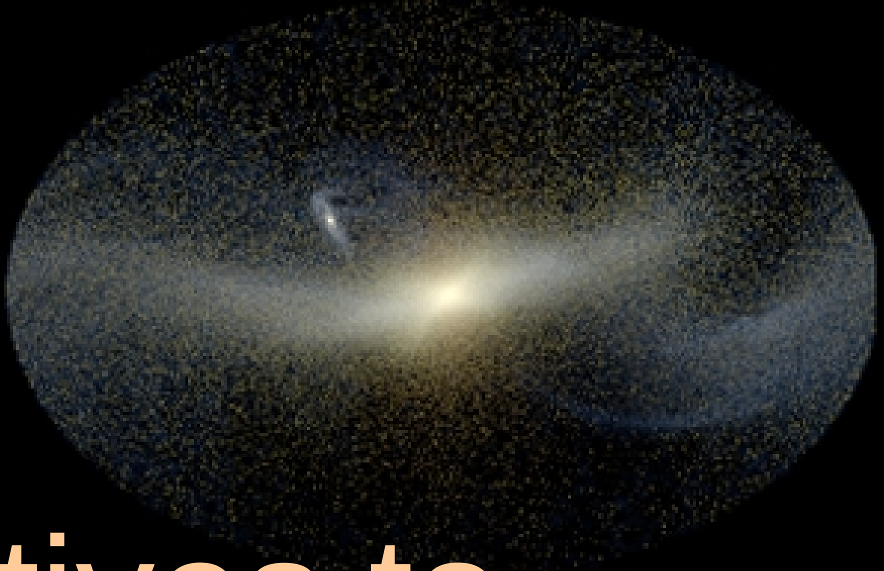
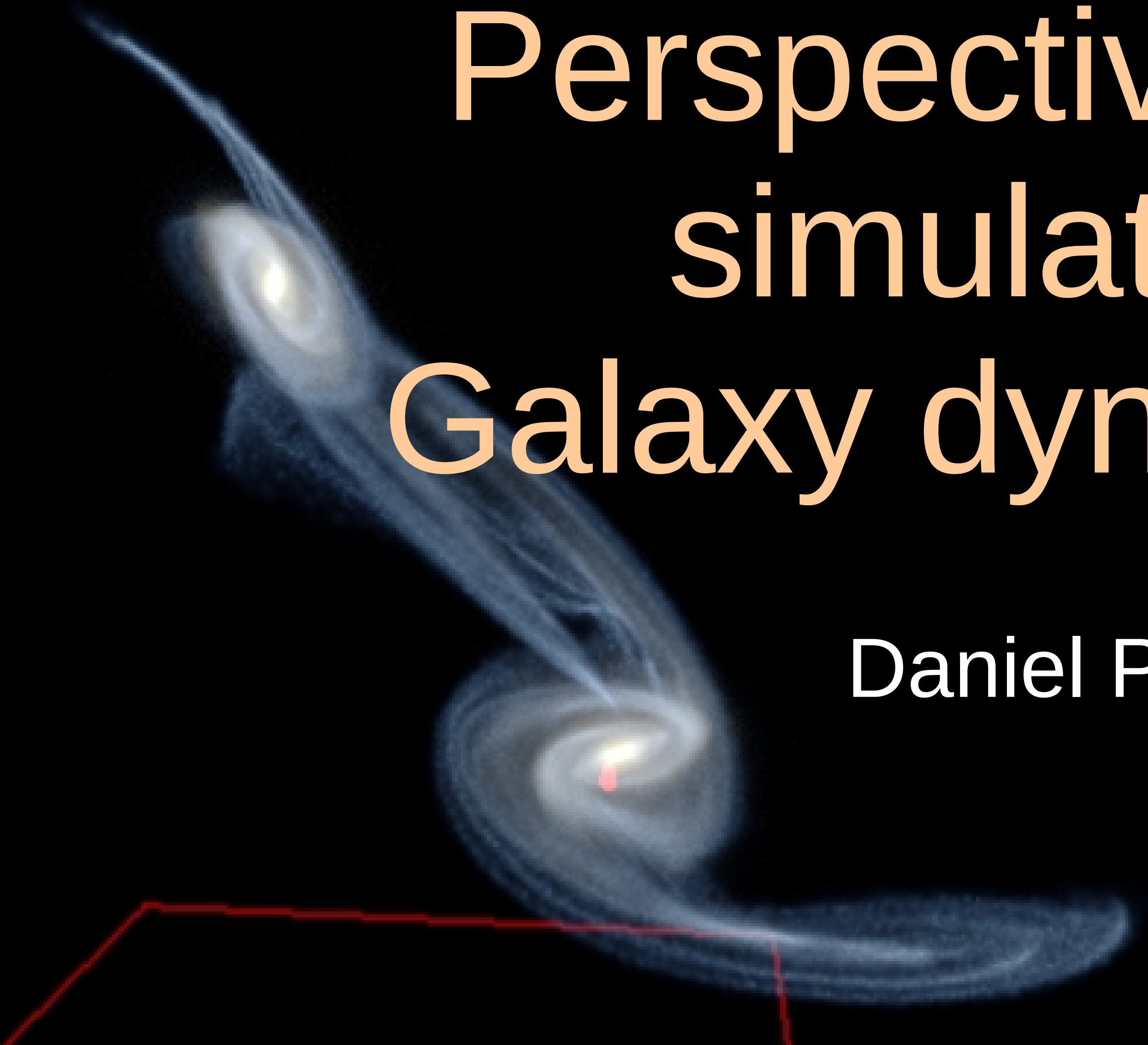


Perspectives to simulate Galaxy dynamics



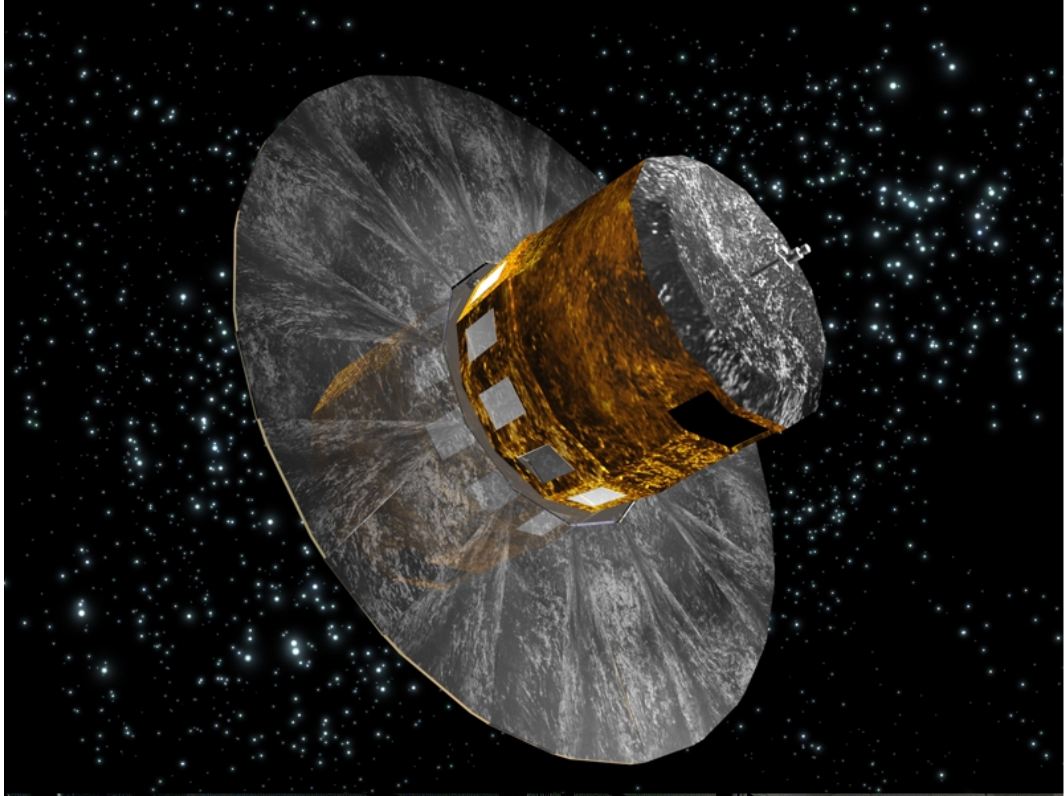
Daniel Pfenniger

OBSERVATOIRE DE GENÈVE
FONDÉ EN 1772

Introduction

Advances in observations and techniques, consequences:

- Changes of perspectives
- Change of methods
- Modelling the Milky Way around 2010-2020

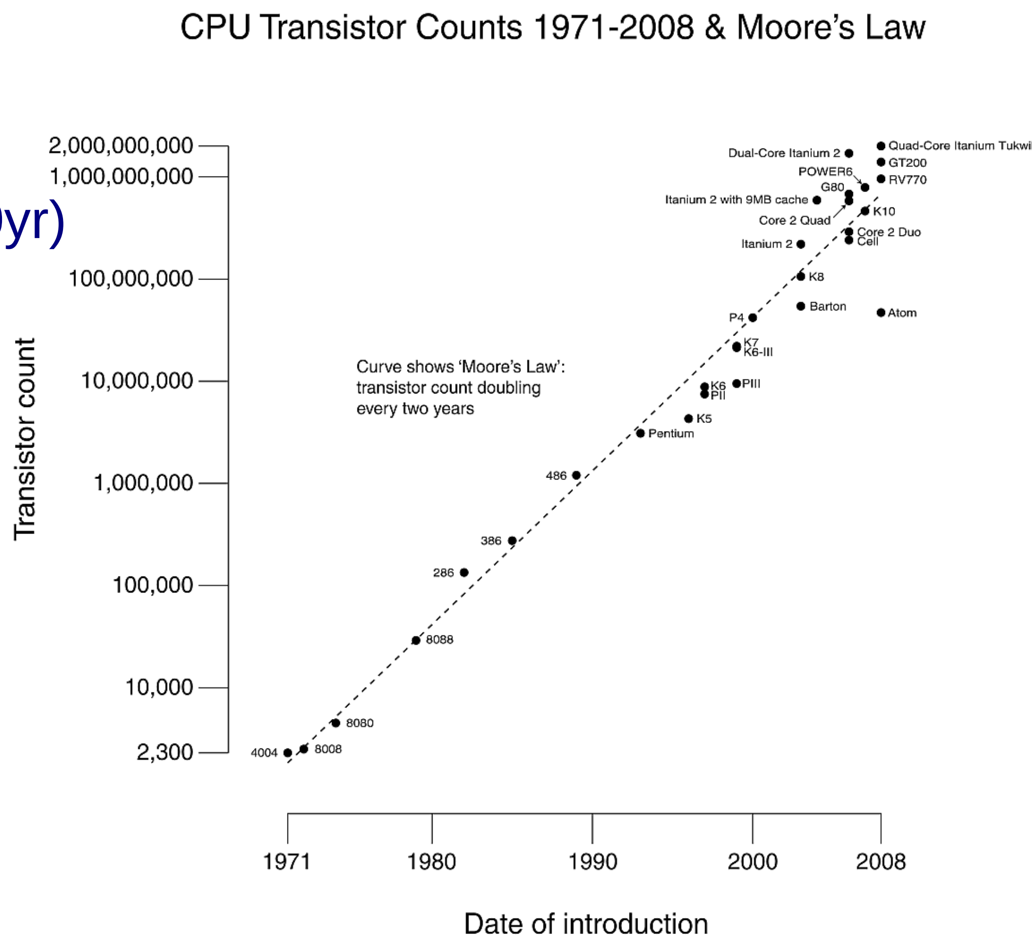


Gordon E. Moore's law (1965)

- Historically unprecedented technological revolution (~10x performance every 5yr over 60yr)
- For complex sciences (biology, astronomy, earth-sciences, chemistry, ...), high performance computing plays the rôle that maths have fullfilled over last centuries for physics
- Perfomance of the present top computers becomes easy to access

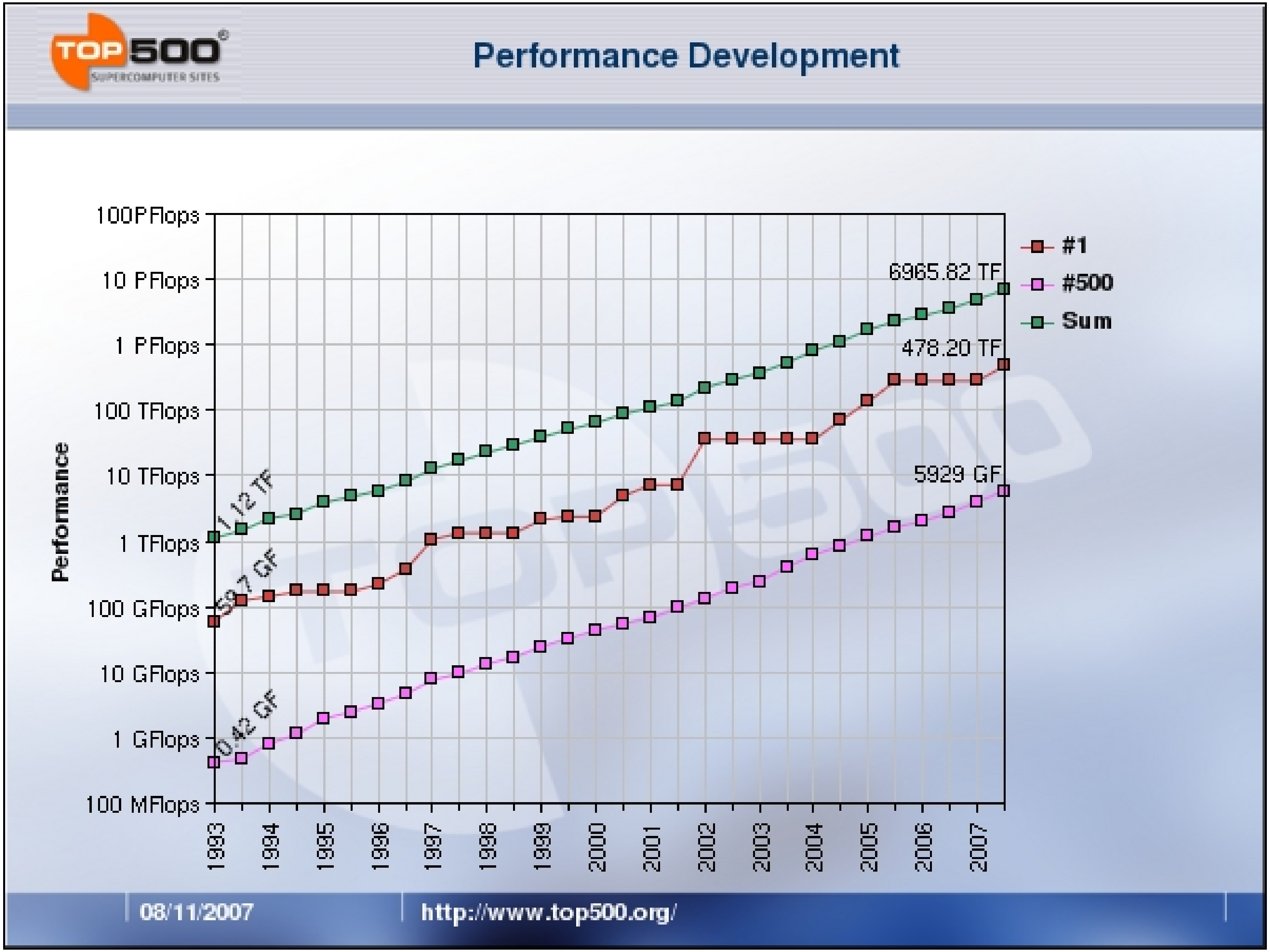
  ~ after 5-15 yr for average scientists

  ~ after 20-30 yr for the public



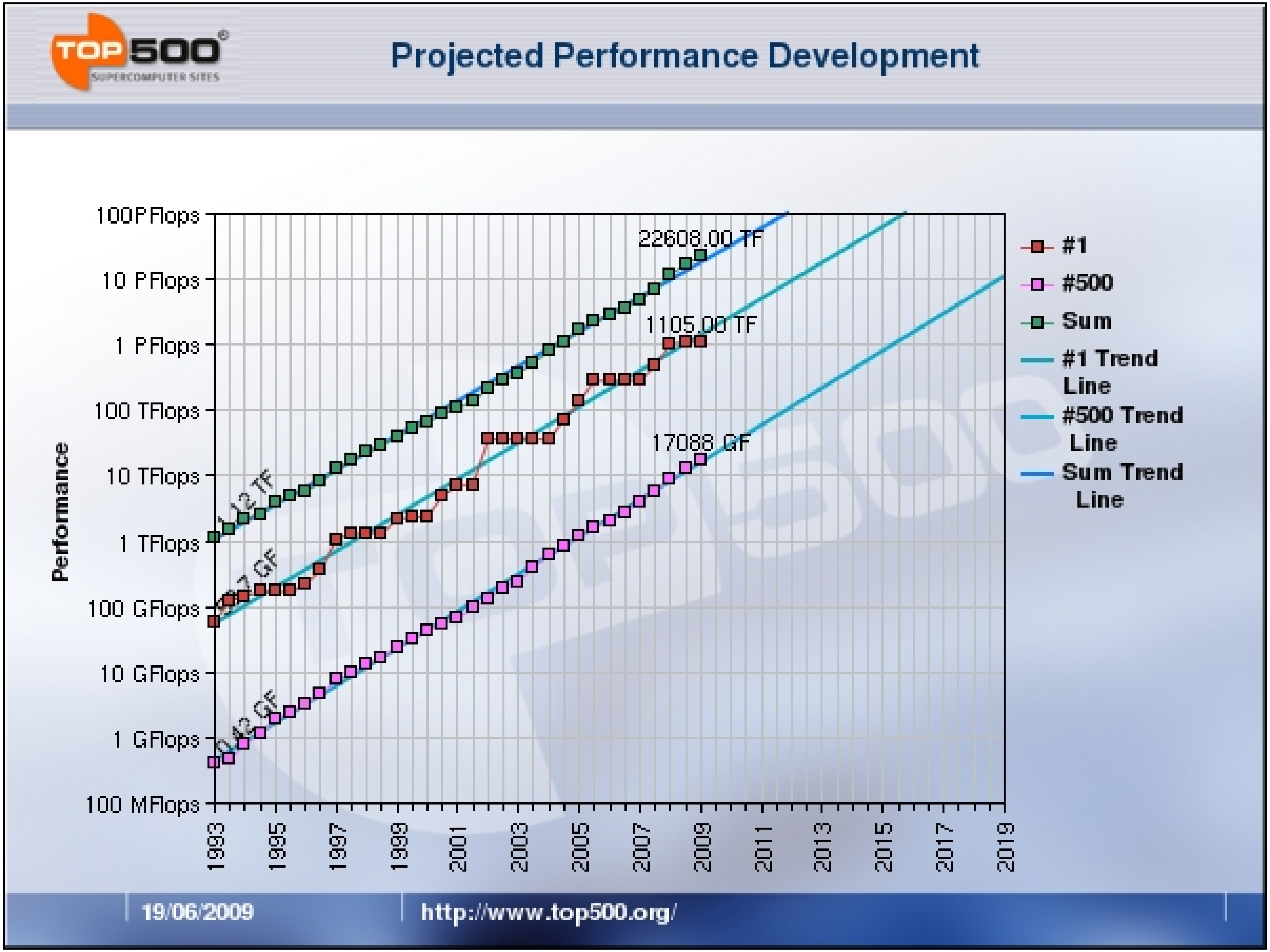
=> as in other sciences, advances in computer technology have a major impact in astronomy

Moore's law @ Top 500 (top500.org)



Moore's law @ Top 500 (top500.org)

Moore's law @ Top 500 (top500.org)



2020 SCIENCE

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Overview

In the summer of 2005, an international expert group was brought together for a workshop to define and produce a new vision and roadmap of the evolution, challenges and potential of computer science and computing in scientific research in the next fifteen years.

The resulting document, *Towards 2020 Science*, sets out the challenges and opportunities arising from the increasing synthesis of computing and the sciences. It seeks to identify the requirements necessary to accelerate scientific advances –particularly those driven by computational sciences and the 'new kinds' of science the synthesis of computing and the sciences is creating. Already this synthesis has led to new fields and advances spanning genomics and proteomics, earth sciences and climatology, nanomaterials, chemistry and physics.

We hope *Towards 2020 Science* will act as a 'pathfinder' to new research dire computing. We also hope that it will contribute to, and inform, national and int and science policy. It is also just a start, a catalyst for more discussion, so las and provocative.

The *Towards 2020 Science* workshop and the consequent report were run anc Research Cambridge.

Nature '2020 Computing' Special Issue

(2006 Nature 440)

The *Towards 2020 Science* report inspired a special issue of Nature on '2020

Call for proposals

Purpose of computer simulations

- Like maths for theoretical physics, but for complex systems

  => additional tool to traditional maths

- Provide ability to summarize complex systems like a galaxy by a deterministic controlled scheme

  => understanding, insight

- Provide the ability to predict facts, from better insight, estimate effects without computer

  => possibility to steer observations by precise goals

Change of paradigm

- For galaxies, computer simulations are more and more providing more faithfull models than traditional models based on maths
- Indeed: with $\sim 10^{11}$ stars

  => with 100 stars/phase space cell to represent a reasonably smooth distribution function: 10^9 cells

  => $(10^9)^{1/6} \sim$ 32 bins / coordinate only

  => the smooth phase space flow model is not a better description of stellar galaxies than a N-body model with $N \sim 10^9$

Today $N > 10^{10}$ becomes increasingly accessible
(Teyssier et al 2009, Springel et al 2005, Boylan-Kolchin et al 2009)

Local stellar kinematics from Hipparcos

No. 6, 1998 DISTRIBUTION OF NEARBY STARS 2391

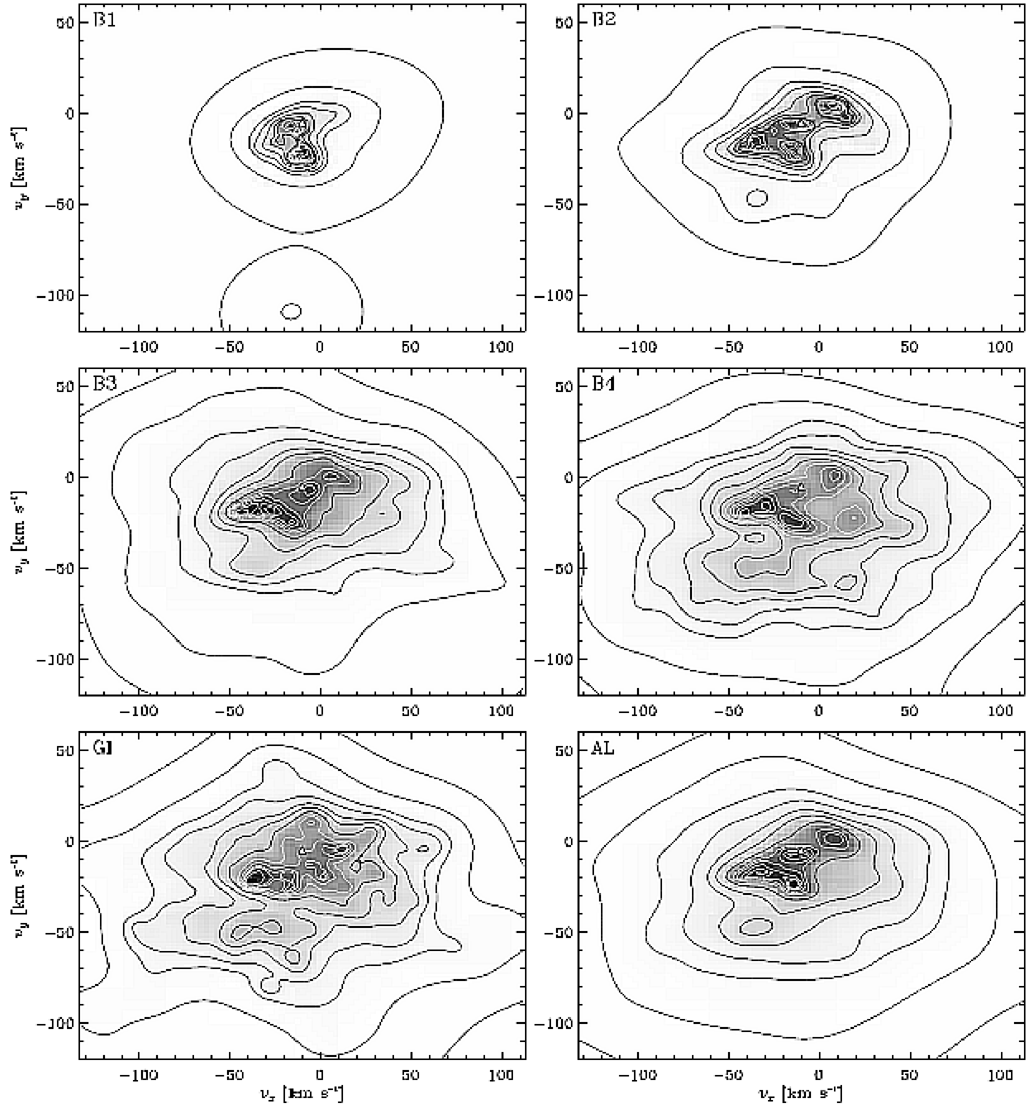

FIG. 3.—Distributions in v_x (toward the Galactic center) and v_y (in direction of Galactic rotation): projection of $f(v)$ obtained as MPLE for the sets listed in Table 1. Gray scales are linear and the contours contain, from inside outward, 2, 6, 12, 21, 33, 50, 68, 80, 90, 95, 99, and 99.9 percent of all stars; i.e., half the stars are within the innermost dark contour. The origin is at the solar velocity, while the velocity derived for the LSR in Paper I is indicated by a triangle. Note that the smoothing is optimal for the full sample (AL) only, while the results for the subsets are undersmoothed. However, since the subsets are distinct, any feature common to more than one of them is likely to be real.

Dehnen 1998

=> Complicated, non-smooth phase space structure

Infrared view of the spiral stellar content

Mon. Not. R. Astron. Soc. 299, 685–698 (1998)

The structure of spiral galaxies – II. Near-infrared properties of spiral arms

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ABSTRACT

We have imaged a sample of 45 face-on spiral galaxies in the *K* band, to determine the morphology of the old stellar population, which dominates the mass in the disc. The *K*-band images of the spiral galaxies have been used to calculate different characteristics of the underlying density perturbation such as arm strengths, profiles and cross-sections, and spiral pitch angles. Contrary to expectations, no correlation was found between arm pitch angle and Hubble type, and combined with previous results this leads us to conclude that the morphology of the old stellar population bears little resemblance to the optical morphology used to classify galaxies.

The arm properties of our galaxies seem inconsistent with predictions from the simplest density wave theories, and some observations, such as variations in pitch angle within galaxies, seem hard to reconcile even with more complex modal theories. Bars have no detectable effect on arm strengths for the present sample.

We have also obtained *B*-band images of three of the galaxies. For these galaxies we have measured arm cross-sections and strengths, to investigate the effects of disc density perturbation on star formation in spiral discs. We find that *B*-band arms lead *K*-band arms and are narrower than *K*-band arms, apparently supporting predictions made by the large-scale shock scenario, although the effects of dust on *B*-band images may contribute towards these results.

Key words: galaxies: fundamental parameters – galaxies: spiral – galaxies: structure – infrared: galaxies.

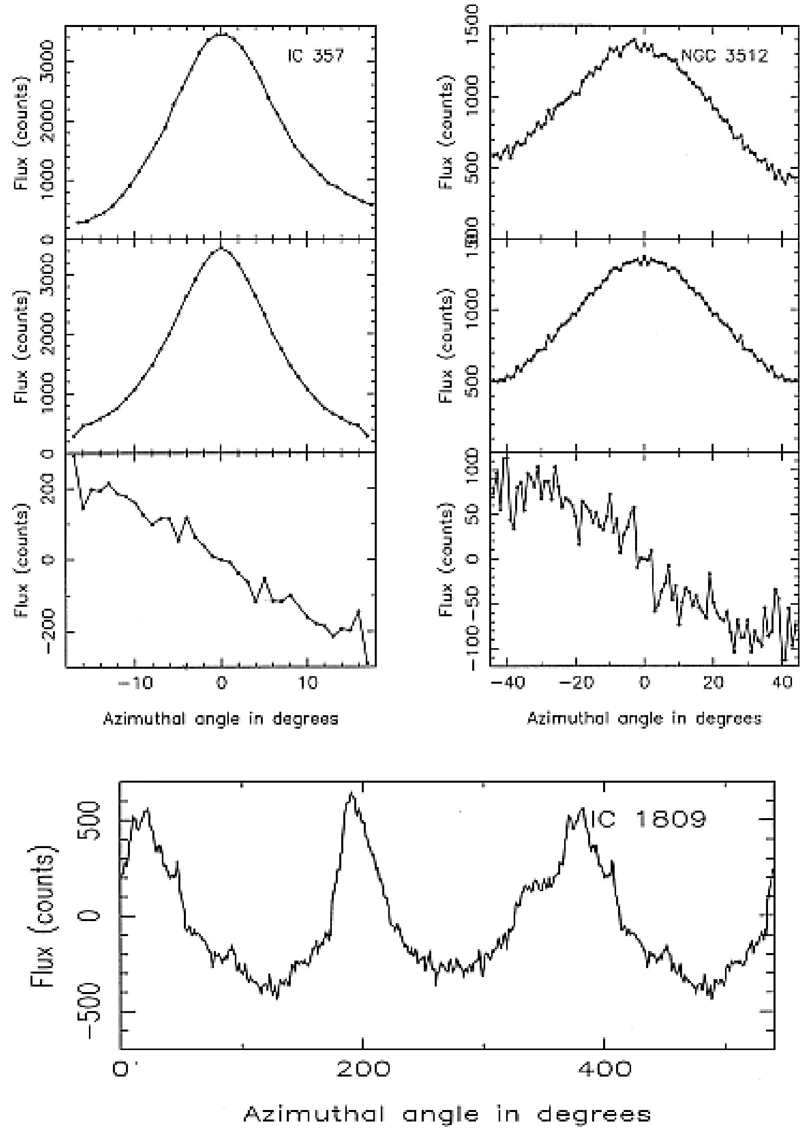
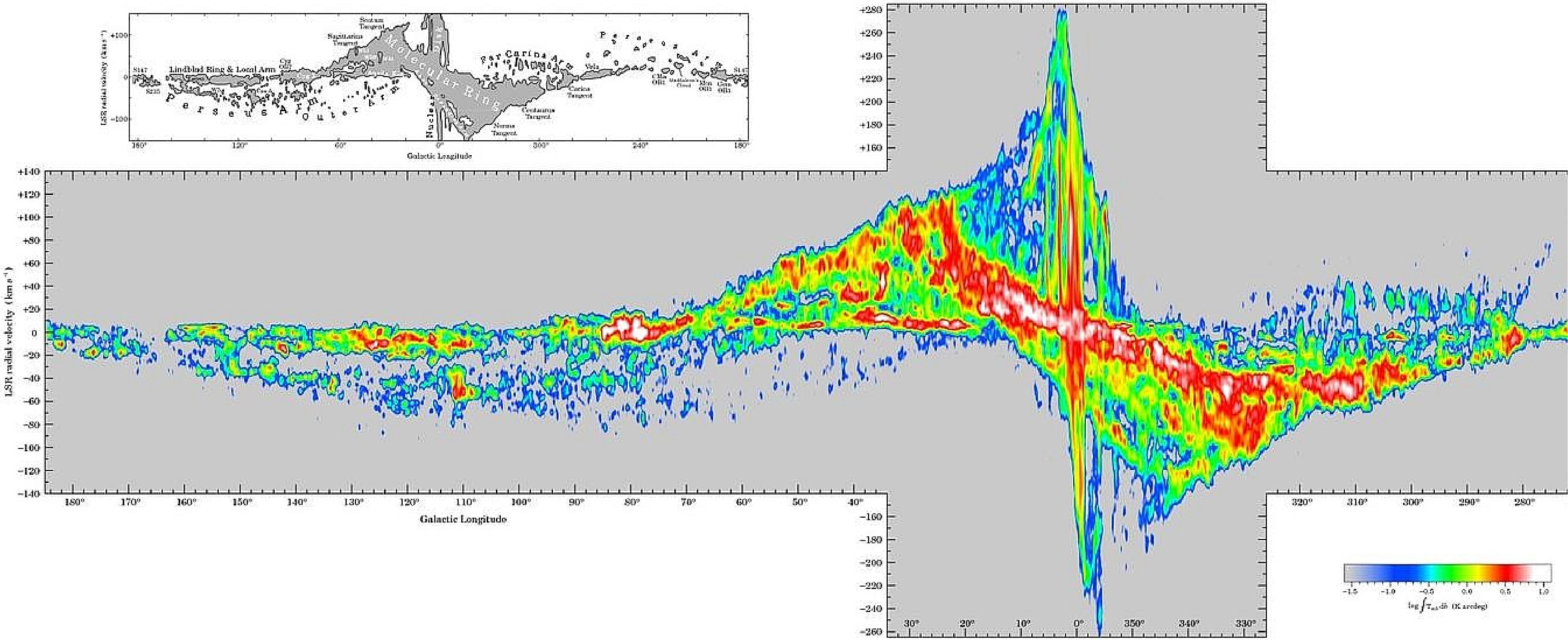


Figure 2. Upper panels: arm cross-sections (top), symmetric components (central) and antisymmetric components (lower). Leading edges (i.e. the convex sides) of arms are plotted on the right. Lower panel: a 540° cut of IC 1809.

=> bars and spiral arms are strong non-linear density perturbations, self-gravity is locally dominant

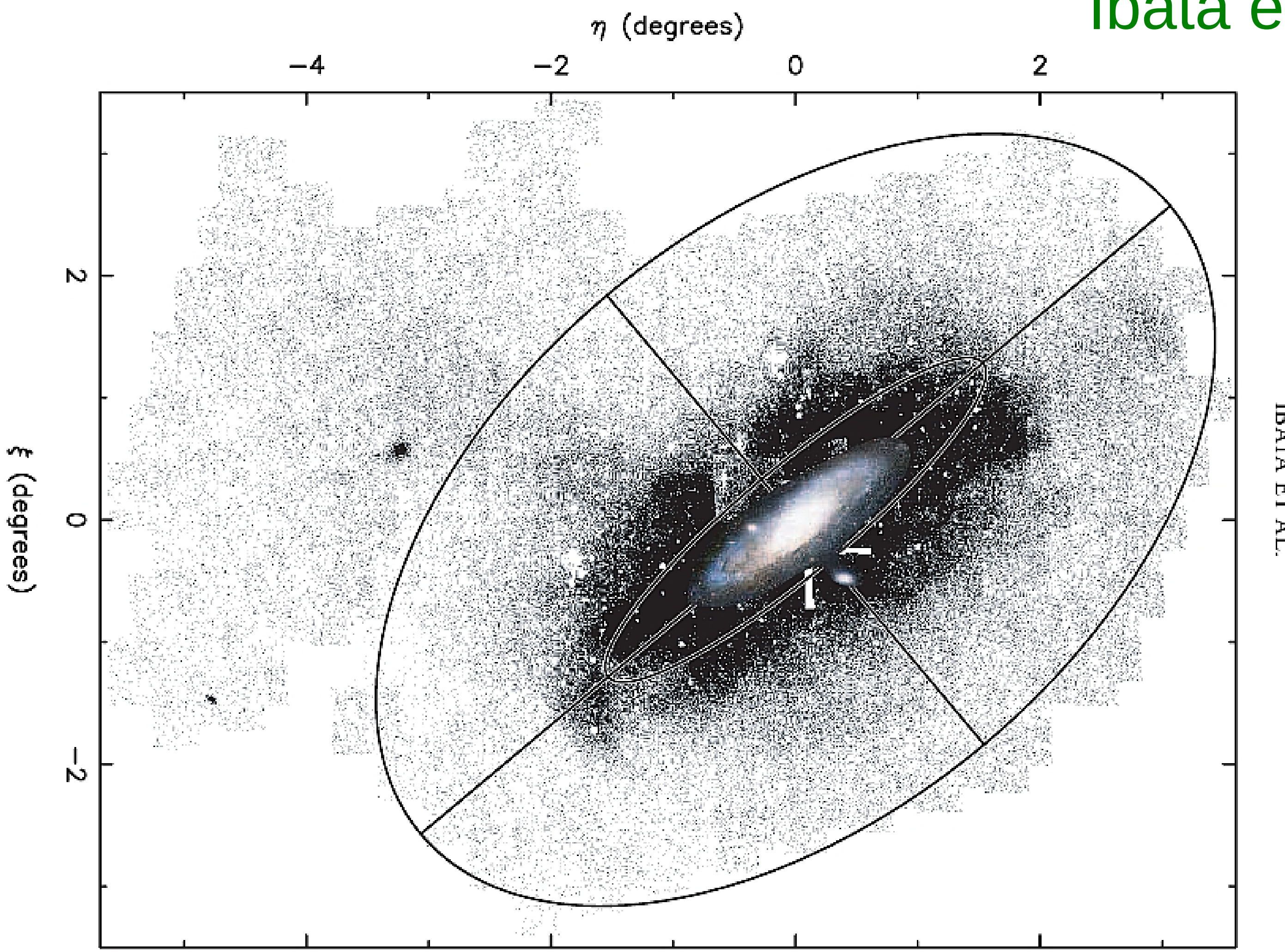
Milky Way CO survey (Dame et al 2001)



=> Complicated clumpy gas structures and kinematics

Milky Way and Andromeda stellar halos

Ibata et al. 2005



=> Complicated non-virialized stellar halos

Theoretical understanding of spiral galaxies

Mon. Not. R. astr. Soc. (1988) **231,** *Short Communication,* 25P–31P

Pattern speeds in barred spiral galaxies

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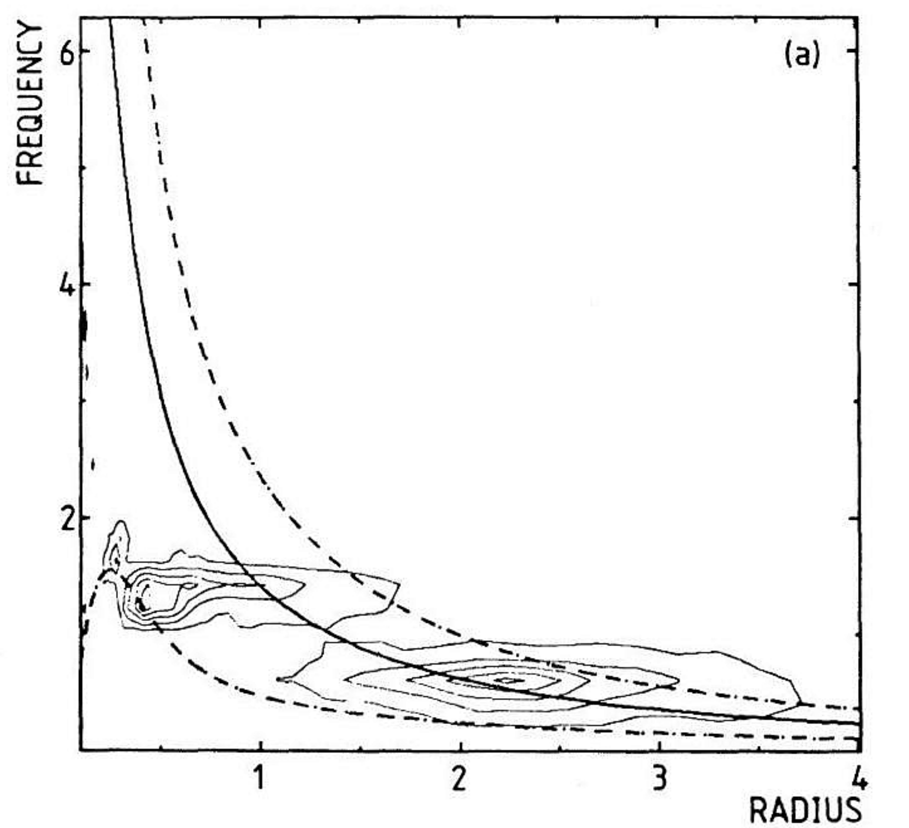
Accepted 1988 January 4. Received 1987 December 23

Summary. Current theoretical ideas of the pattern speeds of the bar arms in SB galaxies appear to conflict with the observational evidence. This difficulty can be avoided if the spiral arms have a lower pattern speed than the bar. We present evidence of multiple pattern speeds in our *N*-body simulations, and show that, though the spiral continually breaks from and reconnects to the bar, the morphology of the pattern at all times resembles that of barred galaxies in the sky. We briefly discuss how the gas might respond to the multiple patterns.

Pattern speeds in barred spiral galaxies



=> time-dependent galactic potential

Theoretical understanding of spiral galaxies (Fux 1997,1999)

Astron. Astrophys. 327, 983–1003 (1997)

ASTRONOMY
AND
ASTROPHYSICS

3D self-consistent N-body barred models of the Milky Way

I. Stellar dynamics

R. Fux

Geneva Observatory, Ch. des Maillettes 51, CH-1290 Sauverny, Switzerland

Received 23 April 1997 / Accepted 20 June 1997

Astron. Astrophys. 345, 787–812 (1999)

ASTRONOMY
AND
ASTROPHYSICS

3D self-consistent N-body barred models of the Milky Way

II. Gas dynamics

R. Fux

Geneva Observatory, Ch. des Maillettes 51, CH-1290 Sauverny, Switzerland

Received 26 November 1998 / Accepted 5 February 1999

(Fux 1999)

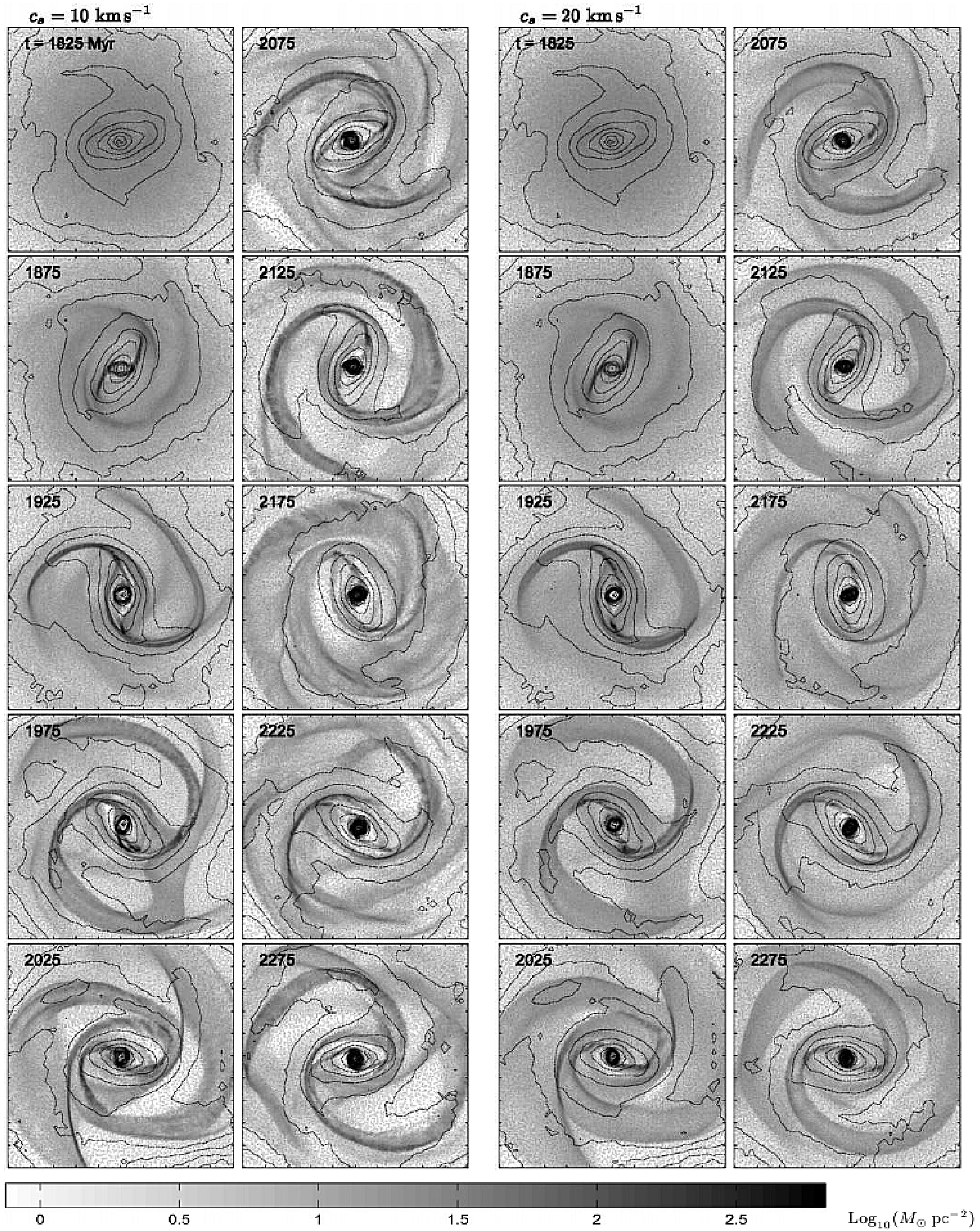


Fig. 12. Face-on view of the gas flow evolution in simulations l10 and l20, which differ only by the value of the sound speed c_s. Each frame is 20 kpc on a side in initial units. The dotted lines indicate the stellar surface mass density contours spaced by 0.75 magnitude.

(Fux 1999)

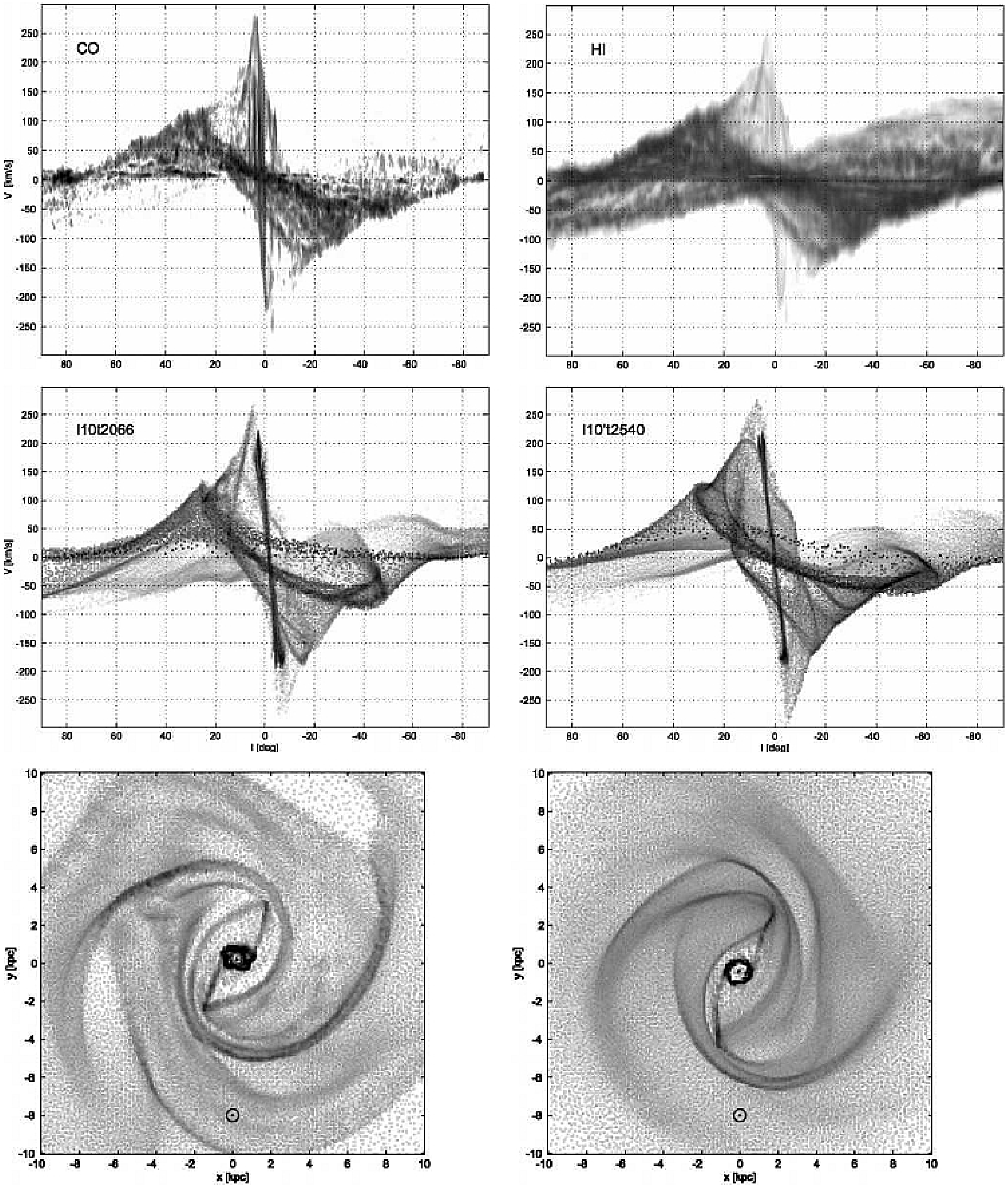


Fig. 15. Confrontation of a selection of two models with observed gas kinematics. *Top:* ^{12}CO and HI $\ell - V$ diagrams integrated over $|b| \leq 2°$ and $|b| < 1.25°$ respectively; the data are from Dame et al. (1999) for the CO, and Hartmann & Burton (1997), Burton & Liszt (1978) and Kerr et al. (1986) for the HI. *Middle:* synthetic $\ell - V$ diagrams of models l10t2066 and l10′t2540 for a bar inclination angle $\varphi_\circ = 25°$, including all particles within $|b| < 2°$. *Bottom:* face-on projections of the gas spatial distribution in these models, rescaled such as to put the observer at $(x, y) = (0, -8)$ kpc ($\odot$ symbol). In these units, corotation lies at $R_L = 4.5$ kpc (l10t2066) and 4.4 kpc (l10′t2540). The model on the left reproduces almost perfectly the connecting arm, while the model on the right provides a fair global qualitative agreement to the data.

=> only time-dependent galactic potential can match observations

- All these works point to the need to consider the Milky-Way as a time-dependent and non-axsymmetric
- Only fully self-consistent N-body models can achieve the level of detail required by future observational data.

Future simulations

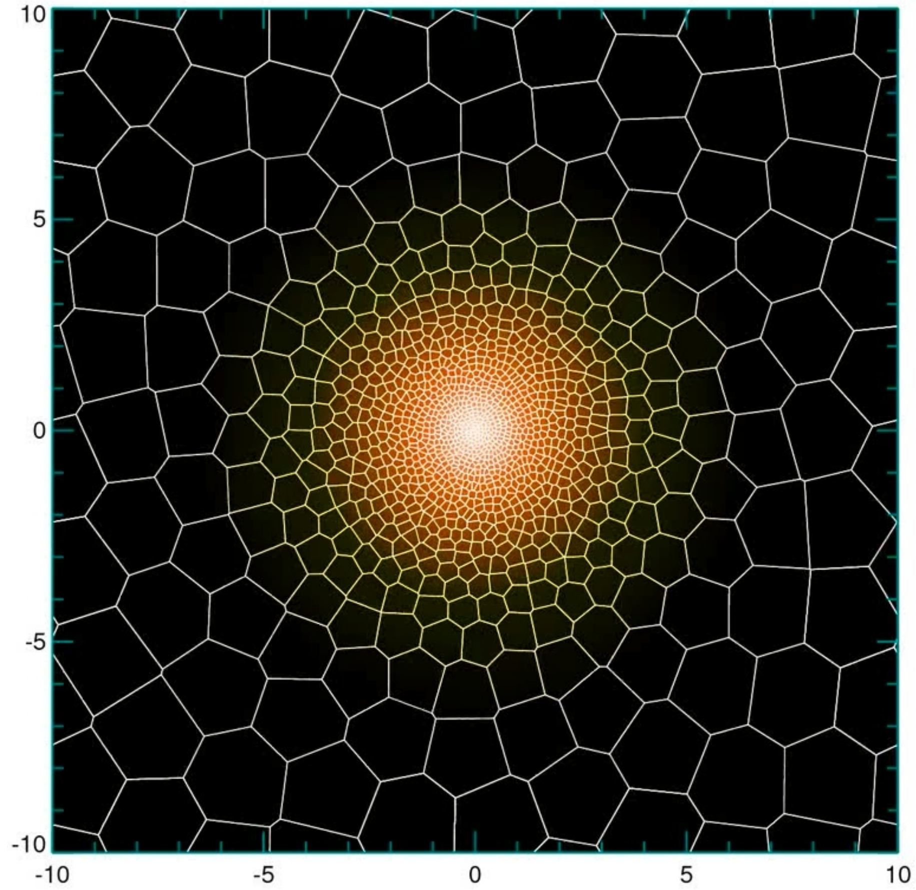
- With $N=10^{10}-10^{11}$ particles each (bright) star can be represented in a Milky Way N-body model where particles can represent at least all the massive stars, and groups of low mass stars/binaries

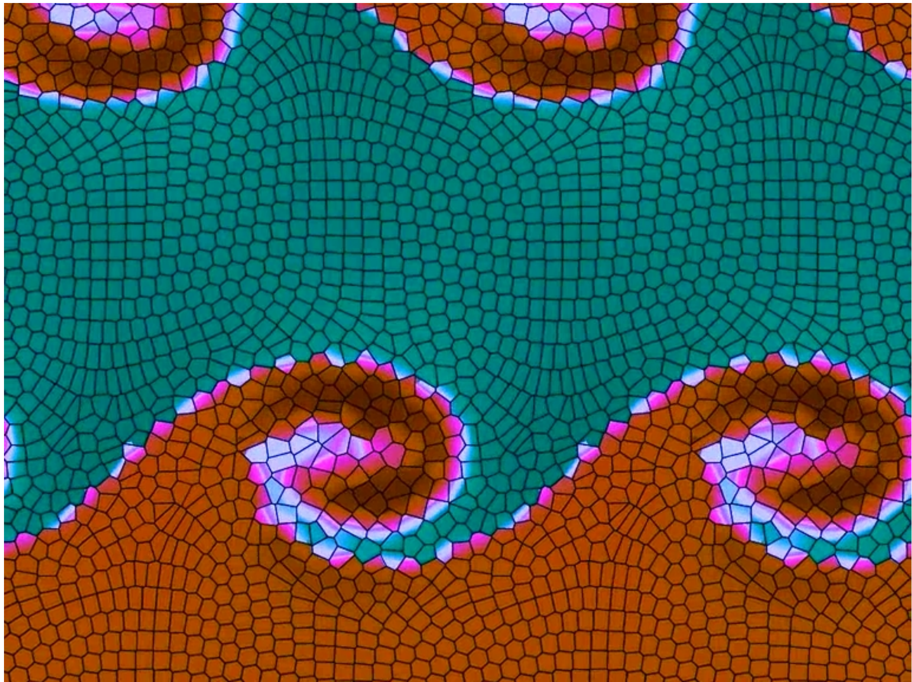
  => Phase space correlations (streams) can be studied and compared
- The problem of softening almost disapears
- Large sets of smaller N-body models with different initial conditions can be performed
- Precise simulations of observations are possible at a level matching GAIA results

Galactic gas dynamics is still a very hard problem though.

Springel (2009) using computational geometry (Voronoi space decomposition + volume preserving scheme) solve several problems:

- The respective shortcomings of AMR and SPH methods
- Natural evolution of lagrangian meshes without cell streching
- Refining and derefining lagrangian schemes while conserving integrals





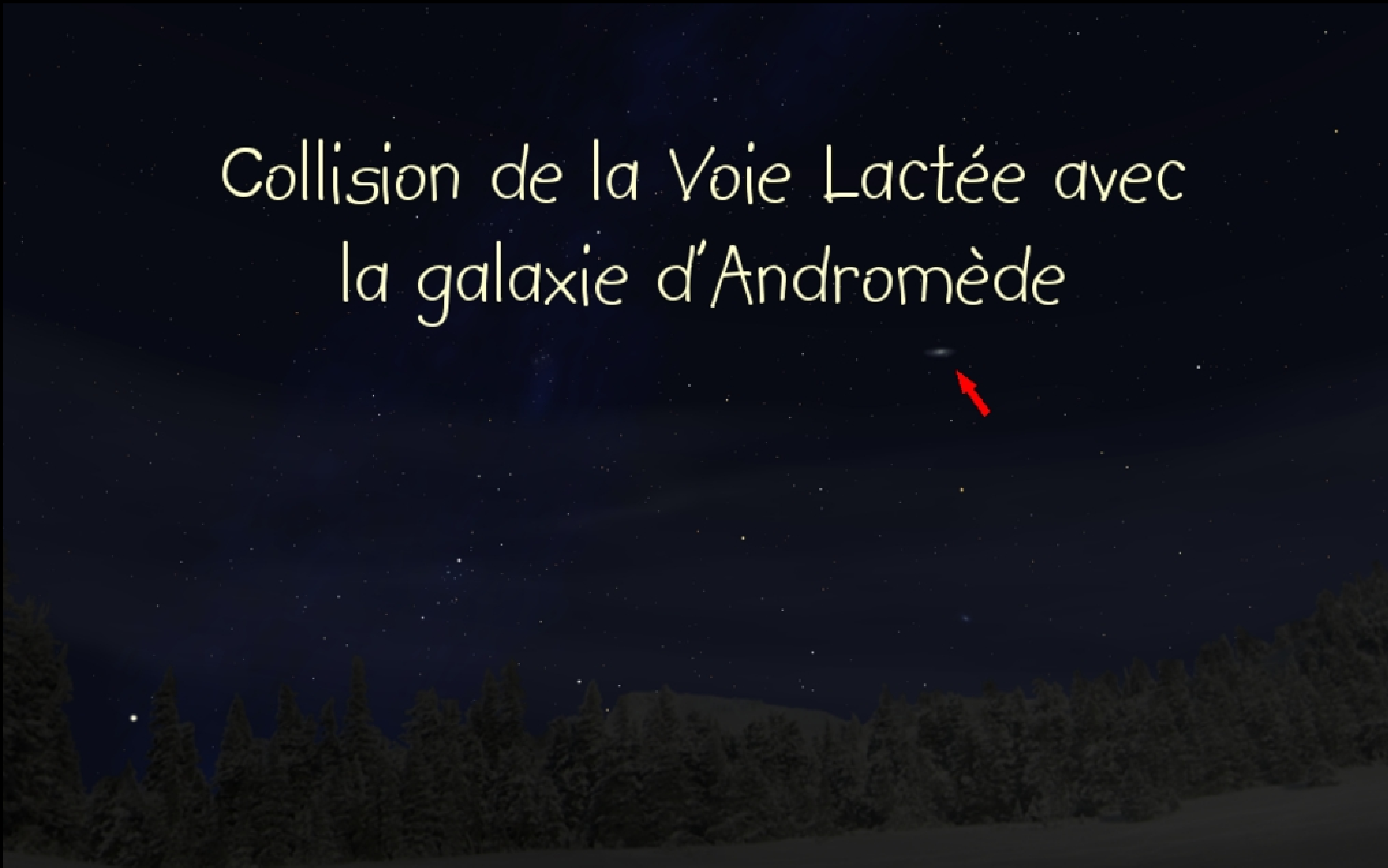
AREPO software (Springel 2009)

Conclusions

- At the level of precision reached by present and future instruments disk galaxies must be seen as time-dependent structures with multiple patterns rotating at different speeds
- Modelling the optical part of the Milky-Way with with N-body models containing as much particles as stars is feasible during the next decade
- Gas and dust modelling will remain a problem for a longer time

A 30 million body model of the future Milky Way with gas (with Yves Revaz)

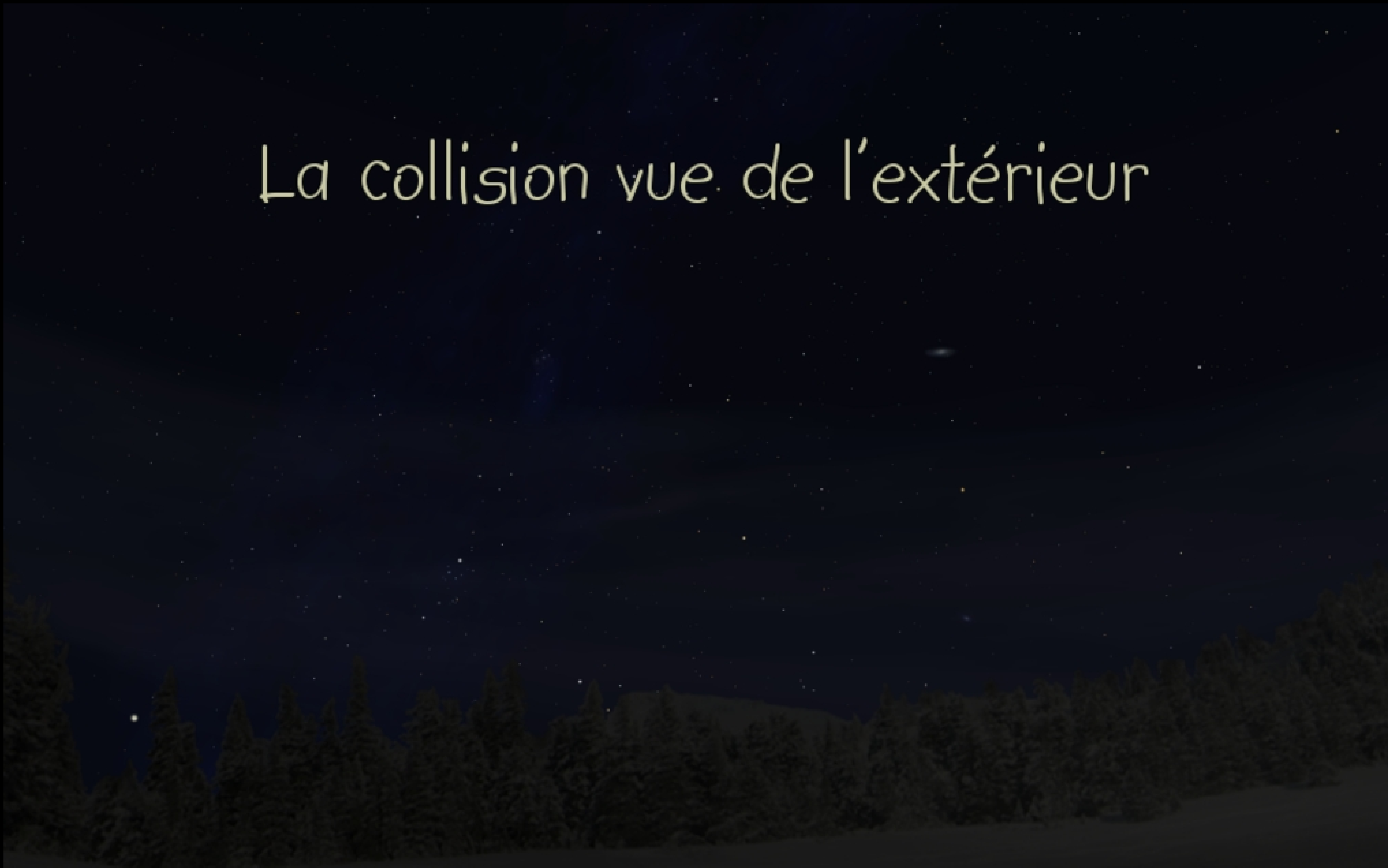

Prévisions du ciel futur


Collision de la Voie Lactée avec
la galaxie d'Andromède

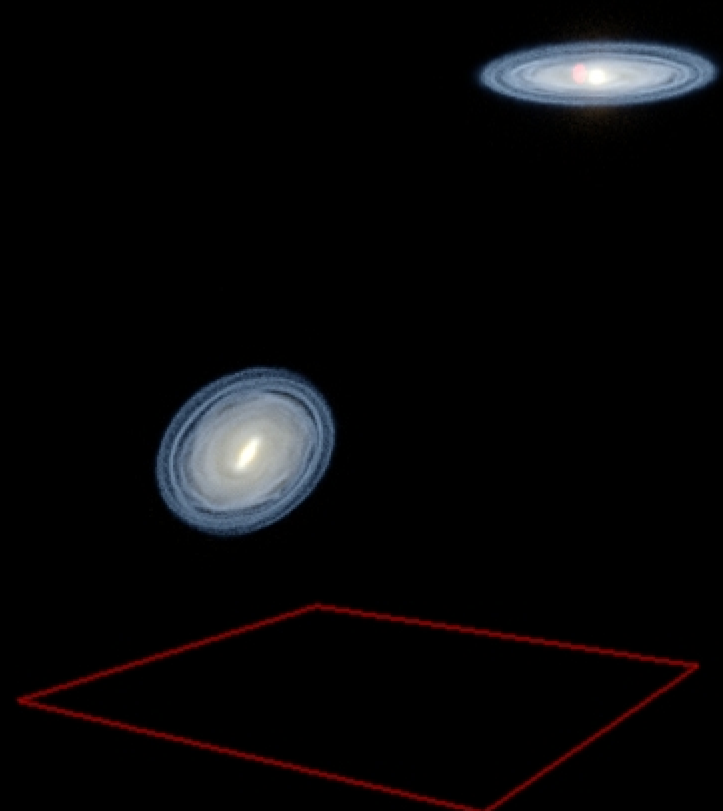
Yves Revaz
Daniel Pfenniger

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

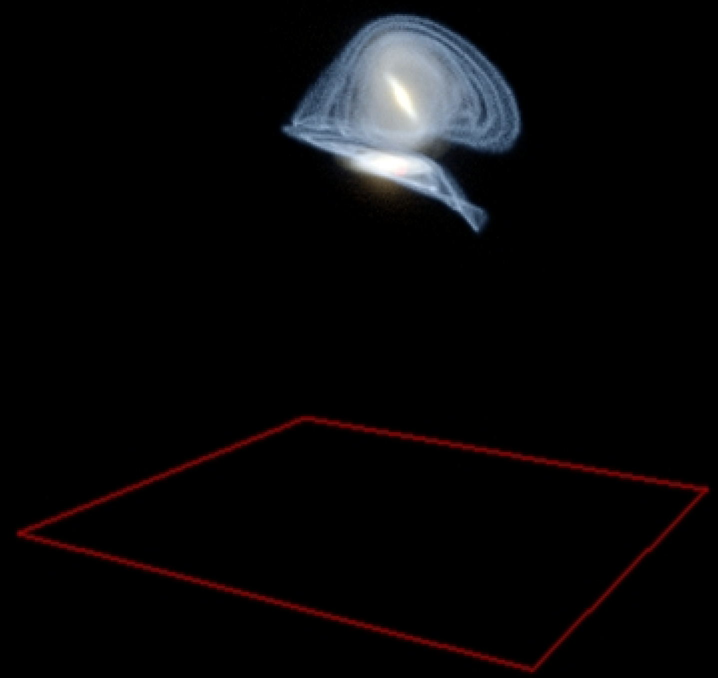
UNIVERSITÉ DE GENÈVE


La collision vue de l'extérieur

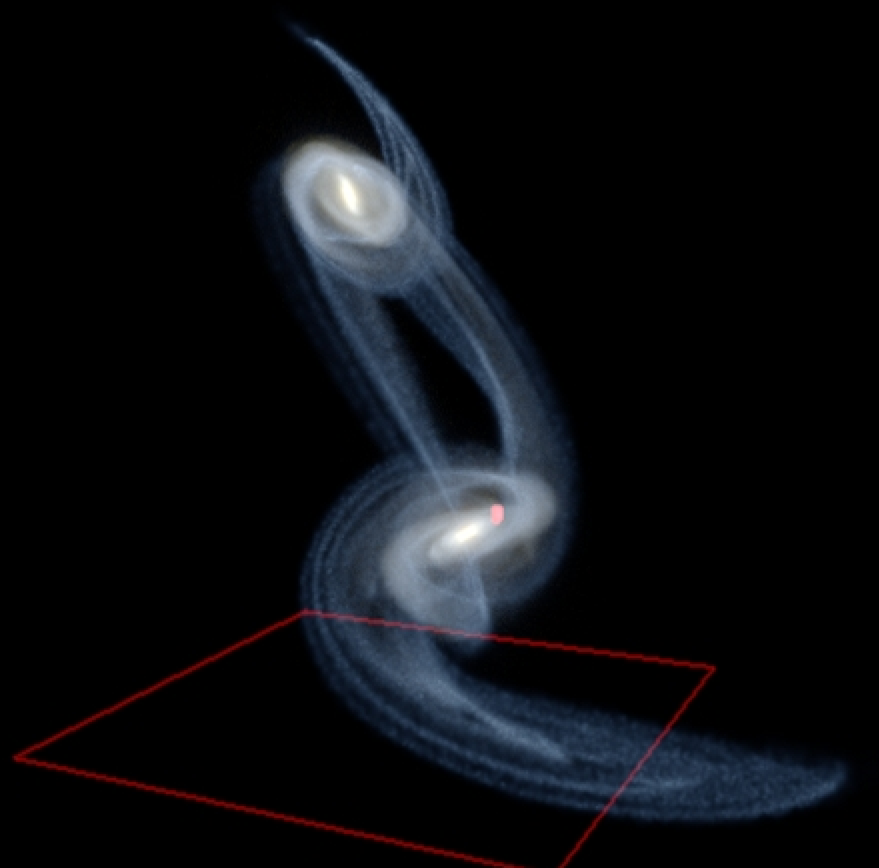
Temps = 3269 Millions d'années



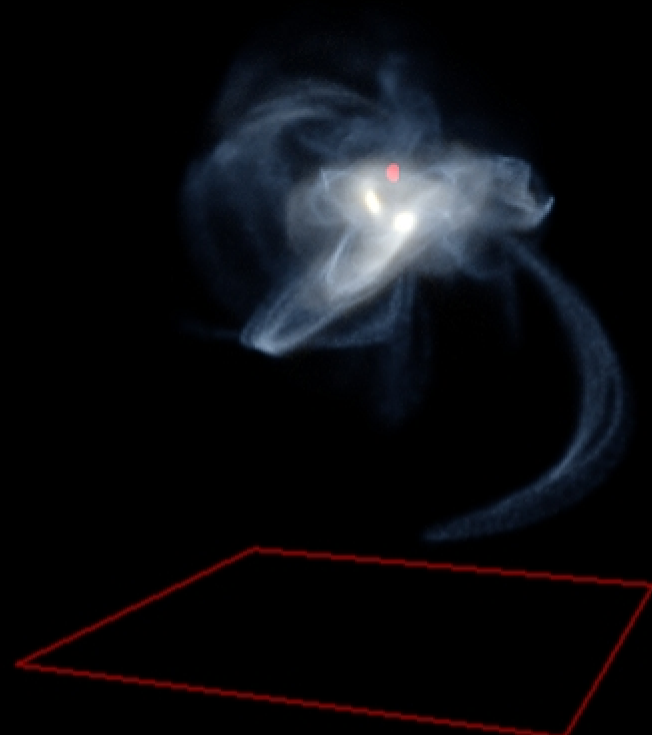
Temps = 3817 Millions d'années



Temps = 4365 Millions d'années



Temps = 5463 Millions d’années



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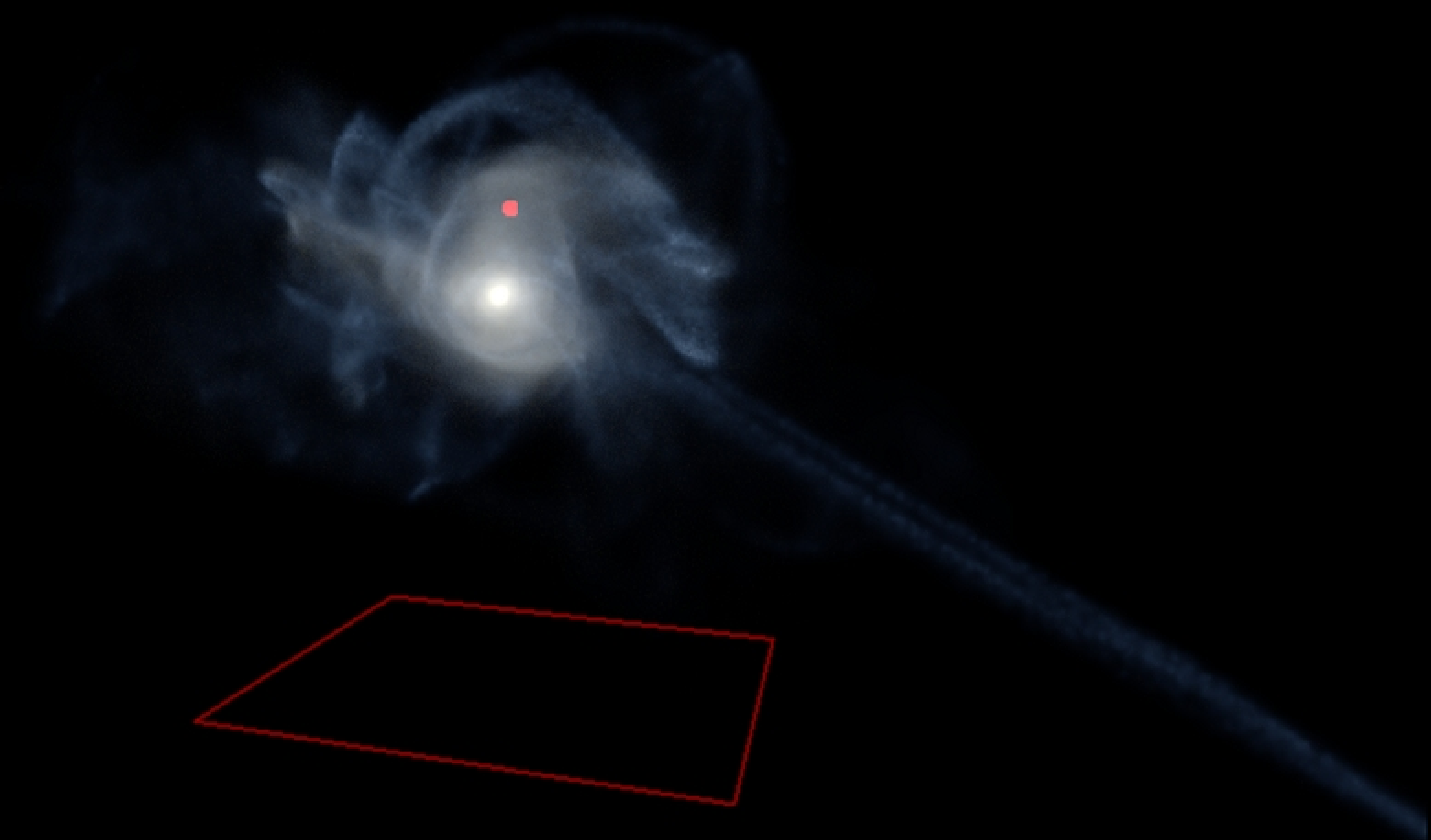

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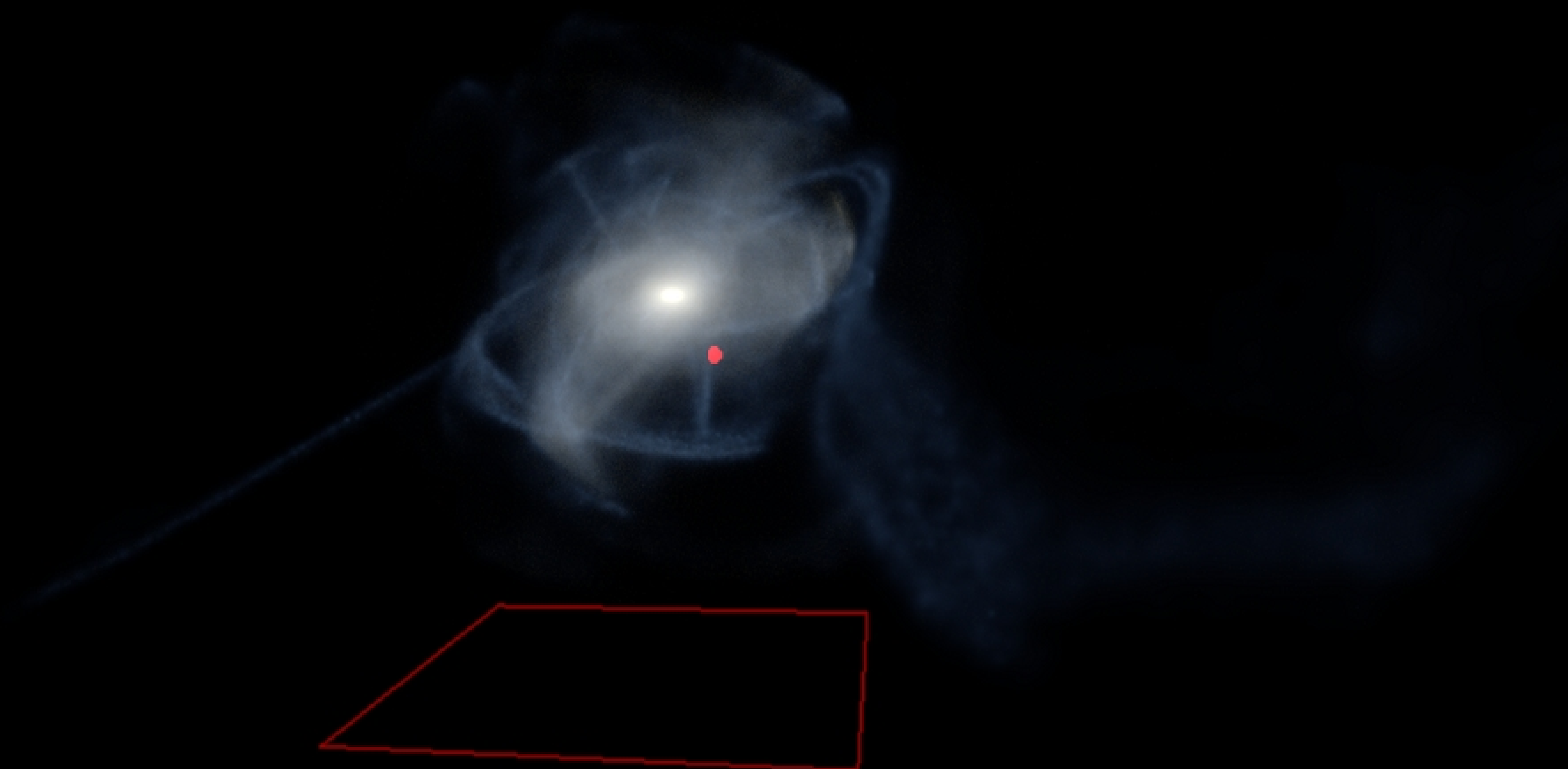
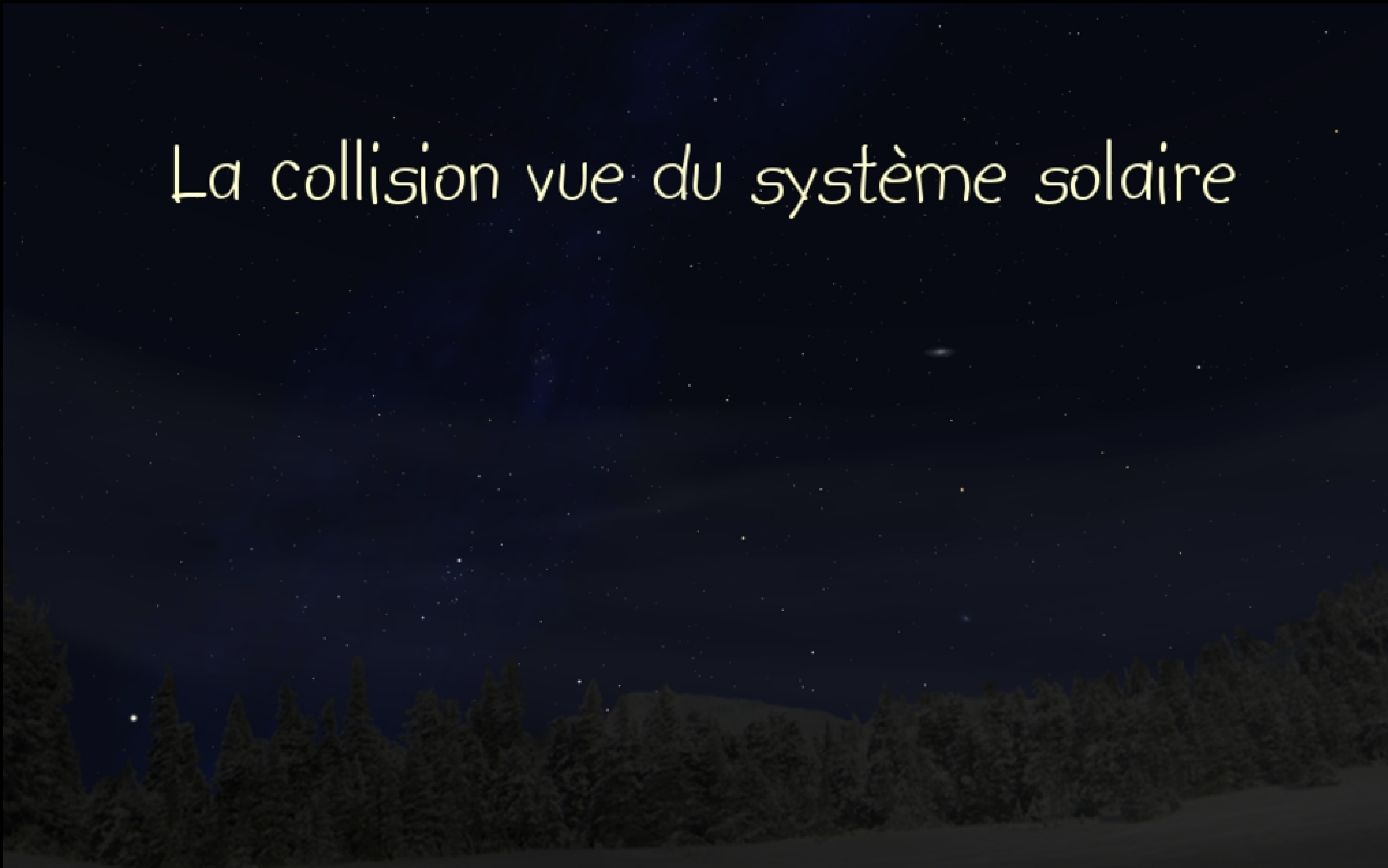
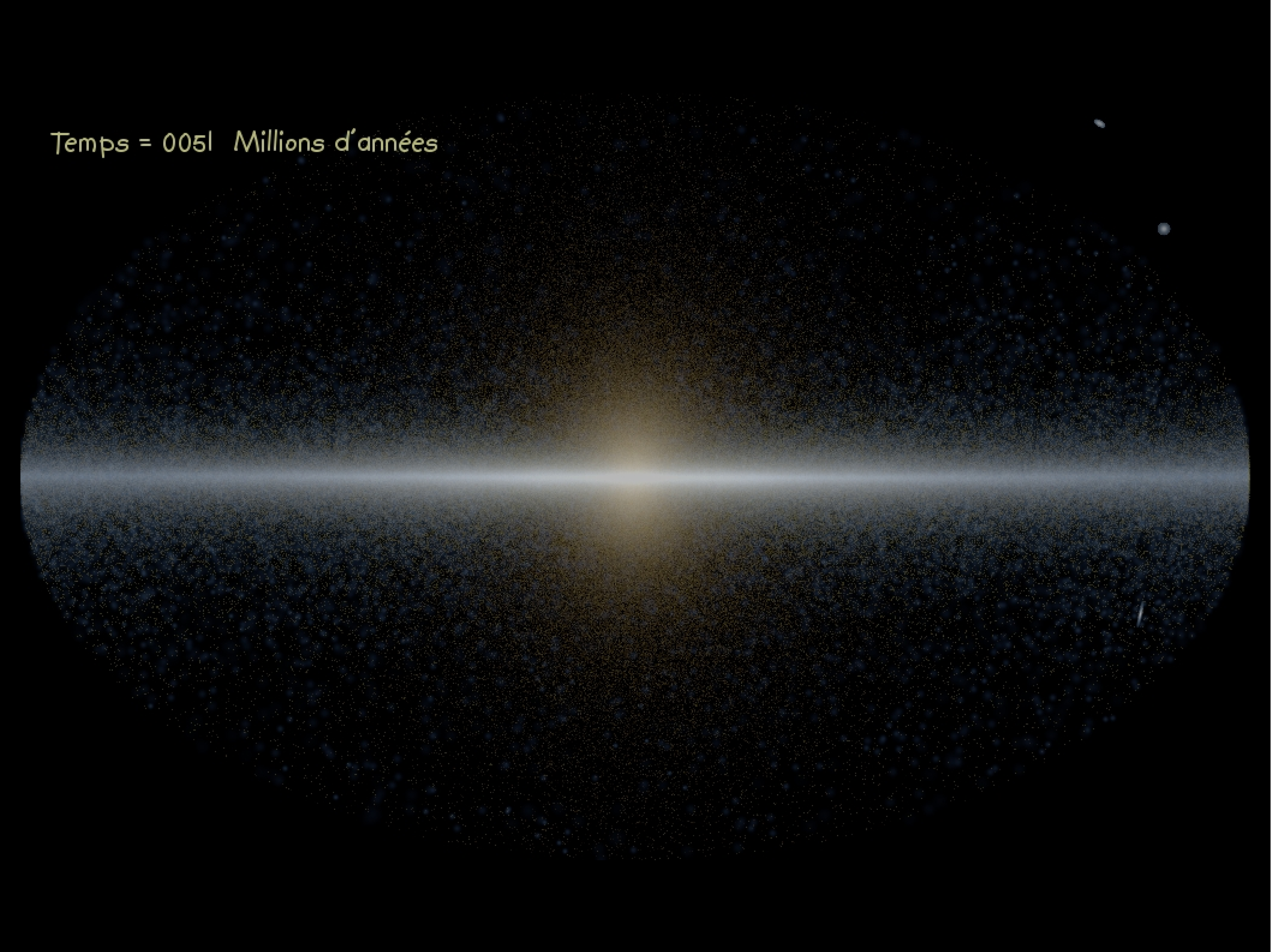



La collision vue du système solaire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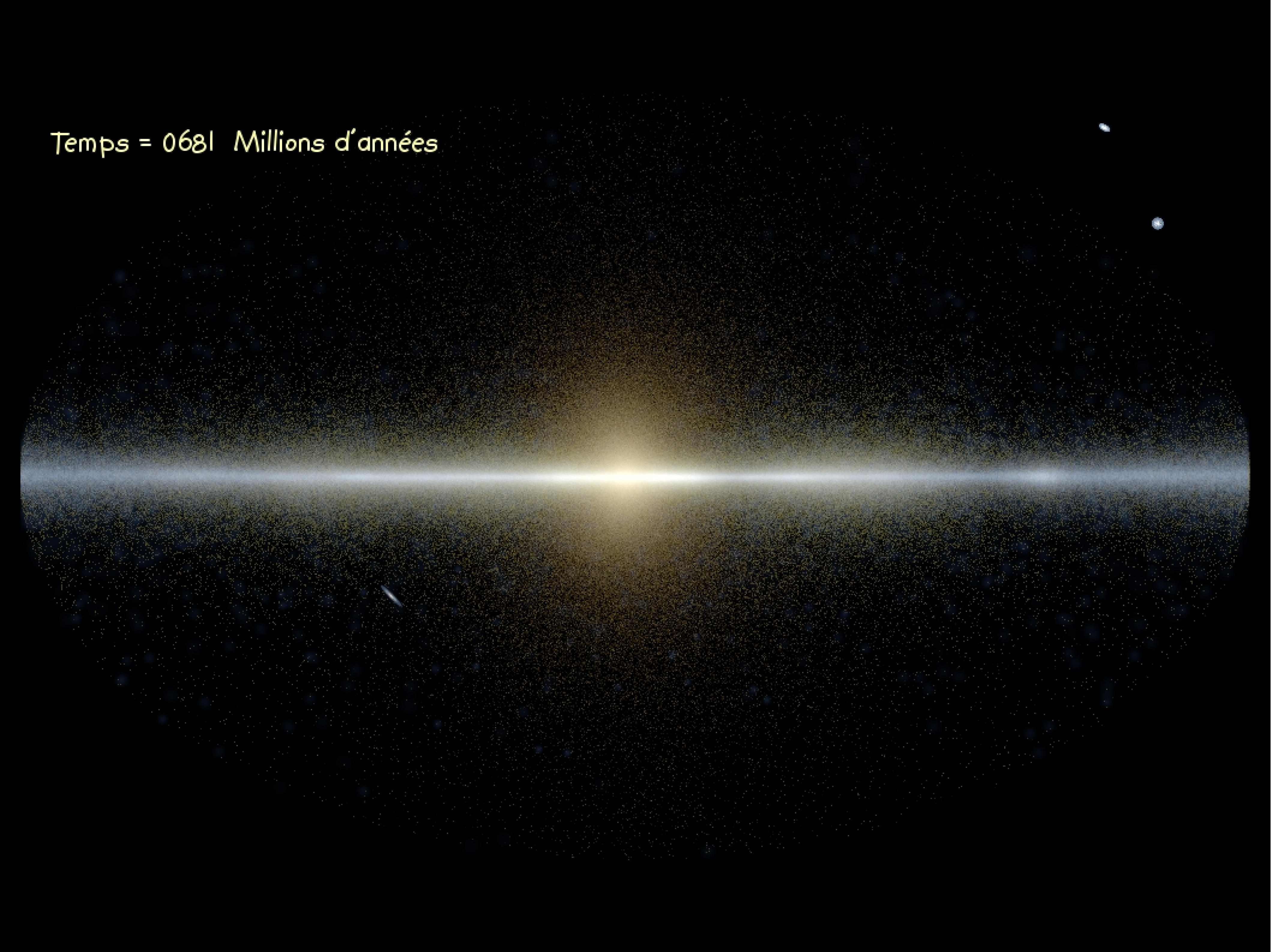
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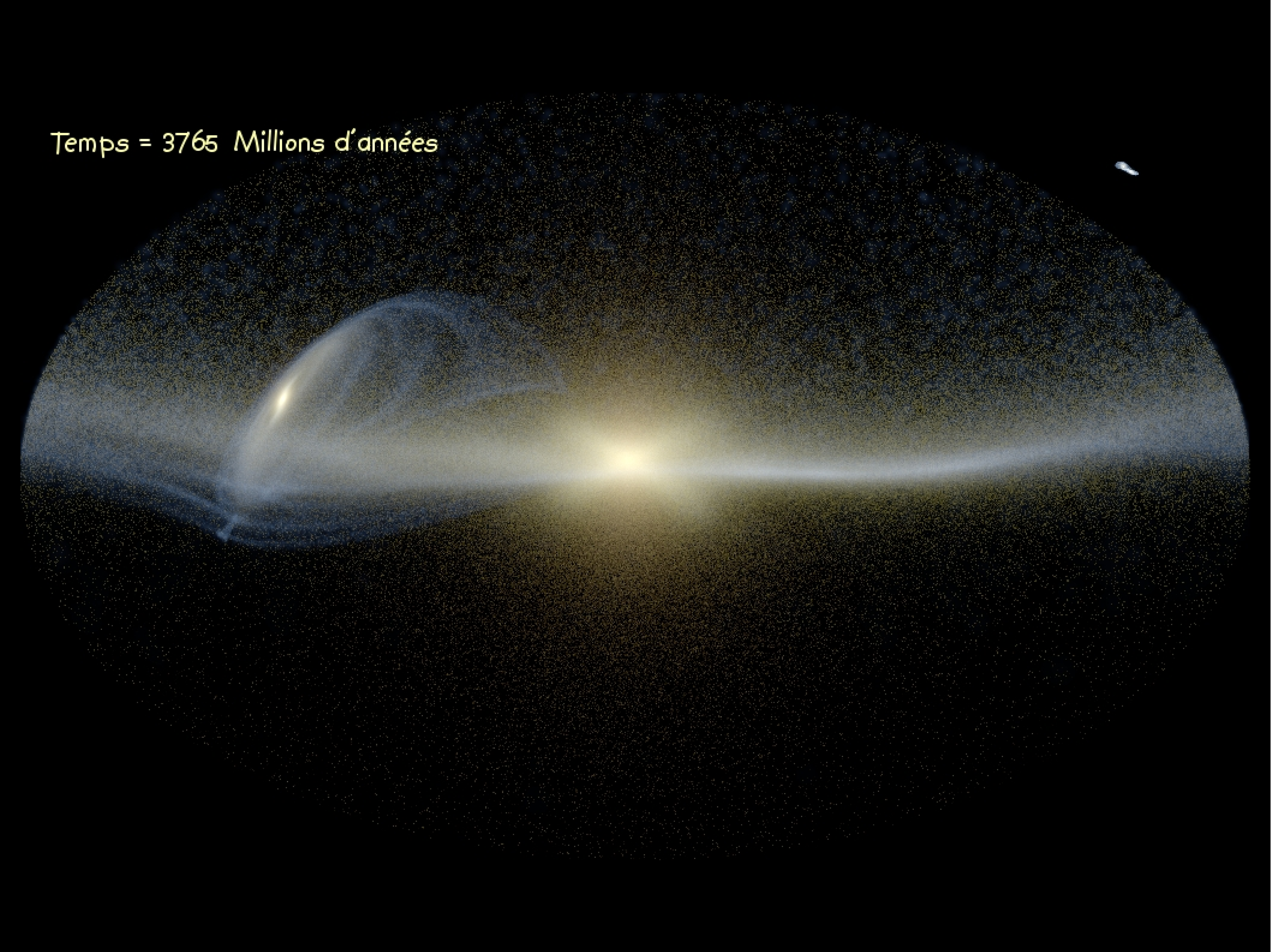
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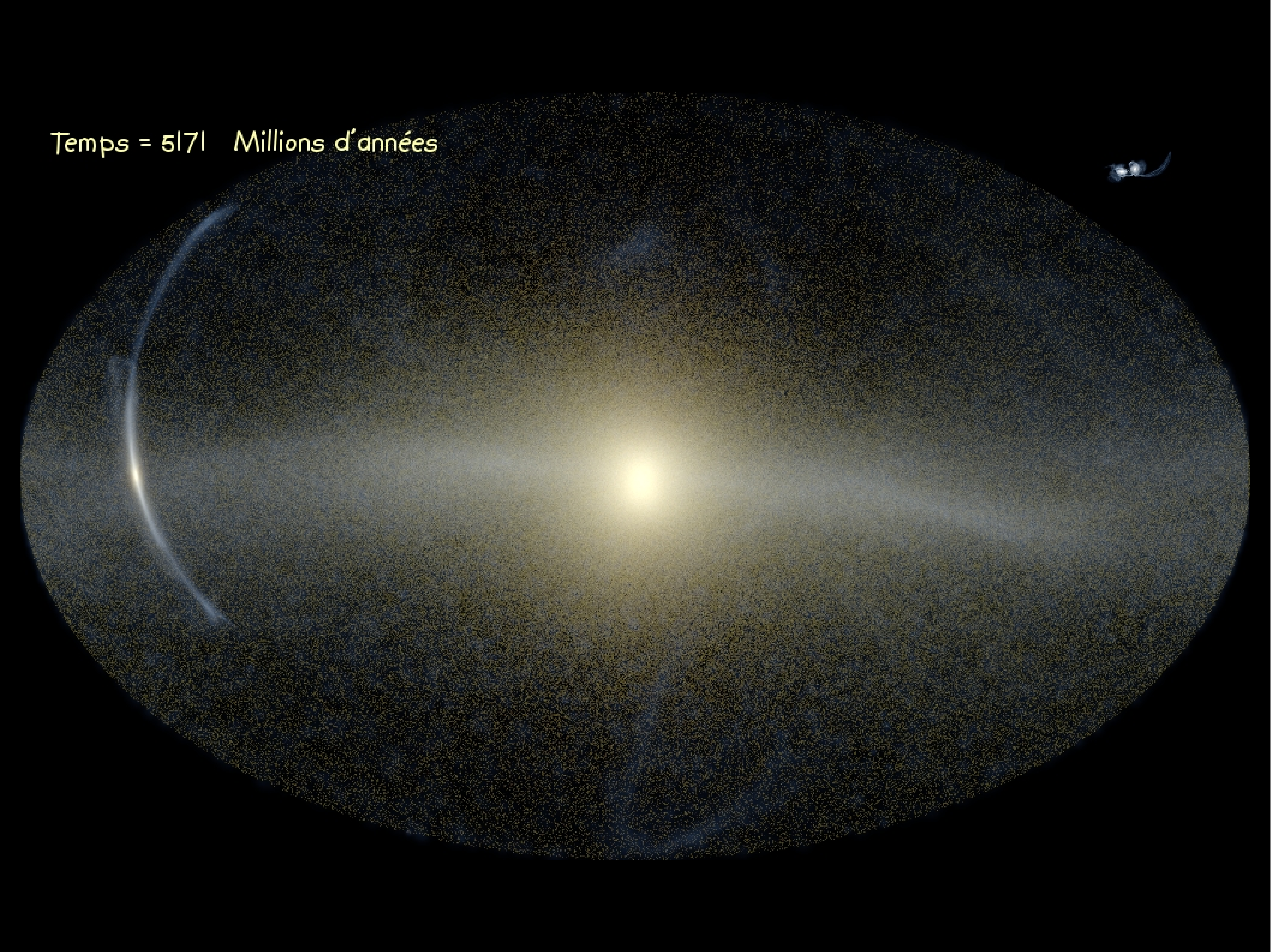
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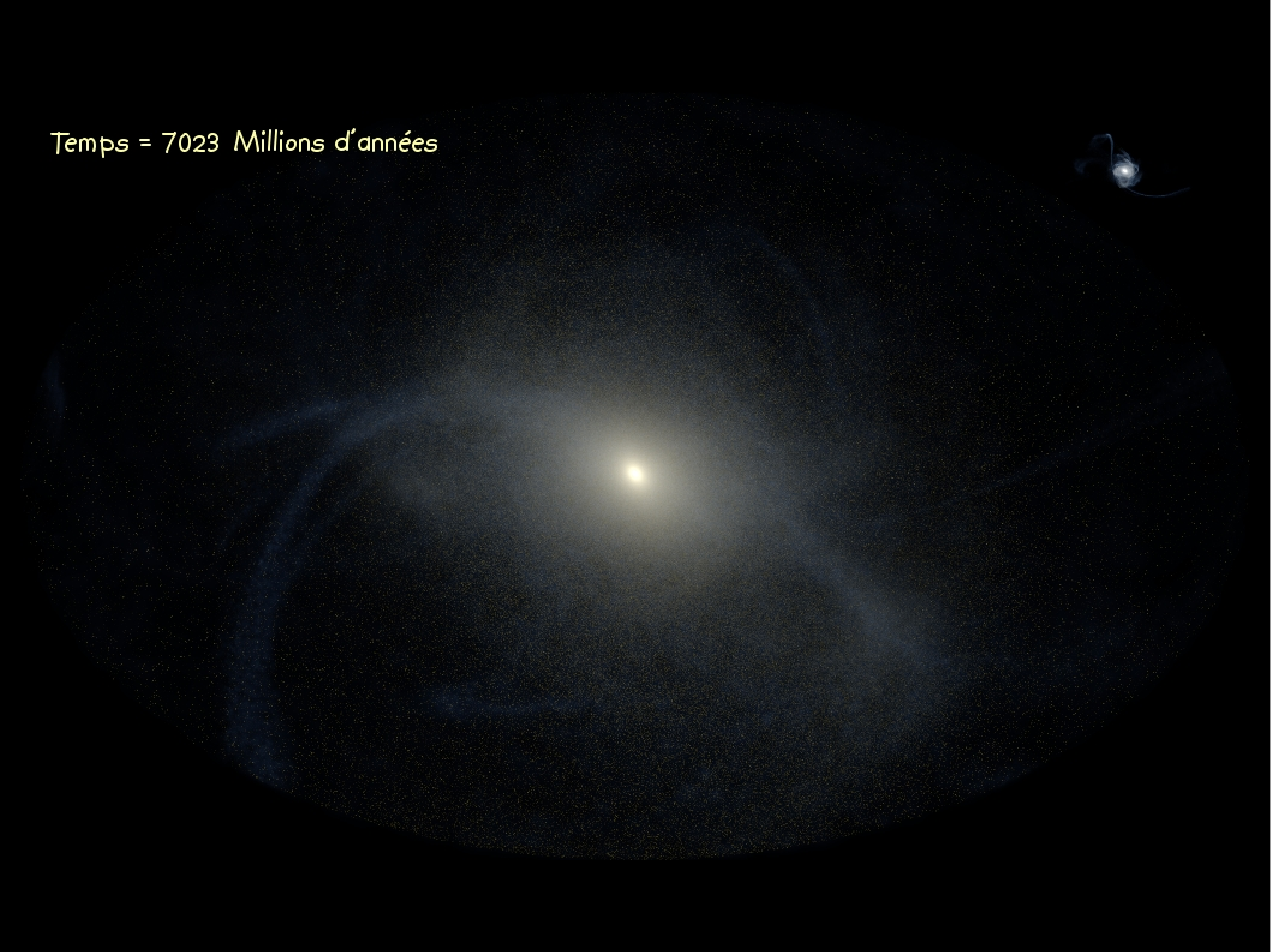
Temps = 7023 Millions d'années


The End