Impact of LSST systematics on stellar-stream density fluctuations measurement for dark matter

Matthieu Pélissier, Peter Ferguson, Alex Drlica-Wagner, Marine Kuna and David Maurin

Probe Combination for Dark Matter Physics in the Era of Large Surveys

GRENOBLE | MODANE

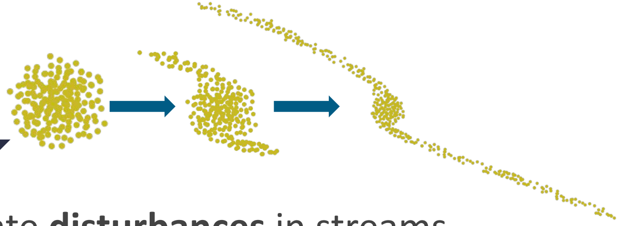
Université Grenoble Alpes

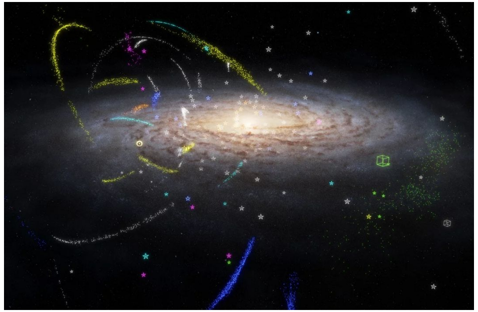
Dark Energy Science Collaboration

Introduction: stellar streams for dark matter

Using **stellar streams** as probes

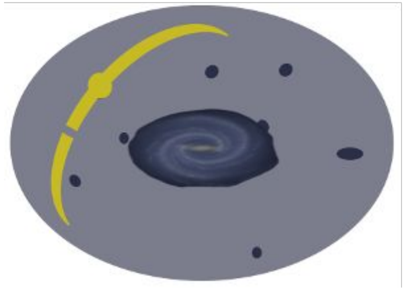
= Globular cluster or dwarf galaxy distorted by **tidal effects**

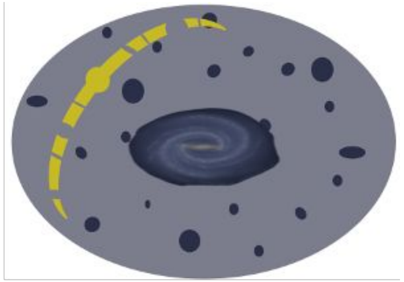




(@ S. Payne-Wardenaar)

The **impact** of subhalos can create **disturbances** in streams
(*Ibata 2002*)



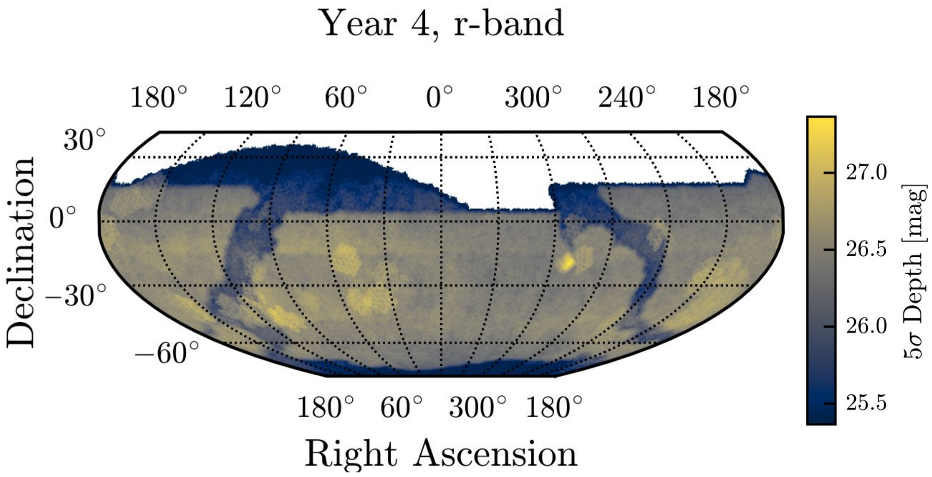


Statistical study to characterize the population of dark matter structures

LSST systematics impact on density fluctuations measurement

Legacy Survey of Space and Time (LSST)

- Deep **optical** survey for 10 years
- Started in **july 2026**
- Number of **detected stars** : 10^{10}



Survey properties impact **density fluctuations**:

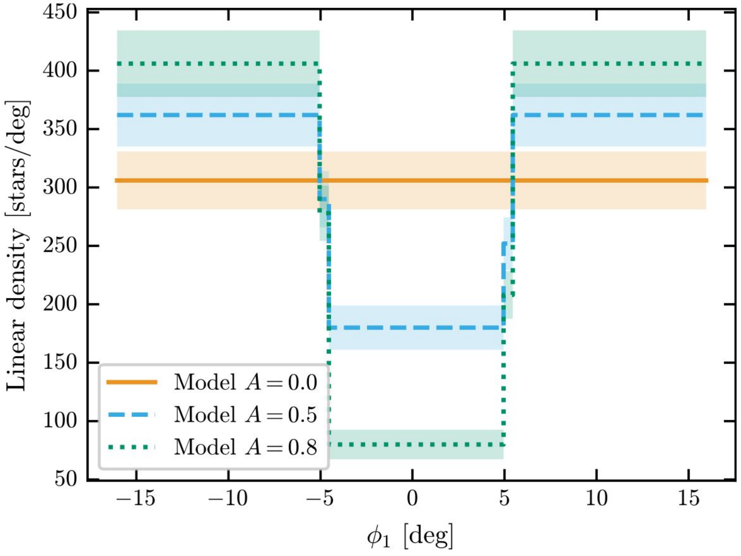
- non-uniformity of the depth
- stars-galaxies separation
- extinction due to dust

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

Mock data generation

Parametric model for density fluctuation measurement

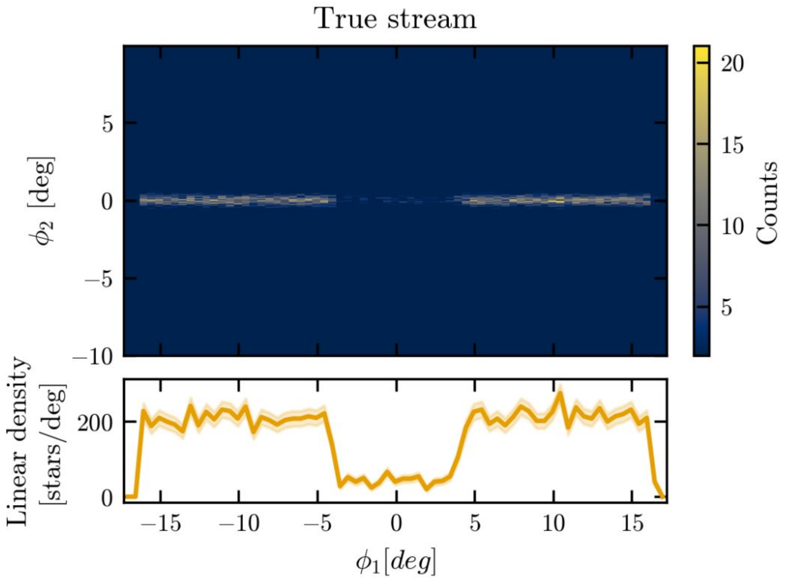
Stream model ➡ True stars



A = maximum relative modulation of the linear density

Simple box hole density **model** chosen to sit in the regime where **density fluctuations are most tractable**

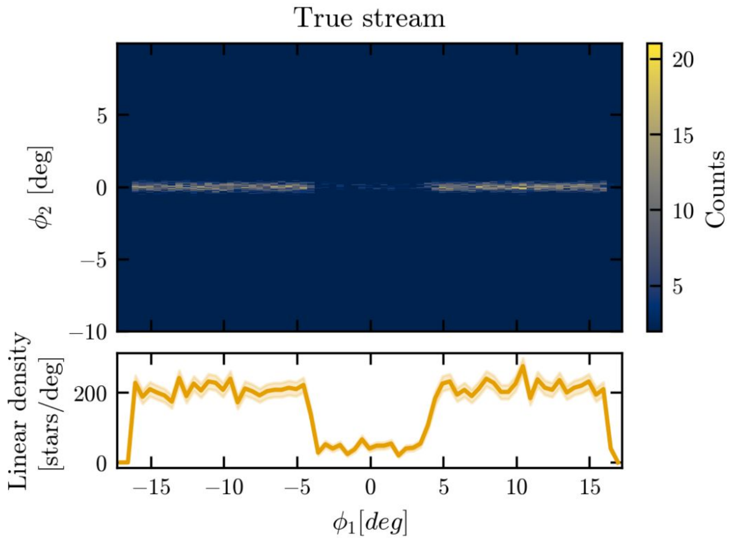
+ **Additional fixed stream parameters** (AAU length, isochrone, distance …)

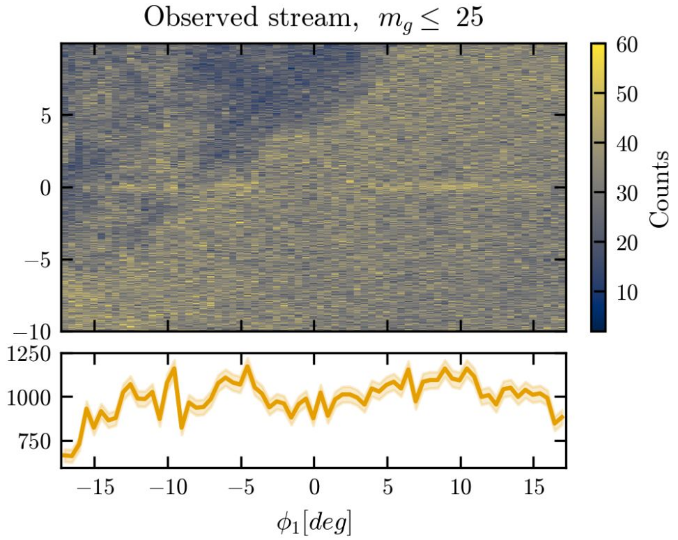


Convert into observed data like

Stream model → True stars → **StreamObs** (Co developer) → Observed stars

Mimic LSST observation (completeness, magnitudes and errors according to depth maps)
Also works for DES and Roman





Analysis pipeline

Fluctuation detection efficiency

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

Fluctuation detection efficiency

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

Also tested with Poisson fit

↓

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

↓

Fluctuation detection

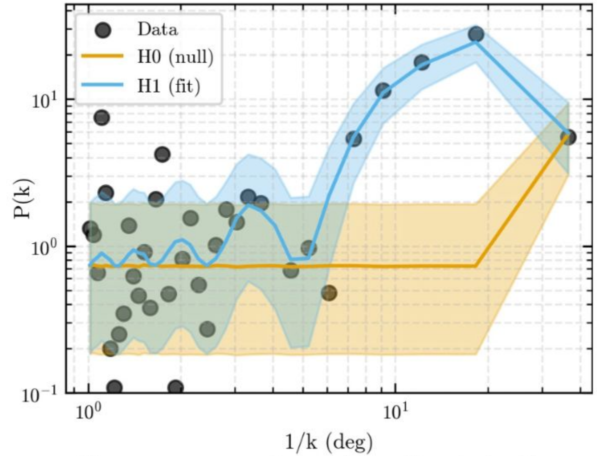


Fig: power spectrum hypothesis testing

Fluctuation detection efficiency

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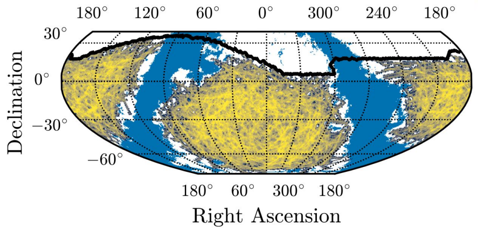

Mask high-dust regions to isolate systematics

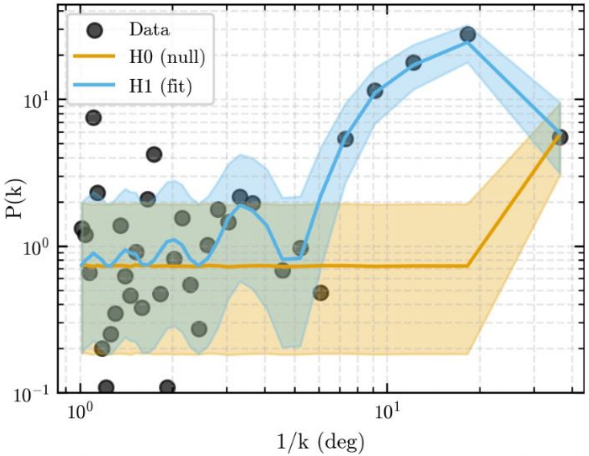

Fig: power spectrum hypothesis testing

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

Survey configurations

Gap detection efficiency can be estimated for **different survey scenarios**

Ideal survey

Uniform survey

Realistic survey

Survey configurations

Gap detection efficiency can be estimated for **different survey scenarios**

Ideal survey

Uniform survey

Perfect star galaxy **classification**

Realistic survey

Survey configurations

Gap detection efficiency can be estimated for **different survey scenarios**

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Perfect star galaxy **classification**

No background

Realistic survey

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Depth variations + **Mitigation** strategy (magnitude cut)

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Observed star galaxy **classification**

Survey configurations

Gap detection efficiency can be estimated for **different survey scenarios**

Ideal survey

Uniform survey

Perfect star galaxy **classification**

No background

Realistic survey

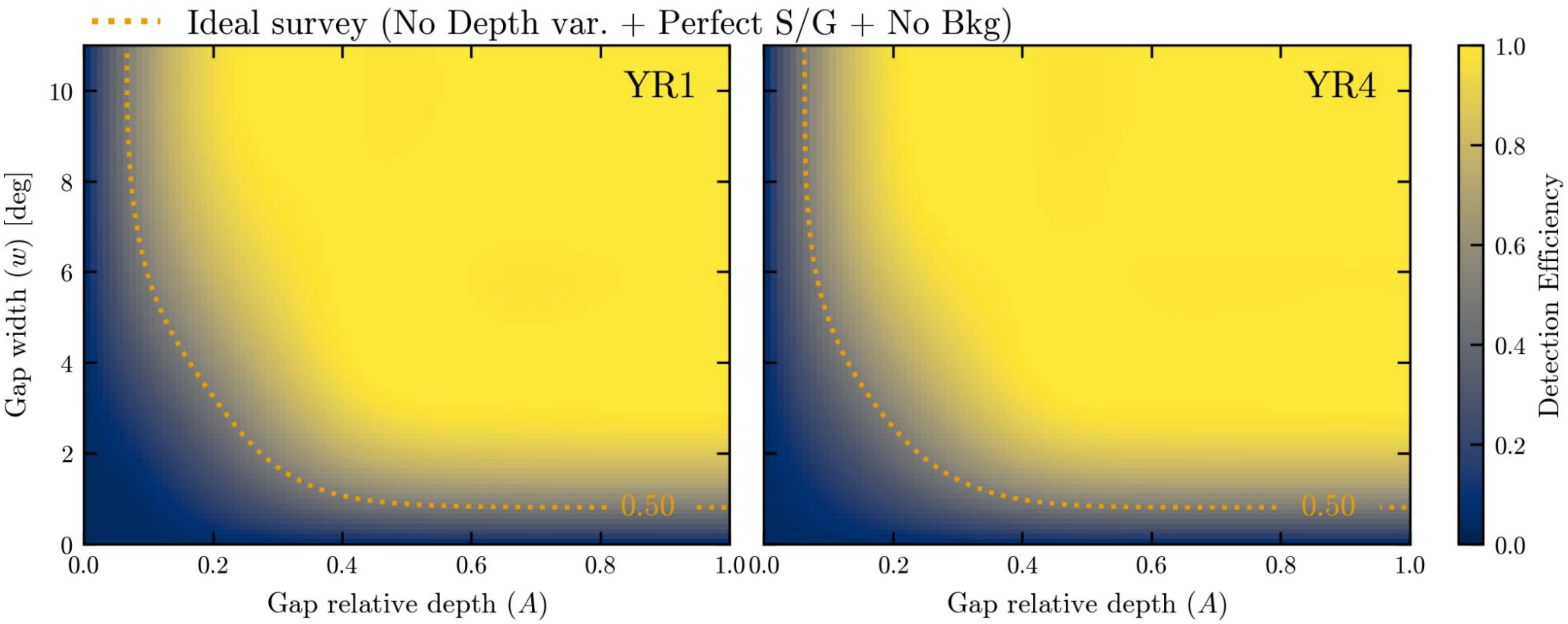
Depth variations + **Mitigation** strategy (magnitude cut)

Observed star galaxy **classification**

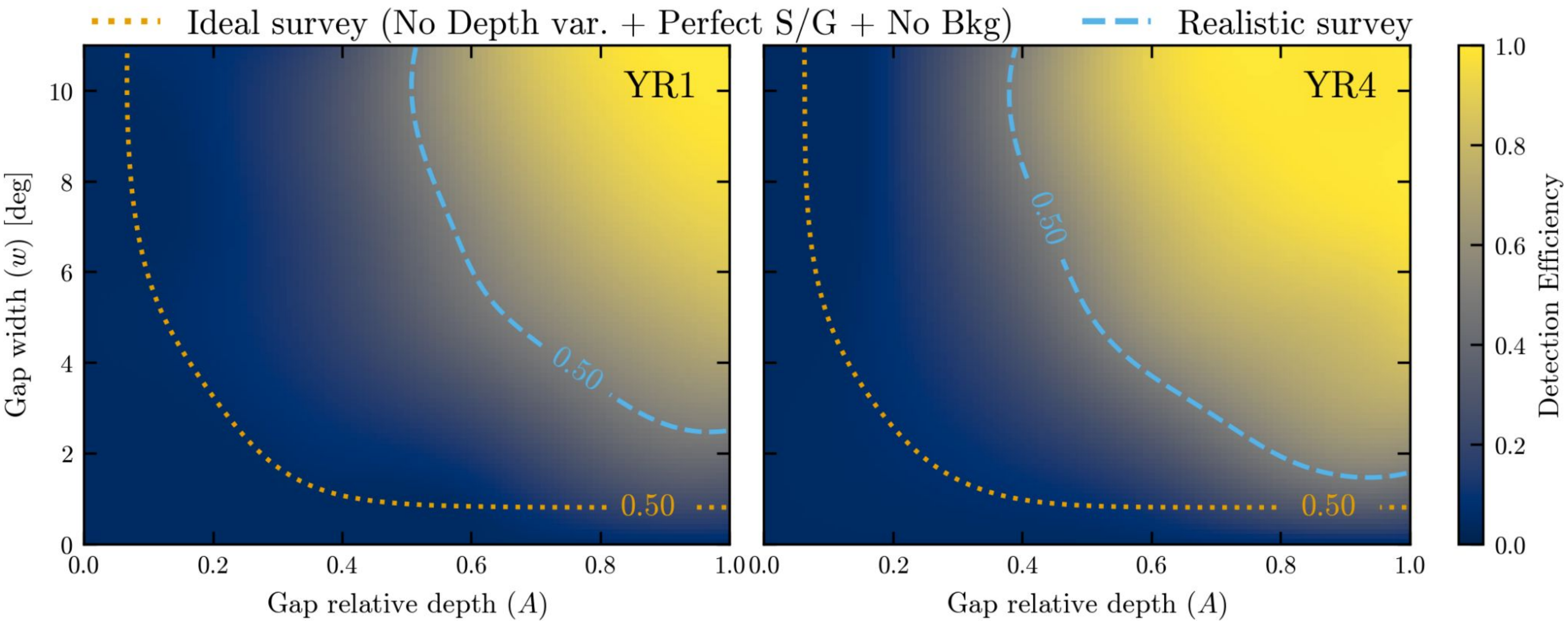
Background (galaxies and non-member stars)

Results

Gap detection efficiencies



Gap detection efficiencies



Major impact from systematics: gaps must be 5 times deeper

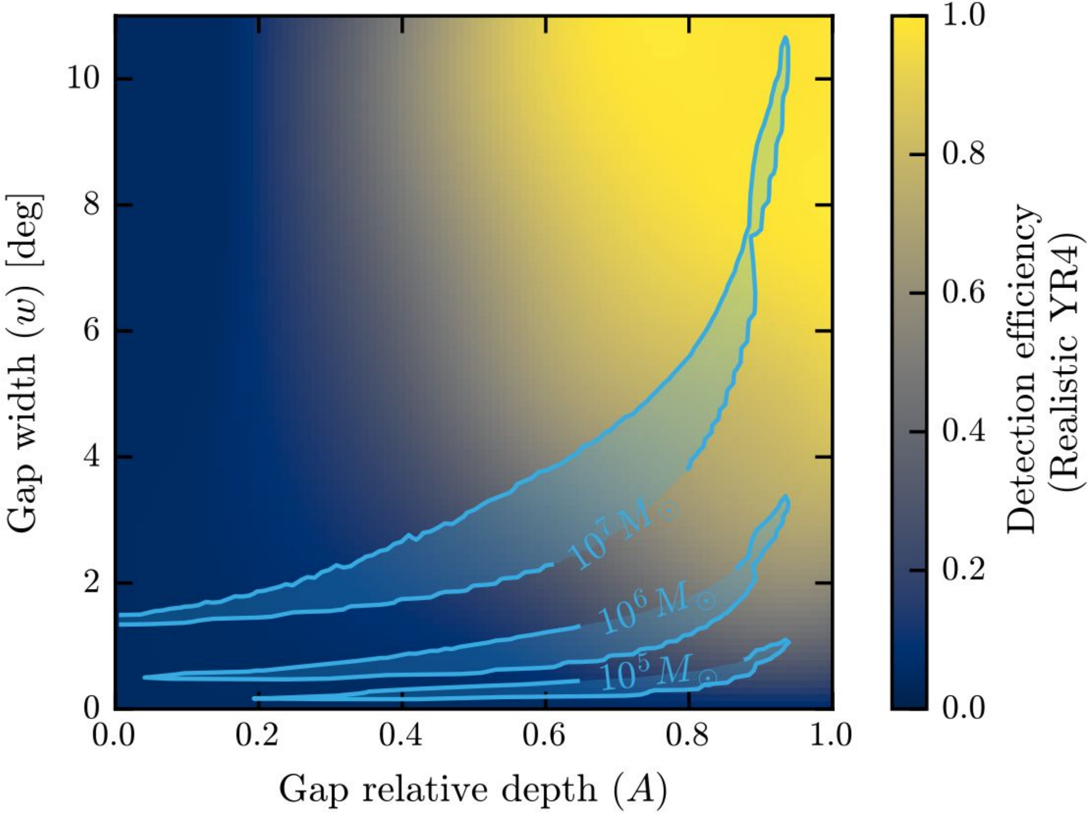
Smallest detectable subhalo

Gap (A,w) detectability

Use analytical formulae to **convert gap properties to subhalo mass**
(Erkal 2016)

P(A,w|Msub)

Combine with gap **detection efficiency**



Smallest detectable subhalo

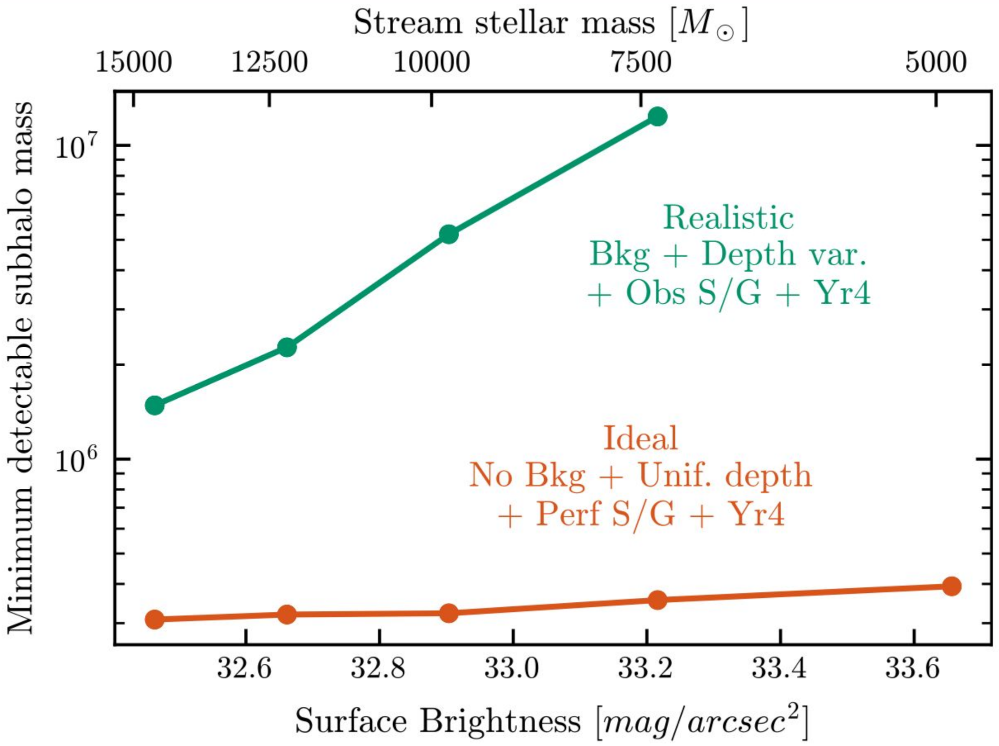
Gap (A,w) detectability

Use analytical formulae to **convert gap properties to subhalo mass**
(*Erkal 2016*)

P(A,w|Msub)

Combine with gap **detection efficiency**

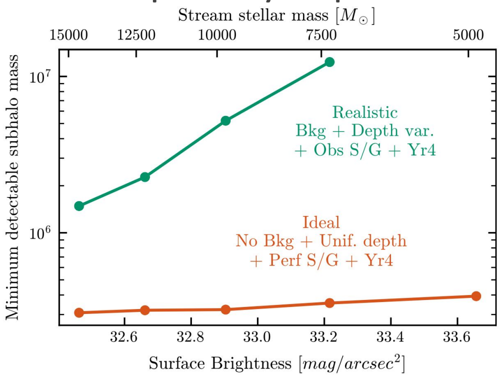
Estimate the **minimal detectable subhalo mass**

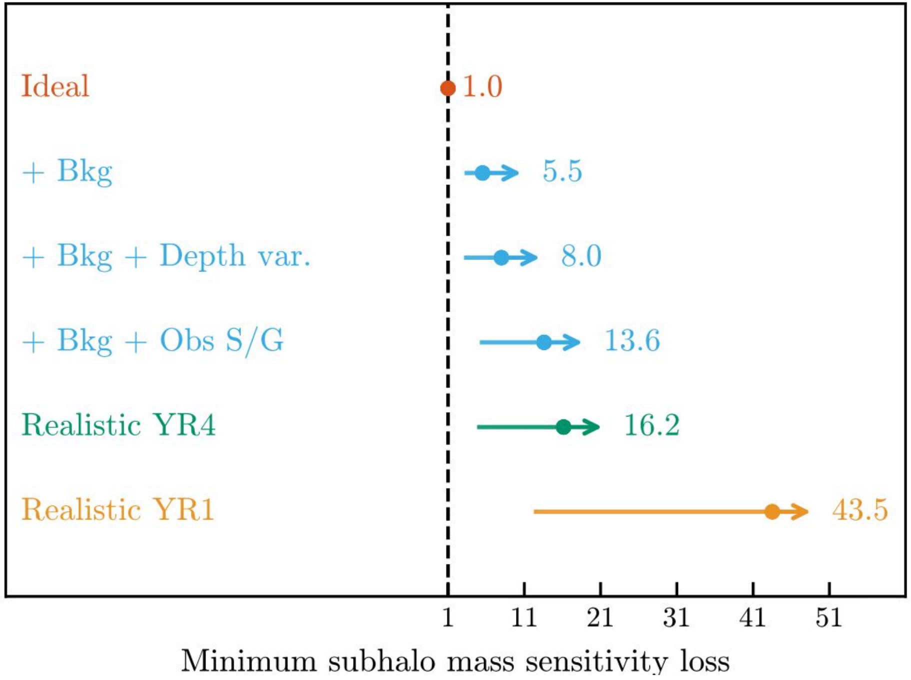


Detection of **subhalos** down to $\mathbf{10^7 M_\odot}$ with an AAU-type stream using only gaps

Impact of systematics on subhalo mass measurement

Compute their **ratio**
to quantify impact





- **Background** impact: subhalo detectable only if x5.5 heavier
- **Systematics**: x2.9 degradation
- **Release** Yr1: x2.7 degradation compared to Yr4

Impact of systematics on subhalo mass measurement

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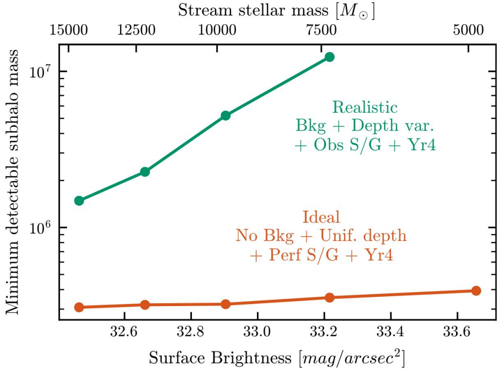

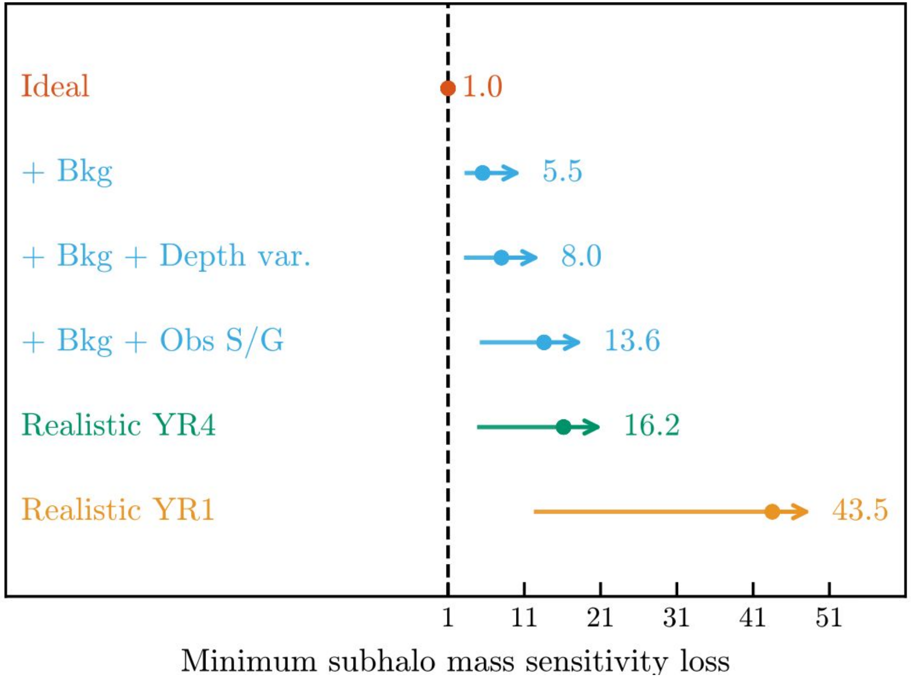

- **Background** impact: subhalo detectable only if x5.5 heavier
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- **Release** Yr1: x2.7 degradation compared to Yr4

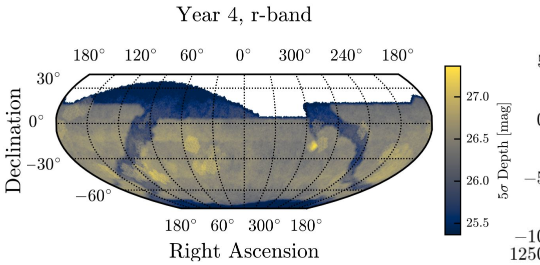
A **loss** of sensitivity by **an order of magnitude** due solely to **observational effects**

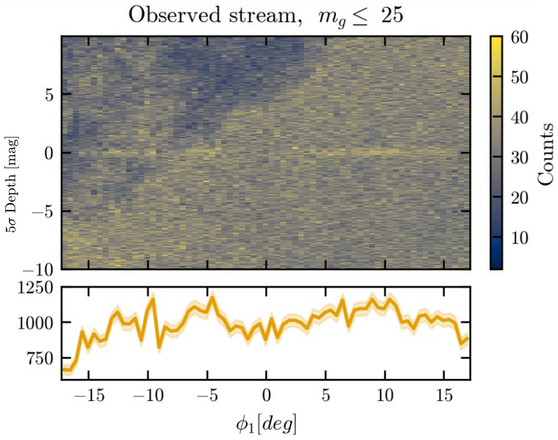
Conclusion

Conclusion

Developed:

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





Results:

- Systematics and background can **degrade minimal subhalo mass** by **an order of magnitude**
- **Background** and **systematics** modeling are essential
- **Improved star–galaxy separation** is critical

Currently in DESC-wide review

Soon on Arxiv

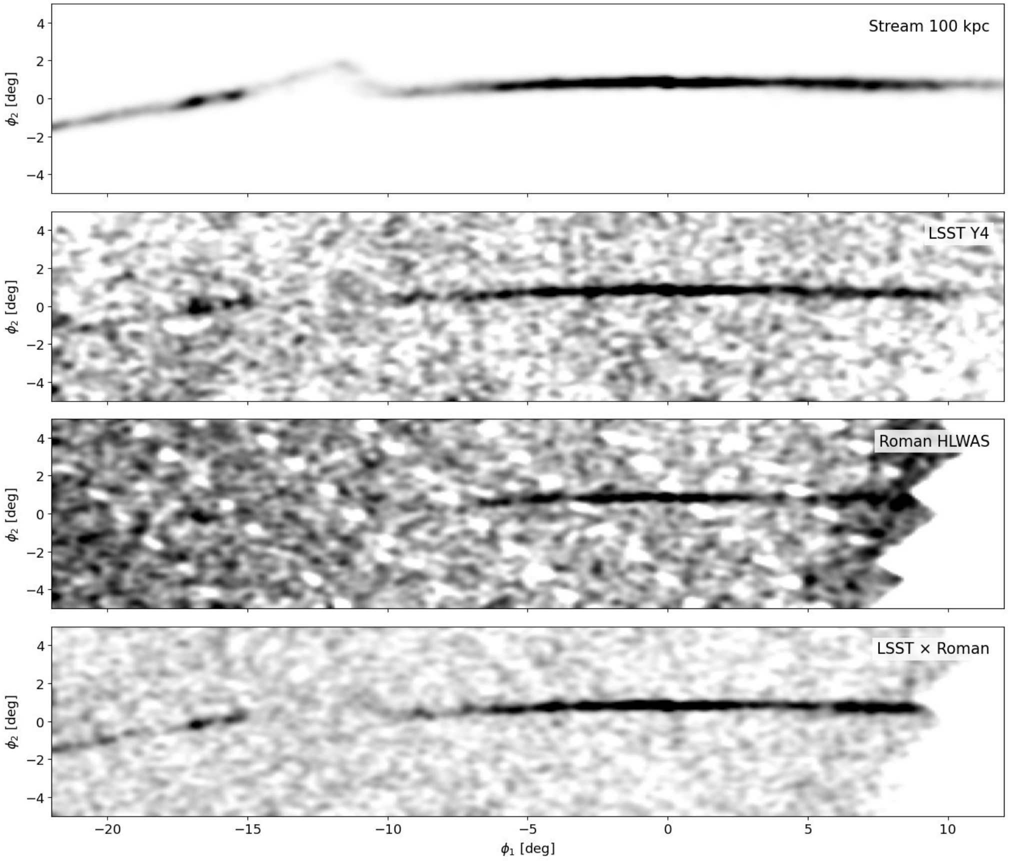
Looking for a post-doc for fall 2027

Outlooks

Study survey combination: Roman x LSST

DESC project (518) led by Peter Ferguson

Inject dynamical simulations using **StreamObs** in **LSSTxRoman** surveys to study **stellar streams observability**



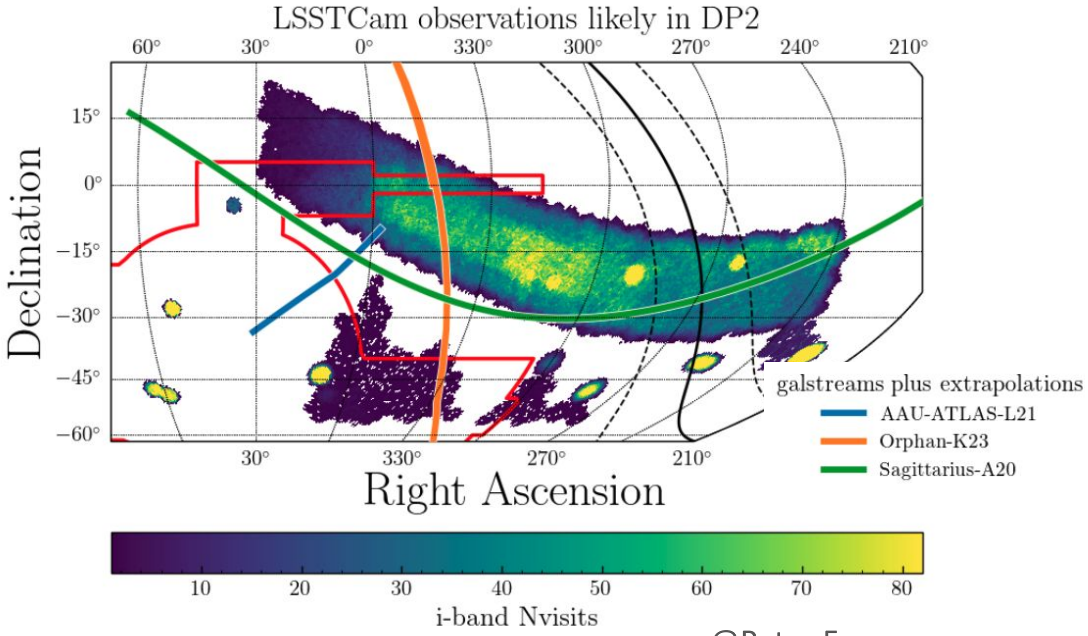
DP2

Streams detectability in real Rubin data

Can we observe them? If not, what are the constraints on their distance?

Characterize / improve **stars sample**

- **Selection** functions using SSI
- Improved **stars/galaxy separation** (Théotime Hallouin)
- Euclid/HST **matching** (Kayleigh Excell)
- **Dwarf galaxies**' detection (Aashay Pai)



@Peter Ferguson

Appendix

Discussion

So far in the literature (Drlica-Wagner 2019, Lu 2025):

- No systematics ← We find similar minimal detectable subhalo mass for ideal case
- Use any stars down to the magnitude limit ← We consider selection functions, mitigation strategies, background, stream detection analysis

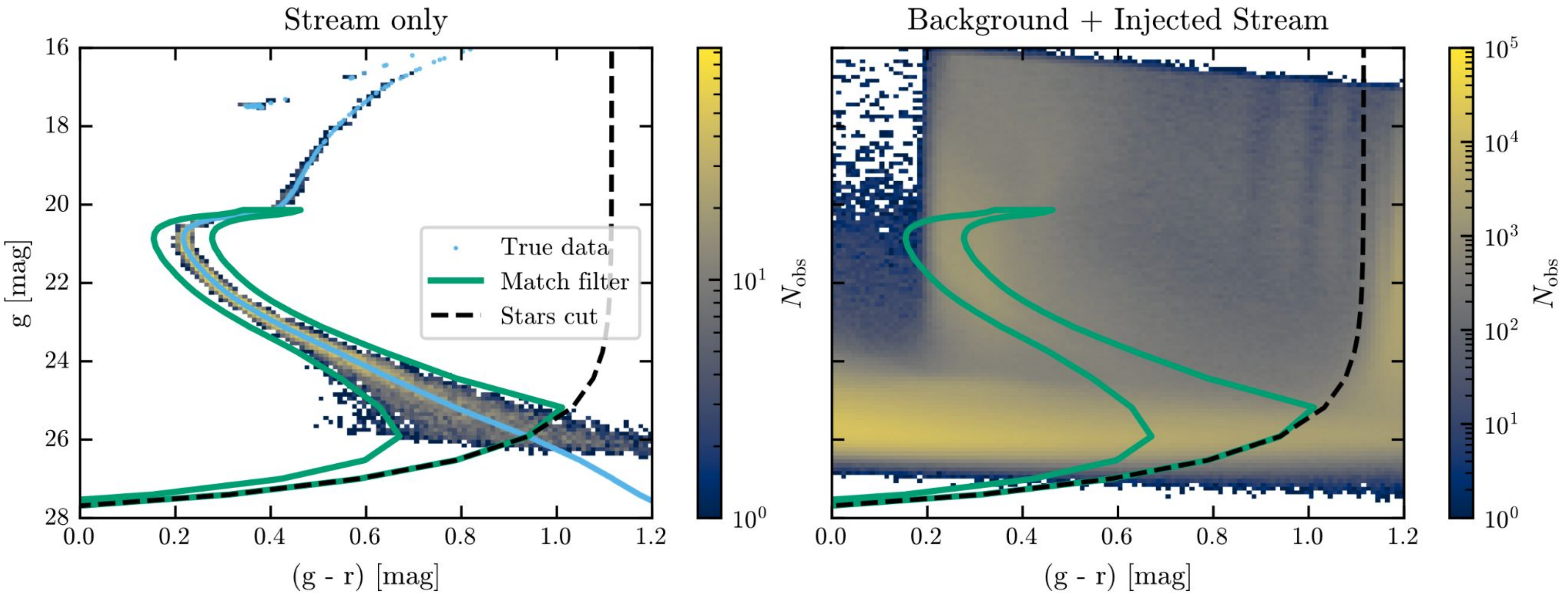
Also tested

- Stream not homogeneous in reality => only 1% change with density gradient
- Gap model used has a negligible impact
- Similar results doing fitting analysis in real space rather than power spectrum

Extensions

- Inject directly dynamical stream simulations
- Include 2D information, kinematic observables

Other paper results



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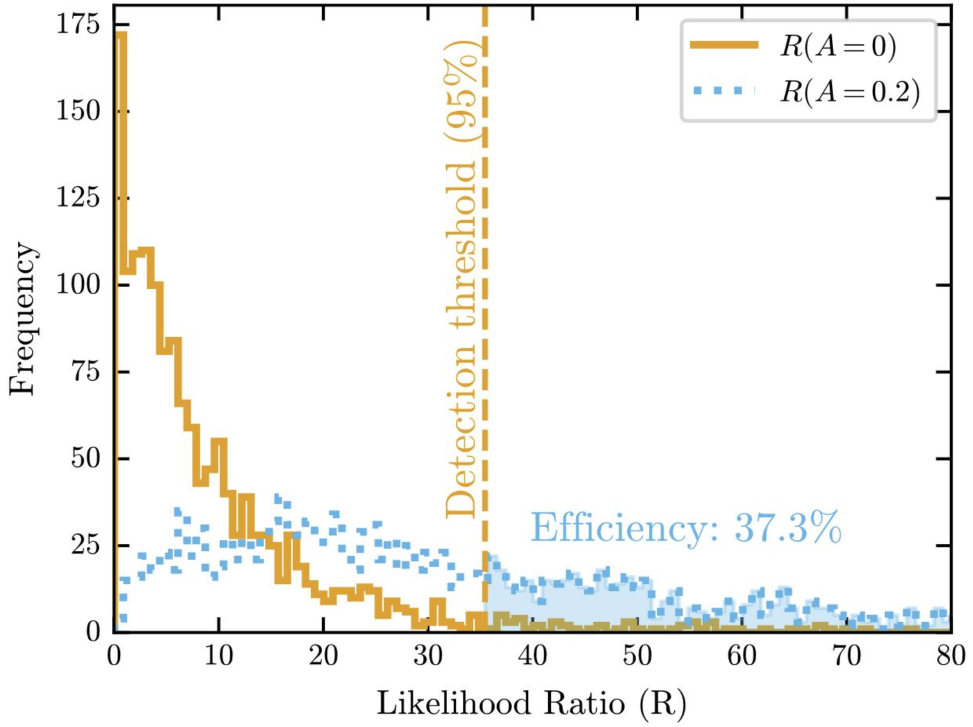
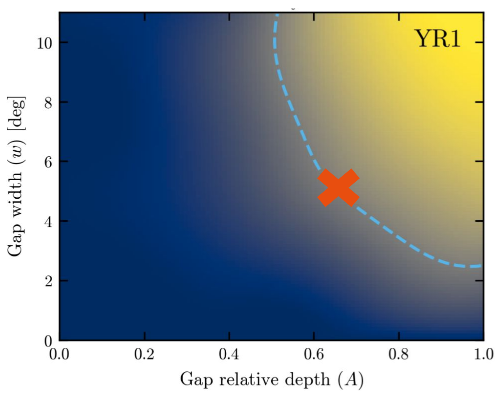
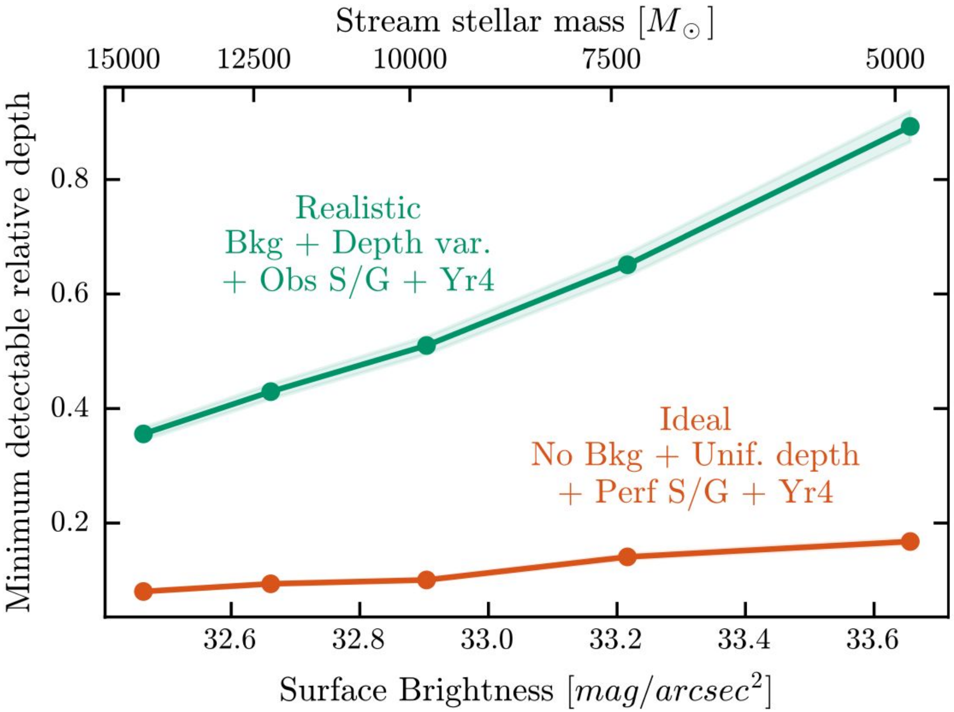


Smallest gap detectable with LSST

Find smallest depth with w=5deg,

such as efficiency > 0.5



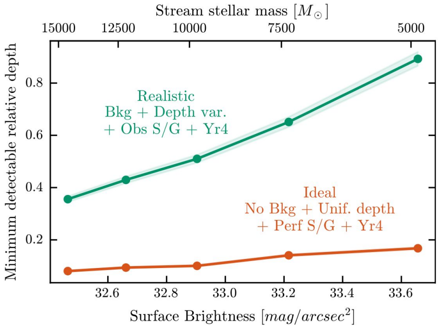


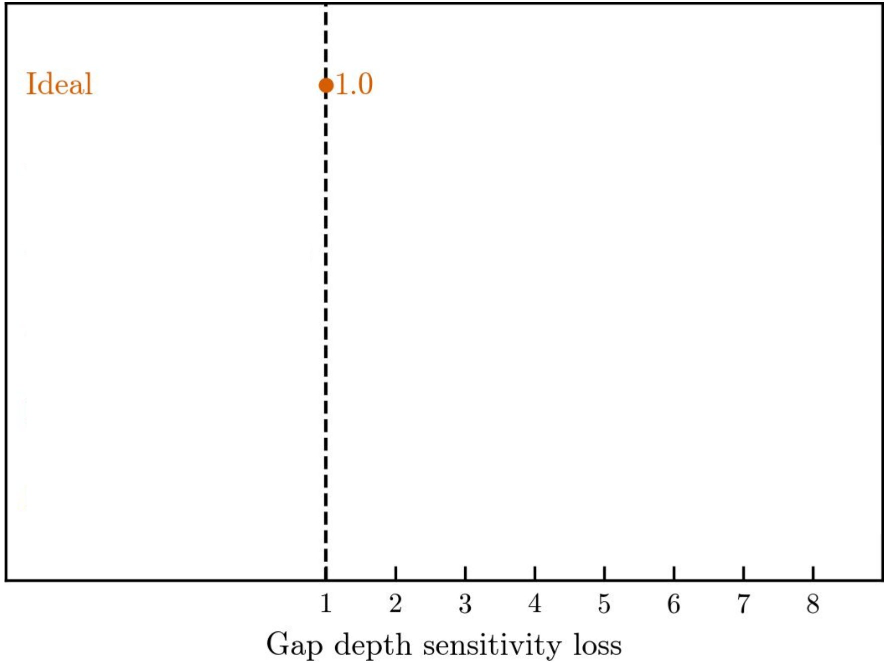
- **Decrease** with the stream stellar mass
- Quantify impact from **survey depth variations**, stars-galaxy **separation** and **background**

Impact of systematics on gap measurements

Compute their **ratio**

to quantify impact





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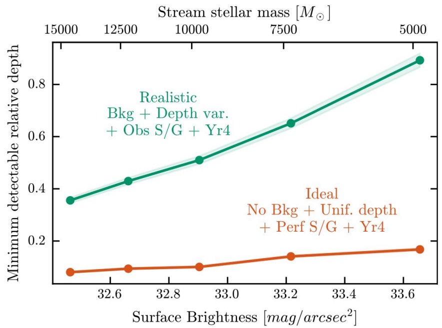

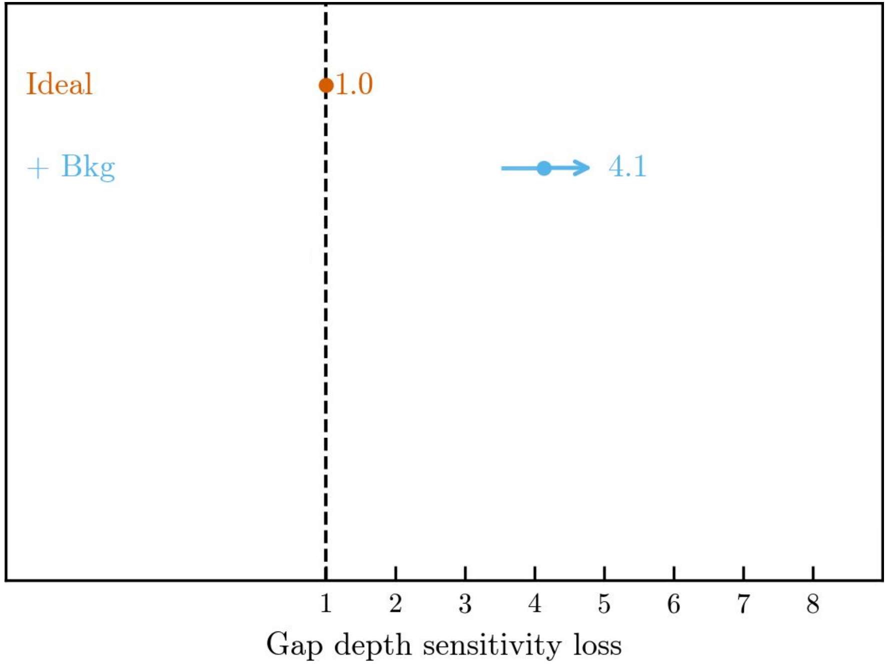

- Important **background** impact: gaps detectable only if 4.1× deeper

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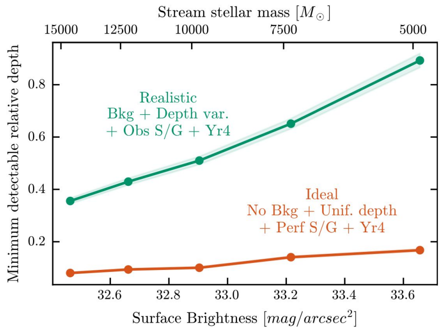

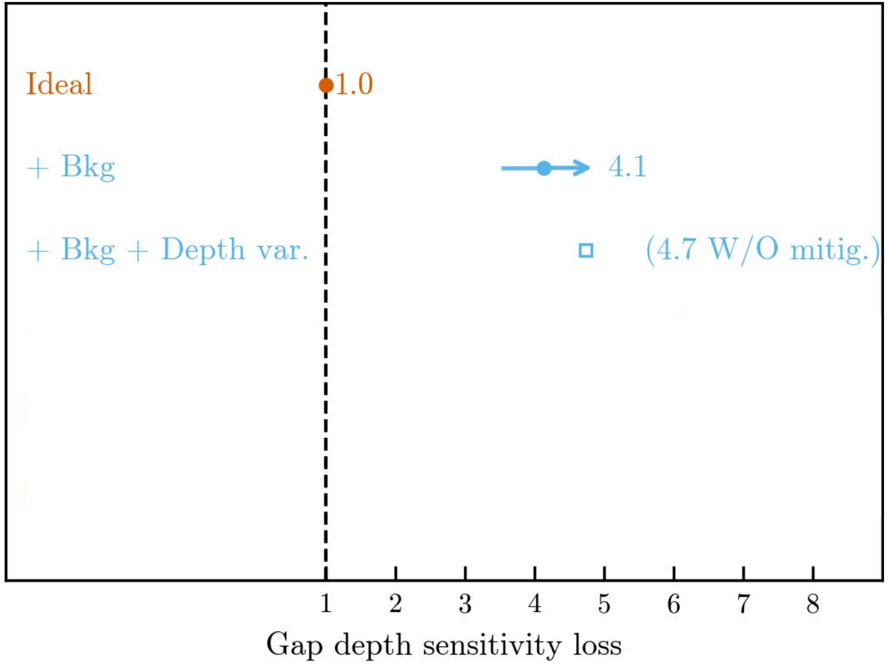

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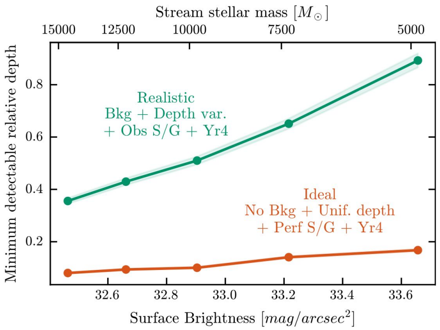

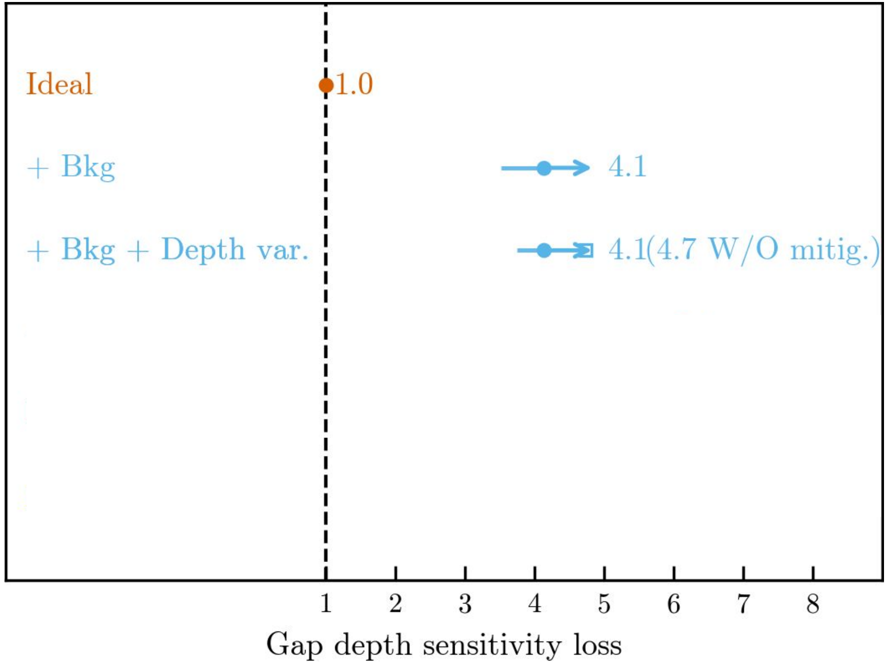

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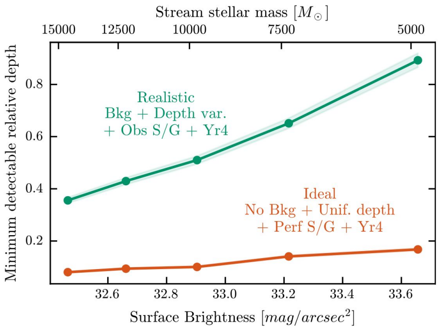
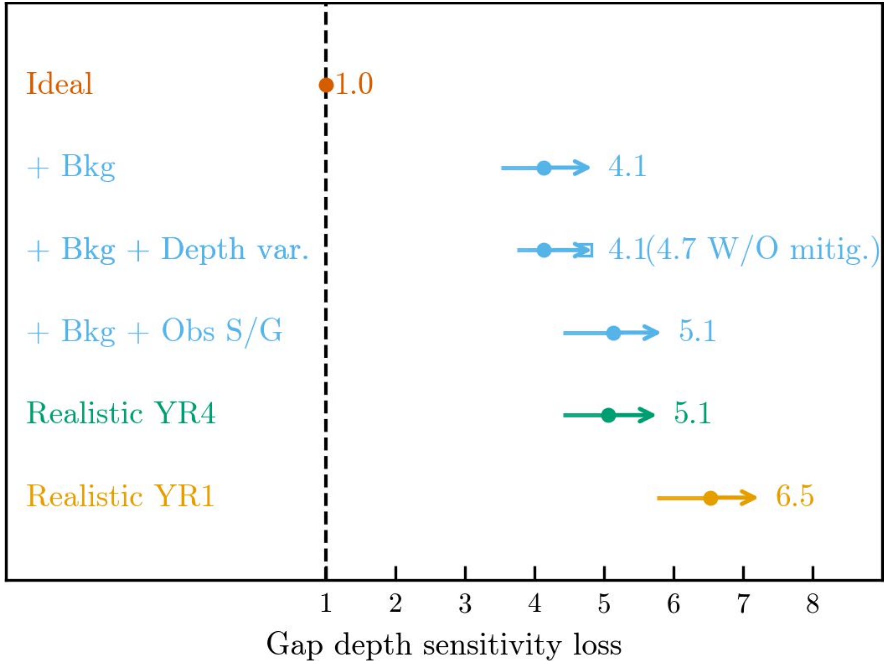
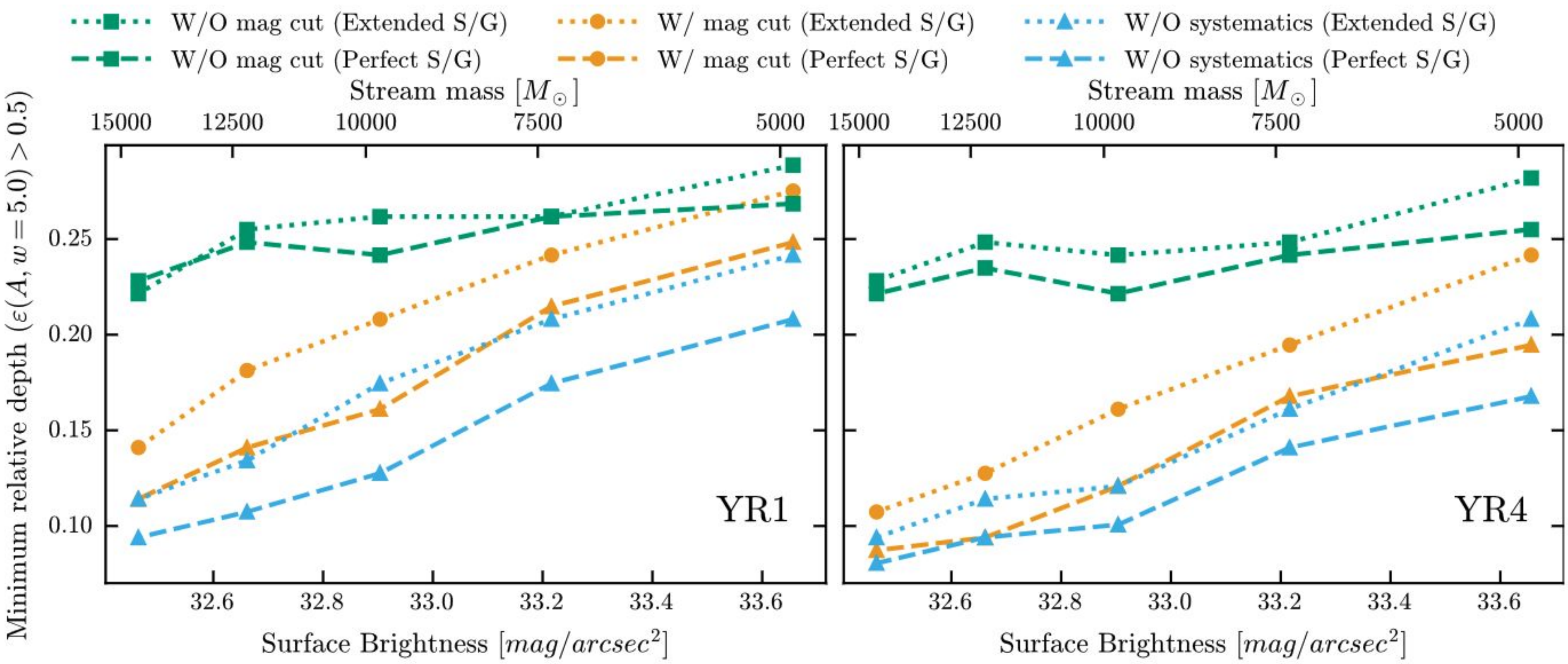




- Important **background** impact: gaps detectable only if 4.1× deeper
- **Systematics**: 23% degradation
- **Release** Yr1: 30% degradation compared to Yr4

Other paper results



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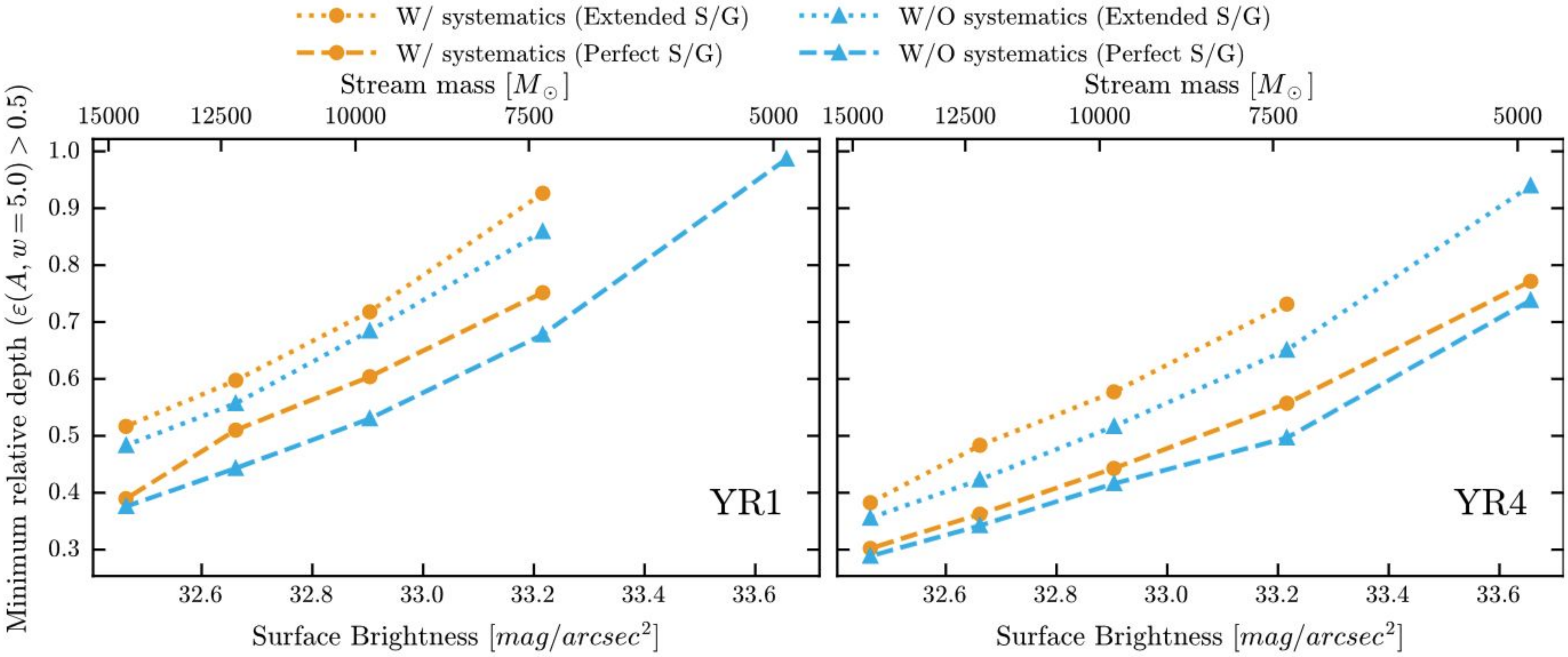
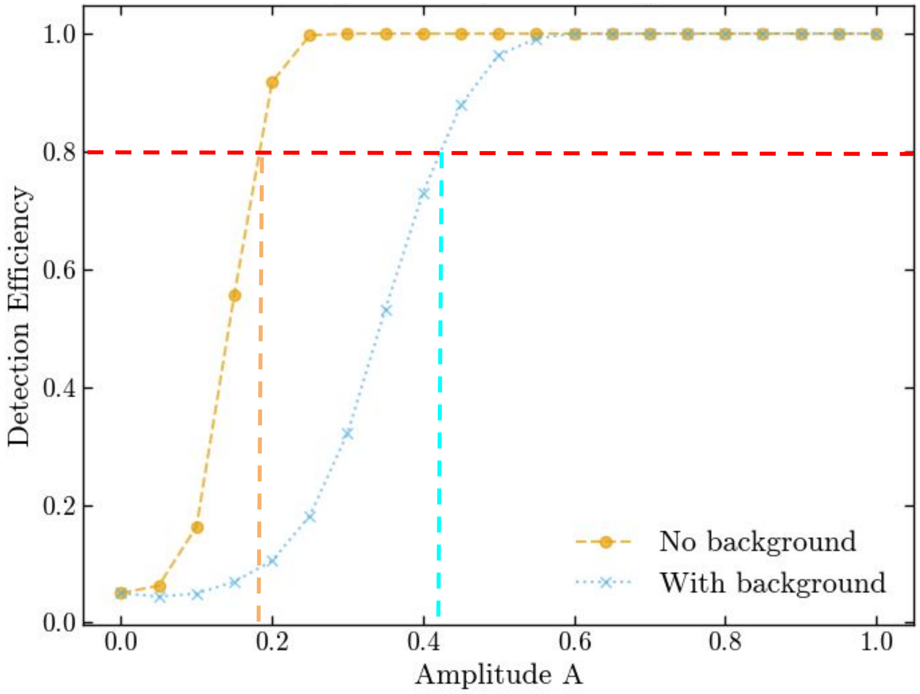


Find the smallest detectable amplitude



- Increases with A
- Smaller with background

Find the smallest detectable fluctuation:

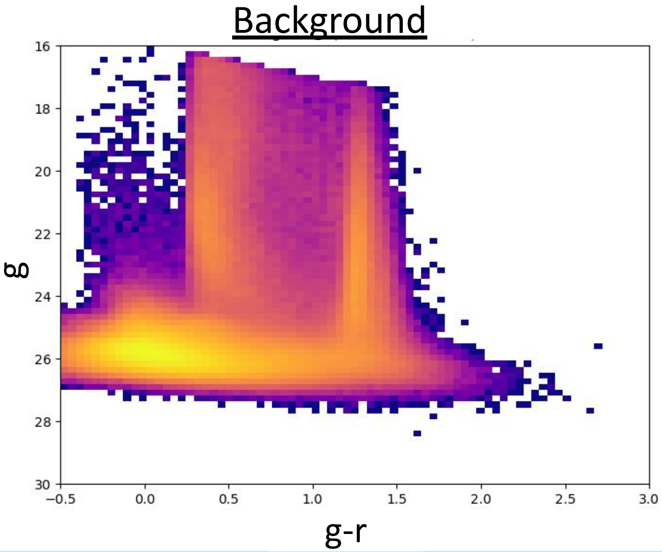
- Choose an arbitrary efficiency **threshold** (e.g. 0.8)
- Infer the corresponding **detectable amplitude**

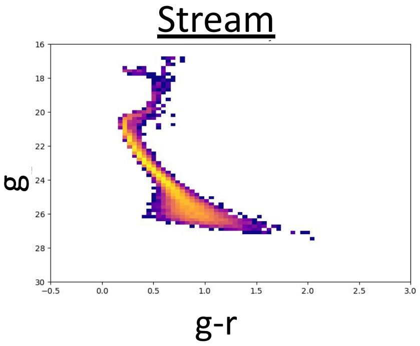
Adding background

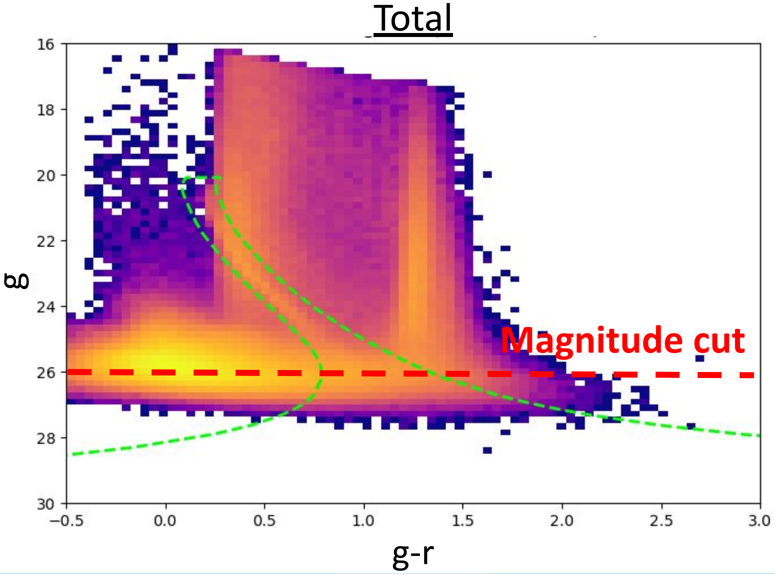
Background for stellar streams:

- **○** Non-member **stars**
- **○** **Galaxies** identified as stars

Estimate density and color magnitude distribution → Add stream's stars → Realistic **match filter** selection and mag **cut** to maximize signal-to-noise ratio

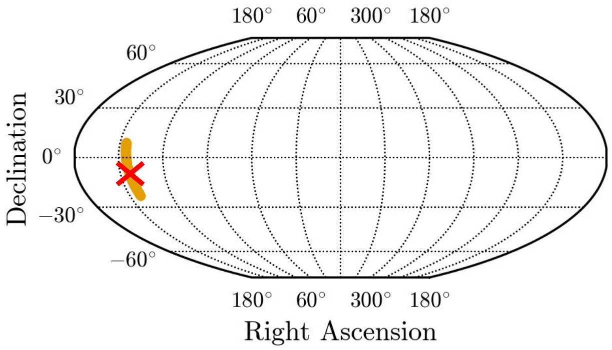




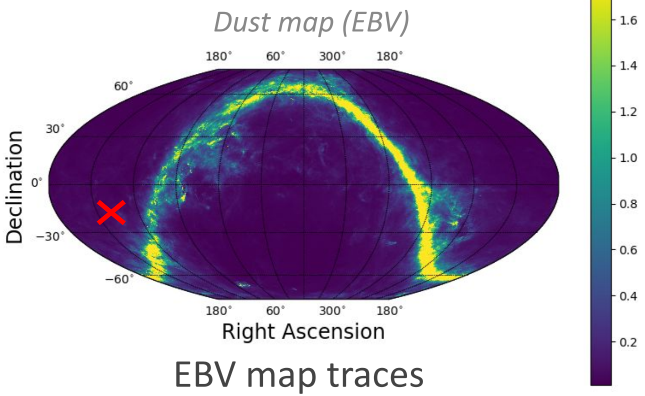


Conversion to observed data-like: magnitude limits

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



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

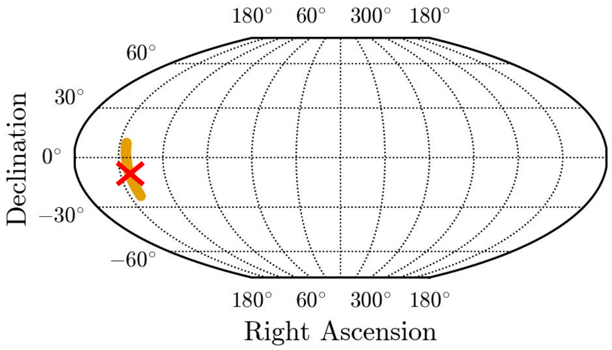


EBV map traces
dust distribution

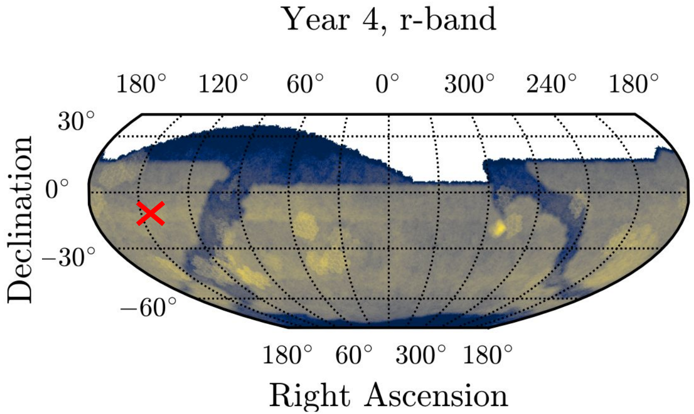
Apparent magnitude

Conversion to observed data-like: magnitude limits

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



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



Built from [rubin_sim]

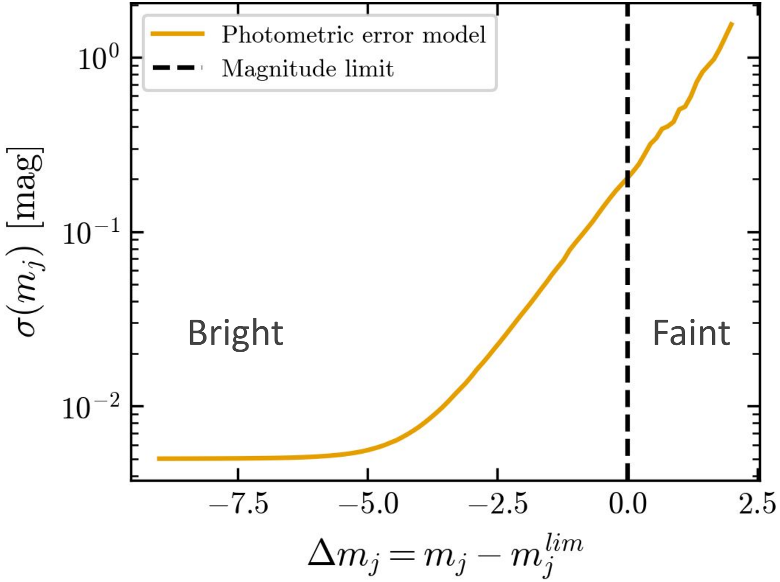
Delta magnitude

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

Conversion to observed data-like: magnitude and errors

Errors scale with distance to magnitude limits
Delta magnitude

Assign photometric errors



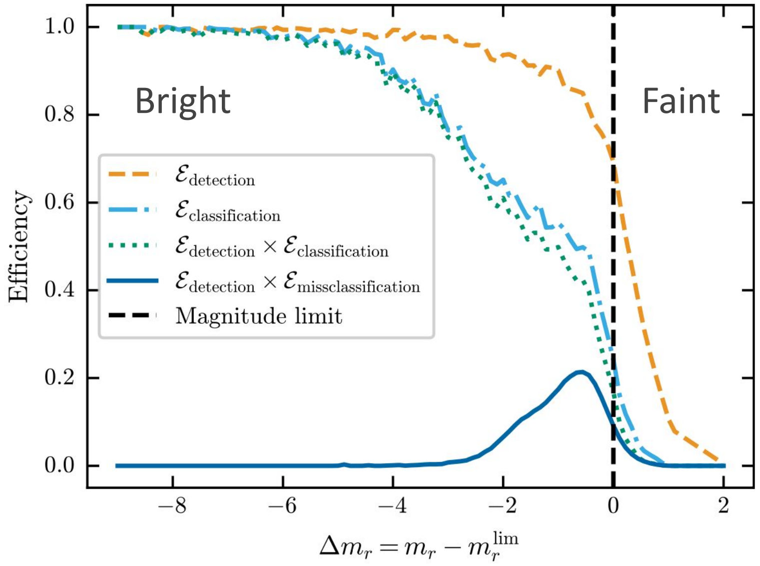
Estimated using LSST simulations
([Kabelo Tsiane et al.](#))

Sample observed magnitudes
(gaussian in flux)

Conversion to observed data-like: detection and classification

Stars detection decreases near magnitude limit **Delta magnitude**

Estimated completeness



Probabilistic approach to rule if a star is observed or not

Estimated using LSST simulations
(Similar to Kabelo Tsiane et al.)

Conversion to observed data-like: pipeline

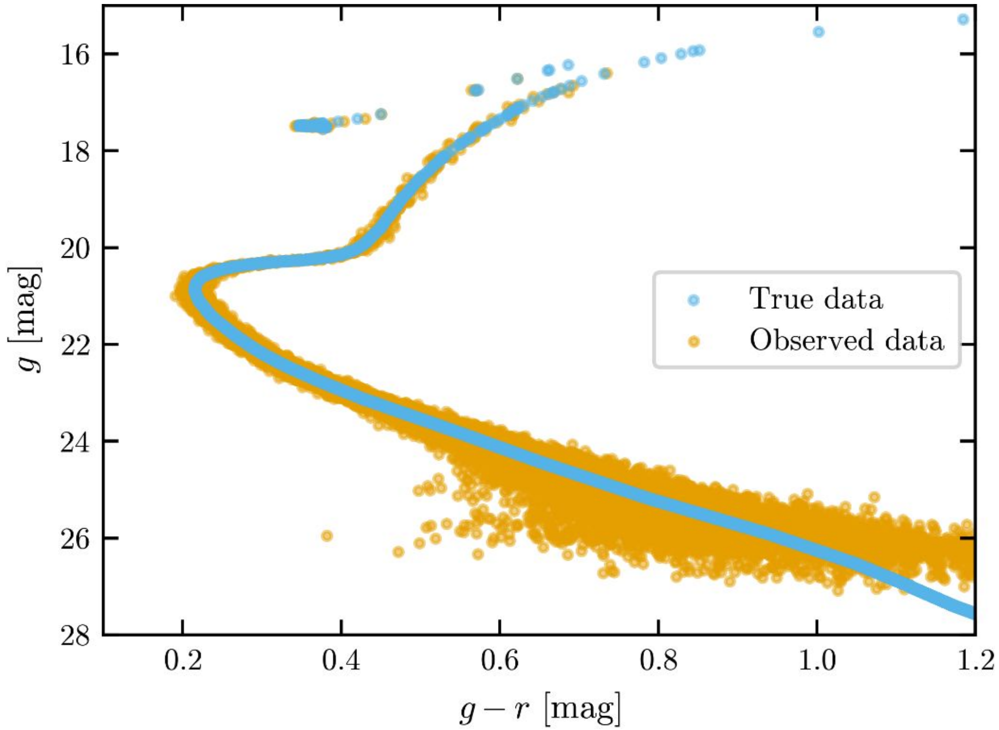
(ra, dec), apparent magnitudes

↓

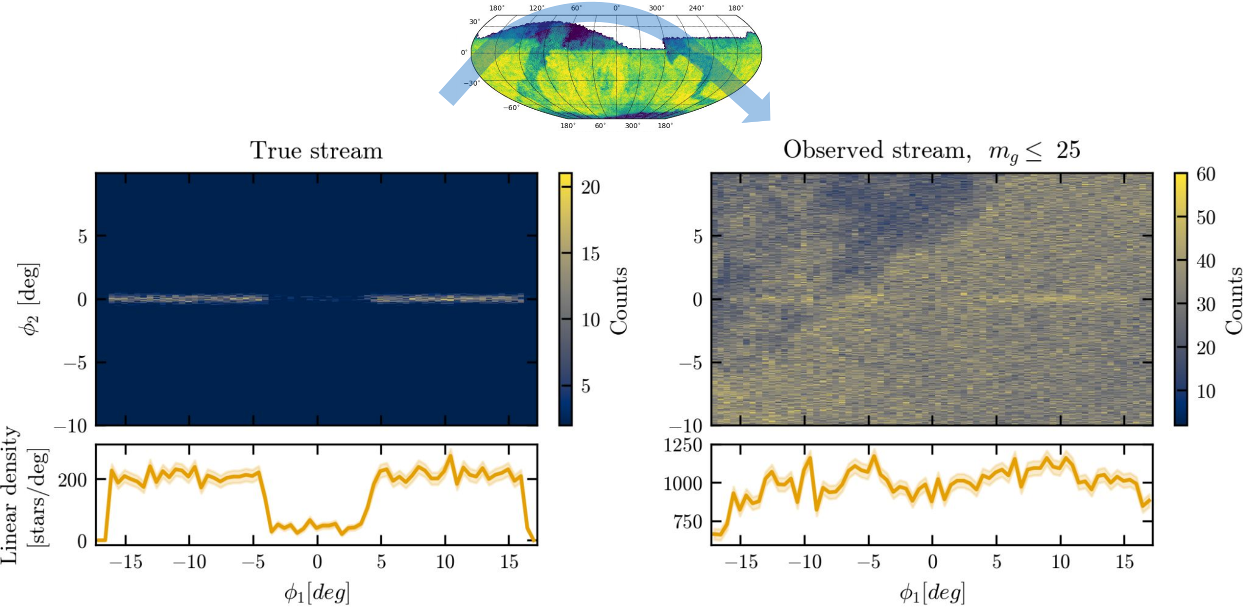
Injection pipeline

↓

Observed magnitudes + errors, detection + classification boolean



Conversion to observed data-like: pipeline



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