

19 janvier 2023
Enseigner l'Univers (Université de Paris)

La recherche de la **Matière Noire**

Marco Cirelli
(CNRS LPTHE Jussieu)



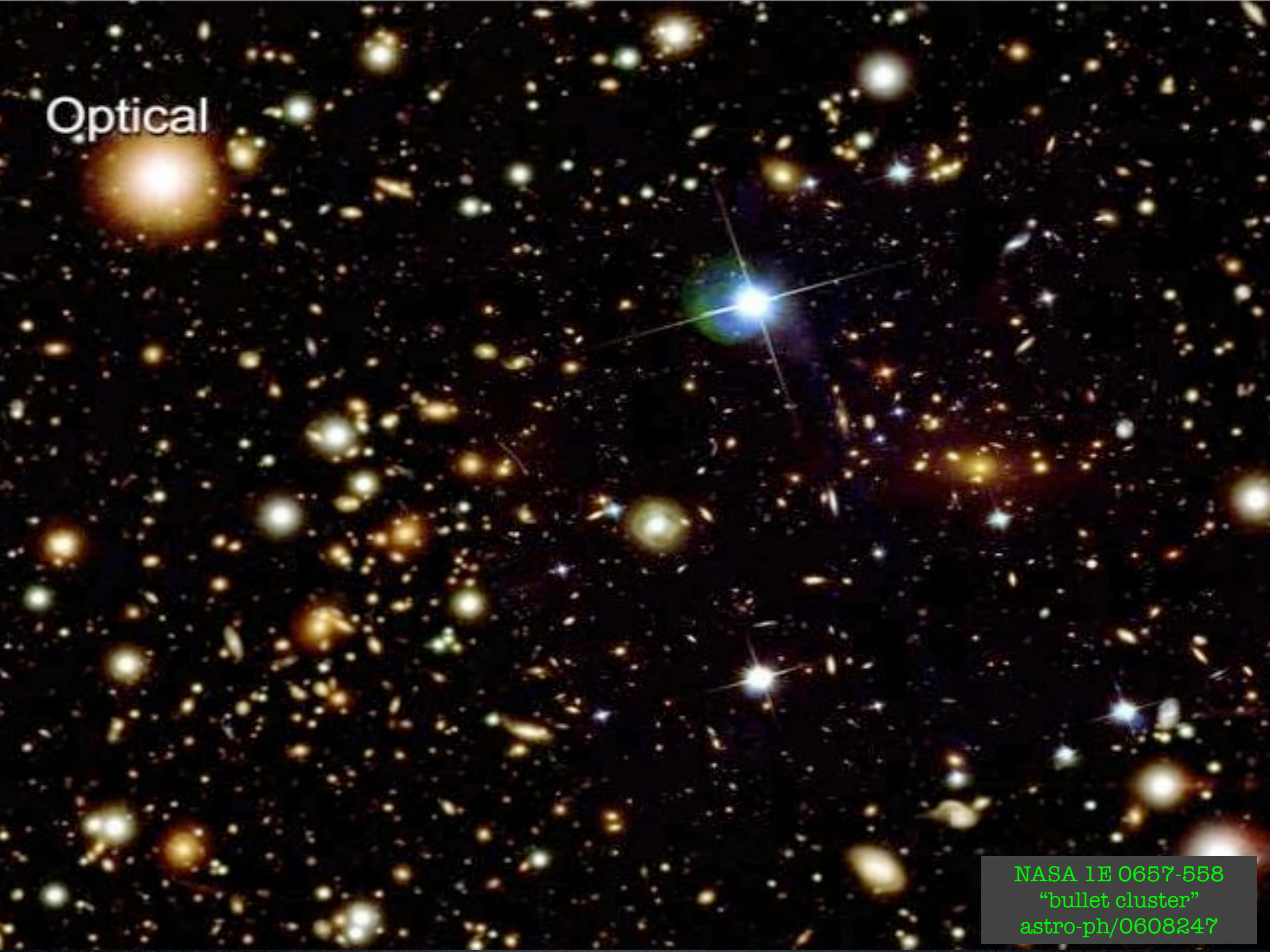
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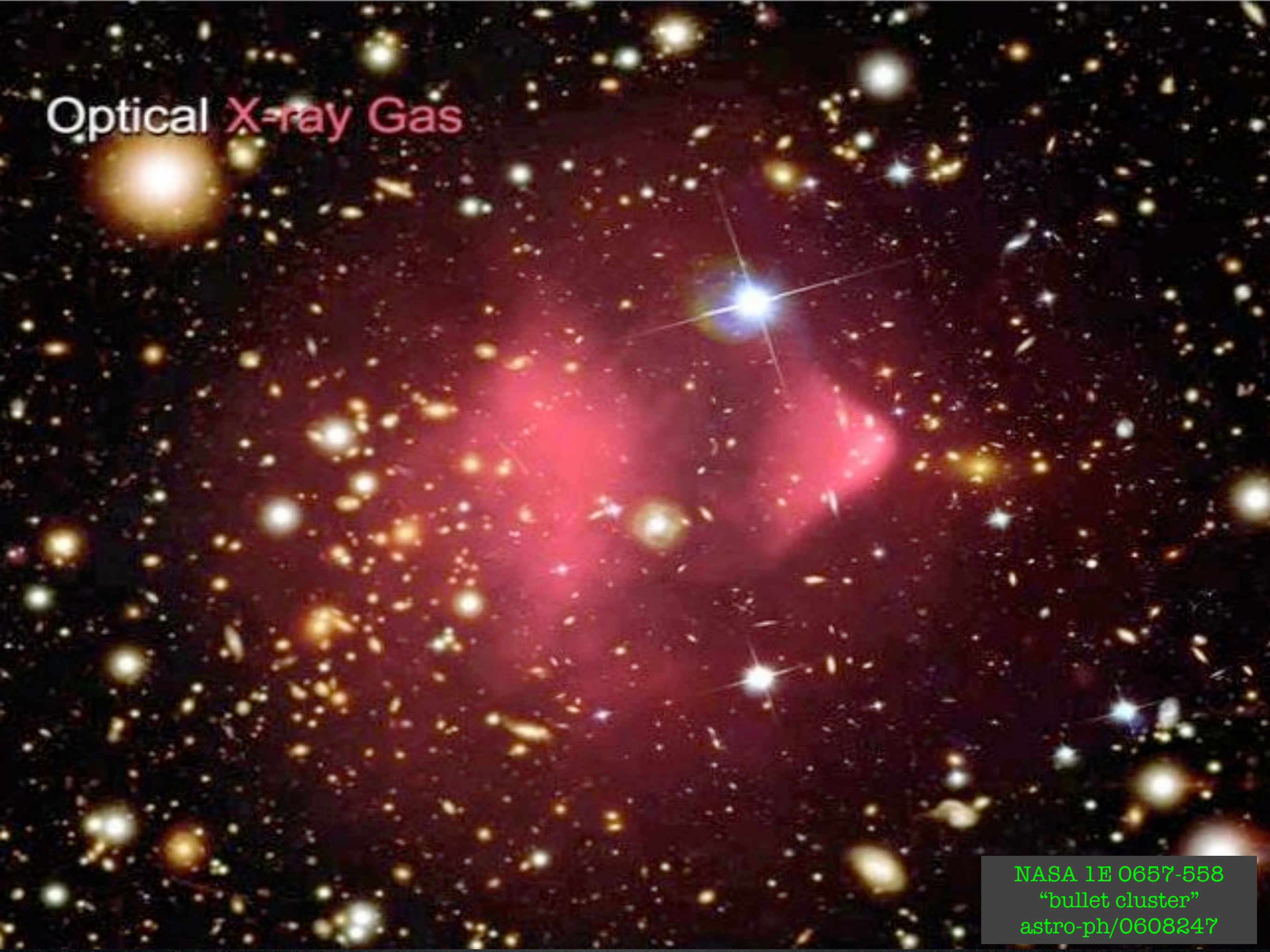


Optical



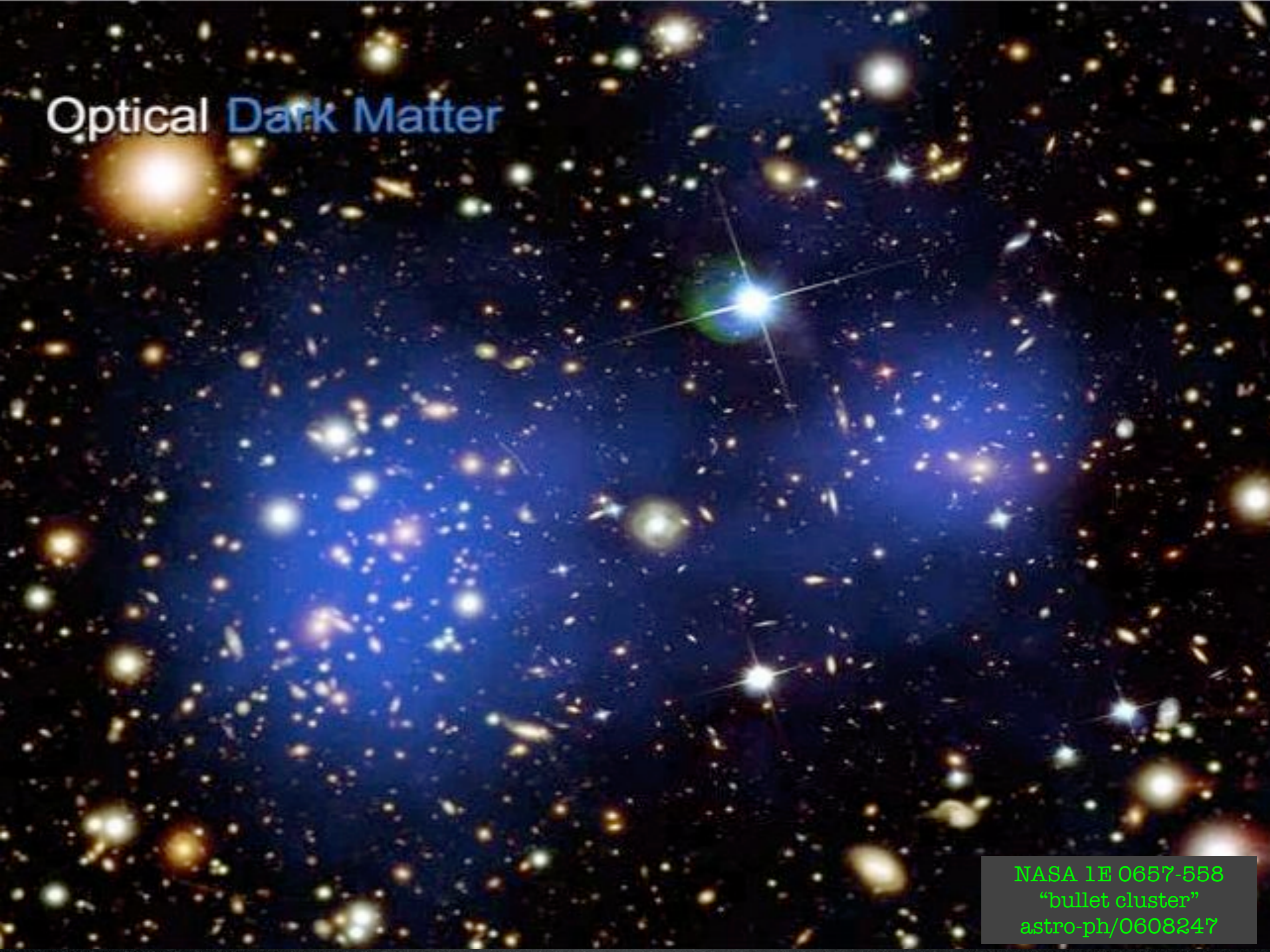
NASA 1E 0657-558
"bullet cluster"
astro-ph/0608247

Optical X-ray Gas



NASA 1E 0657-558
"bullet cluster"
astro-ph/0608247

Optical Dark Matter



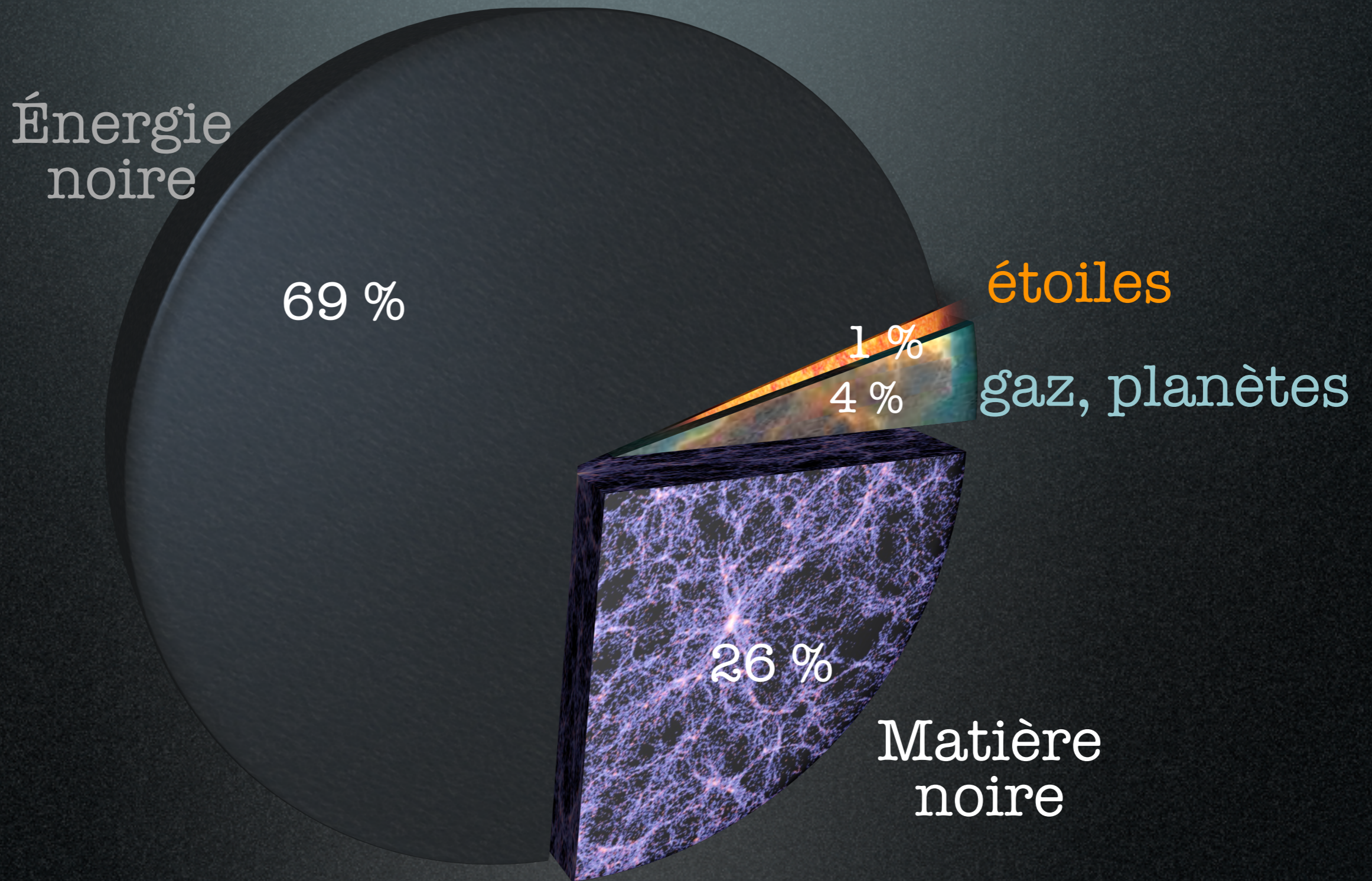
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Optical Dark Matter X-ray Gas

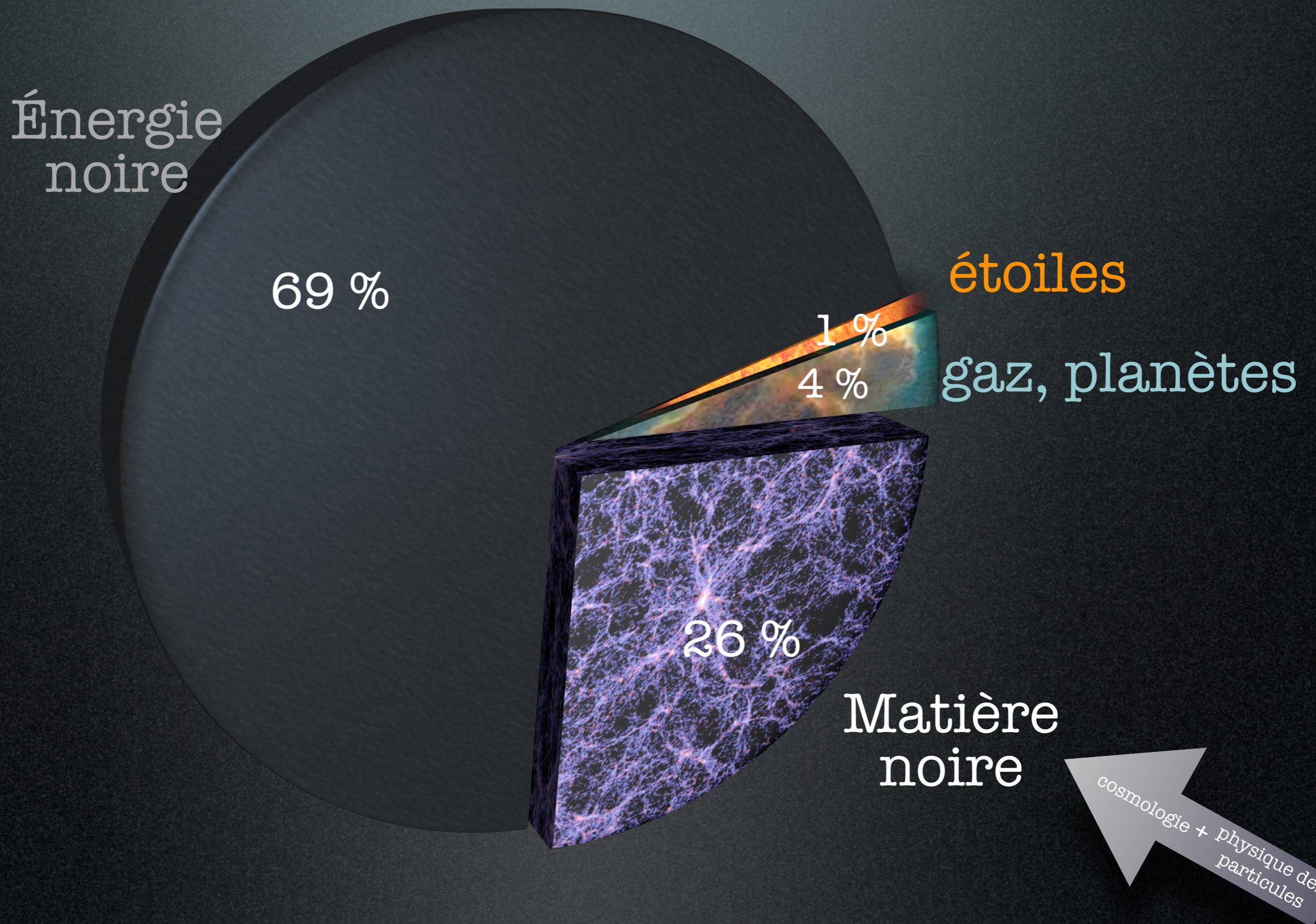


NASA 1E 0657-558
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95% de notre Univers est inconnu, noir



95% de notre Univers est inconnu, noir



Comment prouver
l'**existence**
de la Matière Noire ?

Preuves d'existence

1) courbes de rotation
galactiques

2) amas de galaxies

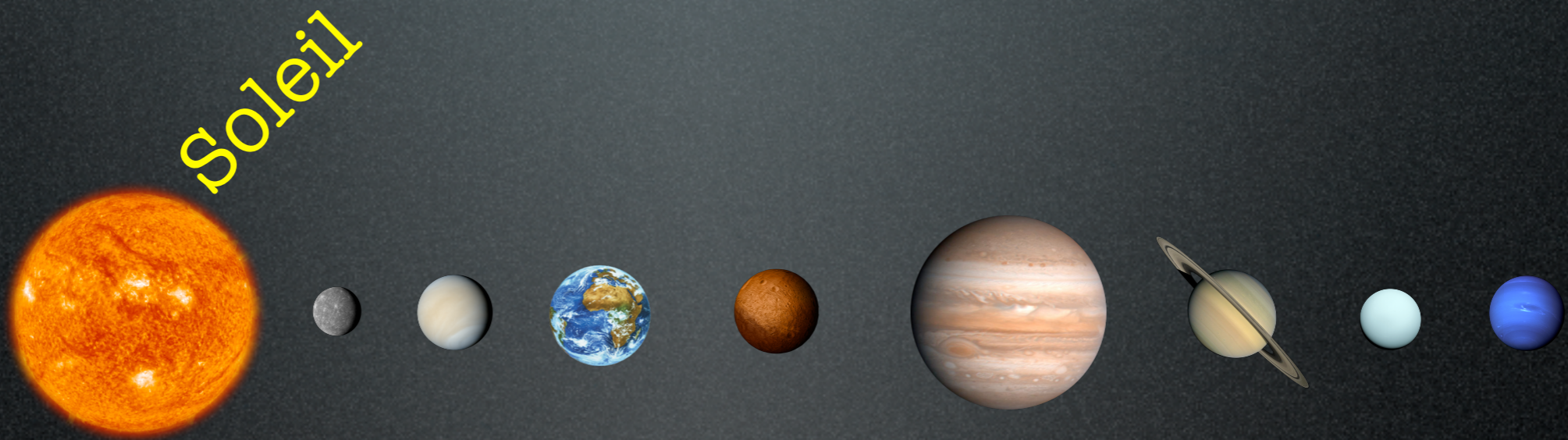
3) 'cosmologie
de précision'

Preuves d'existence

1) courbes de rotation
galactiques

Preuves d'existence

1) courbes de rotation galactiques



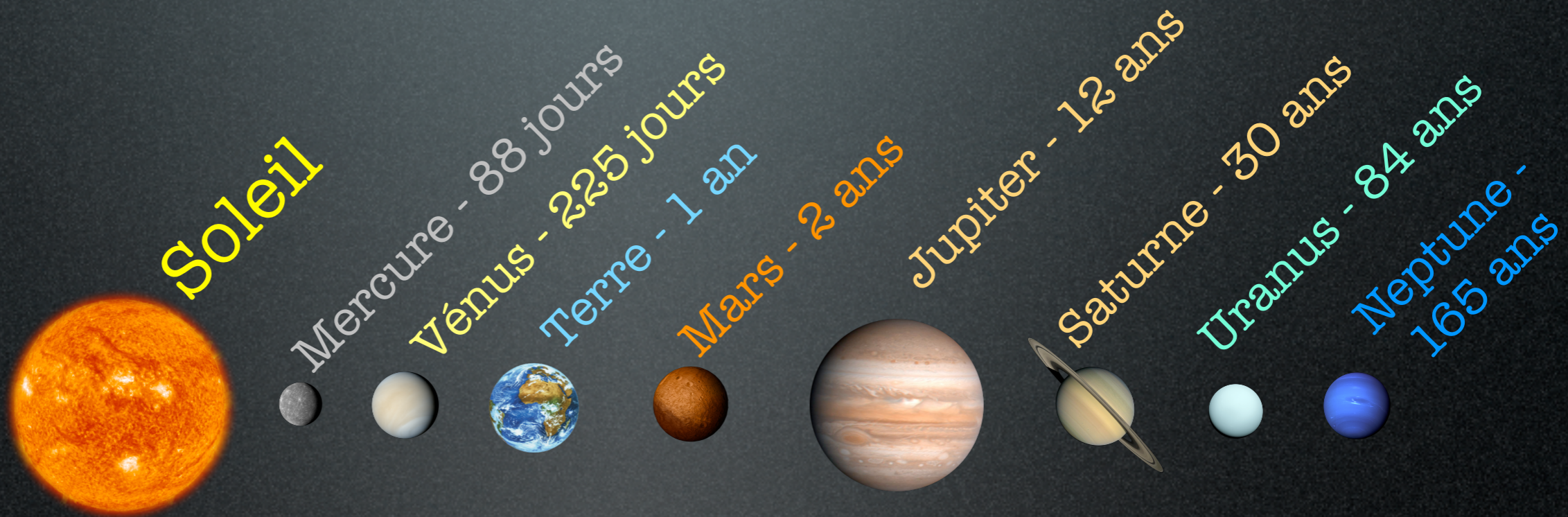
Preuves d'existence

1) courbes de rotation galactiques



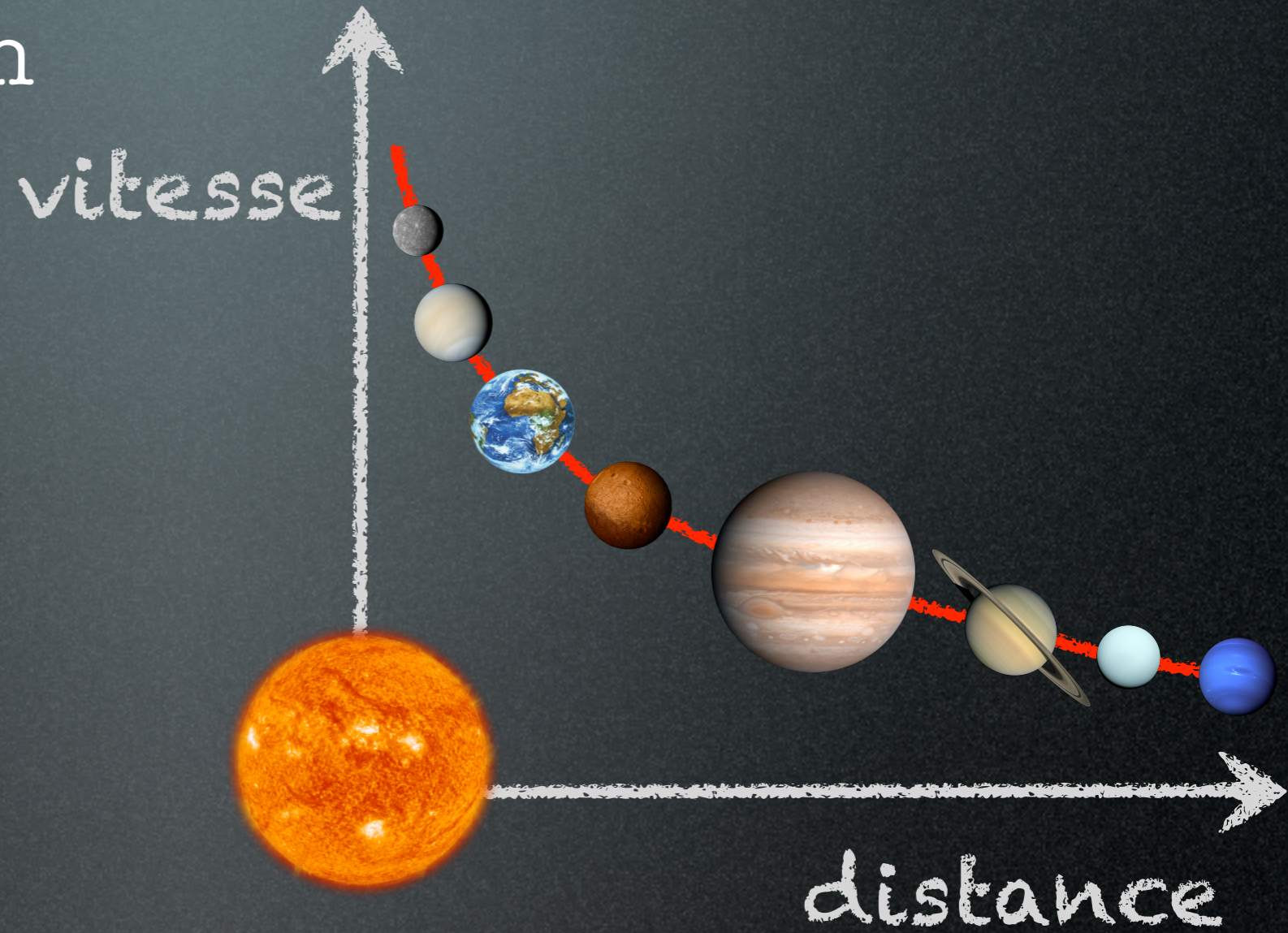
Preuves d'existence

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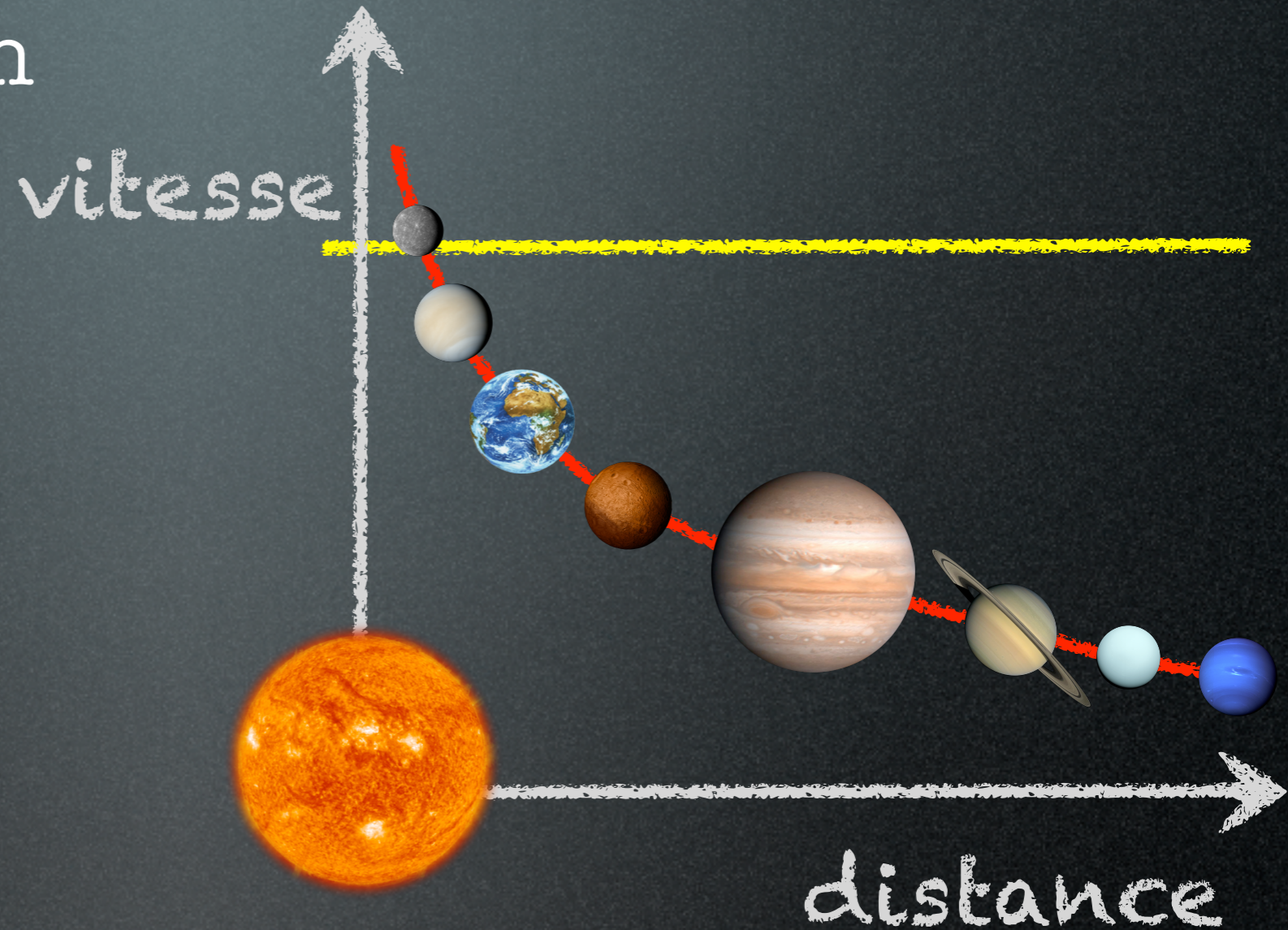
Preuves d'existence

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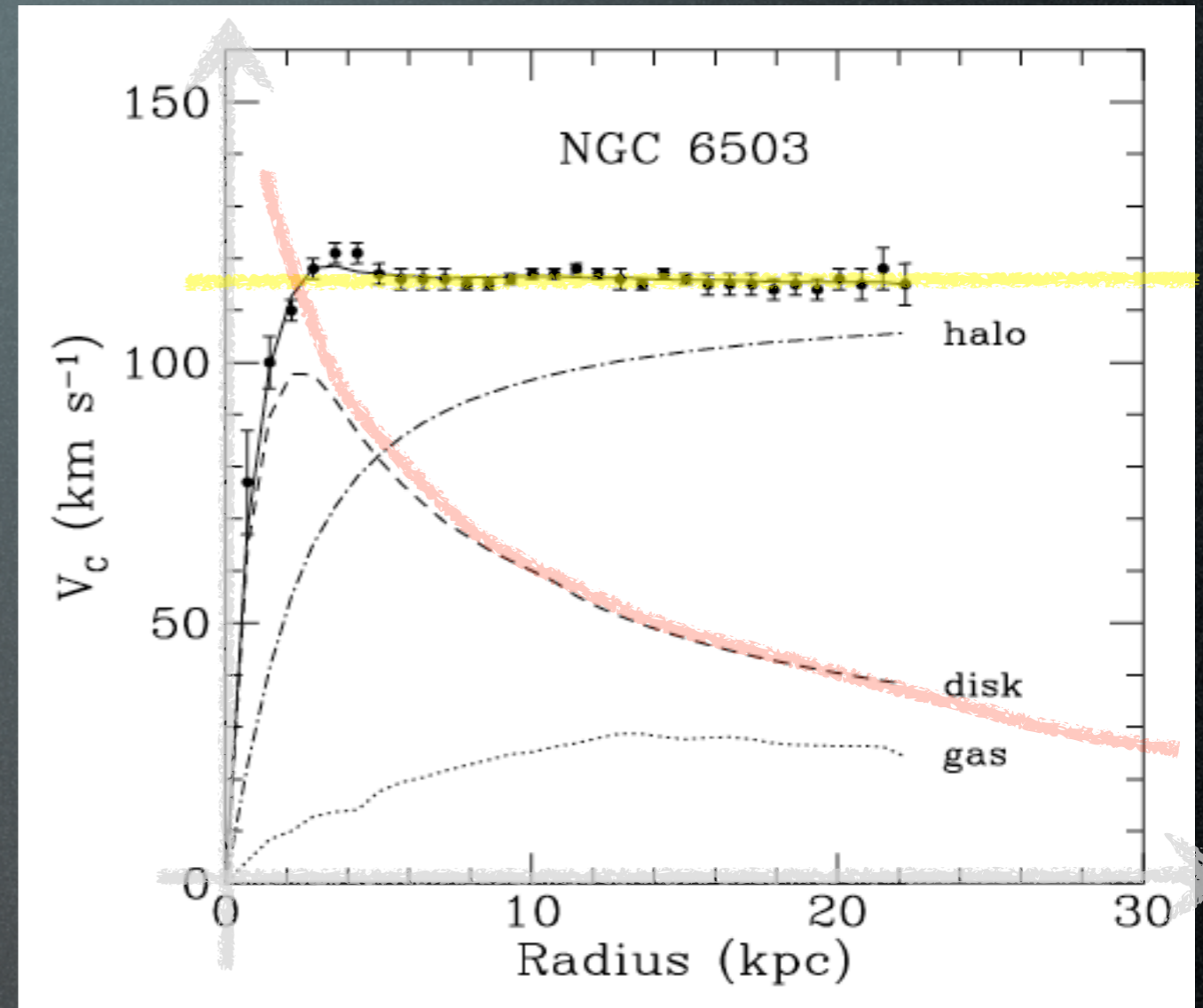
Preuves d'existence

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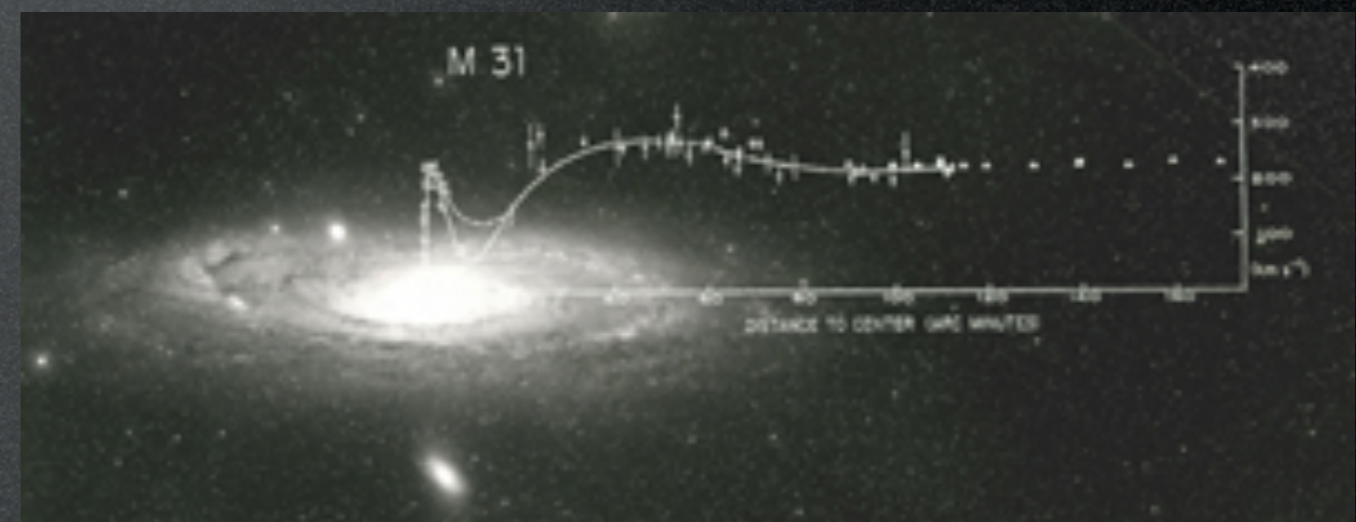


Preuves d'existence

1) courbes de rotation galactiques



Begelman et al., MNRAS 249 (1991)



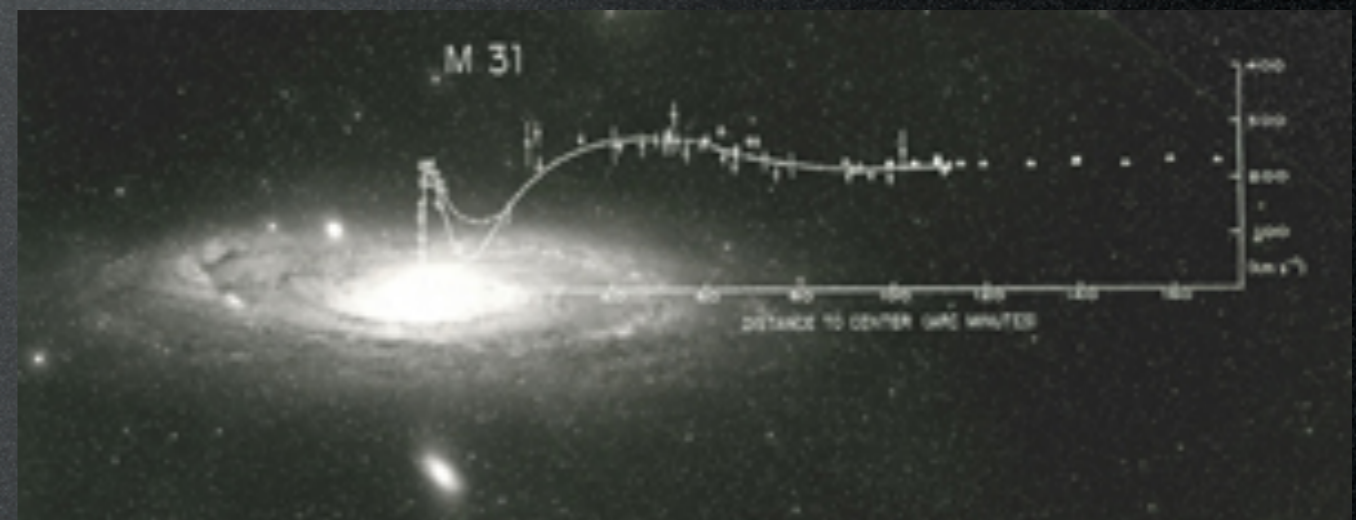
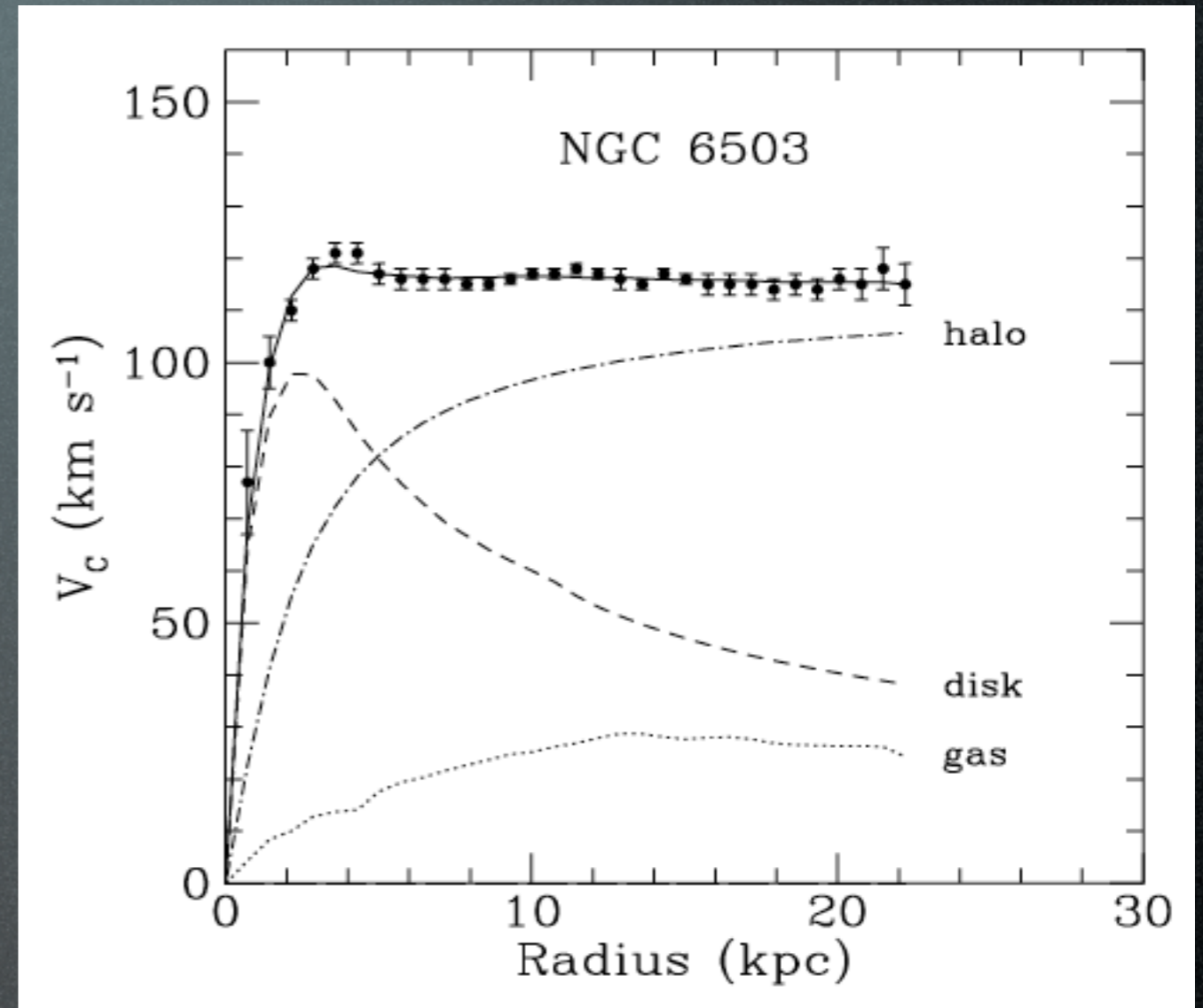
Preuves d'existence

1) courbes de rotation galactiques

$$m \frac{v^2}{r} = G_N \frac{mM}{r^2}$$

'centrifuge'

'centripète'



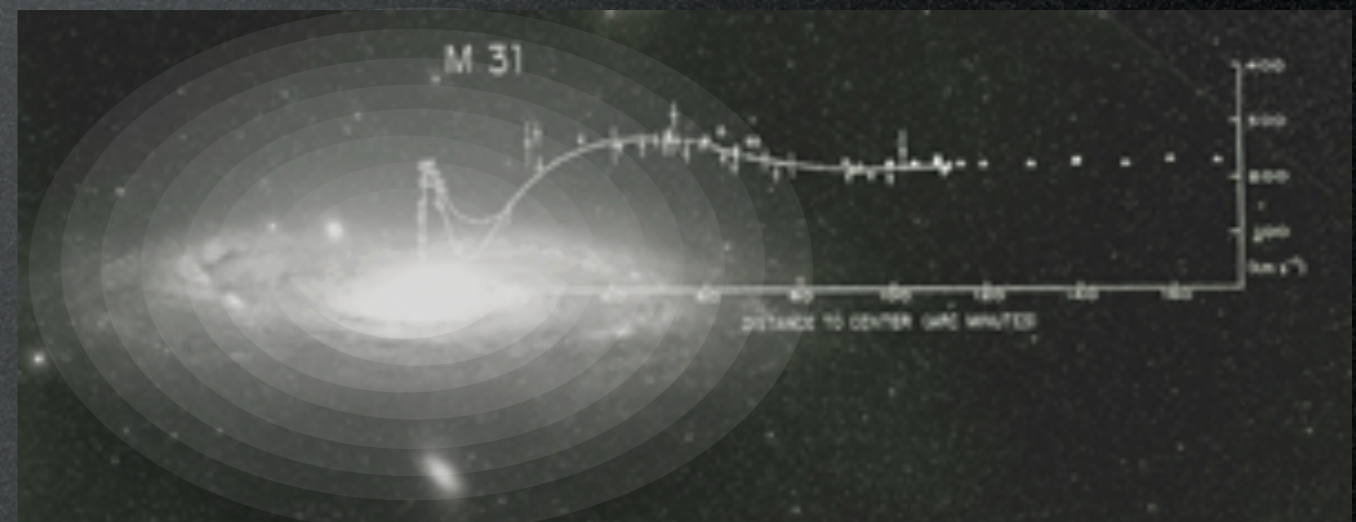
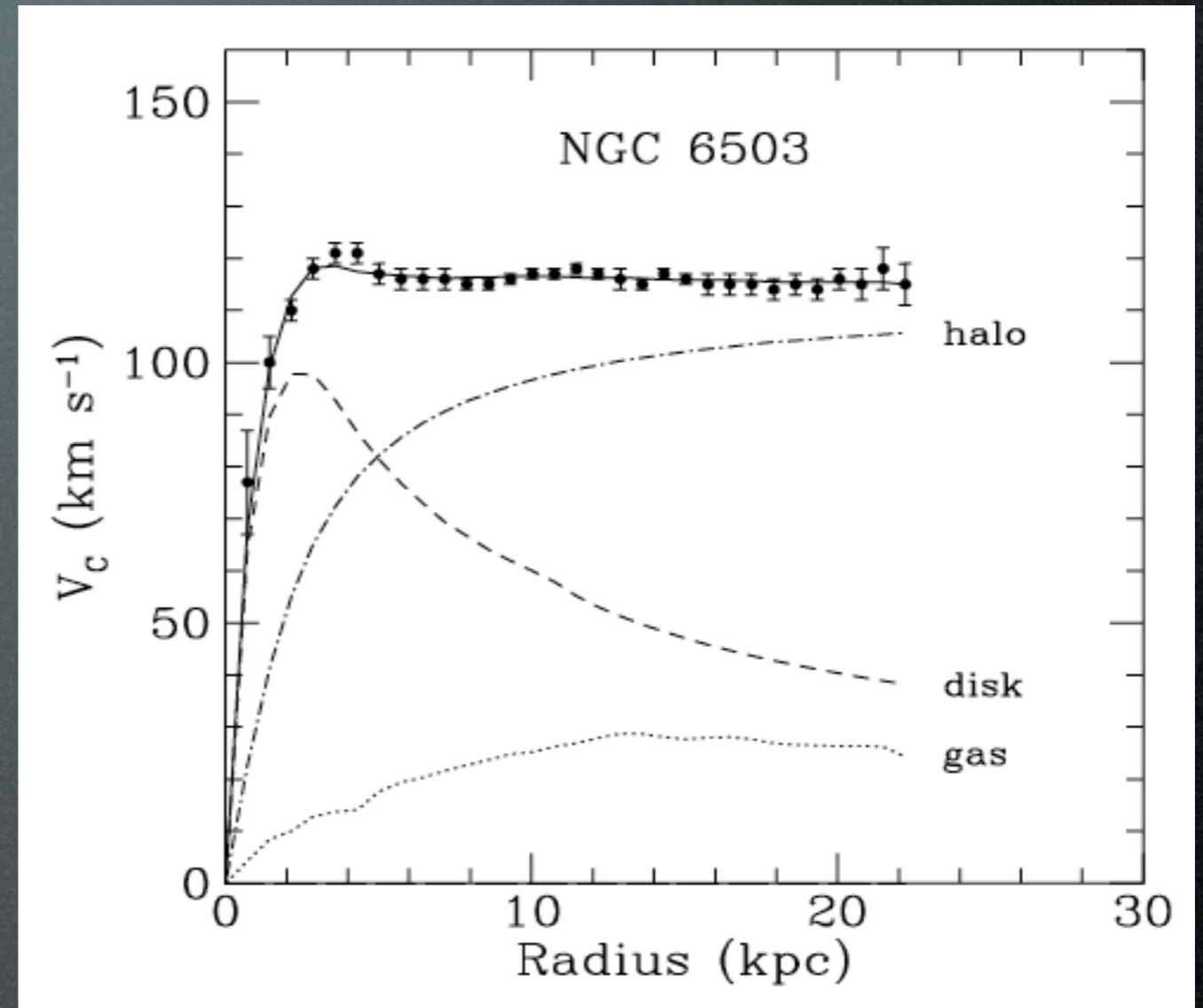
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Preuves d'existence

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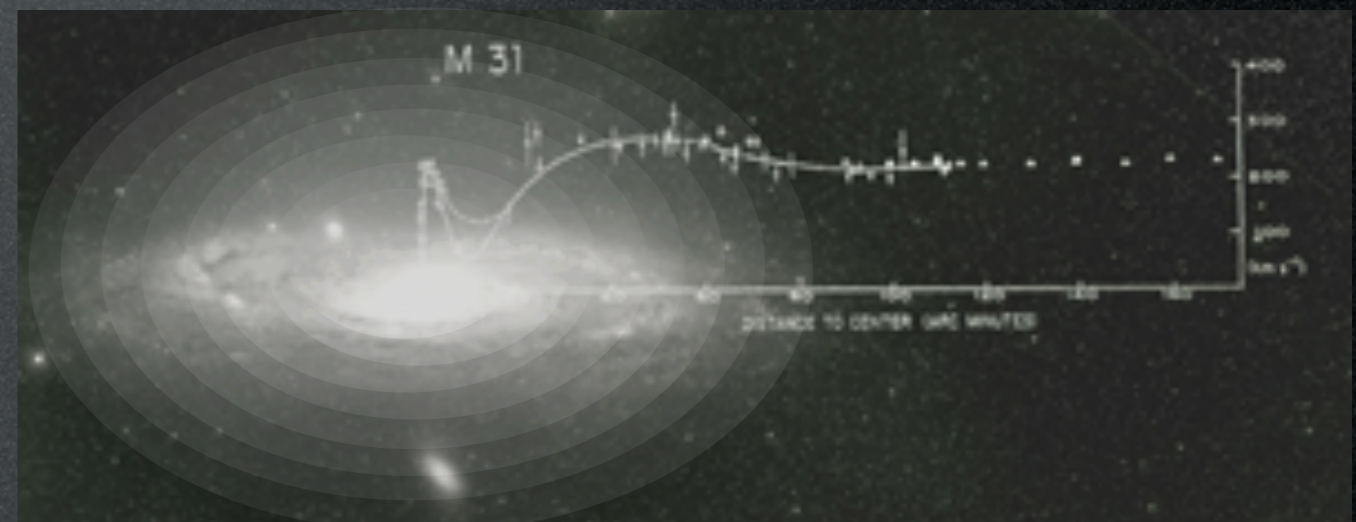
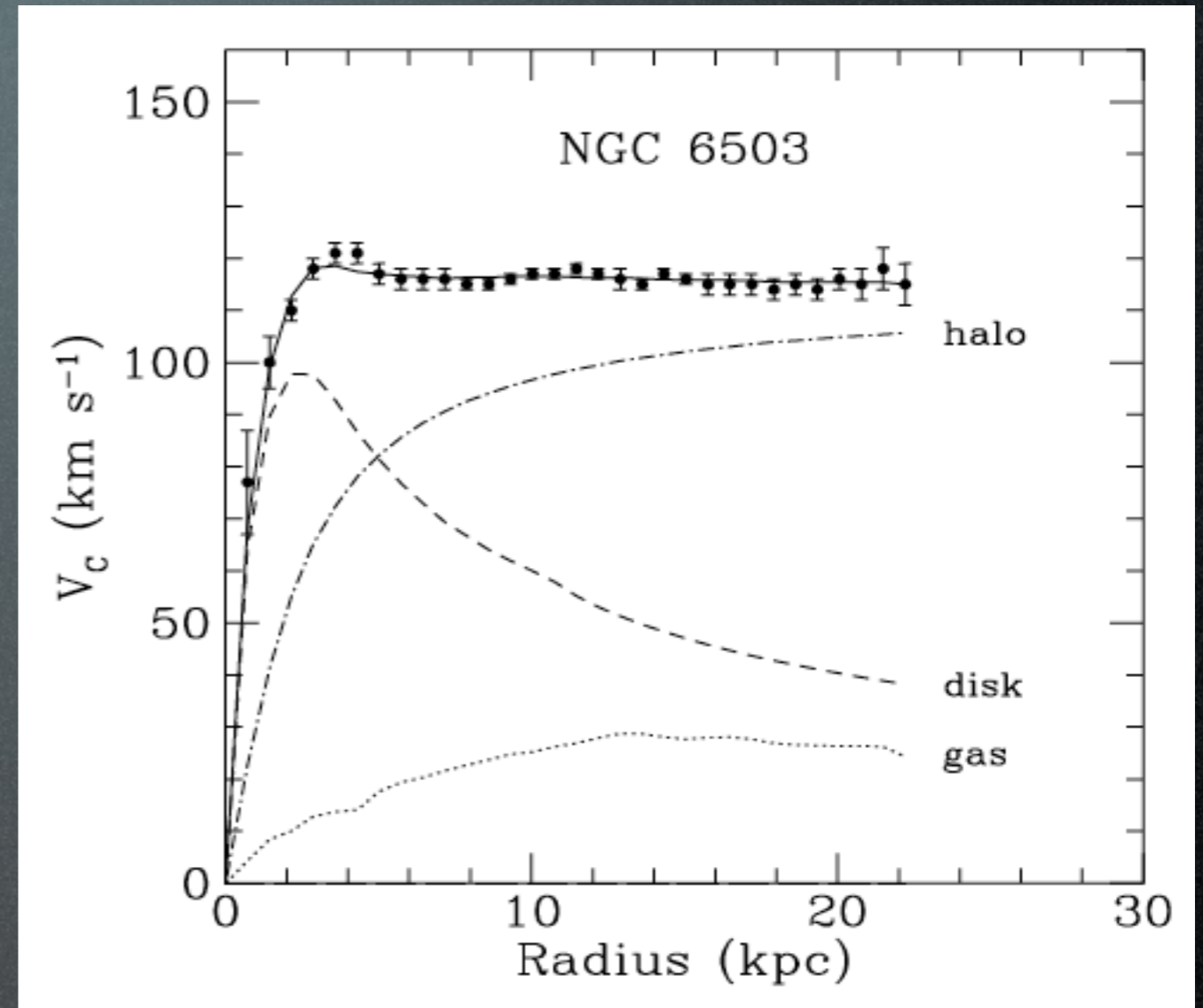
'centrifuge'

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1933



Fritz Zwicky
(1898-1974)



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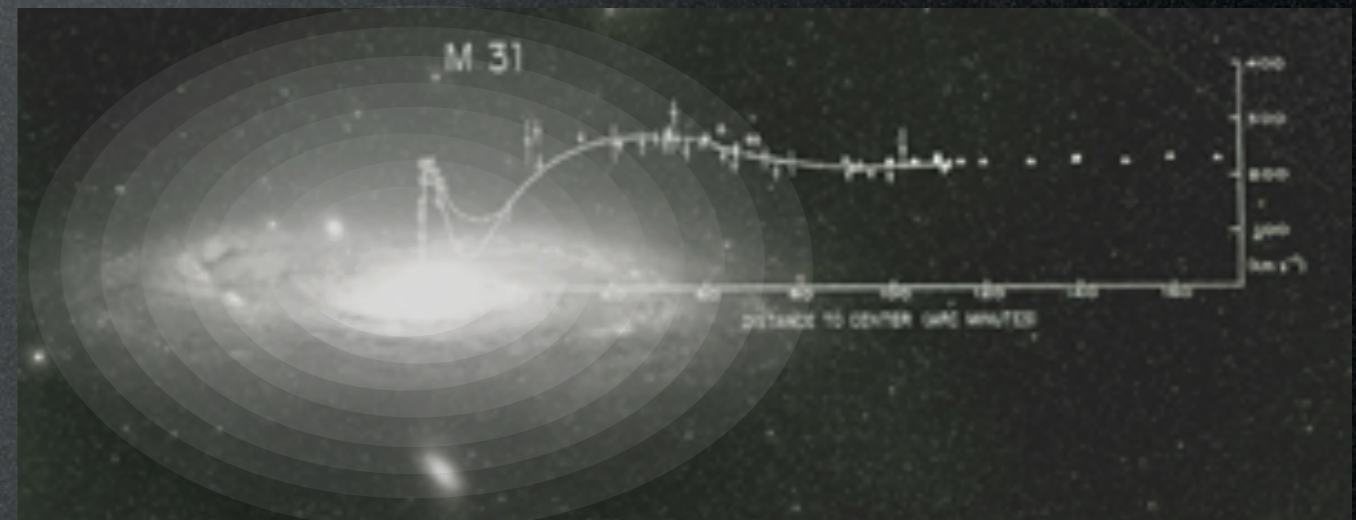
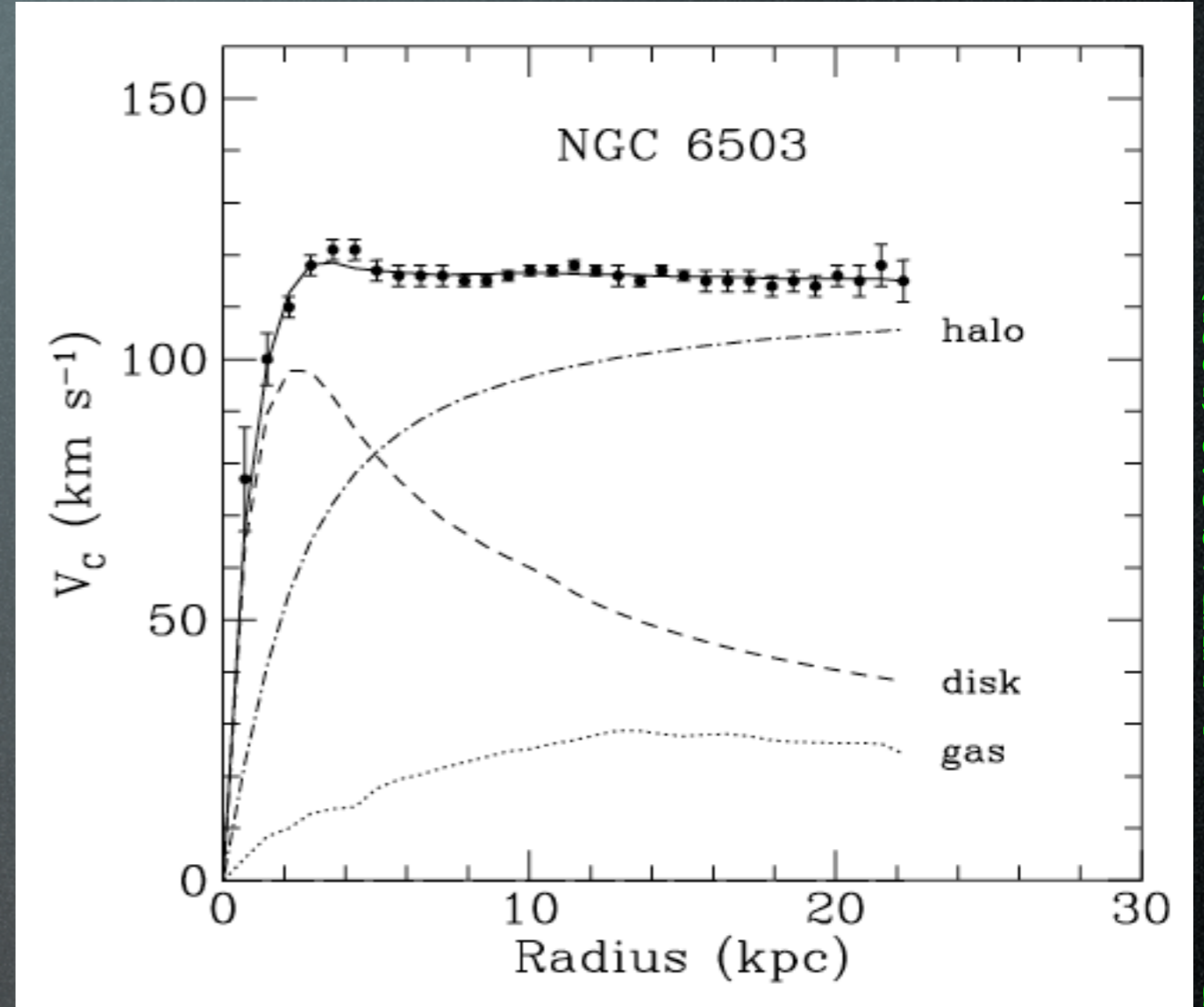
1933

~ 1970



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Vera Rubin
(1928-2016)



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$$m \frac{v^2}{r} = G_N \frac{mM}{r^2}$$

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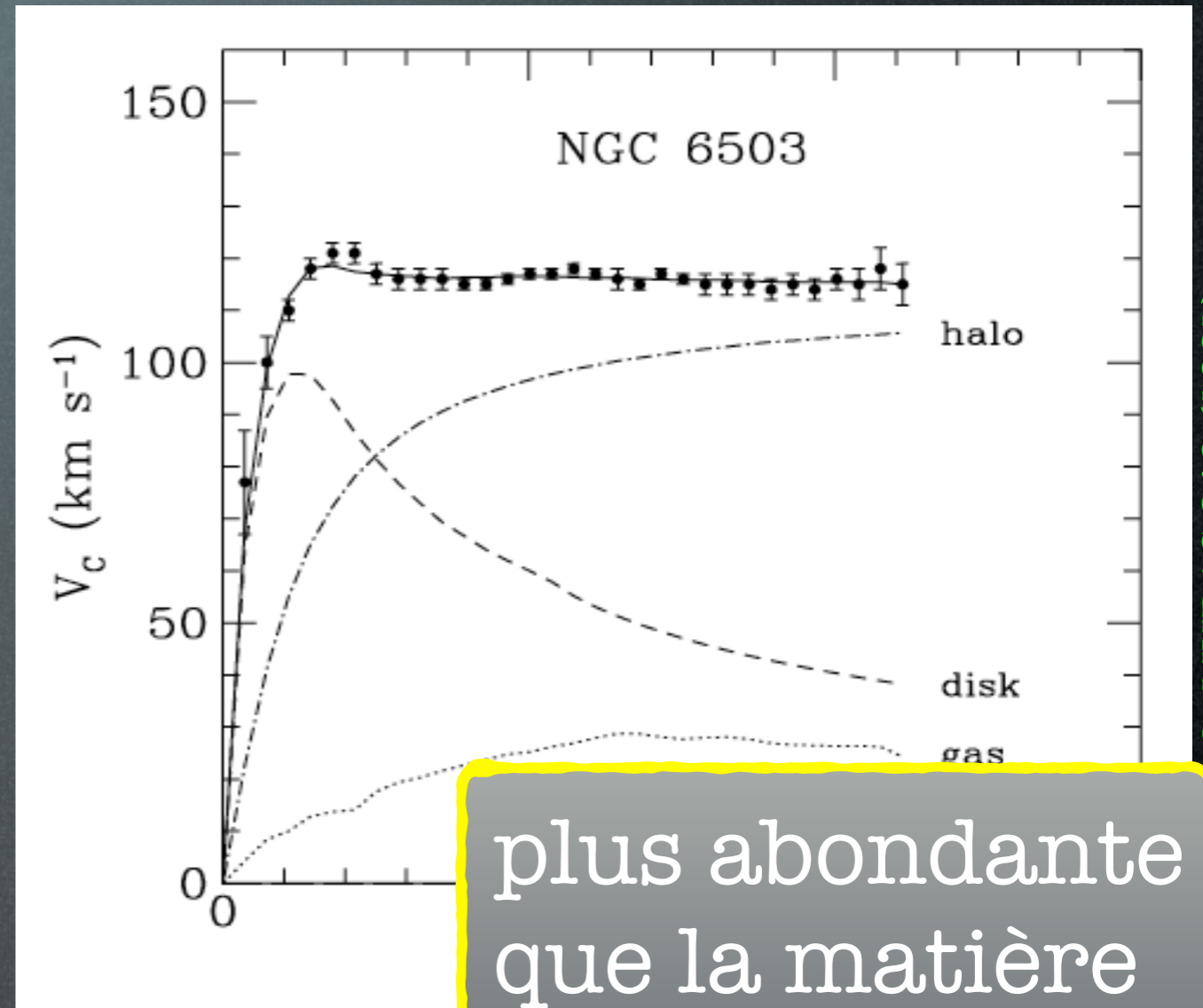
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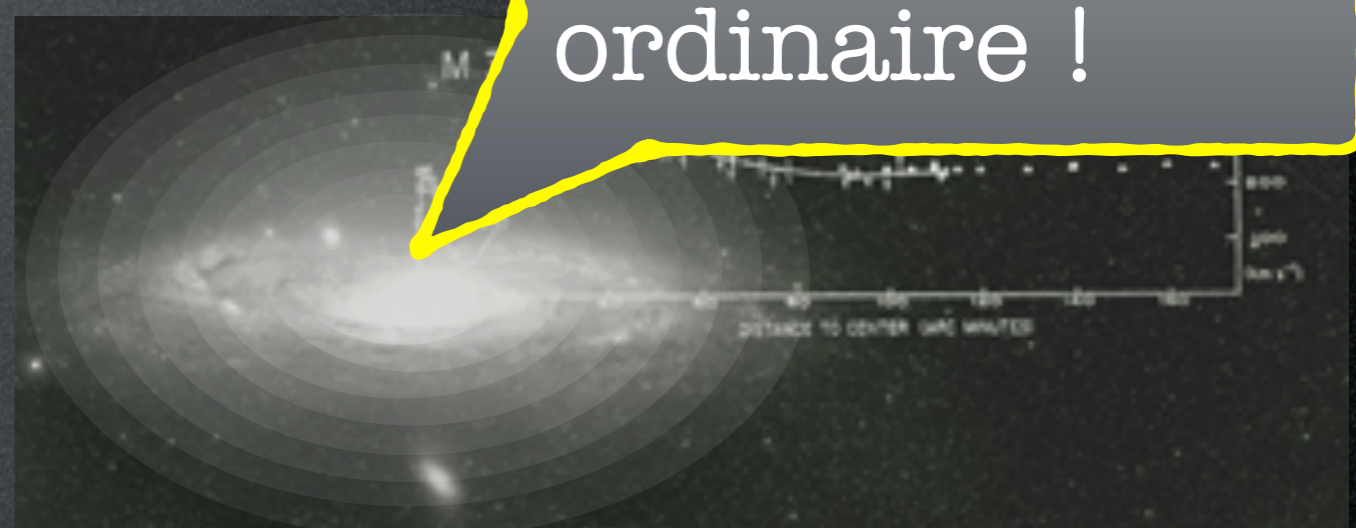


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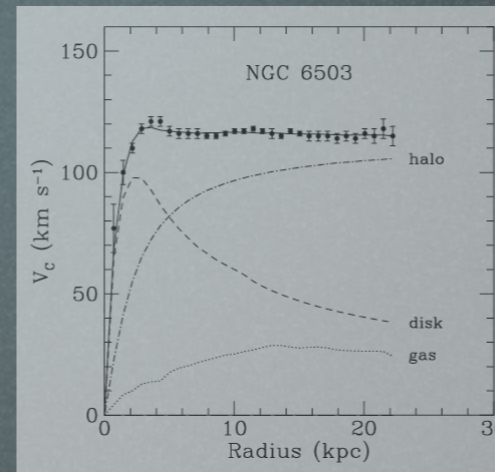


plus abondante
que la matière
ordinaire !



Preuves d'existence

1) courbes de rotation galactiques



2) amas de galaxies
- lentille gravitationnelle

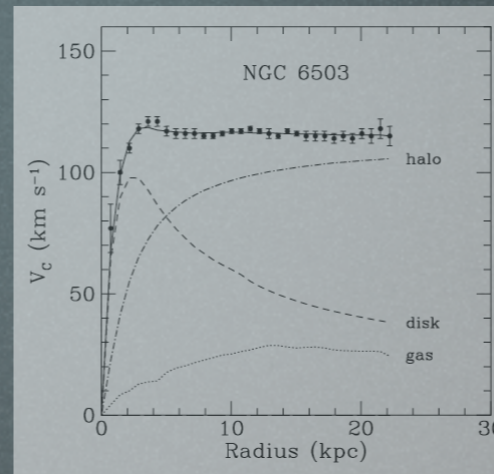


“bullet cluster” - NASA
astro-ph/0608247

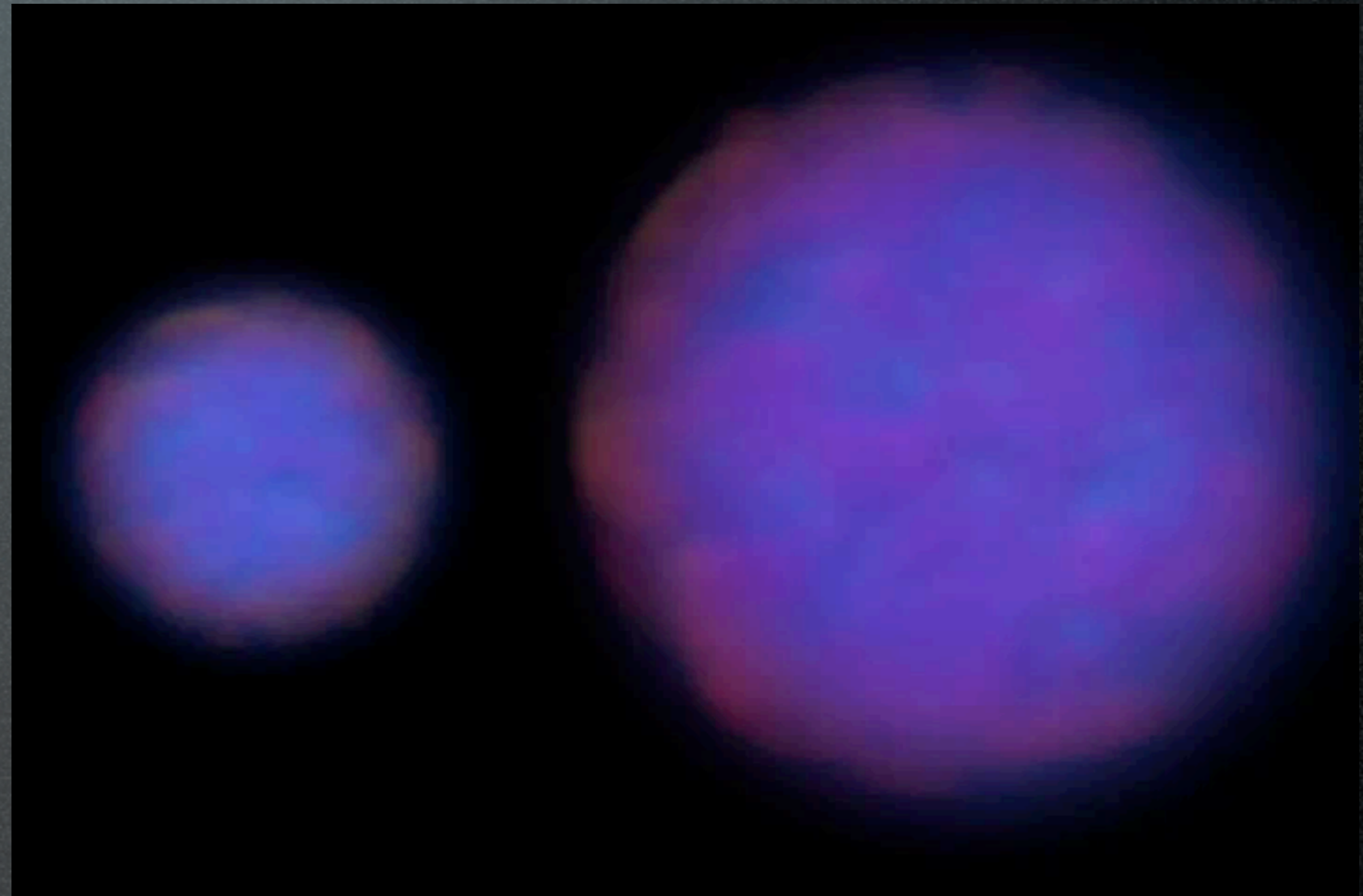
[further developments]

Preuves d'existence

1) courbes de rotation galactiques

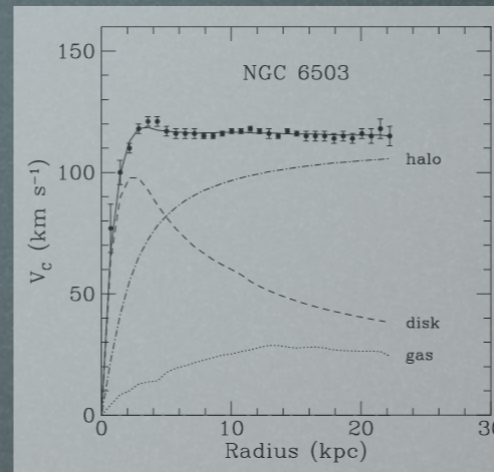


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Preuves d'existence

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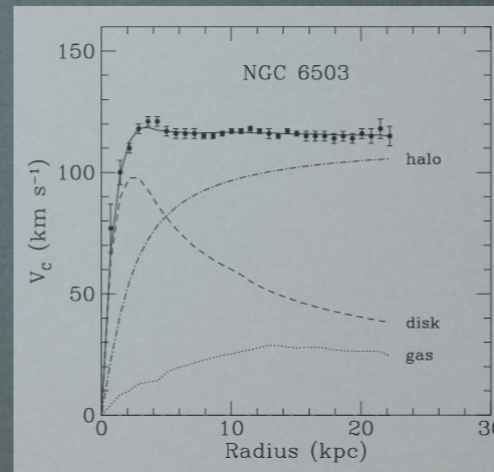
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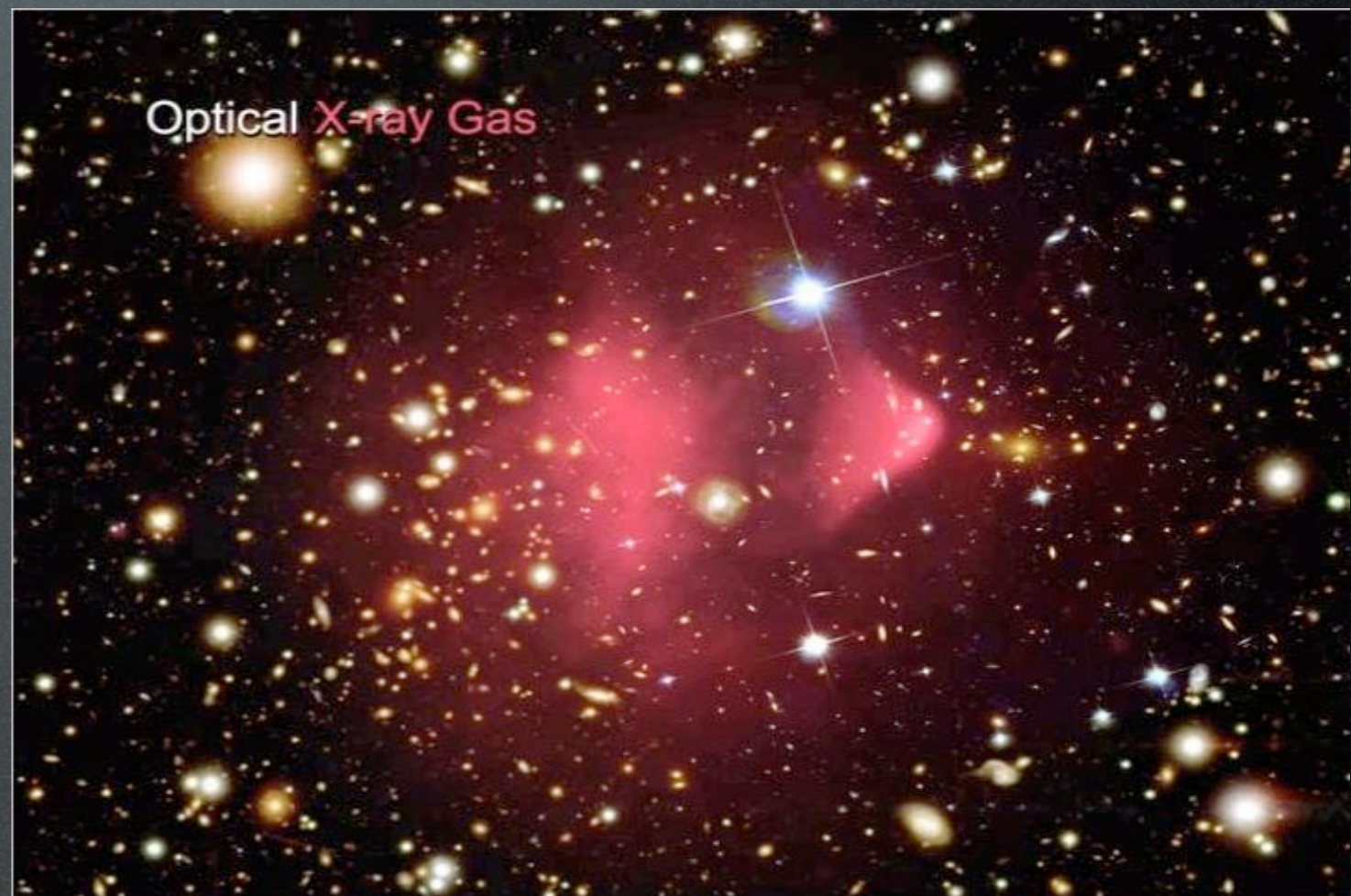
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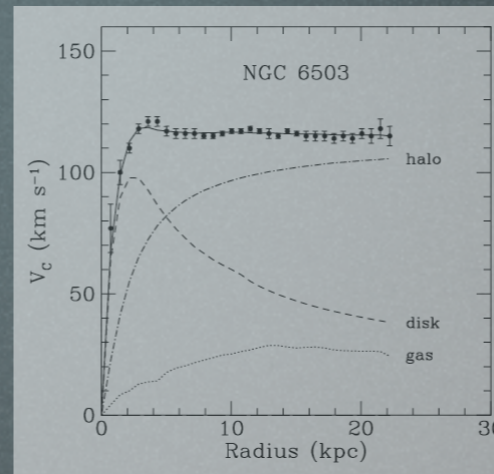
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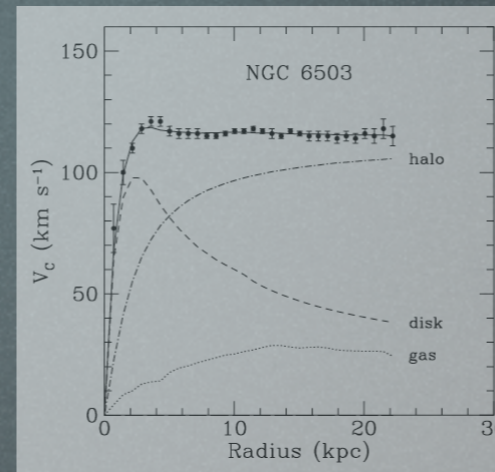
2) amas de galaxies
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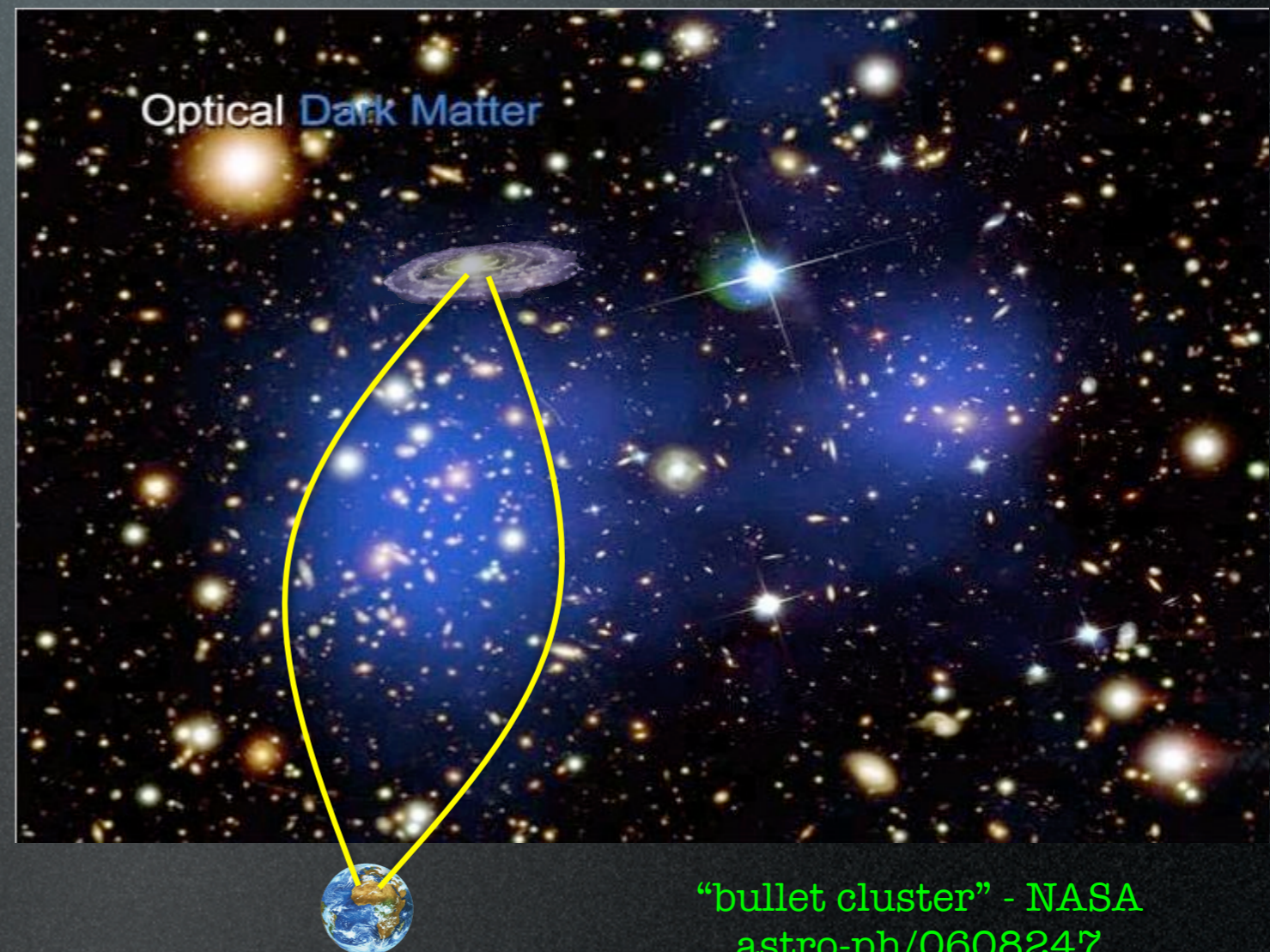
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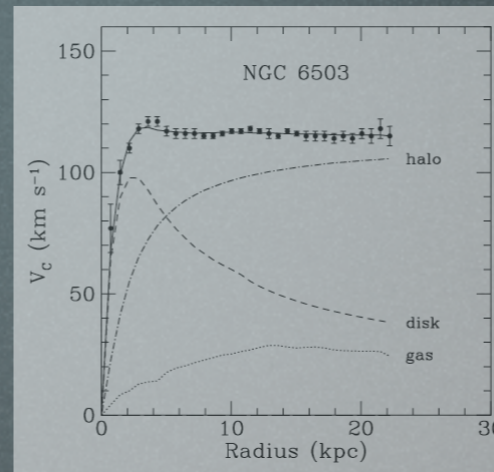
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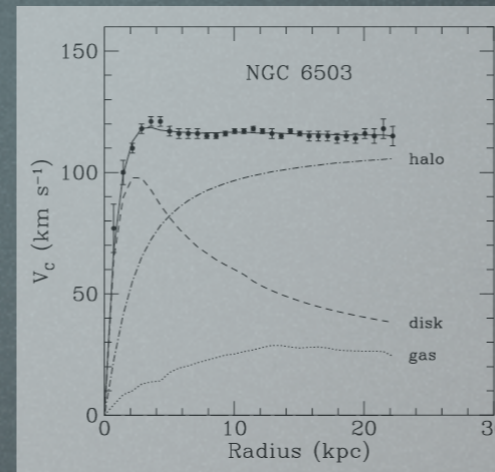
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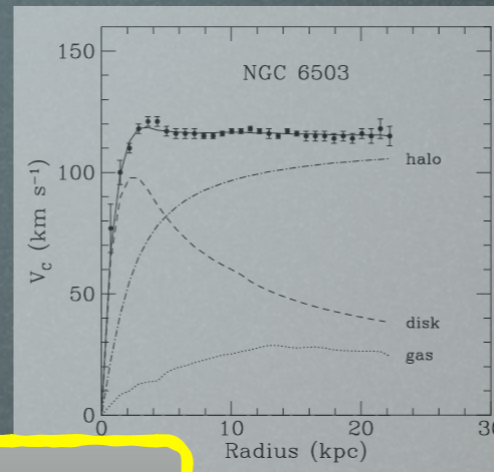
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“bullet cluster” - NASA
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Preuves d'existence

1) courbes de rotation galactiques



2) elle n'émet pas de lumière, elle est 'neutre'

n'émet pas de lumière, elle est 'neutre'

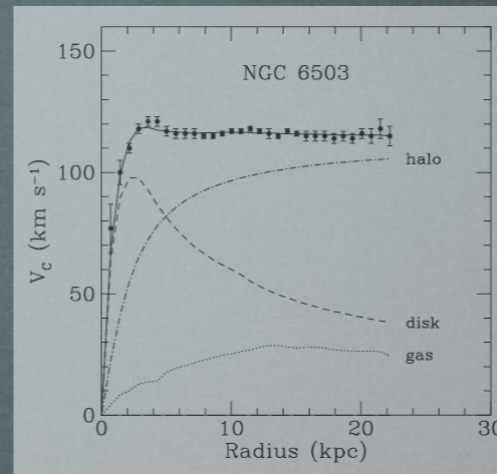
aucune ou très peu d'interaction



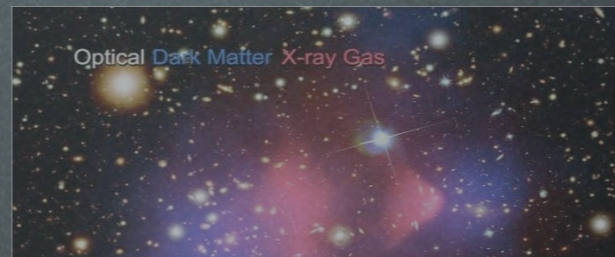
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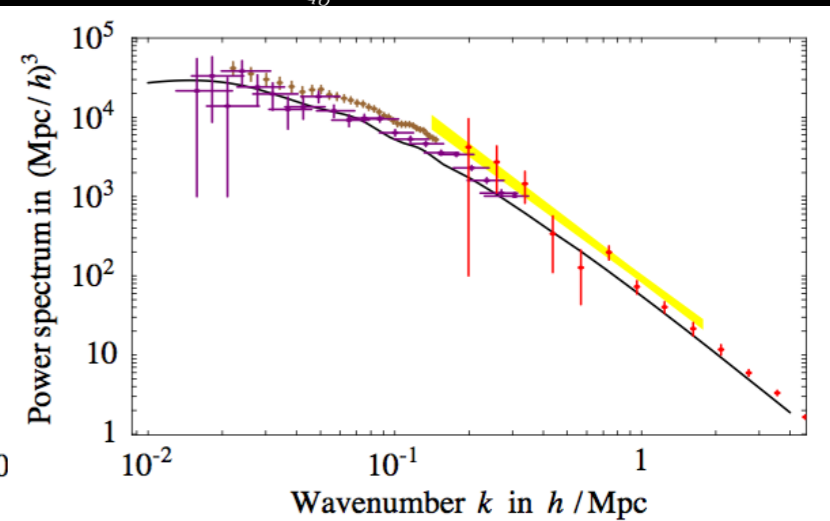
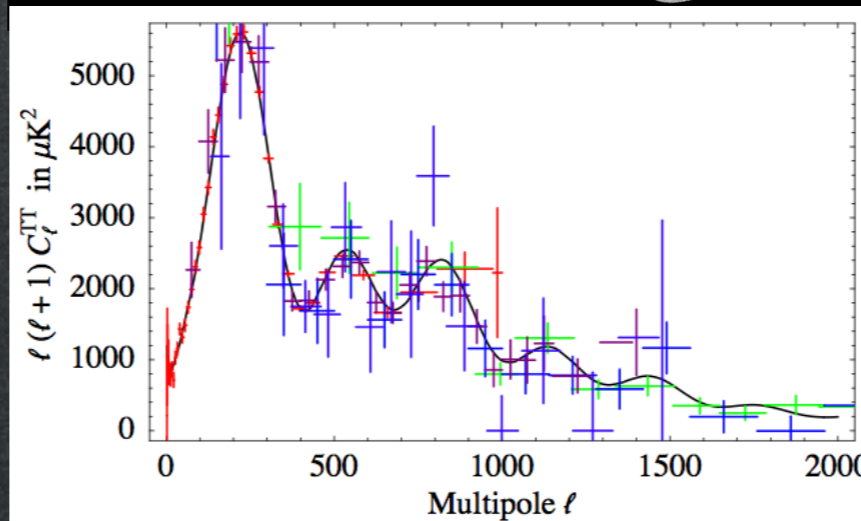
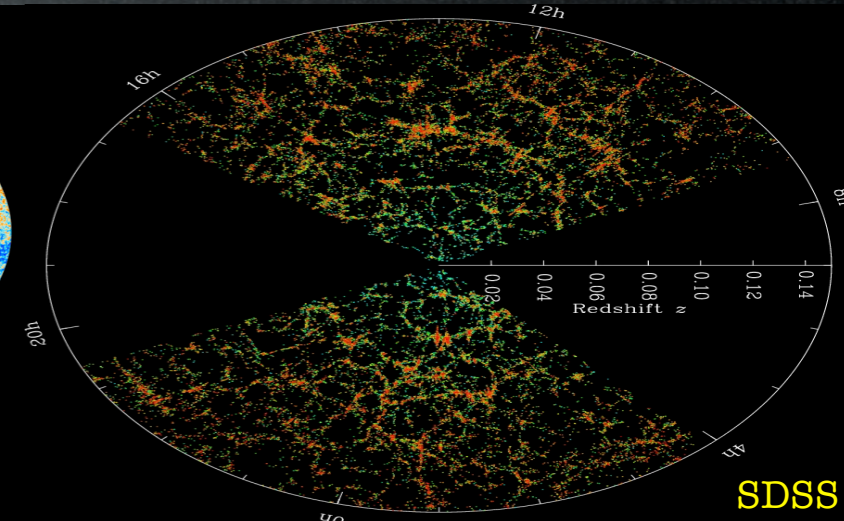
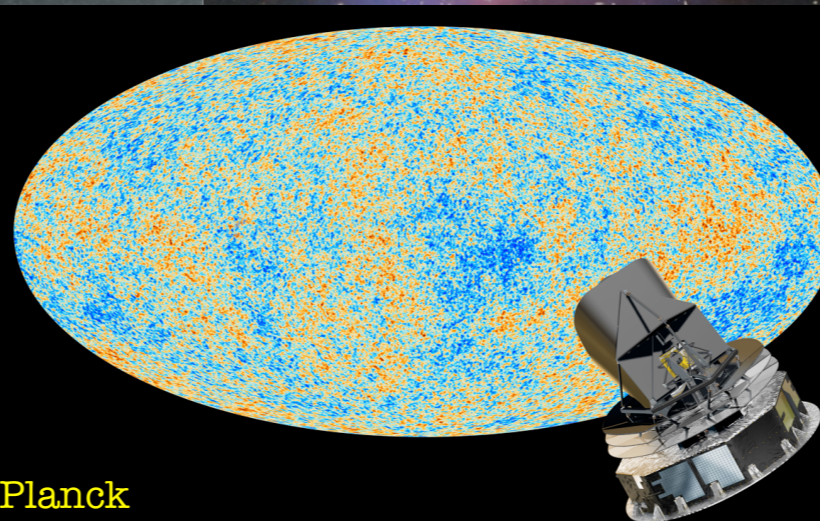
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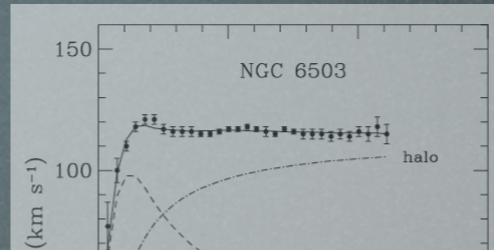


3) 'cosmologie de précision'



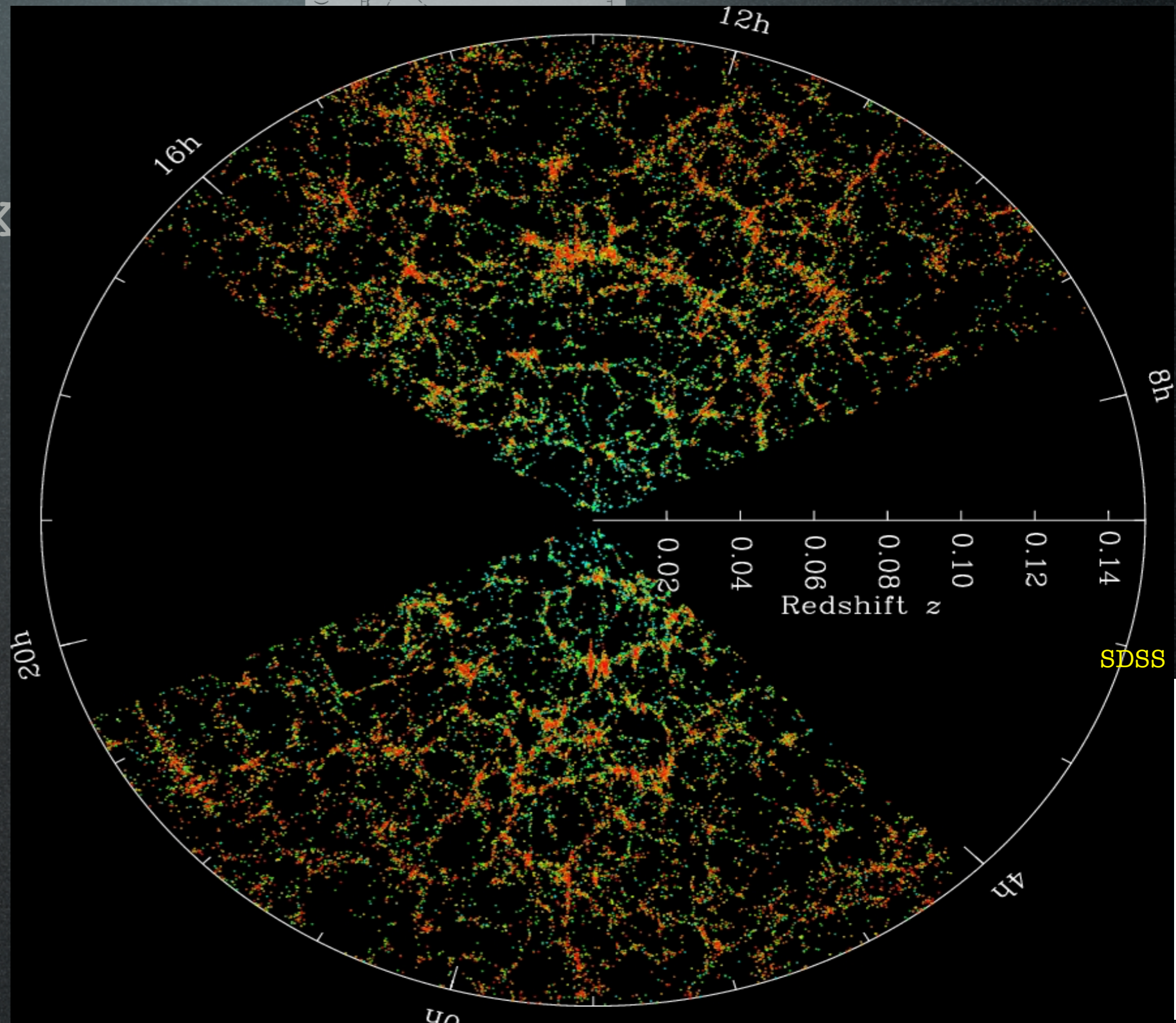
Preuves d'existence

1) courbes de rotation galactiques



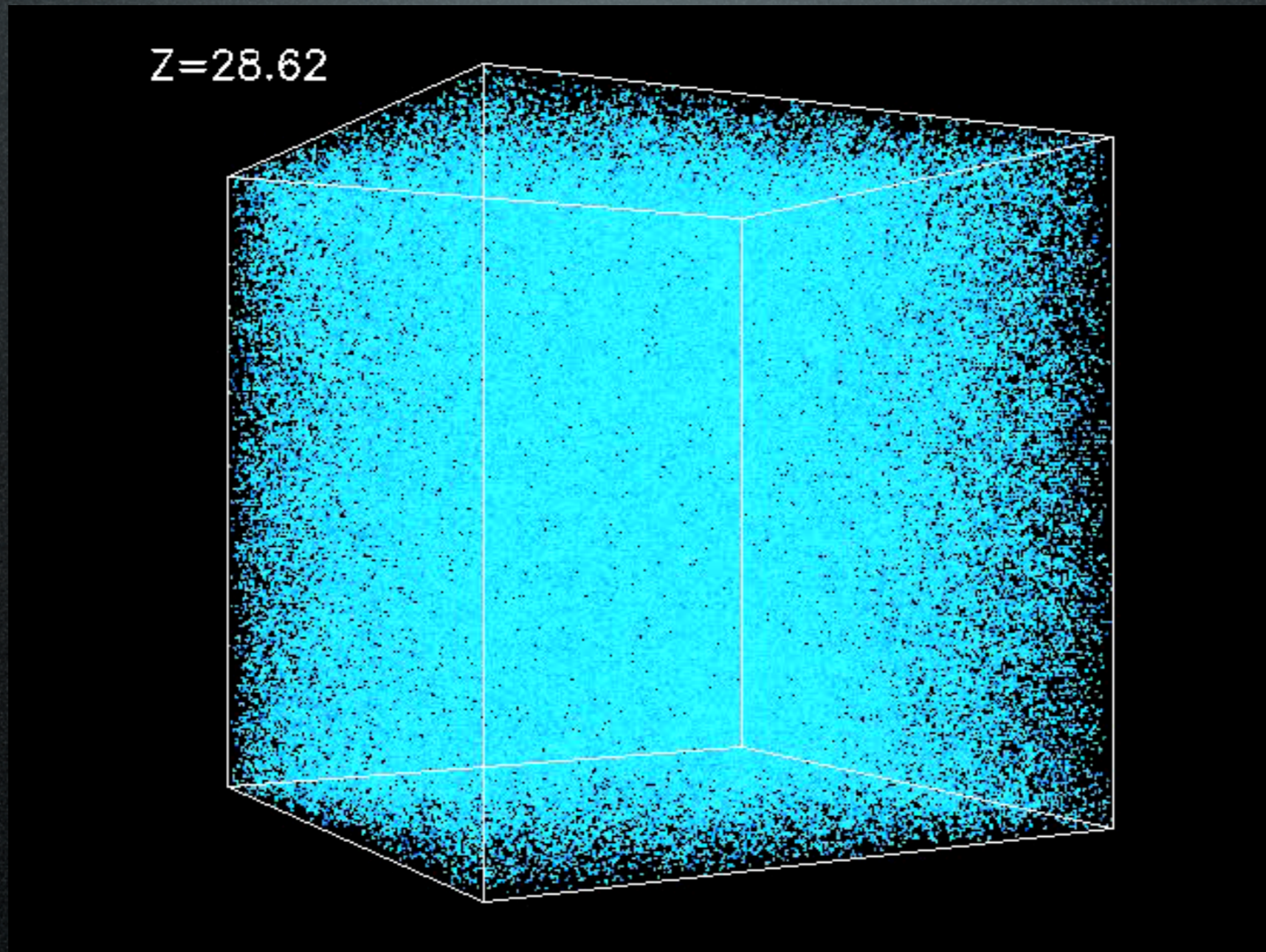
2) amas de galaxies

3) 'cosmologie de précision'



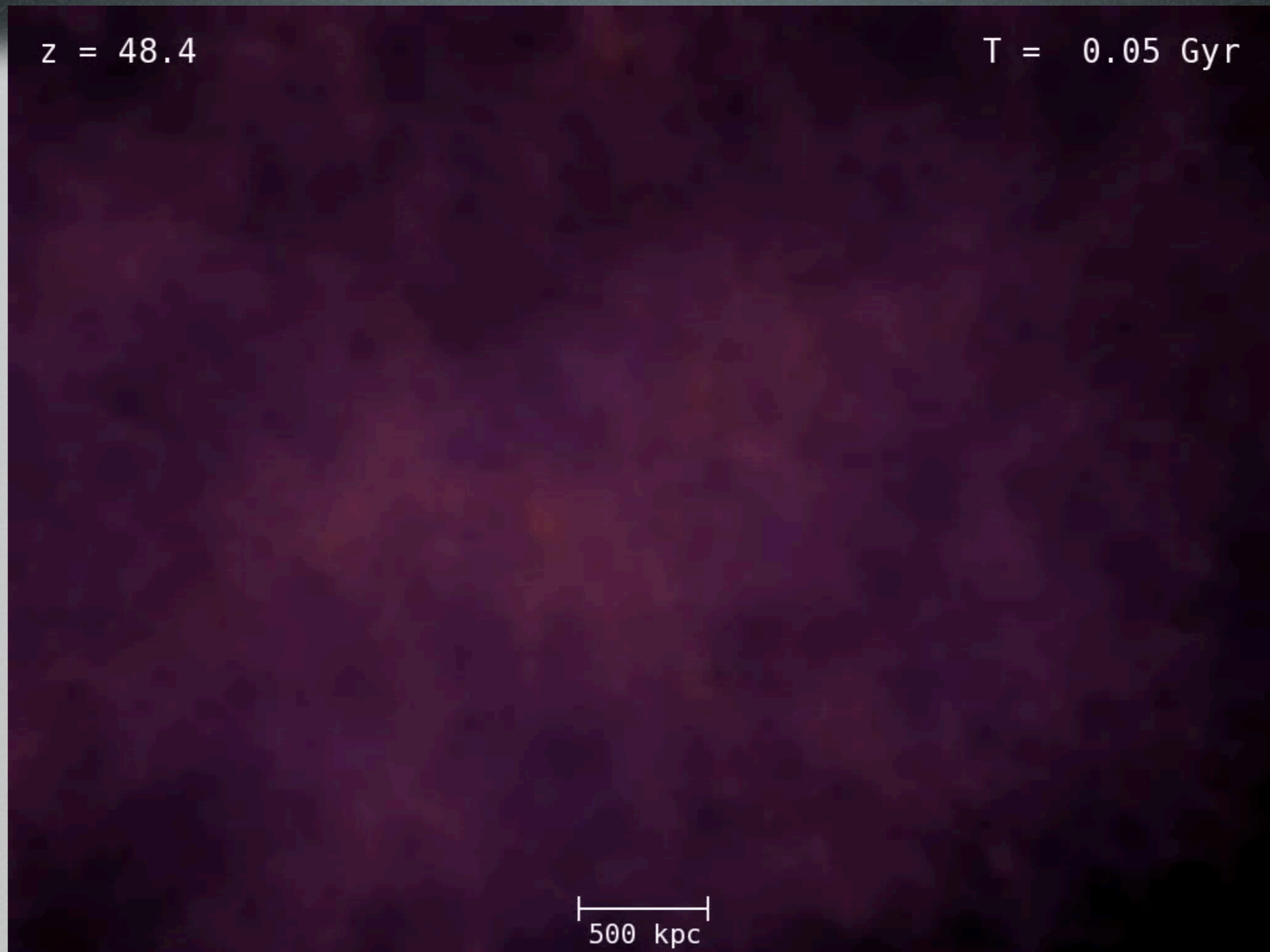
Preuves d'existence

2×10^6 CDM particules, 43 Mpc cubic box



Preuves d'existence

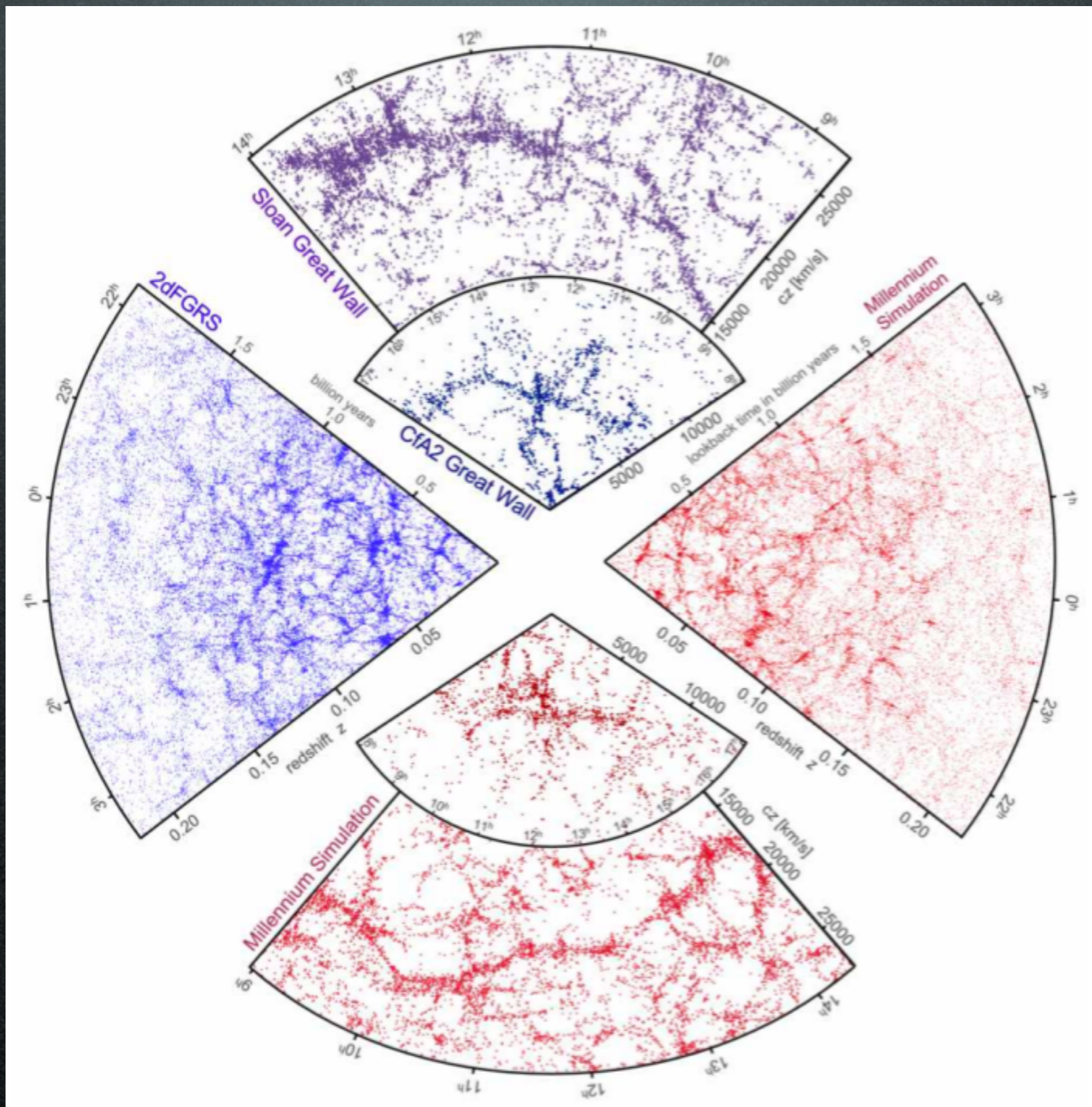
Projet Aquarius de la collaboration VIRGO:
1.5 10^9 CDM particules, un seul halo galactique



Preuves d'existence

2dF: $2.2 \cdot 10^5$ galaxies

SDSS: 10^6 galaxies,
2 billions
d'années lumière



Millennium:
 10^{10} particules,
 $500 h^{-1} \text{ Mpc}$

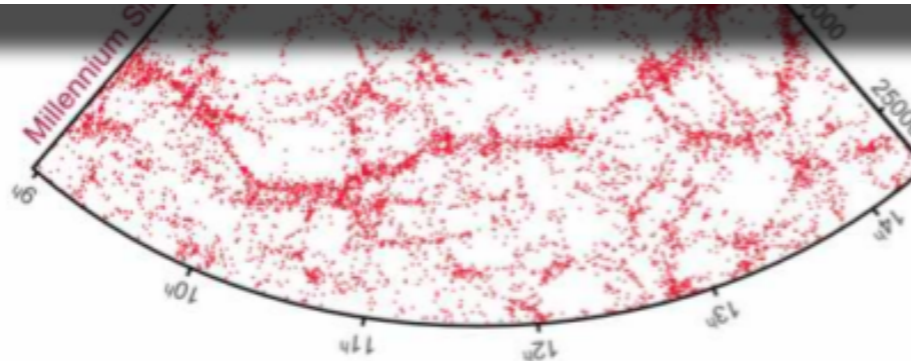
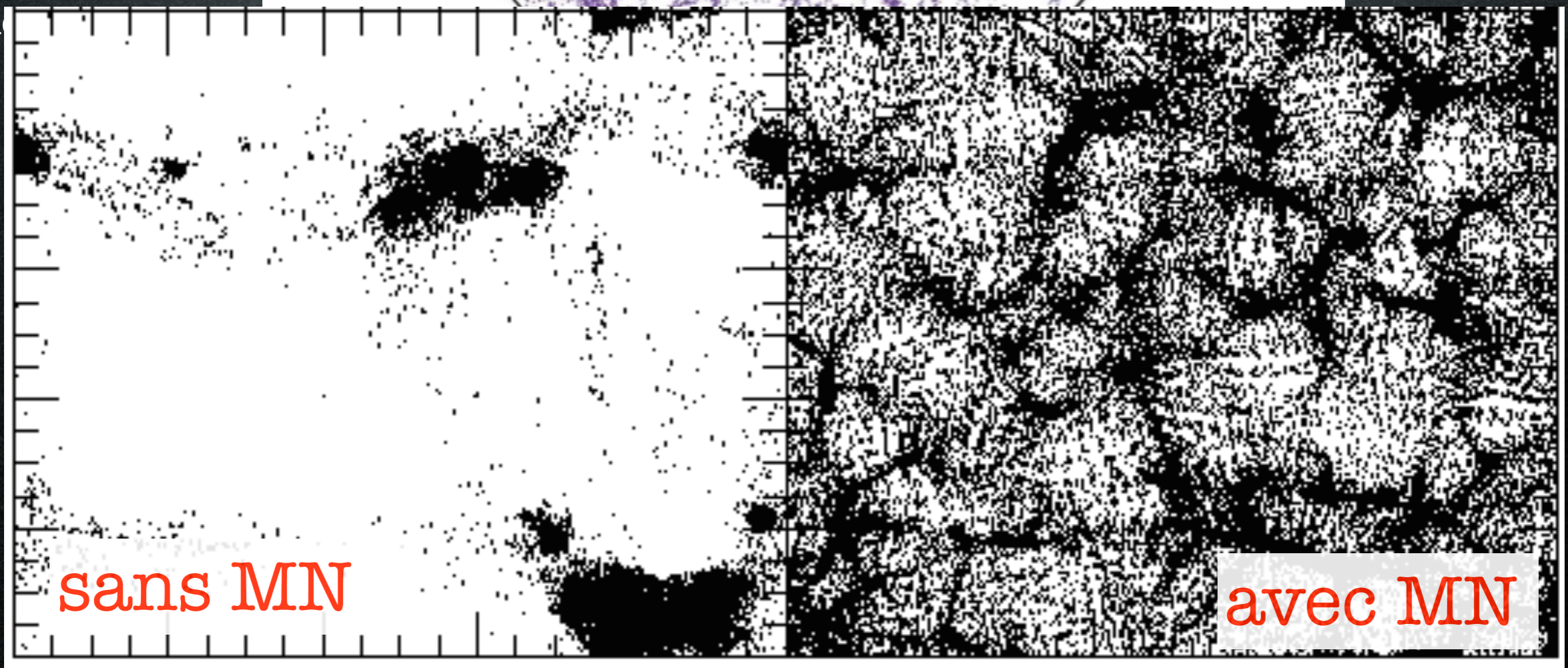
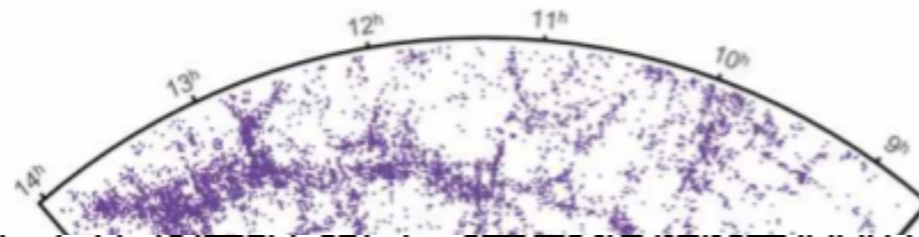
Springel, Frenk, White, Nature 440 (2006)

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d'ann



Springel, Frenk, White, Nature 440 (2006)

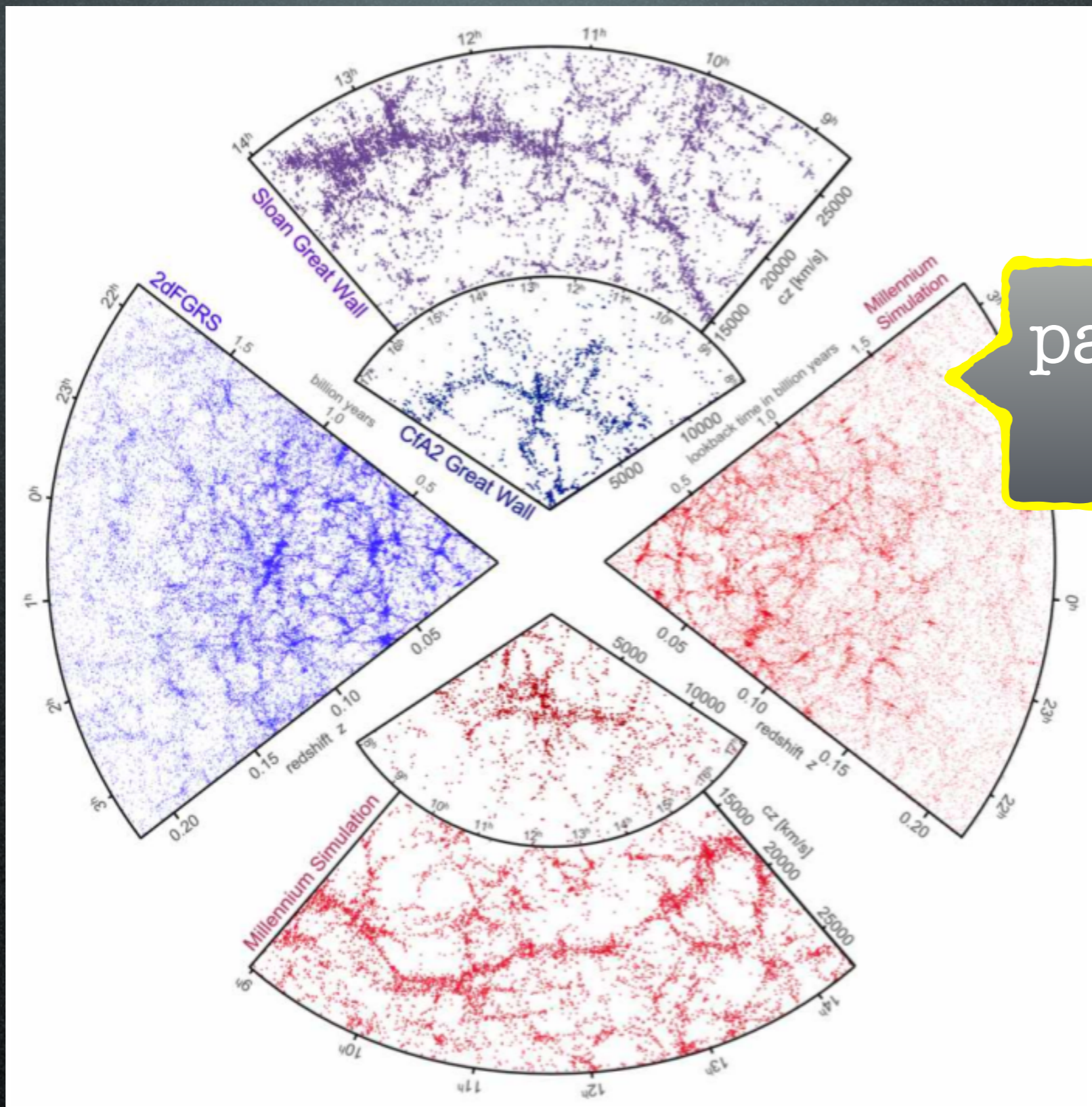
Millennium:
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A. Nusser, 0109016, MNRAS 331 (2002)

Preuves d'existence

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particules

Millennium:
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Springel, Frenk, White, Nature 440 (2006)

DETOUR



Modifier la loi de gravité ?

Modifier la loi de gravité ?

1846



Urbain Le Verrier

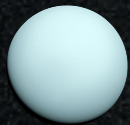
Modifier la loi de gravité ?

1846



Urbain Le Verrier

Uranus



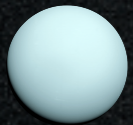
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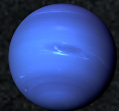


Urbain Le Verrier

Uranus



Neptune



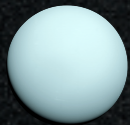
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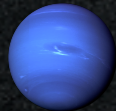


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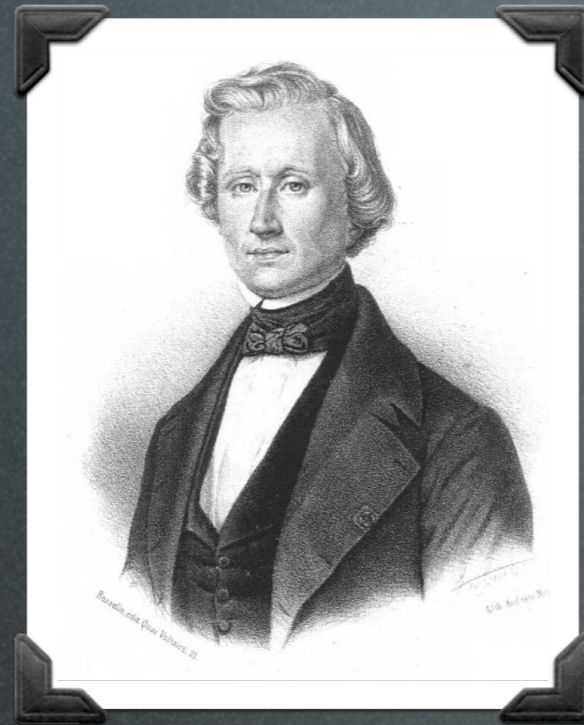
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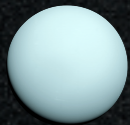
Urbain Le Verrier

1859

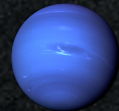


Urbain Le Verrier

Uranus



Neptune



Mercure



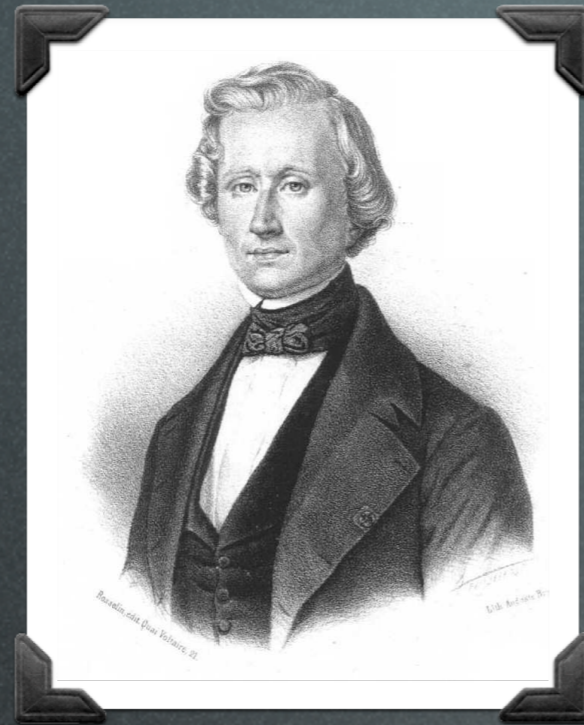
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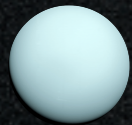
Urbain Le Verrier

1859

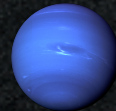


Urbain Le Verrier

Uranus



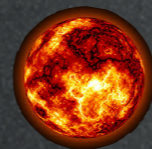
Neptune



Mercure



Vulcain ?



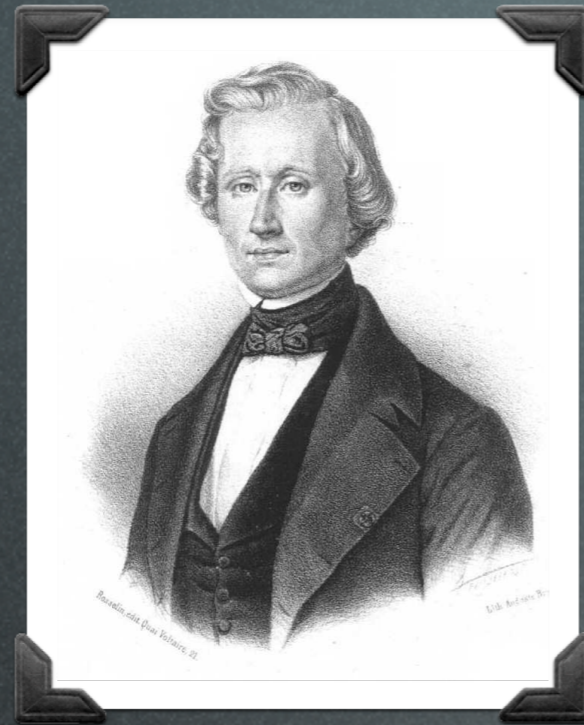
Modifier la loi de gravité ?

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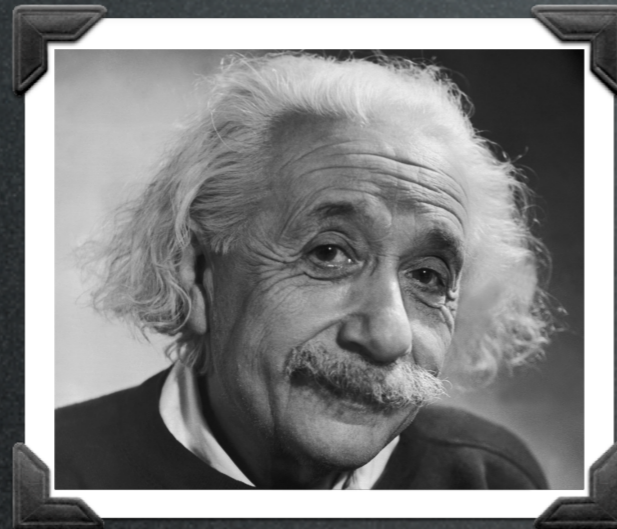


Urbain Le Verrier

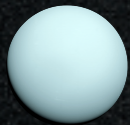
1859



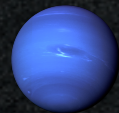
Urbain Le Verrier



Uranus



Neptune



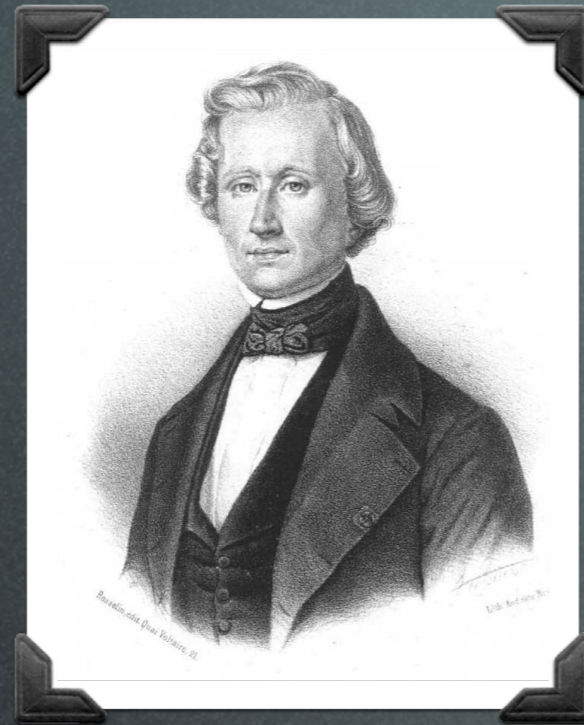
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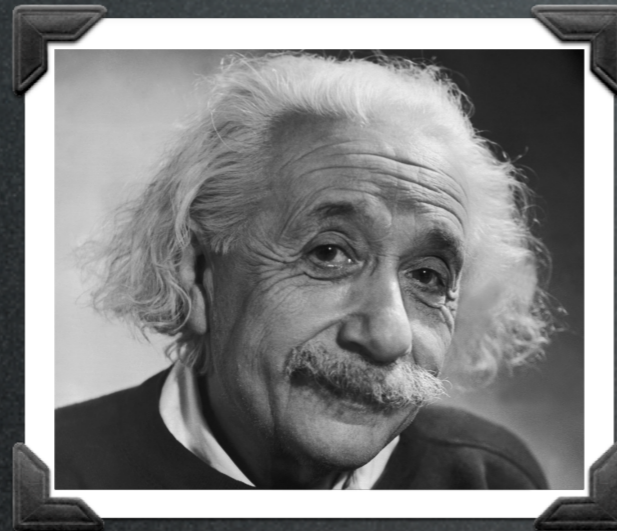


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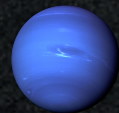
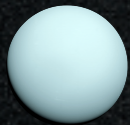


Urbain Le Verrier



Uranus

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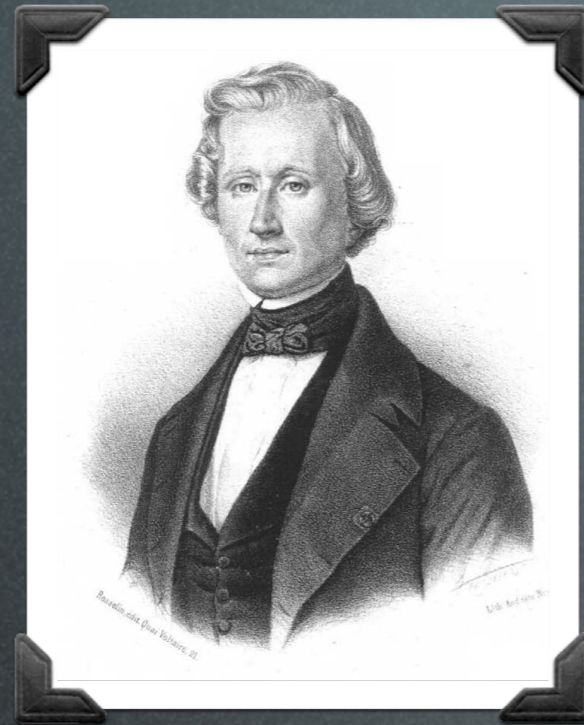
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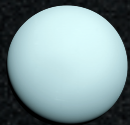
Urbain Le Verrier

1981

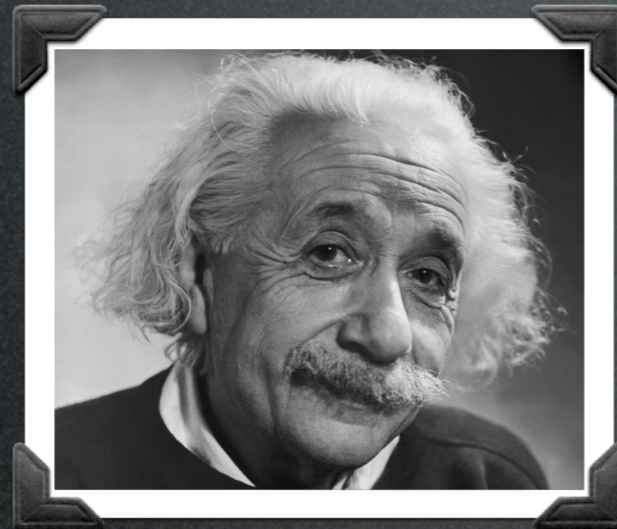
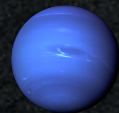


Mordehai Milgrom

Uranus



Neptune



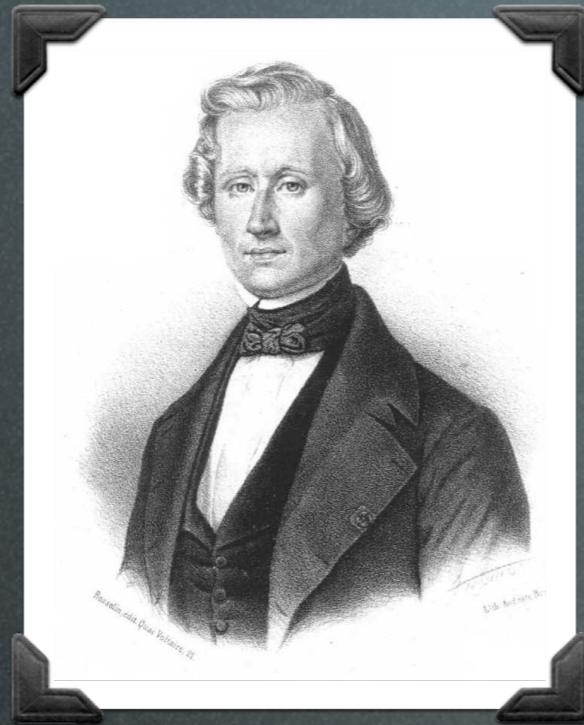
Modifier la loi de gravité ?

1846



Urbain Le Verrier

1859

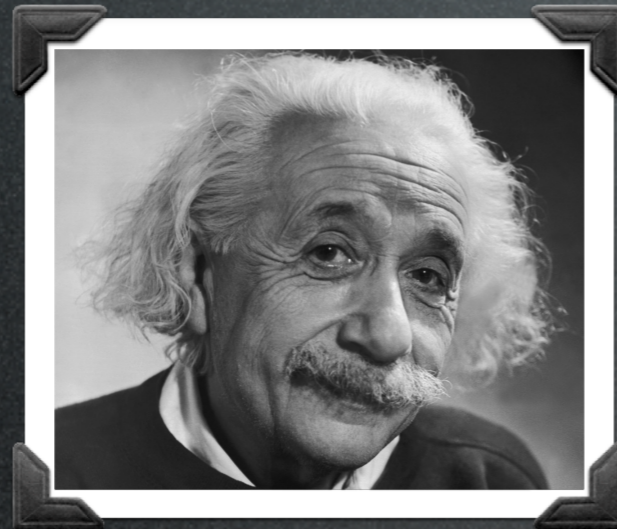


Urbain Le Verrier

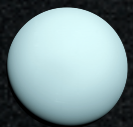
1981



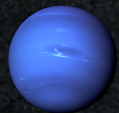
Mordehai Milgrom



Uranus



Neptune



$$F = m a \longrightarrow F = m a \cdot \mu(a)$$

$$\mu(a) = \begin{cases} 1 & a > a_0 \\ a/a_0 & a \sim a_0 \end{cases}$$

$$a_0 = 1.2 \cdot 10^{-10} m/s^2$$

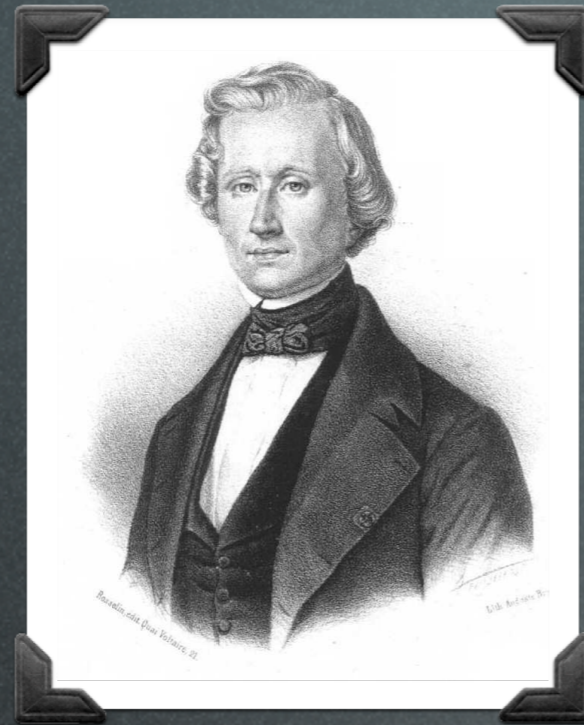
Modifier la loi de gravité ?

1846



Urbain Le Verrier

1859



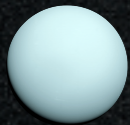
Urbain Le Verrier

1981

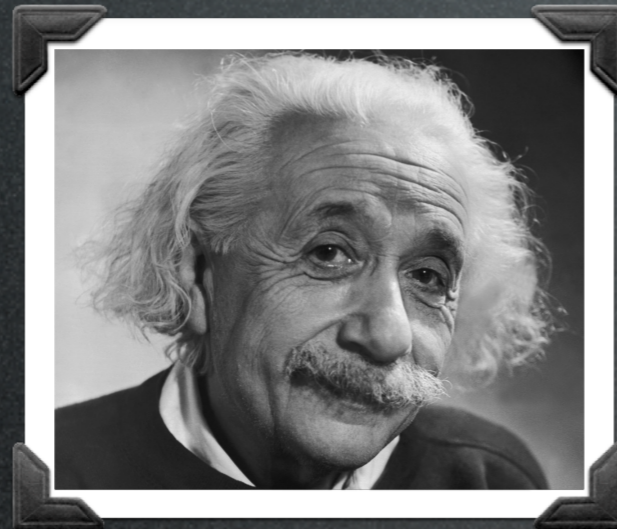
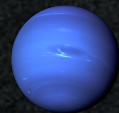


Mordehai Milgrom

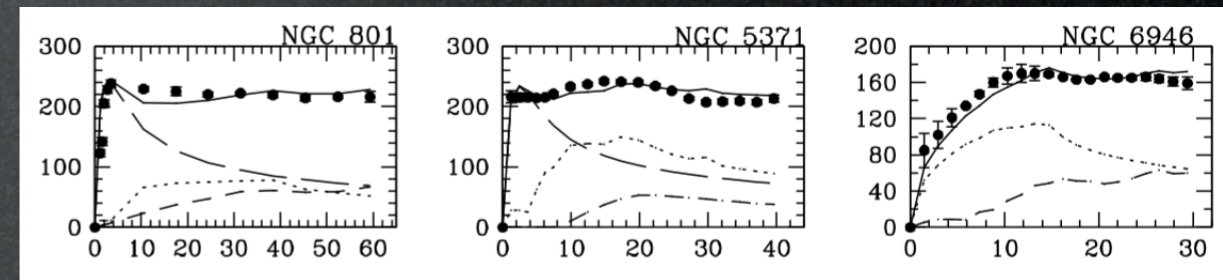
Uranus



Neptune



$$F = ma \longrightarrow F = ma \cdot \mu(a)$$



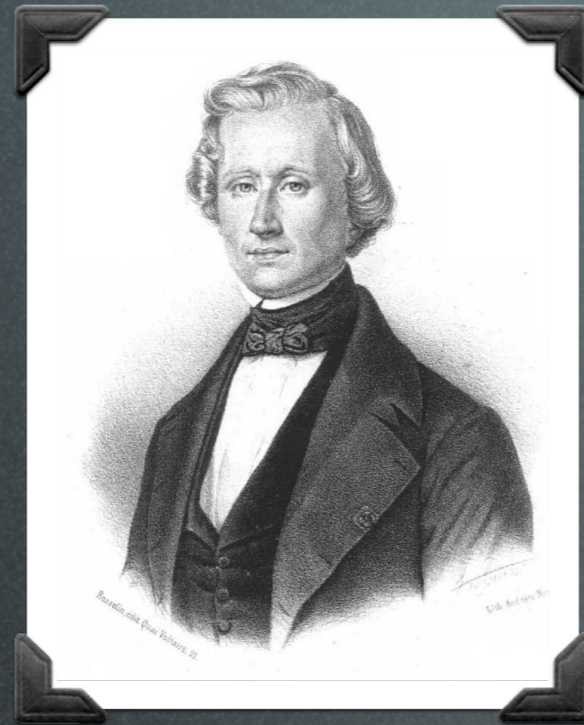
Modifier la loi de gravité ?

1846



Urbain Le Verrier

1859

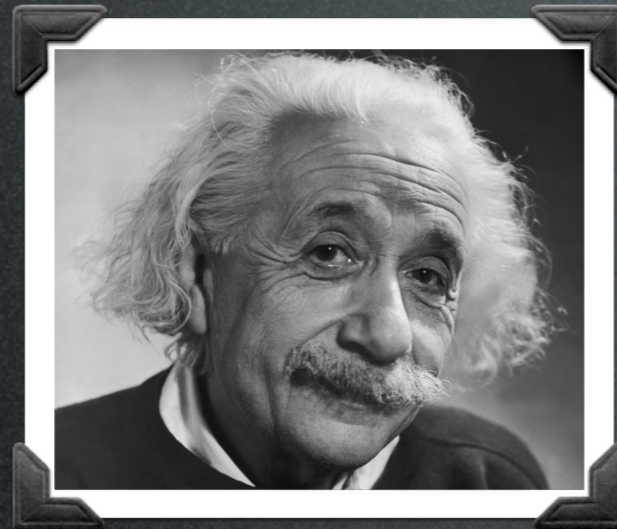


Urbain Le Verrier

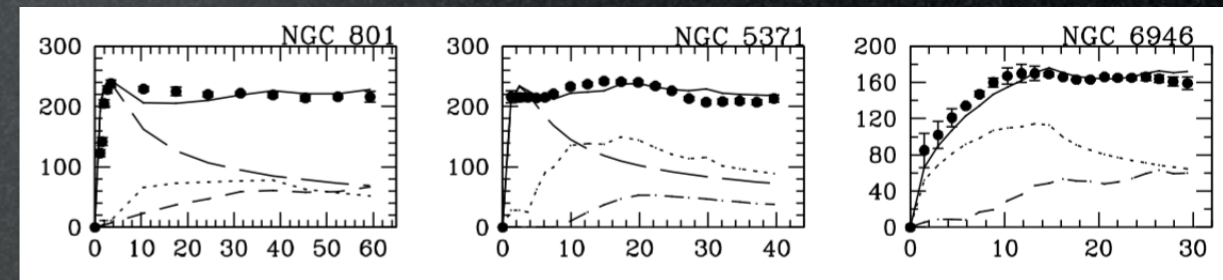
1981



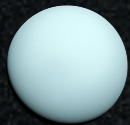
Mordehai Milgrom



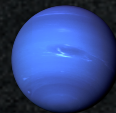
$$F = m a \longrightarrow F = m a \cdot \mu(a)$$



Uranus

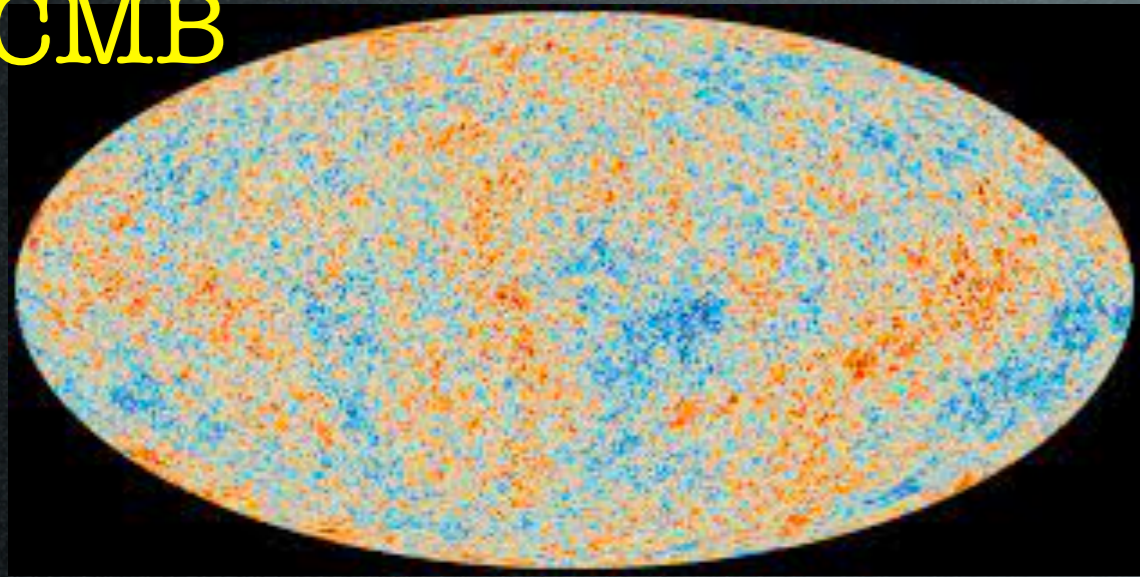


Neptune

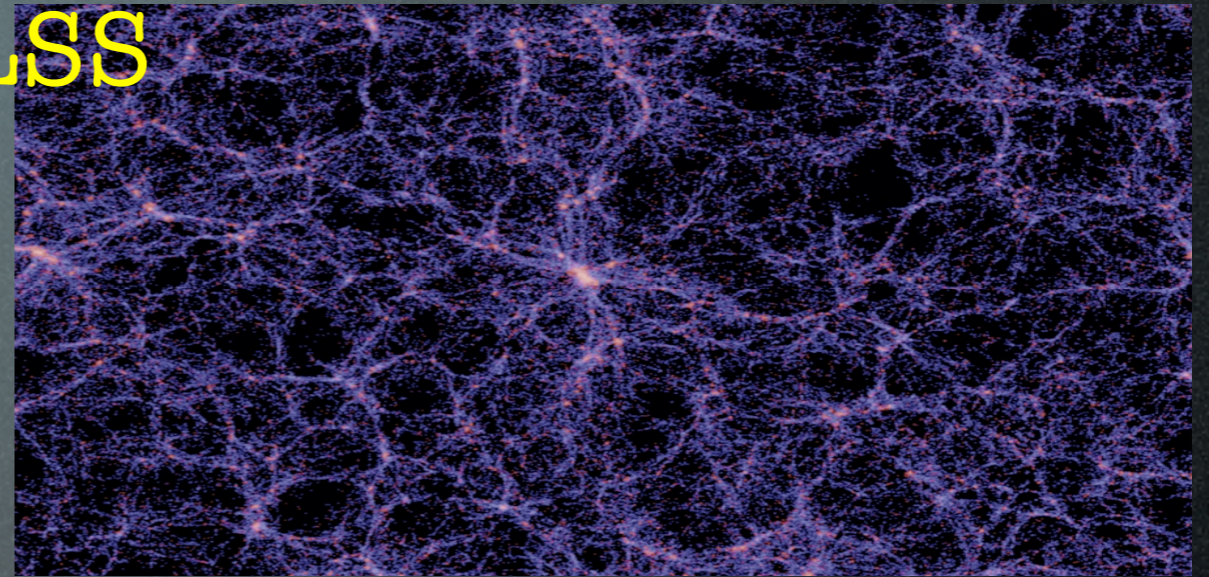


The Evidence for DM

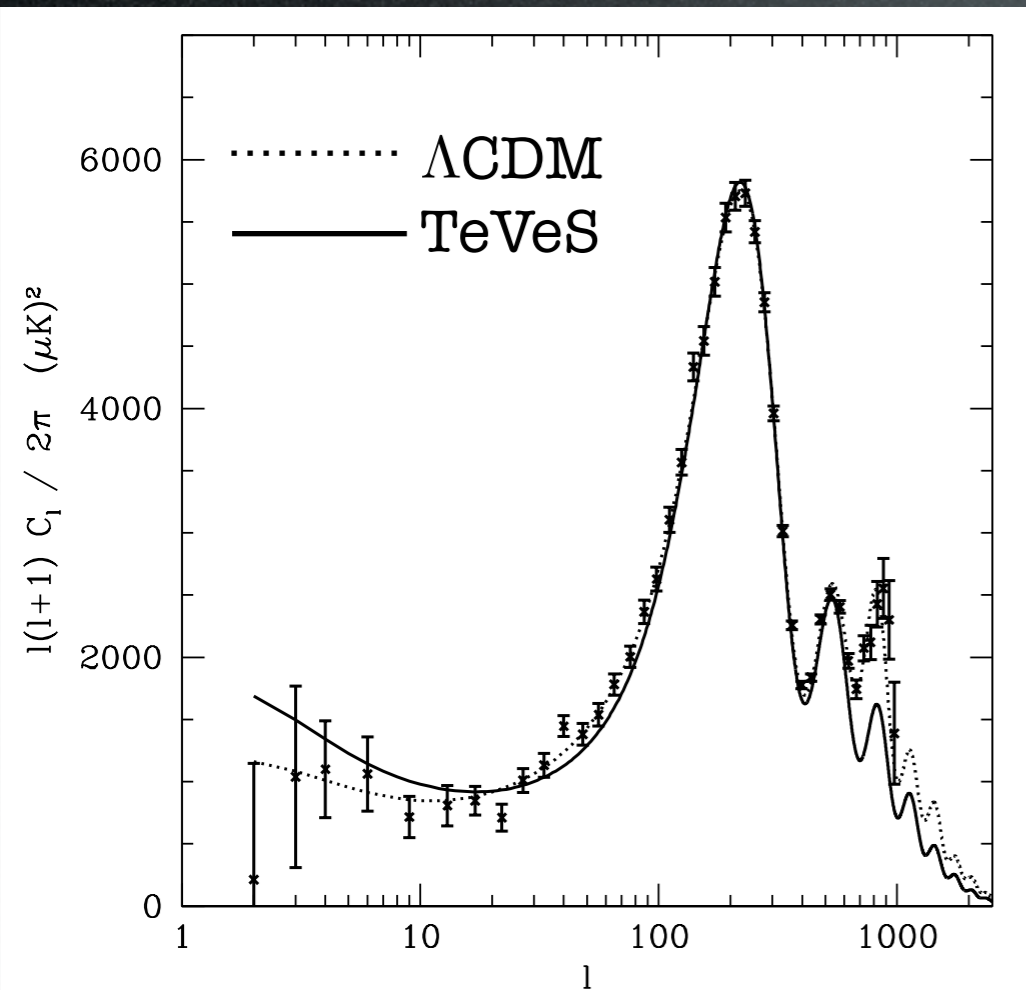
CMB



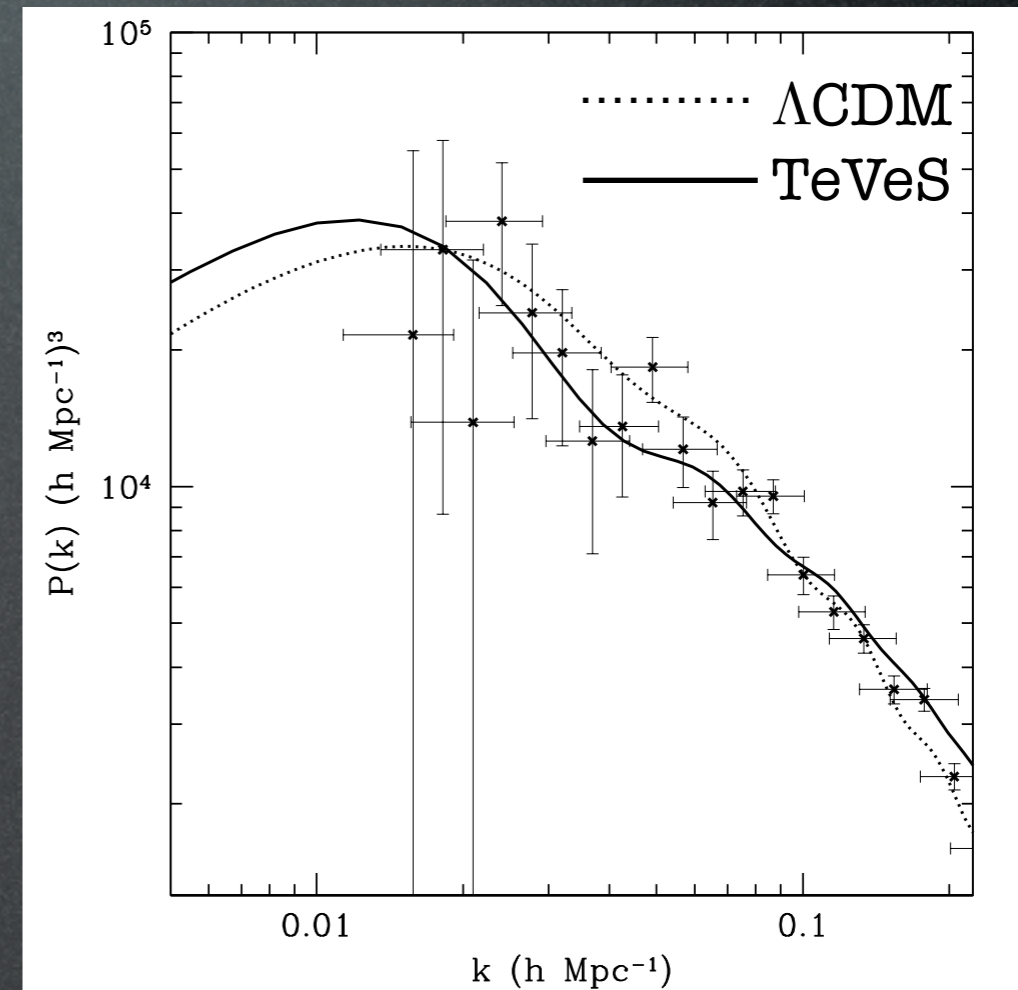
LSS



How would the power spectra be in MOND/TeVS, without DM ?



C.Skordis, Review, 0903.3602



C.Skordis, Review, 0903.3602

(in particular: no DM => no 3rd peak!)

(here you can make it)

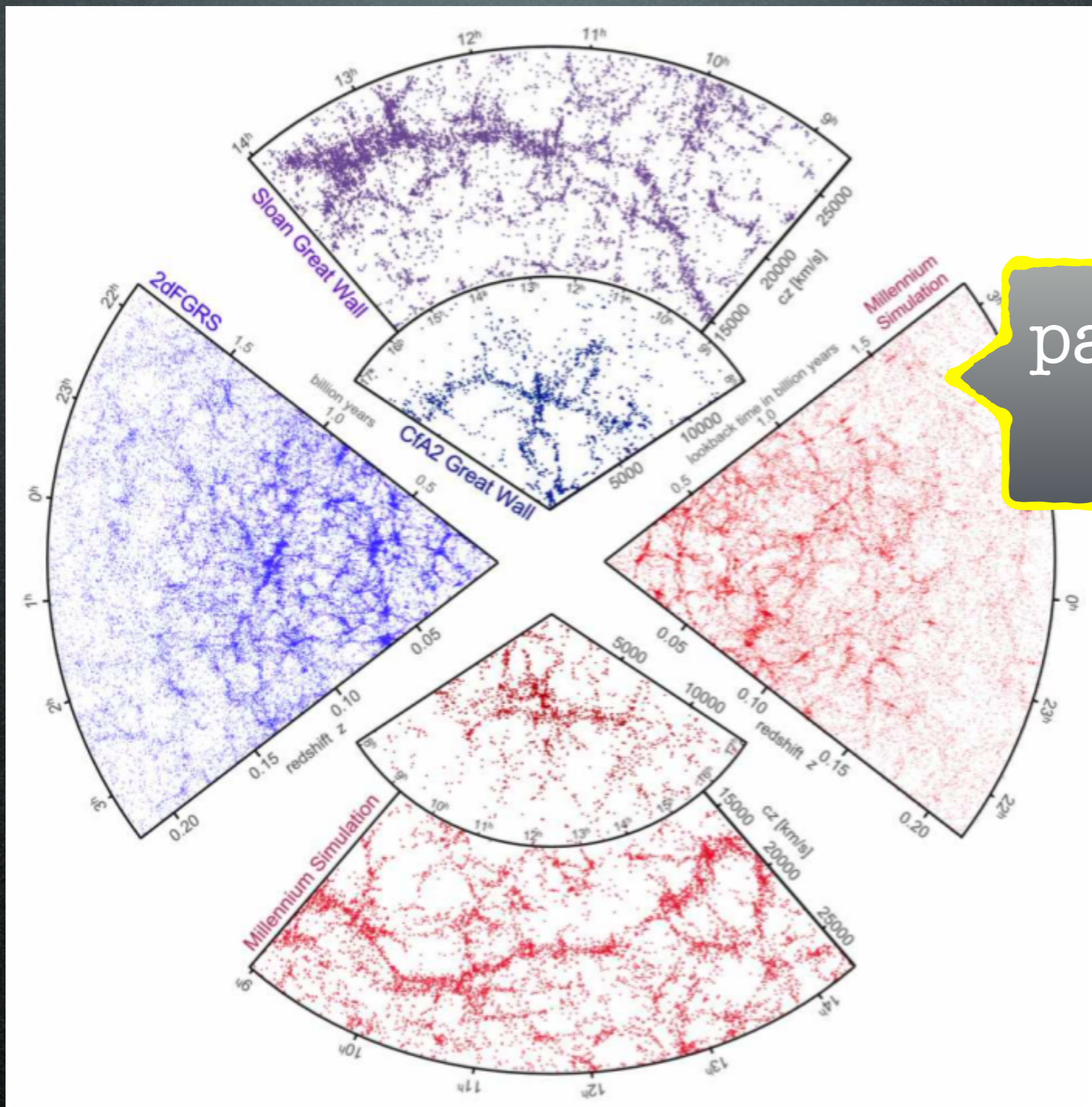
DETOUR



Preuves d'existence

2dF: $2.2 \cdot 10^5$ galaxies

SDSS: 10^6 galaxies,
2 billions
d'années lumière



particules

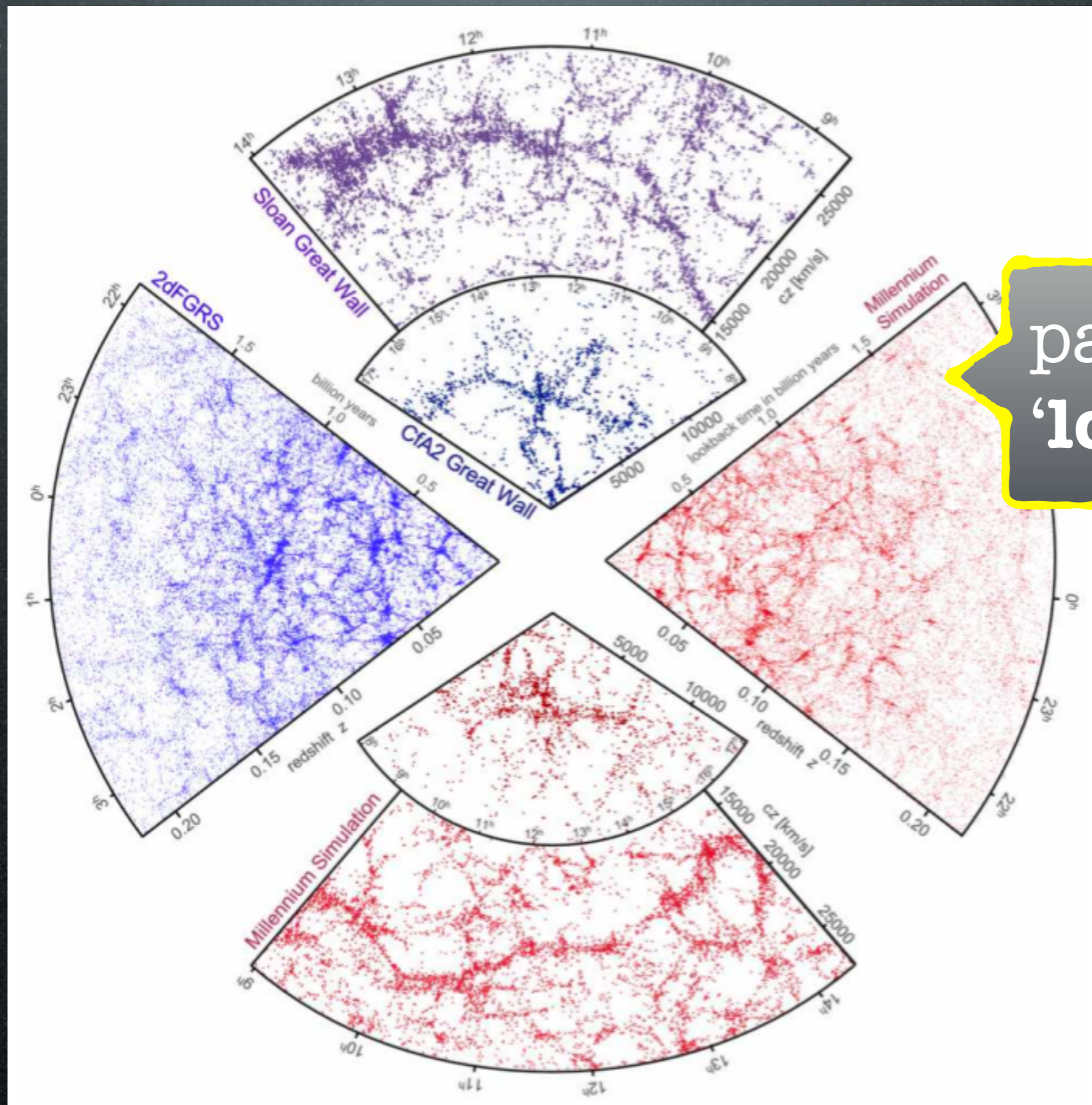
Millennium:
 10^{10} particules,
 $500 h^{-1}$ Mpc

Springel, Frenk, White, Nature 440 (2006)

Preuves d'existence

2dF: $2.2 \cdot 10^5$ galaxies

SDSS: 10^6 galaxies,
2 billions
d'années lumière



particules
'lourdes'

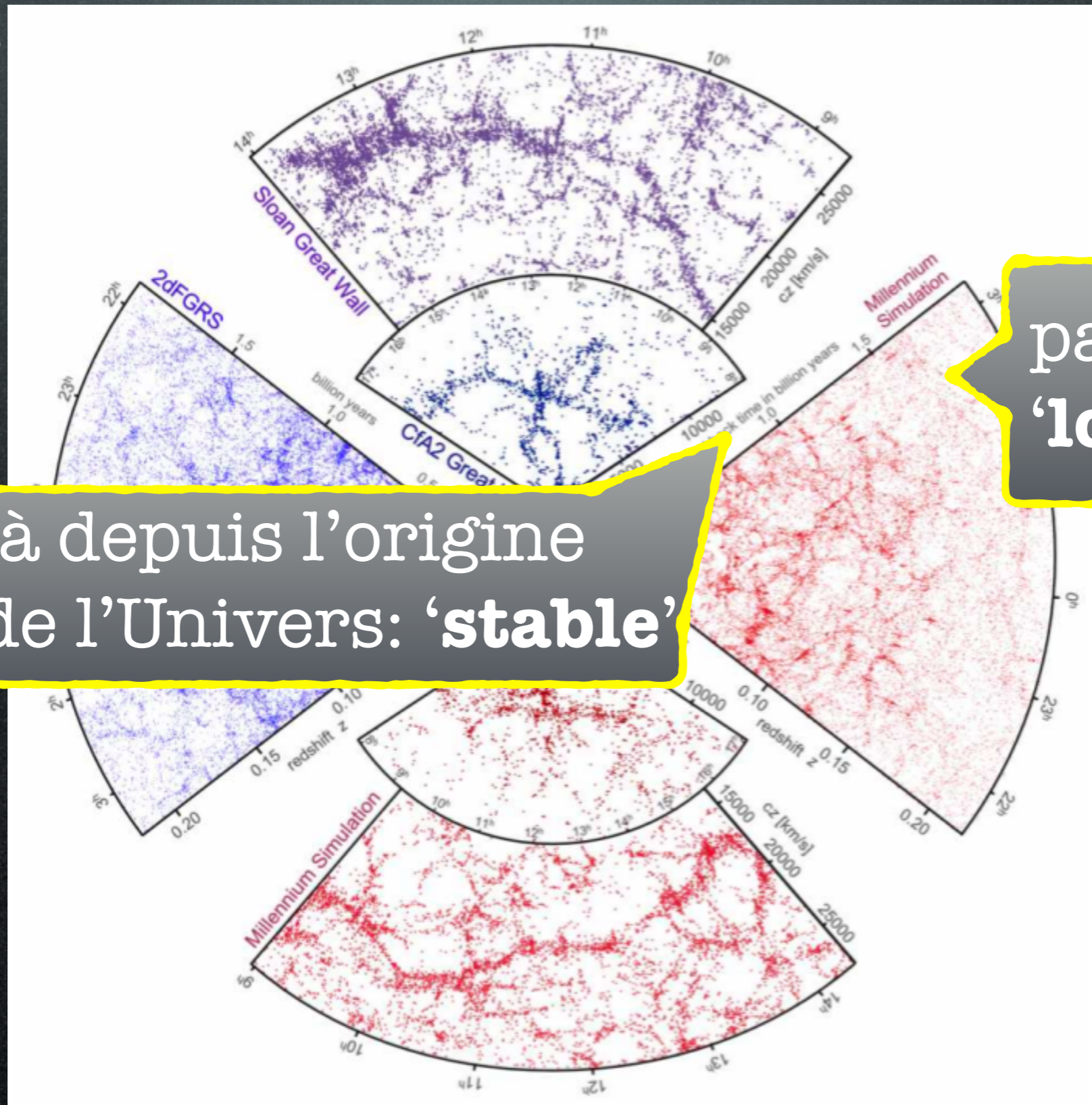
Millennium:
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Springel, Frenk, White, Nature 440 (2006)

Preuves d'existence

2dF: $2.2 \cdot 10^5$ galaxies

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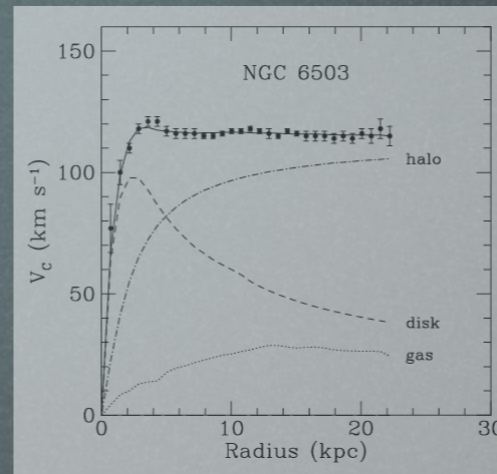
là depuis l'origine
de l'Univers: **'stable'**

particules
'lourdes'

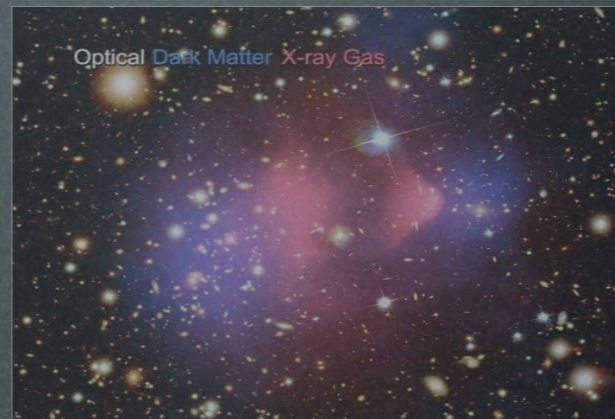
Millennium:
 10^{10} particules,
 $500 h^{-1} \text{ Mpc}$

Preuves d'existence

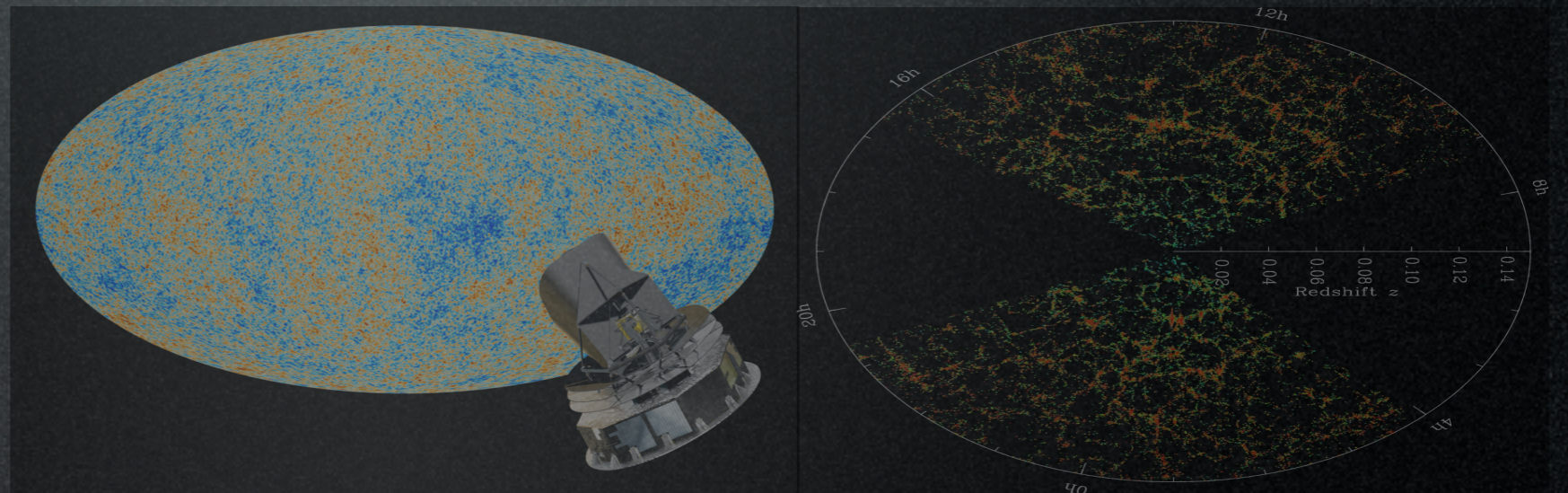
1) courbes de rotation galactiques



2) clusters of galaxies



3) 'cosmologie de précision'



NB: tous effets de force de gravité

Que savons-nous
de ses
propriétés ?

Propriétés et nature

n'émet pas de lumière,
elle est '**neutre**'

particules
'**lourdes**'

là depuis l'origine
de l'Univers: '**stable**'

plus abondante
que la matière
ordinaire

aucune ou très peu
d'interaction

Propriétés et nature

particules
'lourdes'

'neutre'

'stable'

presque sans
interactions

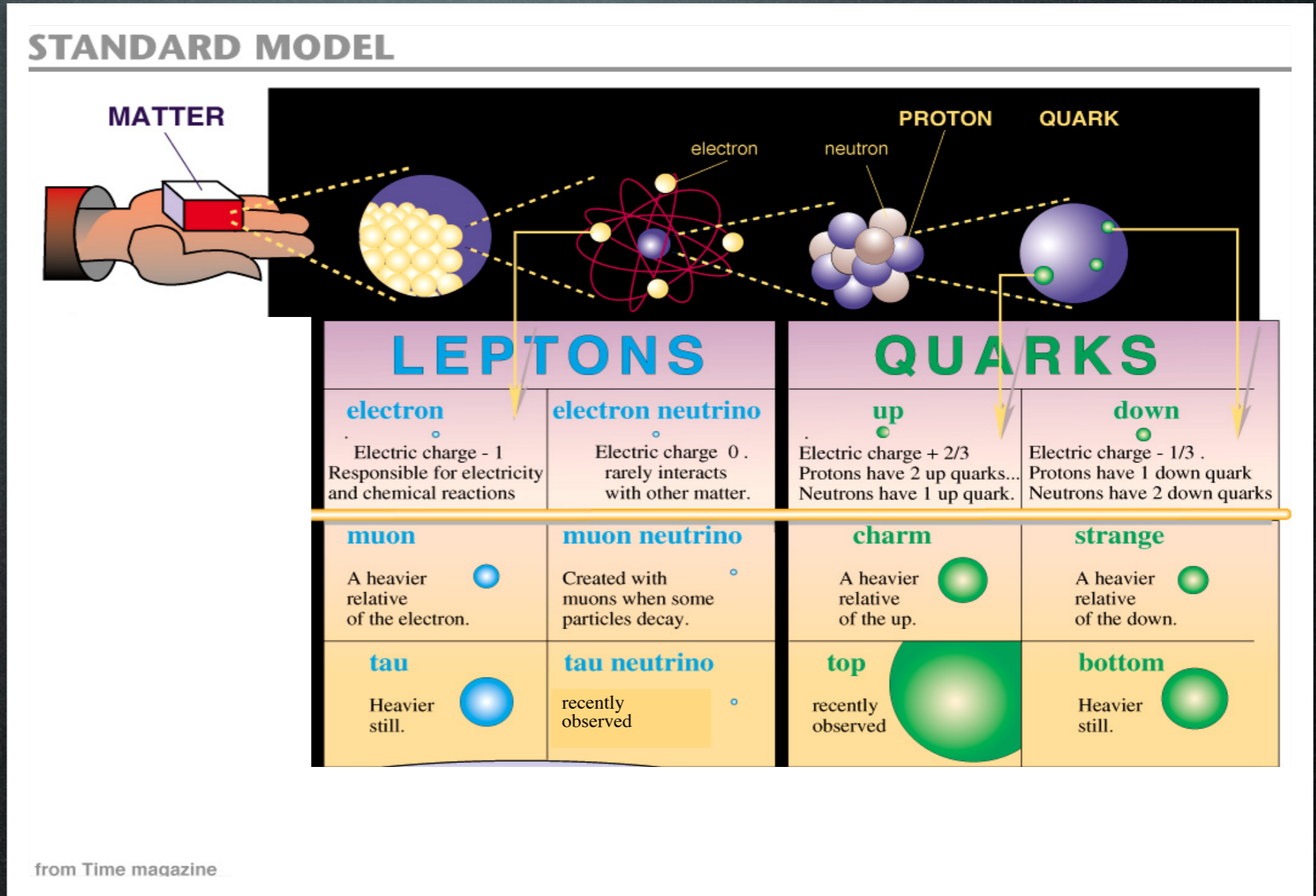
Propriétés et nature

particules
'lourdes'

'neutre'

'stable'

presque sans
interactions



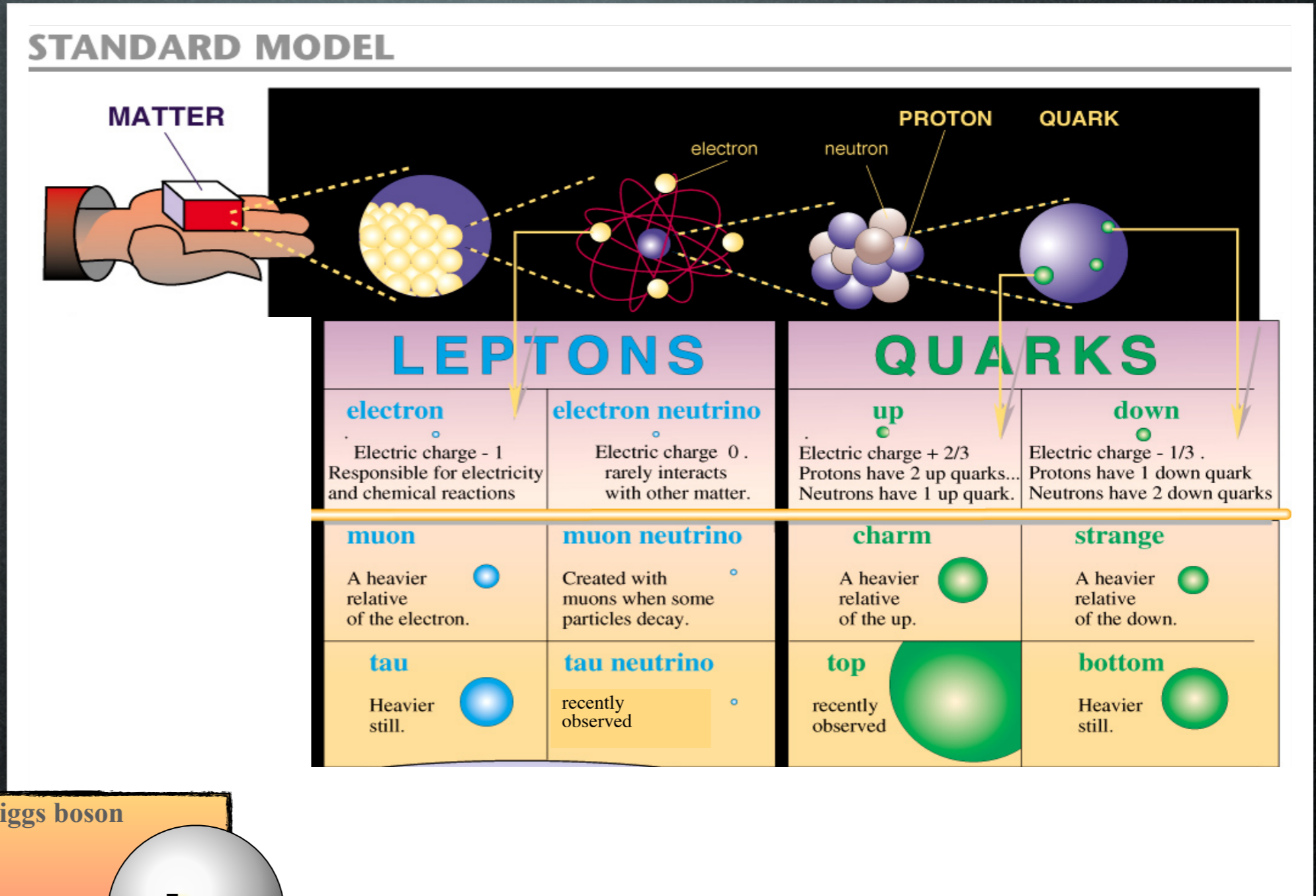
Propriétés et nature

particules
'lourdes'

'neutre'

'stable'

presque sans
interactions



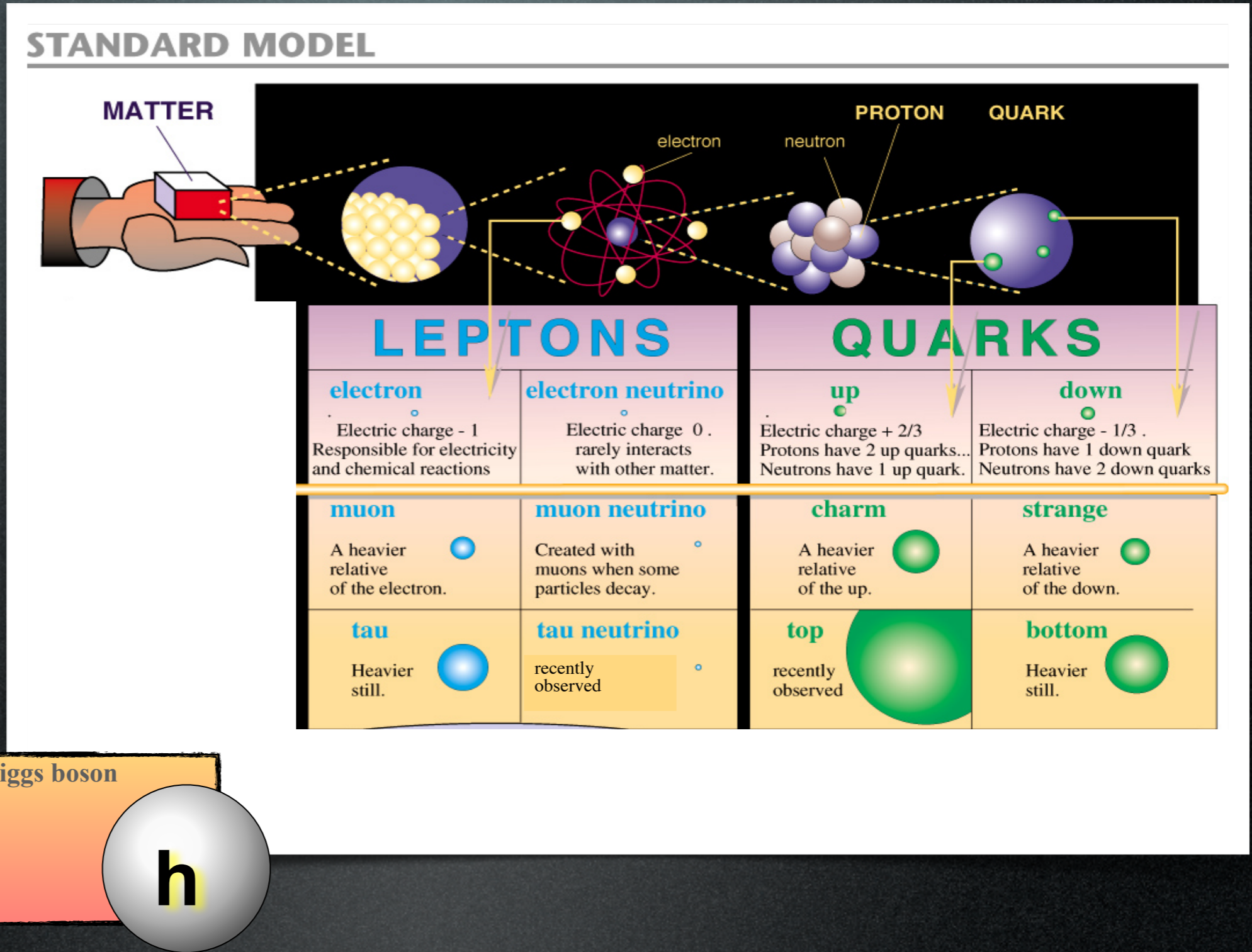
Propriétés et nature

particules
'lourdes'

'neutre'

'stable'

presque sans
interactions



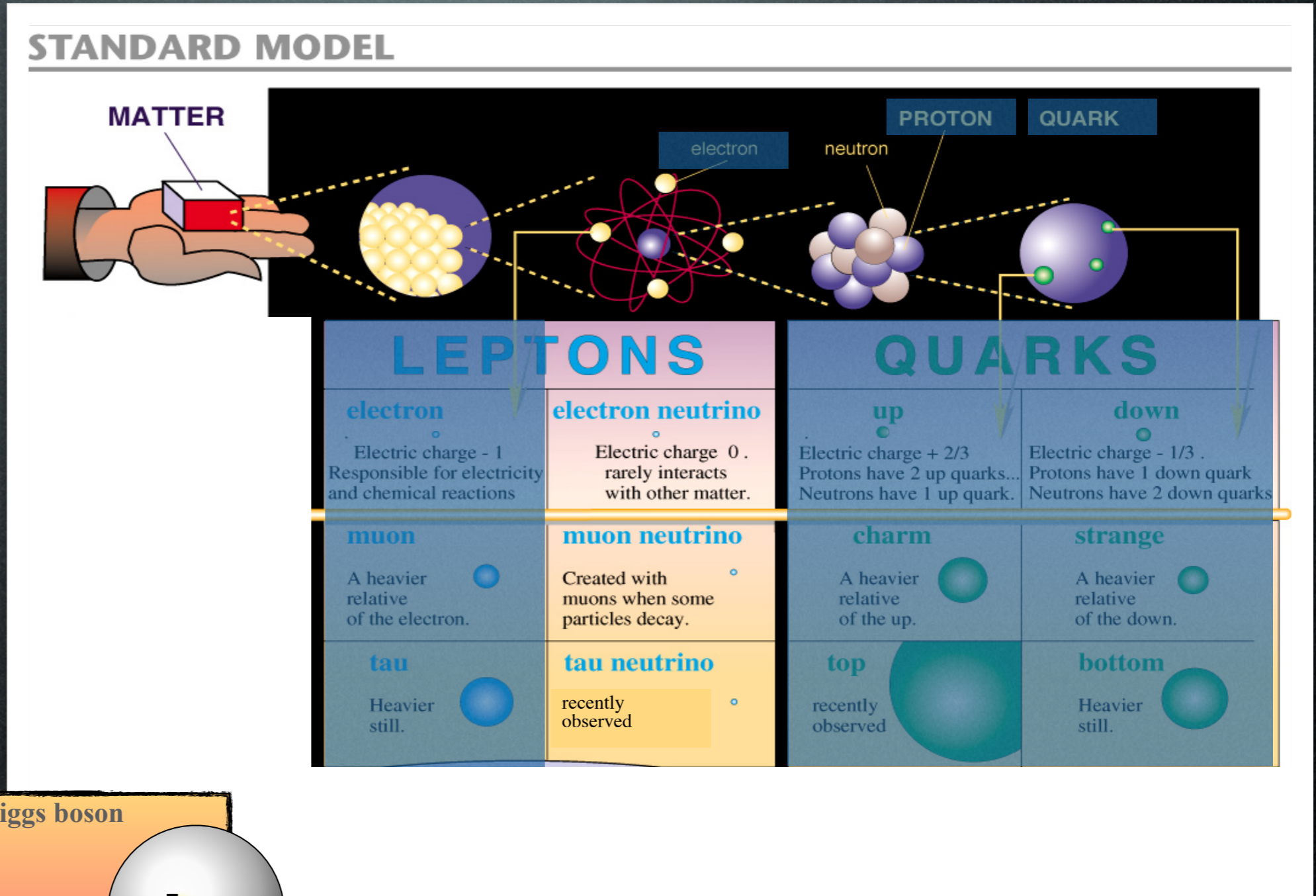
Propriétés et nature

particules
'lourdes'

'neutre'

'stable'

presque sans
interactions



Propriétés et nature

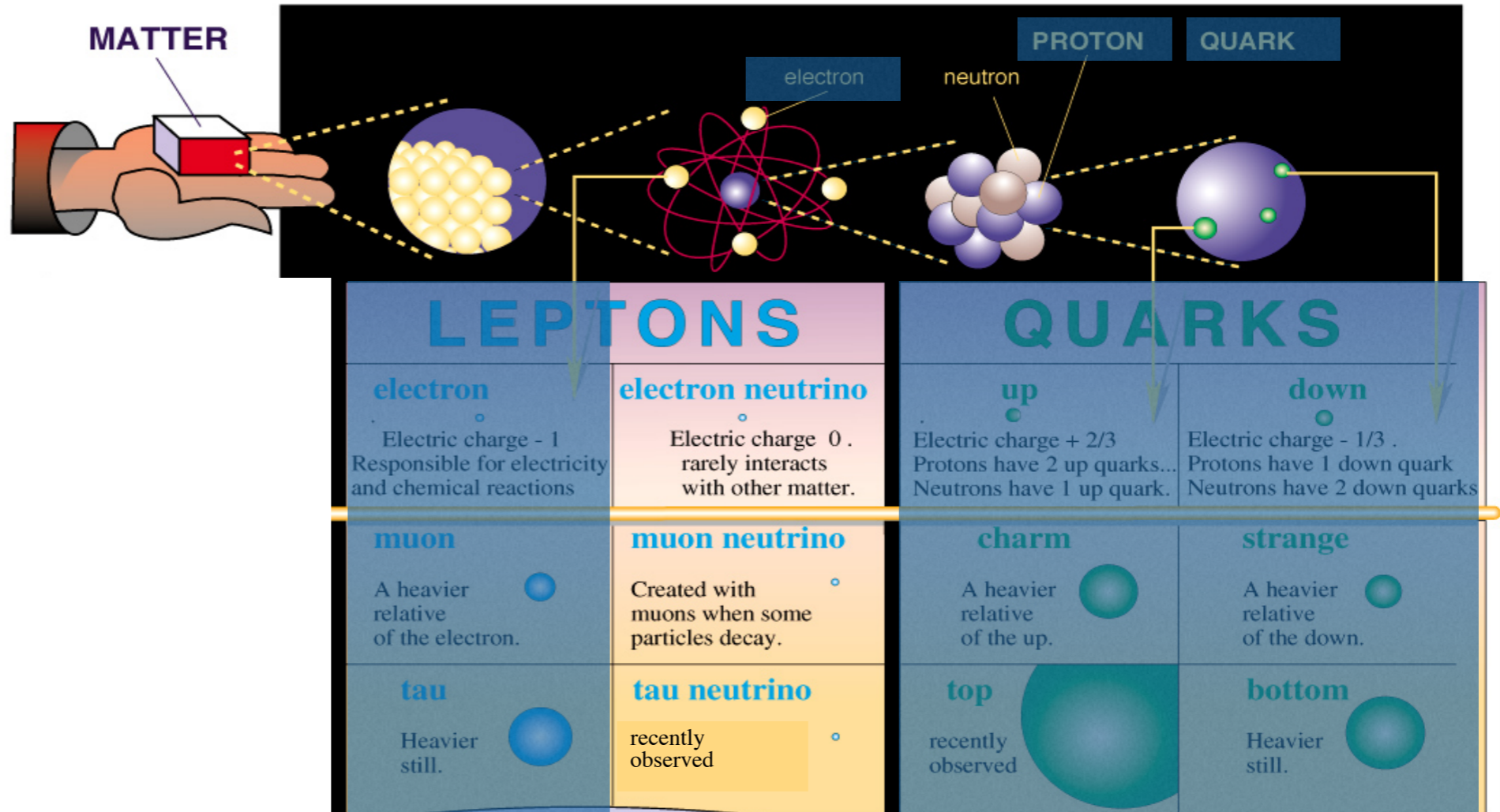
particules
'lourdes'

'neutre'

'stable'

presque sans
interactions

STANDARD MODEL



Higgs boson

h

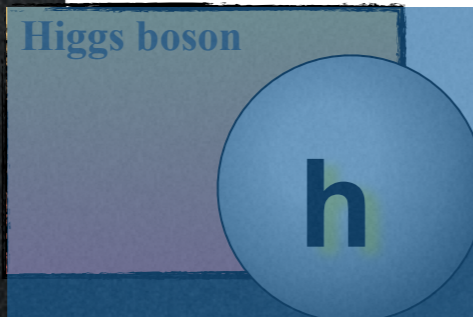
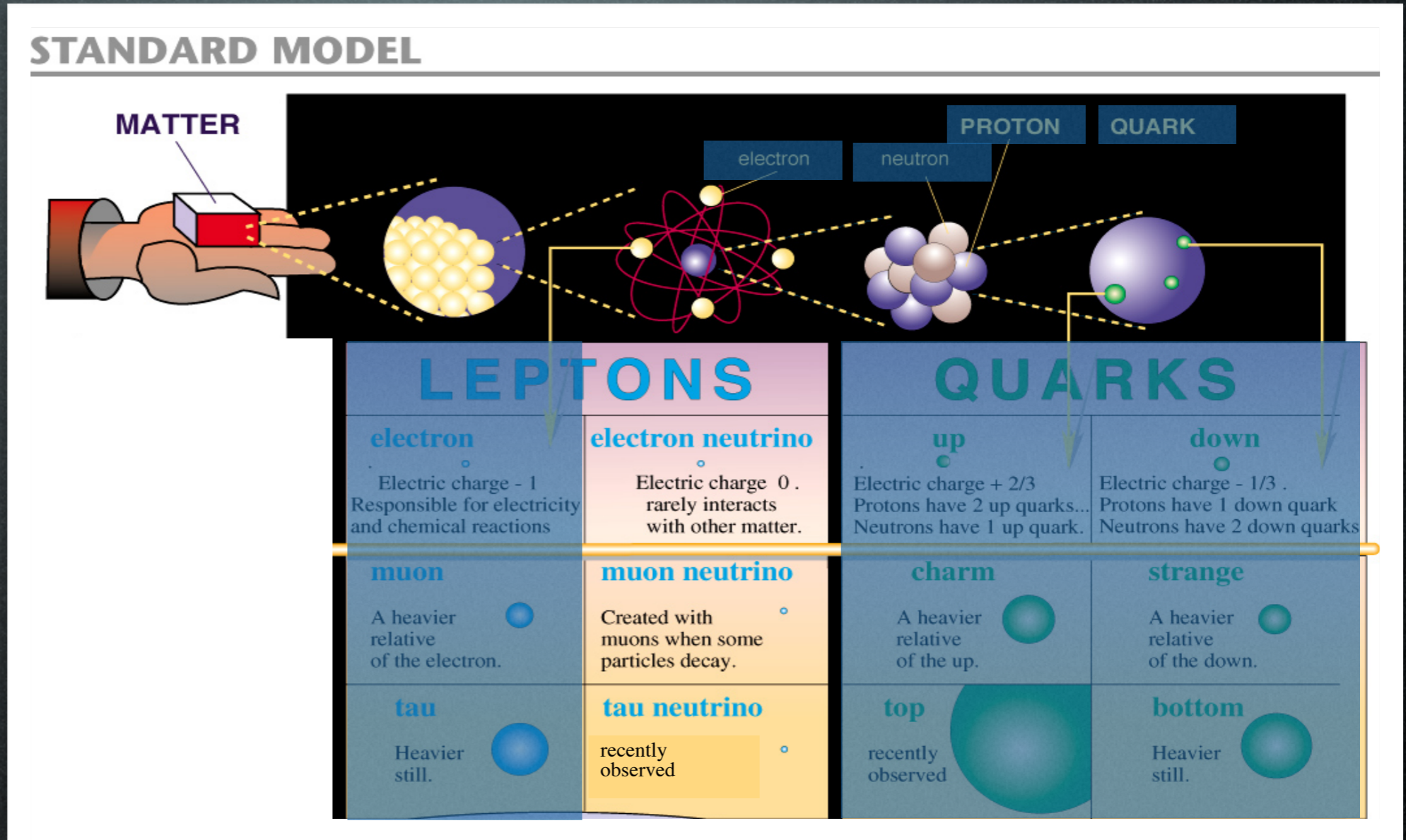
Propriétés et nature

particules
'lourdes'

'neutre'

'stable'

presque sans
interactions



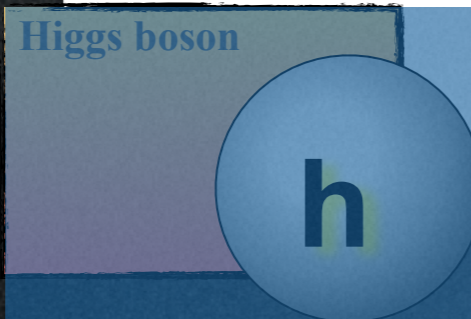
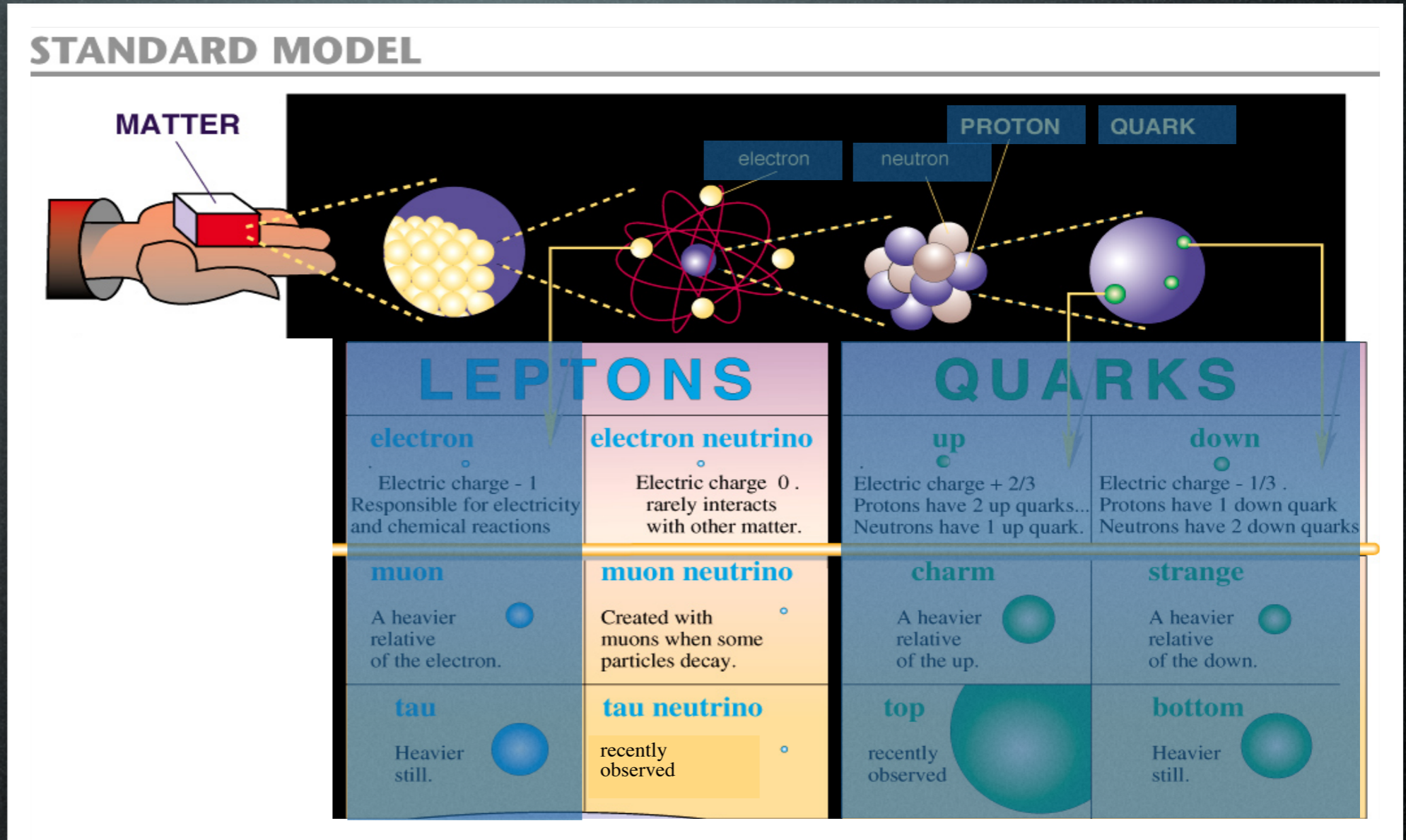
Propriétés et nature

particules
‘lourdes’

‘neutre’

‘stable’

presque sans
interactions



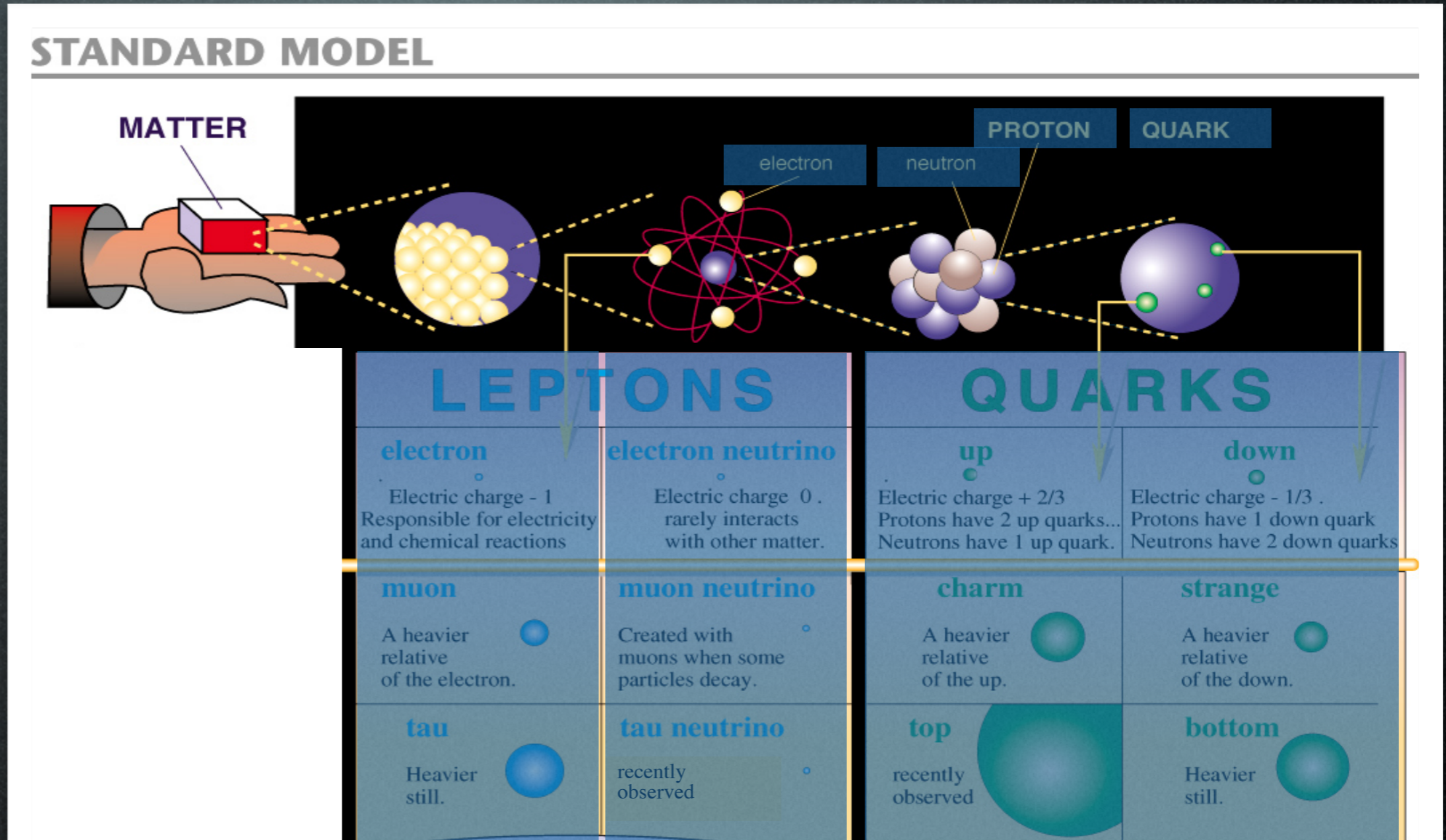
Propriétés et nature

particules
'**lourdes**'

'**neutre**'

'**stable**'

presque sans
interactions



Higgs boson

h

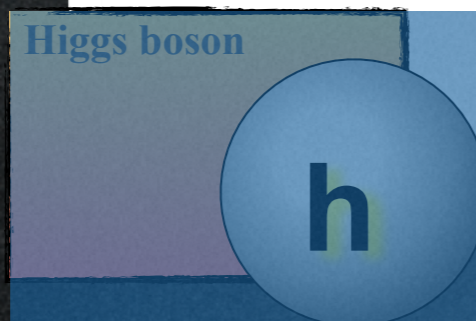
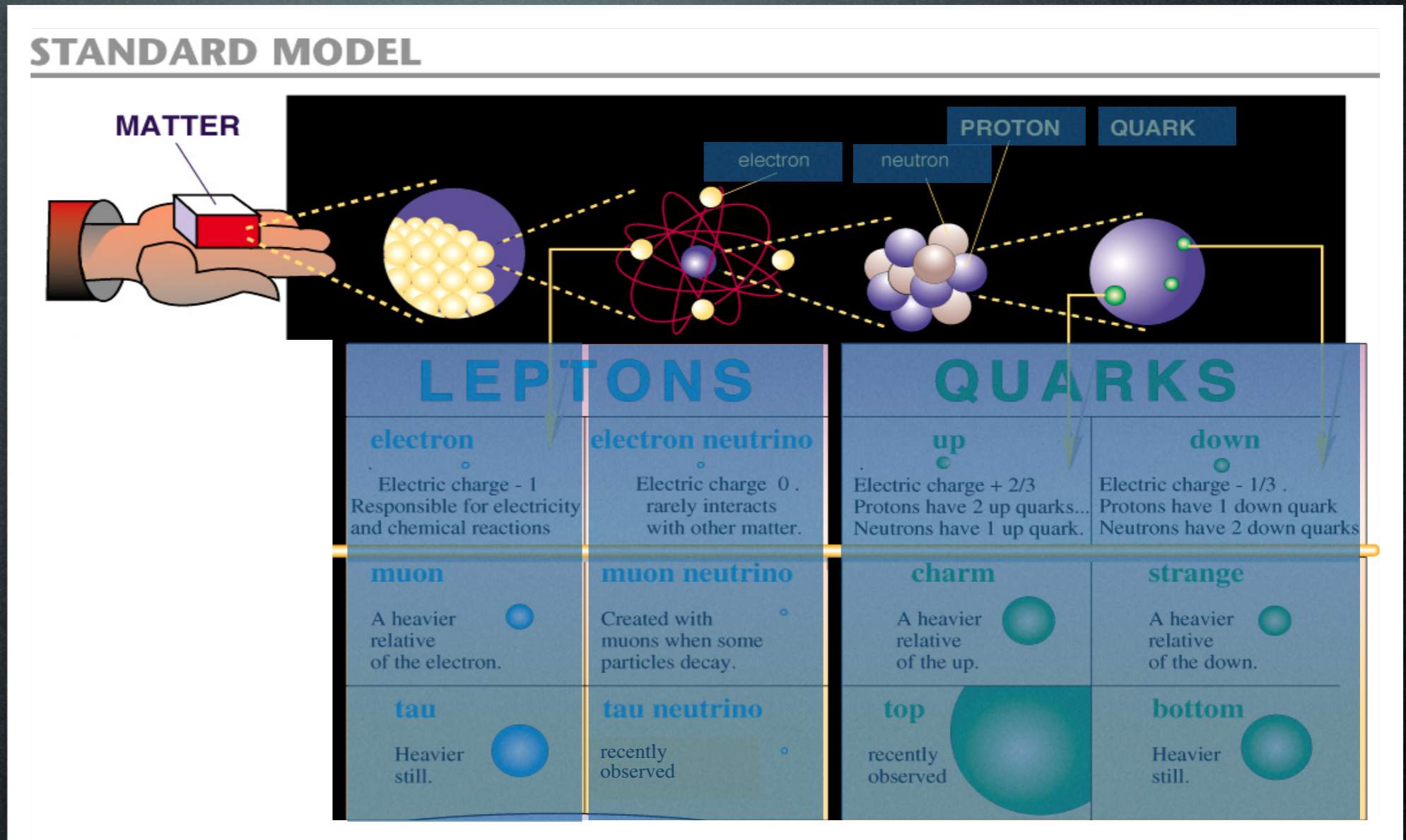
Propriétés et nature

particules
‘lourdes’

‘neutre’

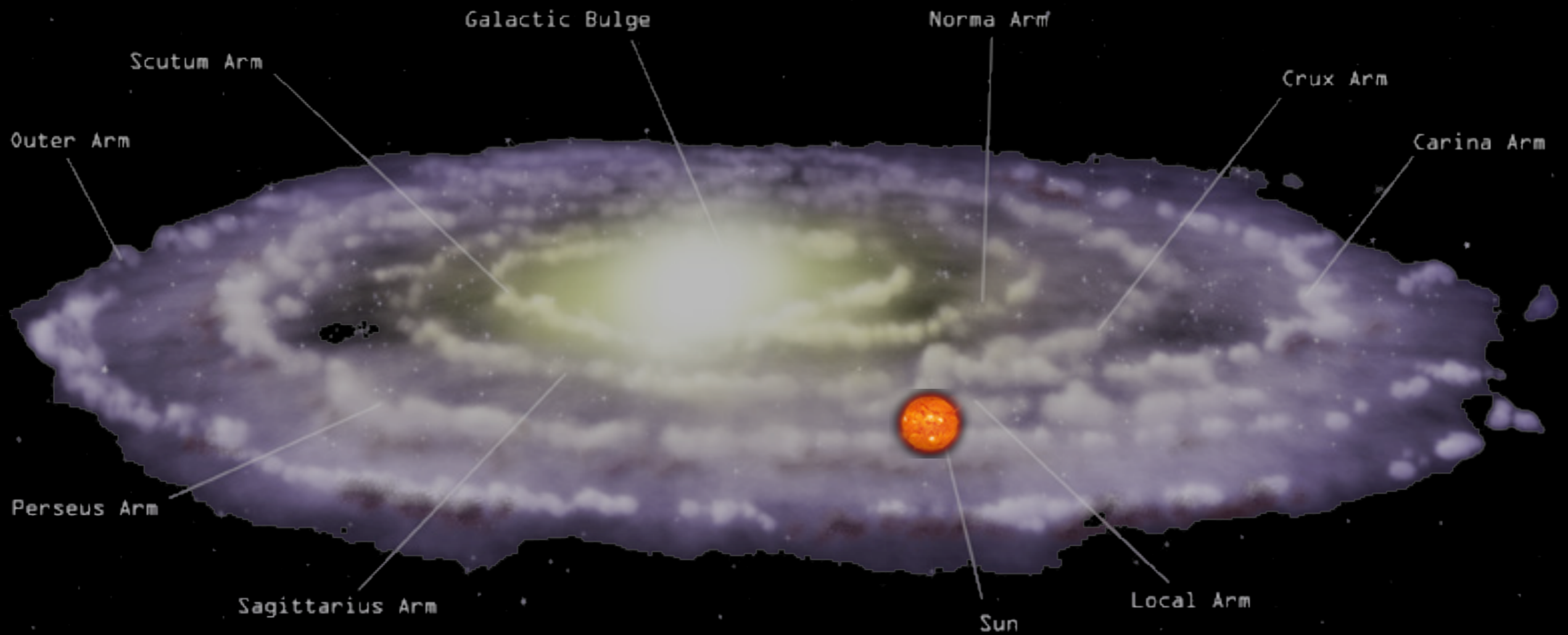
‘stable’

presque sans
interactions



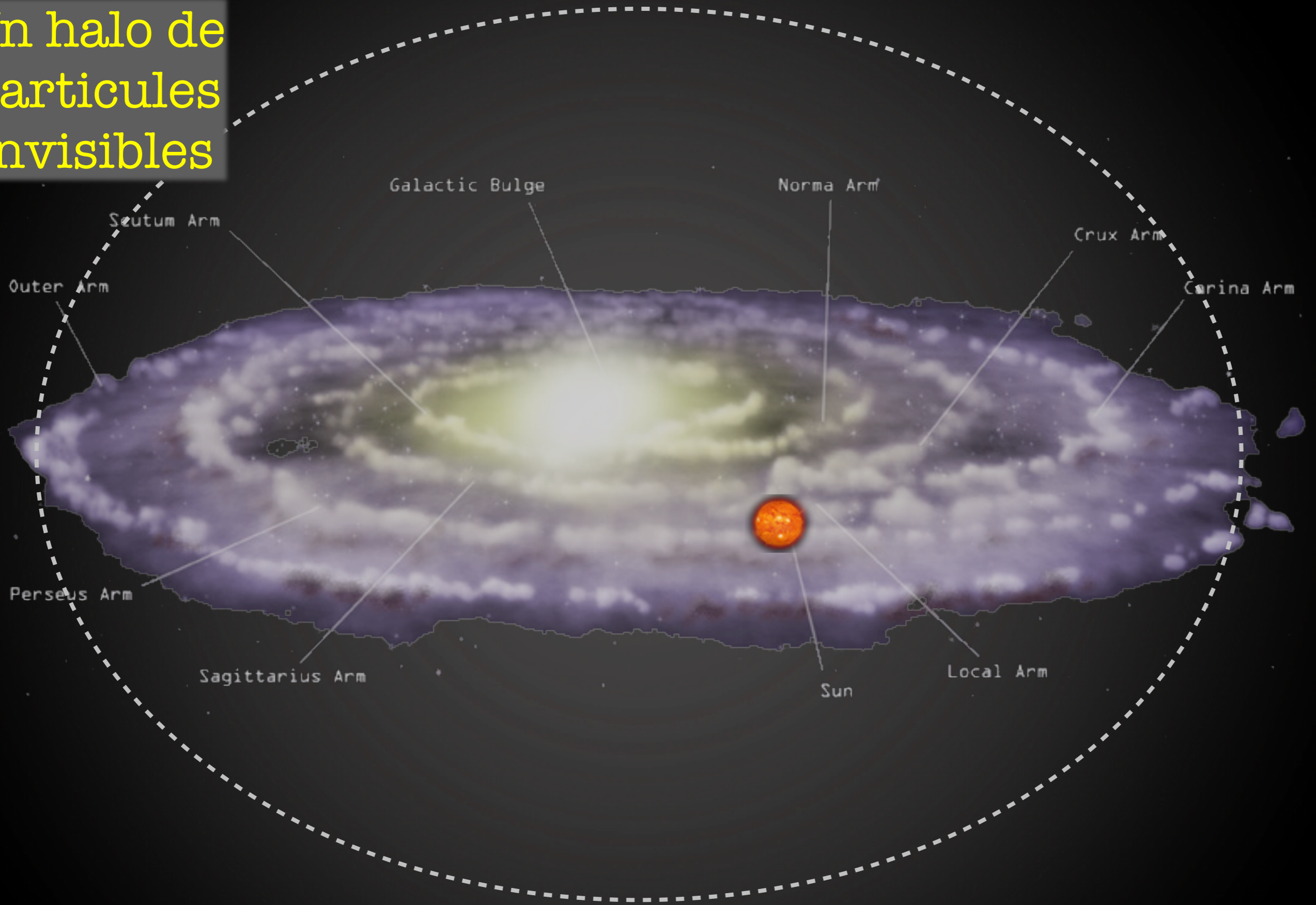
une **nouvelle** particule,
encore **inconnue**

Et dans la Voie Lactée ?



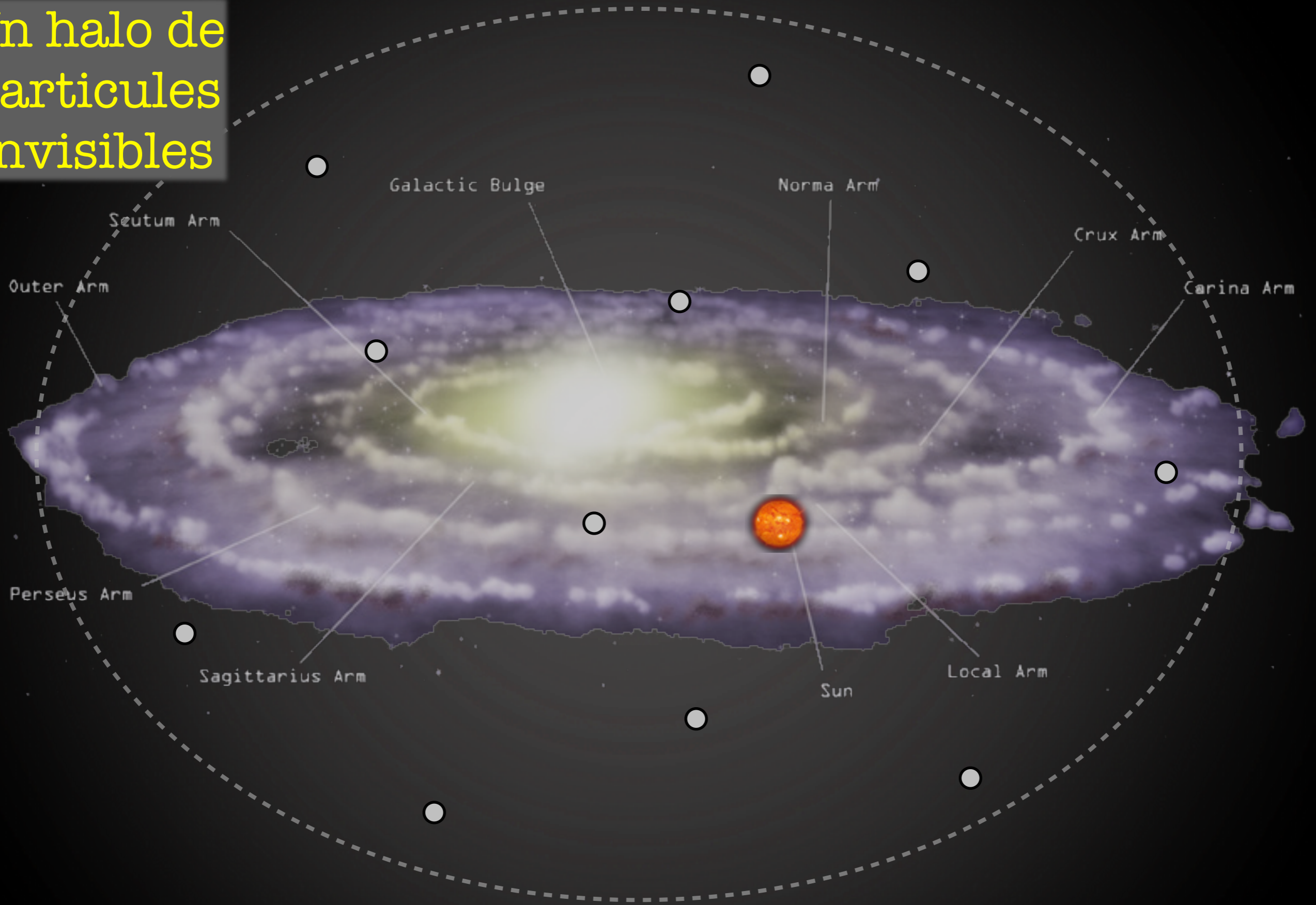
Et dans la Voie Lactée ?

Un halo de
particules
invisibles



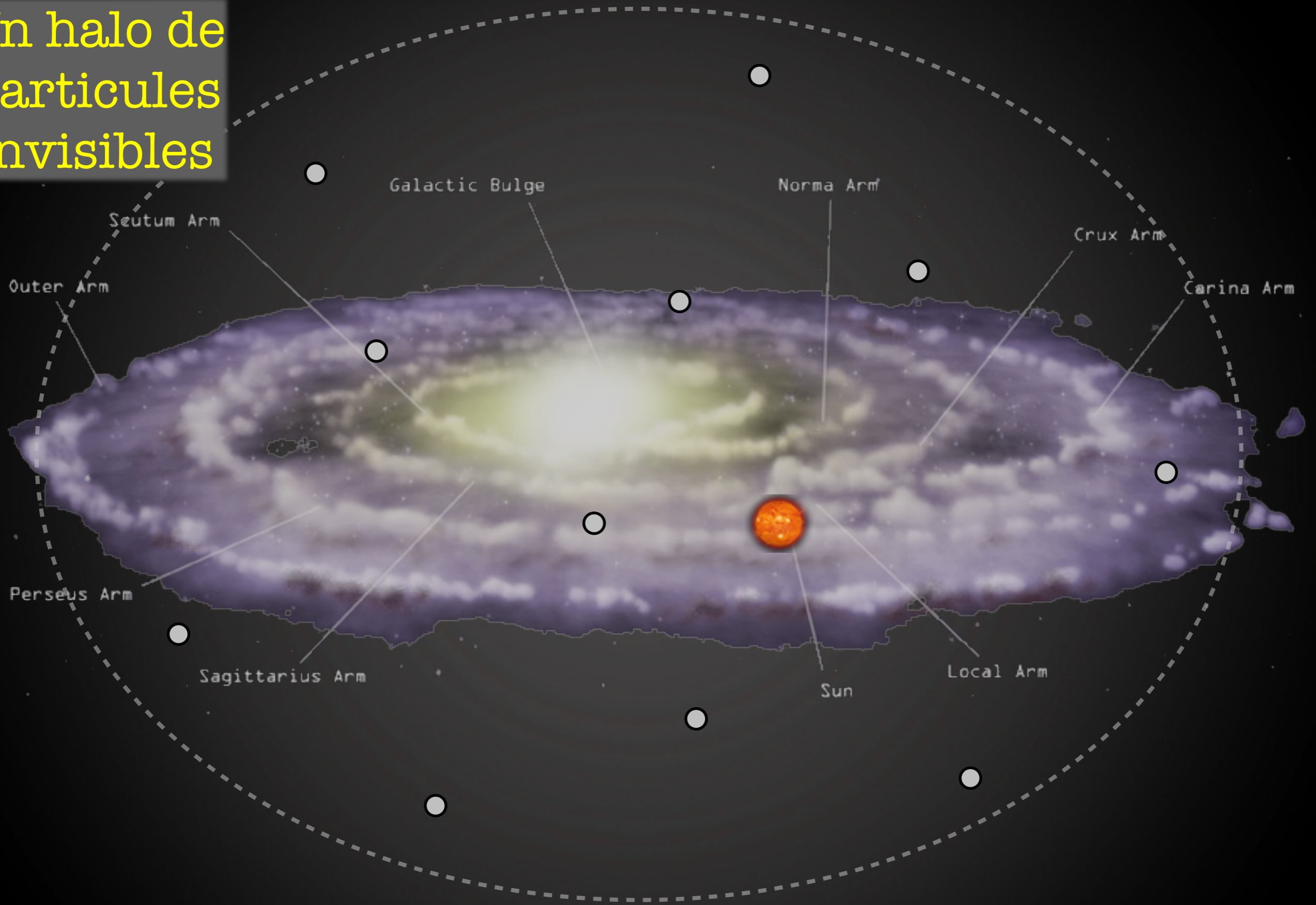
Et dans la Voie Lactée ?

Un halo de
particules
invisibles



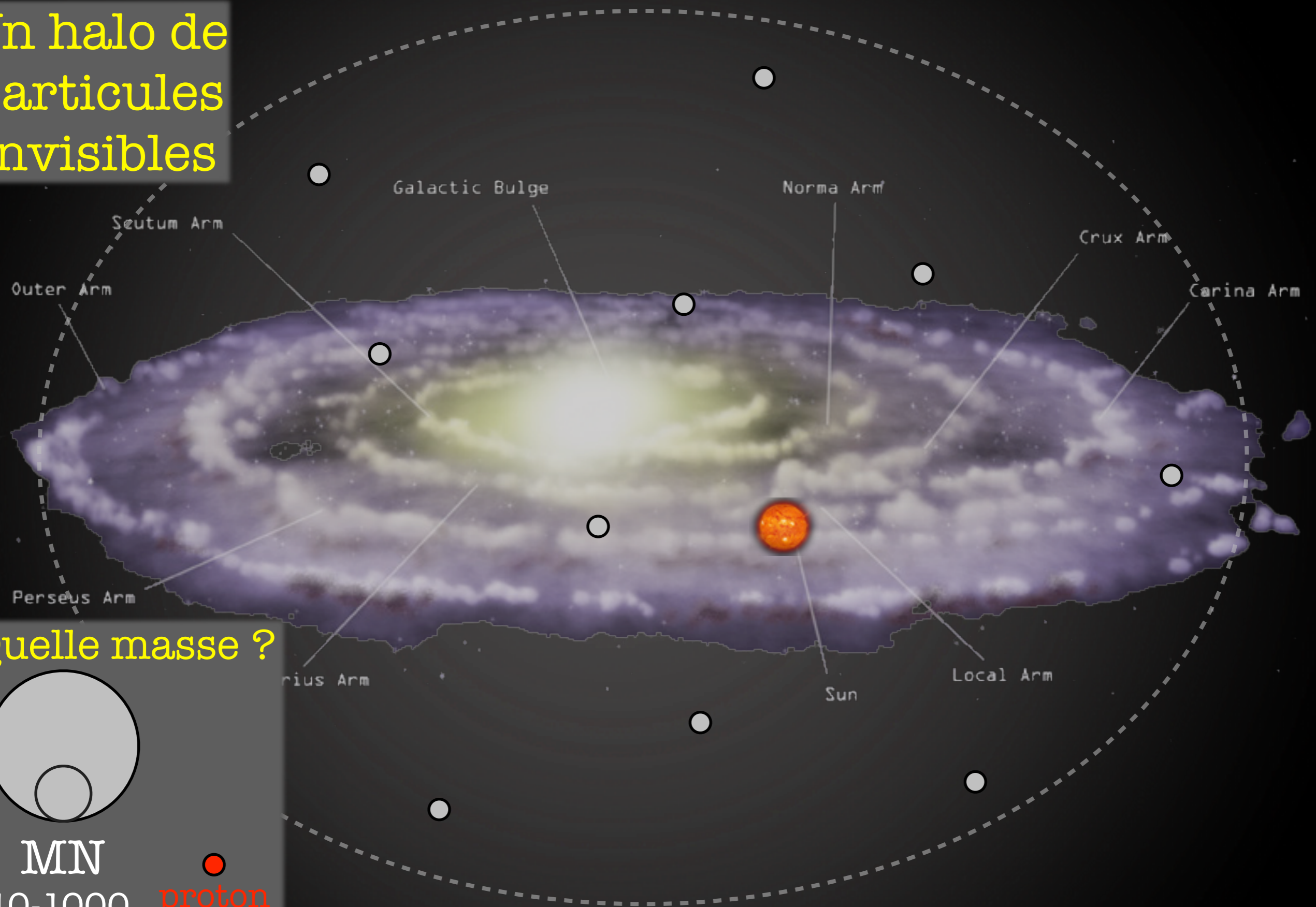
Et dans la Voie Lactée ?

Un halo de
particules
invisibles

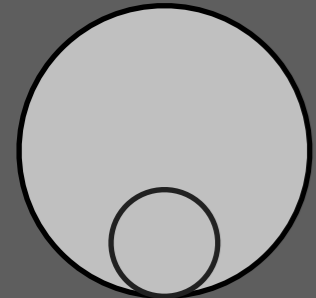


Et dans la Voie Lactée ?

Un halo de
particules
invisibles



Quelle masse ?

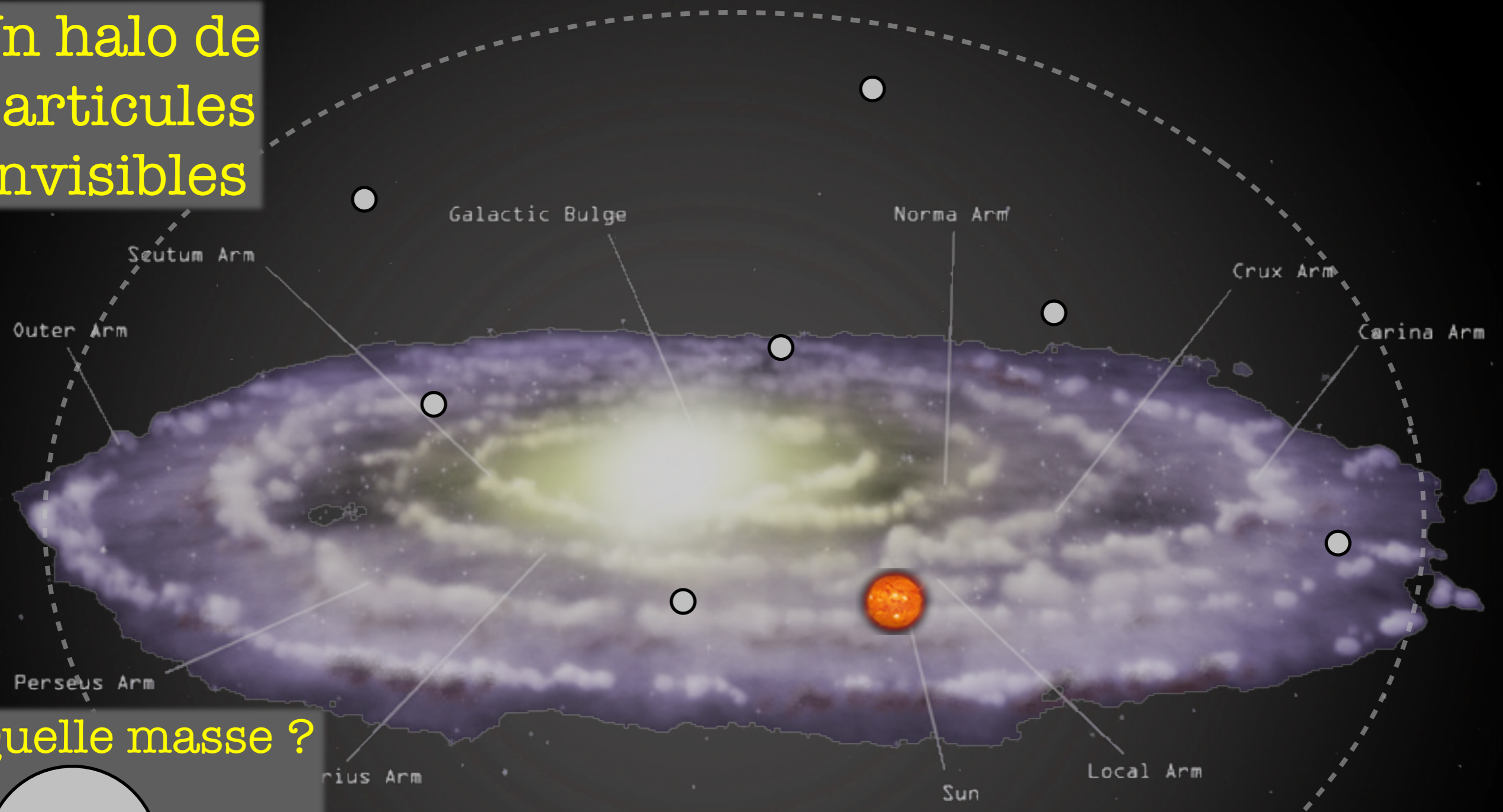


MN
10-1000
GeV

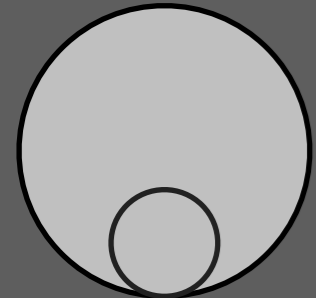
proton
1 GeV

Et dans la Voie Lactée ?

Un halo de
particules
invisibles



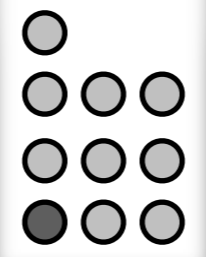
Quelle masse ?



MN
10-1000
GeV

● proton
1 GeV

Quelle densité ?

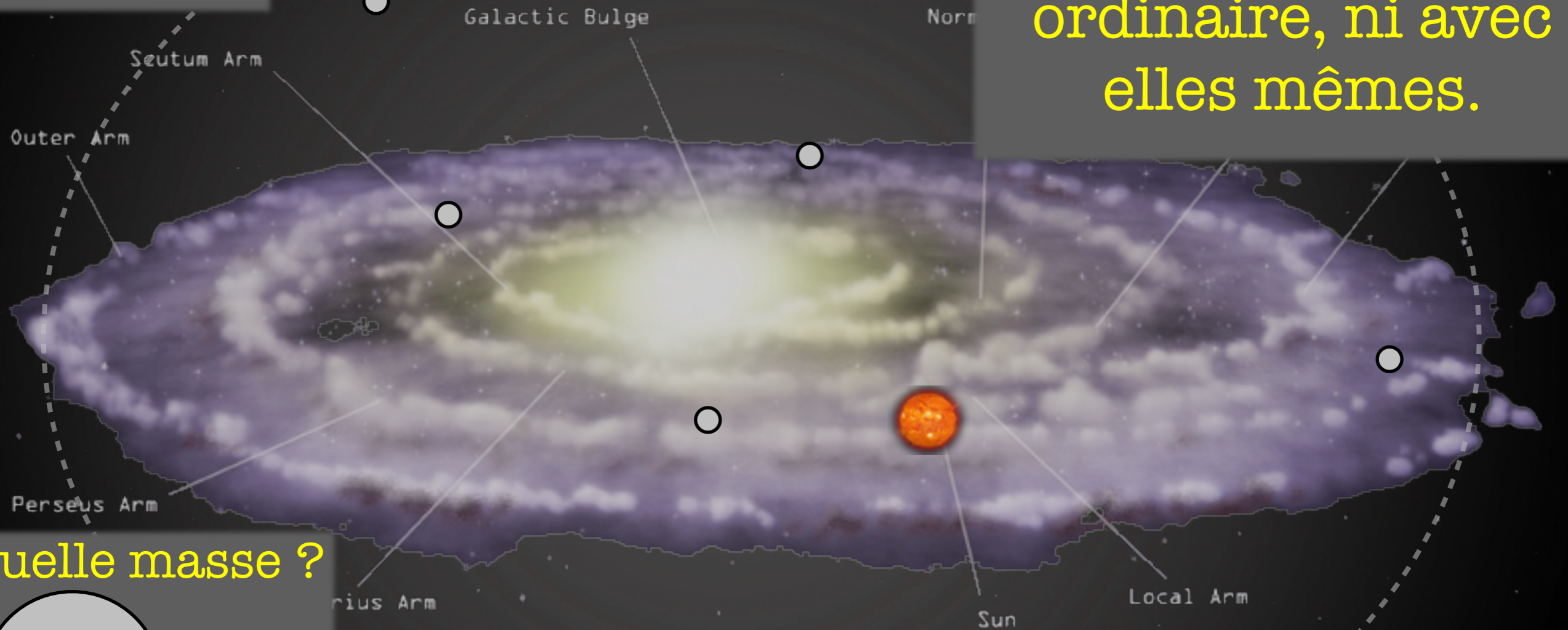


10 GeV
100 GeV

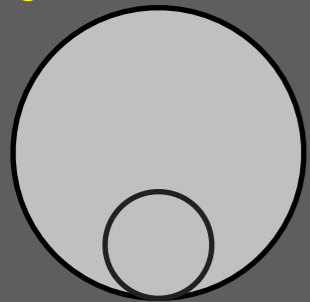
Et dans la Voie Lactée ?

Un halo de particules invisibles

Elle n'interagissent pas avec la matière ordinaire, ni avec elles mêmes.

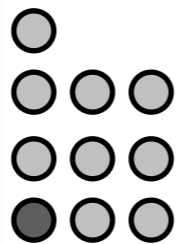


Quelle masse ?



MN
10-1000 GeV
proton
1 GeV

Quelle densité ?

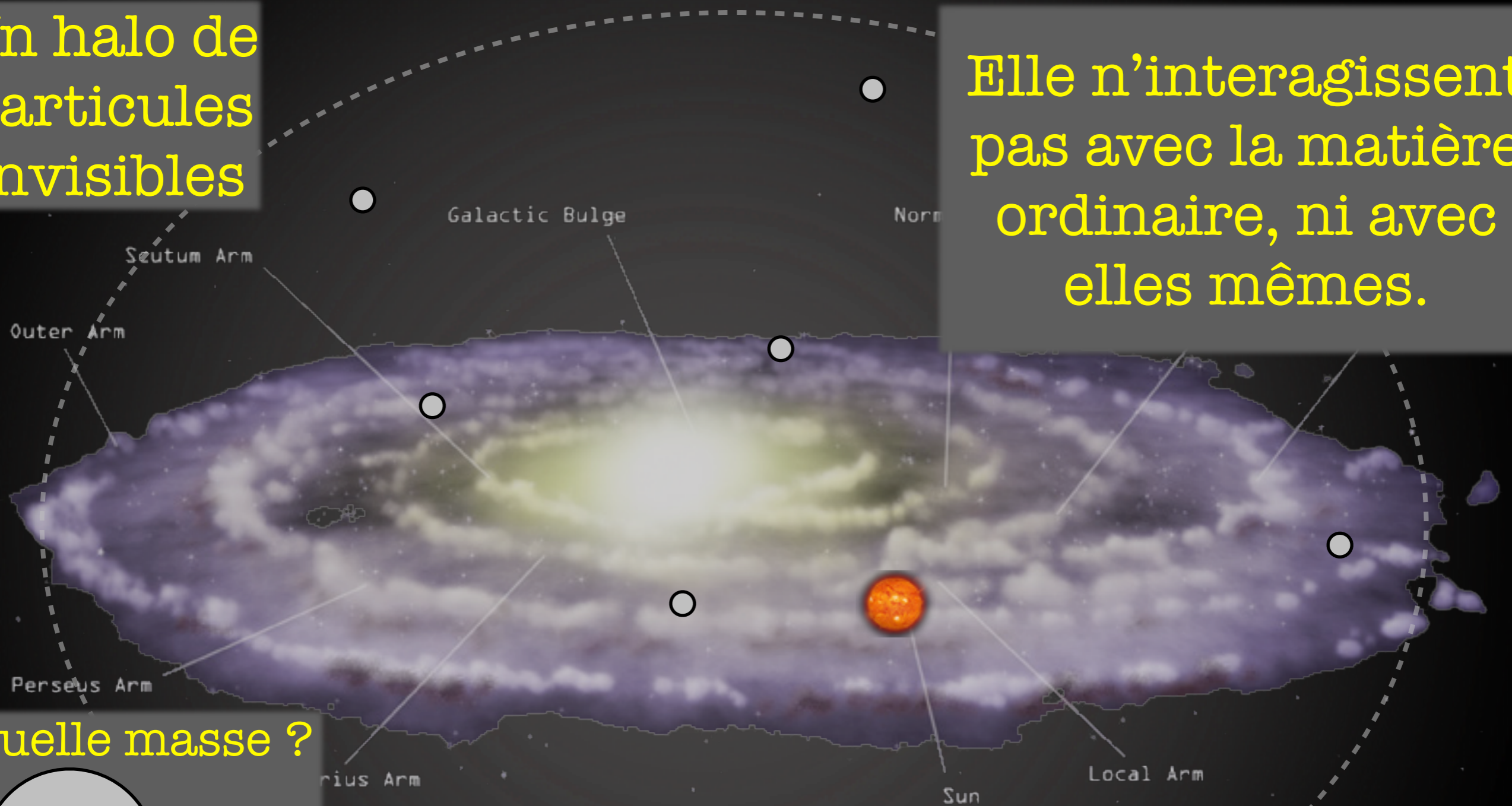


10 GeV
100 GeV

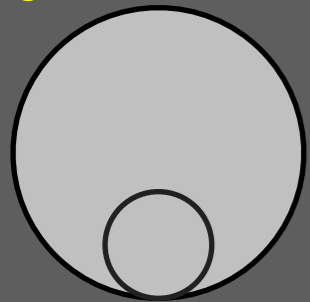
Et dans la Voie Lactée ?

Un halo de particules invisibles

Elle n'interagissent pas avec la matière ordinaire, ni avec elles mêmes.

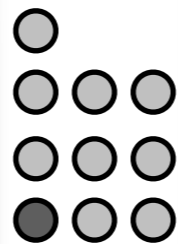


Quelle masse ?



MN
10-1000 GeV
proton
1 GeV

Quelle densité ?



10 GeV
100 GeV

Ou si, peut-être elles interagissent un peu...

Comment
détecter
la Matière Noire ?





Physique souterraine



'détection directe'



Physique souterraine

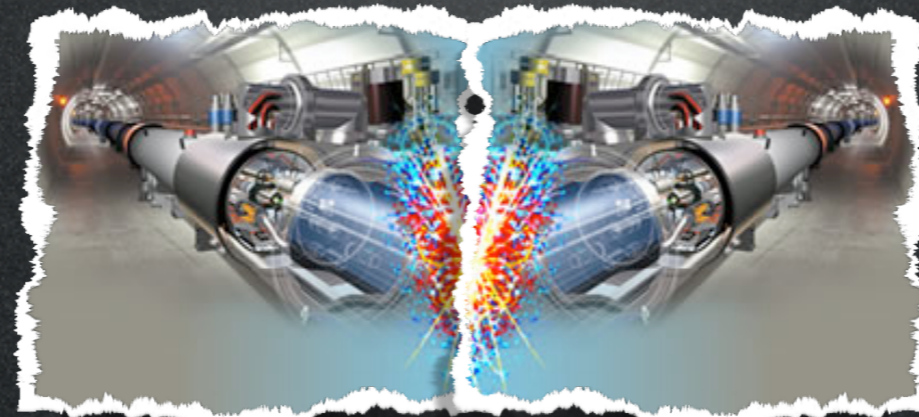


'détection directe'



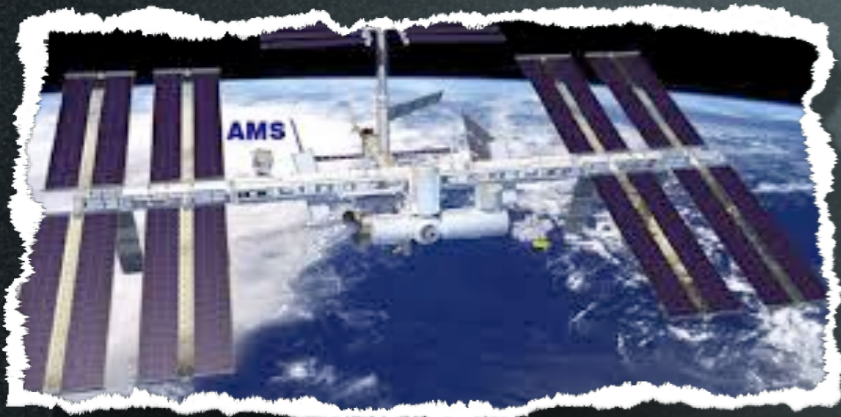
Matière
Noire

'production'



Physique aux collisionneurs

Physique spatiale



Physique souterraine



‘déttection indirecte’

‘déttection directe’



‘production’



Physique aux collisionneurs

Détection directe



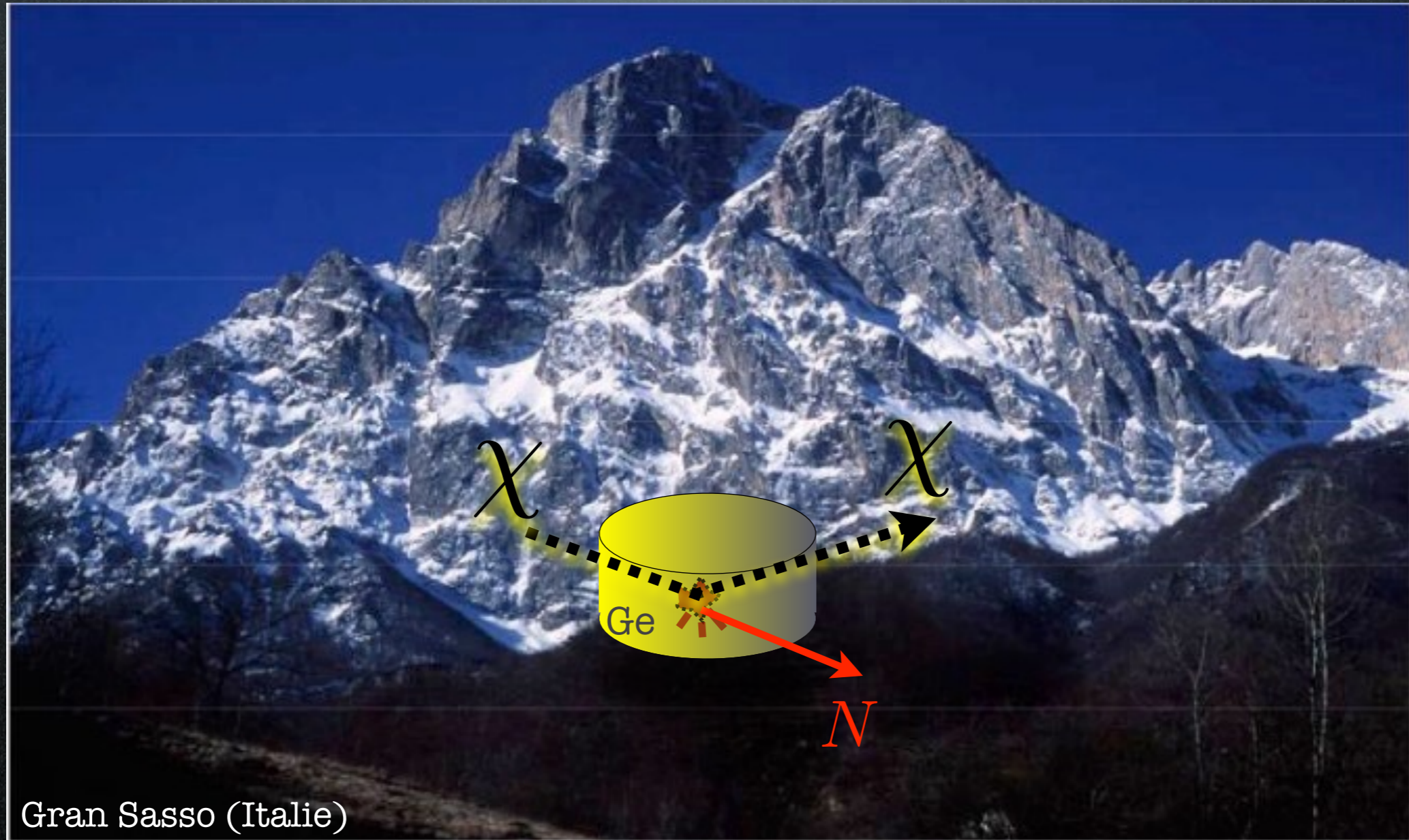
Gran Sasso (Italie)

Détection directe



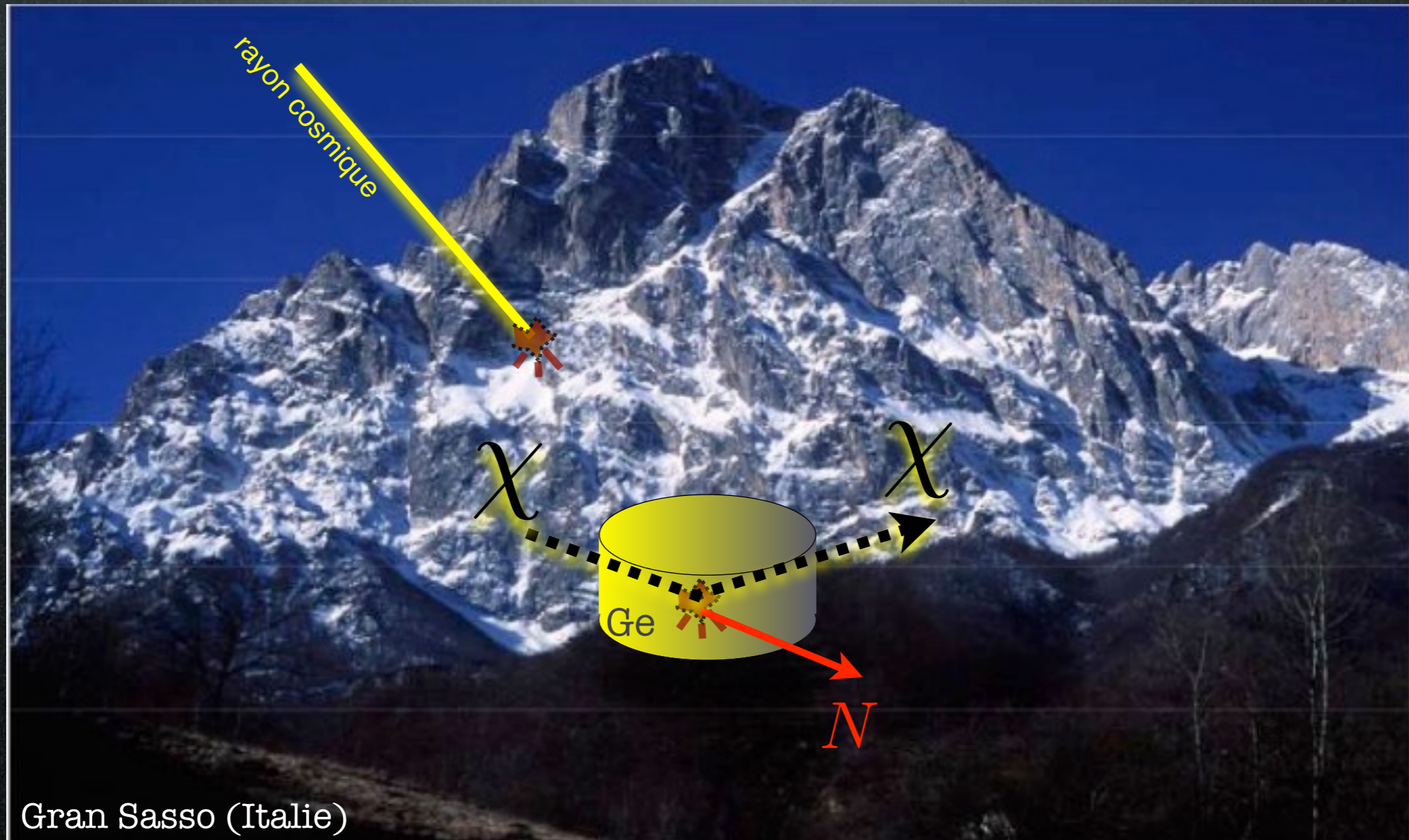
Gran Sasso (Italie)

Détection directe



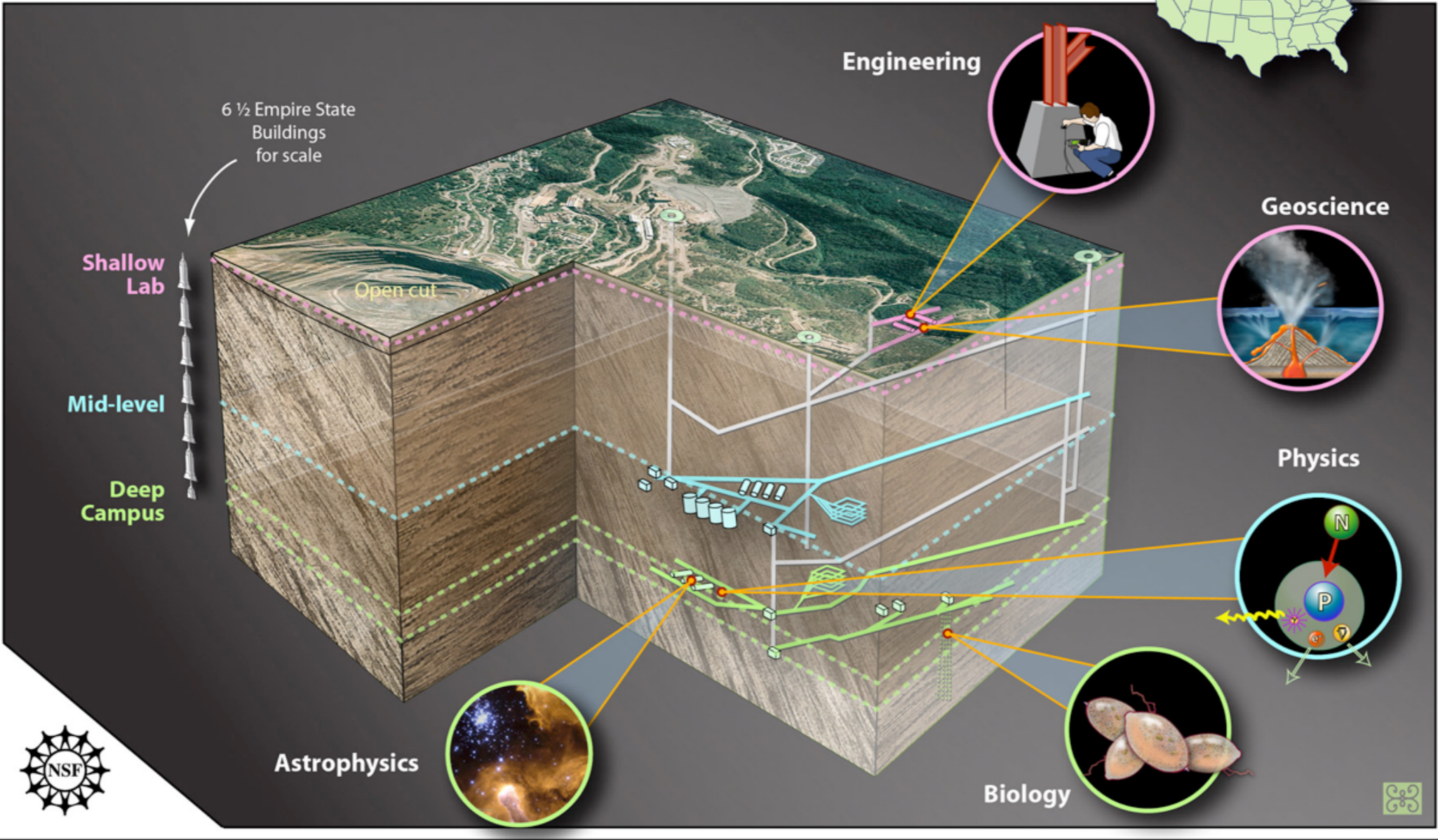
Gran Sasso (Italie)

Détection directe



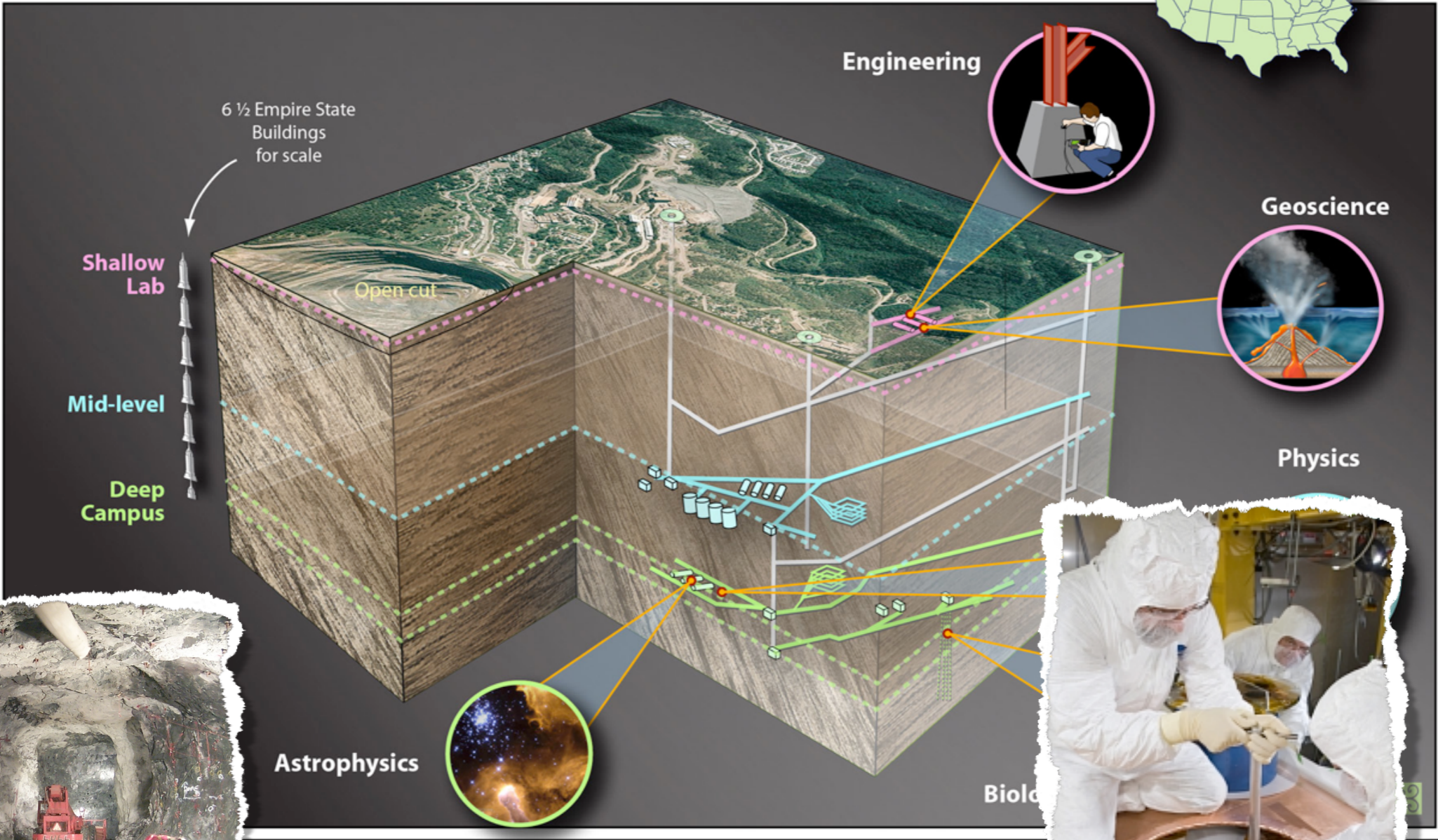
Détection directe

DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD



Détection directe

DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD



Détection directe

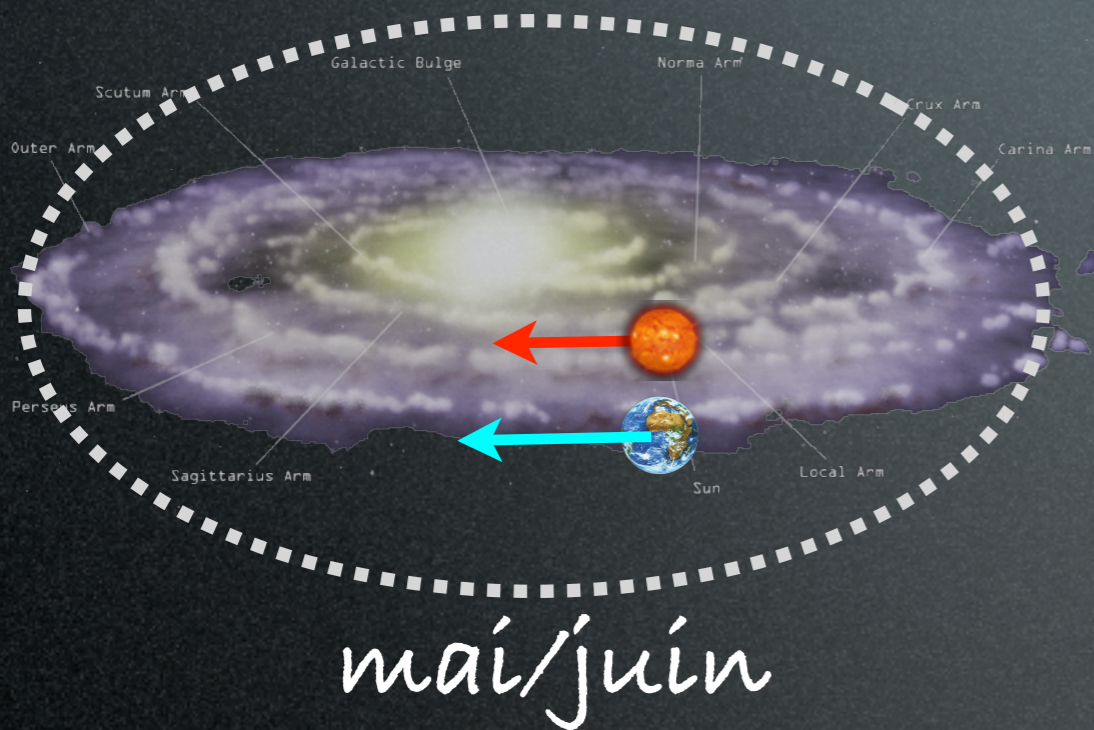
Stratégie n.2: surfer sur la vague noire

collecter tous les évènements,
et détecter une modulation annuelle

Détection directe

Stratégie n.2: surfer sur la vague noire

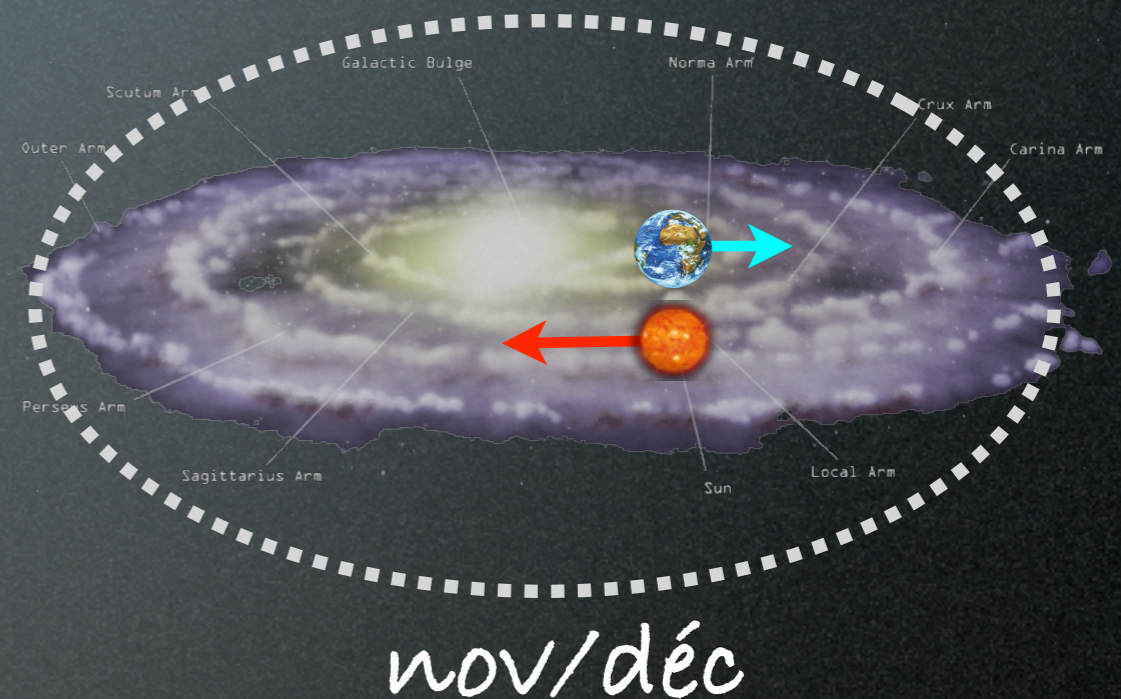
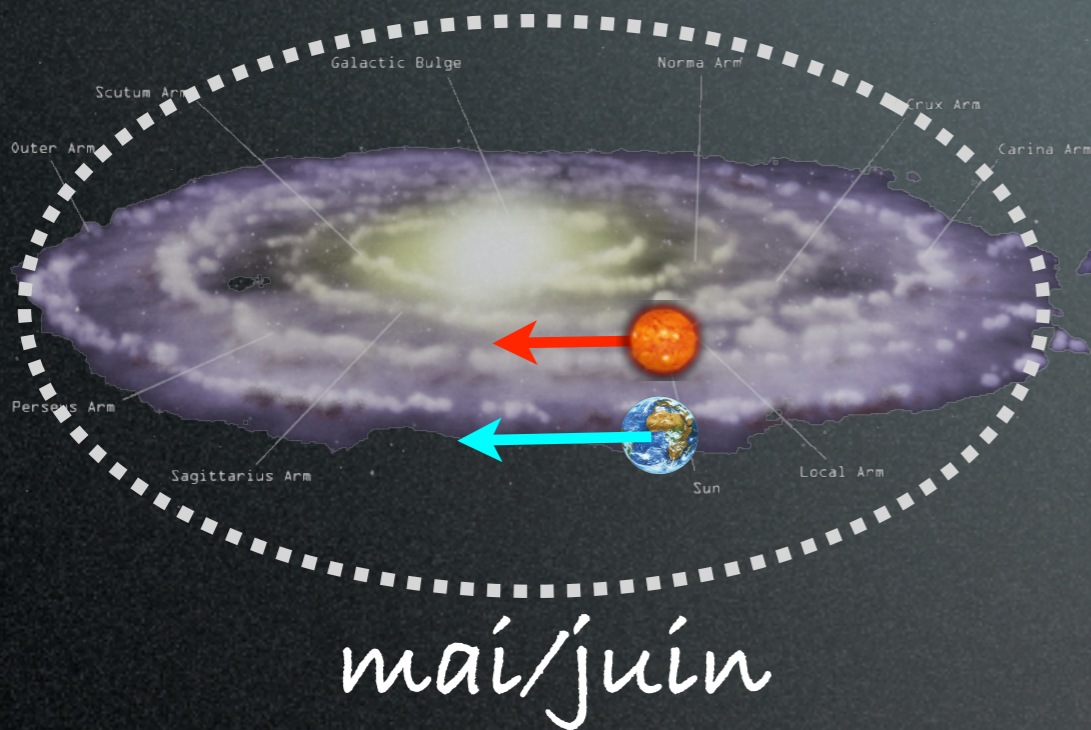
collecter tous les évènements,
et détecter une modulation annuelle



Détection directe

Stratégie n.2: surfer sur la vague noire

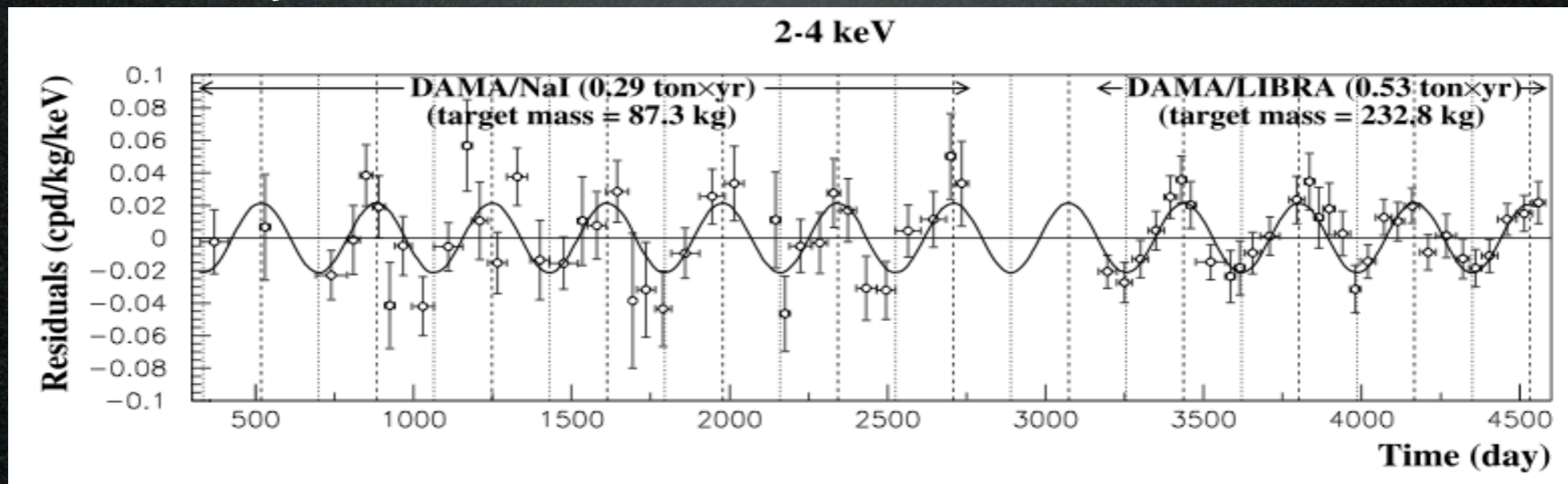
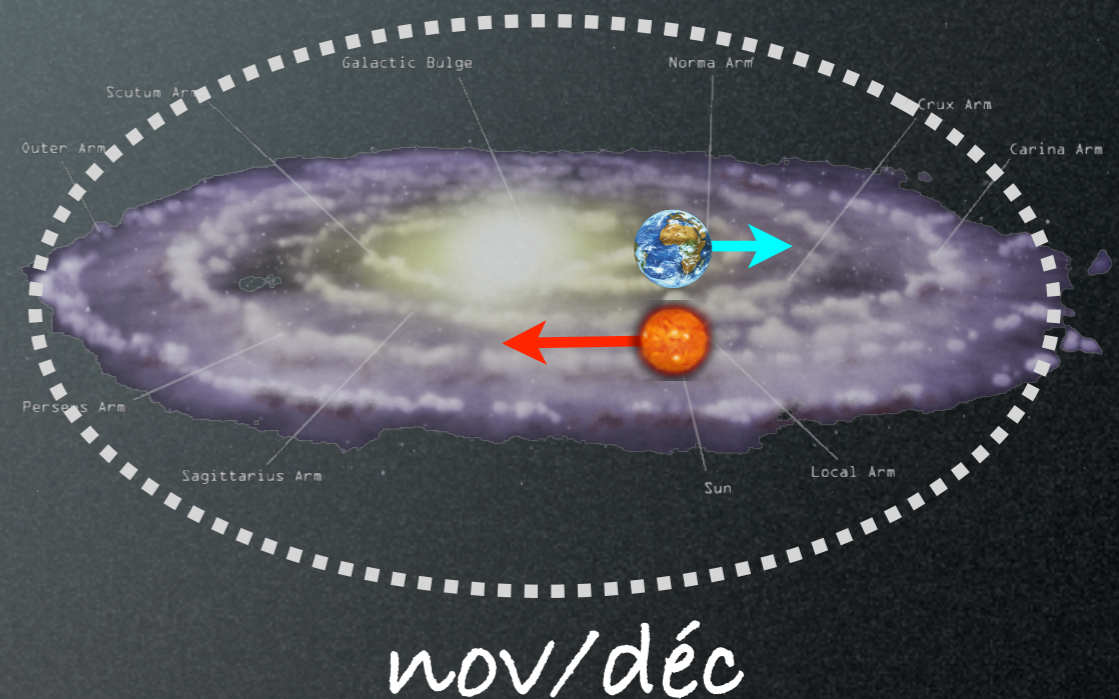
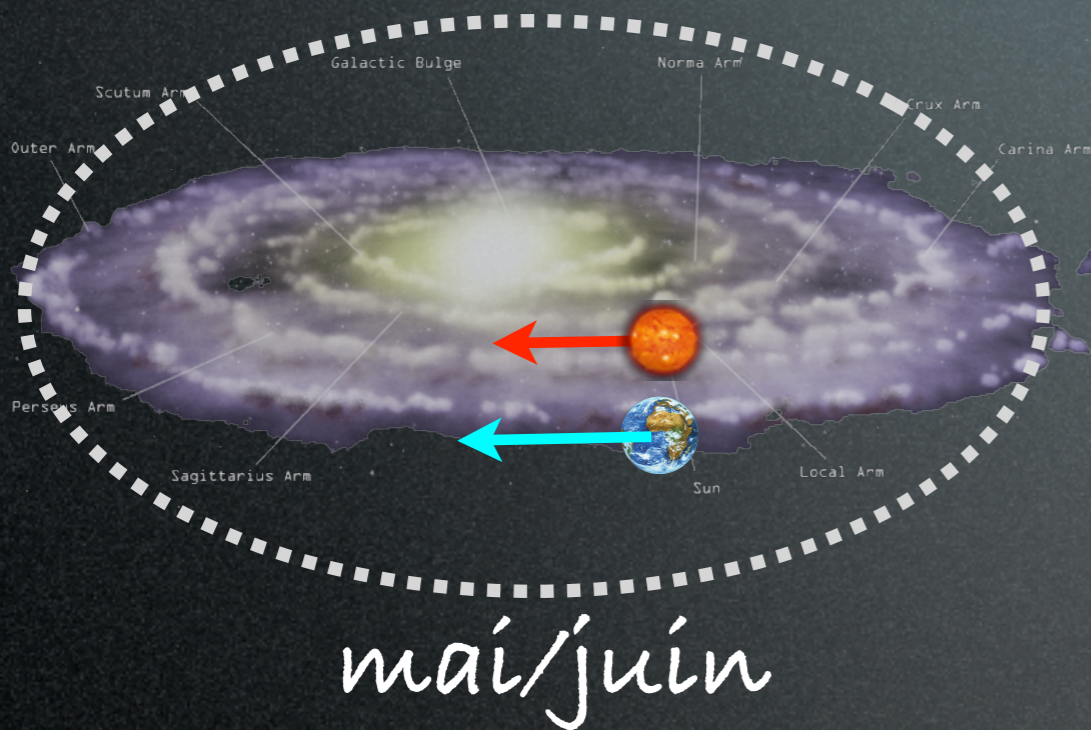
collecter tous les évènements,
et détecter une modulation annuelle



Détection directe

Stratégie n.2: surfer sur la vague noire

collecter tous les événements,
et détecter une modulation annuelle



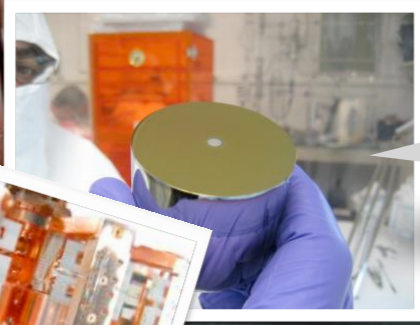
Détection directe: état de l'art

Détection directe: état de l'art

DAMA/Libra
(1998-2011)



CoGeNT
(2010-2011)



CRESST
(2011)

Oui!
Matière Noire!

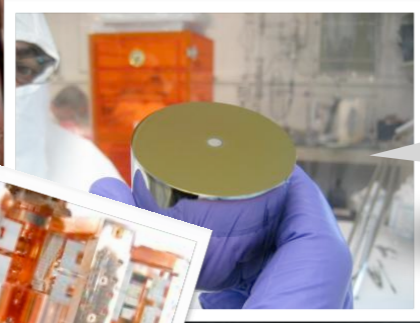
Excès d'évènements et/ou **modulation** annuelle.

Détection directe: état de l'art

DAMA/Libra
(1998-2011)



CoGeNT
(2010-2011)



CRESST
(2011)

Oui!
Matière Noire!
Excès d'évènements et/ou **modulation** annuelle.

Pas du tout.
Silence cosmique,
rien à signaler.

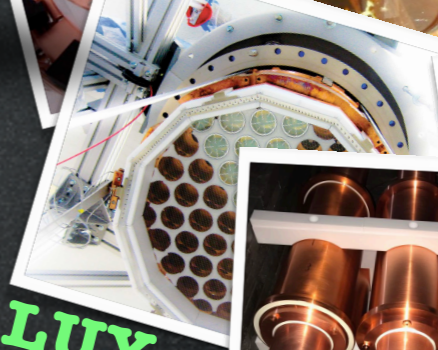
XENON100
(2009-2011)



CDMS (2009)



LUX
(2017)



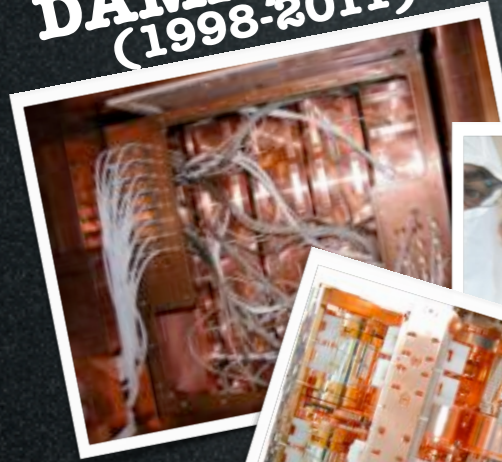
XENON 1ton
(2017)



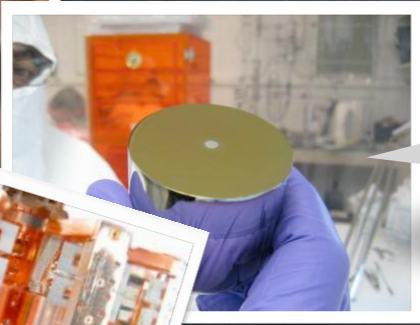
Anais
(2021)

Détection directe: état de l'art

DAMA/Libra
(1998-2011)



CoGeNT
(2010-2011)



CRESST
(2011)

Oui!
Matière Noire!
Excès d'évènements et/ou modulation annuelle.

Pas du tout.
Silence cosmique,
rien à signaler.

XENON100
(2009-2011)



CDMS (2009)



LUX
(2017)



XENON
1ton
(2017)



Anais
(2021)

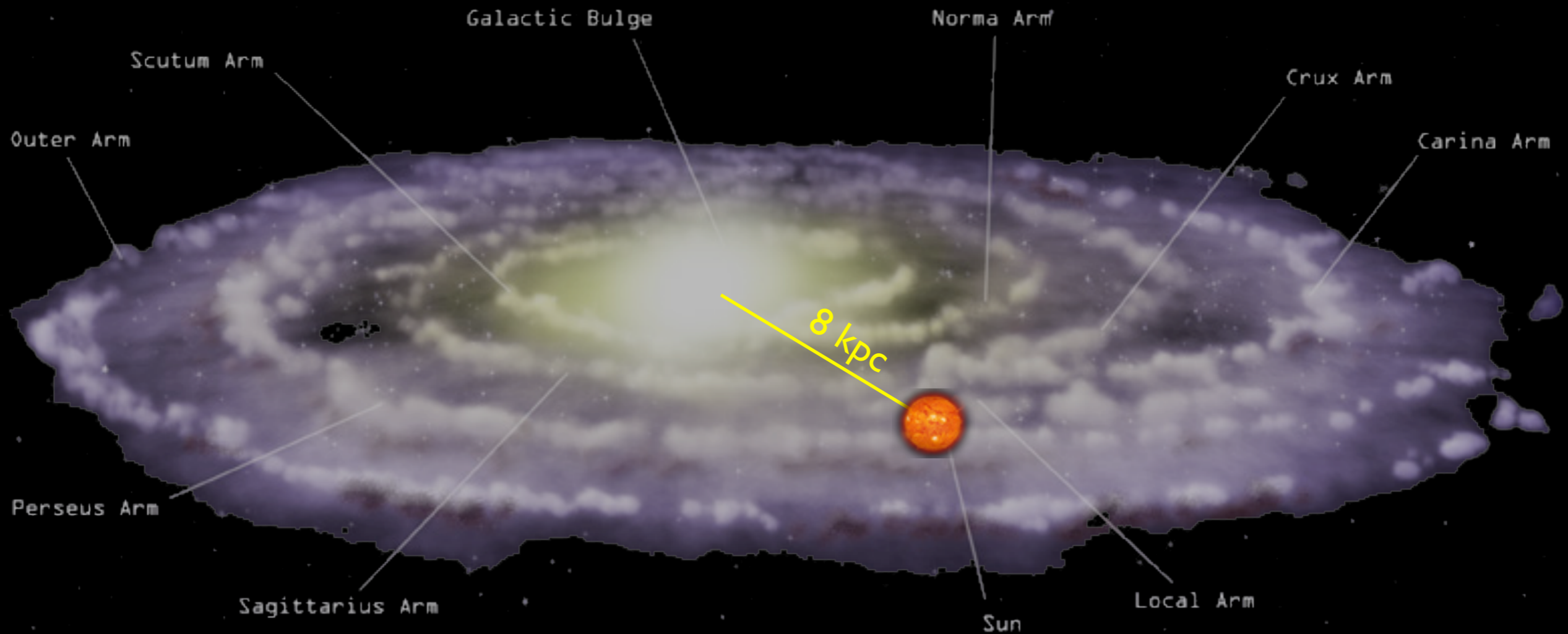


Un théoricien lambda

Détection indirecte

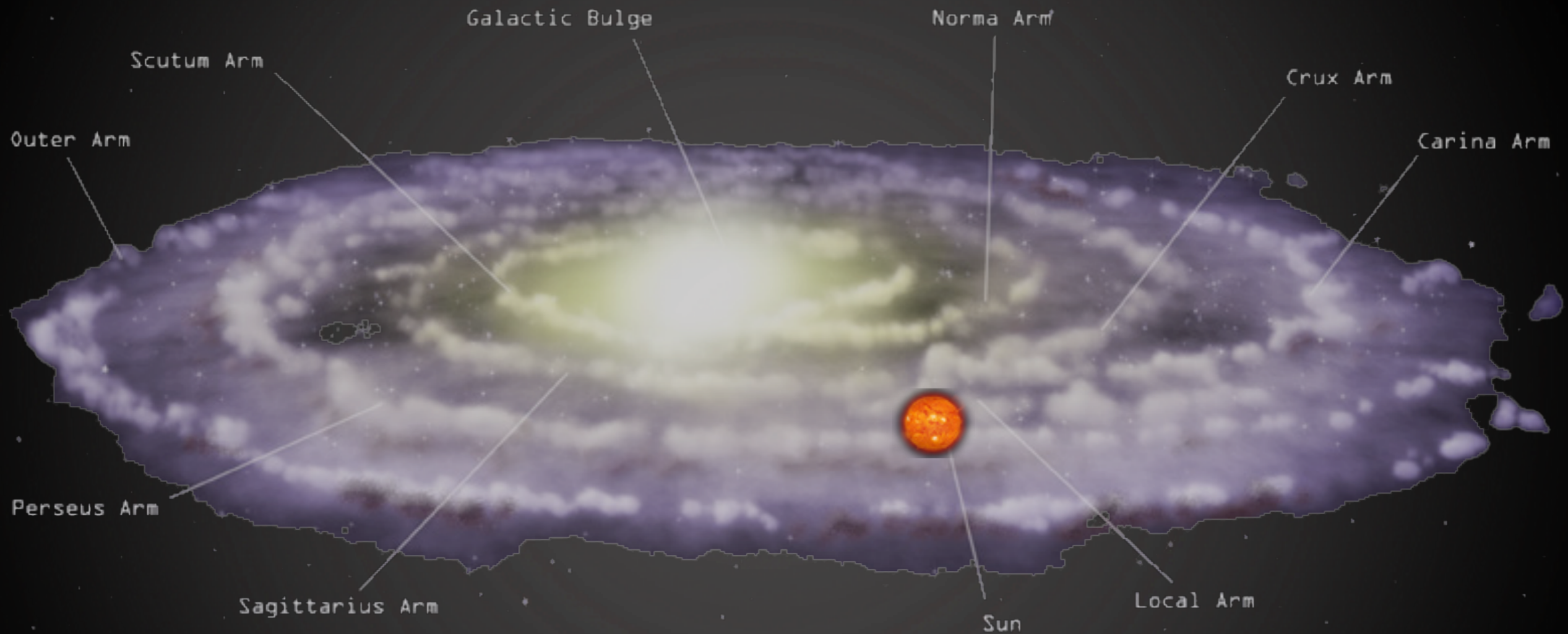
Détection indirecte

\bar{p} et e^+ de l'annihilation de MN dans l'halo



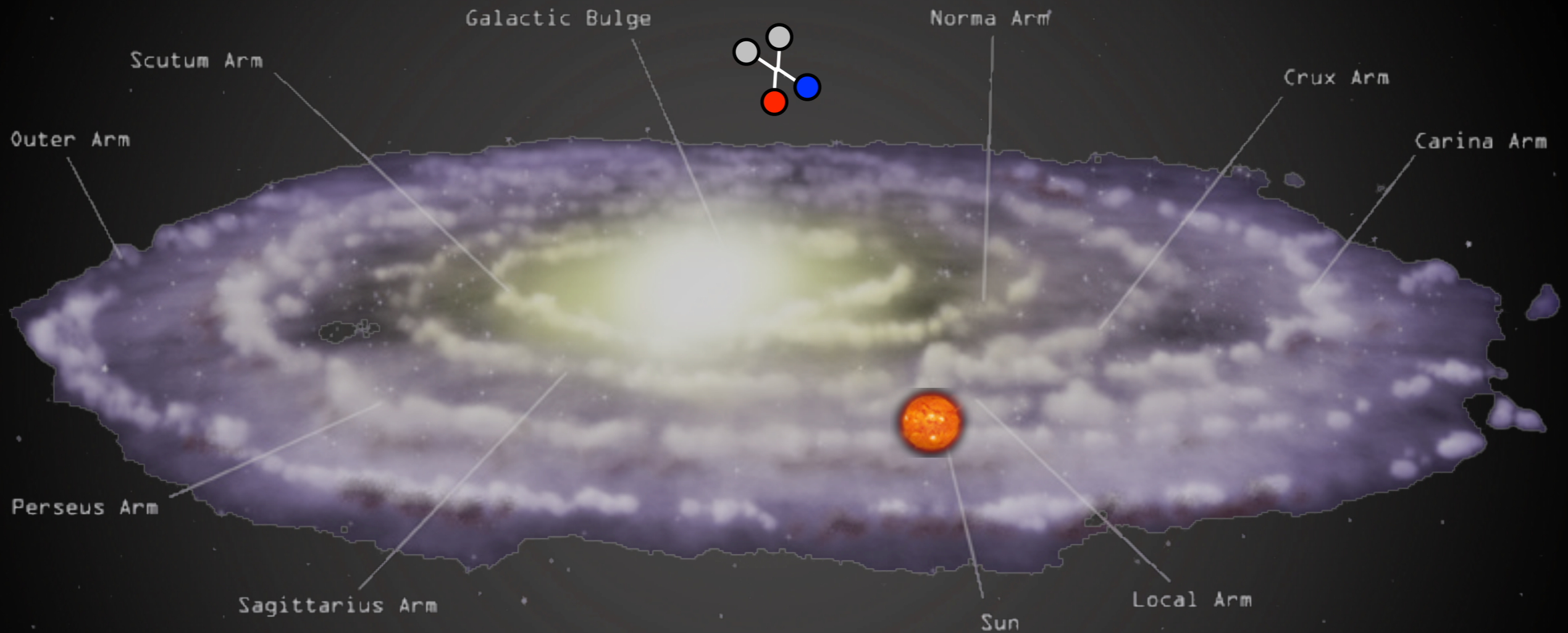
Détection indirecte

\bar{p} et e^+ de l'annihilation de MN dans l'halo



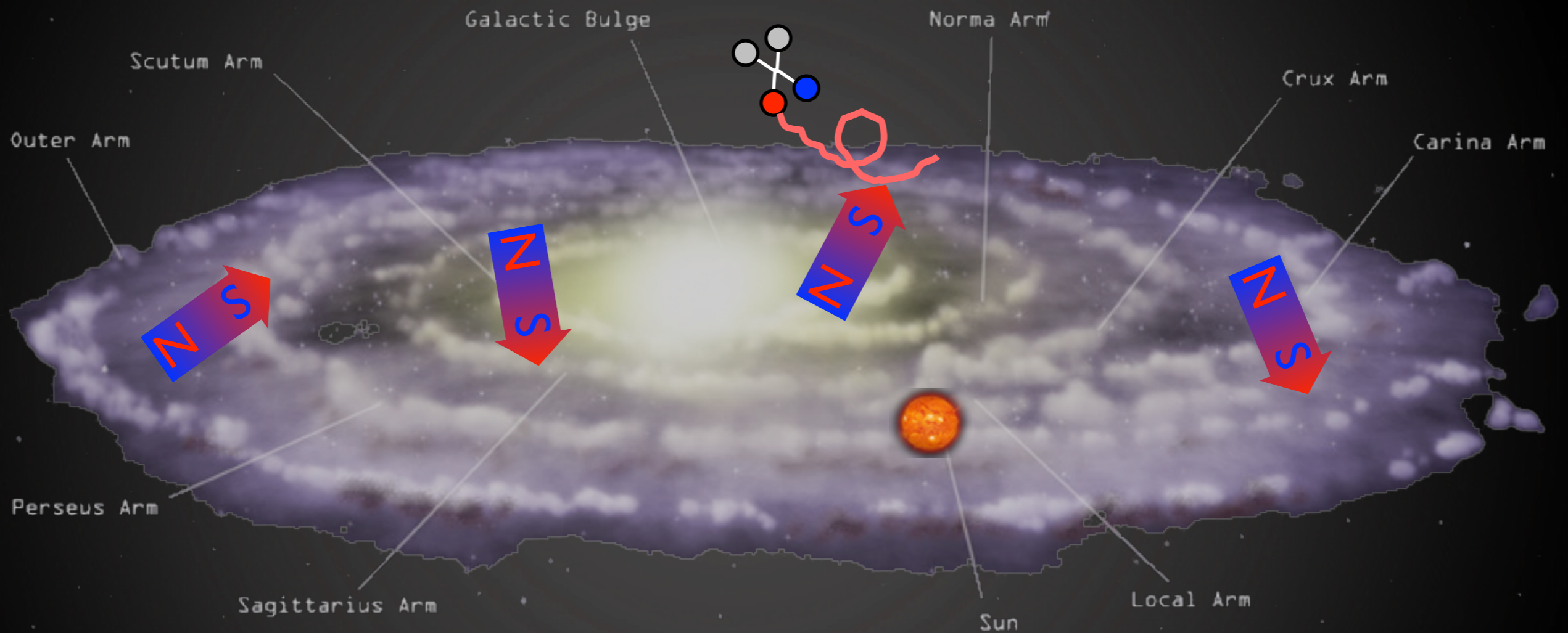
Détection indirecte

\bar{p} et e^+ de l'annihilation de MN dans l'halo



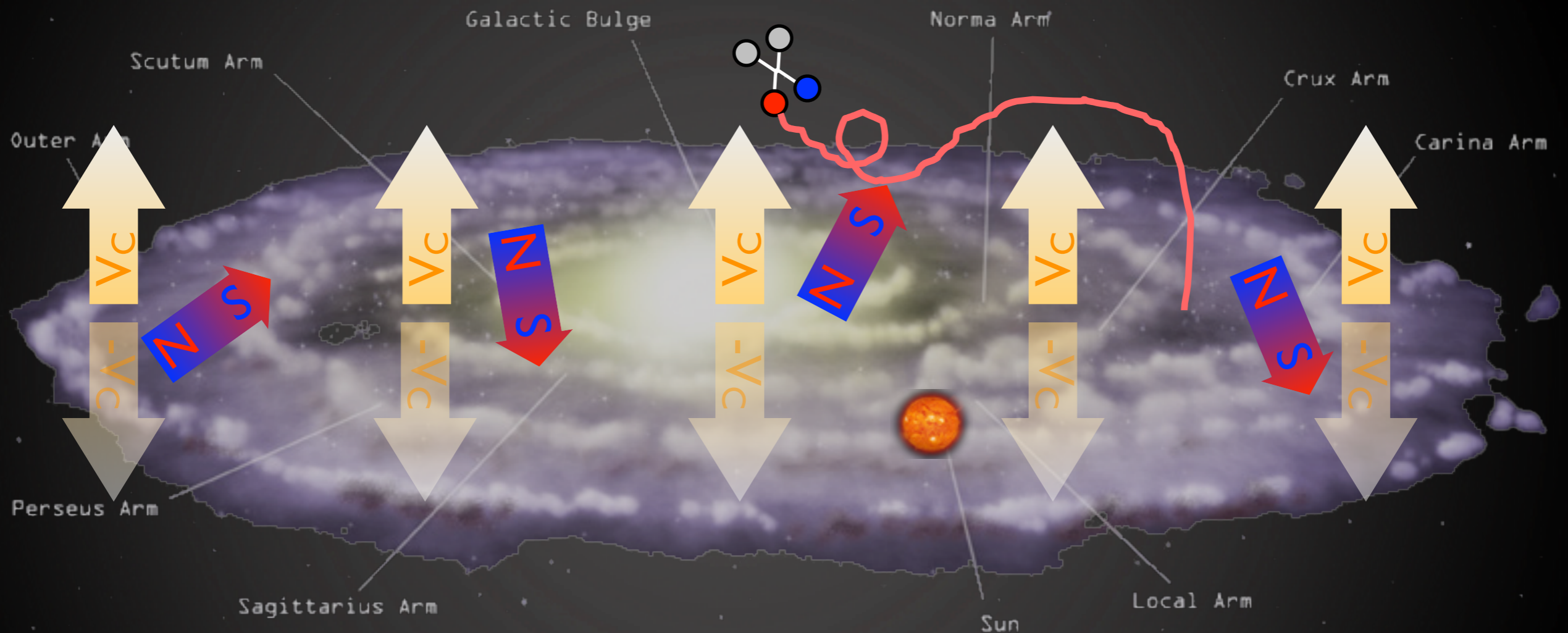
Détection indirecte

\bar{p} et e^+ de l'annihilation de MN dans l'halo



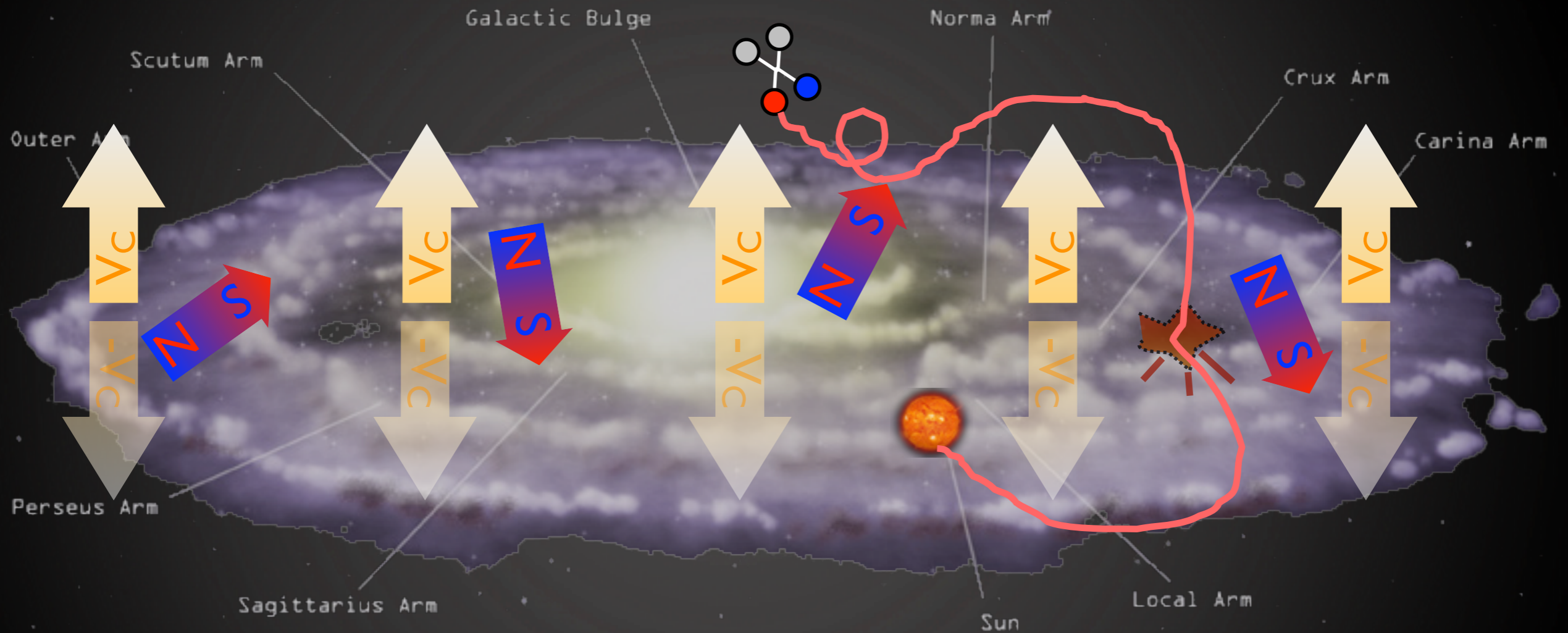
Détection indirecte

\bar{p} et e^+ de l'annihilation de MN dans l'halo



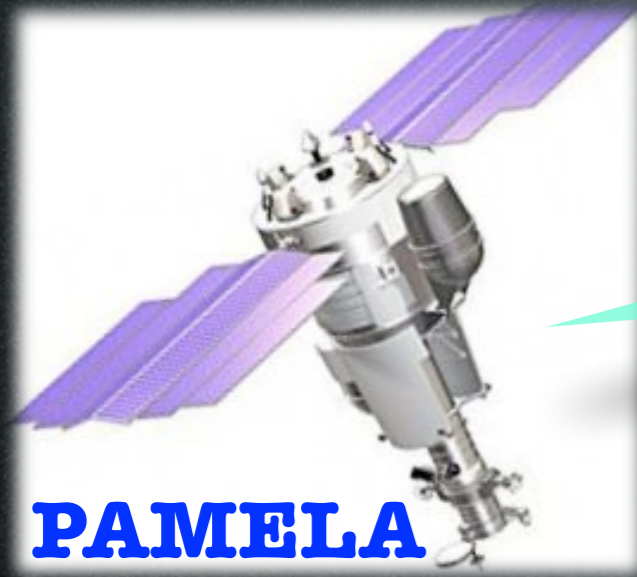
Détection indirecte

\bar{p} et e^+ de l'annihilation de MN dans l'halo



Détection indirecte: état de l'art

Détection indirecte: état de l'art

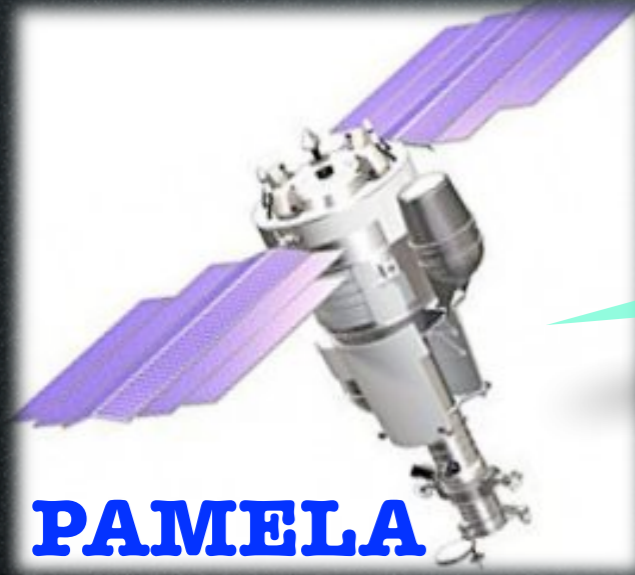


Oui! Matière noire!

Excès en **positrons**

2008

Détection indirecte: état de l'art



Oui! Matière noire!

Excès en **positrons**

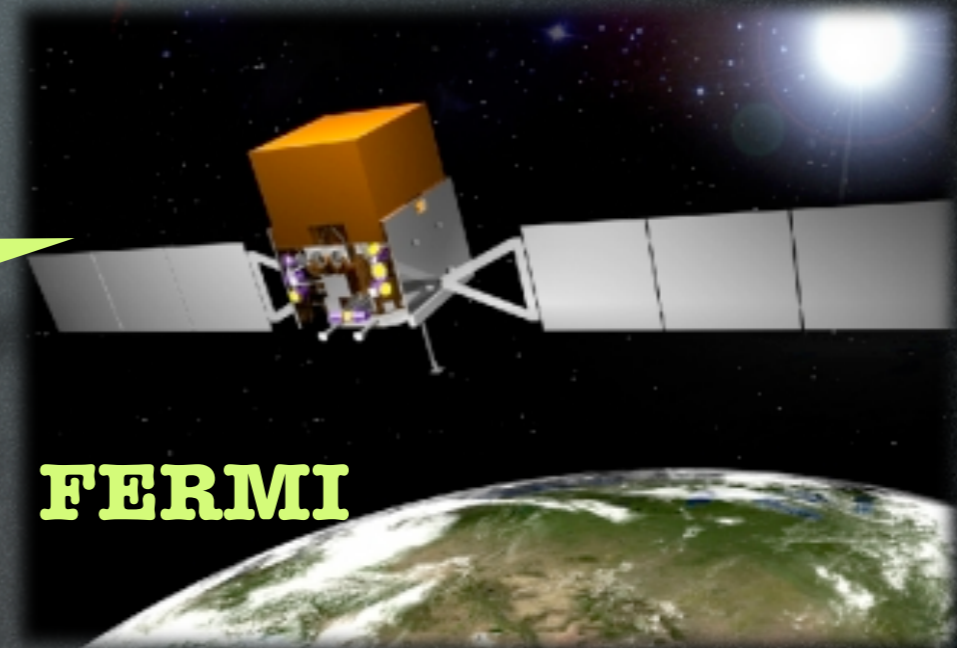
2008

Mmm, pas trop vite...

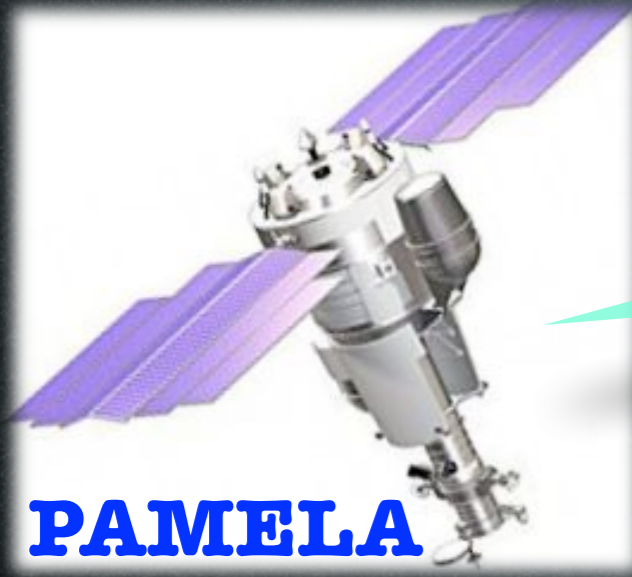
Oui, excès de **positrons**,
mais pas de **rayons gamma**.

En fait, si, mais ailleurs...

2009-2016



Détection indirecte: état de l'art



PAMELA

Oui! Matière noire!

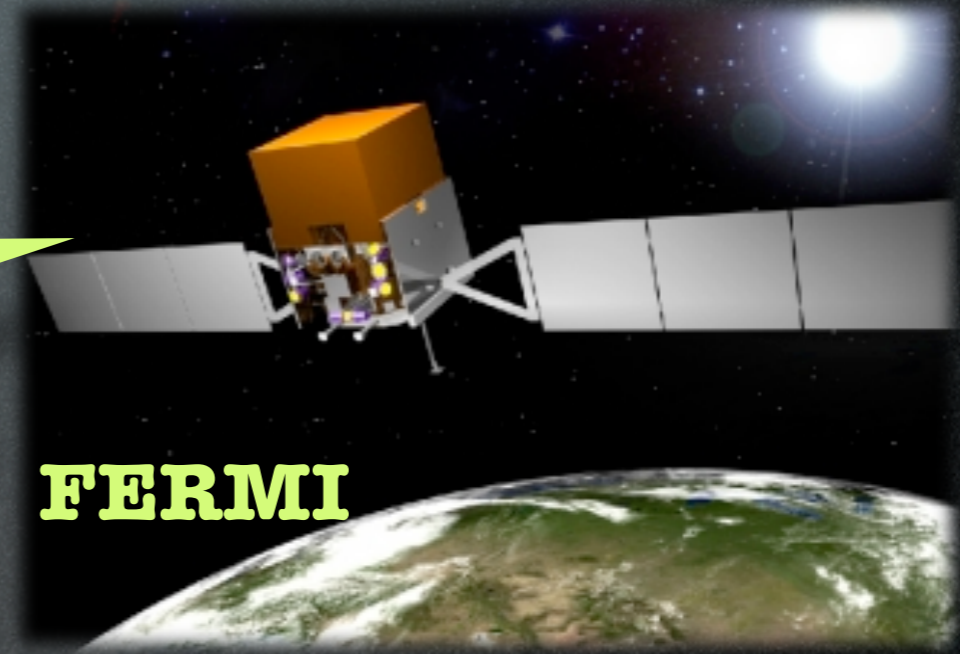
Excès en **positrons**

2008

Mmm, pas trop vite...

Oui, excès de **positrons**,
mais pas de **rayons gamma**.
En fait, si, mais ailleurs...

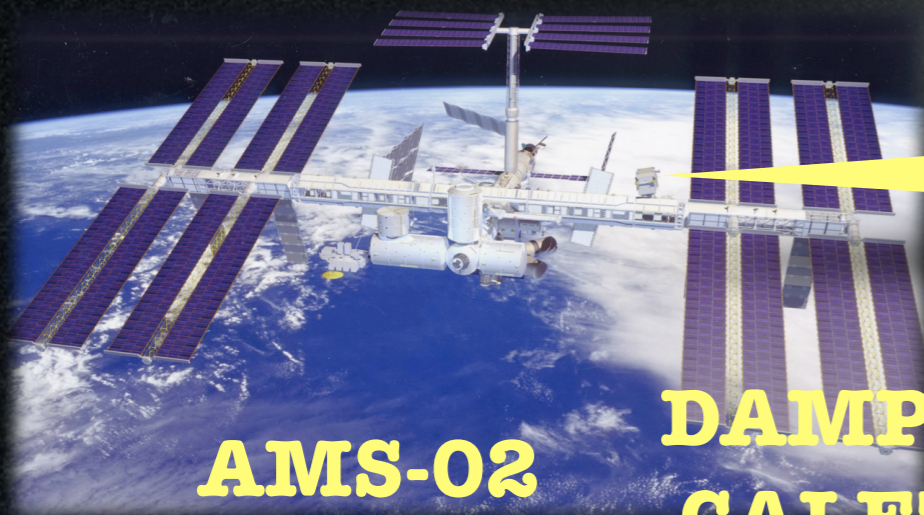
2009-2016



FERMI

Voyons voir...

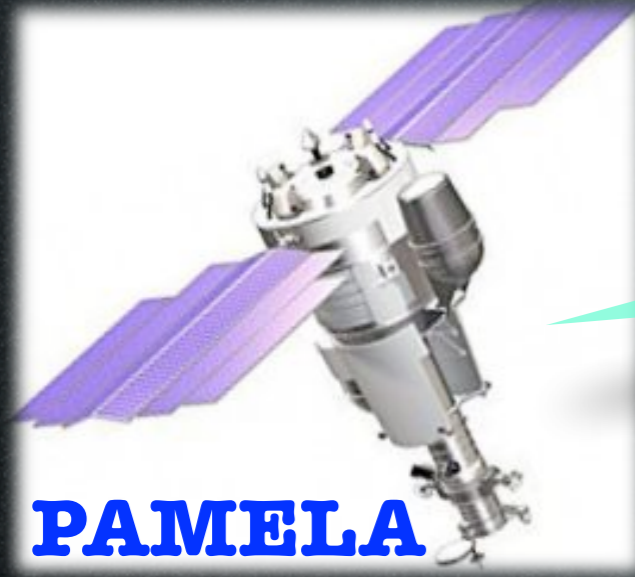
2011-2021...



AMS-02

**DAMPE
CALET**

Détection indirecte: état de l'art



PAMELA

Oui! Matière noire!

Excès en **positrons**

2008

Mmm, pas trop vite...

Oui, excès de **positrons**,
mais pas de **rayons gamma**.
En fait, si, mais ailleurs...

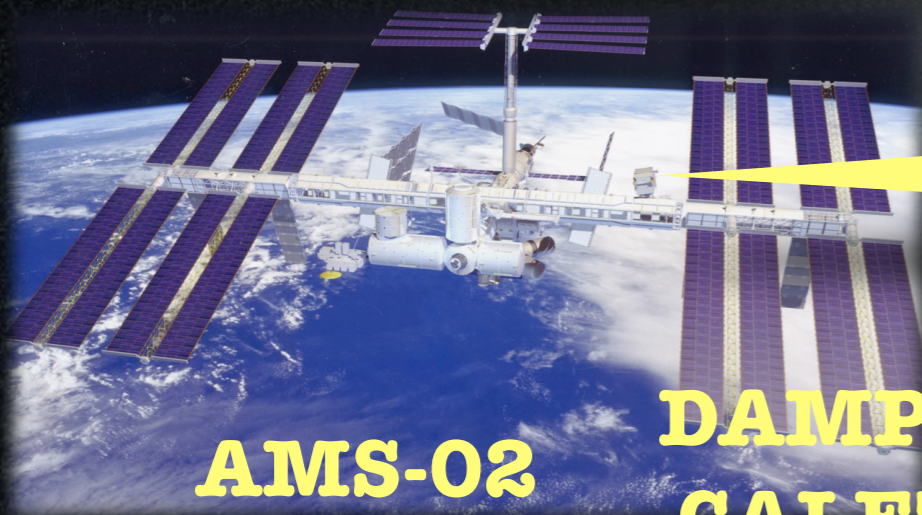
2009-2016



FERMI

Voyons voir...

2011-2021...



AMS-02

DAMPE
CALET

Un théoricien lambda

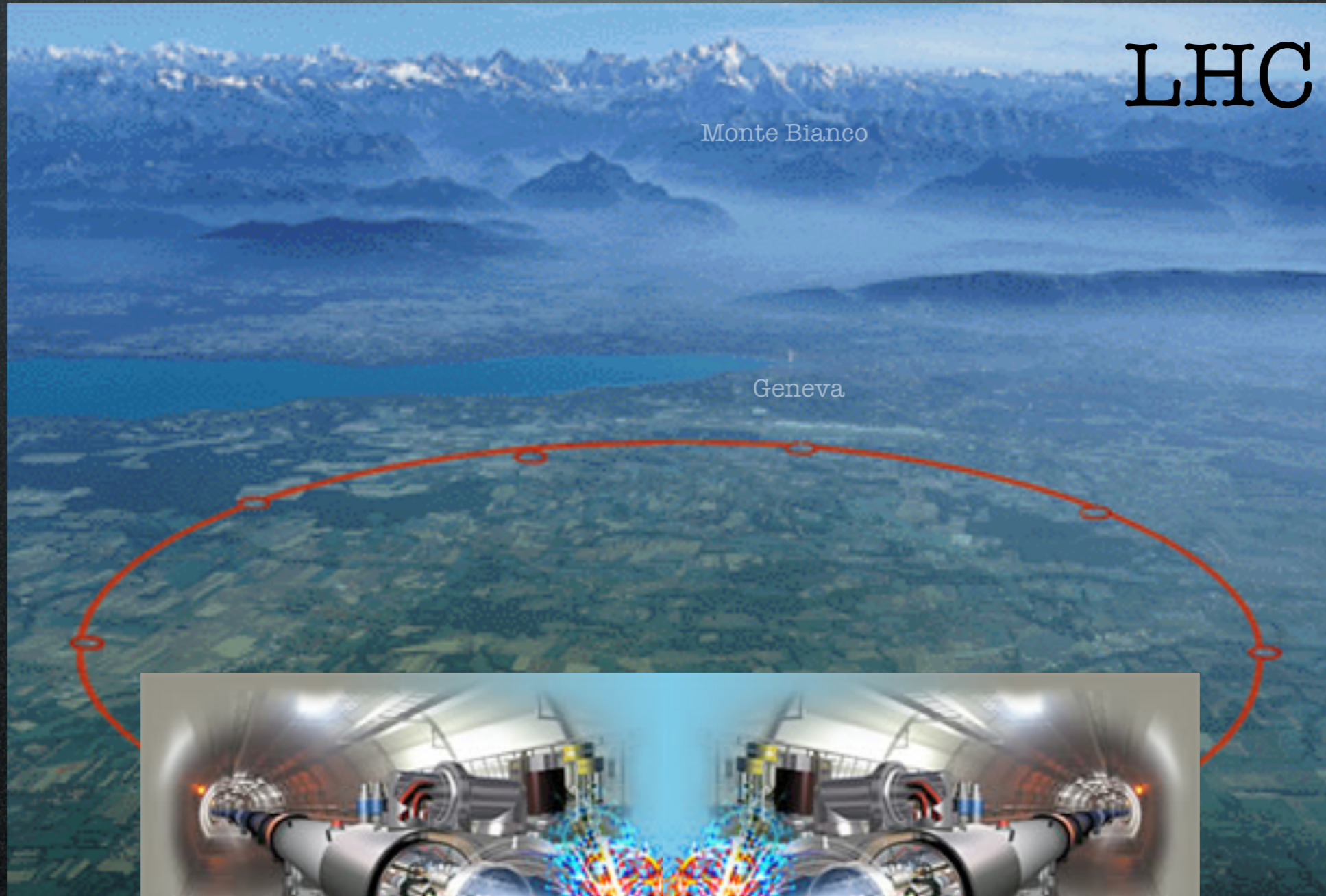


Production aux collisionneurs

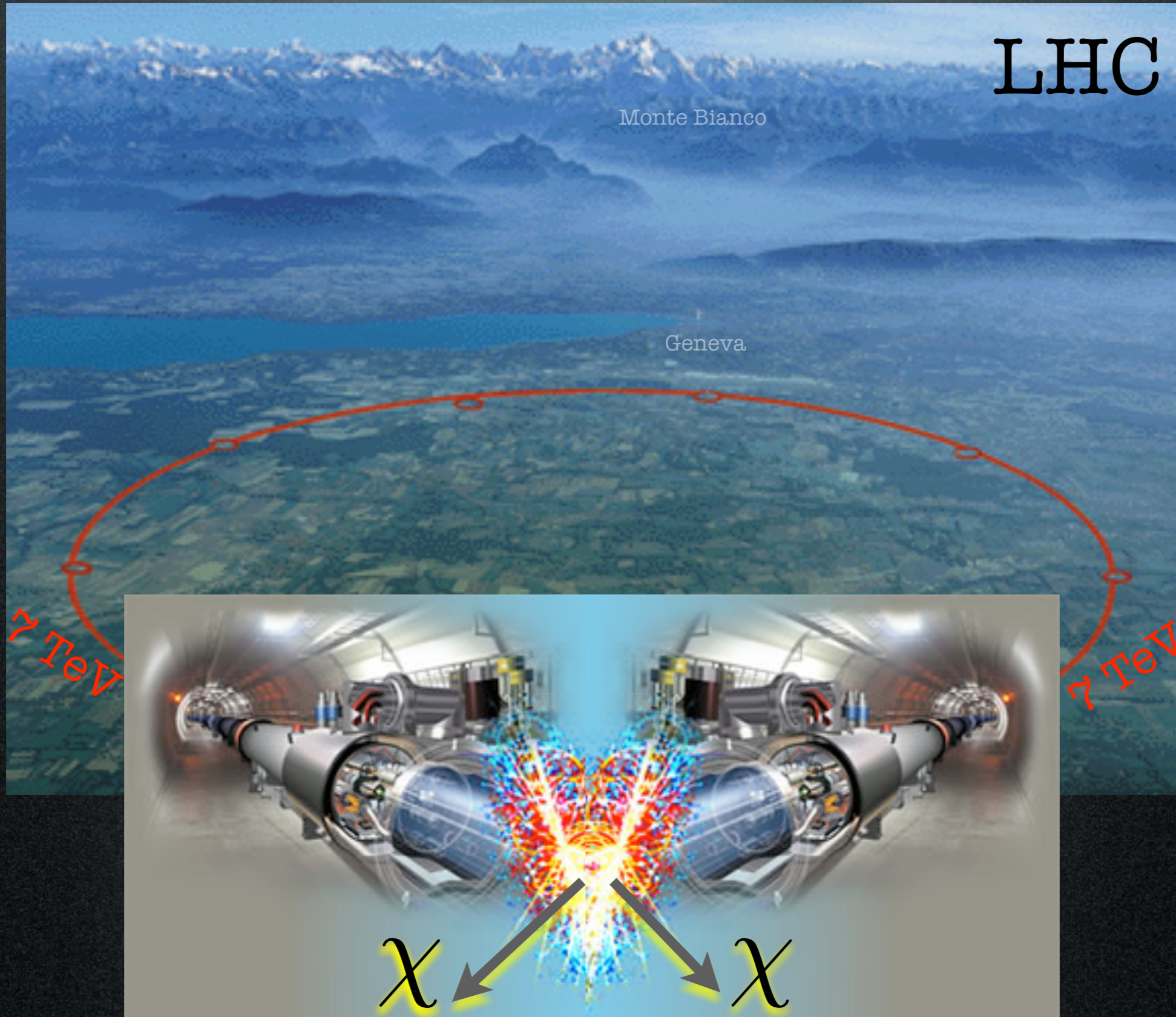


Special guest star:
Fabio Cirelli

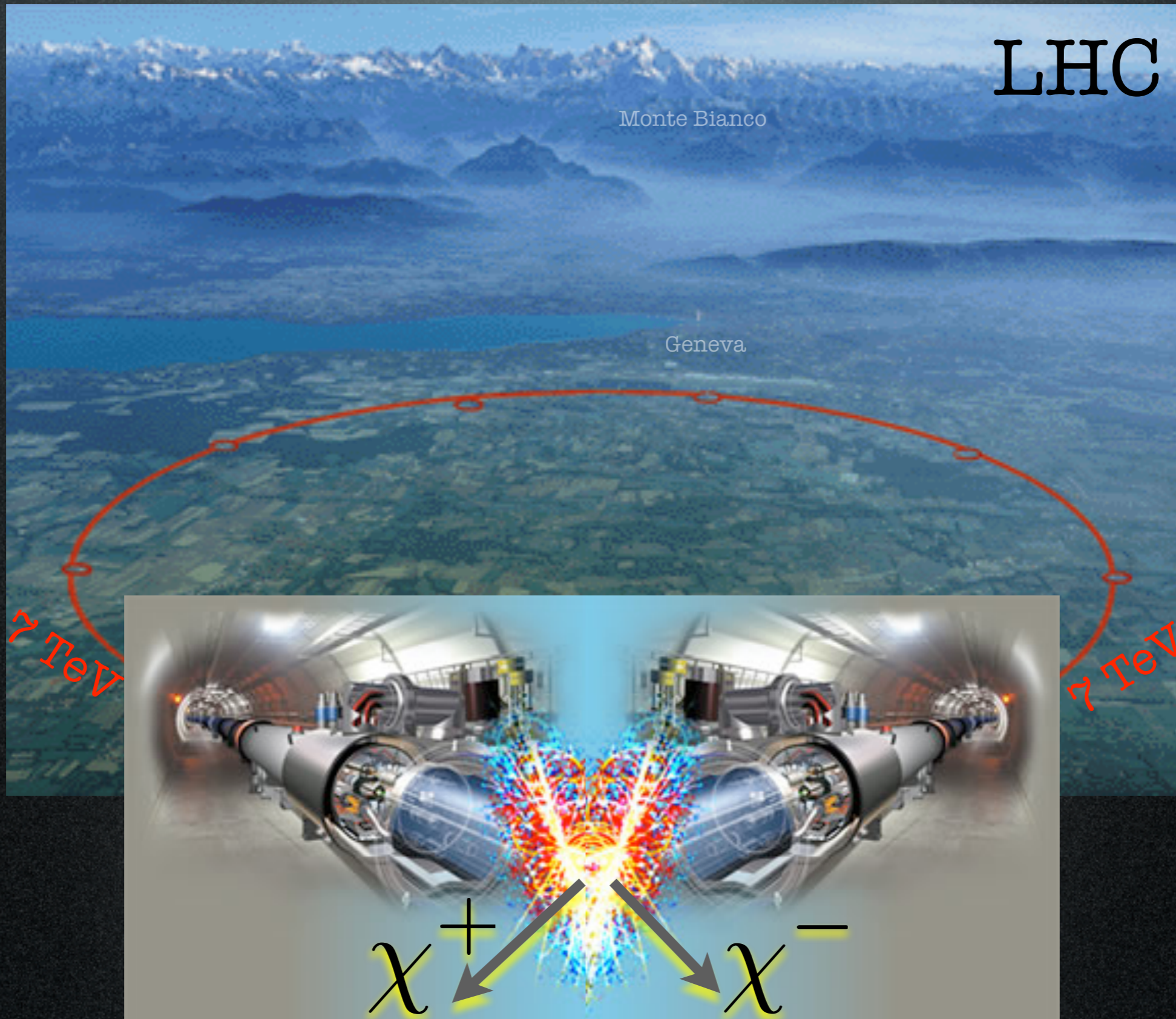
Production aux collisionneurs



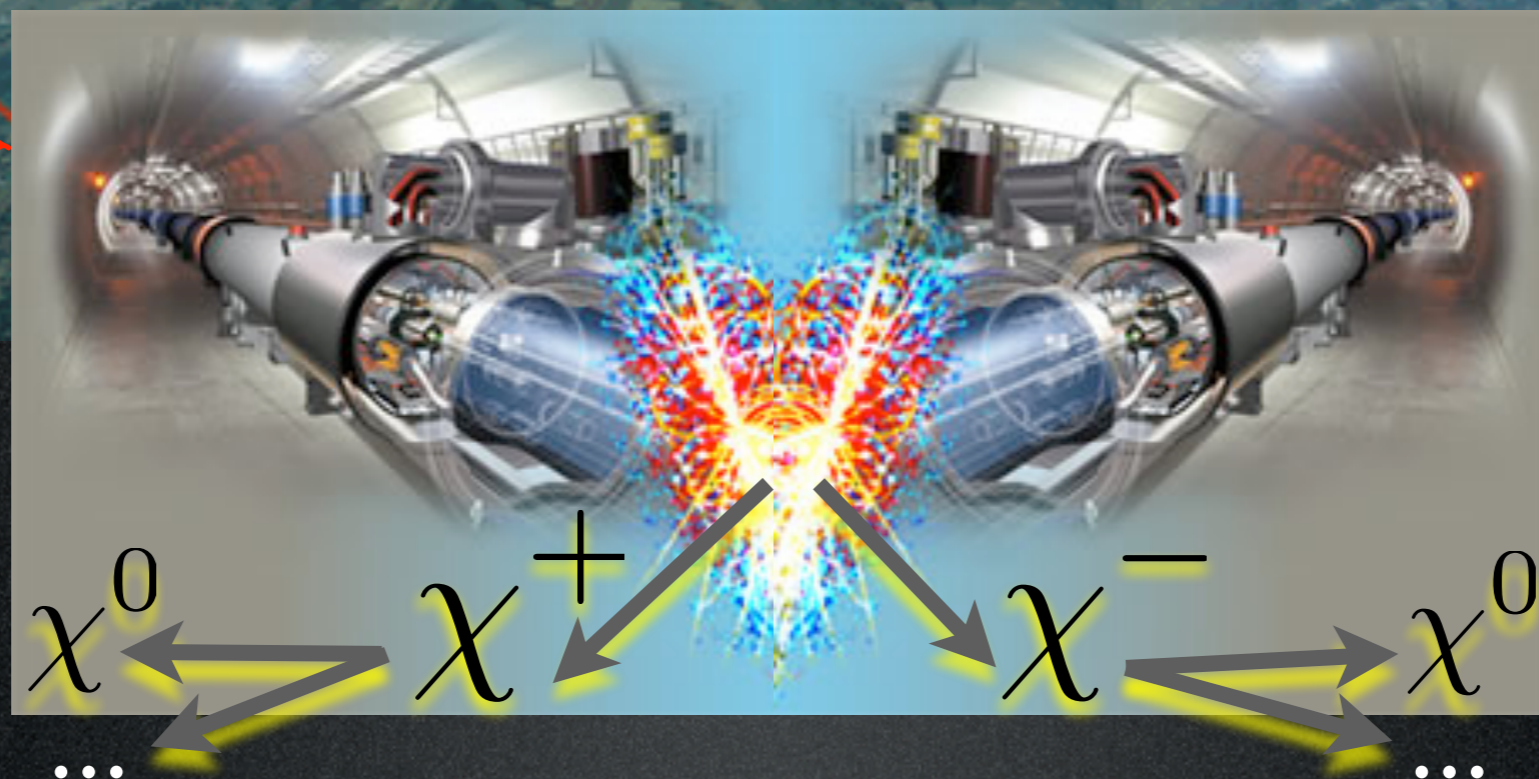
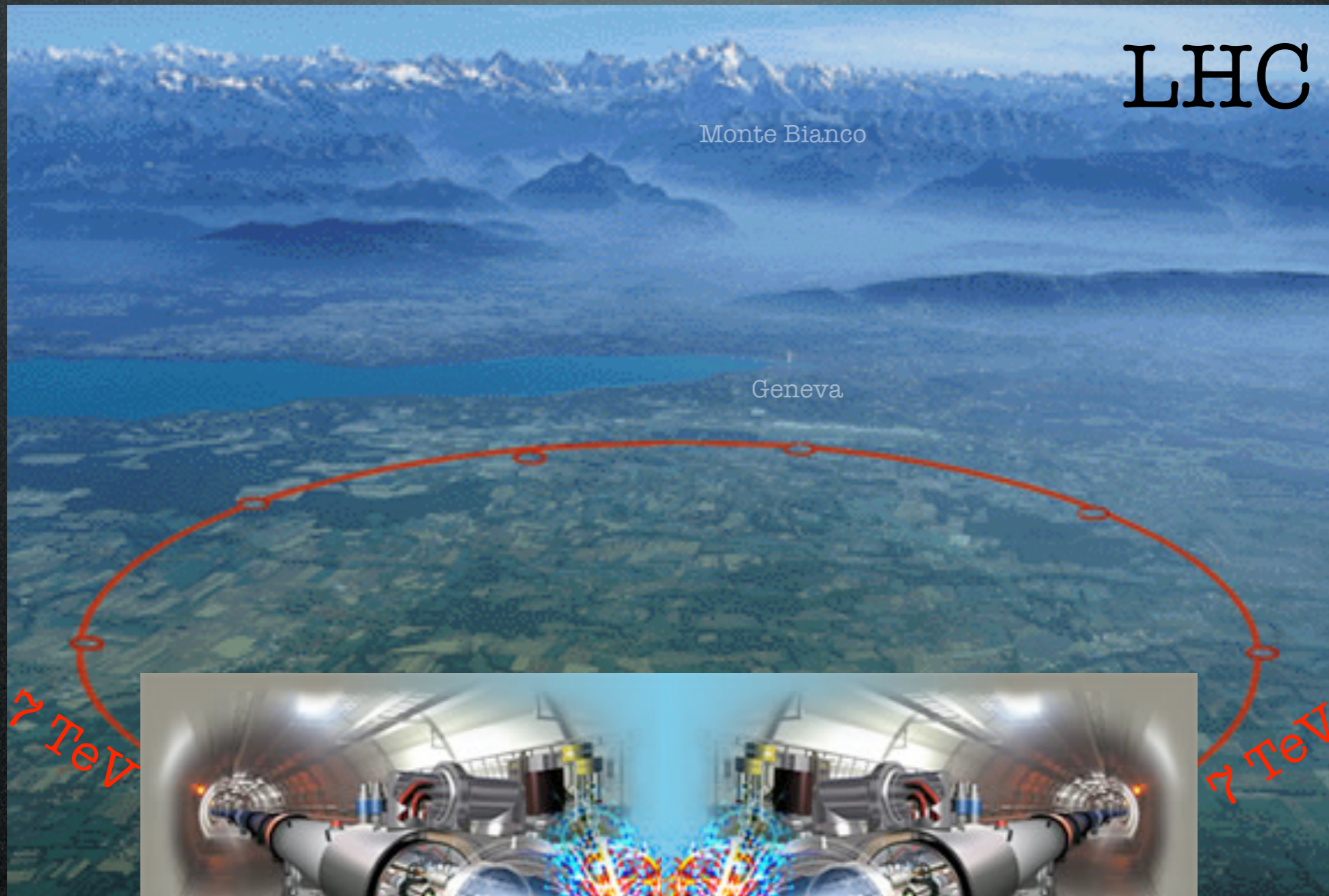
Production aux collisionneurs



Production at colliders

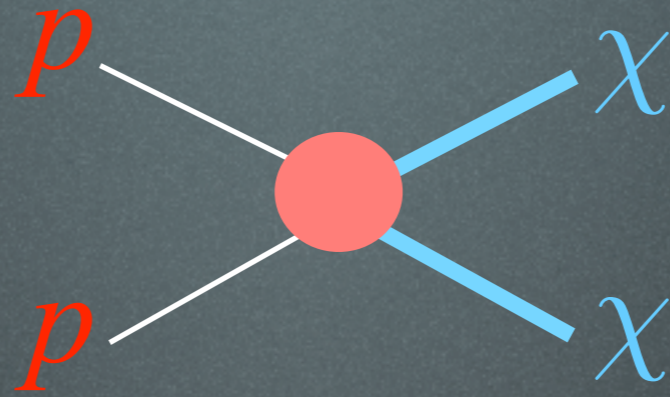


Production at colliders

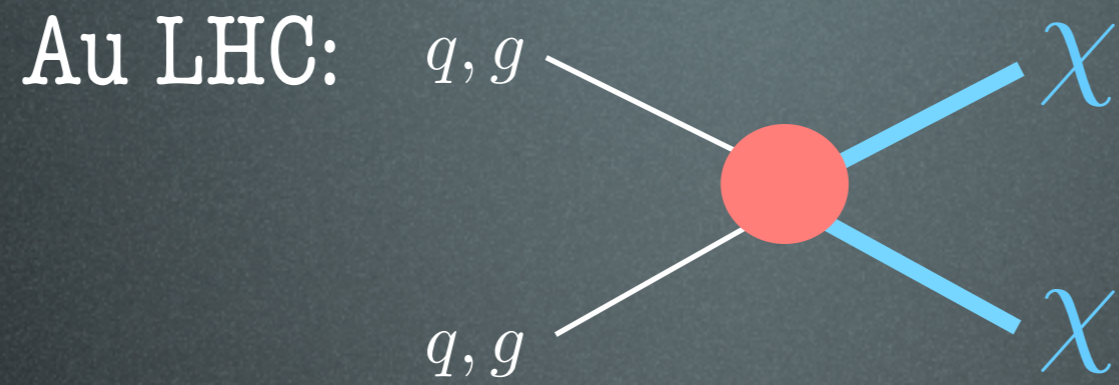


Production aux collisionneurs

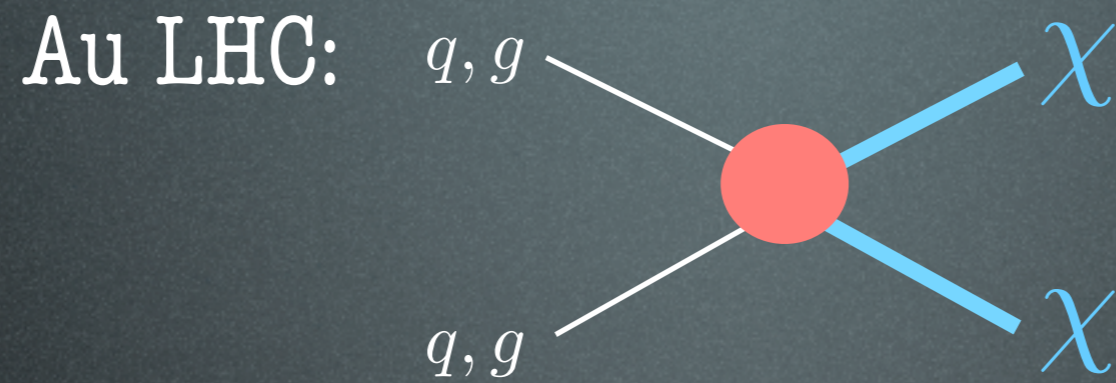
Au LHC:



Production aux collisionneurs

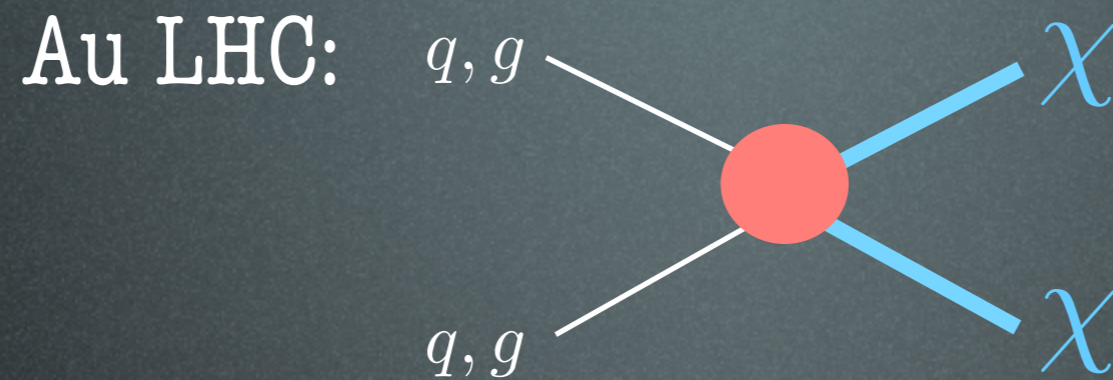


Production aux collisionneurs



Le 'problème' est: la matière noire ne laisse pas de traces

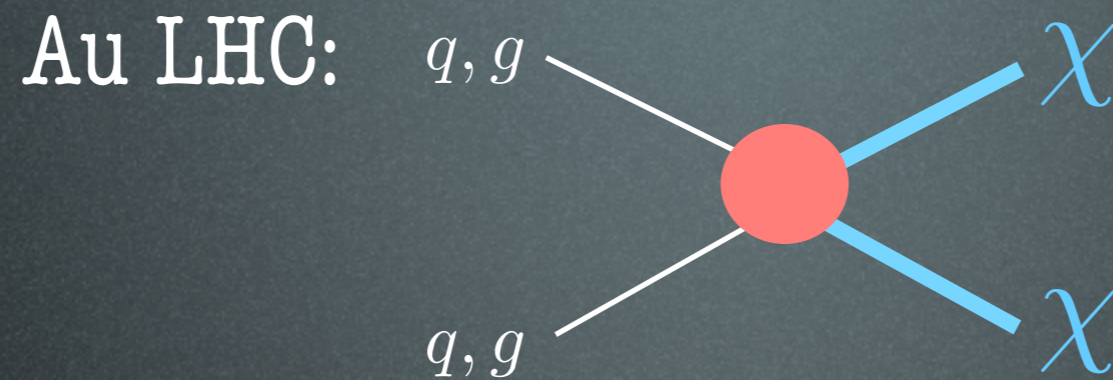
Production aux collisionneurs



Le 'problème' est: la matière noire ne laisse pas de traces

L'évidence est: **énergie manquante**

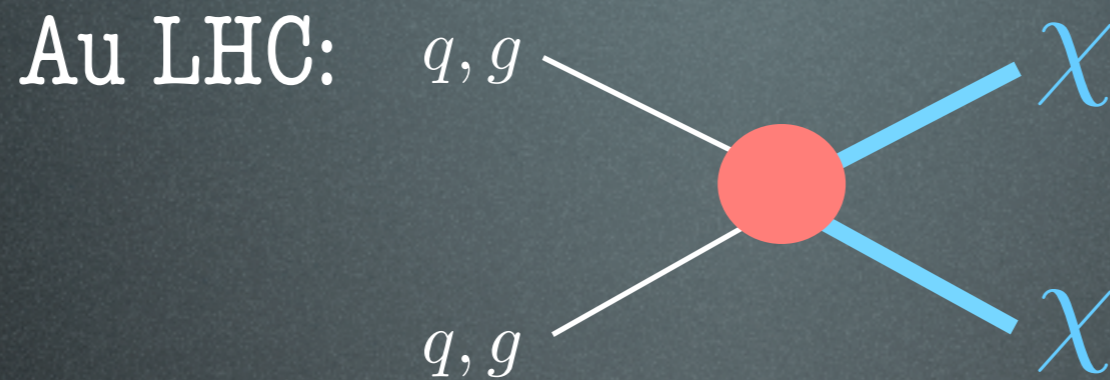
Production aux collisionneurs



Le 'problème' est: la matière noire ne laisse pas de traces

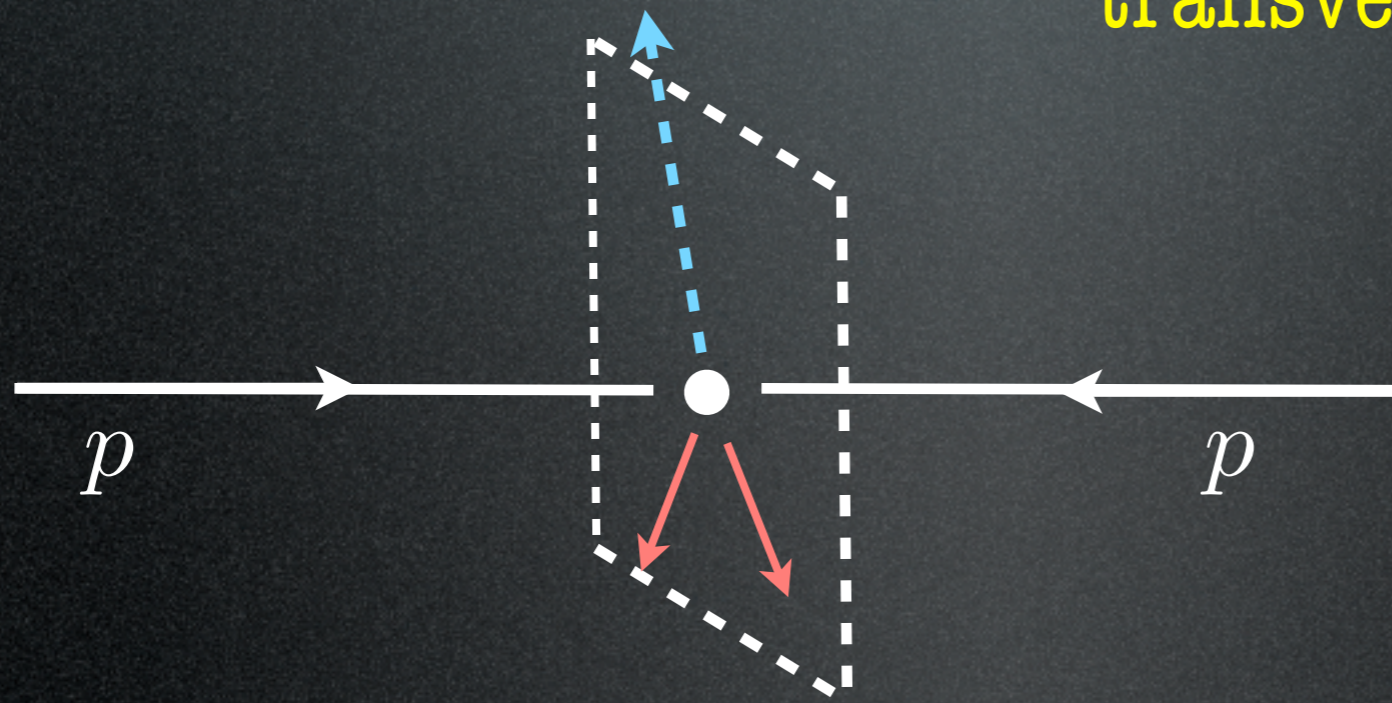
L'évidence est: énergie manquante
transverse

Production aux collisionneurs

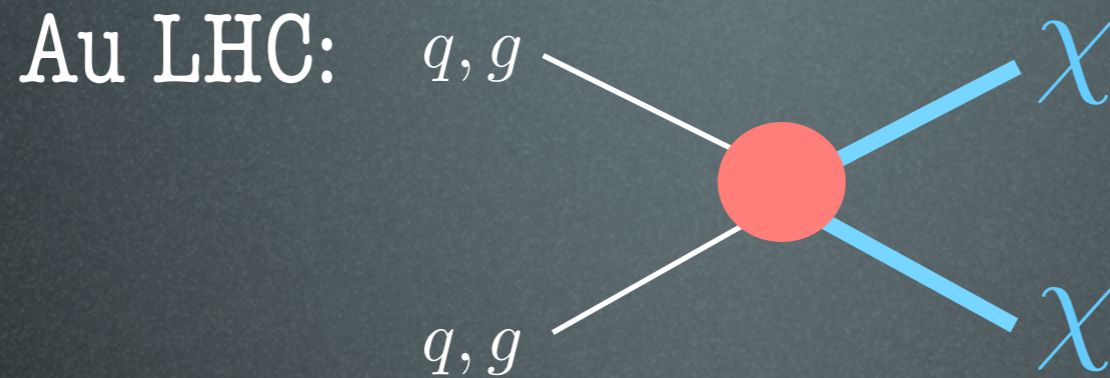


Le 'problème' est: la matière noire ne laisse pas de traces

L'évidence est: **énergie manquante**
transverse

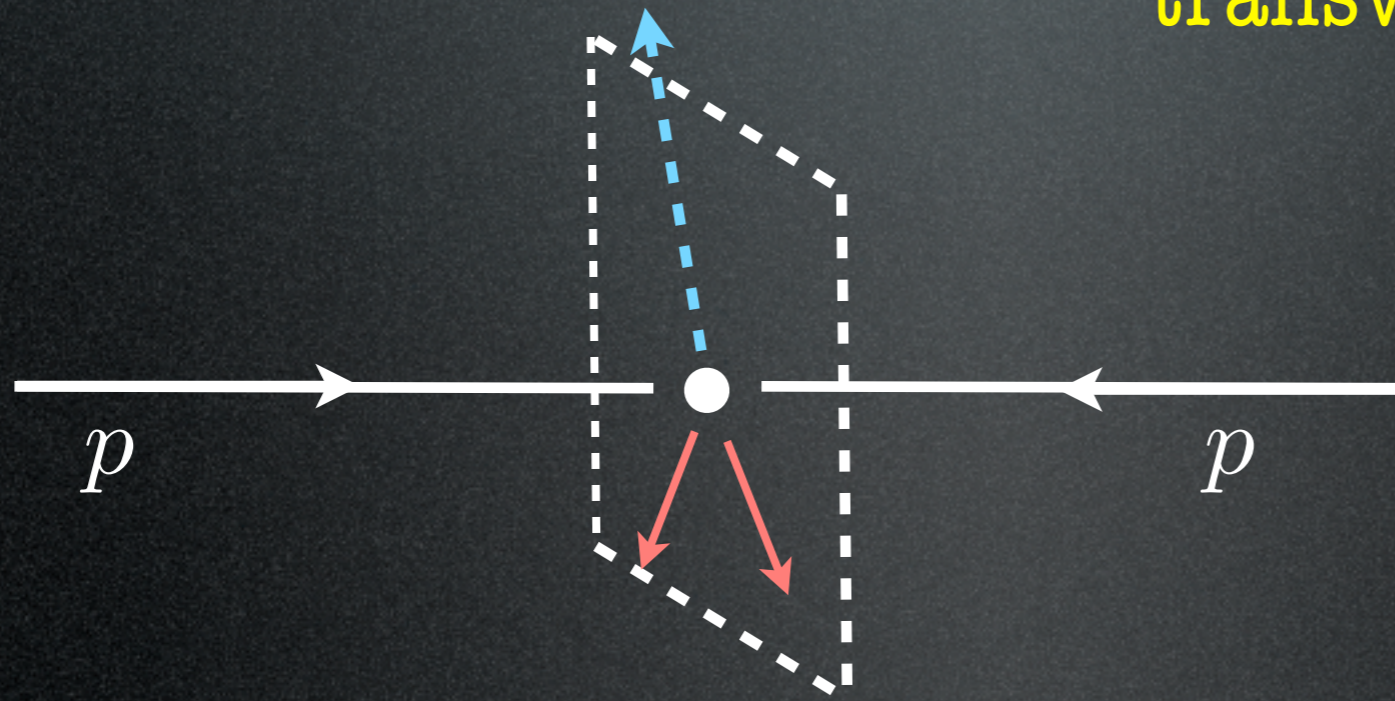


Production aux collisionneurs



‘Problem’ is: DM flies away

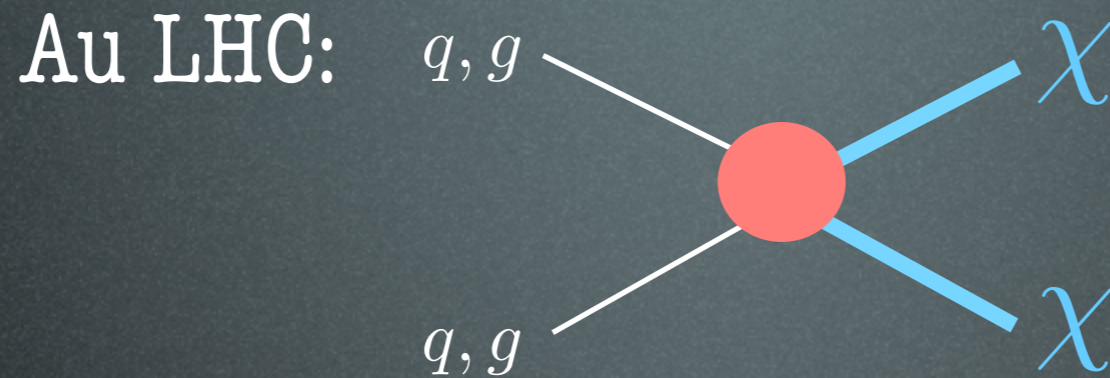
Signature is: **missing energy**
transverse



Before collision: $\vec{P}_T^{\text{tot}} \equiv 0$
(NB: $\vec{P}_L^{\text{tot}} \neq 0$ in general)

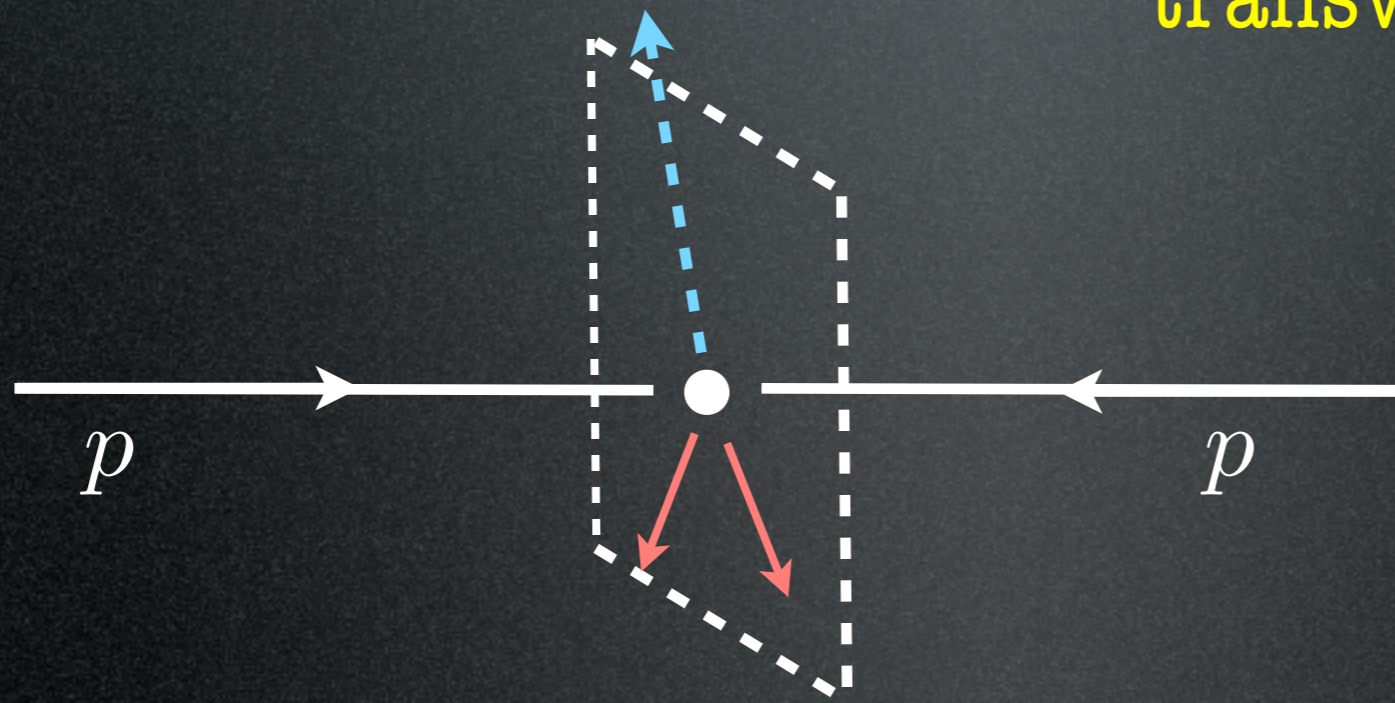
After collision: $\vec{P}_T^{\text{vis}} \stackrel{?}{=} 0$
If \neq , then ‘**MET**’

Production aux collisionneurs



‘Problem’ is: DM flies away

Signature is: **missing energy**
transverse



Before collision: $\vec{P}_T^{\text{tot}} \equiv 0$

(NB: $\vec{P}_L^{\text{tot}} \neq 0$ in general)

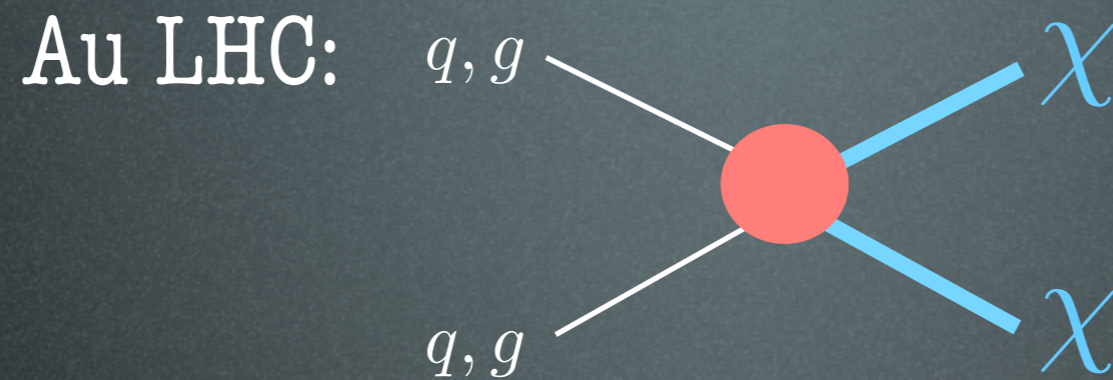
After collision: $\vec{P}_T^{\text{vis}} \stackrel{?}{=} 0$

If \neq , then ‘**MET**’

Background: neutrinos (e.g. $W \rightarrow e\nu$)

- model your background and look for anomalies
- construct kinematic variables sensitive to χ mass

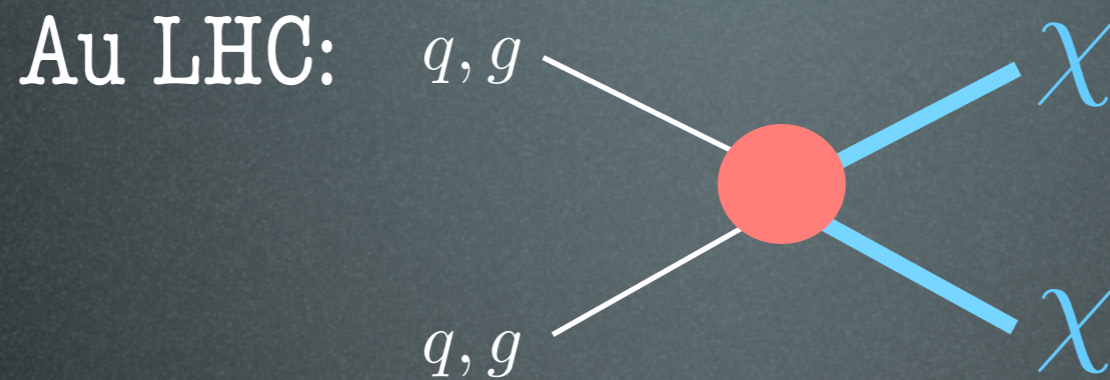
Production aux collisionneurs



Le 'problème' est: la matière noire ne laisse pas de traces

L'évidence est: énergie manquante
transverse

Production aux collisionneurs

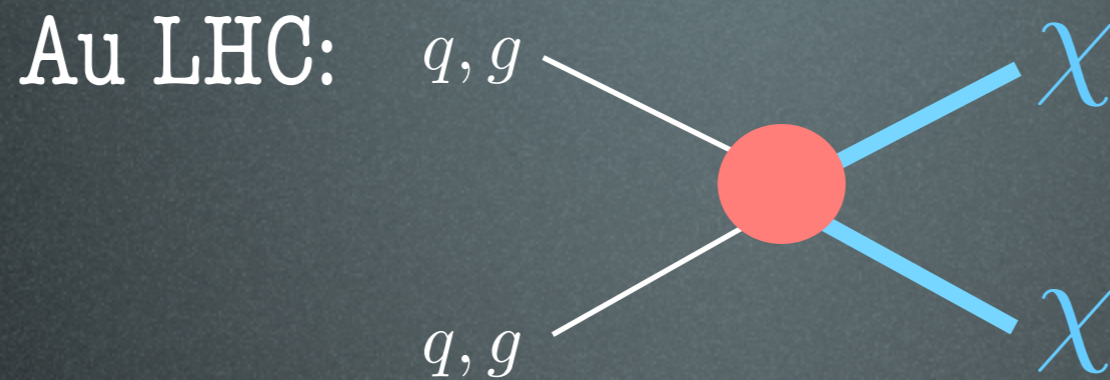


Le 'problème' est: la matière noire ne laisse pas de traces

L'évidence est: énergie manquante
transverse

Status: Pour le moment,
pas d'énergie
manquante.
Du tout.

Production aux collisionneurs



Le 'problème' est: la matière noire ne laisse pas de traces

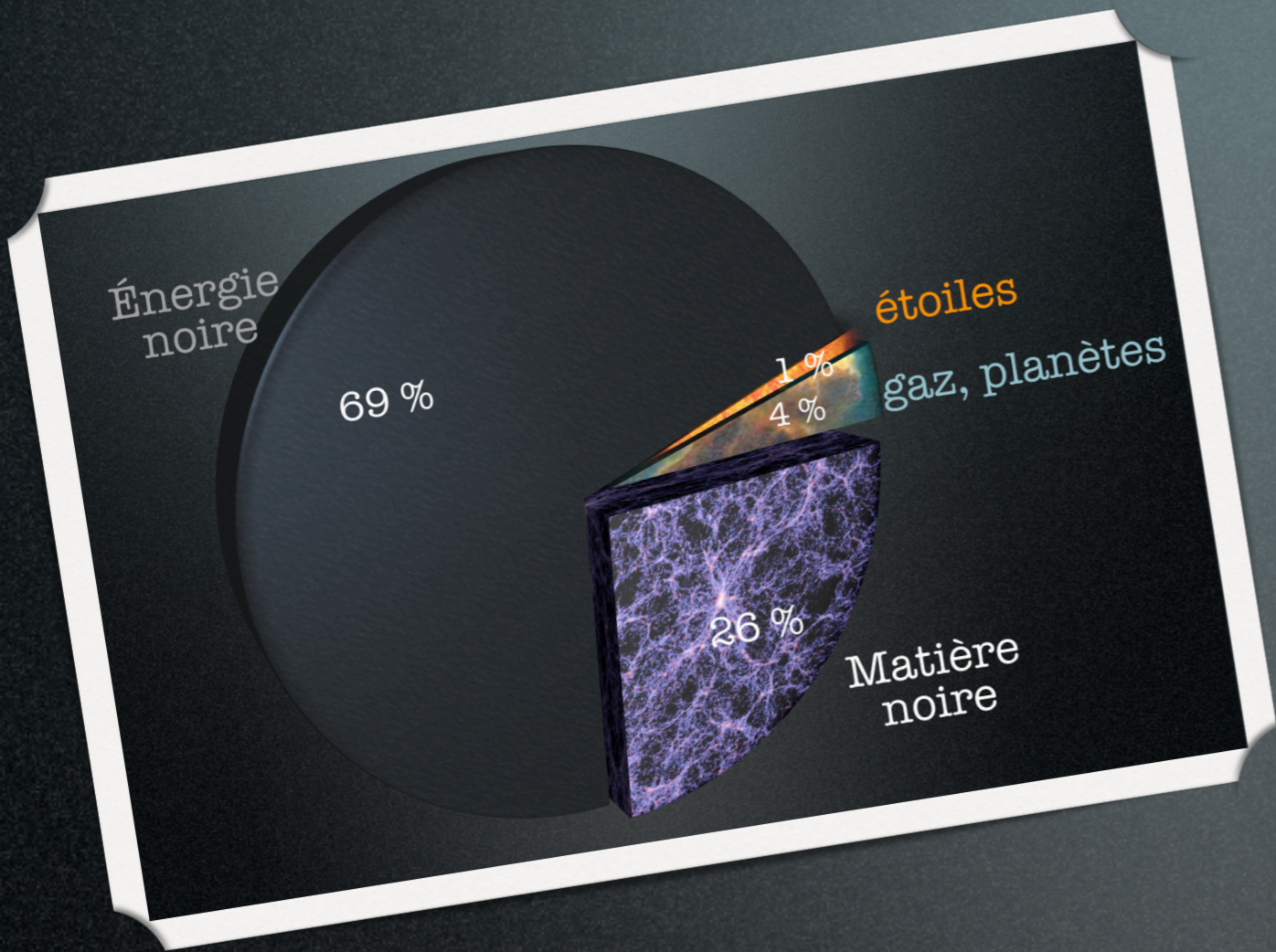
L'évidence est: énergie manquante
transverse

Status: Pour le moment,
pas d'énergie
manquante.
Du tout.



De quoi est fait notre Univers ?

De quoi est fait notre Univers ?



De quoi est fait notre Univers ?

Énergie
noire

69 %

étoiles

1 %

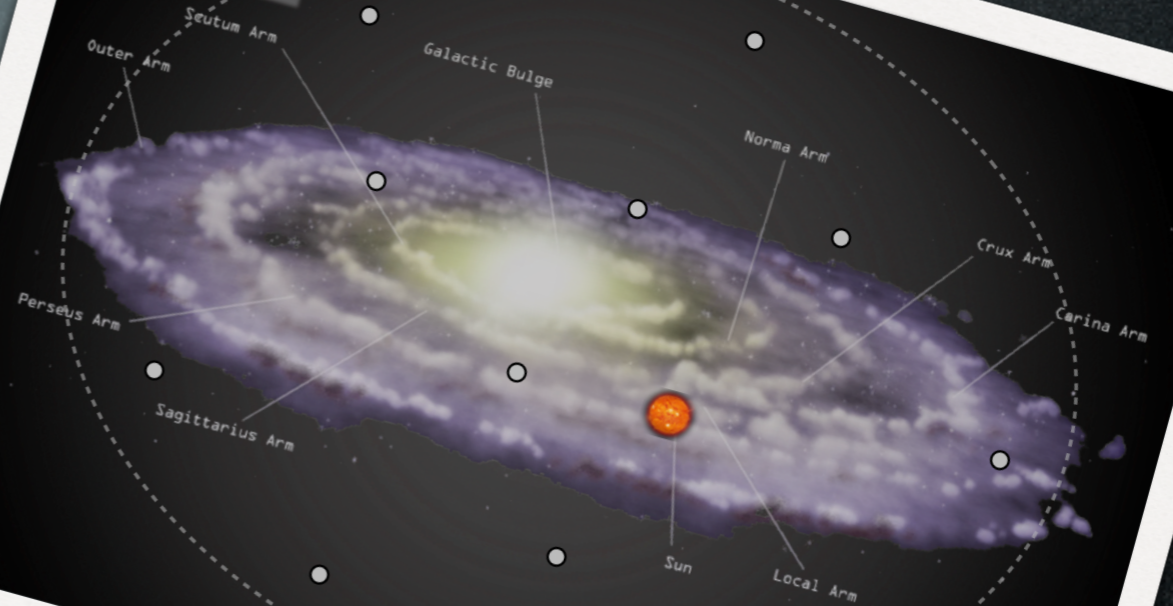
4 %

gaz, planètes

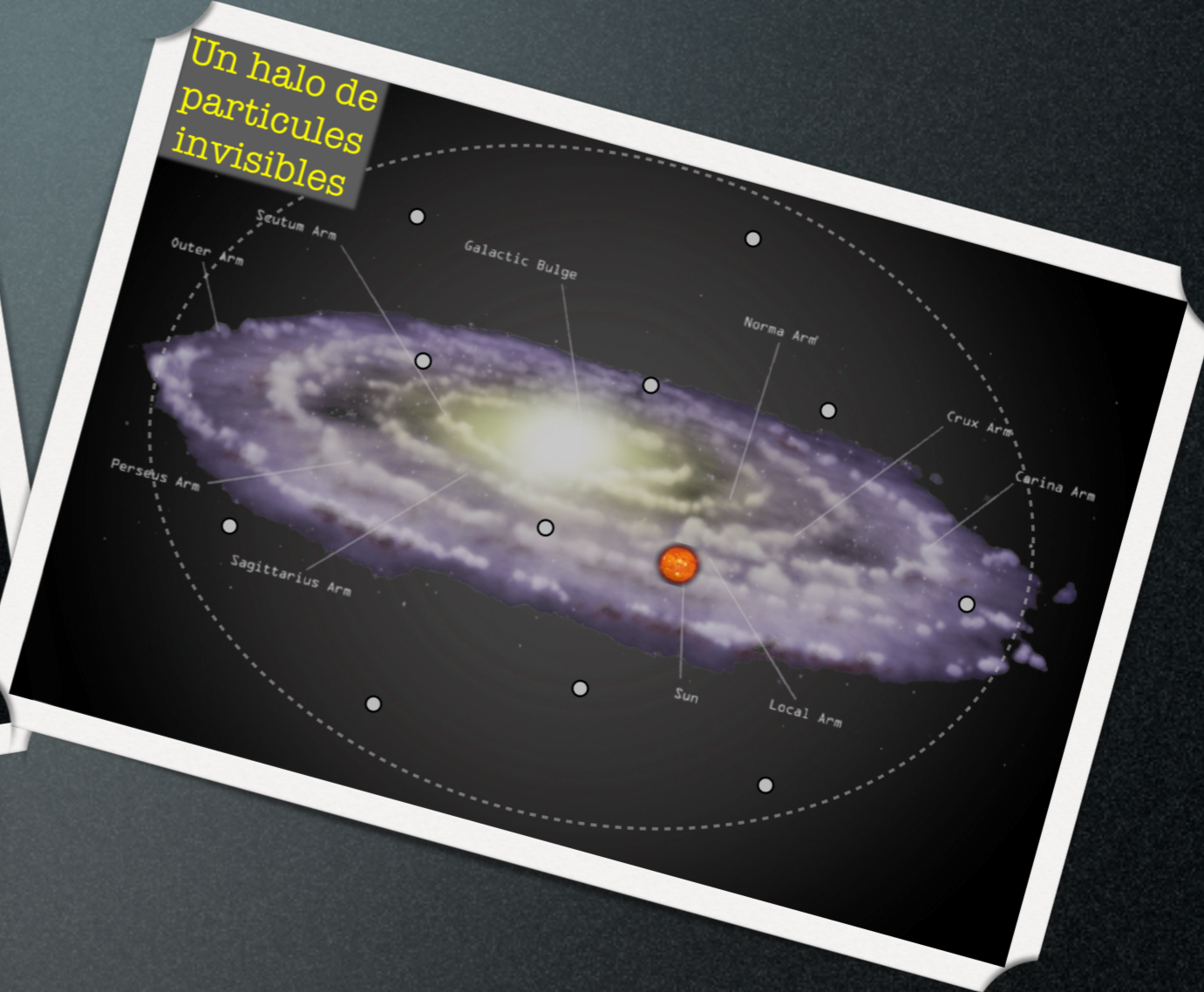
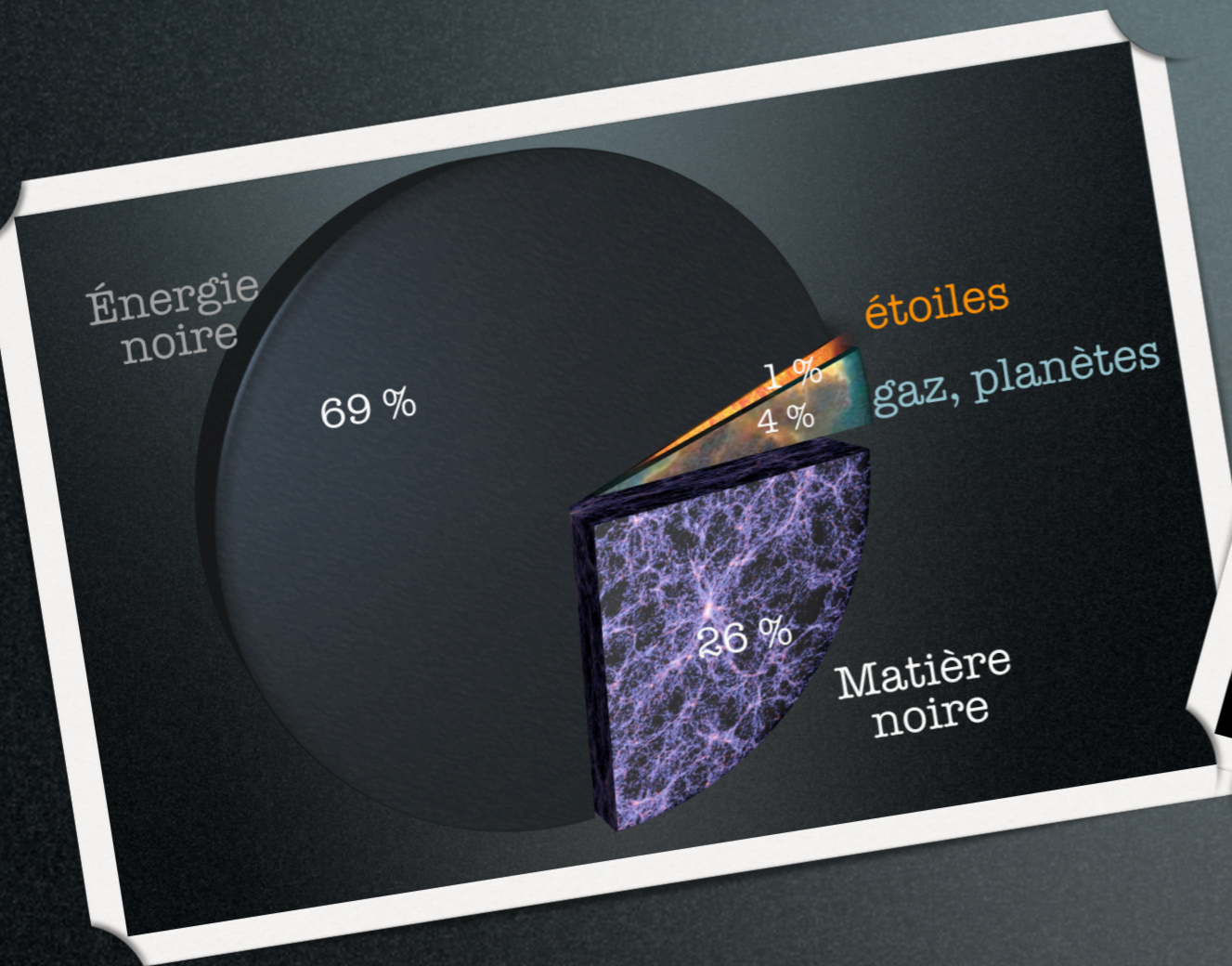
26 %

Matière
noire

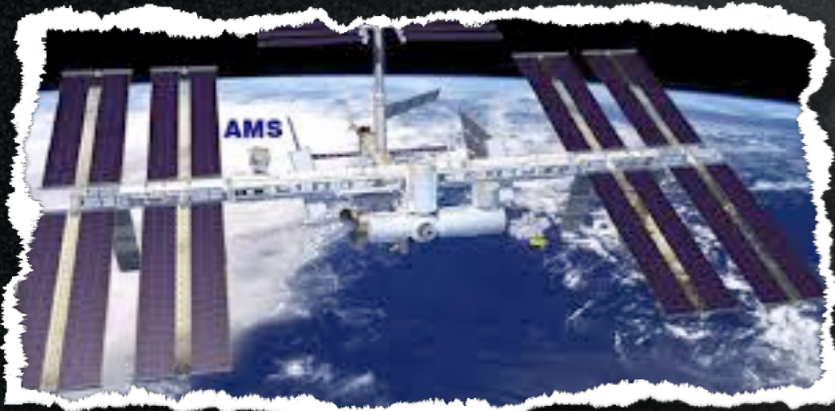
Un halo de
particules
invisibles



De quoi est fait notre Univers ?



Physique spatiale



Physique aux collisionneurs



Physique souterraine

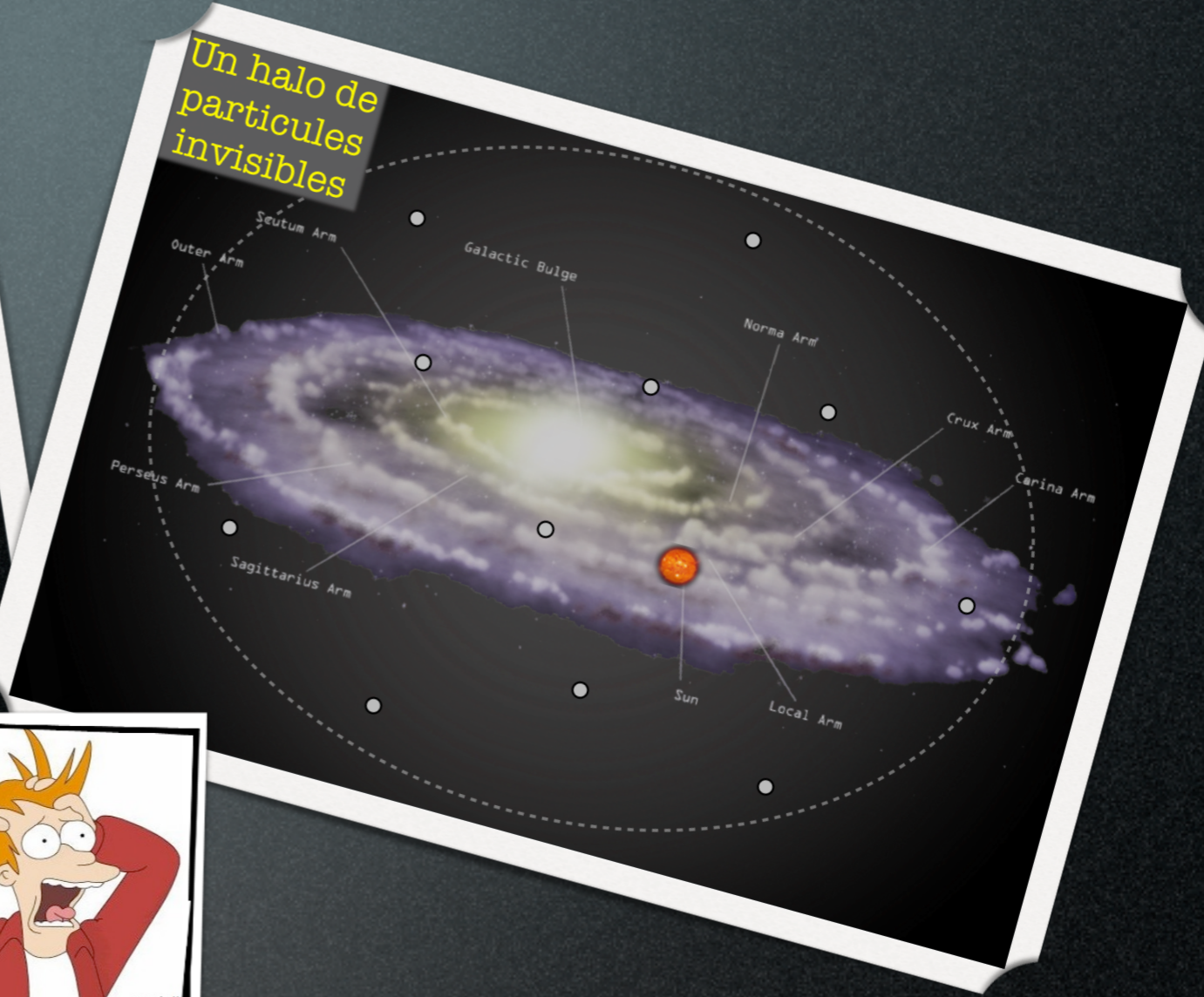
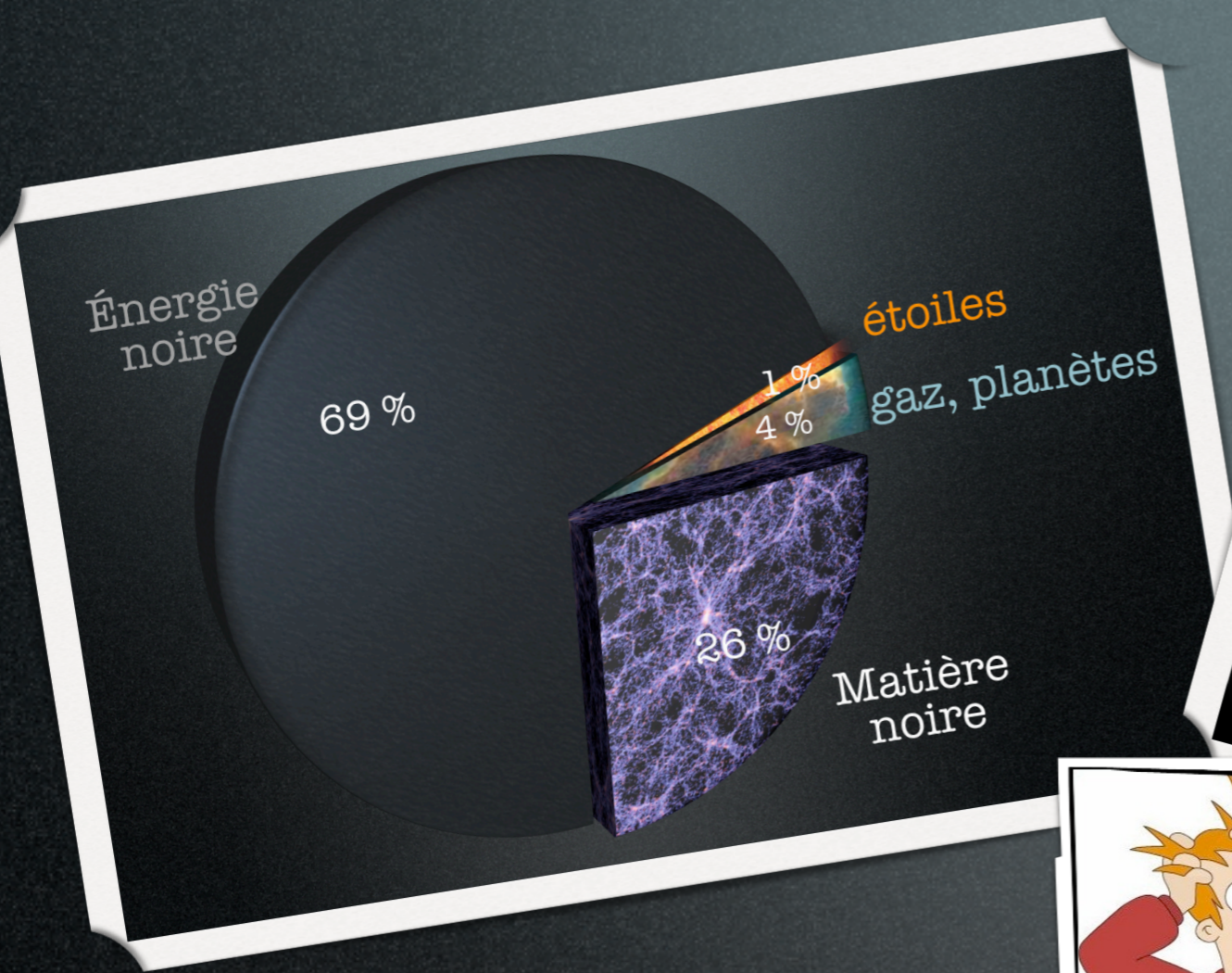


‘détection indirecte’

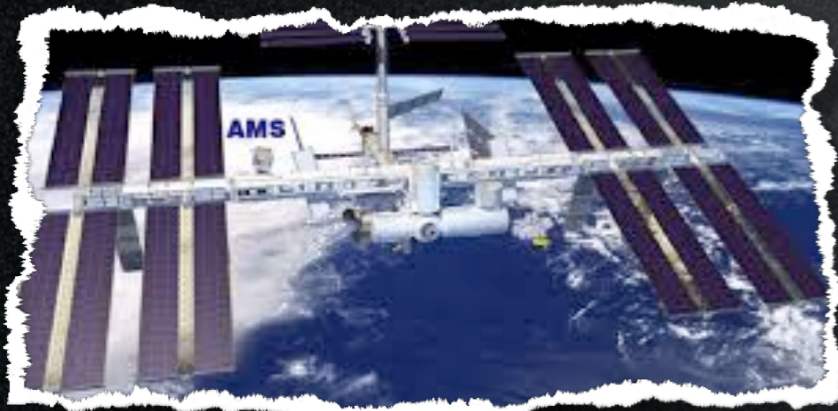
‘production’

‘détection directe’

De quoi est fait notre Univers ?



Physique spatiale



Physique aux collisionneurs



Physique souterraine



‘détection indirecte’

‘production’

‘détection directe’

Back-up slides

DETOUR



Modifier la loi de gravité ?

Modifier la loi de gravité ?

1846



Urbain Le Verrier

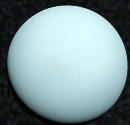
Modifier la loi de gravité ?

1846



Urbain Le Verrier

Uranus



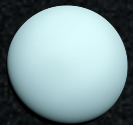
Modifier la loi de gravité ?

1846

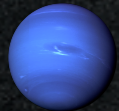


Urbain Le Verrier

Uranus



Neptune



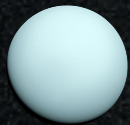
Modifier la loi de gravité ?

1846

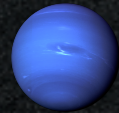


Urbain Le Verrier

Uranus



Neptune



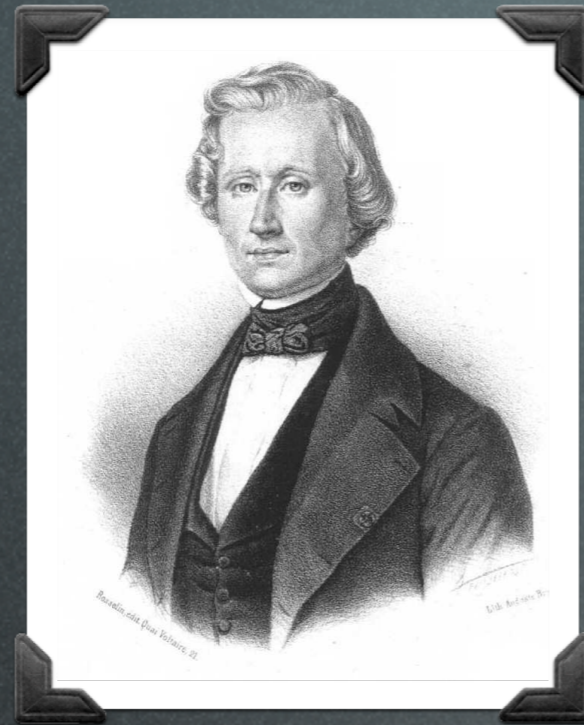
Modifier la loi de gravité ?

1846



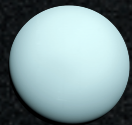
Urbain Le Verrier

1859

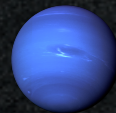


Urbain Le Verrier

Uranus



Neptune



Mercure



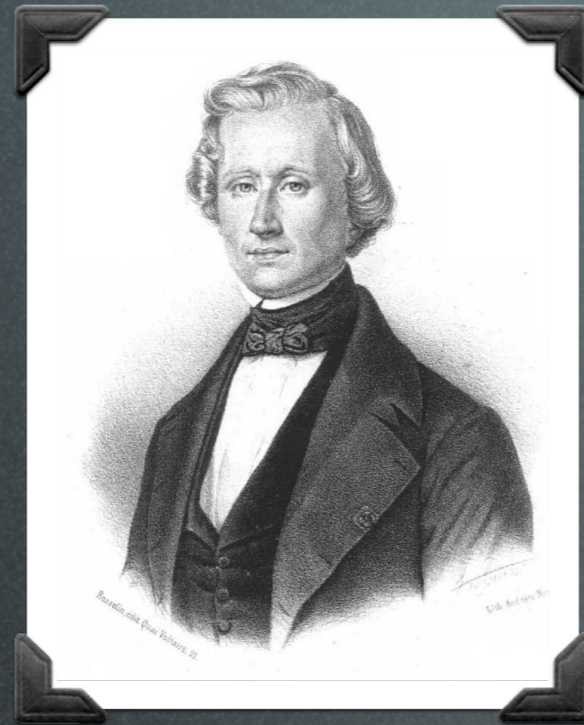
Modifier la loi de gravité ?

1846



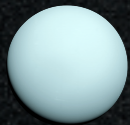
Urbain Le Verrier

1859

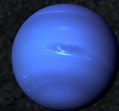


Urbain Le Verrier

Uranus



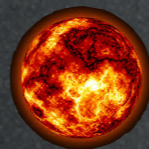
Neptune



Mercure



Vulcain ?



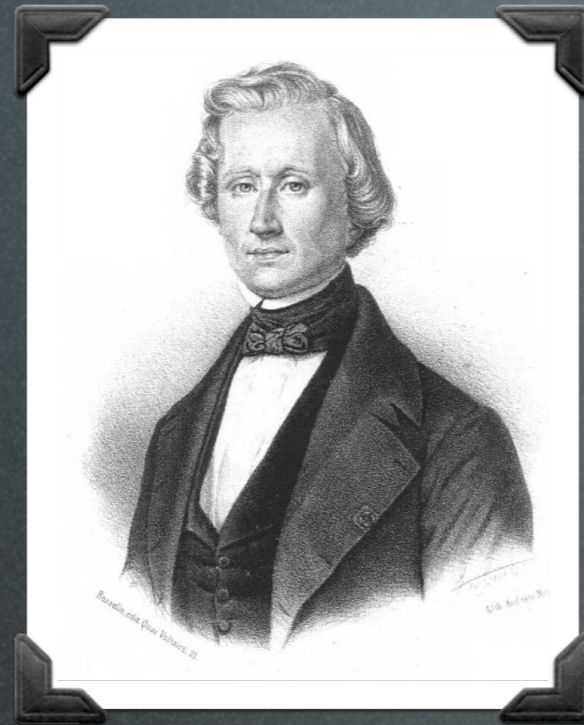
Modifier la loi de gravité ?

1846

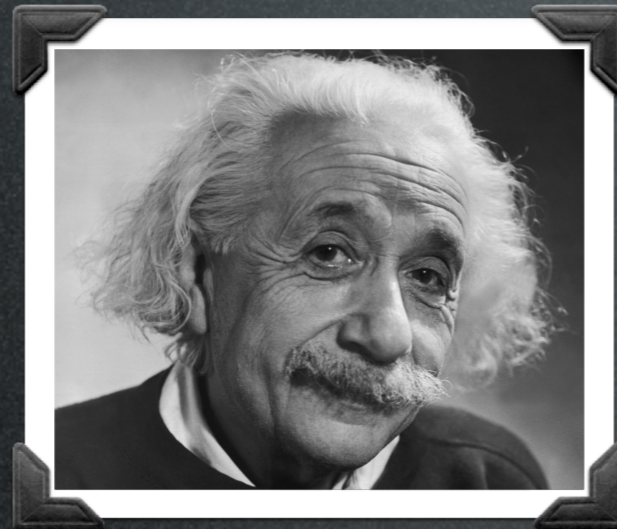


Urbain Le Verrier

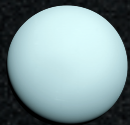
1859



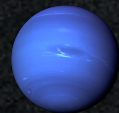
Urbain Le Verrier



Uranus



Neptune



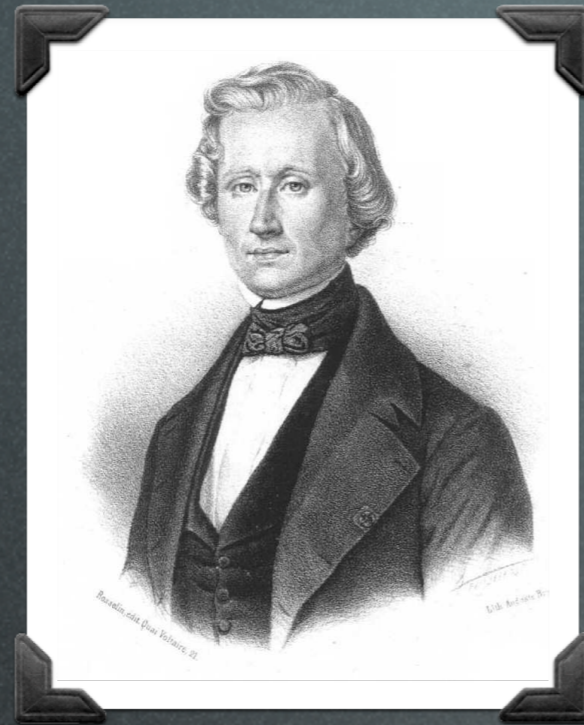
Modifier la loi de gravité ?

1846

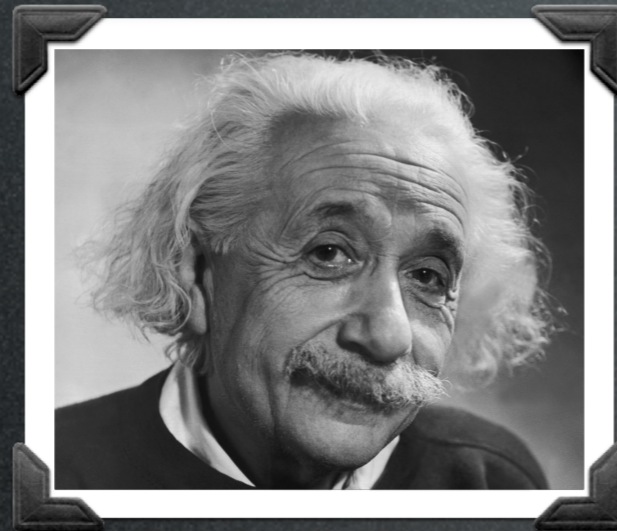


Urbain Le Verrier

1859

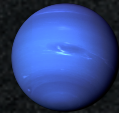
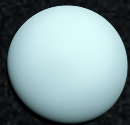


Urbain Le Verrier



Uranus

Neptune



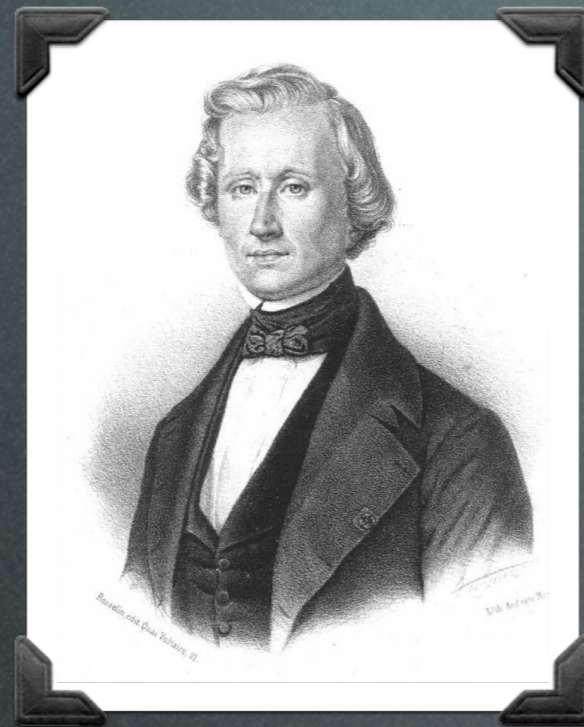
Modifier la loi de gravité ?

1846



Urbain Le Verrier

1859



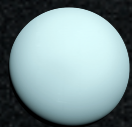
Urbain Le Verrier

1981

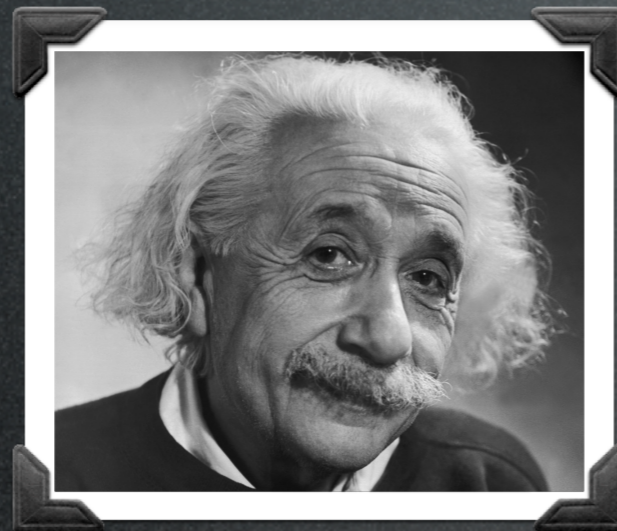
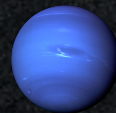


Mordehai Milgrom

Uranus



Neptune



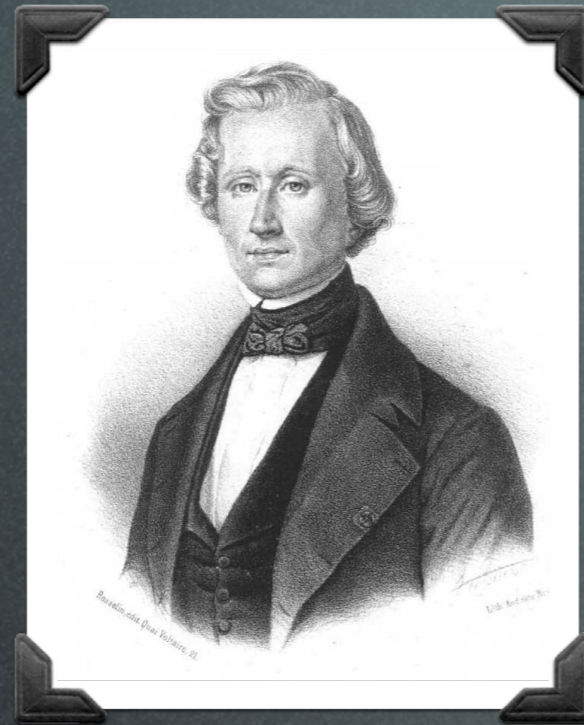
Modifier la loi de gravité ?

1846



Urbain Le Verrier

1859



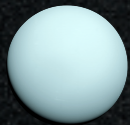
Urbain Le Verrier

1981

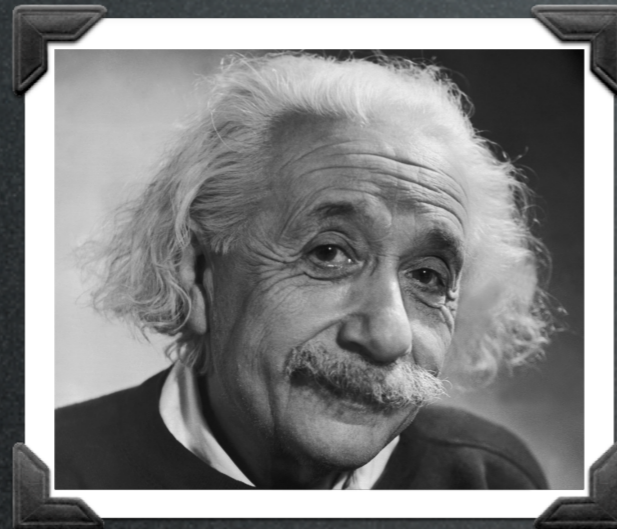
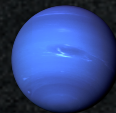


Mordehai Milgrom

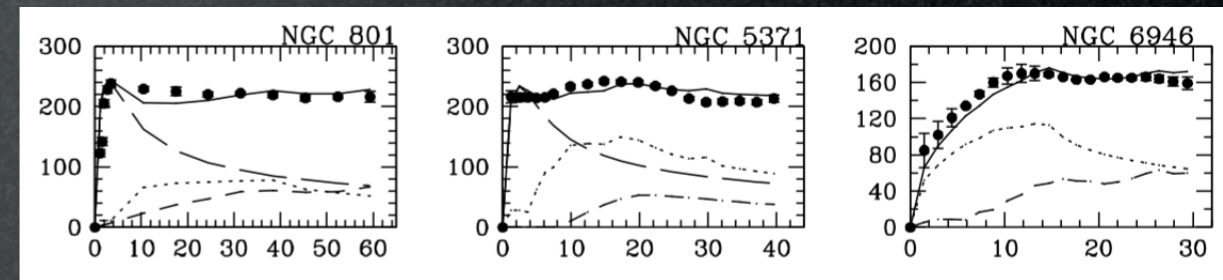
Uranus



Neptune



$$F = m a \longrightarrow F = m a \cdot \mu(a)$$



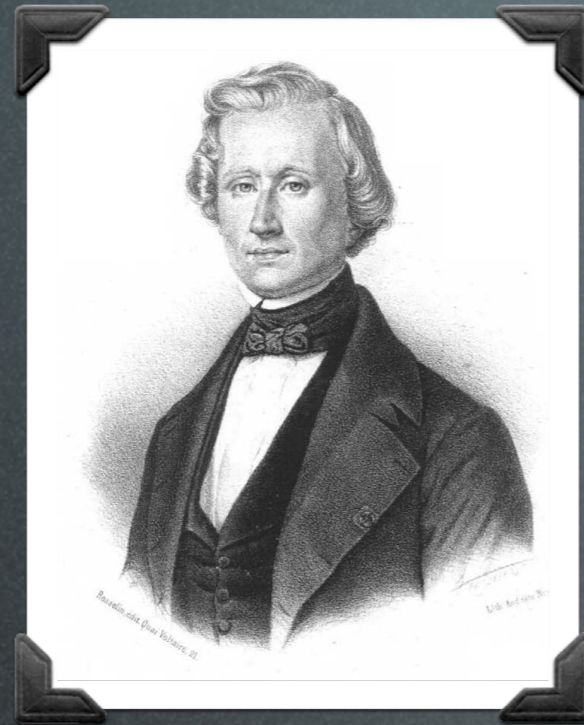
Modifier la loi de gravité ?

1846



Urbain Le Verrier

1859

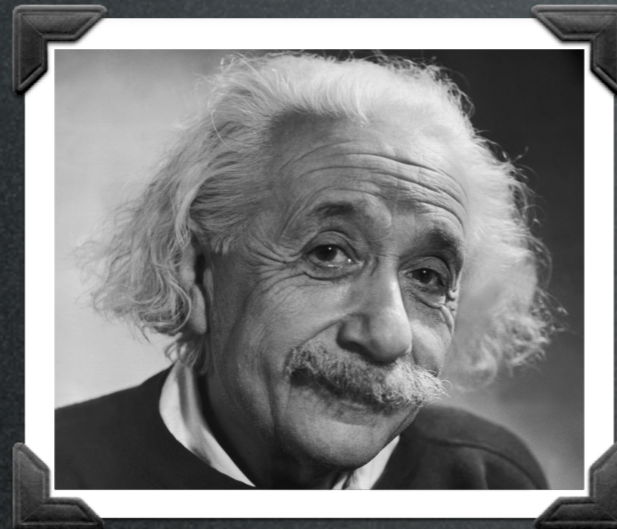


Urbain Le Verrier

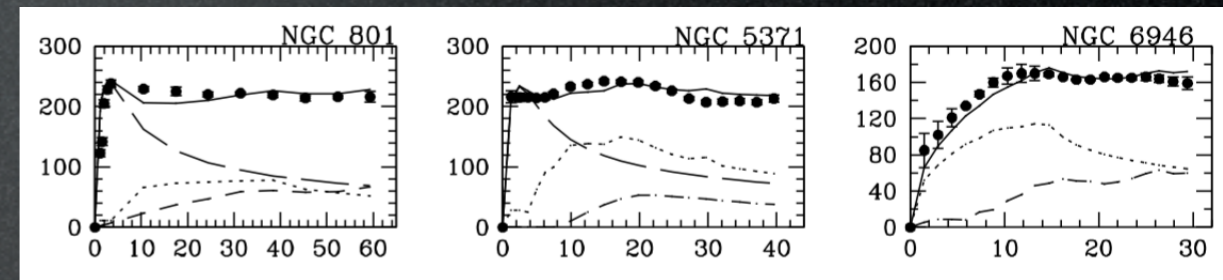
1981



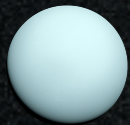
Mordehai Milgrom



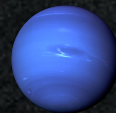
$$F = m a \longrightarrow F = m a \cdot \mu(a)$$



Uranus



Neptune



DETOUR



DM can **NOT** be:

an astro *je ne sais pas quoi*:

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- neutrons
- gas
- Black Holes
- brown dwarves

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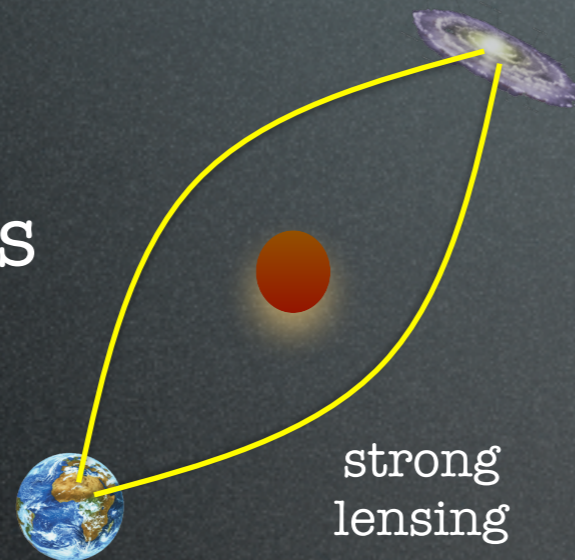
an astro *je ne sais pas quoi*:

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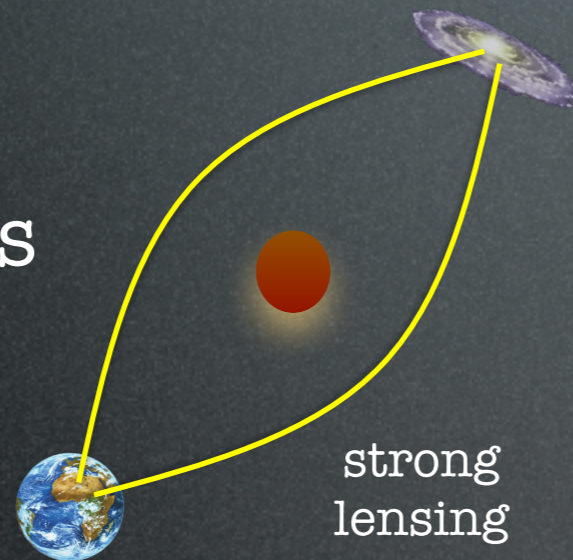
~~- brown dwarves~~



DM can **NOT** be:

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a baryon of the SM:

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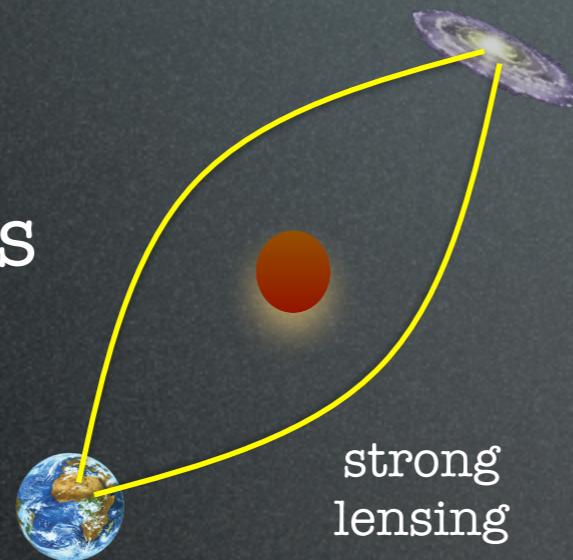
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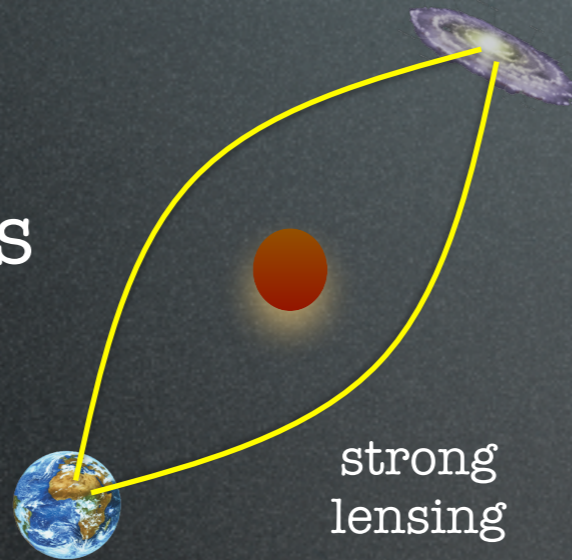
a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons:
too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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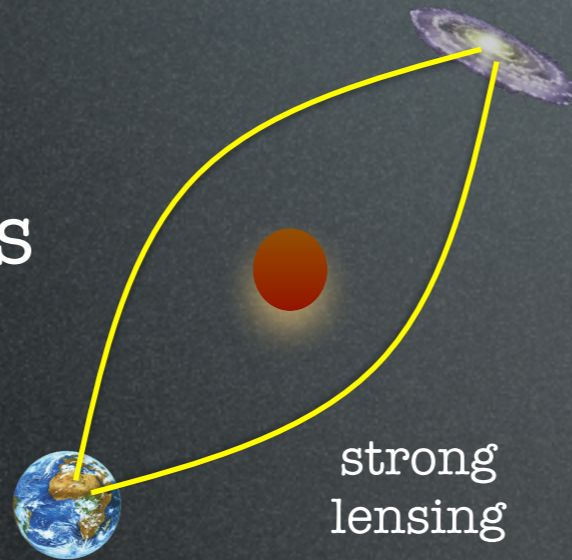
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neutrinos:

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- ~~gas~~
- ~~Black Holes~~
- ~~brown dwarves~~



~~a baryon of the SM:~~

- BBN computes the abundance of He in terms of primordial baryons:
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- CMB says baryons are 4% max

~~neutrinos:~~
too light!

$$m_\nu \lesssim 1 \text{ eV}$$

do not have enough mass to act as gravitational attractors in galaxy collapse

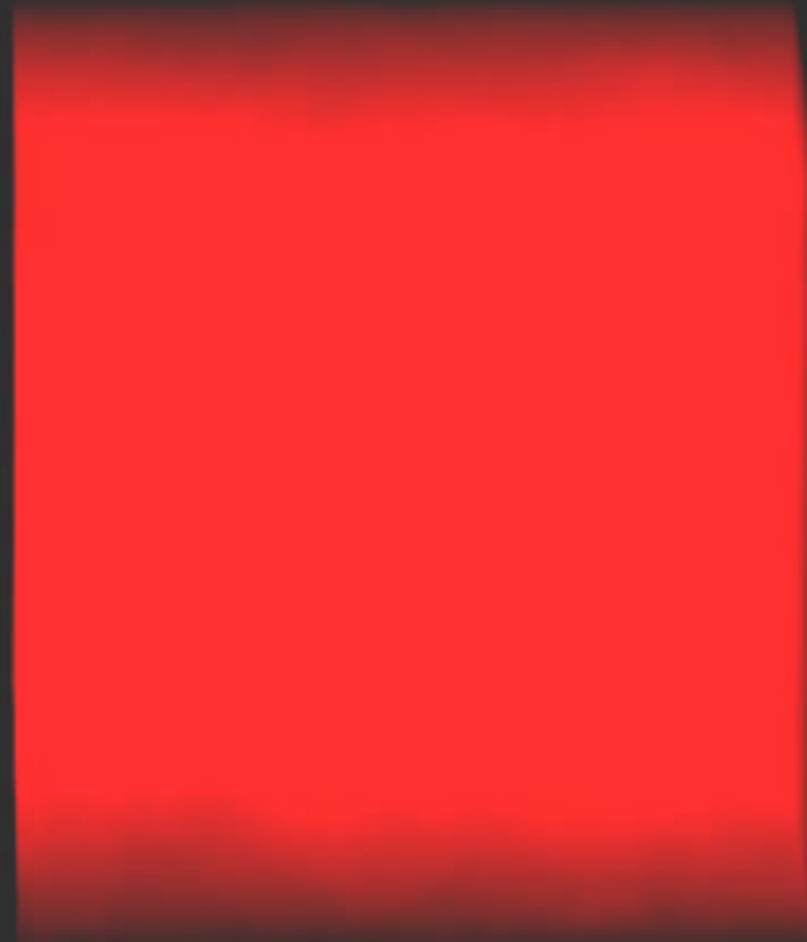
(Neutrino) DM

Z=32.33



no HDM

$$\sum m_\nu = 0$$



some HDM

$$\sum m_\nu = 6.9 \text{ eV}$$

Λ CDM - Gadget2 - 768 Mpc³