToAs) avec une précision pouvant atteindre $\sim 30\text{ns}$.

De nombreuses applications

- recherche d'un fond d'ondes gravitationnelles
- tests des différentes théories de la Gravitation
- propagation et turbulence du milieu interstellaire
- évolution stellaire
- amas globulaires et potentiel gravitationnel de la Galaxie
- contraintes sur les éphémérides du système solaire
- détection de planètes extra-solaires
- processus d'émission des pulsars
- stabilité à long terme des échelles de temps terrestres
- raccordement des repères célestes (équatorial et écliptique)

Les pulsars dans les systèmes binaires



mouvement autour de centre de masse

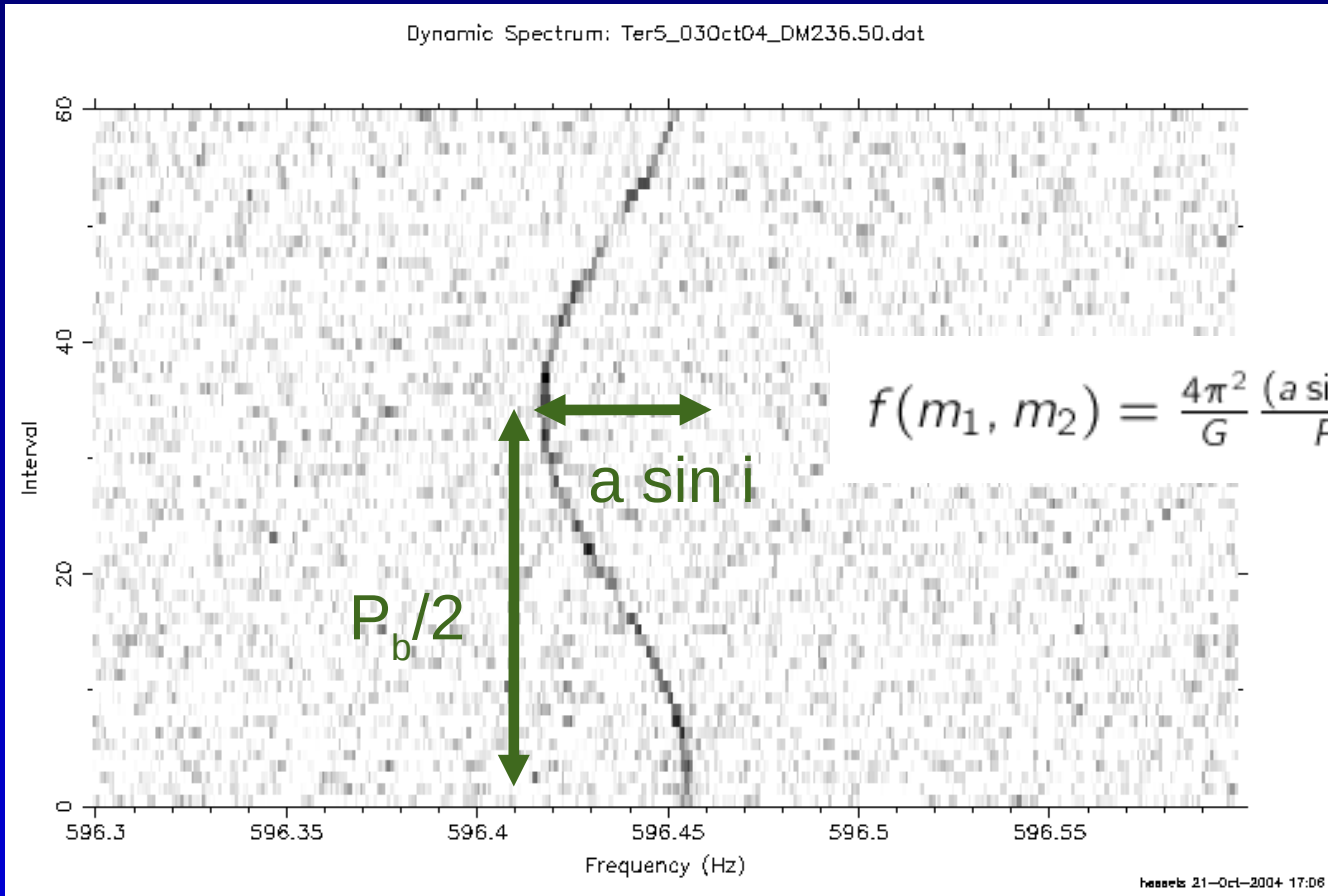


changement des TOAs



variation de la période

Pulsars binaires



Mass function
(compare with single-line
spectroscopic binary)

$\Rightarrow m_2 \sin i$

Des planètes autour des pulsars

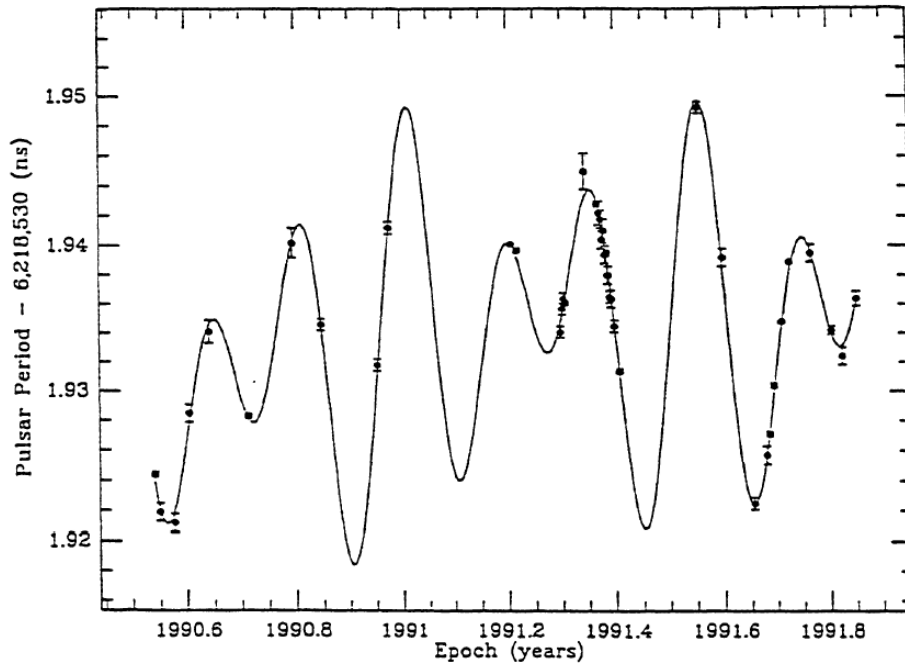


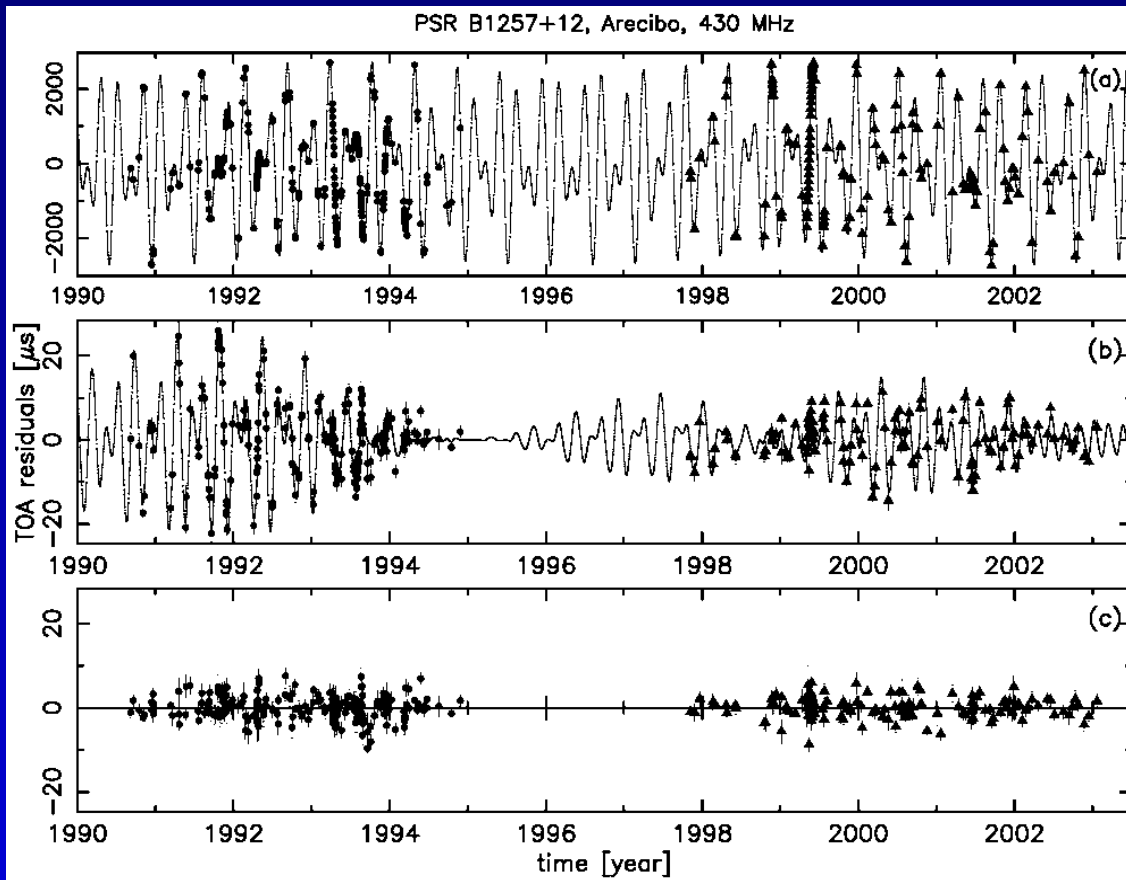
Figure 2. A comparison of period variations of PSR1257+12 (filled circles) with a two-planet model prediction (solid line).

[Wolszczan et al. 1992]

découverte de la première exoplanète en 1992!

Planet Δ	Mass	Radius	Period	a	e	i	Ang. dist.	Status	Discovery	Update
PSR 1257 12 b	7e-05	—	25.262	0.19	—	—	0.00038	R	—	2013-07-12
PSR 1257 12 c	0.013	—	66.5419	0.36	0.0186	53.0	0.00072	R	—	2013-07-12
PSR 1257 12 d	0.012	—	98.2114	0.46	0.0252	47.0	0.00092	R	—	2013-07-12
PSR 1719-14 b	1.0	0.4	0.090706293	0.0044	0.06	—	—	R	2011	2012-07-24
PSR B1620-26 b	2.5	—	36525.0	23.0	—	—	0.006053	R	2003	2013-07-11

Des planètes autour des pulsars



pulsar

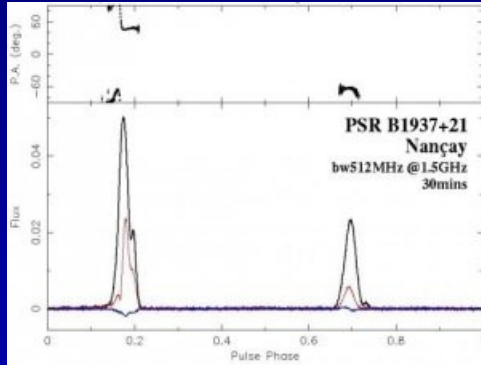
pulsar
+ 3 planètes
(Kepler)

pulsar
+ 3 planètes
(Kepler +
non-Kepler)

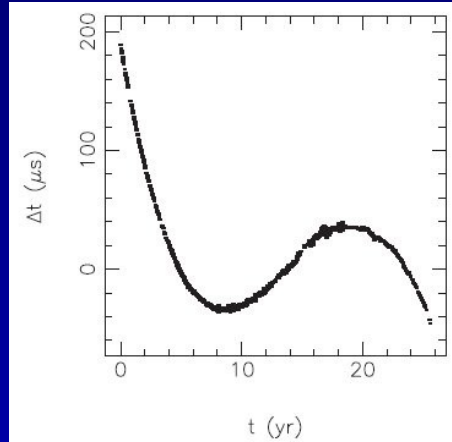
[Konacki et al. 2003]

Des astéroïdes autour PSR B1937+21

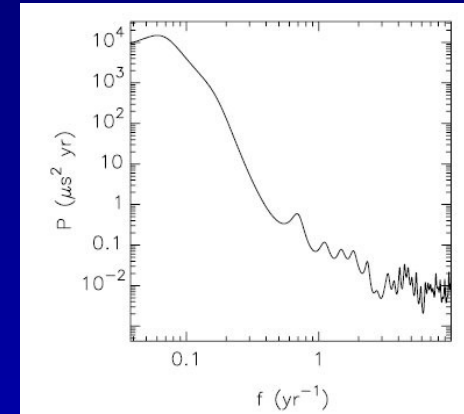
observation



1 pulse de
PSR B1937+21



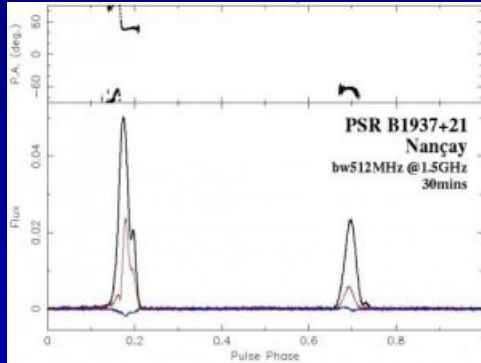
residu du TOA



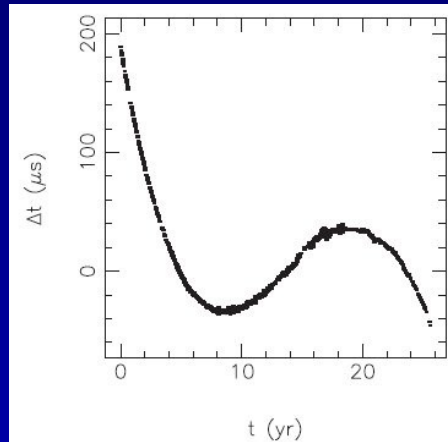
analyse du bruit

Des astéroïdes autour PSR B1937+21

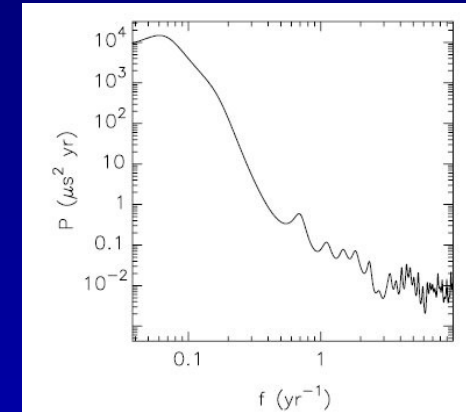
observation



1 pulse de
PSR B1937+21

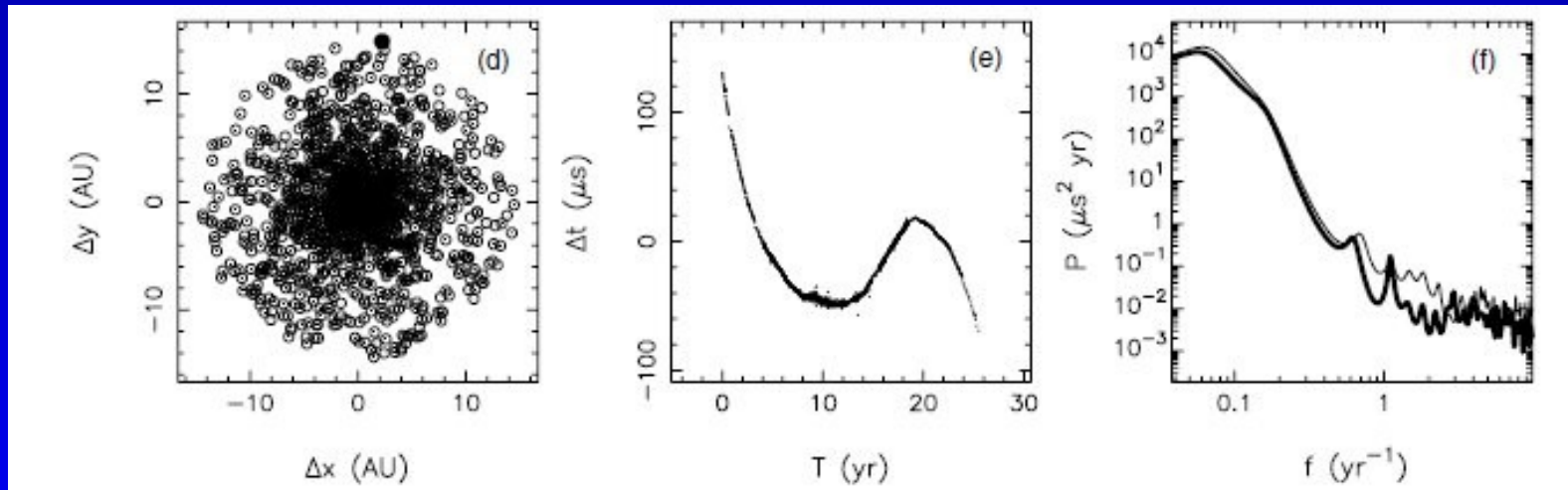


residu du TOA



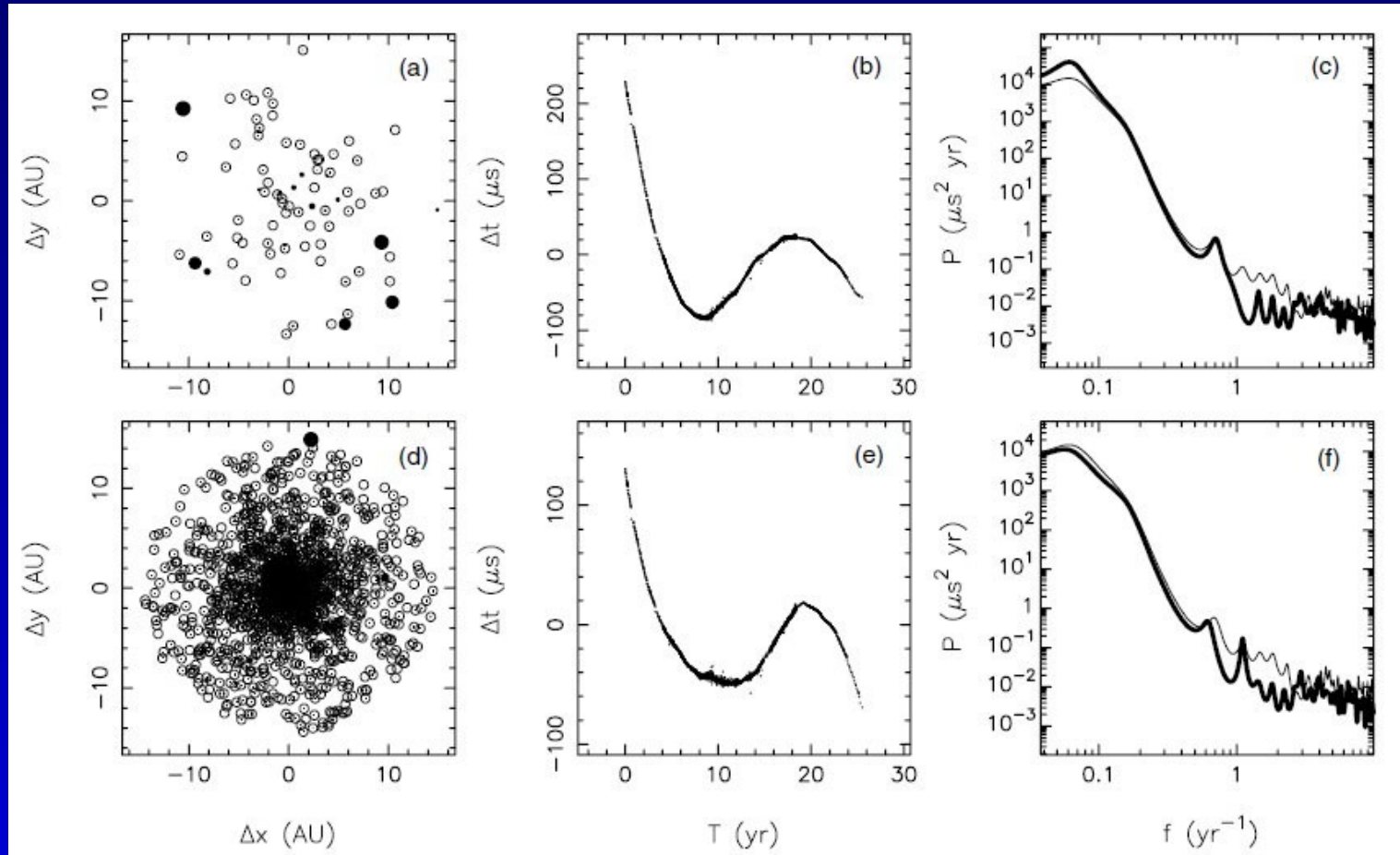
analyse du bruit

modèle



[Shannon et al. 2013]

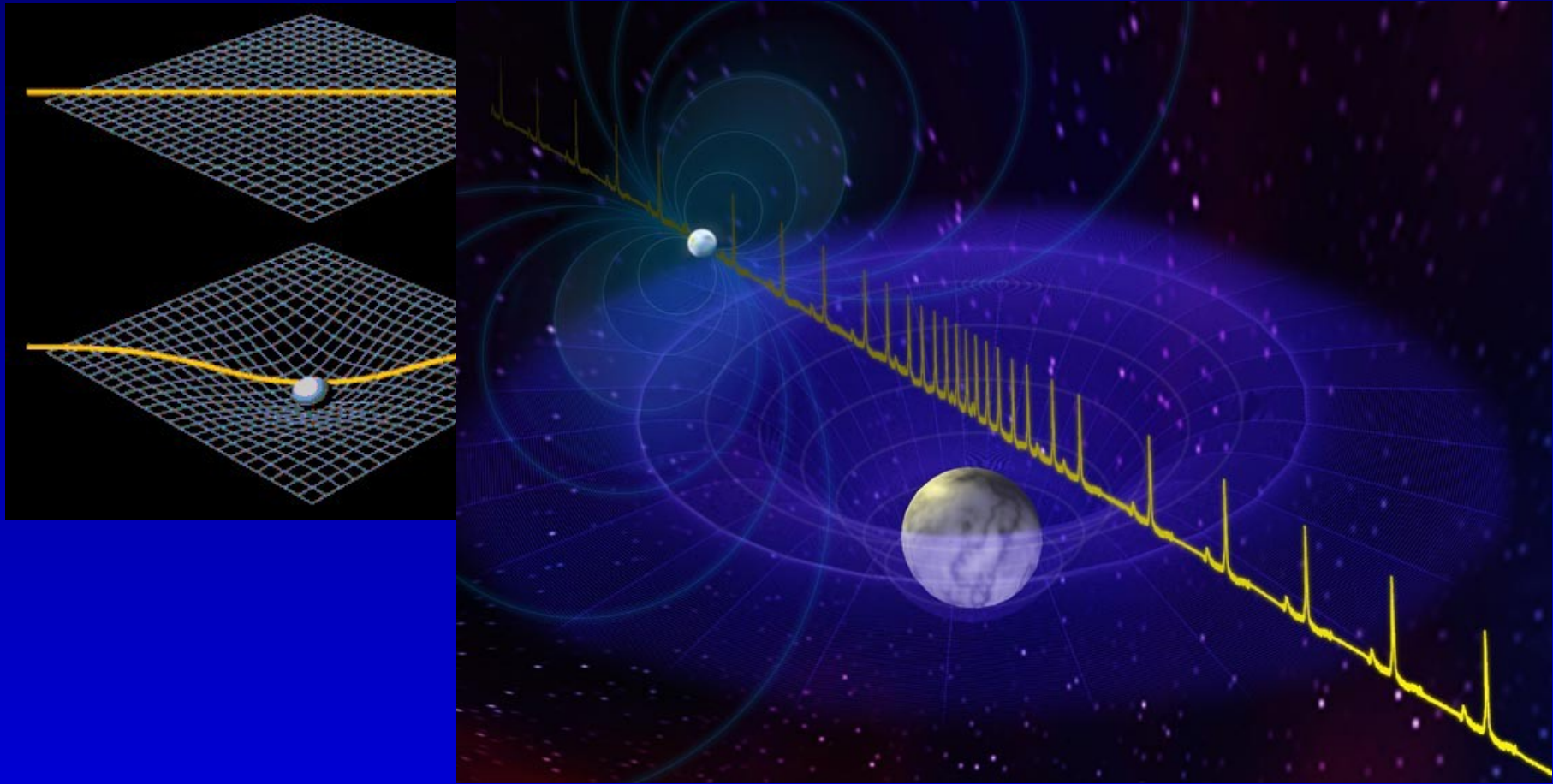
Des astéroïdes autour PSR B1937+21



26 années d'observation
avec 4 télescopes $\rightarrow M \approx 0.05 M_{\text{terre}}$

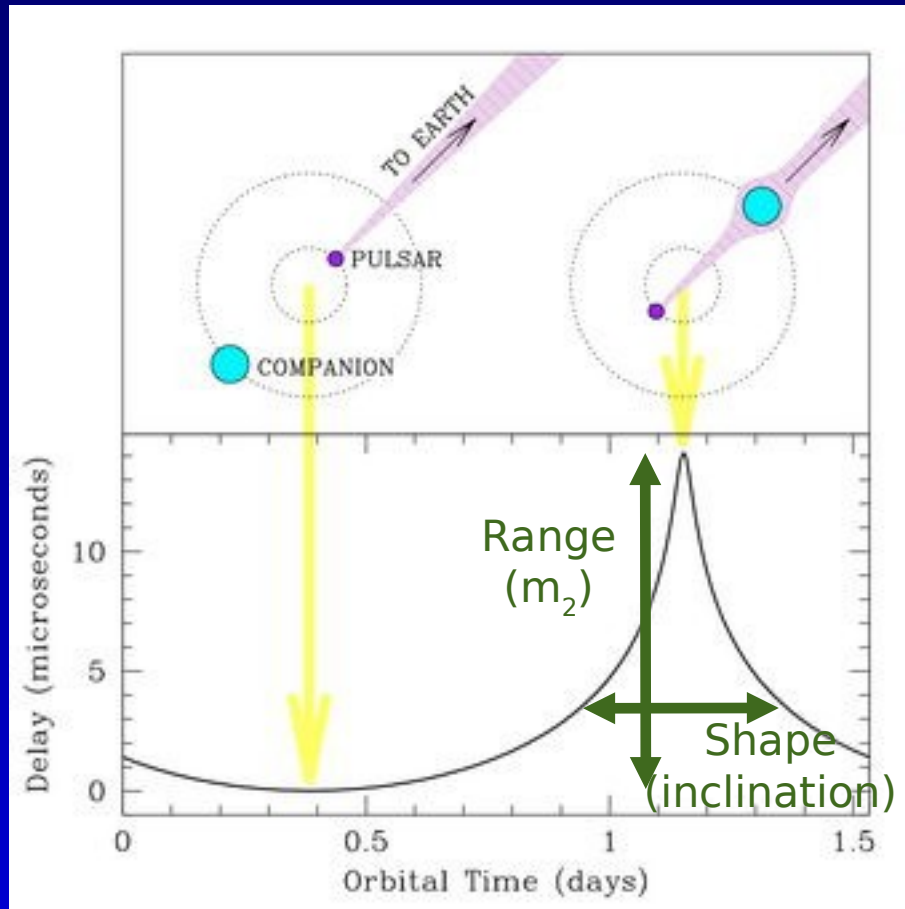
[Shannon et al. 2013]

Pulsars binaires: Effet Shapiro



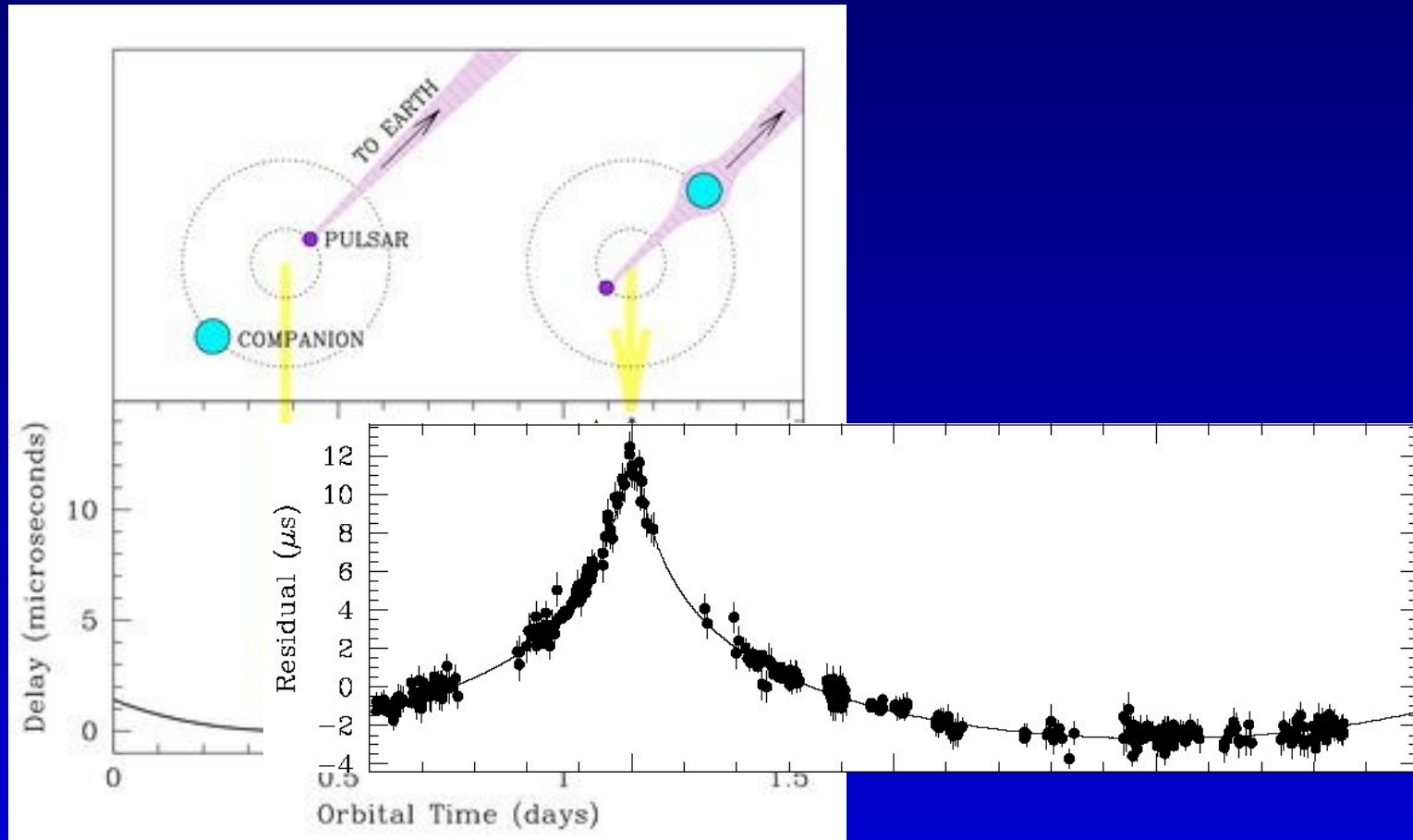
effet Shapiro au passage d'une onde electromagnétique proche d'un corps massif

Pulsars binaires: Effet Shapiro



Combiner r, s avec $f(m_1, m_2)$ pour obtenir m_1, m_2 , et $\sin i$ séparément!

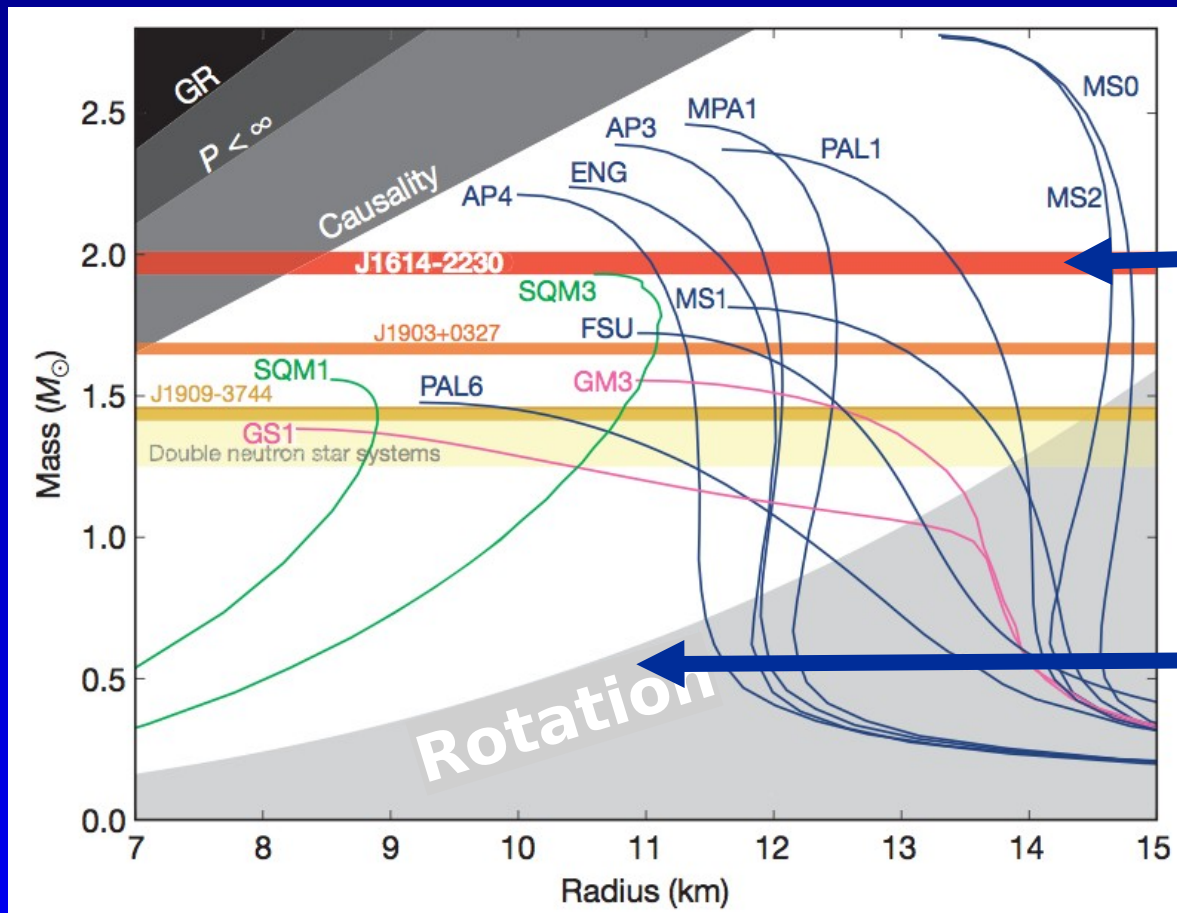
Pulsars binaires: Effet Shapiro



Combiner r, s avec $f(m_1, m_2)$ pour obtenir m_1, m_2 , et $\sin i$ séparément!

Equation d'état

Masse du pulsar
⇒ information sur la composition!

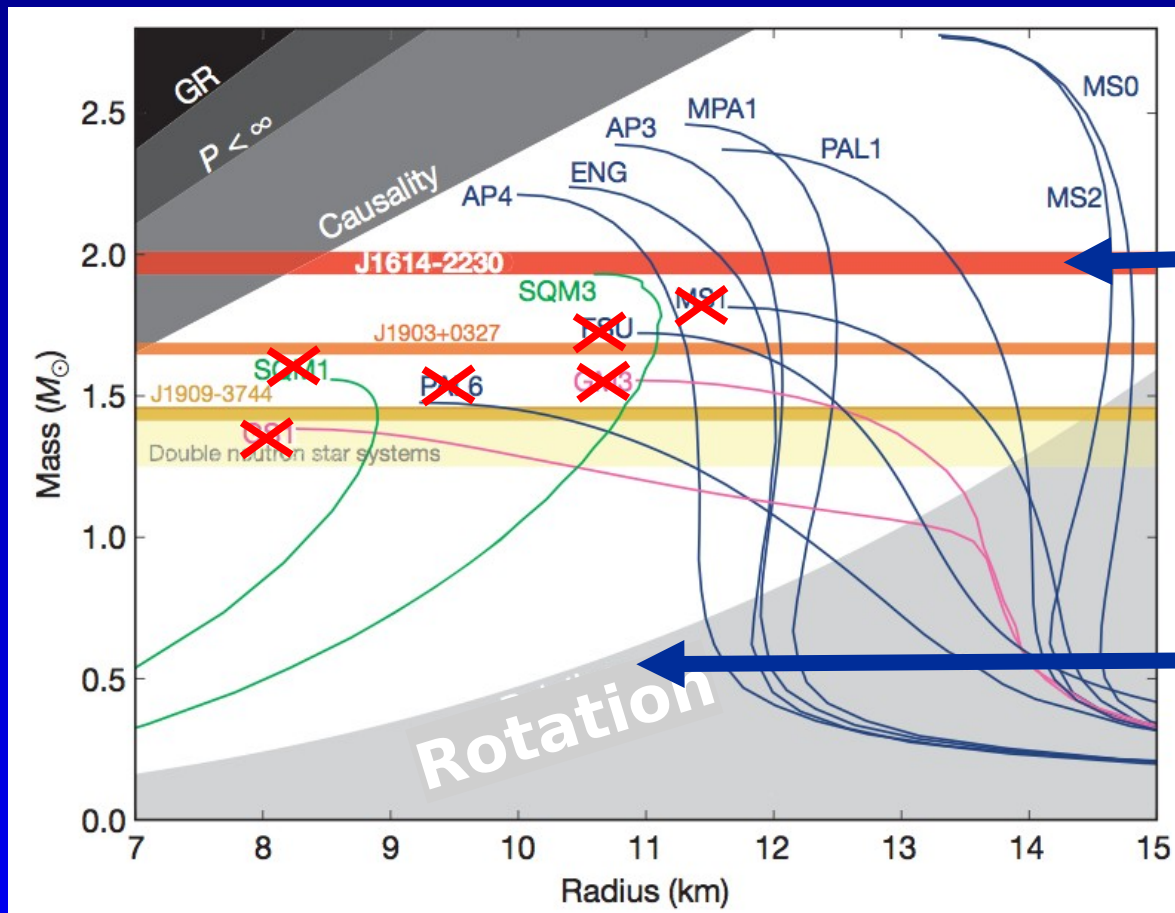


2M_{Sun} Pulsar
[Demorest et al. 2010]

716Hz Pulsar
[Hessels et al. 2006]

Equation d'état

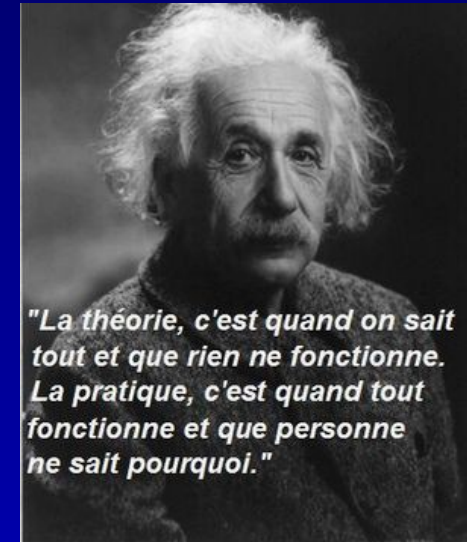
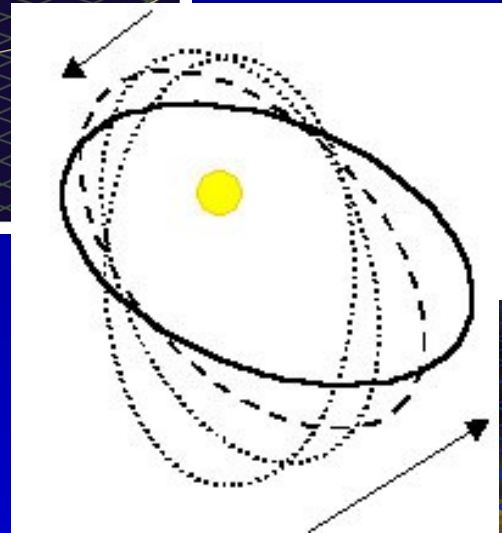
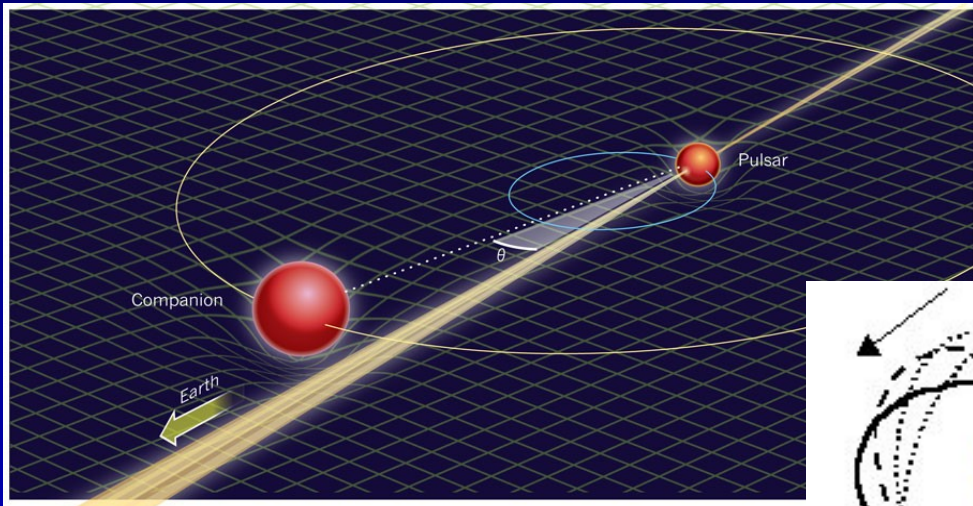
Masse du pulsar
⇒ information sur la composition!



$2M_{\text{Sun}}$ Pulsar
[Demorest et al. 2010]

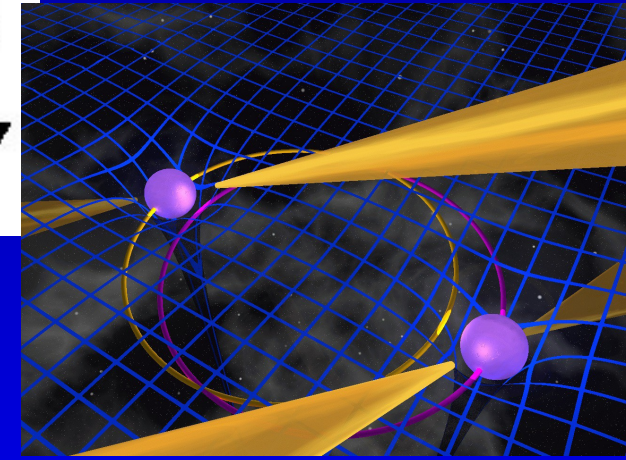
716Hz Pulsar
[Hessels et al. 2006]

Test de gravitation

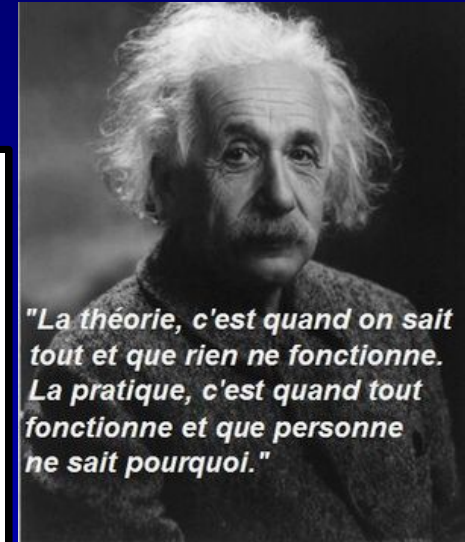
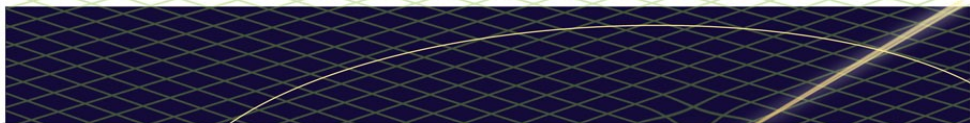


effets relativistes :

- retard Shapiro (r, s)
- précession du périastre ($d\omega/dt$)
- diminution de la période orbitale (dP_b/dt)



Test de gravitation



"La théorie, c'est quand on sait tout et que rien ne fonctionne. La pratique, c'est quand tout fonctionne et que personne ne sait pourquoi."

$$\dot{\omega} = 3T_{\odot}^{2/3} \left(\frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1-e^2} (M_A + M_B)^{2/3},$$

$$\gamma = T_{\odot}^{2/3} \left(\frac{P_b}{2\pi} \right)^{1/3} e \frac{M_B(M_A + 2M_B)}{(M_A + M_B)^{4/3}},$$

$$\dot{P}_b = -\frac{192\pi}{5} T_{\odot}^{5/3} \left(\frac{P_b}{2\pi} \right)^{-5/3} \frac{(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4)}{(1-e^2)^{7/2}} \frac{M_A M_B}{(M_A + M_B)^{1/3}},$$

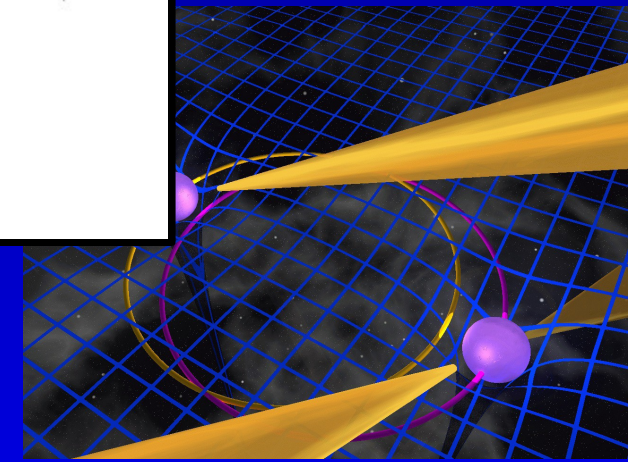
$$r = T_{\odot} M_B,$$

$$s = T_{\odot}^{-1/3} \left(\frac{P_b}{2\pi} \right)^{-2/3} x \frac{(M_A + M_B)^{2/3}}{M_B},$$

effets relativistes :

- retard Shapiro (r, s)
- précession du périastre ($d\omega/dt$)
- diminution de la période orbitale (dP_b/dt)

→ test de théories de la gravitation en champ fort



Test de gravitation

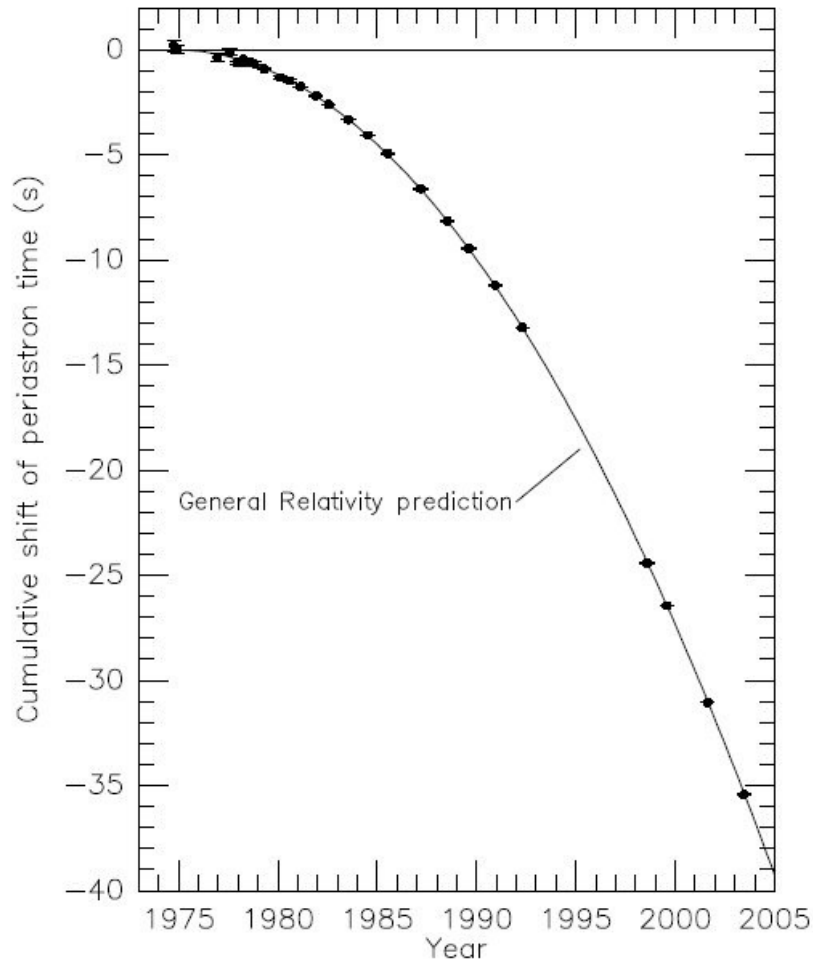


Figure 1. Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity.

[Weisberg et al. 2005]

- 1974 : découverte de PSR B1913+16 à Arecibo
- observations pendant ~20 ans
- diminution de la période orbitale confirme l'émission d'ondes gravitationnelles !
- 1993 : Prix Nobel pour Hulse et Taylor



The Nobel Prize in Physics 1993

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



Russell A. Hulse

1/2 of the prize
USA

Princeton University
Princeton, NJ, USA
b. 1950

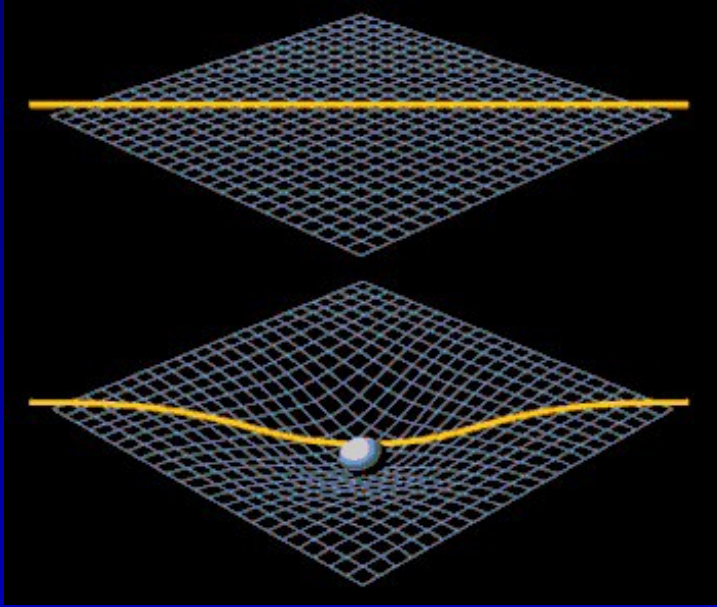


Joseph H. Taylor Jr.

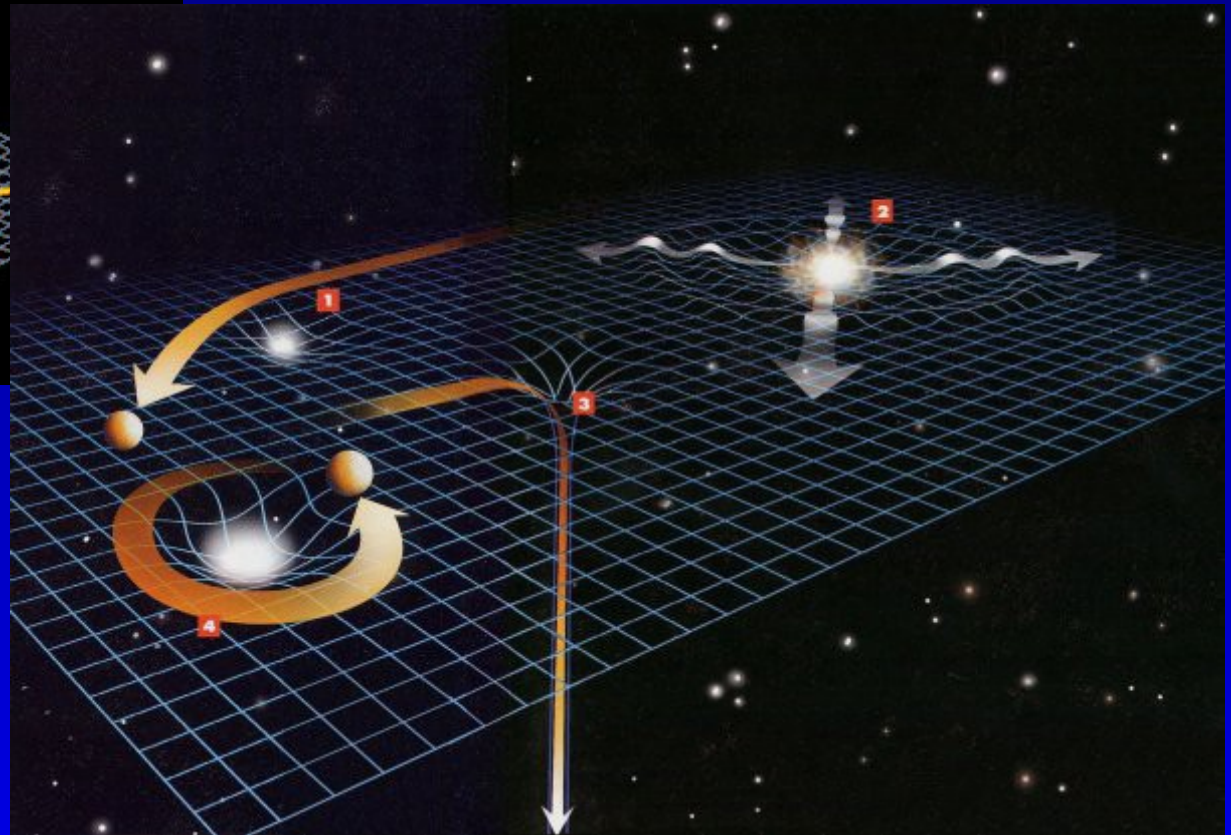
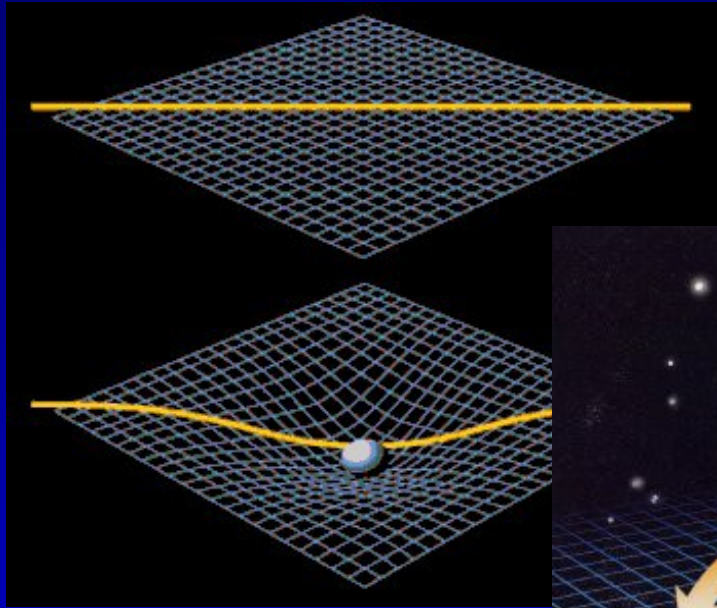
1/2 of the prize
USA

Princeton University
Princeton, NJ, USA
b. 1941

Ondes gravitationnelles

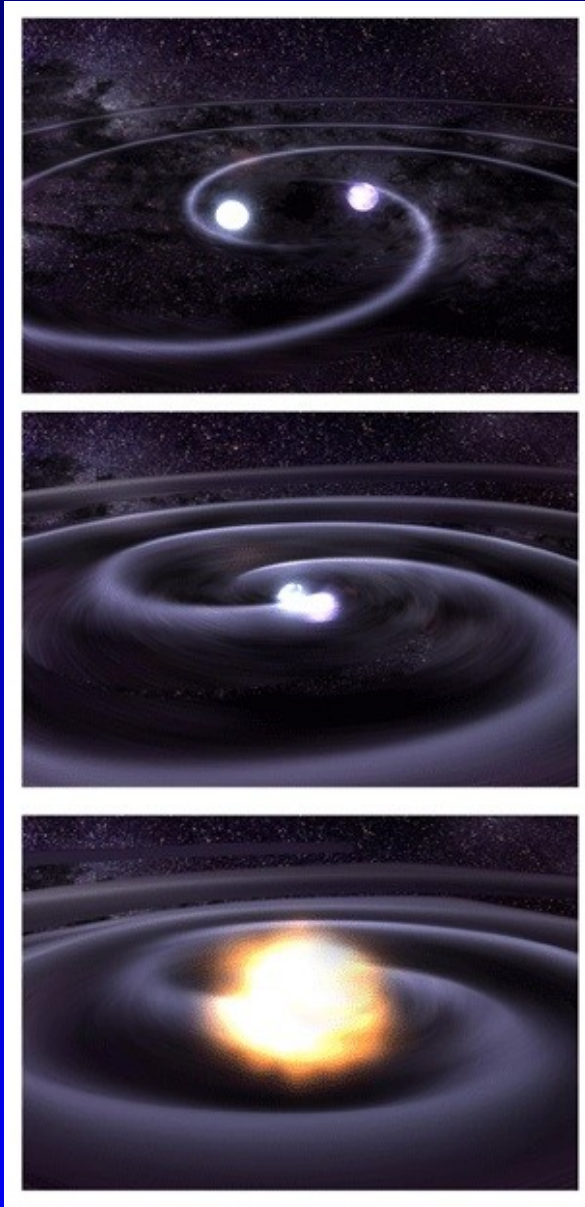


Ondes gravitationnelles



masses accélérées → déformation de l'espace-temps
se propage dans l'univers avec c

Ondes gravitationnelles



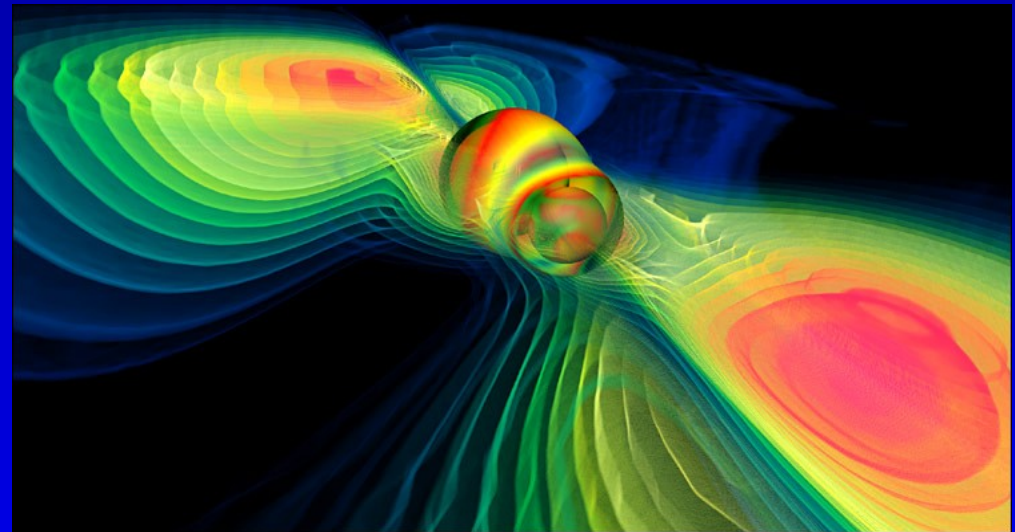
Diverses sources...

Trous noirs binaires
super-massifs ($M \sim 10^7 - 9 M_{\odot}$)

Fond cosmologique

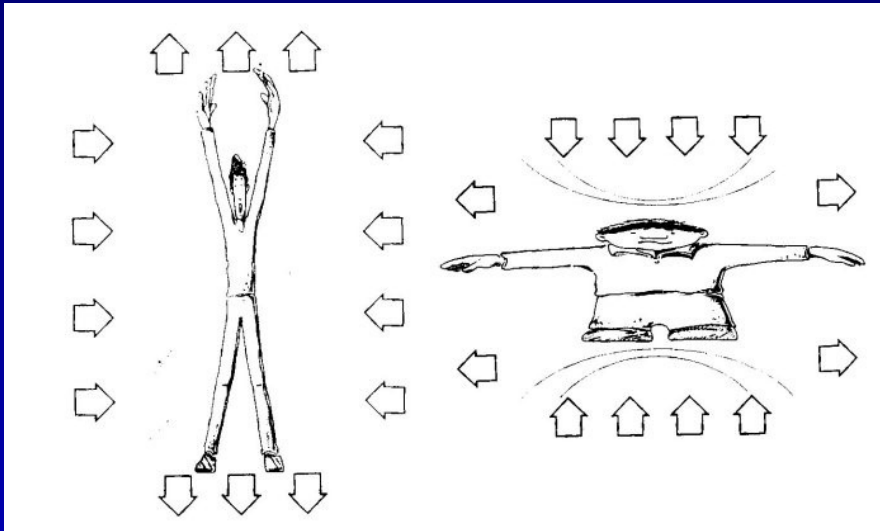
ondes gravitationnelles primordiales

cordes cosmiques vibrantes

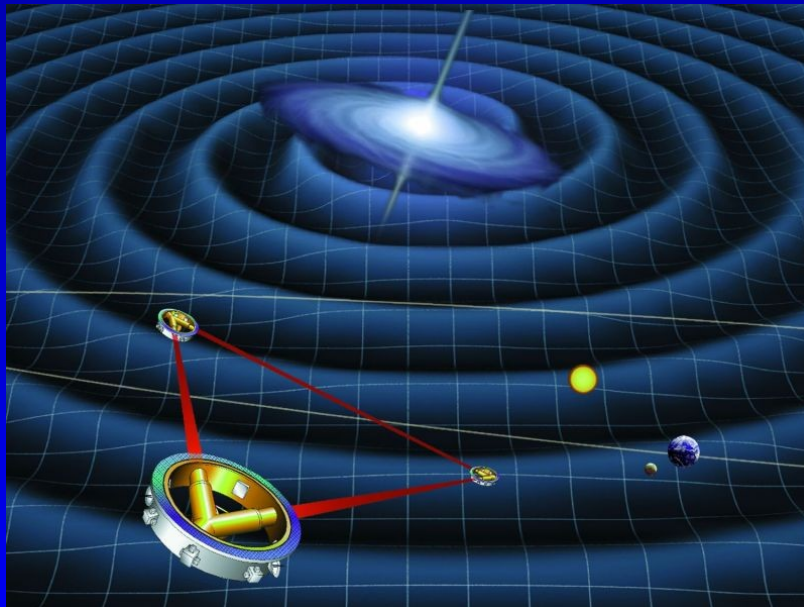


colaescence de deux trous noirs

Ondes gravitationnelles

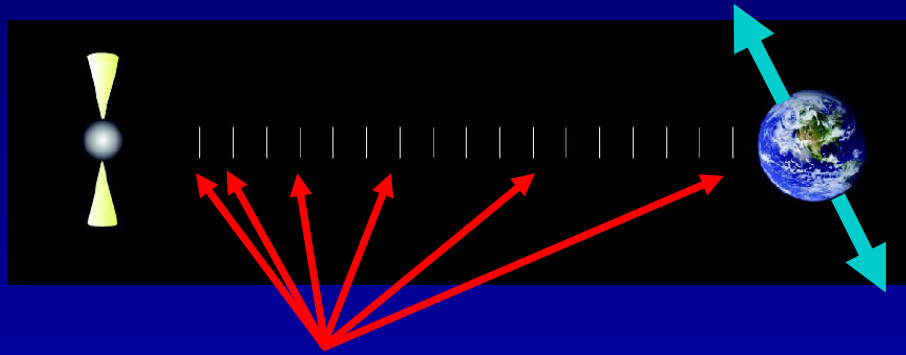


$2 \text{ m} \pm 10^{-21} \text{ m}$
→ 10^6 fois plus
petit qu'un proton!

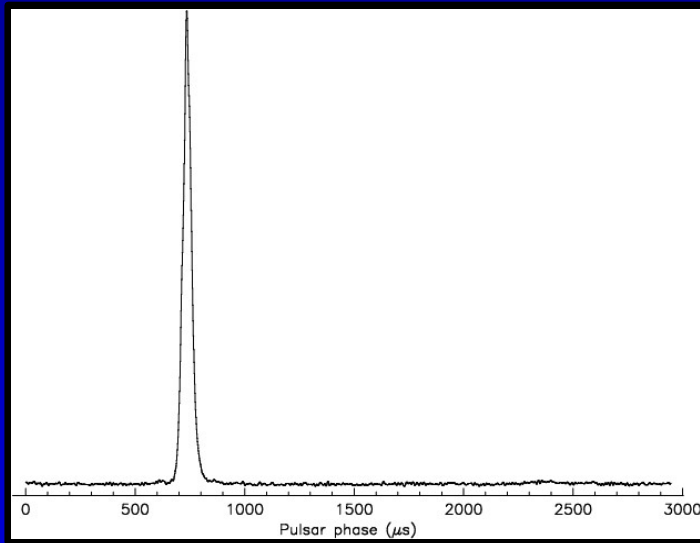


LISA :
 $5 \cdot 10^6 \text{ km}$ (→ $1 \cdot 10^6 \text{ km}$)
 $\pm 20 \text{ pm}$
→ plus petit qu'un
proton!

Fond d'ondes gravitationnelles

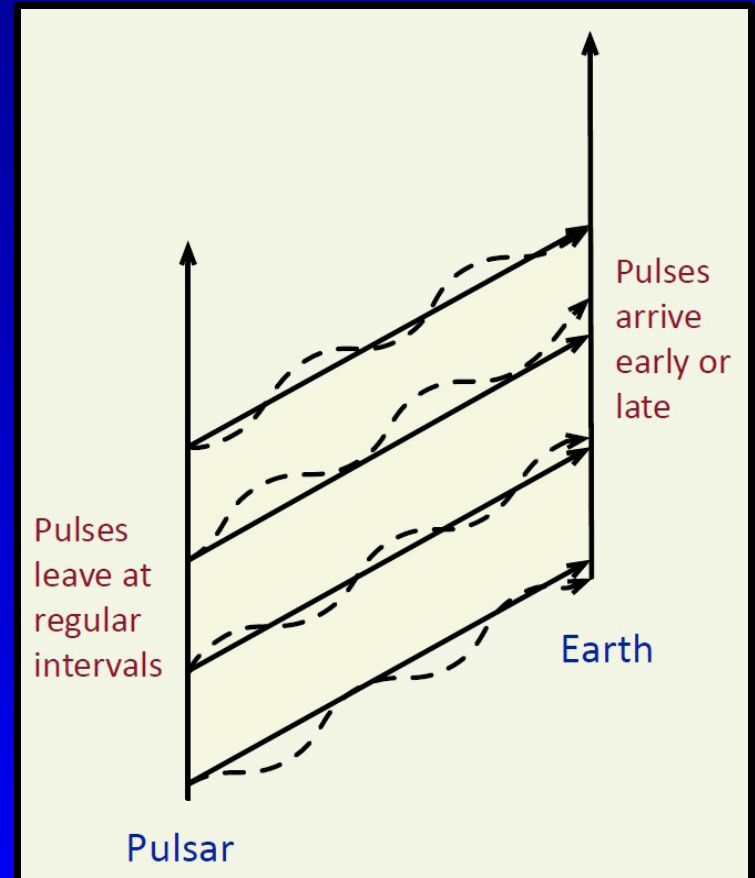


onde gravitationnelle

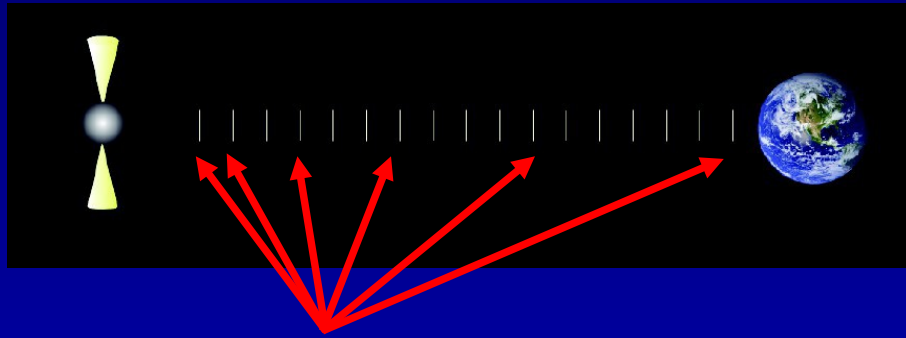


necessite

- mesure précise des TOAs
- pulsars très stables



PSR J1909-3744

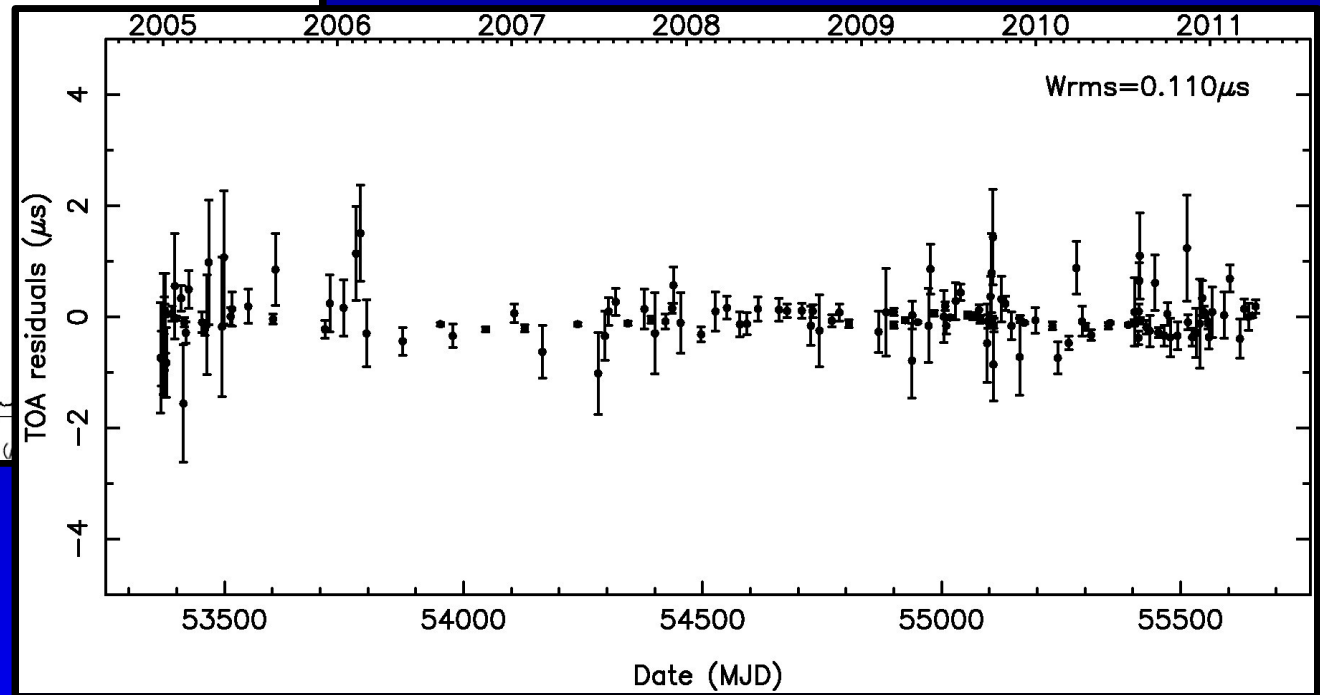
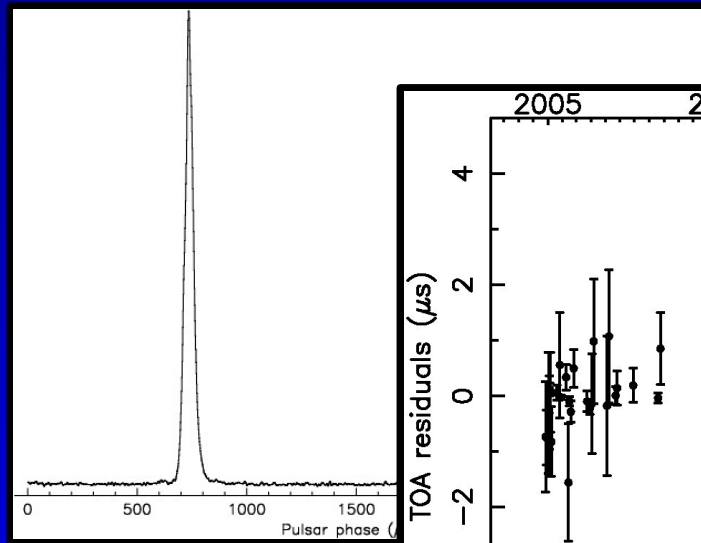


pulsar binaire

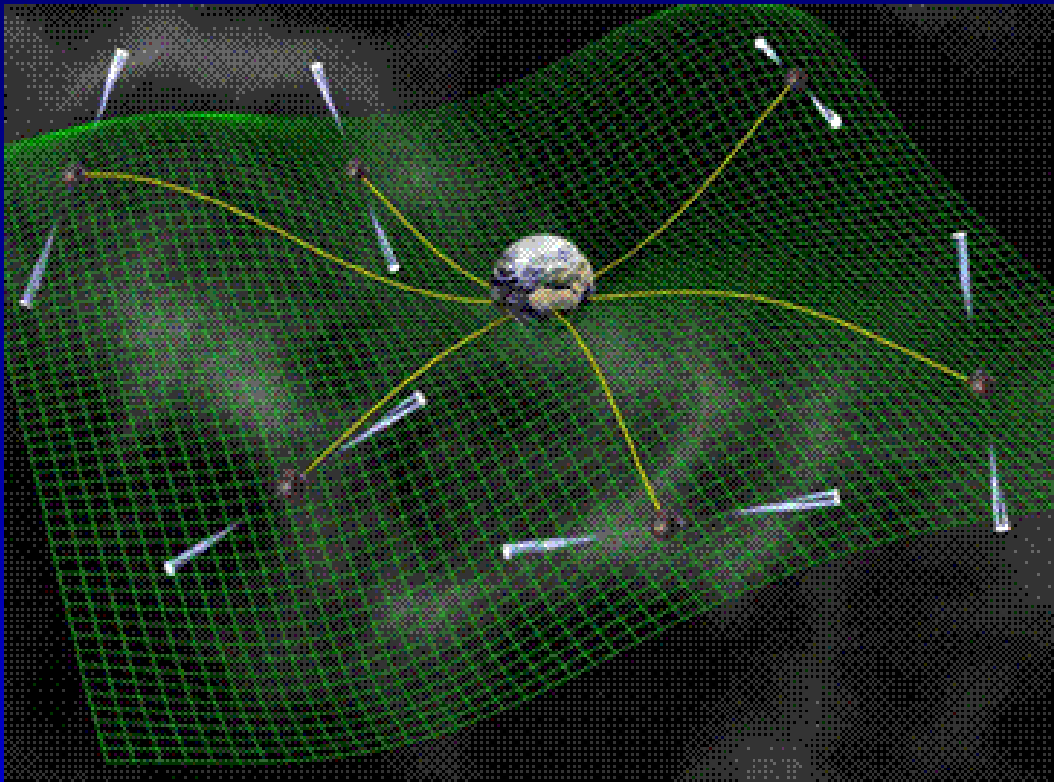
$P=2.95$ ms

$P_b=1.53$ d

rms des TOA: 110 ns!



Fond d'ondes gravitationnelles



Corréler...

Sur un ensemble de pulsars bien répartis sur le ciel, il s'agit de chercher un bruit corrélé provenant de l'effet des ondes gravitationnelles sur la Terre.

→ Pulsar Timing Array
(PTA : EPTA, PPTA, ...)

necessite

- mesure précise des TOAs
- un ensemble de pulsars très stables

Pulsar Timing Array

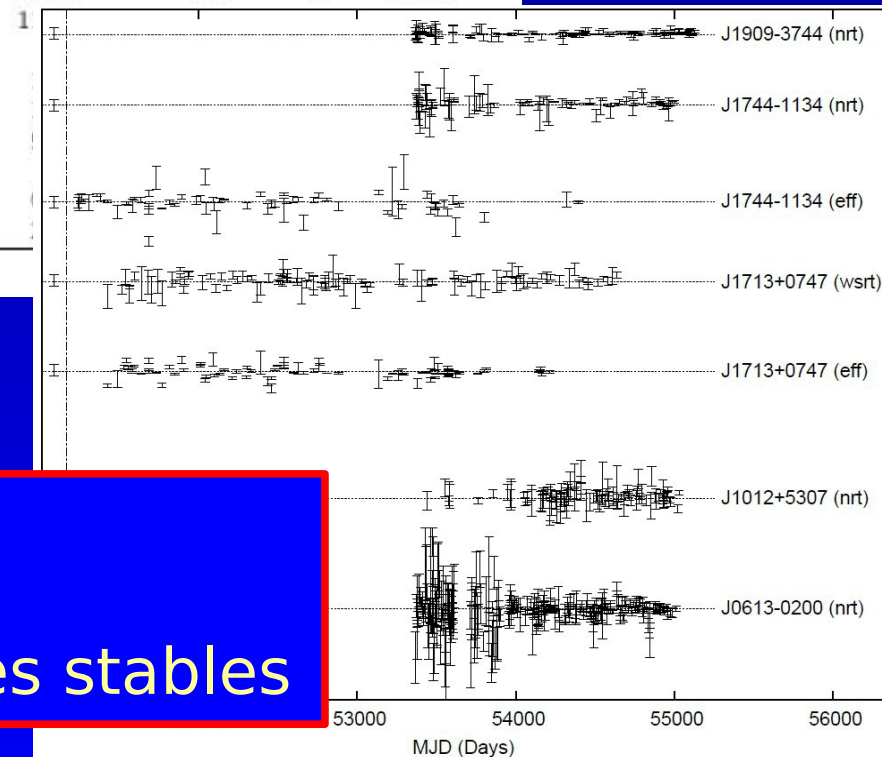
Beaucoup et très bien

sur plus de 20 pulsars stables
suivis régulièrement à Nançay :
10 sont à mieux que $1\mu\text{s}$,
5 à mieux que 500ns ...

EPTA

Nançay contribue grandement
à l'établissement du réseau
européen EPTA
(European Pulsar Timing Array),
collaboration entre les 5 grands
radiotélescopes : Jodrell (UK),
WSRT (NL), Nançay (F),
Effelsberg (G) et Cagliari (I).

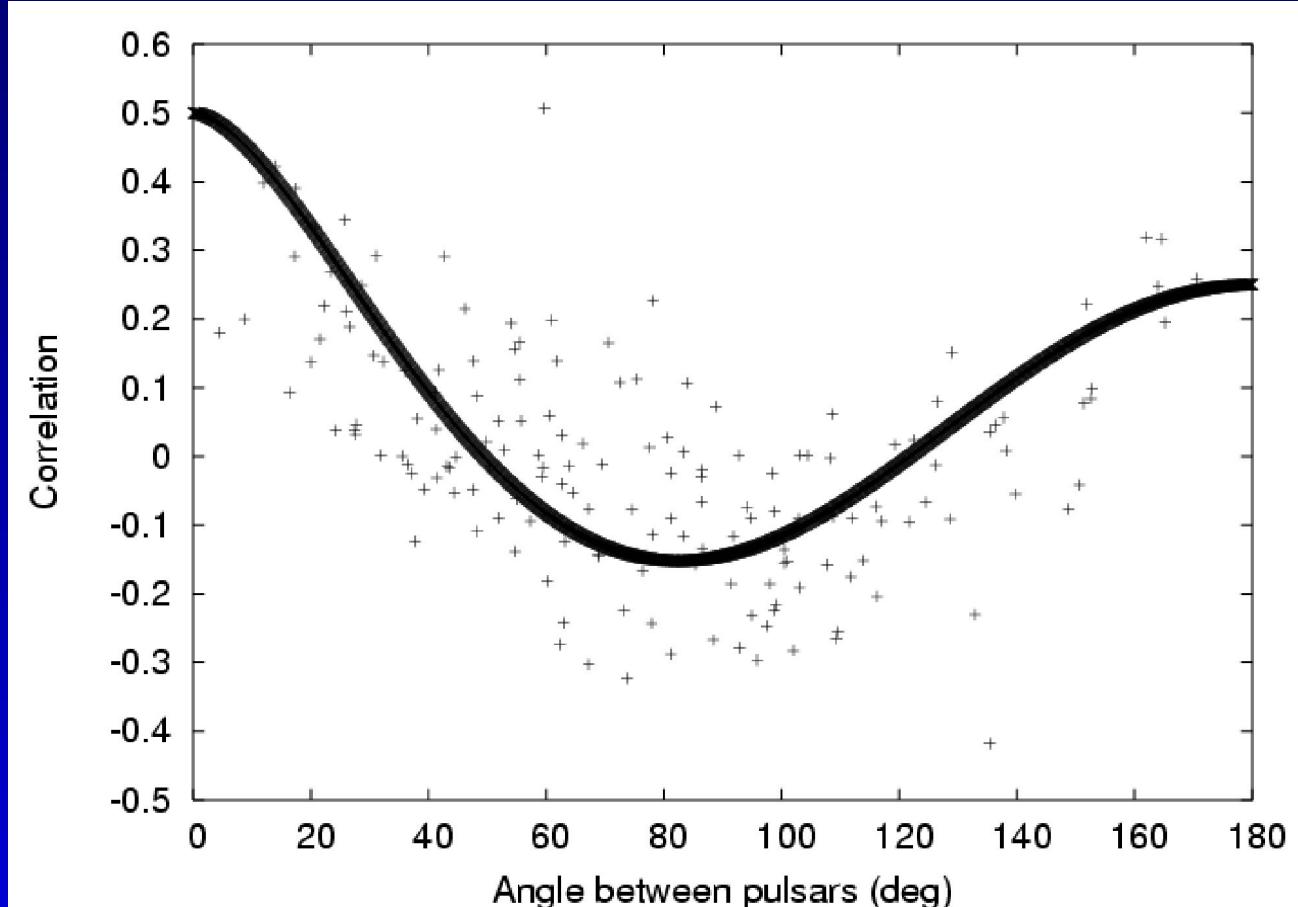
Pulsar	P (ms)	P_b (jours)	T (années)	N_{toa}	σ (μs)
J0030+0451	4.87	—	4.6	402	1.84
J0613-0200	3.06	11.2	4.5	280	0.913
J0751+1807	3.48	0.26	4.5	158	1.73
J0900-3144	11.10	18.7	2.0	199	2.87
J1012+5397	5.25	0.6	4.3	107	0.771
J1022+1001	16.45	7.8	4.5	136	1.97
J1024-0719	5.16	—	3.6	128	1.23
J1455-3330	7.99	76.2	4.5	139	2.33
J1600-3053	3.60	14.3	2.8	211	0.495
J1643-1224	4.62	147	4.5	271	1.7
J1713+0747	4.57	67.8	4.5	260	0.350
J1730-2304	8.12	—	4.5	85	1.55
J1744-1134	4.07	—	4.5	87	0.343
J1751-2857	3.91	—	—	—	—
J1824-2452	3.05	—	—	—	—
J1857+0943	5.36	—	—	—	—
J1909-3744	2.95	—	—	—	—
J1910+1256	4.98	—	—	—	—
J1939+2134	1.55	—	—	—	—
J2145-0750	16.05	—	—	—	—
J2317+1439	3.44	—	—	—	—



nécessite

- mesure précise des TOAs
- un ensemble de pulsars très stables

Fond d'ondes gravitationnelles



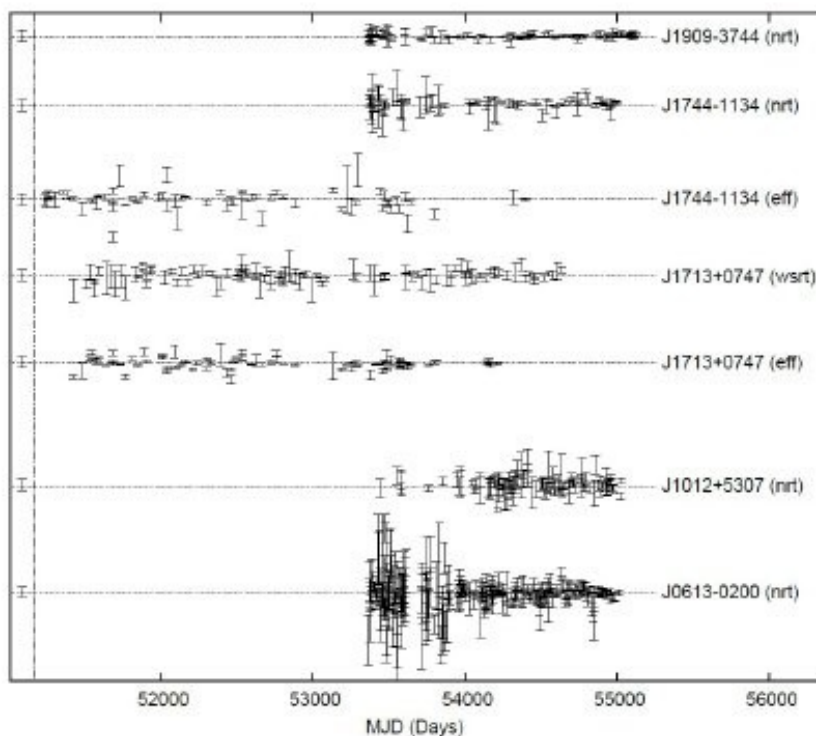
Corrélation attendue dans les résidus de temps d'arrivée d'une paire de pulsars en fonction de leur séparation angulaire, pour un fond d'ondes gravitationnelles isotropique

Hellings and Downs, ApJ 265, L39 (1983)

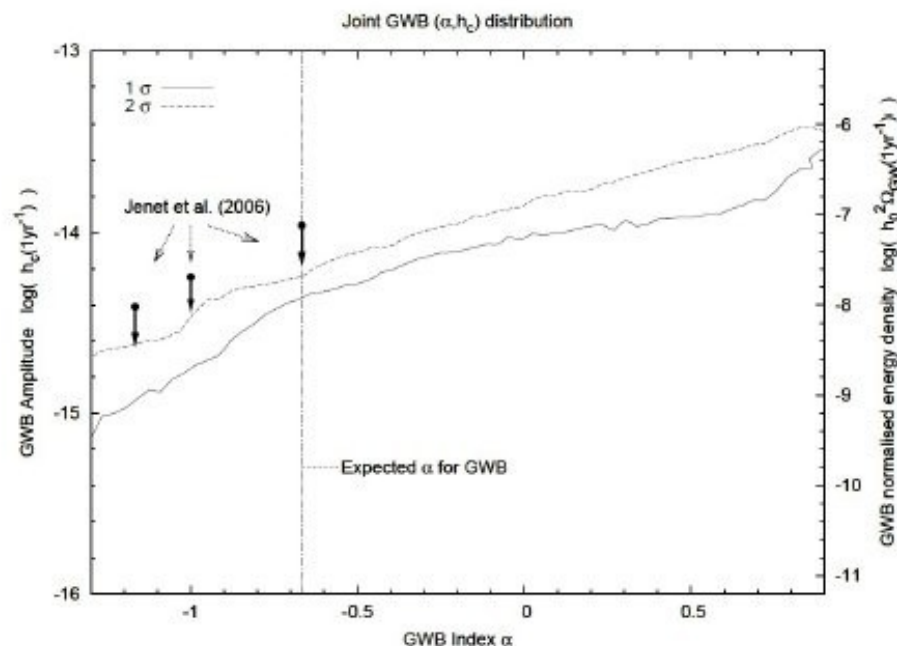
La meilleure limite actuelle

Les pulsars ultra-stables de l'EPTA (4NRT+2EFF+1WSRT) produisent la meilleure limite supérieure actuelle (approche Bayésienne)

vanHaasteren, in prep, 2010



Résidus de Temps d'Arrivée

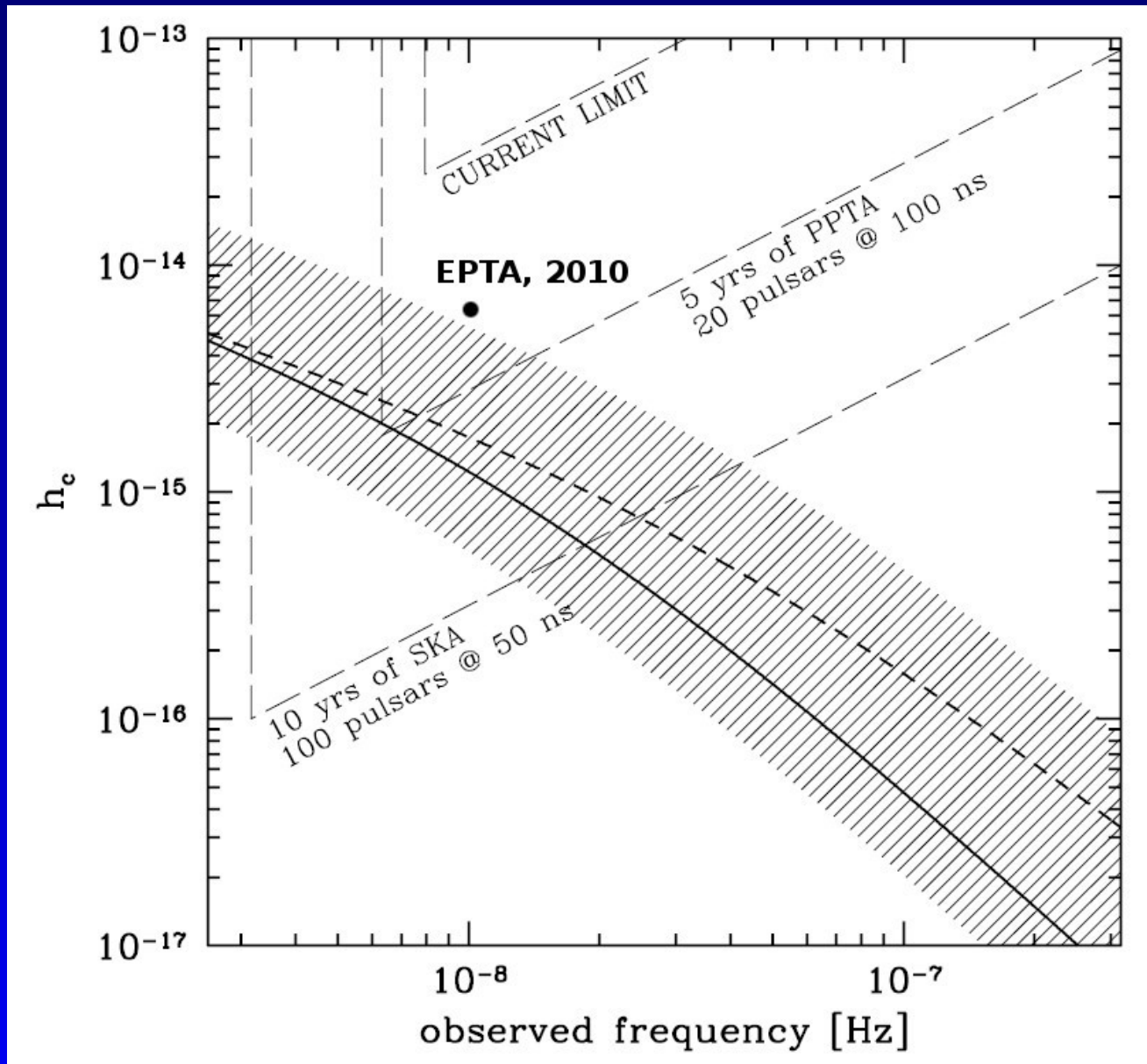


Joint GWB distribution

$$\text{Characteristic strain } h_c(f) = A(f/\text{yr}^{-1})^\alpha$$

Limit on amplitude $A = 6 \times 10^{-15}$ (2-sigma, $\alpha = 2/3$)

La meilleure limite actuelle



Mesure de temps et astronomie

Horloges astronomiques

Les pulsars

Les pulsars : horloges astronomiques

Utiliser ces horloges

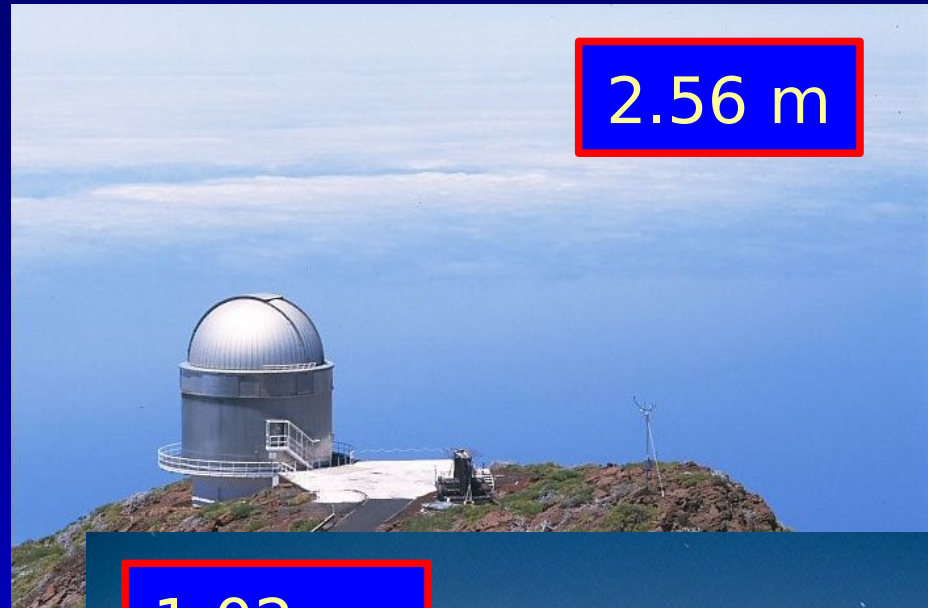
Les radiotélescopes

Une observation

Les télescopes optiques



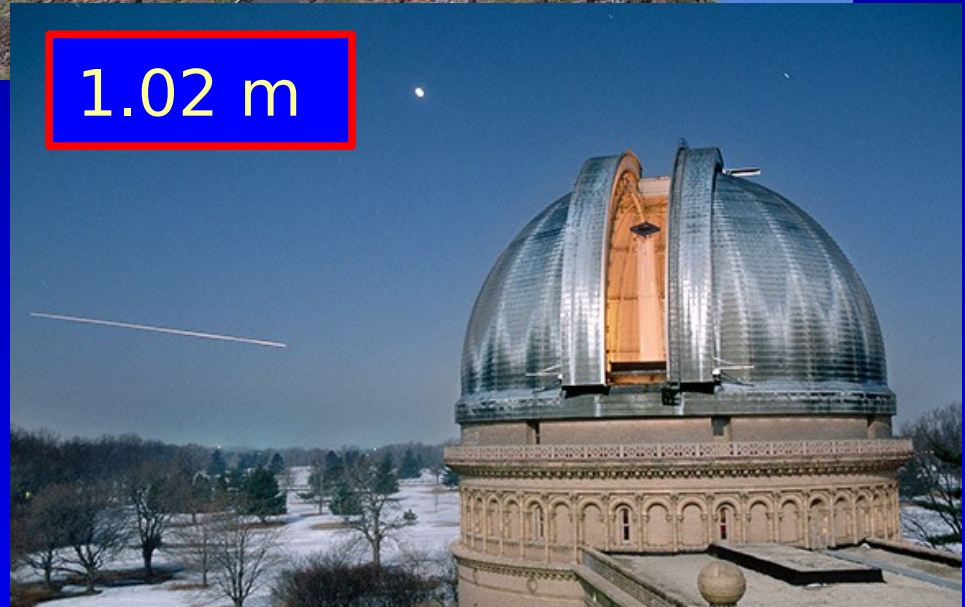
0.09 m



2.56 m



1.93 m



1.02 m

Les télescopes optiques



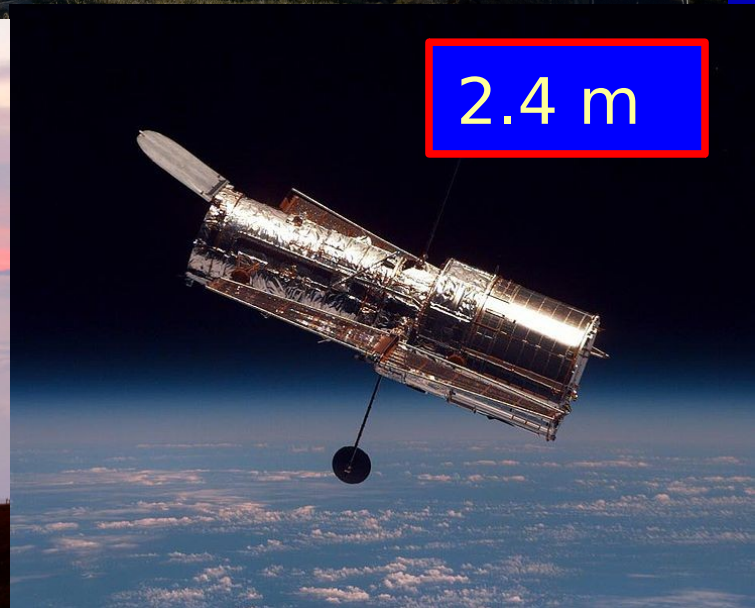
4x8.2m



10.4 m

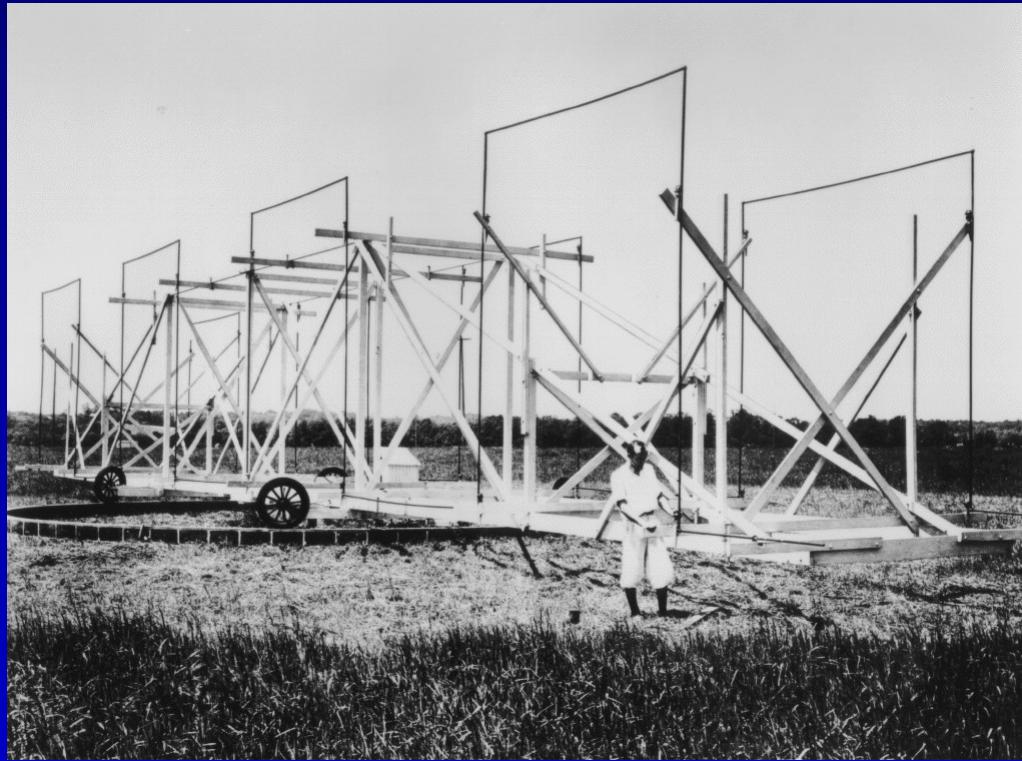


2x10m



2.4 m

Les radiotelesopes

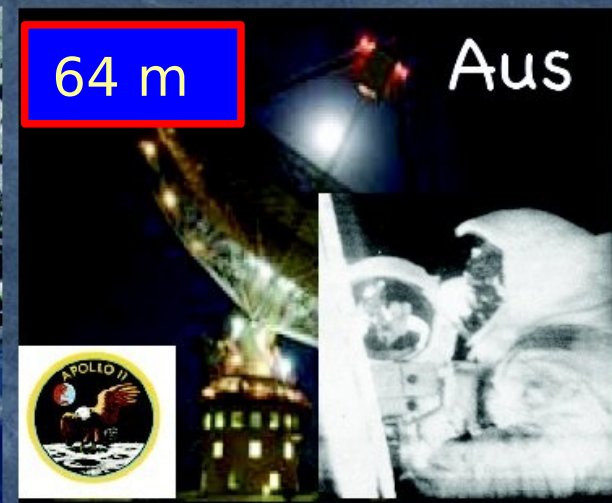


Pour étudier les parasites des émissions radio transatlantiques alors naissantes, Karl jansky, ingénieur chez Bell Labs, construit une antenne à Holmdel, New Jersey il découvre alors un signal en provenance du centre de notre Galaxie en 1933

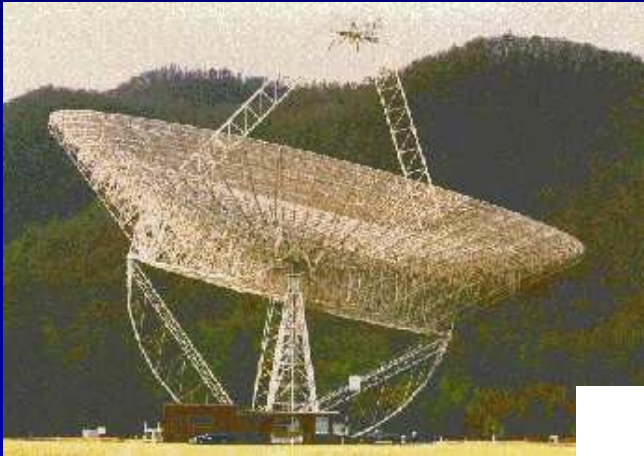
Les radiotelesopes (1950-1960)

1950-60's: Construction of Large Telescopes

cm wavelengths:



Limit de taille: $\sim 100\text{m}$



1962

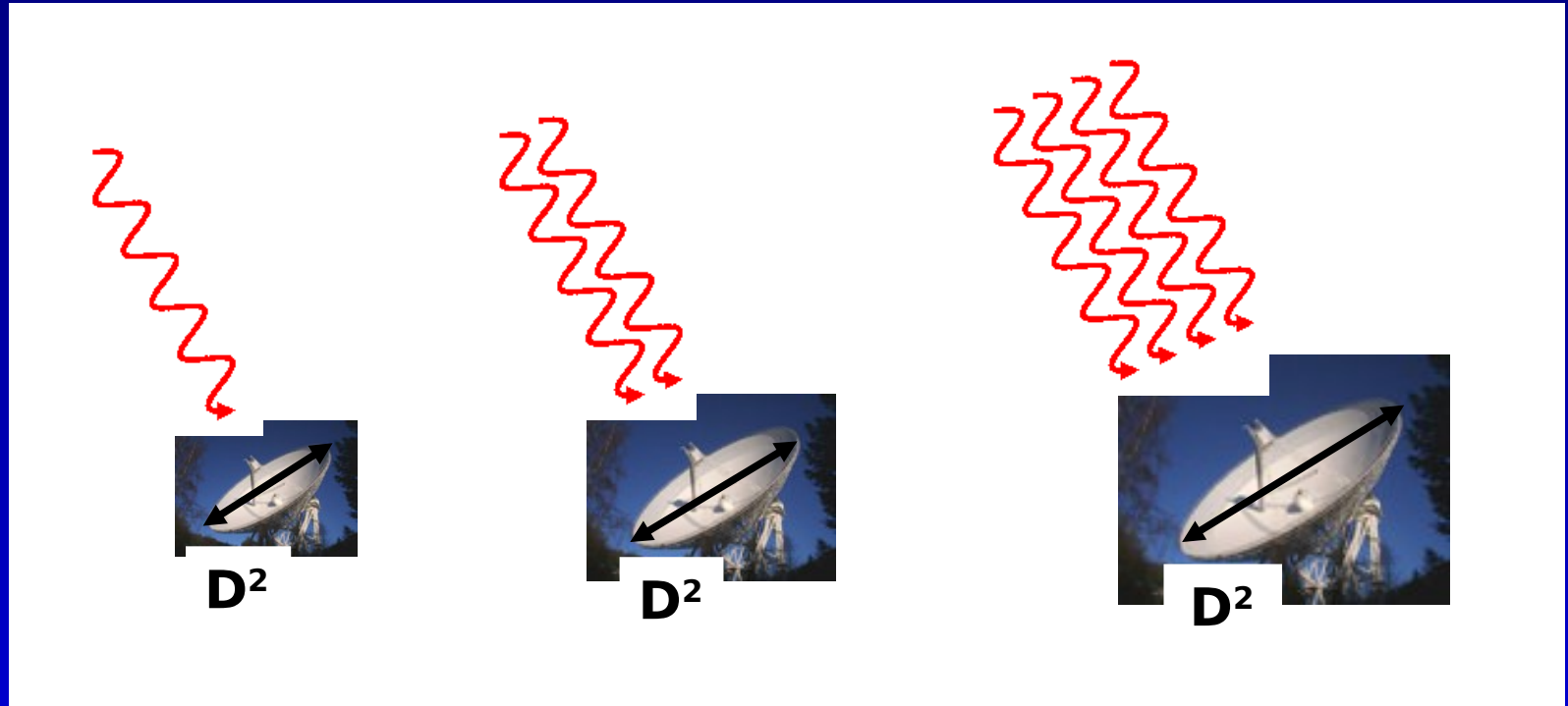


1988



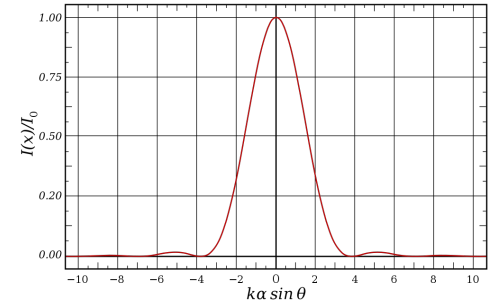
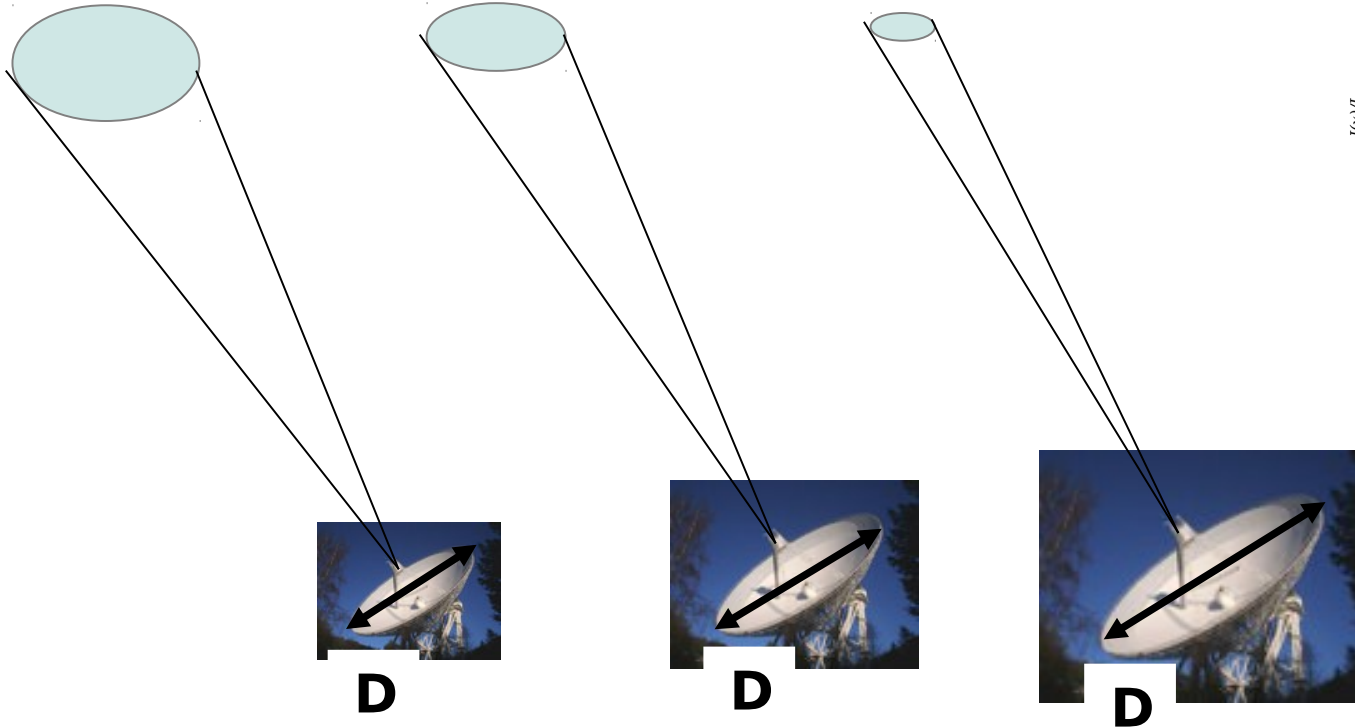
2002

Pourquoi des grands télescopes (1)?



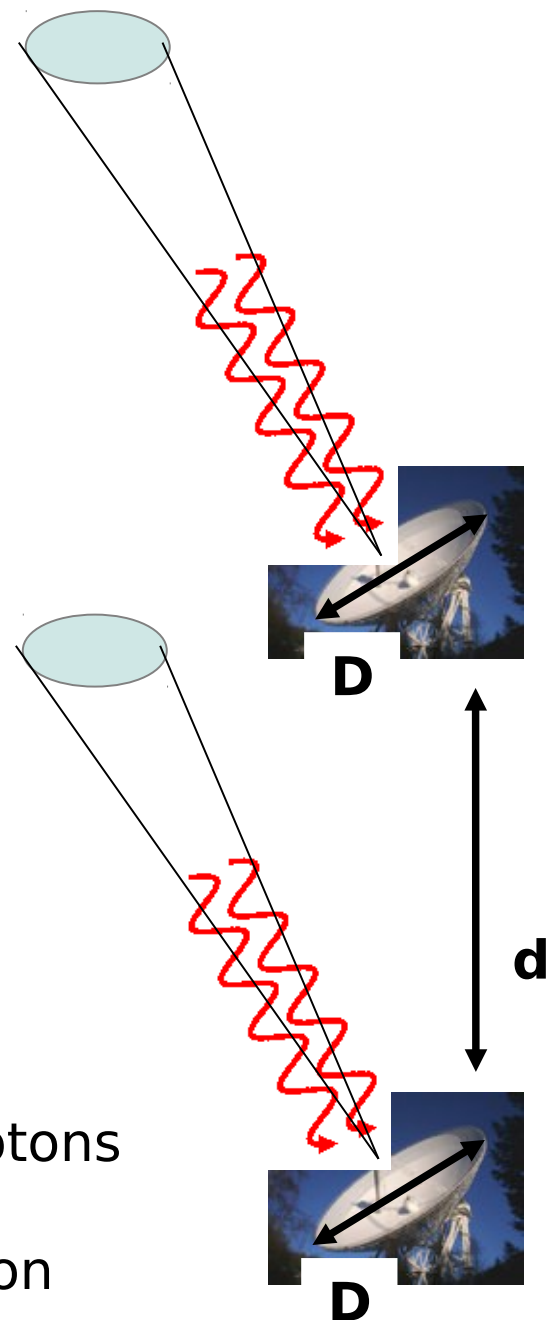
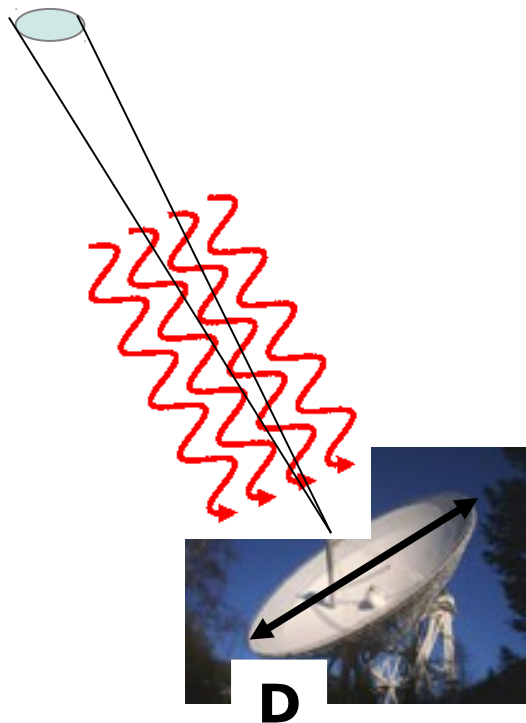
more collecting area \rightarrow more photons

Pourquoi des grands télescopes (2)?

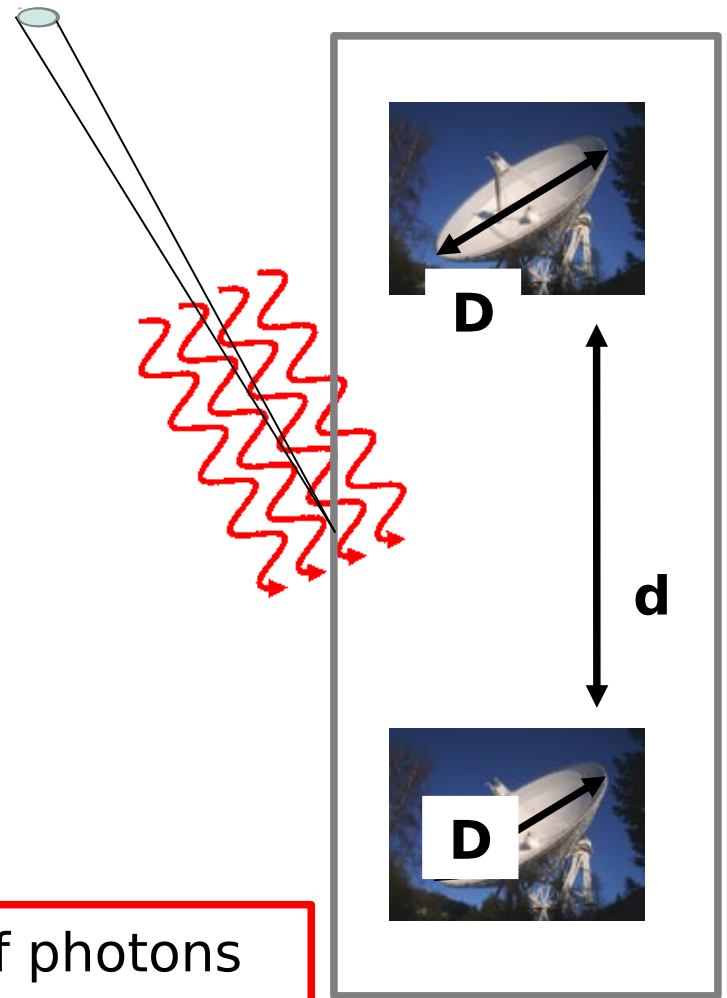
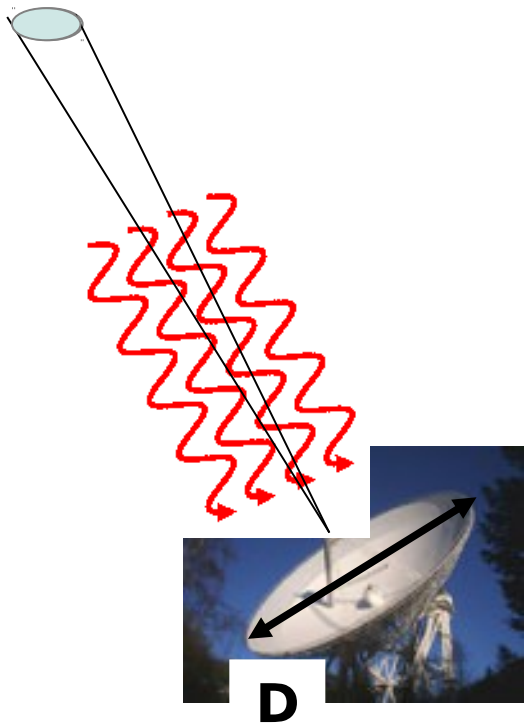


$$\sin \theta = 1.220 \frac{\lambda}{D}$$

better angular resolution
→ fine (spatial) structure of sources



- same number of photons
- simpler and cheaper
- bad angular resolution



$$\theta \approx \frac{\lambda}{D}$$

- same number of photons
- simpler and cheaper
- better angular resolution!

$$\theta \approx \frac{\lambda}{d}$$

Des réseaux de télescopes



Un radiotélescope moderne : LOFAR



Effelsberg



Nancay



Garching



Tautenburg



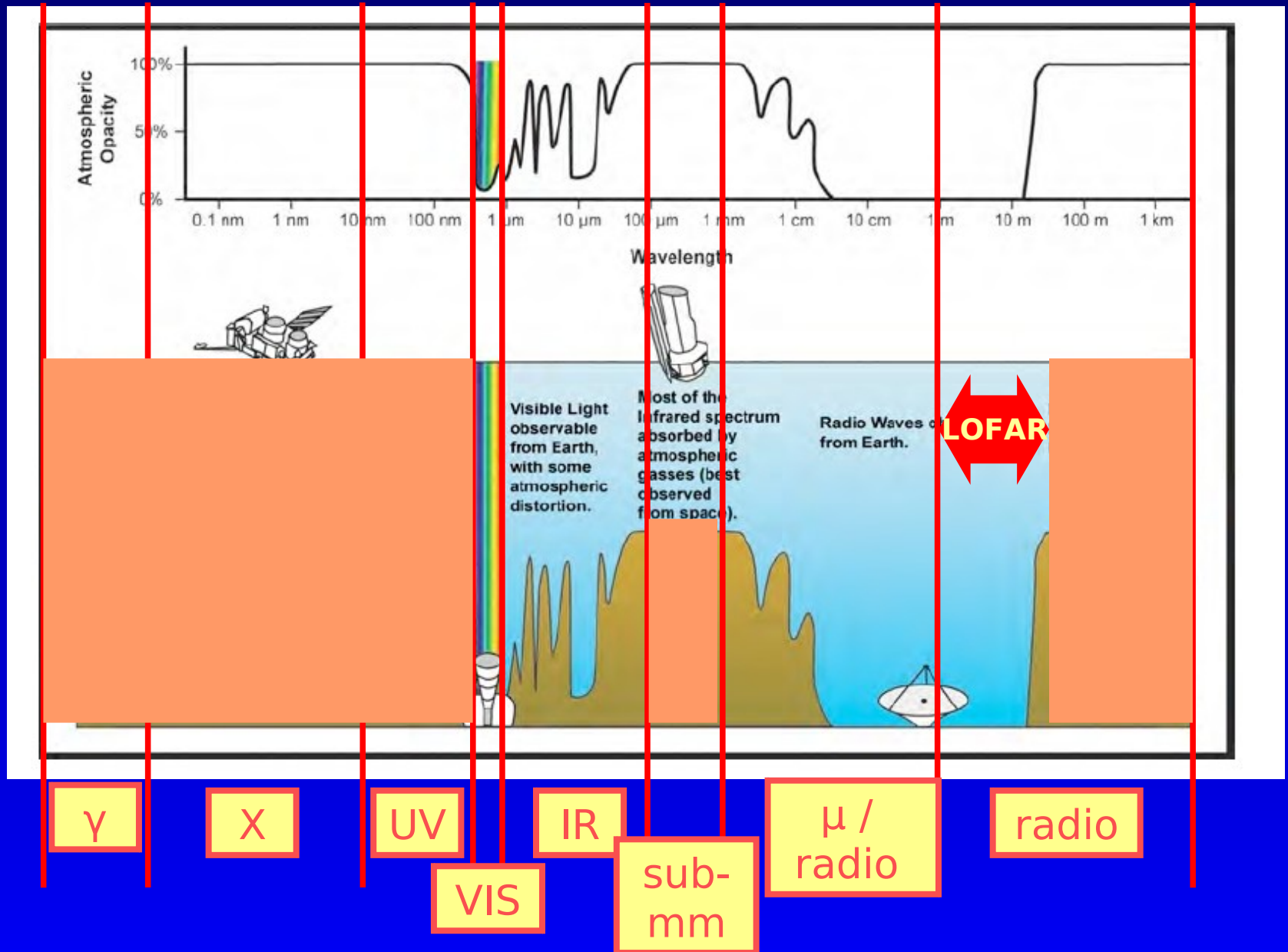
Potsdam



Chilbolton



Le radiotelescope LOFAR



Le radiotelescope LOFAR

40 stations in NL

8 stations in Europe (x2)

48 stations

$[48 + 48(*16)]$ ant./station

Σ 45696 antennas

frequency: 10/30-250 MHz

baselines: 0-1000 km

angular resolution: 2-40''

temporal resolution: $> 5.12 \mu\text{s}$

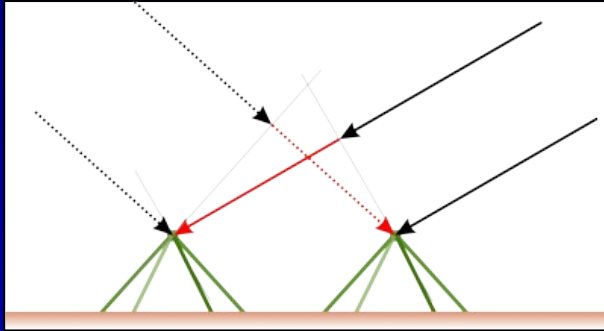
spectral resolution: kHz

sensitivity: $< \text{mJy}$

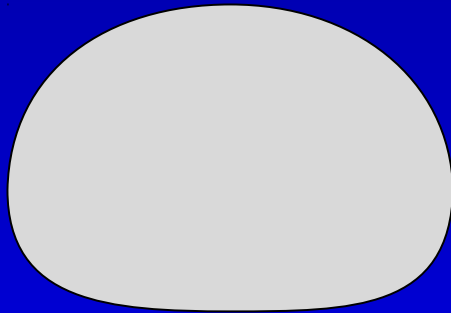


station in Nancay

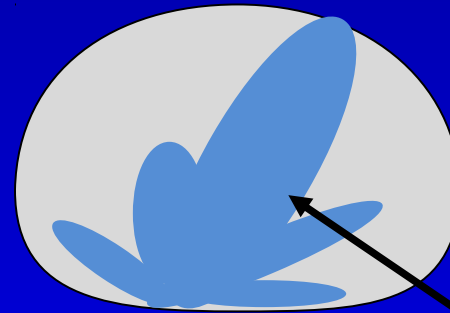
Le radiotelescope LOFAR



Total signal =
Interference pattern of signal
from individual dipole
antennae



beam of 1 antenna



beam of N antennae

Number of dipoles \Rightarrow sensitivity
Longest baseline \Rightarrow angular resolution

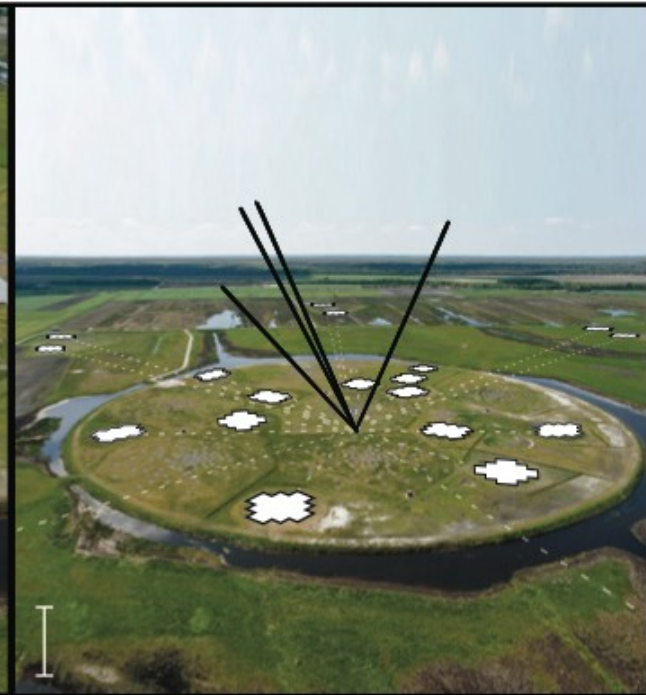
Un télescope hiérarchique et flexible



Element beam



Stations beam(s)

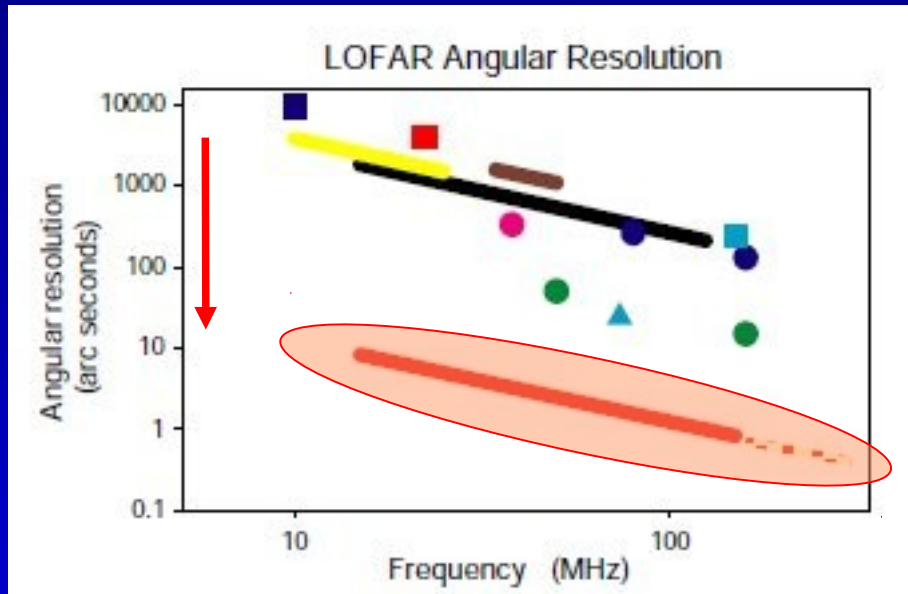


Tied-array beam(s)

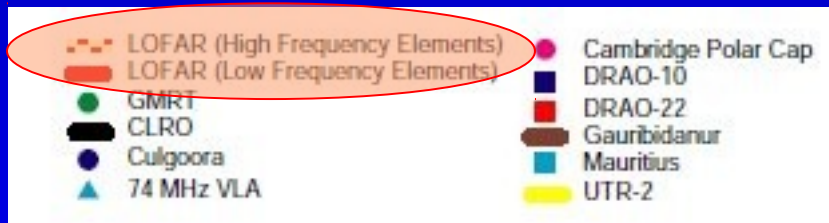
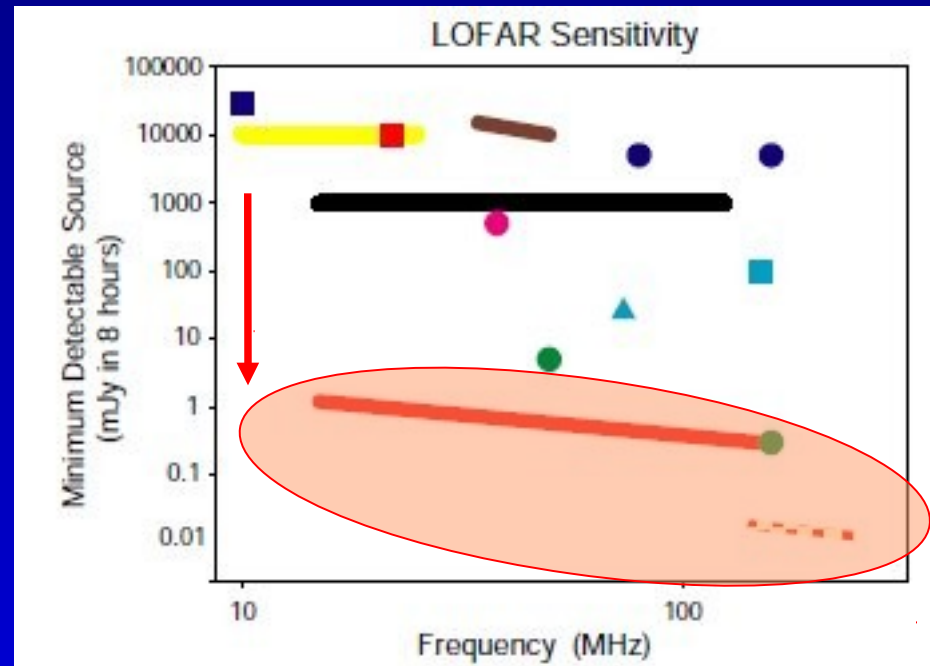
[van Leeuwen]

Le radiotelescope LOFAR

Angular resolution

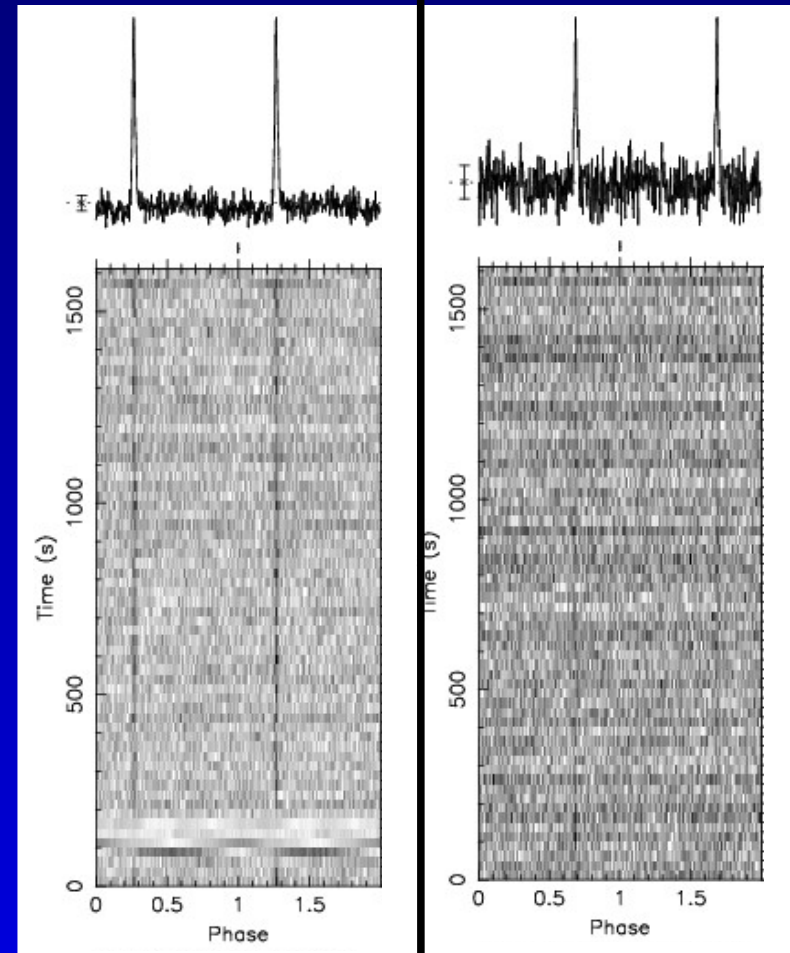


Sensitivity



Premières pulsars de LOFAR!

taux de découvertes :
1/100 sq.deg.
ciel : ~41250 sq.deg.
>100 pulsars à découvrir!



periode
DM

1.8 sec
 102 pc cm^{-3}

0.6 sec
 19 pc cm^{-3}

PSR B0943+10: Mode switching

Science



Science



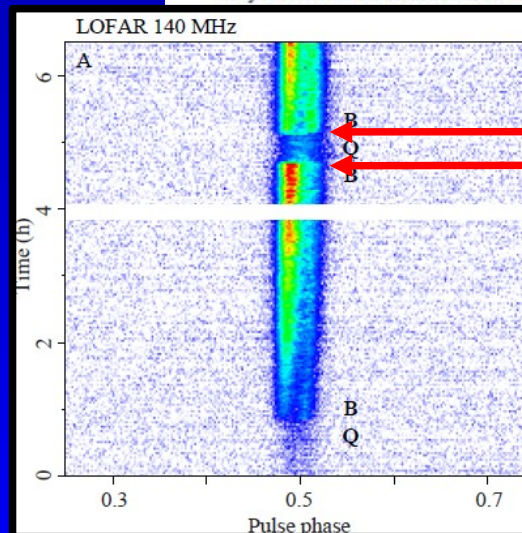
REPORTS

Synchronous X-ray and Radio Mode Switches: A Rapid Global Transformation of the Pulsar Magnetosphere

W. Hermsen,^{1,2*} J. W. T. Hessels,^{2,3} L. Kuiper,¹ J. van Leeuwen,^{2,3} D. Mitra,⁴ J. de Plaa,¹ J. M. Rankin,^{2,5} B. W. Stappers,⁶ G. A. E. Wright,⁷ R. Basu,⁴ A. Alexov,⁸ T. Coenen,² J.-M. Grießmeier,^{9,10} T. E. Hassall,^{6,11} A. Karastergiou,¹² E. Keane,¹³ V. I. Kondratiev,^{3,14} M. Kramer,^{6,13} M. Kuniyoshi,¹³ A. Noutsos,¹³ M. Serylak,^{9,10} M. Pilia,³ C. Sobey,¹³ P. Weltevrede,⁶ K. Zagkouris,¹² A. Asgekar,³ I. M. Avruch,^{1,3,15} F. Batejat,¹⁶ M. E. Bell,^{11,17} M. R. Bell,¹⁸ M. J. Bentum,^{3,19} G. Bernardi,²⁰ P. Best,²¹ L. Bîrzan,²² A. Bonafede,²³ F. Breitling,²⁴ J. Broderick,¹¹ M. Brüggen,²⁵ H. R. Butcher,^{3,25} B. Ciardi,¹⁸ S. Duscha,³ J. Eislöffel,²⁶ H. Falcke,^{3,13,27} R. Fender,¹¹ C. Ferrari,²⁸ W. Frieswijk,³ M. A. Garrett,^{3,22} F. de Gasperin,²³ E. de Geus,³ A. W. Gunst,³ G. Heald,³ M. Hoeft,²⁶ A. Homeffer,¹³ M. Iacobelli,²² G. Kuper,³ P. Maat,³ G. Macario,²⁸ S. Markoff,² J. P. McKean,³ M. Mevius,^{3,25} J. C. A. Miller-Jones,^{2,29} R. Morganti,^{3,15} H. Munk,³ E. Orrù,^{3,27} H. Paas,³⁰ M. Pandey-Pommier,^{22,31} V. N. Pandey,³² R. Pizzo,³ A. G. Polatidis,³ S. Rawlings,¹² W. Reich,¹³ H. Röttgering,²² A. M. M. Scaife,¹¹ A. Schoenmakers,³ A. Shulevski,³⁵ J. Sluiman,³ M. Steinmetz,²⁴ M. Tagger,⁹ Y. Tang,³ C. Tasse,^{33,34,35} S. ter Veen,²⁷ R. Vermeulen,³ R. H. van de Brink,³ R. J. van Weeren,^{3,24,22} R. A. M. J. Wijers,² M. W. Wise,^{2,3} O. Wucknitz,^{13,36} S. Yatawatta,³ P. Zarka³³

Pulsars emit from low-frequency radio waves up to high-energy gamma-rays, anywhere from the stellar surface out to the edge of the magnetosphere. Detecting correlated

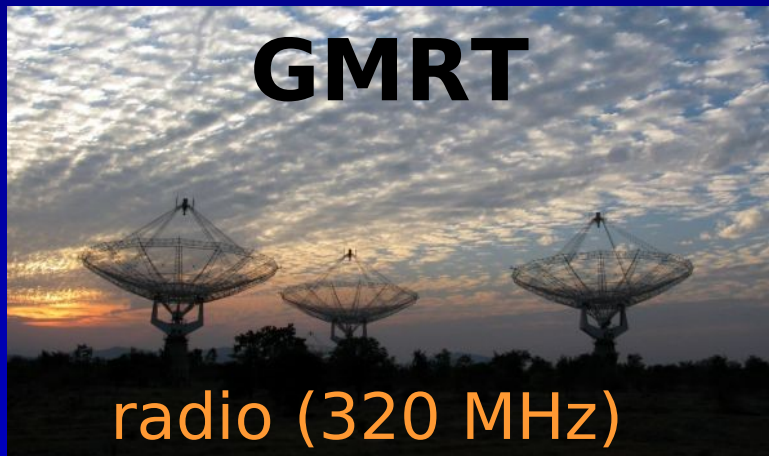
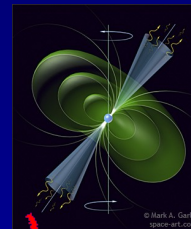
[Hermsen et al. 2013]



rapid
transition
(few sec)

PSR B0943+10: Mode switching

PSR B0943+10
(visible in radio & X)



GMRT

radio (320 MHz)



LOFAR (NL)

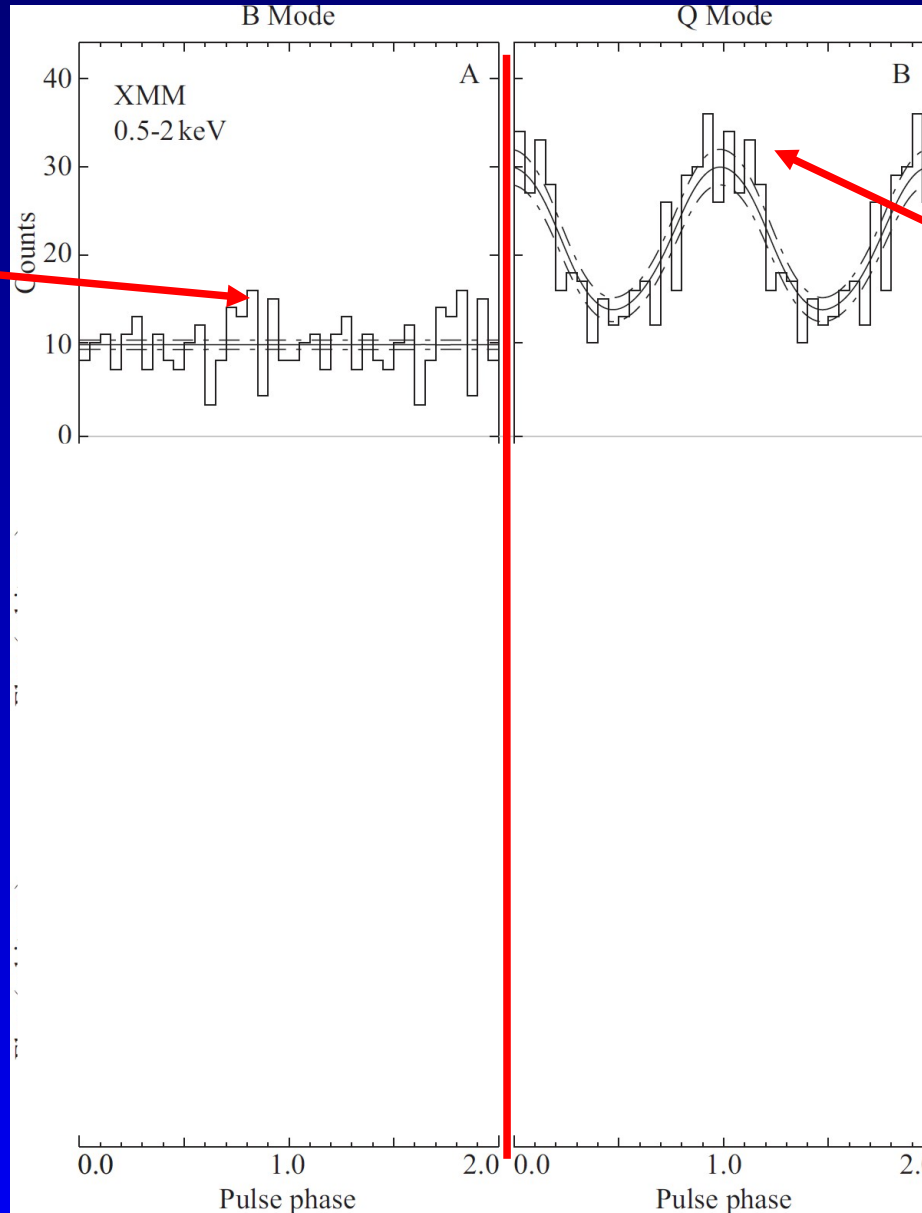
radio (140 MHz)



XMM Newton

X (1 keV)

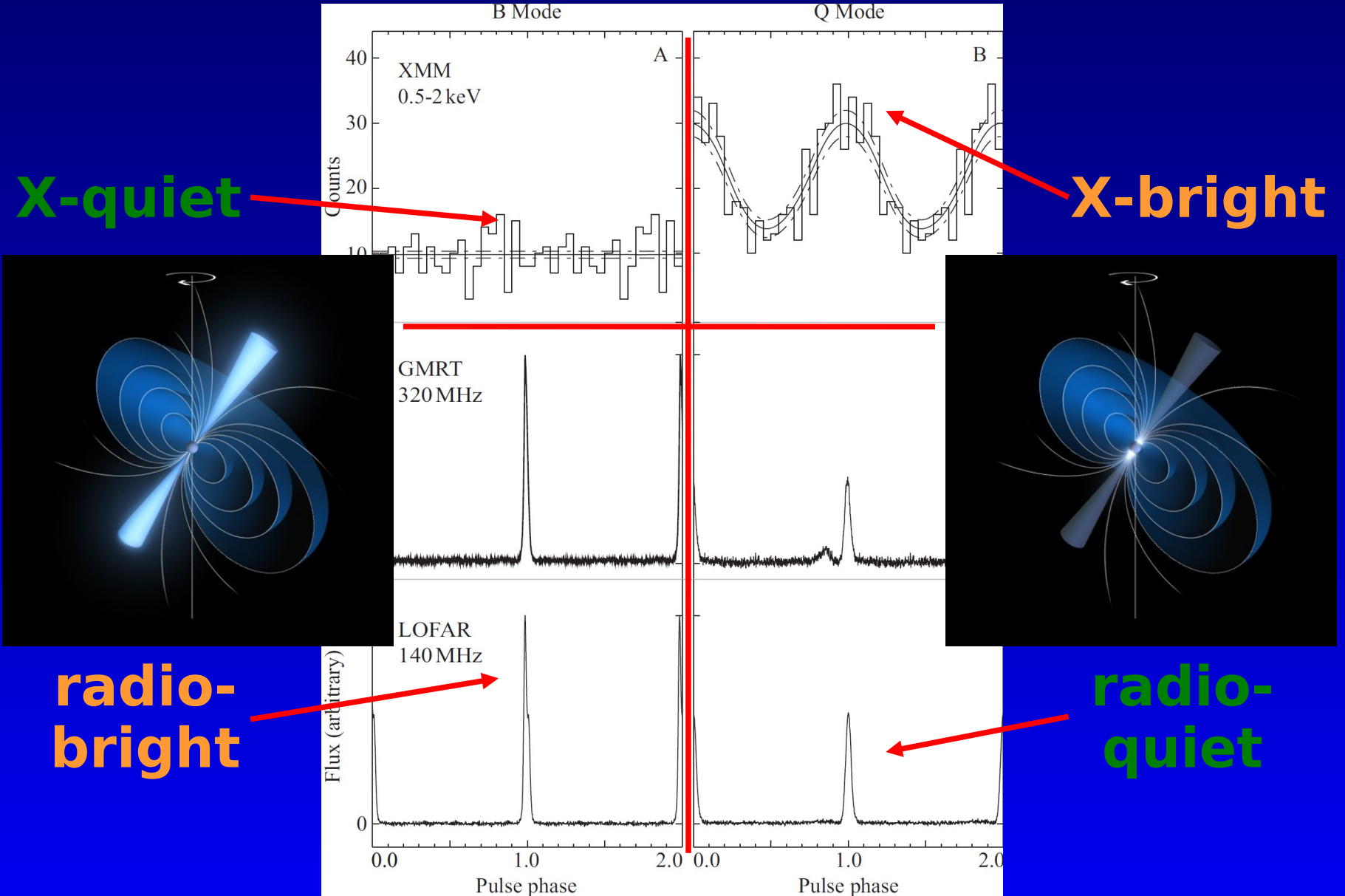
PSR B0943+10: Mode switching



X-quiet

X-bright

PSR B0943+10: Mode switching



Effelsberg



Nancay



Garching



Tautenburg



Potsdam



Chilbolton

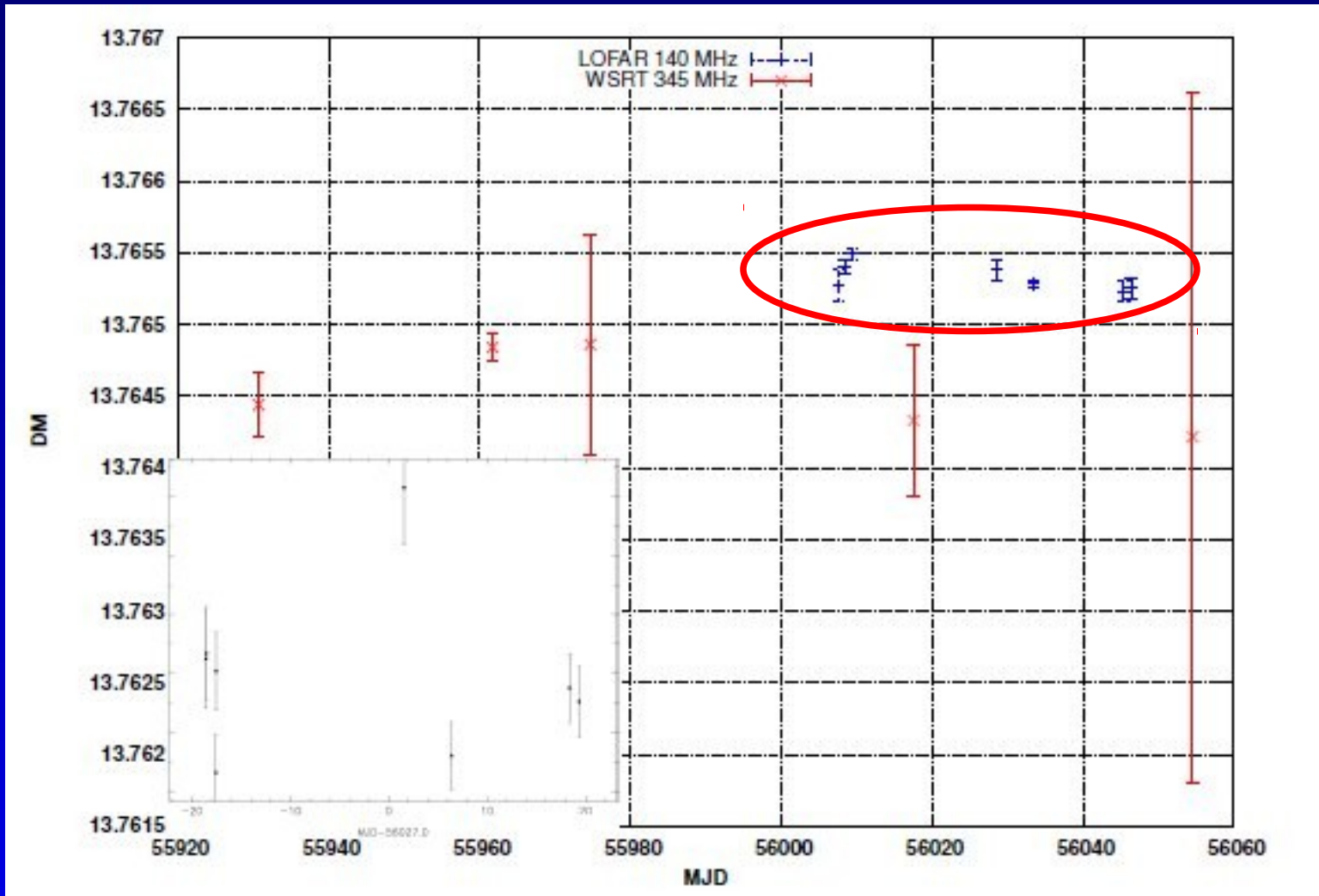


ARTEMIS

- 4 machines,
- 2 x Intel Xeon X5650,
- 48 GB RAM per box,
- nVidia GTX 580,
- water cooling,
- Gentoo Linux,
- 500 GB system disk,
- 2 TB HDD archive/backup,
- 8 TB RAID0 (4 x 2 TB HDD),
- Intel C/C++ compiler,
- pulsar software packages
(TEMPO2, PSRCHIVE, DSPSR,
SIGPROC etc.),
- AMPP processing pipeline.

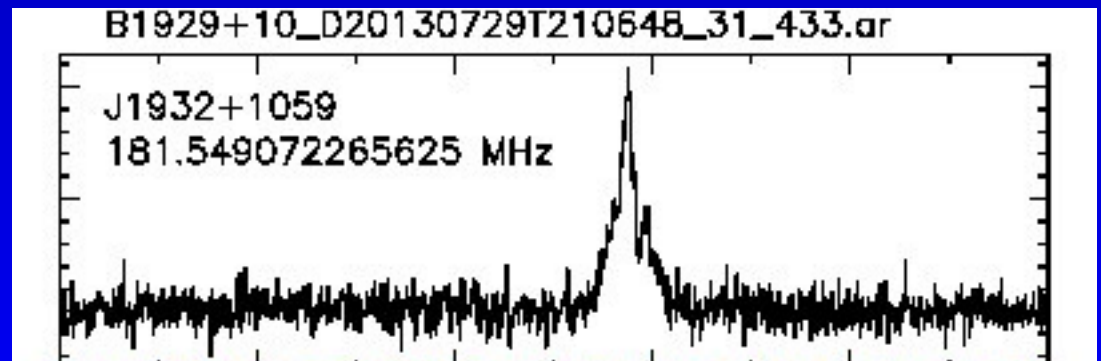


Monitoring du DM



MSP J0034-0534

Observation avec LOFAR/FR606

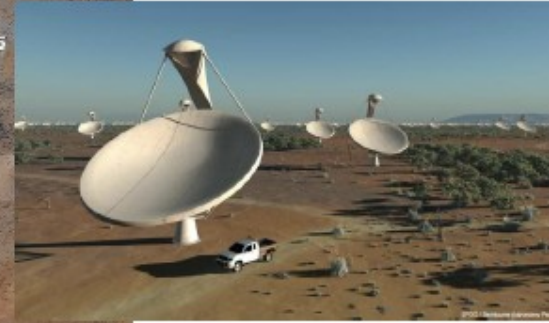
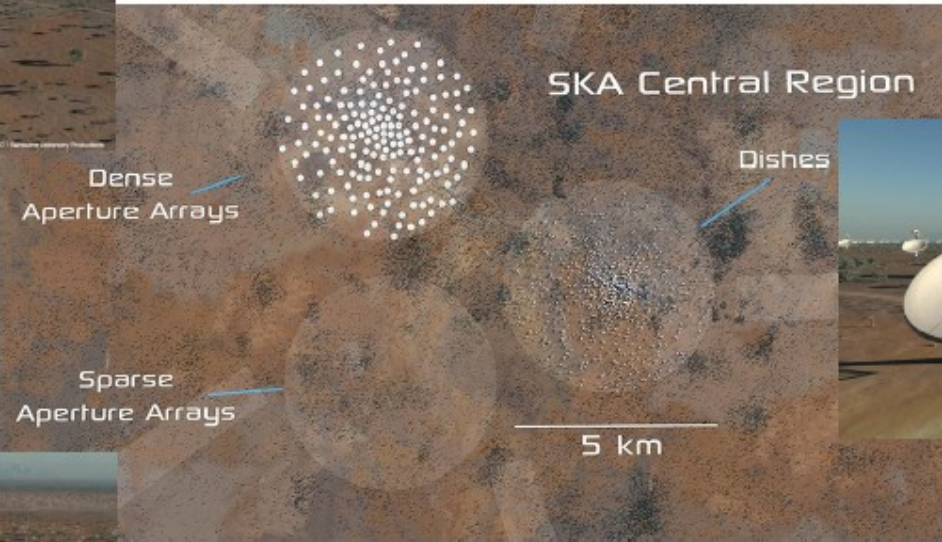


Le "Square Kilometre Array"



Réseau phasé dense

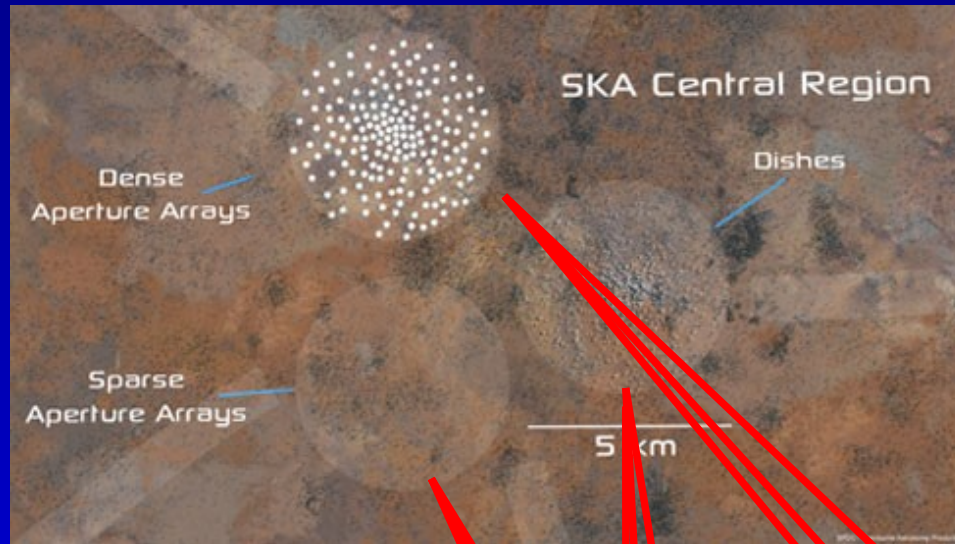
Réseau phasé



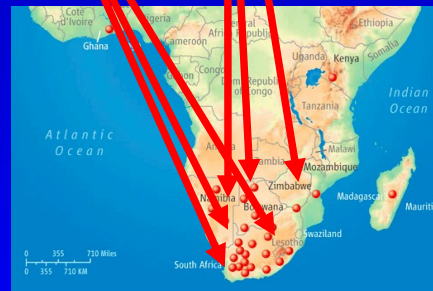
Paraboles
+ PAFs

Le “Square Kilometre Array”

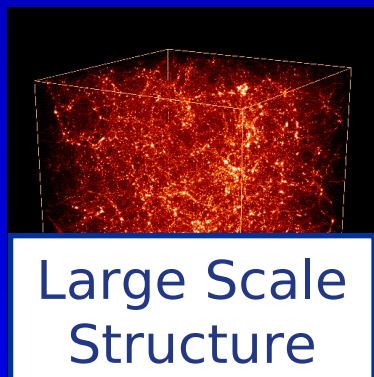
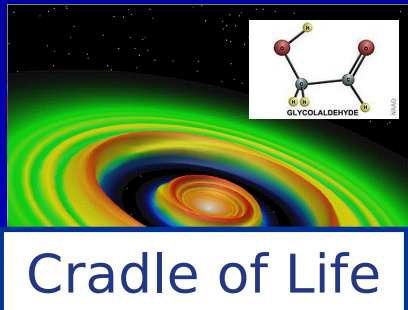
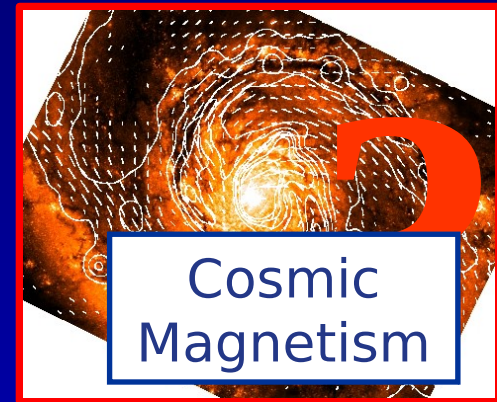
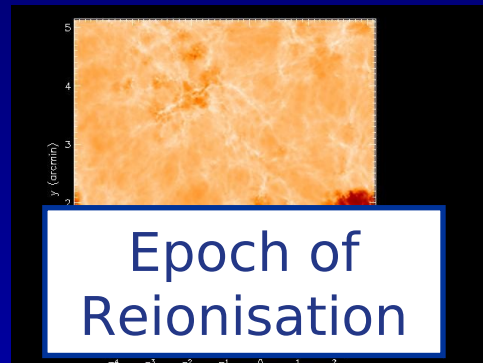
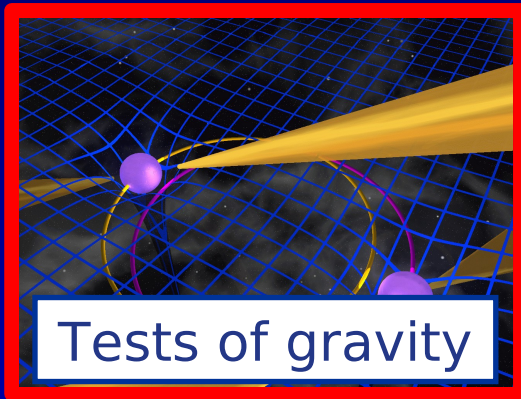
[www.skatelescope.org]



Choix du site : 2012
phase 1 : 2016-2020
Phase 2 : 2020-2024



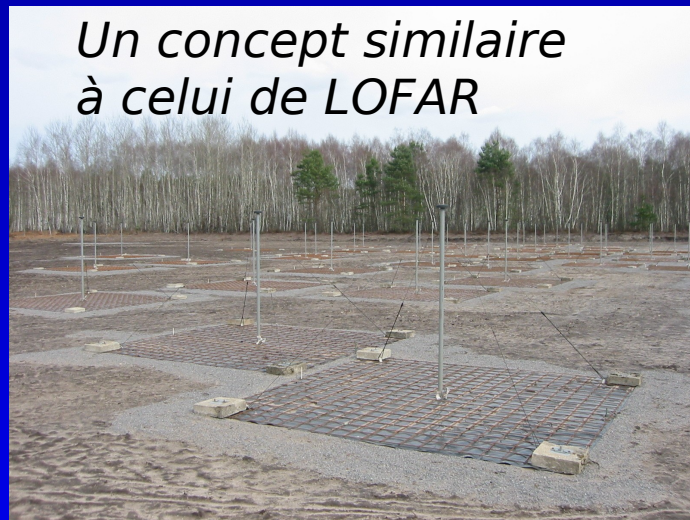
Projets clé du SKA



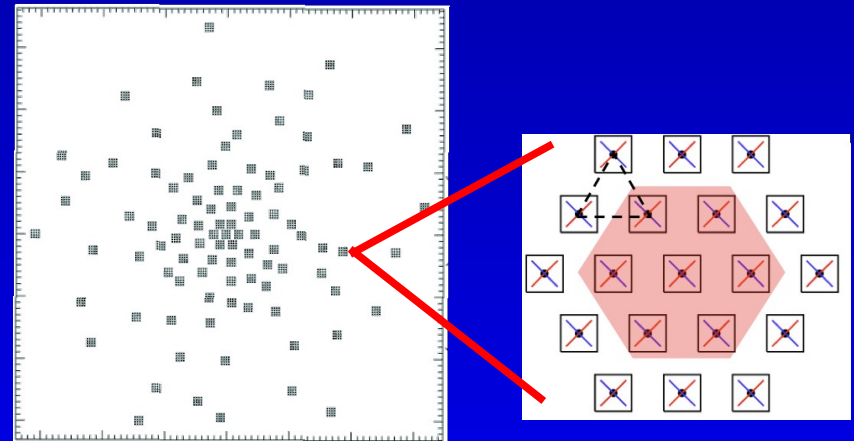
Le "Square Kilometre Array"



Le réseau phasé « éparpillé »
basses fréquences
70-450 MHz, 50 stations,
11000 antennes/station



30-250 MHz, 48 stations,
192 antennes/station



Le projet de station LOFAR
étendue à Nançay (LSS)

Le “Square Kilometre Array”

SKA-mid



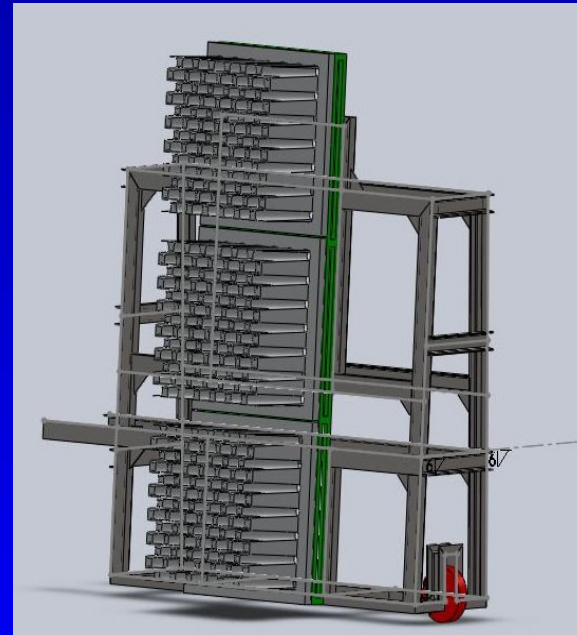
Réseau phasé dense
moyennes fréq.,
250 stations
30 millions d'antennes

FAN, PAF-SKA

EMBRACE,
AAVP



Image by SATorchinsky



Mesure de temps et astronomie

Horloges astronomiques

Les pulsars

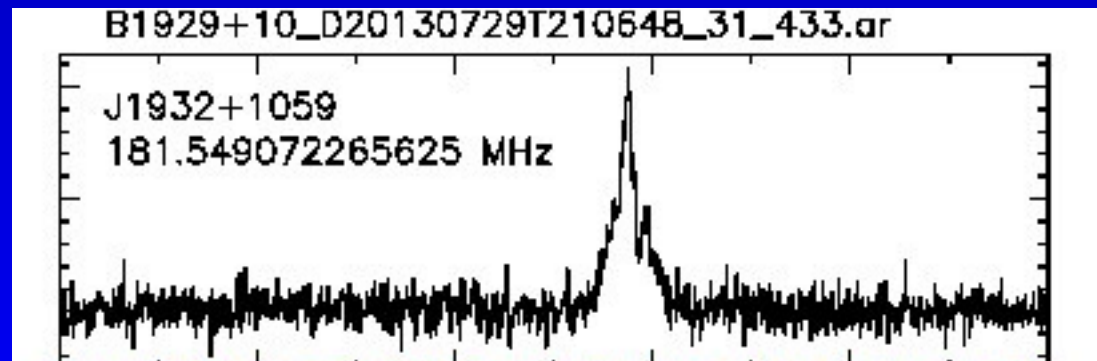
Les pulsars : horloges astronomiques

Utiliser ces horloges

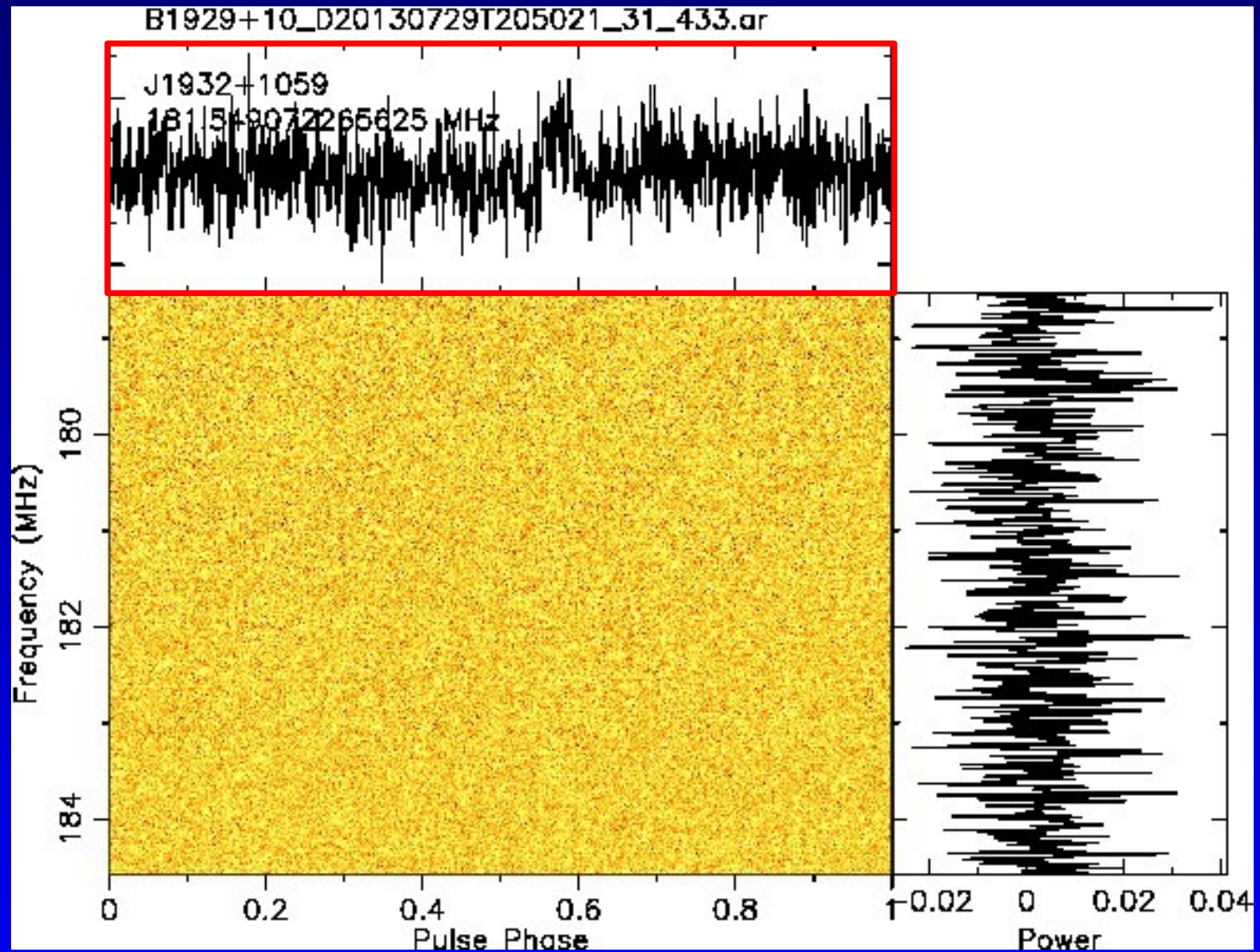
Les radiotélescopes

Une observation

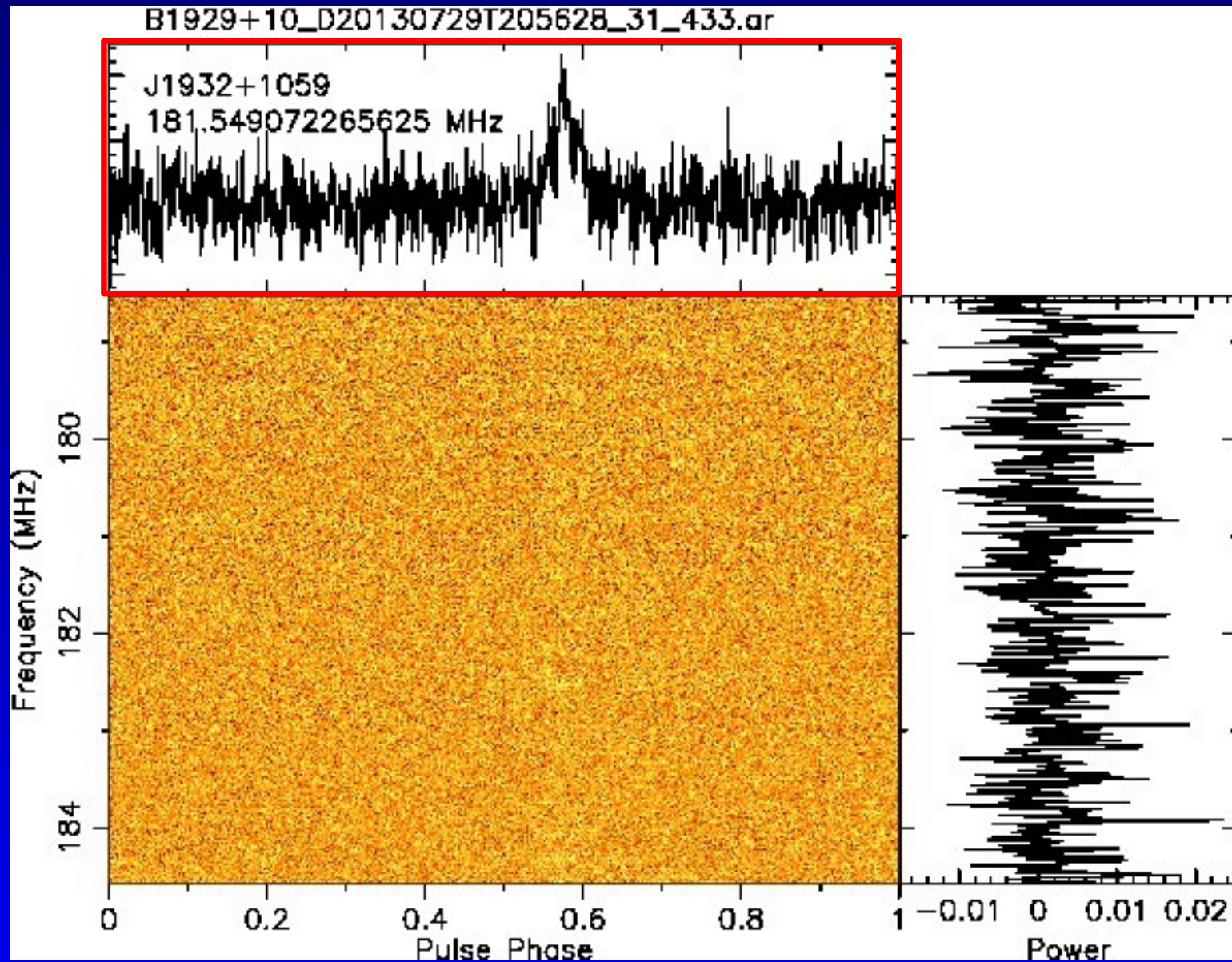
Observation avec LOFAR/FR606



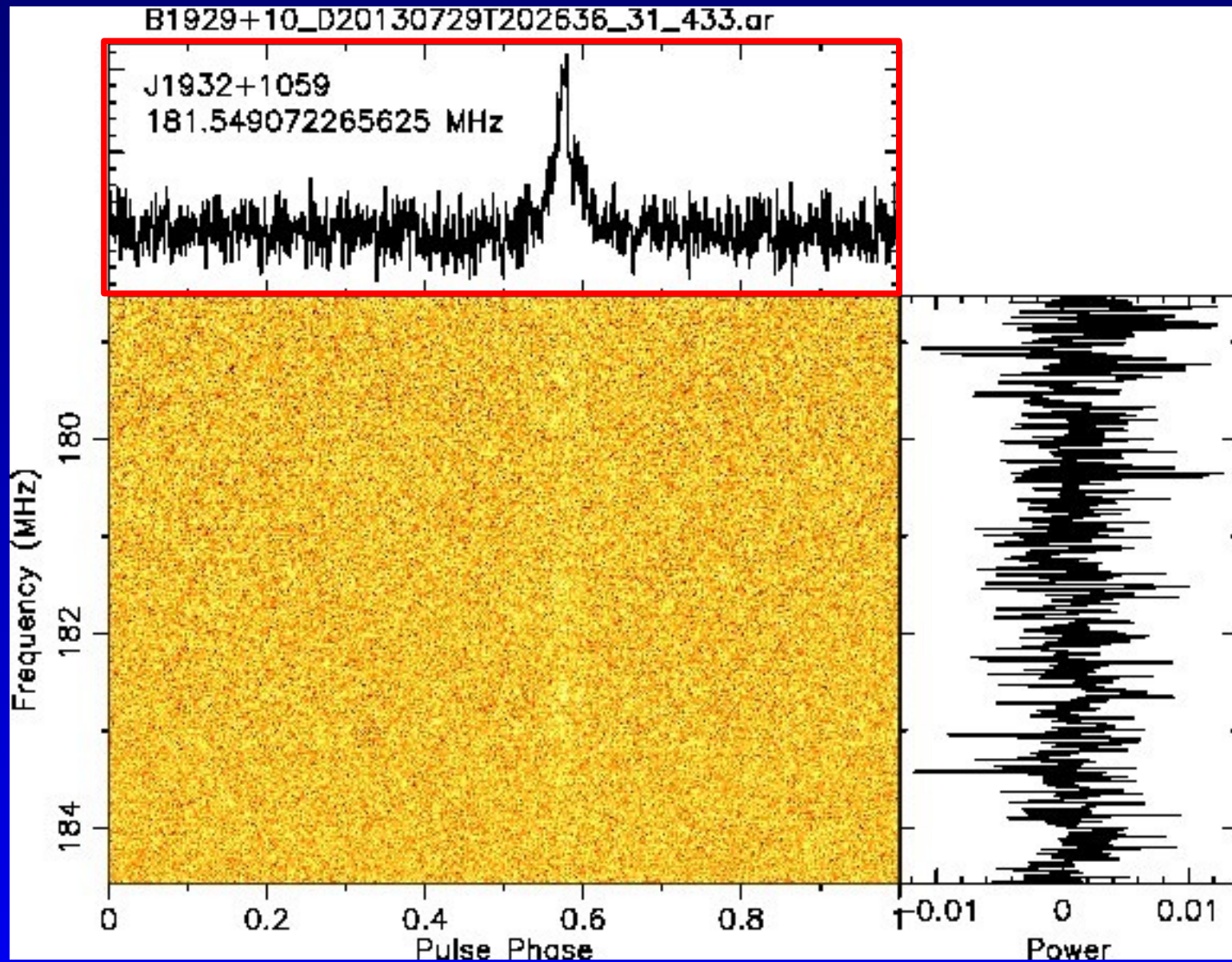
Observation (1 min)



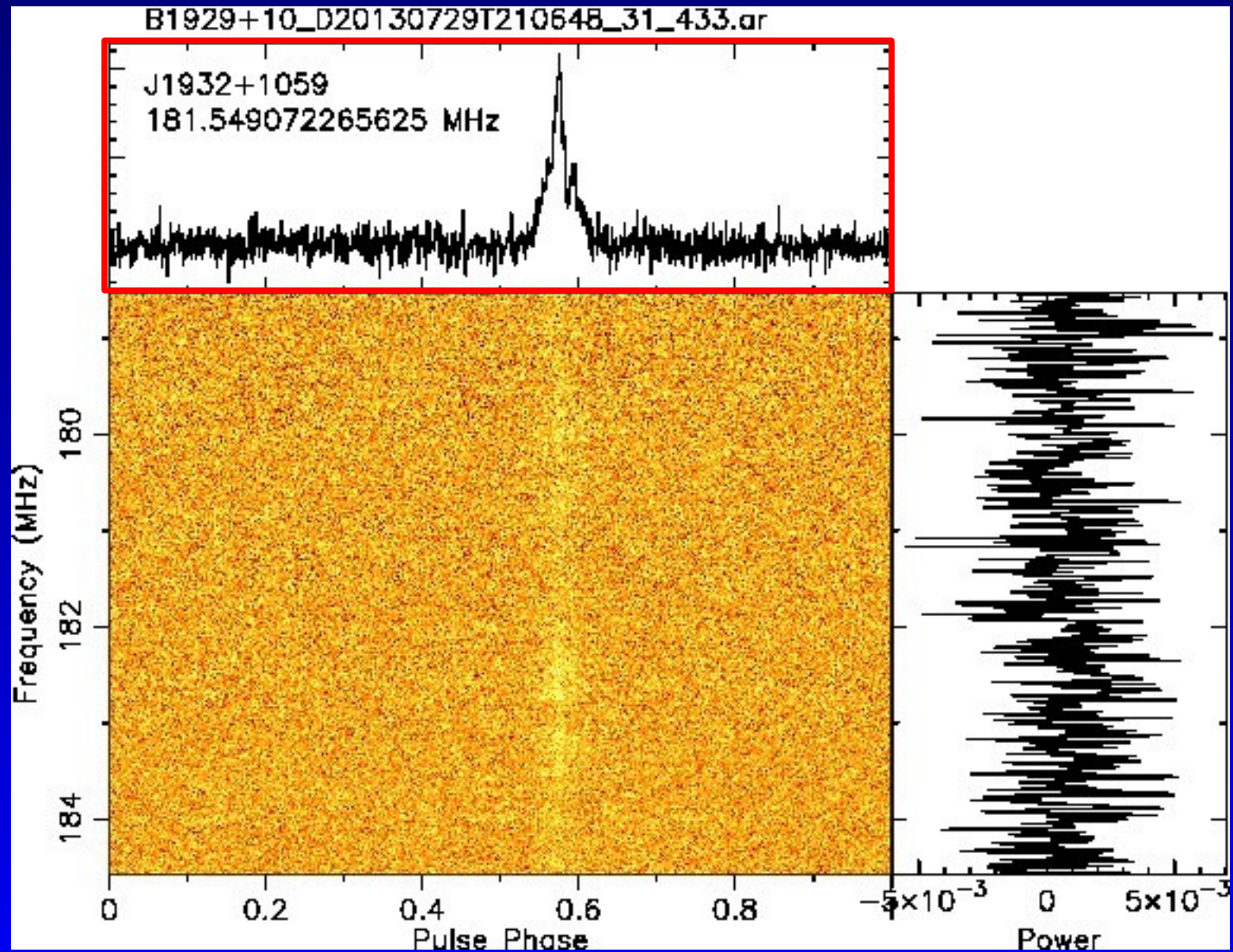
Observation (3 min)



Observation (10 min)



Observation (30 min)



Mesure de temps et astronomie

Horloges astronomiques

Les pulsars

Les pulsars : horloges astronomiques

Utiliser ces horloges

Les radiotélescopes

Une observation