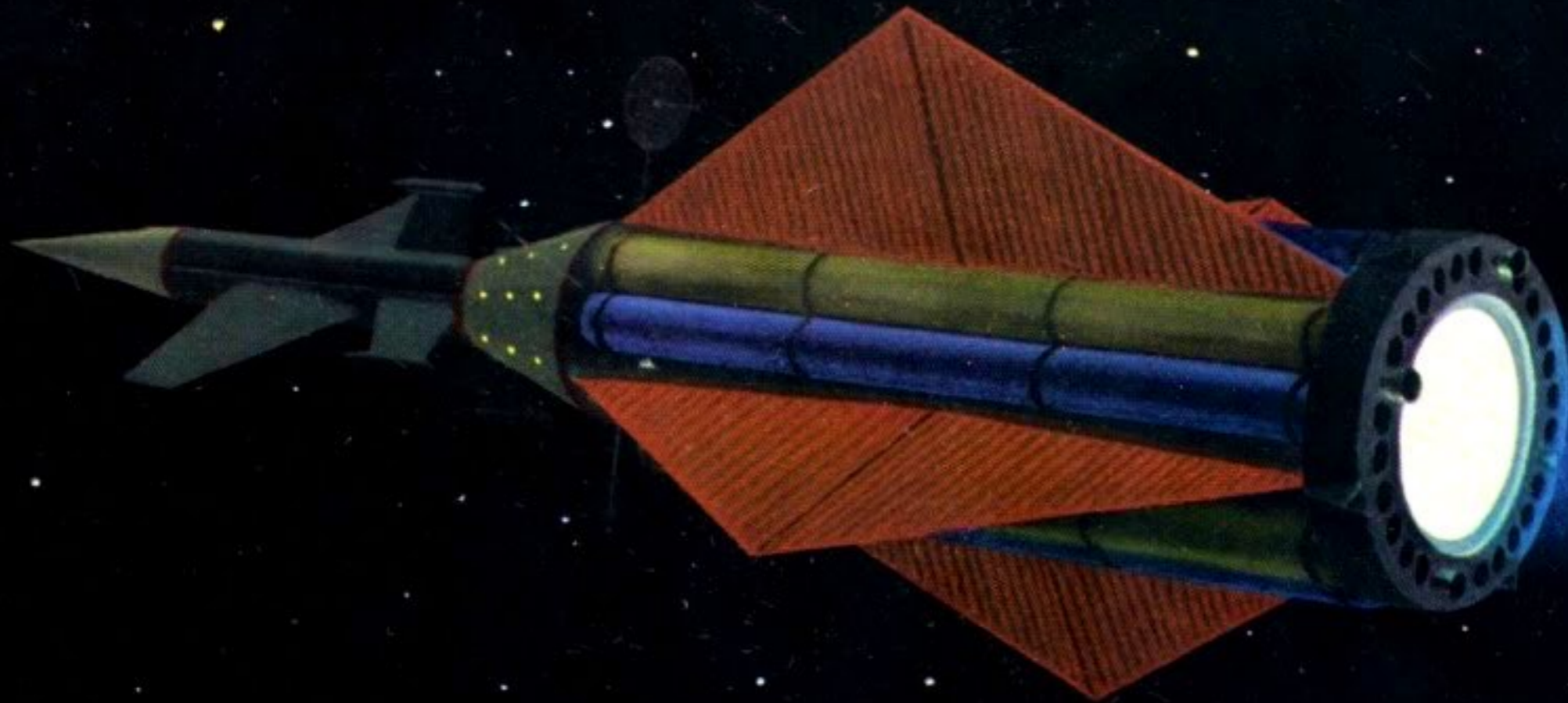


Antimatière

Entre fiction et réalité



Roland Lehoucq - CEA Saclay
Département d'astrophysique

Une « fiction » scientifique

I have an equation, do you have one too ?

Question de Paul Dirac à Richard Feynman, lors de leur première rencontre.



Paul Dirac (1902-1984).

Un des fondateurs de la mécanique quantique,
Co-lauréat du prix Nobel de physique de 1933, avec Erwin Schrödinger
« pour la découverte de formes nouvelles et utiles de la théorie atomique »

Équation de Schrödinger (1925) : décrit l'évolution de l'onde de matière
postulée par Louis de Broglie.

Problème : cette équation n'est pas compatible avec la relativité restreinte
car elle n'est pas invariante par changement de référentiel inertiel.

Équation de Dirac (1928) : corrige le problème. Bonus : elle intègre la notion
de spin introduite juste avant (Pauli 1924 ; Uhlenbeck et Goudsmit 1925).

Mais cette équation a des solutions dont l'énergie est négative...

1929 : Dirac les interprète comme associées à des « électrons positifs ».

« The Dirac Equation », vidéo de Physics Explained : <https://www.youtube.com/watch?v=upX1MmQwGBU>

Découverte de « l'électron positif »

Carl Anderson, 1932

L'antimatière ? C'est un trou avec rien autour.

Raymond Devos

Prix Nobel 1936

Chambre à brouillard traversée par des particules issues du rayonnement cosmique.

Cette trace est au moins 10 fois plus longue que celle laissée par un proton ayant le même rayon de courbure.

Il s'agit d'un « électron positif » nommé positron !

Un champ magnétique permet de courber la trajectoire des particules chargées.

6 mm de plomb

Charge +e



Première mention du positron dans un texte de SF.

The Great Thirst, Nat Schachner, Astounding Stories, November 1934.

Cerveau positronique des robots d'Isaac Asimov (1939-1940) !

Photographie de la trajectoire d'un positron dans une chambre à brouillard.
C. Anderson, *The Positive Electron*, Physical Review 43, 491-494 (1933).

Antimatière ?

Matière « contraterrene »

1898 - Arthur Schuster forge le mot *anti-matter* dans un article intitulé « Potential Matter - A Holiday Dream ».

Matter and anti-matter may further coexist in bodies of small mass.

1935 - Vladimir Rojansky forge le mot « contraterrene ». Concerning the Possibility of a Unified Interpretation of Electrons and Protons. Physical Review Letters 48, 108-109 (1935).

Surely something is wanted in our conception of the universe. We know positive and negative electricity, north and south magnetism, and why not some extra-terrestrial matter related to terrestrial matter as the source is to the sink, gravitating towards its own kind, but driven away from the substances of which the solar system is composed.

LETTERS TO THE EDITOR

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. No notice is taken of anonymous communications.]

Potential Matter.—A Holiday Dream.

WHEN the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream about the unknown, perhaps the unknowable? And what should more frequently cross our dreams than what is so persistently before us in our serious moments of consciousness—the universal law of gravitation. We can leave our spectrosopes and magnets at home, but we cannot fly from the mysterious force which causes the rain-drops to fall from the clouds, and our children to tumble down the staircase. What is gravity? We teach our students to accept the fact and not to trouble about its cause—most excellent advice—but this is vacation time, and we are not restricted to lecture-room science.

Lasage's particles are not satisfactory; they are too materialistic for the holiday mind; but I have always been fascinated by a passage occurring somewhere in Maxwell's writings, where Lord Kelvin is quoted as having pointed out that two sources or two sinks of incompressible liquid will attract each other with the orthodox distance law.

Let us dream, then, of a world in which atoms are sources through which an invisible fluid is pouring into three-dimensioned space. What becomes of this fluid? Does it go on for ever increasing the volume of that all-pervading medium which already fills a vast, but not necessarily infinite, space? When we speak of the constancy of matter, we mean only the constancy of inertia, and how are we to prove that what we call matter is not an endless stream, constantly renewing itself and pushing forward the boundaries of our universe? The conception of atoms as sources of fluid does not, however, necessarily involve such a perpetual increase of substance, for an equal number of sinks may keep withdrawing the increment.

These sinks would form another set of atoms, possibly equal to our own in all respects but one; they would mutually gravitate towards each other, but be repelled from the matter which we deal with on this earth. If matter is essentially dynamical, and we imagine the motion within an atom to be reversed, the question arises whether the reversed motion is similar to the original one; in other words, whether the new atom so formed may by a change of position be brought into coincidence with the old one. And if this is not the case, we must ask ourselves whether the new atom will behave gravitationally like the old one. If atoms are sources of liquid there would be no reciprocity, and the sinks would form another and so far unrecognised world. But sources and sinks compel us to the supposition of a fourth dimension, which belongs to the domain of nightmares, not of dreams, and we try to shake ourselves free from the idea.

I, for one, cannot quite succeed in this effort, for something has been left behind, which is not easily got rid of, when once its symmetrical beauty is perceived. Surely something is wanting in our conception of the universe. We know positive and negative electricity, north and south magnetism, and why not some extra terrestrial matter related to terrestrial matter as the source is to the sink, gravitating towards its own kind, but driven away from the substances of which the solar system is composed. Worlds may have formed of this stuff, with elements and compounds possessing identical properties with our own, undistinguishable in fact from them until they are brought into each other's vicinity. If there is negative electricity, why not negative gold, as yellow and valuable as our own, with the same boiling point and identical spectral lines; different only in so far that if brought down to us it would rise up into space with an acceleration of 981. The fact that we are not acquainted with such matter does not prove its non-existence; for if it ever existed on our earth, it would long have been repelled by it and expelled from it. Some day we may detect a mutual repulsion between different star groups, and obtain a sound footing for what at present is only a random flight of the imagination.

Even now some might argue that we possess some substantial evidence of repulsive forces. In our glorification of the Newtonian system we are apt to overlook some obvious facts which the law of gravitation fails to explain. One of these is the rota-

tional velocity of our solar and of many stellar systems, which cannot be self-generated. Unless we threw our laws of dynamics overboard, or imagine the rotation to have been impressed by creation, we must conclude that some outside body or system of bodies is endowed with an equal and opposite angular momentum. What has become of that outside body, and how could it have parted company with our solar system, if attractive forces only were acting? Another unexplained fact is found in the large velocities of some of the fixed stars, which, according to Prof. Newcomb's calculations, cannot be explained by gravitational attractions only.

The atom and the anti-atom may enter into chemical combination, because at small distances molecular forces would overpower gravitational repulsions. Large tracts of space might thus be filled unknown to us with a substance in which gravity is practically non-existent, until by some accidental cause, such as a meteorite flying through it, unstable equilibrium is established, the matter collecting on one side, the anti-matter on the other until two worlds are formed separating from each other, never to unite again.

Matter and anti-matter may further coexist in bodies of small mass. Such compound mixtures flying hither and thither through space, coming during their journey into the sphere of influence of our sun, would exhibit a curious phenomenon. The matter circulating in a comet's orbit, the anti-matter repelled and thrown back into space, forming an appendage which is always directed away from the sun. Has any one yet given a satisfying explanation of comets' tails; is the cause of coronal streamers known, and can any one look at a picture of the great prominence of the 1885 eclipse, and still believe that gravitational attraction or electric repulsion is sufficient to account for its extravagant shape? But this is not a scientific discussion. I do not wish to argue in favour of the existence of anti-atoms, but only to give my thoughts a free course in the contemplation of its possibility.

What is inertia? When the atom and anti-atom unite, is it gravity only that is neutralised, or inertia also? May there not be, in fact, potential matter as well as potential energy? And if that is the case, can we imagine a vast expanse, without motion or mass, filled with this primordial mixture, which we cannot call a substance because it possesses none of the attributes which characterise matter ready to be called into life by the creative spark? Was this the beginning of the world? Is our much-exalted axiom of the constancy of mass an illusion based on the limited experience of our immediate surroundings? Whether such thoughts are ridiculed as the inspirations of madness, or allowed to be the serious possibilities of a future science, they add renewed interest to the careful examination of the incipient worlds which our telescopes have revealed to us. Astronomy, the oldest and yet most juvenile of sciences, may still have some surprises in store. May anti-matter be commended to its care! But I must stop—the holidays are nearing their end—the British Association is looming in the distance; we must return to sober science, and dreams must go to sleep till next year.

Do dreams ever come true?

ARTHUR SCHUSTER.

Live Frog taken out of a Snake.

YOUR correspondent, Colonel Major, may be interested to hear of another instance of a Batrachian returning alive from the stomach of a snake. A grass snake of about 24 inches, kept in captivity, had not fed for three weeks: it was then given a very large specimen of the common frog, full-grown; this was swallowed at once, in the usual way by taking the hind leg first. In about an hour and a half the frog was a third of the way down the snake's body. Then, on the snake being played with and handled, after some minutes the lump began to move up rapidly towards the head of the snake, the mouth opened and out slid the frog; rather off colour, and not very happy-looking, but quite able to hop about in a shuffling fashion, though decidedly shaky on his legs. To an amphibian imprisonment without air could not be very hurtful for a few hours, were it not for the poison of the gastric juices. When the grass snake was left again with the frog it re-swallowed its prey. A snake will often take half an hour swallowing a frog: the distension of the jaws during the operation is extraordinary to witness. In about an hour's time the frog will be a third of the way down the snake's body.

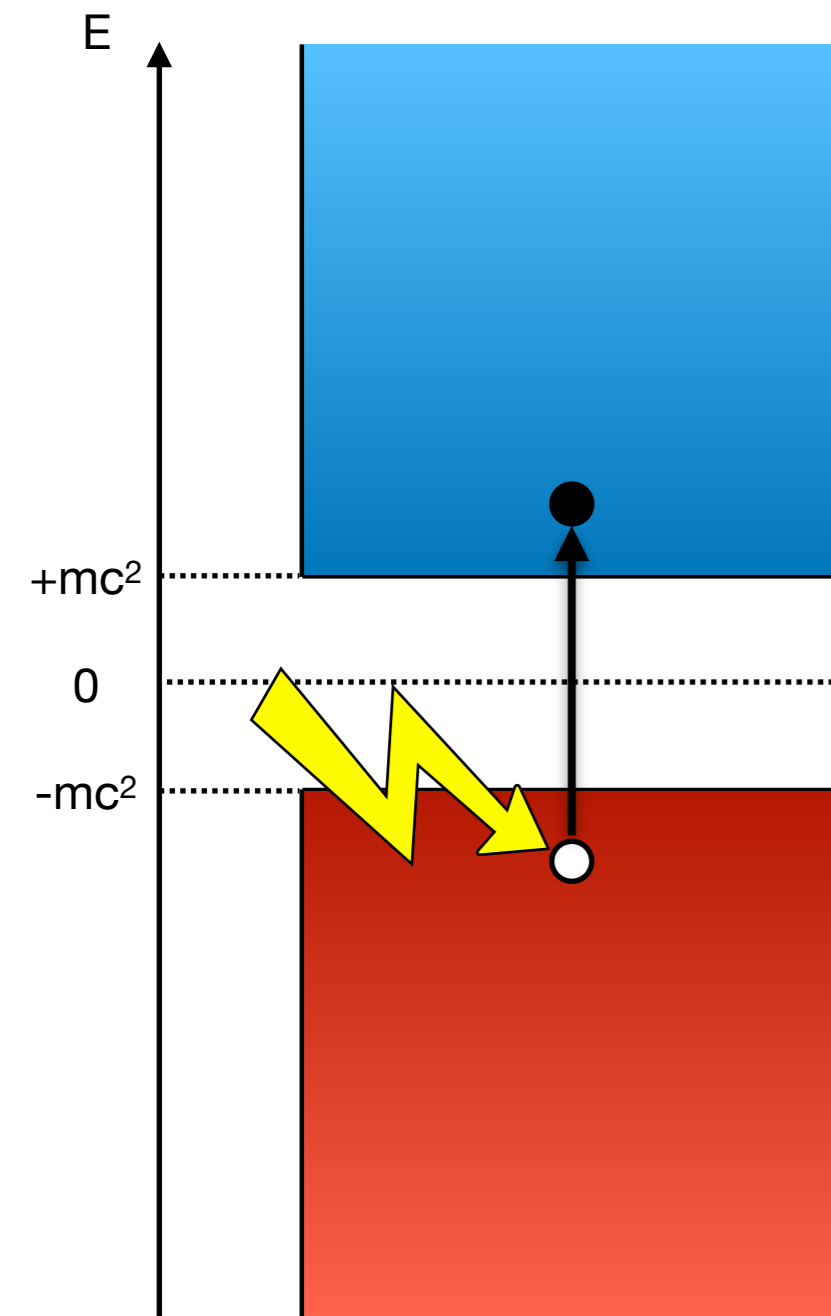
ROSE HAIG THOMAS.

Badenweiler, August 14.

La SF entre en scène

All of you gentlemen, I suppose, are familiar with the theories of P. A. M. Dirac, the young British physicist. Dirac holds that there is no such thing as a completely empty vacuum, that a perfect vacuum is simply a region of space where all that exists is composed of negatively charged electrons. He holds that matter as we know it is simply a hole or vent in this sea of negative energy. In other words, only negative energy is real, basic.

The Roaring Blot, Frank Belknap Long (Astounding Stories, mars 1936)



Créer un « trou » dans la mer d'énergie négative produit un électron d'énergie positive. Le « trou » dans la mer d'énergie négative se comporte comme un « électron positif » d'énergie positive. Formation d'une paire électron – positron !

Mer de Dirac (1930) : ensemble d'électrons remplissant une *infinité* de niveaux d'énergie négative. Il s'agit d'éviter (grâce au principe de Pauli) qu'un électron puisse tomber dans le puits infiniment profond des états d'énergie négative, rayonnant ainsi une énergie infinie...

Ça fait boum !

MINUS PLANET

There was one projectile big enough to make a dent in the planet's path—the Moon—and they could spare it.

by John D. Clark, Ph. D.

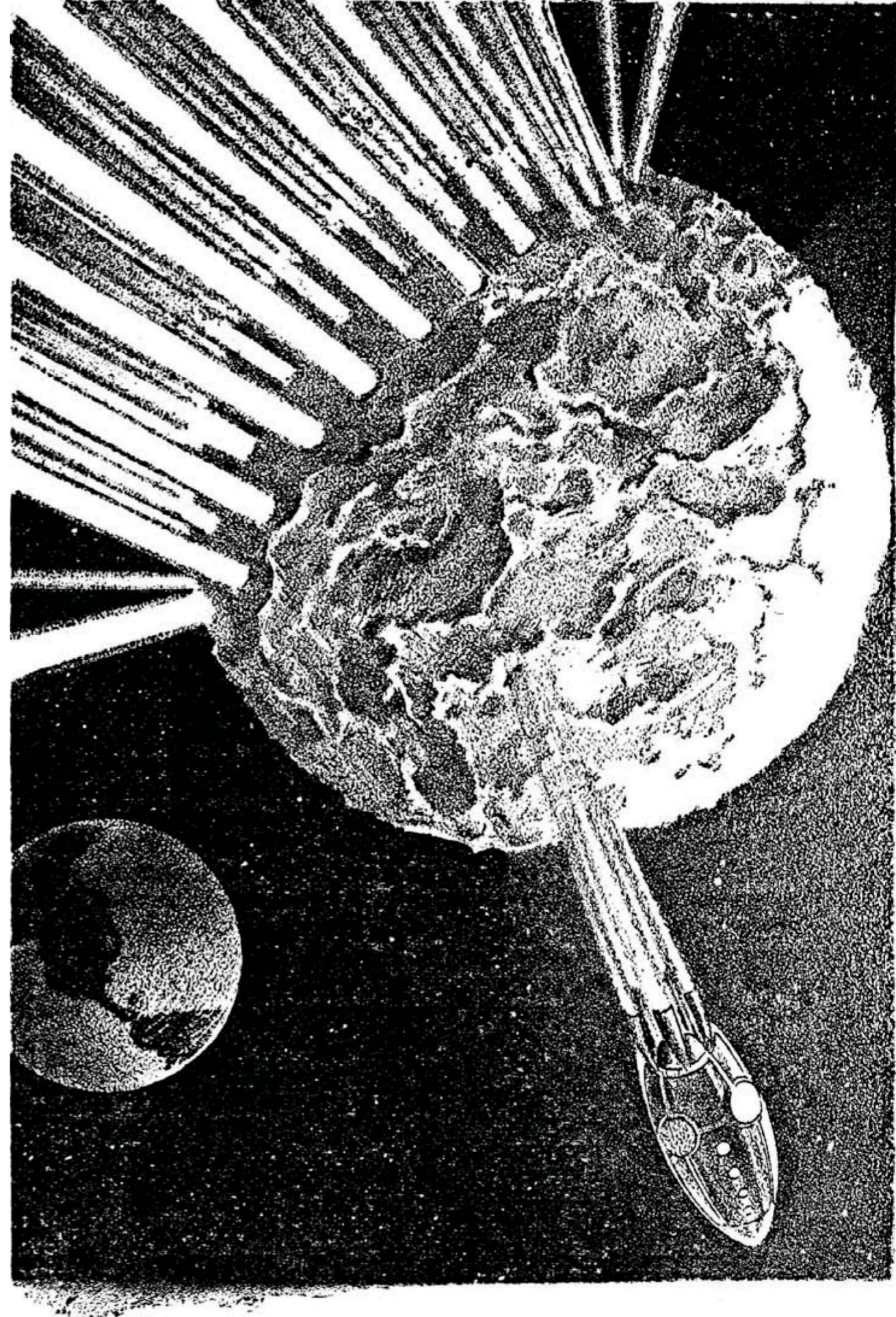
Astounding Stories, avril 1937

*First the outer electrons in our matter will neutralise the outer positrons in the reverse matter - and there'll be a hell of a lot of light or other radiation - UV, gamma, cosmic and what not. Then the nuclei will get together. Nothing will happen to either set of neutrons. But the positrons on the **protons** will neutralize the electrons on the **antrons**, and there'll be another burst of radiation and a lot of neutrons left over. So the net result will be a mob of neutrons and a flock of radiation.*

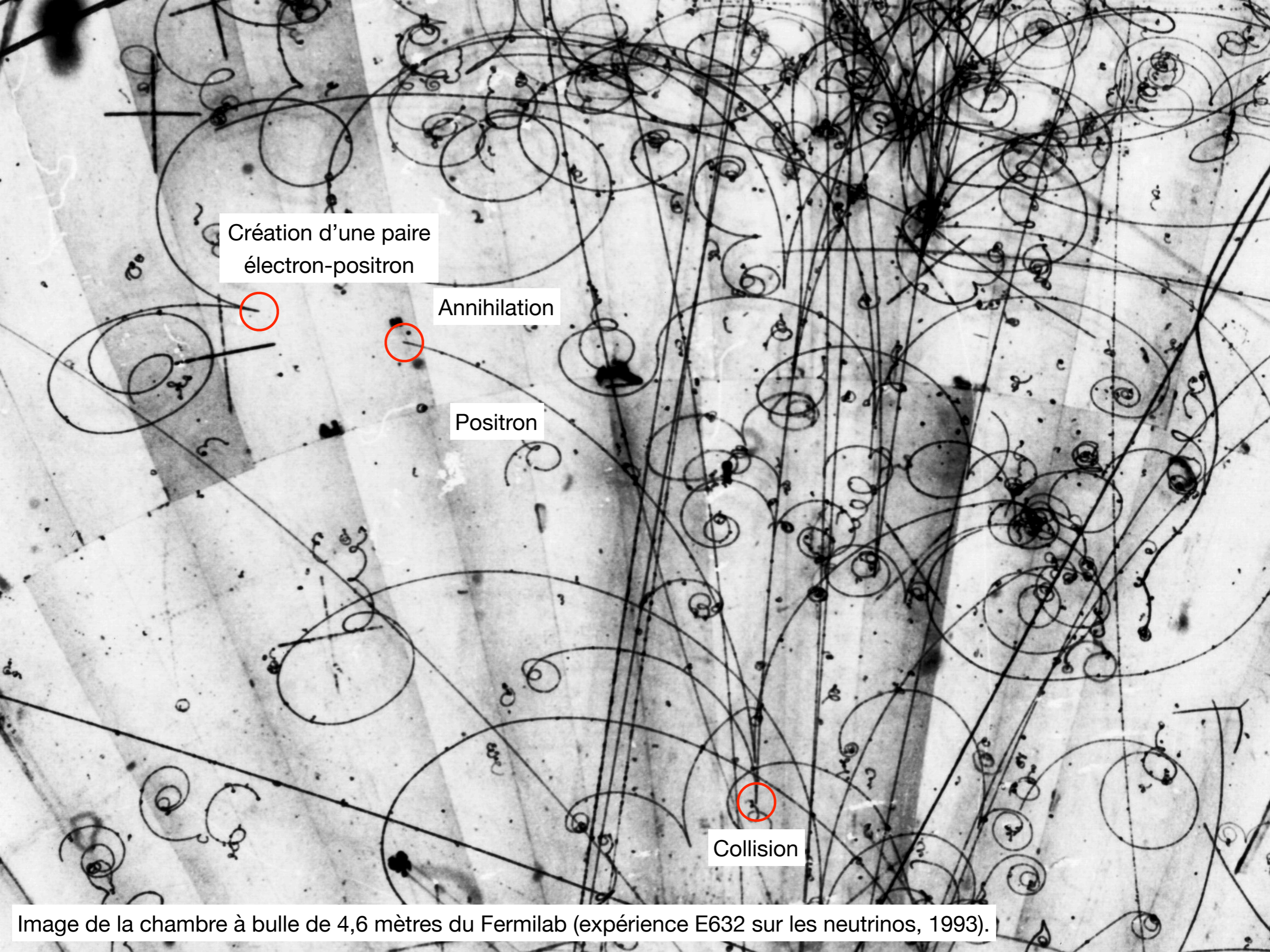
neutron + électron

neutron + positron

Matière + antimatière = lumière !



There was the sudden, baffling sensation of weightlessness, as all acceleration left the ship, which was falling freely after the Moon—



Création d'une paire
électron-positron



Annihilation



Positron

Collision



Image de la chambre à bulle de 4,6 mètres du Fermilab (expérience E632 sur les neutrinos, 1993).

Où est la matière contraterrenne ?

1933 — Conclusion de la conférence Nobel de Dirac : existe-t-il des étoiles d'antimatière ?

*If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. **It is quite possible that** for some of the stars it is the other way about, **these stars being built up mainly of positrons and negative protons.** In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.*

1940 — Vladimir Rojansky envisage la possibilité d'astéroïdes ou de comètes constitués de matière contraterrene.

The Hypothesis of the Existence of Contraterrene Matter. Astrophysical Journal 91, 257-260 (1940).

Si le flux de matière est identique à celui qui frappe la Terre, la température d'un astéroïde contraterrenne serait d'environ 900 °C (1 200 K). Il pourrait donc rayonner en lumière visible !

1941 — L'astronome américain Lincoln LaPaz, fait une hypothèse osée.

Meteorite Craters and the Hypothesis of the Existence of Contraterrene Meteorites. Contributions of the Society for Research on Meteorites 2, 244-247 (1941).

Dans cet article, LaPaz propose d'expliquer la présence de certains impacts sans trace de bolide (Tunguska 1908 par exemple) par l'arrivée d'une météorites contraterrene !

1941 — Un spécialiste des météorites, Harvey Nininger, critique sévèrement LaPaz.

Contraterrene (?) meteorites. Contributions of the Society for Research on Meteorites 2, 271-272 (1941).

[...] he could see not the slightest excuse to call upon a type of matter not known to exist to explain baffling problems. The apparent lack of meteorites at Tunguska might well be due to the difficulty of performing field work in that region.

ASTOUNDING

DEC. '41

SCIENCE-FICTION

A STREET & SMITH PUBLICATION

SECOND STAGE LENSMEN

by E. E. SMITH, Ph. D.

20¢

DEC • 1941

112

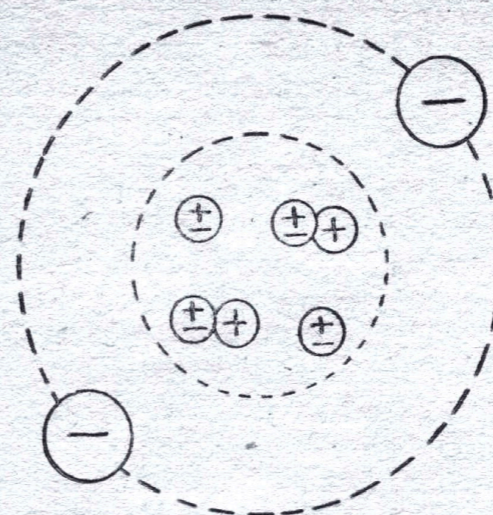
INSIDE OUT MATTER

by R. S. Richardson

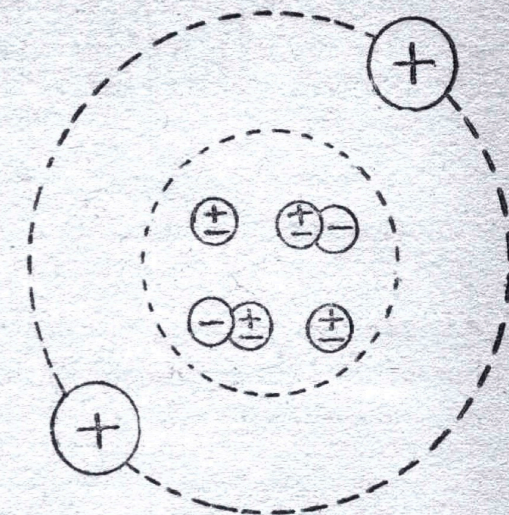
A discussion of one of the most intriguing discoveries of recent years; not only is inverse, or contraterrene matter a theoretical possibility—it exists and we're constantly bombarded with bits of it!

Before landing a rocketship on a strange planet, perhaps it would be a good idea to drop something overboard to see if it explodes on landing.

113



TERRENE ATOM
(HELIUM)



CONTRA TERRENE ATOM
(HELIUM)

WHERE ⊕⊖ MEANS NEUTRON, ⊕ MEANS POSITRON, ⊖ MEANS ELECTRON, ⊕⊕ MEANS PROTON AND ⊖⊖ IS A NEGATRON, OR NEGATIVE PROTON.

INDIVIDUAL PARTICLES REACT:

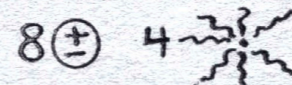


BOTH PARTICLES ANIHILATED TO PRODUCE A BURST OF GAMMA RAYS



⊕ — UNAFFECTED

FINAL PRODUCT OF REACTION:



kind have long been known. Of half a dozen examples scattered over the globe probably the best known are the funnels in Siberia and the Carolina Bays in the United States. In both cases, despite the obvious evidence of impact origin, geologists and

mineralogists have reluctantly abandoned this solution because no meteors could be found in the vicinity. L. Kulik, who investigated the Siberian disaster of 1908, was personally convinced the peculiar funnels were made by meteorites,



Dans trois minutes, dit Joe sans lever les yeux du tableau, nous saurons si c'est fait d'antimatière. Norton sourit au souvenir des plus effarantes théories sur l'origine de Rama. Si cette hypothèse peu vraisemblable était vraie, le plus énorme bang depuis la formation du système solaire se produirait dans quelques secondes. L'annihilation totale d'une masse de dix mille tonnes doterait pour un instant les planètes d'un second soleil. Le plan de mission avait cependant fait place à ce risque, si minime fût-il ; à la distance respectueuse d'un millier de kilomètres, l'Endeavour avait fait essuyer à Rama le feu d'une de ses fusées. Il ne s'était rien produit de particulier lorsque le nuage de vapeurs en expansion toucha la cible : une réaction matière-antimatière ne mettant en jeu que quelques milligrammes aurait déjà produit un assez terrifiant feu d'artifice.

Arthur C. Clarke, Rendez-vous avec Rama (1973).

Astounding Science Fiction
juillet 1942, p. 80-106.



COLLISION ORBIT

By Will Stewart pseudonyme de
Jack Williamson

● Introducing a new author and a fascinating idea: the control and use of "seete"—contraterrene matter. Science-fiction's discussed the danger of meteors; astronomers are pretty certain there are very many contraterrene meteors. How about the danger from those!

Illustrated by Orban

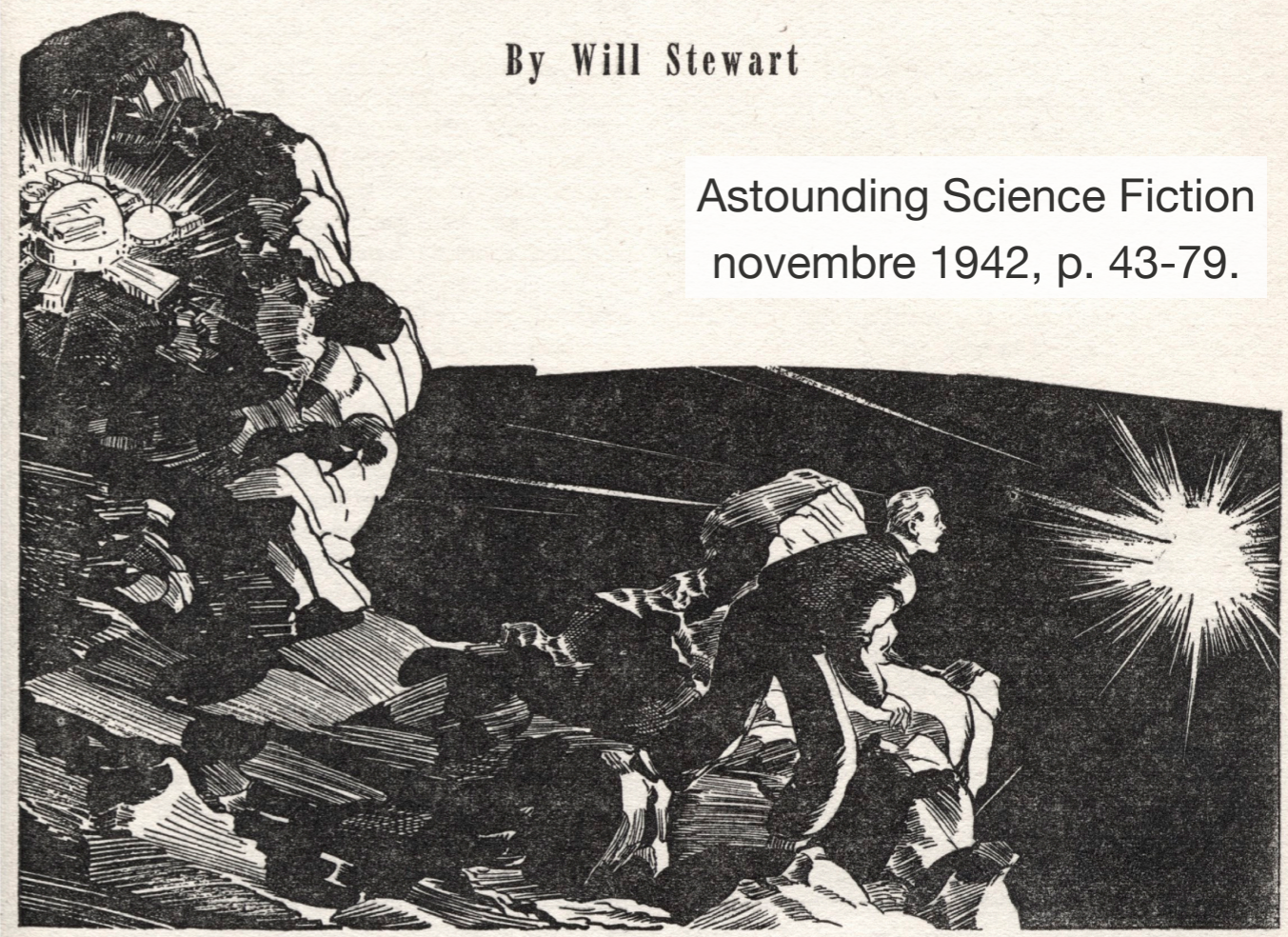
A young man spoke the scornful words—he was Kurt von Sudenhort, the blond, ray-burned Martian-German subaltern, in command of the small base of the High Space Guard on the tiny asteroid's polar plateau. Strutting down the quiet

old street, he was loud with a young man's arrogance. "Excitement, you say?" Hard heels clacked impatiently on the worn sidewalk, as he kept step with another trim young officer in black. "Ex-

MINUS SIGN

By Will Stewart

Astounding Science Fiction
novembre 1942, p. 43-79.



● They sought a chance to study minus matter—contraterrene stuff that was the electrical inverse of normal matter. But the planetoid they visited was more strange even than that!

Illustrated by Kolliker

I.

Pallas didn't turn on Mandate time. This five o'clock, it was midnight over Pallasport. Rick Drake strode down the curving street of glaring fluorescent signs and gaudy glass-and-metal fronts with the black sky reflected on his face.

"Hi, engineer!"

Karen Hood called her eager greeting from the corner where she had been waiting for him in front of the huge, magnificent Interplanet Building. In sheer black dress-pajamas, Karen was a red-haired cataclysm. Now he thought her warm, husky voice sounded a little too deliberately light and gay.

"Hello, Kay." A lean, space-bronzed giant, he towered over her slim tallness. The way her tawny hair struck back a sign's red-changing glow somehow made a sharp little pain in his throat. In a low, careful voice, he said, "On the phone you just said you wanted to see me after work. What's up?"

"I'm taking you to dinner"—she slipped a bare white arm through his and her high-cheeked face, smiling, took his breath—"because I've something to tell you. No, I insist on paying the bill, this time, because I think you won't like what I have to say. Shall we go to the Mandate House?"

She saw the protest on his spare, space-bronzed face. The Mandate House was the exclusive,



OPPOSITES—REACT!

By Will Stewart

First of Two Parts

● Sequel to "Collision Orbit" and "Minus Sign," this novel tells of men against men—and against the strange and deadly problem of minus matter, contraterrene matter. Men against men—for the men who learned the trick of fixing a tool to work "seetee" in a baseplate of normal matter, could wrest control of the System!

Illustrated by Kolliker

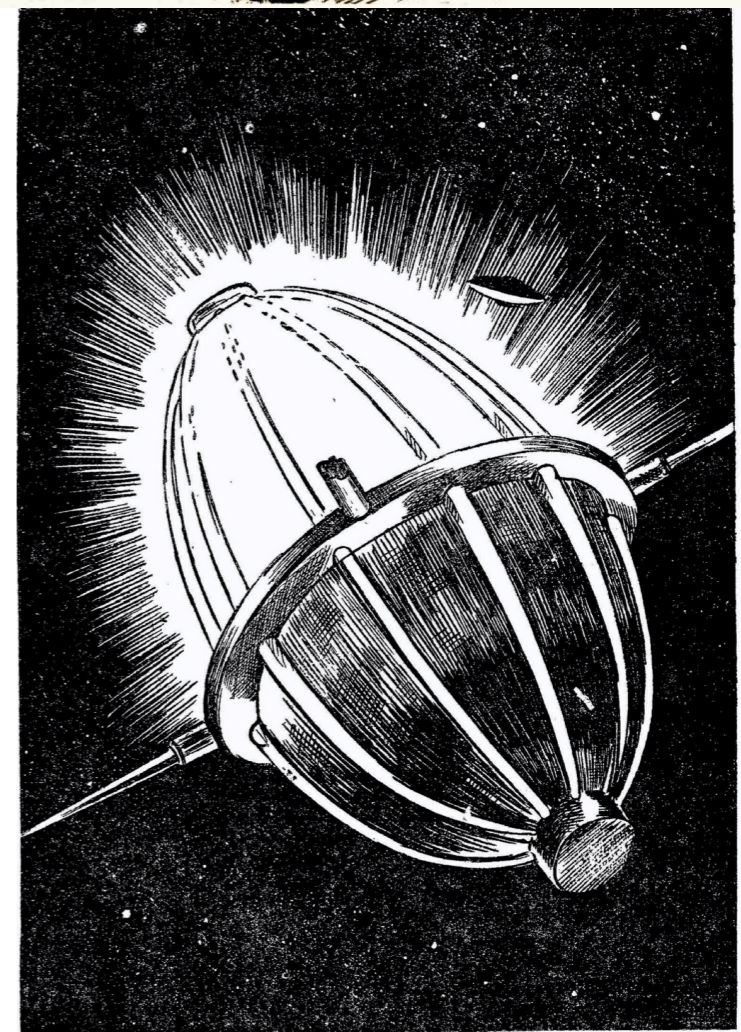
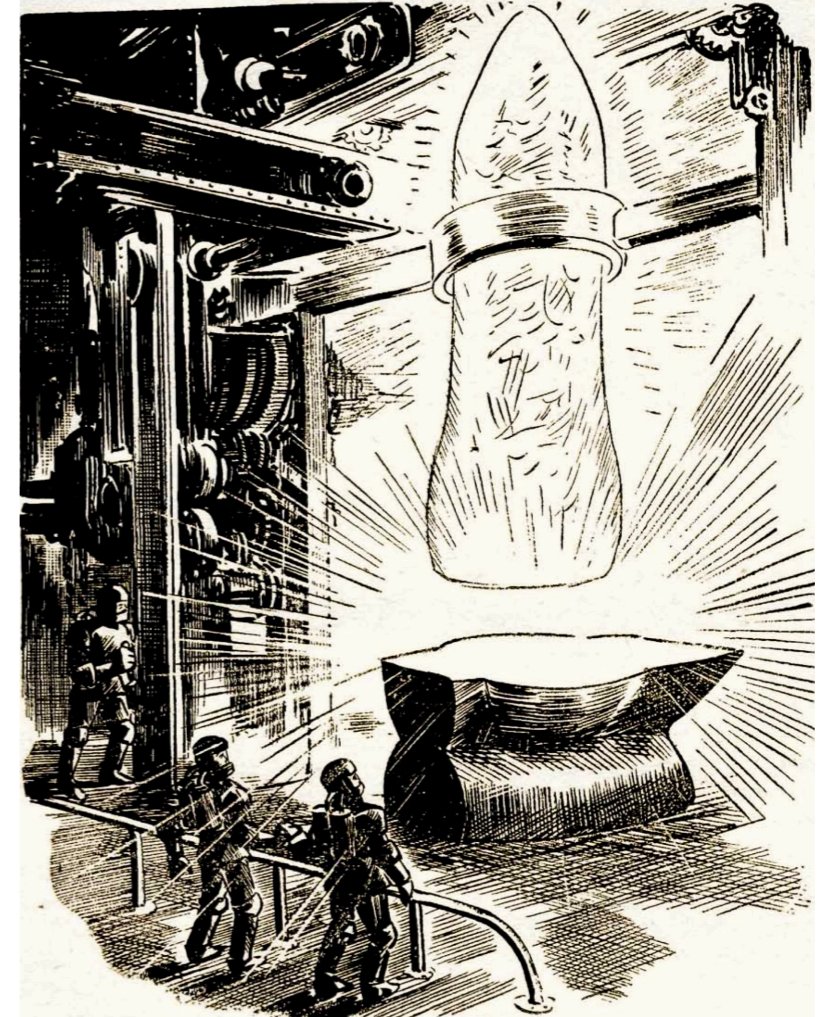
"Captain Paul Anders!"

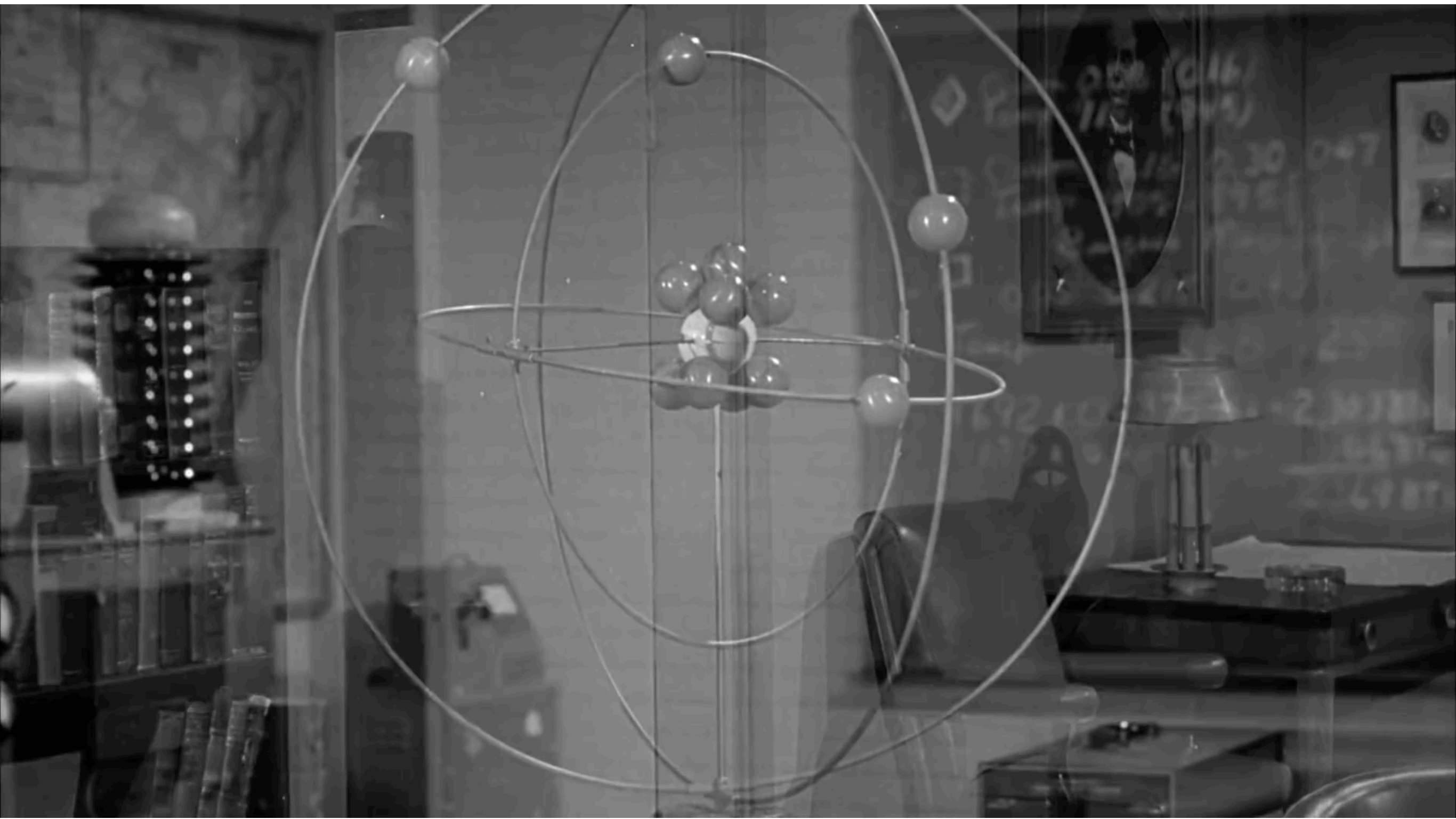
Announcing him, the aid's curt, impersonal voice made a hollow echo in the enormous metal room ahead. Lean and spare in the black of the High Space Guard, he came to straight attention. He knew the man before him in the glittering official room, and he was prepared for a trying interview.

"At ease, old man!" Austin Hood, Chief Com-

missioner of the High Space Mandate, returned his crisp salute with a genial, unmilitary gesture. Beyond the shimmer of the famous iridium desk, Hood was red and bulky, loud with a bluff assurance. "Glad to see you back here on the rocks. Sit down and tell me all about your leave."

Hood's red fat face was smiling, with a politician's ready smile. But his small eyes remained shrewd and cold—they were used to judging men,





Extrait de *The giant claw* (Fred Sears, 1957).



La Carcagne créature originaire d'une galaxie d'antimatière, in *The giant claw* (Fred Sears, 1957).

Y5150/\$1.95/A JOVE BOOK

Seetee

First time in one volume!
SEETEE SHIP and its stunning sequel, SEETEE SHOCK

by Jack Williamson



La nef d'antim

WILL
STEWART

Le vieux professeur pensait que l'antimatière a dû se former dans une autre partie de l'espace, où le temps va à l'envers.



LE RAYON
FANTASTIQUE

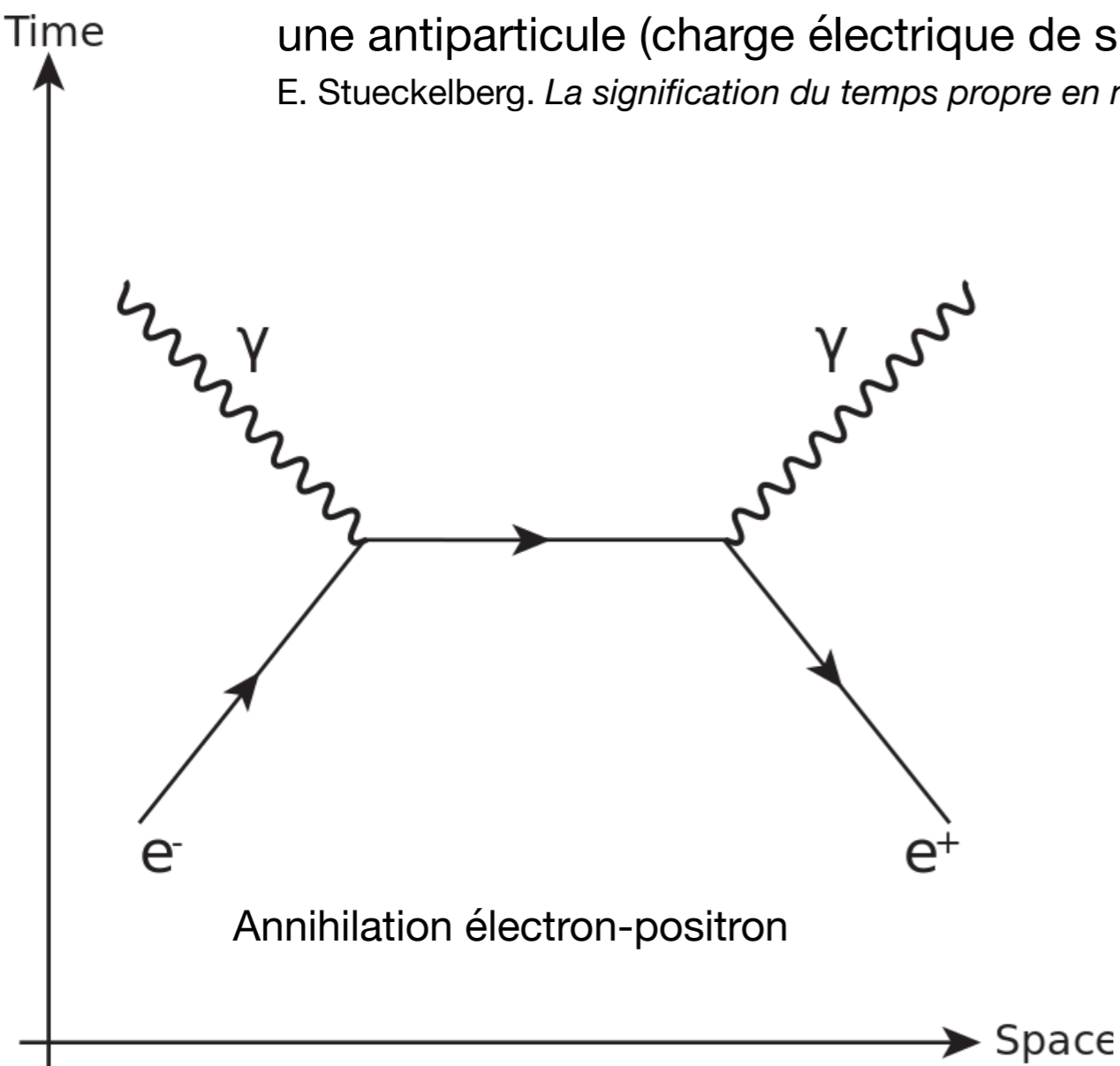
Une particule qui remonte le temps ?

Dans l'équation décrivant la propagation d'une particule chargée dans un champ électromagnétique, changer le signe de la charge a le même effet que changer le signe de son temps propre.

Une particule se propageant vers le futur est identique à une particule de charge opposée se propageant vers le passé !

Ernst Stueckelberg (1941) : on peut considérer une particule d'énergie négative comme une antiparticule (charge électrique de signe opposé) remontant le temps.

E. Stueckelberg. *La signification du temps propre en mécanique ondulatoire*. Helv. Phys. Acta 14, 322–323 (1941).



Diagrammes de Feynman (1948) : représentations graphiques d'équations décrivant les interactions de particules dans le cadre de la théorie quantique des champs.

Dans ce diagramme, un électron et un positron s'annihilent en produisant une paire de photons.

Les orientations des flèches ne désignent pas le sens de déplacement des particules, mais leur type :

- particules, flèche dirigée vers le futur ;
- antiparticules, flèche dirigée vers le passé.

La quête se poursuit...

1958 — Philip Wyatt, revient sur l'épisode de la Tunguska.

Possible Existence of Anti-Matter in Bulk. Nature 181, 1194 (1958).

Il suggère que l'événement de la Tunguska pourrait être dû à une météorite d'antimatière.

1965 — Clyde Cowan et al., posent une nouvelle fois la question de la nature du météore de la Tunguska.

Possible Anti-Matter Content of the Tunguska Meteor of 1908. Nature 206, 861–865 (1965).

1973 — Rojansky suggère d'observer en lumière gamma la comète Kohoutek (dont l'orbite est parabolique).

Comet Kohoutek and Penetrating Rays. Physical Review Letters 31, 1591 (1973).

1996 — Charles Dermer propose une explication des sursauts gamma, les plaçant à $10^4 - 10^5$ UA.

Gamma-ray bursts from comet-antimatter comet collisions in the Oort cloud. American Institute of Physics (AIP) Conference Proceedings 384, 744-748 (1996).

Un sursaut est un flash très intense de rayonnement gamma (les plus brillants ont un flux qui atteint plusieurs milliers de photons par seconde et par centimètre carré). Ils se classent en deux catégories : les sursauts « courts » d'une durée allant de quelques millisecondes à quelques secondes, et les « longs » d'une durée typique de quelques dizaines de secondes, mais pouvant atteindre quelques minutes.

2021 — S. Dupourqué, L. Tibaldo, P. von Ballmoos, contraignent la densité d'anti-étoiles (< 1 tous les 10^5 pc³).

Constraints on the antistar fraction in the Solar system neighborhood from the 10-years Fermi Large Area Telescope gamma-ray source catalog. Physical Review D (2021).

Vers les étoiles grâce à l'antimatière ?



[...] Cependant, indépendamment de tous ces propos téméraires, il n'en reste pas moins vrai que nous devons considérer l'antim comme un des éléments les plus importants de l'astronavigation.

Manuel de l'Astronaute par le capitaine Paul Anders, G.H.E.



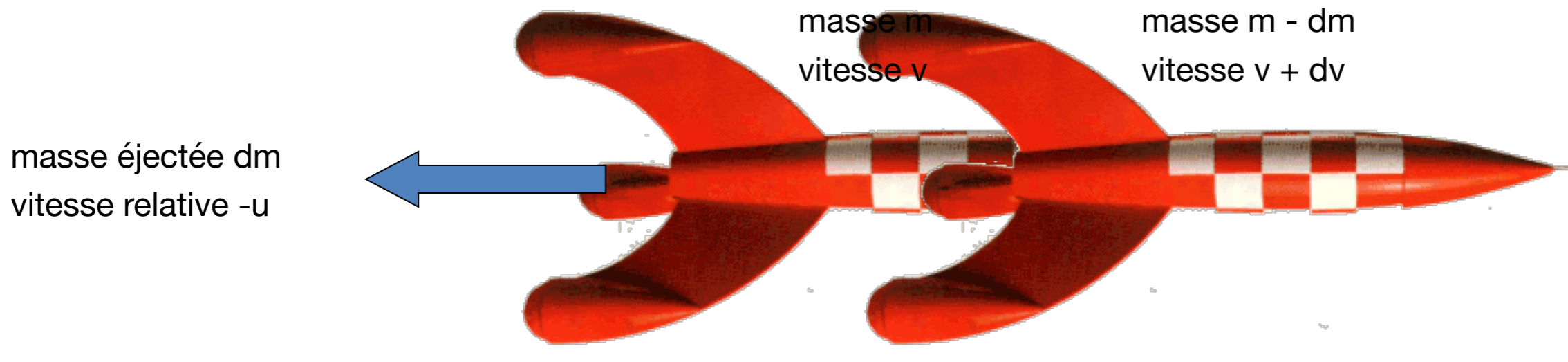
Leslie Shepherd (1918 - 2012)

Interstellar Flight

Journal of the British Interplanetary Society 11, p. 149–167 (1952).

L'antimatière pour aller plus vite ?

Un voyage interstellaire d'une durée raisonnable nécessite une vitesse élevée.



$$\frac{v}{c} = \tanh \left[\frac{u}{c} \ln \left(\frac{M_i}{M_f} \right) \right] \quad \text{Équation de Tsiolkovsky relativiste}$$

Comment estimer la vitesse d'éjection ?

On extrait la fraction ε de l'énergie de masse pour la transformer en énergie cinétique.

$$\frac{u}{c} = \sqrt{\varepsilon (2 - \varepsilon)} \sim \sqrt{2\varepsilon}$$

Propulsion	Fraction ε	u/c
Chimique	$10^{-9} - 10^{-10}$	$2 \cdot 10^{-5}$
Fission	0,08 %	0,04
Fusion	0,4 %	0,09
Antimatière	40 %	0,80

Le Venture Star

Le voyage a duré 5 ans, 9 mois et 22 jours
Une voix anonyme à l'arrivée

Distance parcourue = 4,37 a.-l.

Radiateurs

Réservoirs

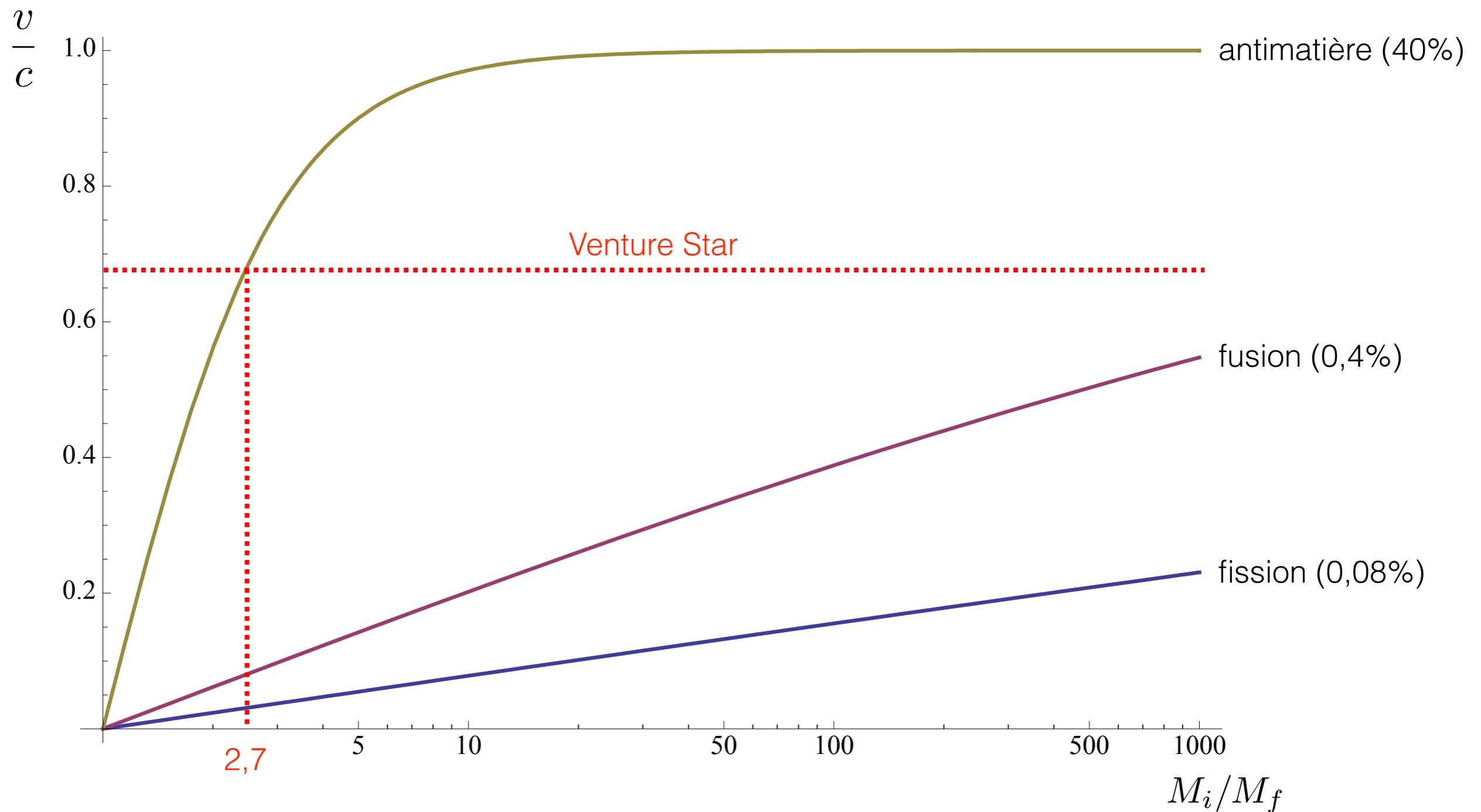
Que contiennent-ils ?

Le Venture Star en orbite autour de Pandora ; Avatar (J. Cameron, 2009).

Le Venture Star

Quel est son mode de propulsion ?

$$\frac{v}{c} = \tanh \left[\frac{u}{c} \ln \left(\frac{M_i}{M_f} \right) \right]$$



En pratique, c'est compliqué...

L'annihilation proton – antiproton

$$p + \bar{p} \rightarrow 1.5 \pi^+ + 1.5 \pi^- + 2 \pi^0$$

$$\pi^0 \rightarrow 2\gamma \quad \text{Durée de vie 90 attosecondes et perte de 37,8 \% de l'énergie initiale.}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{Durée de vie 26 nanosecondes (en vol @0.94c 70 ns)}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad \text{Énergie cinétique des pions = 39,9 \% de l'énergie initiale.}$$

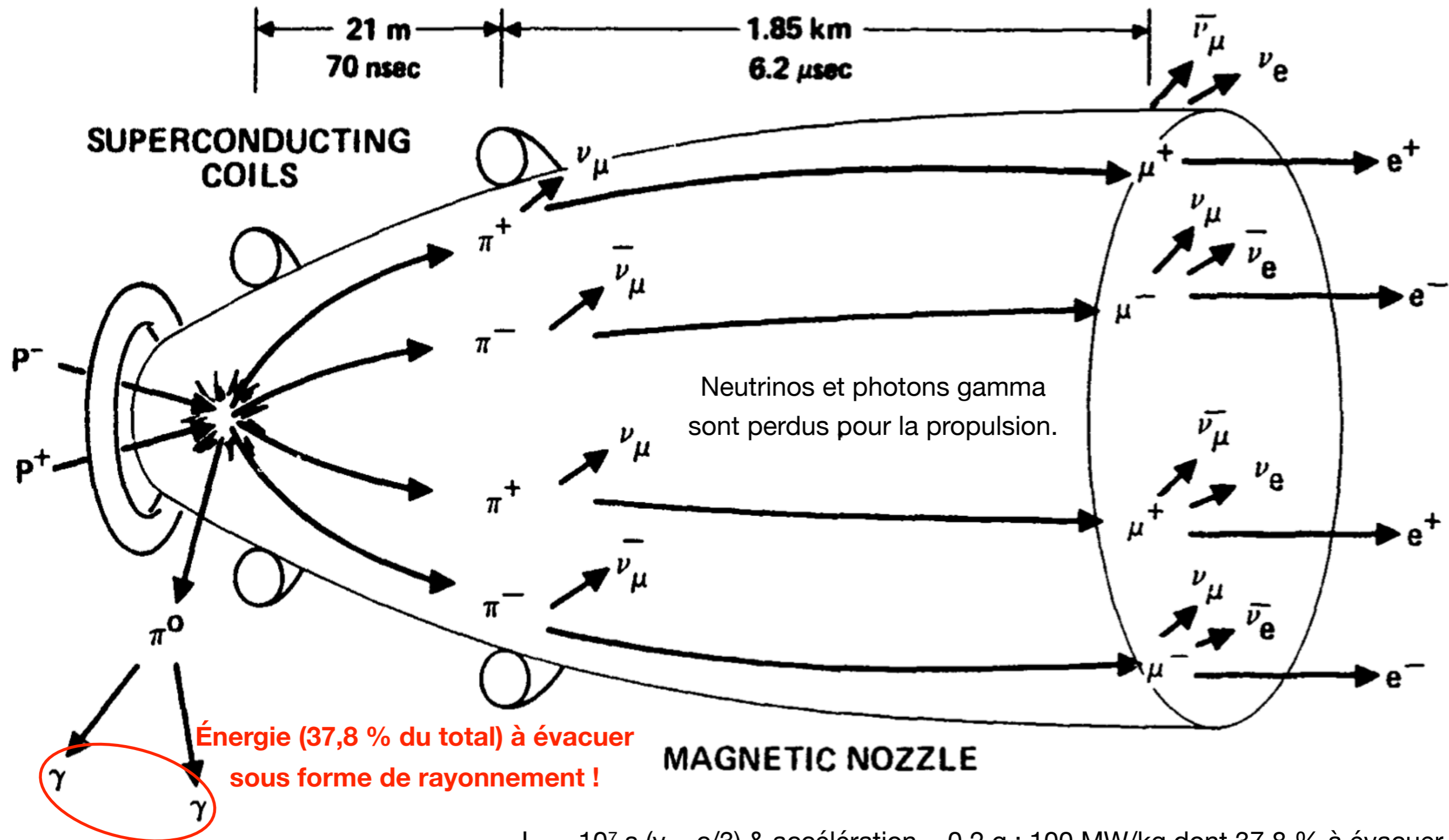
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad \text{Durée de vie 2.2 microsecondes (en vol @0.94c 6.2 \mu s)}$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad \text{Énergie cinétique des muons = 30,7 \% de l'énergie initiale.}$$

$$e^- + e^+ \rightarrow 2\gamma \quad \text{Énergie cinétique = 15,9 \% de l'énergie initiale.}$$

Propulsion directe à antimatière

9780 1R1

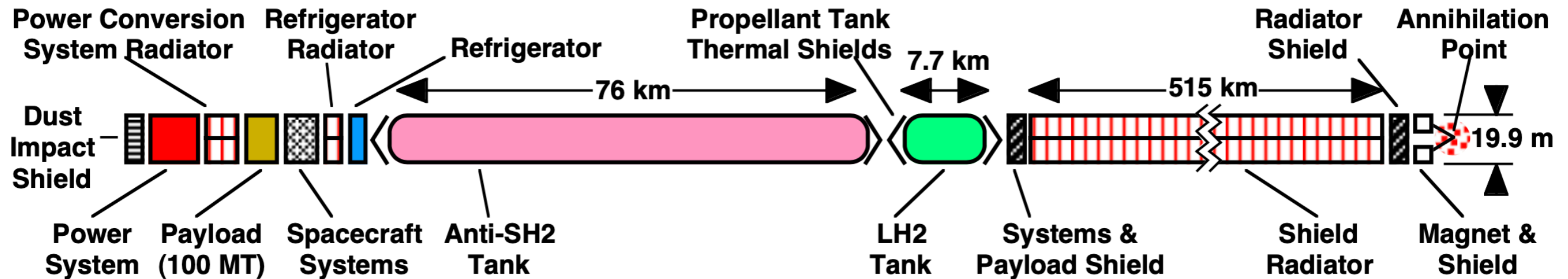


$I_{sp} = 10^7$ s ($v = c/3$) & accélération = 0,2 g : 100 MW/kg dont 37,8 % à évacuer.
25 m² de panneaux rayonnants par kg : T = 1 000 K !

Un vaisseau pas facile à faire...

Depuis quatre jours, le Deucalion plongeait vers Jupiter, en poussée constante. Son système de propulsion exploitait une source d'énergie parfaite : une balle de glace d'antihydrogène confinée dans une chambre à vide réfrigérée.

Wonderland, Serge Lehman – L'intégrale F.A.U.S.T., Au diable Vauvert (2019).



$$I_{sp} = 10^7 \text{ s } (v = c/3)$$

$$a = 0,01 \text{ g}$$

$$v_{max} = 0,5 \text{ c}$$

$$D = 40 \text{ a.-l.}$$

$$\text{Durée du voyage} = 130 \text{ ans.}$$

Masse à vide = 70 000 tonnes

Masse d'antimatière = 165 000 tonnes

Production d'antimatière actuelle

10^{16} antiprotons (10 nanogrammes) par an !

Merci de votre attention !

