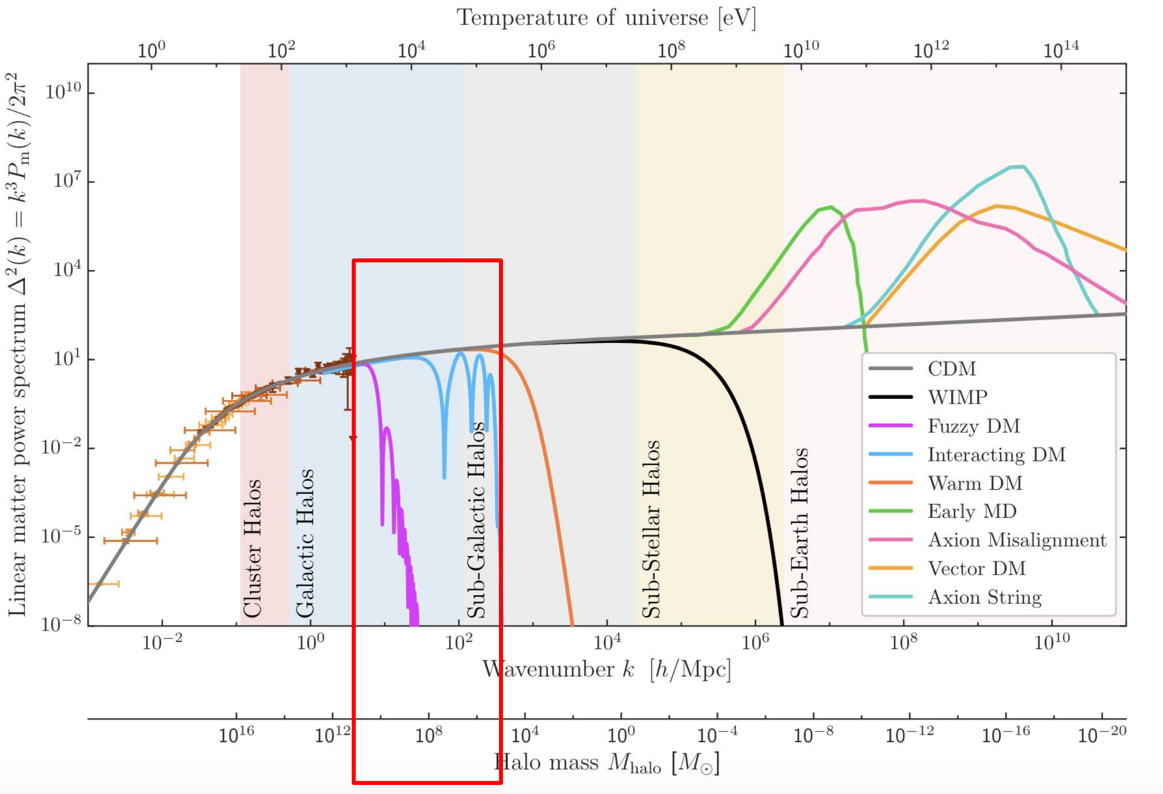
DETECTABILITY OF DARK MATTER SUBHALO IMPACTS IN MILKY WAY STELLAR STREAMS

University of California San Diego
[2502.07781] Junyang Lu, Tongyan Lin, Mukul Sholapurkar, Ana Bonaca

Background

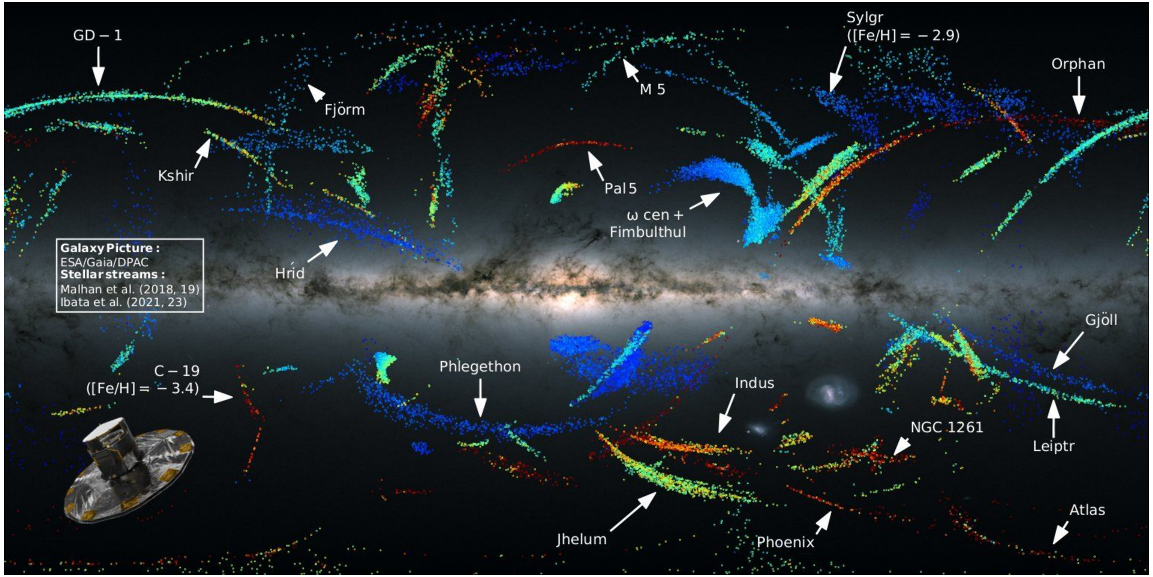
- ΛCDM agrees with measurements at large scales
- We lack reliable measurements at small scales
- Small scales are important for probing the nature of dark matters



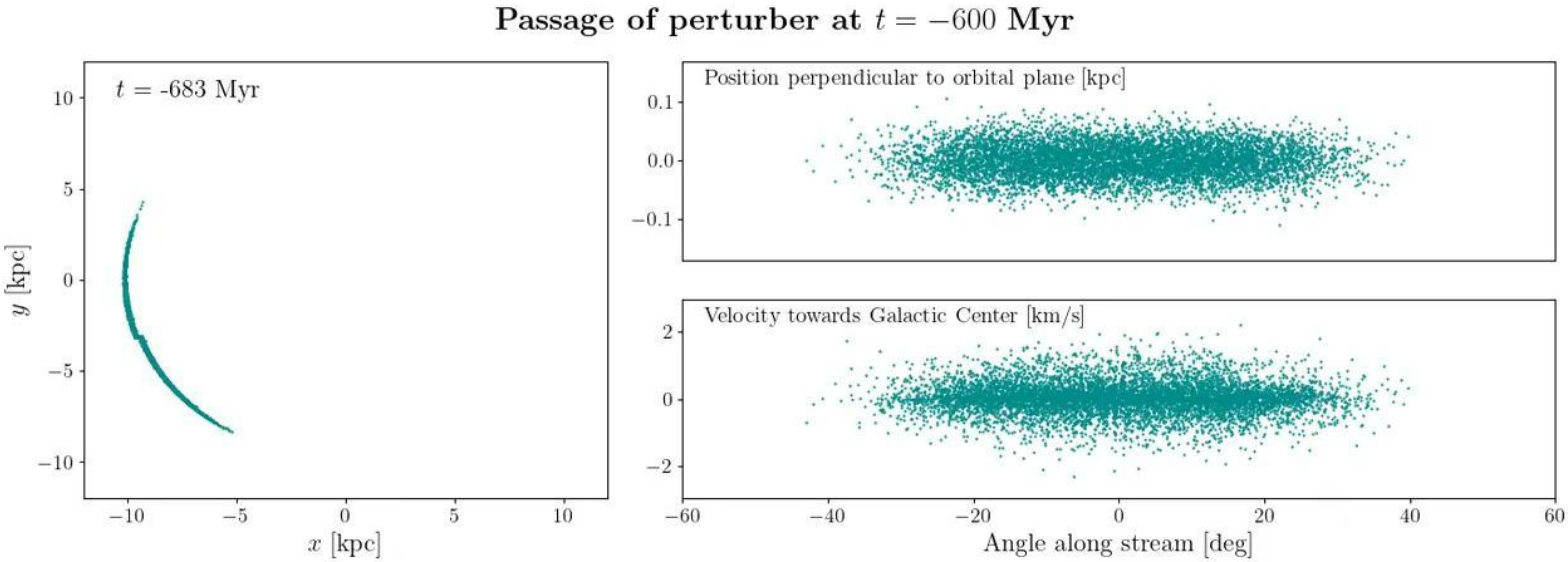
Snowmass 2021 [2203.07354]

Stellar streams

- Tidal debris of globular clusters or dwarf galaxies
- Thin and dynamically cold structures
- Sensitive to dark matter subhalo down to 10^5 solar mass



A DM subhalo passes by a stellar stream

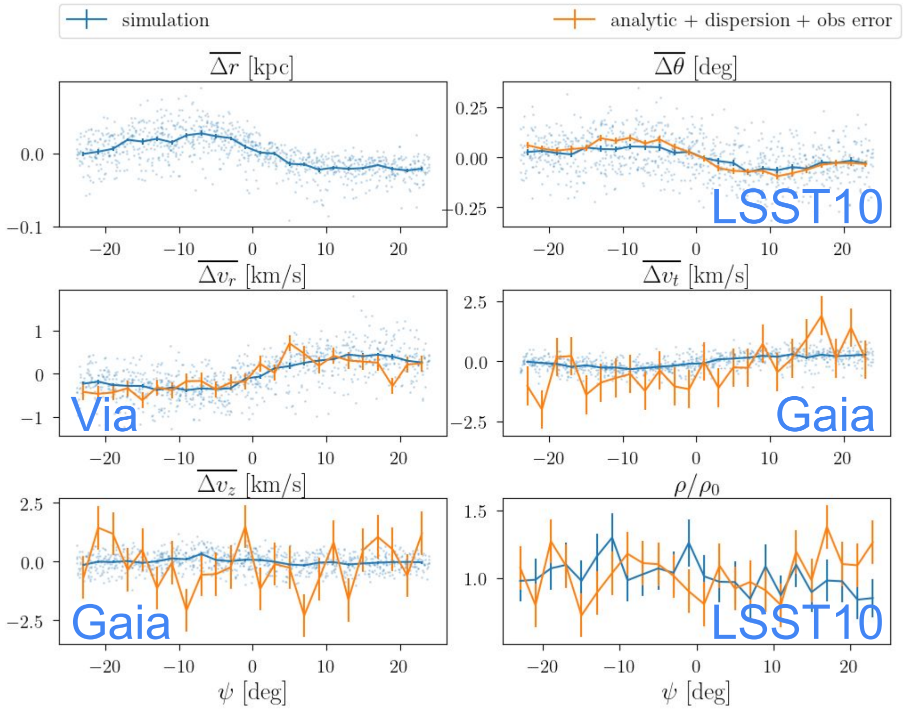


Motivation

- With the explosion in the number of known Milky Way streams
  - O(100) discovered
  - Hundreds more to be discovered
- Quickly estimate detectability of a stellar stream from its properties
  - Stream width
  - Stream distance
  - Stream density
  - Stream length
- Select the most promising streams for further study

Quickly generate simulated impact data

- Mean value from analytic model
- Noises
  - Internal Dispersion
  - Observational errors
    - Gaia
    - DESI + Gaia
    - Via + Gaia + LSST
    - Via + Gaia + LSST10



[1507.05625] Denis Erkal, Vasily Belokurov

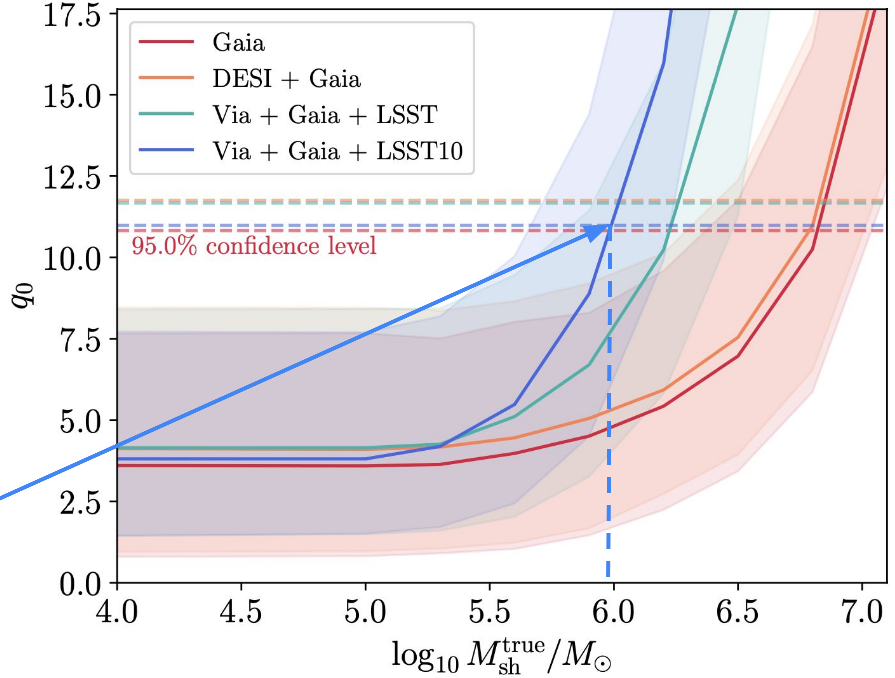
Test statistics to probe minimum detectable subhalo mass

$$q_0 = \begin{cases} 2\ln \frac{L(\hat{M}_{\rm sh},\ \hat{\boldsymbol{\theta}})}{L(0)} & \hat{M}_{\rm sh} \geq 0 \\ 0 & \hat{M}_{\rm sh} < 0 \end{cases}$$

"Likelihood ratio for best-fit impact vs no impact"

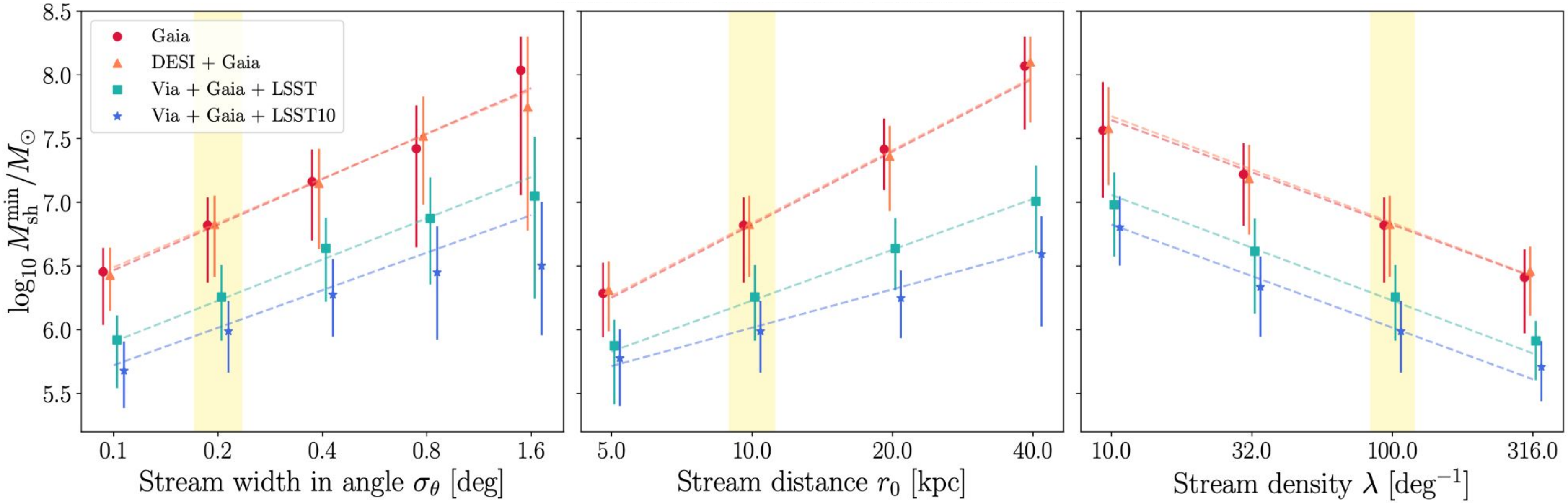
Intersection corresponds to minimum detectable subhalo mass

GD-1 like stream



[1007.1727] Glen Cowan, Kyle Cranmer, Eilam Gross, Ofer Vitells

Dependence of minimum detectable subhalo mass on stream properties



$$M_{\rm sh}^{\rm min} = \left(\frac{\sigma_\theta}{\rm deg}\right)^{c_{\sigma_\theta}} \left(\frac{r_0}{\rm kpc}\right)^{c_{r_0}} \left(\frac{\lambda}{\rm deg^{-1}}\right)^{c_\lambda} 10^{c_{\rm base}}\ {\rm M}_\odot$$

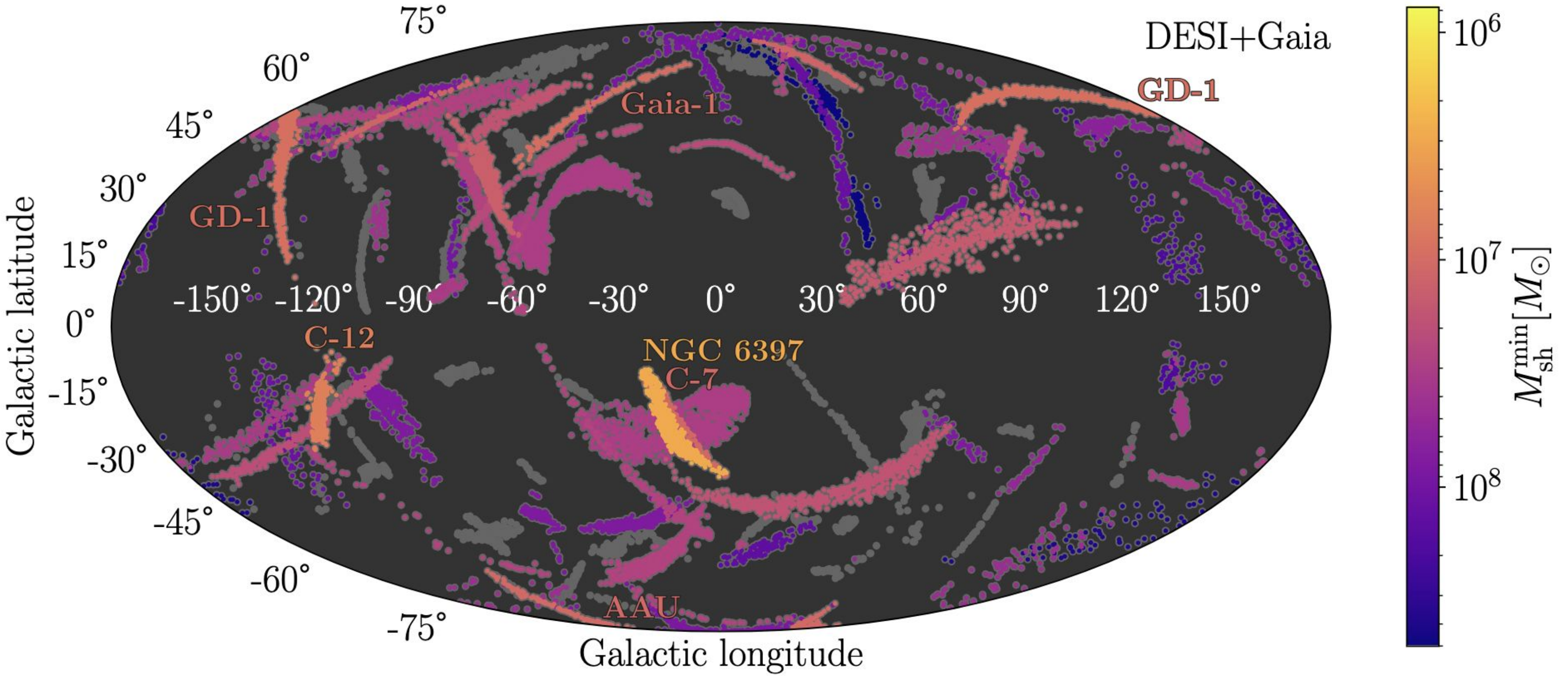
Stream ranking

- Using stream catalog from Bonaca and Price Whelan with stellar mass reported, length > 20 deg, #observable_star > 1 per 2 deg bin under Gaia

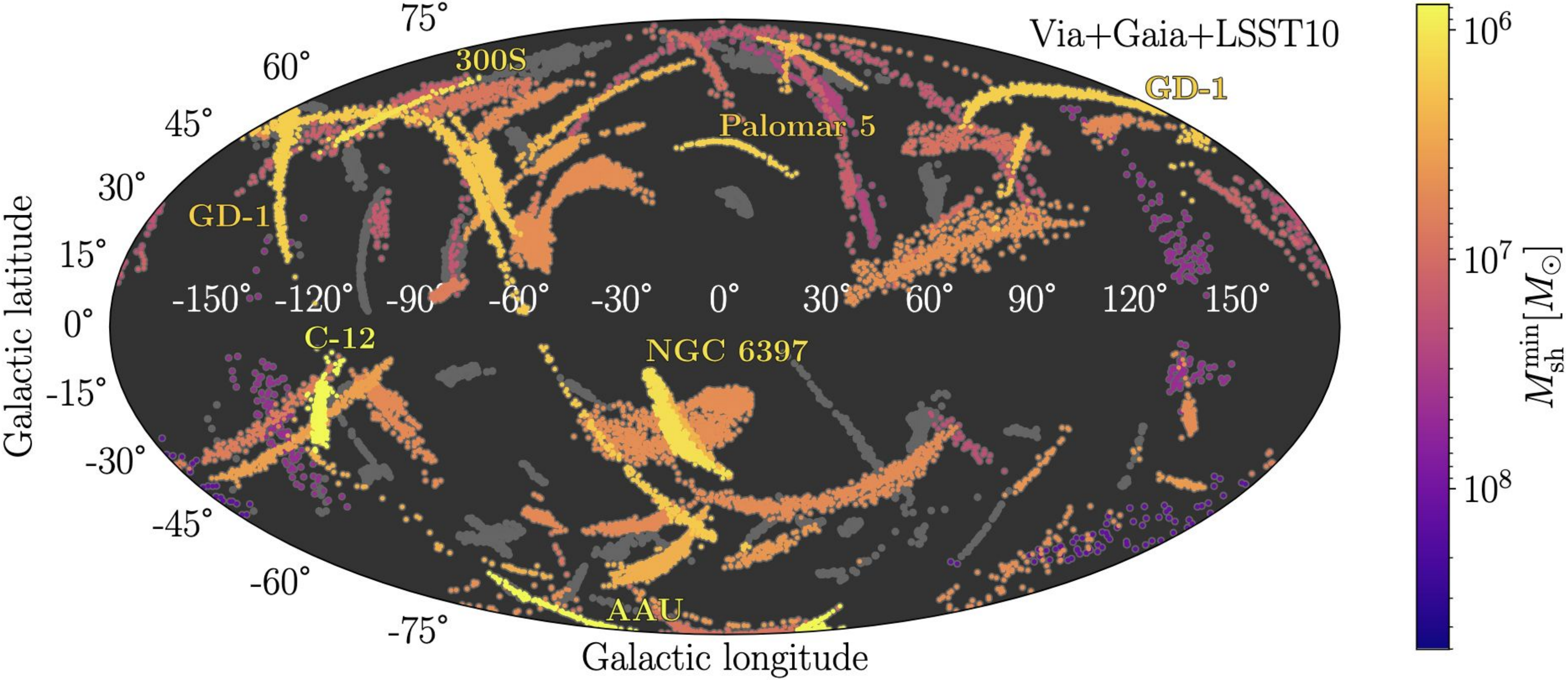
Name	σ_θ [°]	l [°]	r_h [kpc]	$M_{\rm stellar}$ [$M_\odot$]	λ [deg^{-1}]	Retro /Prograde	$M_{\rm sh}^{\rm min}$ [$M_\odot$] Gaia	$M_{\rm sh}^{\rm min}$ [$M_\odot$] DESI + Gaia	$M_{\rm sh}^{\rm min}$ [$M_\odot$] Via + LSST	$M_{\rm sh}^{\rm min}$ [$M_\odot$] Via + LSST10
C-12	0.51	28	11.5	14000	528	P	6.75e+06	6.58e+06	1.40e+06	7.75e+05
ATLAS-Aliqa Uma	0.26	41	21.4	19000	490	P	1.05e+07	1.05e+07	1.65e+06	7.94e+05
300S	0.34	25	15.9	7600	321	R	1.16e+07	1.16e+07	2.10e+06	1.08e+06
NGC 6397	0.79	32	2.5	2500	83	P	2.85e+06	2.84e+06	1.38e+06	1.16e+06
Palomar 5	0.54	32	21.3	17000	561	P	2.23e+07	2.15e+07	3.20e+06	1.45e+06
GD-1	0.43	119	8.0	14000	124	R	9.06e+06	9.11e+06	2.39e+06	1.47e+06
Orphan-Chenab	1.02	137	20.7	130000	1003	P	2.79e+07	2.62e+07	3.77e+06	1.64e+06
Ylgr	0.72	49	9.5	11000	237	R	1.36e+07	1.33e+07	3.05e+06	1.72e+06
Gaia-6	0.4	21	8.3	1800	91	R	1.16e+07	1.17e+07	3.02e+06	1.84e+06
Kshir	0.23	37	10.7	2200	63	R	1.31e+07	1.36e+07	3.16e+06	1.86e+06
C-7	0.42	34	5.8	1500	47	R	1.07e+07	1.09e+07	3.43e+06	2.31e+06
NGC 5466	0.23	23	17.4	1900	87	R	2.53e+07	2.60e+07	4.59e+06	2.31e+06
Gaia-1	0.34	40	5.0	1100	29	R	9.22e+06	9.59e+06	3.32e+06	2.37e+06
Jhelum	0.65	97	13.0	17000	185	P	2.69e+07	2.65e+07	5.09e+06	2.60e+06

[2405.19410] Ana Bonaca, Adrian M. Price-Whelan

Stream ranking - Gaia era



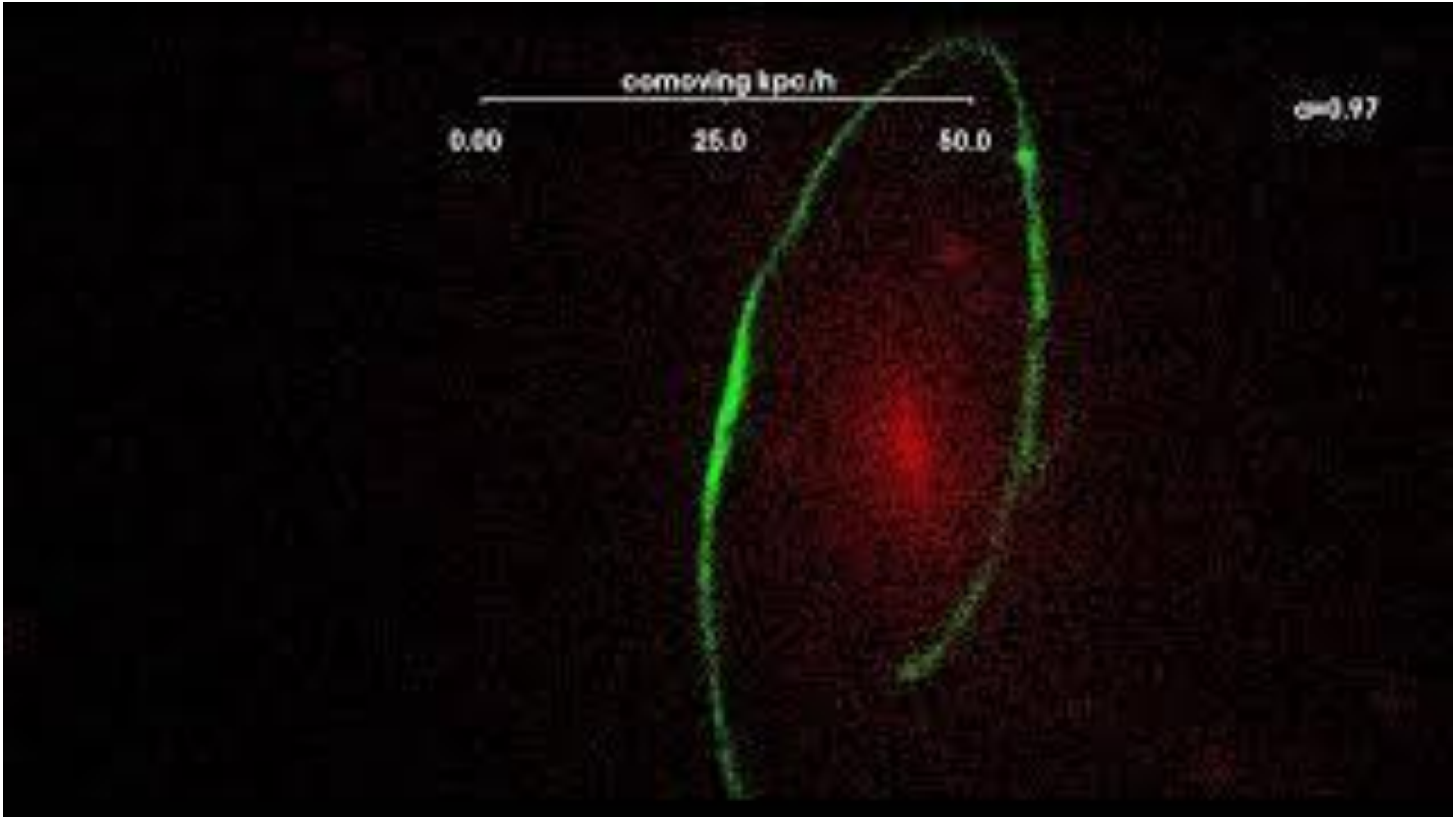
Stream ranking - LSST 10 year sensitivity



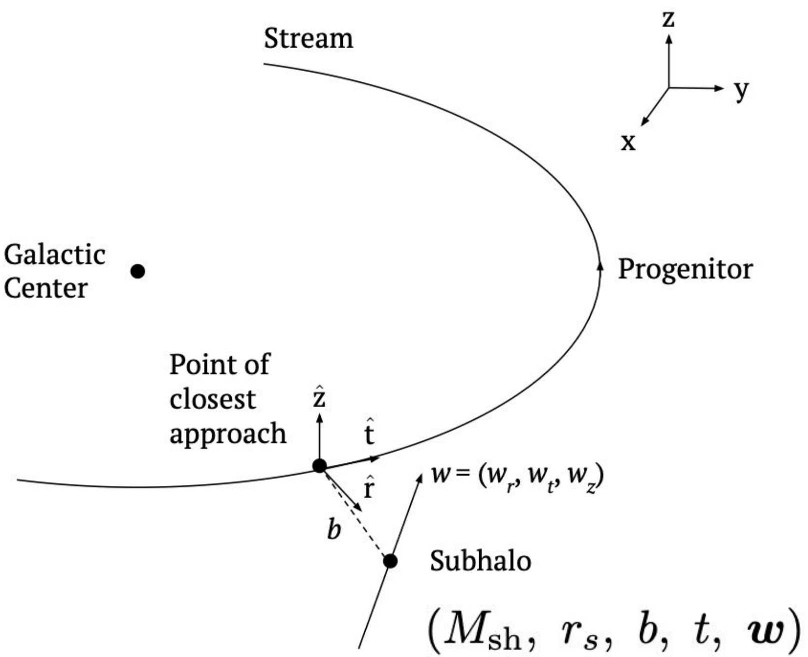
Future work

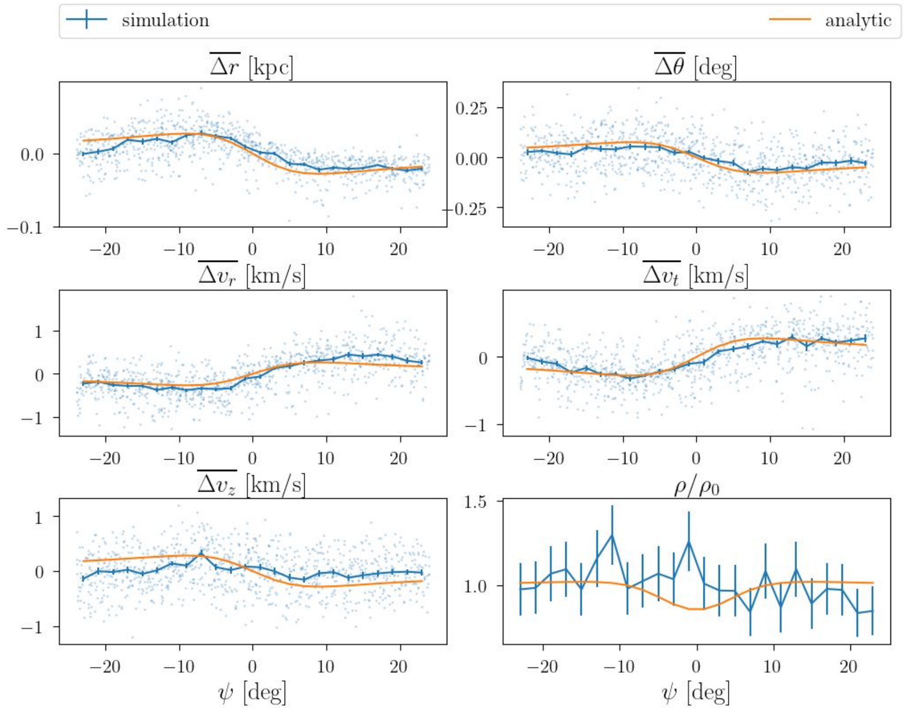
- Take **stream age** and **stream length** into consideration and predict the **expected number of detectable impacts** for each MW stream under certain dark matter models (CDM, WDM, FDM, SIDM, etc)
- Can compare the predictions against the observations and put constraints on different dark matter models


Thanks!


comoving kpc/h
0.00
25.0
50.0
a=0.97

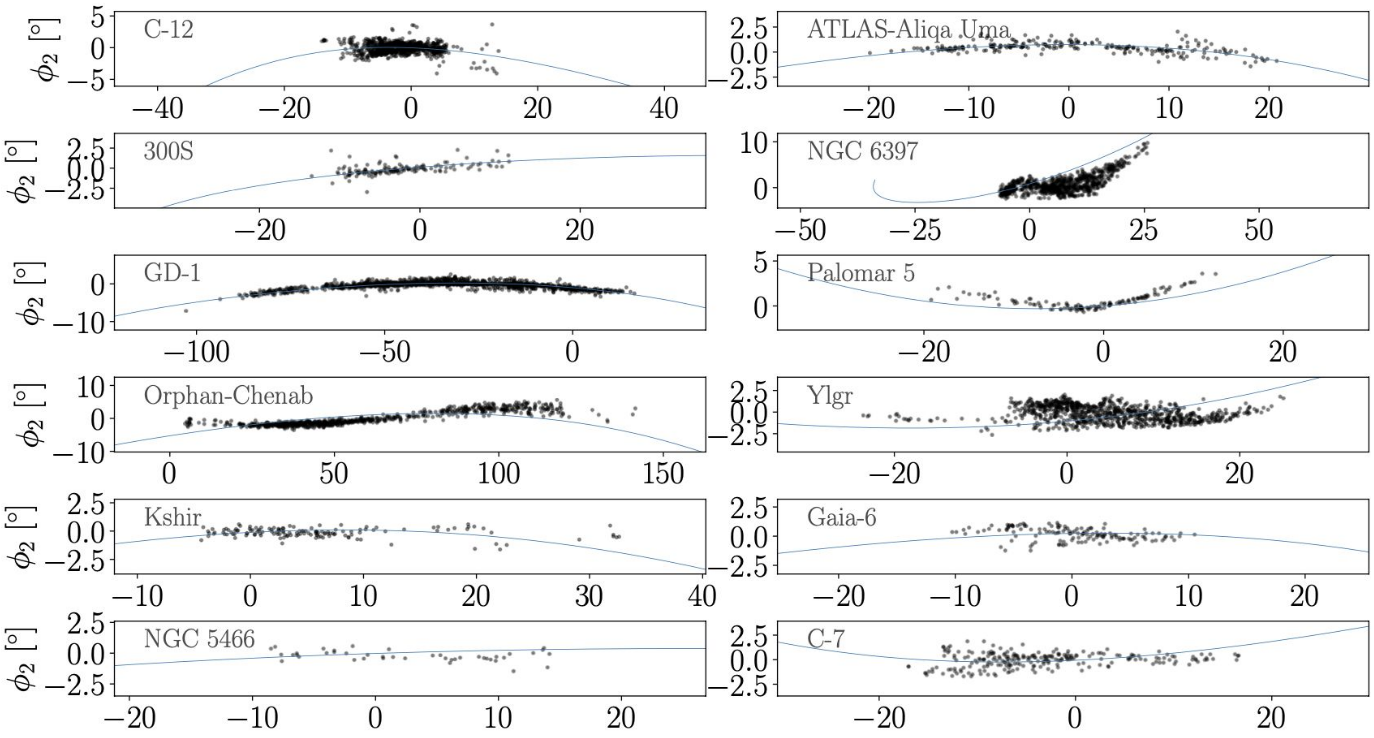
Analytic model for subhalo impacts





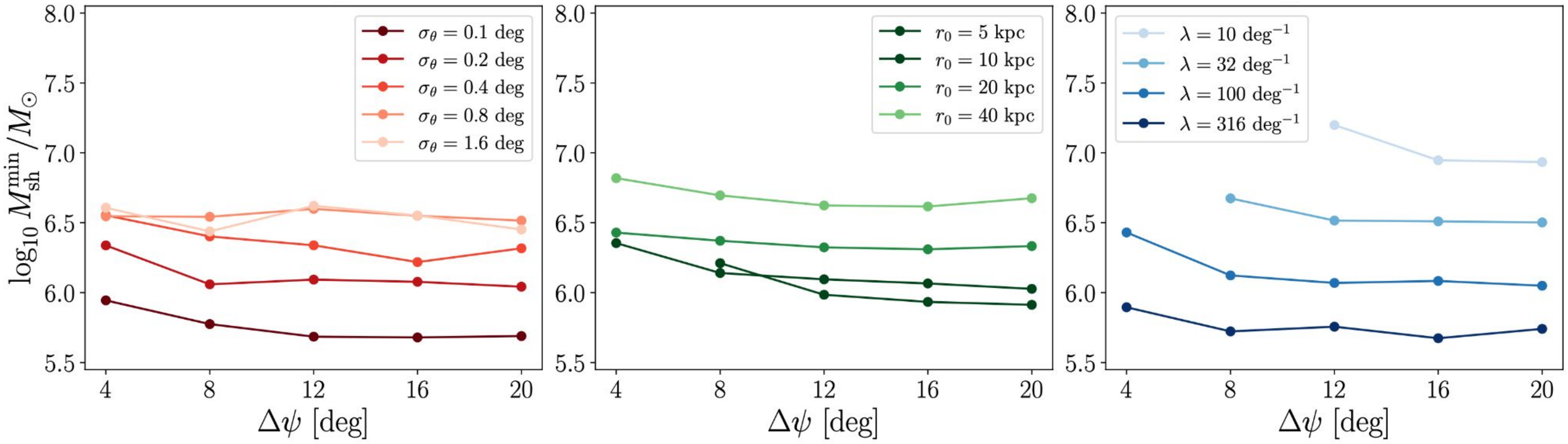
[1507.05625] Denis Erkal, Vasily Belokurov

Stream ranking

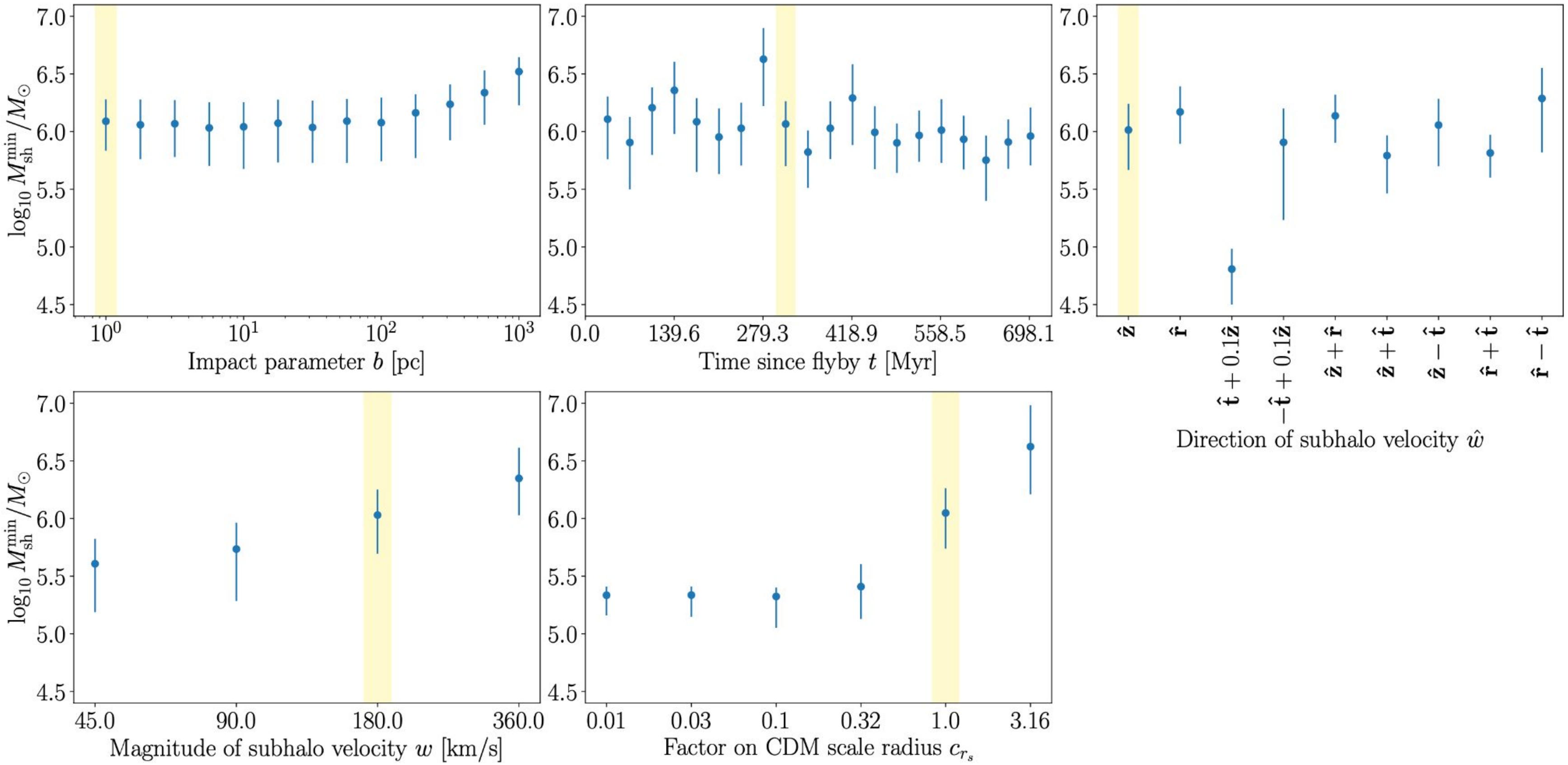


Minimum stream length in angle

- 8 degree of region required for those most promising streams
- Corresponding to 20 degree of total stream length



Dependence on nuisance parameters

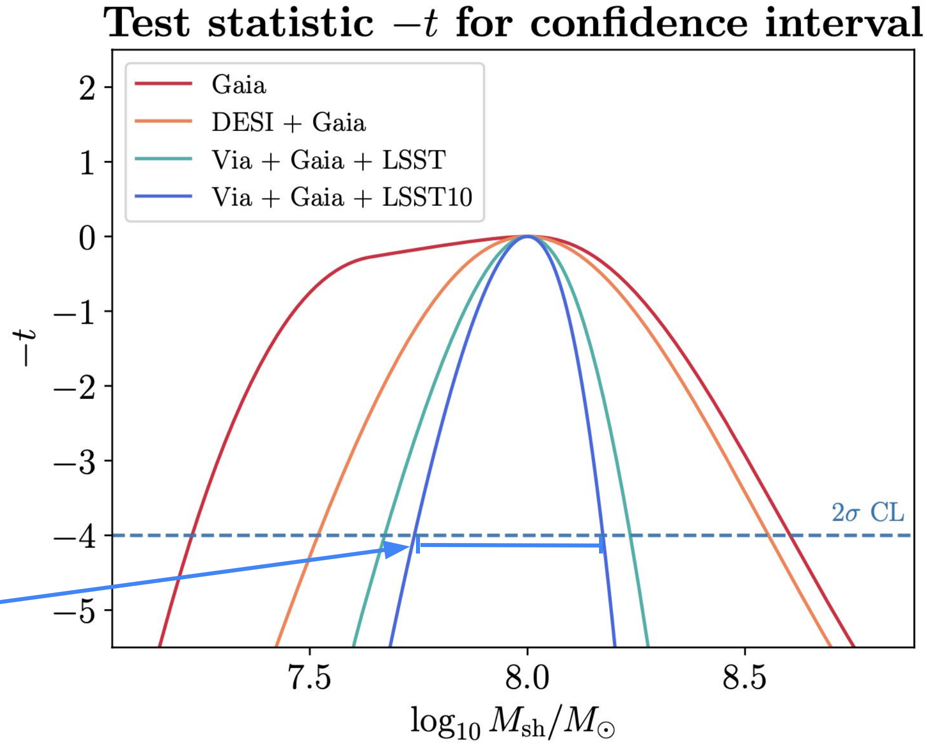


Test statistics for mass estimation

$$t(M_{\mathrm{sh}}) = 2\ln\frac{L(\hat{M}_{\mathrm{sh}},\ \hat{\boldsymbol{\theta}})}{L(M_{\mathrm{sh}},\ \hat{\hat{\boldsymbol{\theta}}})}.$$

"Likelihood ratio for true model vs model with deviated mass"

$t = n^2$ decides the $n\sigma$ CI



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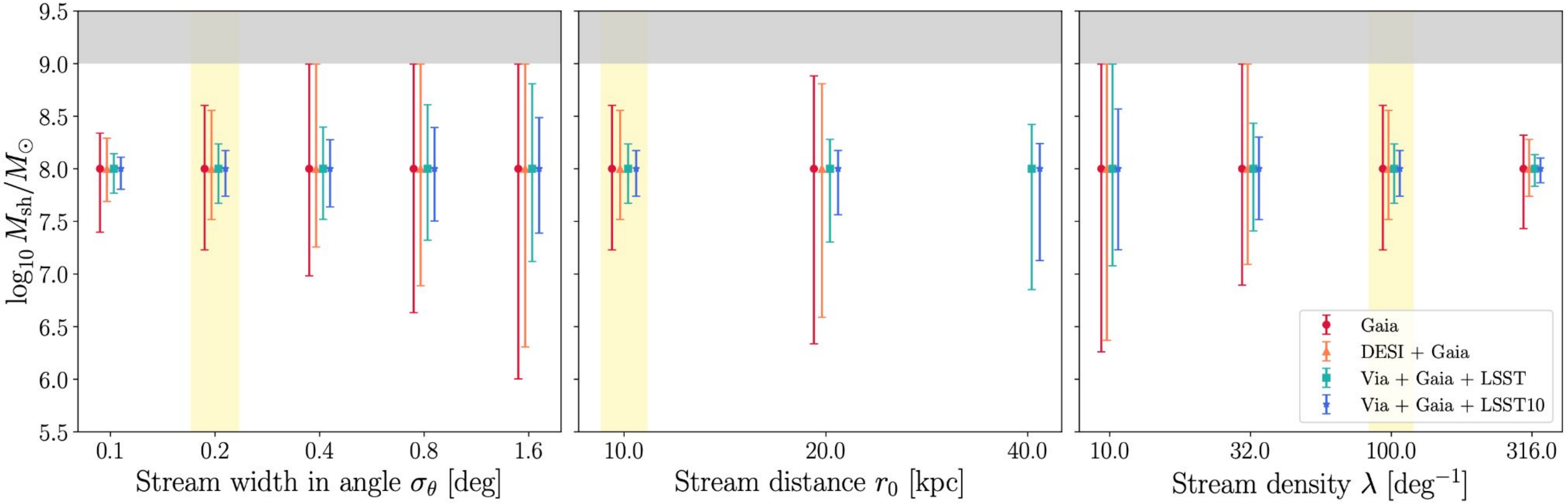
Confidence interval on subhalo mass



Conclusions

- Subhalo detectability strongly depends on stream width, stream distance, stream density and observational scenario.
- We found fitting functions for the minimum detectable subhalo mass. Specifically, $M_{\rm sh}^{\rm min} \propto \sigma_\theta^{1.2} r_0^{1.9} \lambda^{-0.8}$ for Gaia and $M_{\rm sh}^{\rm min} \propto \sigma_\theta^{0.98} r_0^{1.0} \lambda^{-0.8}$ for LSST10.
- We rank order the Milky Way streams based on their subhalo detectability. C-12, ATLAS-Aliqa Uma, 300S, NGC 6397, and GD-1 are among the most promising ones for further study.

Conclusions

- Both the angular shift in z direction and the radial velocity are important observables for detecting a subhalo impact.
- Streams less than 20° generally lack subhalo detectability.
- Subhalo detectability decreases as the subhalo velocity, scale radius, or impact parameter increase.
- More aspects to consider (ongoing work):
  - Stream length and age affect number of detectable impacts
  - Size of impact constrained by stream length
  - Intrinsic fluctuations along the stream due to the epicyclic motion of elliptical orbits

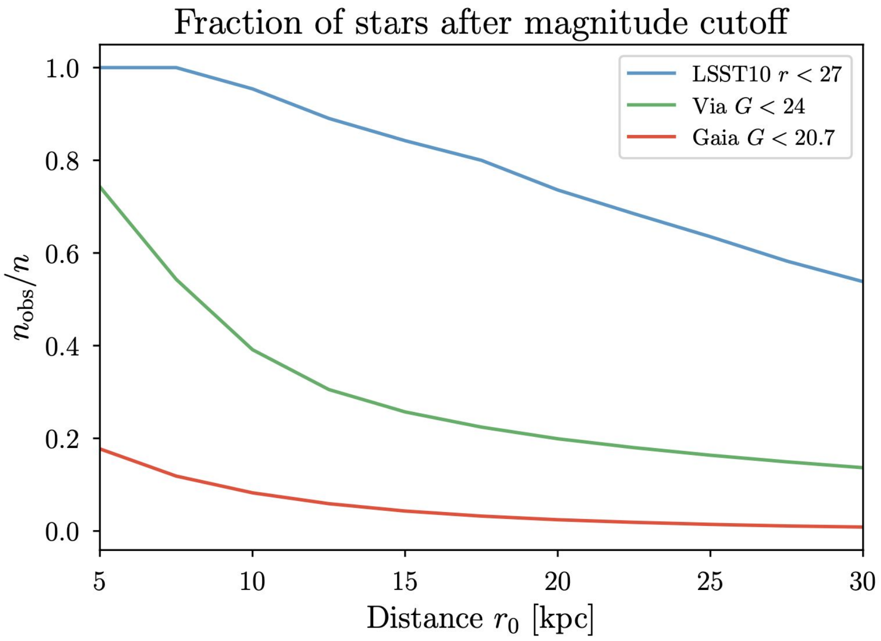
Default values for subhalo impact parameters

	Description	Default value
$M_{\rm sh}$	Subhalo mass	–
r_s	Scale radius	Plummer sphere, Eq. 25
b	Impact parameter	0
t	Time since flyby	$315 \text{ Myr} \times \dfrac{r_0}{10 \text{ kpc}}$
$\boldsymbol{w} = (w_r, w_t, w_z)$	Subhalo velocity	180 km/s in $\hat{z}$ direction

$$r_s = \left(\frac{M_{\rm sh}}{10^8 \ {\rm M}_\odot}\right)^{0.5} \times 1.62 \text{ kpc}.$$

Observational scenarios

- Gaia position + proper motions
- Gaia position + proper motions + **DESI radial velocity**
- **LSST position** + Gaia proper motions + **Via radial velocity**
- **LSST10 position** + Gaia proper motion + Via radial velocity



Test statistics

- Gaussian likelihood function

Analytic model

impacted data

$$L(M_{\rm sh},\ \boldsymbol{\theta}) = \prod_{i,j} \frac{1}{\sqrt{2\pi\sigma_{\nu_{ij}}^2}} \exp\left[-\frac{(\nu_{ij}(M_{\rm sh},\ \boldsymbol{\theta}) - \nu_{ij}^{\rm dat})^2}{2\sigma_{\nu_{ij}}^2}\right]$$

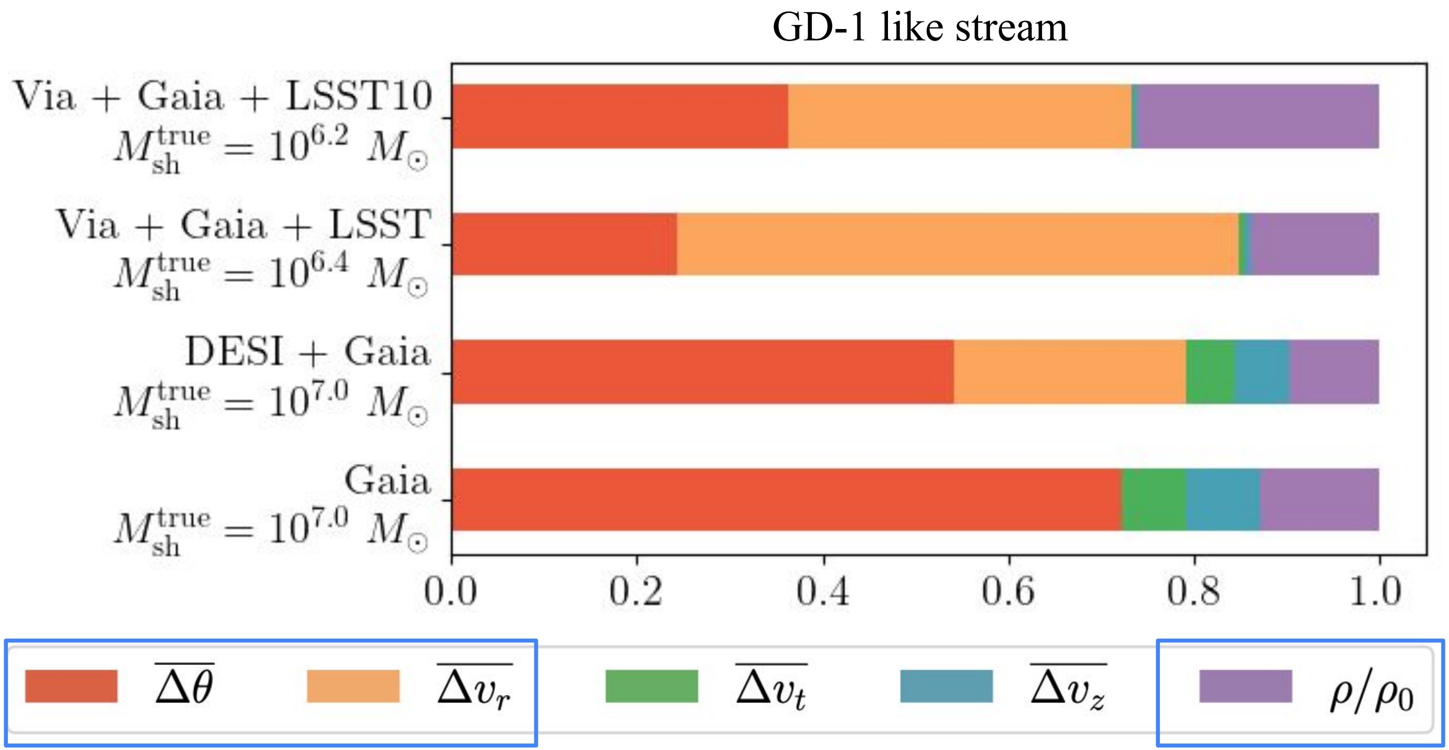
Nuisance parameters

$(b,\ t,\ \boldsymbol{w})$

Combined error
(internal dispersion
+ observational error)

[1007.1727] Glen Cowan, Kyle Cranmer, Eilam Gross, Ofer Vitells

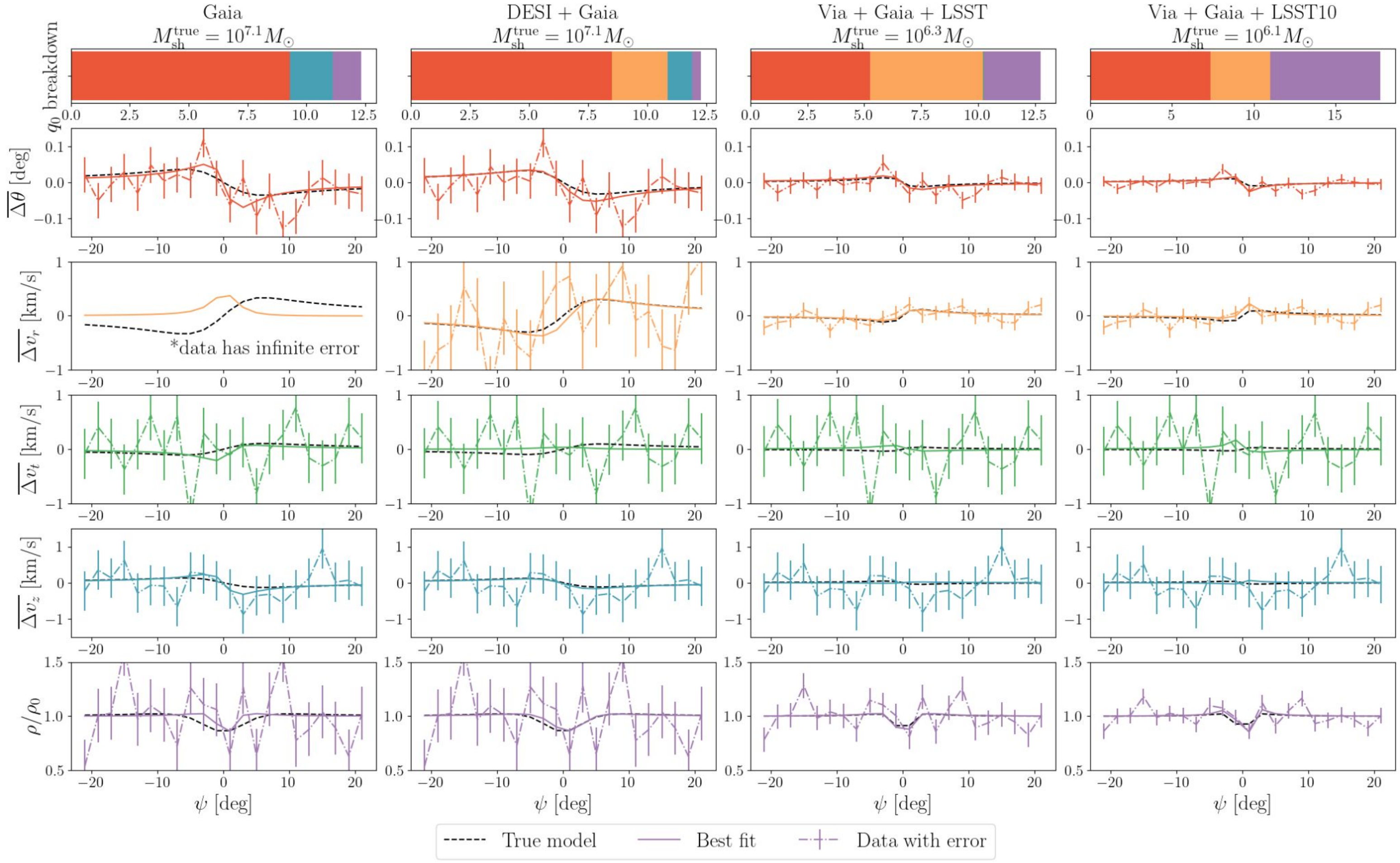
Breakdown of q0 at minimum detectable subhalo mass



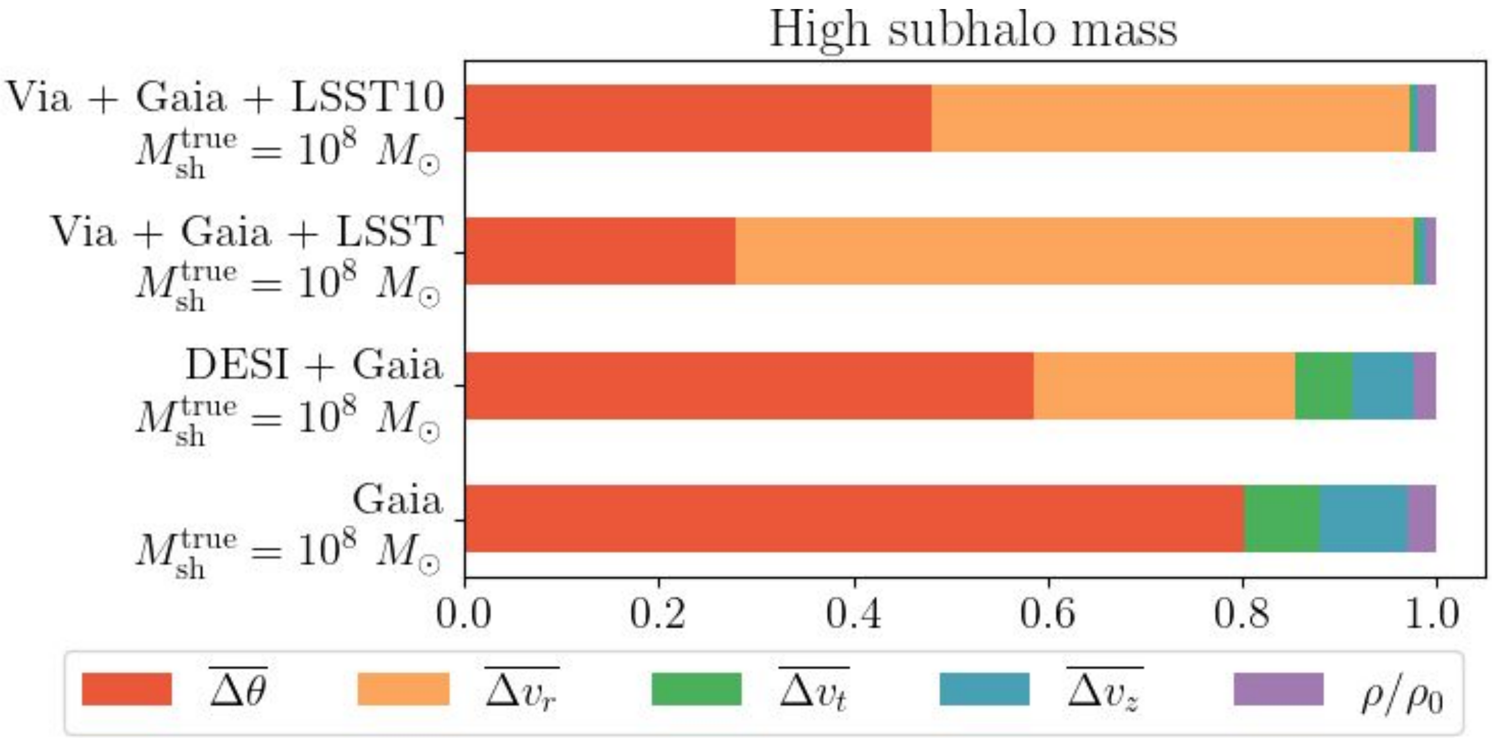
More important for newer impacts

More important for older impacts

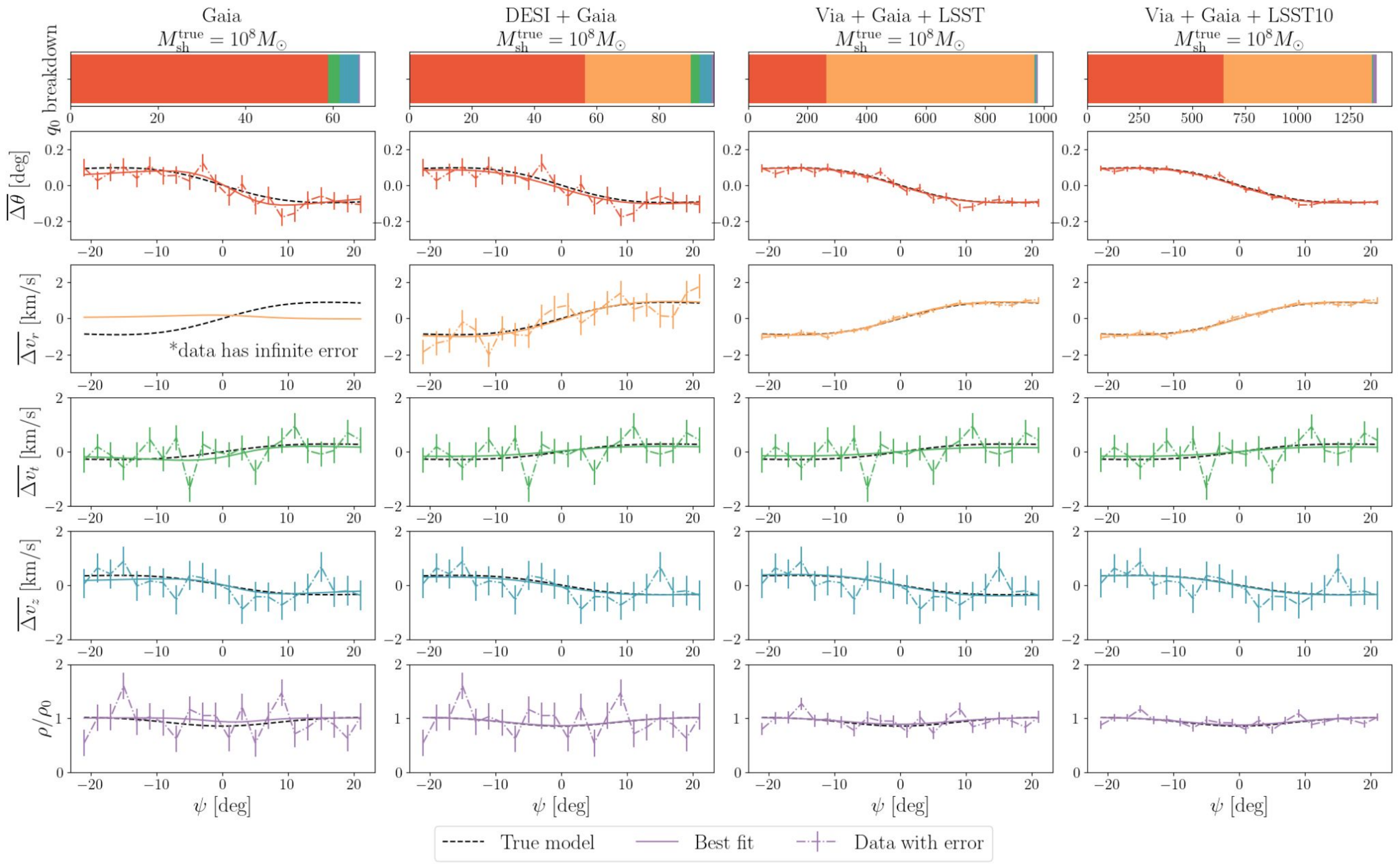
Example data at minimum detectable subhalo mass



Breakdown of q0 from different observables



Example data at high subhalo mass



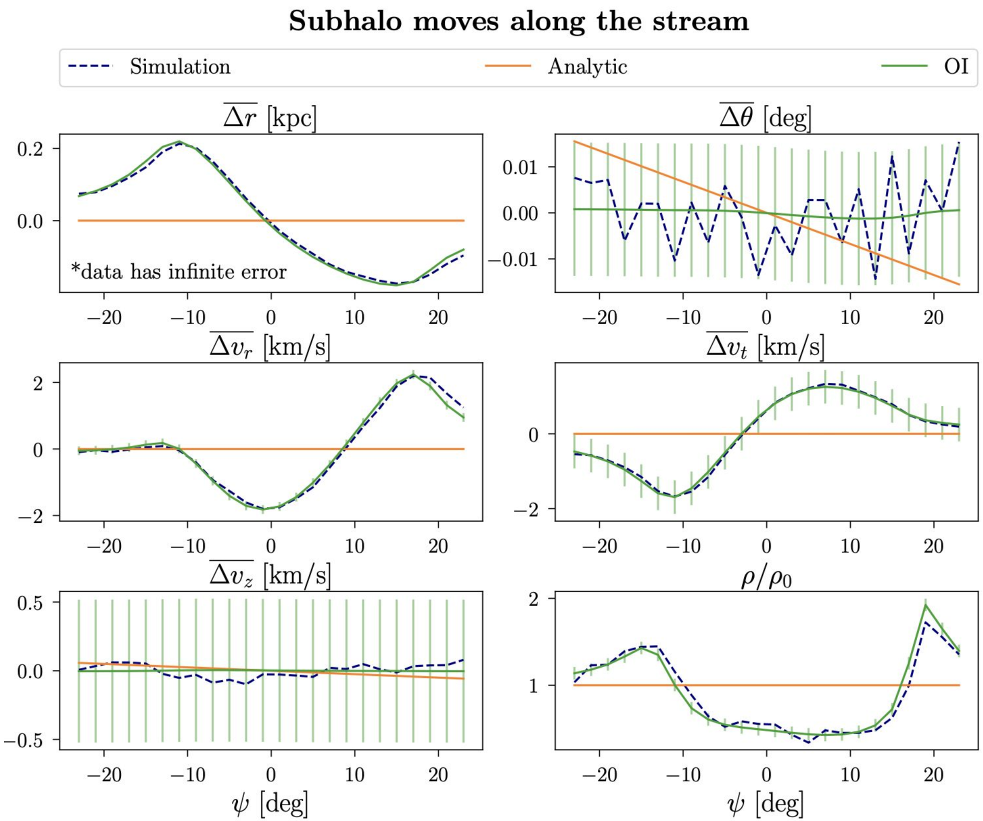
Limitation of analytic model - impulse approximation

- Require

$$\frac{w_{\rm rel}}{w_\perp}\sqrt{b^2+r_s^2} \ll r_0$$

$$\frac{V_c}{w_\perp}\sqrt{b^2+r_s^2} \ll r_0.$$

- A failure example on the right



Limitation of analytic model - mass-velocity degeneracy

- Degeneracy

$$M_{\rm sh} \to \lambda M_{\rm sh}$$
$$\boldsymbol{w}_{\rm rel} \to \lambda \boldsymbol{w}_{\rm rel}$$

- Break the degeneracy by enforcing mass-radius relation

$$r_s = \left(\frac{M_{\rm sh}}{10^8\ {\rm M}_\odot}\right)^{0.5} \times 1.62\ {\rm kpc}.$$

- Or use orbit integration (OI)