INSTITUT NATIONAL DES SCIENCES APPLIQUÉES TOULOUSE

Dynamic Indicators of Gravitational Shocks on Globular Star Clusters

Omega Centauri, largest globular cluster in the Milky Way (10^7 stars, 46 pc diameter)

What is a **globular cluster**?

A **globular star cluster (GC)** is a spherical collection of stars that orbits a galactic core as a satellite. Every **galaxy** contains several GCs which form the globular clusters system.

Most of them are very old formations. They are very tightly bound by self-gravity and their masses vary between $10^3\ M_\odot$ (solar masses) and $10^6\ M_\odot$.

GCs are difficult to make numerical simulations of, because of the several very close interactions between bodies.

What is **ALMA**?

The **Atacama Large Millimeter/Submillimeter Array (ALMA)** is an international partnership of, mainly, the European Southern Observatory (ESO), the United States National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Republic of Chile.

ALMA is the largest astronomical project in existence and is a single telescope of revolutionary design, composed of 66 high precision antennas located on the Chajnantor plateau (5000 meters above sea level) in northern Chile.

The **Joint ALMA Observatory (JAO)** provides the unified leadership and management of the construction, commissioning and operation of ALMA alongside with **research projects**.

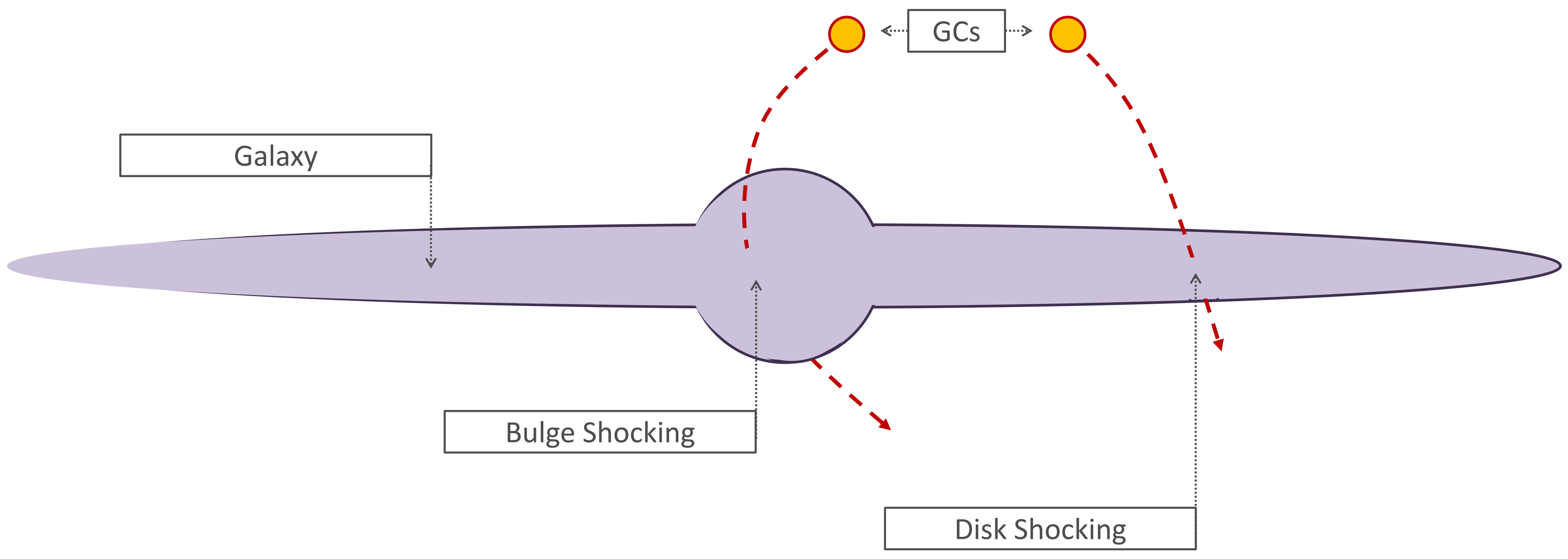
What **gravitational shocks** globular clusters undergo? **Why** and **how to** study them?

The **perturbation of a GC**, a dynamic system, is precious information. The goal of the study was to characterise the dynamics of GCs and to determine indicators of such perturbations, and especially gravitational shocks.

Those disturbances are potentially caused within mergers (galaxies interacting), simply resulting from interactions without merge or by **internal gravitational shocks** within the galaxy itself, which we studied more specifically.

To find such a marker, we use a numerical simulation of a GC. The simulation takes into account **self-gravitation forces** (computed from bodies themselves) and the **gravitational field of the galaxy** (modelled by a force field).

In fact, **9 simulations were ran**, using different set of parameters and trajectories.



Schematic view of the problem.

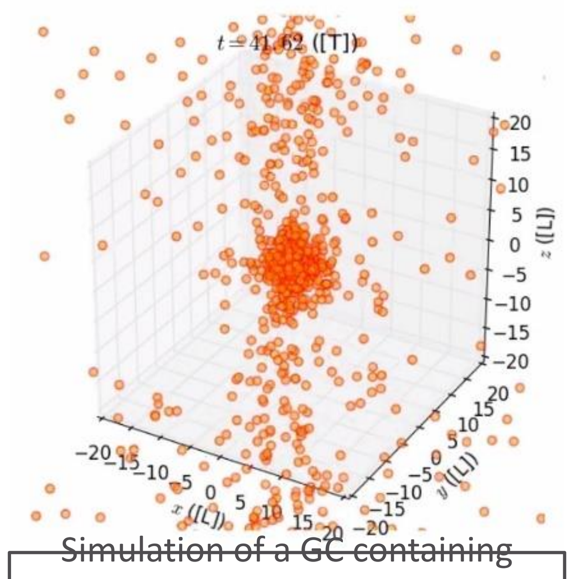
The **N-Body simulator**.

Simulations were made using a N-Body simulator. It was programmed in **C language**, implementing various numerical schemes (from **RK4** to **Adams-Bashforth/Adams-Moulton PECE**).

The goal was to **stabilise** the simulations: indeed, some stars are often **very close to each other** and their behaviours ideally require very small timestep, which is virtually impossible to use in order for simulations to have **acceptable completion duration**.

While extremely efficient and precise N-Body simulators already exist, we chose to create our own to **completely understand it** and to have **entire control** on it.

To cite an example, **NBody6+** (and later versions) by Sverre J. Aarseth and **GADGET** (GAlaxies with Dark matter and Gas intEracT) by Volker Springel are some of the most efficient N-Body simulators existing to this day.



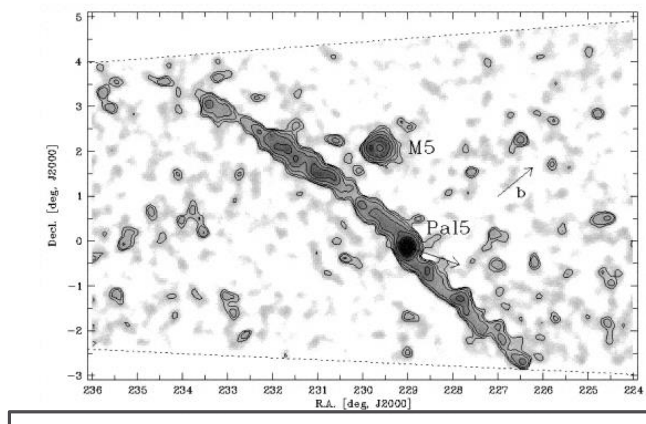
Simulation of a GC containing 3000 stars, after a gravitational shock

A word on **tidal tails**.

The main feature of a GC's **gravitational disk shocks** is the formation of **tidal tails**.

A tidal tail is a thin, elongated region of stars that extends from opposite sides of the GC after disk crossings. Those are particularly studied and well observable. Palomar 5 is a good example of this behaviour (see right hand figure).

We note that this type of behaviour is well reproduced in our simulations, as shown for example on the left hand figure.



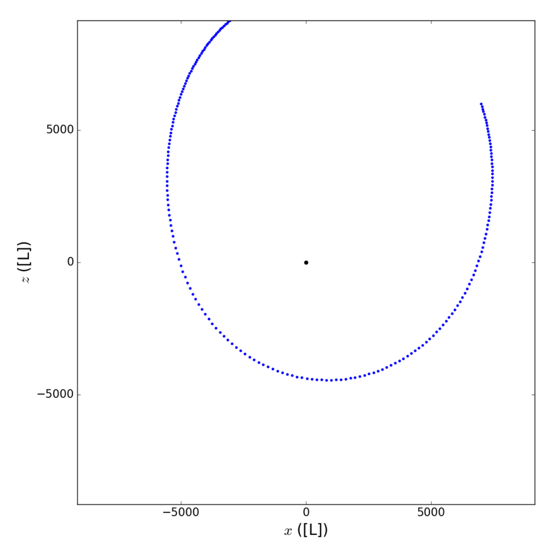
Surface density of stars in Palomar 5 and its tidal tails (SDSS data). From Odenkirchen et al. (2003, AJ, 126, 2385).

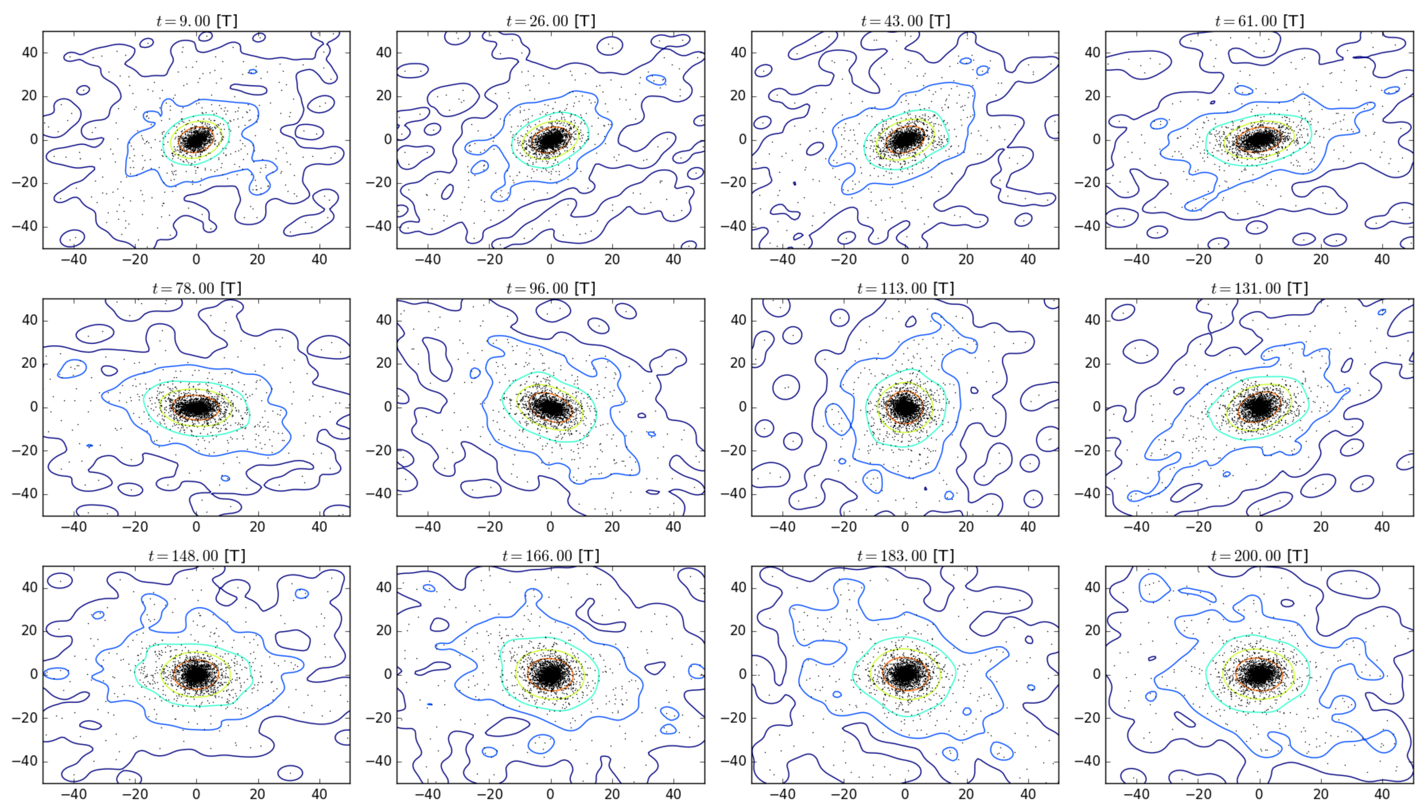
Tidal tails and one **example simulation**.

On this **simulation**, which trajectory is represented on the left figure, disk crossings occur at $t = 44$ [T] (time dimension, which is 10^6 years here) and $t = 123$ [T].

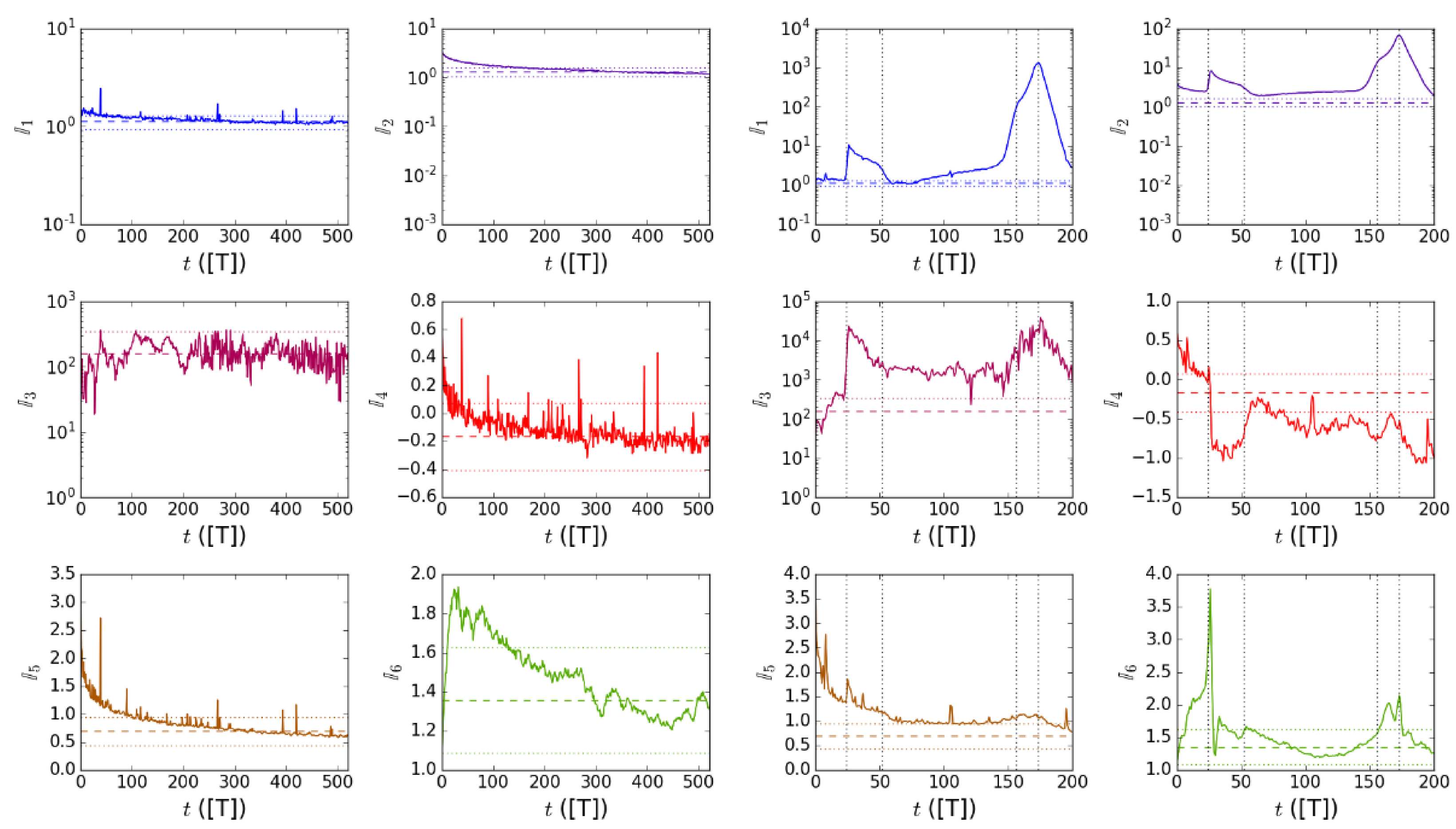
After these rather **soft disk crossings**, tidal tails still appear on the projected lateral surface isodensities (density of stars projected on the plane in which the trajectory is).

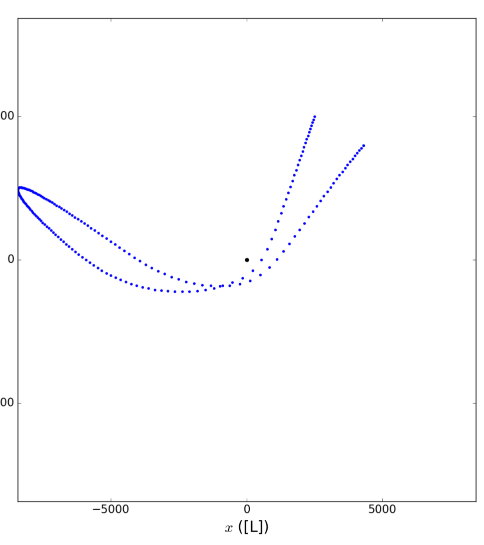
However, the investigation enabled us to define other interesting **dynamical quantities** of interest to follow and study.





Projected lateral surface isodensities (logarithmic scale, for trajectory illustrated).





Left : Indicators for a control simulation (isolated GC).
Right : Indicators for a shocked GC (shocks at dotted lines, trajectory illustrated on the right).

Gravitational shocks **dynamic indicators.**

In the end, **6 indicators** were chosen because of their efficiency in detecting the gravitational shocks. Left hand figure shows results for the **control simulation** (of an isolated cluster) and for a **perturbed simulation** (which trajectory is shown in right hand figure).

The first indicator is the **velocity deviation from isotropy**, the second one is **mean of the velocity modules distribution**. Third one is the norm of the GC's angular momentum, fourth is the anisotropy parameter β. Fifth one is the deviation of the velocity modules' distribution and sixth is deviation from sphericity. See the paper for more detailed definitions.

Indicators n°1, n°2 and n°5 are pure **kinetic indicators**, depending only on the stars' velocities. Indicator n°6 is a **spatial indicator**, depending only on the positions of the stars. Indicators n°3 and n°4 are **mixed indicators**.

While some indicators are more or less efficient in some simulations more than others, kinetic indicators n°1 and n°2 **are working well in every case**.

These results and indicators are now to be tested as well on another case. Huge simulations of 6 interacting galaxies were ran some time ago and the indicators developed in this project can be used on the next scale phenomenon : **the evolution of the globular star clusters' system in those galaxies.**

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