L'Univers de haute énergie

2ème partie

Alexis Coleiro
Laboratoire APC / Université de Paris
coleiro@apc.univ-paris-diderot.fr

université
PARIS
DIDEROT

Plan

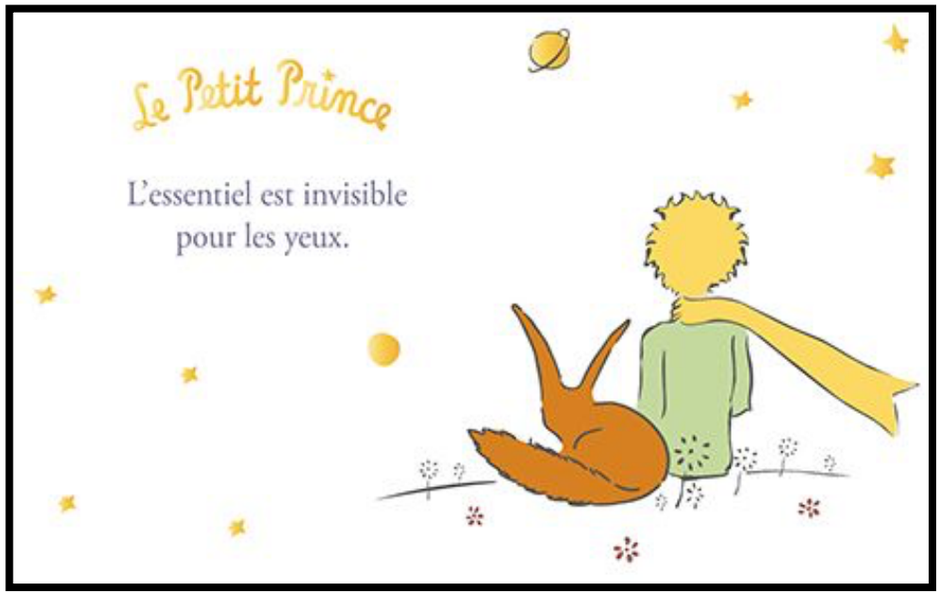
Cours II

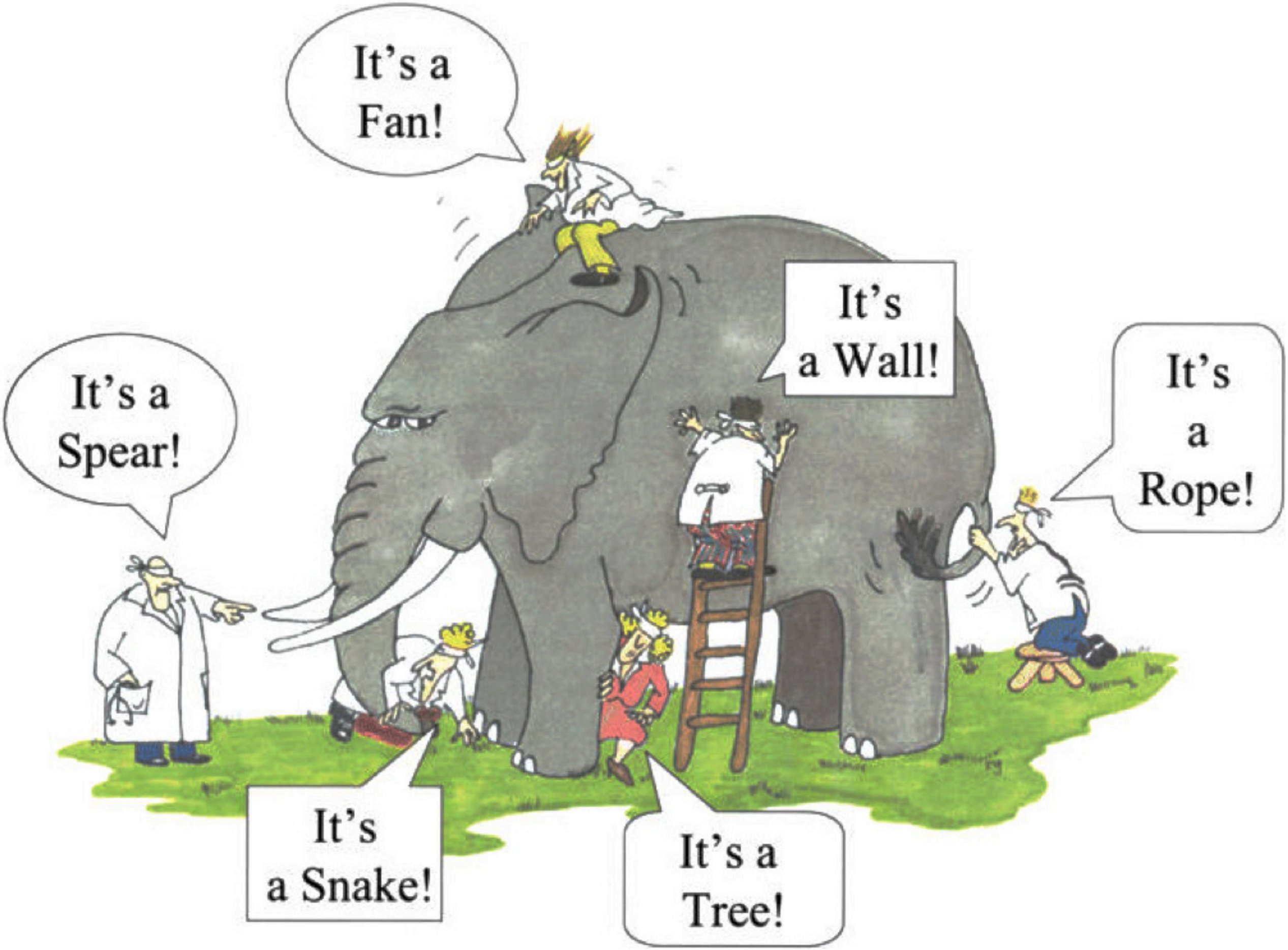
1. **De l'astronomie multi-longueurs d'onde à l'astronomie multi-messager**

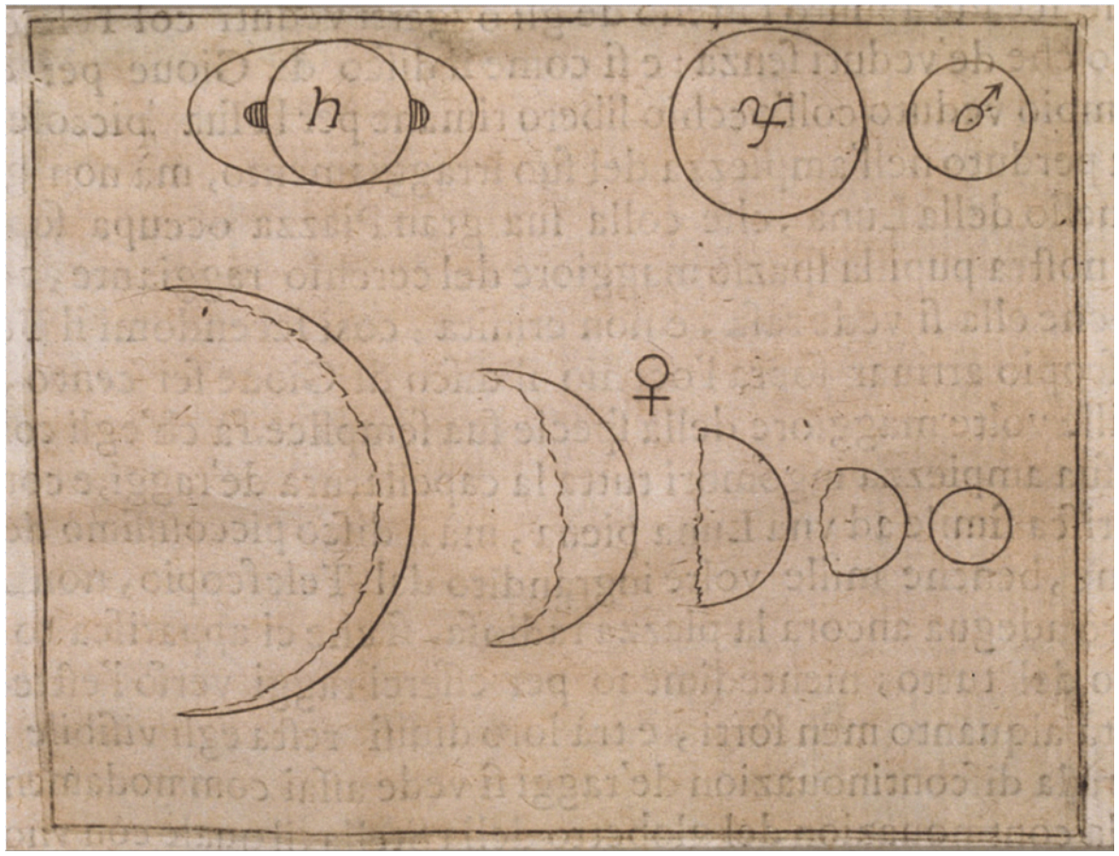
2. **Un (ou deux) exemple(s) marquant(s) et récent(s)**

   A. Coalescences de deux objets compacts

   B. (Jets relativistes des noyaux actifs de galaxies)




It's a Fan!
It's a Wall!
It's a Spear!
It's a Rope!
It's a Snake!
It's a Tree!

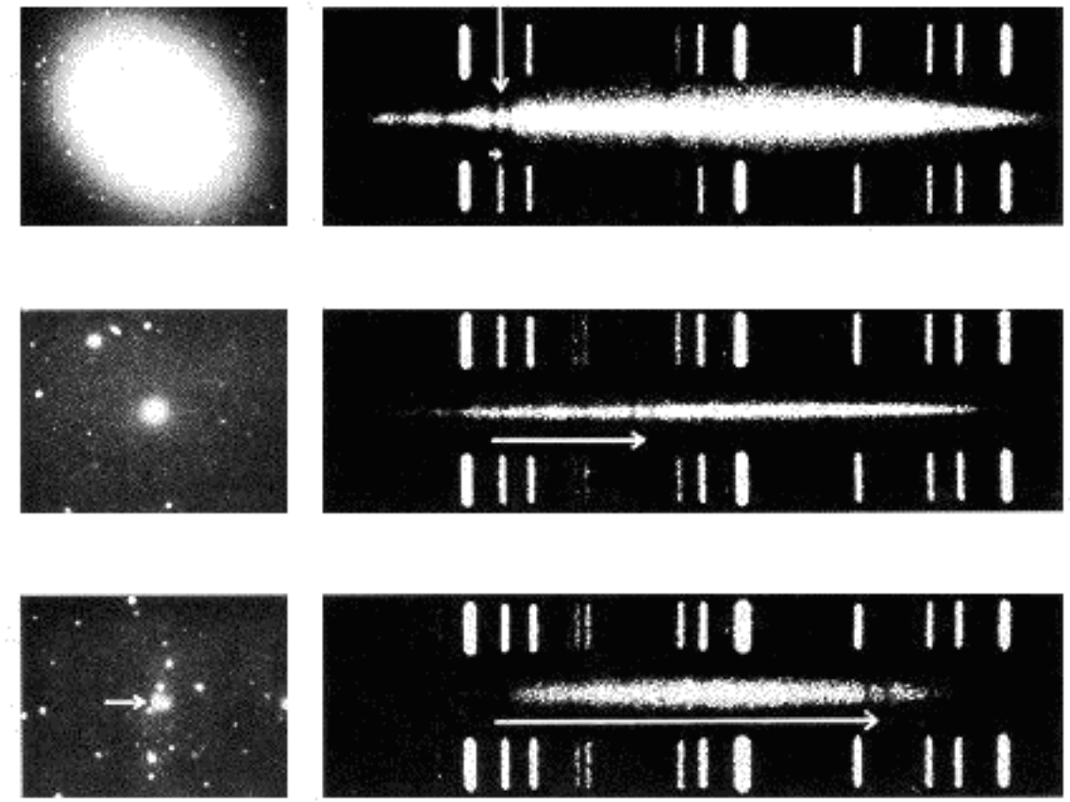


Modèle héliocentrique

Galilée

t

1609 **1700** **1800** **1900** **2000**



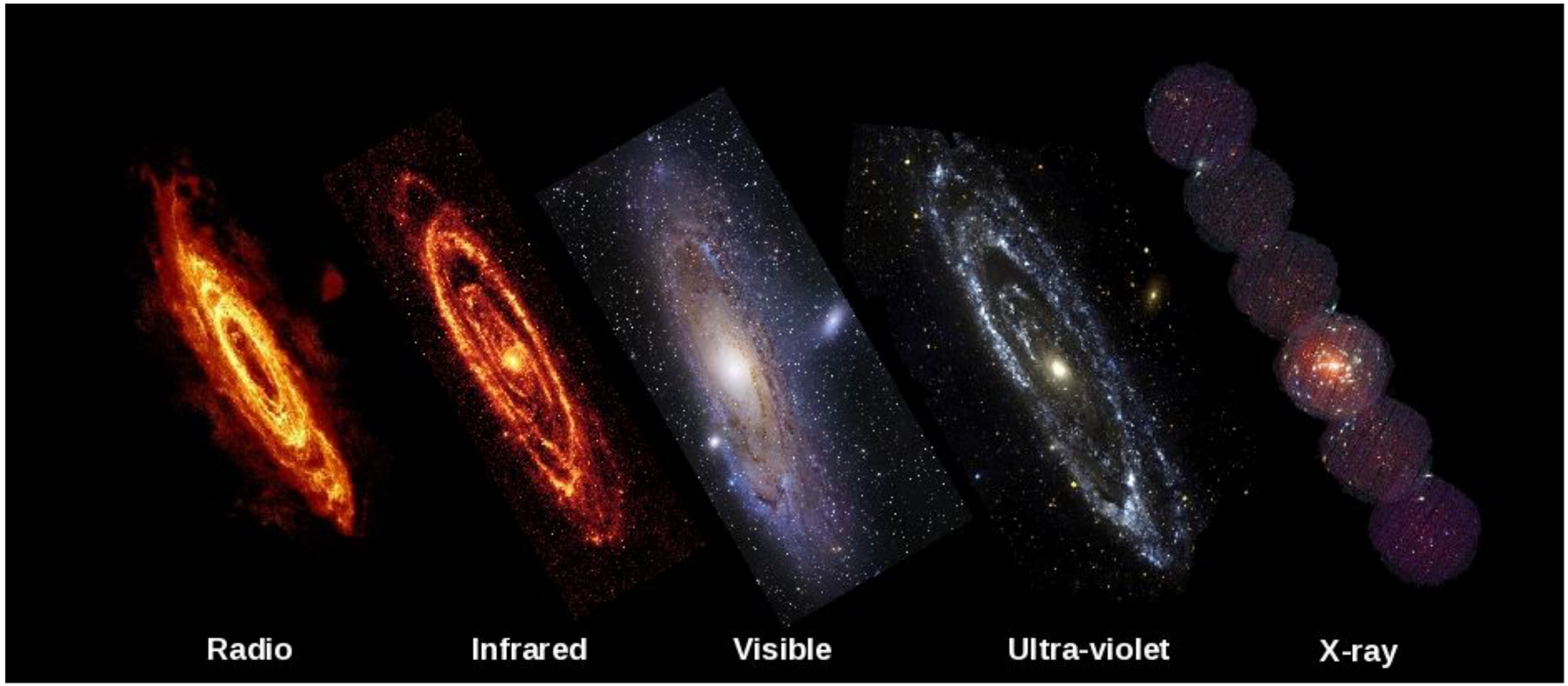
Existence des galaxies
Expansion de l'Univers

Hubble

t

1600 1700 1800 1929 2000

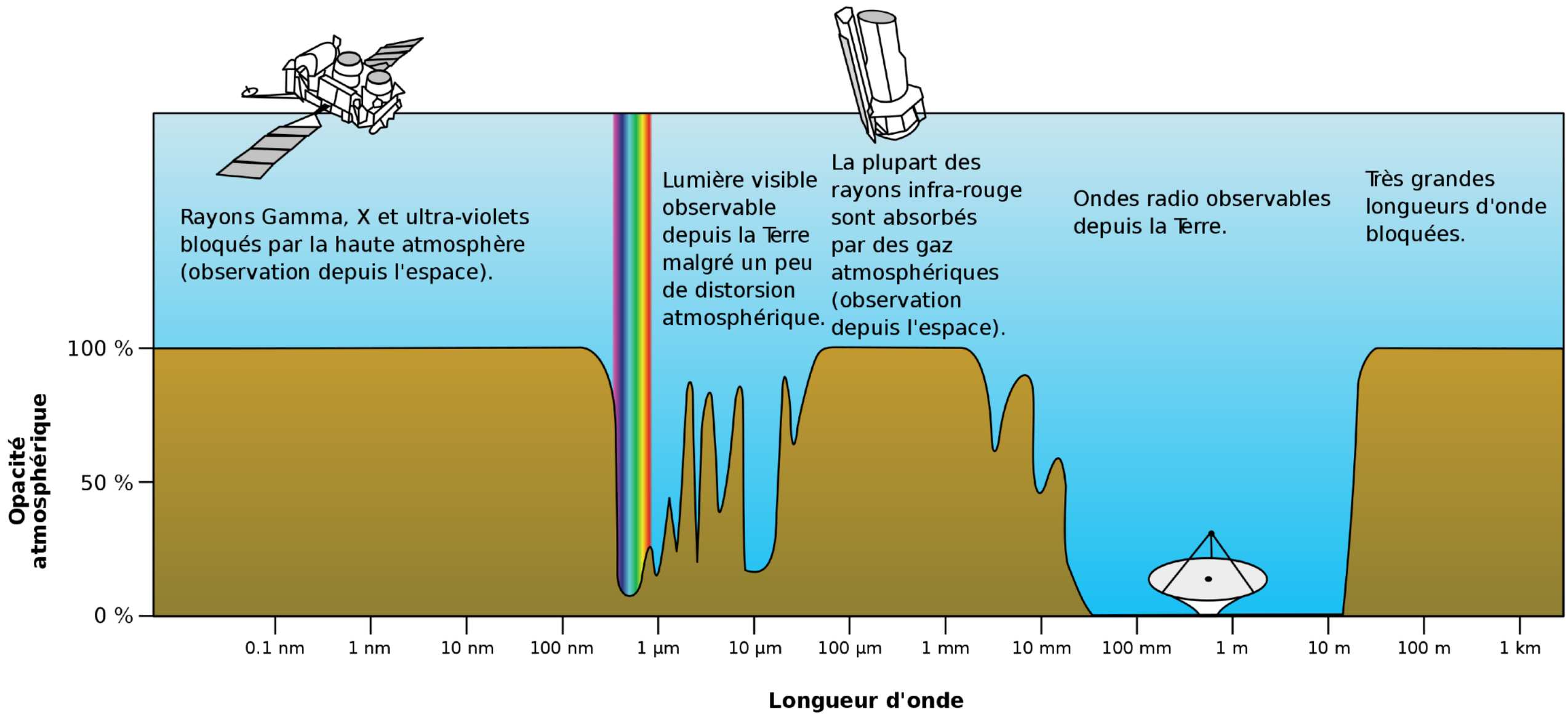
Astronomie multi-longueurs d'onde



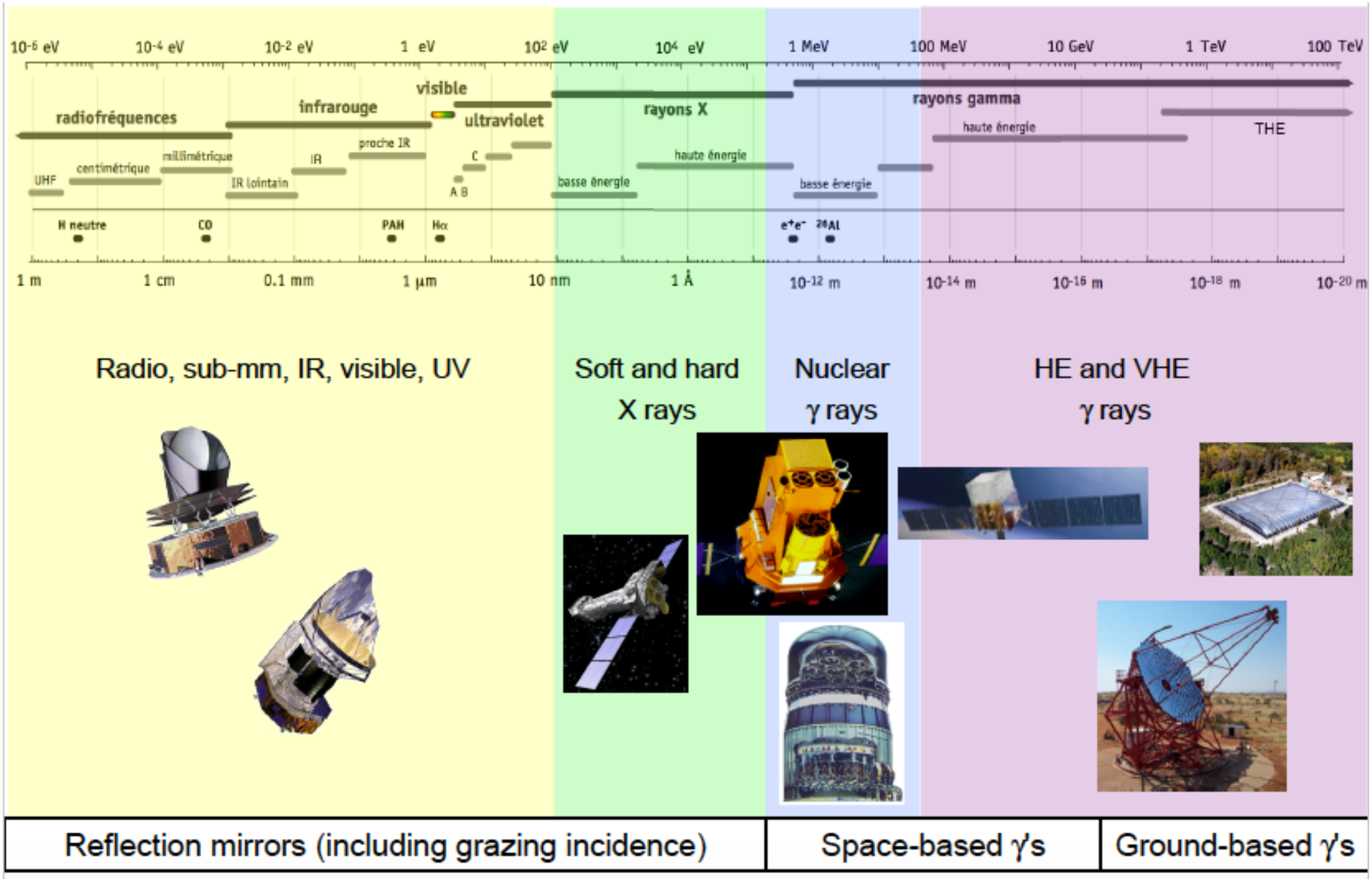
t

1600 1700 1800 1900 1950 -

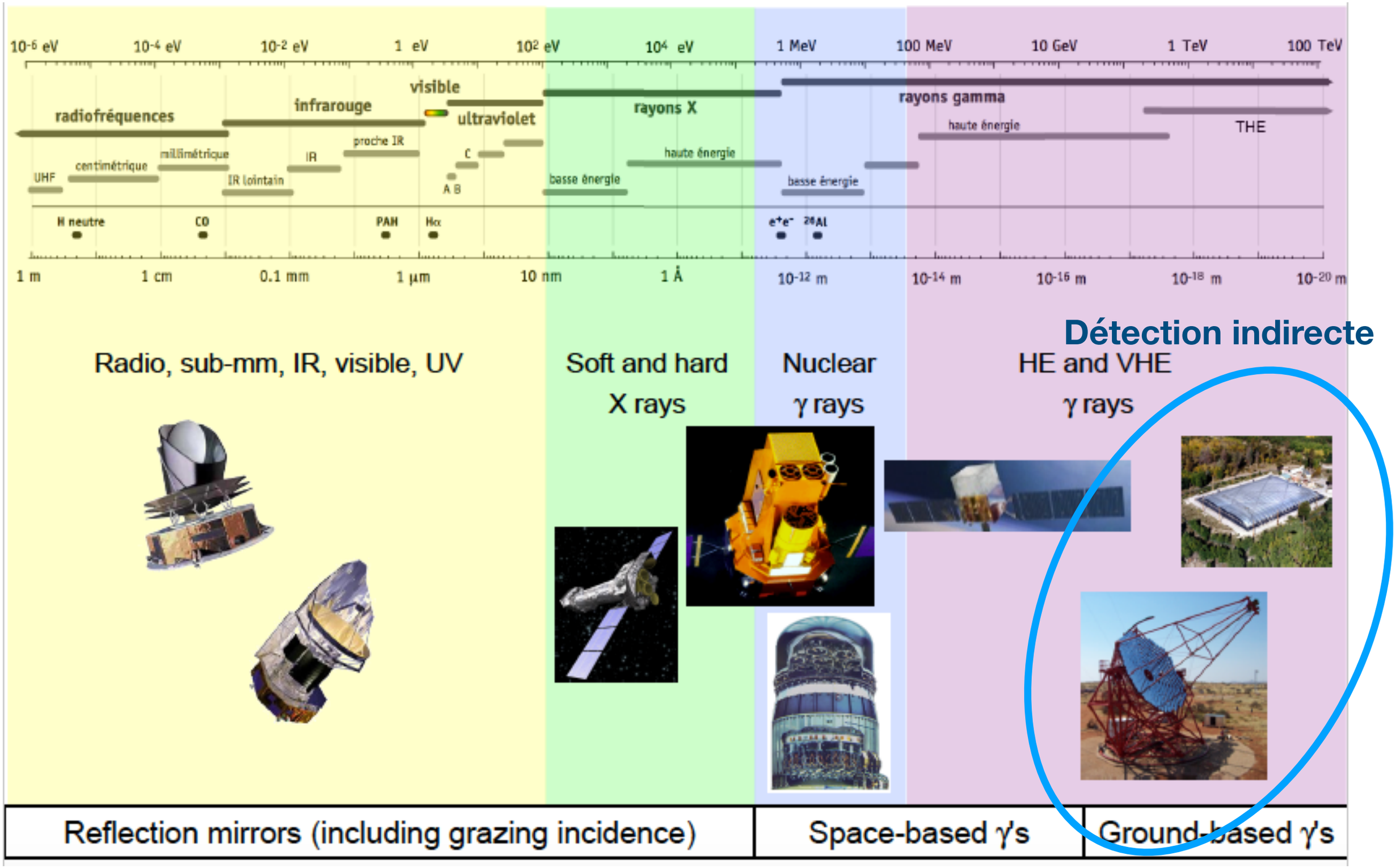
Astronomie multi-longueurs d'onde



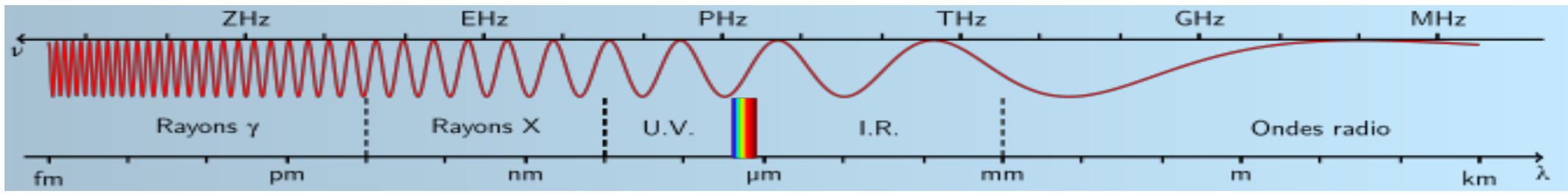
Astronomie multi-longueurs d'onde



Astronomie multi-longueurs d'onde



Astronomie multi-messagers



Météorites

Rayons cosmiques

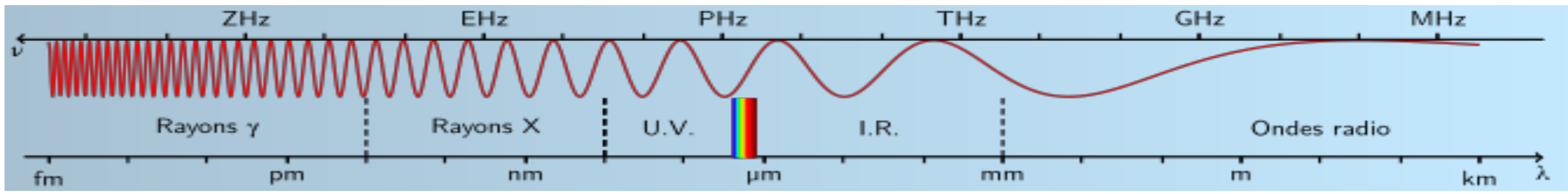
Neutrinos

Ondes gravitationnelles

t

1600 1700 1800 1900 2000

Astronomie multi-messagers



Météorites

Rayons cosmiques

Objets compacts

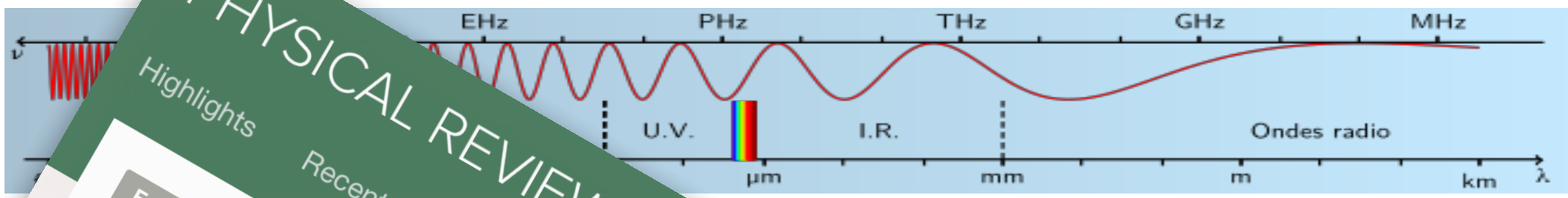
Neutrinos

Ondes gravitationnelles

t

1600 1700 1800 1900 2000

Astronomie multi-messagers



PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About

Featured in Physics

Editors' Suggestion

Interstellar ^{60}Fe in Antarctica

Dominik Koll, Gunther Korschinek, Thomas Faestermann, J. M. Gómez-Guzmán, Sepp Kipfstuhl, Silke Merchel, and Jan M. Welch

Phys. Rev. Lett. **123**, 072701 – Published 12 August 2019

Météorites

Rayons

miques

Objets compa

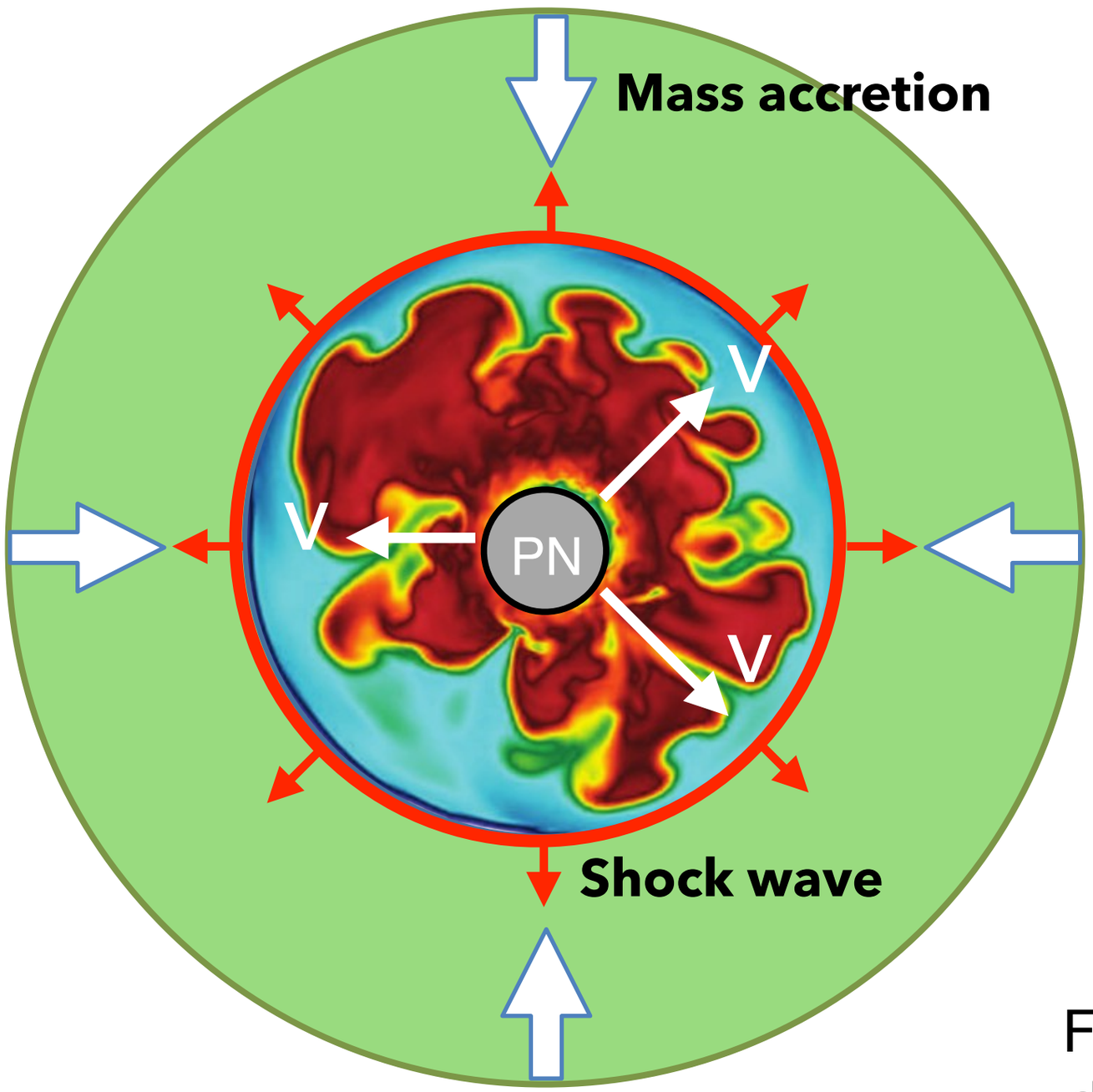
Onde

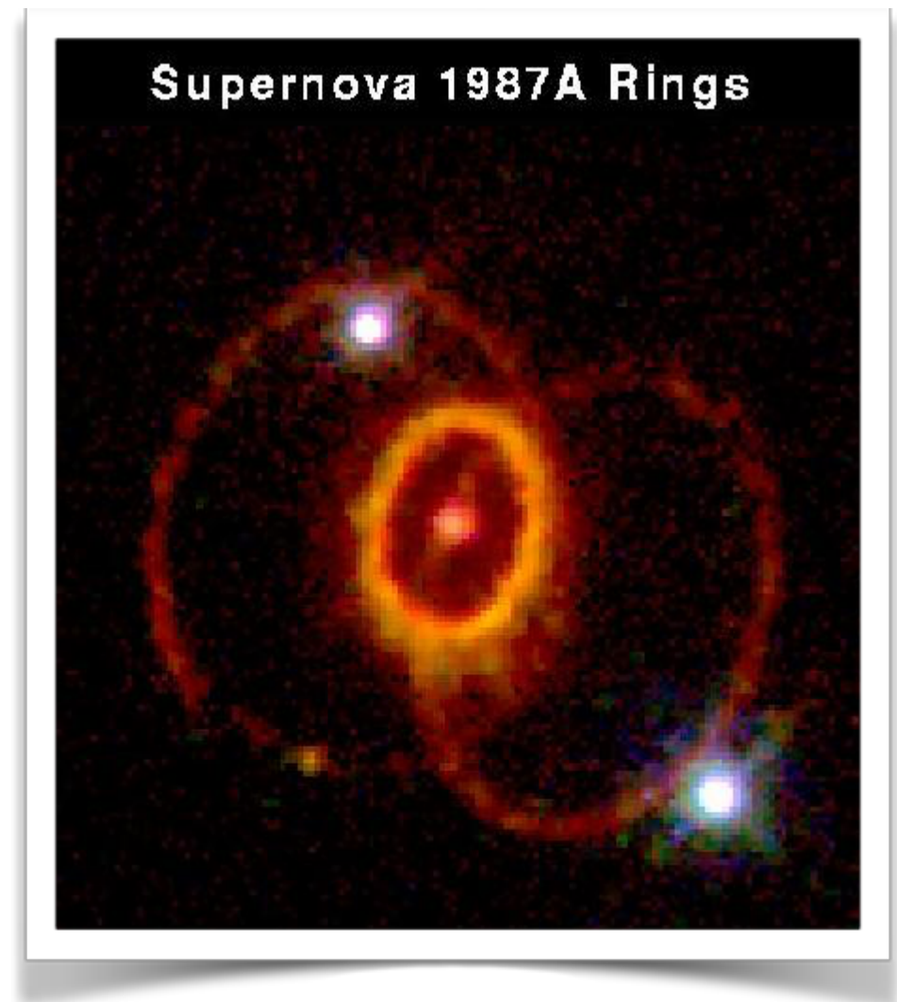
t

1600 1700 1800 1900 2000

Evolution des étoiles massives

Etoiles isolées



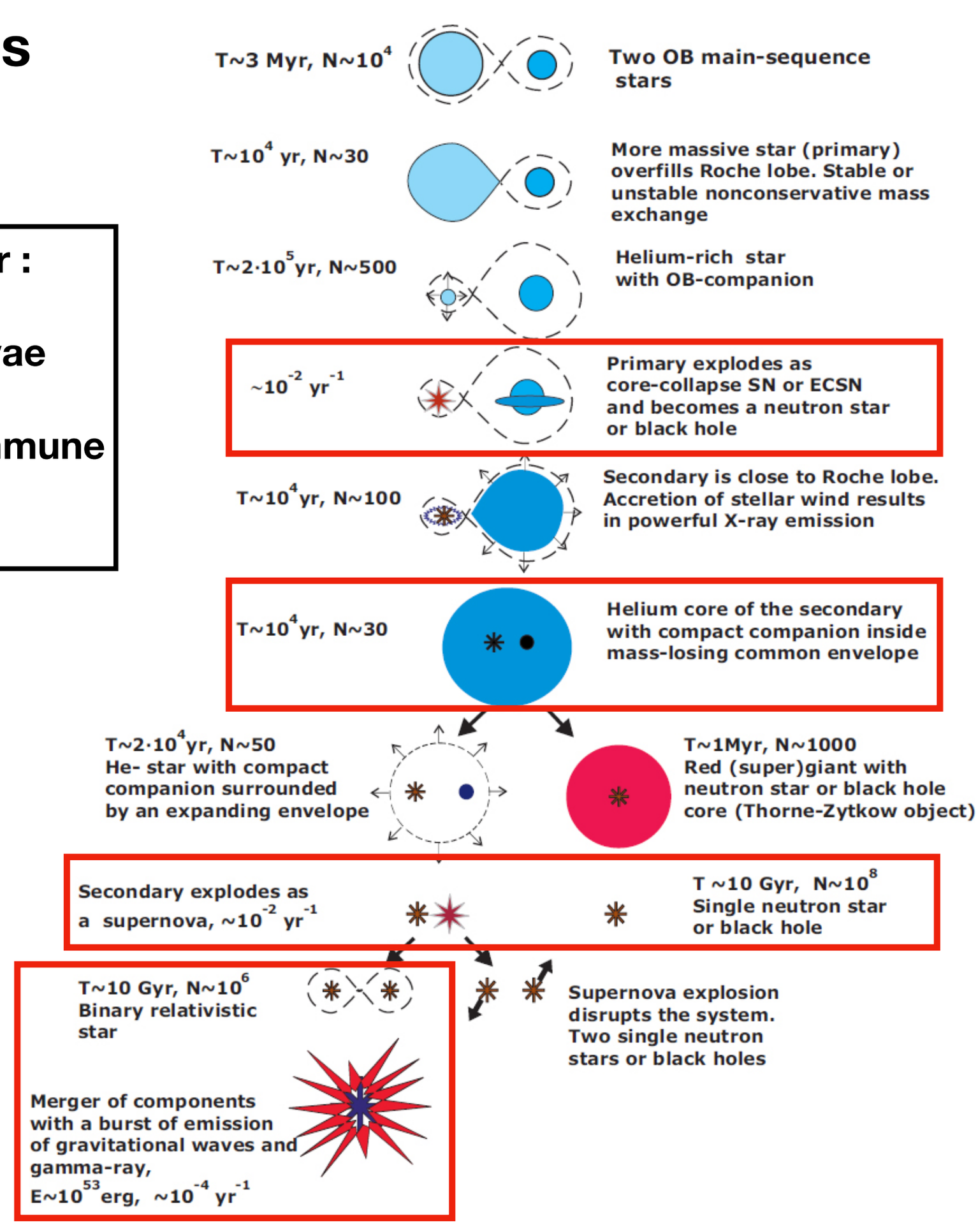


Formation d'une étoile à neutrons ou d'un trou noir dans les cas extrêmes

Systèmes binaires

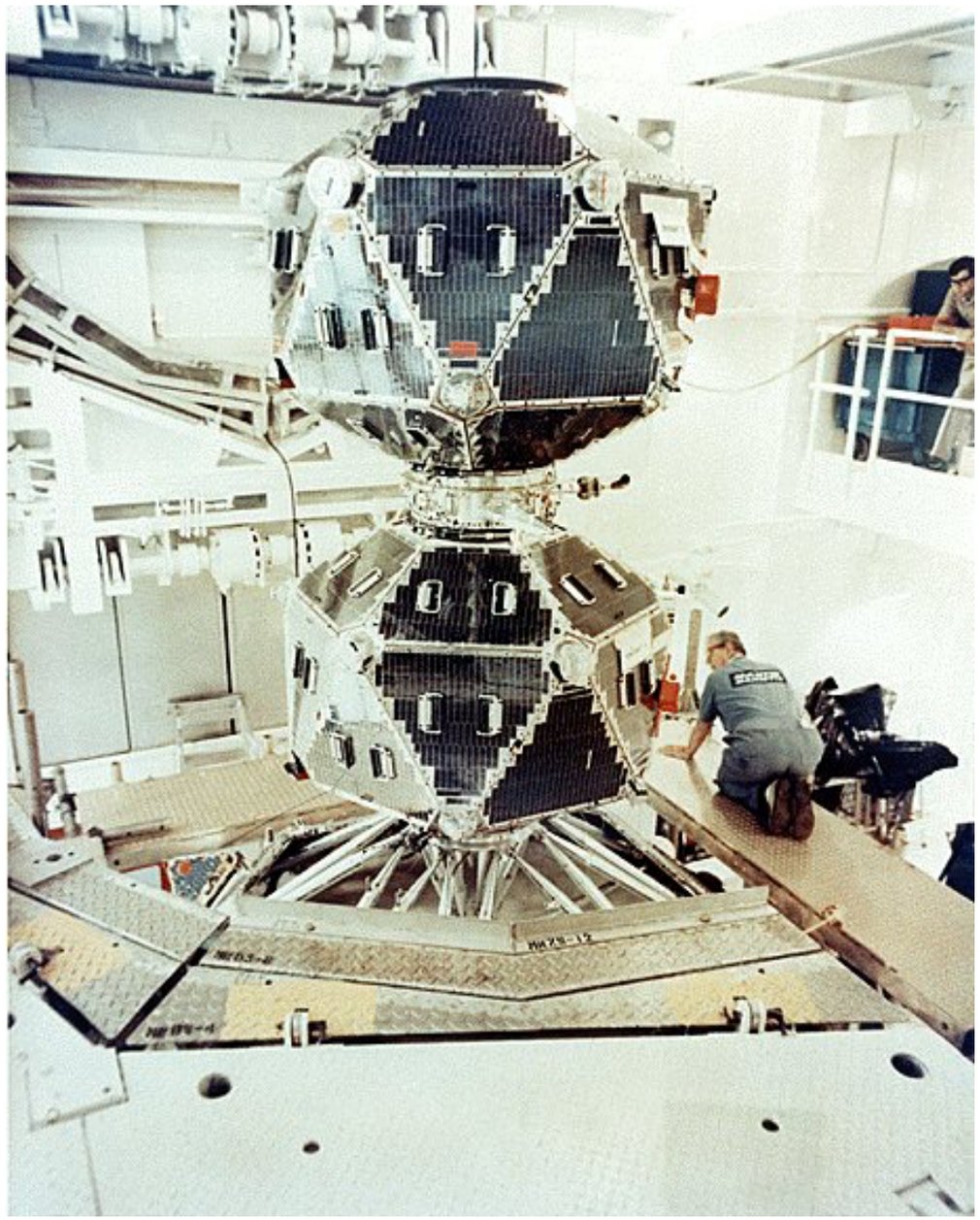
Plusieurs obstacles à franchir :

- **Explosion des supernovae**
- **Phase d'enveloppe commune**
- **Faible période orbitale**



Les sursauts gamma

Cas extrême de la mort des étoiles



OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

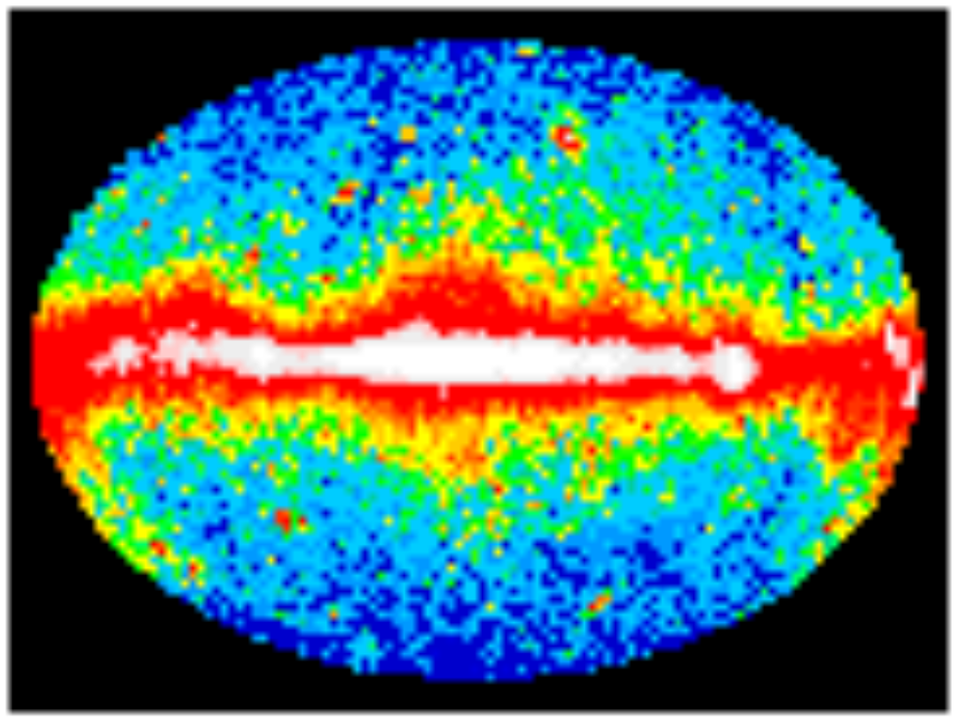
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

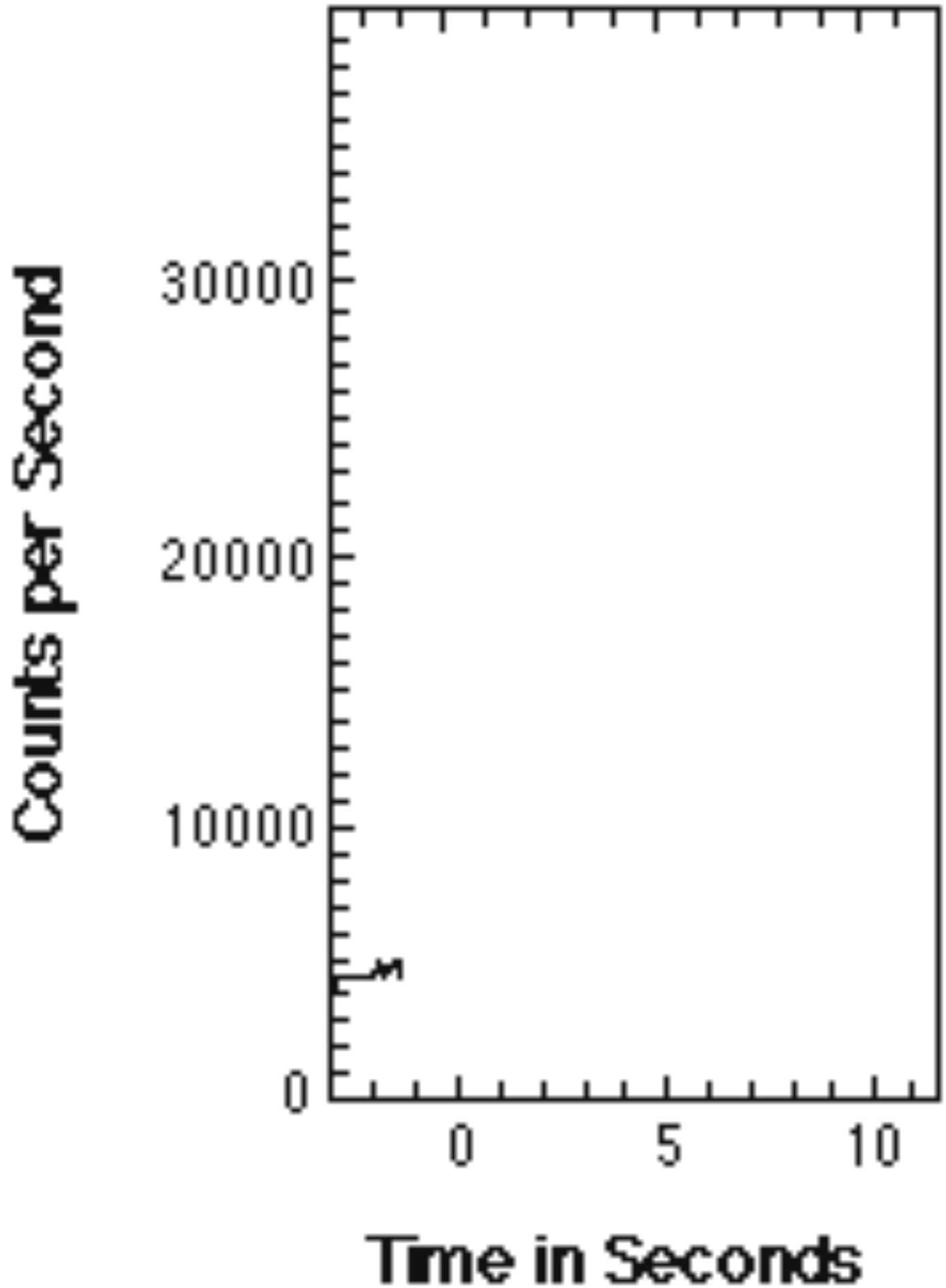
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

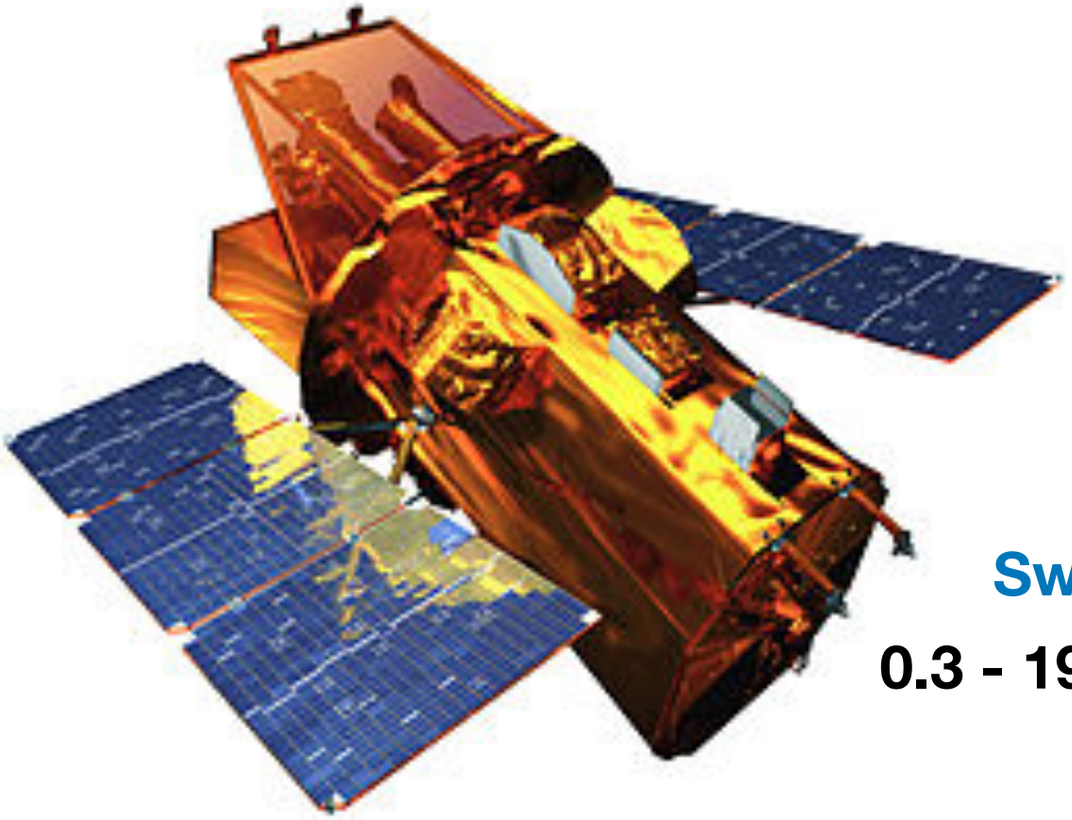
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

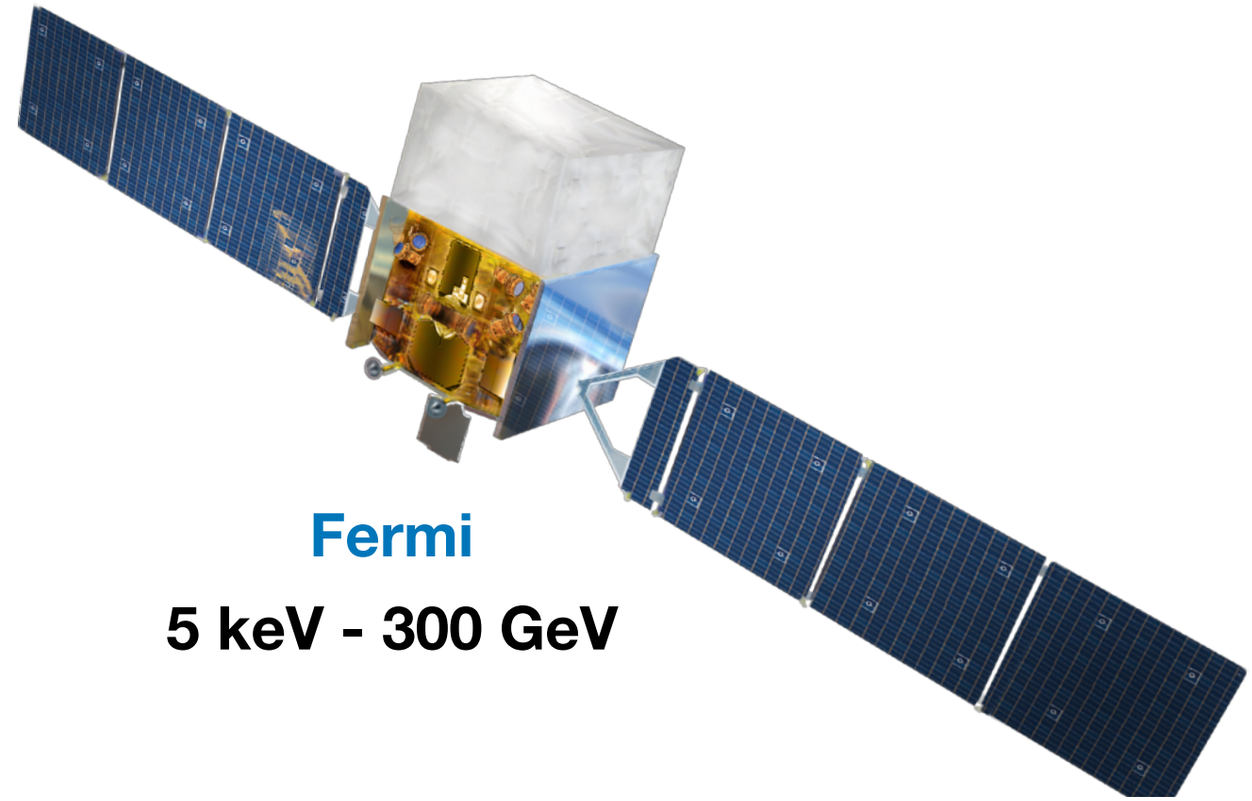



Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds



Swift

0.3 - 195 keV



Fermi

5 keV - 300 GeV

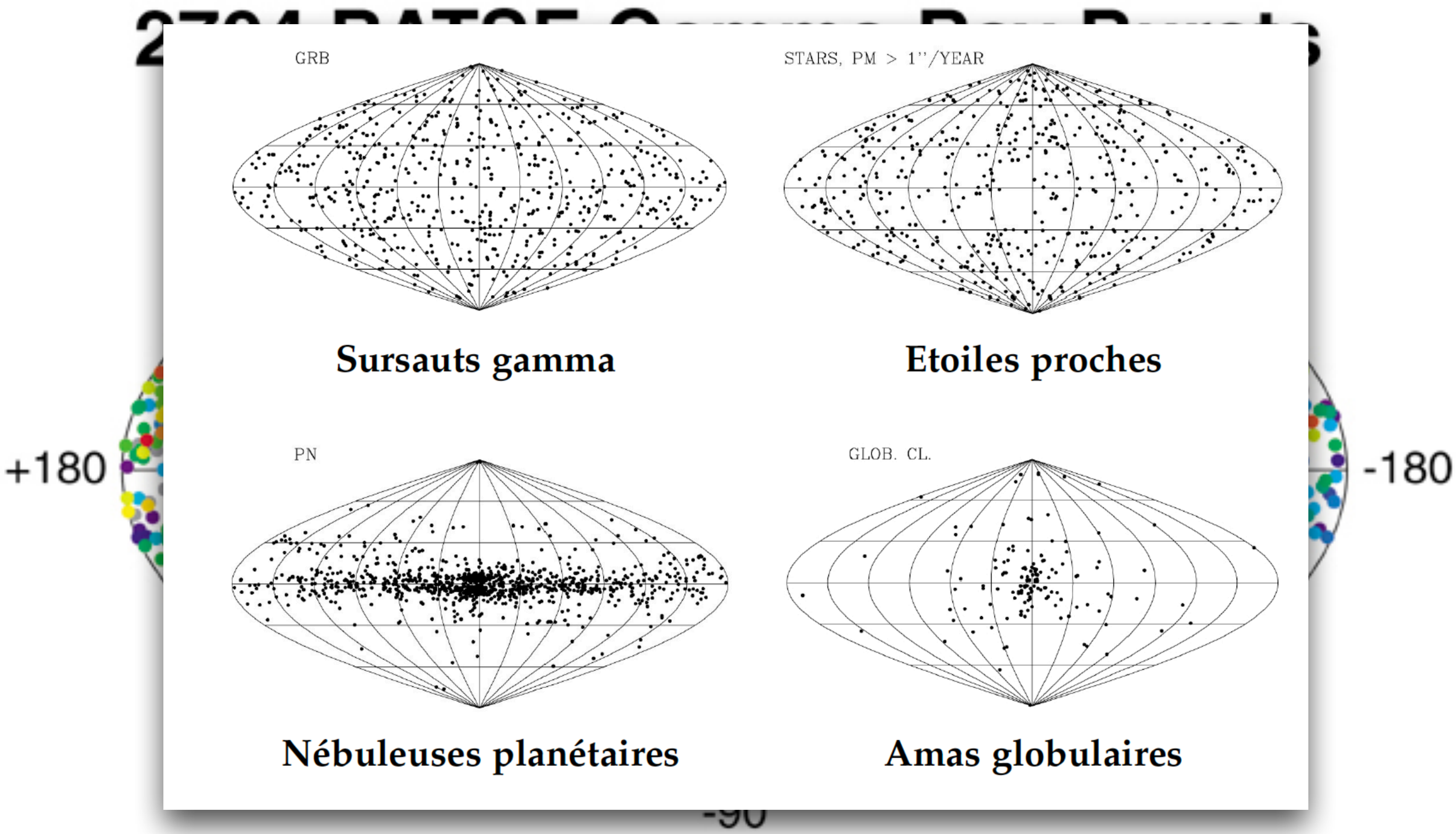
INTEGRAL

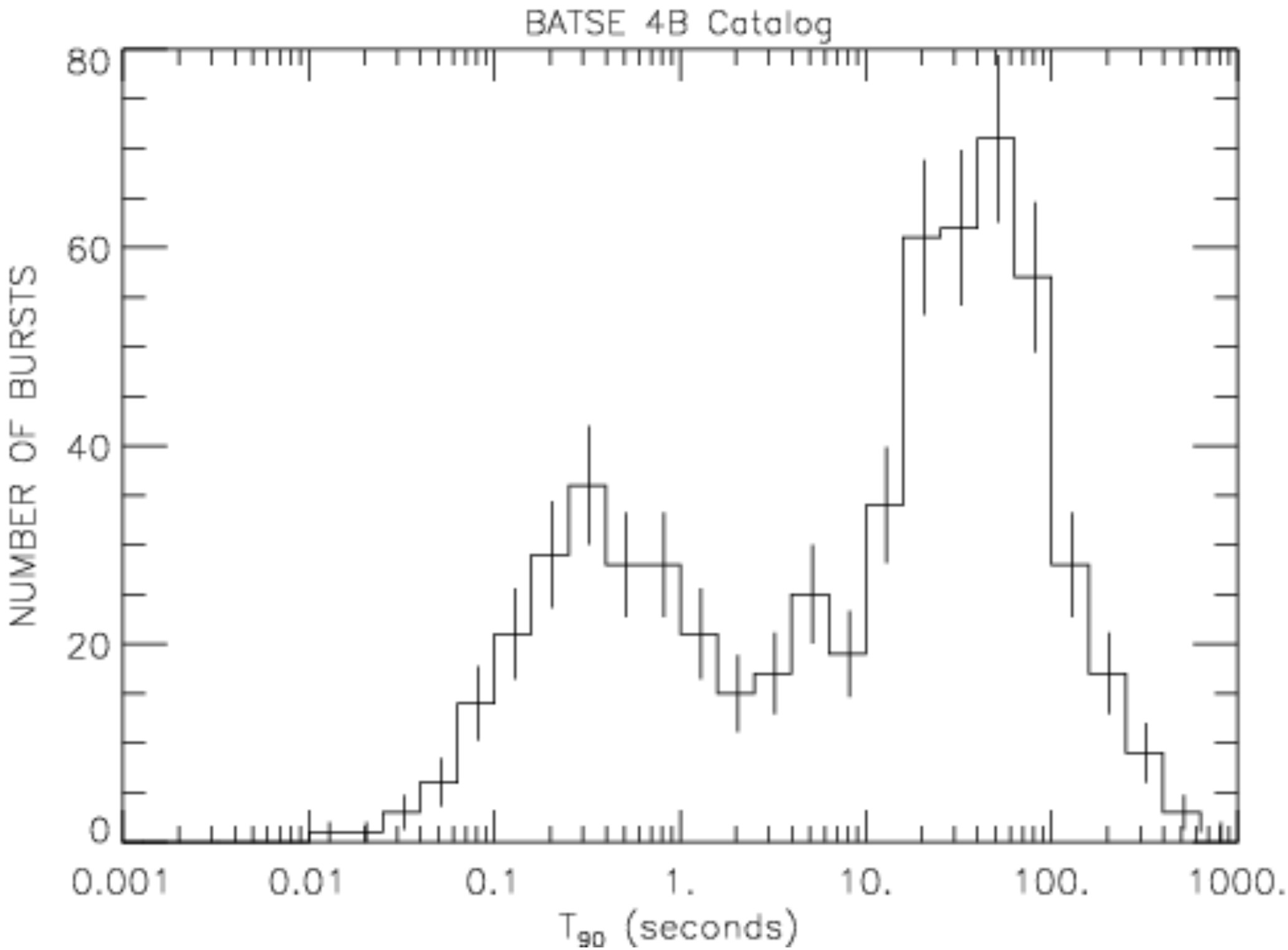
20 keV - 100 MeV

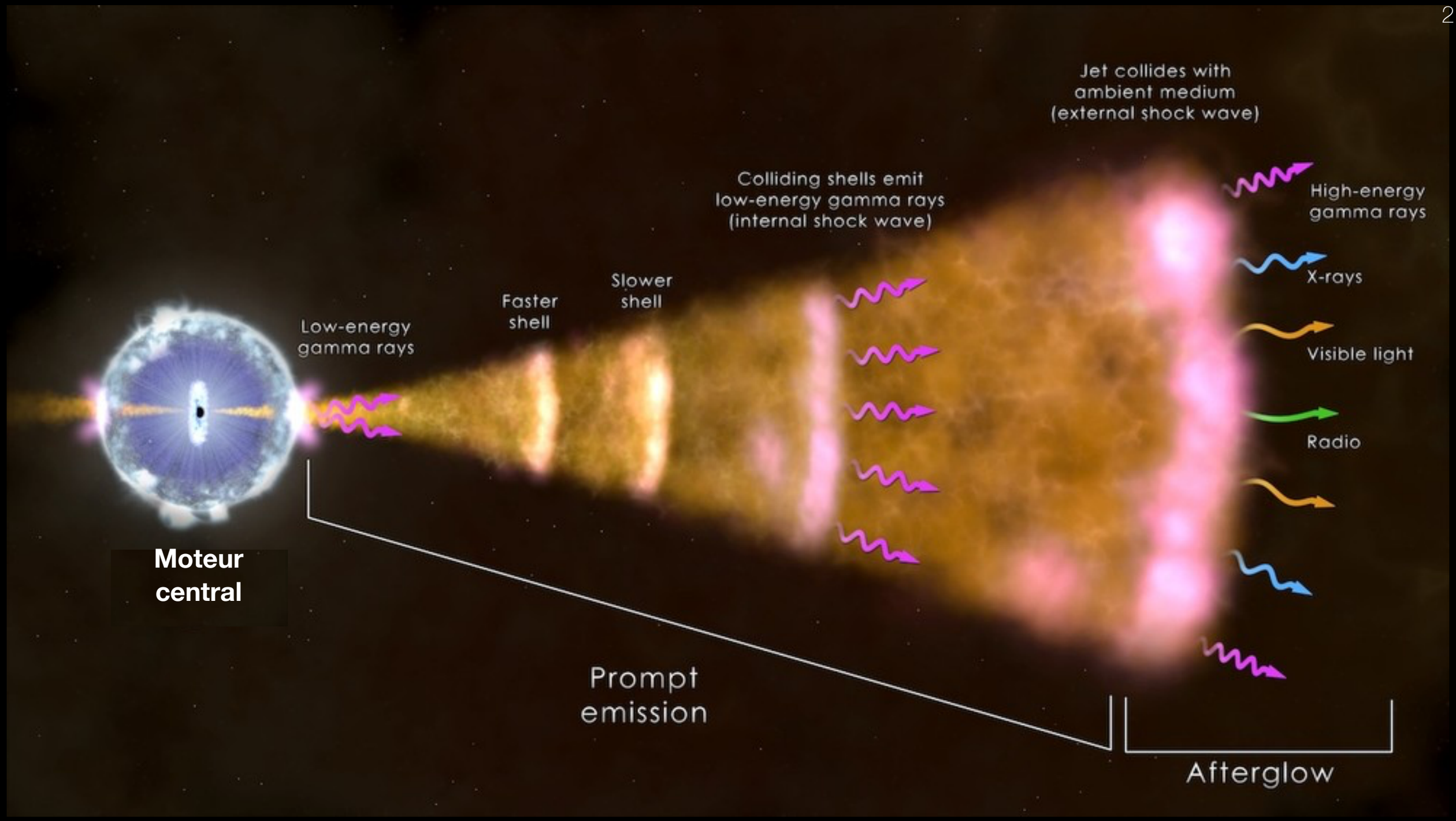
AGILE

10 keV - 50 GeV

~1 GRB / jour détecté actuellement

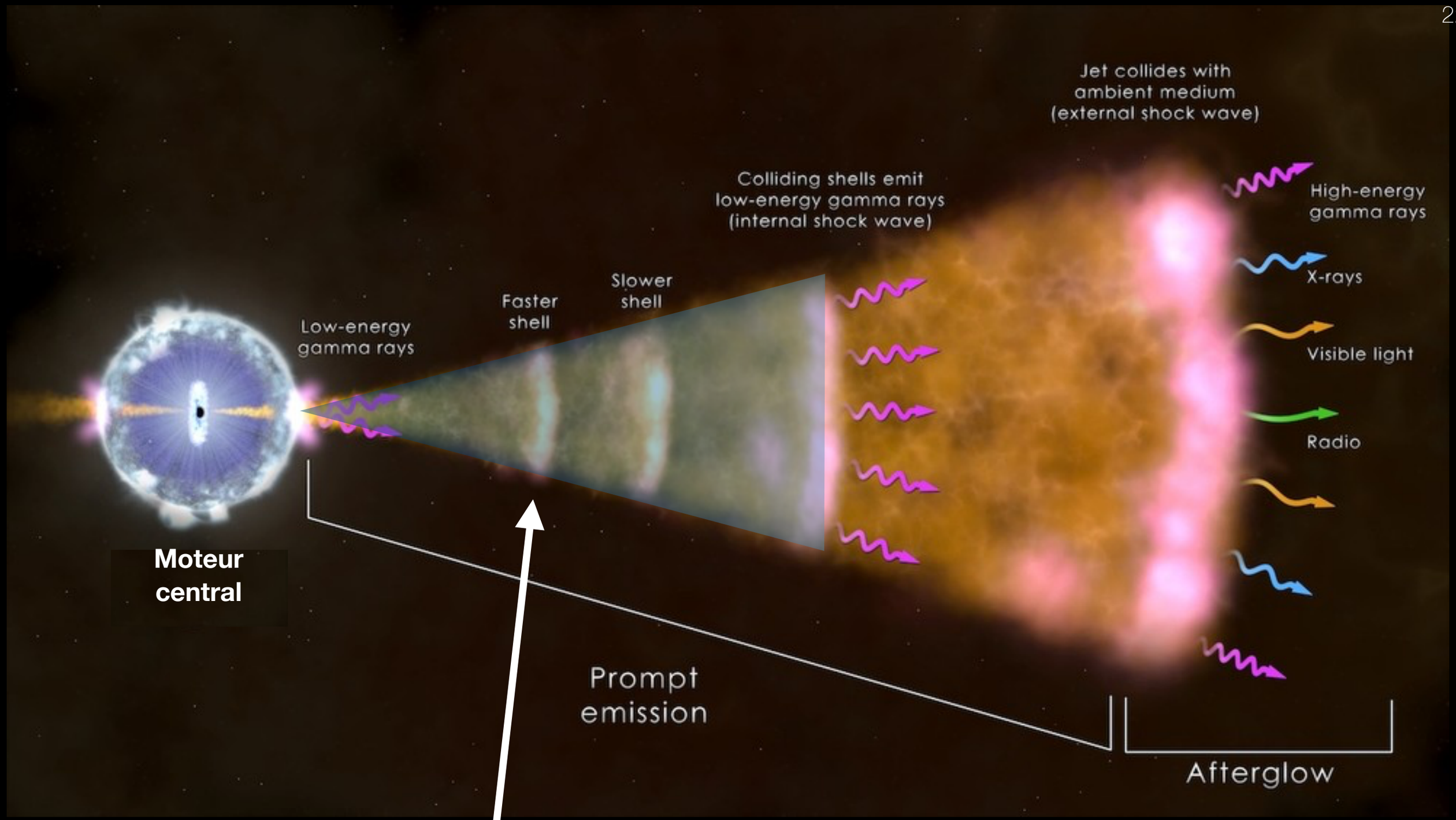

+180
-180
-90
GRB
STARS, PM > 1''/YEAR
Sursauts gamma
Etoiles proches
PN
GLOB. CL.
Nébuleuses planétaires
Amas globulaires


BATSE 4B Catalog
NUMBER OF BURSTS
0
20
40
60
80
0.001
0.01
0.1
1.
10.
100.
1000.
T_{90} (seconds)

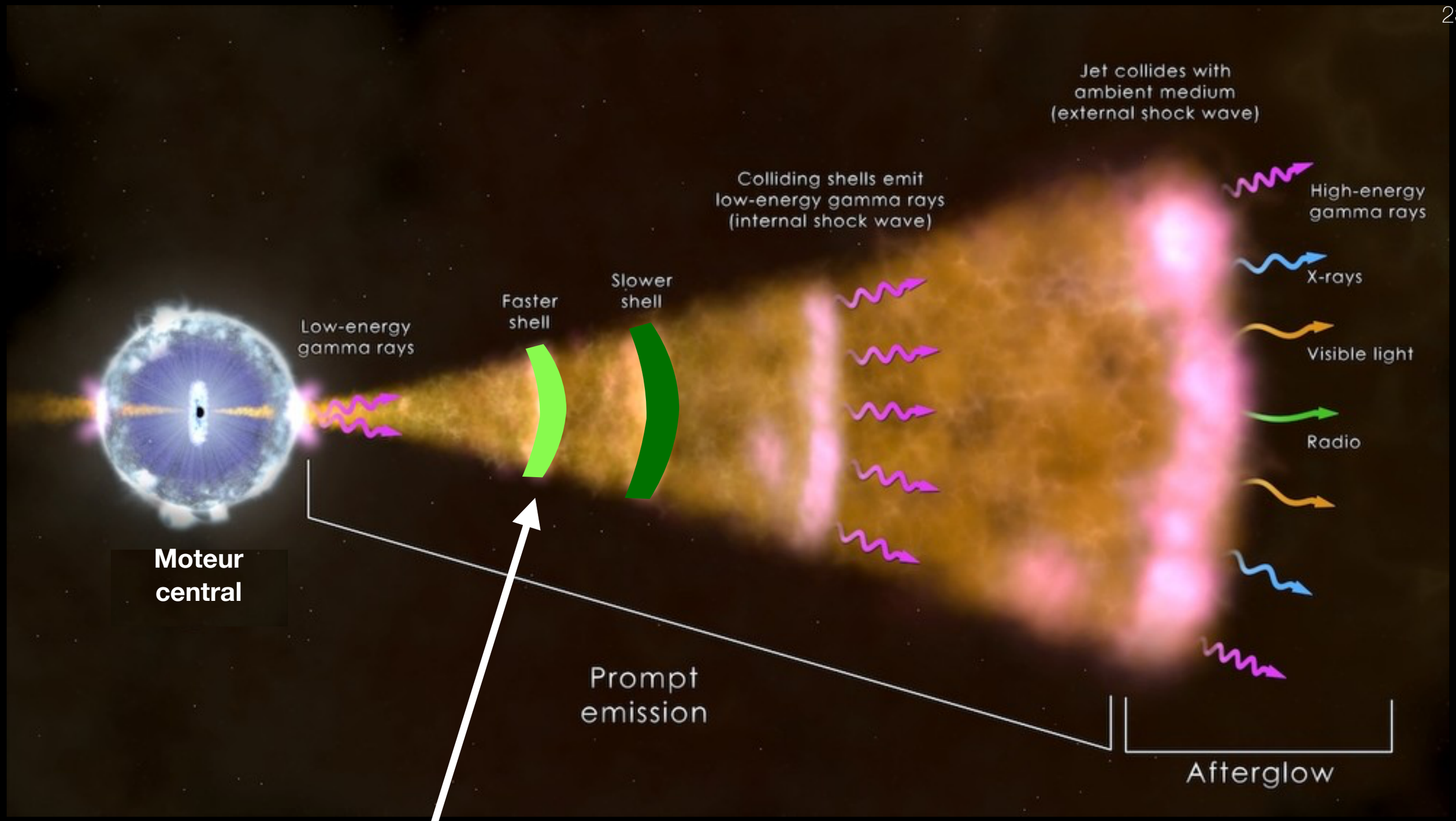


Courte durée donc source probablement de petite taille

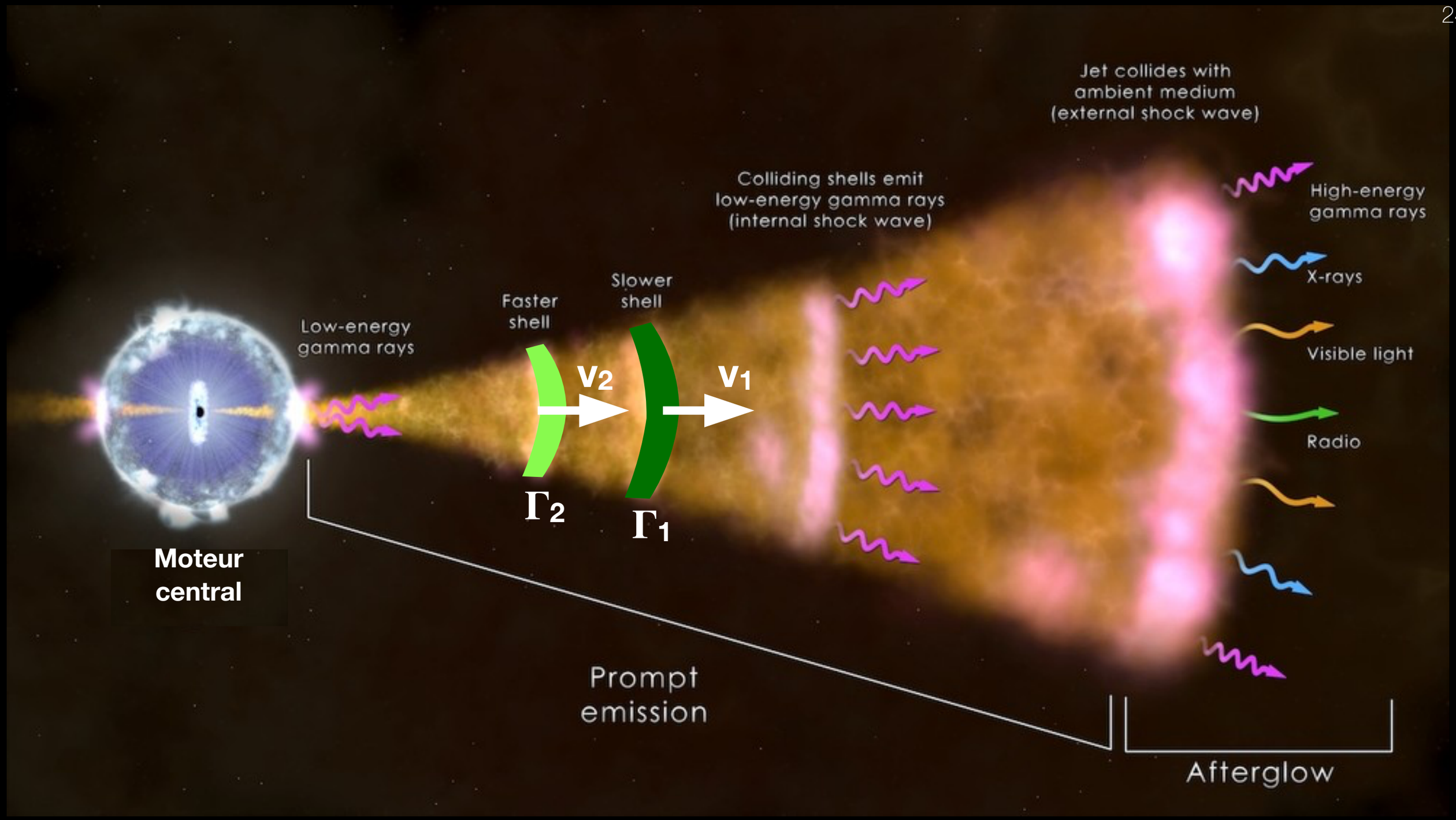
$$l \lesssim c\Delta t$$



Jet relativiste (fraction de la matière accrétée). Distance Terre-Jupiter en ~40min



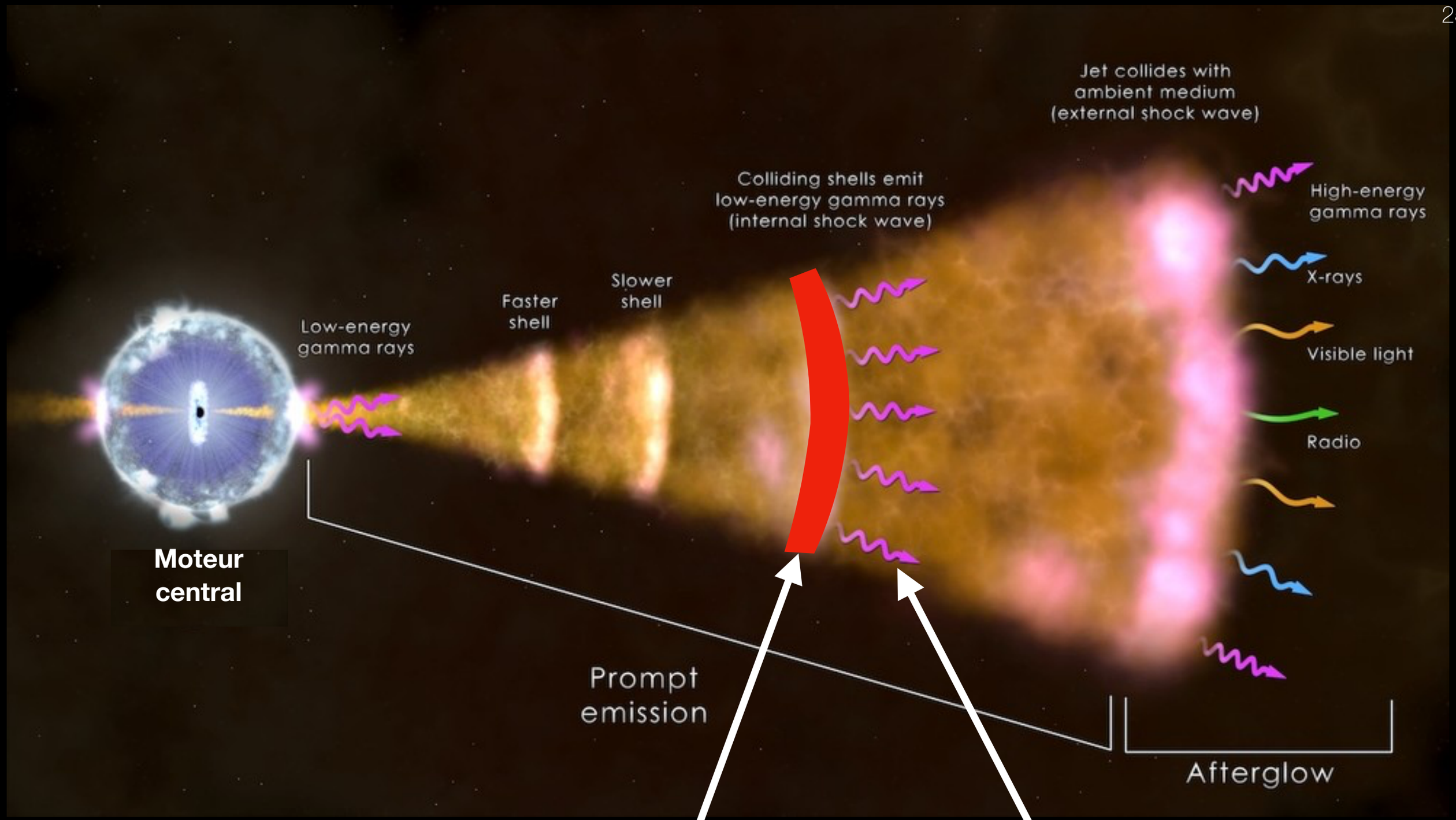
Blobs de matière avec des vitesses différentes (inhomogénéité du jet et variabilité du moteur central)



$$\beta_i = v_i/c \simeq \left(1 - \frac{1}{2\Gamma_i^2}\right)$$

$$E_{\rm diss} = mc^2\left(\Gamma_1 + \Gamma_2 - 2\sqrt{\Gamma_1\Gamma_2}\right)$$

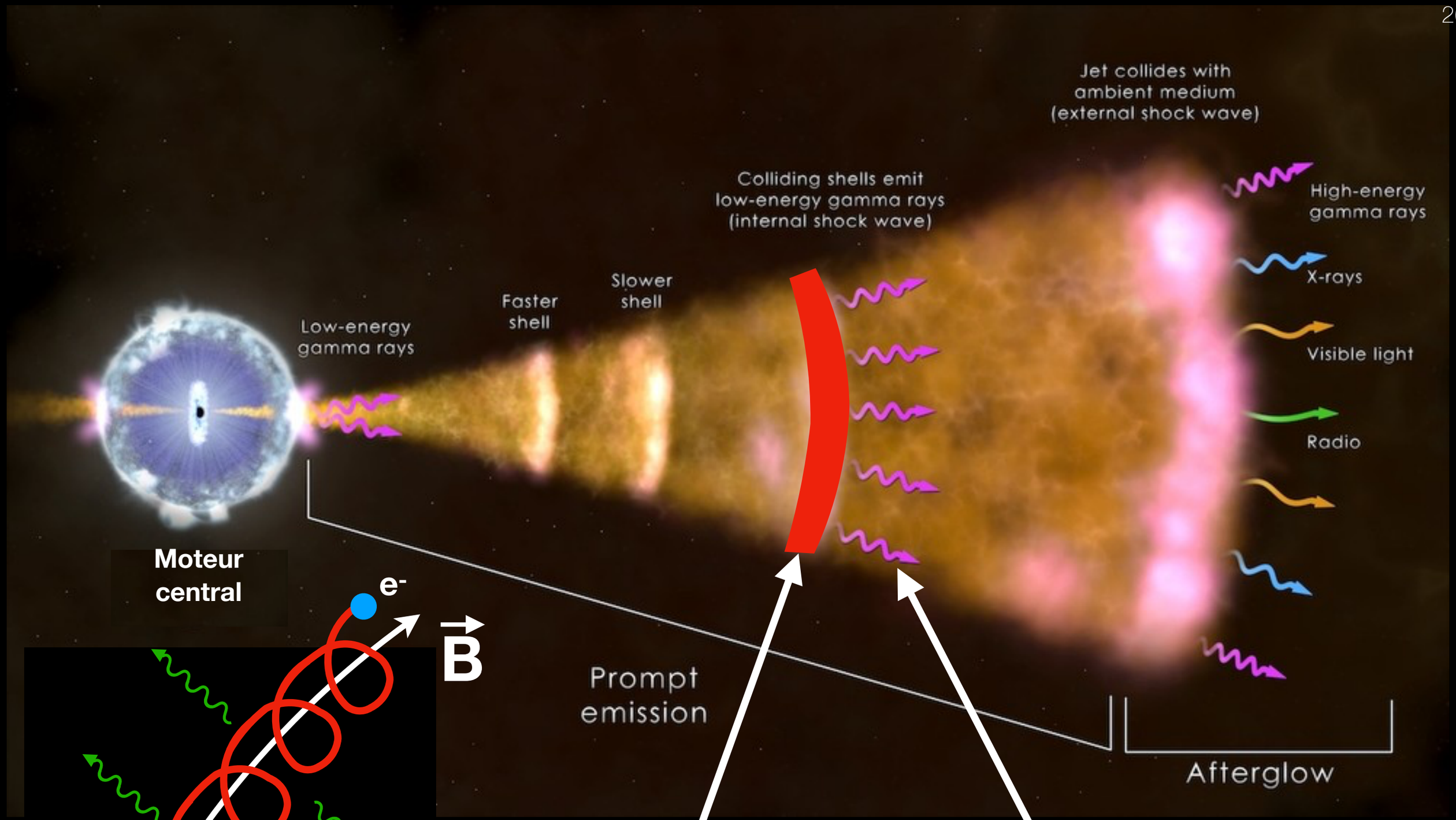
$$R_{\rm choc} = \frac{\beta_1\beta_2}{\beta_2 - \beta_1} c\Delta t \simeq 2c\Delta t \frac{\Gamma_1^2\Gamma_2^2}{\Gamma_2^2 - \Gamma_1^2}$$

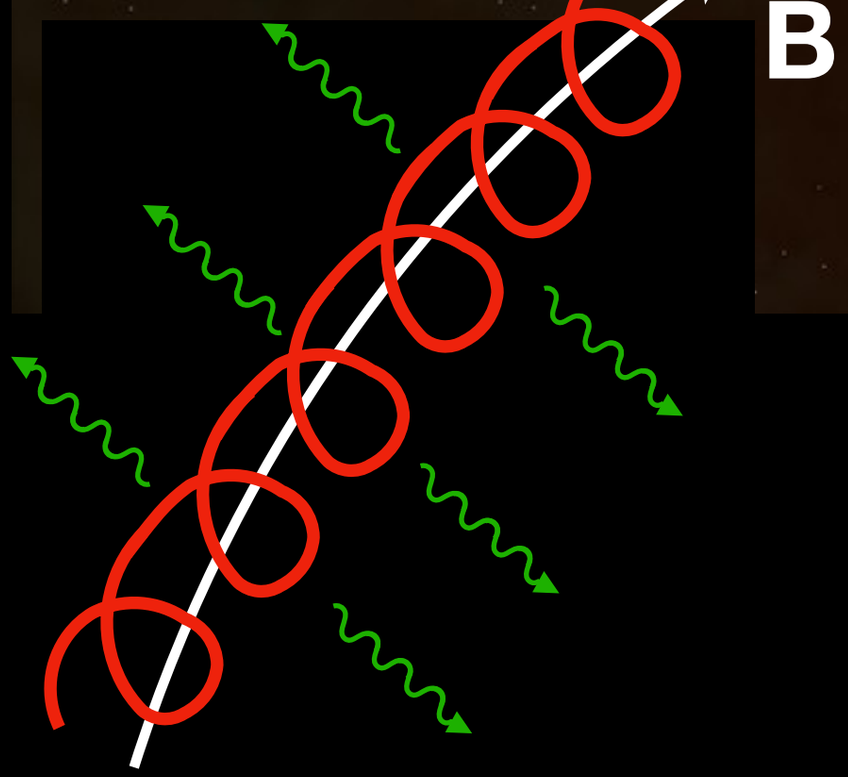


Emission gamma

Chocs internes :
transfert d'énergie

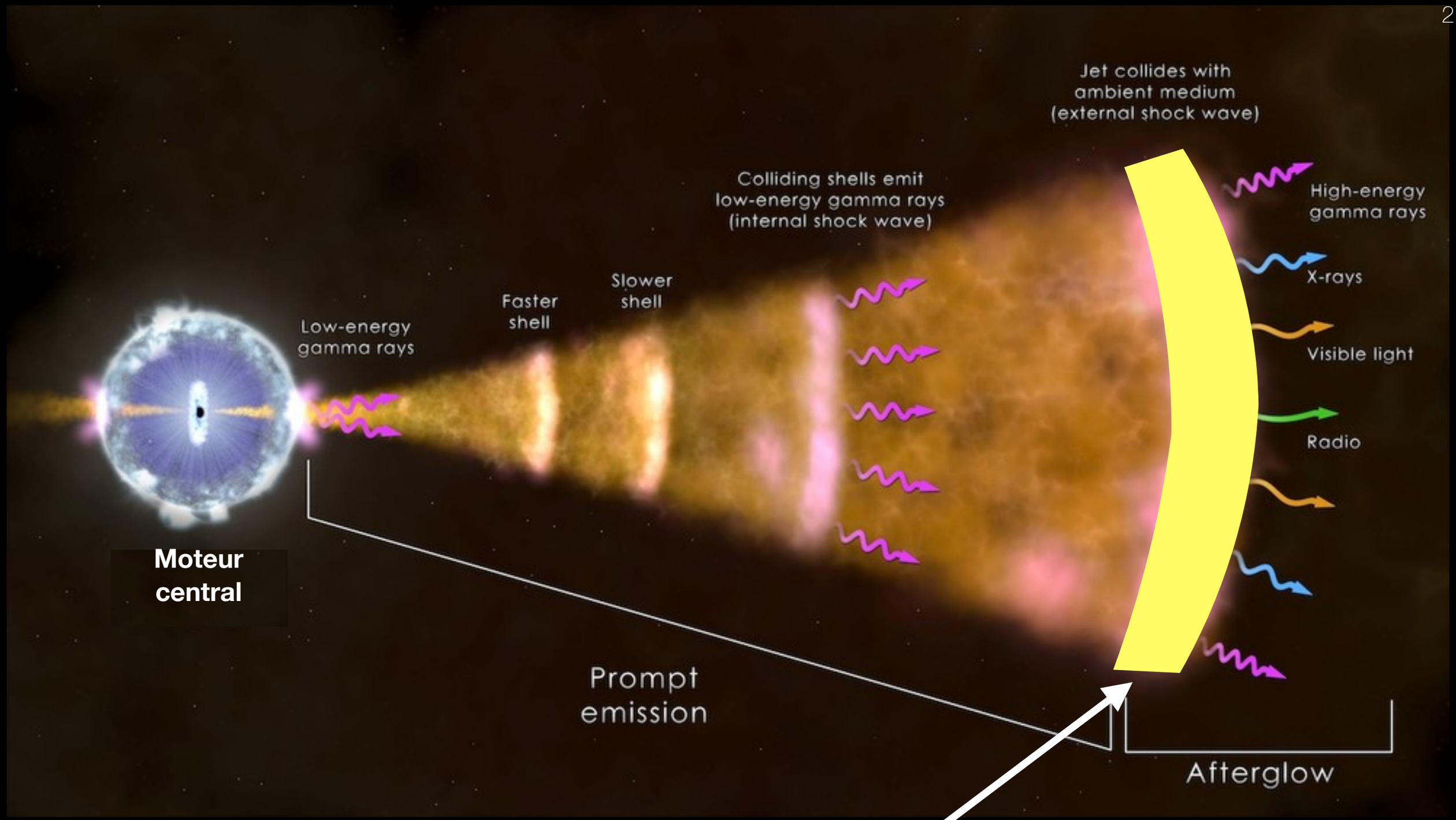
Accélération
des particules



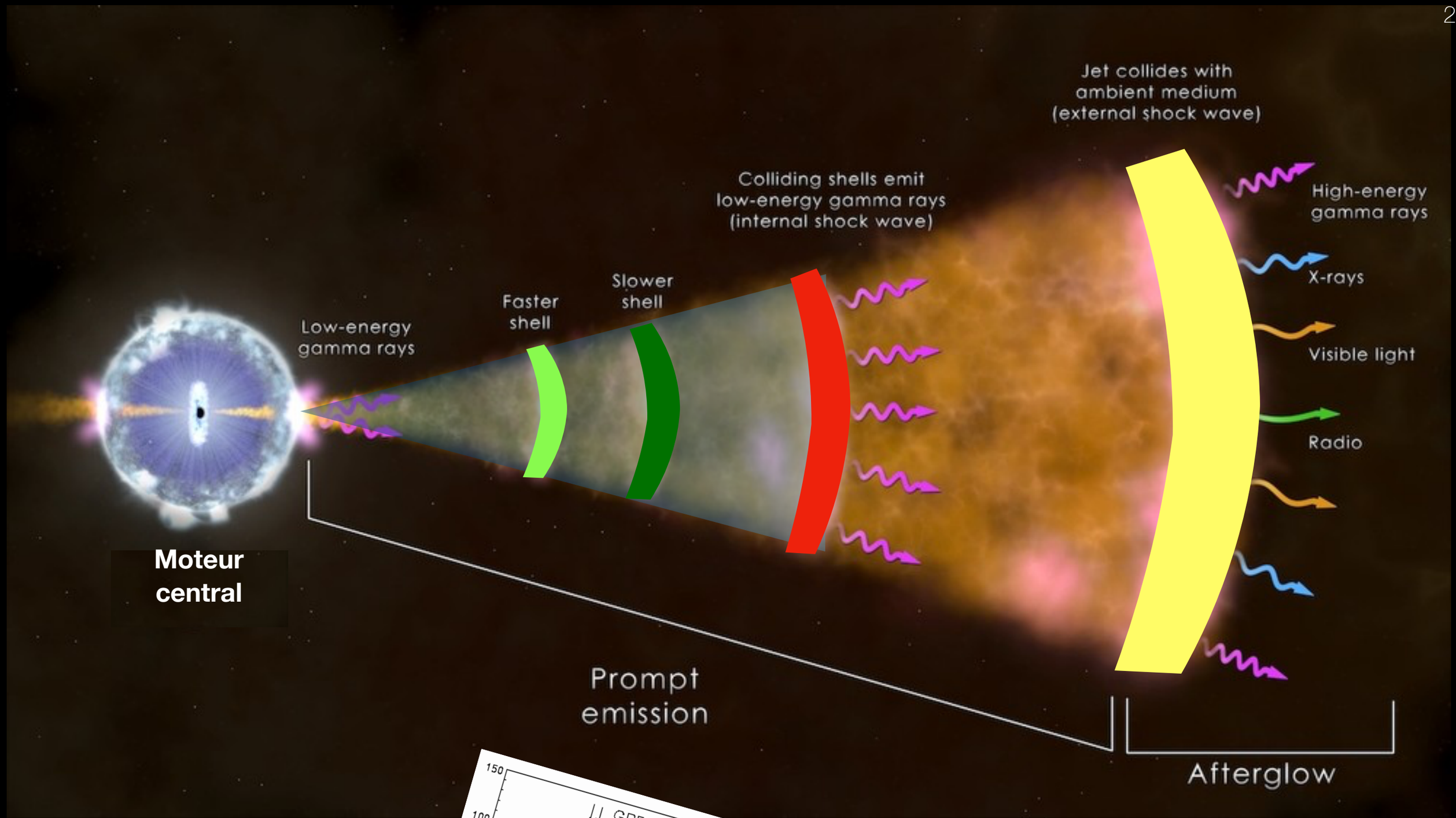


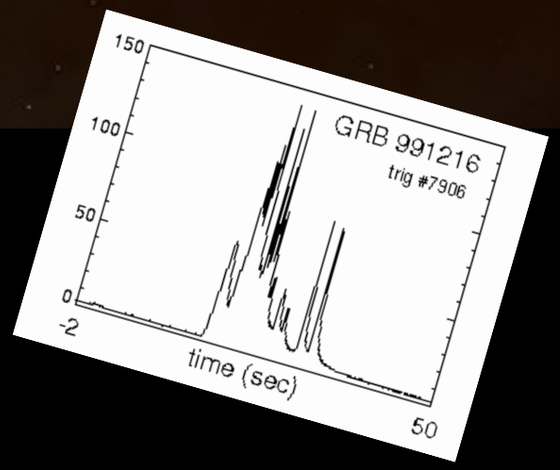
Chocs internes : transfert d'énergie et accélération des particules

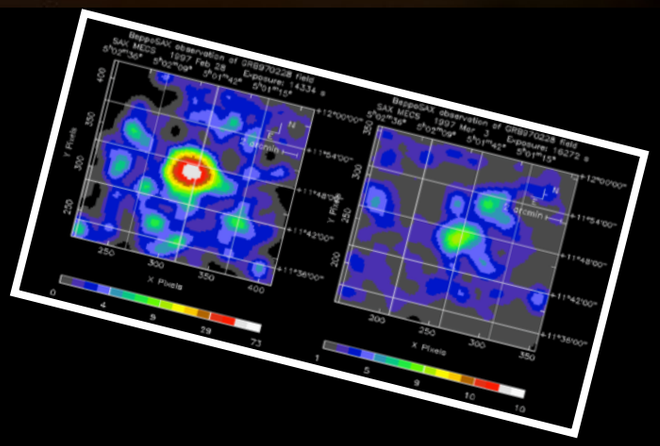
Emission gamma



Décélération au contact du milieu interstellaire


Jet collides with
ambient medium
(external shock wave)
Colliding shells emit
low-energy gamma rays
(internal shock wave)
Slower
shell
Faster
shell
Low-energy
gamma rays
High-energy
gamma rays
X-rays
Visible light
Radio
Moteur
central
Prompt
emission
Afterglow

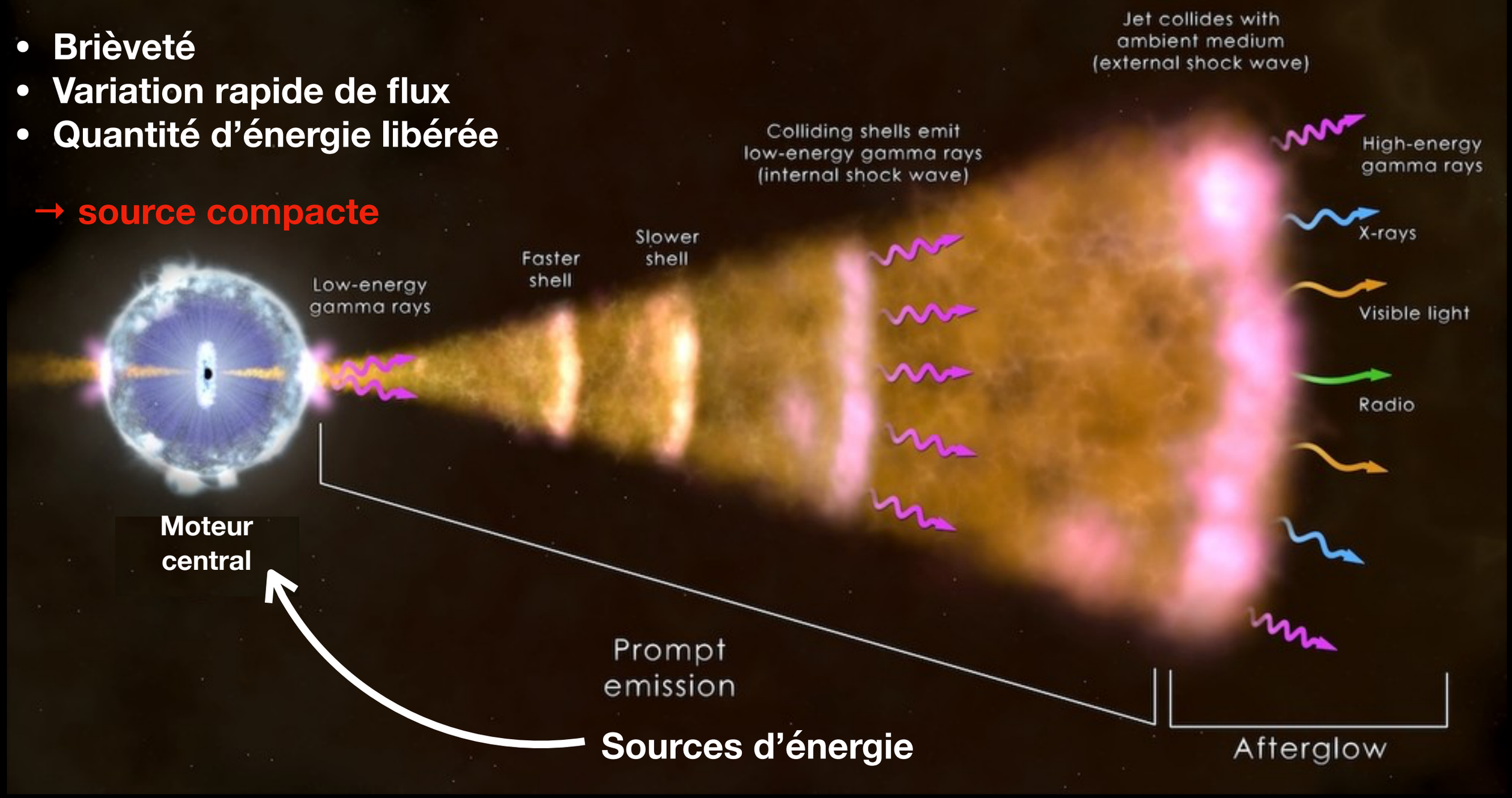

GRB 991216
trig #7906
150
100
50
0
-2
time (sec)
50



Quel est le moteur central ??

- **Brièveté**
- **Variation rapide de flux**
- **Quantité d'énergie libérée**

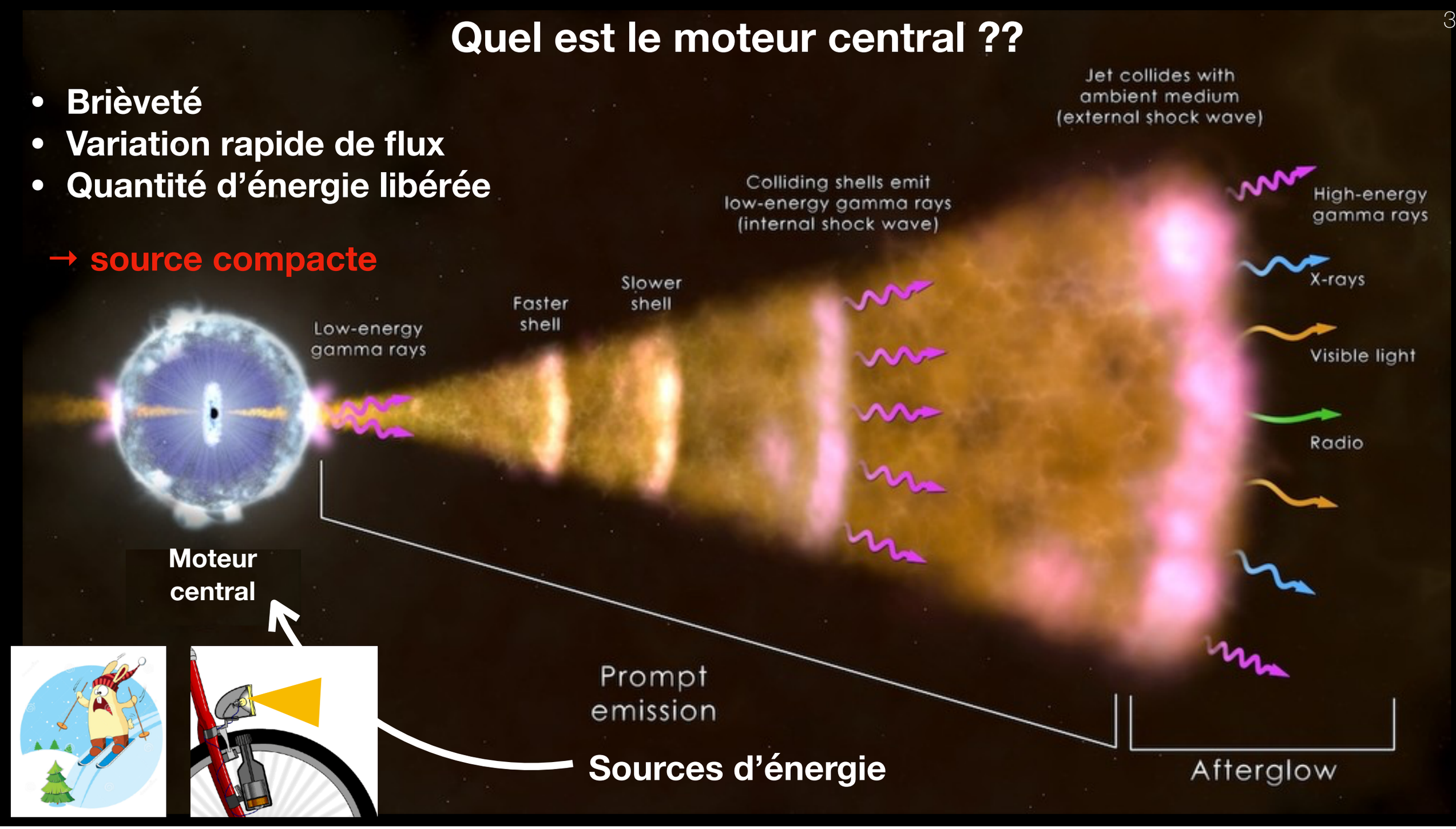
→ source compacte



Quel est le moteur central ??

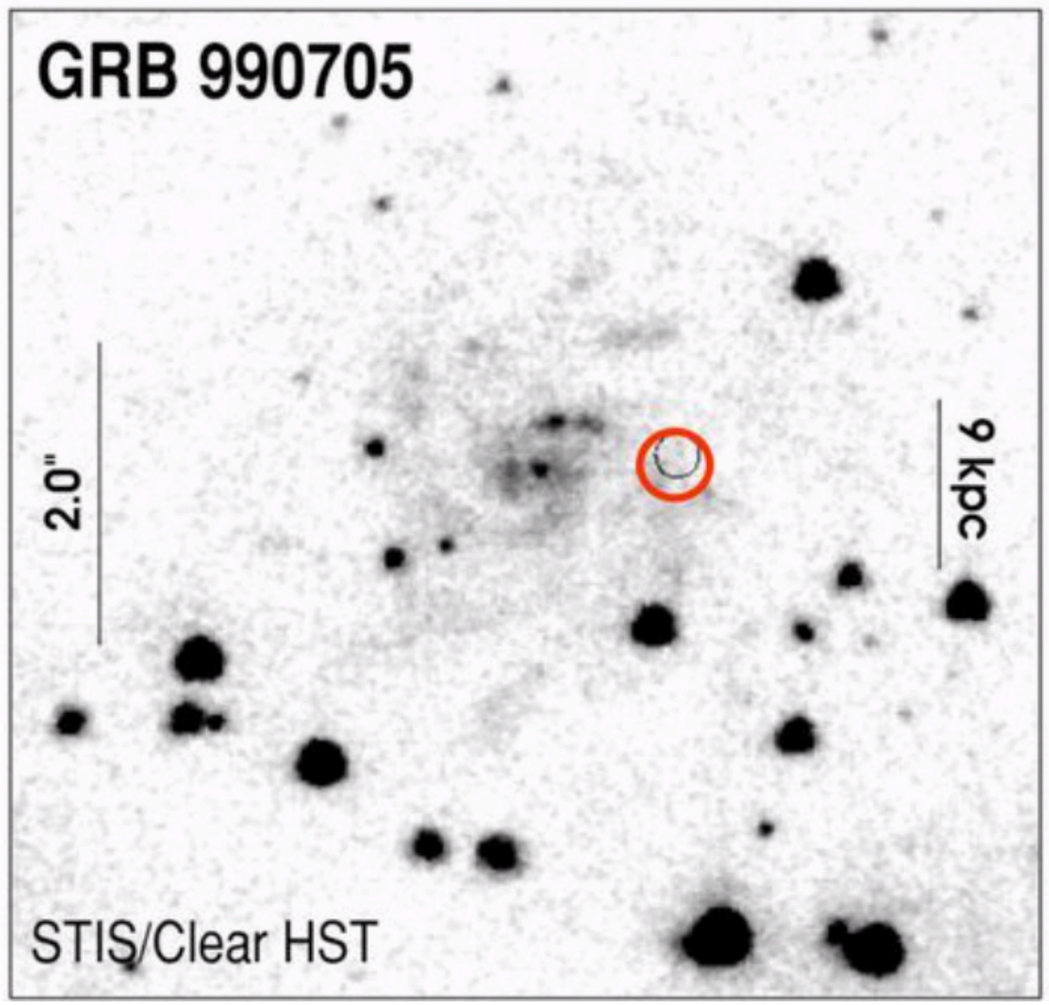
- **Brièveté**
- **Variation rapide de flux**
- **Quantité d'énergie libérée**

→ source compacte

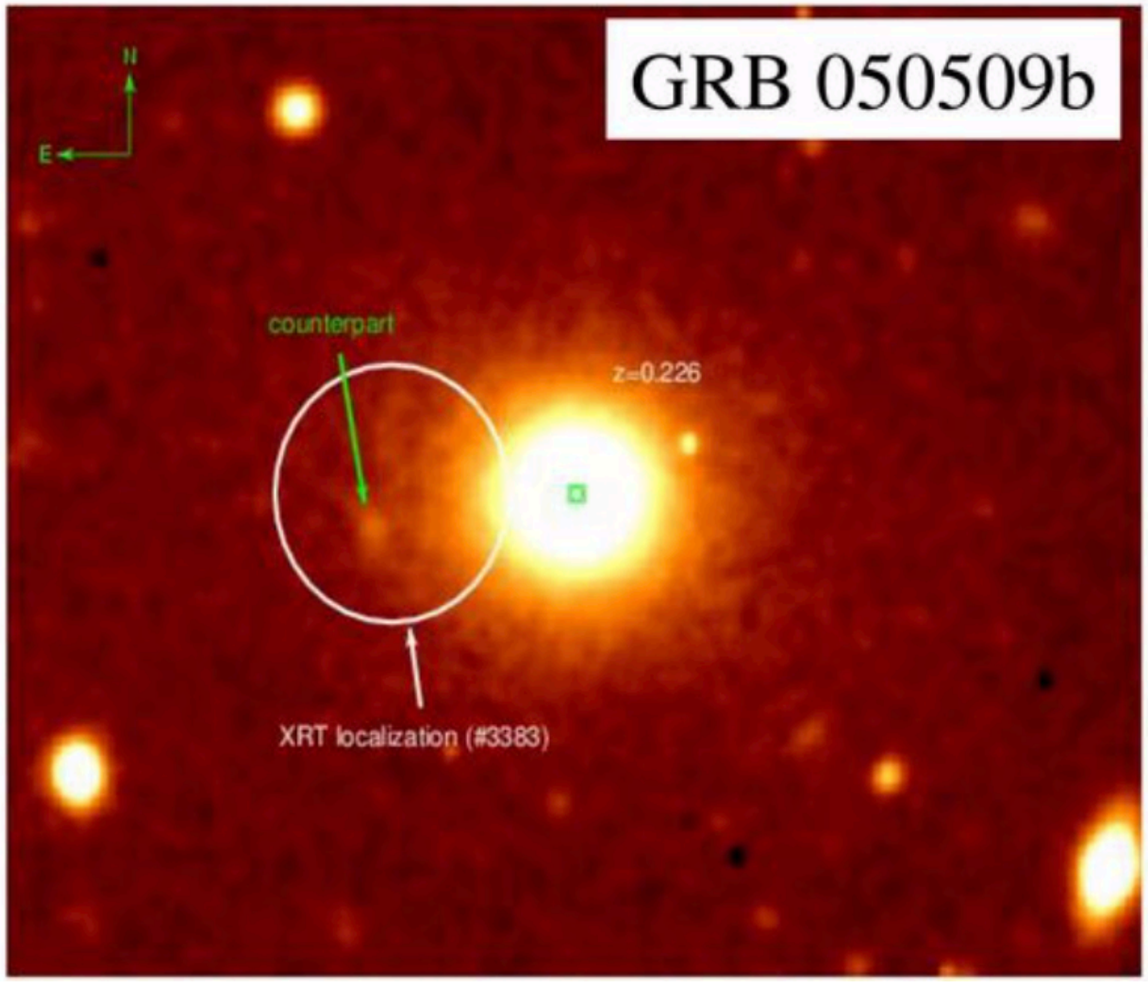


	Collapsar	Merger	Magnétar
$M_{\rm co}$	$5 \to 15\ M_\odot$	$2.5 \to 10\ M_\odot$	$1.5\ M_\odot$
rotation	$a = 0.2 \to 0.8$	$a = 0.5 \to 1$	$P \simeq 1$ ms
$E_{\rm rot}$	$\lesssim 5.2 \times 10^{54} (M/10\ M_\odot)$ erg	$\lesssim 2.6 \times 10^{54} (M/5\ M_\odot)$ erg	2×10^{52} erg $(P/1\ {\rm ms})^{-2}$
$M_{\rm disk}$	$\gtrsim 10\ M_\odot$	$10^{-3} \to 0.1\ M_\odot$	$1\ M_\odot$?
$E_{\rm acc}$	$\lesssim 8 \times 10^{54} (M_{\rm disk}/10\ M_\odot)$ erg	$\lesssim 8 \times 10^{52} (M_{\rm disk}/0.1\ M_\odot)$	$\lesssim 4 \times 10^{53}$ erg

Etude de l'environnement (galaxie hôte)

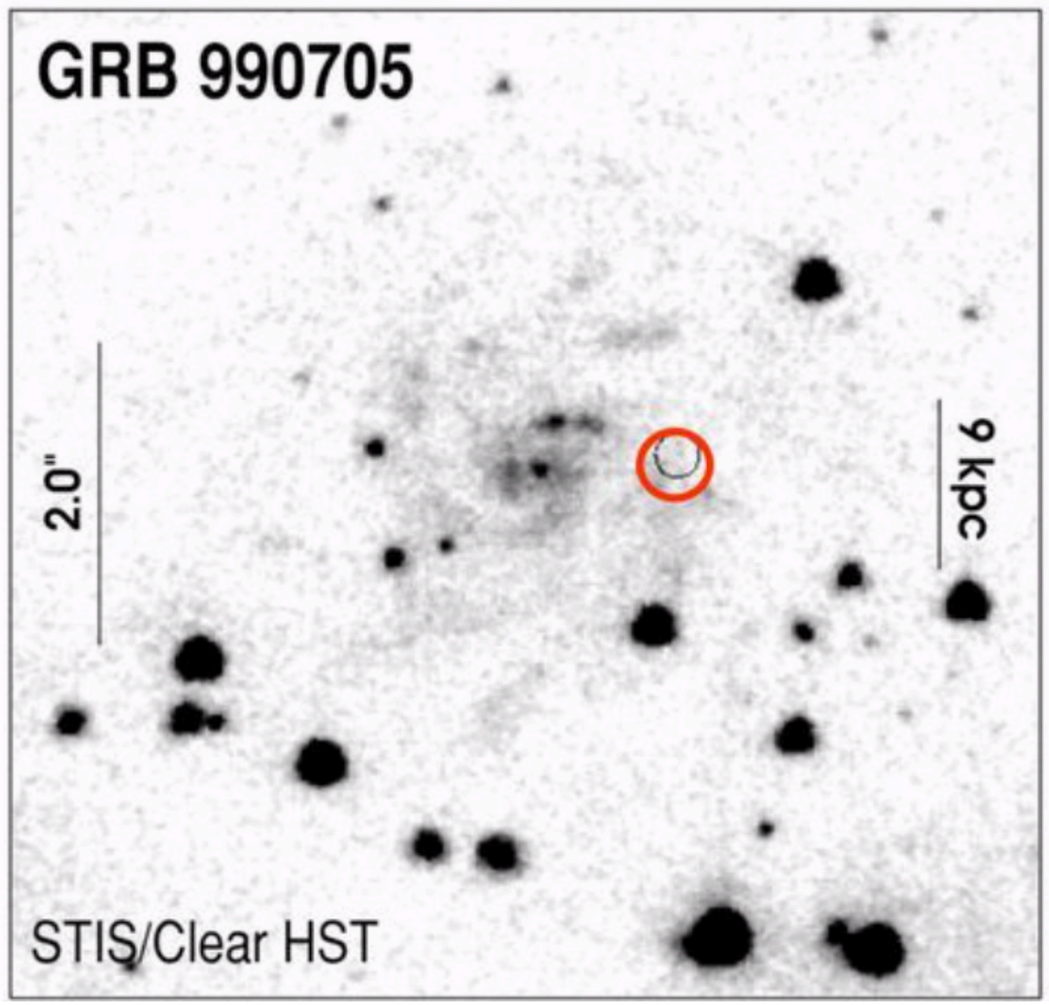


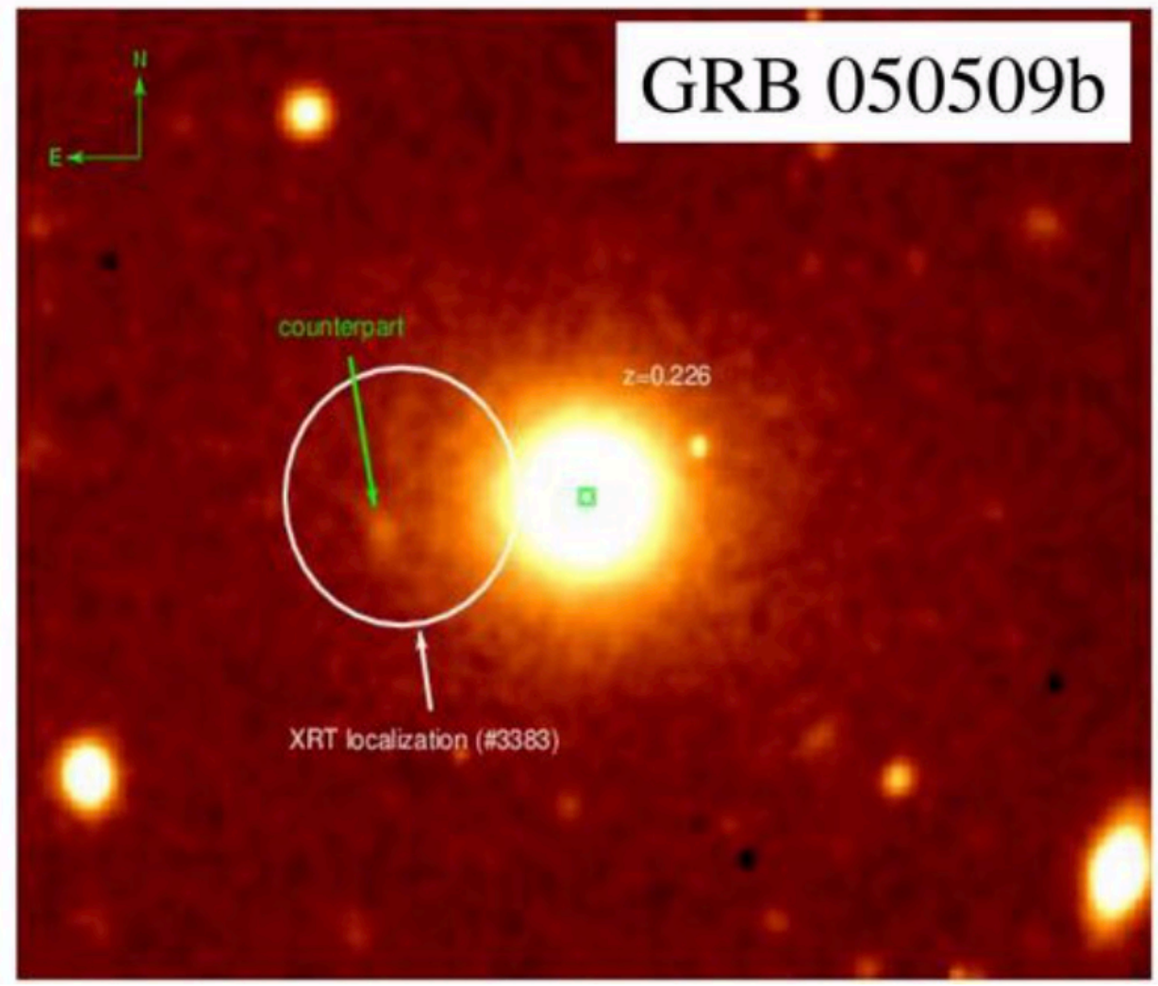
Taux de formation stellaire élevé



Population stellaire âgée

Etude de l'environnement (galaxie hôte)



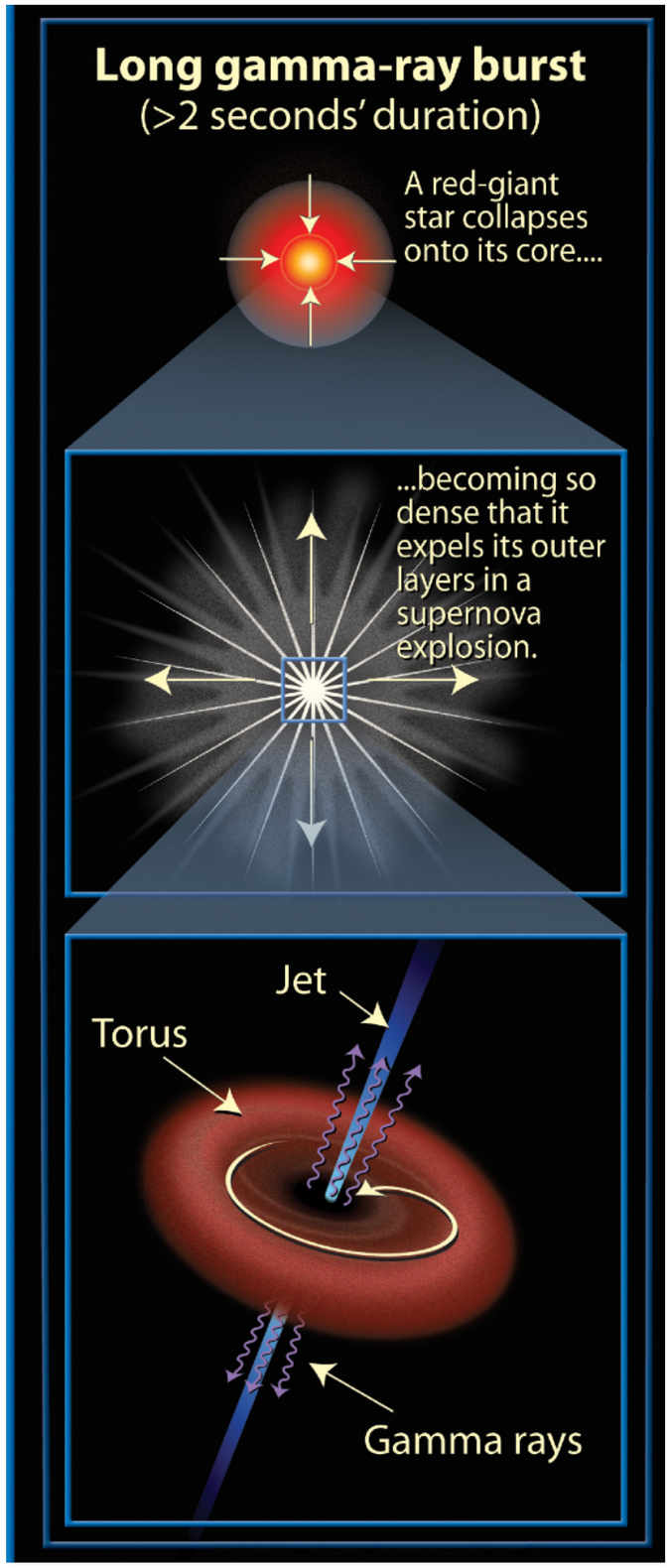


Taux de formation stellaire élevé

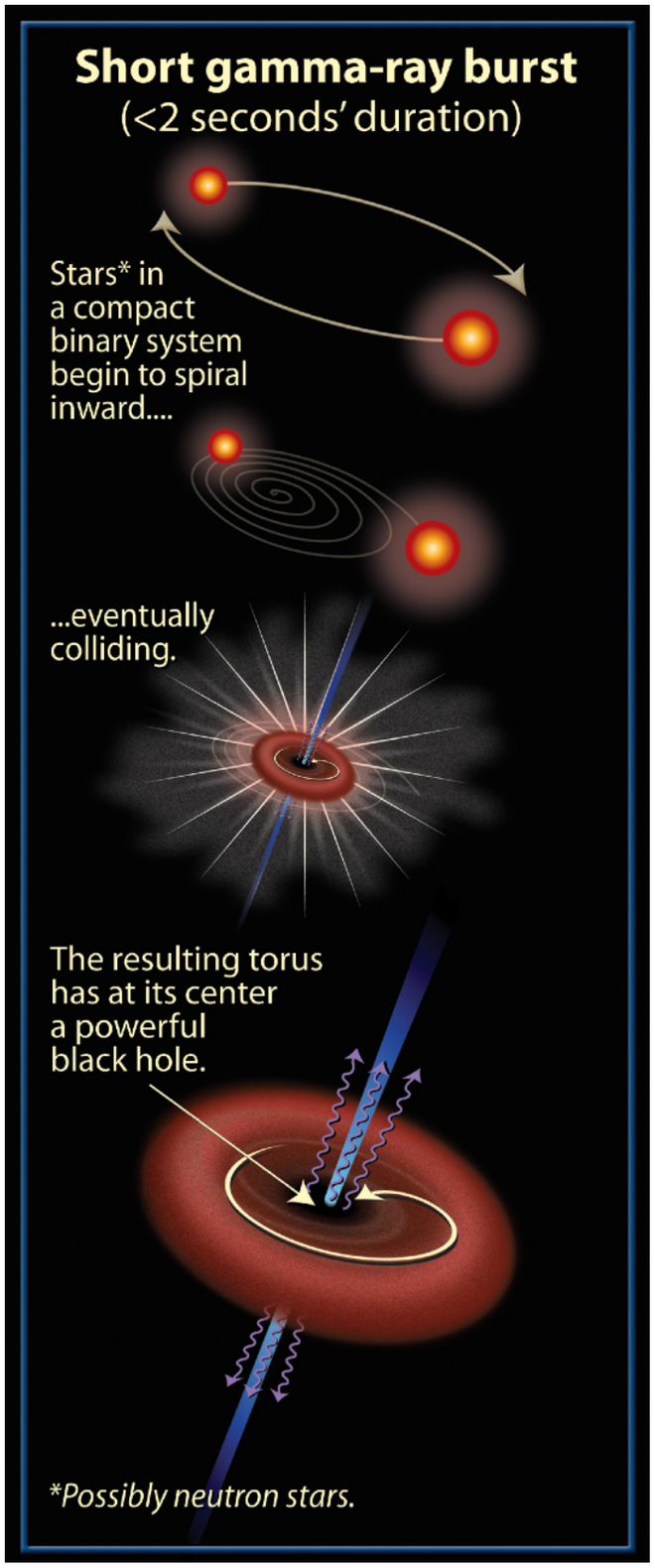
Population stellaire âgée

Sources plutôt jeunes ?

Sources plutôt vieilles ?

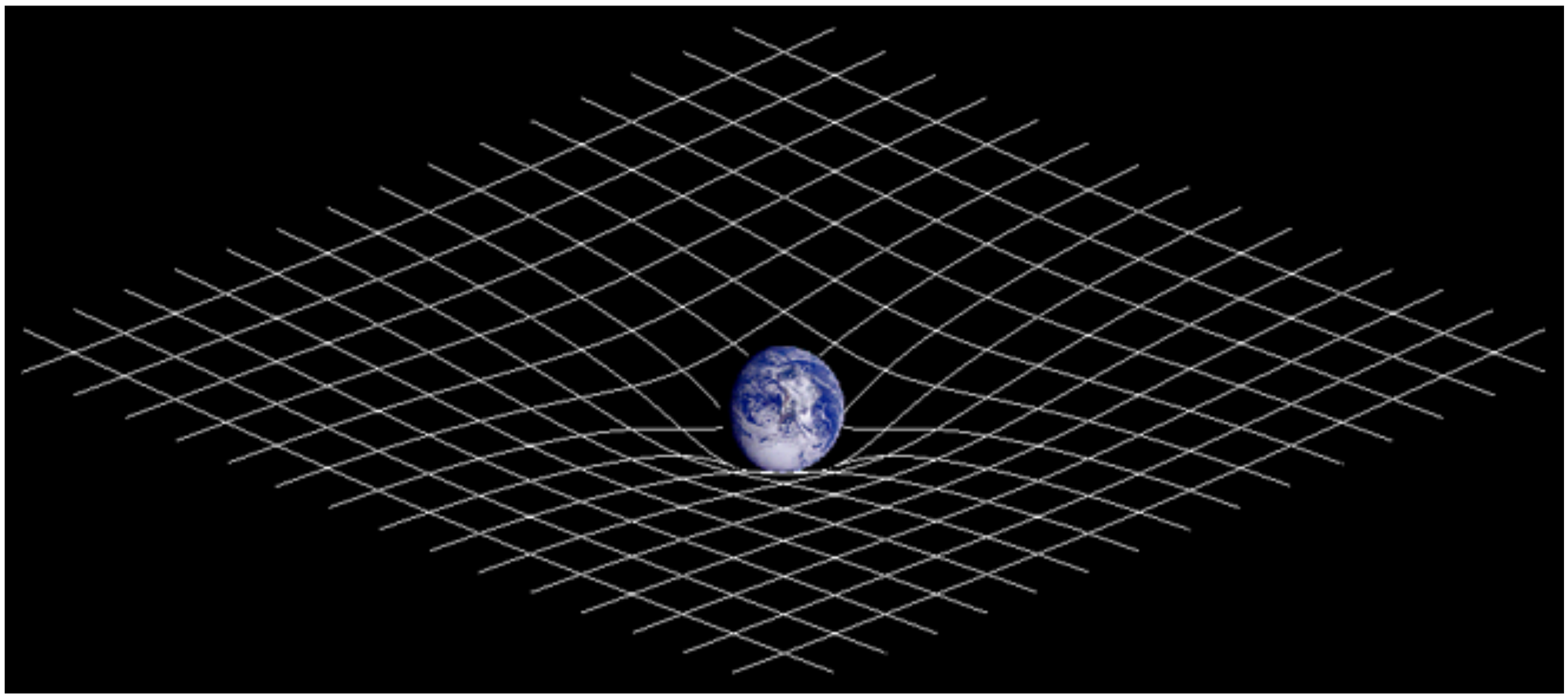


Connexion GRB long / supernova (fin de vie d'une étoile massive) ✓

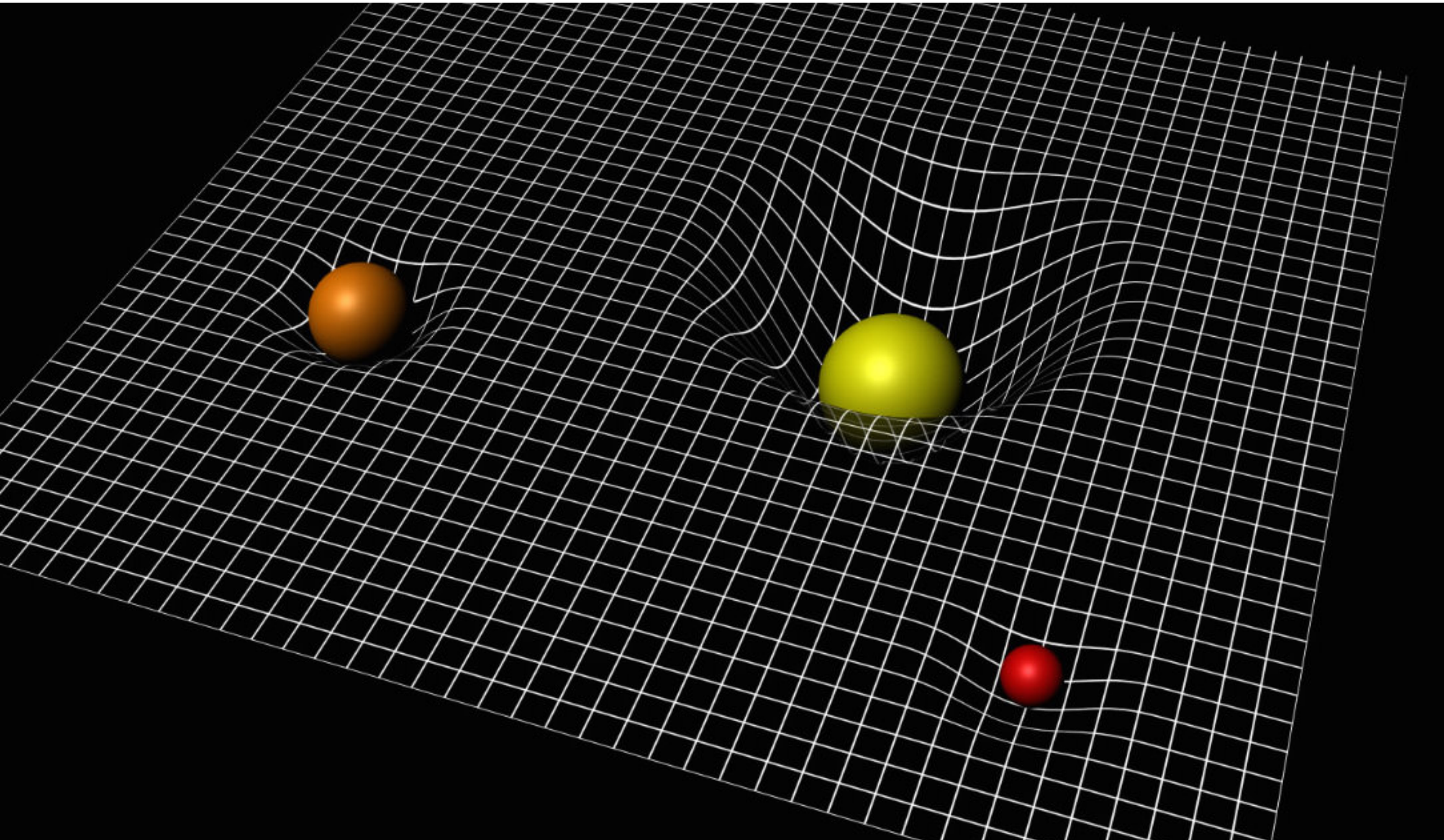


Connexion GRB court / coalescence d'étoiles à neutrons ?

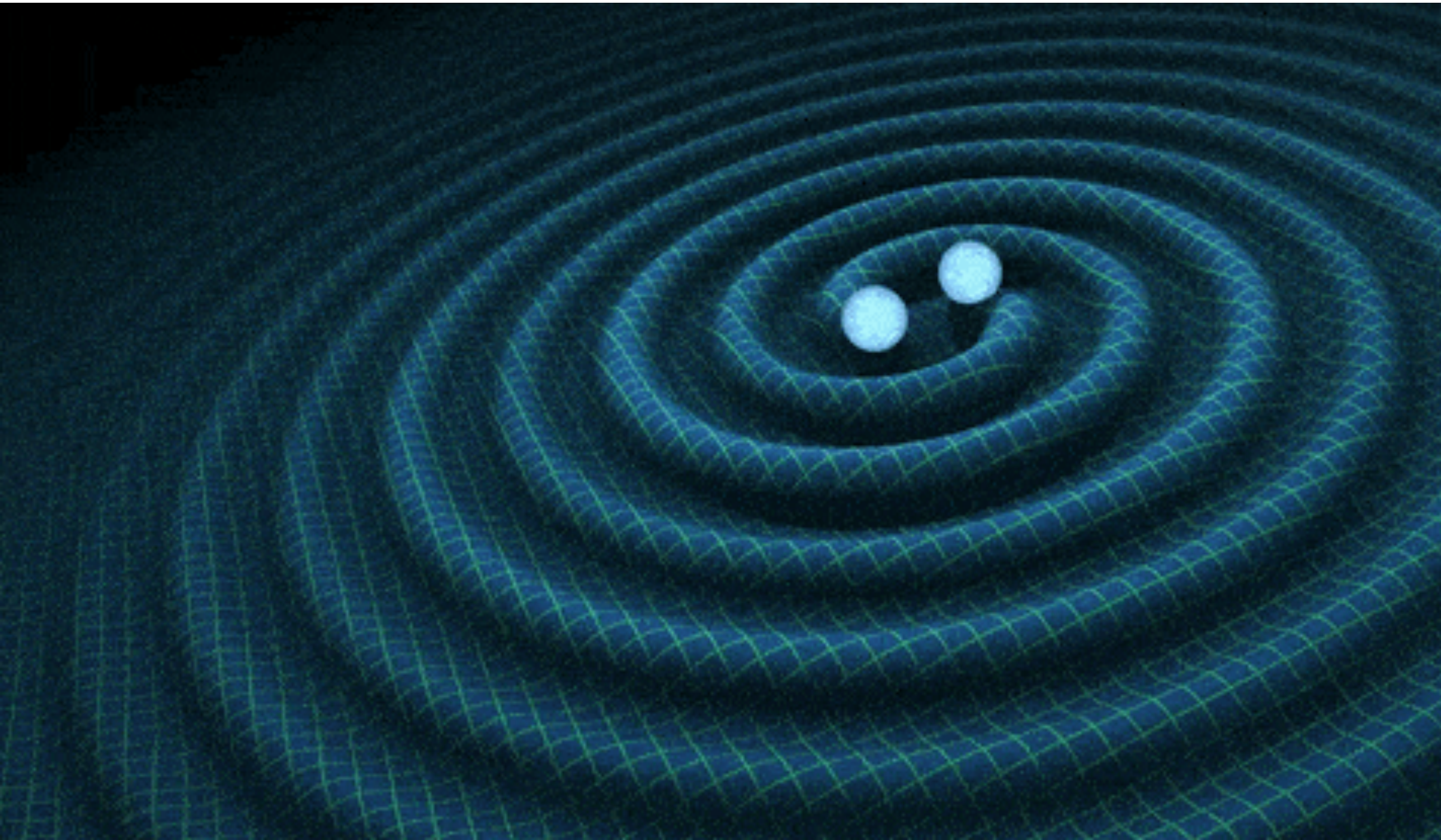
Ondes gravitationnelles



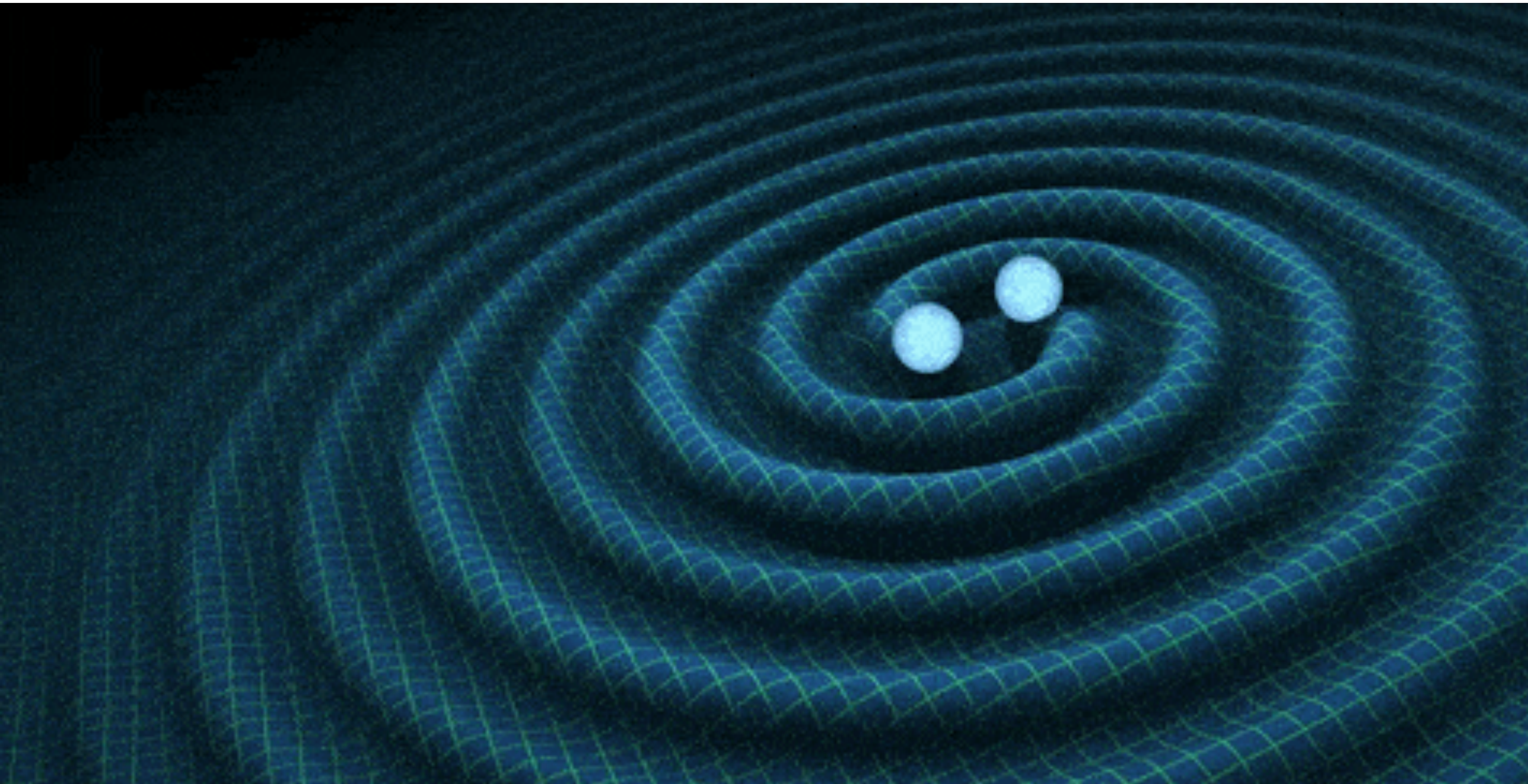
Ondes gravitationnelles



Ondes gravitationnelles

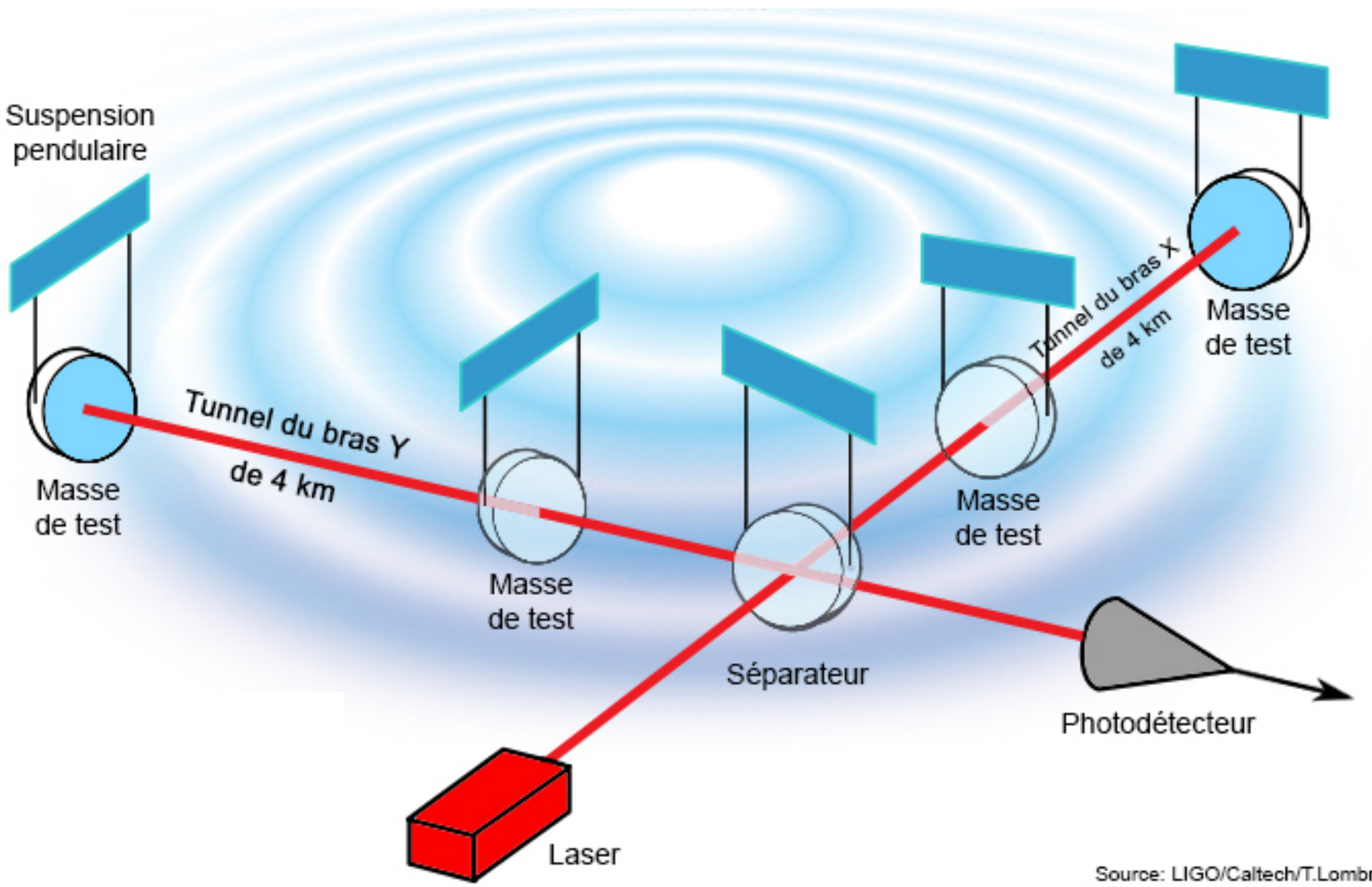


Ondes gravitationnelles



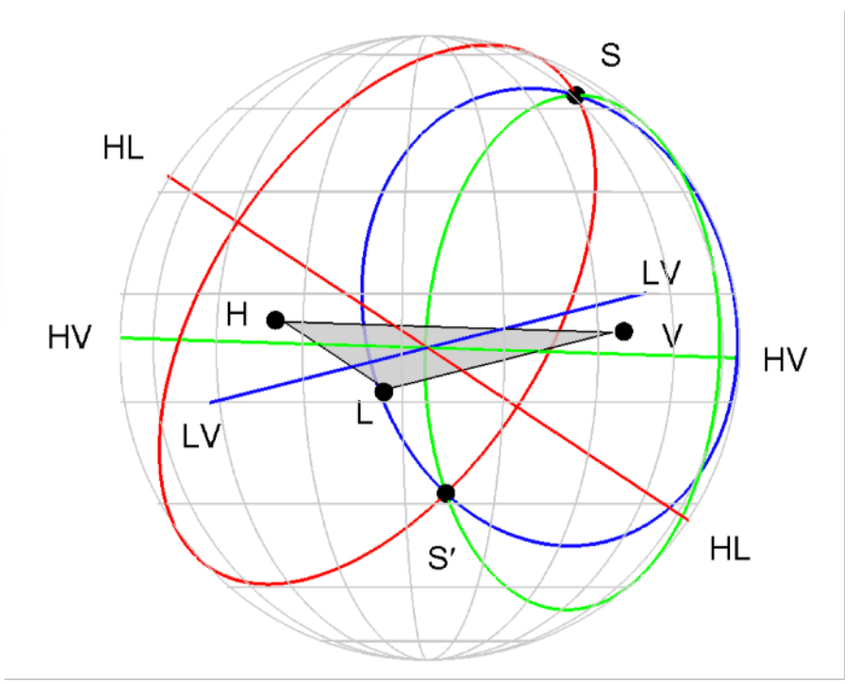
Au passage d’une onde gravitationnelle: déformation des distances (pas la même dans toutes les directions)

Détection des ondes gravitationnelles

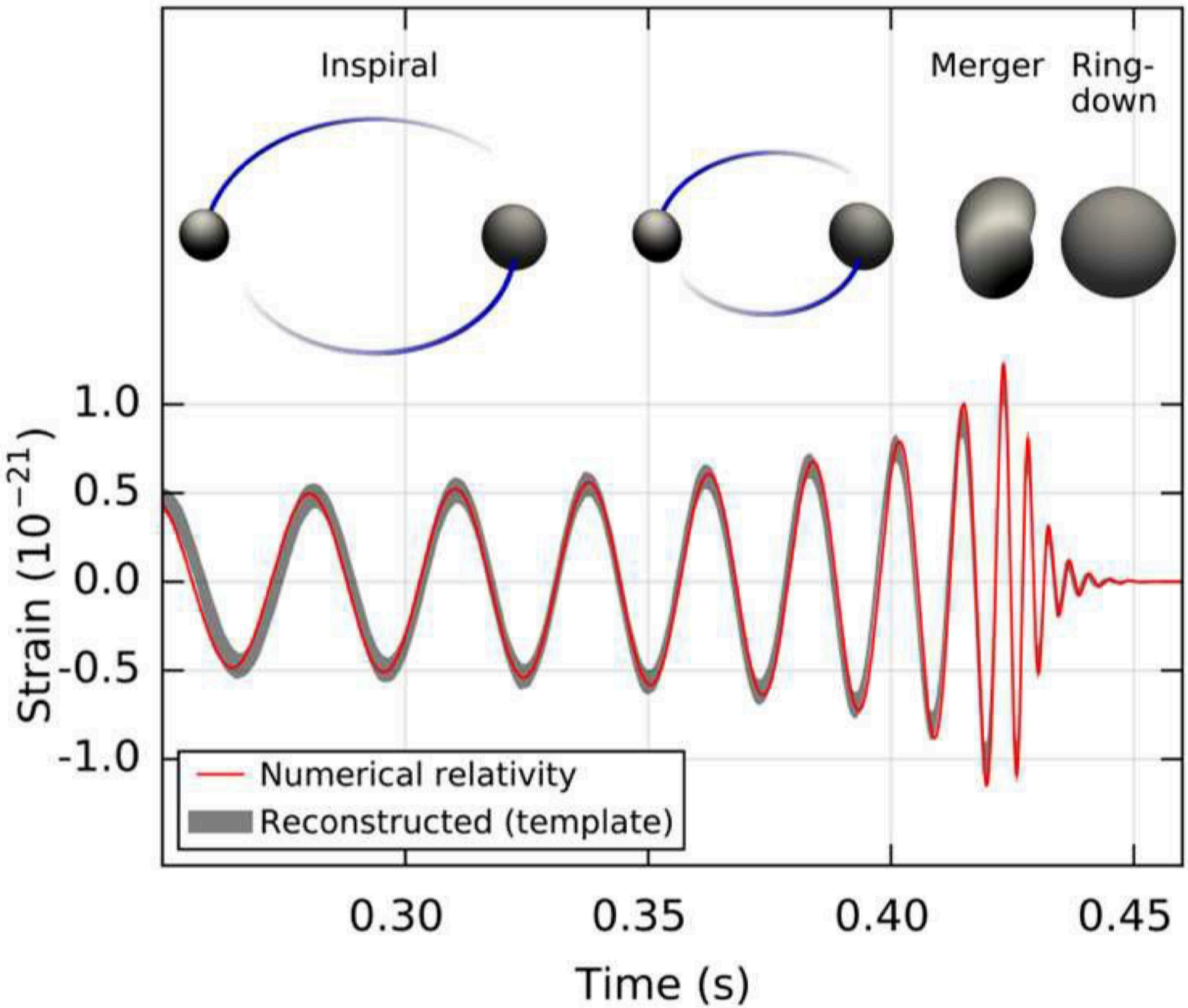


Source: LIGO/Caltech/T.Lombry

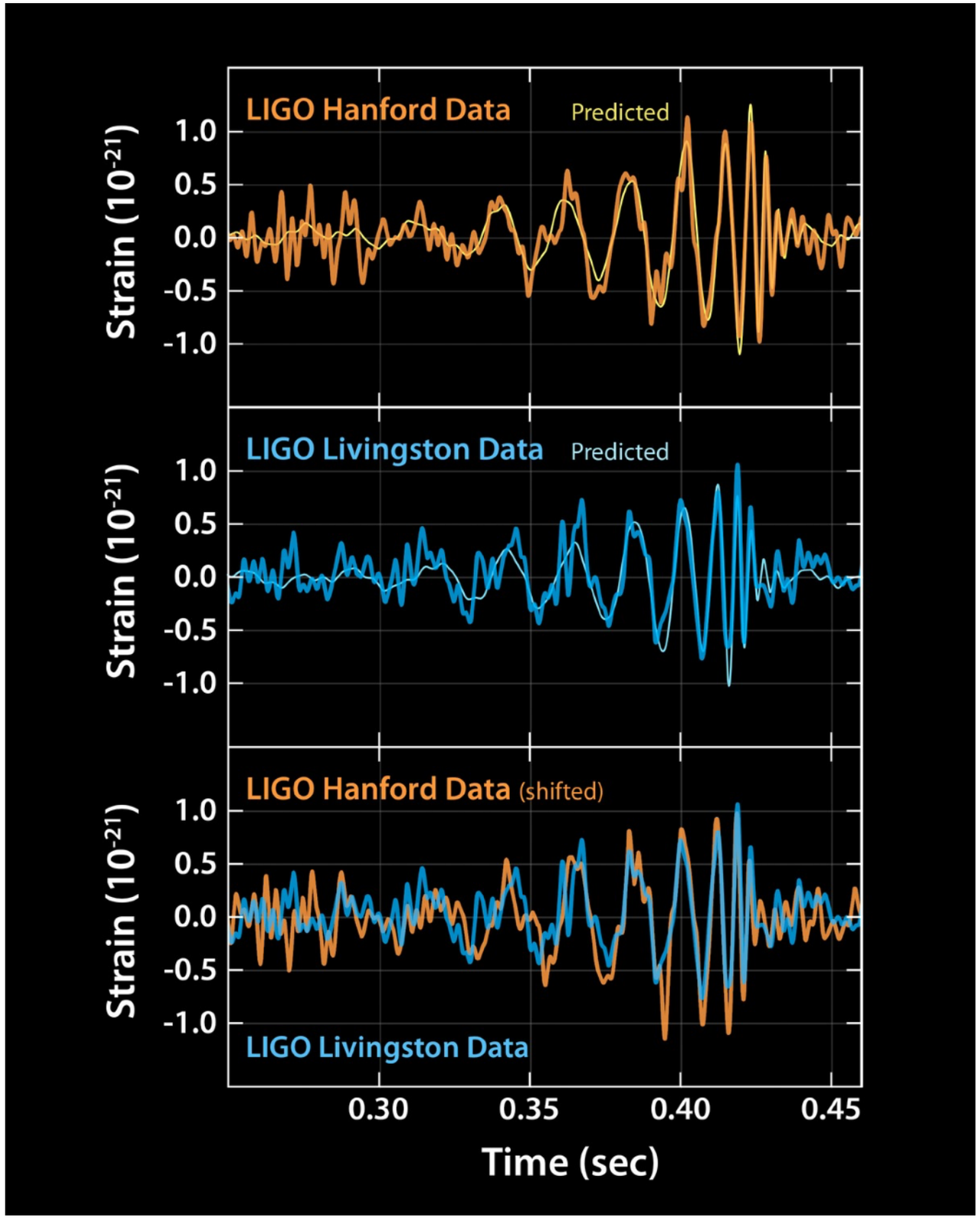
Reconstruction de la position de la source par triangulation



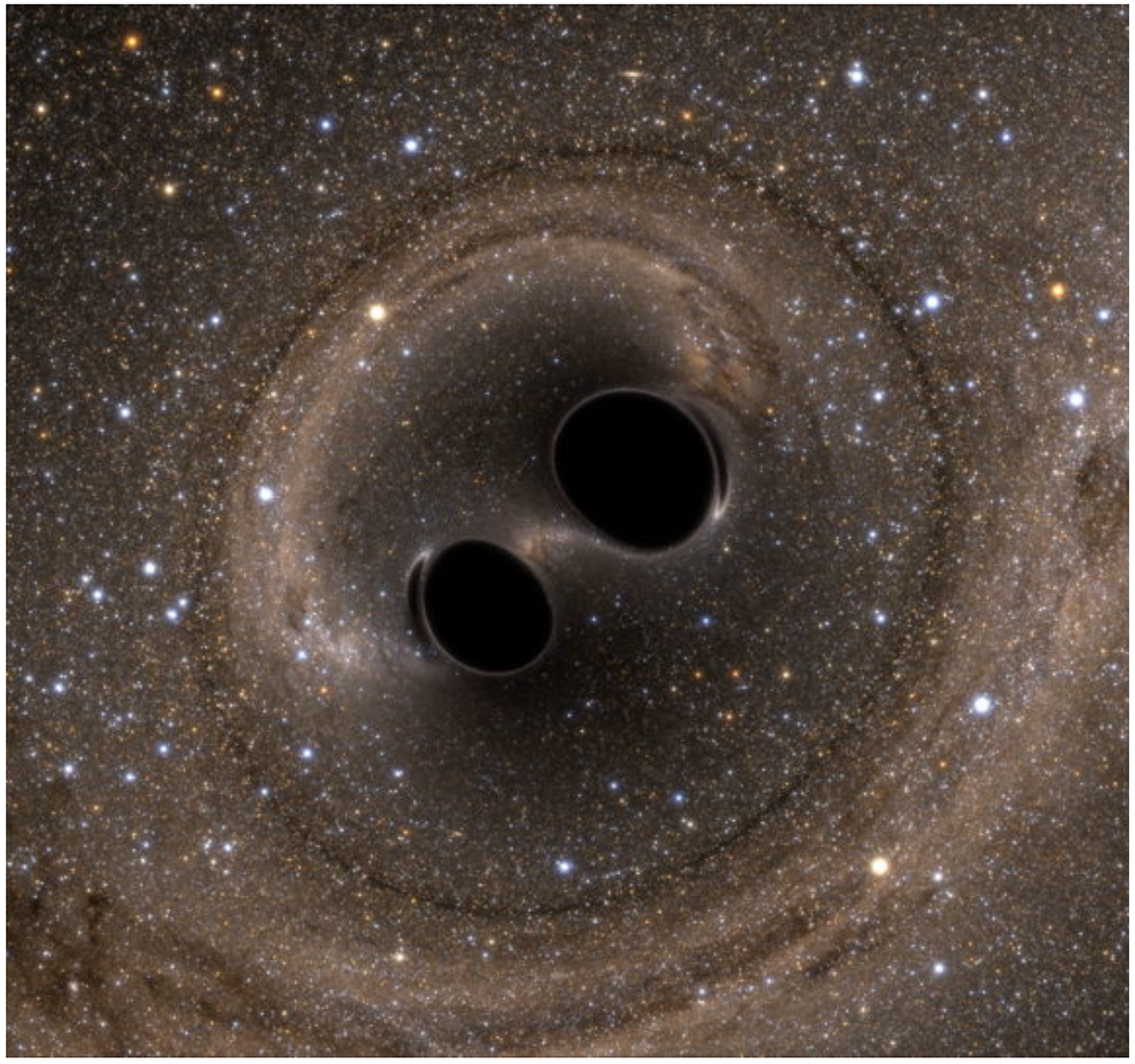
Signal attendu lors d'une coalescence



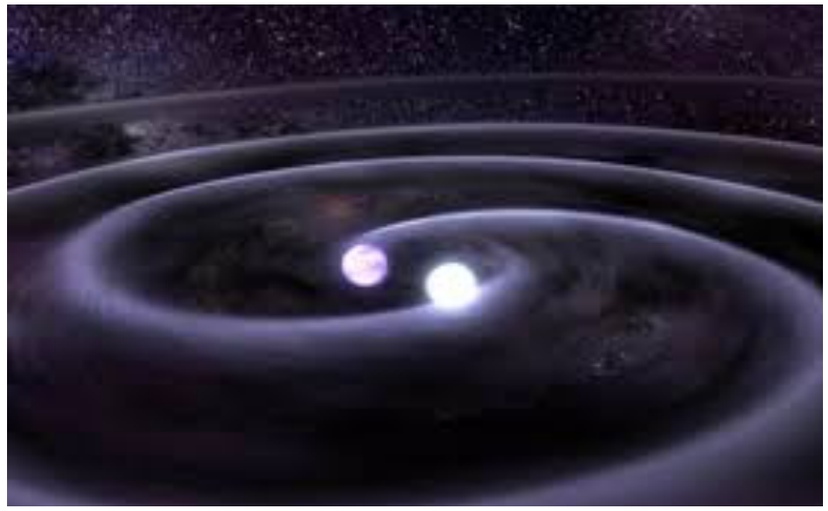
Première détection le 14/09/2015

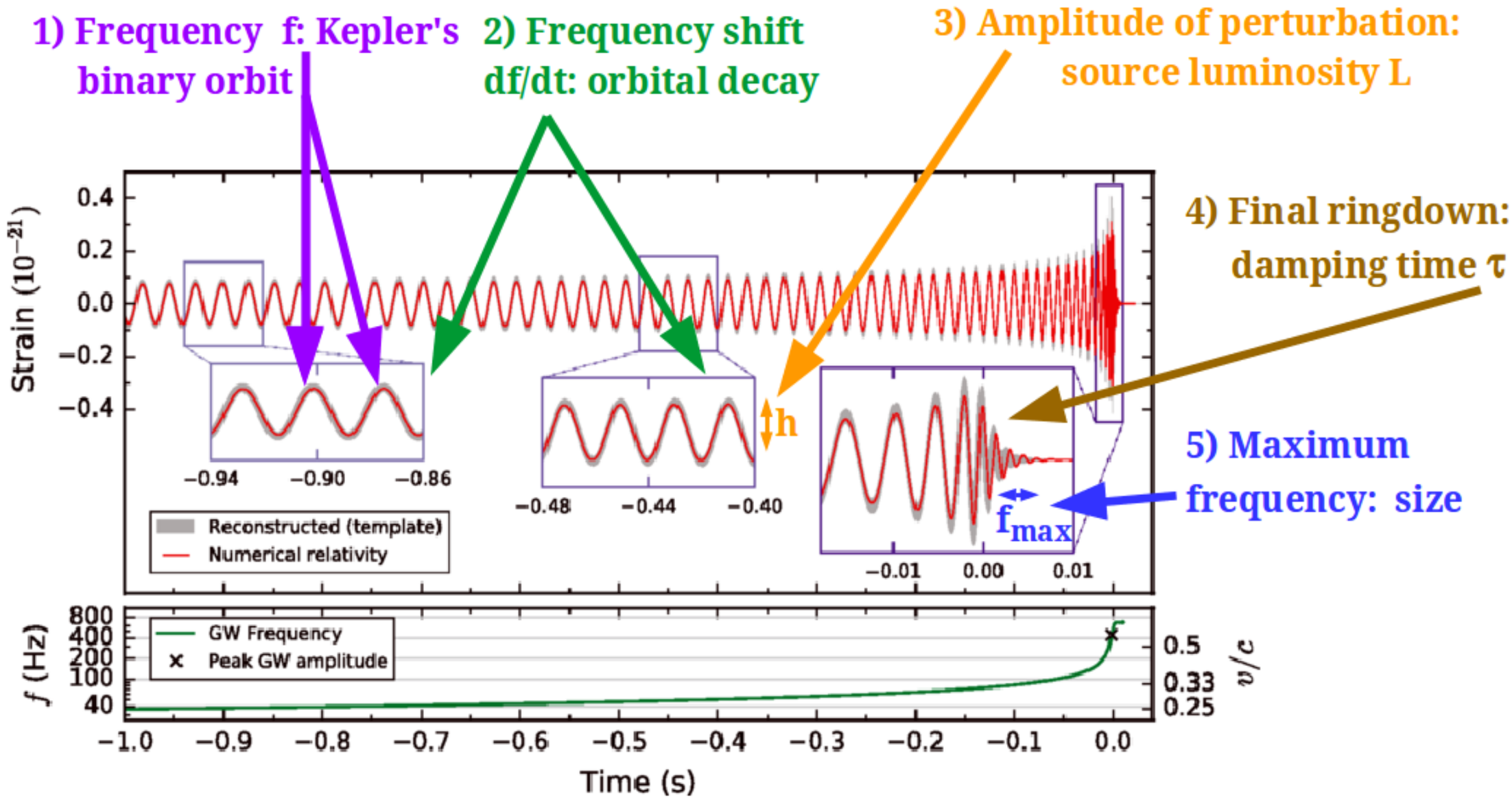


Coalescence de **deux trous noirs** de quelques dizaines de masse solaire

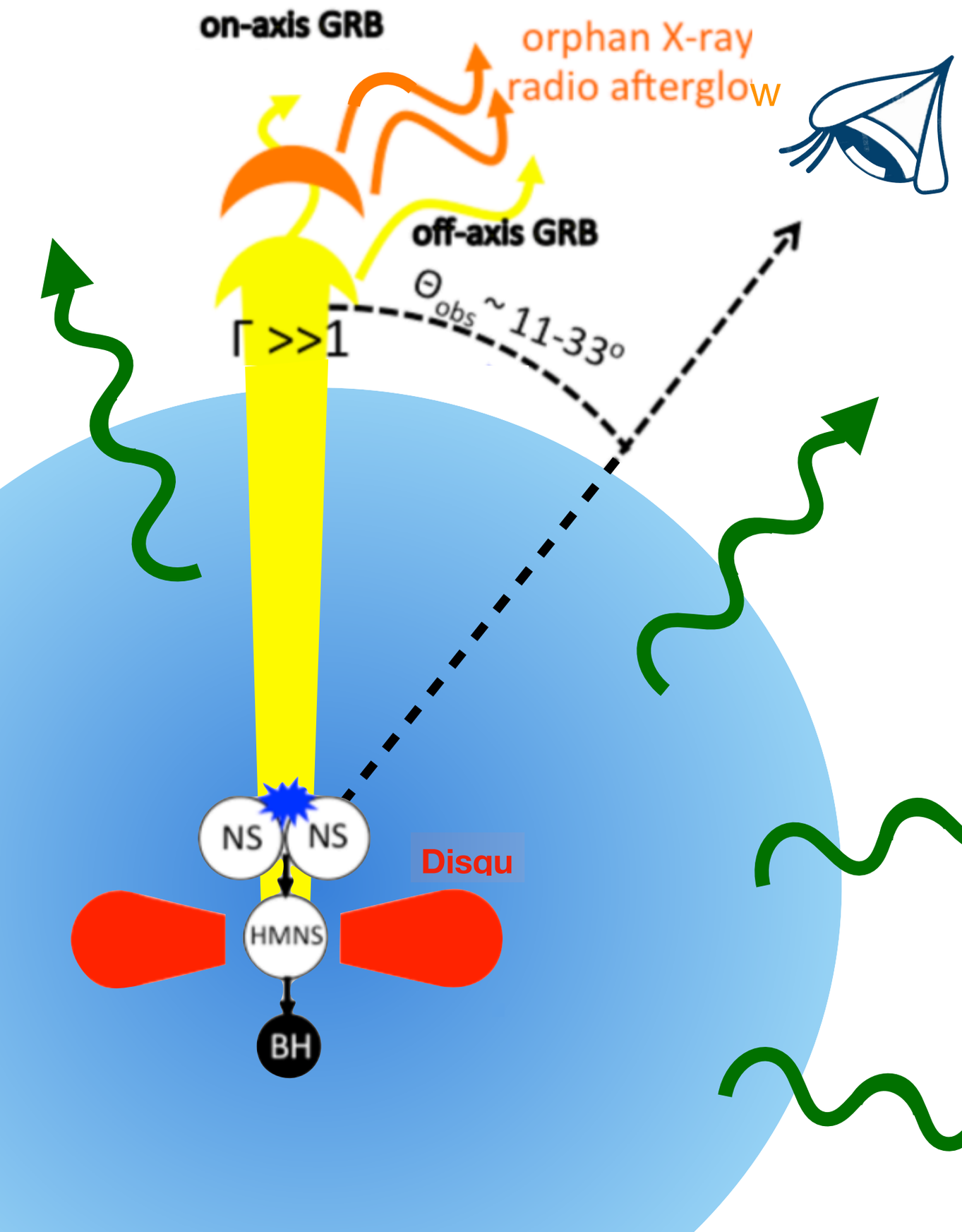


Quelles prédictions observationnelles dans le cas de deux étoiles à neutrons ?



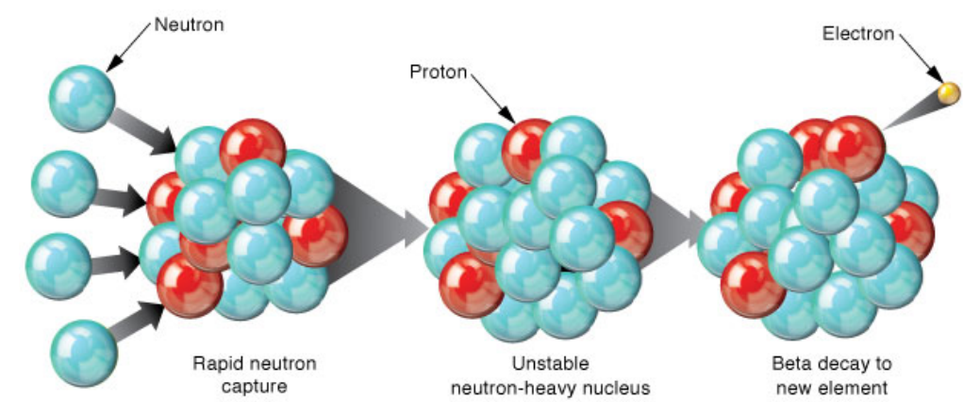


Signal électromagnétique attendu (si étoile à neutrons)



- **Production des éléments au delà du Plomb**
- **« Processus r »**

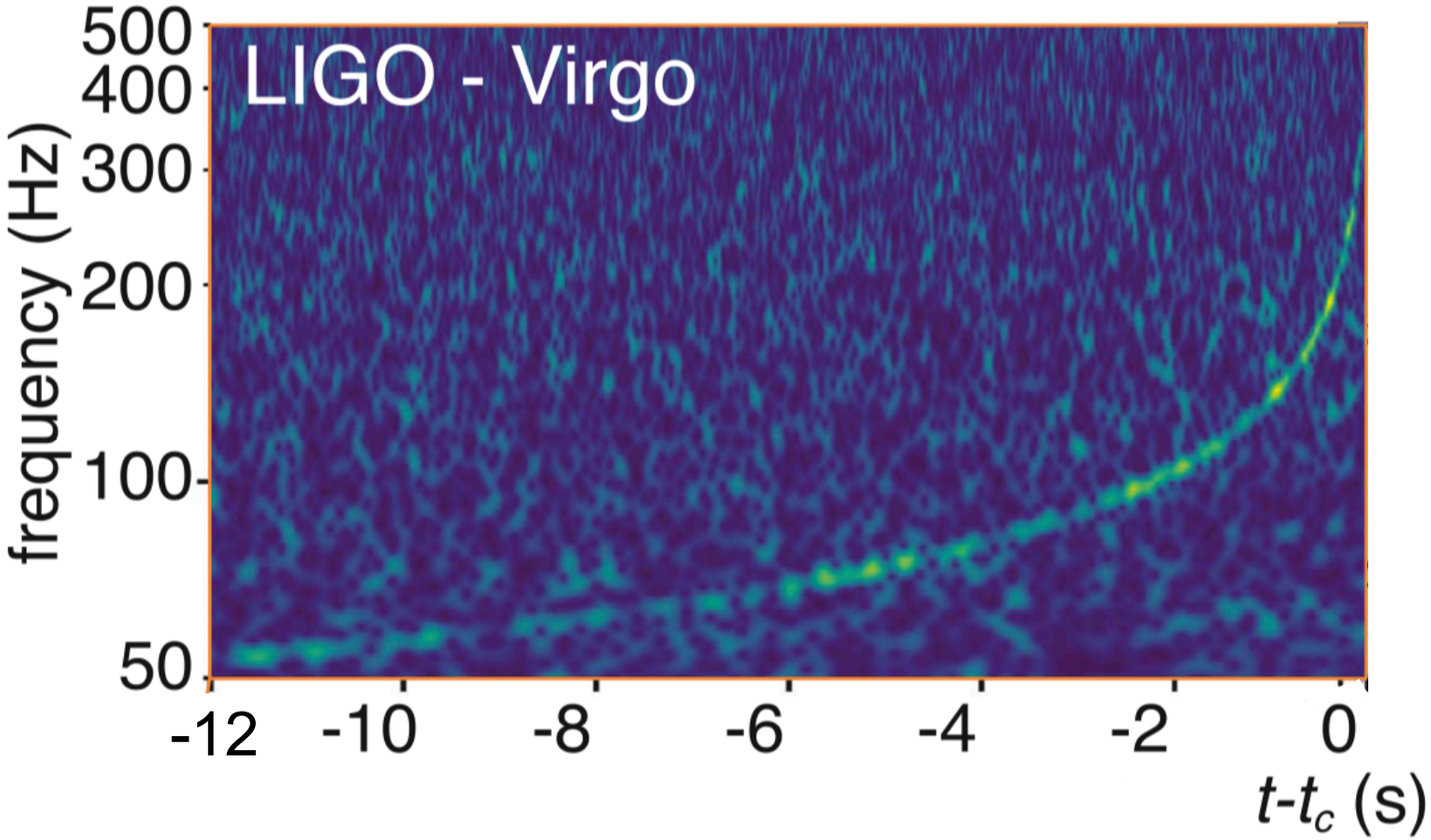
- **Doit intervenir dans un environnement dense en neutrons**



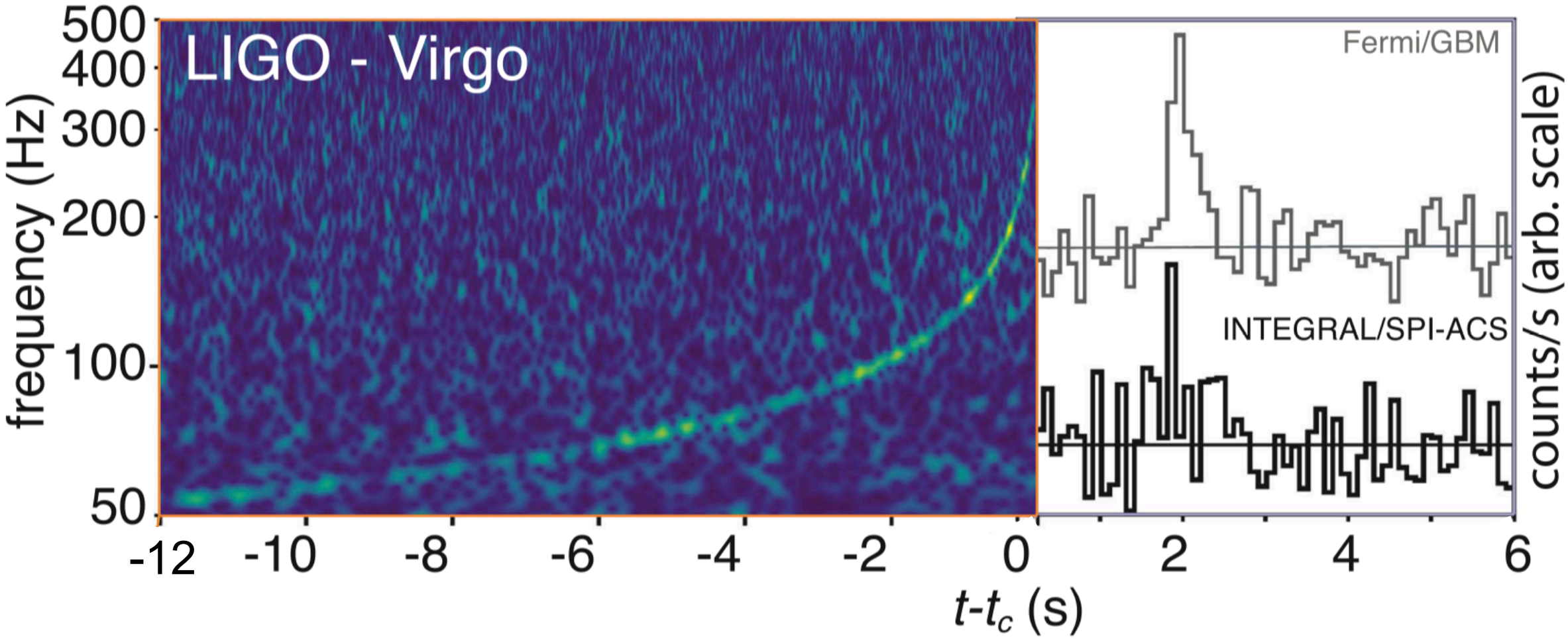
Kilonova (visible / infrarouge)

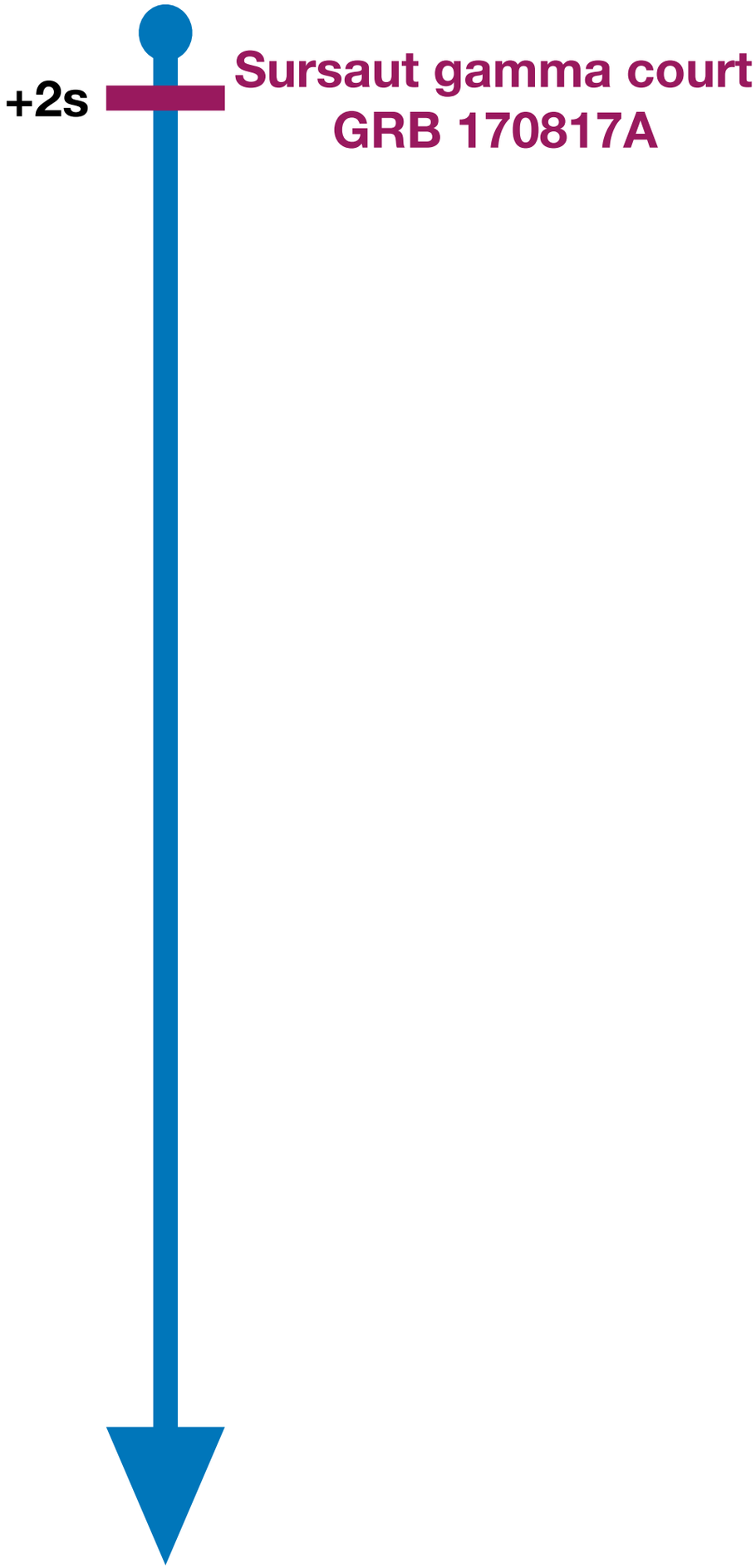
Signal d’ondes gravitationnelles GW170817

17 août 2017 à 14h41m04s …



17 août 2017 à 14h41m04s …



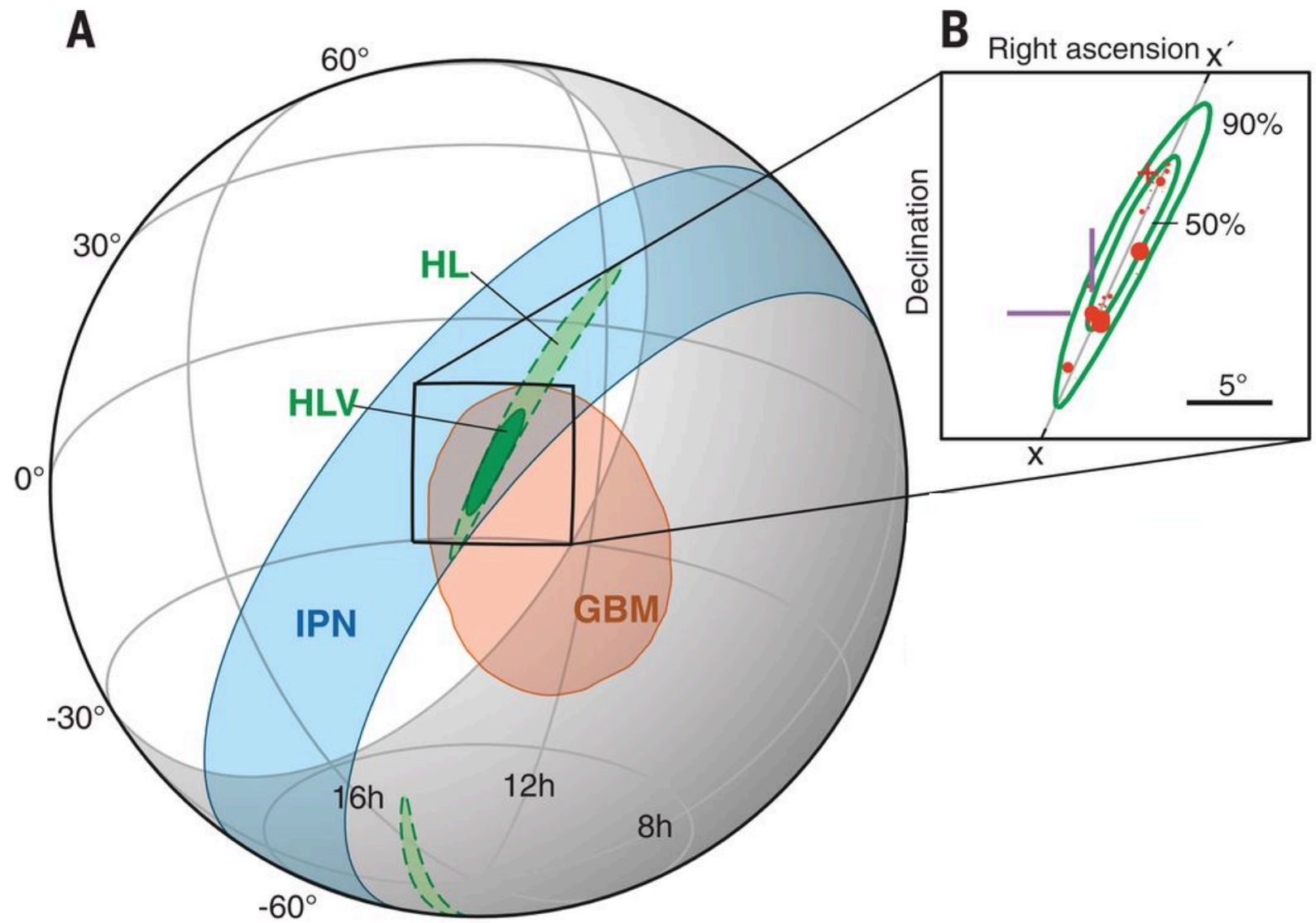

+2s
Sursaut gamma court
GRB 170817A

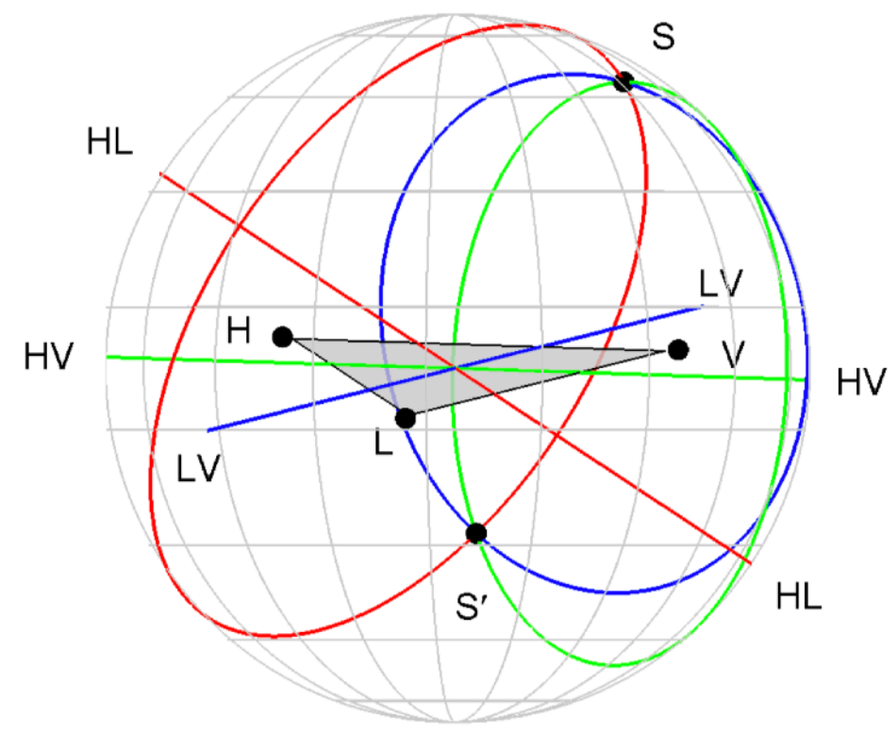
+2s

Sursaut gamma court
GRB 170817A

+5h

Localisation
(30°², 42 Mpc)



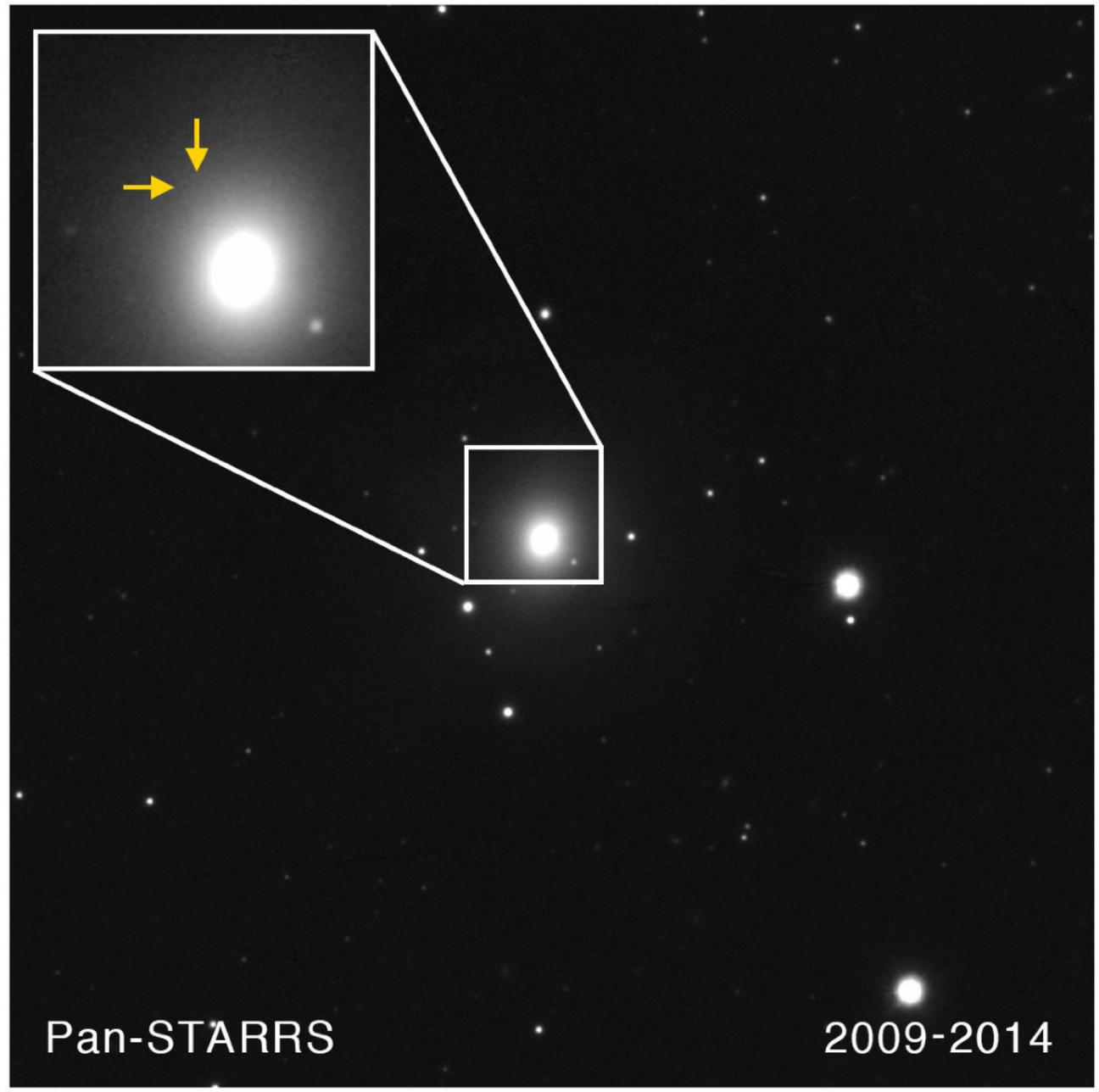


Objectif : localiser la source le plus rapidement possible…

+2s **Sursaut gamma court GRB 170817A**

+5h **Localisation (30°², 42 Mpc)**

+11h **Contrepartie visible AT2017gfo / NGC4993**

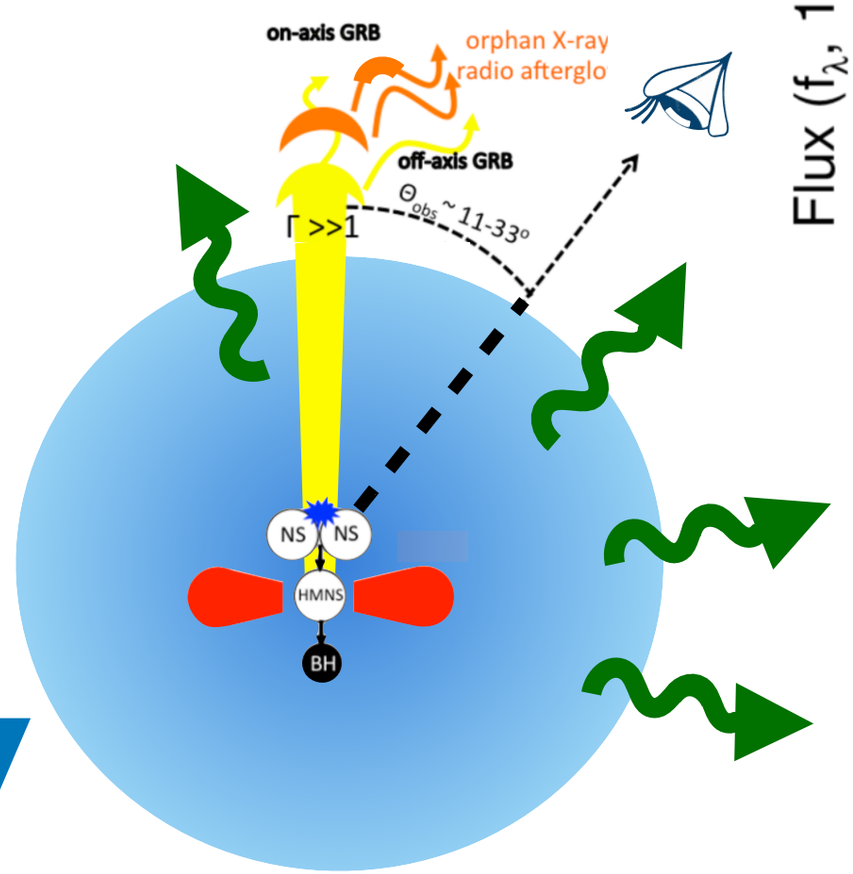


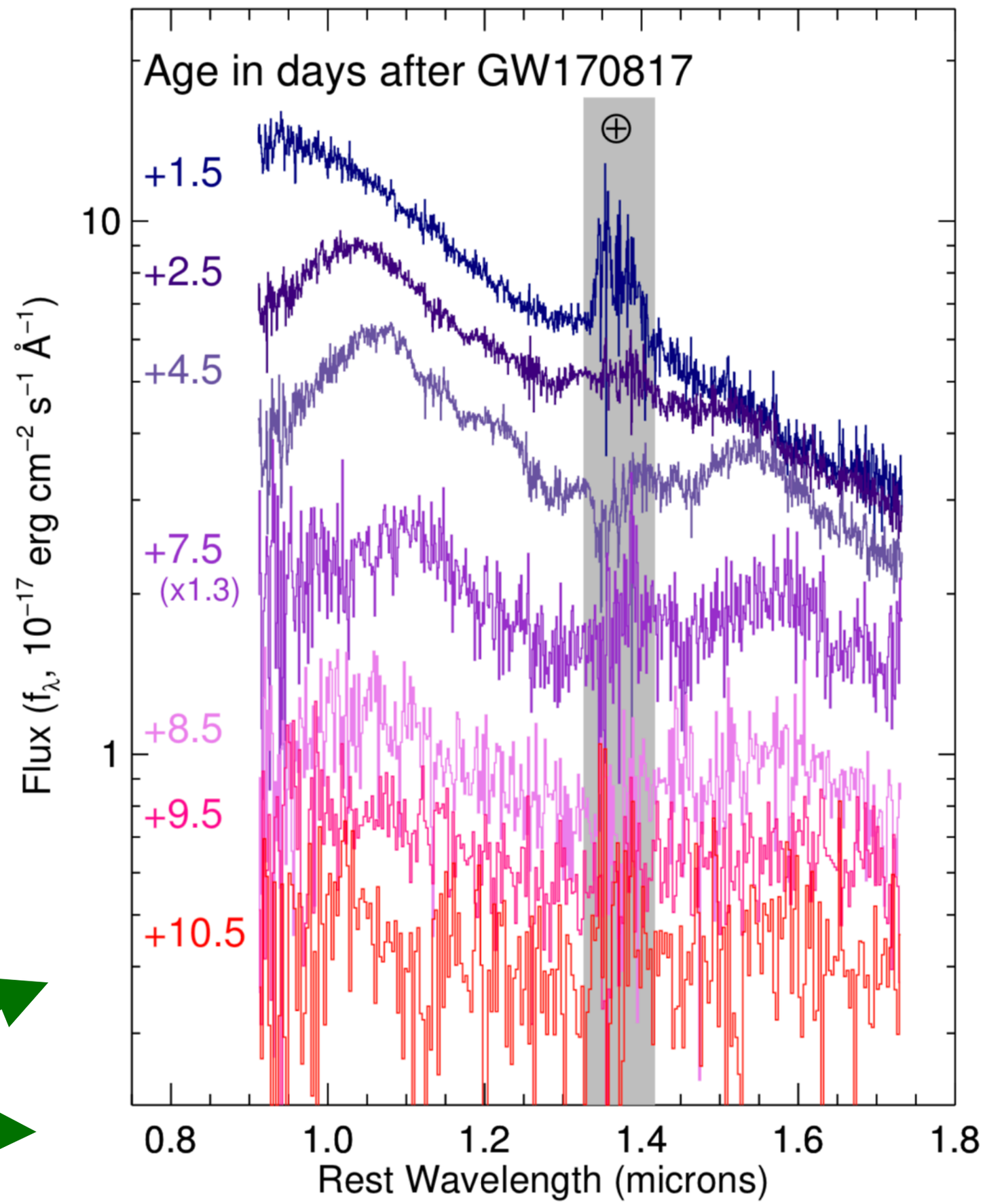
+2s **Sursaut gamma court GRB 170817A**

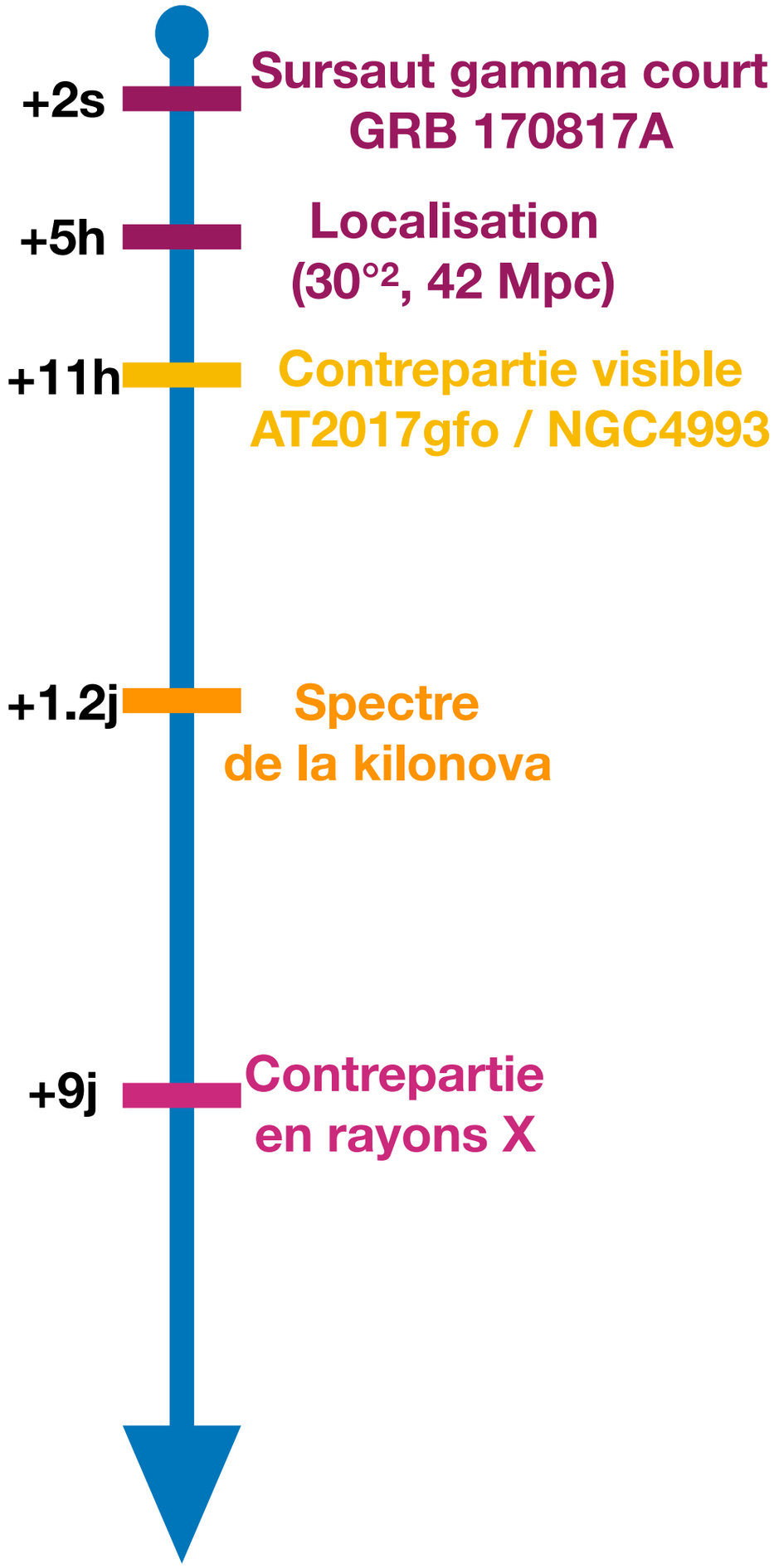
+5h **Localisation (30°², 42 Mpc)**

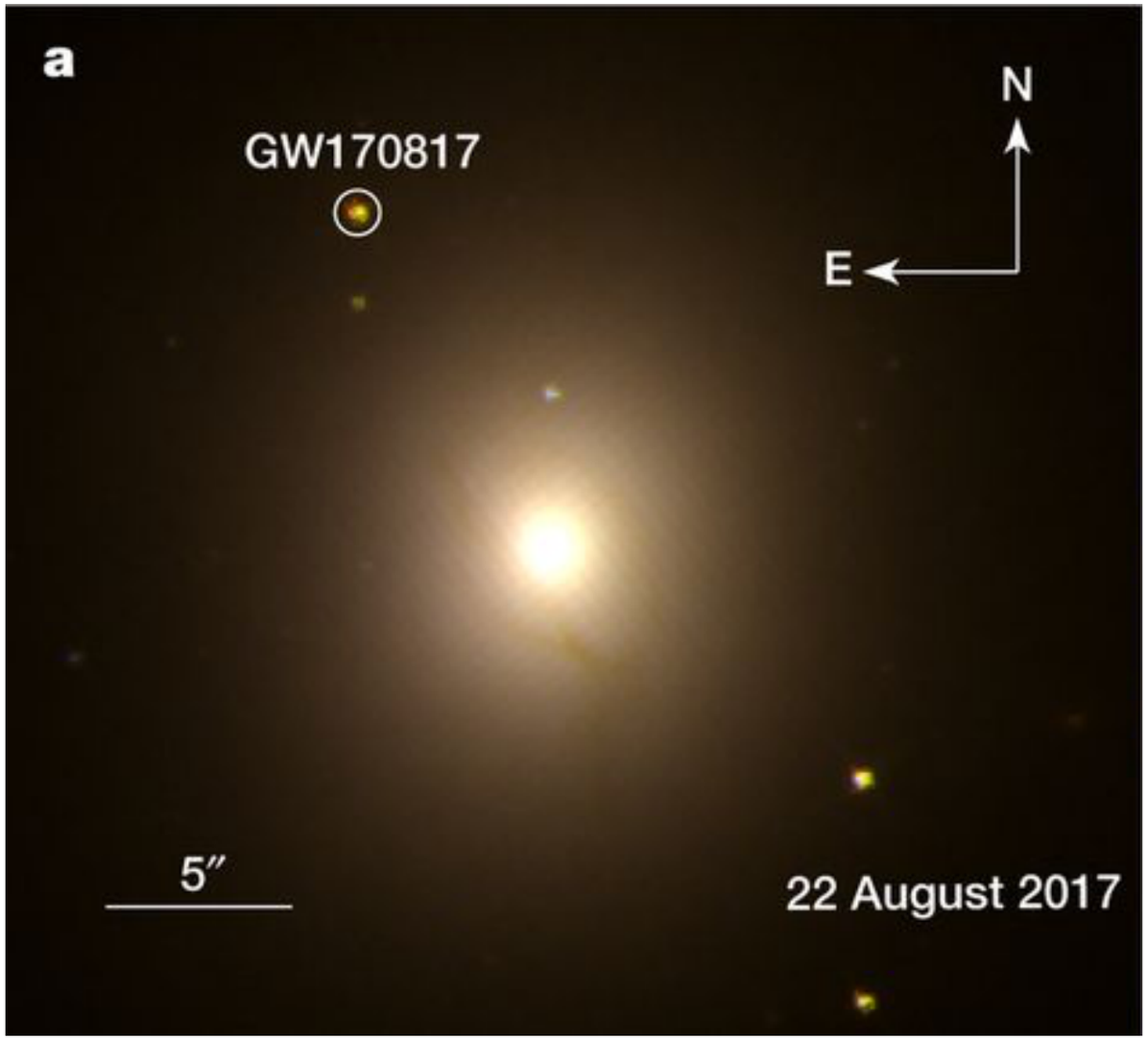
+11h **Contrepartie visible AT2017gfo / NGC4993**

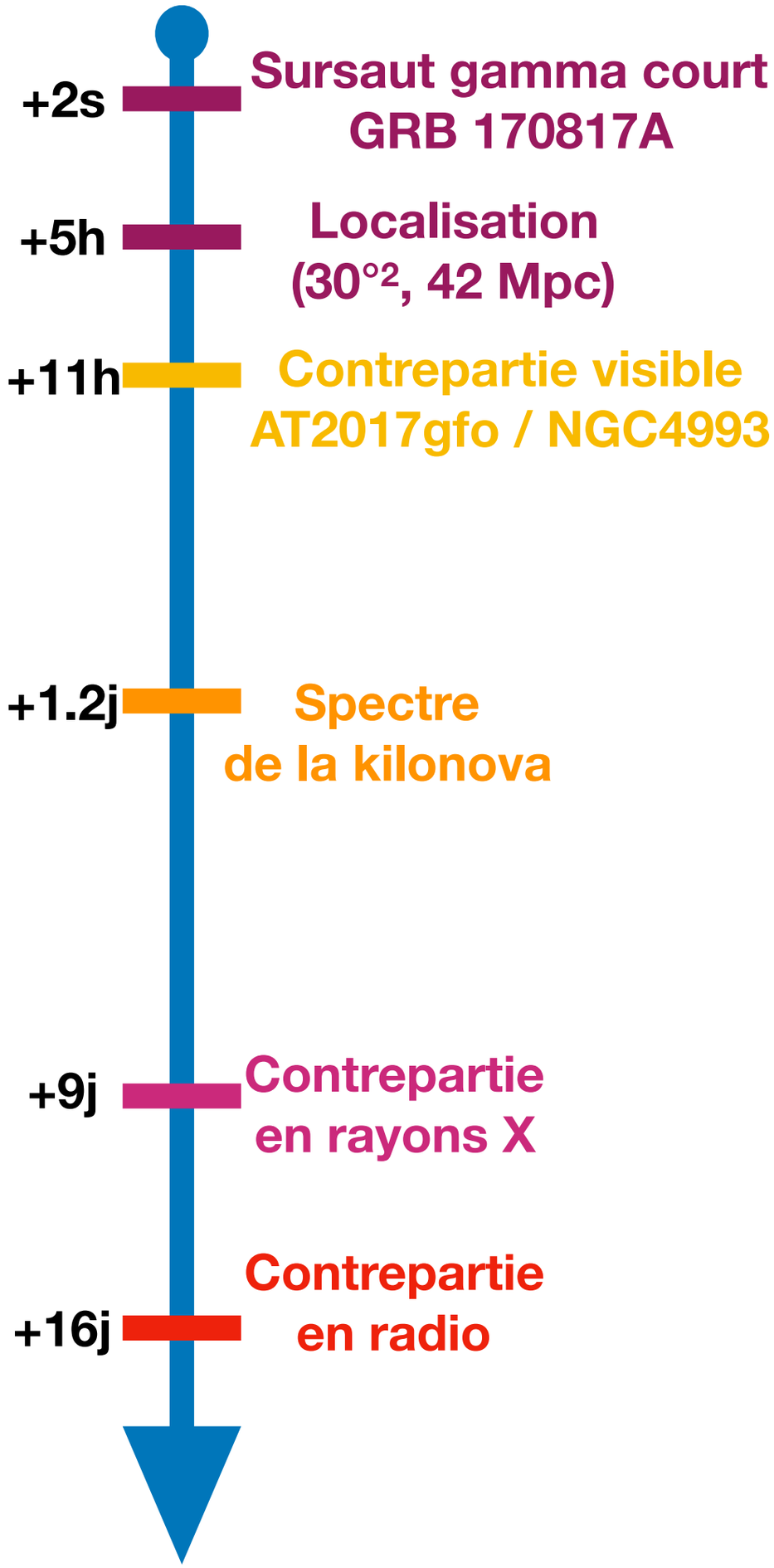
+1.2j **Spectre de la kilonova**

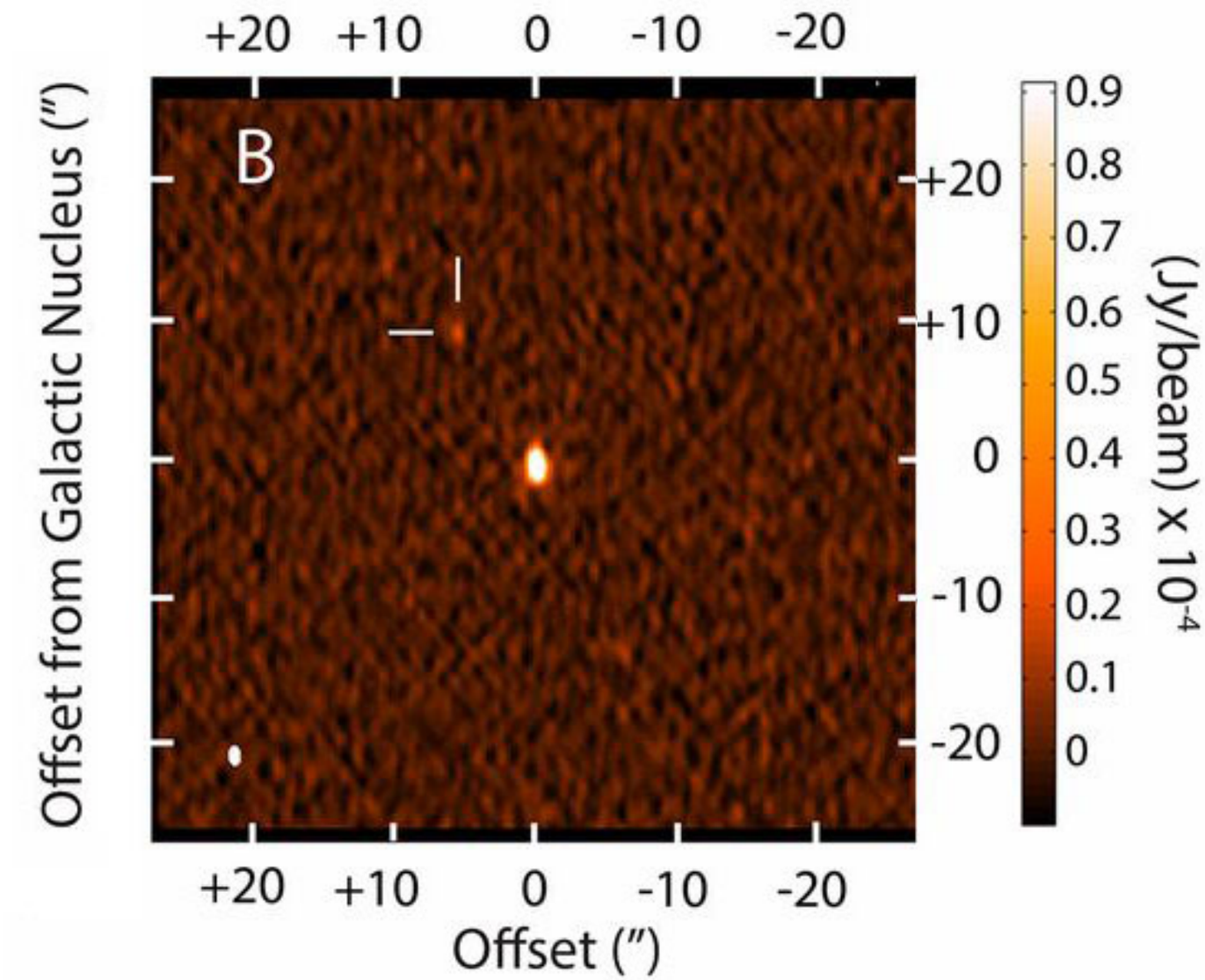




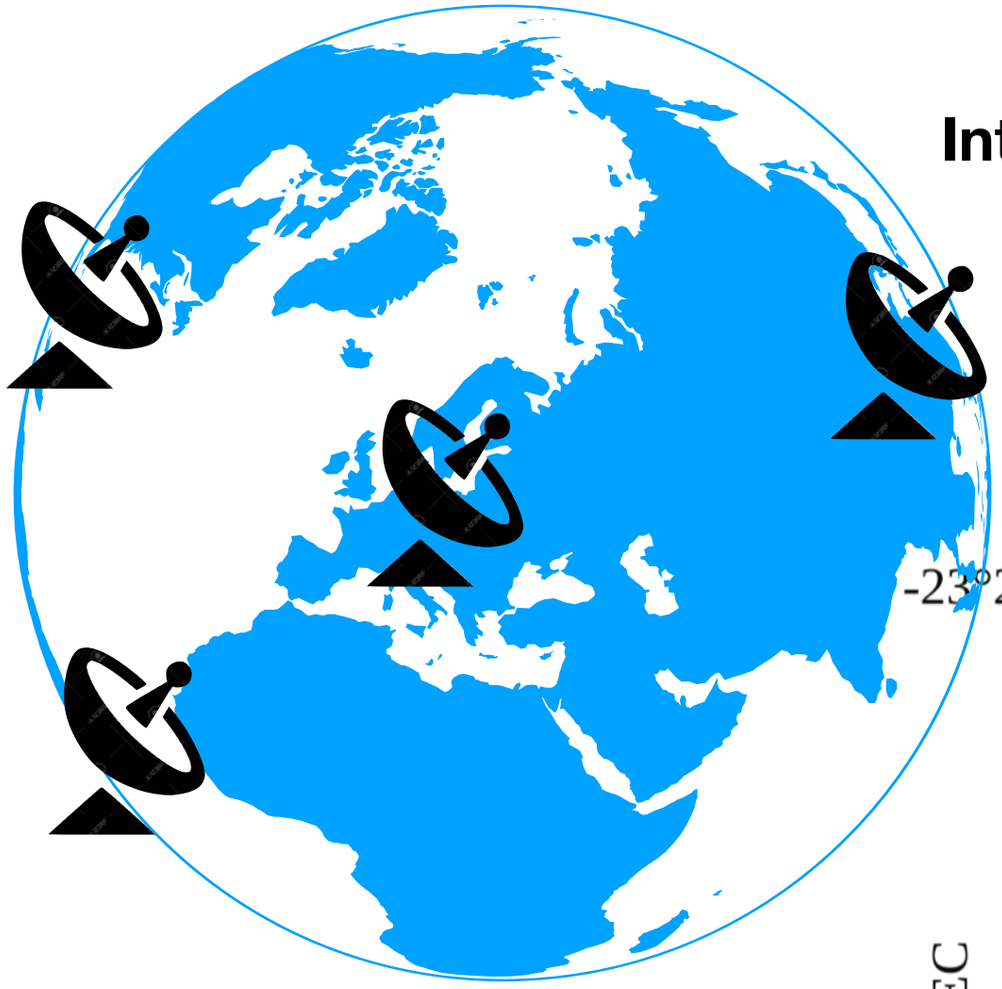

+2s
Sursaut gamma court
GRB 170817A
+5h
Localisation
(30°², 42 Mpc)
+11h
Contrepartie visible
AT2017gfo / NGC4993
+1.2j
Spectre
de la kilonova
+9j
Contrepartie
en rayons X


a
GW170817
N
E
5″
22 August 2017

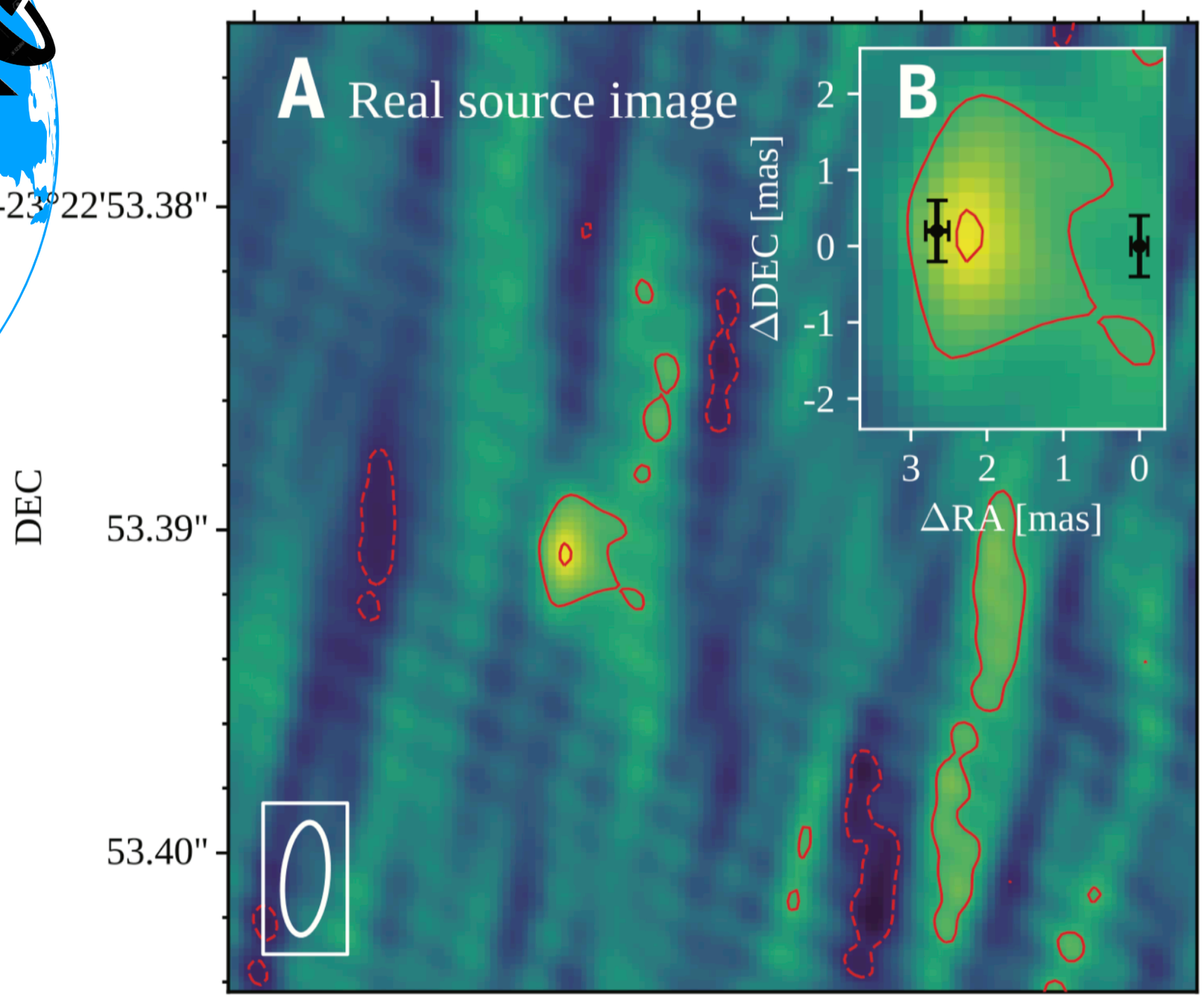

+2s
Sursaut gamma court
GRB 170817A
+5h
Localisation
(30°², 42 Mpc)
+11h
Contrepartie visible
AT2017gfo / NGC4993
+1.2j
Spectre
de la kilonova
+9j
Contrepartie
en rayons X
+16j
Contrepartie
en radio


B
Offset from Galactic Nucleus (″)
Offset (″)
+20
+10
0
-10
-20
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
(Jy/beam) × 10⁻⁴

Confirmation de la présence d'un jet relativiste (février 2019)

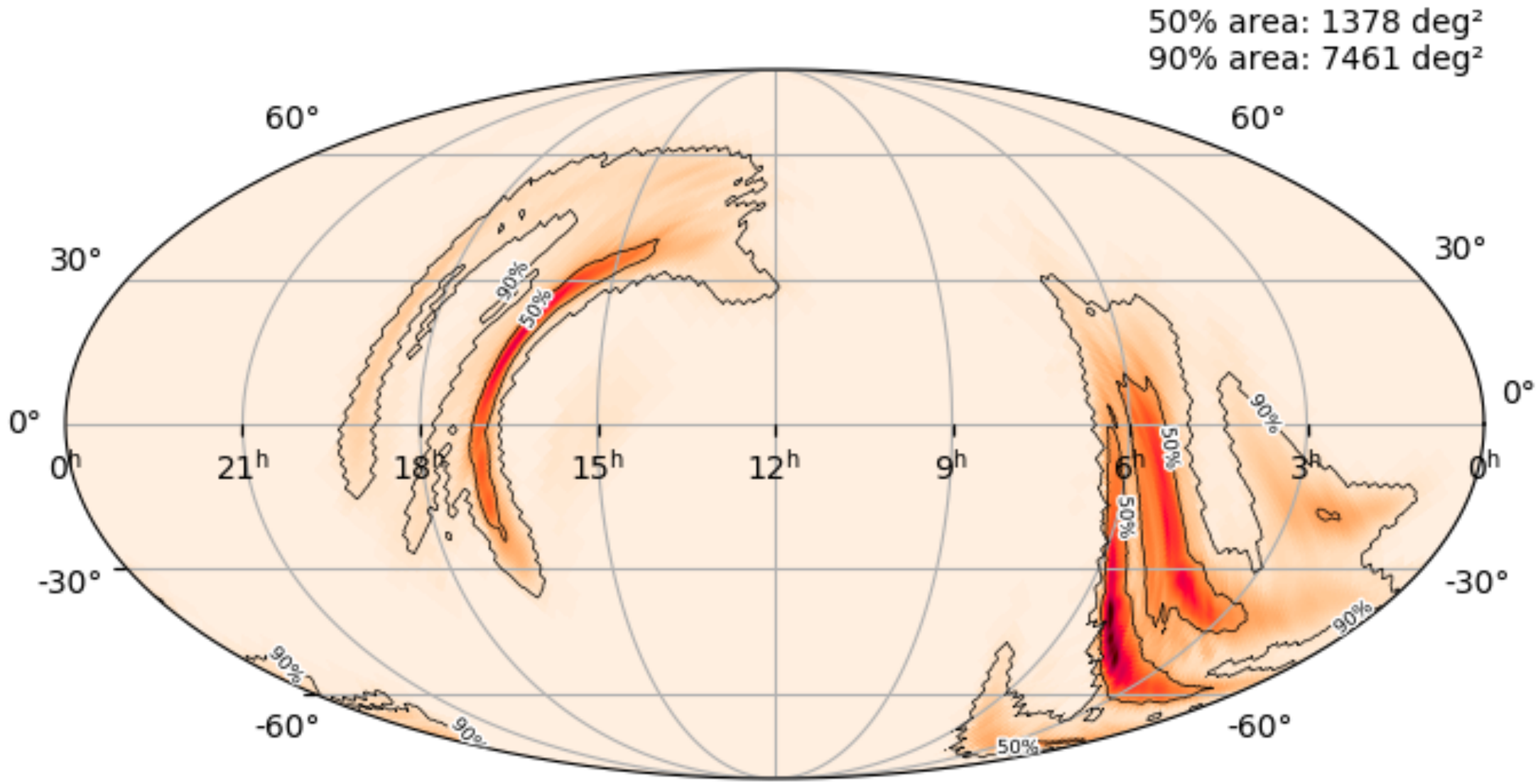


Interférométrie radio R ∝ 1/D ~1mas



25 avril dernier…

Coalescence de deux étoiles à neutrons

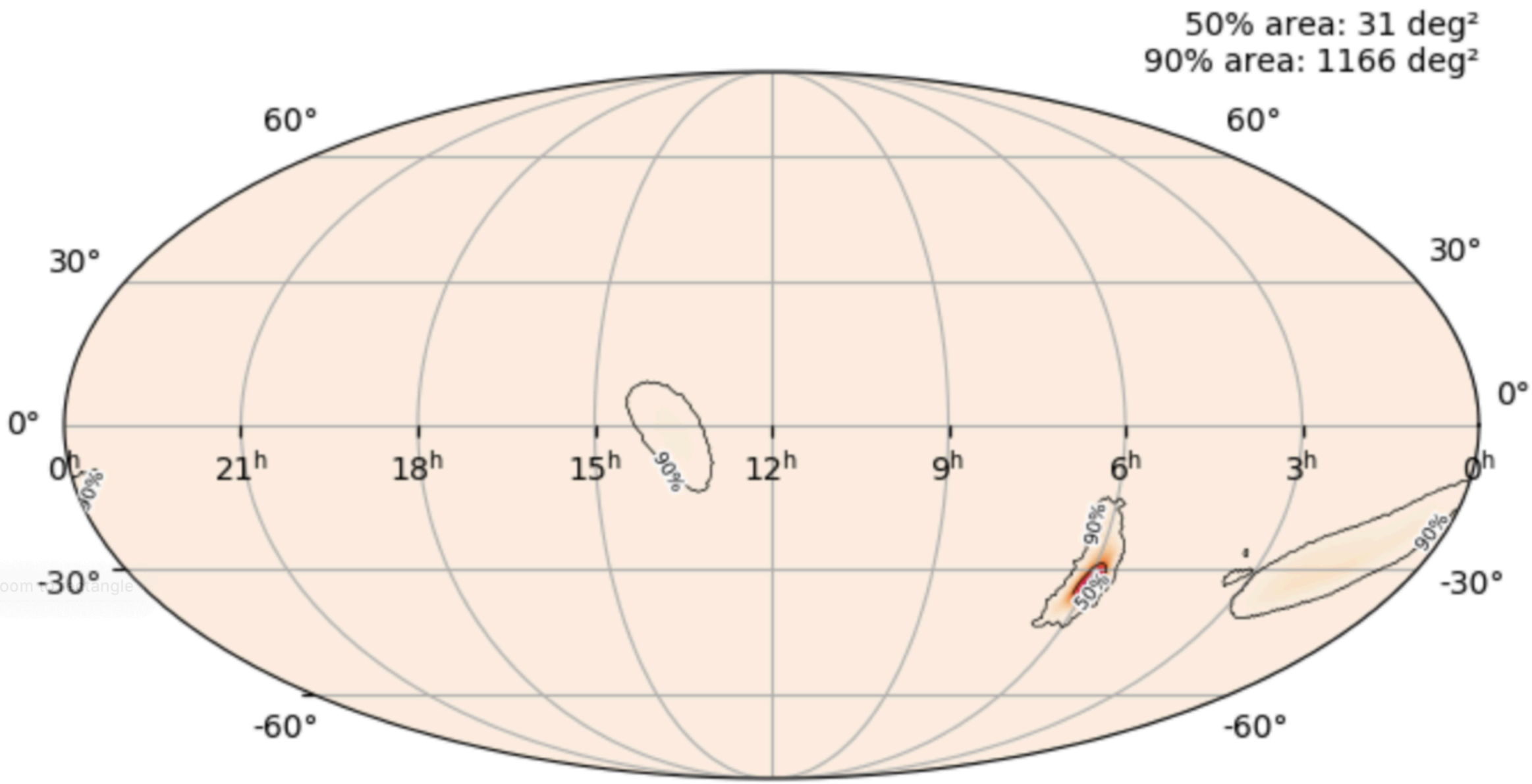


Pas de contrepartie électromagnétique identifiée:

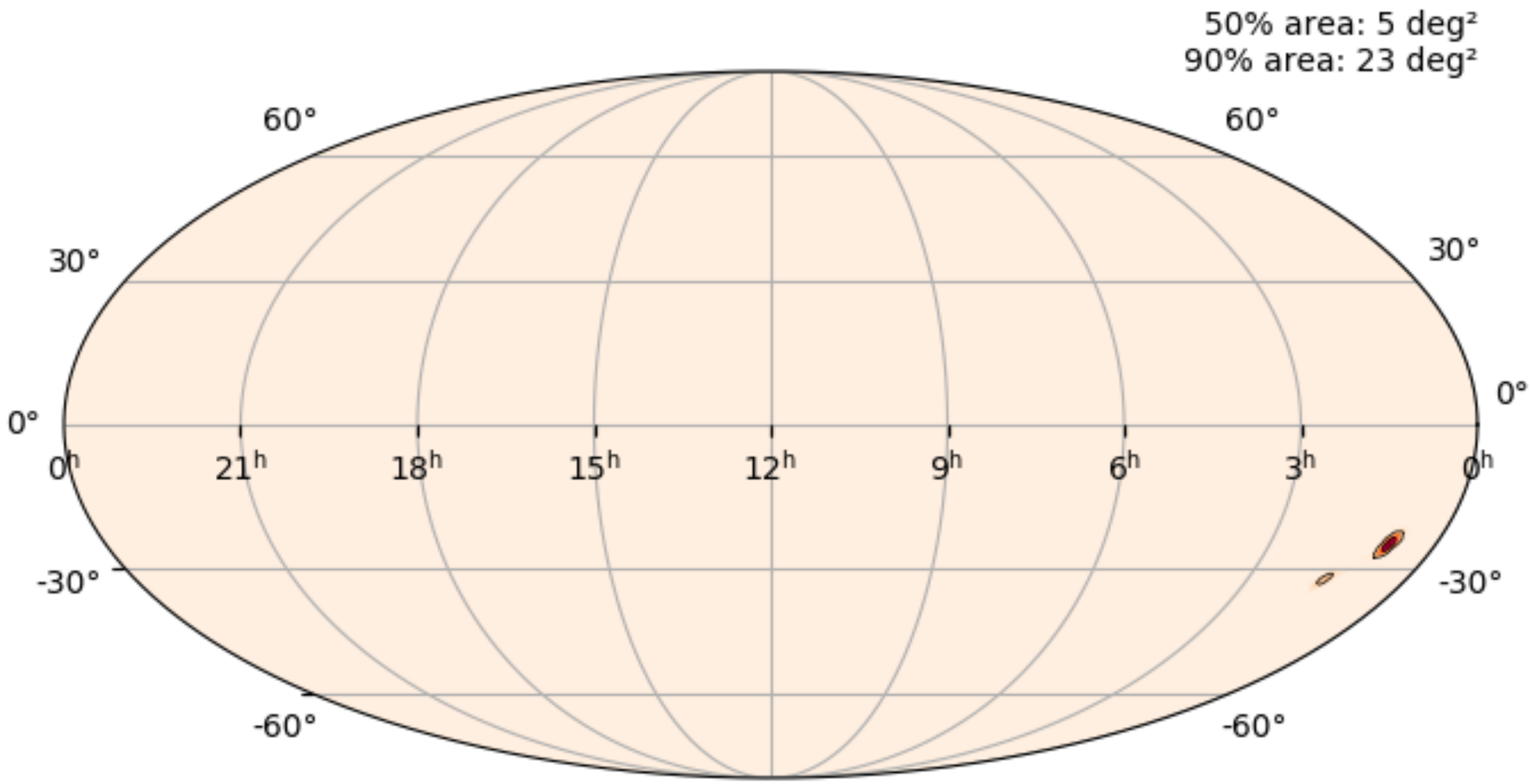
- localisation ?
- distance ?
- inclinaison du jet relativiste ?
- …

10 mai dernier…

Coalescence de deux étoiles à neutrons (?)

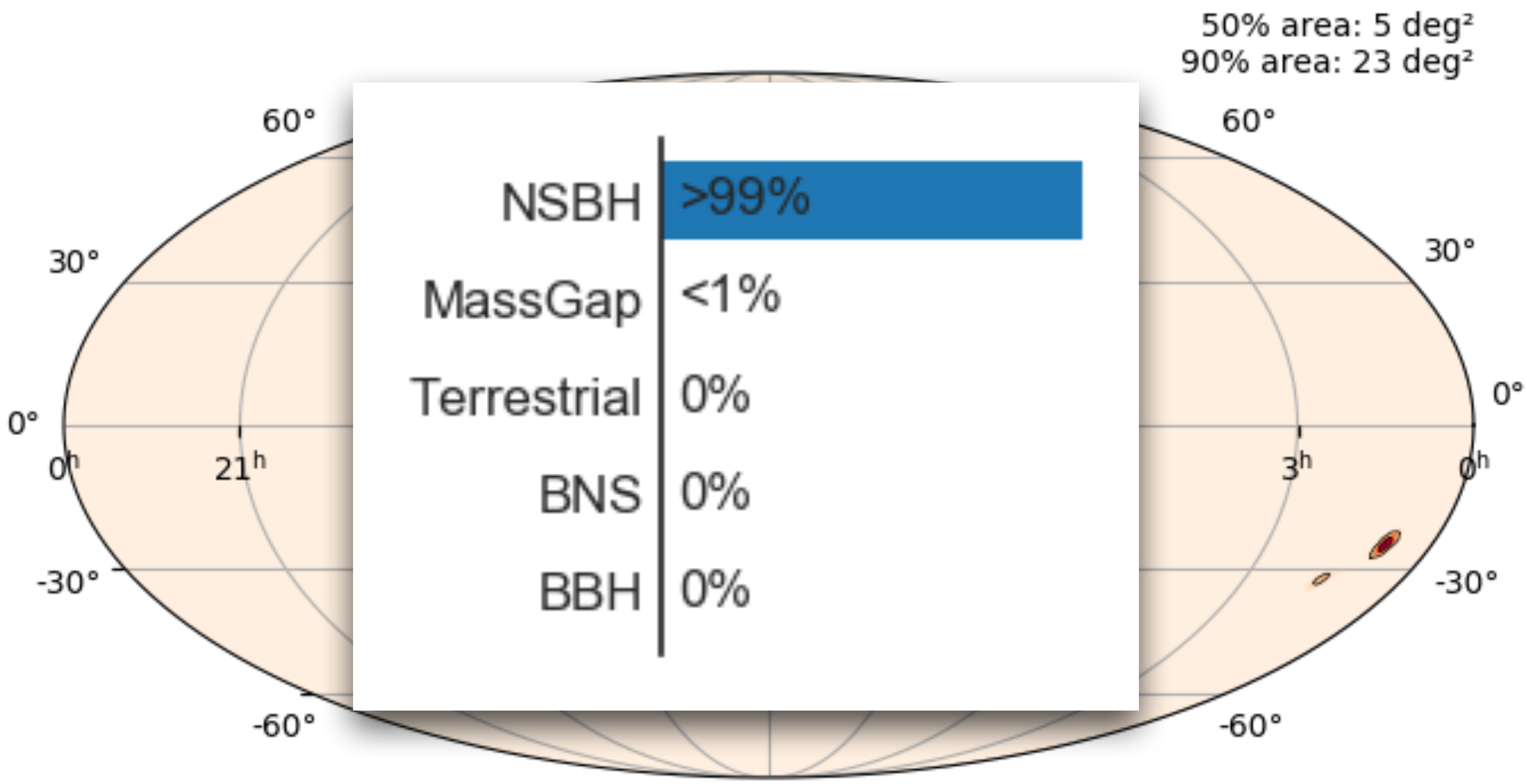


Mercredi dernier…

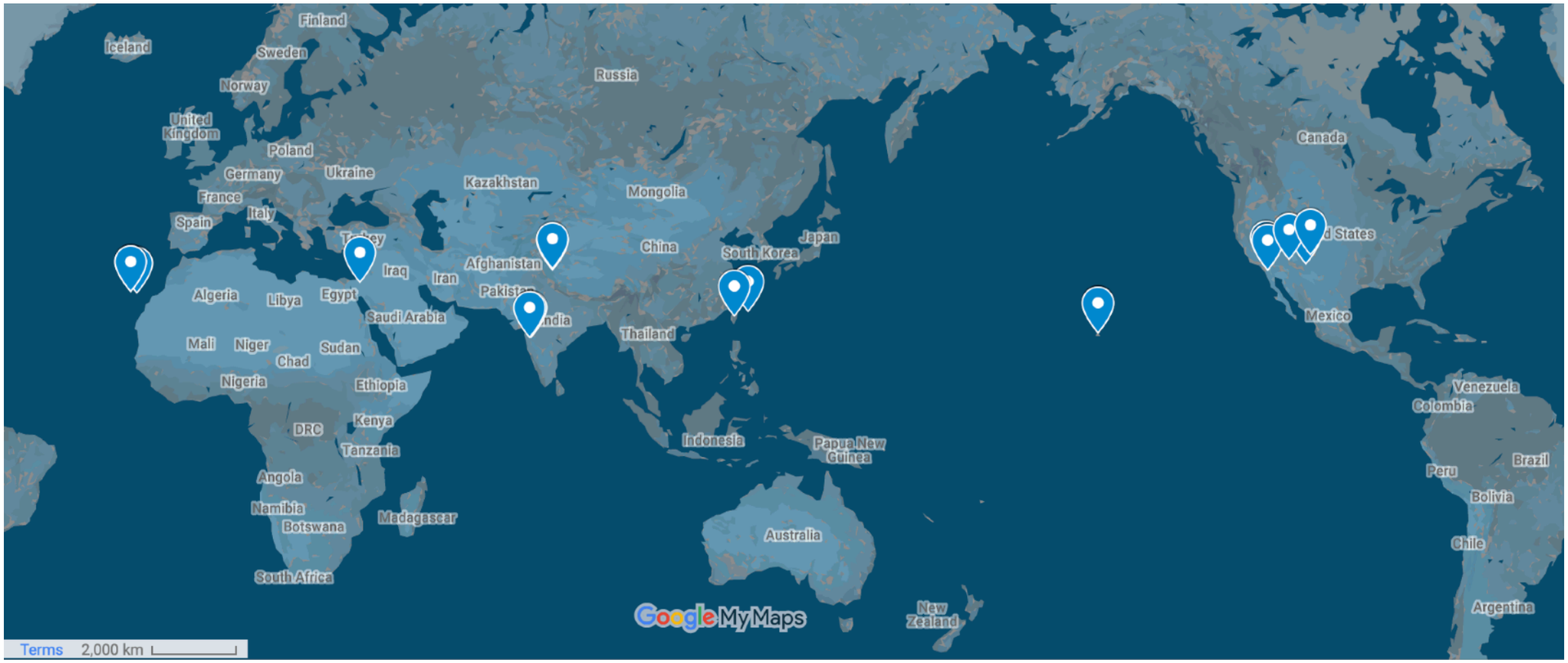


Mercredi dernier…

Coalescence d'une étoile à neutrons et d'un trou noir (?)



Mercredi dernier…



Mercredi dernier…

GCN Circulars

GCN 15 août 2019 à 13:53

GC

LIGO/Virgo S190814bv: Candidates found in initial DESGW search

À : Alexis Coleiro

TITLE: GCN CIRCULAR
NUMBER: 25336
SUBJECT: LIGO/Virgo S190814bv: Candidates found in initial DESGW search
DATE: 19/08/15 11:39:15 GMT
FROM: M. Soares-Santos at Fermi Lab <marcelle.soares.santos@gmail.com>

Marcelle Soares-Santos, Douglas Tucker, Sahar Allam, James Annis, Alyssa Garcia, Ken Herner, Tamara Davis, Nora Sherman, Robert Morgan, Kathy Vivas, Chris Lidman, Umang Malik

On behalf of the DESGW team*:

We report initial results of our DECam search for an optical counterpart of S190814bv (LVC, GCN 25324) using DECam. Starting at 2019-08-15 06:32 UTC (9.5h post merger), we observed 54 sq-deg, covering the 90% localization region provided in the updated sky map released on Aug 14, 2019 22:58:20 UTC. Observations were performed through clouds which limited the depth of our observations to 20.2 mag (10-sigma point source).

Images were processed by our difference imaging pipeline (Herner et al. 2017; see also Soares-Santos et al. 2015, 2017; Doctor et al. 2018; Morgan et al. 2019 for recent applications) using DES images as templates. We employ a machine learning code (autoscan, Goldstein et al. 2015) to reject subtraction artifacts. Candidates were initially selected by requiring at least two high signal to noise detections, rejecting asteroids. We then applied catalog-based vetting to reject variable stars, variable AGNs, and candidates with hosts at redshifts inconsistent with the distance reported by the LVC for S190814bv (276 +/- 56 Mpc). Those catalogs included Gaia DR2, and DES. The final vetting was done via visual inspection. We matched our remaining candidates using the Transient Name Server to avoid reporting those previously reported by other groups. In our initial analysis, we find 2 new transient candidates: one hostless and one with a host at marginally consistent redshift:

NAME TNS_NAME RA DEC DISCOVERY_MJD DISCOVERY_MAG_I DISCOVERY_MAG_Z

desgw-190814a 2019nmd 12.870848 -22.471377 58710.278 20.59 20.26

desgw-190814b 2019nme 12.635660 -22.226027 58710.278 19.33 19.39

Mercredi dernier…

GCN Circulars

GCN 16 août 2019 à 01:19

GC

LIGO/Virgo S190814bv: des-gw190814b is a moving object

À : Alexis Coleiro

TITLE: GCN CIRCULAR
NUMBER: 25355
SUBJECT: LIGO/Virgo S190814bv: des-gw190814b is a moving object
DATE: 19/08/15 23:05:10 GMT
FROM: Daniel Goldstein at Caltech <danny@caltech.edu>

D. A. Goldstein (Caltech), D. Perley (LJMU), I. Andreoni (Caltech), and M. M. Kasliwal (Caltech)

report on behalf of the Global Relay of Observatories Watching Transients Happen (GROWTH) collaboration

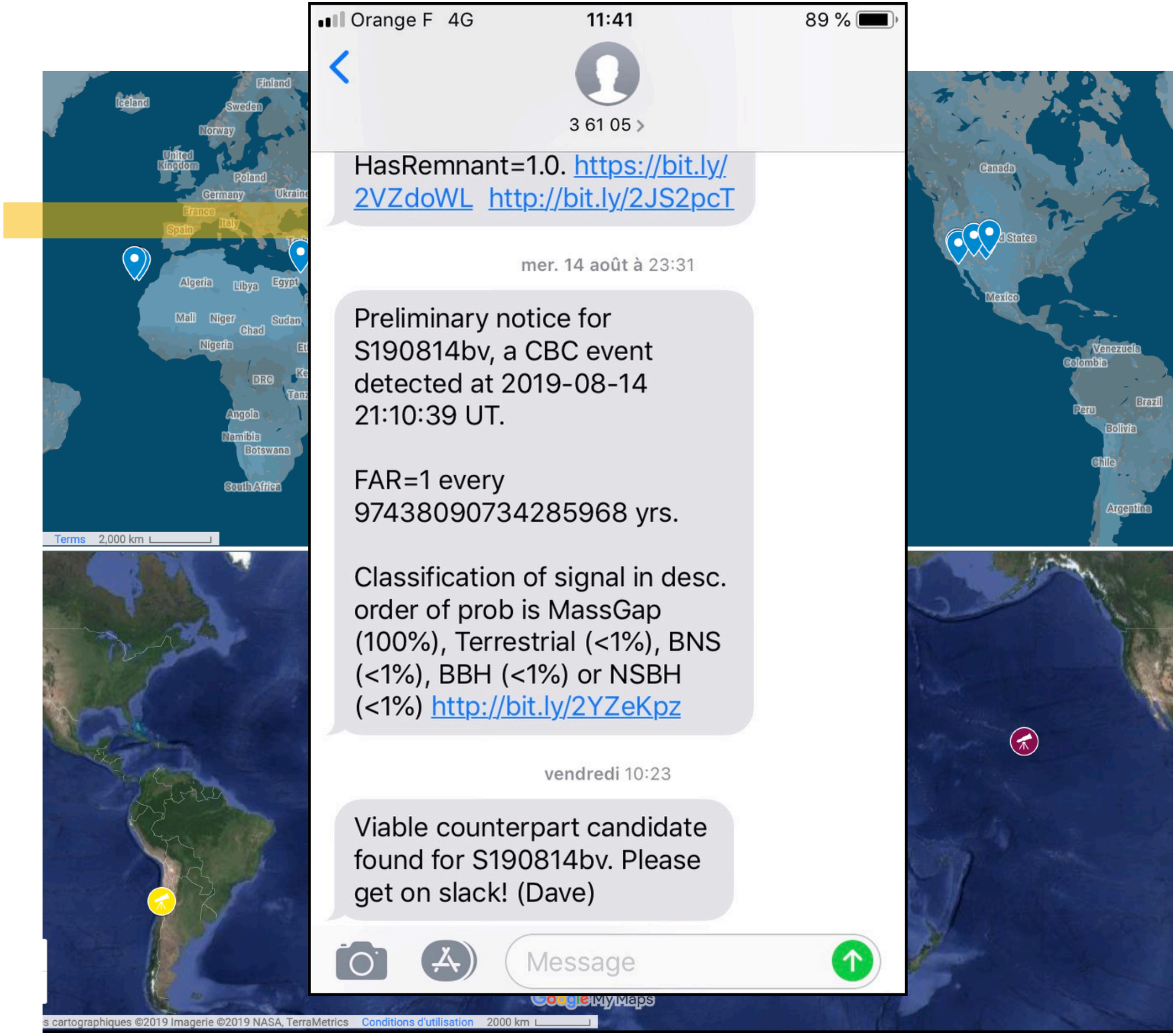
We processed the public data obtained by the DESGW team described in GCN 25336 using the image subtraction pipeline described in Goldstein, Andreoni et al. (2019) and Andreoni, Goldstein et al. (2019). By examining the subtractions in the vicinity of the optical counterpart candidate des-gw190814b (GCN 25336), we observed that the object is moving by 14.3 arcseconds per hour, in the same direction, in both the i- and z-bands. Based on this information it is very likely that this object is a Solar System Object, and thus is unrelated with the S190814bv gravitational wave event (GCN #25324). The object is not listed in the Minor Planet Center.

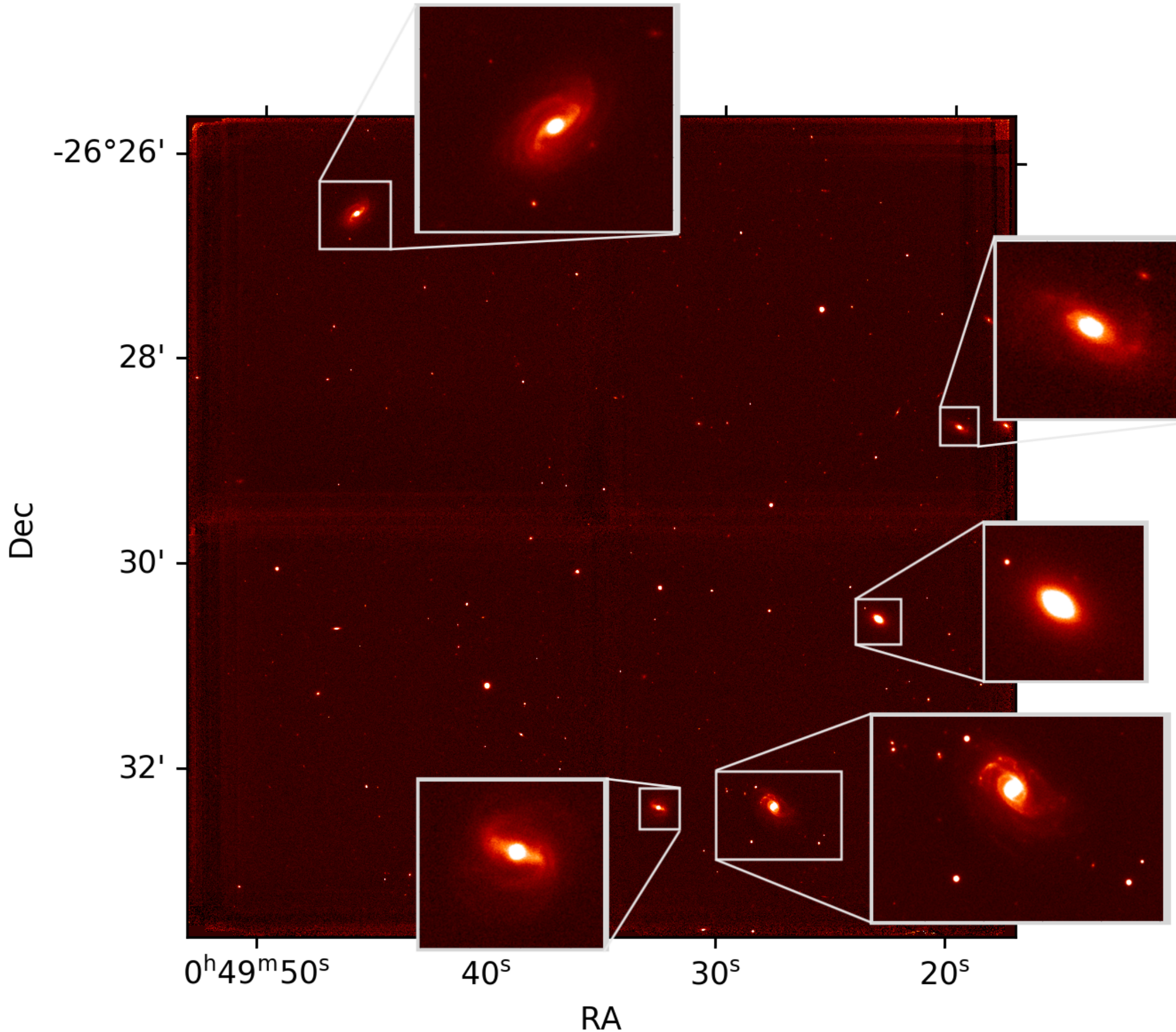
Visual evidence of the object's motion can be seen at this link:

http://astro.caltech.edu/~danny/static/desgw-180814b.001.png

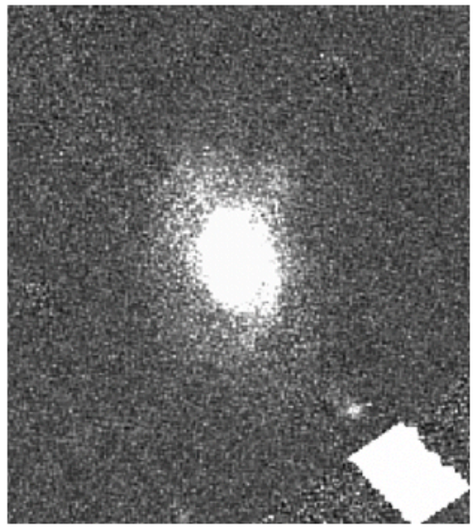
GROWTH is a worldwide collaboration comprising Caltech, USA; IPAC, USA, WIS, Israel; OKC, Sweden; JSI/UMd, USA; U Washington, USA; DESY, Germany; MOST, Taiwan; UW Milwaukee, USA; LANL USA; Tokyo Tech, Japan; IIT-B, India; IIA, India; LJMU, TTU, and USyd, Australia. GROWTH acknowledges generous support of the NSF under PIRE Grant No 1545949.

We gratefully acknowledge Amazon, Inc. for a generous grant that funded our use of the Amazon Web Services cloud computing infrastructure to process the DECam data.

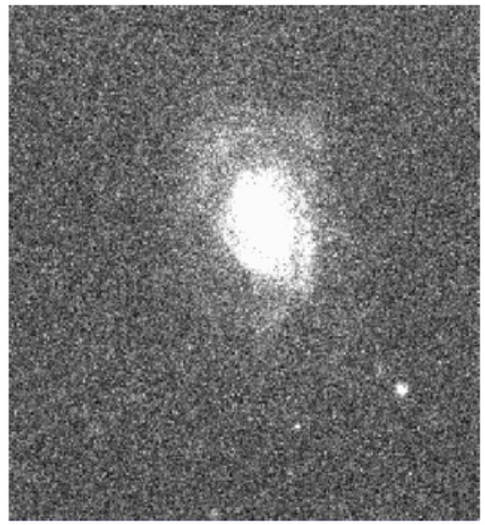

Orange F 4G
11:41
89 %
3 61 05 >
HasRemnant=1.0. https://bit.ly/2VZdoWL http://bit.ly/2JS2pcT
mer. 14 août à 23:31
Preliminary notice for S190814bv, a CBC event detected at 2019-08-14 21:10:39 UT.
FAR=1 every 97438090734285968 yrs.
Classification of signal in desc. order of prob is MassGap (100%), Terrestrial (<1%), BNS (<1%), BBH (<1%) or NSBH (<1%) http://bit.ly/2YZeKpz
vendredi 10:23
Viable counterpart candidate found for S190814bv. Please get on slack! (Dave)
Message
Iceland
Finland
Sweden
Norway
United Kingdom
Poland
Germany
France
Spain
Italy
Algeria
Libya
Egypt
Mali
Niger
Chad
Sudan
Nigeria
DRC
Angola
Namibia
Botswana
South Africa
Terms
2,000 km
Canada
Mexico
Venezuela
Colombia
Peru
Brazil
Bolivia
Chile
Argentina
Conditions d'utilisation
2000 km


-26°26'
28'
30'
32'
Dec
0h49m50s
40s
30s
20s
RA

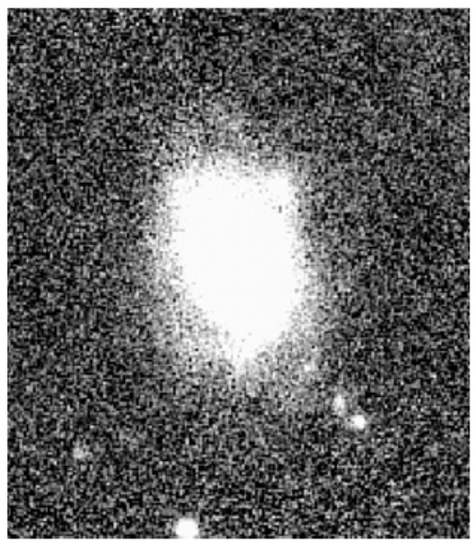
Pan-STARRS g-band reference



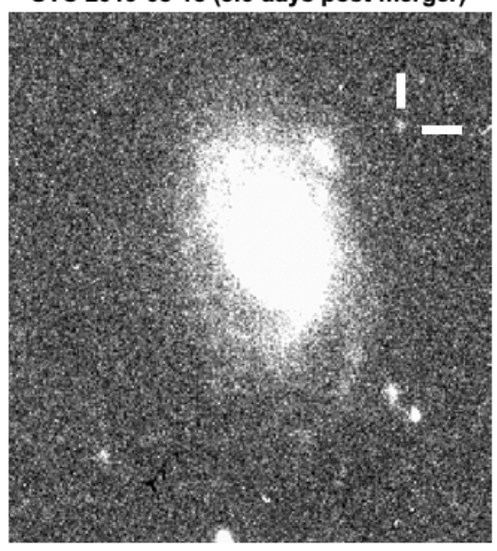
CFHT MegaPrime/MegaCam g-band, UTC 2019-08-16 (1.7 days post-merger)



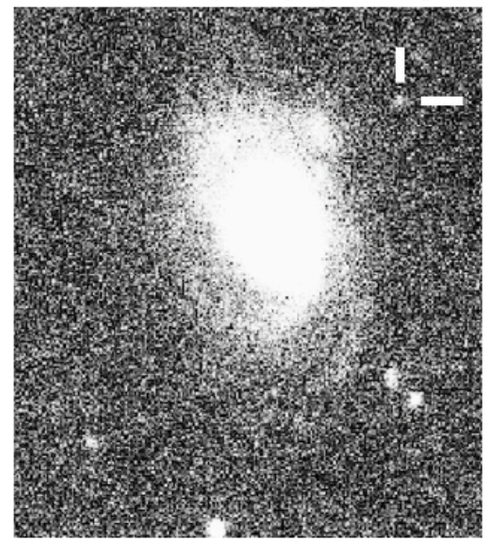
Pan-STARRS i-band reference



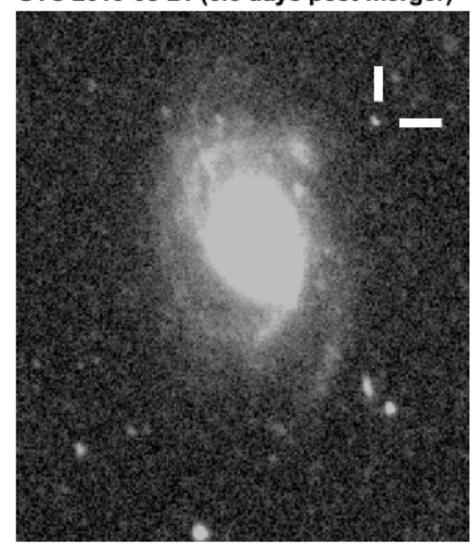
CFHT MegaPrime/ MegaCam i-band, UTC 2019-08-18 (3.6 days post-merger)



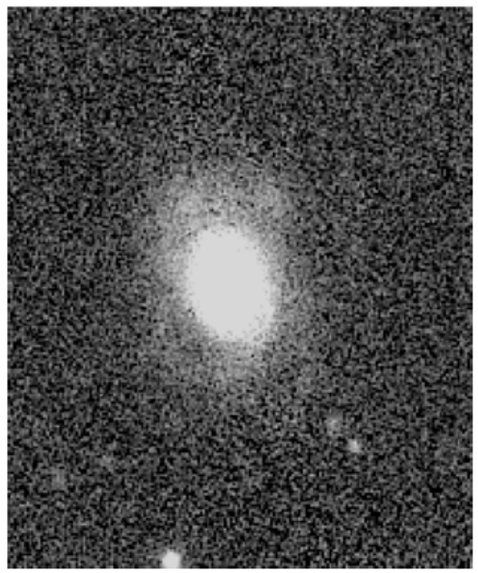
CFHT MegaPrime/ MegaCam i-band, UTC 2019-08-19 (4.6 days post-merger)



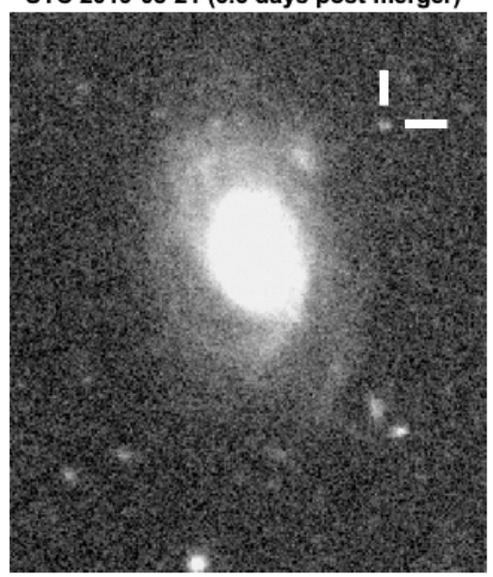
CFHT MegaPrime/ MegaCam i-band, UTC 2019-08-21 (6.6 days post-merger)



Pan-STARRS z-band reference

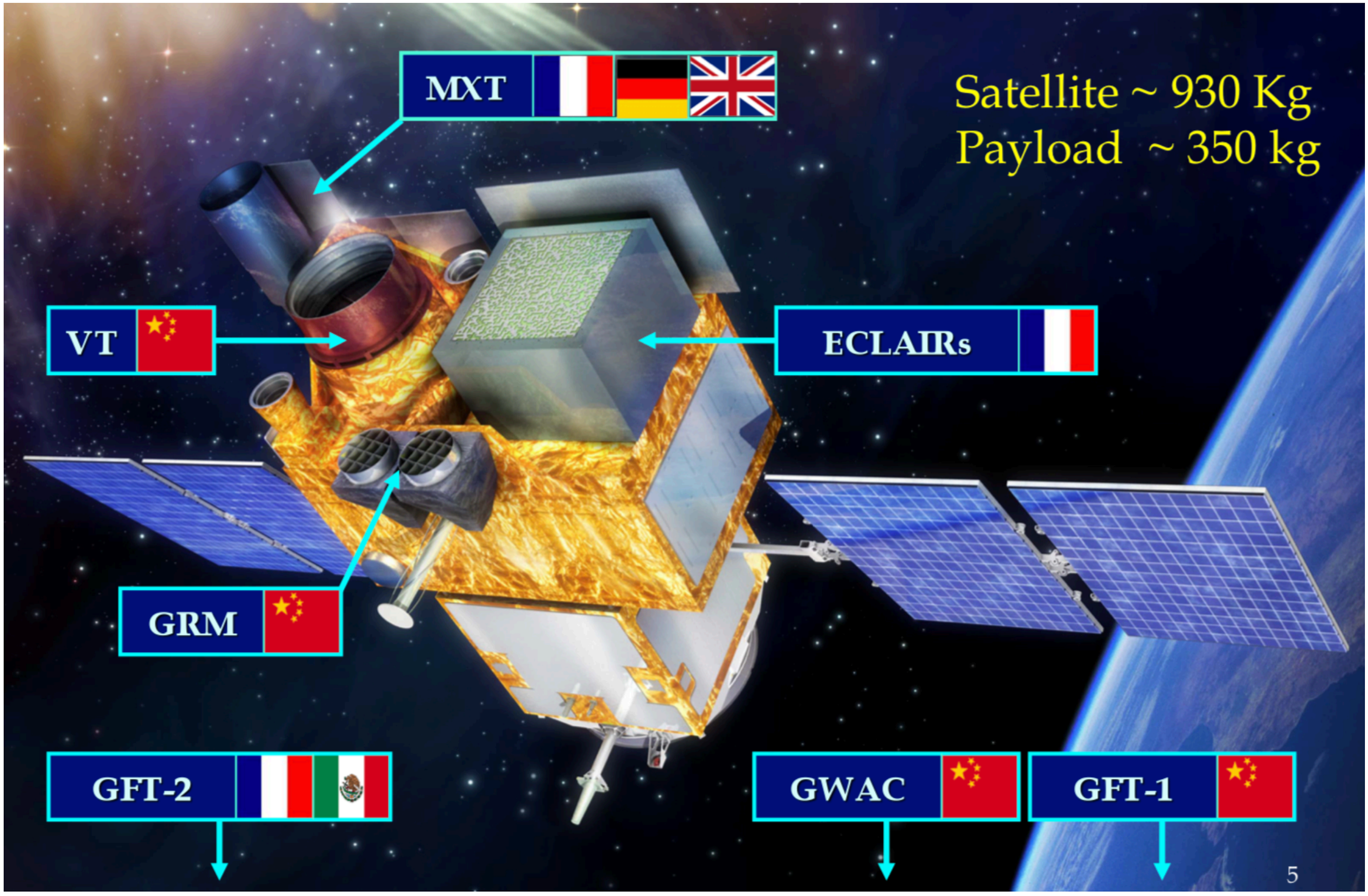


CFHT MegaPrime/ MegaCam z-band, UTC 2019-08-21 (6.6 days post-merger)



Le projet SVOM

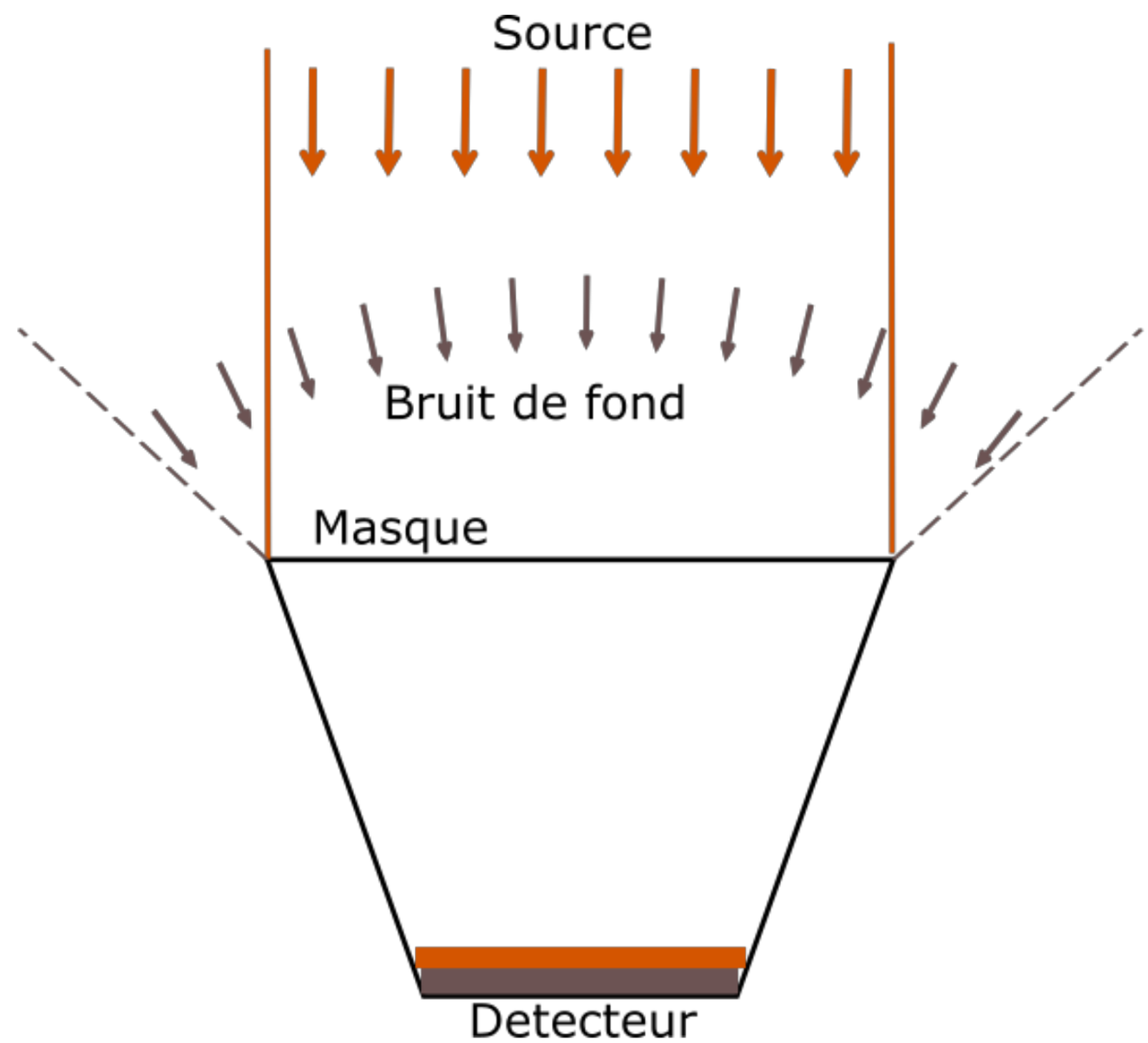
SVOM = Space-based multiband astronomical Variable Objects Monitor



Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

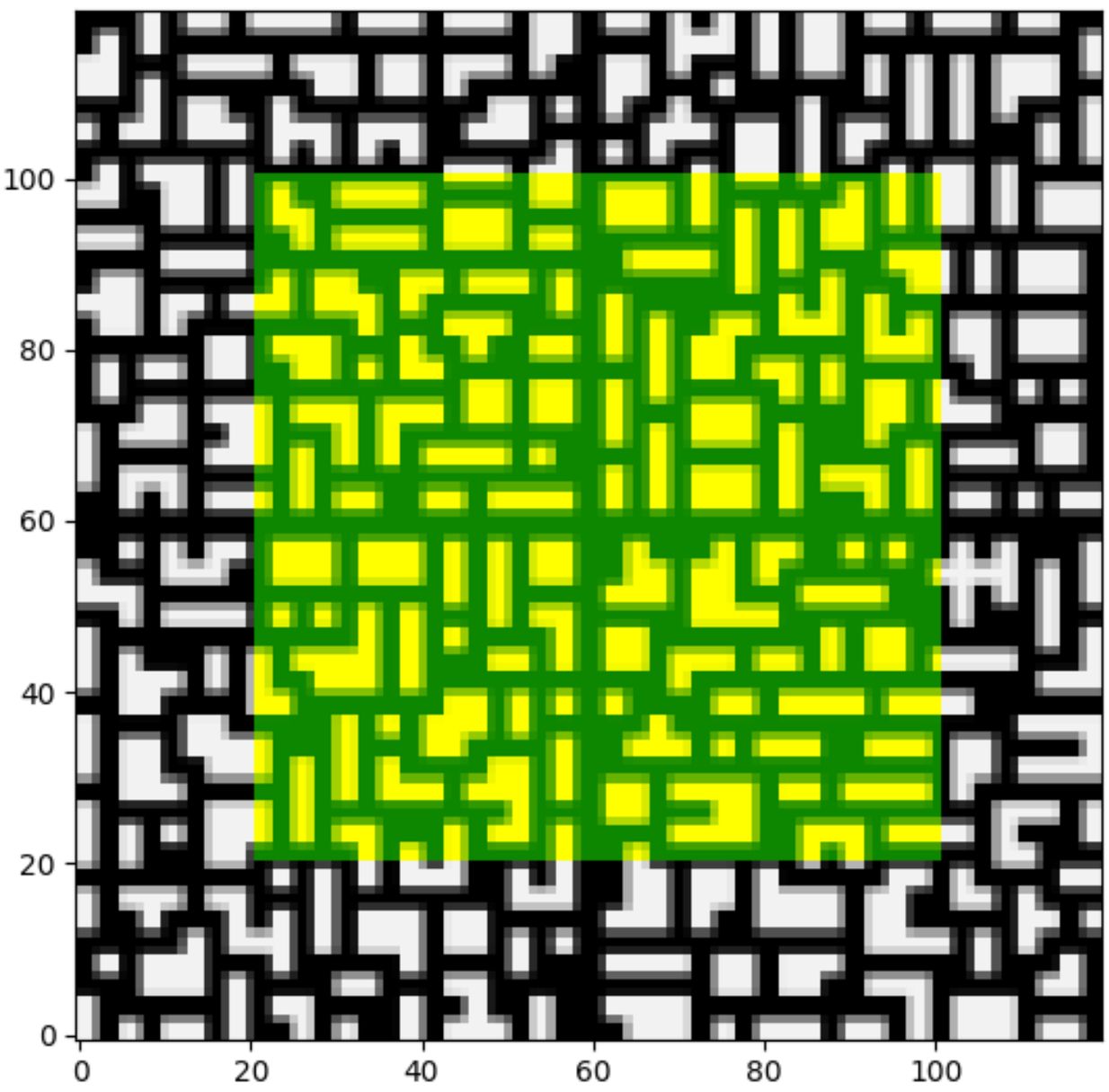
Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.

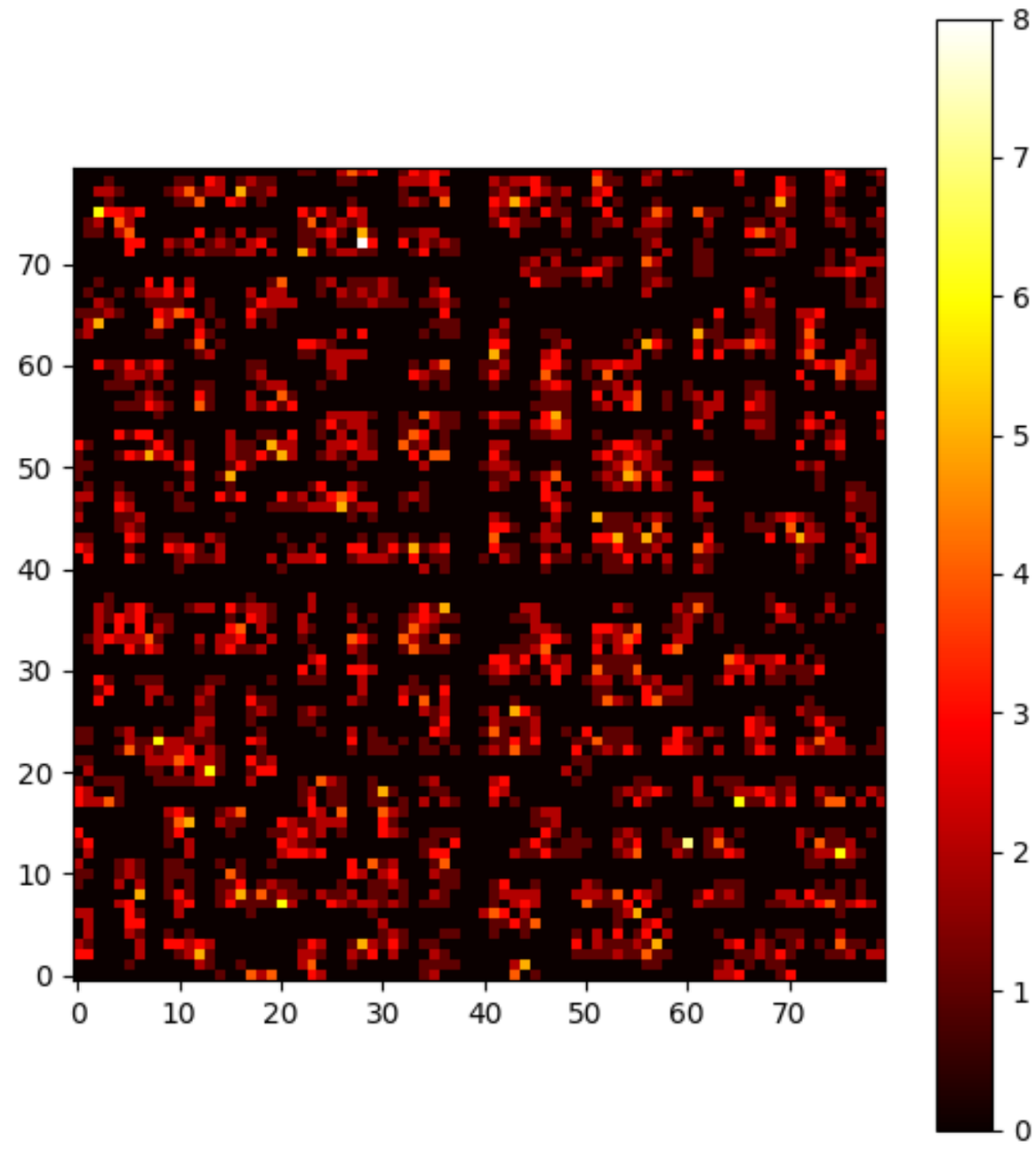


Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.

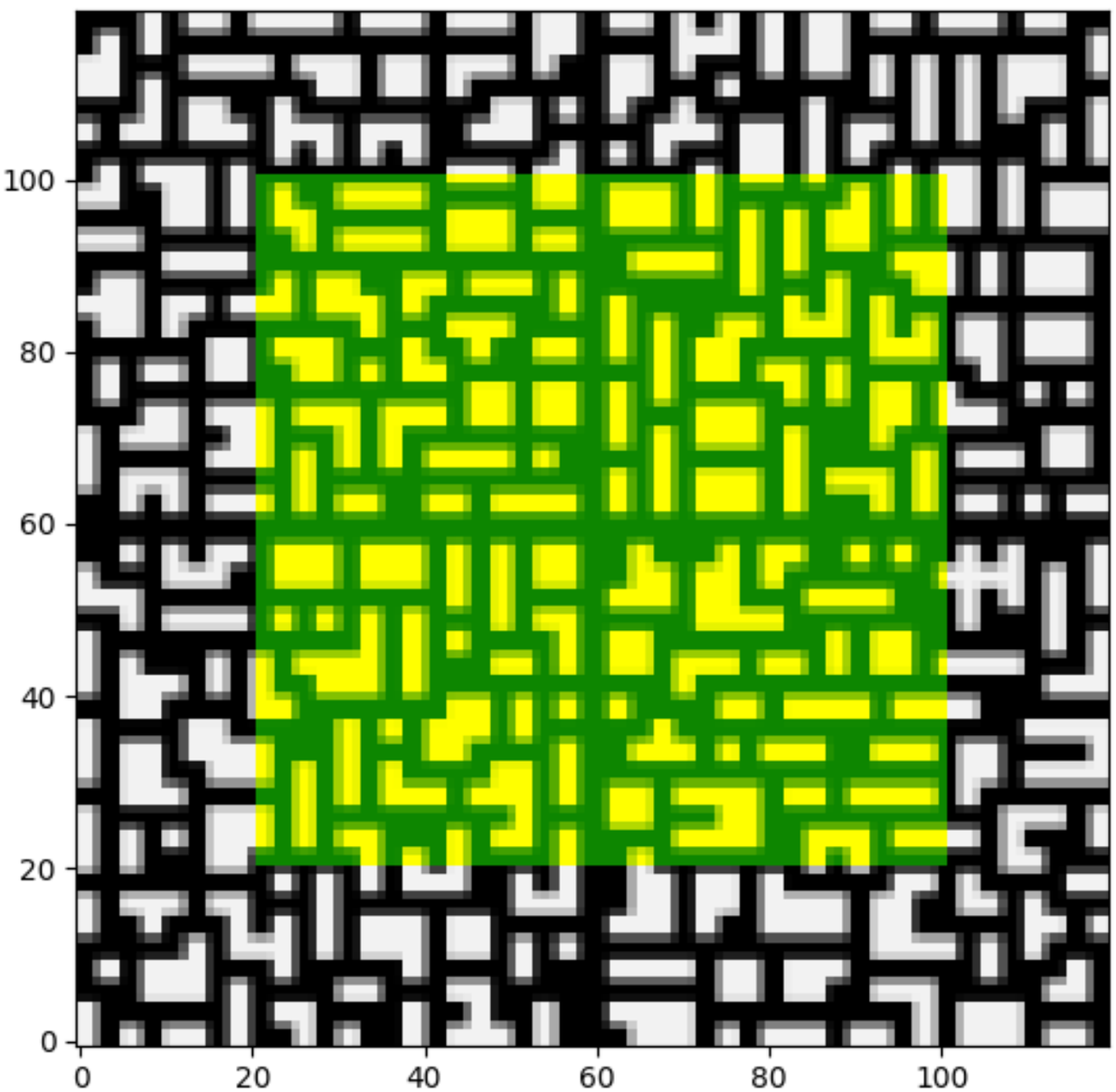


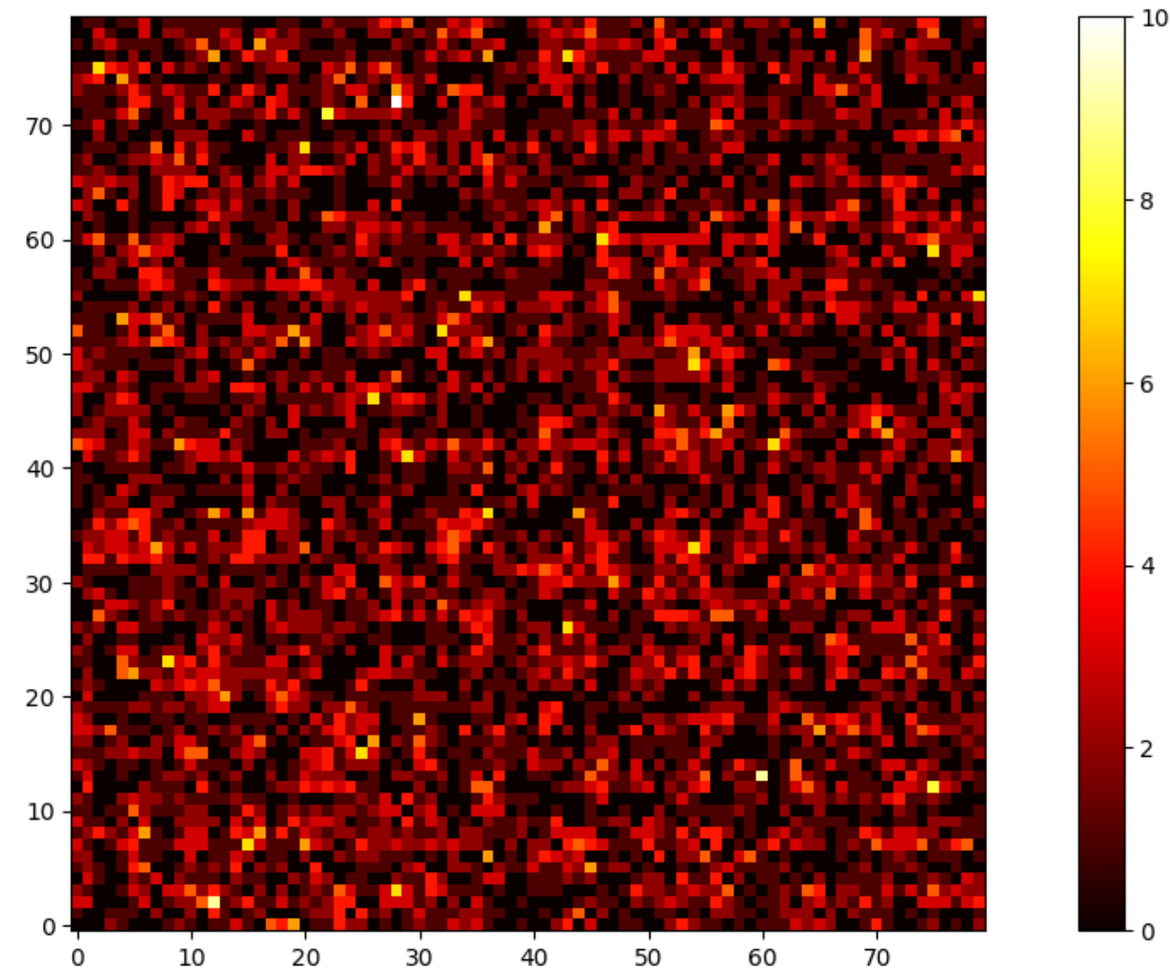


Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.





Le projet SVOM

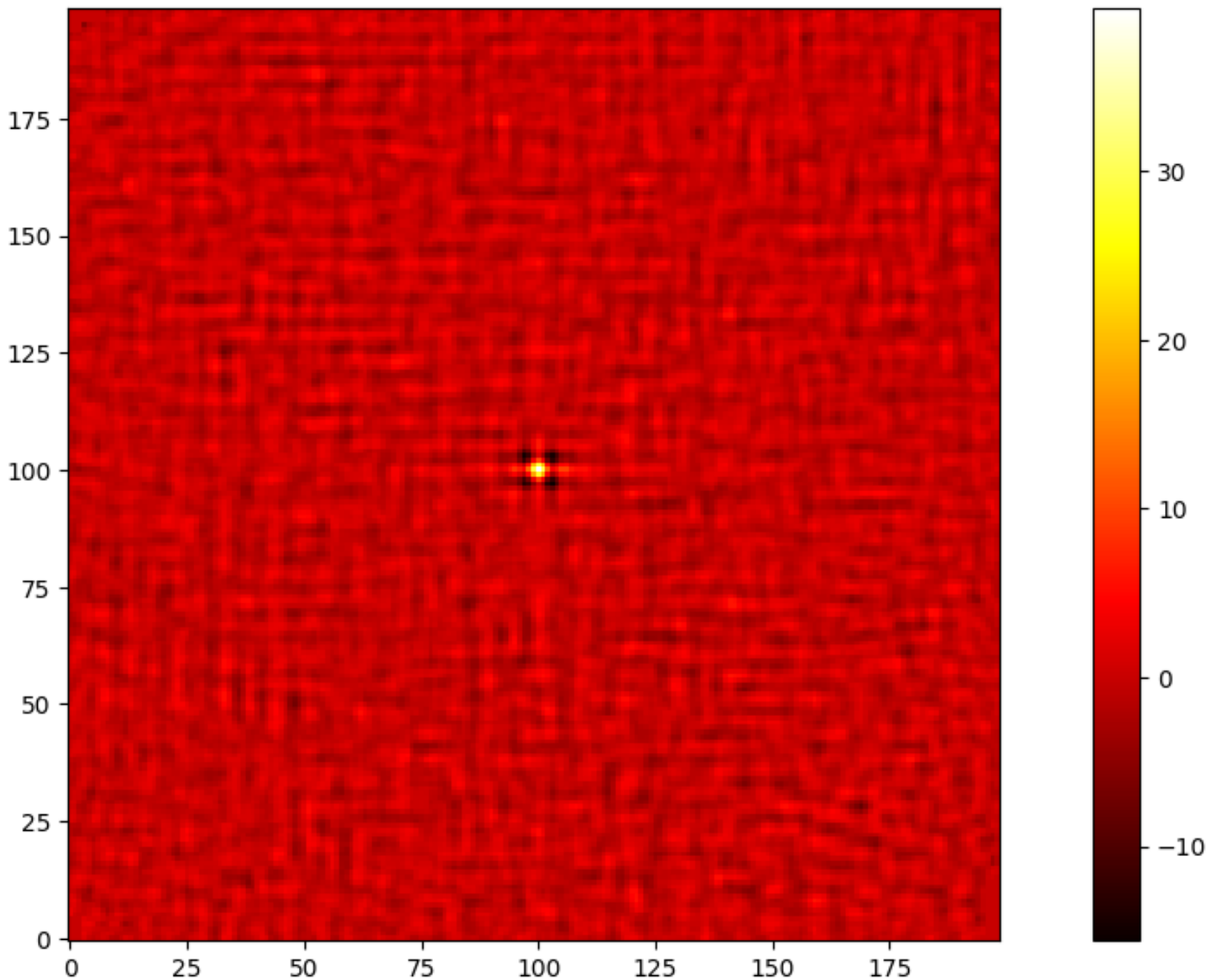
ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.

Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.



Neutrinos astrophysiques: une nouvelle fenêtre sur l’univers de haute énergie

Photohadronic

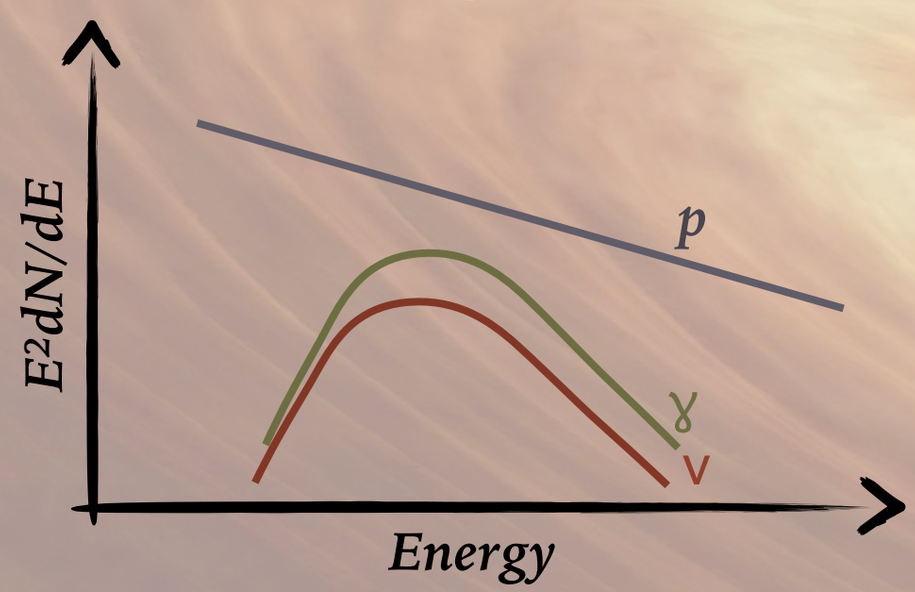
$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$

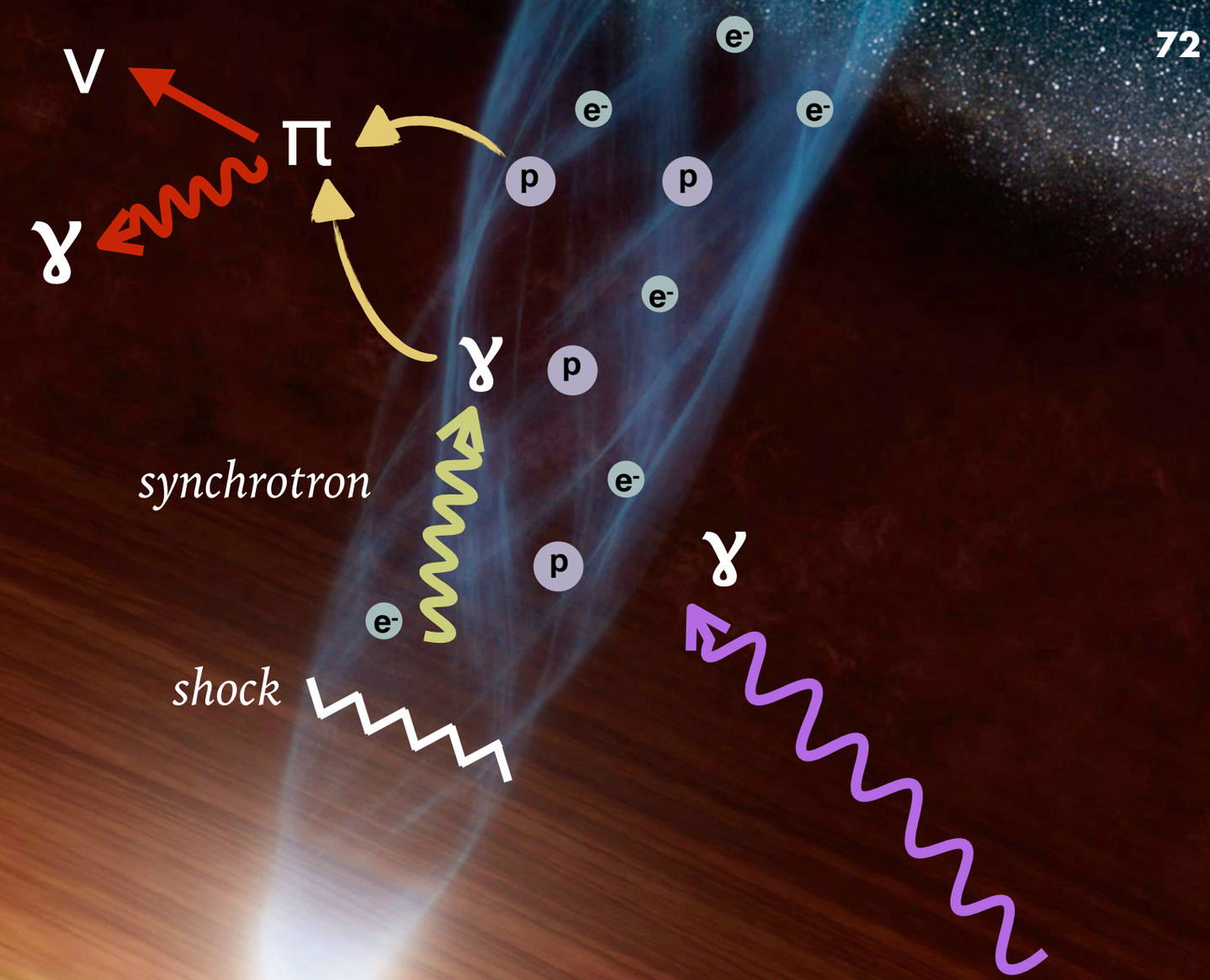
$$\pi^0 \rightarrow \gamma\,\gamma$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$\pi^+ \rightarrow \mu\,\nu_\mu$$

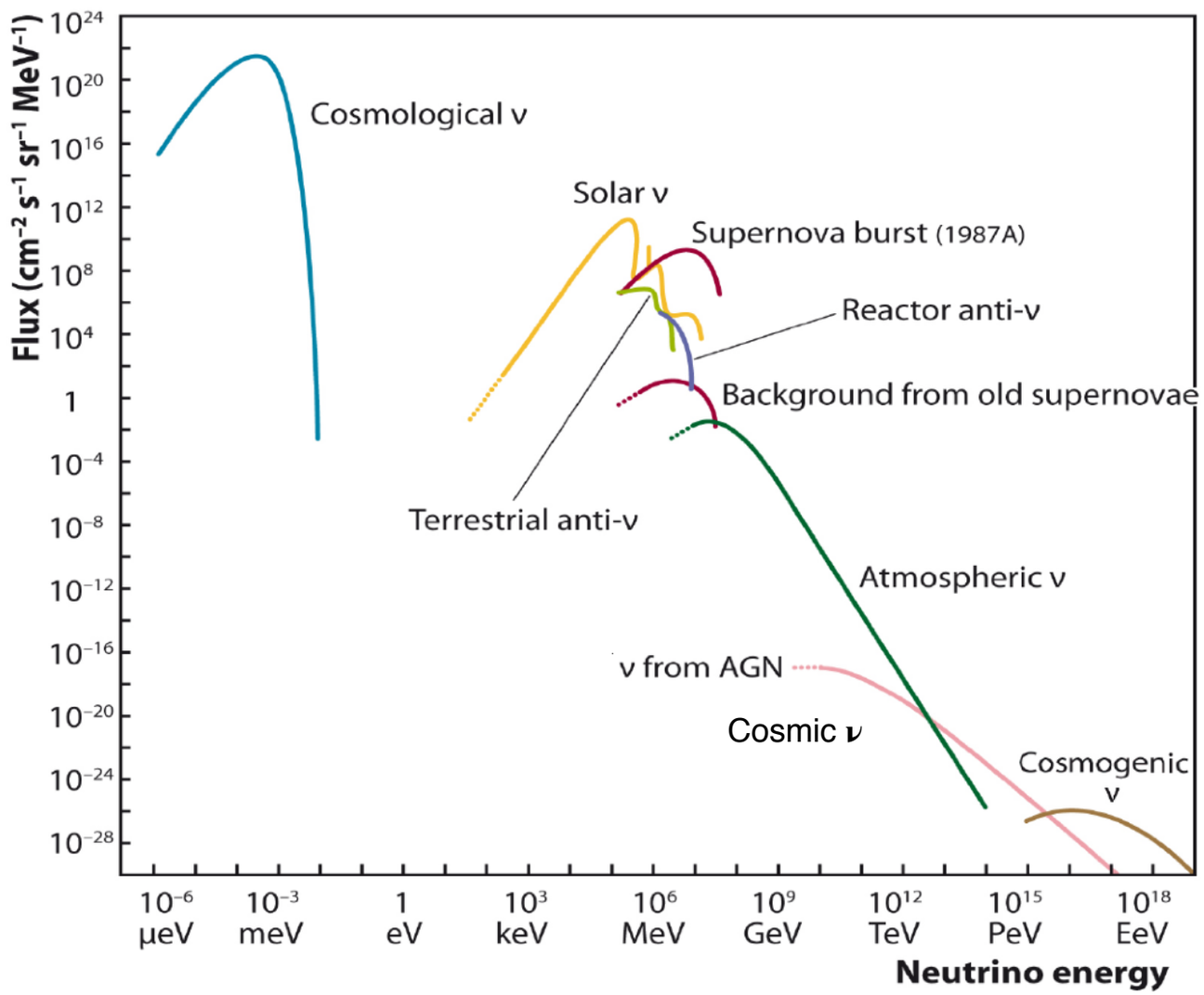
$$\mu \rightarrow \bar{\nu}_\mu\,\nu_e\,e$$



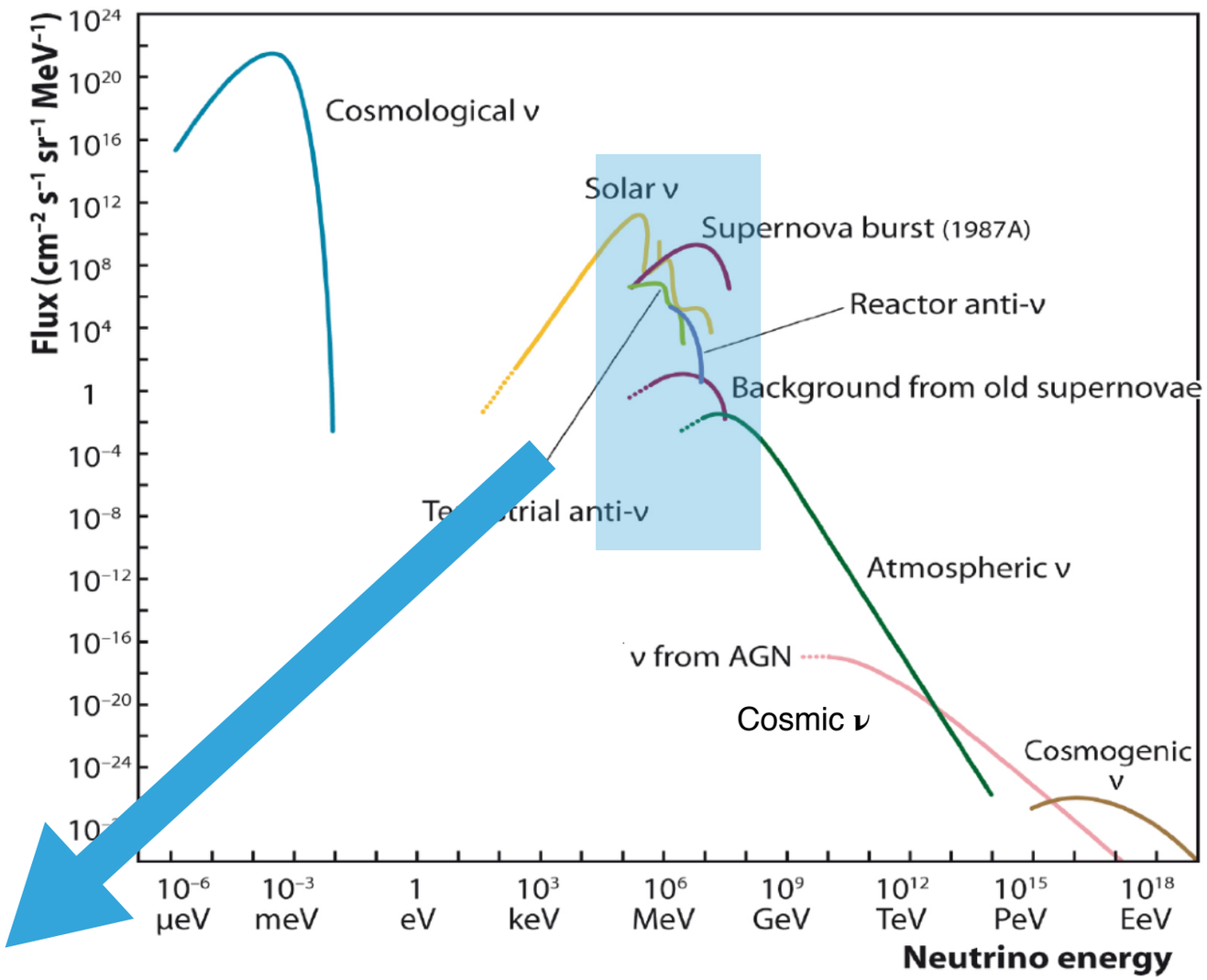


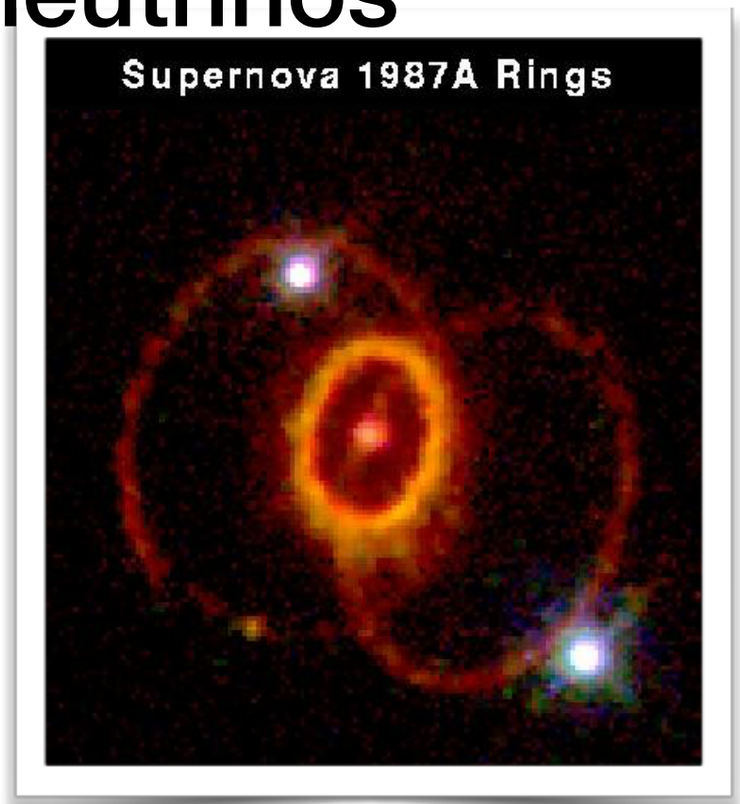
γ (environment : accretion disk, companion star, …)

Spectre en énergie des neutrinos

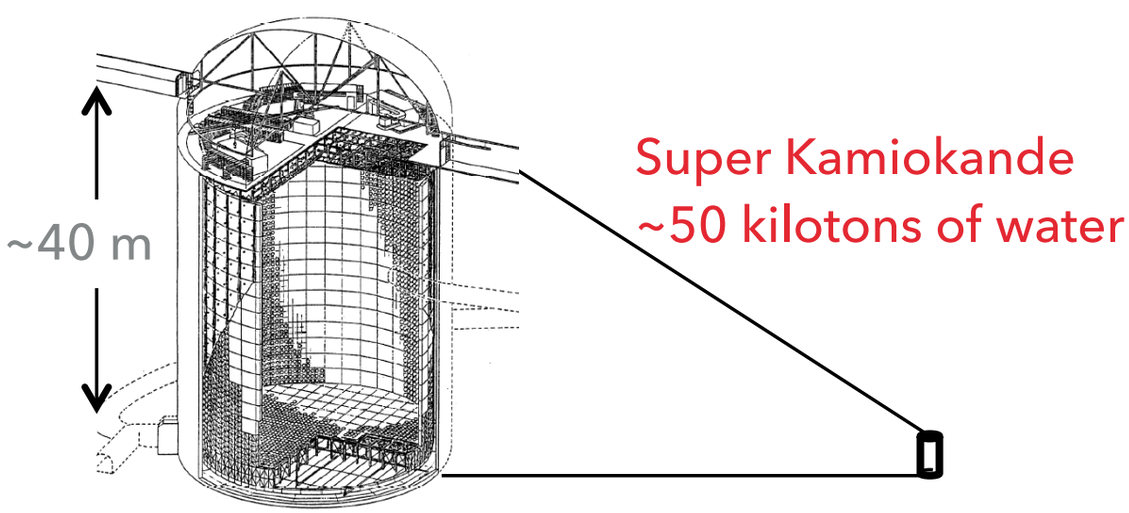


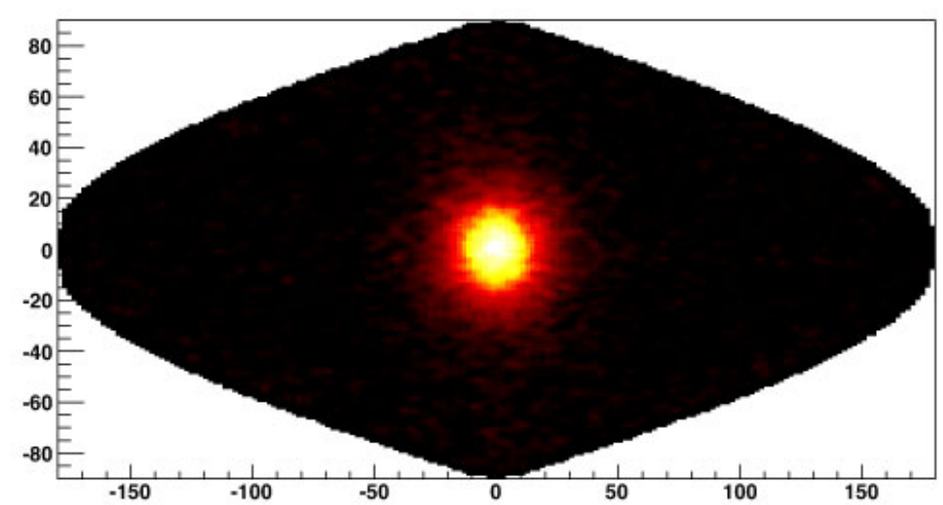
Spectre en énergie des neutrinos



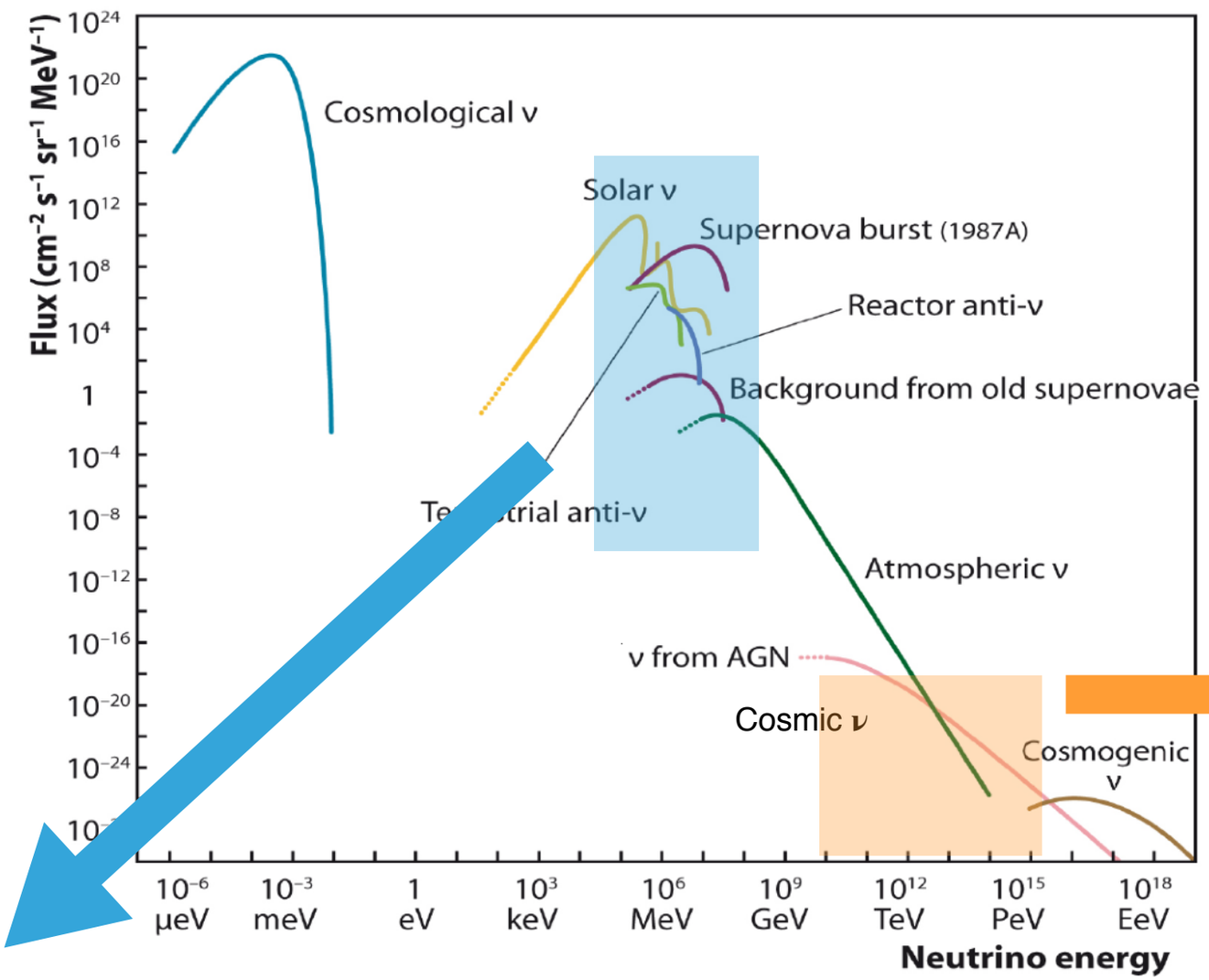


Sun: with 500 days of exposure (90°x90°) from Super-Kamiokande

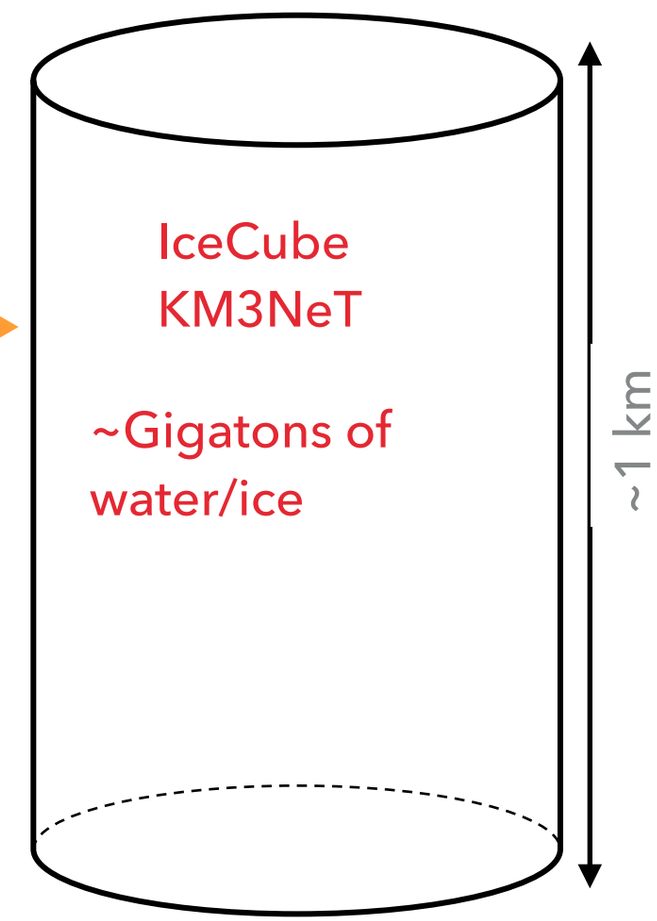


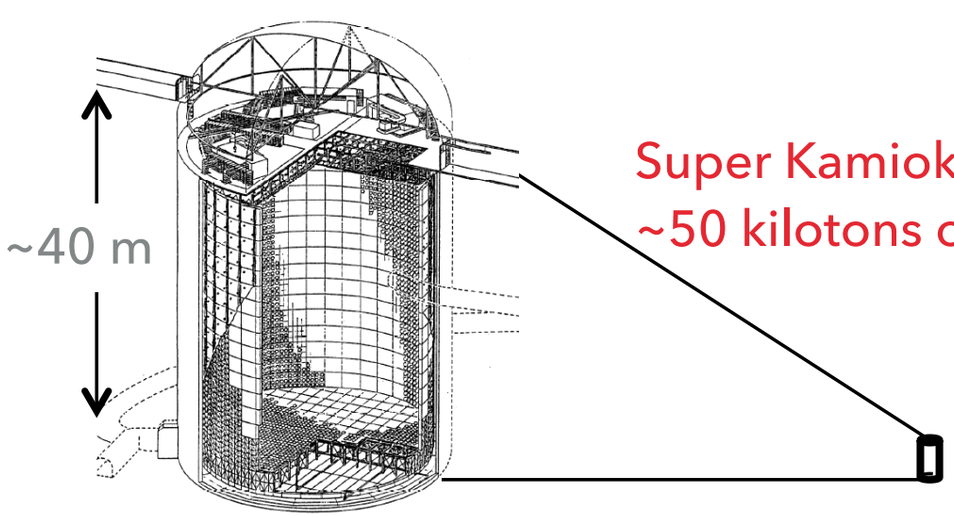


Spectre en énergie des neutrinos



Neutrino astronomy needs km³ scale detectors



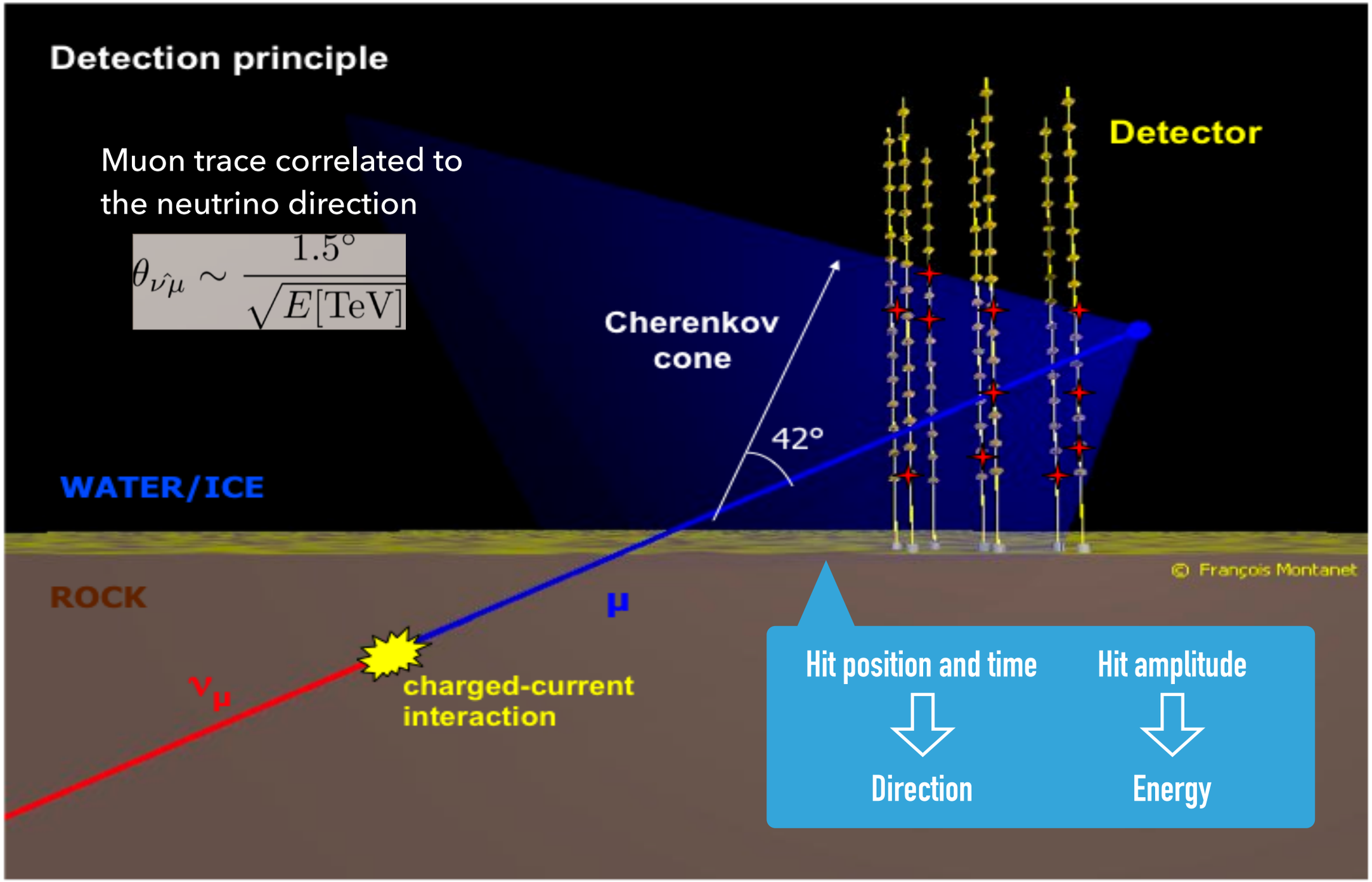


Super Kamiokande
~50 kilotons of water

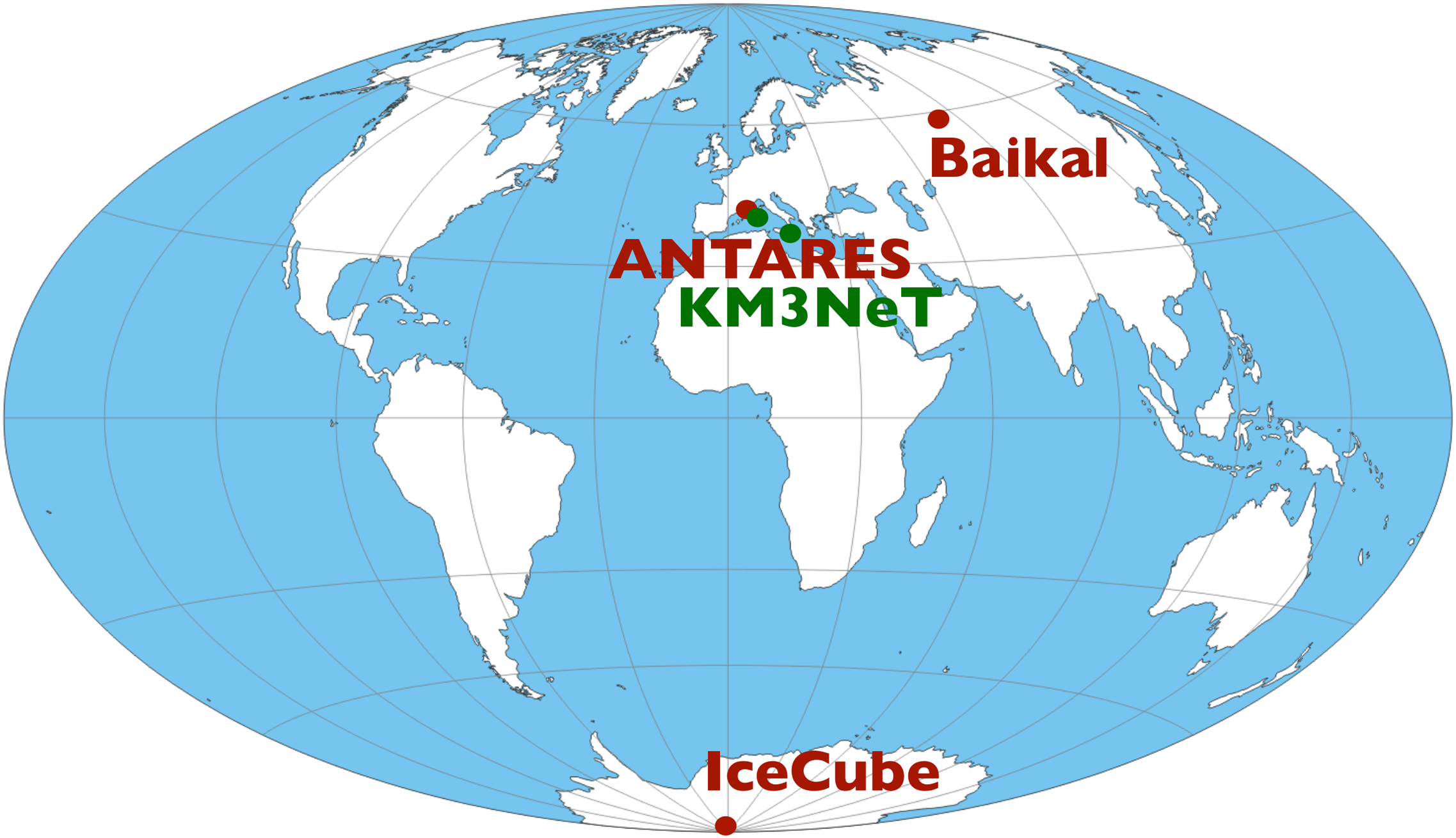
ν are weakly interacting + low cosmic flux → requires large instrumented volumes under sea/ice to reduce the muon background

Méthode de détection

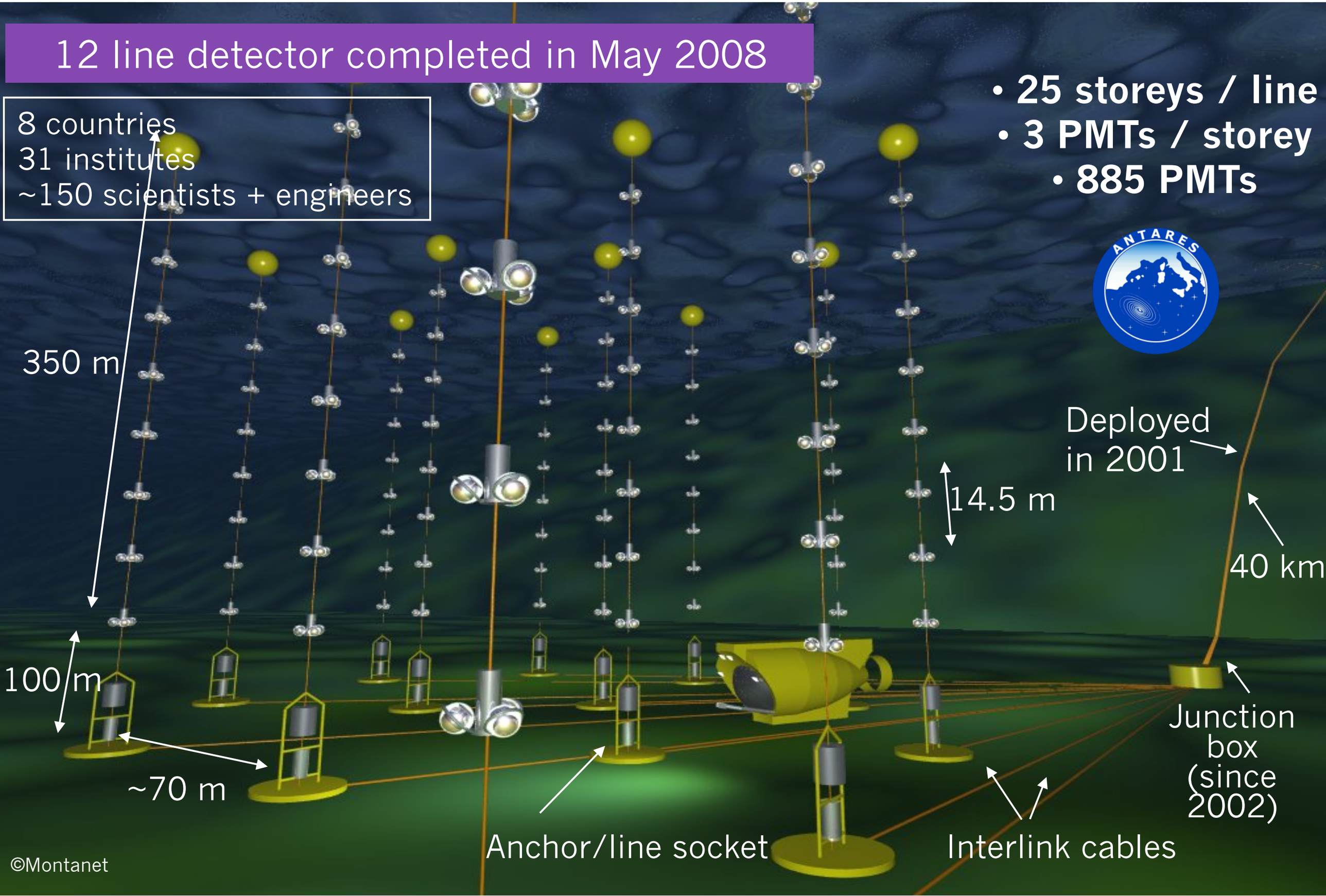
Different ways to detect HE ν.
One way particularly useful in astronomy:
observation of muons produced in CC interaction of ν_μ



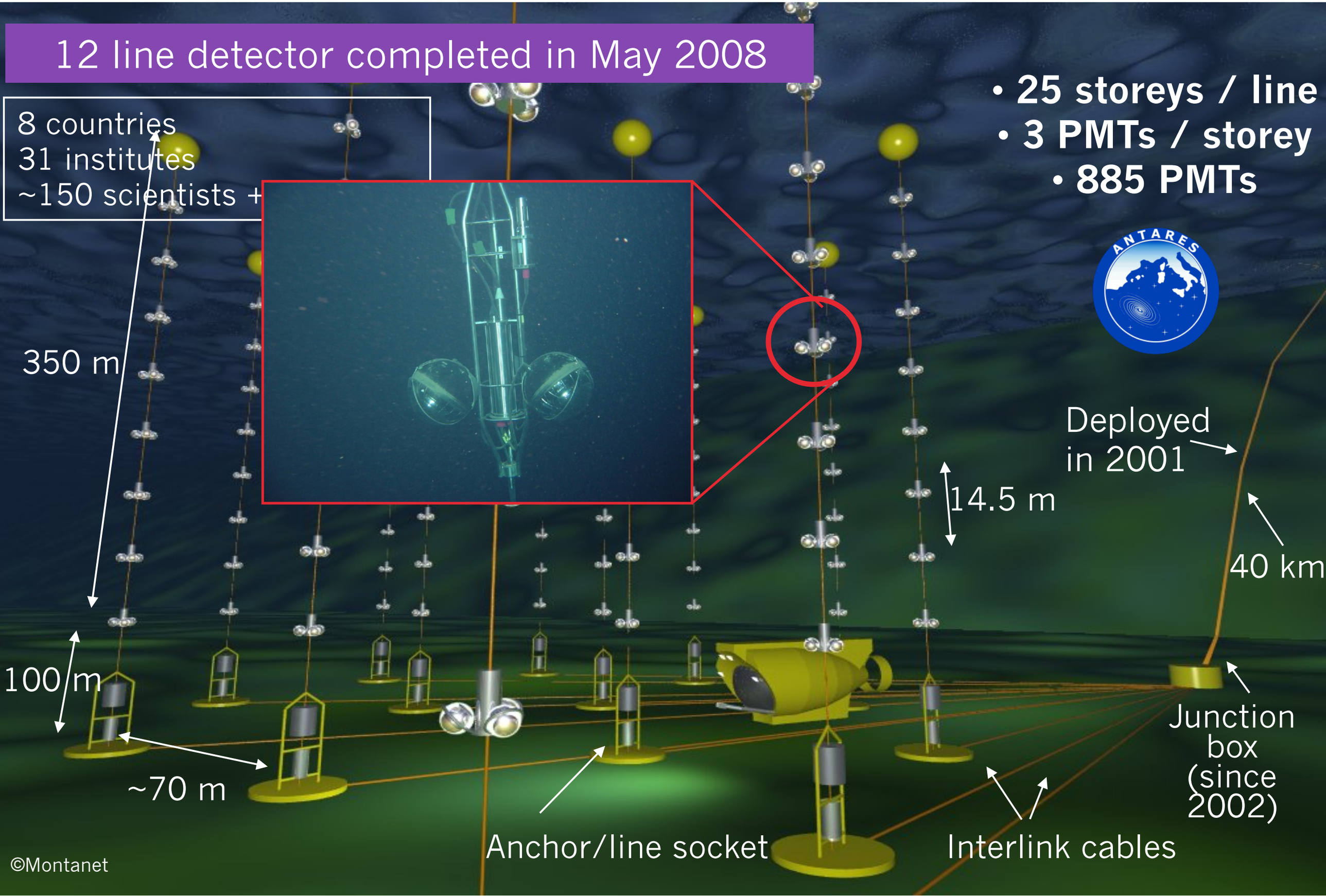
Télescopes à neutrinos



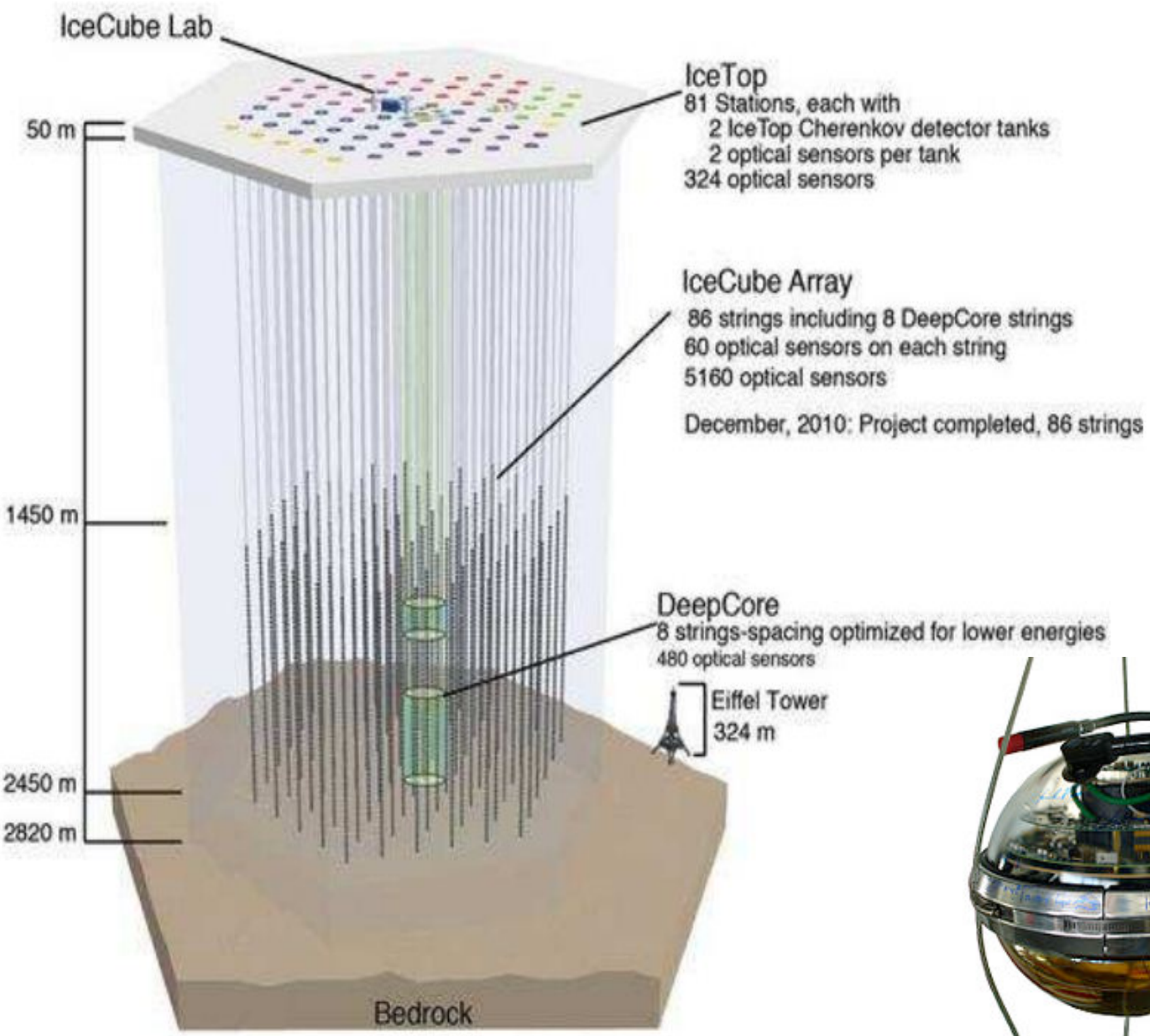
ANTARES


12 line detector completed in May 2008
8 countries
31 institutes
~150 scientists + engineers
• 25 storeys / line
• 3 PMTs / storey
• 885 PMTs
ANTARES
350 m
Deployed in 2001
14.5 m
40 km
100 m
~70 m
Junction box (since 2002)
Anchor/line socket
Interlink cables
©Montanet

ANTARES


12 line detector completed in May 2008
8 countries
31 institutes
~150 scientists +
• 25 storeys / line
• 3 PMTs / storey
• 885 PMTs
350 m
Deployed in 2001
14.5 m
40 km
100 m
~70 m
Junction box (since 2002)
Anchor/line socket
Interlink cables
©Montanet

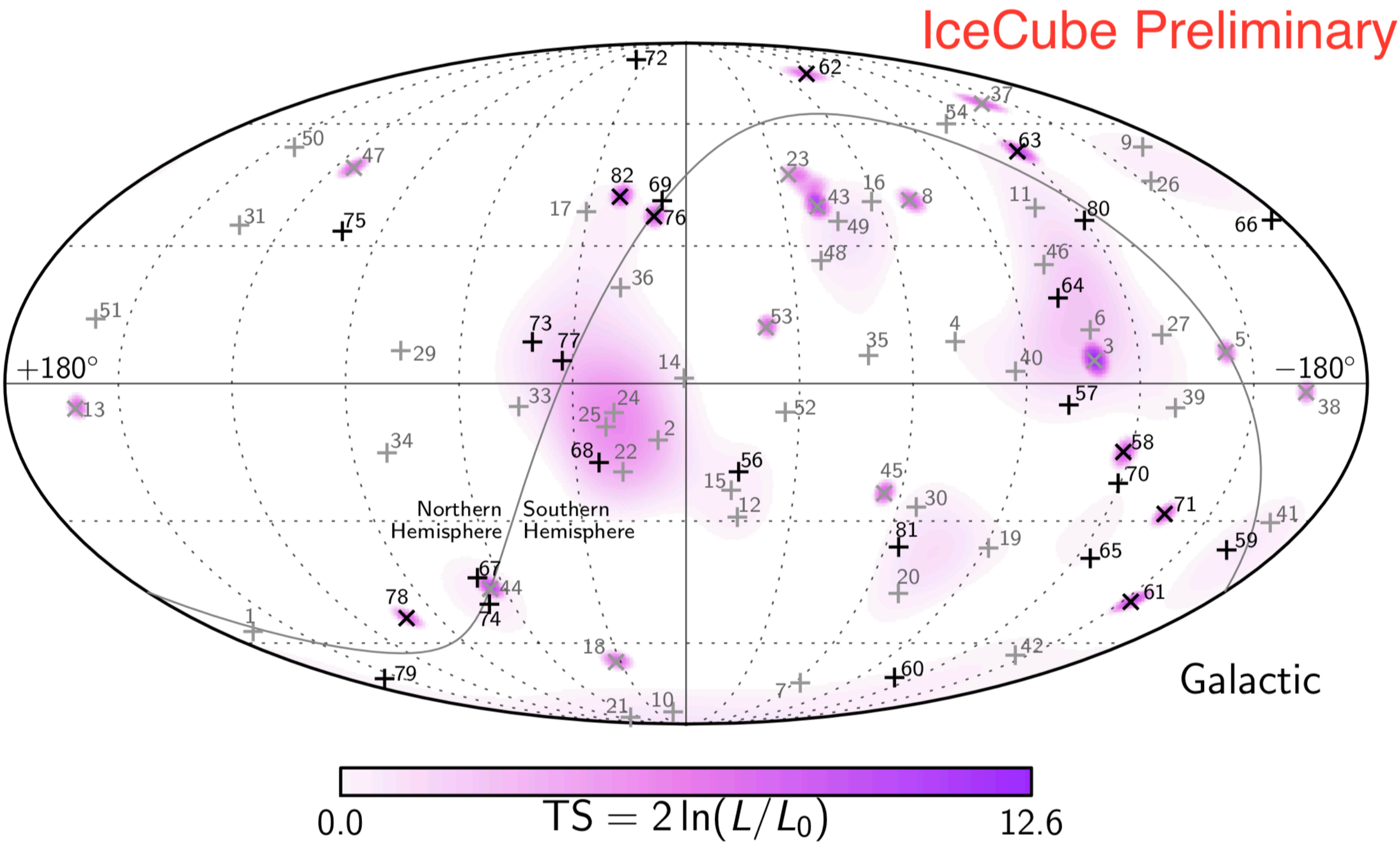
IceCube

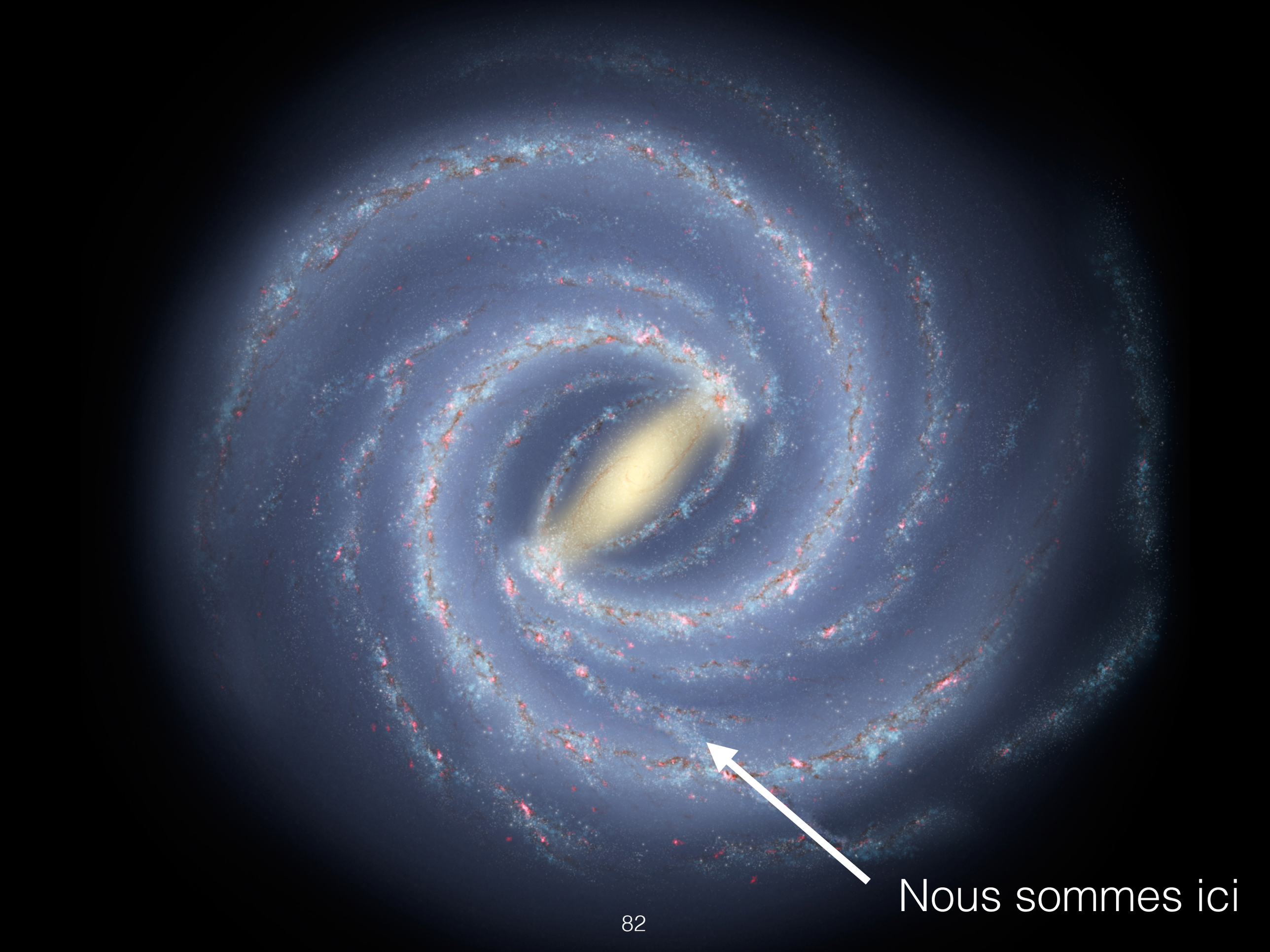


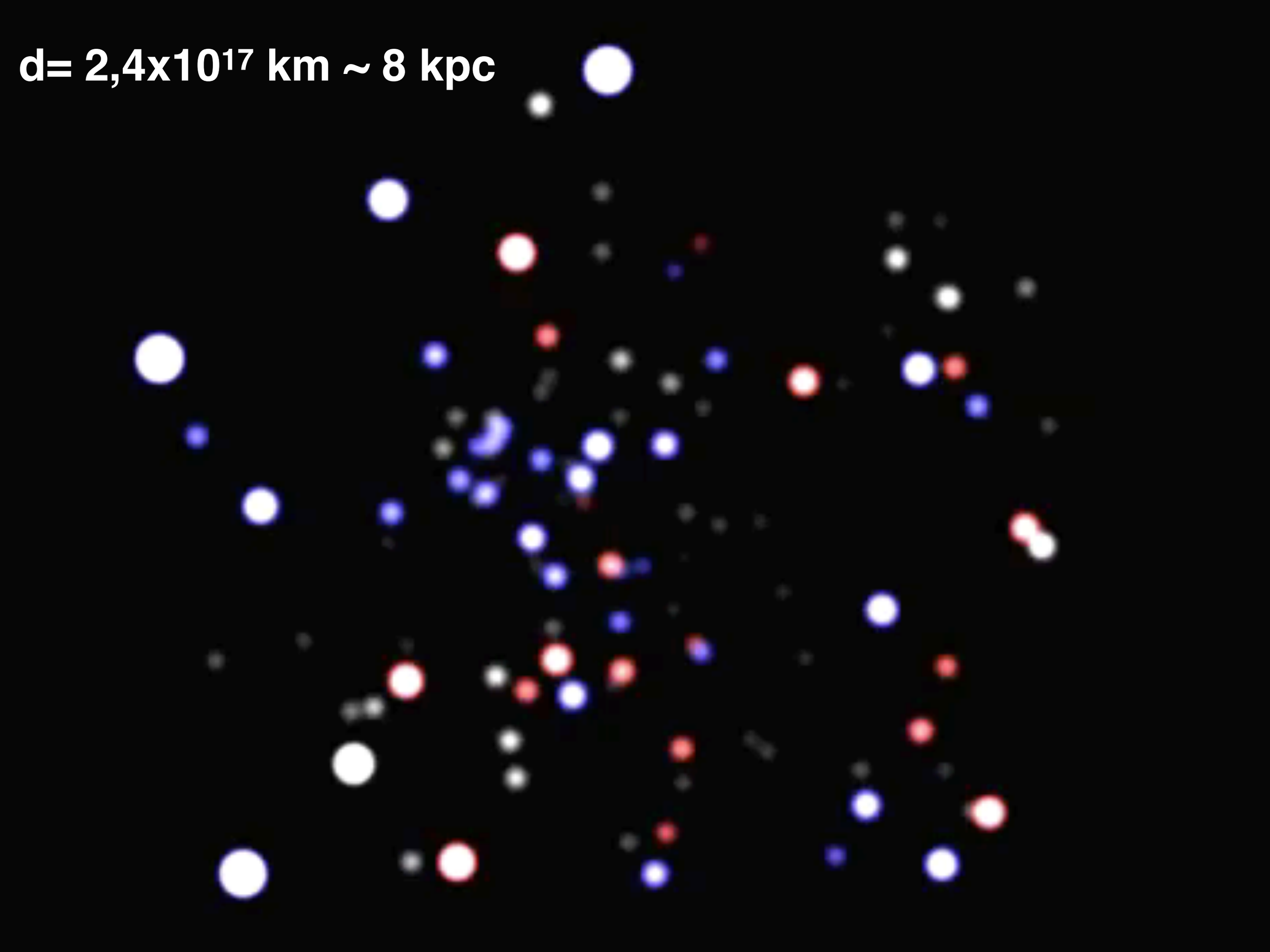
86 lines, completed end 2010
1 km^3 instrumented volume
DeepCore: denser (8 strings)
IceTop: air shower detectors

Different media: different technical challenges

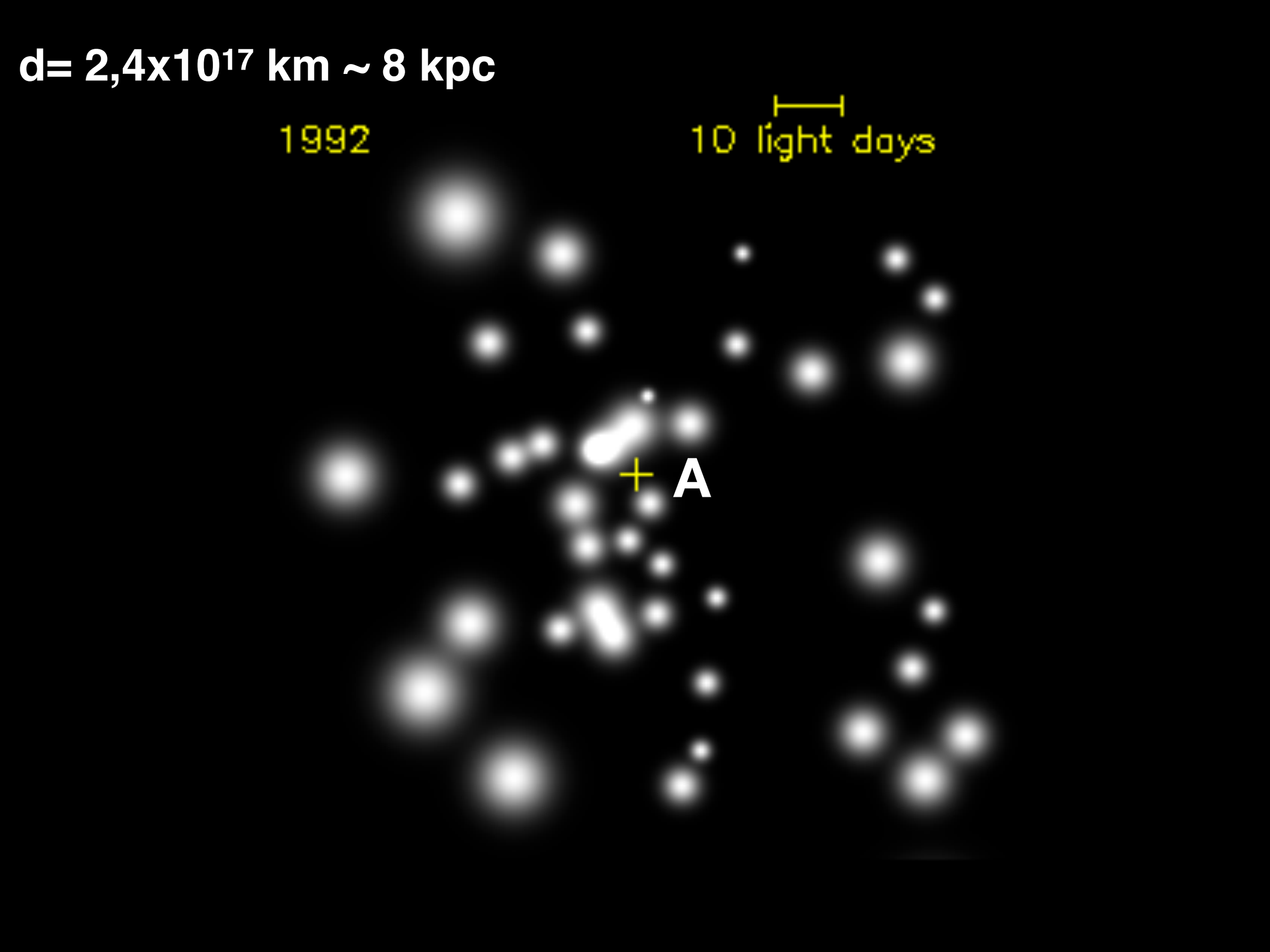
Premières détections



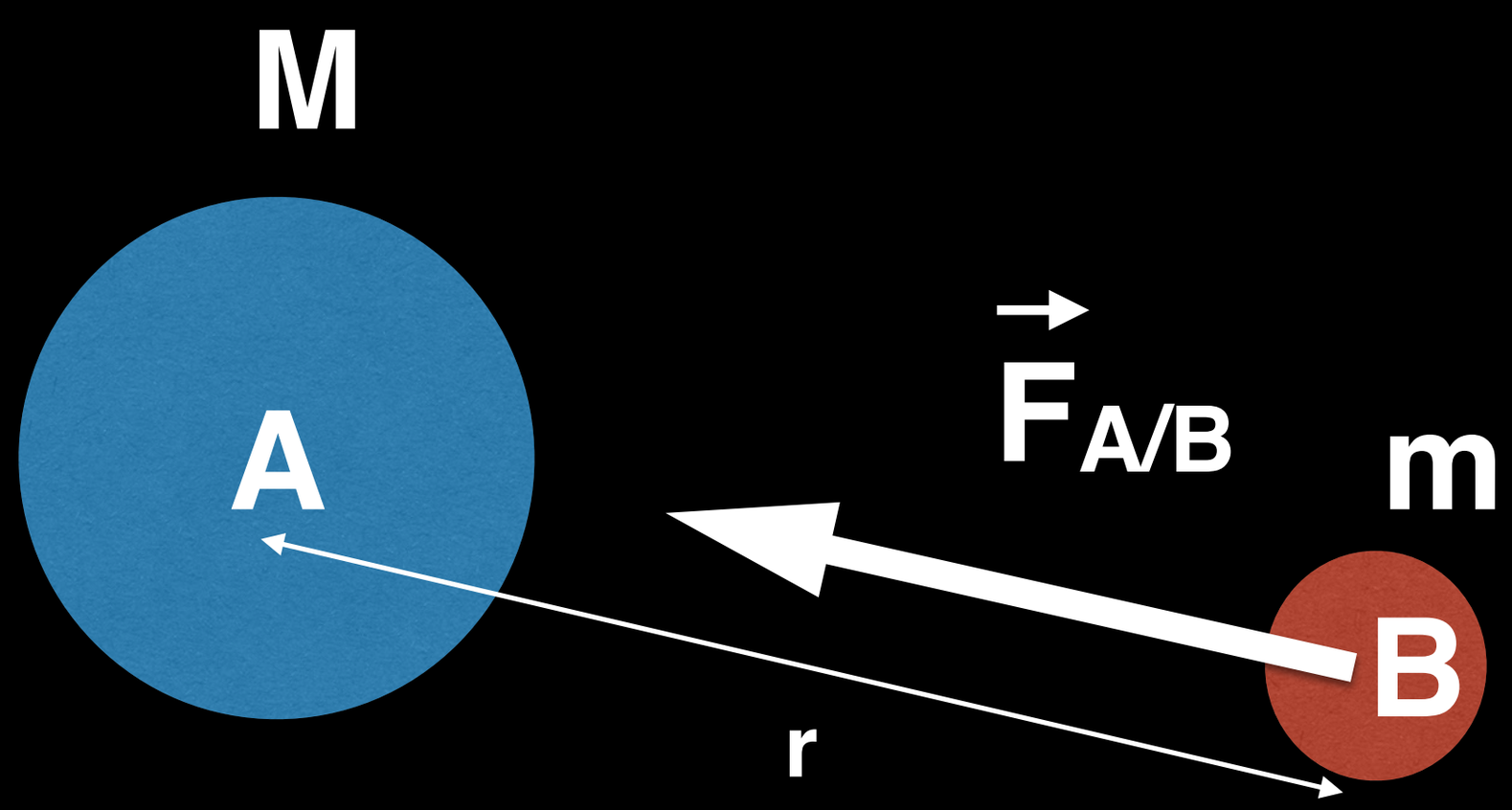

Nous sommes ici

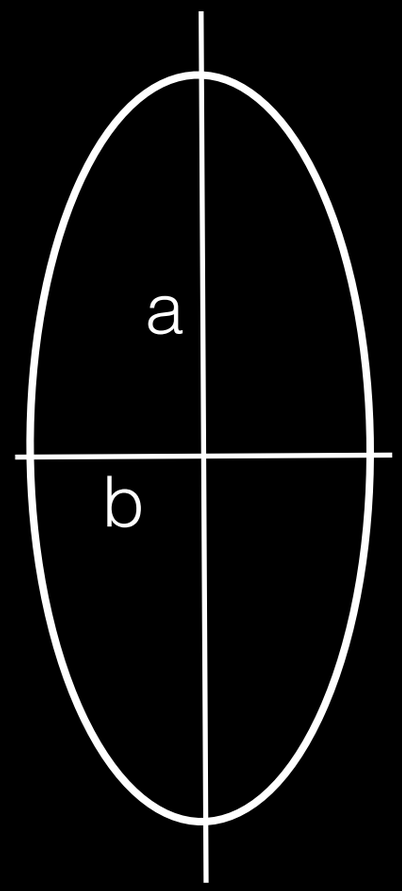

d= 2,4x10^{17} km ~ 8 kpc

d= 2,4x10^{17} km ~ 8 kpc



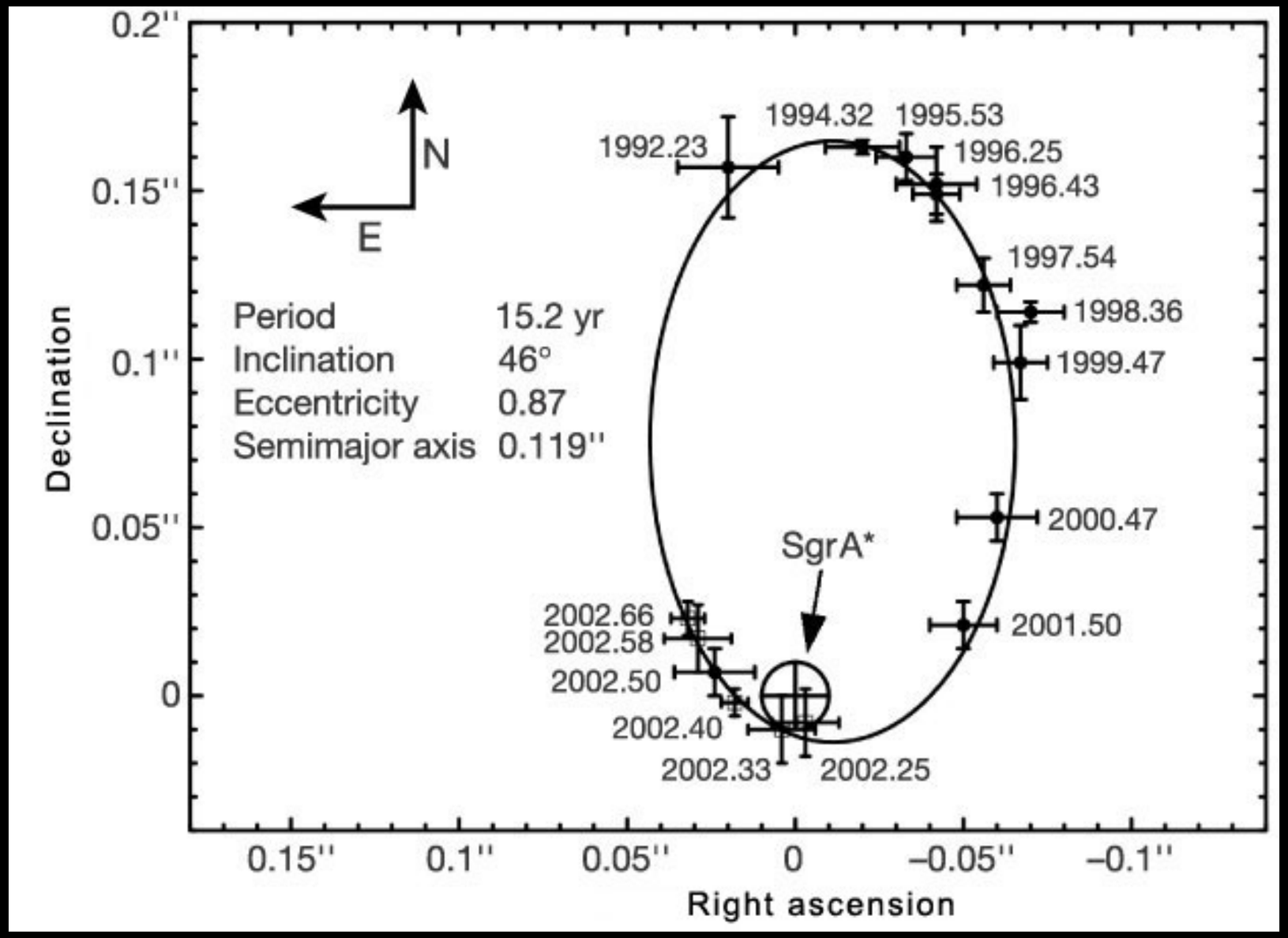
Loi de la Gravitation

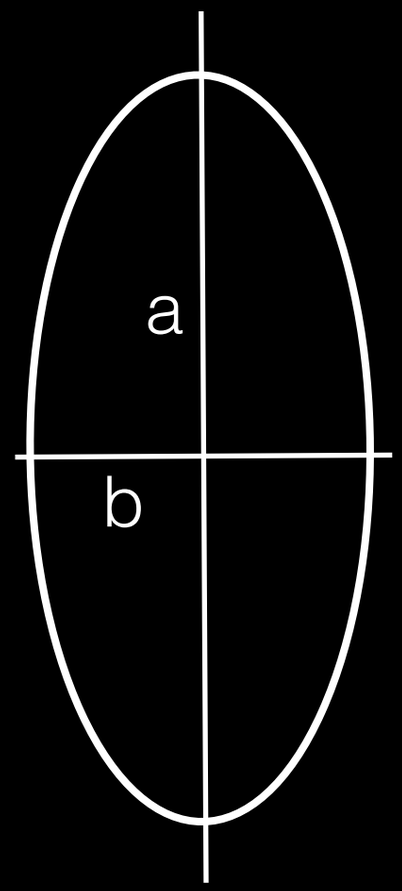




3e loi de Kepler:

$$T^2 / a^3 = 4\pi^2/GM = \text{cste}$$

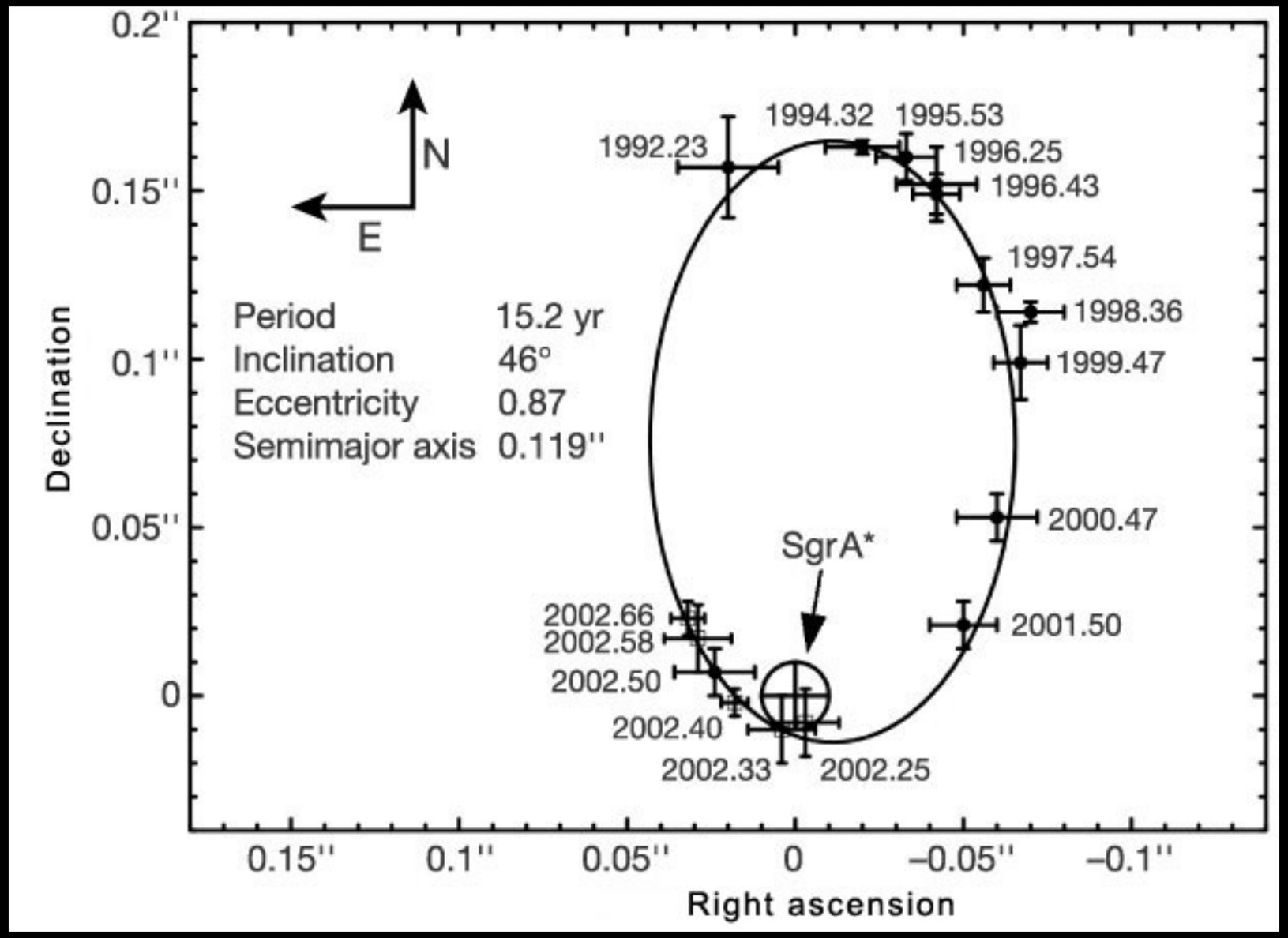


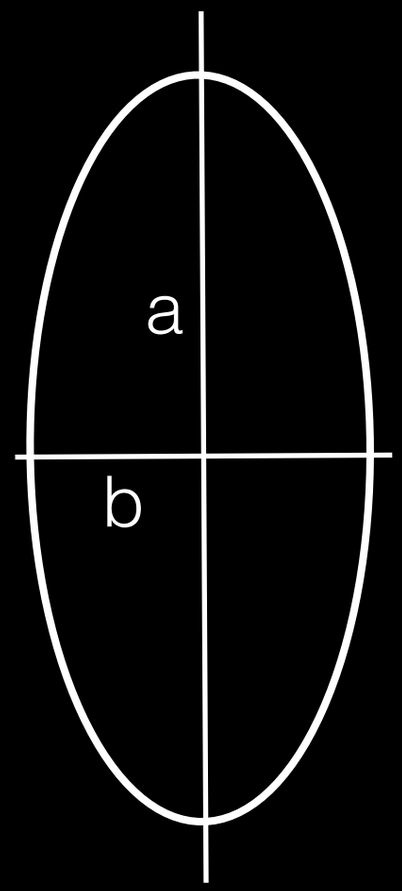


3e loi de Kepler:

$$T^2 / a^3 = 4\pi^2/GM = cste$$

T~15 ans = 4,73 x 10^8 s



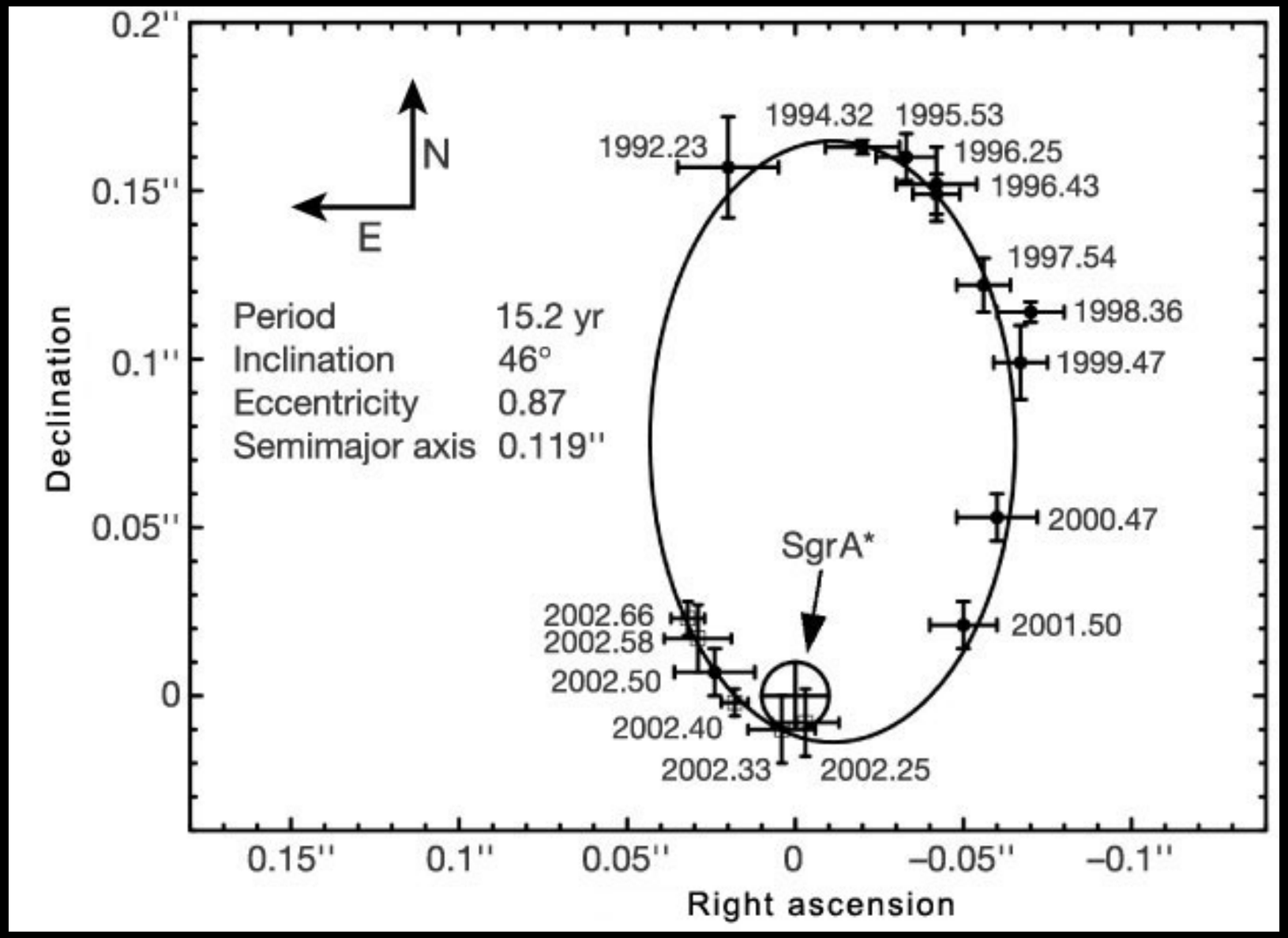


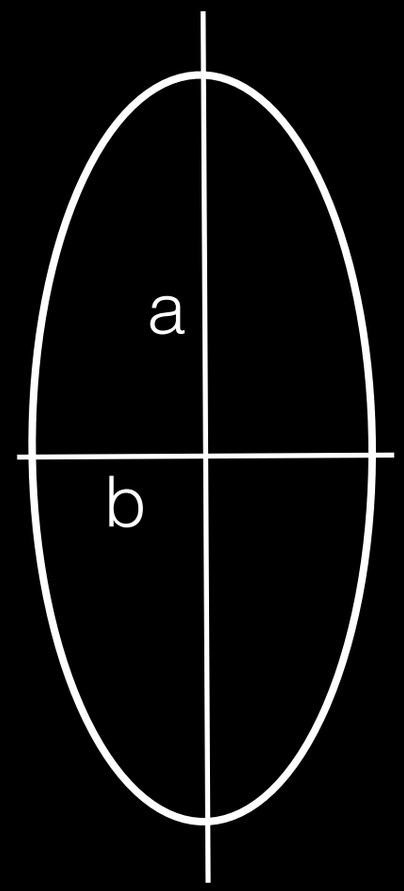
3e loi de Kepler:

$$T^2 / a^3 = 4\pi^2/GM = cste$$

T~15 ans = 4,73 x 10^8 s

2a ~ 3 x 10^{14} m

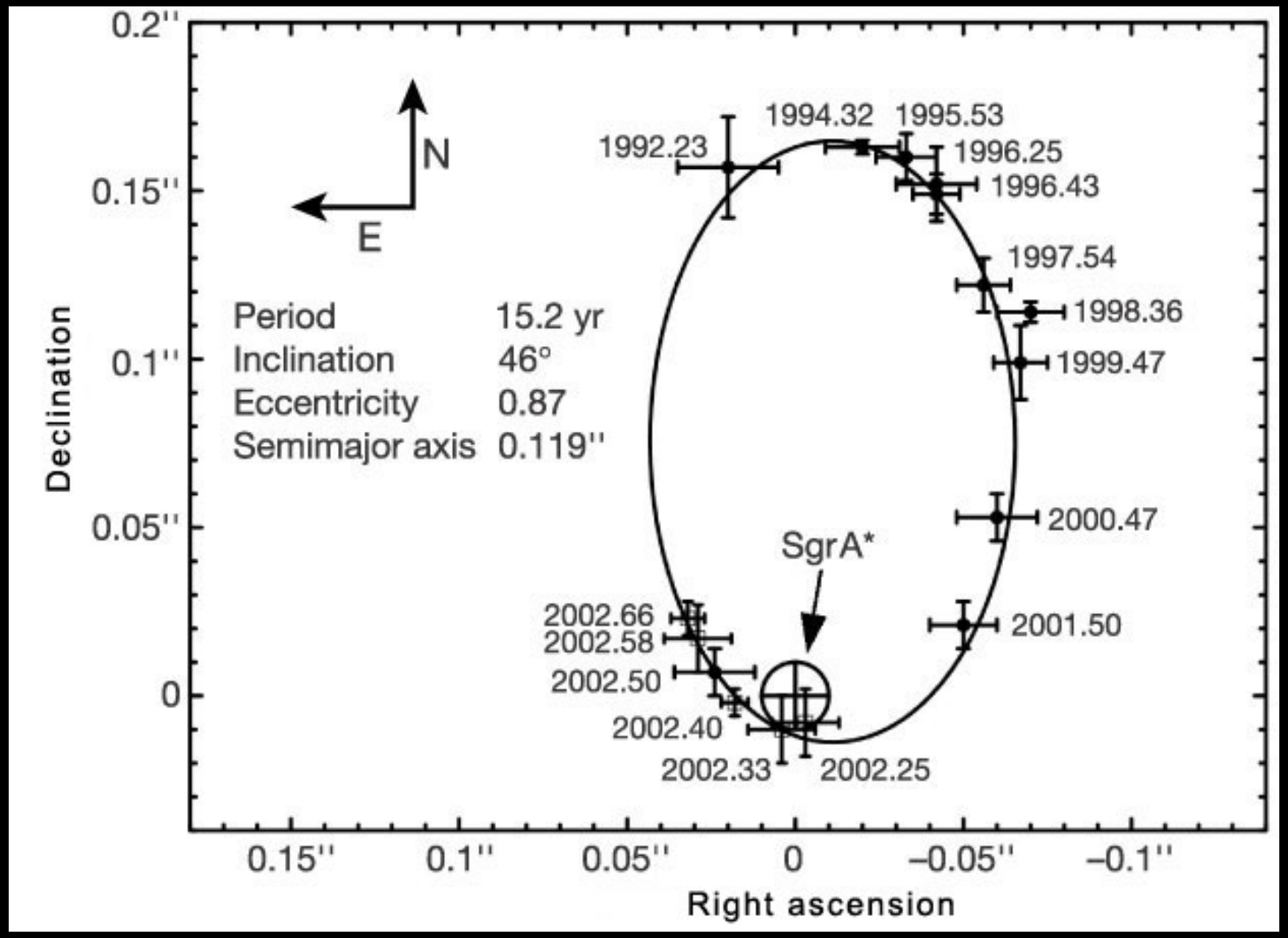


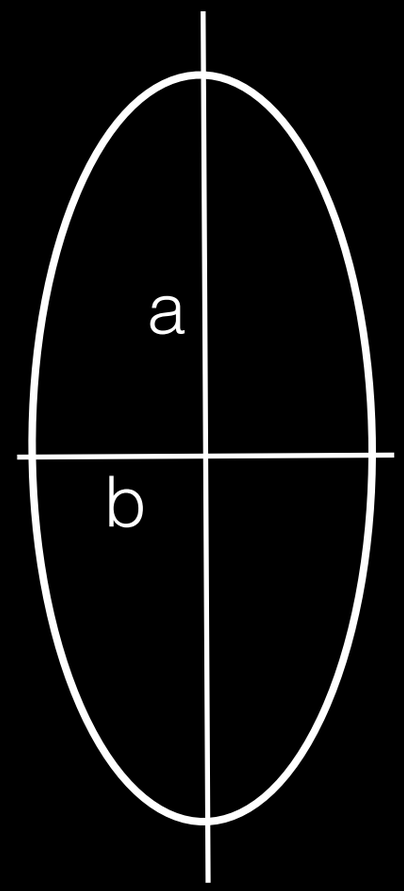


3e loi de Kepler:

$$T^2 / a^3 = 4\pi^2/GM = cste$$

$M = 4\pi^2 \times a^3/(T^2 \times G)$
$= 3.2 \times 10^{36}$ kg



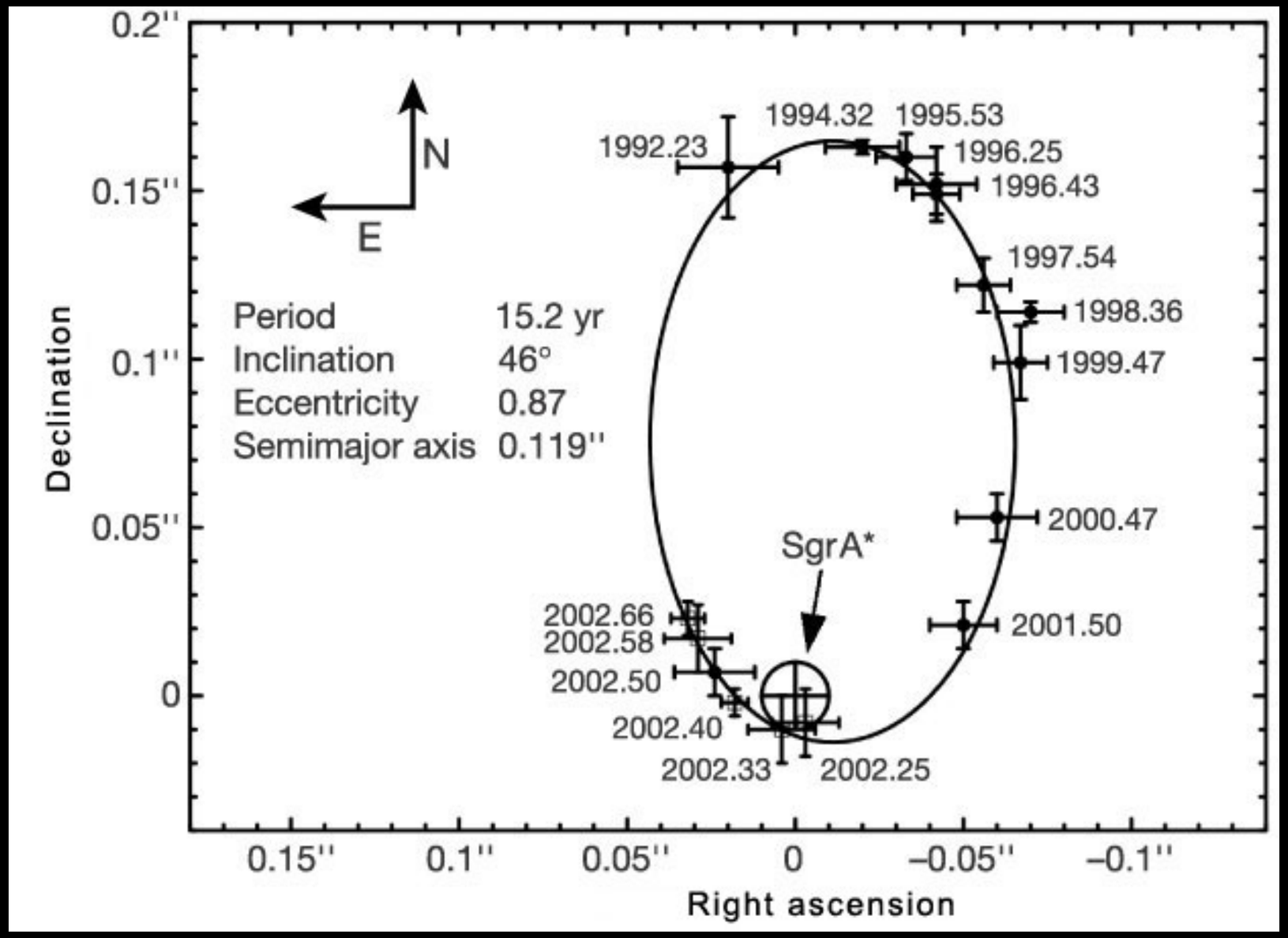


3e loi de Kepler:

$T^2 / a^3 = 4\pi^2/GM = cste$

$M = 4\pi^2 \times a^3/(T^2 \times G)$
$= 3.2 \times 10^{36}$ kg

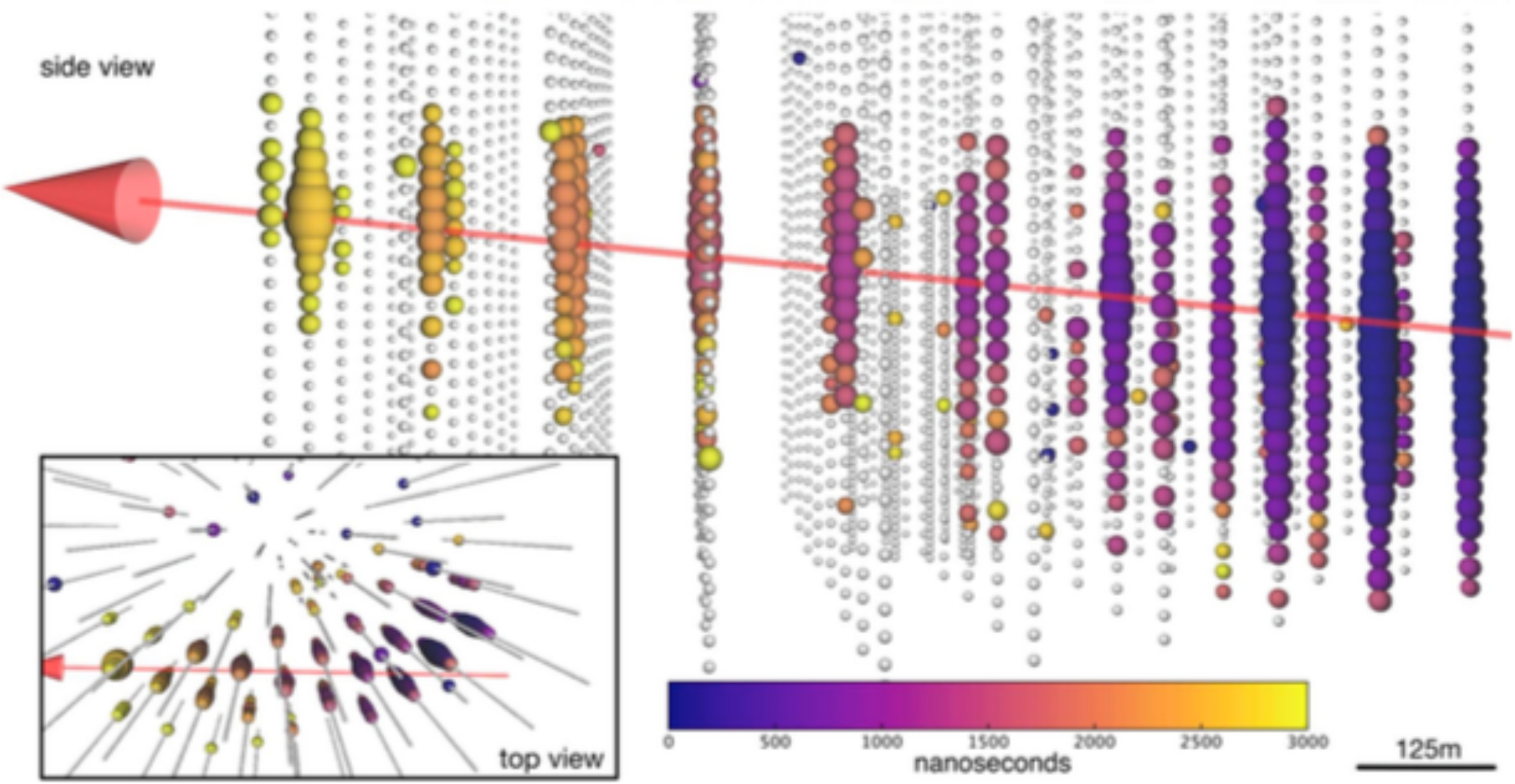
M / M_{soleil}
$= 3.2 \times 10^{36}$ kg $/ 2 \times 10^{30}$ kg
$= 1{,}6 \times 10^6$



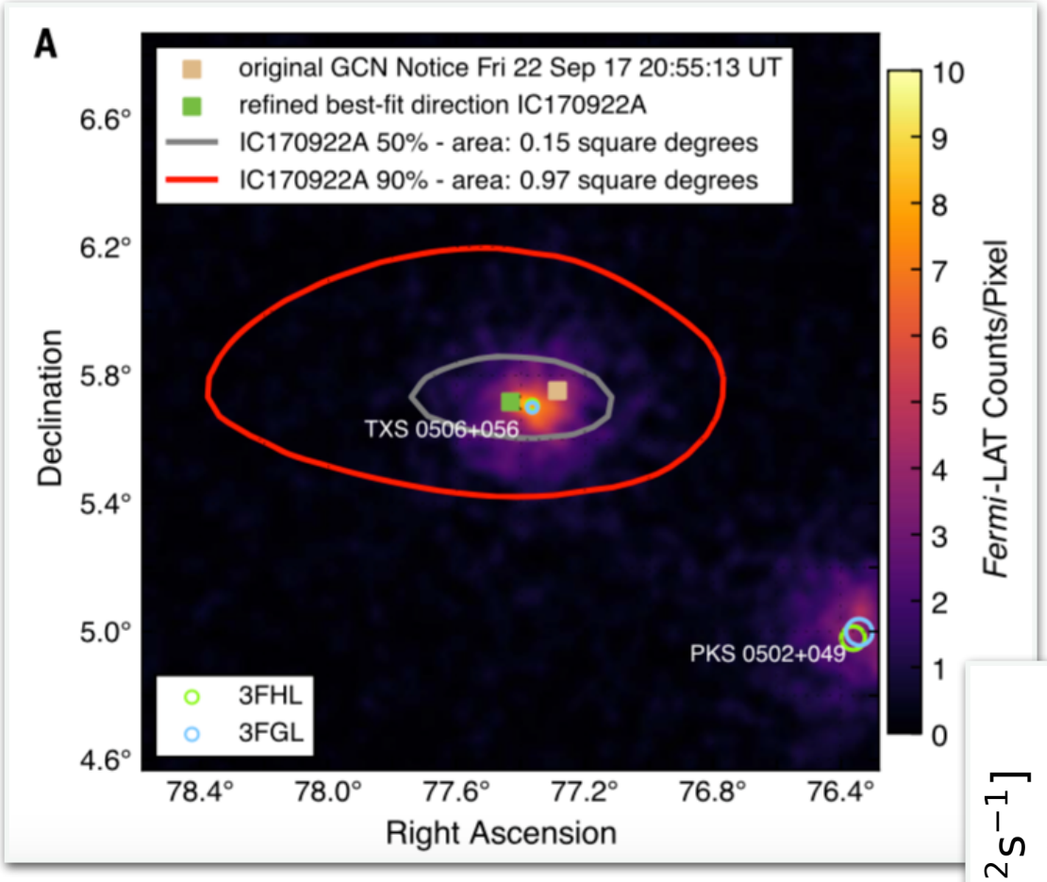
IC170922A / TXS 0506+056

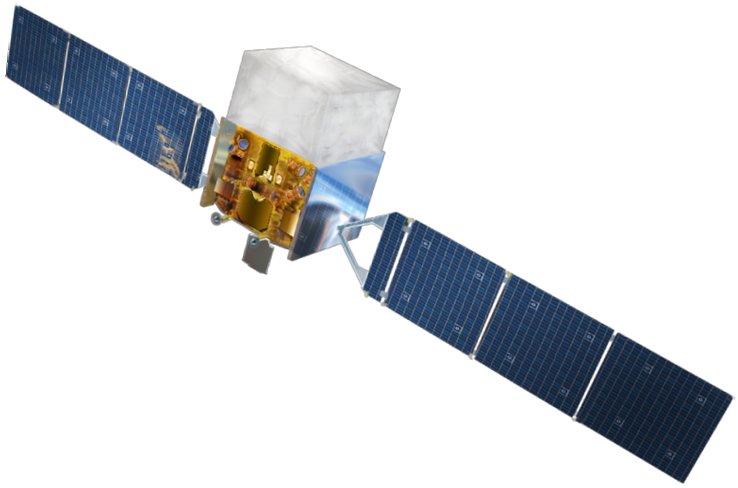
22 septembre 2017
~290 TeV

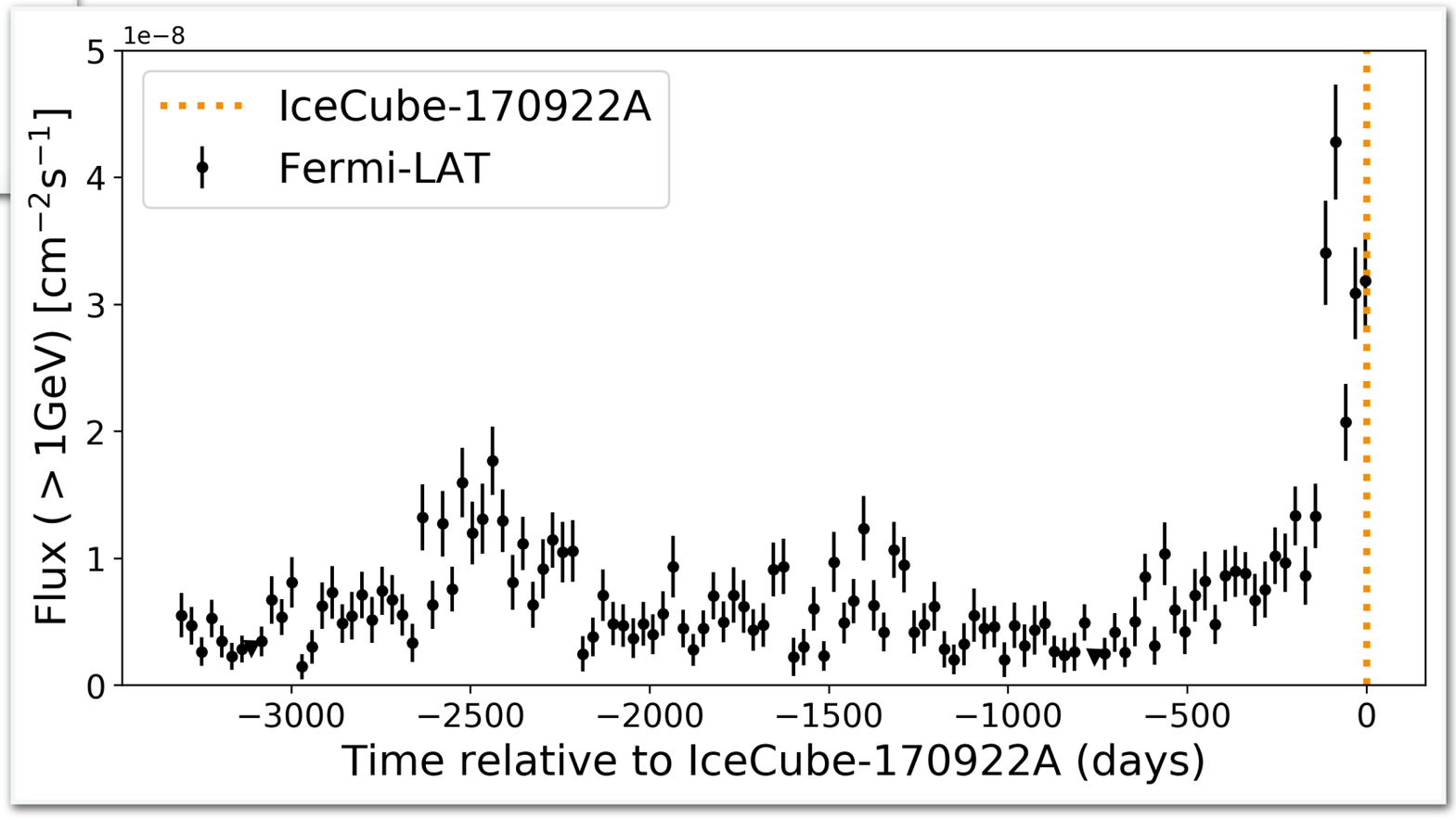
Science 361, 6398, (2018) eaat1378



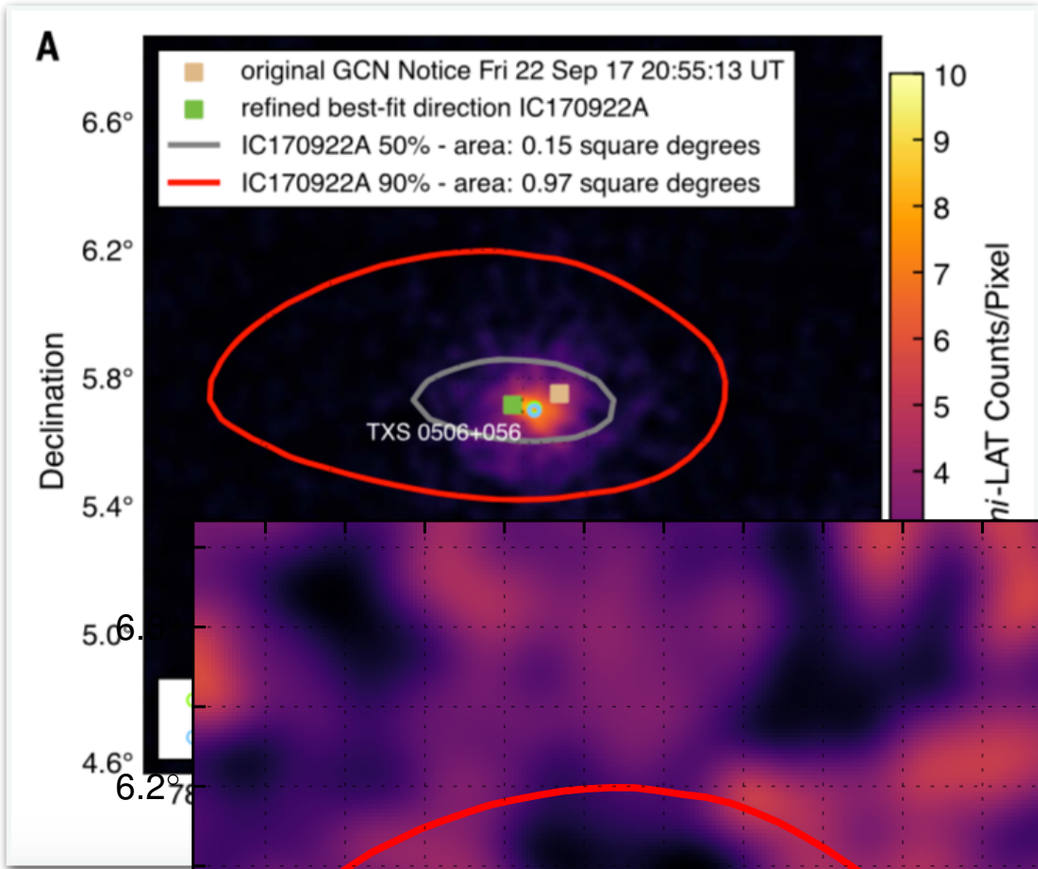
IC170922A / TXS 0506+056

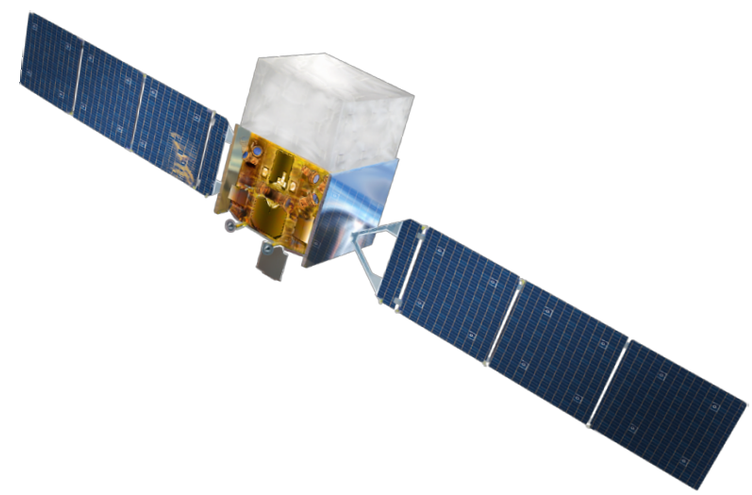


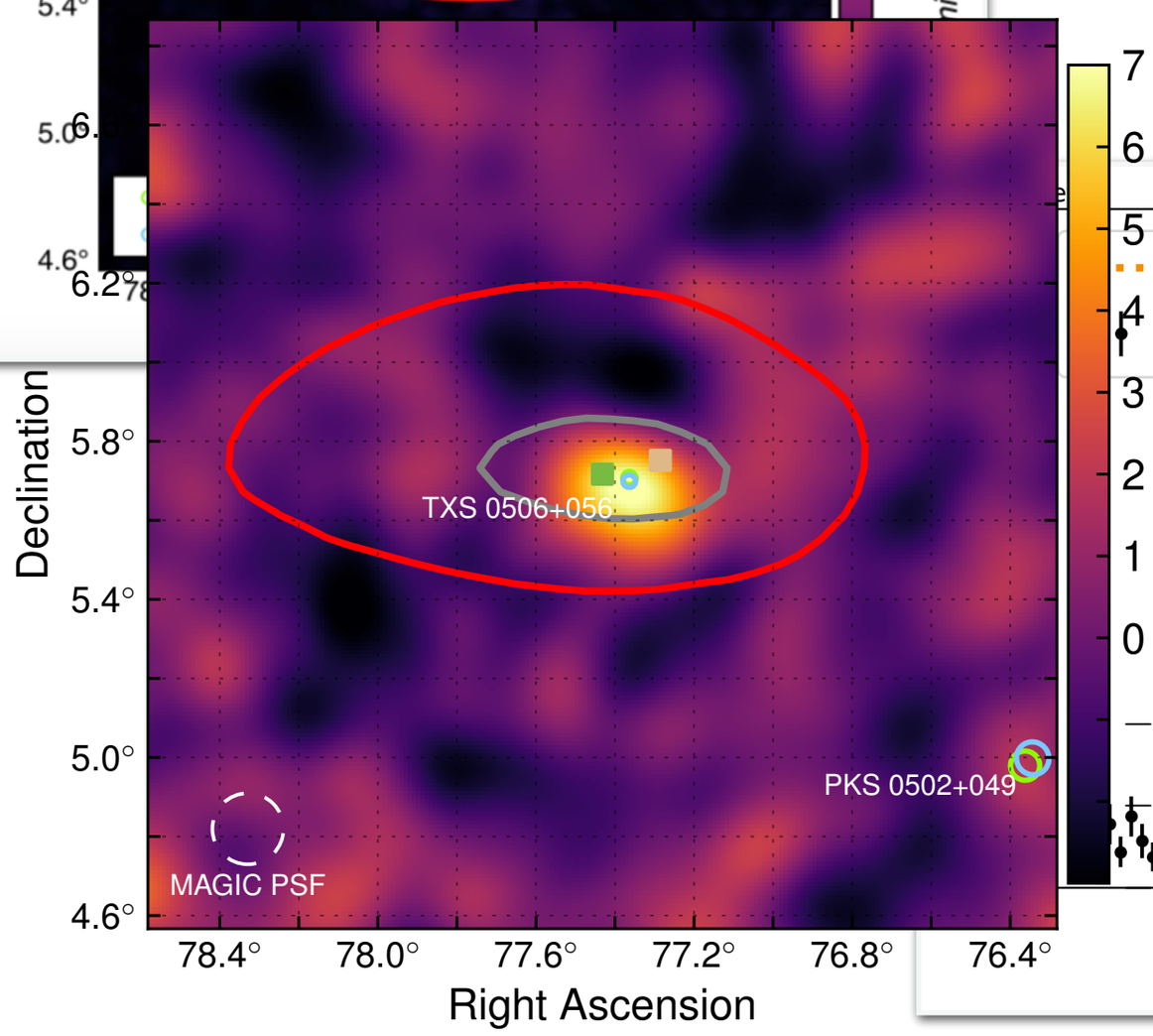


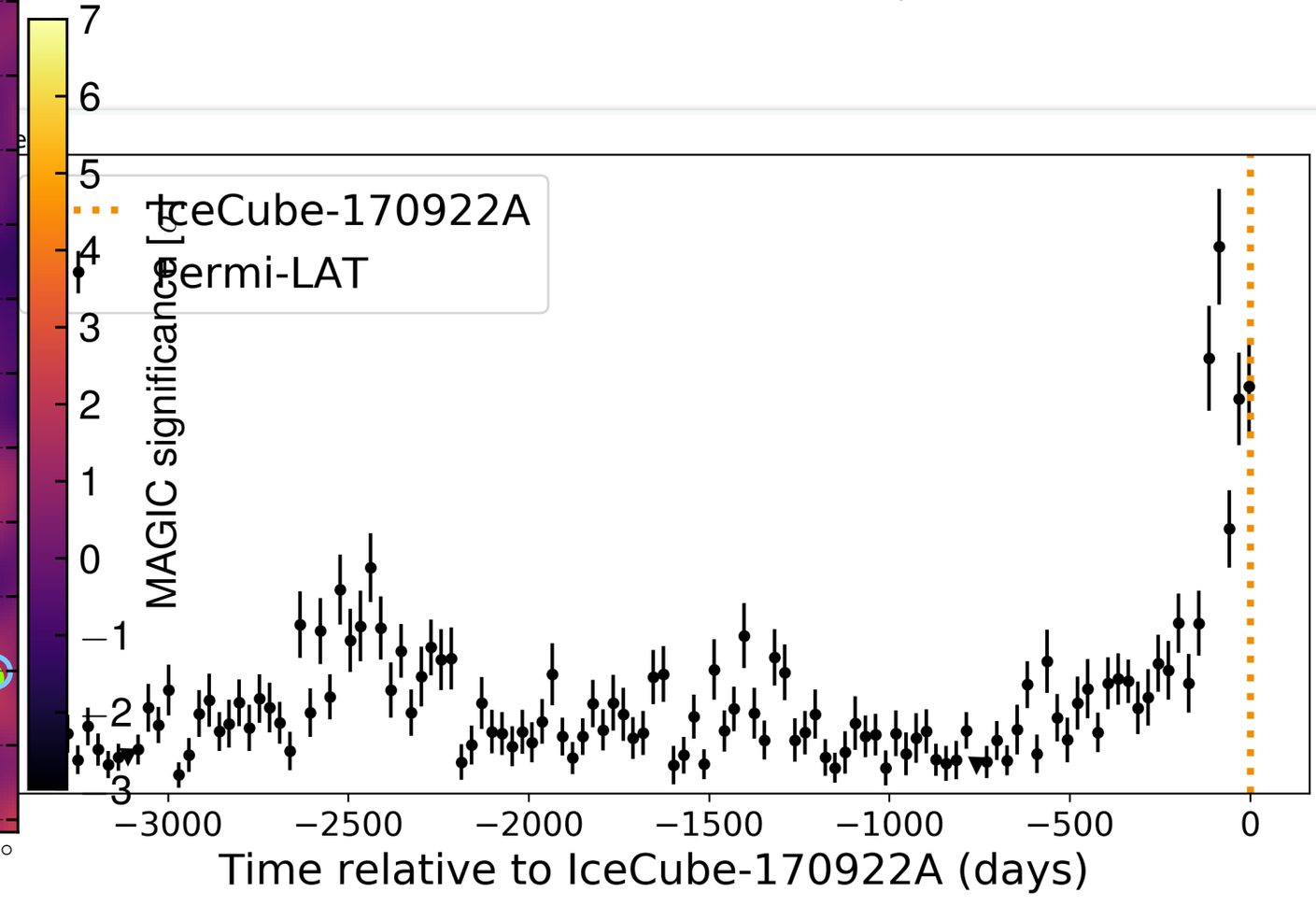


IC170922A / TXS 0506+056

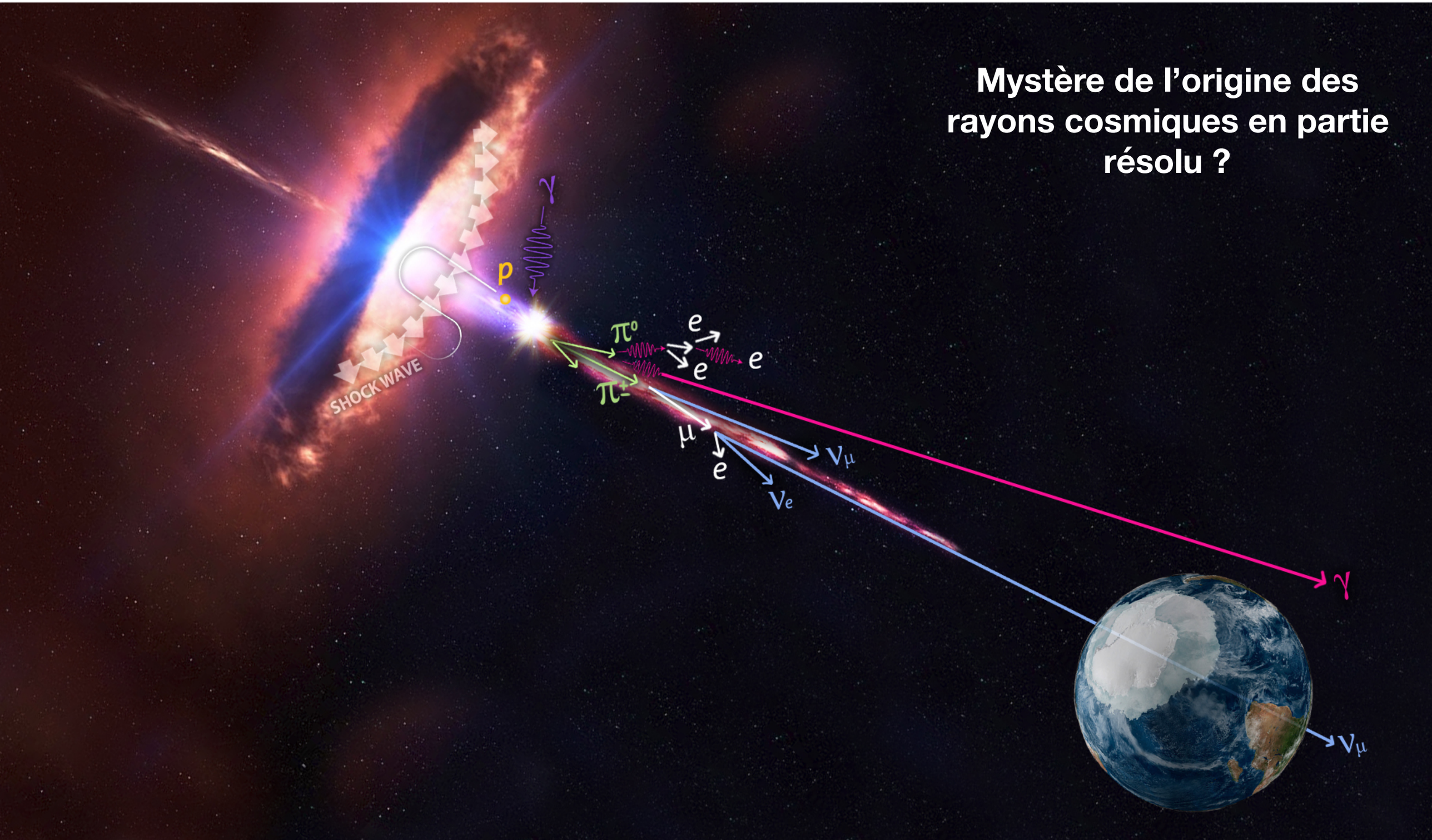




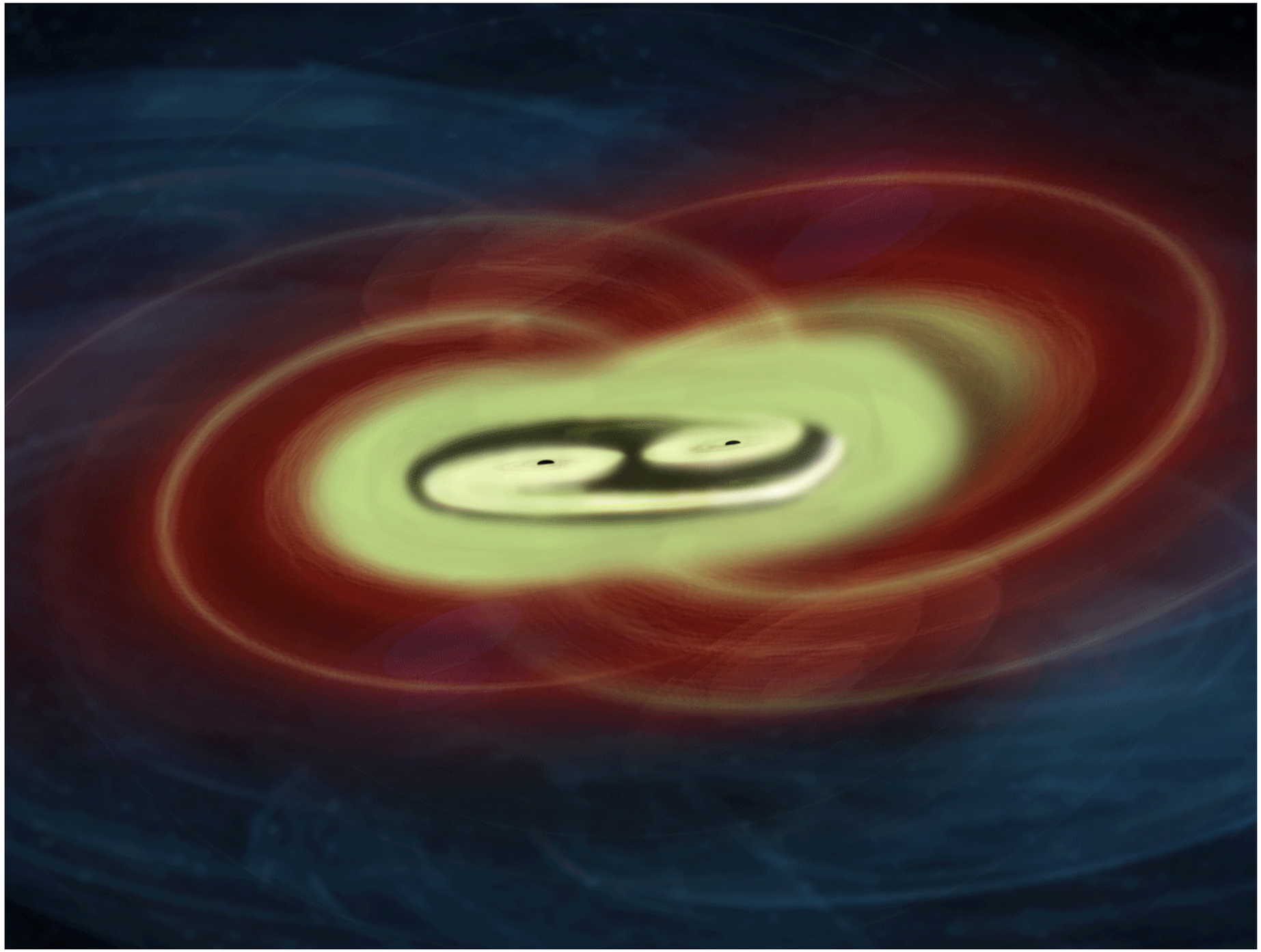




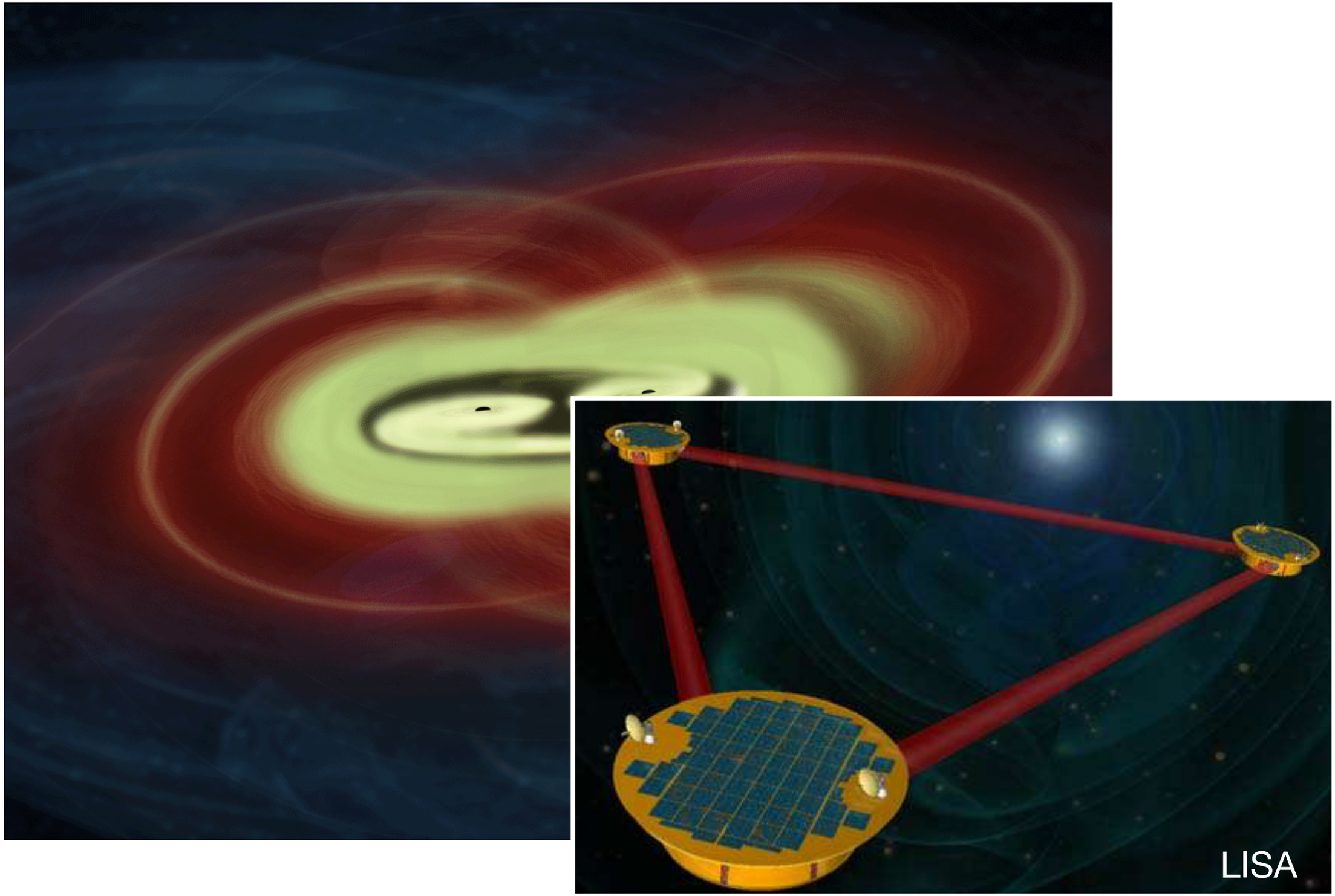
IC170922A / TXS 0506+056



Quel signal multi-messager pour la fusion de deux trous noirs super massifs ?

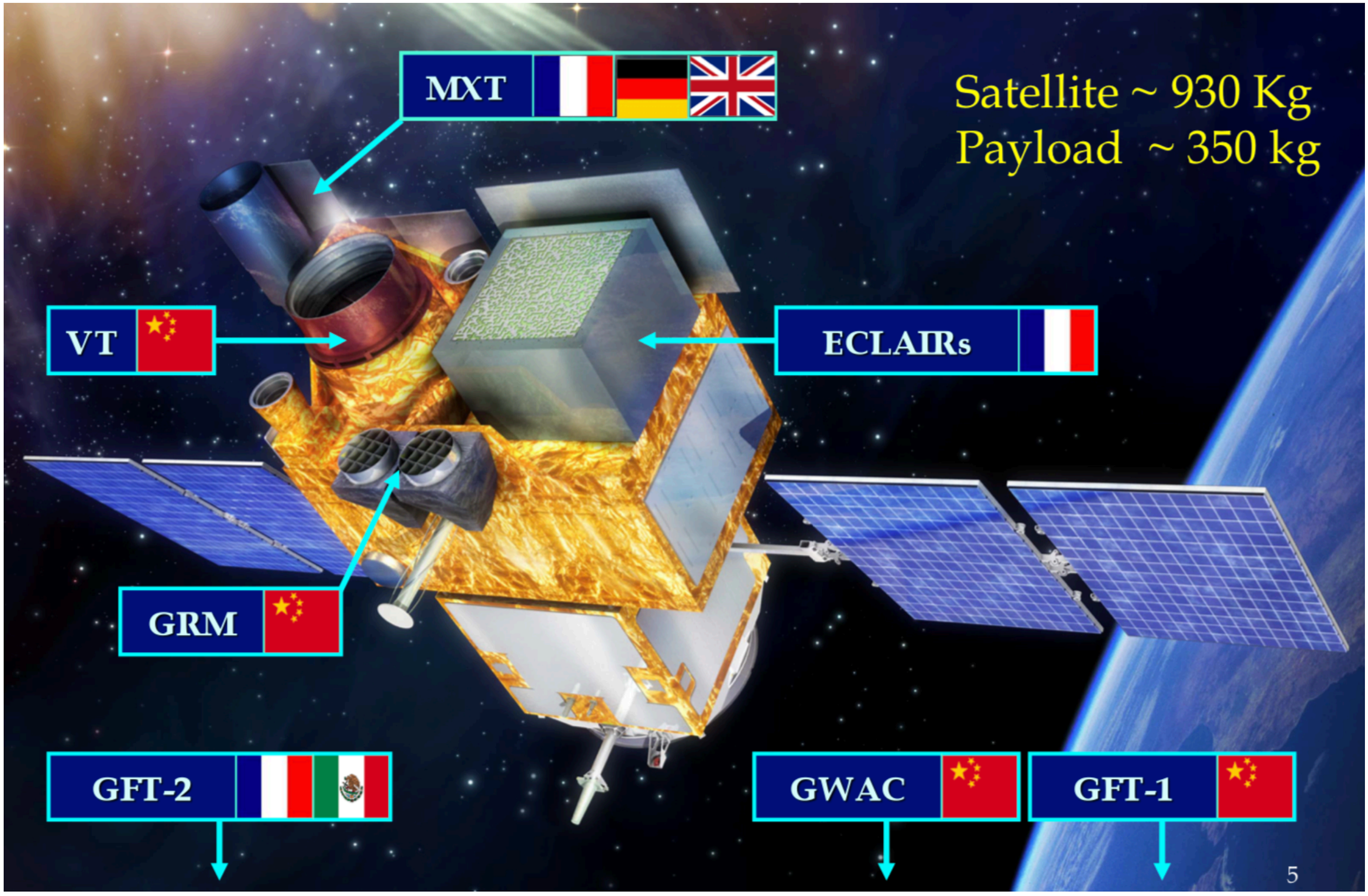


Quel signal multi-messager pour la fusion de deux trous noirs super massifs ?



Le projet SVOM

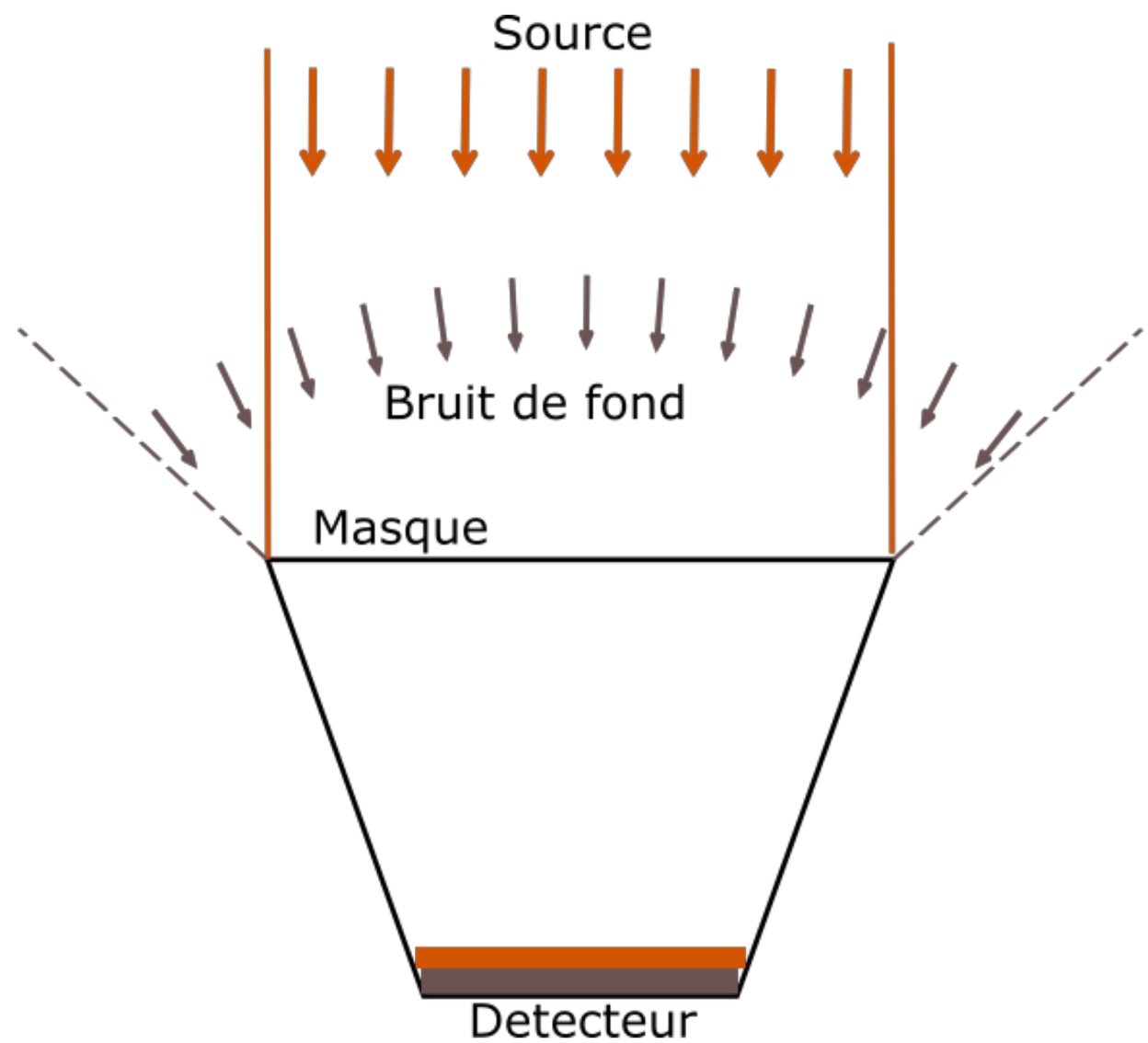
SVOM = Space-based multiband astronomical Variable Objects Monitor



Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

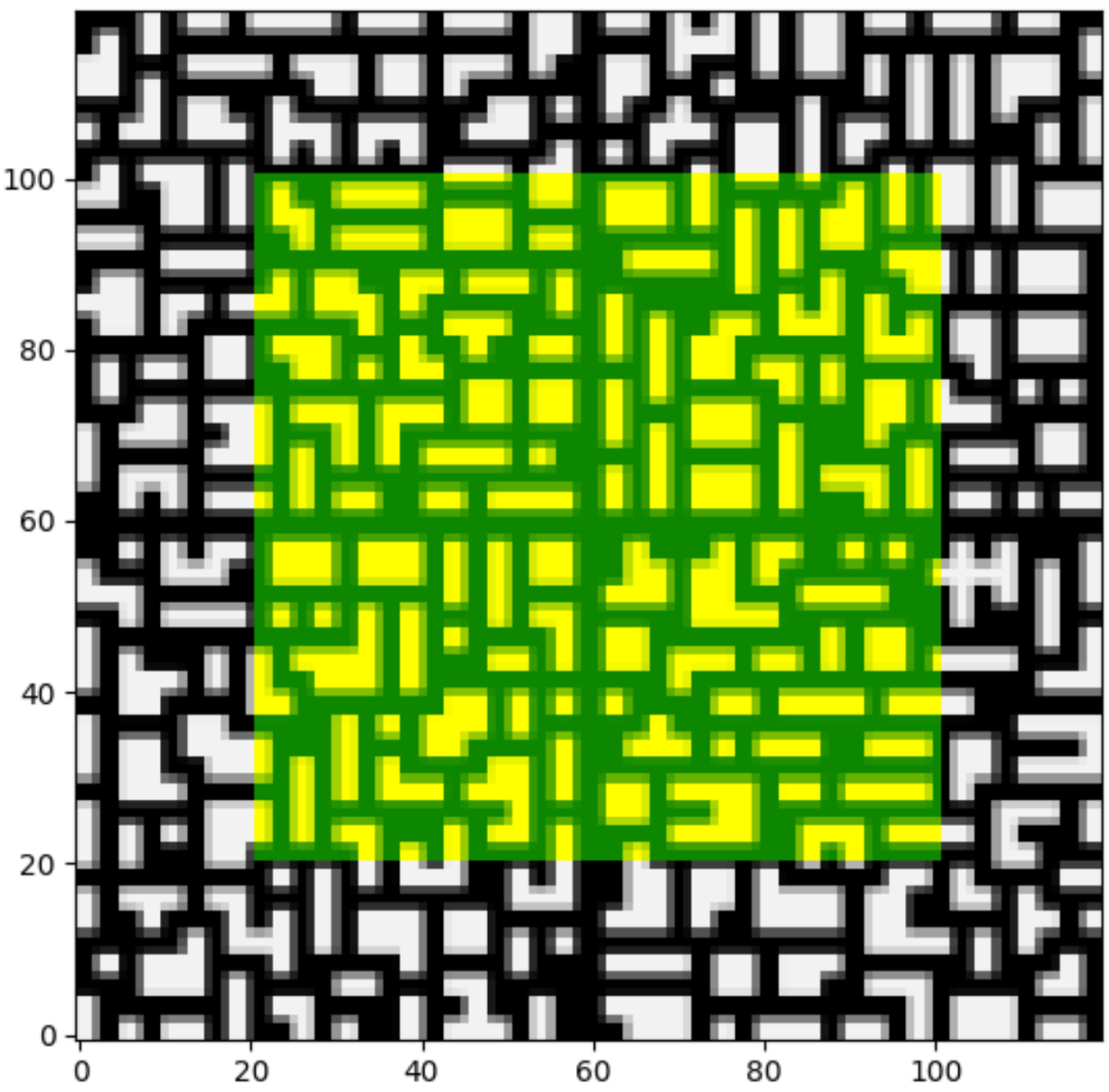
Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.

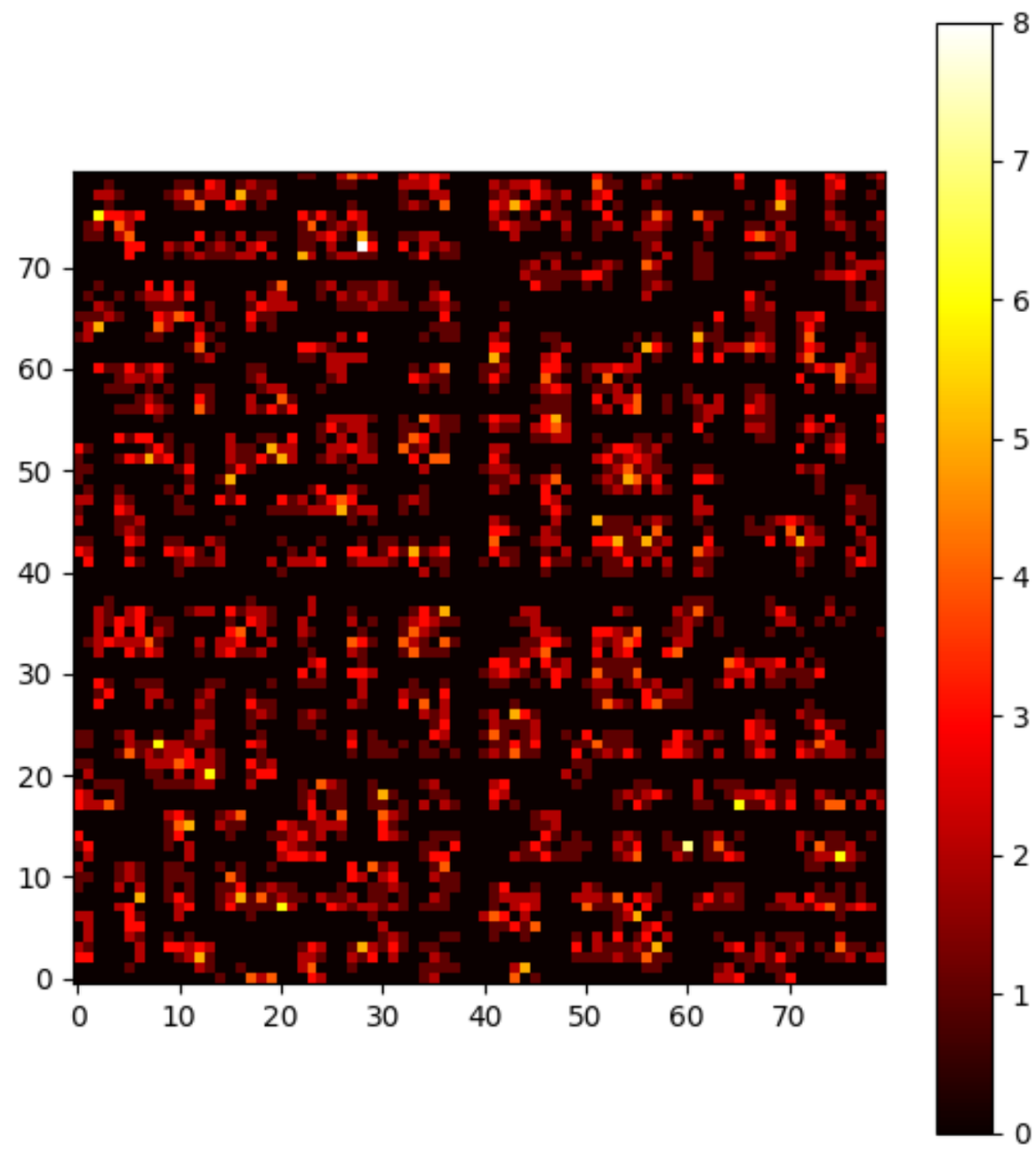


Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.

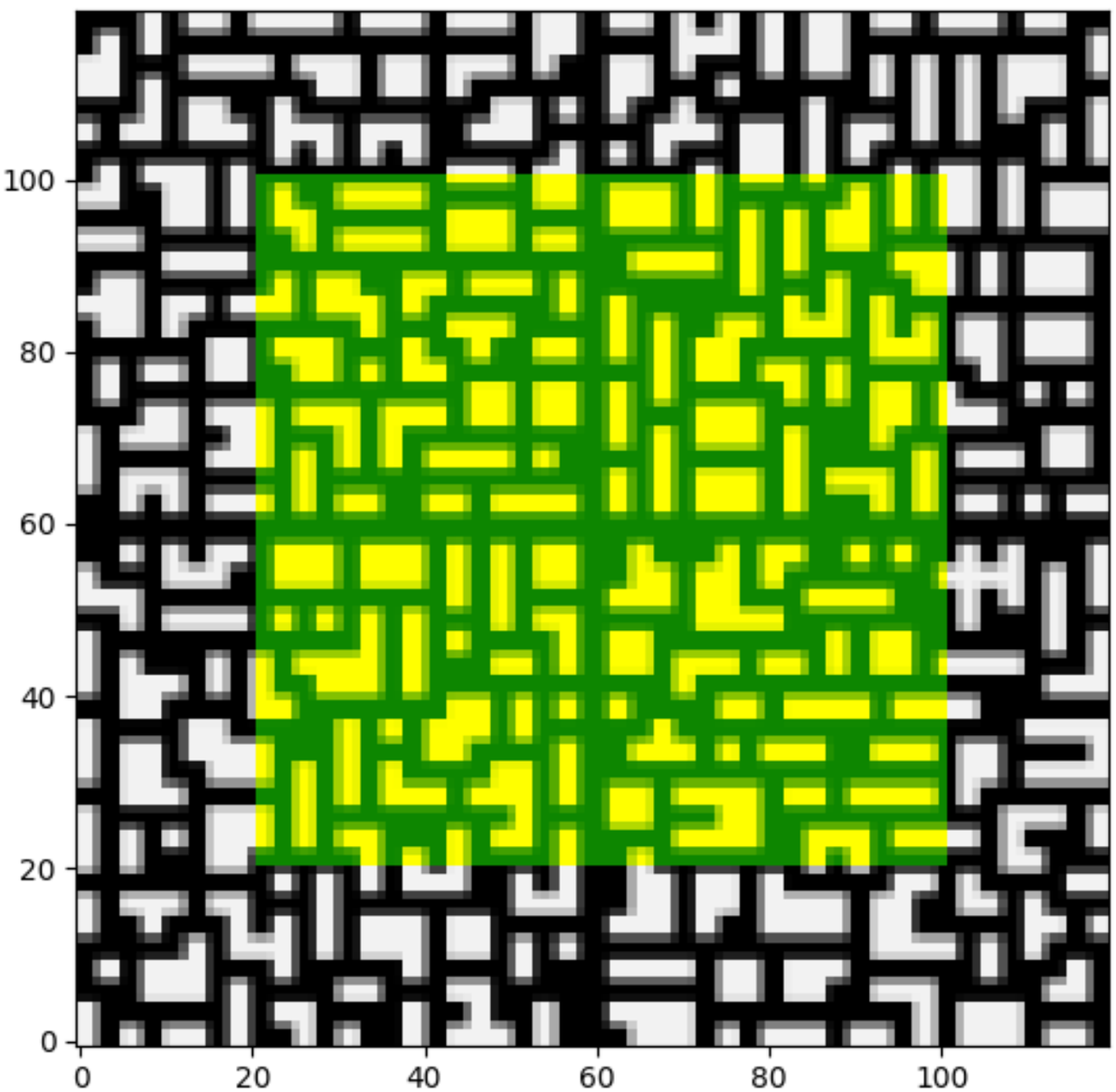


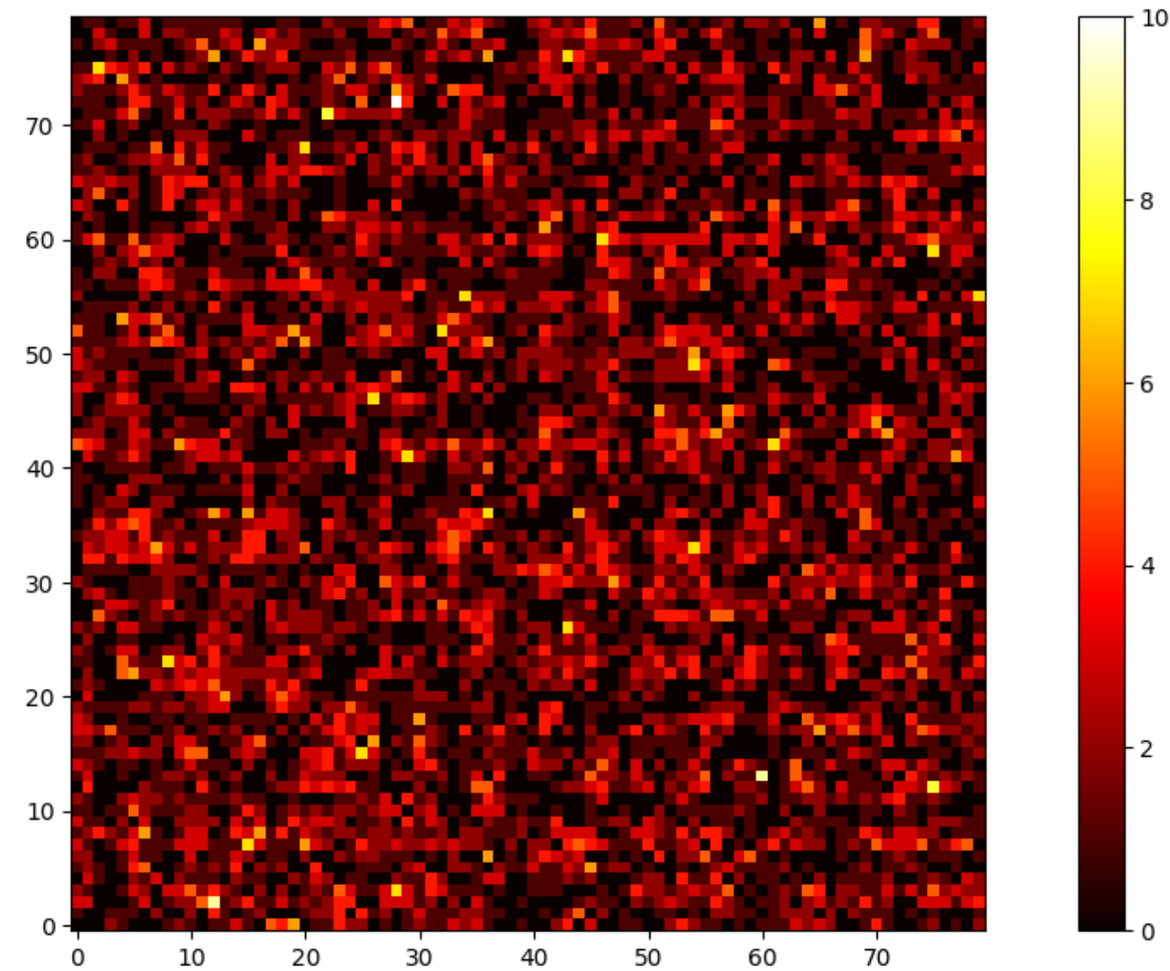


Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.





Le projet SVOM

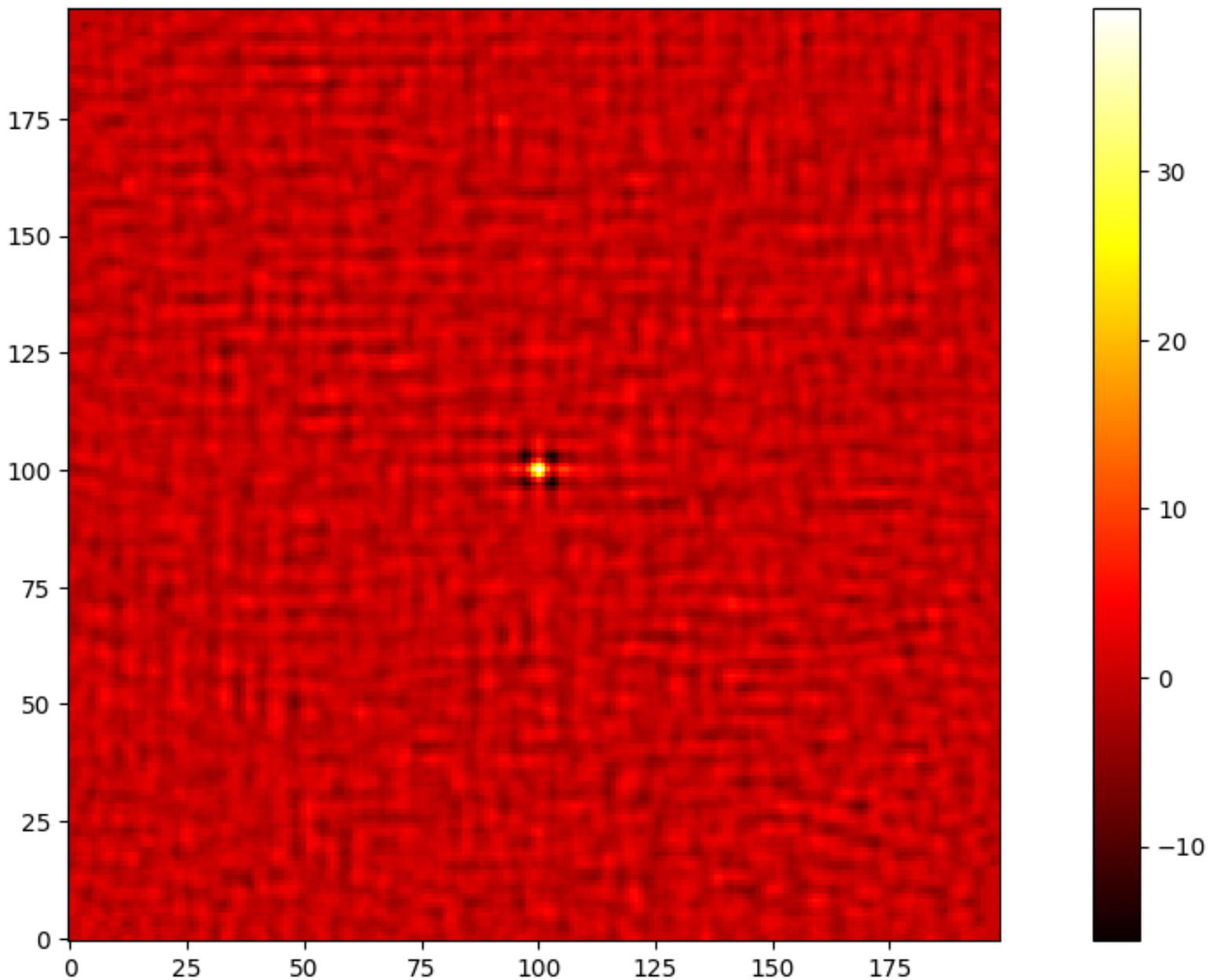
ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.

Le projet SVOM

ECLAIRs: détecteur X durs - gammas mous (4 keV - 150 keV)

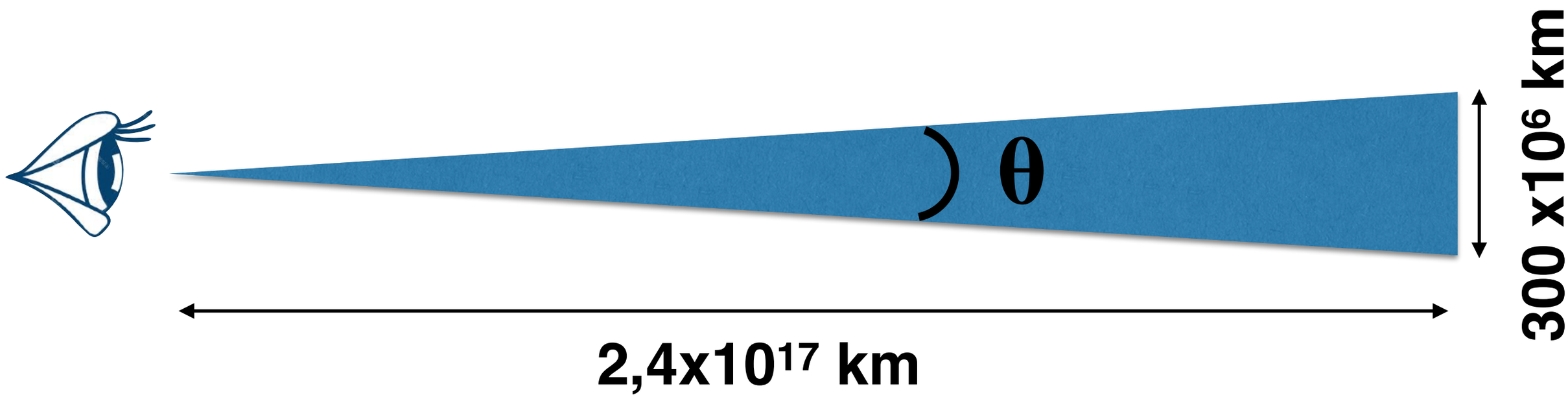
Dans le domaine gamma, on ne cherche pas à focaliser les rayons lumineux: technique du masque codé à la place.



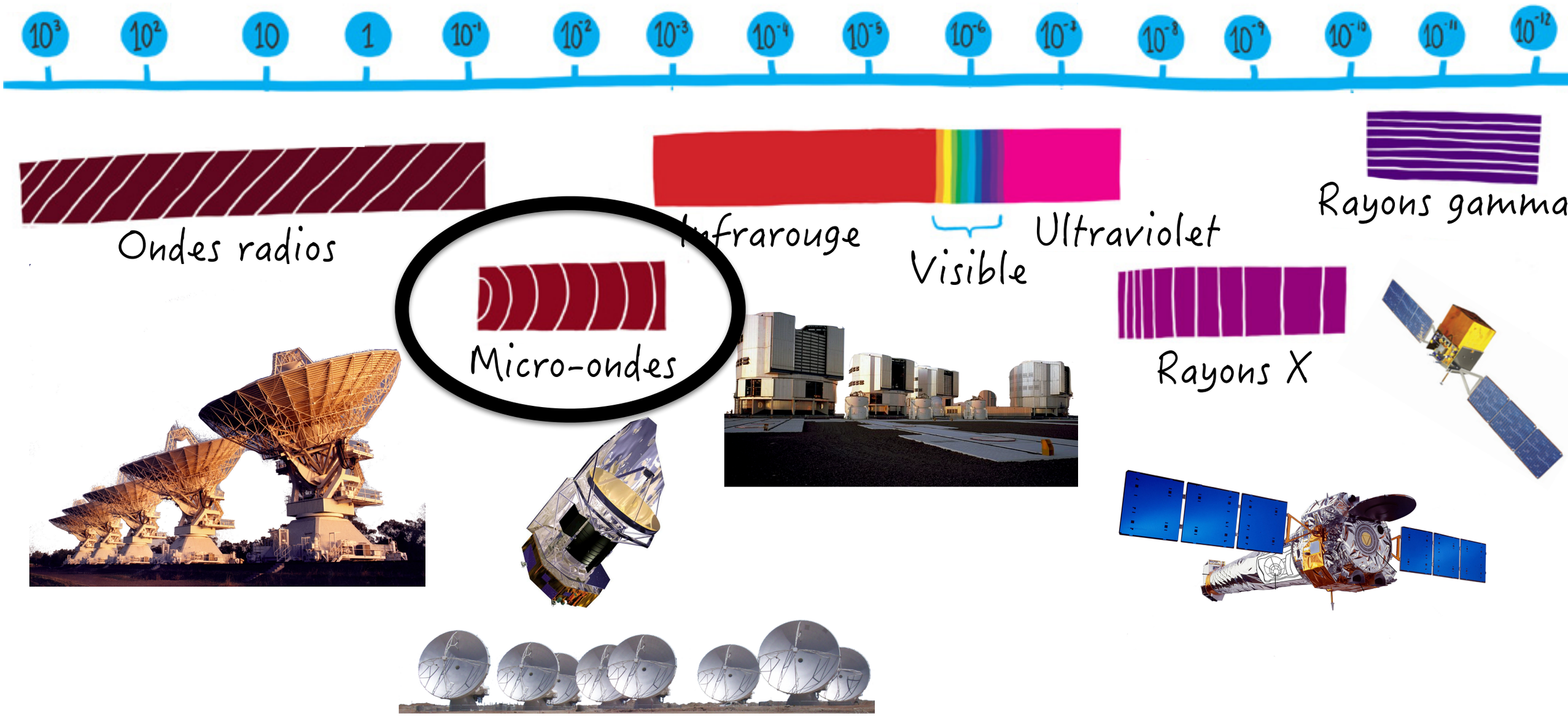
Peut-on imager ce trou noir ?

Peut-on imager ce trou noir ?

Quelle est sa taille angulaire ?

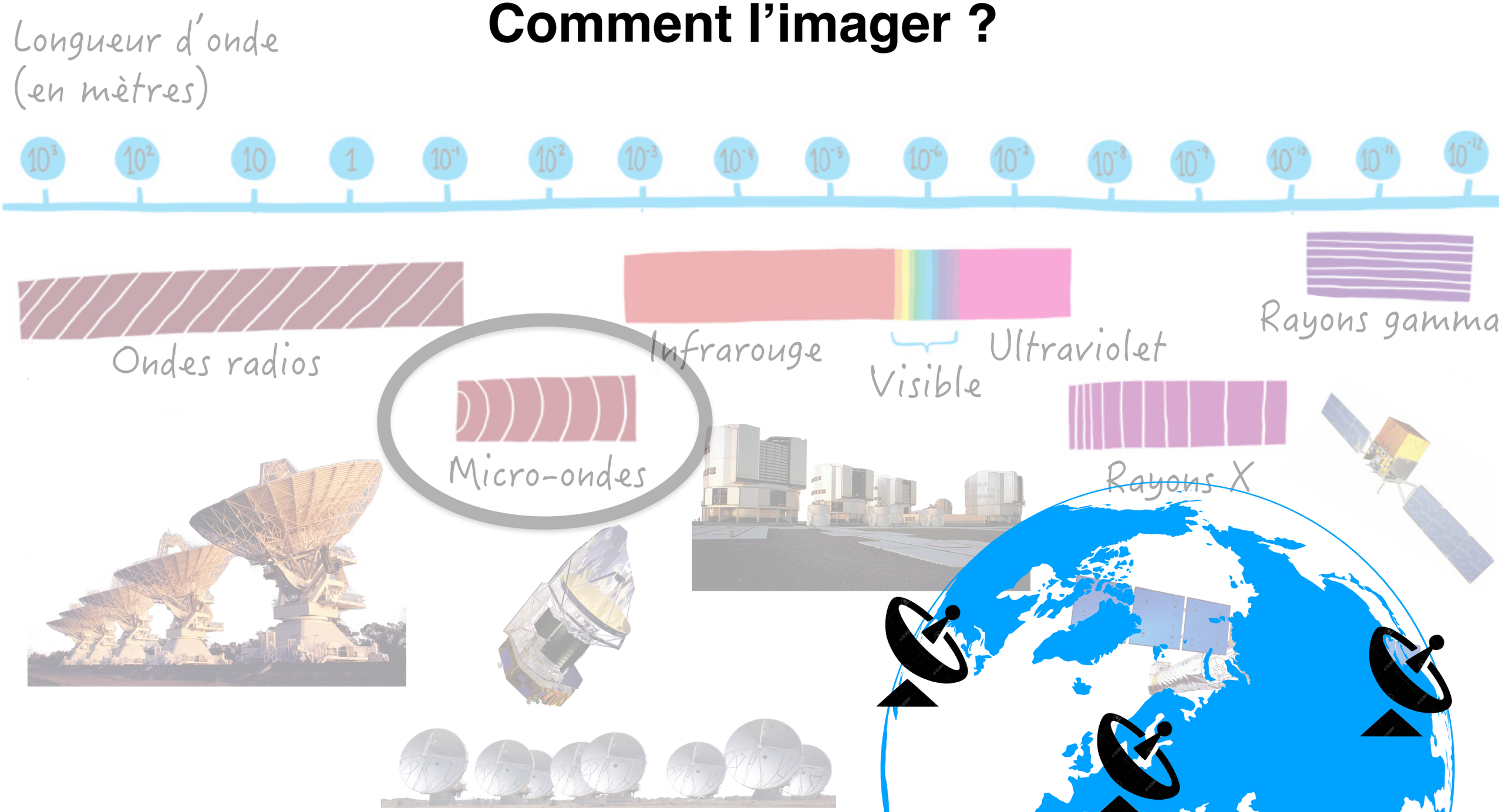
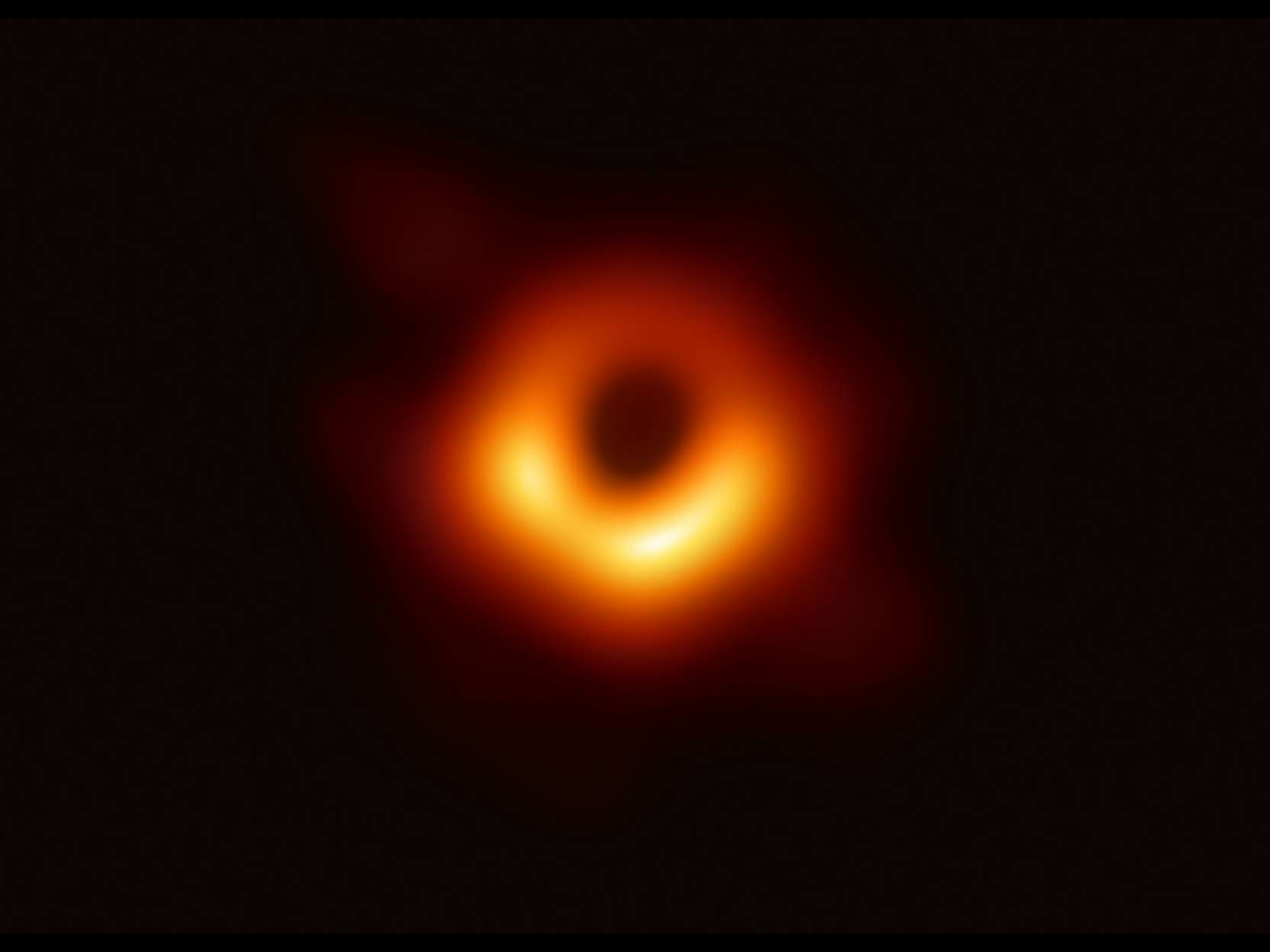


Comment l'imager ?



R ~ λ / D => D= ?

Comment l'imager ?



R ~ 0.01 / D => D= ?