Probing dark matter with stellar-stream density fluctuations in the LSST era

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Supervised by Marine Kuna and David Maurin

LPSC seminar 2026

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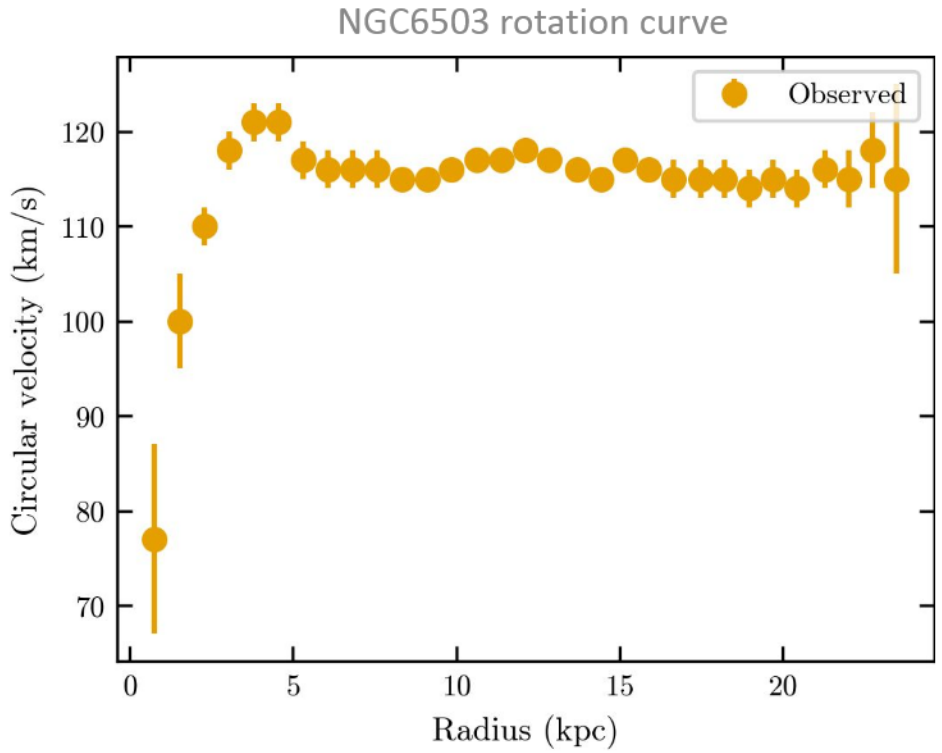
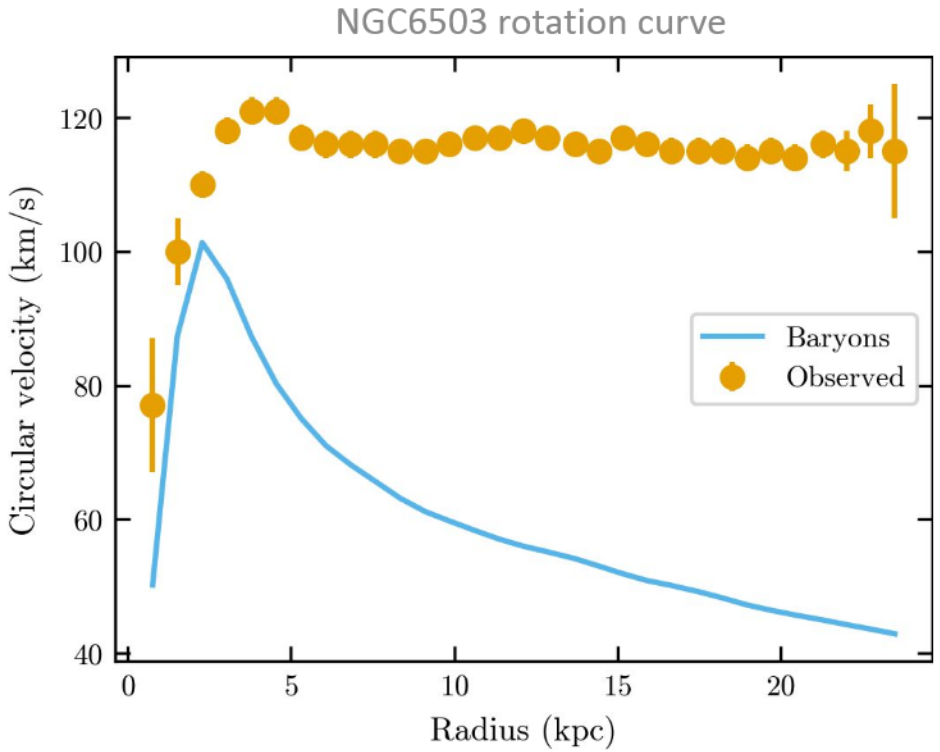
Introduction: Dark Matter

- Pioneering measurements by Vera C. Rubin established this discrepancy
- Evidence from galaxy rotation curves



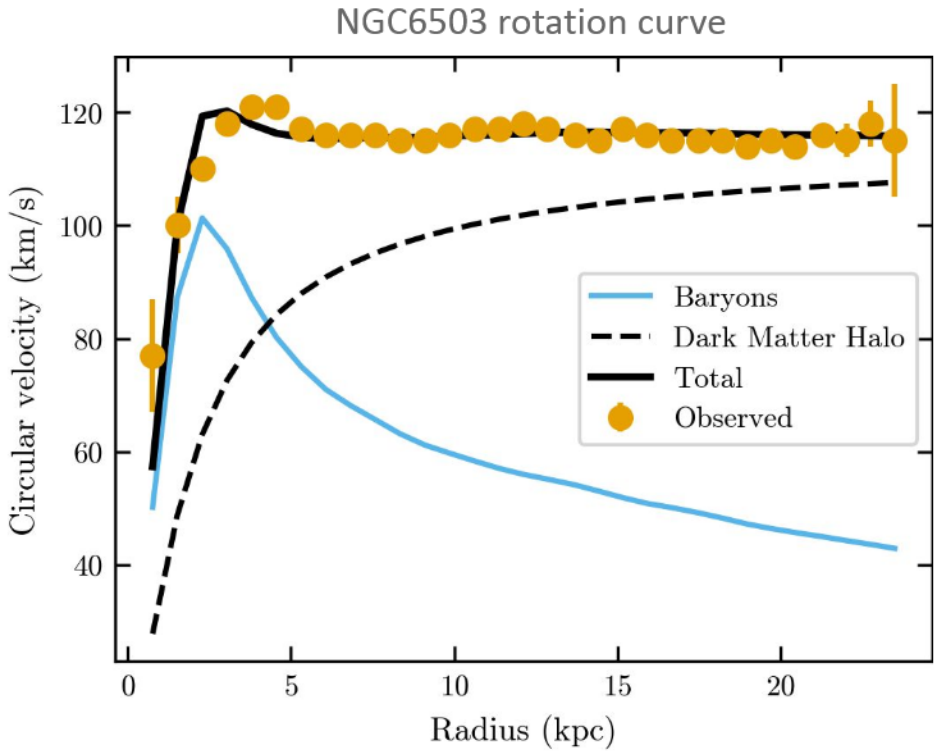
Introduction: Dark Matter

- Pioneering measurements by Vera C. Rubin established this discrepancy
- Evidence from galaxy rotation curves
  - **Baryonic** matter alone **cannot explain** observed stellar velocities



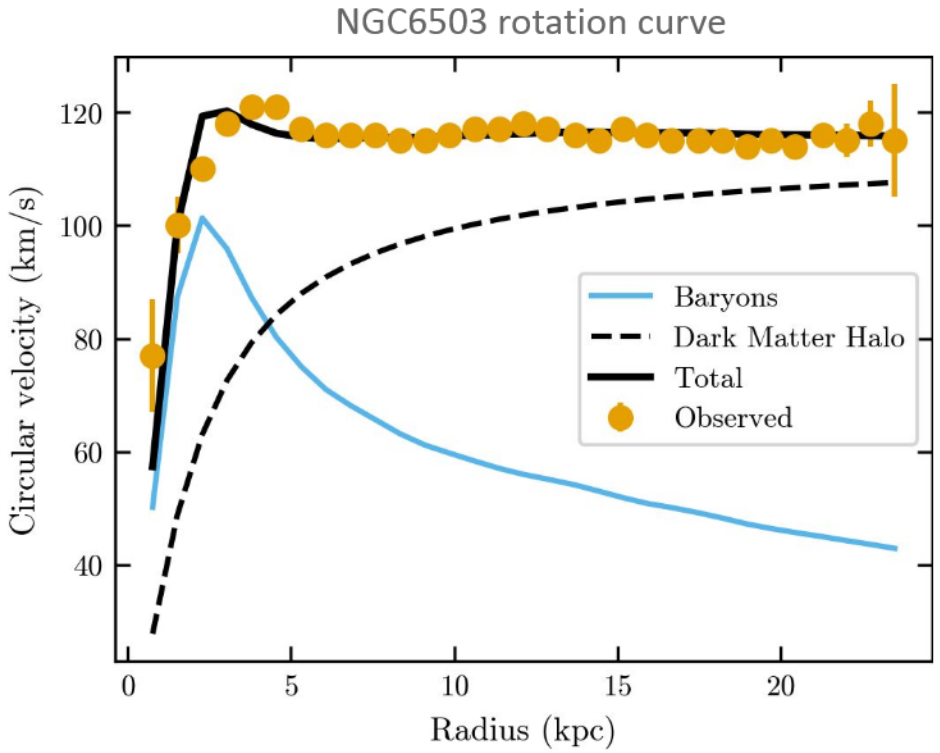
Introduction: Dark Matter

- Pioneering measurements by Vera C. Rubin established this discrepancy
- Evidence from galaxy rotation curves
  - **Baryonic** matter alone **cannot explain** observed stellar velocities
  - **Dark-matter** component is **required**



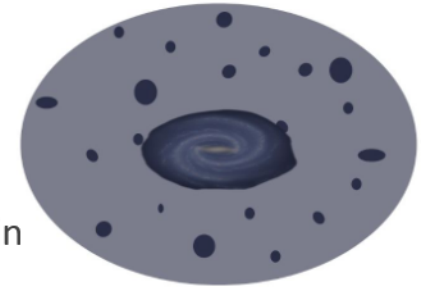
Introduction: Dark Matter

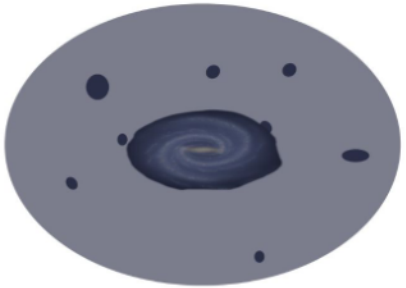
- Pioneering measurements by Vera C. Rubin established this discrepancy
- Evidence from galaxy rotation curves
  - **Baryonic** matter alone **cannot explain** observed stellar velocities
  - **Dark-matter** component is **required**
- Confirmed by **other** cosmological **probes** (CMB, gravitational lensing, …)

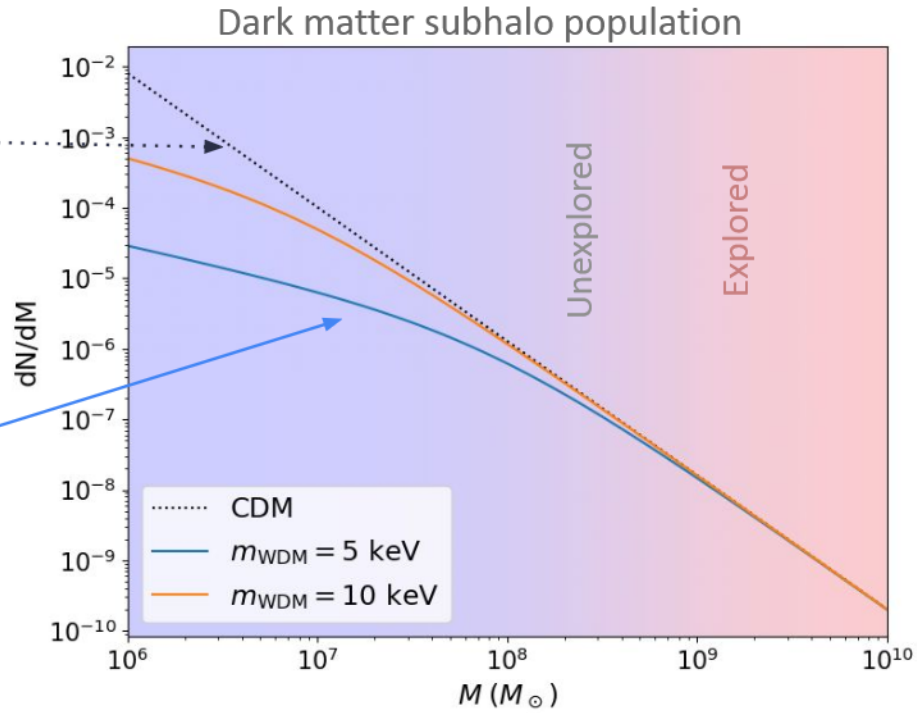


Introduction: subhalos

<u>Known:</u> galaxies reside within dark-matter **halos**
<u>Unknown:</u> **how** these halos are **structured** on small scales





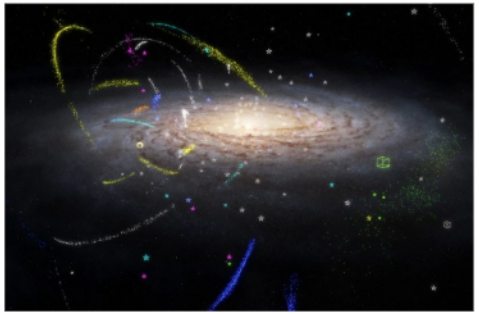


We wish to study the **substructure's population** of the dark matter halo $(10^6 - 10^9\, M_\odot)$ to **constrain dark matter models**

Introduction: stellar streams for dark matter

Using **stellar streams** as probes

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



(@ S. Payne-Wardenaar)

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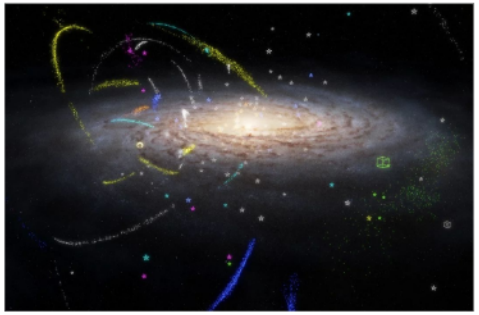
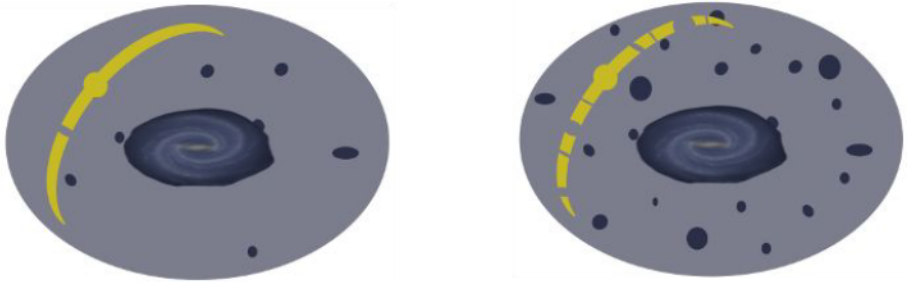


(@ S. Payne-Wardenaar)

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

(Ibata 2002)

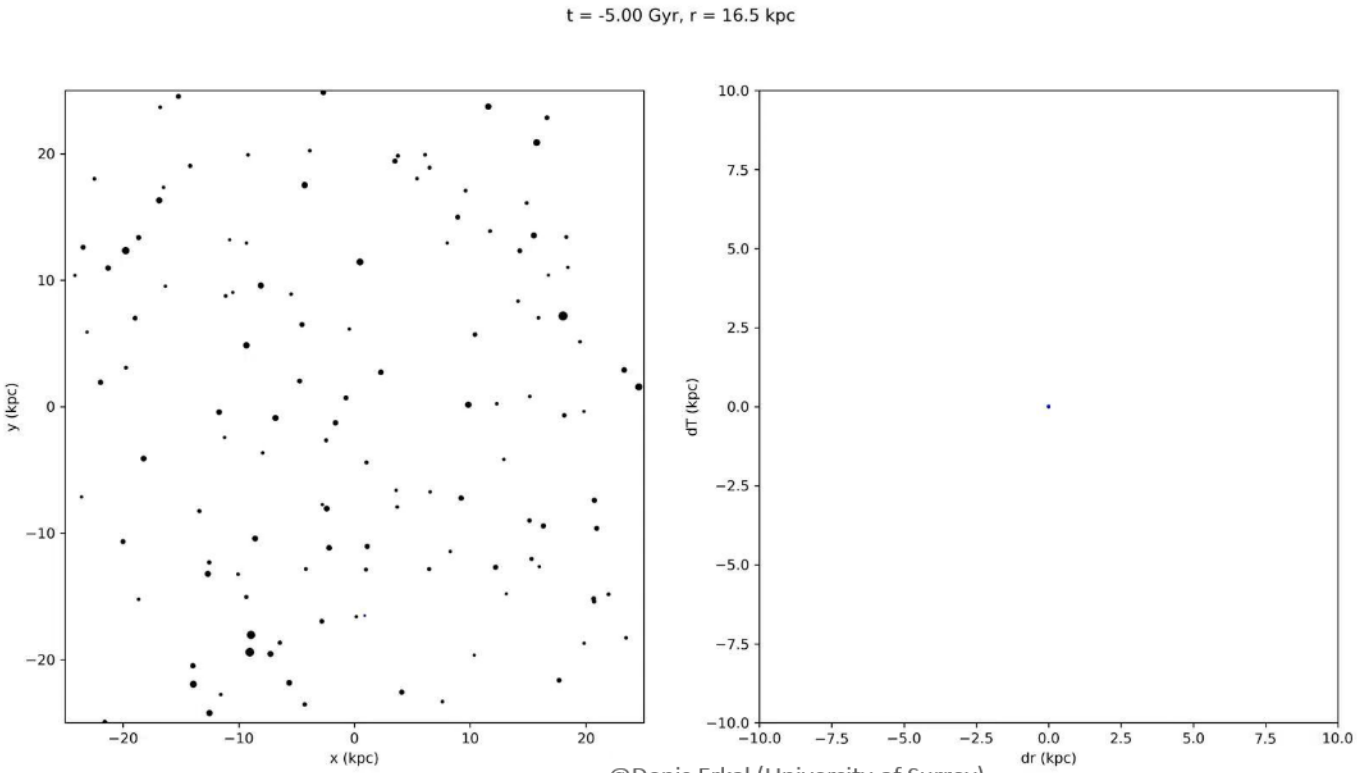


Statistical study to characterize the population of dark matter structures

Introduction: simulation example

Galaxy disc from above

Zoomed view



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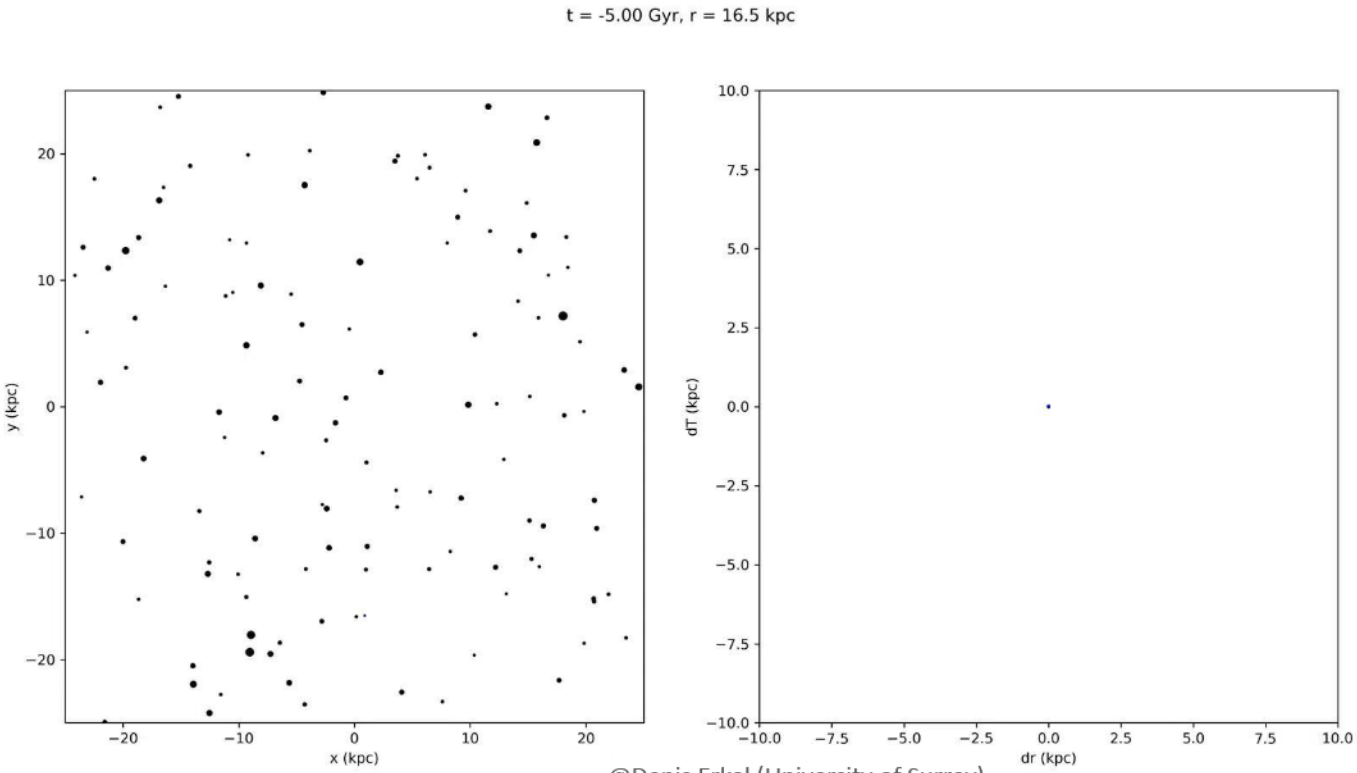
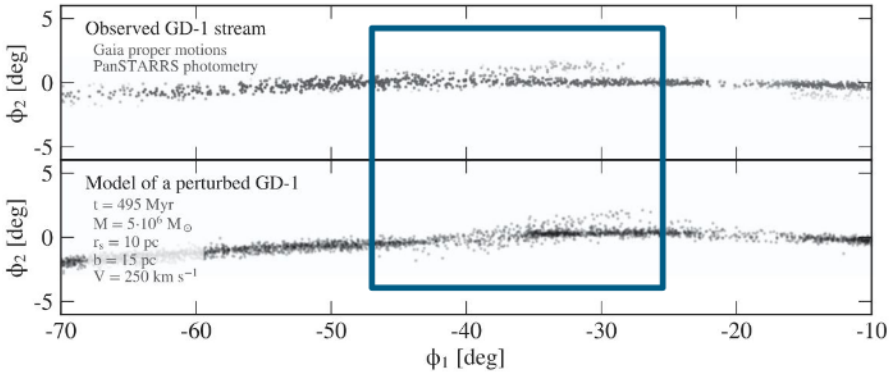


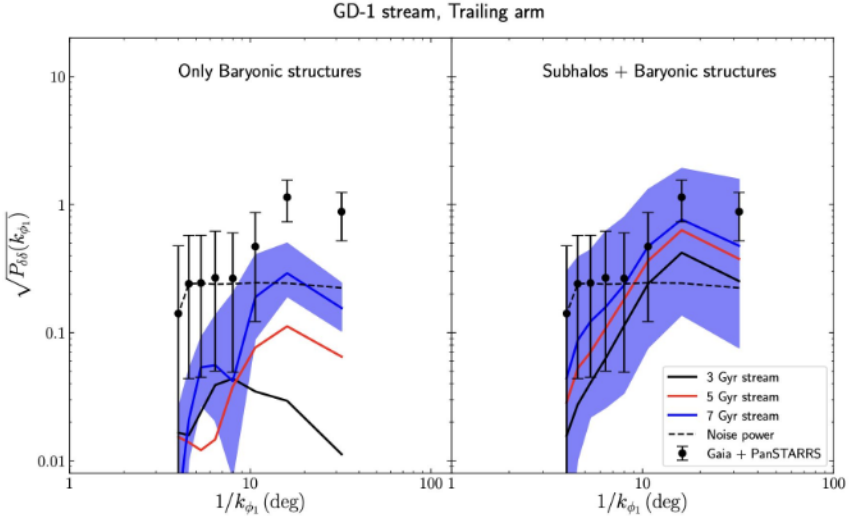
Introduction: studying stellar stream perturbations

Fitting targeted feature



Individual gap and spurs fitting, Bonaca et al. (2019)

Full shape analysis: power spectrum



1D Density Power Spectrum Banik et al. (2021)

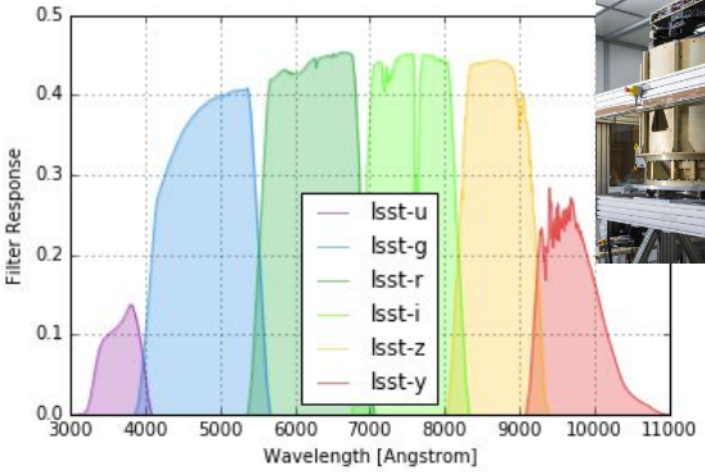
$|FT(f)|^2$ often used in cosmology

➡ Will be **observed** by Rubin observatory

Introduction: Vera C. Rubin observatory

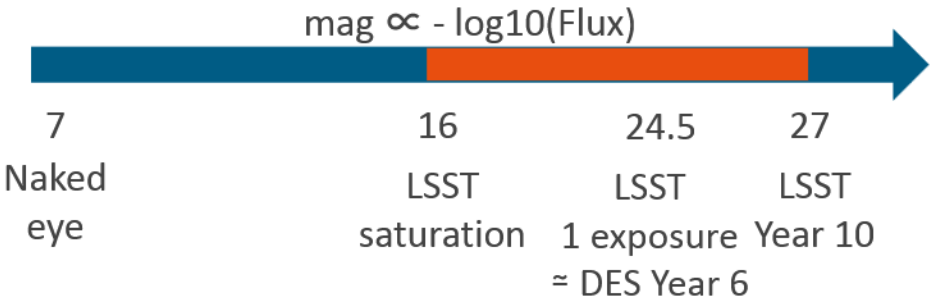
Legacy Survey of Space and Time (LSST)

- Deep **optical** survey for 10 years
- First images in **2025, survey in 2026**
- **6** photometric **filters**
- **LPSC** built filter changer



Introduction: LSST advantage for stellar streams

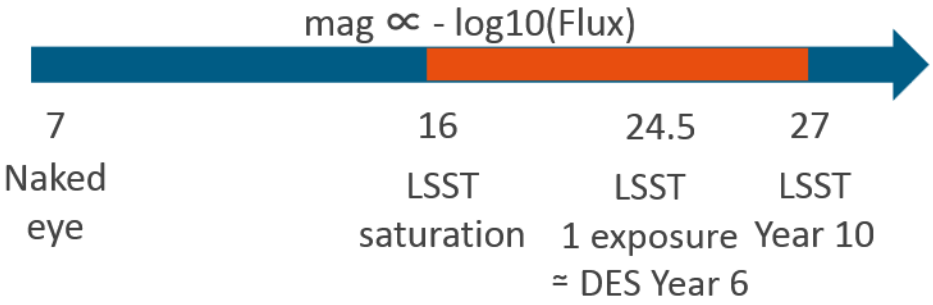
Legacy Survey of Space and Time (LSST)



- Number of detected stars : 10^{10}

Introduction: LSST advantage for stellar streams

Legacy Survey of Space and Time (LSST)

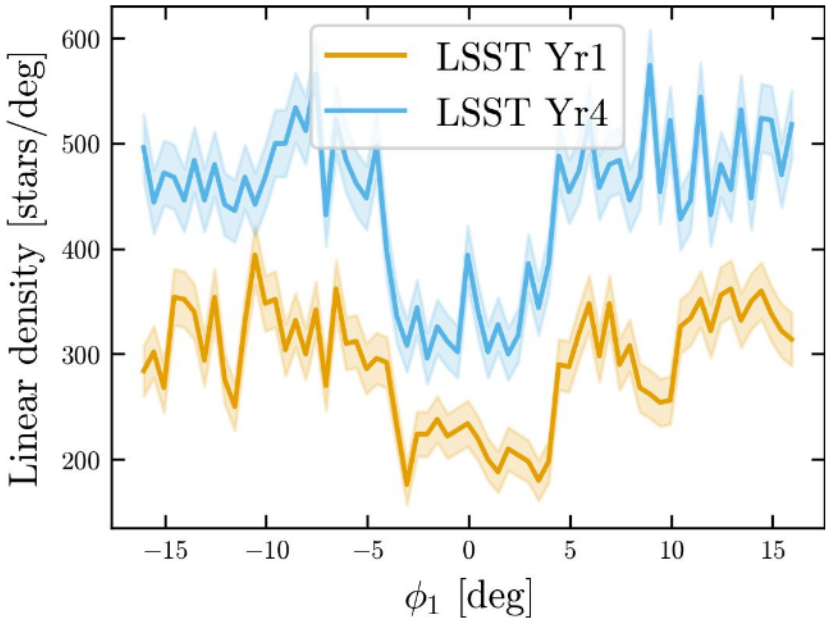


- Number of detected stars : 10^{10}

→ Possible **new streams** and **stars members** detected

→ Measure new density **fluctuations**

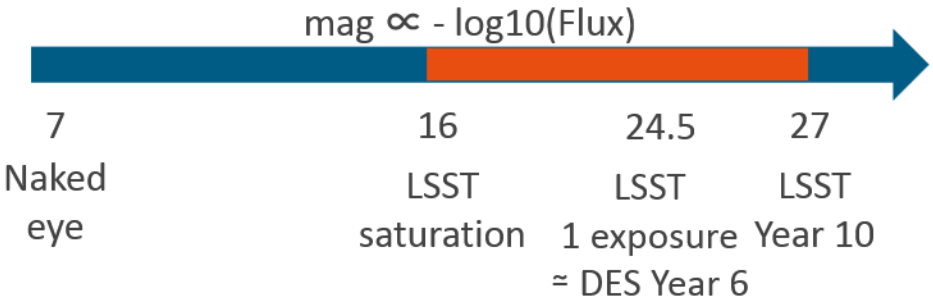
Simulations of stream density observation



Better fluctuation characterization with deeper survey

Introduction: LSST advantage for stellar streams

Legacy Survey of Space and Time (LSST)



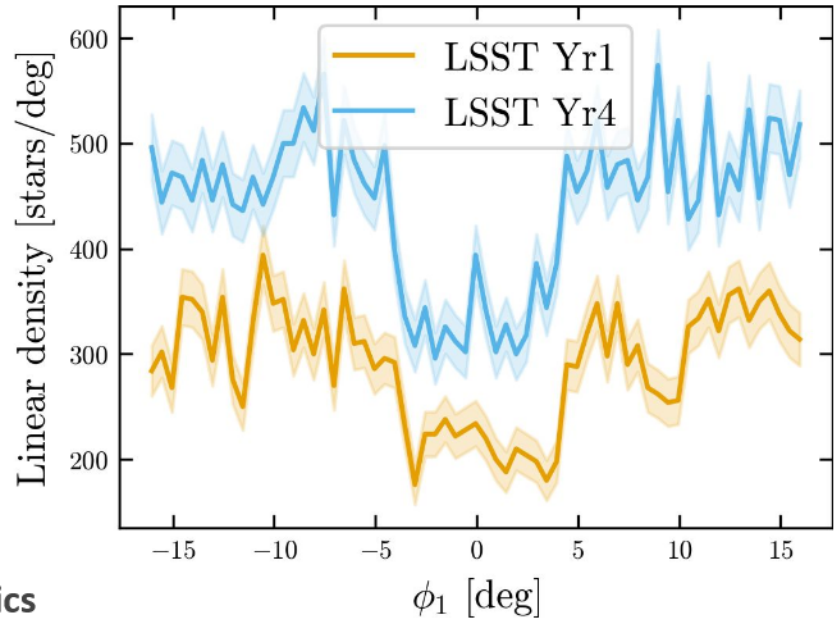
- Number of detected stars : 10^{10}

➡ Possible **new streams** and **stars members** detected

➡ Measure new density **fluctuations**

➡ But **data** can be **impacted by** observational **systematics**

Simulations of stream density observation



Better fluctuation characterization with deeper survey

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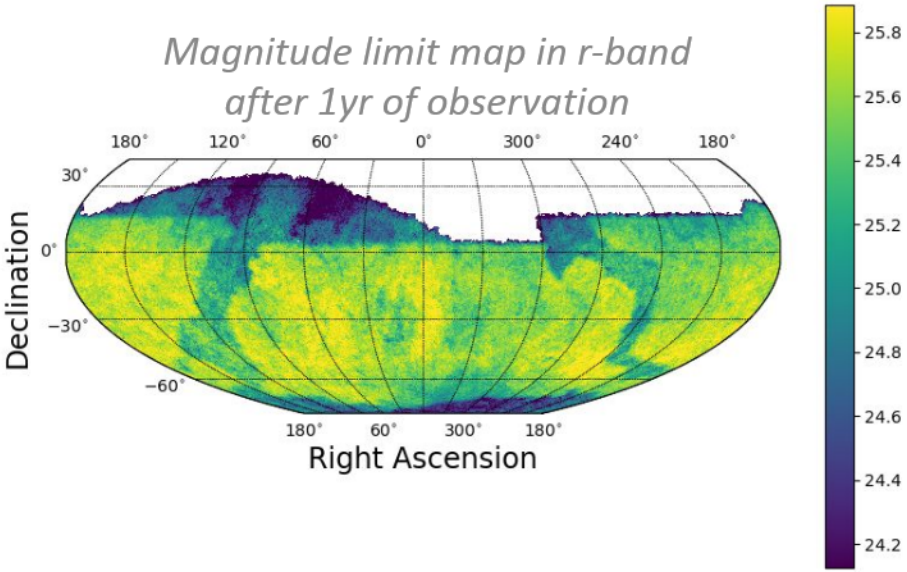
Close collaboration with Alex Drlica Wagner (U. Chicago) and Peter Ferguson (U. Washington)

Systematics impact on density fluctuations measurement



Survey properties impact **density fluctuations**:

- non-uniformity of the depth
- stars-galaxies separation
- extinction due to dust

- **Smallest fluctuation** measurable above LSST systematics?
- **Lightest subhalo** impact detectable in LSST?

Mock data generation

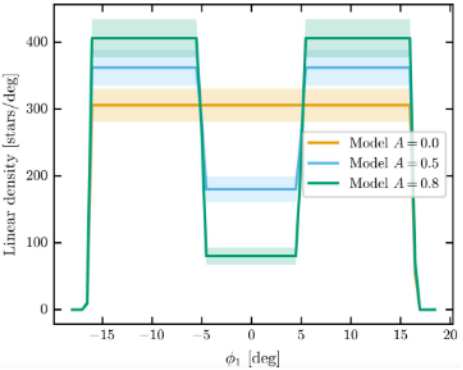
Parametric model for density fluctuation measurement

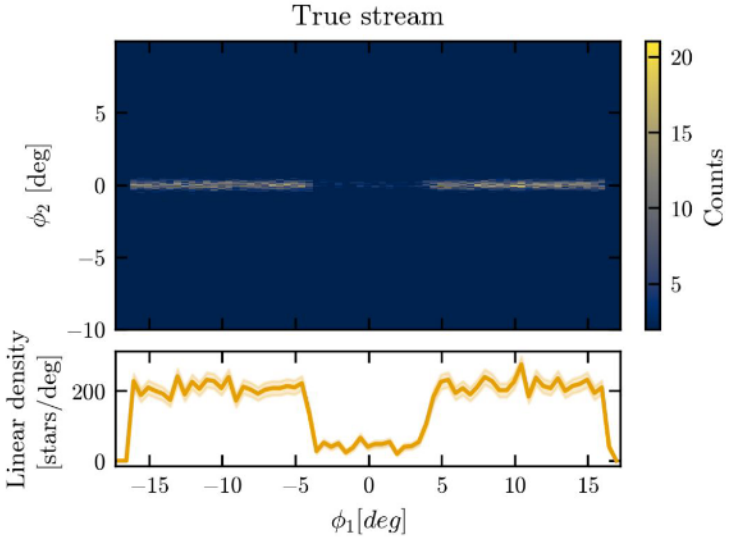
Stream model → True stars

Box hole density model parameters:

- A (amplitude), w (width), h0 (position)
- \+ **Additional fixed stream parameters** (length, isochrone …)

Also tested: sinusoidal model





Parametric model for density fluctuation measurement

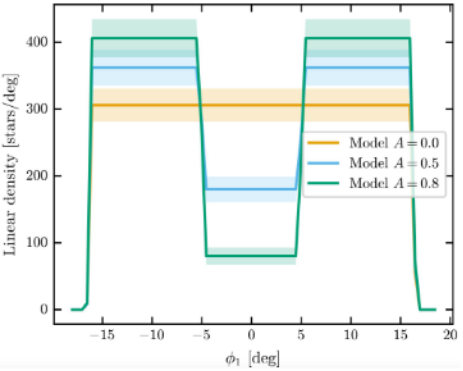
Stream model → True stars → StreamSim (Co developer) → Observed stars

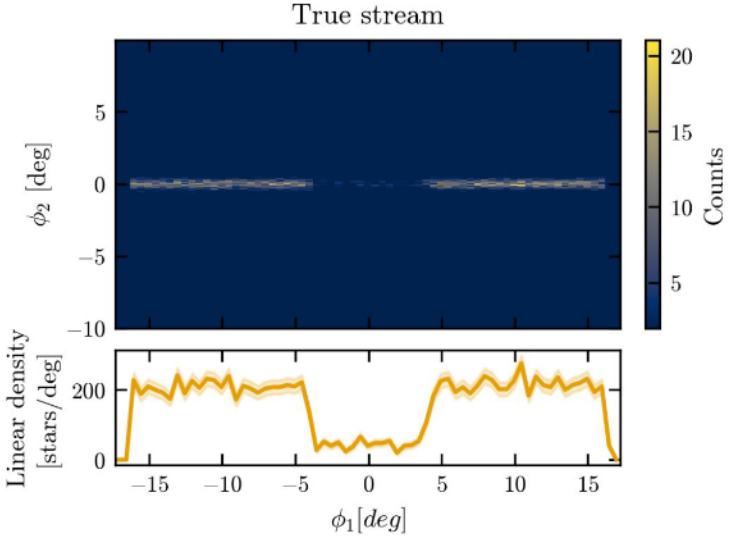
Box hole density model parameters:

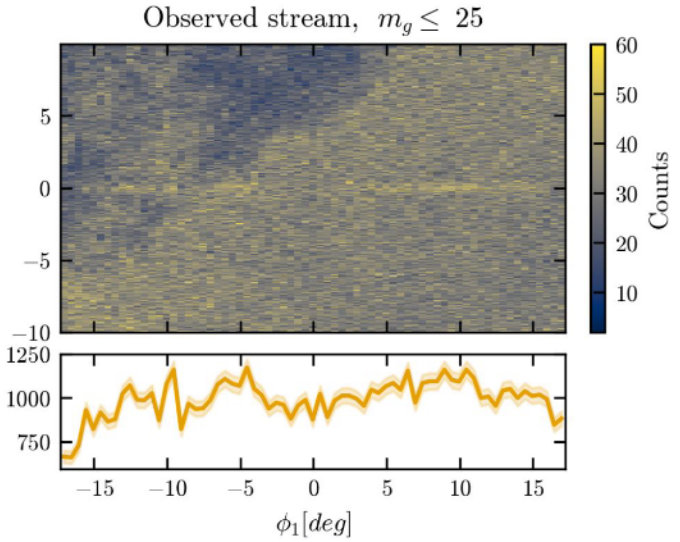
- A (amplitude), w (width), h0 (position)
- \+ **Additional fixed stream parameters** (length, isochrone …)

Mimic LSST observation (completeness, magnitudes and errors according to depth maps)

Also tested: sinusoidal model

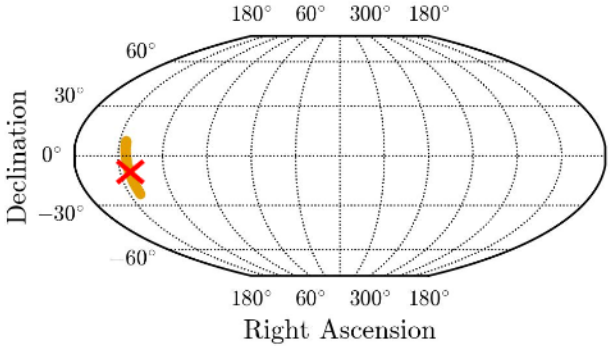




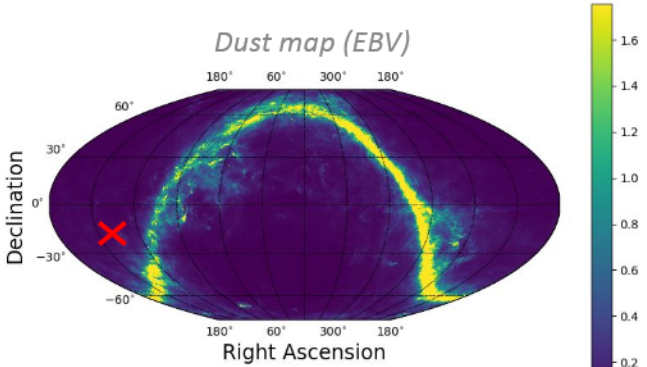


Conversion to observed data-like: magnitude limits

For each stars of the stream
(ra, dec, magnitude)



Estimate **dust** extinction at (ra, dec)



EBV map traces
dust distribution

Apparent magnitude

Conversion to observed data-like: magnitude limits

For each stars of the stream
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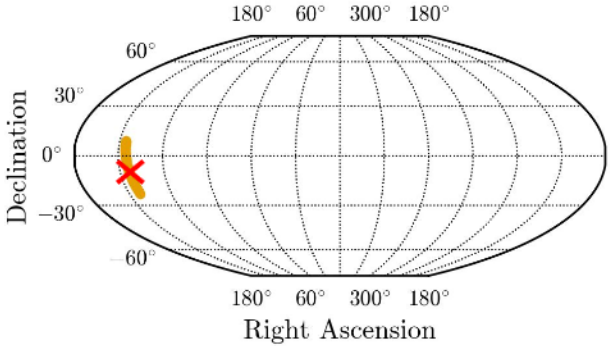
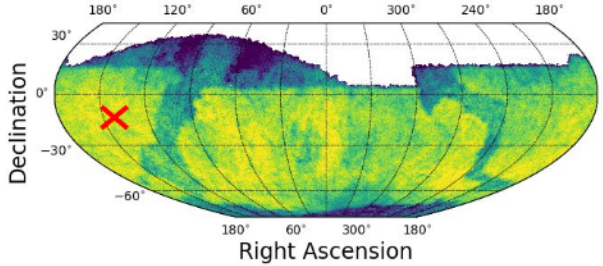


Estimate **magnitude limit** at (ra, dec)
in every bands

Magnitude limit map in r-band
after 1yr of observation



Built from [rubin_sim]

Delta magnitude

$$\Delta m_j = m_j - m_j^{lim}$$

Scale with:

- photometric **errors**
- Detection and classification **efficiencies**

Conversion to observed data-like: pipeline

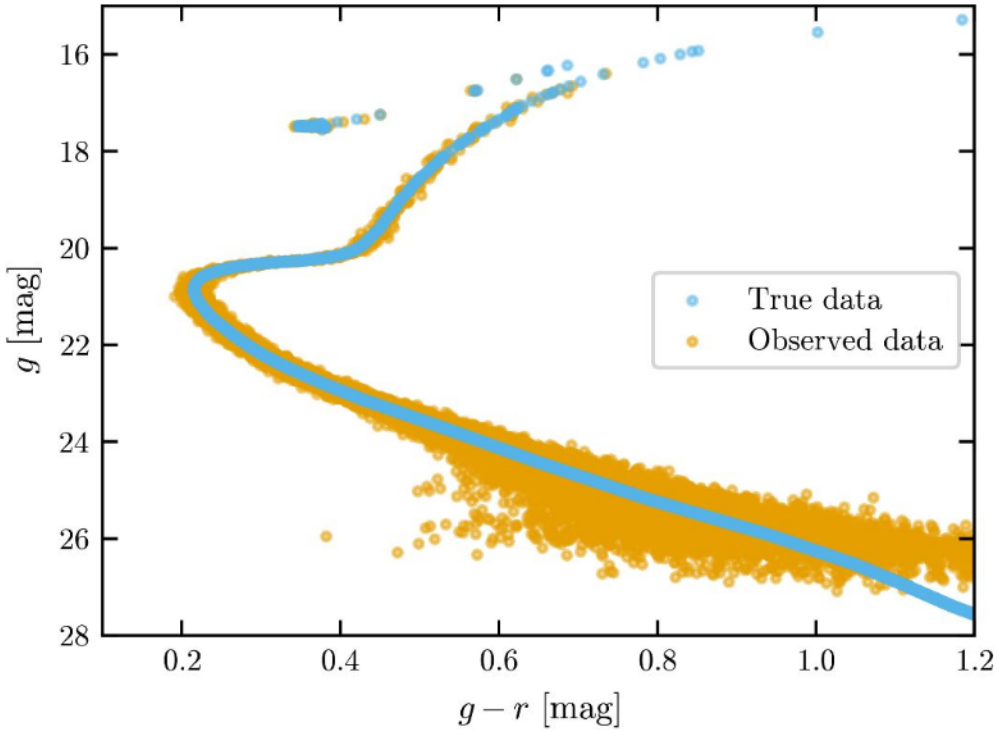
(ra, dec), apparent magnitudes

↓

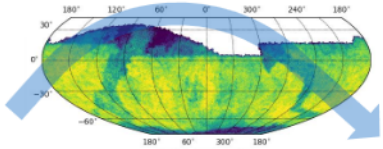
Injection pipeline

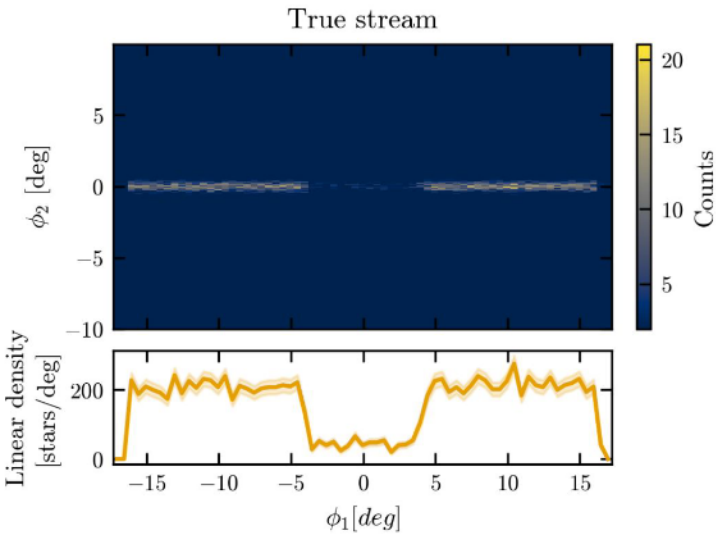
↓

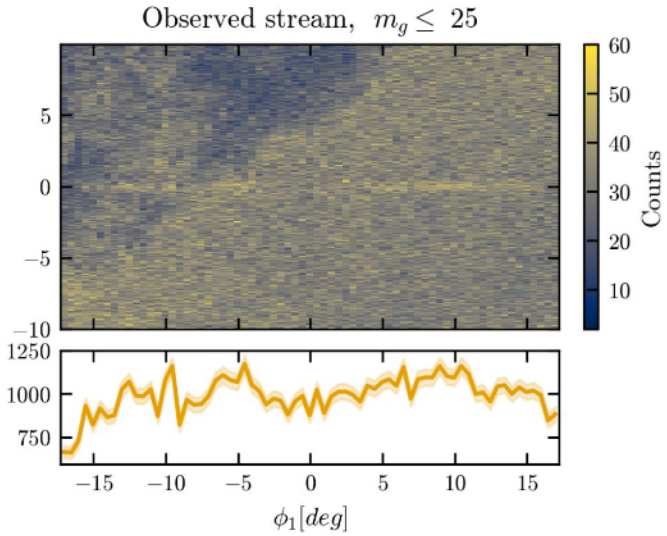
Observed magnitudes + errors, detection + classification boolean



Conversion to observed data-like: pipeline







- **Mimics** observed **statistics**
- **Imprint** expected **correlation** with survey depth

Analysis pipeline

Fluctuation detection efficiency

Fluctuation detection efficiency

Depth (A), width (w) → Simulated observed data → Power spectrum $P(k) = |FT(\rho)|^2$ → Fit $P(k)$

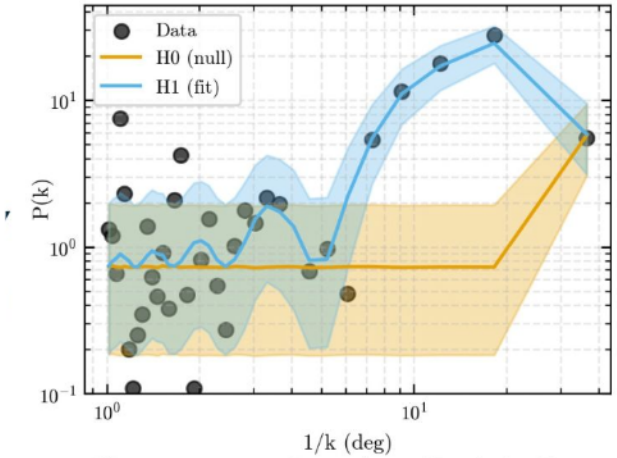
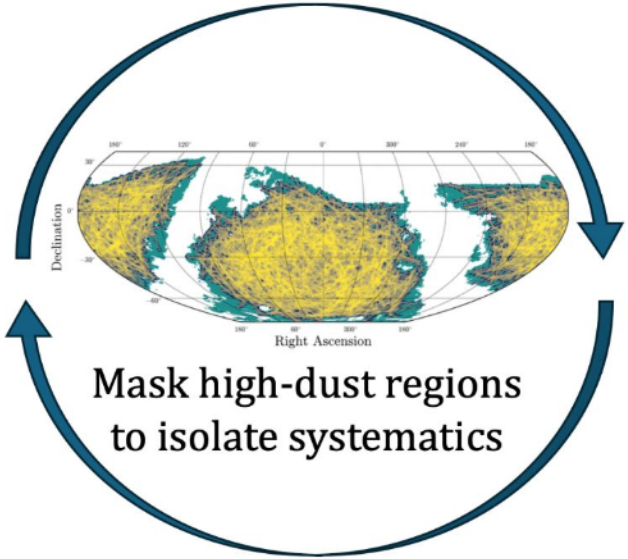


Fig: power spectrum hypothesis testing

Fit $P(k)$ → Likelihood ratio $R = -2log\left(\frac{\mathcal{L}(A=0,\theta|data)}{\mathcal{L}(A,\theta|data)}\right)$ → Fluctuation detection

Fluctuation detection efficiency

Depth (A), width (w) → **Simulated observed data** → **Power spectrum** $P(k) = |FT(\rho)|^2$ → **Fit** $P(k)$



Mask high-dust regions to isolate systematics

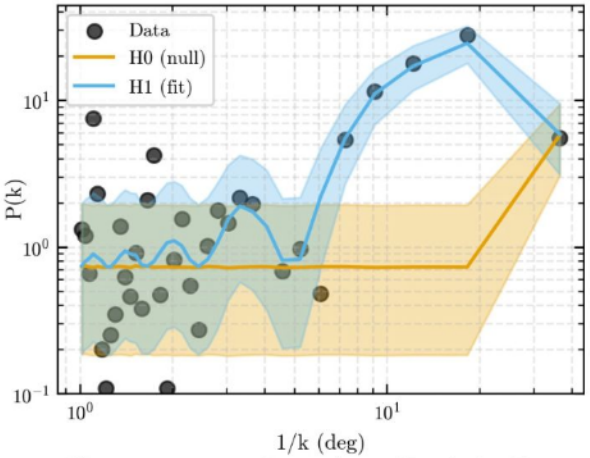


Fig: power spectrum hypothesis testing

Likelihood ratio

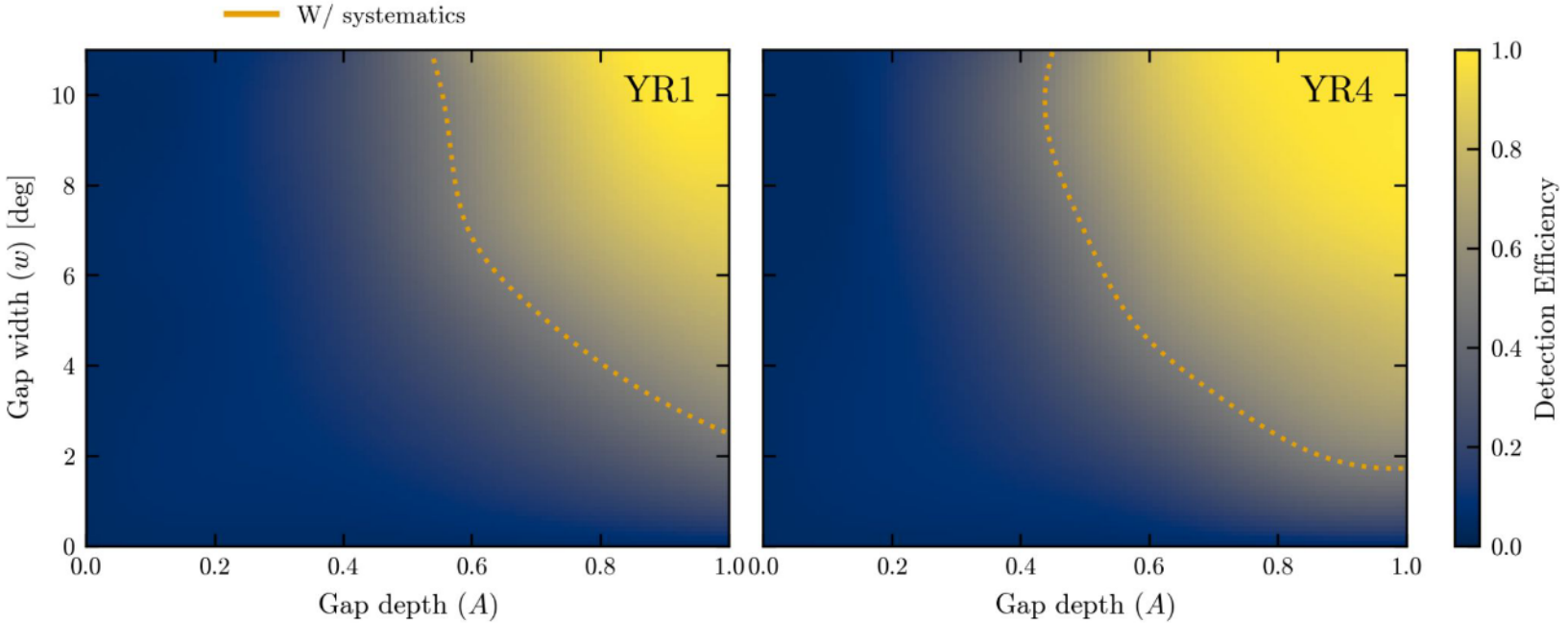
$$R = -2log\left(\frac{\mathcal{L}(A=0,\theta|data)}{\mathcal{L}(A,\theta|data)}\right)$$

Fluctuation detection

Statistical study over the full LSST footprint → Estimate **detection efficiency** at given (A, w)

Results

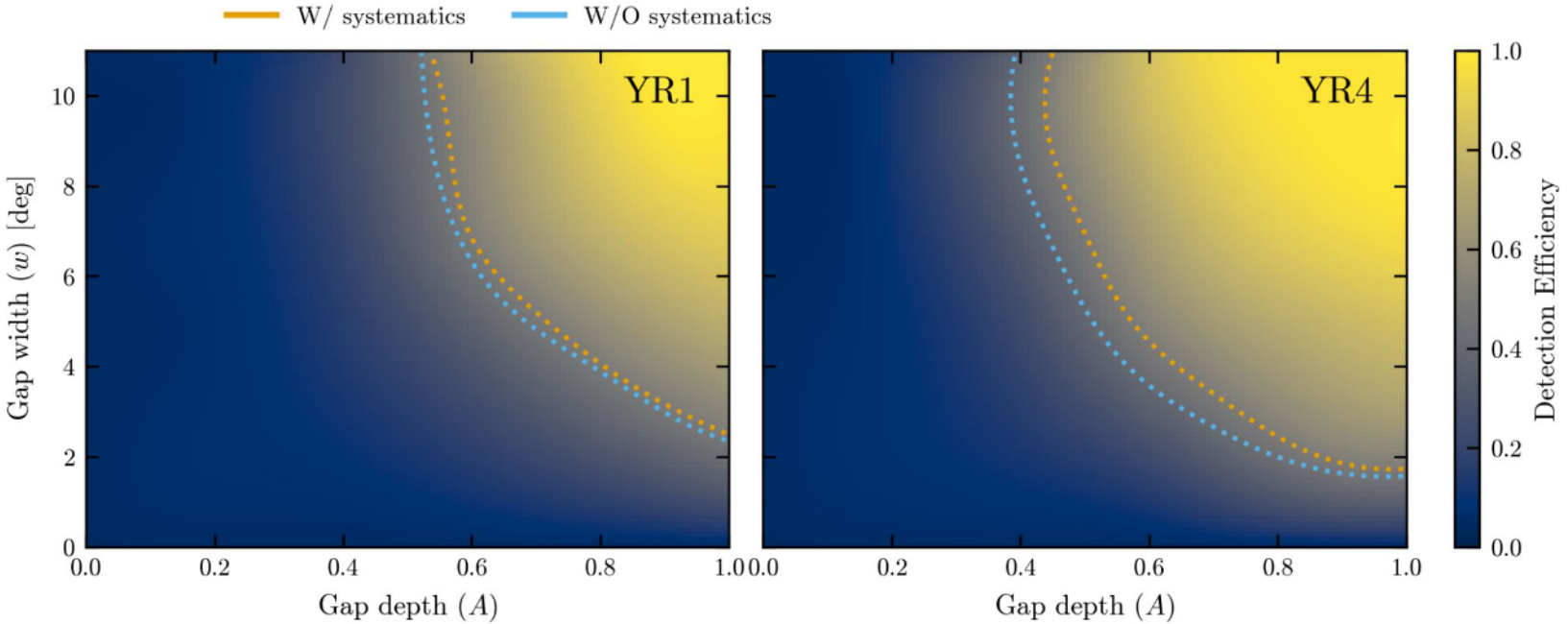
Gap detection efficiencies



Detectability:

- Increases with depth (A)
- Increase with observation time (YR1<YR4)

Gap detection efficiencies

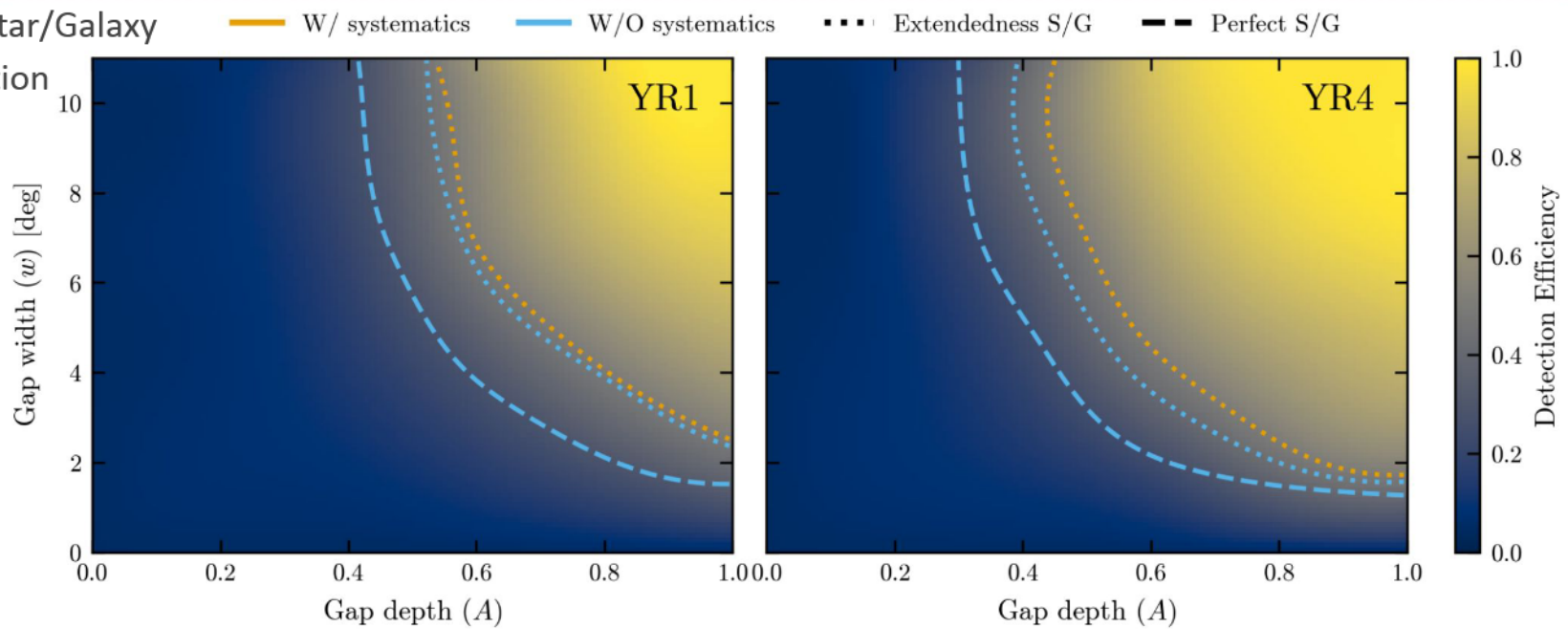


Detectability:

- Increases with depth (A)
- Increase with observation time (YR1<YR4)
- Impacted by the systematics

Gap detection efficiencies

S/G = Star/Galaxy separation

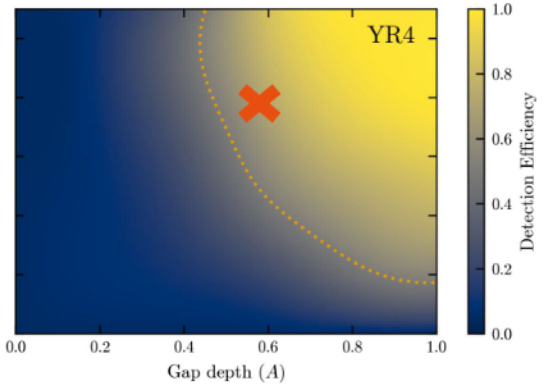


Detectability:

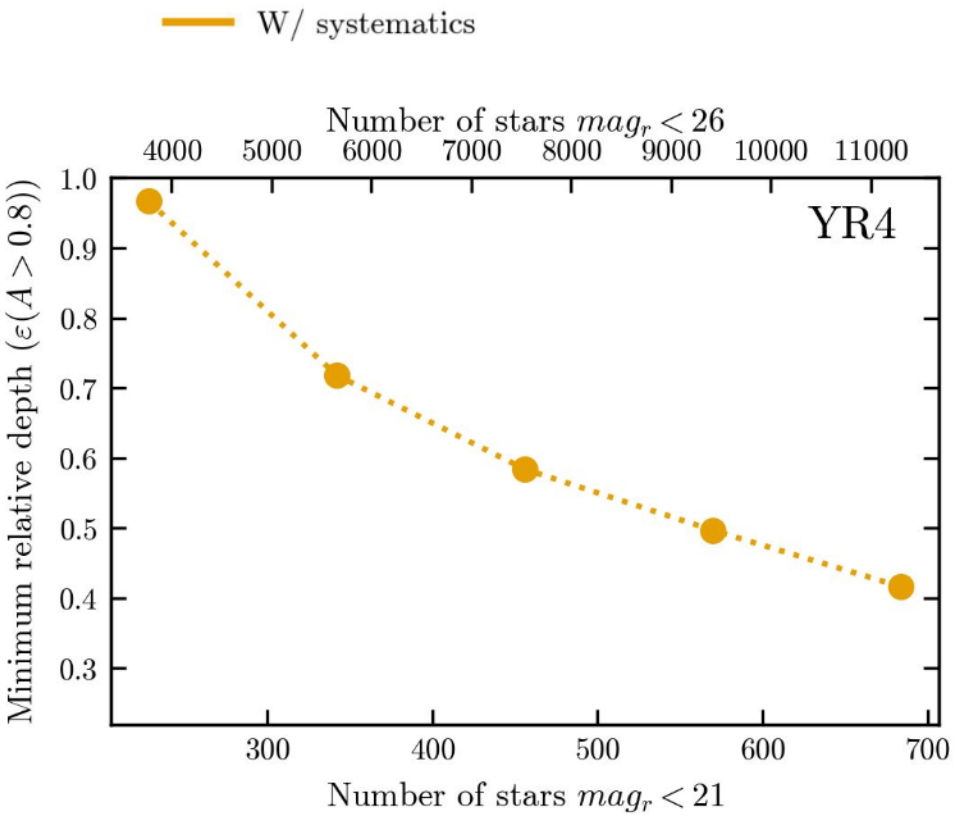
- Increases with depth (A)
- Increase with observation time (YR1<YR4)
- Impacted by the systematics
- Impacted by star galaxy separation

Smallest detectable depth

Find smallest depth such as efficiency > 0.8



- **Decrease** with the number of stars



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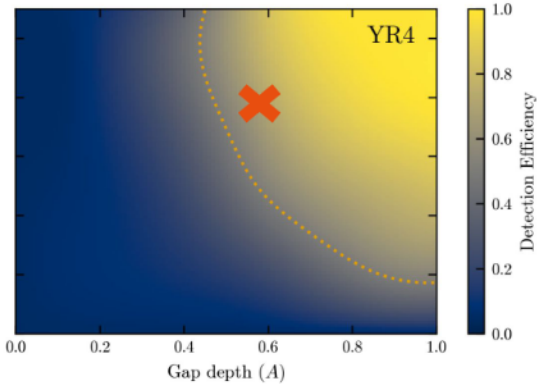
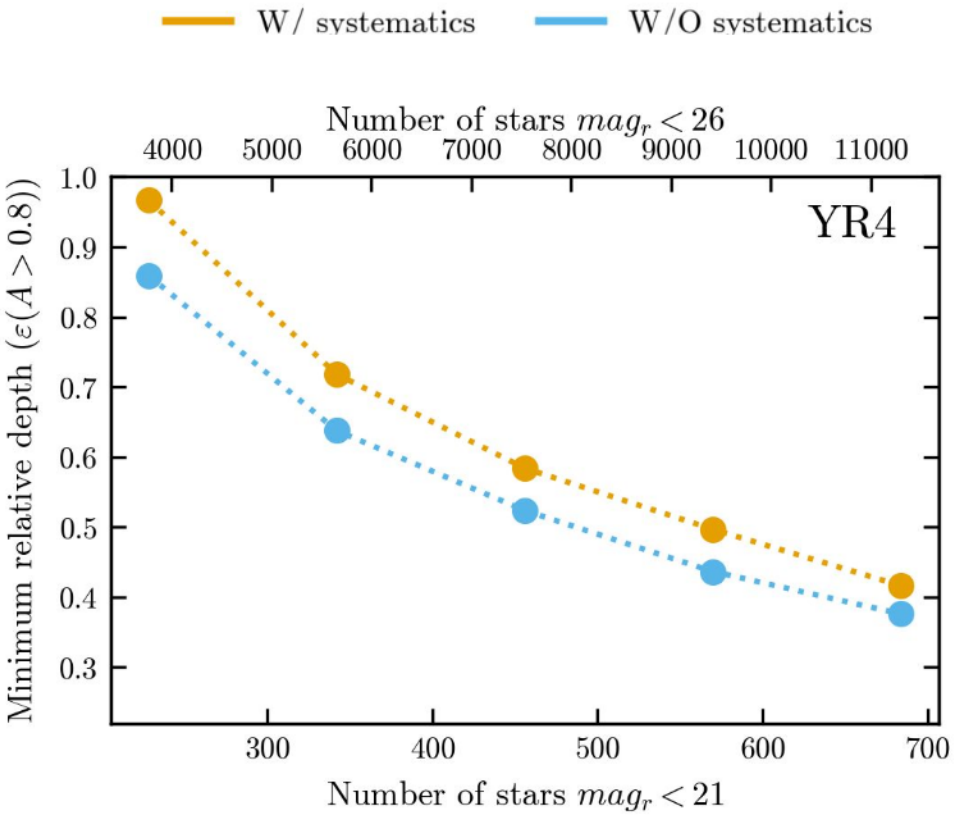


- **Decrease** with the number of stars
- Quantify impact from **systematics**



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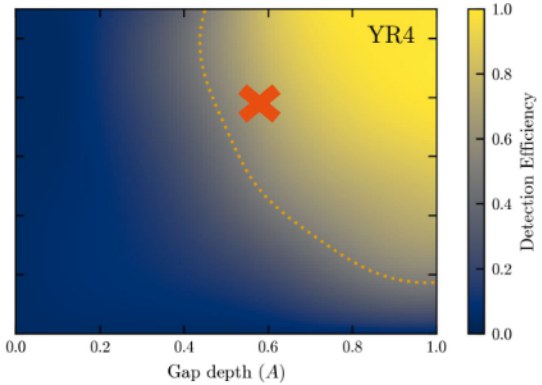

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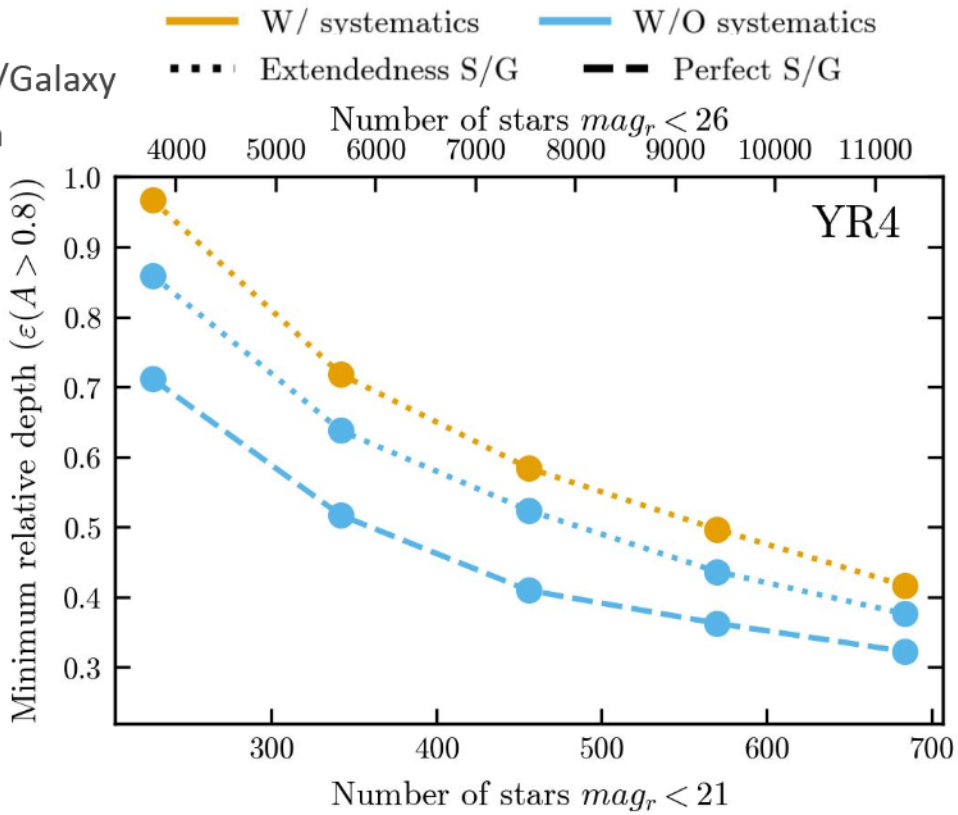


- **Decrease** with the number of stars
- Quantify impact from **systematics** and stars-galaxy **separation**

Also tested: without background, for different cuts and stream models.

Smallest detectable subhalo

Gap (A,w) detectability

Use analytical formulae to **convert gap properties to subhalo mass**

(Erkal 2016)

Subhalo mass

Smallest detectable subhalo

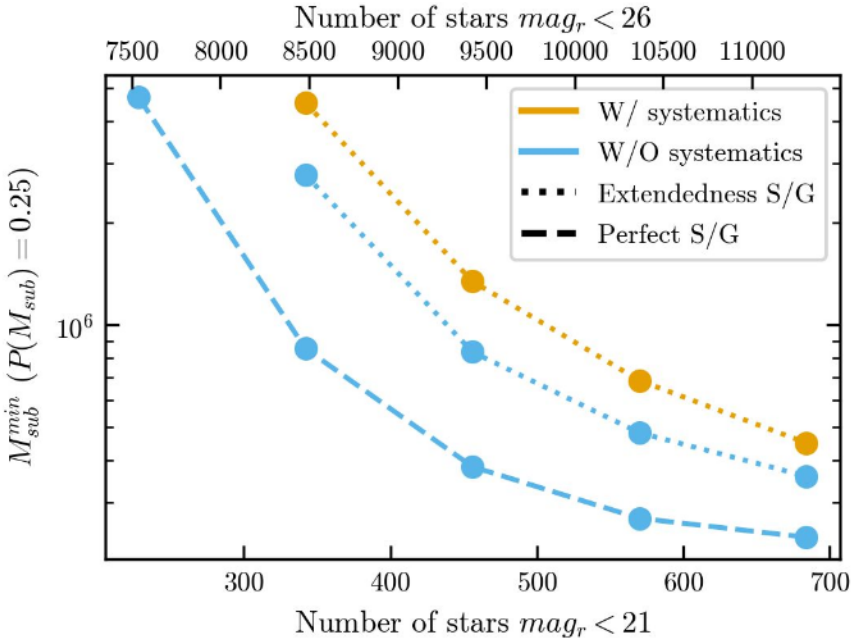
Gap (A,w) detectability

Use analytical formulae to **convert gap properties to subhalo mass**

(*Erkal 2016*)

Subhalo mass

Find the **lightest detectable subhalo**



Systematics and stars galaxy separation decrease subhalo sensitivity by a factor 2-5

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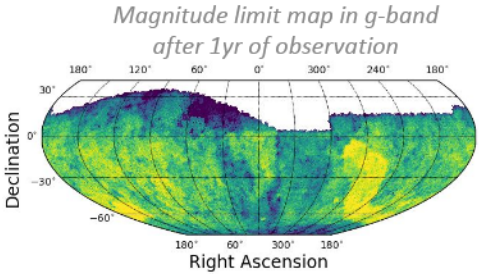
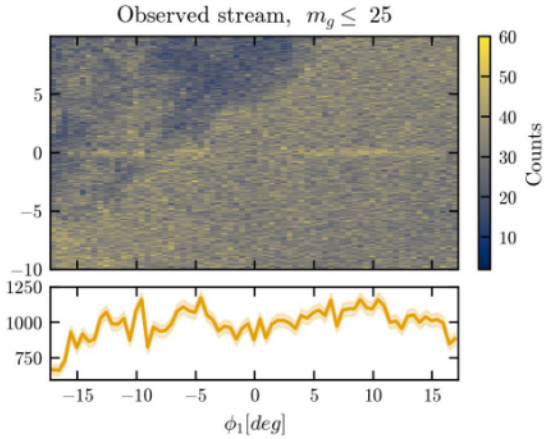
Conclusion

Developed:

- **Public software** to build LSST-like **mock** streams
- Power-spectrum **likelihood** analysis
- Detection **metrics** (likelihood ratio, efficiency)





Results:

- Systematics **corrections** are **essential**
- **Careful background** modeling required
- **Improved star–galaxy separation** is critical

Project presented at:

- DESC Stream sprint week (invited talk)
- LSST France (talks x4)
- Rencontres de Moriond 2026 (poster)
- DESC Stream meeting (talks x3)

Paper in preparation

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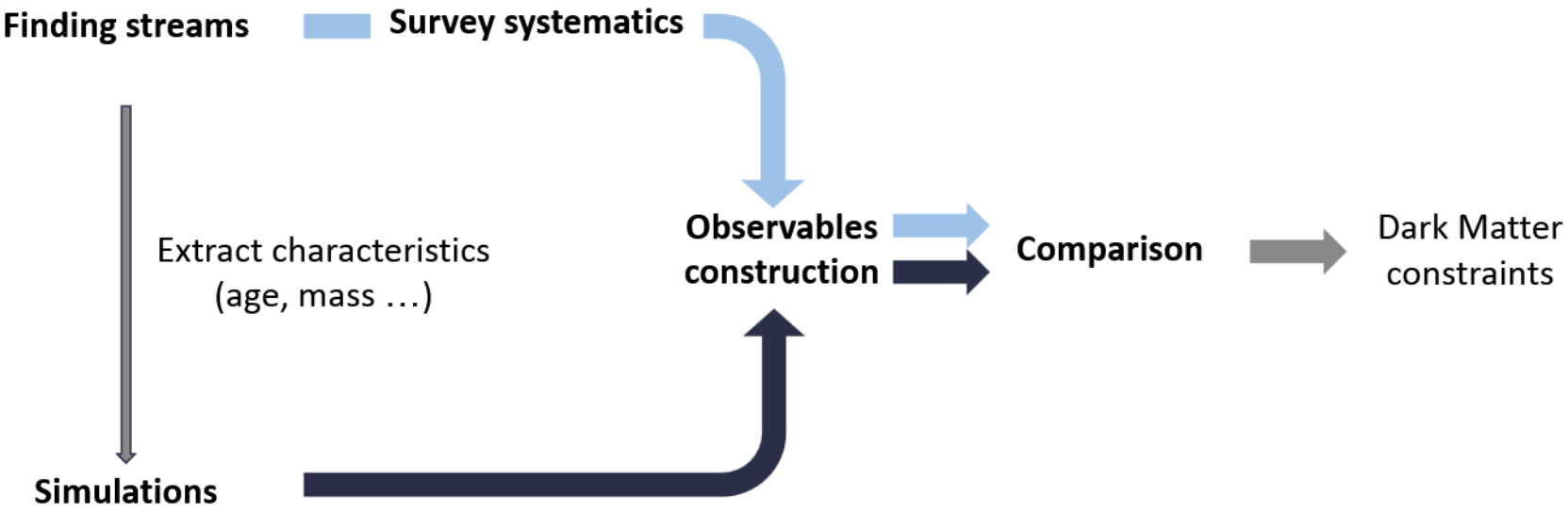
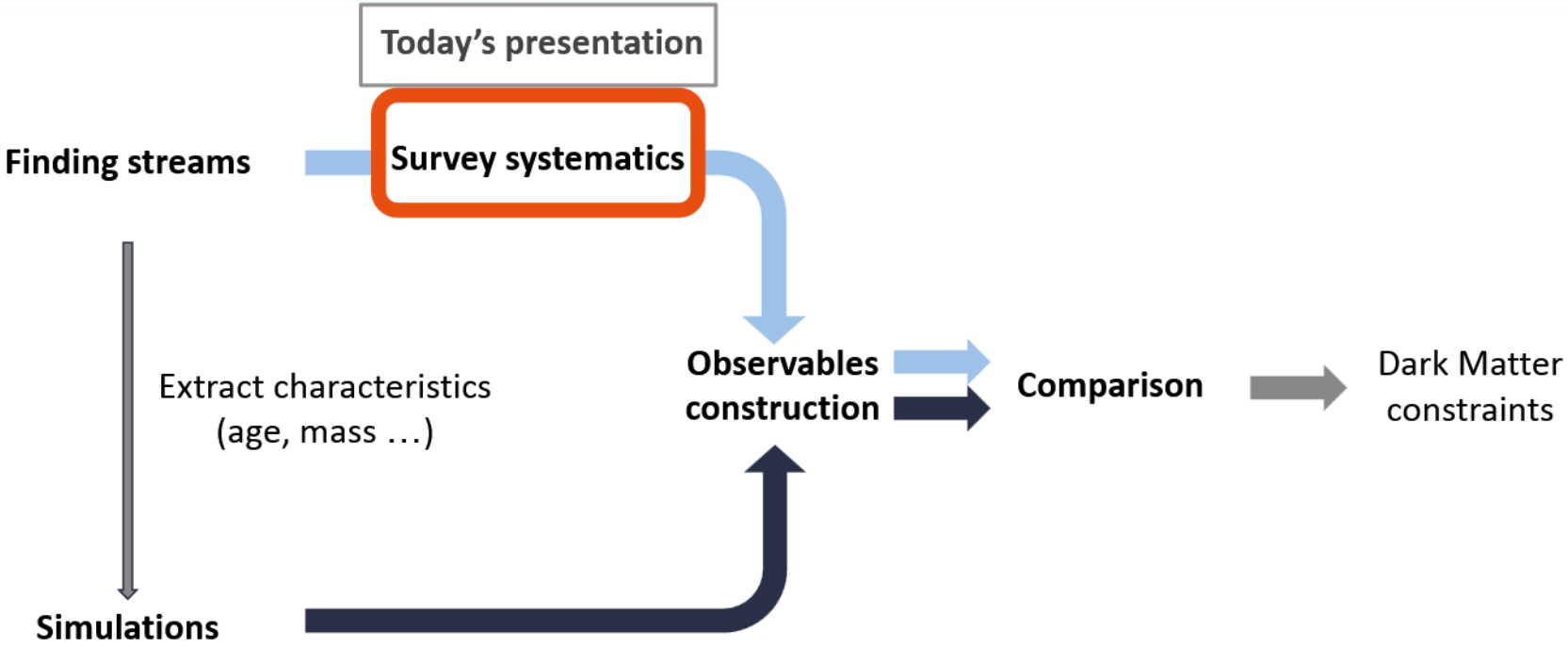
Outlooks: Setting Dark Matter model constrains



Outlooks: Setting Dark Matter model constrains

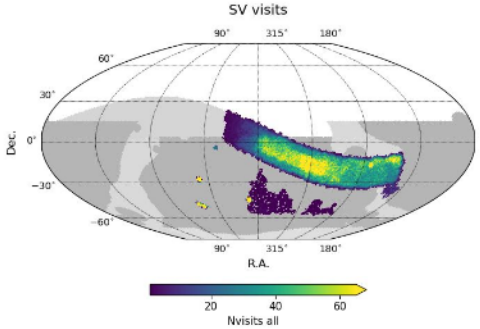


Outlooks: Setting Dark Matter model constrains

Finding streams

Extend known streams with **coming LSST DataProduct**:

- manipulate **real data**
- **characterize** photometric response for star population



Extract characteristics (age, mass …)

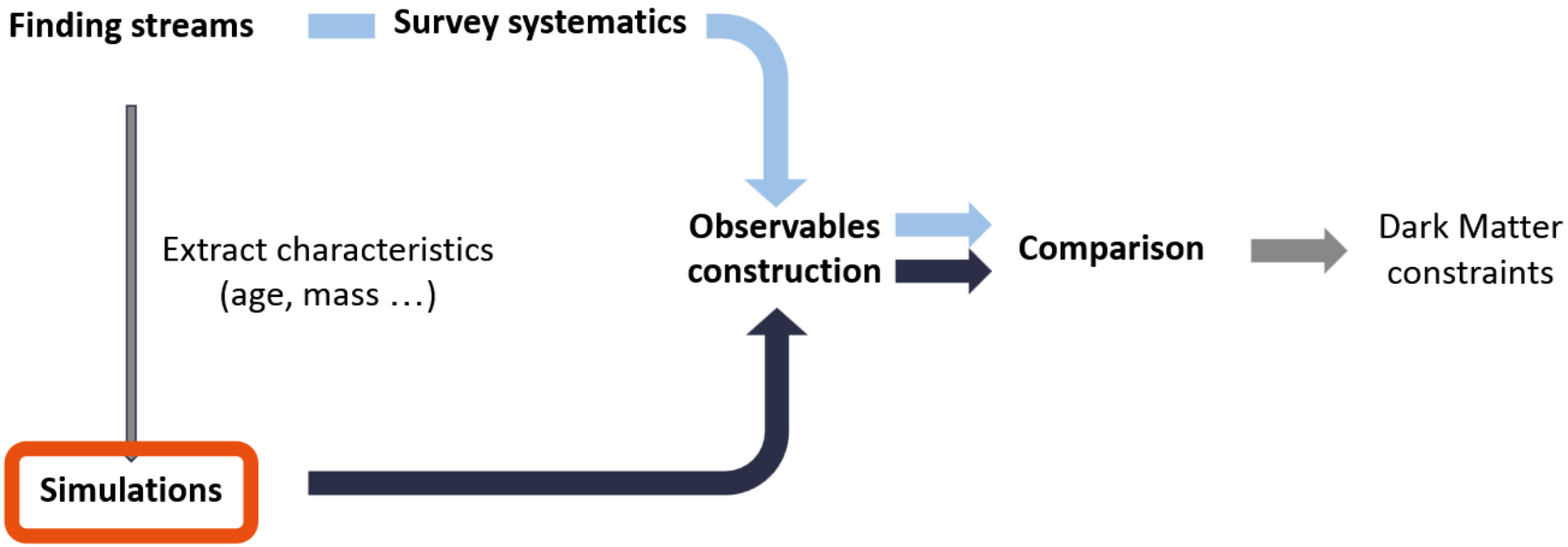
Observables construction

Comparison

Dark Matter constraints

Simulations

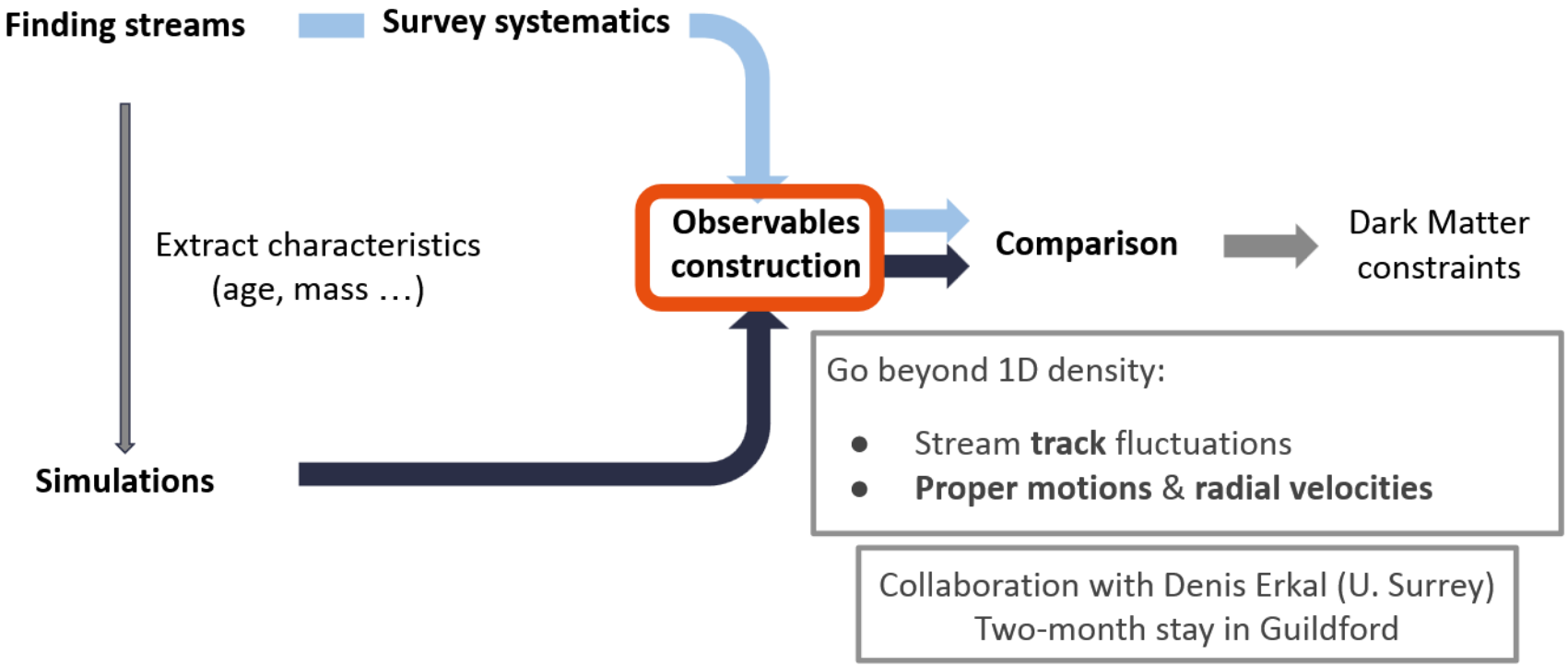
Outlooks: Setting Dark Matter model constrains



New high-precision effective **N-body** simulations of **stream–subhalo interactions**

Collaboration with Denis Erkal (U. Surrey)
Two-month stay in Guildford

Outlooks: Setting Dark Matter model constrains



Thanks for your attention