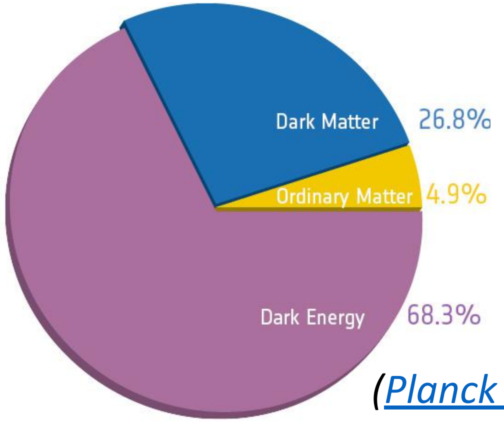
Search for dark matter halos in the Milky Way with stellar streams detected by the Rubin/LSST observatory

Matthieu Pélissier (M2)
Supervised by Marine Kuna

LSST France - June 2024

I. Context : Dark matter

Dark matter

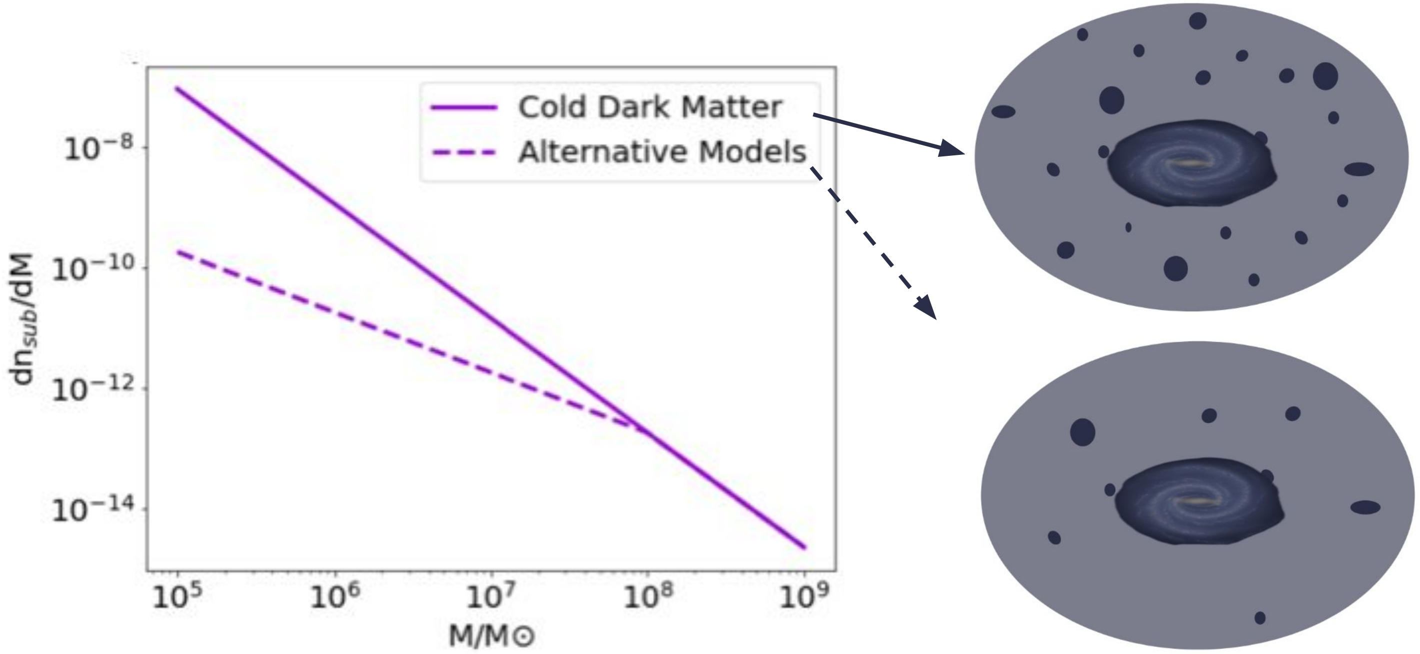


(*Planck 2018*)

- Highlighted by **cosmological probes**
- **Direct detection** has **not been successful yet**

Nature ?

Dark matter cluster population

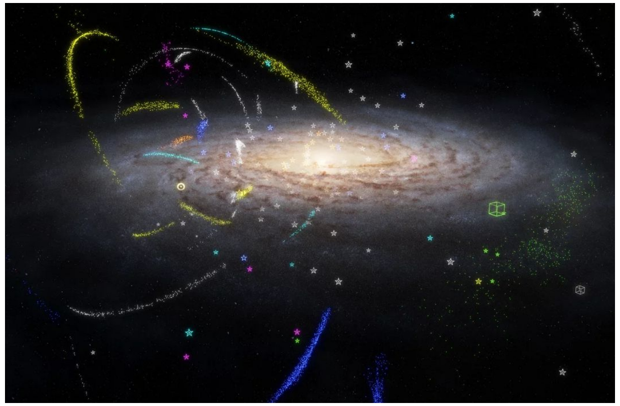


We wish to study the **substructure's population** of the dark matter halo ($10^6 - 10^9 M_\odot$) to **constrain dark matter models**

I. Context : stellar streams

Using **stellar streams** as probes

= Globular cluster or dwarf galaxy distorted by **tidal effects**



(@ S. Payne-Wardenaar)

The **impact** of subhalos can create **disturbances** in streams

(Ibata 2002)

Statistical study to characterize the population of dark matter structures

II. Context : LSST & DESC

LSST advantage for stellar streams ?

- Gaia magnitude limit 20 vs 27.5 for LSST
- Number of stars detected: 10^{10}

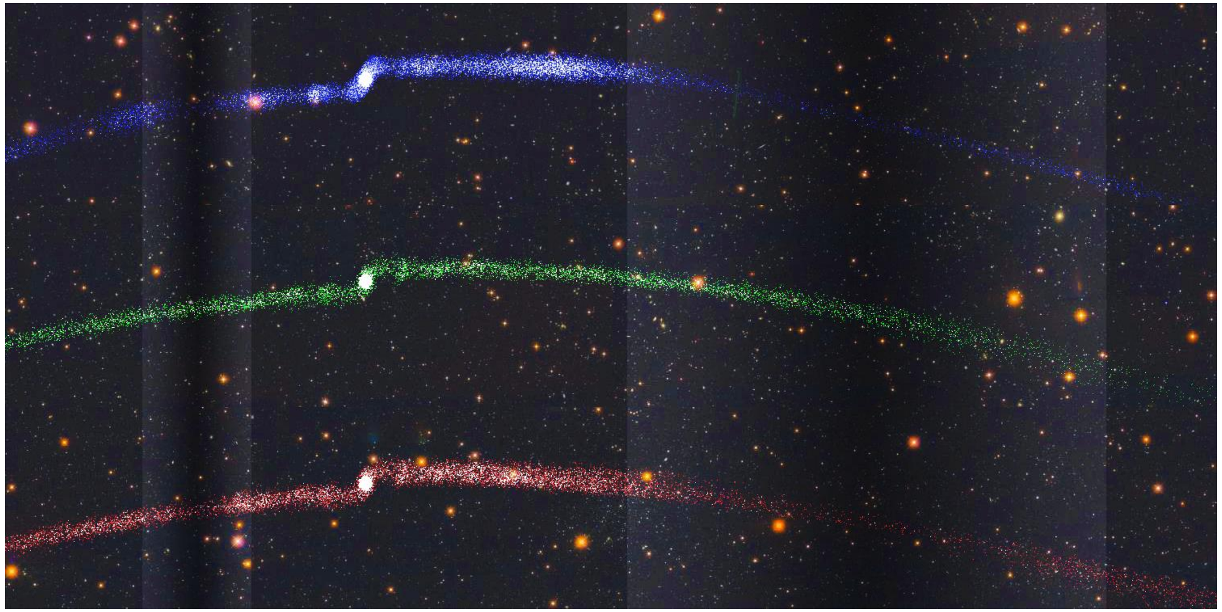
→ Possible **new streams and stars** detected

Dark Energy Science Collaboration (DESC)

- Stellar streams project leader : Marine Kuna
- **Team members experts** in streams detection from photometric surveys (DES) : close collaborators Alex Drlica-Wagner, Peter Ferguson & Nora Shipp (DKM group conveners)

II. Objective

Building **observables sensitive** to the **perturbations** imprinted by dark matter **subhalos** on **stellar streams**



(*Erkal 2017*)

III. Simulations

- **Evolution** of stars in the fixed potential of the Milky Way galaxy *(Bovy 2016)*
- **Free parameters** used**:** number of stars, number of impacts by halos of selected masses, impact time

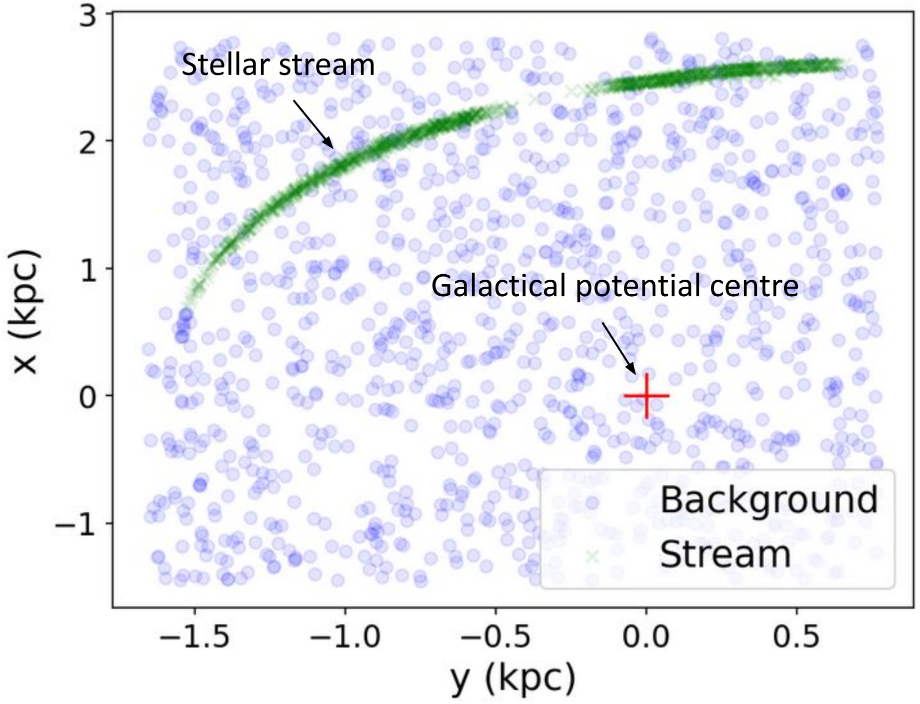
Stars coordinates of the stellar streams

\+ **addition of background noise** to simulate the presence of background stars and galaxies

Building of **observables** for each streams

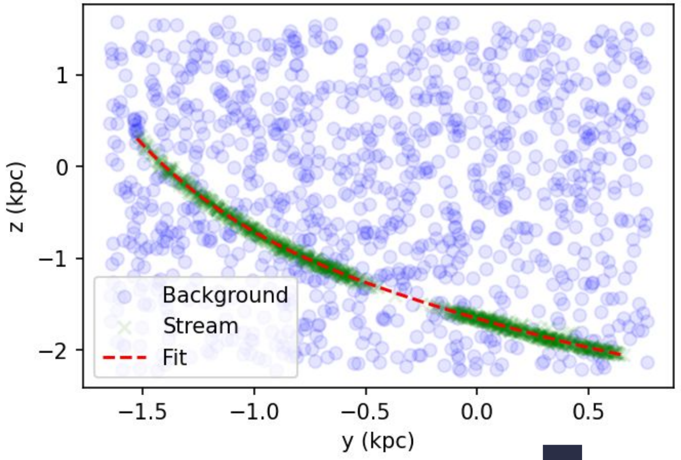
Result example

$N_{impacts} = 10,\ M = 10^8 M_\odot$

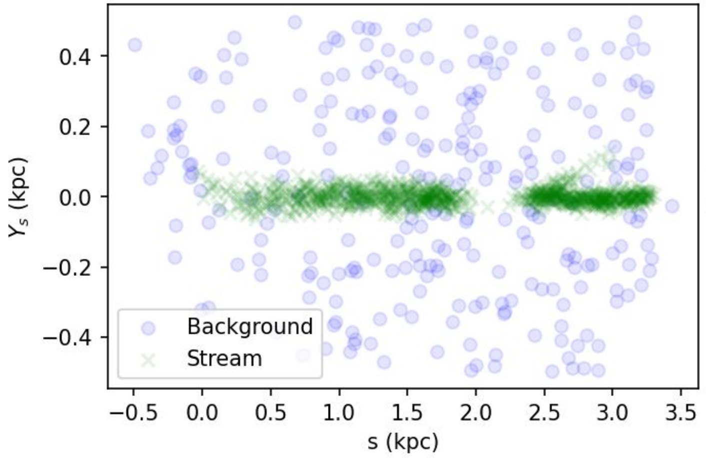


IV. Observables

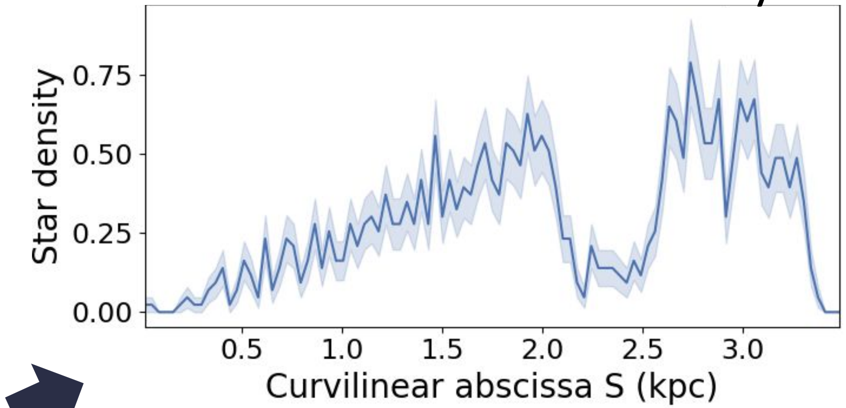
1) Power spectrum P(k)



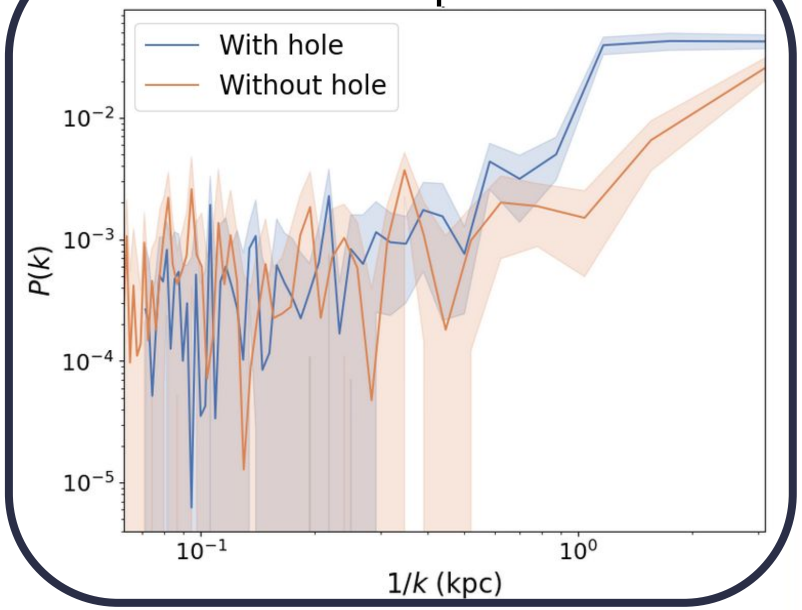
Polynomial fit



Projection



Normalized linear density

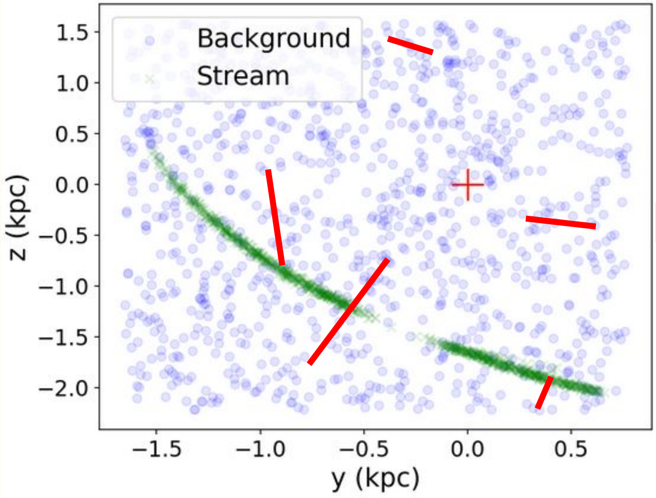


Power spectrum

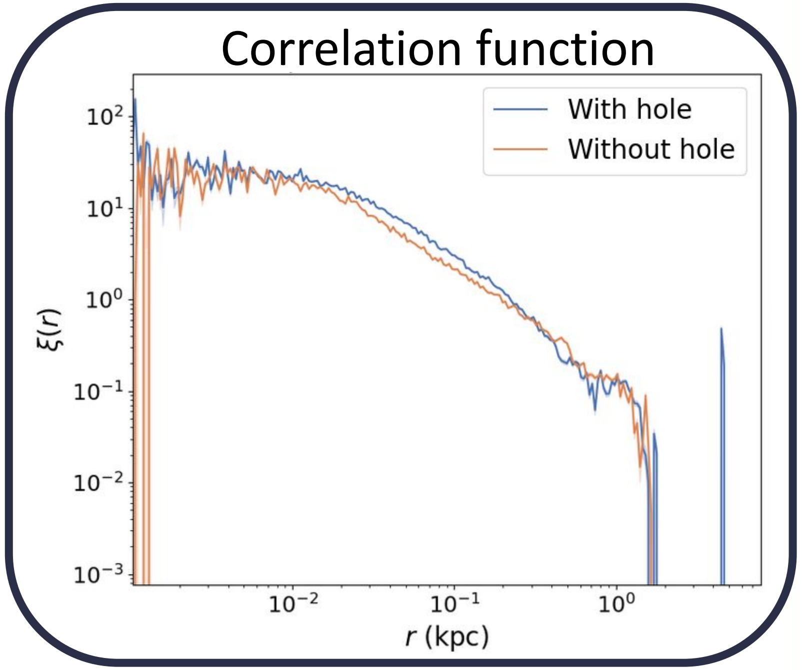
- Sensitive to characteristic sizes and disturbance frequency

IV. Observables

2) Two points correlation function ξ(r)



- Count star pairs
- Uses information in **2 dimensions**



Combining observables from several stellar streams

V. Preliminary results

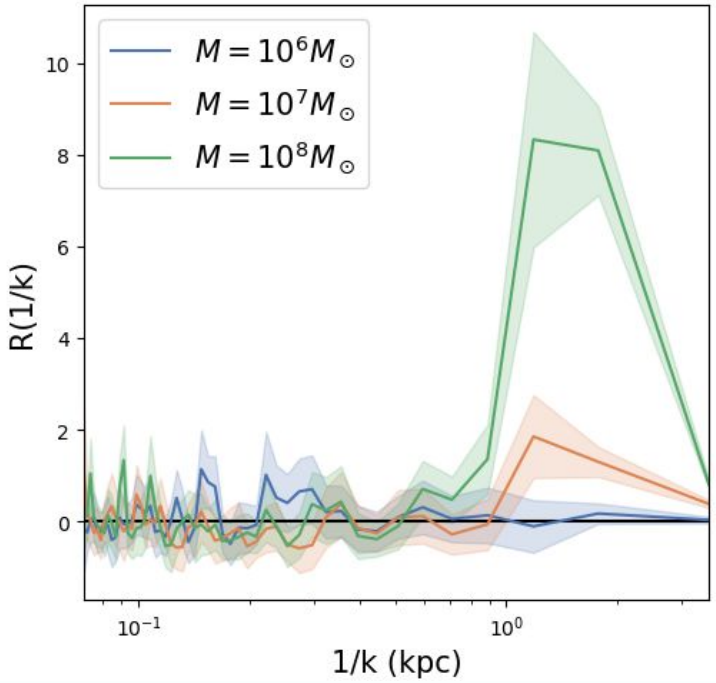
1) Sensitivity study based on encounter masses

Number of impacts = 10, masses = 10^6, 10^7 ou 10^8 $M_\odot$

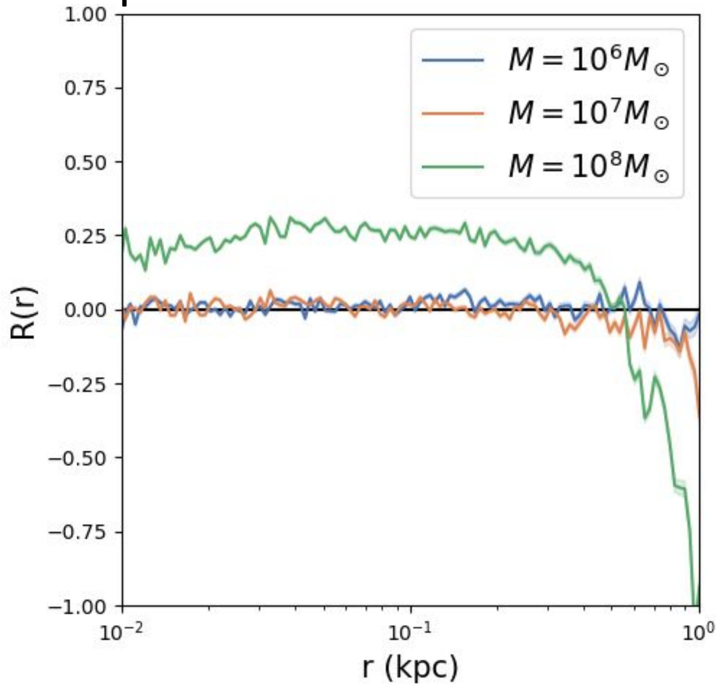
N0 = no suhbalos

$$R(r) = \frac{Obs(r) - Obs^{N_0}(r)}{Obs^{N_0}(r)}$$

Power spectrum $p(k)$



Two points correlation function $\xi(r)$



Observable **sensitivity increases** with halo **mass**

V. Preliminary results

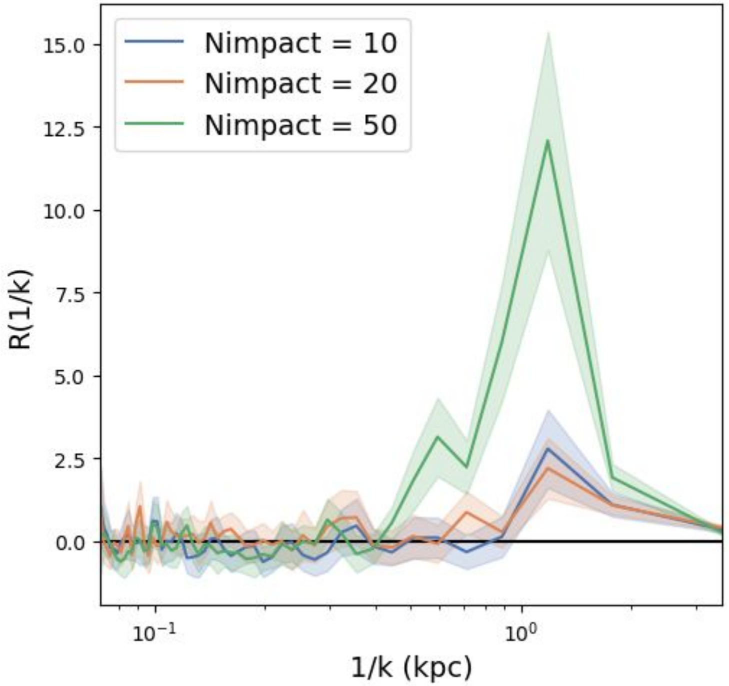
2) Sensitivity study based on number of impacts

Masses = 10^7 M$_\odot$, Number of impacts = 10, 20 or 50

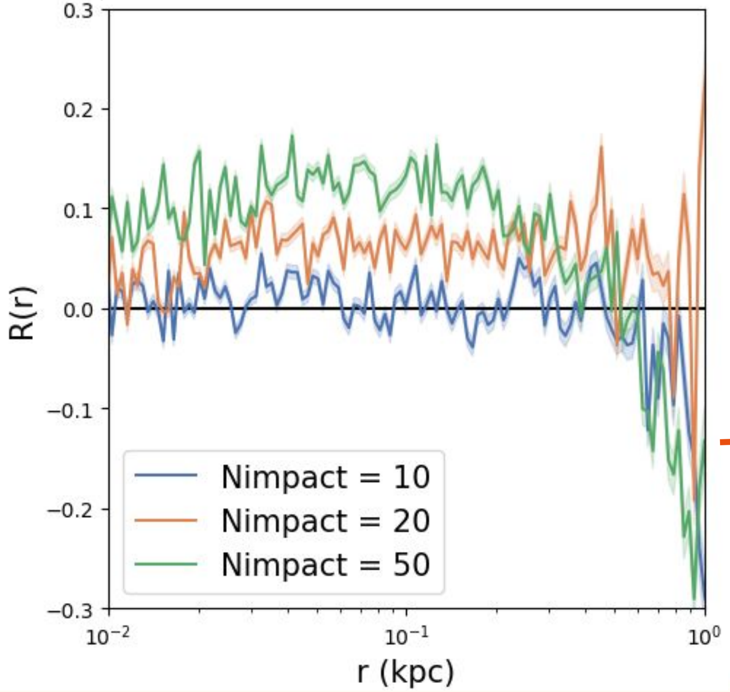
N0 = no suhbalos

$$R(r) = \frac{Obs(r) - Obs^{N_0}(r)}{Obs^{N_0}(r)}$$

Power spectrum $p(\,k)$



Two points correlation function $\xi(r)$



Observable **sensitivity increases** with the **number of impacts**

Observables are sensitive to subhalos population

VI. Conclusions

Internship

- **Simulation** on the Lyon computing centre
- Construction and interpretation of **observables**
- **Sensitivity** testing to different sub-halo populations

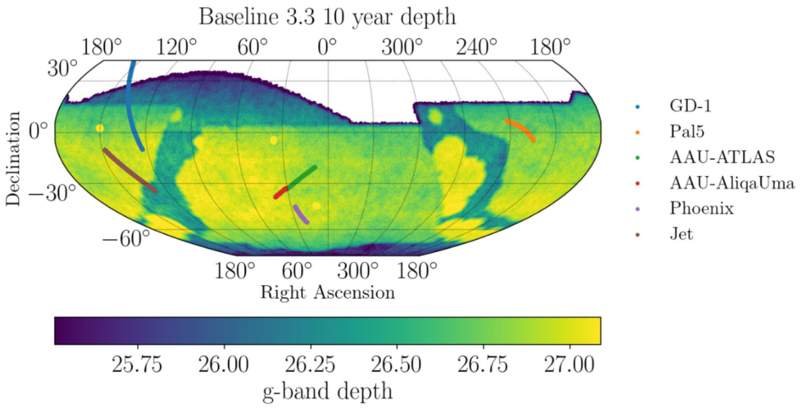
Work in progress

- How to limit **edge effects**
- The response of observables to the **full mass distribution of halos** (power law)
- The influence of **free parameters**, such as impact time

VII. Outlooks

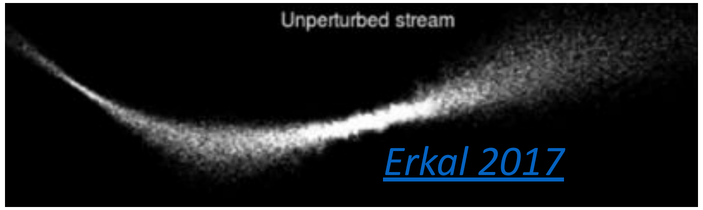
Axis 1: LSST data analysis

- **Continuation of the internship:** sensitivity of observables, other methods
- Testing the impact of **survey non-uniformity**



(@ Peter Ferguson)

Axis 2 : Stellar streams modelling



Erkal 2017

N-body simulation:
Accurate **subhalos population**
Baryonic effects (Milky Way arms, globular clusters)

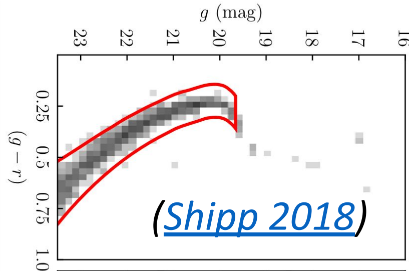
+

StreamSim :
Develop collaborative code with stellar streams experts (Alex Drlica-Wagner, Peter Ferguson, Nora Shipp)

Axis 3 : Stellar streams detection

Injection into a precursor **data catalogue**

Find injection with **DES algorithm adaptation** on a colour-magnitude diagram



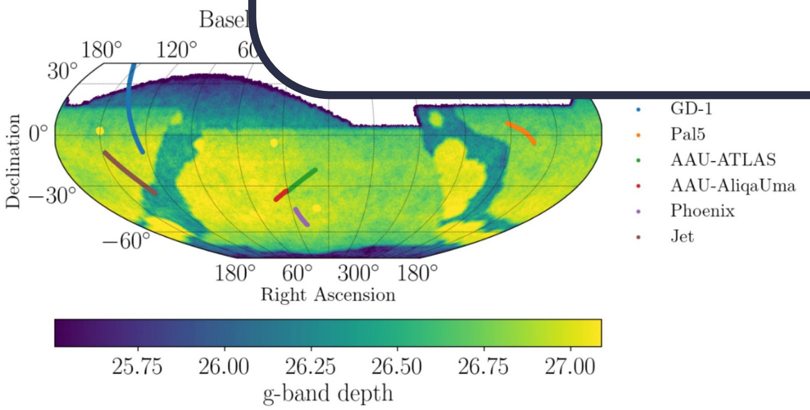
(Shipp 2018)

Application to **data** (2025)

VII. Outlooks

Axis 1: LSST data <u>analysis</u>

- **Continua n of the internship:** sensitiv metho
- Testing **non-ur**



(@ Peter Ferguson)

Axis 2 : Stellar streams <u>modelling</u>

+

[StreamSim](#) :

Develop collaborative code

with stellar streams experts (Alex Drlica-Wagner, Peter Ferguson, Nora Shipp)

Axis 3 : Stellar streams <u>detection</u>

Injection into a ecursor

lgorithm

agnitude

(*[Shipp 2018](#)*)

Application to **data** (2025)

<u>Constraints on dark matter models with stellar streams</u>

VIII. Summary

Internship

Demonstrating the **discriminatory** potential of currents on dark matter halo populations

Outlooks

Preparing to **observe** stellar streams with the **first LSST data** and their **constraints** on dark matter models

Vera C. Rubin Observatory

V. Appendix

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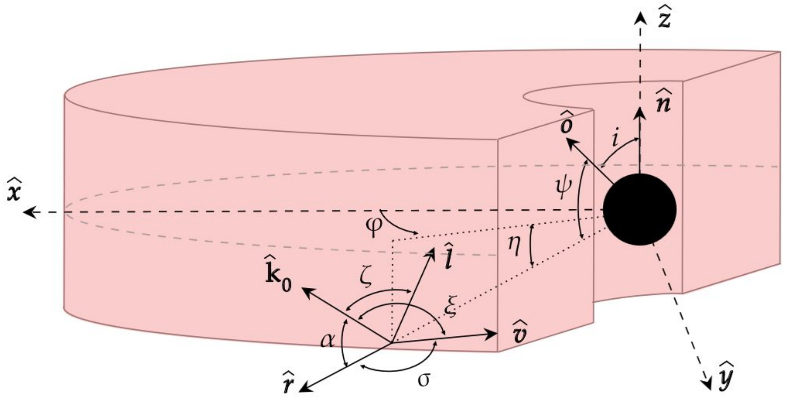
V. Annexes

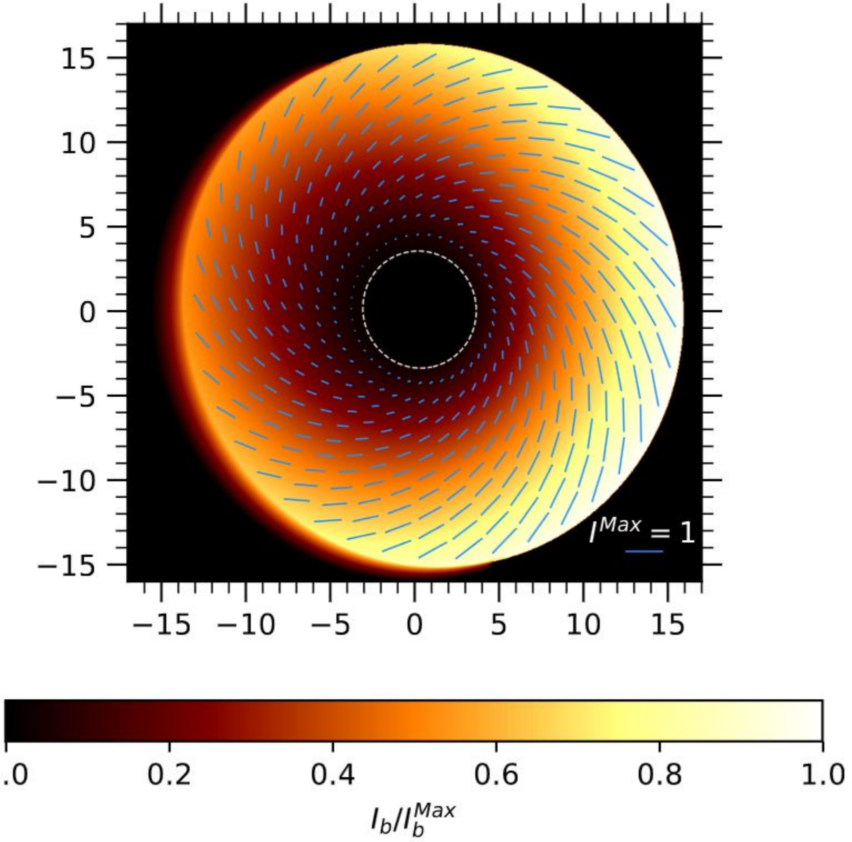
Stage L3

Analyse vectorielle



$$\chi = \chi^0 + \chi^B + \chi^{SR} + \chi^{GR}$$

Formules analytique de l'angle de polarisation



Caractéristique de polarisation du disque d'accrétion d'un trou noir dans la métrique de schwarzschild

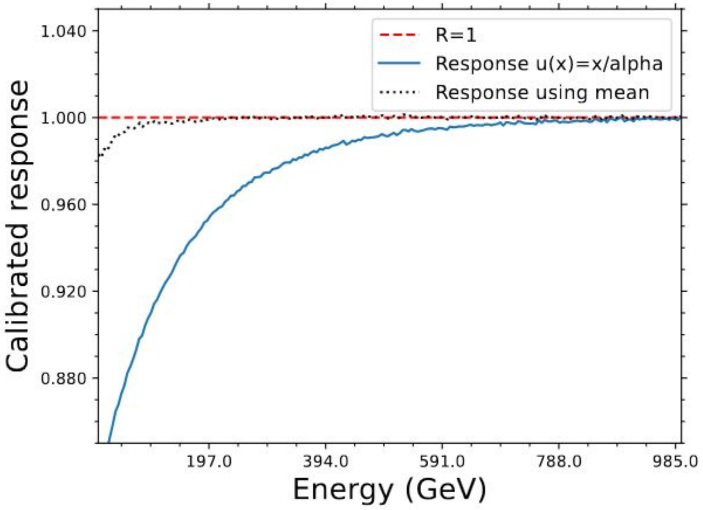
V. Annexes

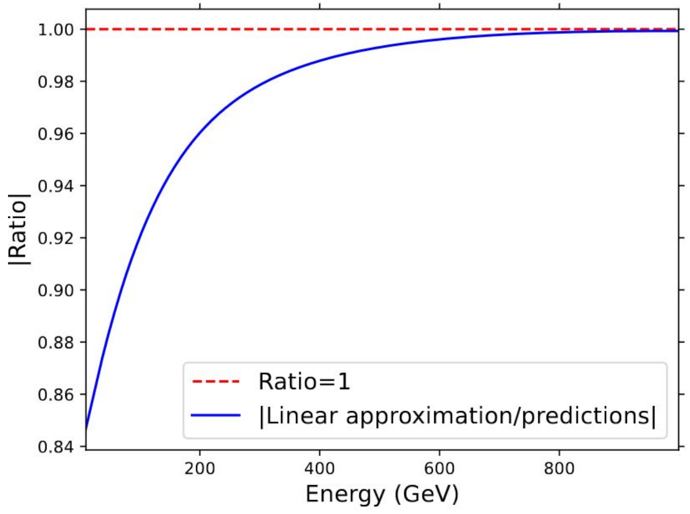
Stage M1

Équation différentielle sur la fonction de calibration du détecteur ATLAS

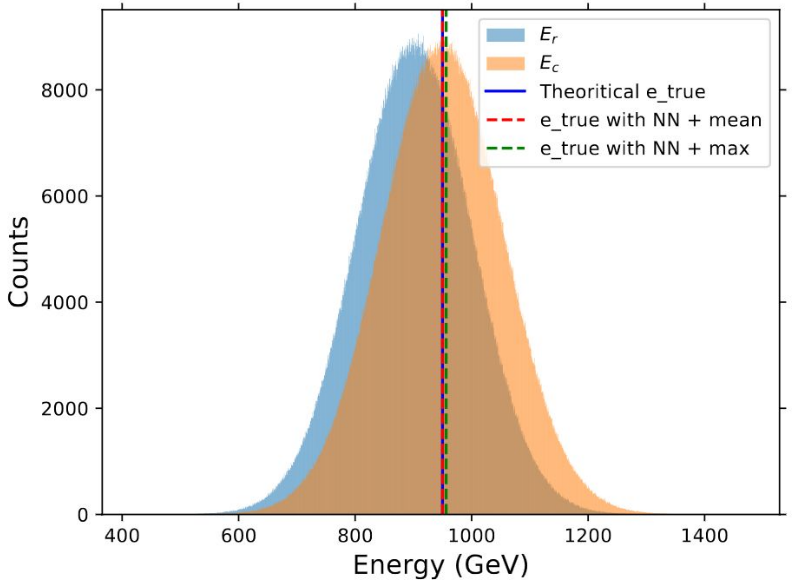
$$u''(E)\sigma(E)^2 + u'(E)(x - u(E)R(u(E))) = 0$$

Calibration linéaire non suffisante





Résolution avec un réseau de neurones



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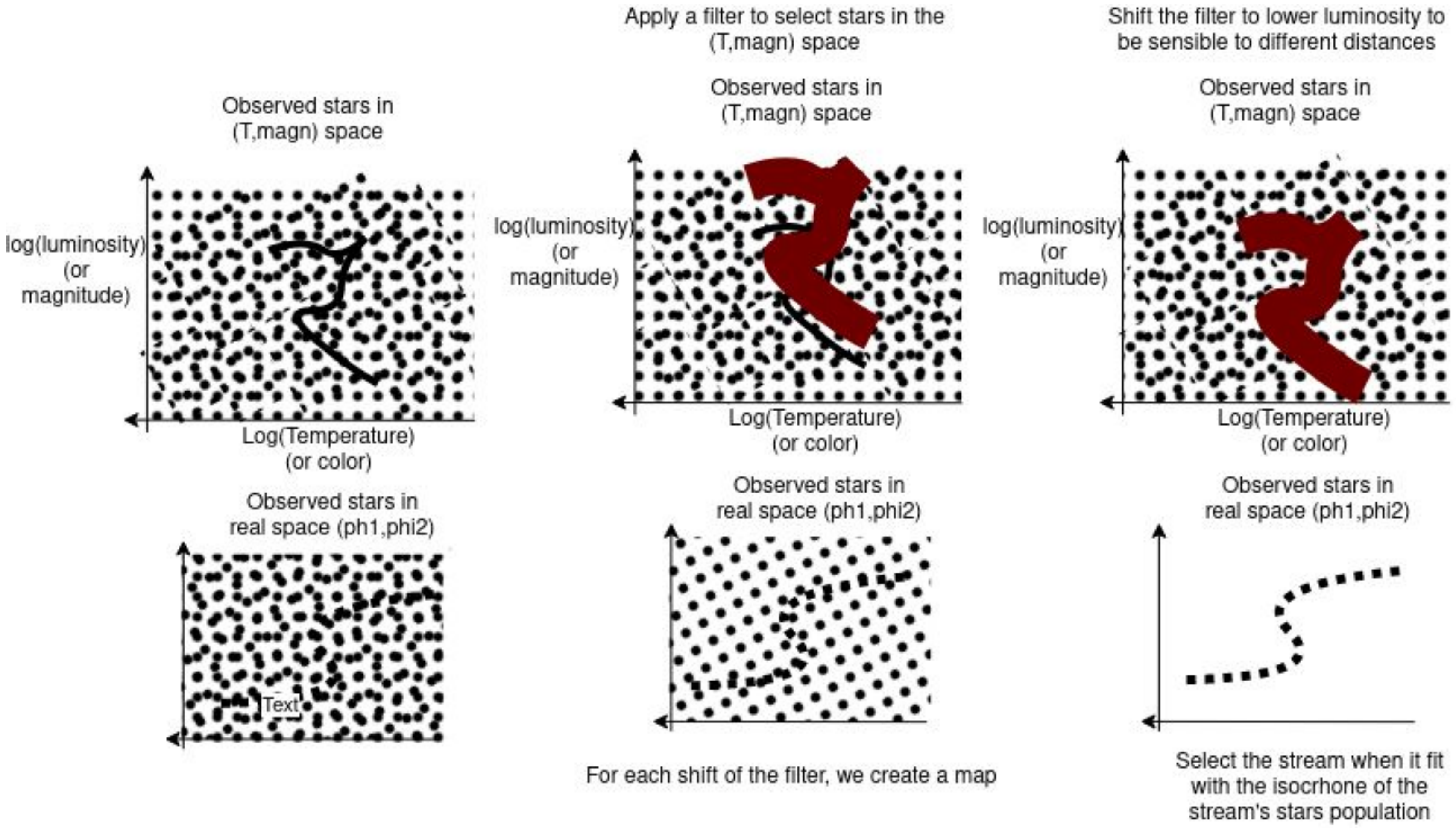
Détection courants stellaires



Apply a filter to select stars in the (T,magn) space

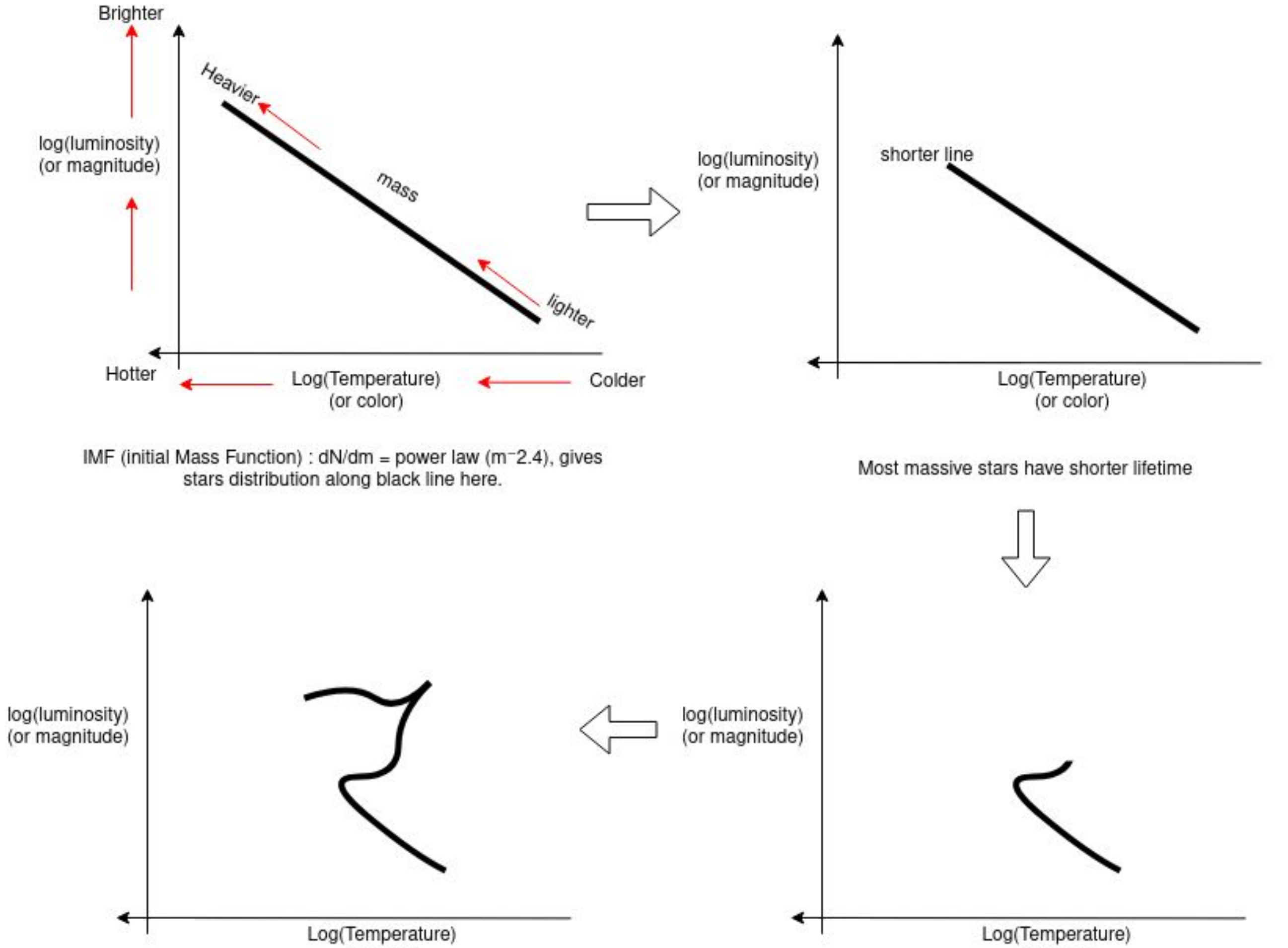
Shift the filter to lower luminosity to be sensible to different distances

For each shift of the filter, we create a map

Select the stream when it fit with the isocrhone of the stream's stars population

V. Annexes

H-R diagrams



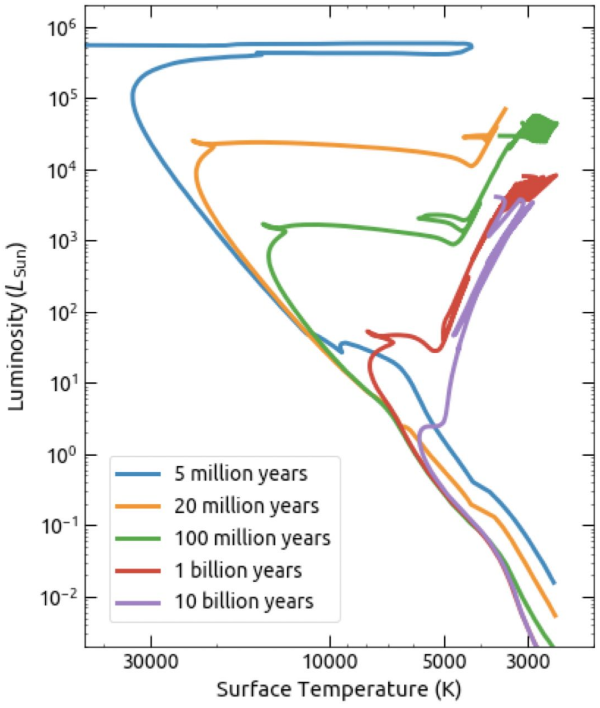
IMF (initial Mass Function) : dN/dm = power law ($m^{-2.4}$), gives stars distribution along black line here.

Most massive stars have shorter lifetime

Apparition of a cutoff : heavier stars leave the main sequence. it determines the age of the cluster. For 10Gy it corresponds to a cut off at the solar mass.

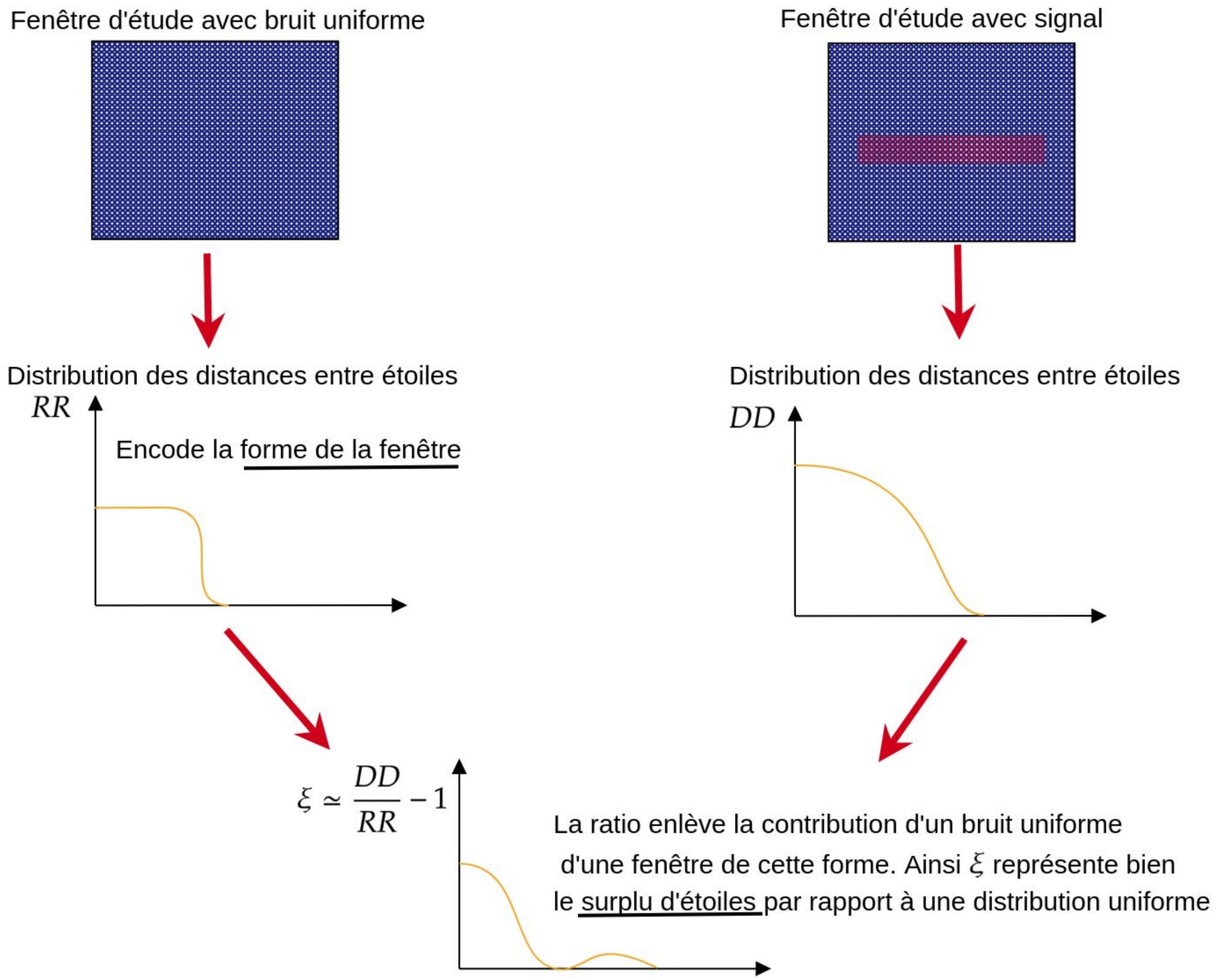
Typicall isochrone. With structure related to red giants, helium flash. Distributions can be more complicated, because all stars doesn't have to be created at the same time for example.

Isochrones



V. Annexes

Estimation fonction de corrélation à deux points



Fenêtre d'étude avec bruit uniforme

Fenêtre d'étude avec signal

Distribution des distances entre étoiles

Encode la forme de la fenêtre

Distribution des distances entre étoiles

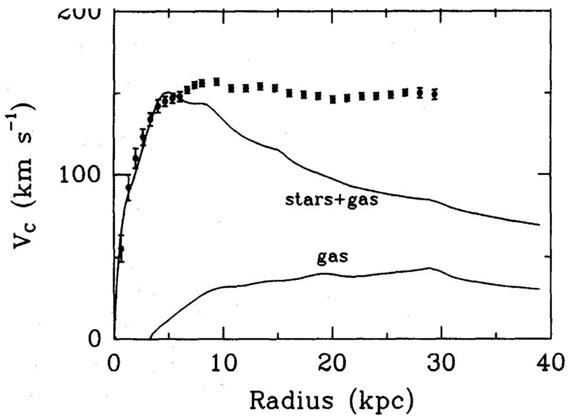
$$\xi \simeq \frac{DD}{RR} - 1$$

La ratio enlève la contribution d'un bruit uniforme d'une fenêtre de cette forme. Ainsi ξ représente bien le surplu d'étoiles par rapport à une distribution uniforme

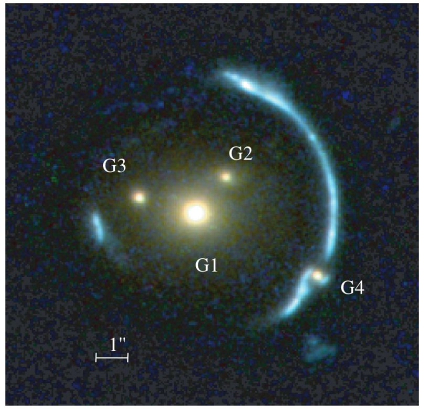
V. Annexes

Matière noire

- **Évidences matière noire**

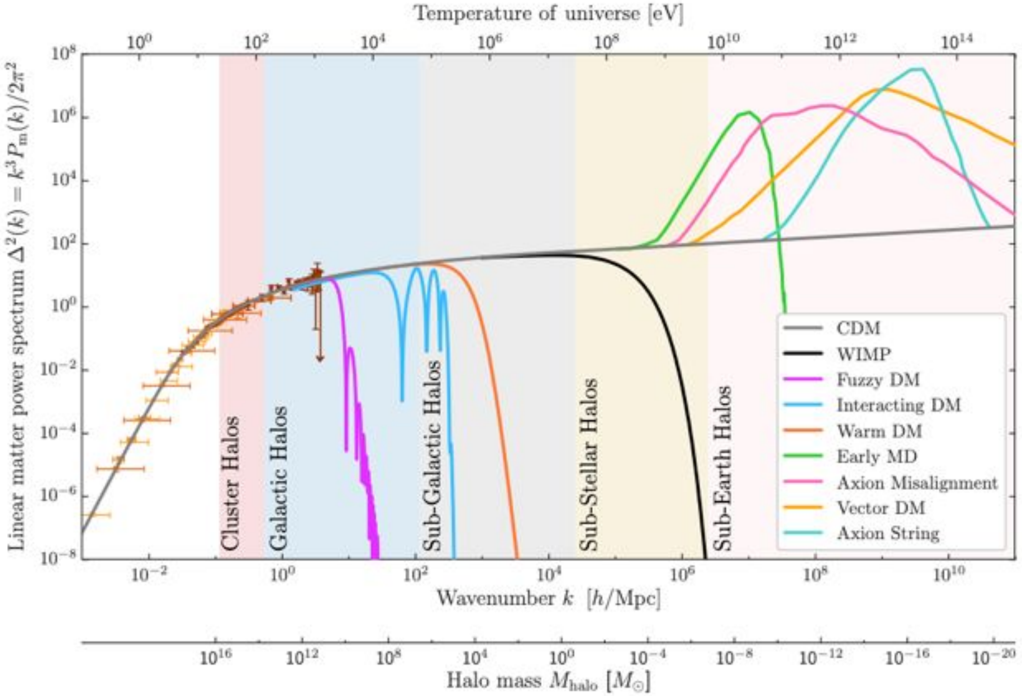


(*[Kent 1986](#)*)



(*[Vegetti 2010](#)*)

- **Population de sous halos pour différents modèles**

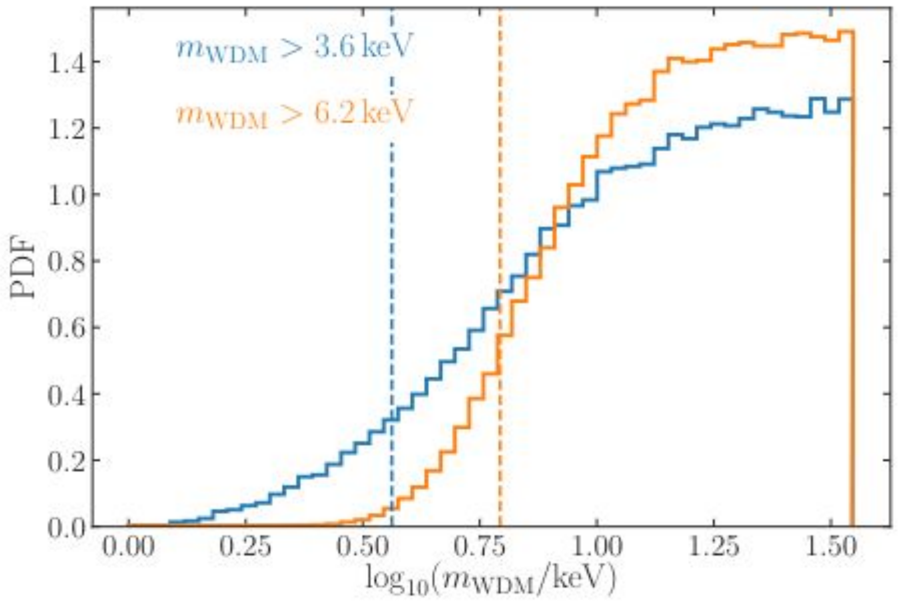


(*[Snowmass 2021)](#)*)

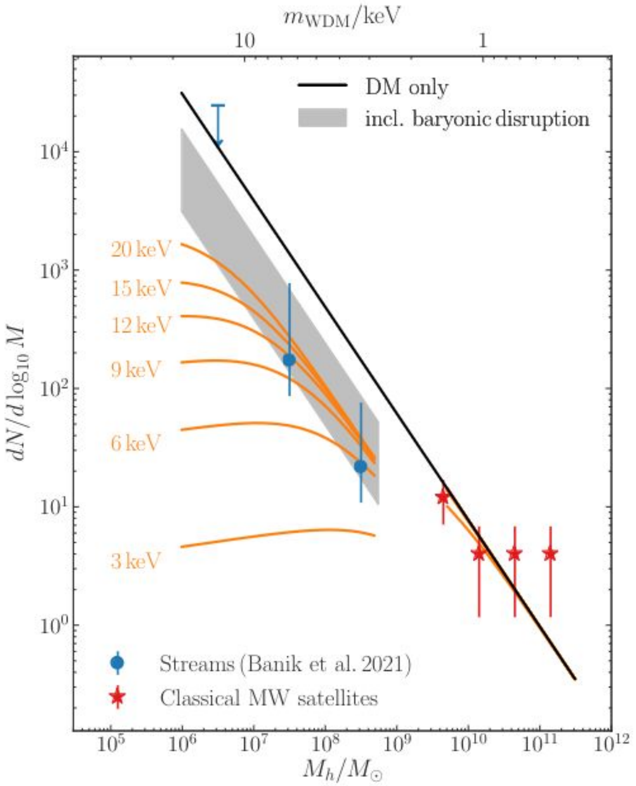
V. Annexes

Contraintes DM

Warm dark matter



(Banik 2021)



En bleu : posterior en utilisant GD1

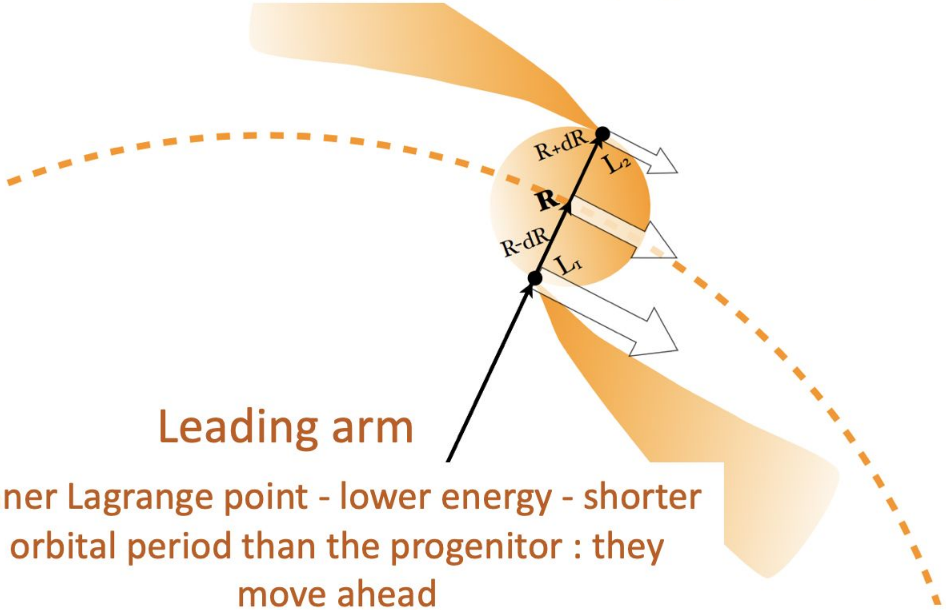
En orange : posterior en comptant les sattelites

V. Annexes

Formation des streams

Trailing arm

outer Lagrange point - higher energy - longer orbital period than the progenitor : they fall behind



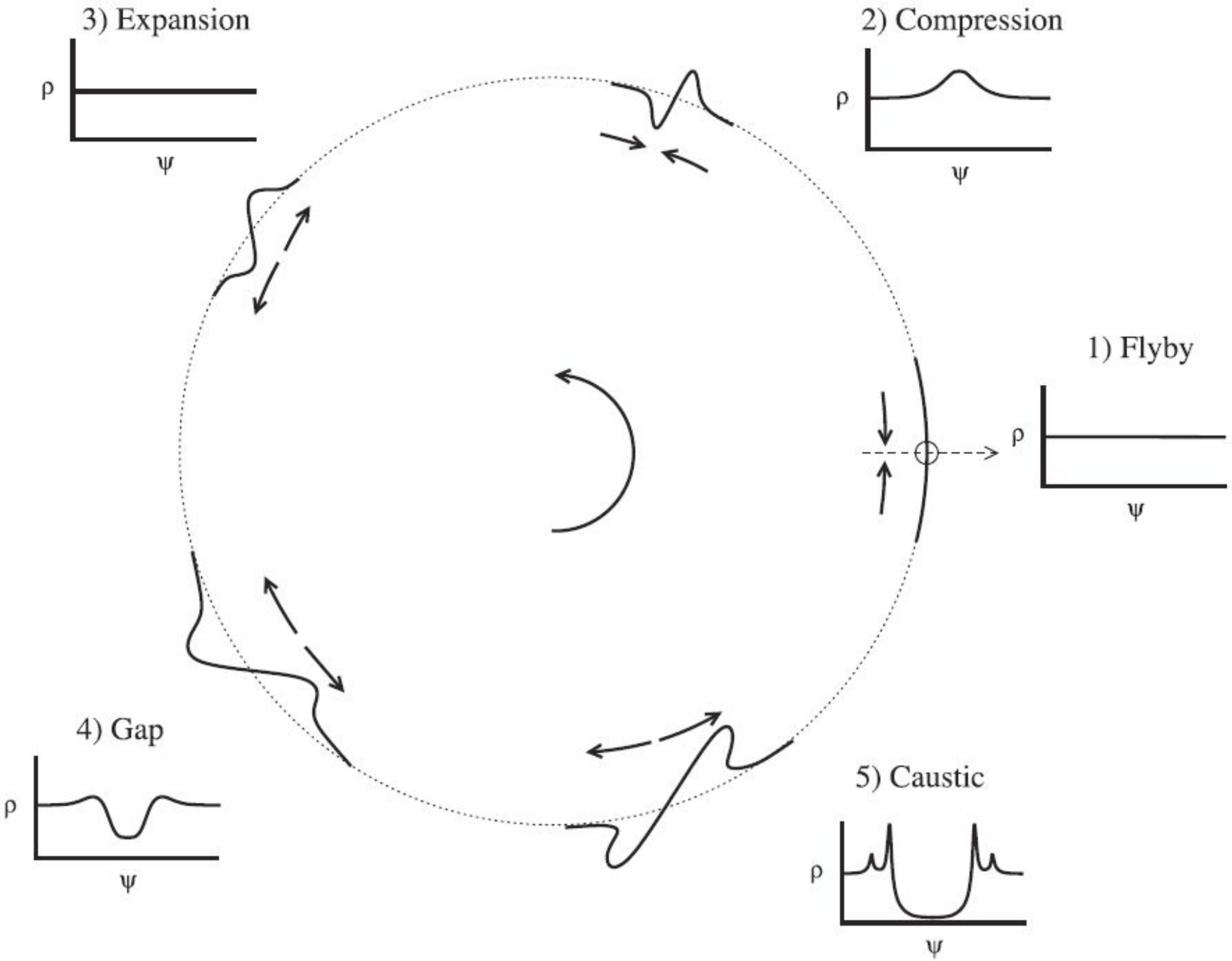
Leading arm

inner Lagrange point - lower energy - shorter orbital period than the progenitor : they move ahead

(@Belokurov)

V. Annexes

Formation des gaps



$$N_{\text{enc}} = \sqrt{\frac{\pi}{2}}\, l_{\text{obs}} b_{\text{max}} n_{\text{sub}} \sigma t\,.$$

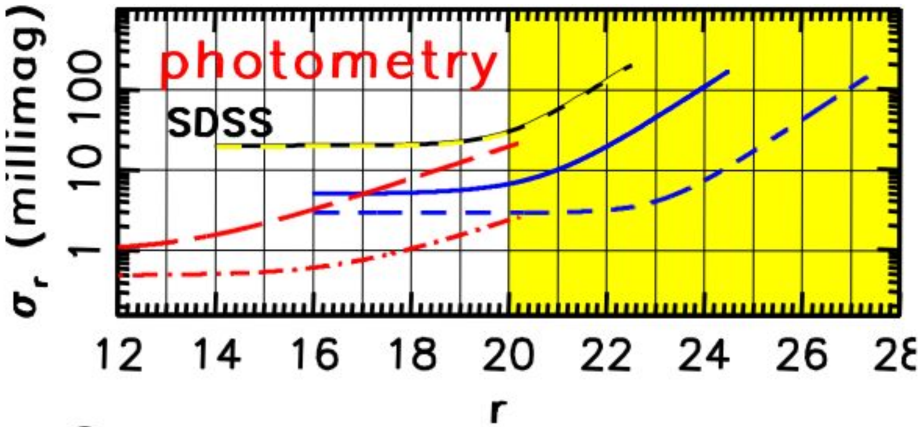
$$\frac{dN_{halos}}{dM} = c_0 \left(\frac{M}{m_0}\right)^n exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]\right)$$

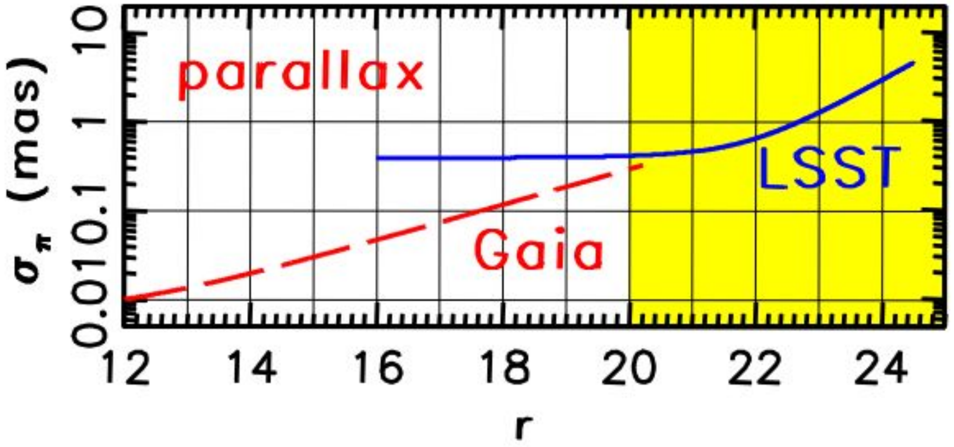
$$\frac{dN_{halos}}{dM} = K_{abs} M^n$$

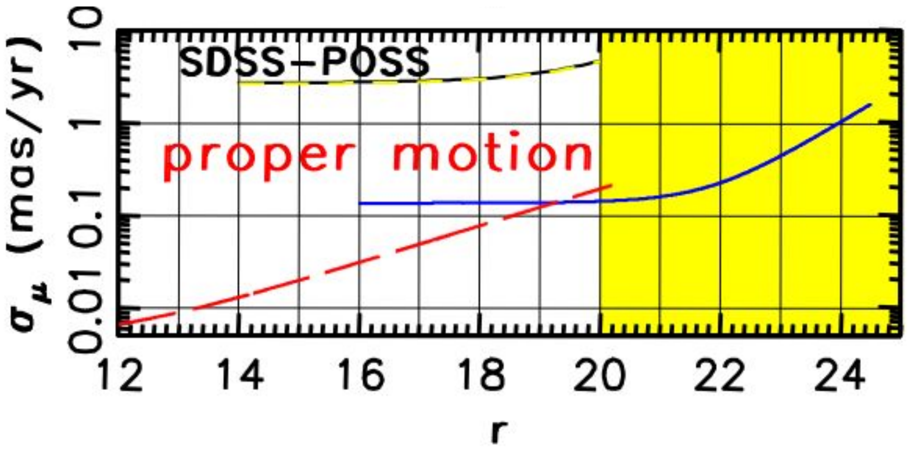
(Erkal 2016)

V. Annexes

Comparaison GAIA







Pour la r-band, supposant r = G, où G est la bande large de Gaia

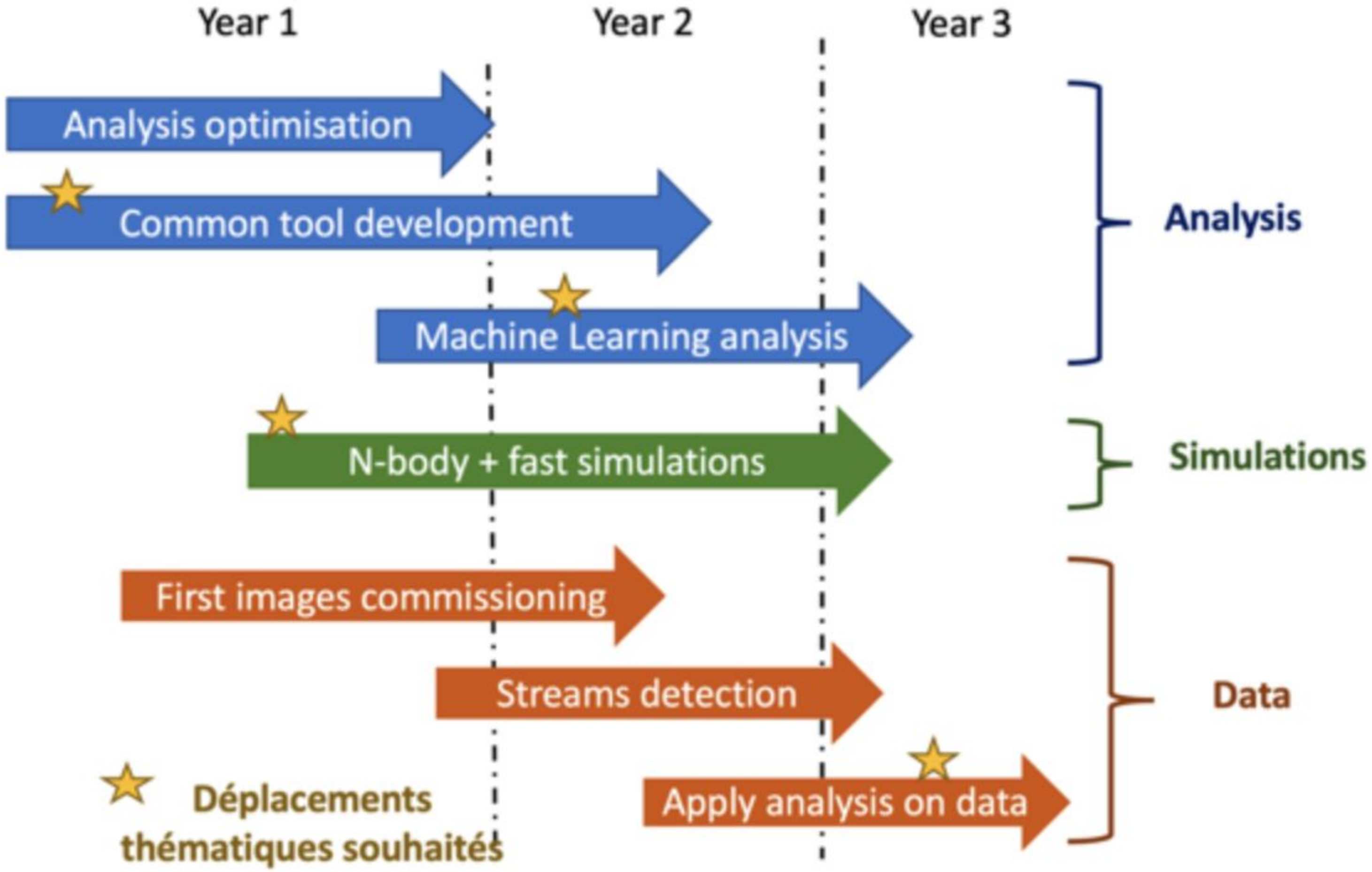
	Magnitude maximale	Nombre d’étoiles détectées
LSST	24.5 (1 exposition), 27.5 (10 ans)	10^{10}
GAIA	20	10^{9}

(*LSST Science Collaborations 2009*)

mas/yr = milli-second of arc per *year*

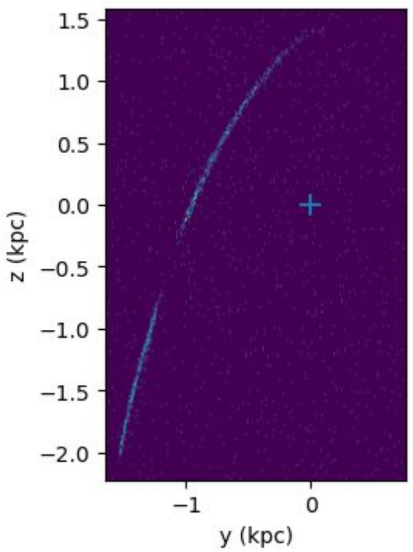
V. Annexes

Déroulement thèse



II. Framework

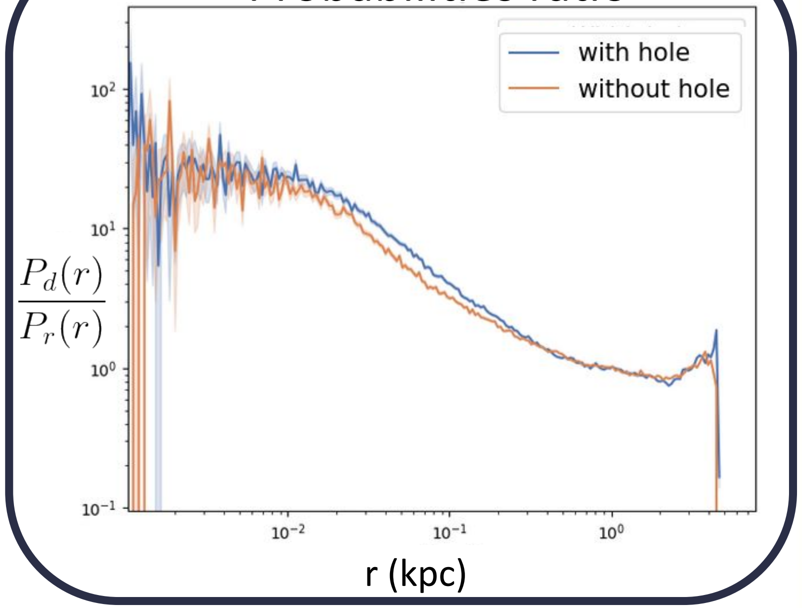
2) Observables : probabilities ratio



$$\frac{P_d(r)}{P_r(r)} = \frac{DD \times RR.tot}{DD.tot \times RR}$$

- Uses information in **2 dimensions**
- Estimated using ***treecorr*** library by counting star pairs

Probabilities ratio

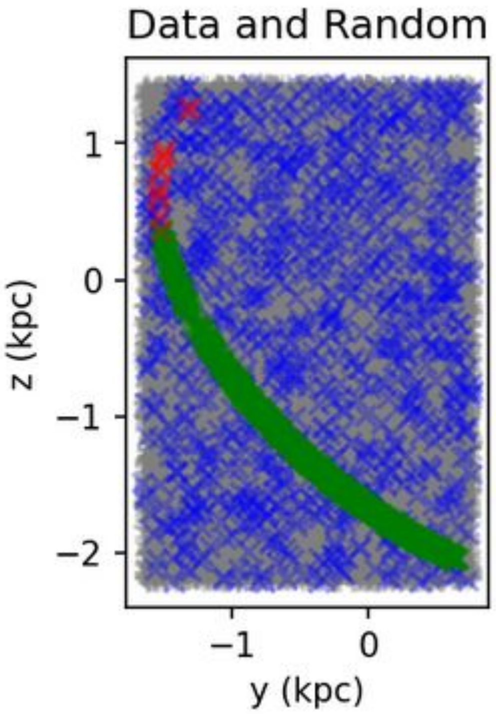


- Only positive part → **easier to read**

I - Framework

Spline → Only to calculate P(k) of linear density

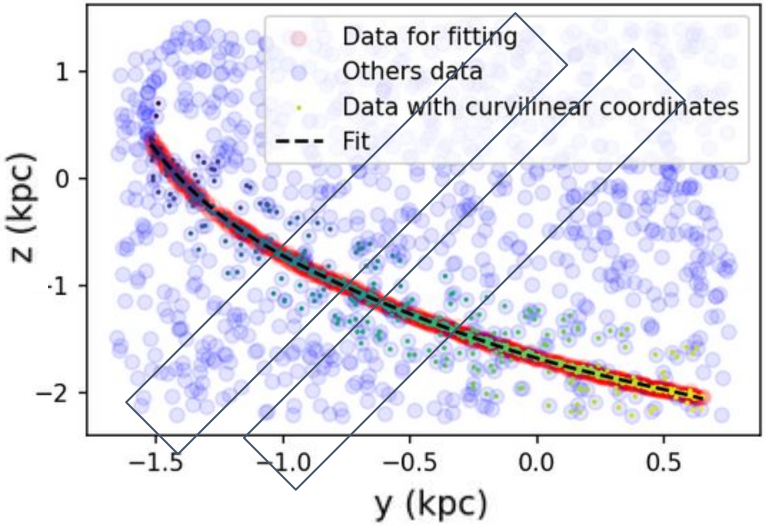
Data selection using velocities



Green : stream's stars selected
Red : stream's stars rejected
Blue : hand made added uniform background
Grey : random used for 2-pt correlation function

Spline

Stream, bruit de fond, fit.



- spline only on selected stream's stars (without noise)
- Works better with k=5. We select s=Nstars.

Projection + cut (0.5kpc)

stream, bruit de fond