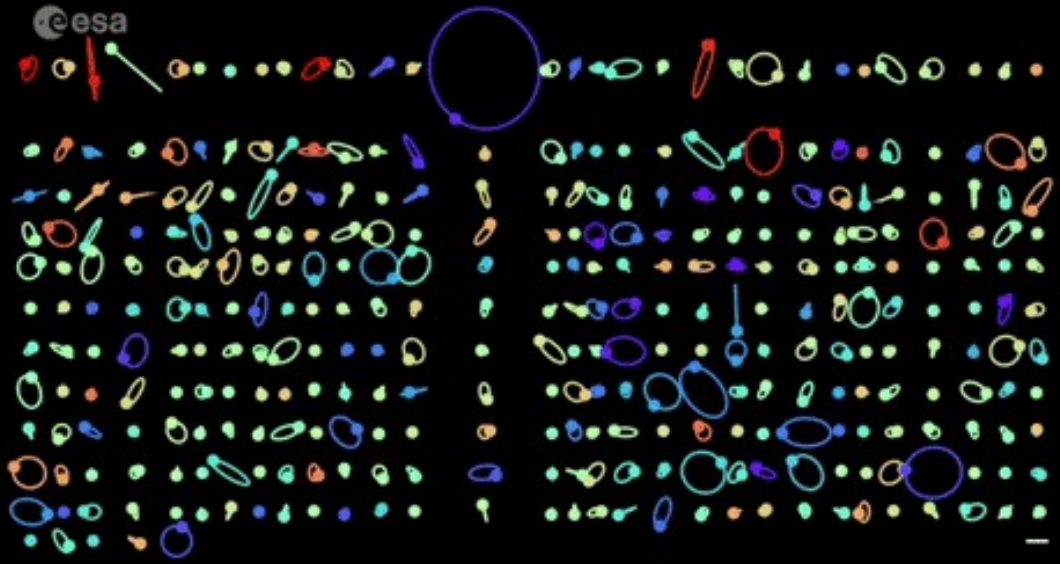
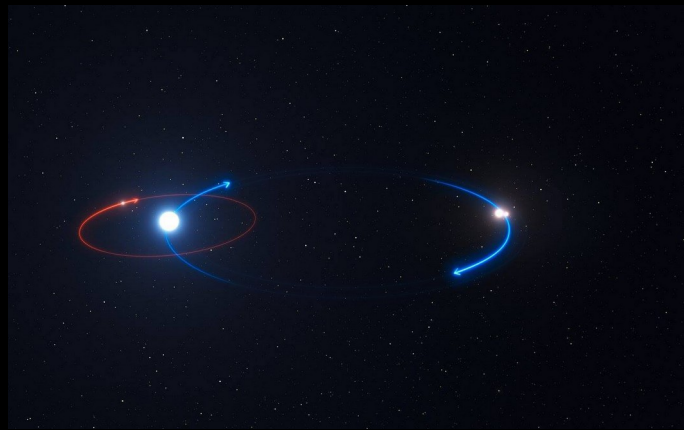


OBSERVATOIRE CENTRE ARDENNE

Samedi 20 mai 2023

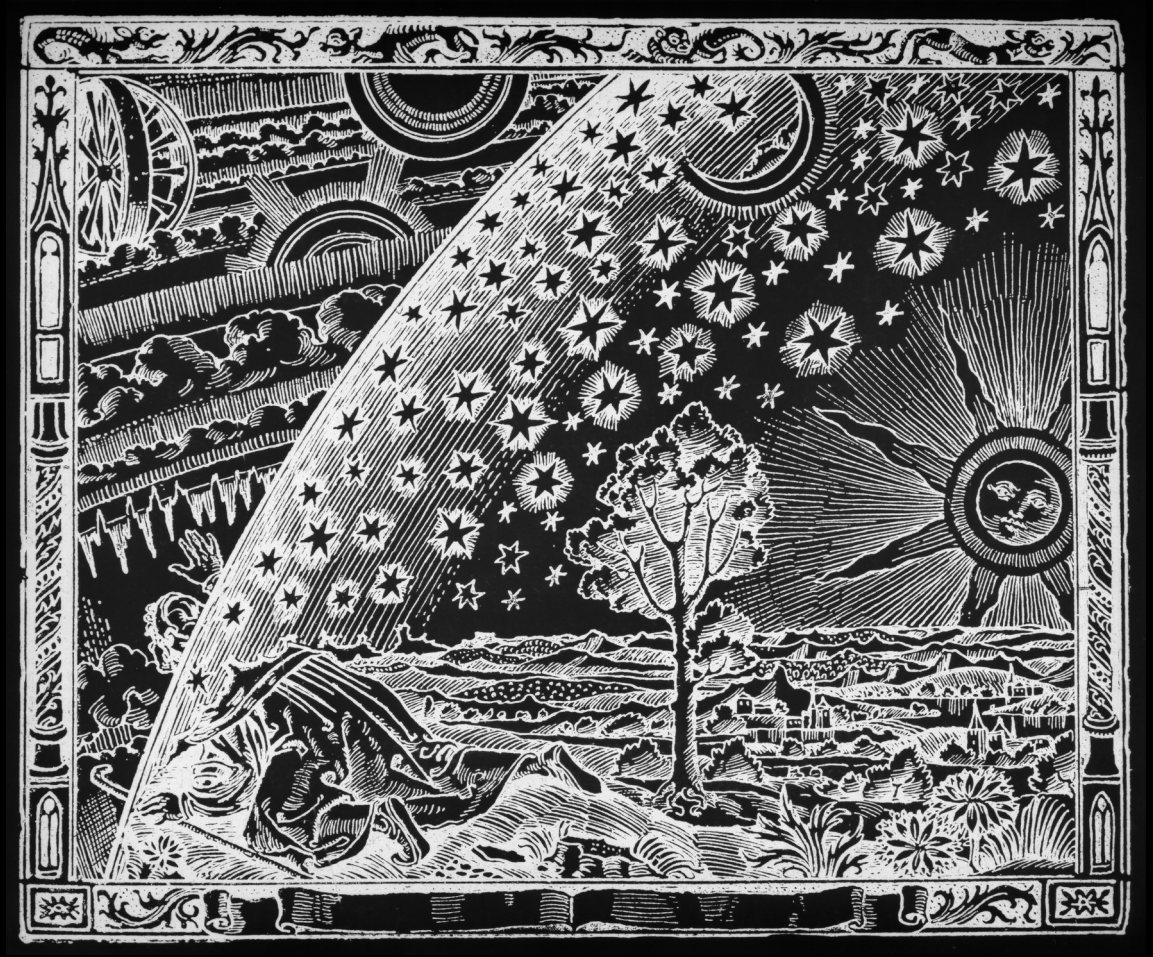
La valse des étoiles doubles

Thibault Merle – Astrophysicien
Université Libre de Bruxelles
Observatoire Royal de Belgique



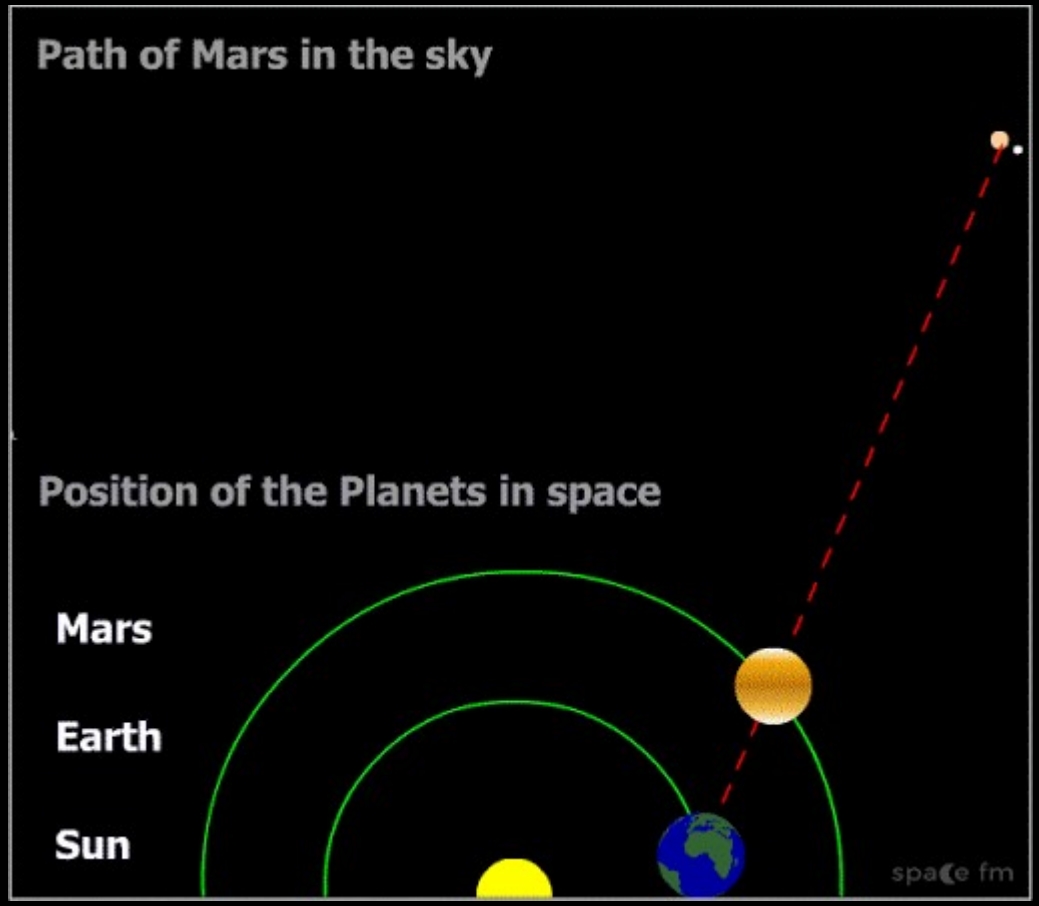
FED-tWIN belspo

La sphère des fixes



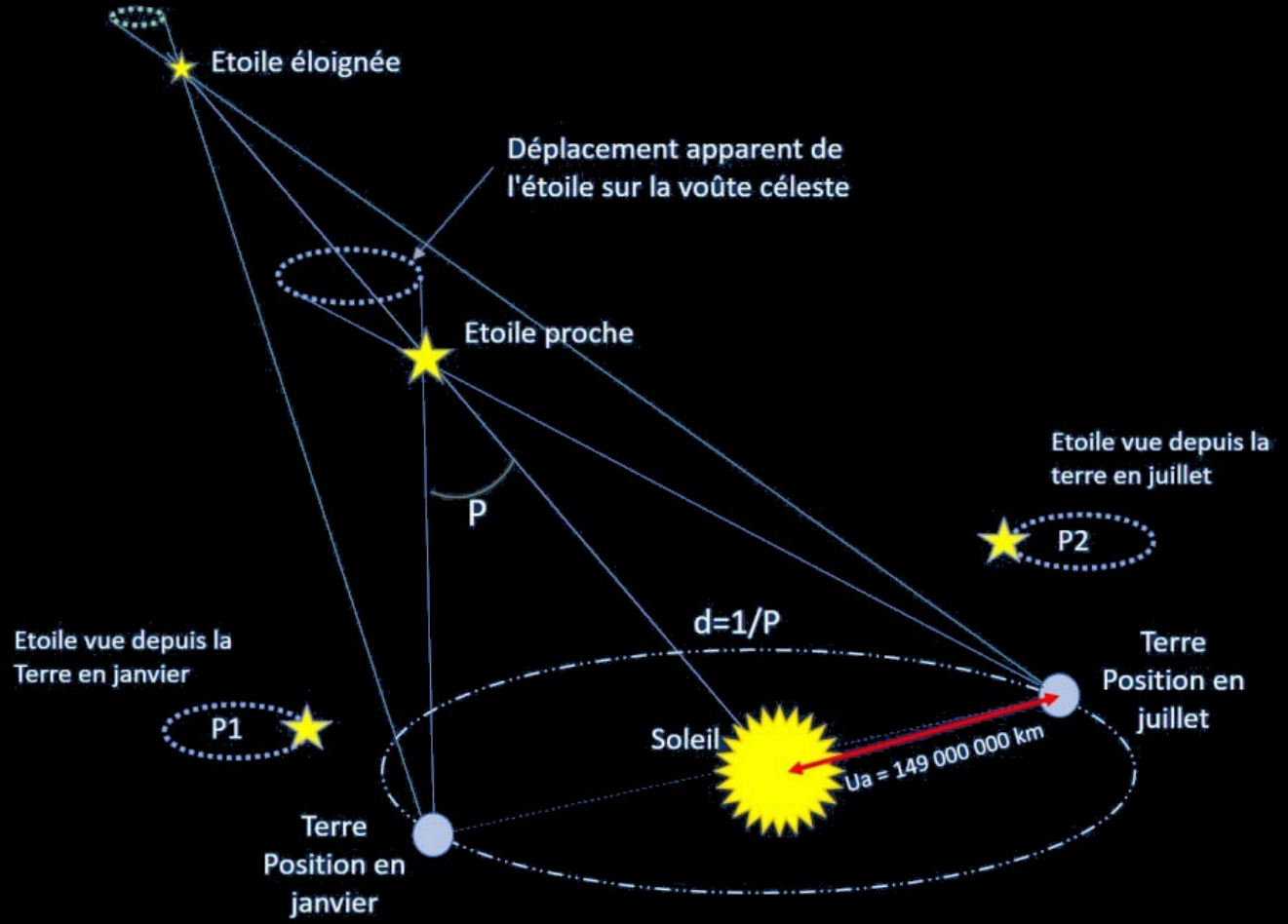
Mouvement apparent de Mars

Mouvement apparent de Mars

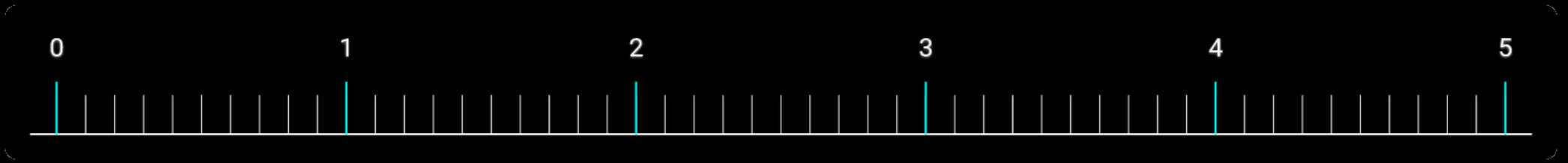


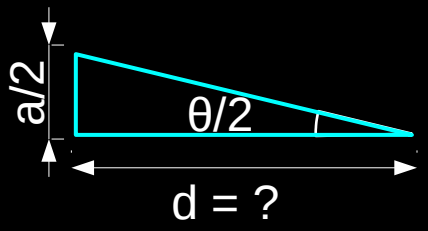
Mouvement apparent des étoiles

La parallaxe annuelle

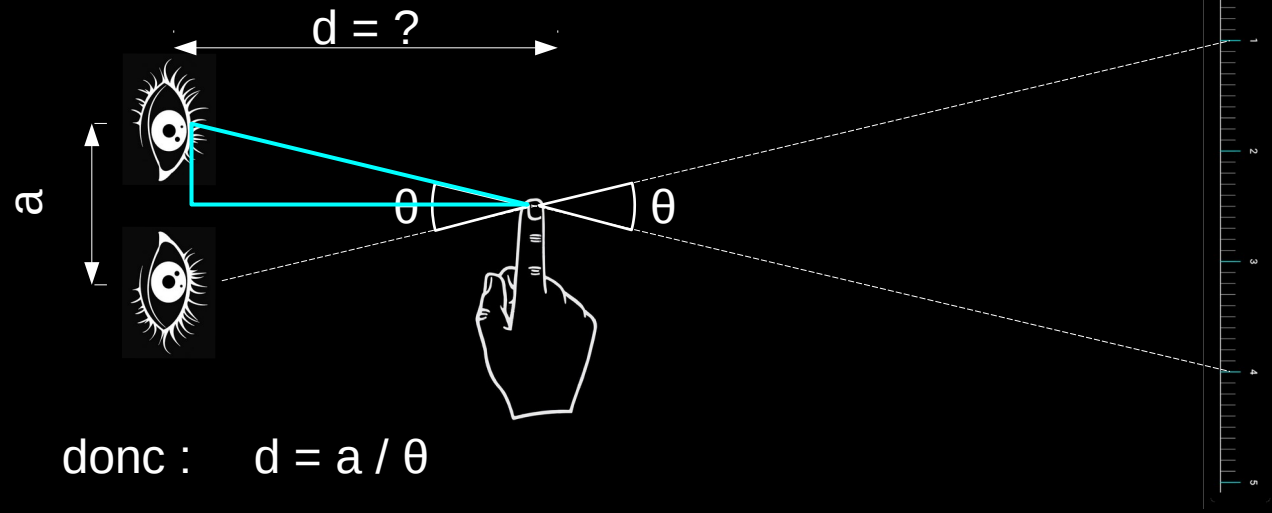


Triangulation



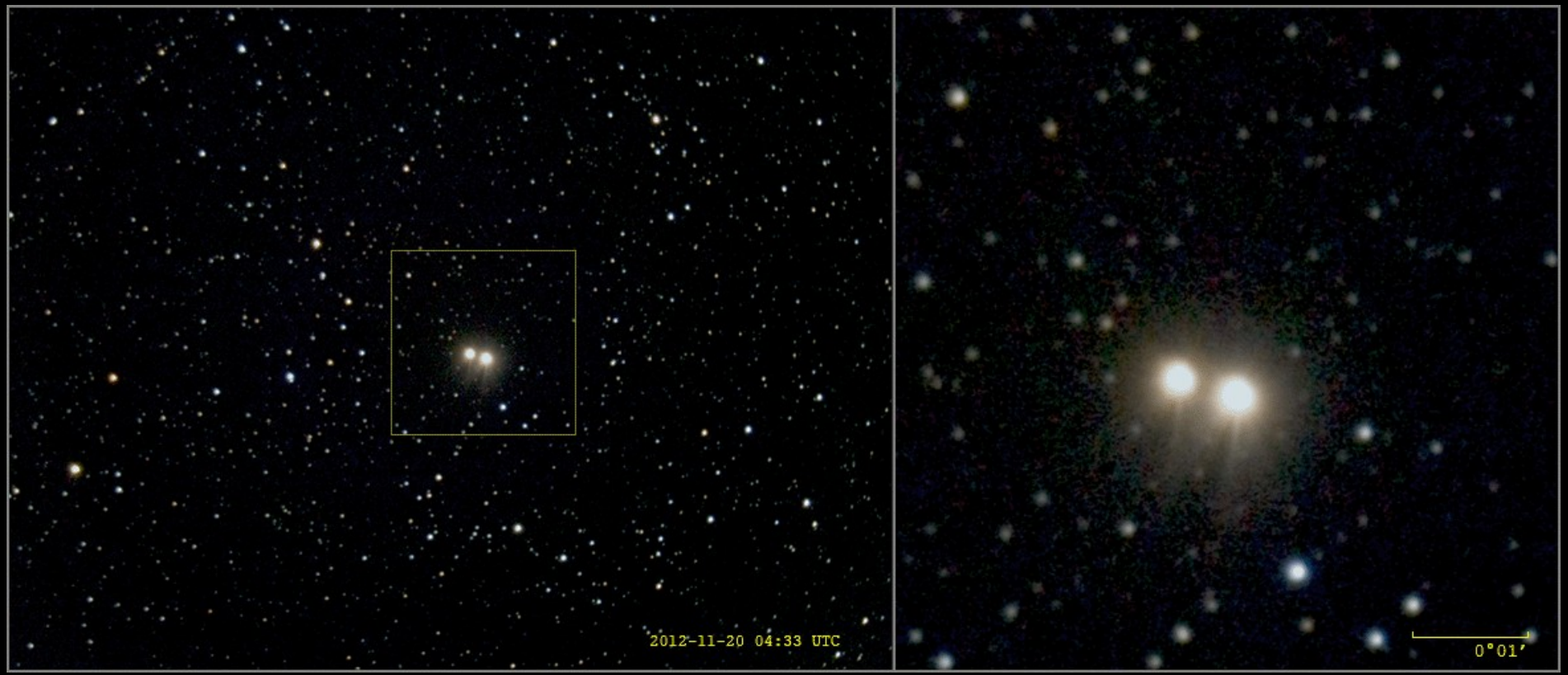


tan (θ/2) = a / (2d)
d = (a/2) / tan (θ/2)



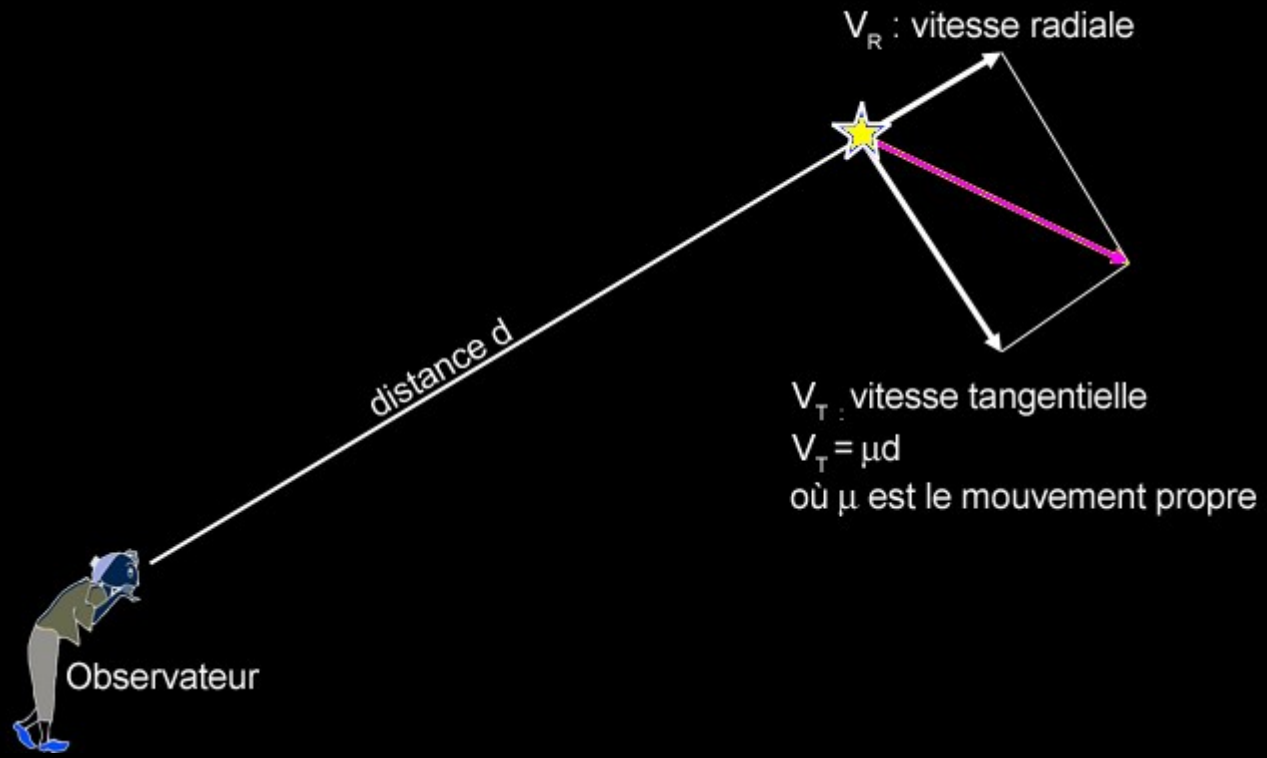
Pour les étoiles : tan θ = θ donc : d = a / θ

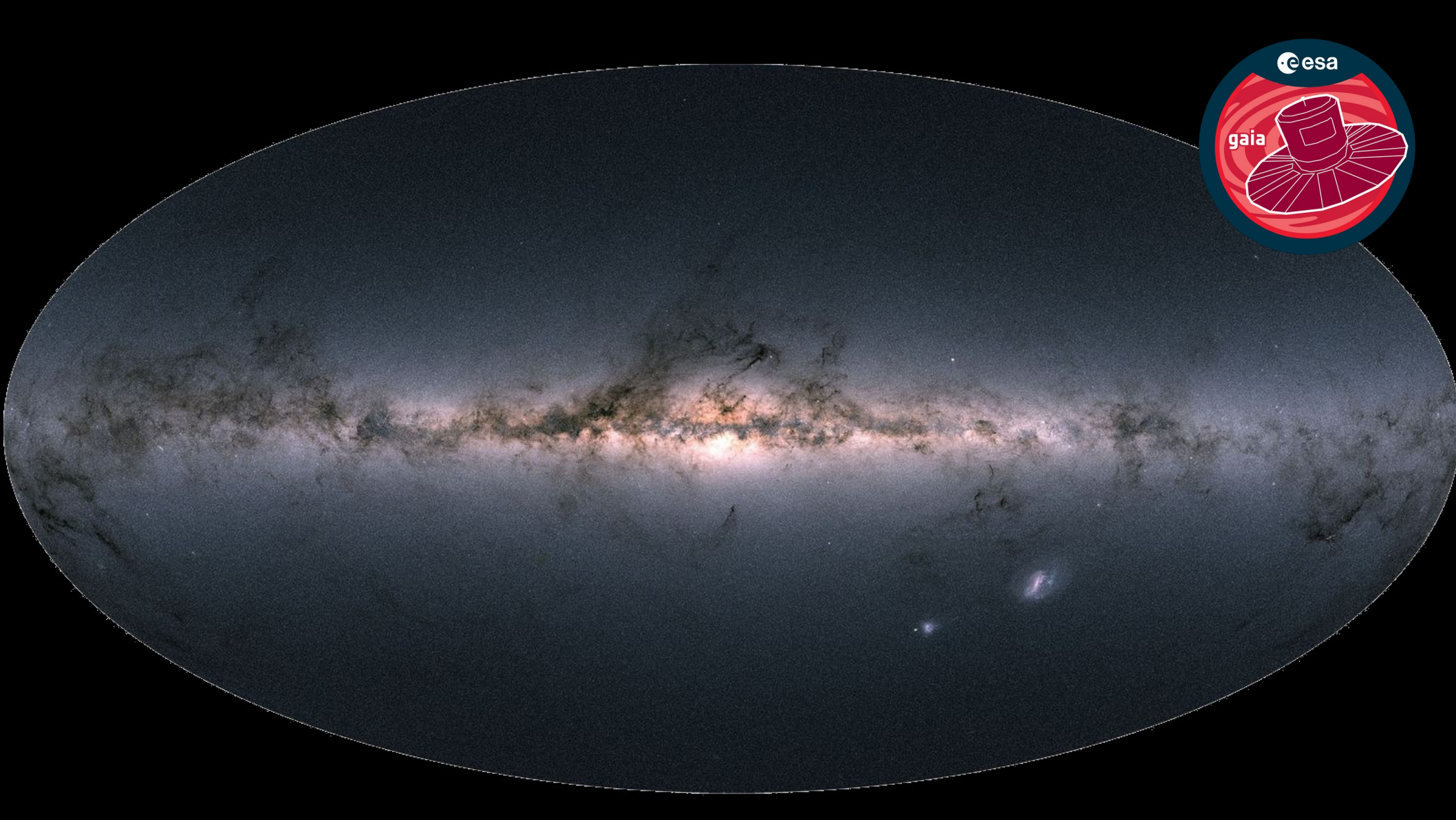
Mouvement propre des étoiles

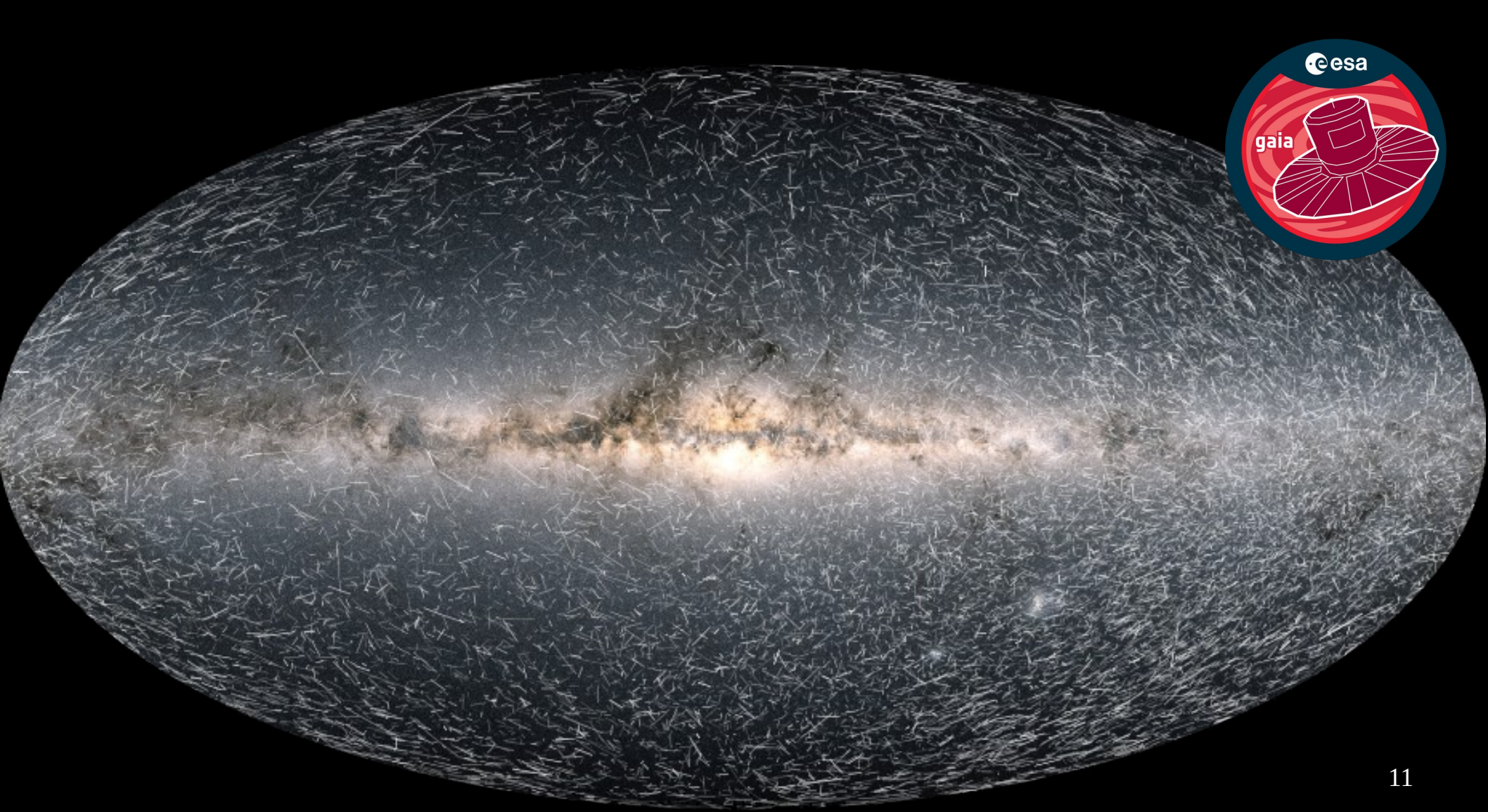


61 Cyg a un déplacement de 5 arcsec / an

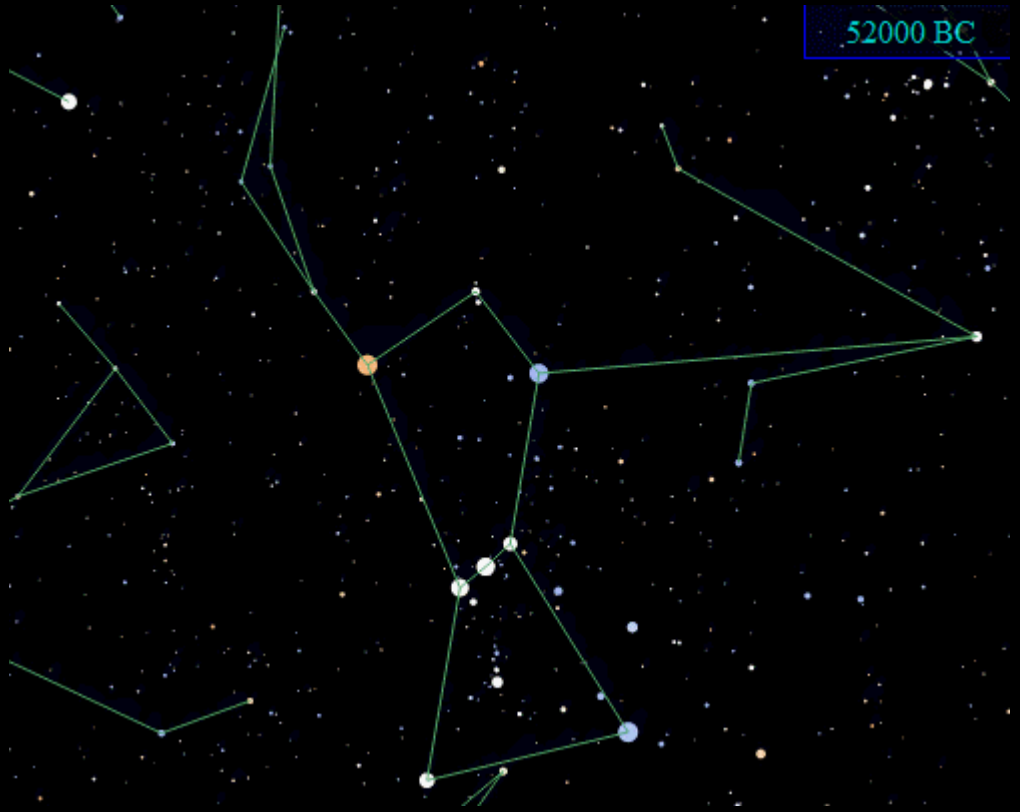
Vitesse tangentielle




esa
gaia

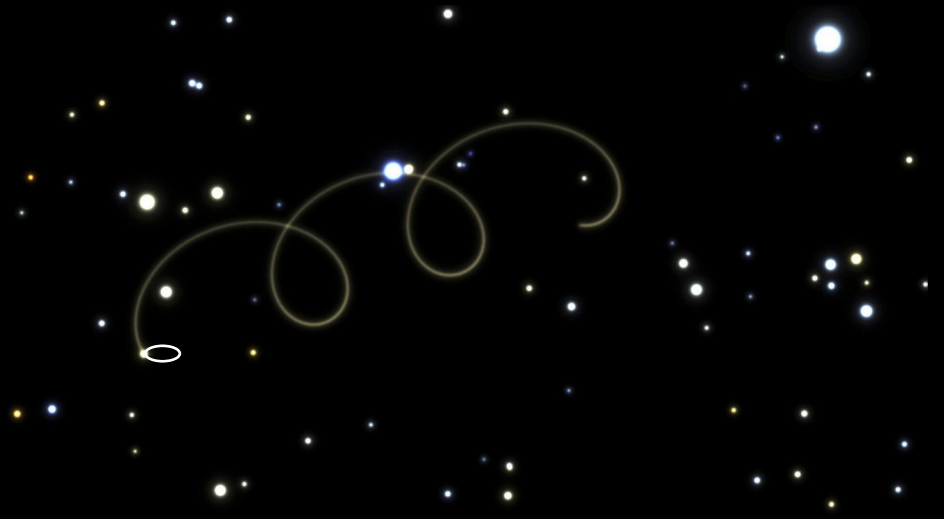

esa
gaia

La sphère des fixes ?



Composition des mouvements

parallaxe annuelle

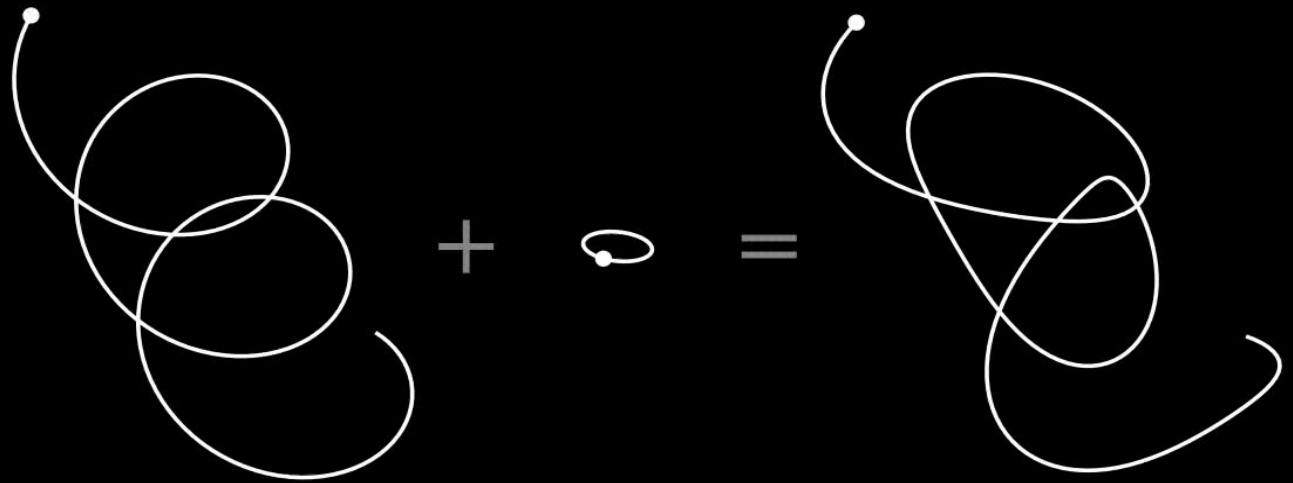


parallaxe annuelle + mouvement propre

Composition des mouvements

parallaxe annuelle + mouvement propre + mouvement orbital

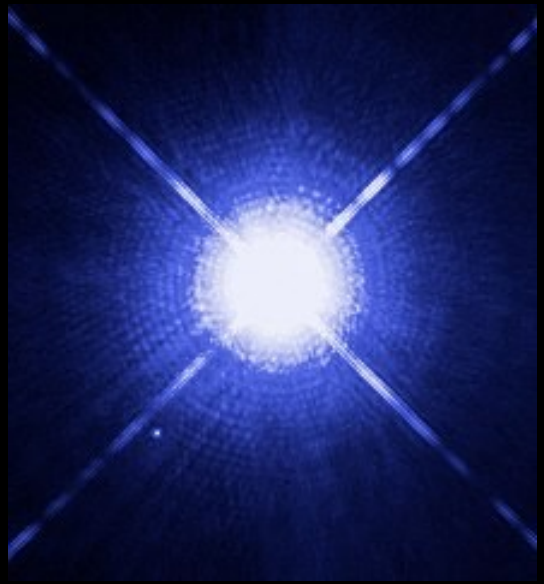
Composition des mouvements



Systèmes binaires

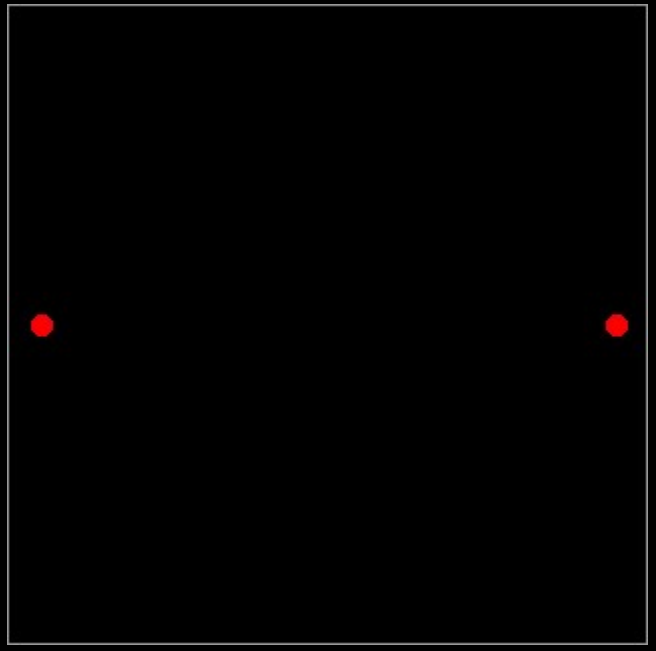
Quelle est l’étoile la plus brillante du ciel ?

Constellation du Grand Chien

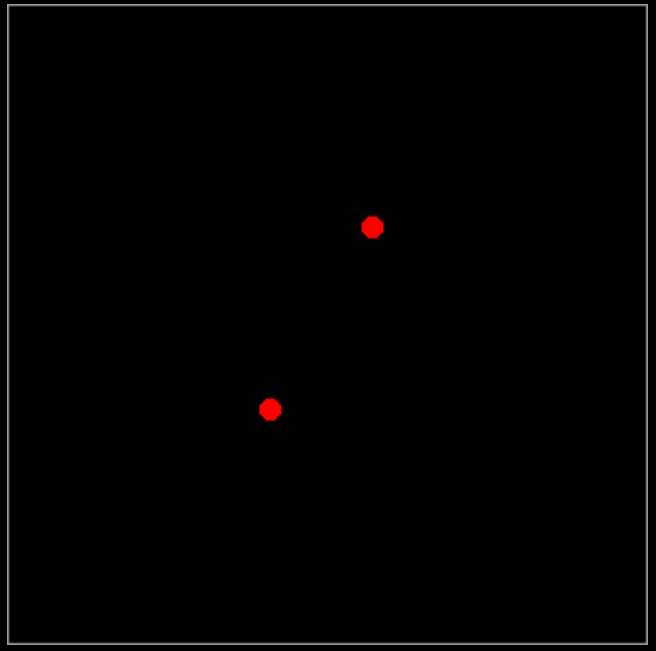


Sirius

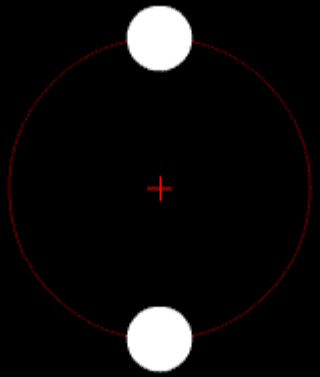
Orbite circulaire



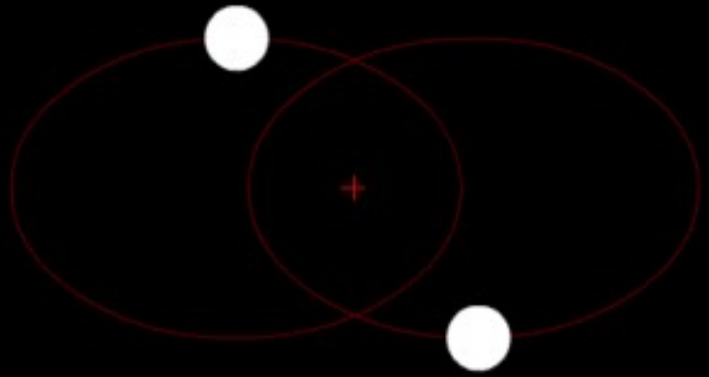
Orbite elliptique



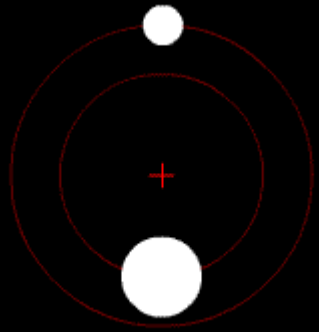
Centre de masse d’une binaire



Etoiles doubles jumelles

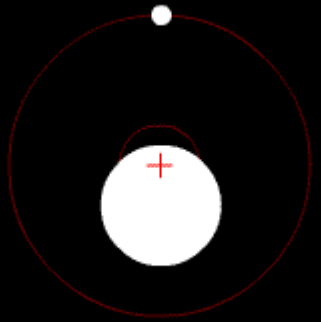


Etoiles doubles jumelles



Etoiles doubles de différentes masses

Centre de masse d’une binaire



Sans mouvemement propre

Avec mouvement propre

Les lois de Kepler

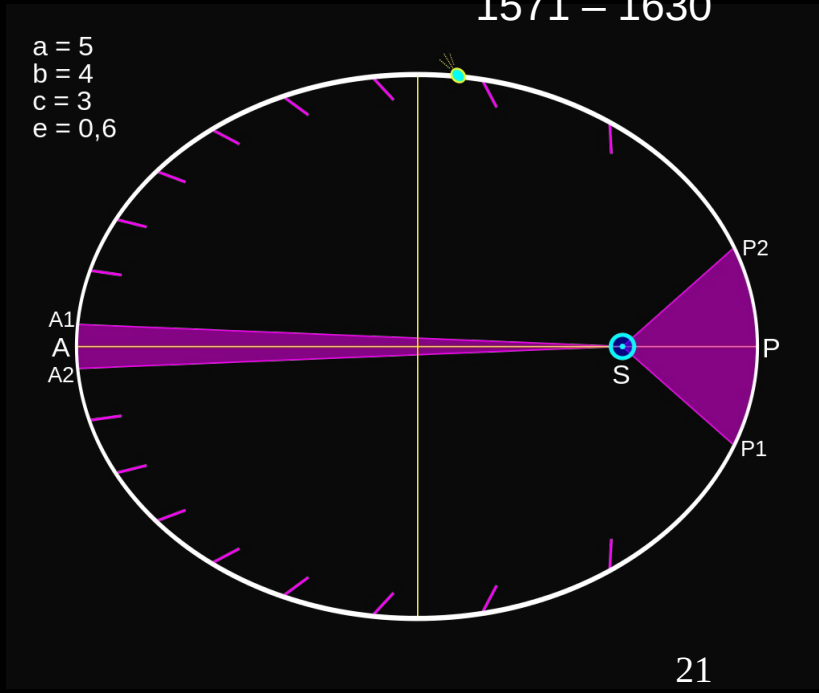
1571 – 1630

1. <u>Loi des orbites</u>
Les planètes du Système Solaire décrivent des ellipses dont le Soleil occupe l'un des foyers

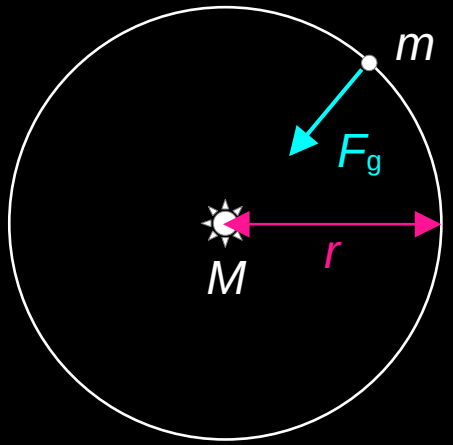
2. <u>Loi des aires</u>
La ligne joignant le Soleil à une planète balaie des aires égales en des temps égaux

3. <u>Loi des périodes</u>
Le carré de la période orbitale *P* d'une planète est directement proportionel au cube du demi grand-axe *a* de la trajectoire elliptique

$P^2 / a^3 = k$ avec *k* constant



La 3ème loi de Kepler démontrée par Newton



Force gravitationnelle : $F_g = GMm / r^2$

$G = 6.67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-1}$

Mouvement circulaire uniforme : $F_c = mv^2 / r$

Système à l'équilibre du point de vue de la rotation :

$F_g = F_c \Leftrightarrow GMm / r^2 = mv^2 / r$

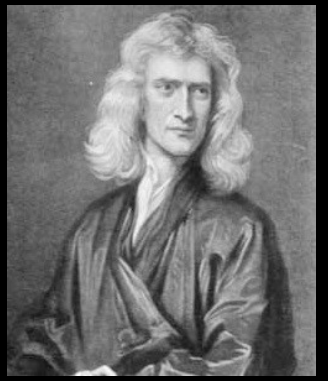
Vitesse de révolution : $v = 2\pi r / P$

P : période de révolution

$GM / r^2 = (2\pi r / P)^2 / r \Leftrightarrow GM / r^2 = 4\pi^2 r / P^2$

$\Leftrightarrow GM / 4\pi^2 = r^3 / P^2$

En inversant : $P^2 / r^3 = 4\pi^2 / GM$

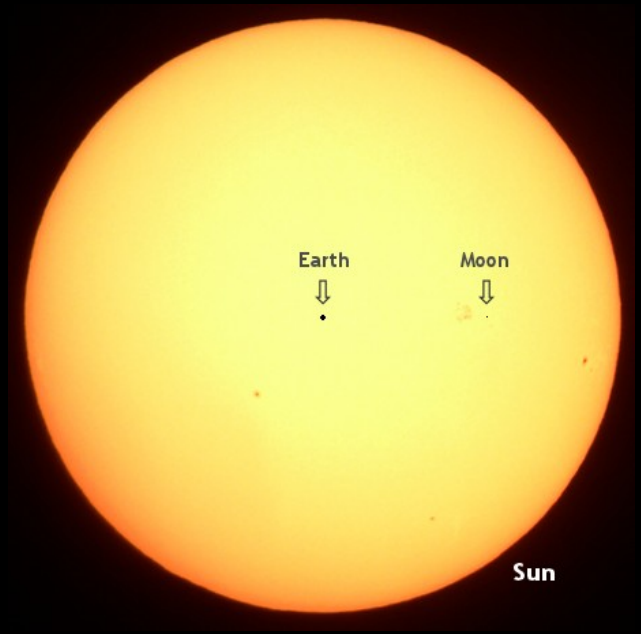


1643 – 1727

La 3ème loi de Kepler avec les bonnes unités !

3ème loi de Kepler : $P^2 / r^3 = 4\pi^2 / GM$ avec $G = 6{,}67 \times 10^{-11}$ m^3 kg^{-1} s^{-1}

Pour le système Soleil – Terre :
$P = 1$ a $= 365{,}25 \times 24 \times 60 \times 60 = 3{,}1557 \times 10^7$ s
$r = 1$ ua $= 150$ millions de km $= 1{,}50 \times 10^{11}$ m



La masse du Soleil est :

$M = (4\pi^2 / G)\ (r^3 / P^2)$
$M = 2{,}01 \times 10^{30}$ kg

On note cette masse $M_\odot = 2{,}01 \times 10^{30}$ kg

Pour comparaison la masse de la Terre est : $5{,}97 \times 10^{24}$ kg

La 3ème loi de Kepler avec les bonnes unités !

3ème loi de Kepler : $P^2 / r^3 = 4\pi^2 / GM$ (1) avec $G = 6{,}67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-1}$

<u>Nouveau choix d'unités basé sur le système Soleil – Terre</u> :

- Périodes de révolution exprimées en années (a)
- Rayons (demi-grand axes) exprimés en unités astronomiques (ua)
- Masses exprimées en masses solaires ($M_\odot$)

3ème loi de Kepler : $P^2 / r^3 = 1/M$ (2)

Système Soleil – Mars : on connait la période de révolution de Mars P = 1.88 a

- $r = (GM/4\pi^2)^{1/3}\ P^{2/3} = (6{,}67 \times 10^{-11} \times 2{,}01 \times 10^{30} / 4\pi^2)^{1/3}\ (1.88 \times 365{,}25 \times 24 \times 3600)^{2/3}$
  $r = 2{,}29 \times 10^{11}$ m

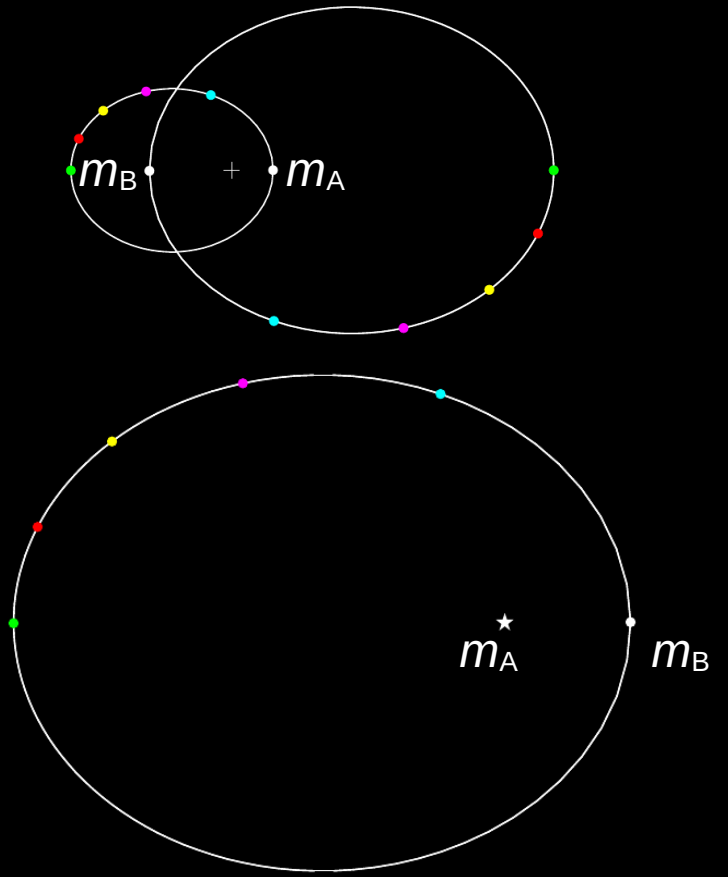
- $r = M^{1/3}\ P^{2/3} = 1.88^{2/3} = 1{,}52$ ua

Les lois de Kepler adaptées aux binaires

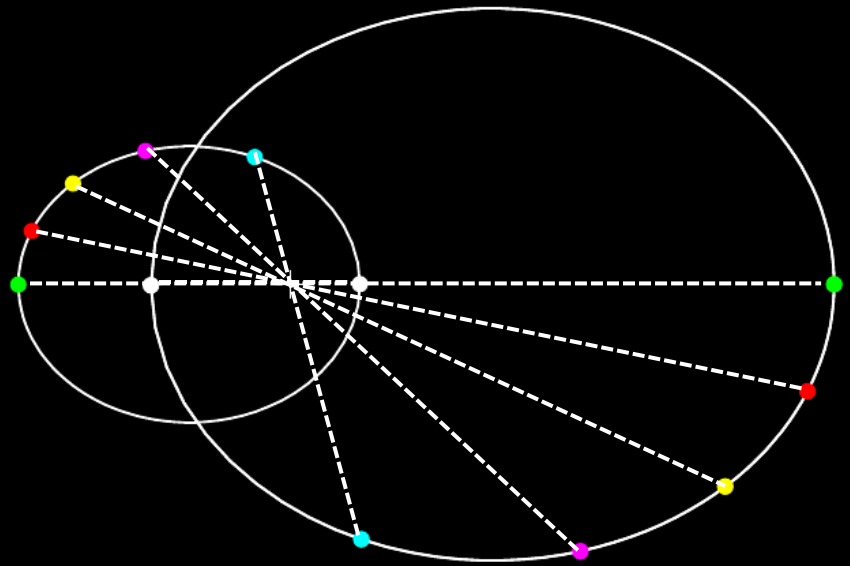
1. <u>Loi des orbites</u>
Les étoiles décrivent des orbites elliptiques autour d'un centre de masse qui est le foyer commun des orbites absolues

2. <u>Loi des aires</u>
La ligne joignant les étoiles balaie des aires égales en des temps égaux

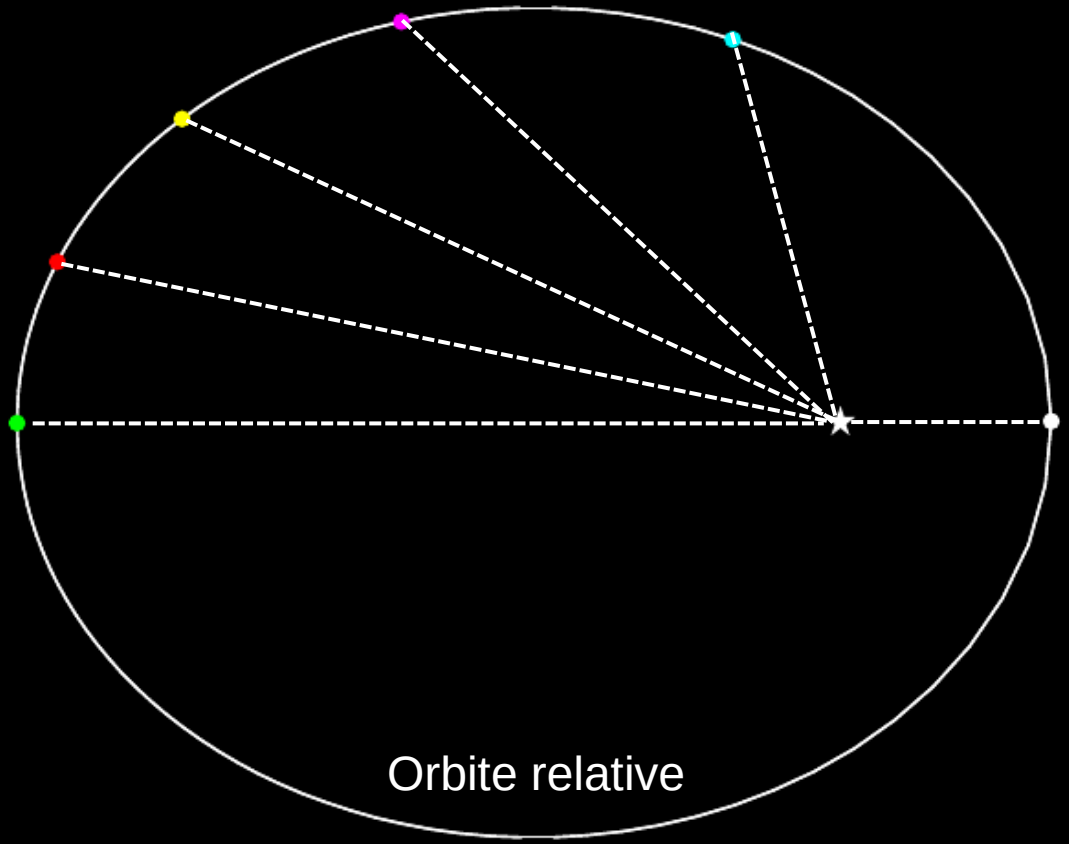
3. <u>Loi des périodes</u>
Le carré de la période orbitale P est proportionnel au cube du demi grand-axe a
$P^2 / a^3 = 4\pi^2 / G(m_A + m_B)$ en unités SI
$P^2 / a^3 = 1 / (m_A + m_B)$ en unités Soleil – Terre



Choix du référentiel



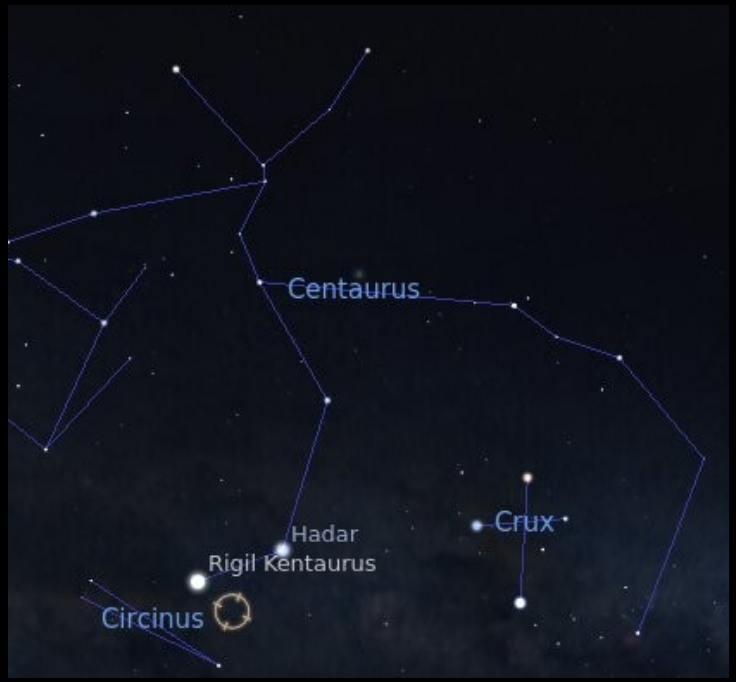
Orbites absolues



Orbite relative

Systèmes triples

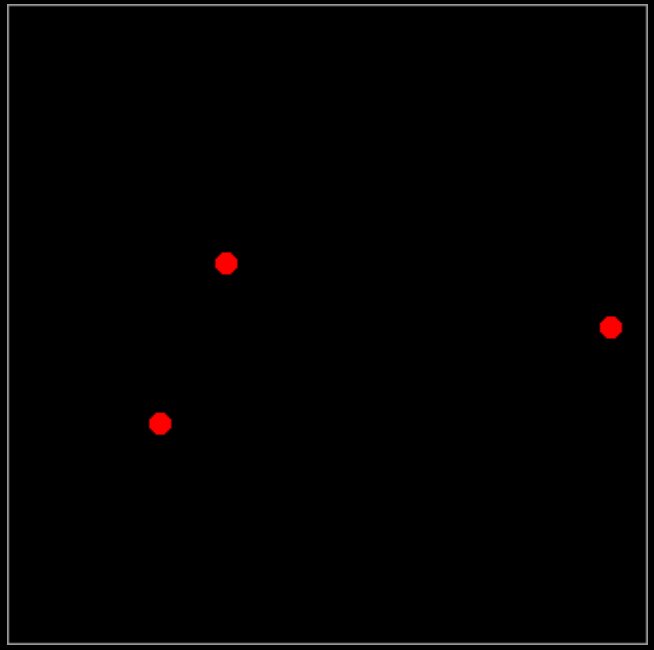
Quelle est l’étoile la plus proche de nous ?



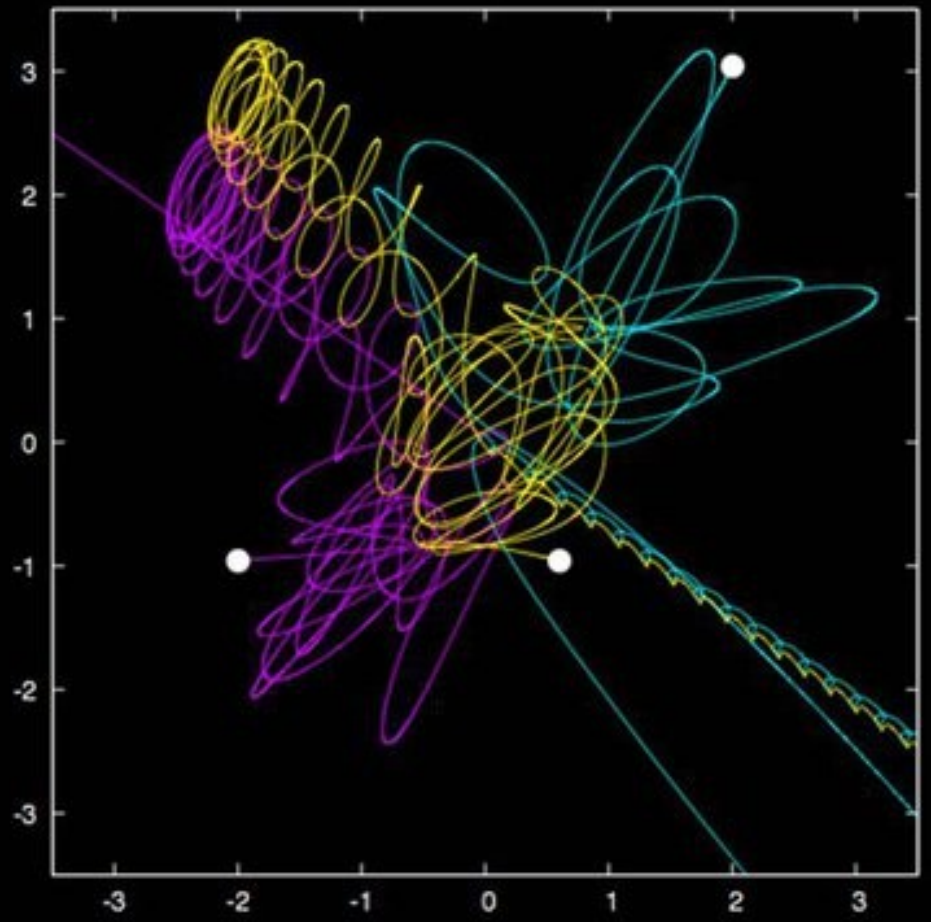
Constellation du Centaure

Proxima Cen

Triple démocratique (instable)

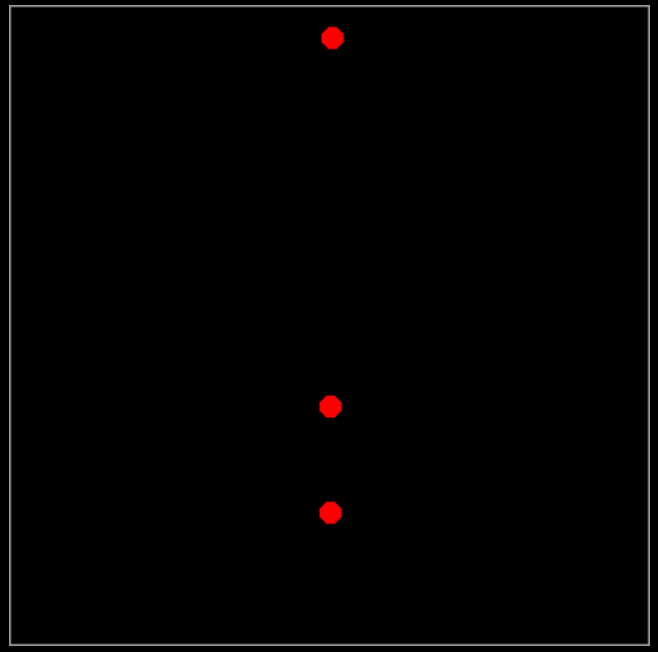


Triple démocratique (instable)

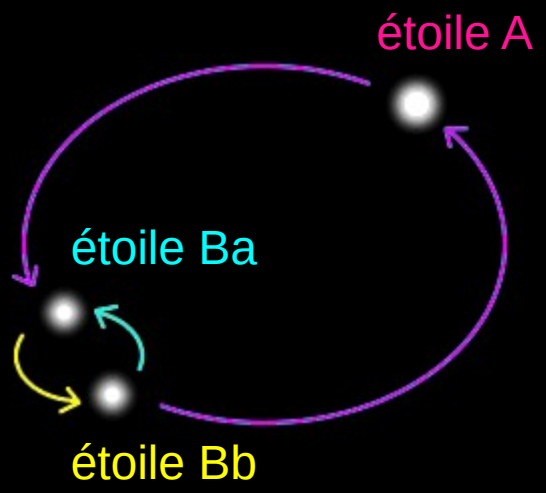


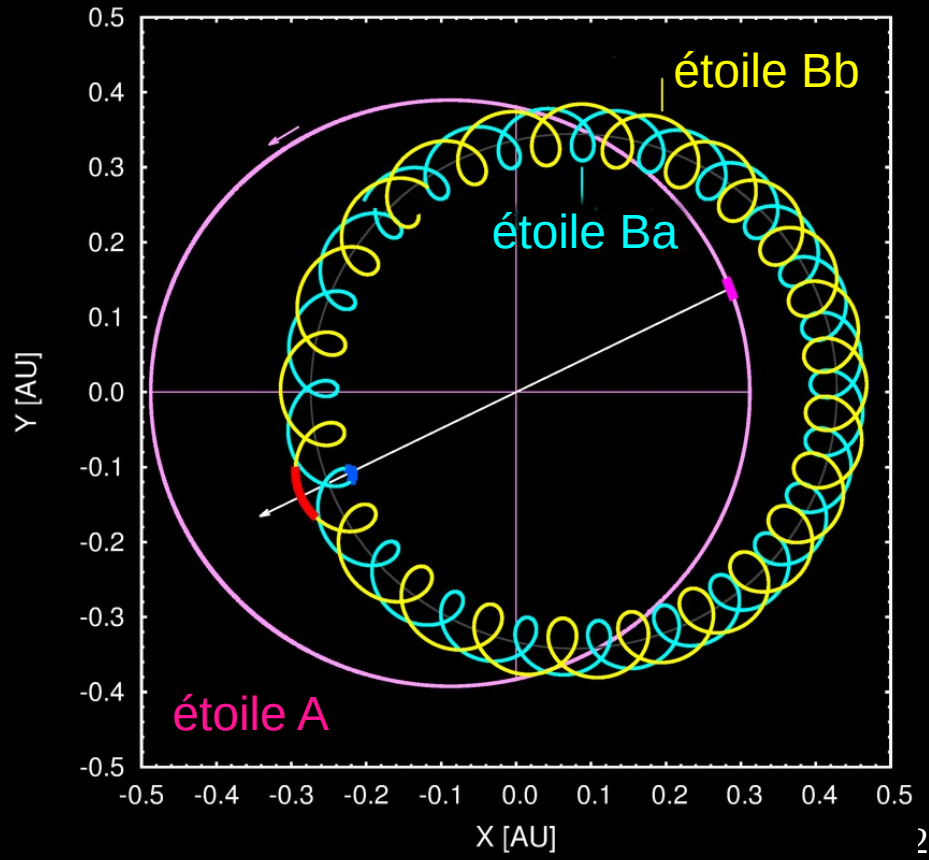
Instabilité gravitationnelle

Triple hiérarchique (stable)



Triple hiérarchique (stable)

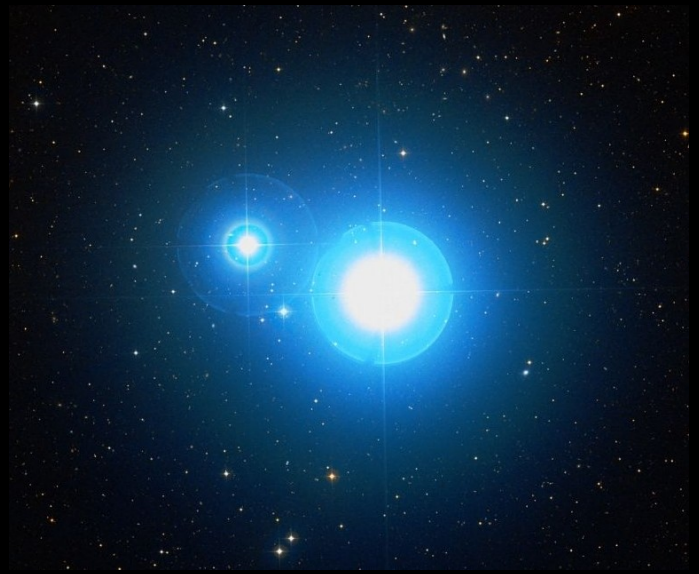




Systèmes quadruples

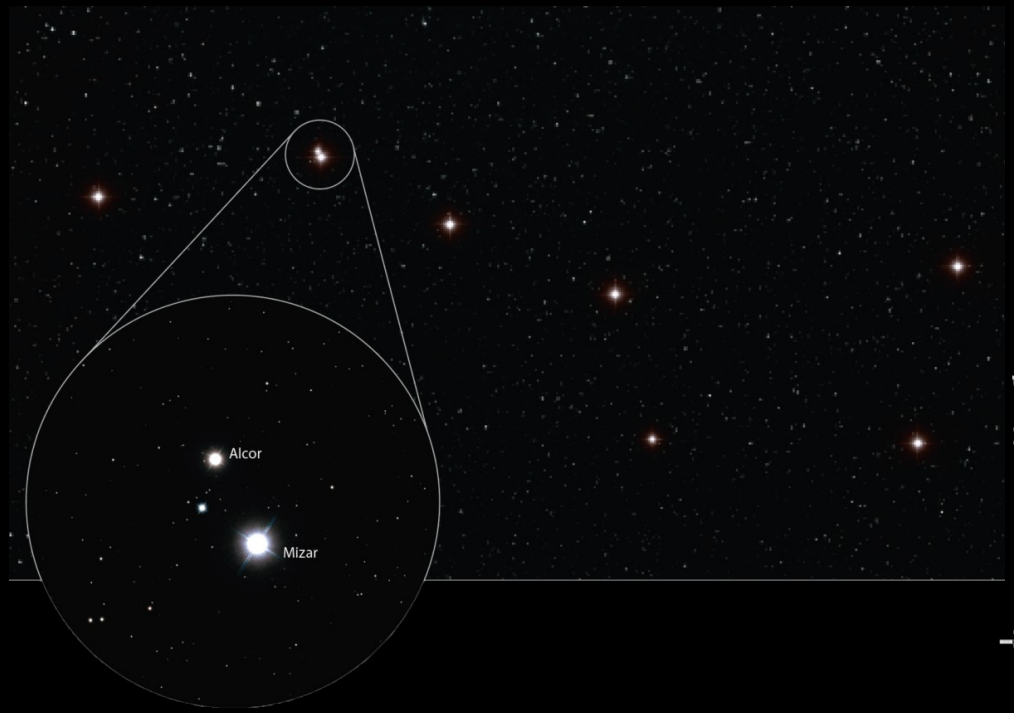
Quelle est la première étoile double connue ?

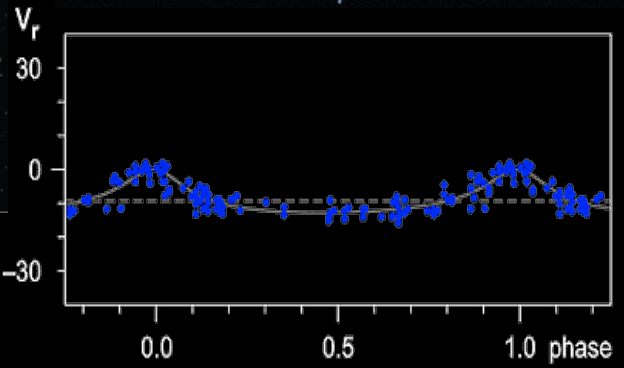
Constellation de la Grande Ourse



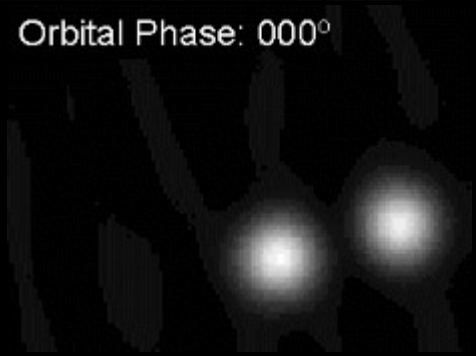
Mizar & Alcor

Systèmes quadruples



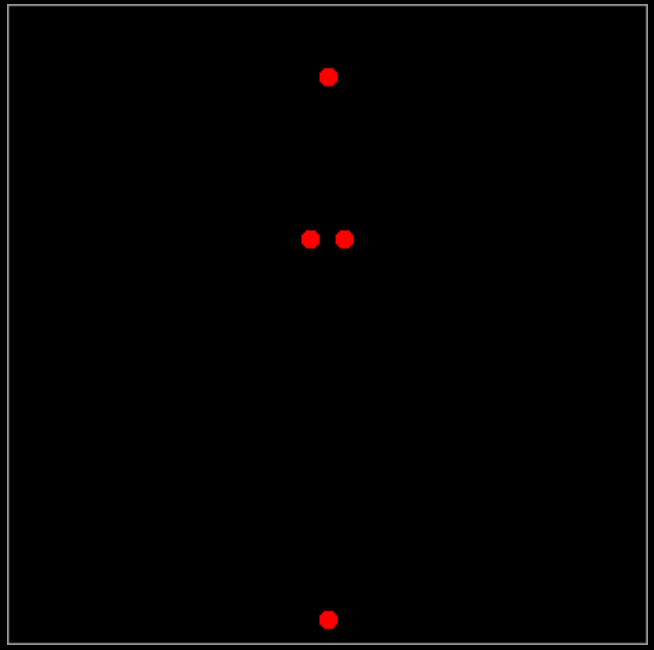


Mizar Ba

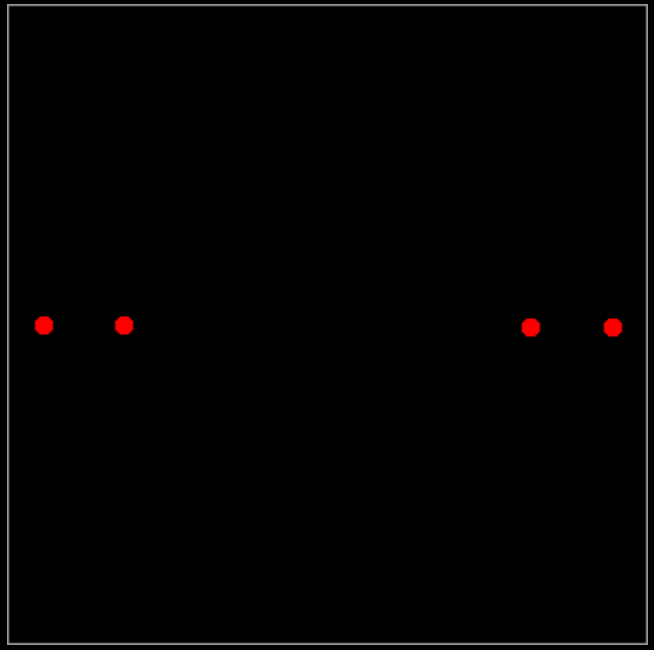


Mizar Aa,Ab

Quadruple 1+3 (stable)

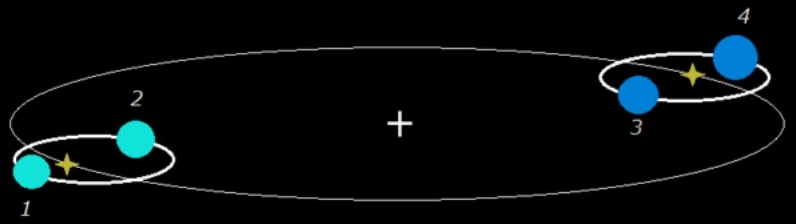


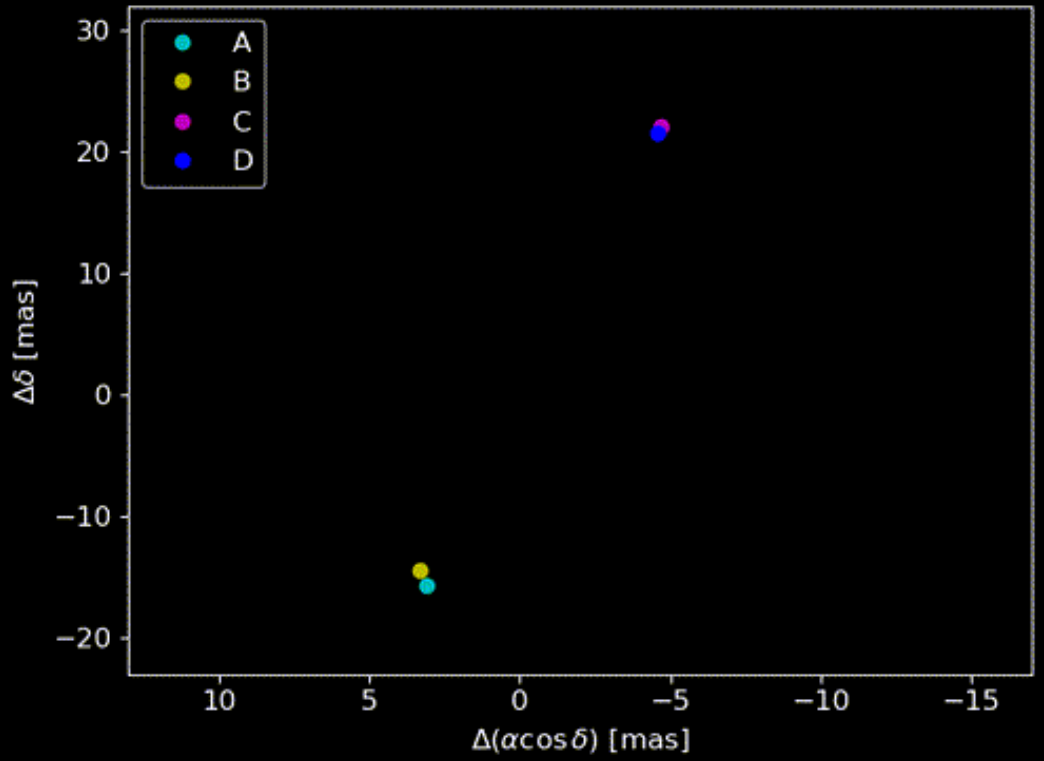
Quadruple 2+2 (stable)



Quadruple 2+2

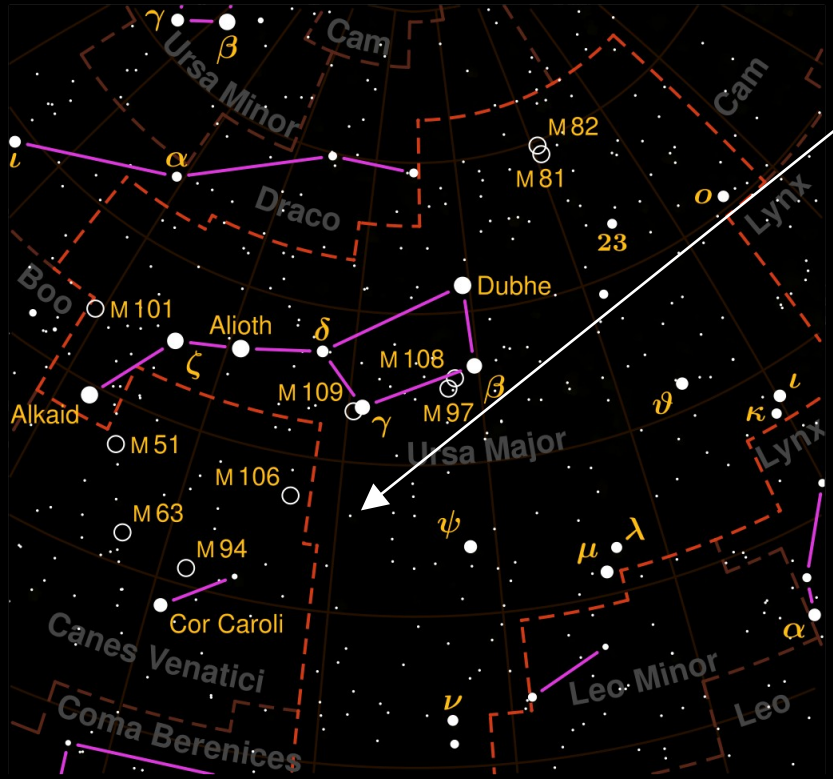
HD 74438





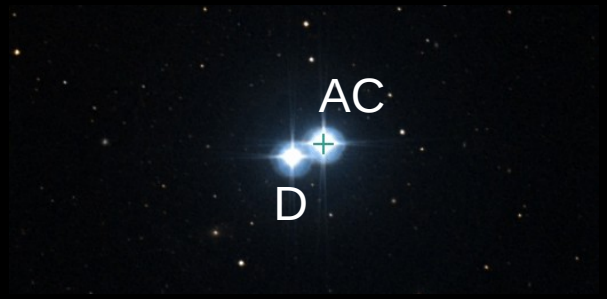
Merle *et al.*, *Nature Astronomy*, 2022

Systèmes à plus haut degré de multiplicité



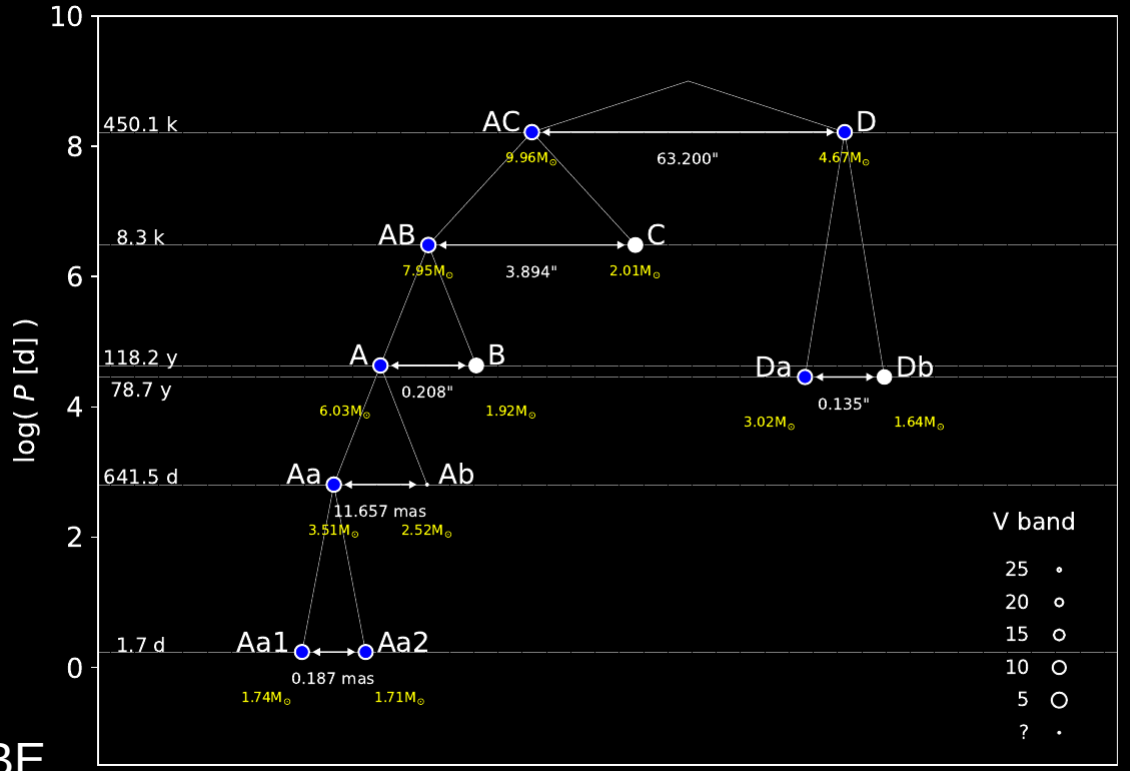
65 UMa
740 al
V = 6.5

Systèmes à plus haut degré de multiplicité



65 UMa A = DN UMa

65 UMa AB, C est une binaire à mouvement propre commun
65 UMa A, B est une BV
65 UMa Aa, Ab est une BS2 et BE
65 UMa Aa1, Aa2 est une BS2 et BE
65 UMa Da,Db est une BA

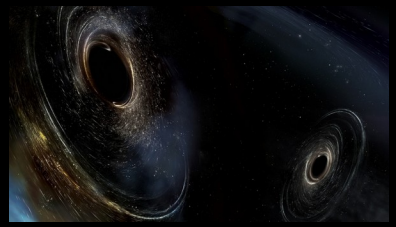


65 UMa : 5 niveaux hiérarchiques !

Les systèmes multiples, mais pourquoi ?

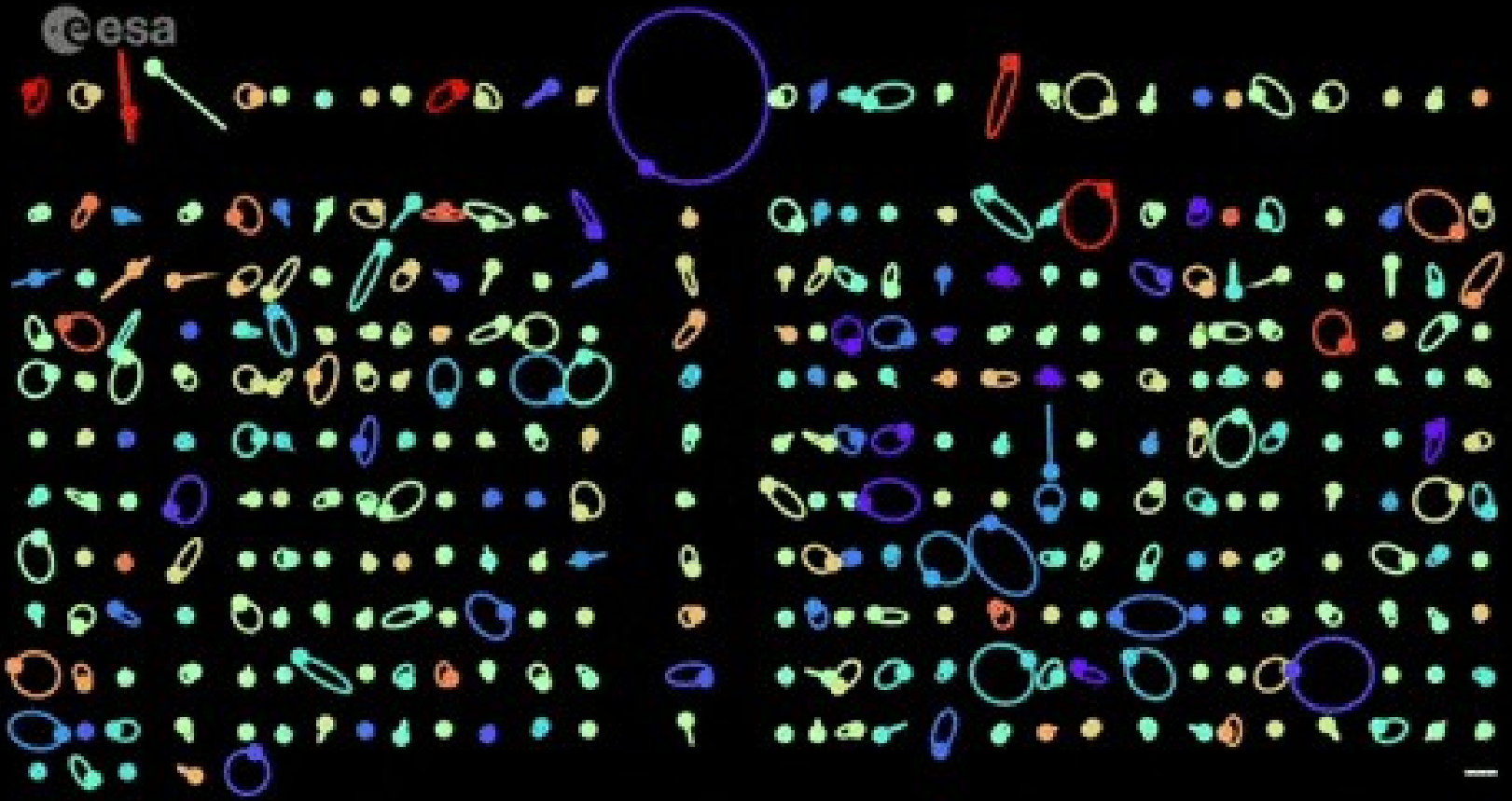
Chandra/Hubble/Spitzer

GW 150914

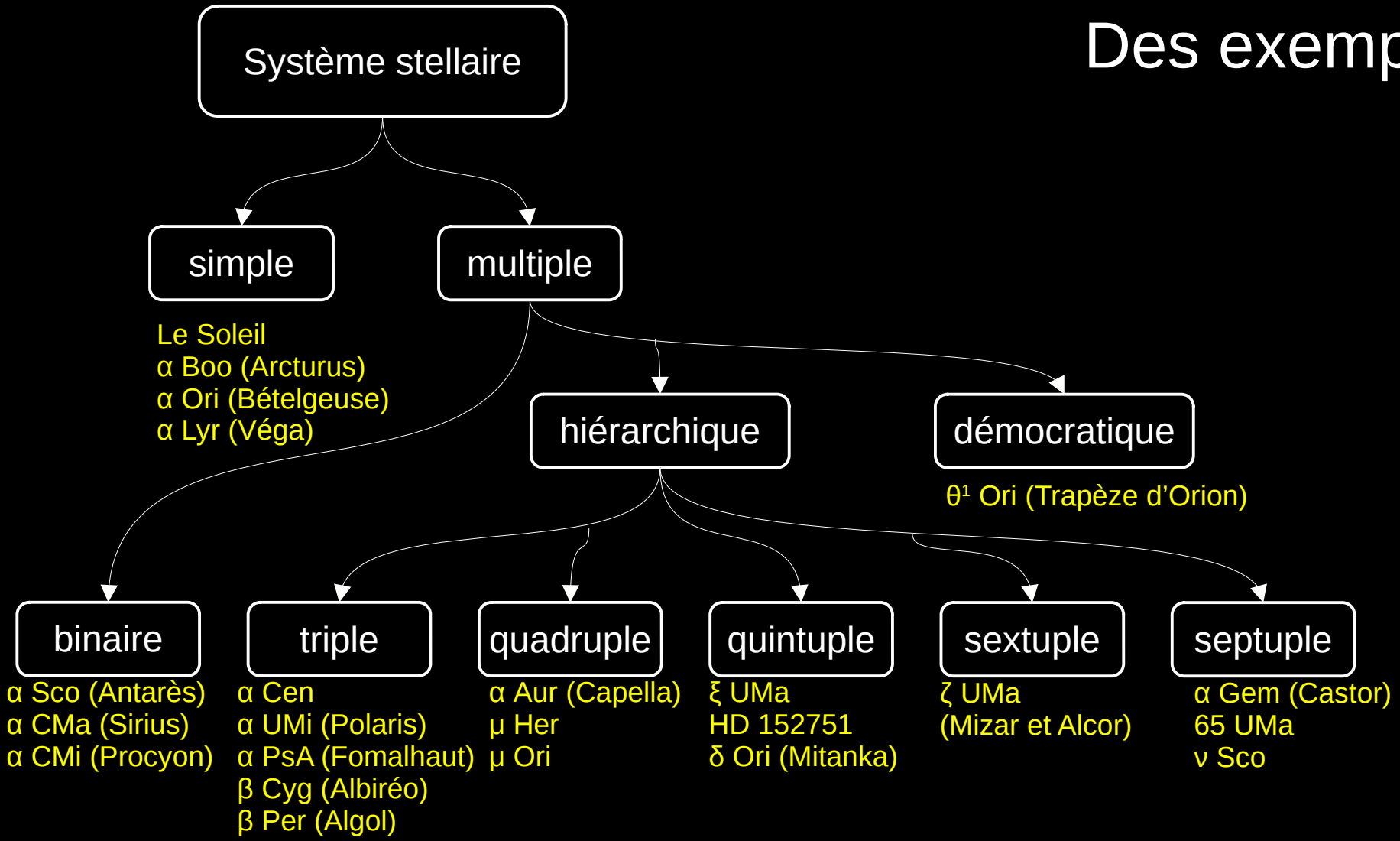


La valse des étoiles doubles

Merci de votre attention !



Des exemples

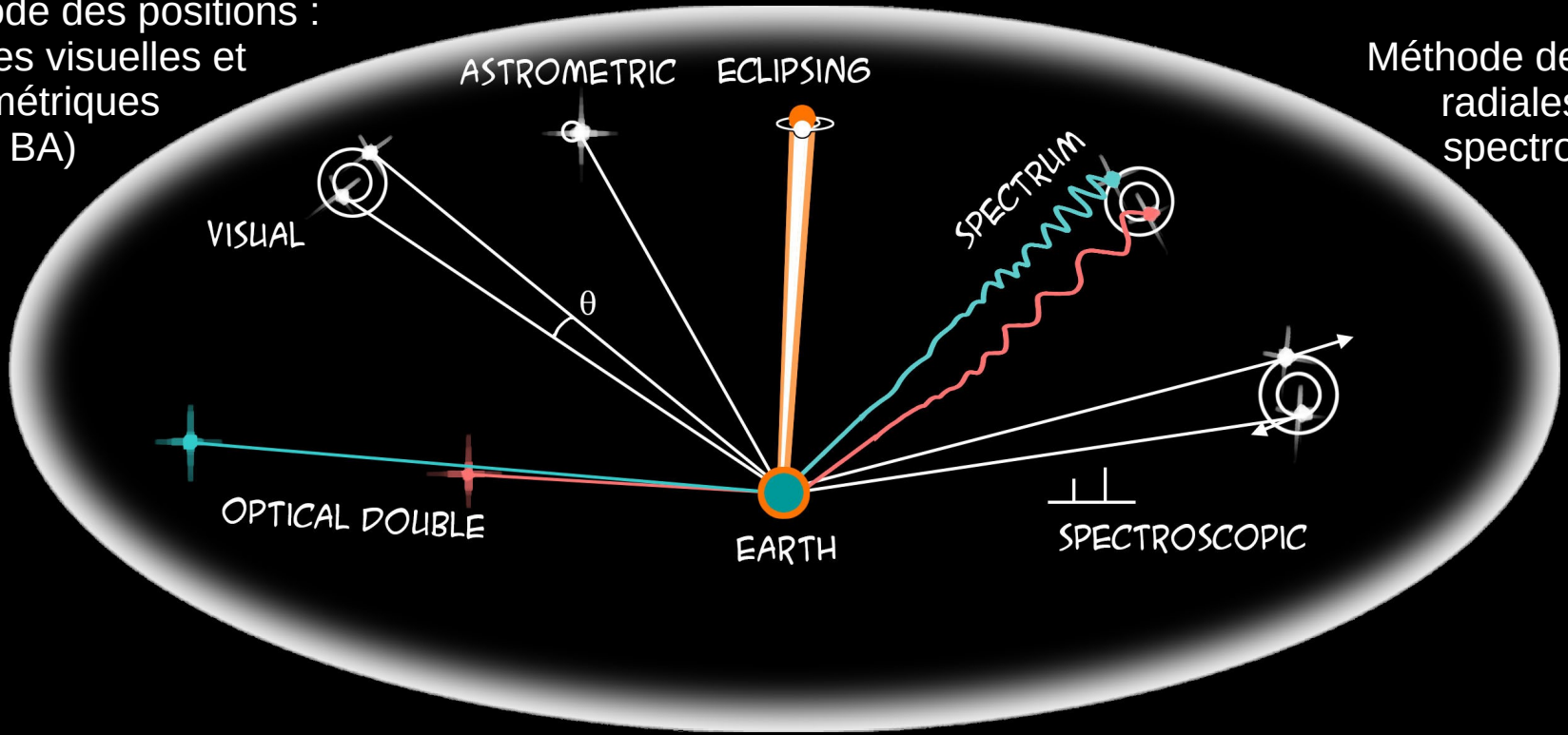


Comment les détecte-t-on ?

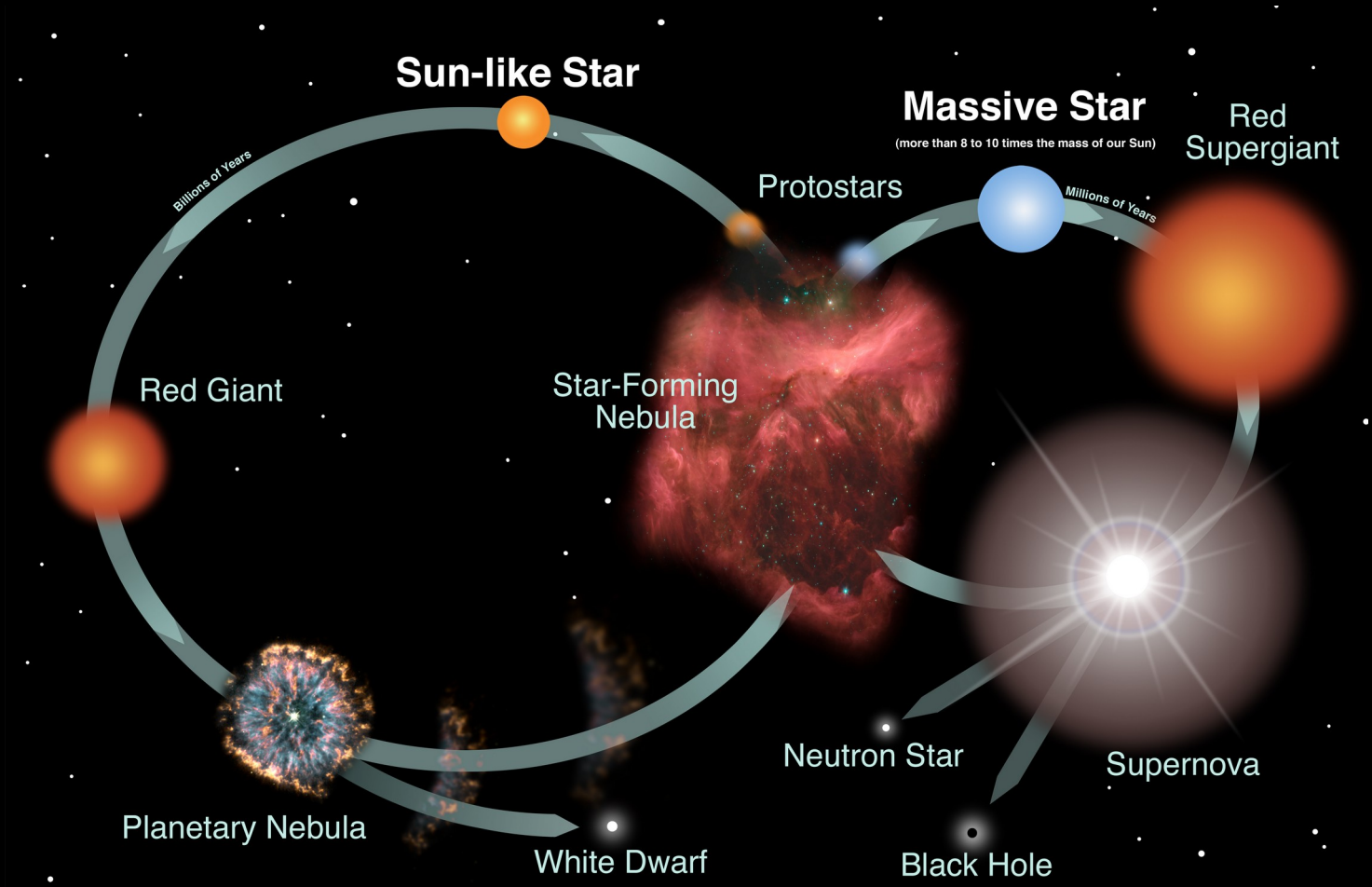
Méthode des transits :
binaires à éclipses (BE)

Méthode des positions :
binaires visuelles et
astrométriques
(BV & BA)

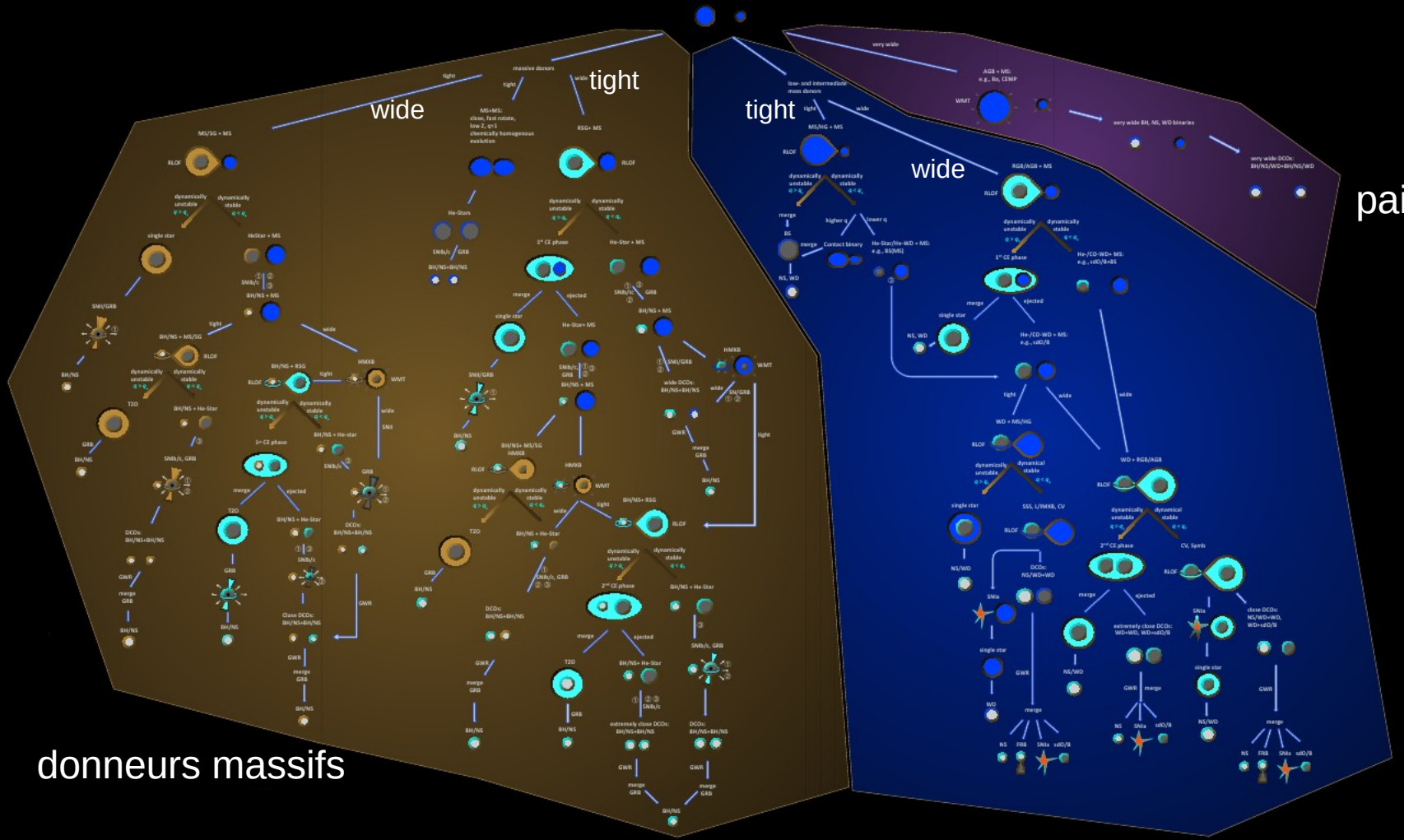
Méthode des vitesses
radiales : binaires
spectroscopiques
(BS)



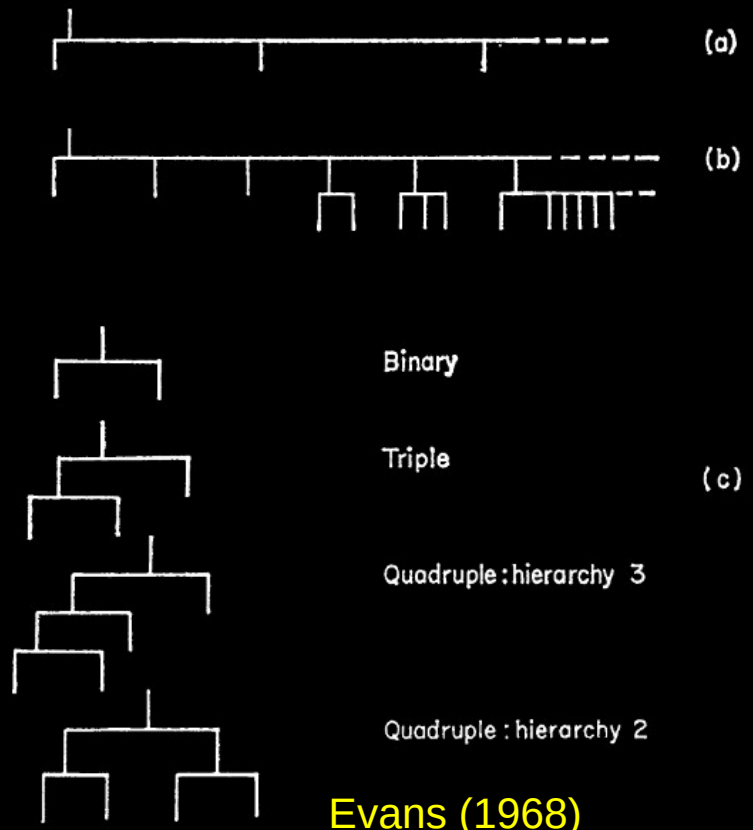
Evolution stellaire des étoiles solitaires



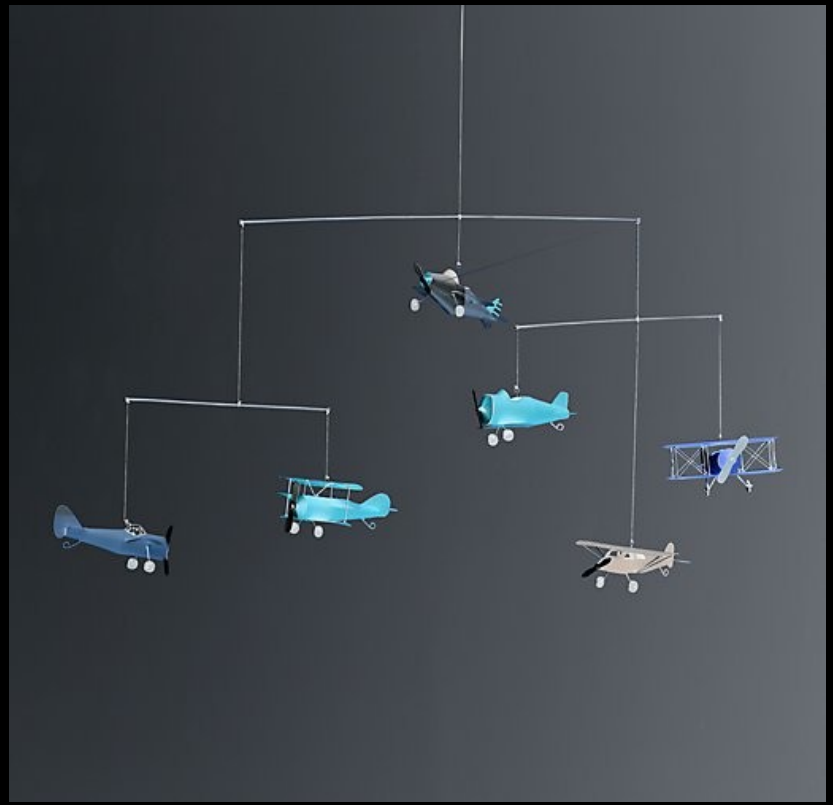
Evolution des étoiles binaires



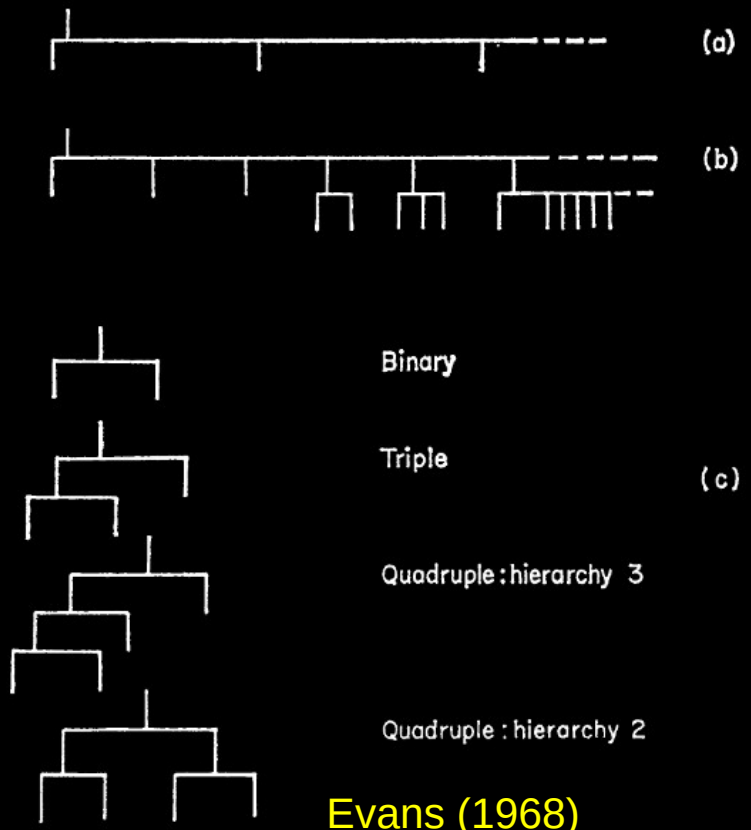
Diagrammes en mobile



Evans (1968)



Diagrammes en mobile



Evans (1968)

<u>Multiplex</u>

(a) Diagramme mobile du Soleil et des planètes: 1 seul niveau hiérarchique

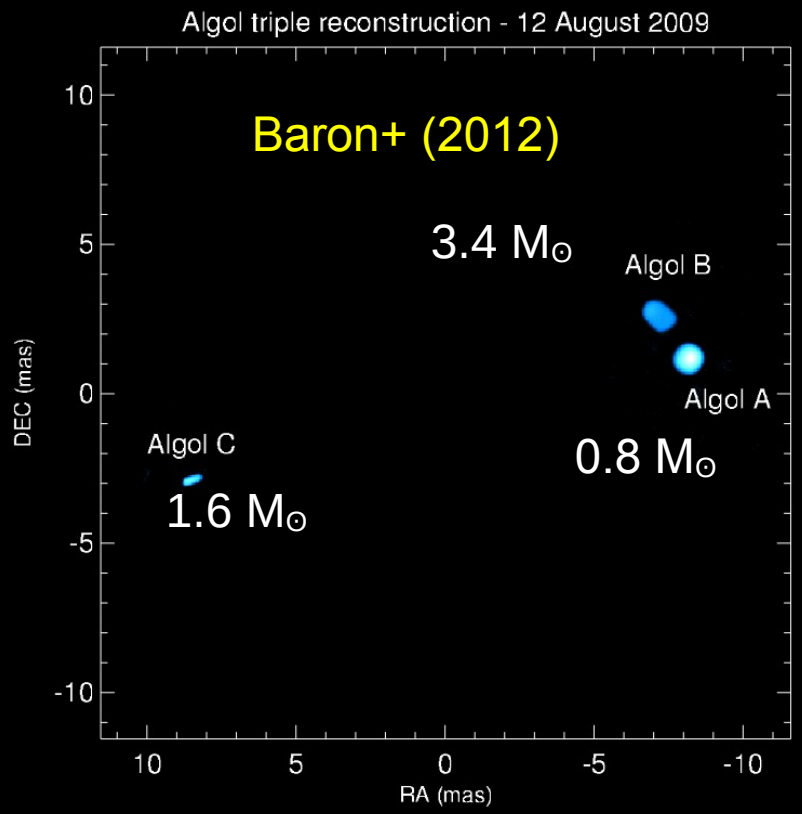
Soleil (Sol a), Mercure (Sol b), Vénus (Sol c), Terre (Sol d), ...

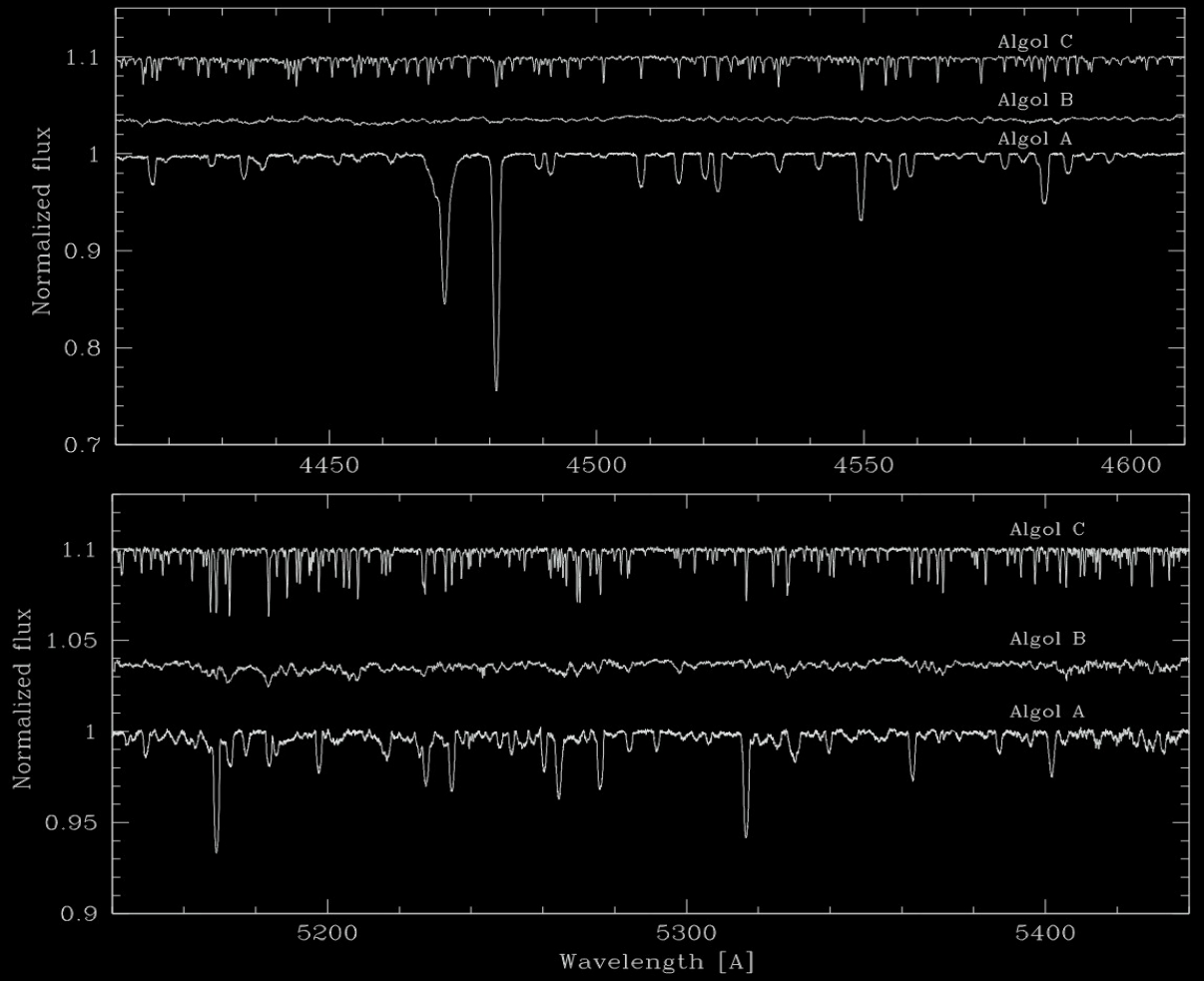
(b) Diagramme mobile du Soleil, des planètes et de leurs satellites : 2 niveaux hiérarchiques

<u>(c) Simplex</u>

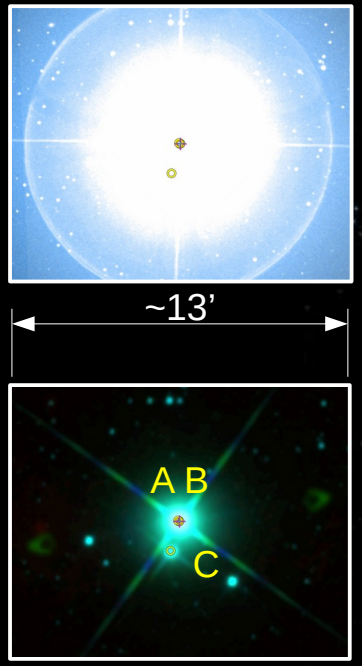
- Binaire : 1 niveau hiérarchique
- Triple : 2 niveaux hiérarchiques
- Quadruples : 2 architectures possibles
  - 3 niveaux hiérarchiques
  - 2 niveaux hiérarchiques

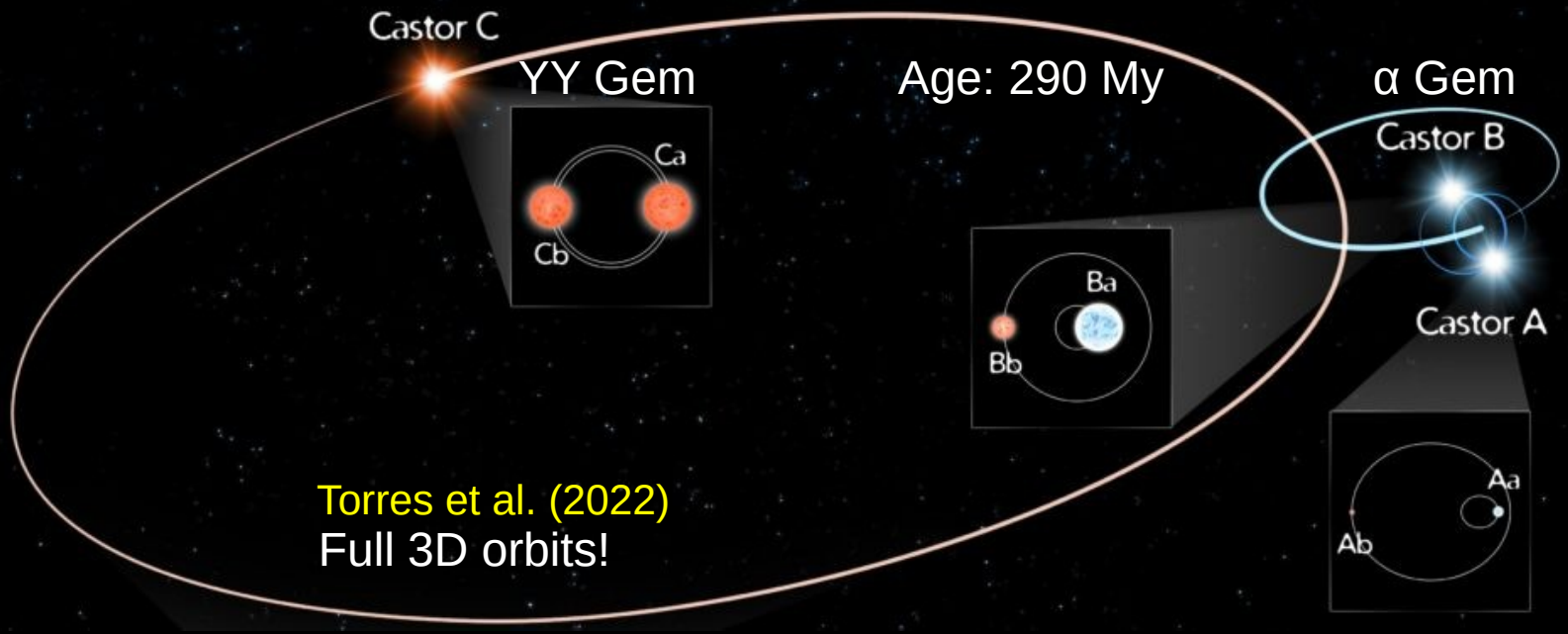
The Algol system





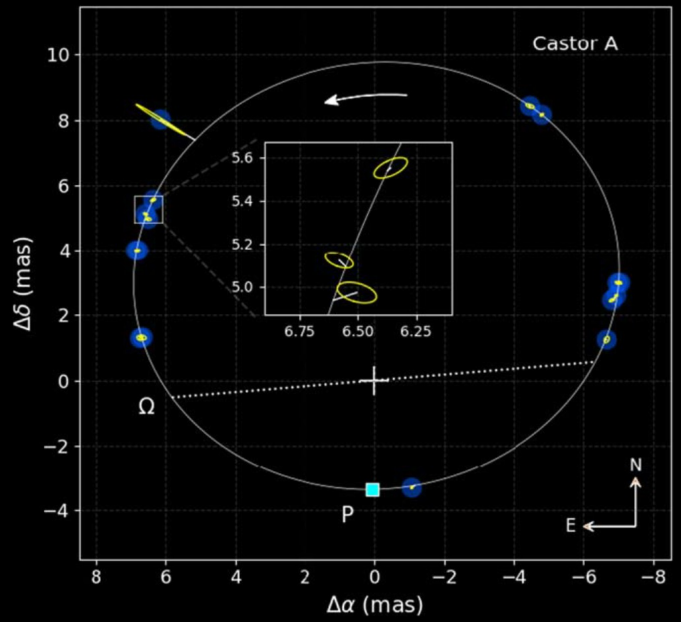
The Castor sextuplet (α Gem (2+2) + YY Gem)

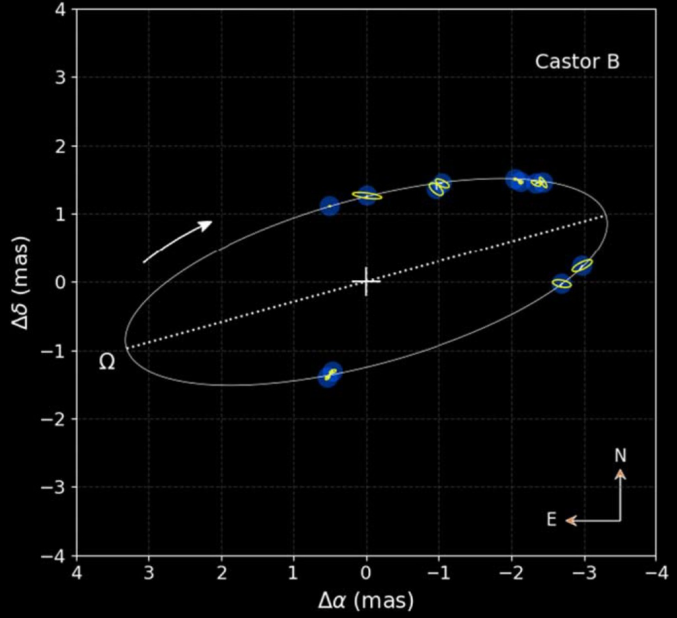


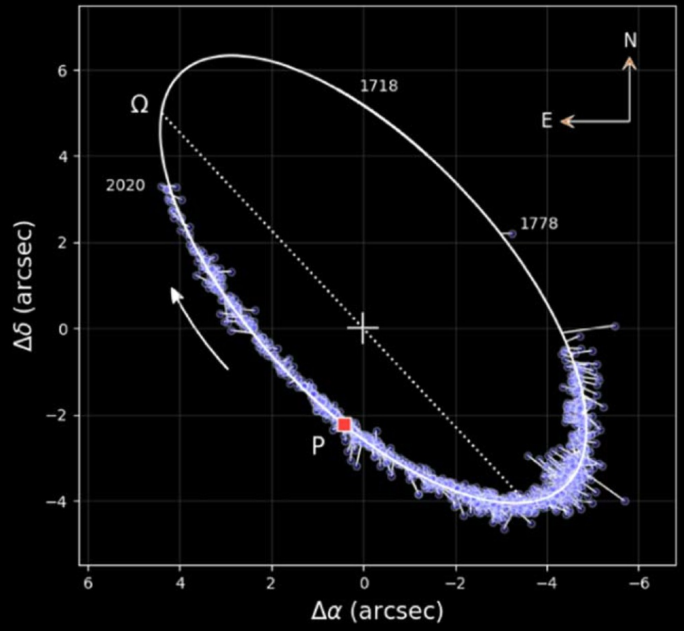


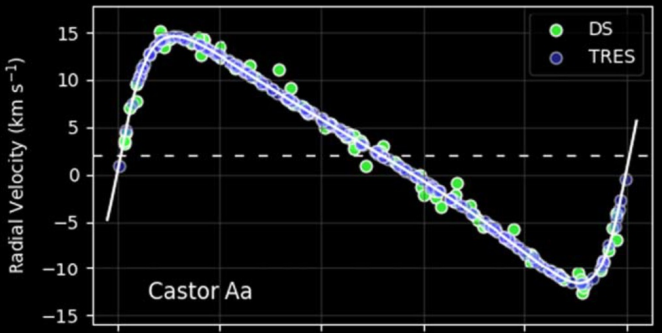
Castor Aa, Ab (AIV+MV): 9.2 d, *e* = 0.48, *a* = 0.12 au (SB1)
Castor Ba, Bb (AIV+MV): 2.9 d, *e* = 0, *a* = 0.05 au (SB1)
Castor A,B: 459.1 y, e = 0.34, *a* = 102 au (VB)
Castor Ca, Cb (MV+MV): 0.8 d, e = 0, *a* = 0.02 au (EB+SB2)
Castor AB,C: ~14.5 ky, a > 1060 au

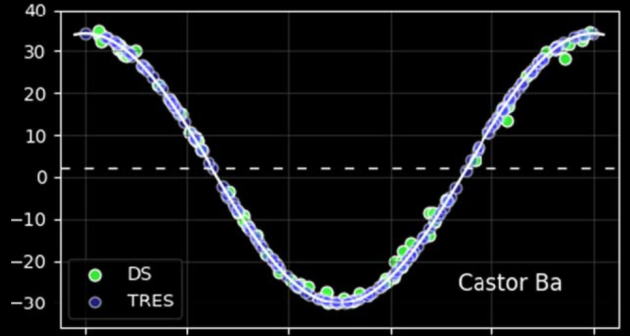
The Castor sextuplet (α Gem (2+2) + YY Gem)







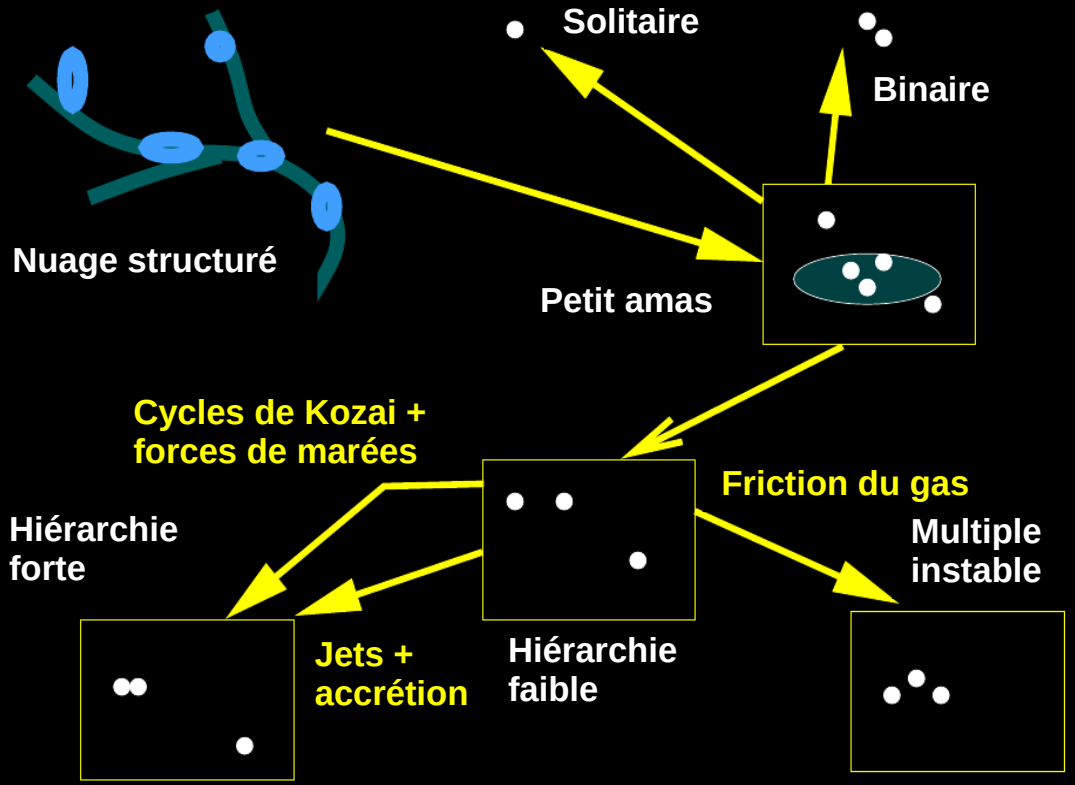




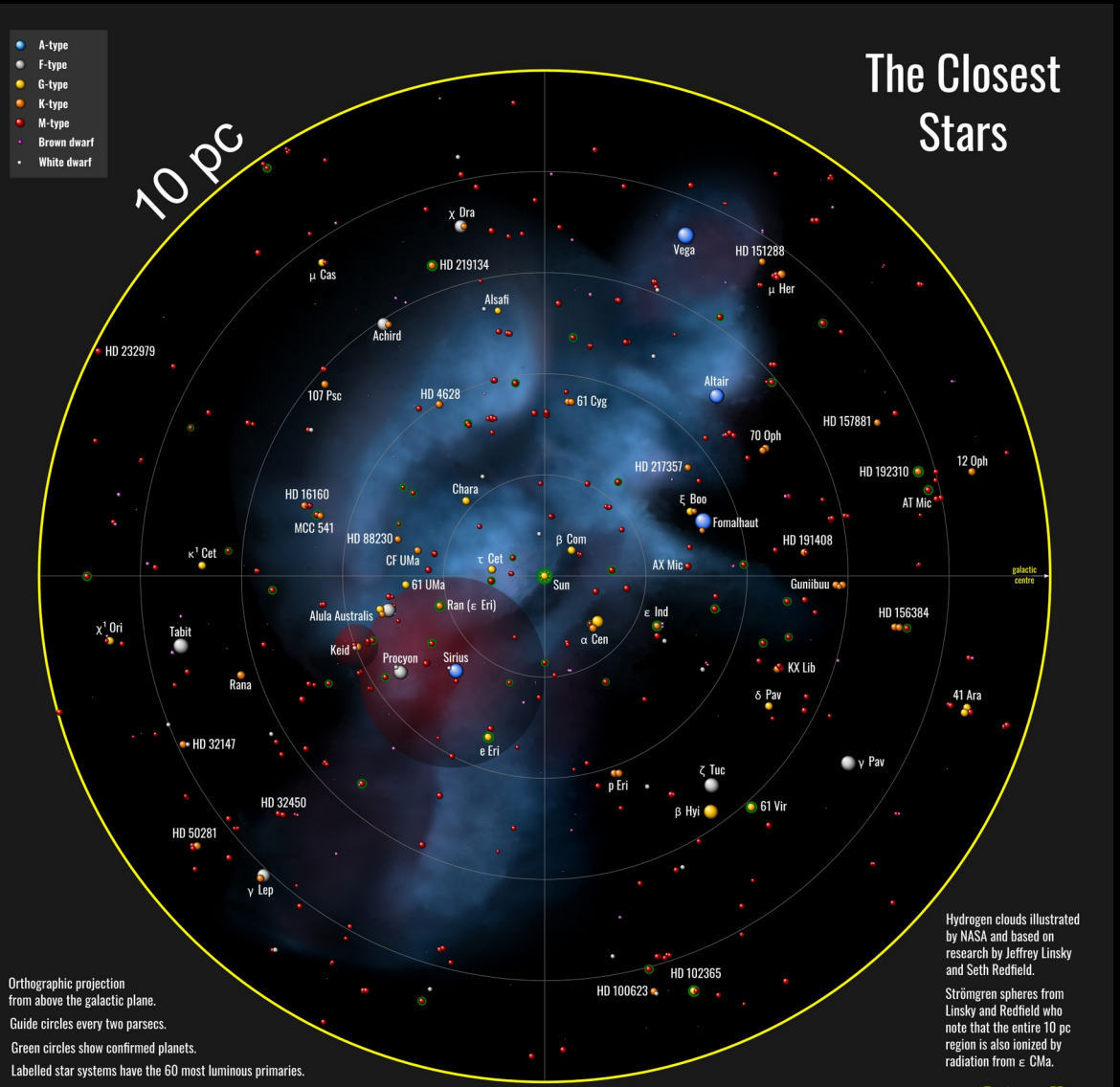
M_{Aa} = 2.37 ± 0.02 $M_\odot$
M_{Ab} = 0.386 ± 0.002 $M_\odot$

M_{Ba} = 1.79 ± 0.02 $M_\odot$
M_{Bb} = 0.387 ± 0.002 $M_\odot$

Comment se forment-ils ?



nuages moléculaires
↓
amas ouverts
↓
mini-amas
↓
associations
↓
groupes mobiles
↓
étoiles de champ et
étoiles à haute vélocité



Le voisinage solaire

10 pc = 33 années-lumières

		~340 systèmes stellaires	~460 étoiles
O	0		
B	0		
A	4		
F	8		
G	18		
K	38		
M	249		
Naines brunes	95		
Naines blanches	20		
Etoiles solitaires	246	73%	53%
Binaires	69	20%	30%
Triples	19	6%	12%
Quadruples	3	1%	3%
Quintuples	2		2%

Le voisinage solaire jusqu'à 10 pc