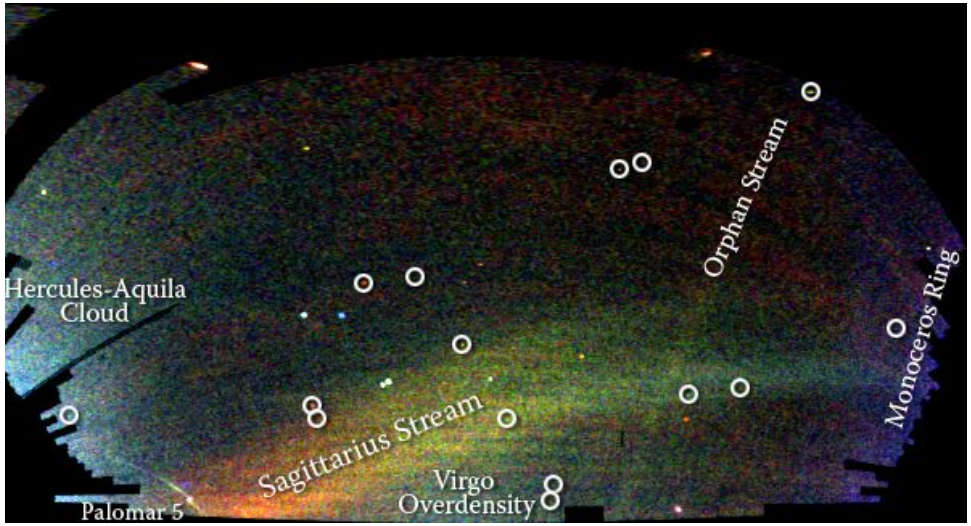
Southern Stellar Streams in 6D+1

Ting S. Li

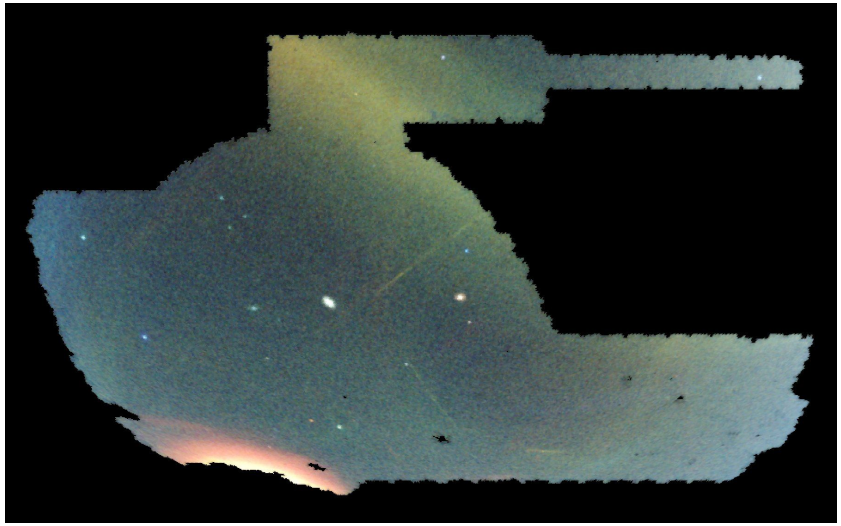
Leon Lederman Fellow, Fermilab

KICP Associated Fellow, the University of Chicago

April 3rd, 2019, KITP, Santa Barbara



Credit: Vasily Belokurov and SDSS



Credit: Alex Drlica-Wagner and DES

Collaborations:

DES: Dark Energy Survey

S^5: Southern Stellar Stream Spectroscopy Survey

OATs: Orphan Aspen Treasury

How many streams do we believe are real?

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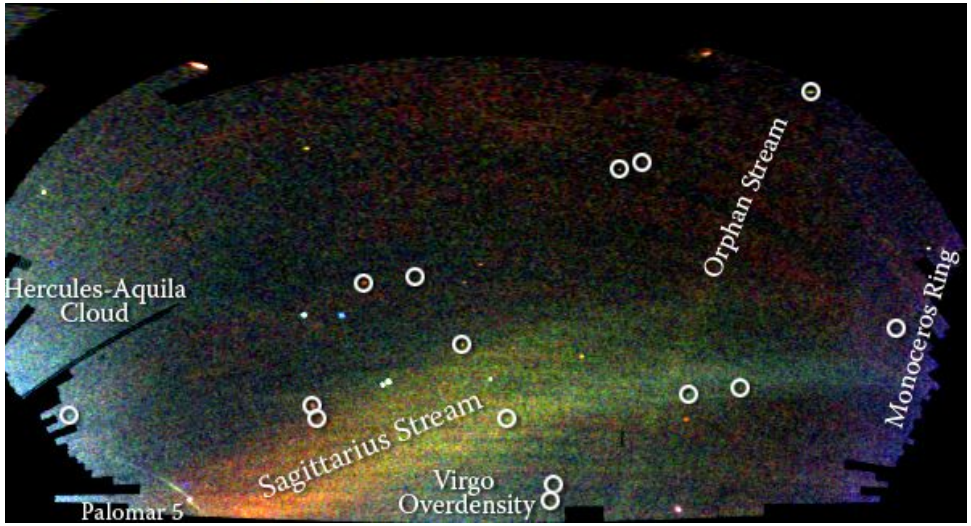

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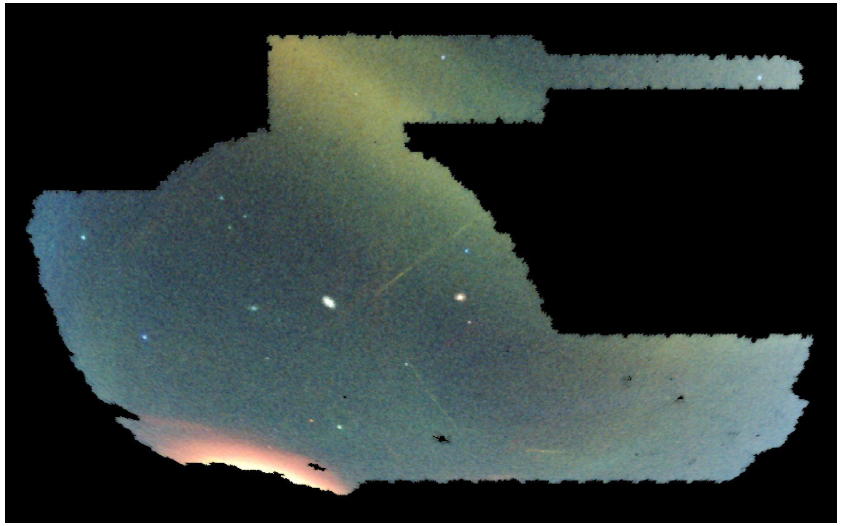

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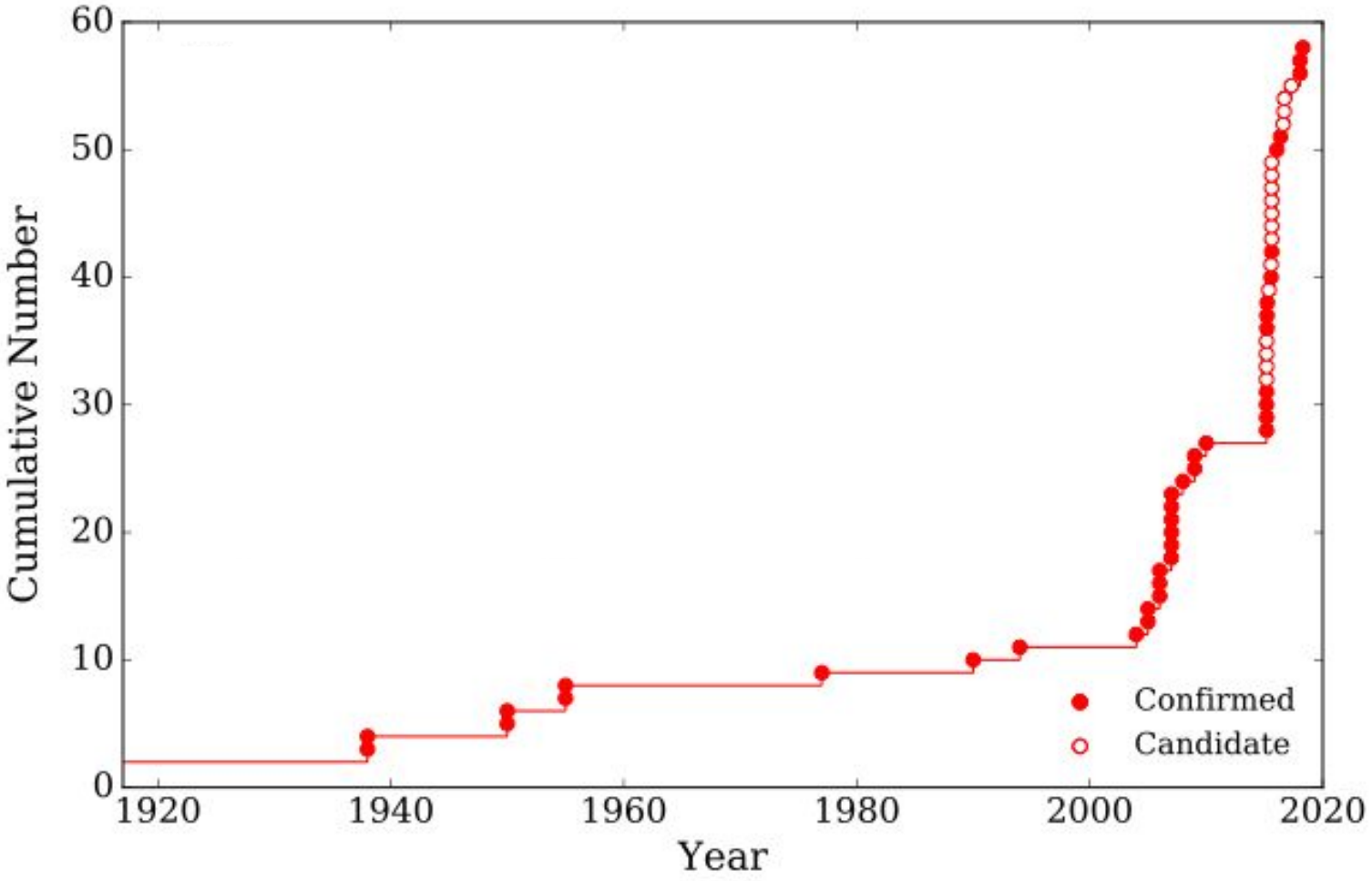
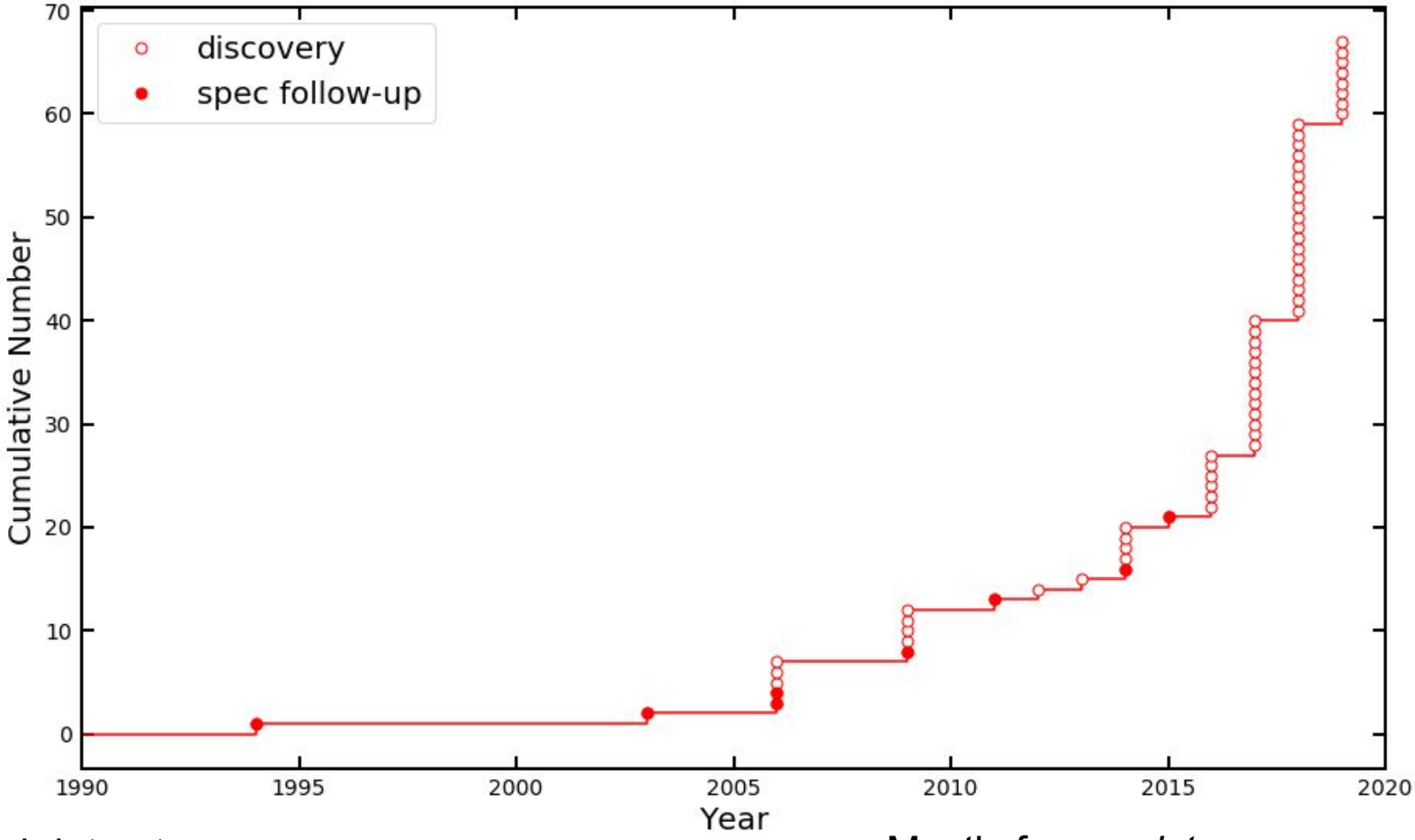
Milky Way Dwarf Galaxy Discovery Timeline



Credit: Keith Bechtol, Alex Drlica-Wagner

Milky Way Stellar Stream Discovery Timeline



Compiled data at
https://tinyurl.com/y6gggvee

Mostly from *galstream*
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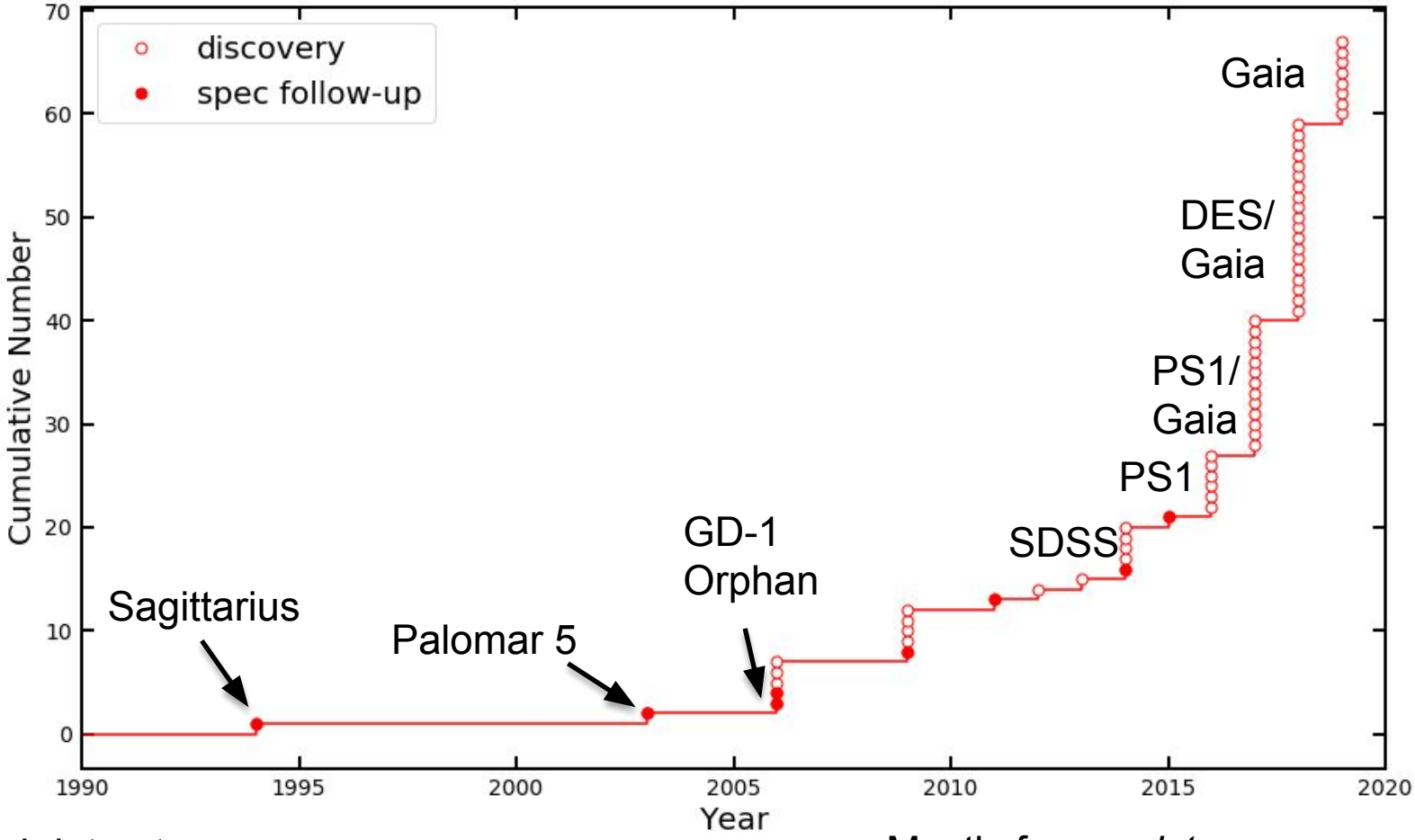
Milky Way Stellar Stream Discovery Timeline



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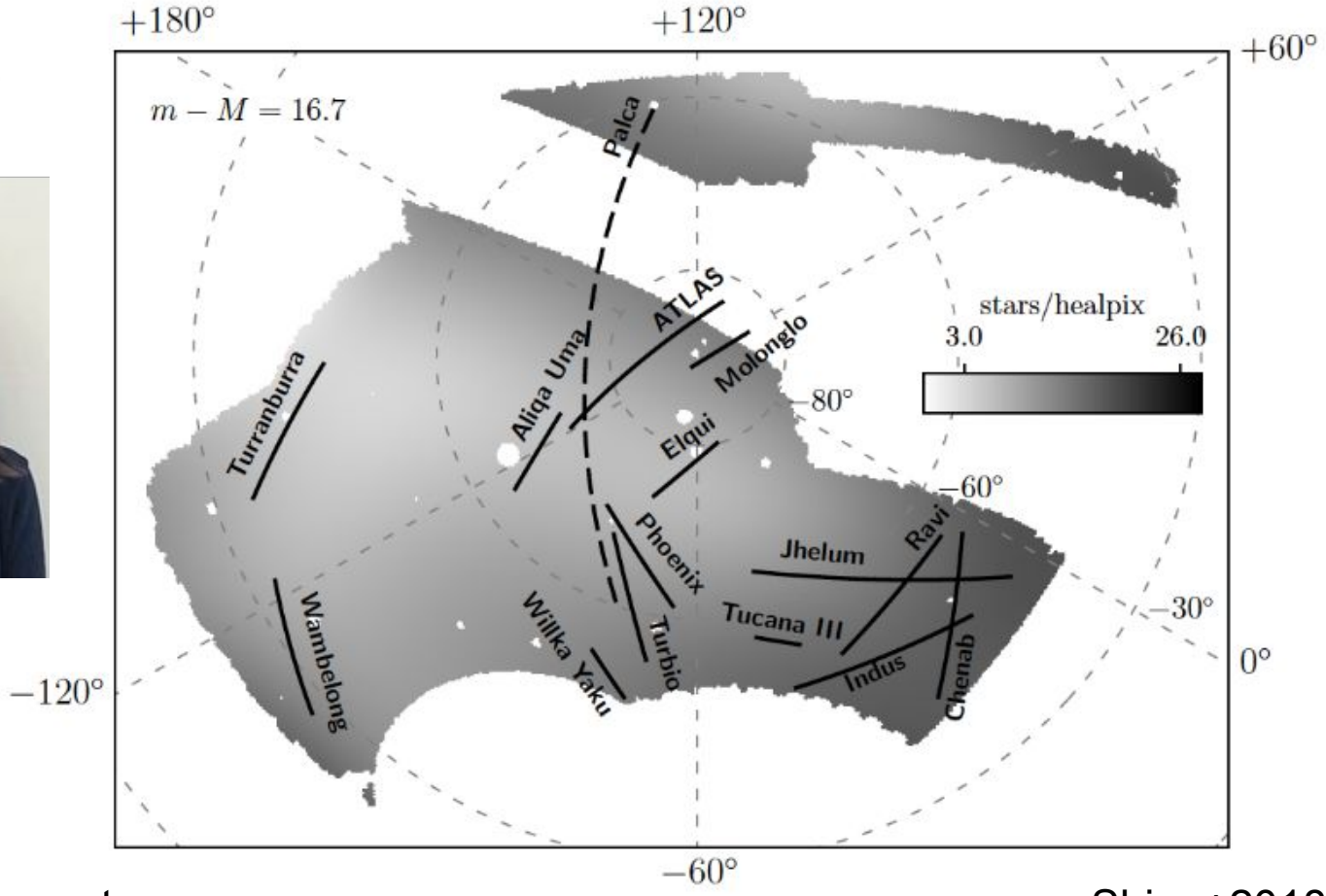
New Streams from DES

Nora Shipp
UChicago

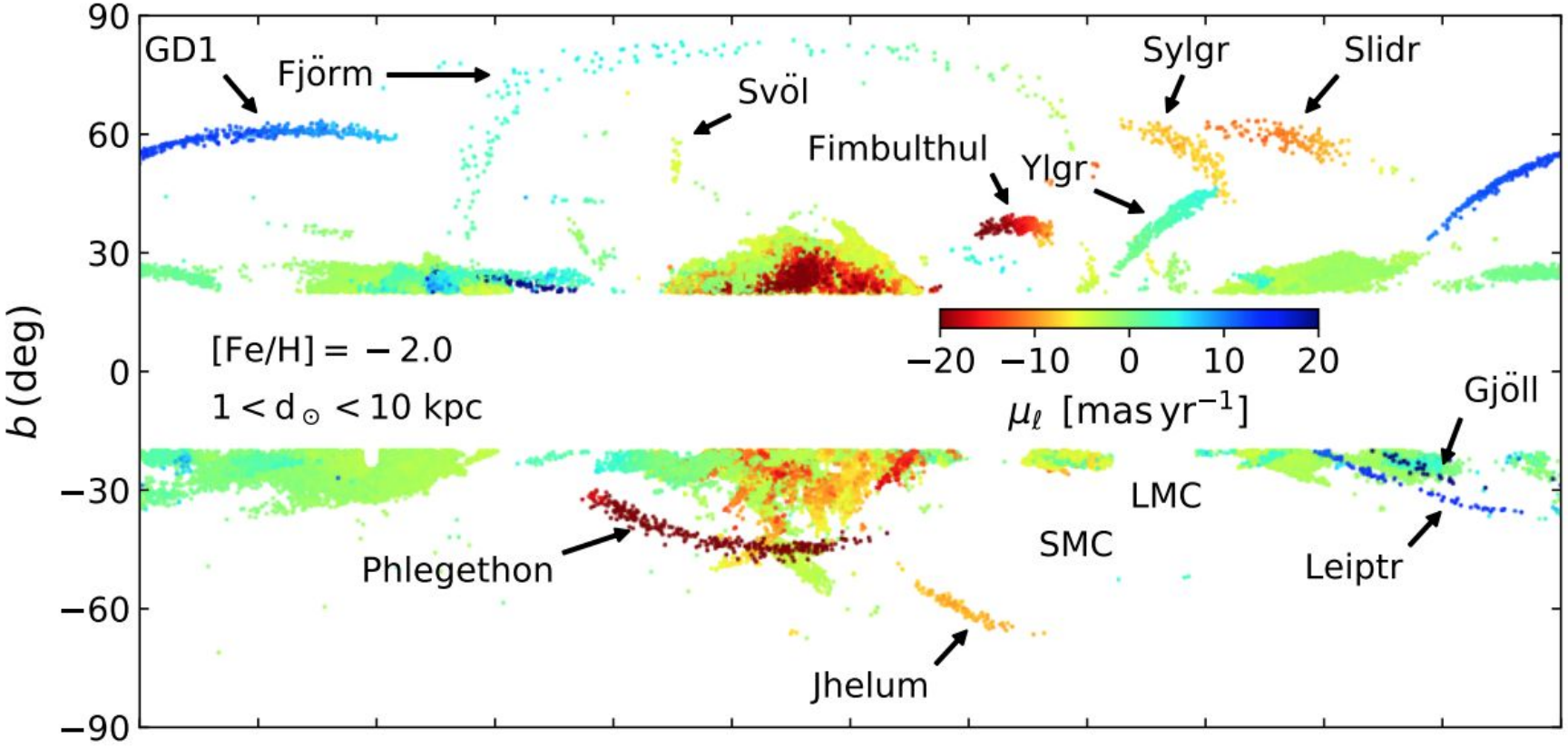


11 new stream
+ 4 previous known (including 2 from DES)

Shipp+2018
(DES Collaboration)

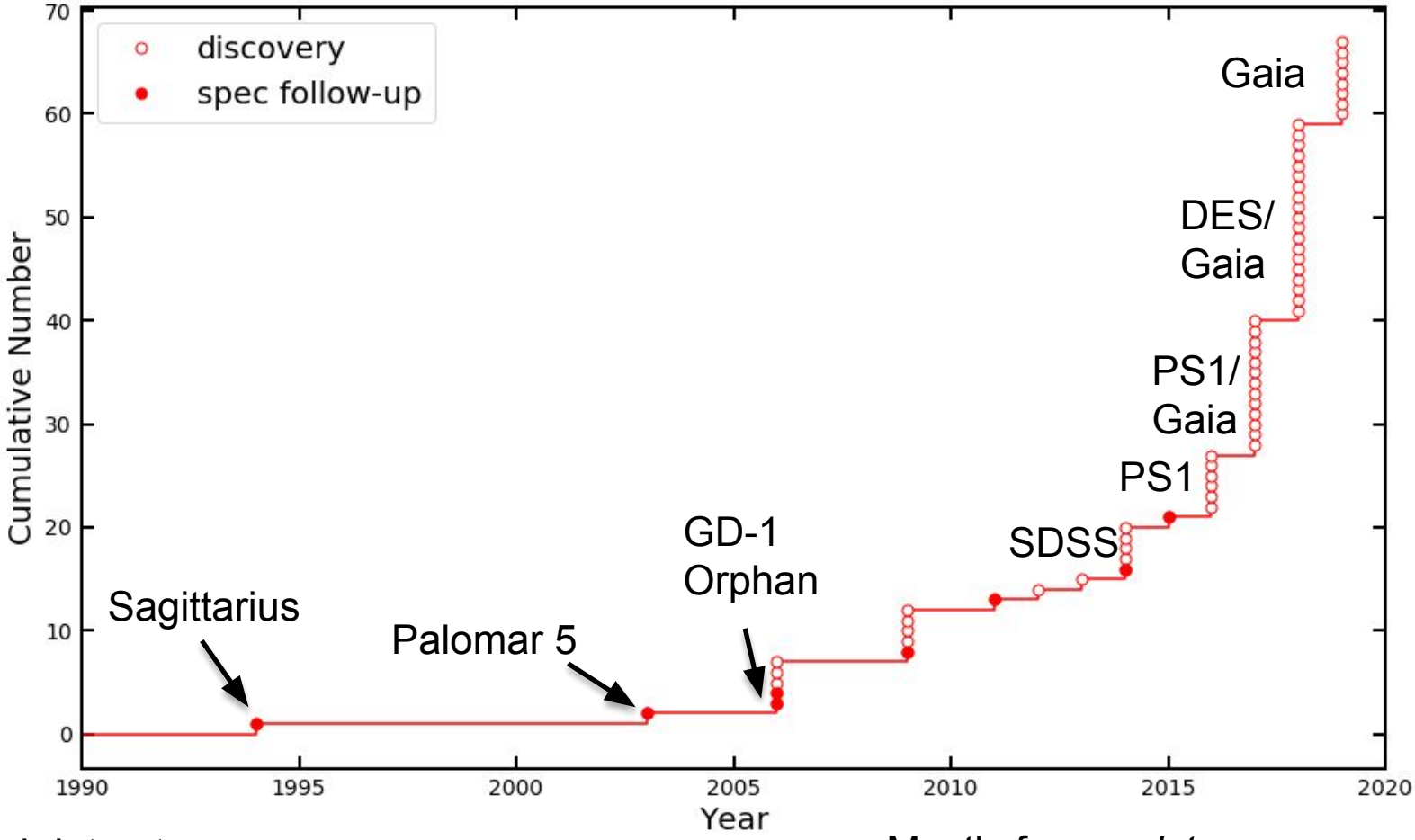
New Streams from Gaia

Photometry + Proper Motion



Ibata+2019

Milky Way Stellar Stream Discovery Timeline



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Not Including…

- Stellar Overdensity/Cloud: Monoceros, Tri-And, VOD, POD, Her-Aq...

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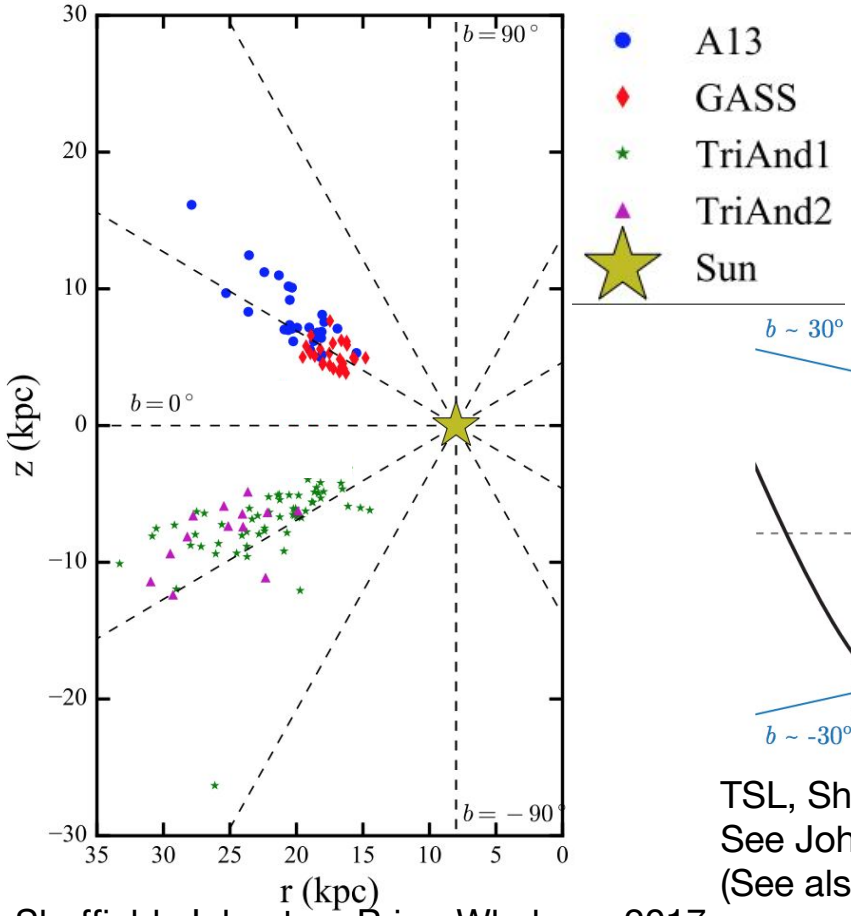
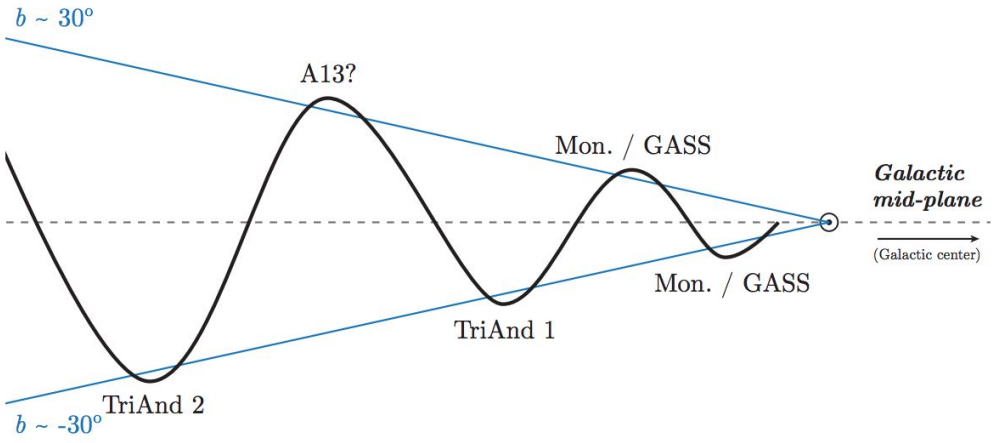


TSL, Sheffield, Johnston, Price-Whalen + 2017



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See Johnston et al 2017 for a review (arXiv: 1709.00491)
(See also Xu et al 2015, Bland-Hawthorn et al. 2019)

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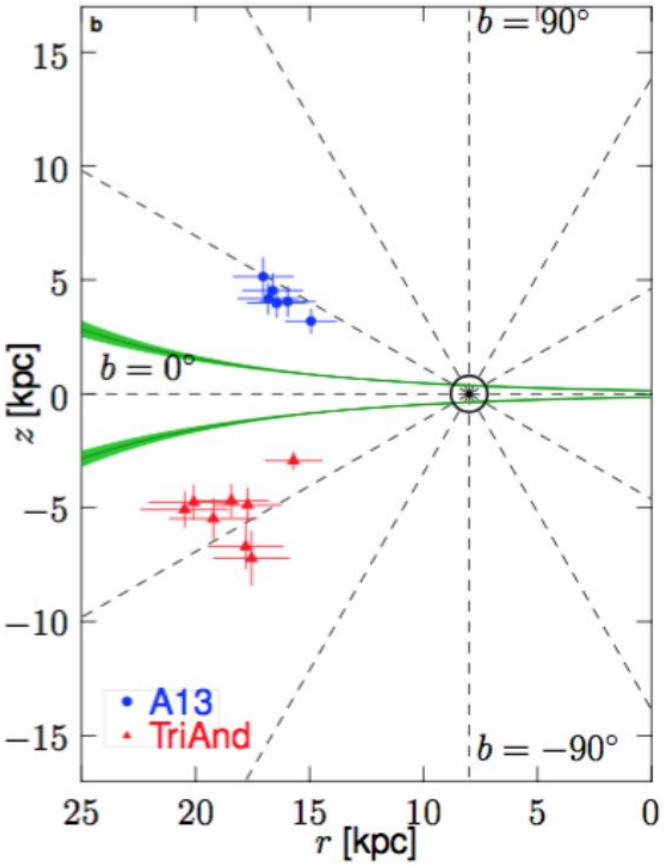
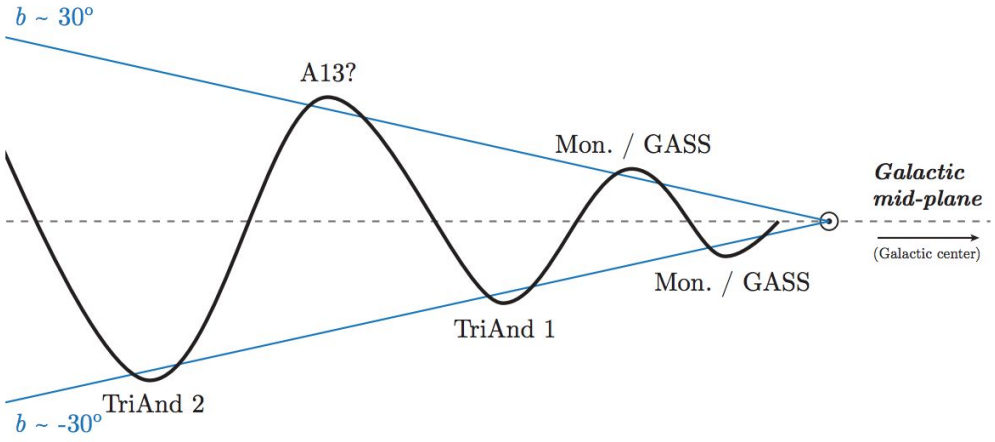


Bergemann et al. 2018



TSL, Sheffield, Johnston, Price-Whalen + 2017
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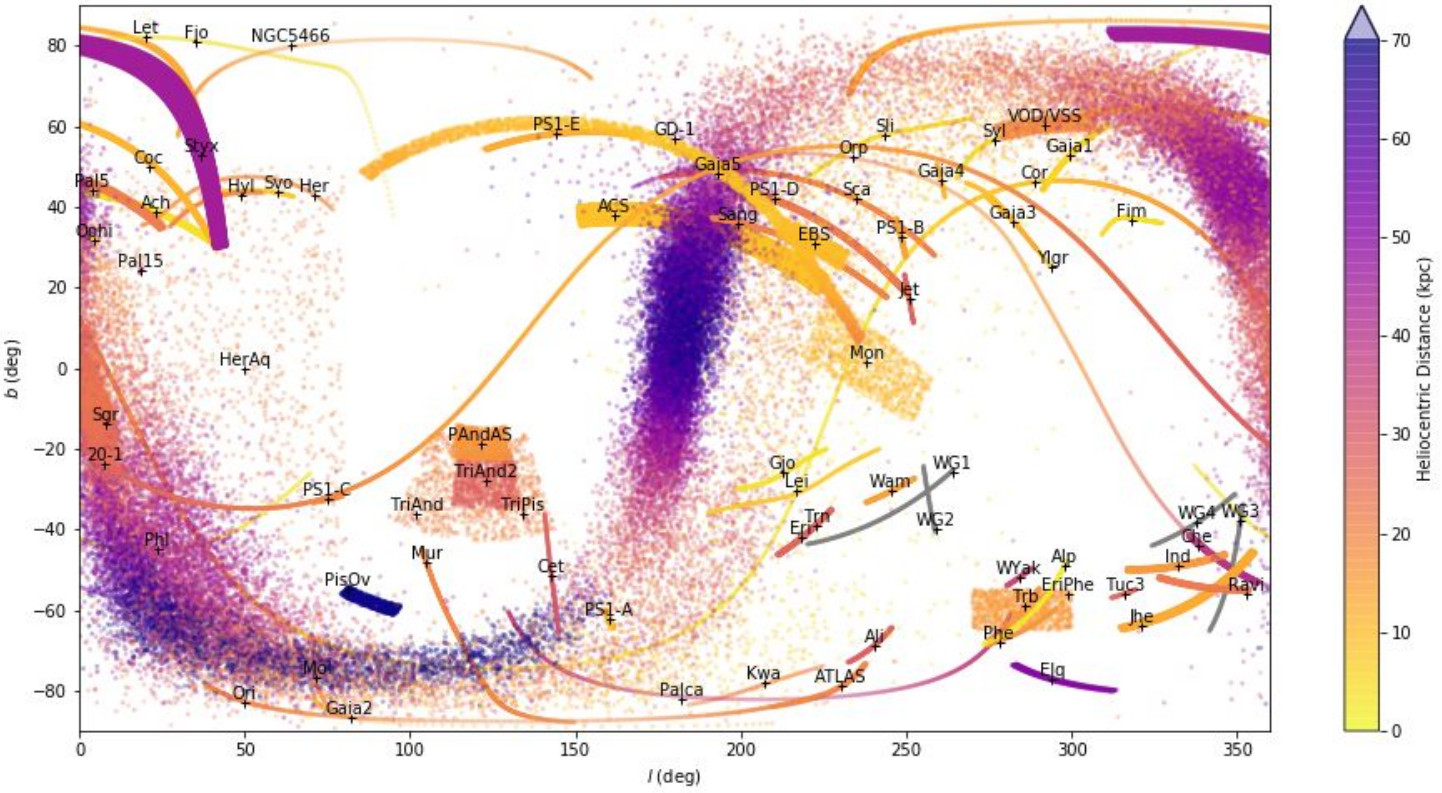
Not Including…

Discovered in velocity or action space

- Not in galstream
  - Helmi Stream (Helmi et al. 1999)
  - Hercules Stream (Dehnen 2000) or any solar neighborhood “streams”
  - ECHOS (Schlaufman et al. 2009)
  - V3, N1-N6 from LAMOST DR1/DR2 (Zhao et al 2014, 2015)
  - NEW1-NEW4 from LAMOST DR3+Gaia (Liang et al. 2017)
  - S1-S4 (Myeong et al. 2018a)
  - Rg1-Rg8 (Myeong et al. 2018b)

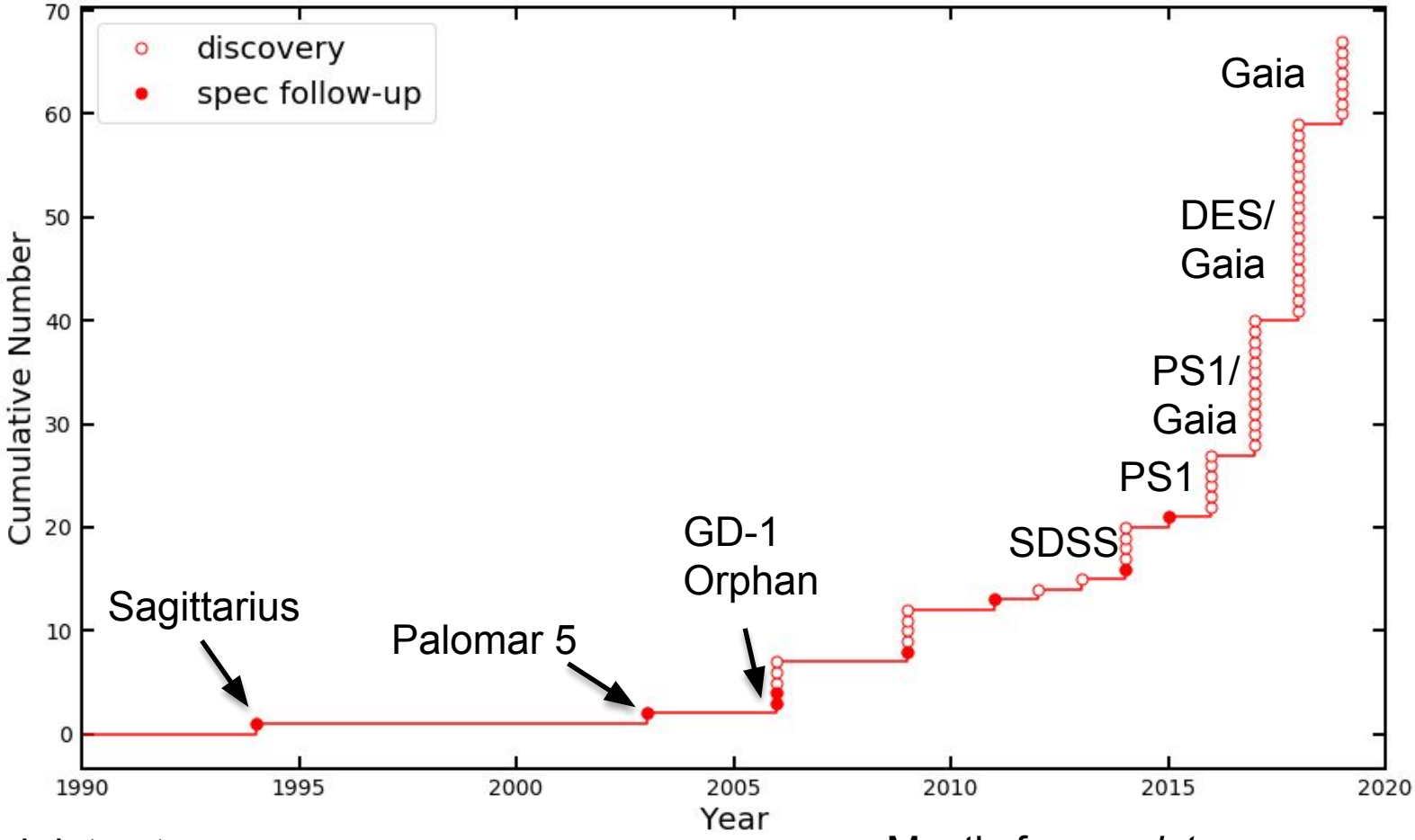
streams vs **moving groups** vs **debris flow** vs **clumps** vs **…..**

Define what is a stream….



Galstream (Cecilia Mateu)
https://github.com/cmateu/galstreams

Milky Way Stellar Stream Discovery Timeline



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How many streams are real?

a) 100%

b) 80%

c) 50%

d) 30%

How many streams are real?

a) 100%

b) 80%

c) 50%

d) 30%

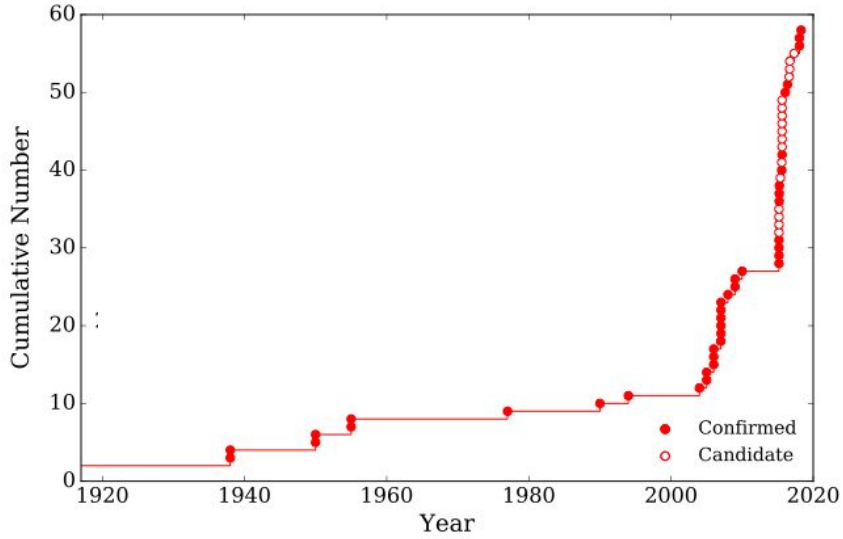
e) I do not know most of these streams

Photometry vs Spectroscopy

- **Photometry**
  - Discovery
  - Morphology (length, width)
  - Location (distance, position)
  - Luminosity

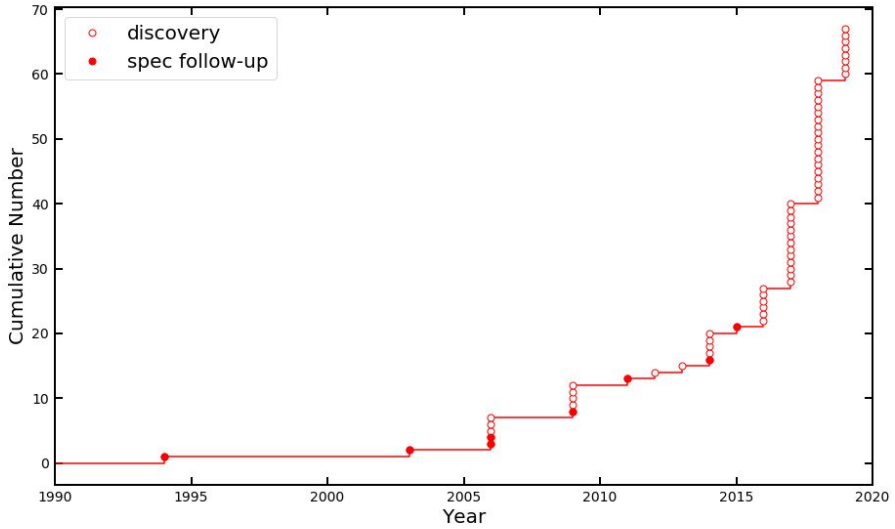
- **Spectroscopy + Proper motion**
  - Confirmation
  - Orbit, accretion history
  - Kinematics (dispersion, cold vs hot) — progenitor
  - Metallicities / chemical abundance — progenitor
  - Milky Way Mass Constraints

Spectroscopic Follow-up (Published)



Dwarf Galaxies: > 70%

Stellar Streams: ~ 10%



Why most streams have not been followed spectroscopically?

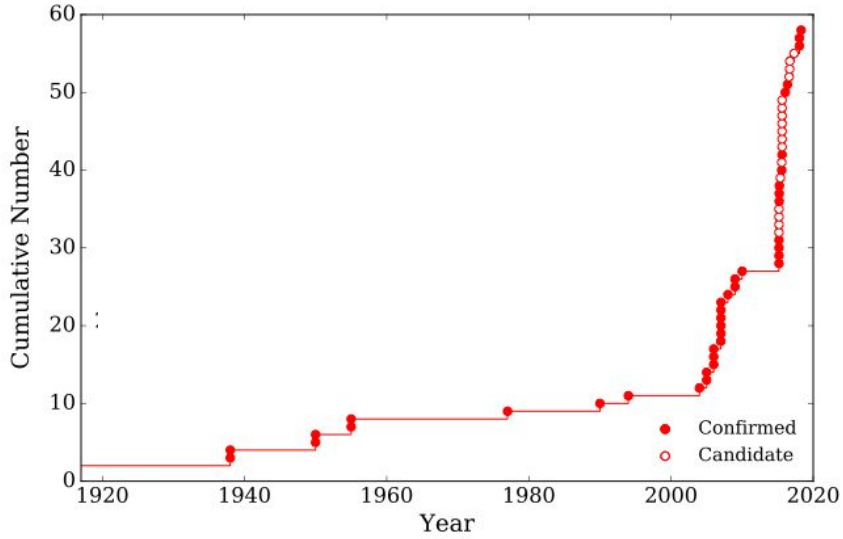
a) Spectroscopically follow-up a few dozens of streams are less interesting scientifically compared to dwarf galaxies.
b) We do not have someone like Joshua Simon, who had/have “infinite” telescope time on Keck/Magellan.
c) Some streams were followed up but were not confirmed and therefore not published.
d) Streams are technically much harder to follow-up because they are more diffuse (i.e. lower member density and higher contaminations).
e) It’s too much work so no one wants to do it; everyone is waiting for 4MOST, DESI, WEAVE to do it for us.
f) All of the above.
g) None of the above.

Best time for following up the stellar streams spectroscopically!

- Great photometry from deep imaging surveys
- Gaia DR2:

  Parallax + Proper motion
- Tools/Experiences from dwarf galaxy follow-up

Spectroscopic Follow-up (Published)



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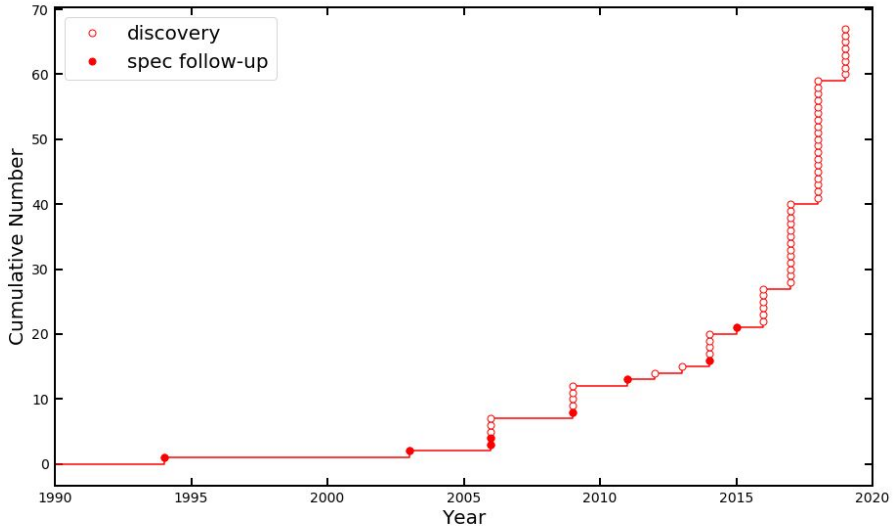
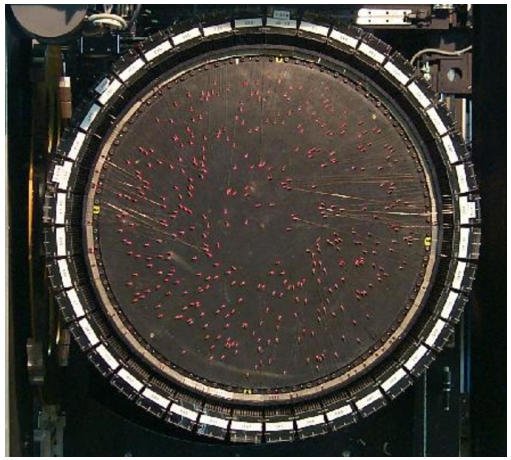


Southern Stellar Stream Spectroscopic Survey (S^5)

- AAT + 2df/AAOmega

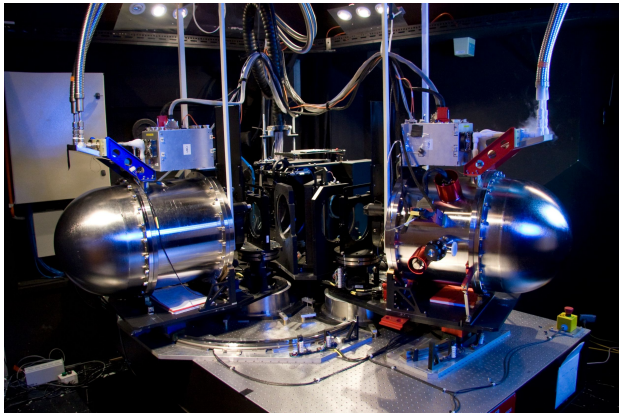
High Multiplexity, wide FOV = ideal for streams

AAT: Anglo-Australian Telescope (4 meter) at Siding Spring Observatory



2df: 2-deg (in diameter) field fiber positioner w/ 400 fibers

AAOmega: a dual-arm optical spectrograph



Southern Stellar Stream Spectroscopic Survey (S^5)

- AAT + 2df/AAOmega
- ~30 members in the collaborations

S^5 Collaboration

- **DES Milky Way**
  - **Ting Li*** (co-PI)
  - Kyler Kuehn*
  - **Nora Shipp**
  - **Andrew Pace**
  - Alex Drlica-Wagner
  - Vasily Belokurov
  - Jennifer Marshall
  - Sahar Allam
  - Douglas Tucker
  - **Eduardo Balbinot**
  - Keith Bechtol
  - Kathy Vivas
  - Risa Wechsler
  - Brian Yanny
- **DES-External Collaborators**
  - Denis Erkal
  - Sergey Koposov
  - Marla Geha
  - Josh Simon
  - **Yao-Yuan Mao**
  - **Alexander Ji**
- **Australians**
  - Daniel Zucker* (co-PI)
  - Geraint Lewis*
  - Jeffrey Simpson
  - Gary Da Costa
  - **Dougal Mackey**
  - **Zhen Wan**
  - Sarah Martell
  - Gayandhi De Silva
  - Jeremy Mould
  - **Andrew Casey**
  - Joss Bland-Hawthorn
  - Ken Freeman
  - Prajwal Kafle
  - **Sanjib Sharma**
  - Helmut Jerjen

*** S^5 Leadership**

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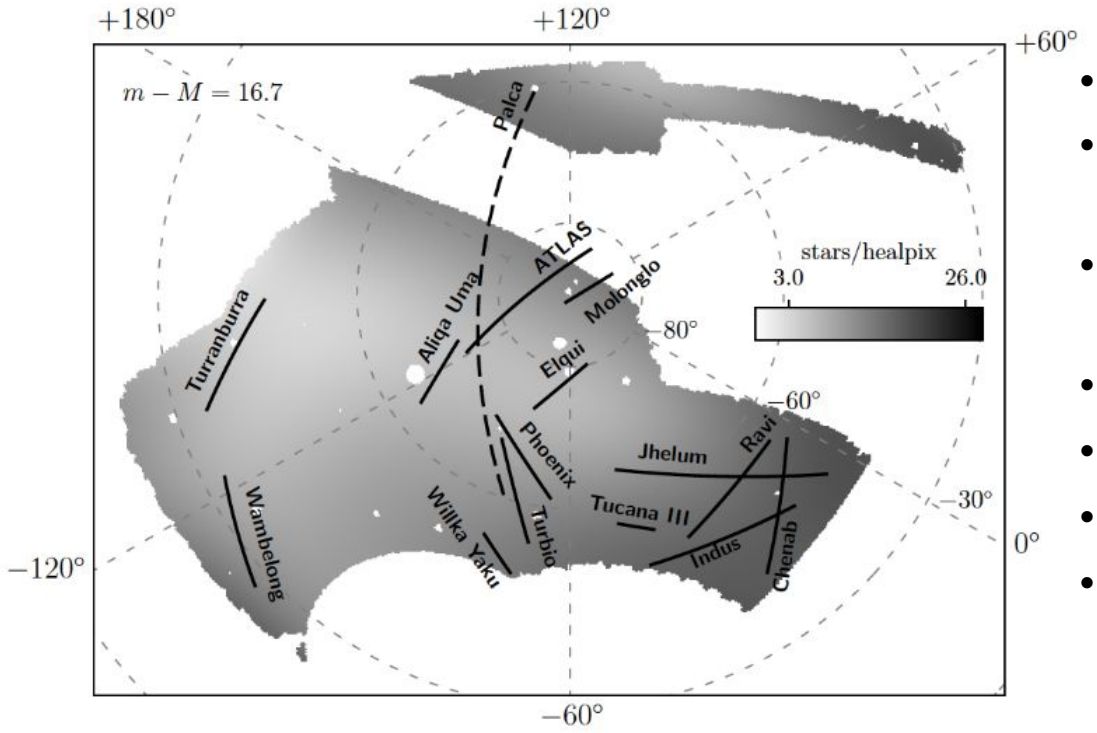

- AAT + 2df/AAOmega
- ~30 members in the collaborations
- Initially started for 14 DES streams (10-50 kpc)
- Targets with 15 < g < 19.5
- R ~ 10,000 @ 8400-8800A
- R ~ 1,300 @ 3700-5700 A
- RV precision ~ 1-5km/s

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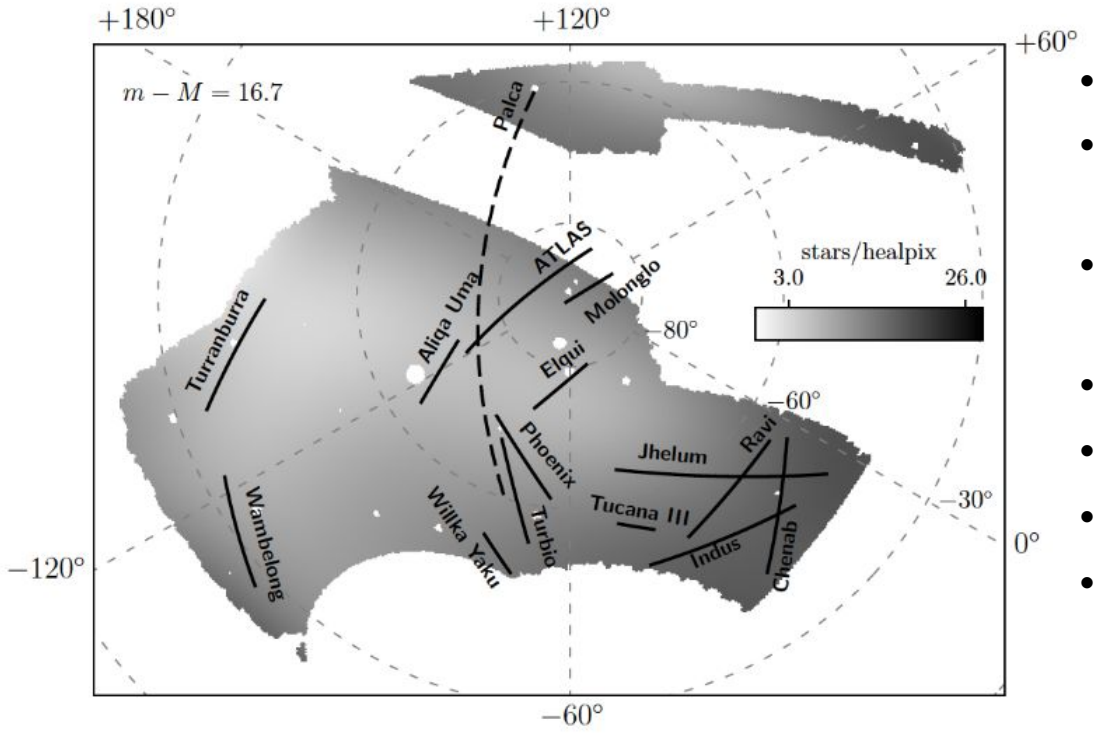

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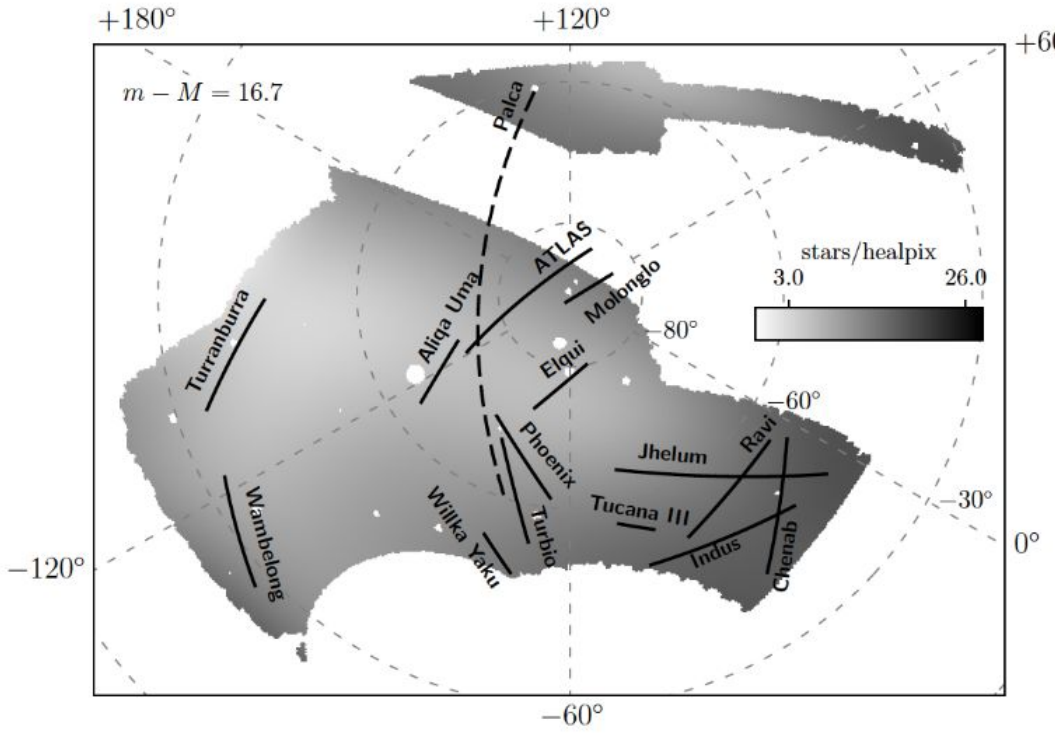

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Goals:

- Measure 6D + metallicity
- Characterize stream progenitors
- Constrain the Milky Way mass

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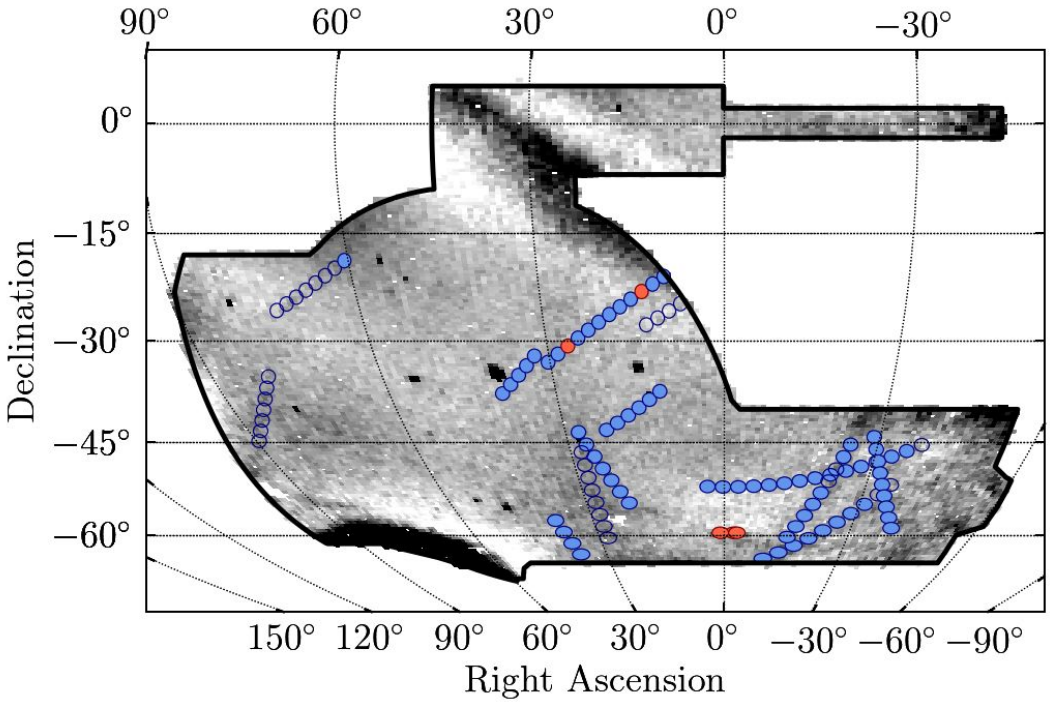
S^5 Status



Observed

Pilot program

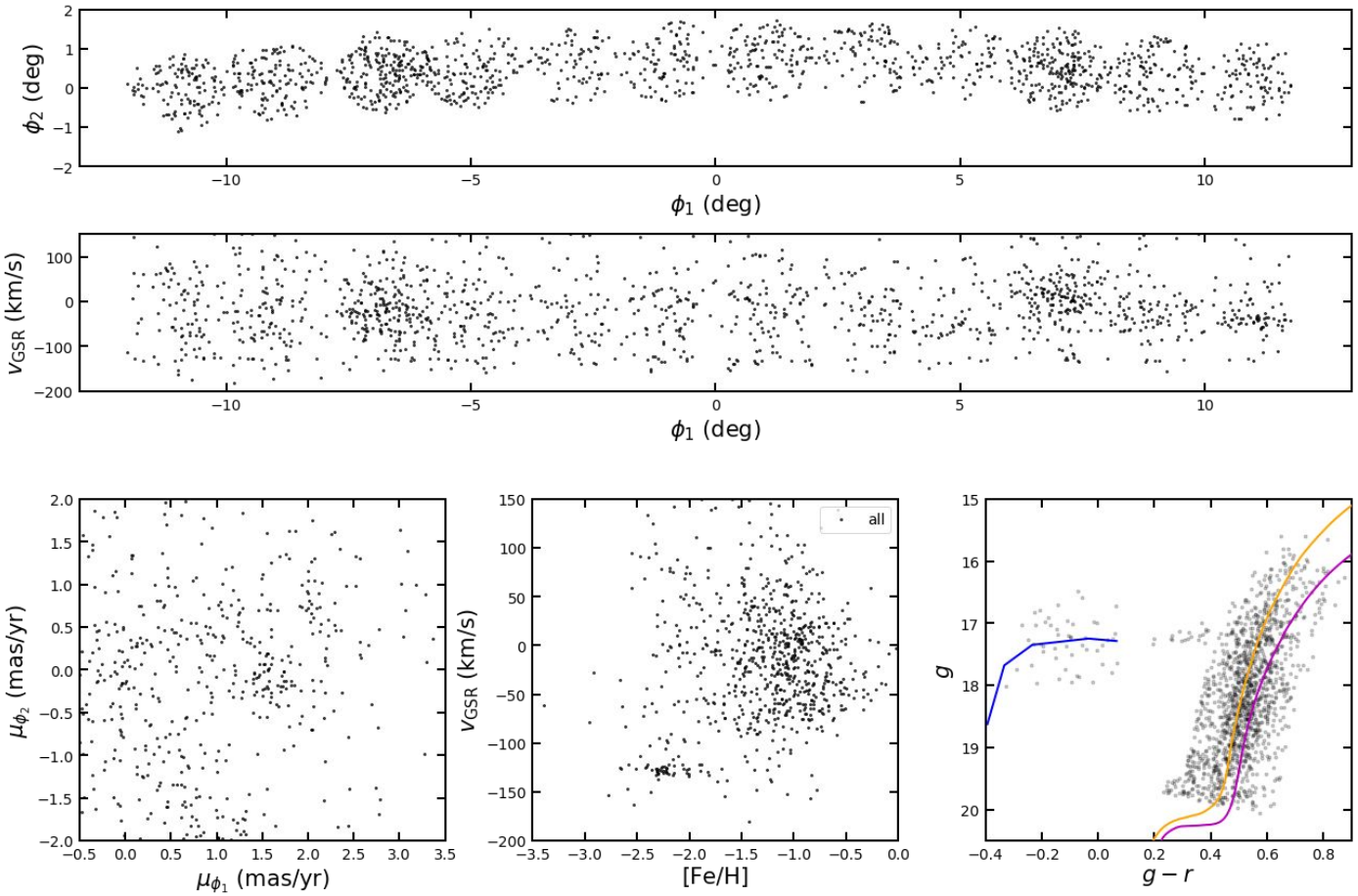
- Started in August 2018
- ~25 nights in 2018B
- **10** DES streams fully mapped; 8 streams are reduced and confirmed

Already double the number of streams with 6D info.

- Expand beyond DES footprint in 2019 for a total of **20** streams

TSL et al. in prep
(S^5 Collaboration)

Example: ATLAS Stream (w/ 12 AAT pointings)



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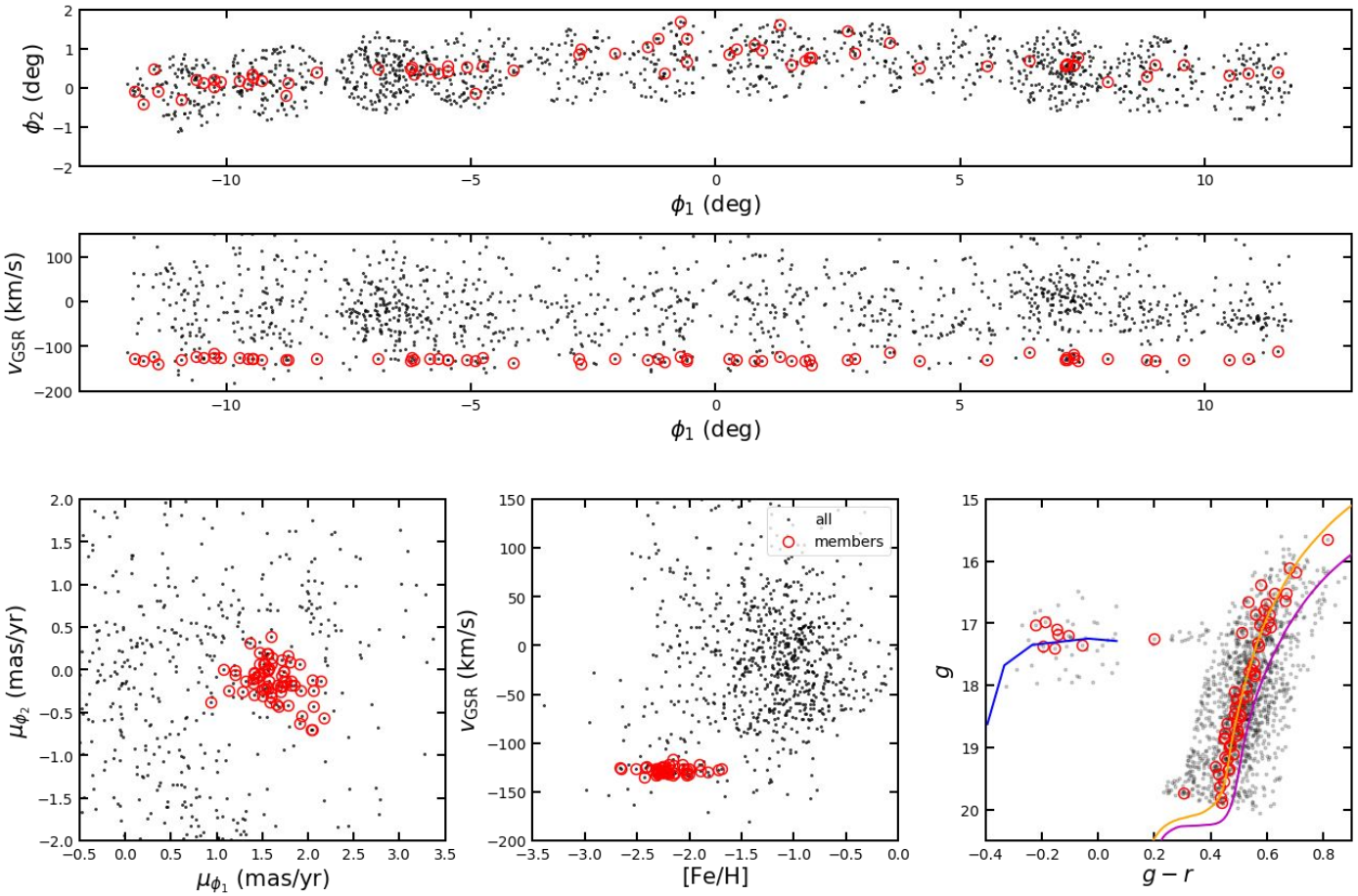

TSL et al. in prep
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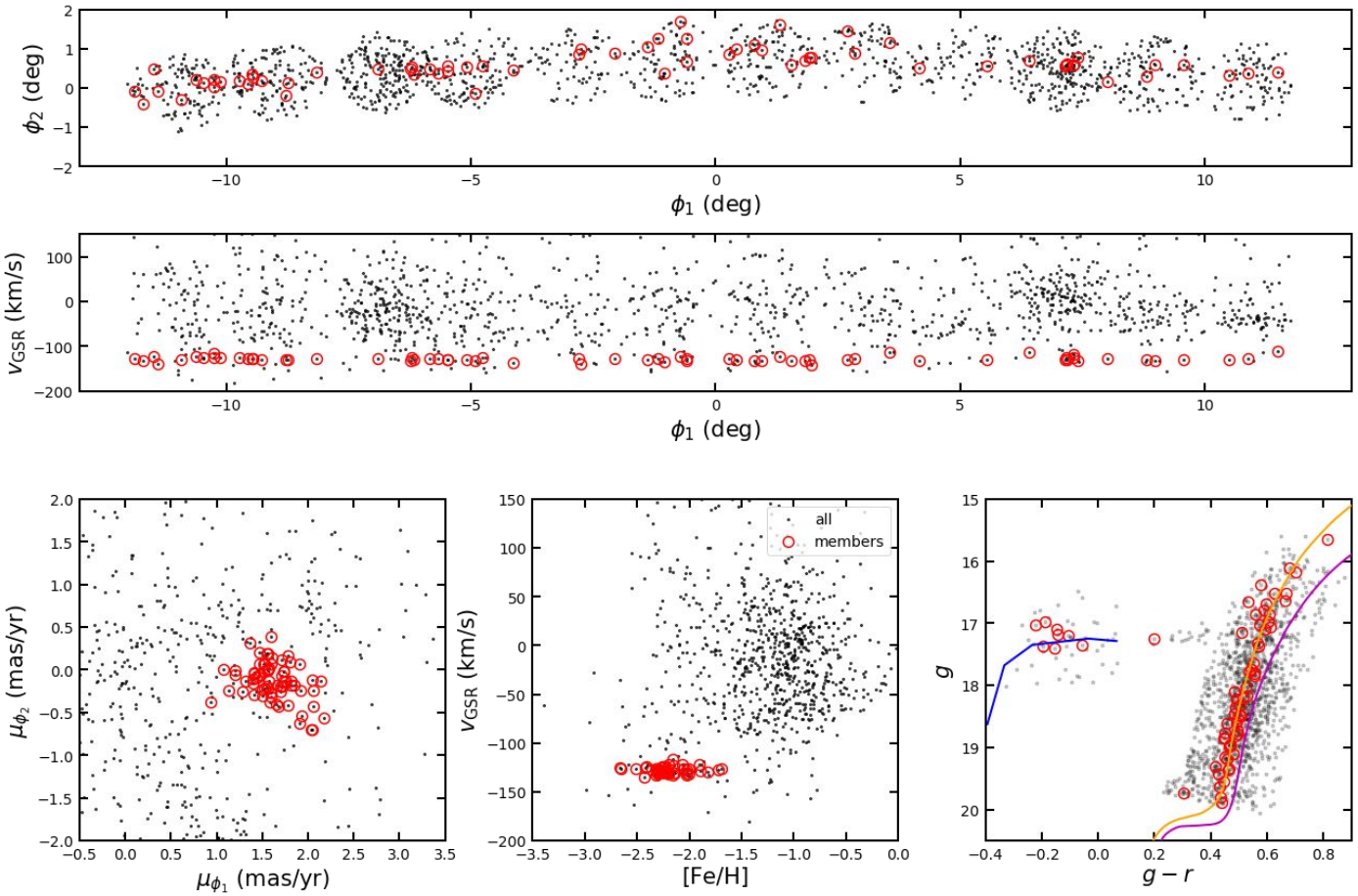
Example: ATLAS Stream (w/ 12 AAT pointings)

- ➔ Line-of-sight velocities
- ➔ Velocity dispersion
- ➔ Metallicities and dispersion
- ➔ Proper motions (Gaia DR2)
- ➔ Orbits (peri/apo)
- ➔ Chemical Abundance (high-resolution follow-up)
- ➔ Progenitors
- ➔ ….



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What does 6D+1 tell us?

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What does 6D+1 tell us?

Goals:

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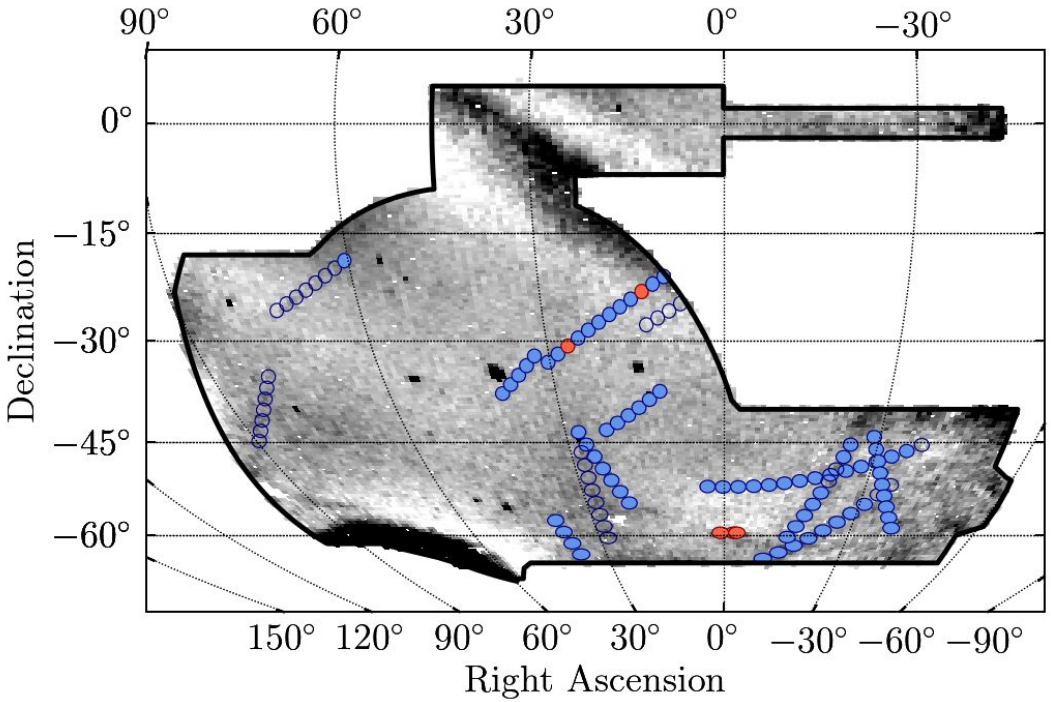
influence of the LMC

- ❑ **Tuc III stream**
- ❑ **Orphan stream**

Denis Erkal

S^5 Status



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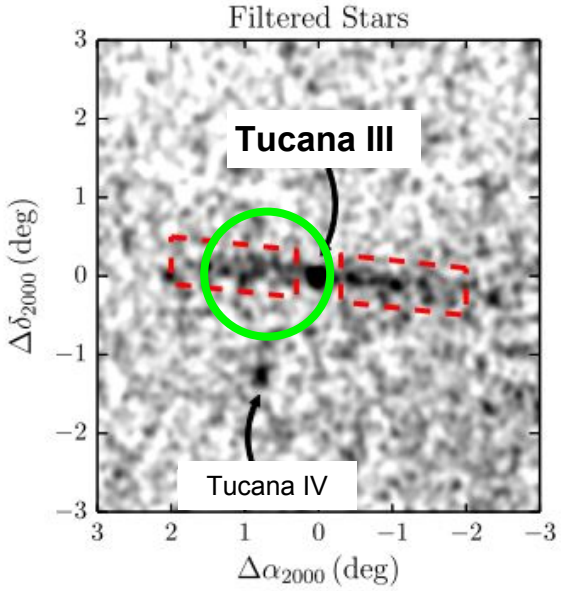
Discovery: Tidal tails around Tucana III

Galactocentric
distance ~ 25 kpc

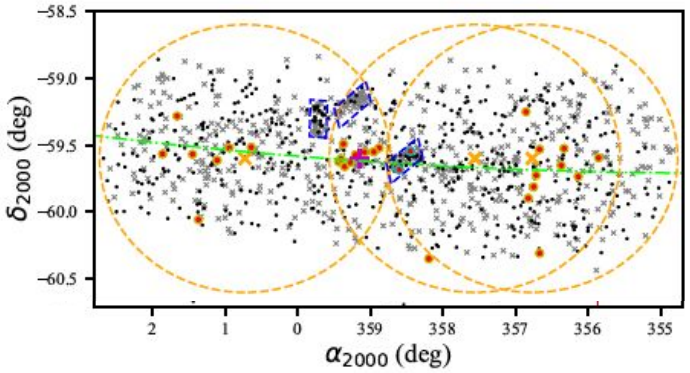


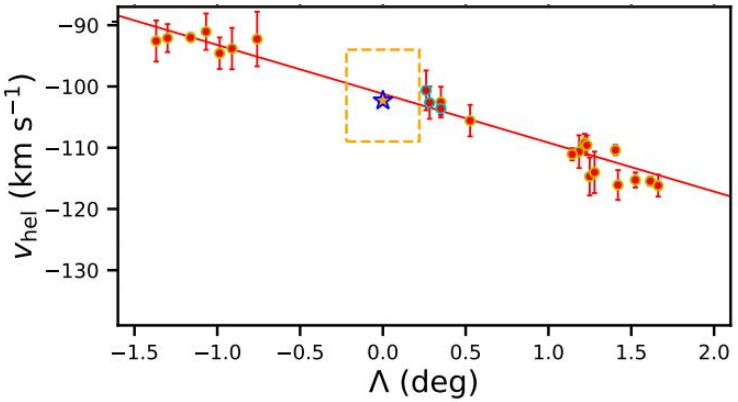
Tidal tails of Tucana III

Drlica-Wagner et al. 2015
(DES Collaboration)

Tucana III Stream

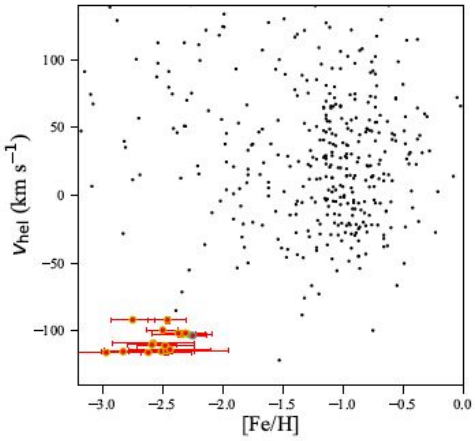
Observed with AAT before Gaia DR2

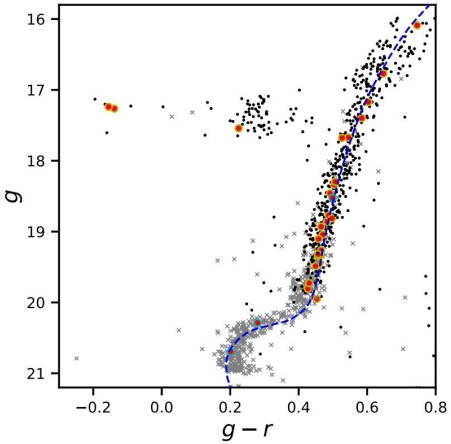




a velocity gradient of 8 km/s/deg

radial orbit





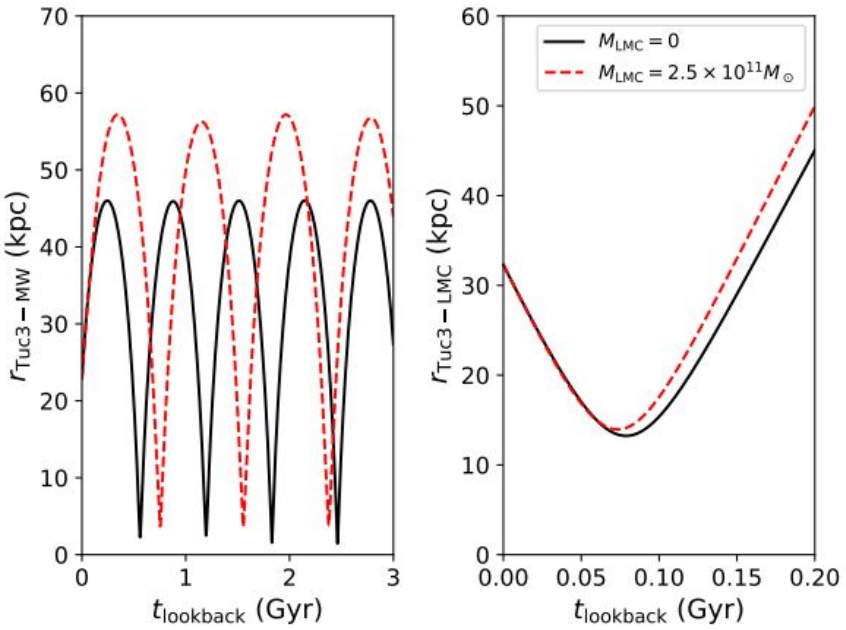
~1000 targets observed
~25 members confirmed

very metal poor
stream [Fe/H] ~ -2.5

TSL et al. 2018
(DES Collaboration)

Fitting the orbit

Erkal, TSL et al. 2018
(DES Collaboration)



a pericenter ~ 2-3 kpc

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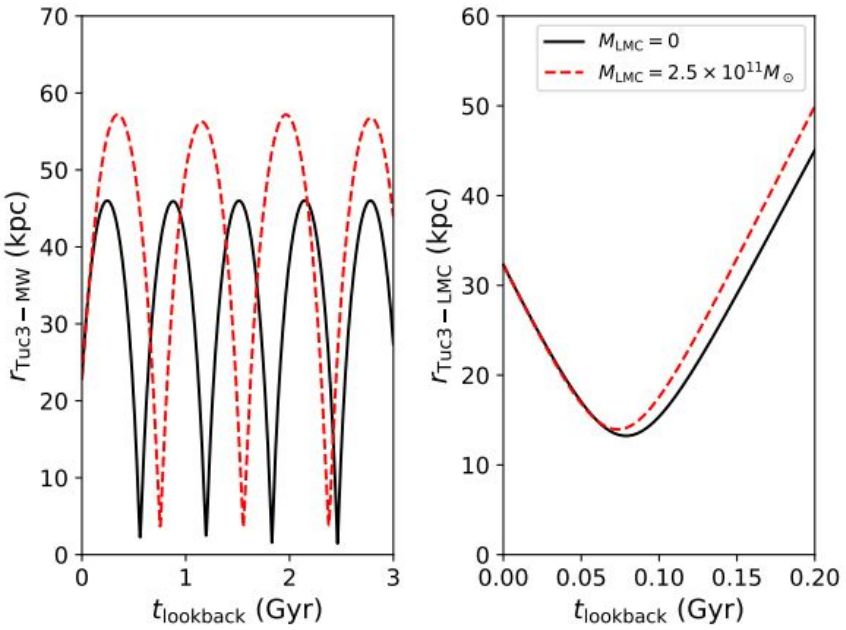
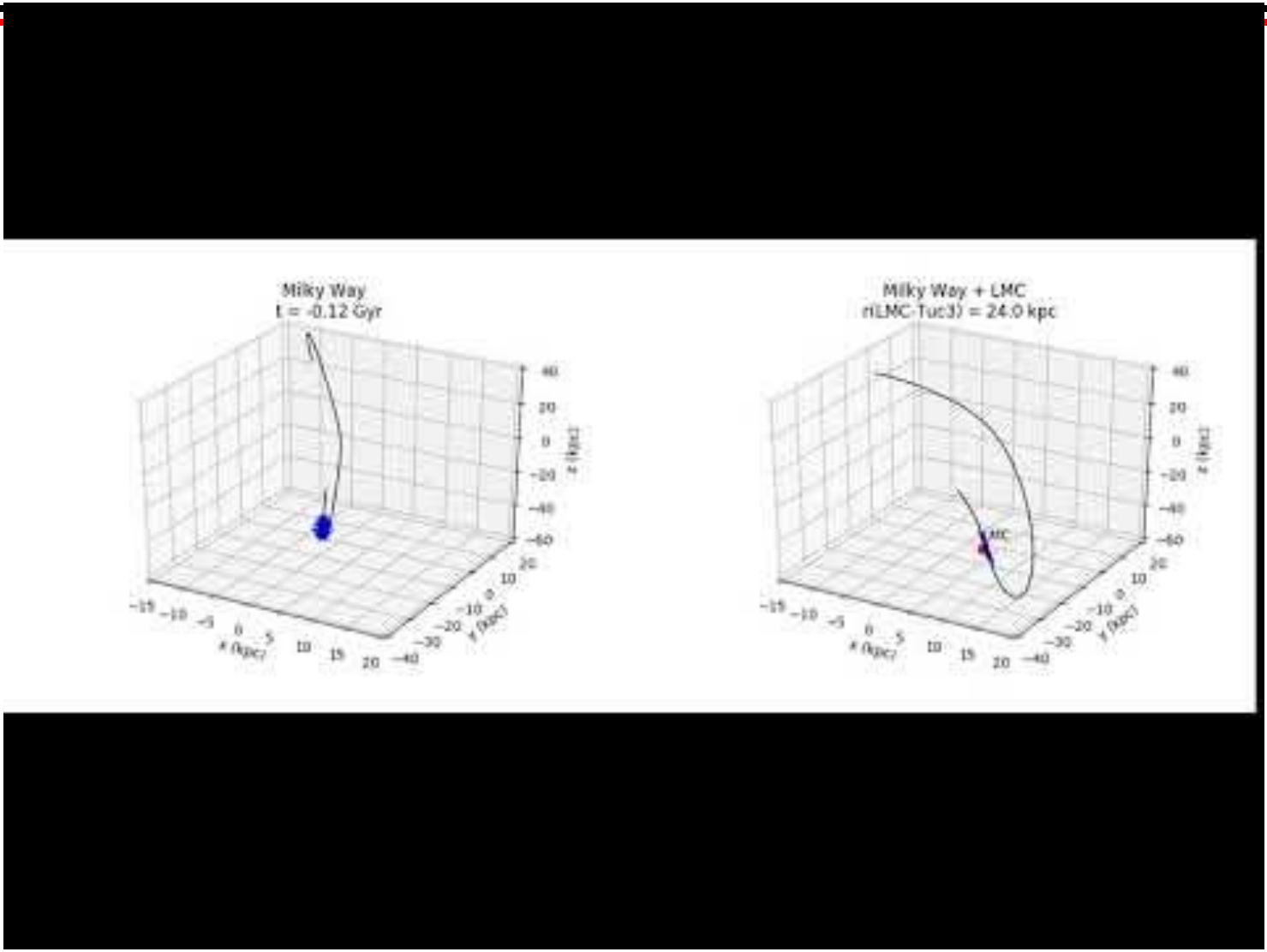


a pericenter ~ 2-3 kpc
minimum approach to LMC — ~12 kpc

LMC cannot be ignored

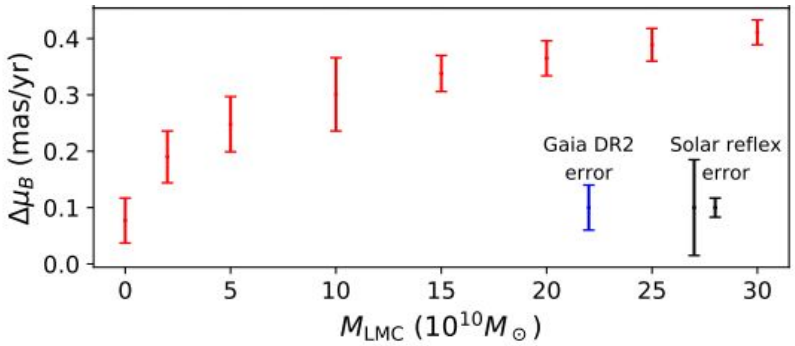
Tuc III stream in the presence of LMC



Credit: Denis Erkal

Prediction for the Proper Motion

Proper motions perpendicular to the stream

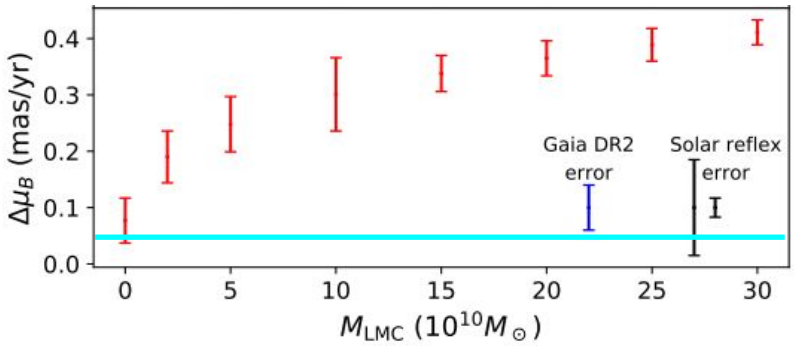


Erkal, TSL et al. 2018
(DES Collaboration)

Constrain the LMC mass w/ Tucana III

Prediction for the Proper Motion

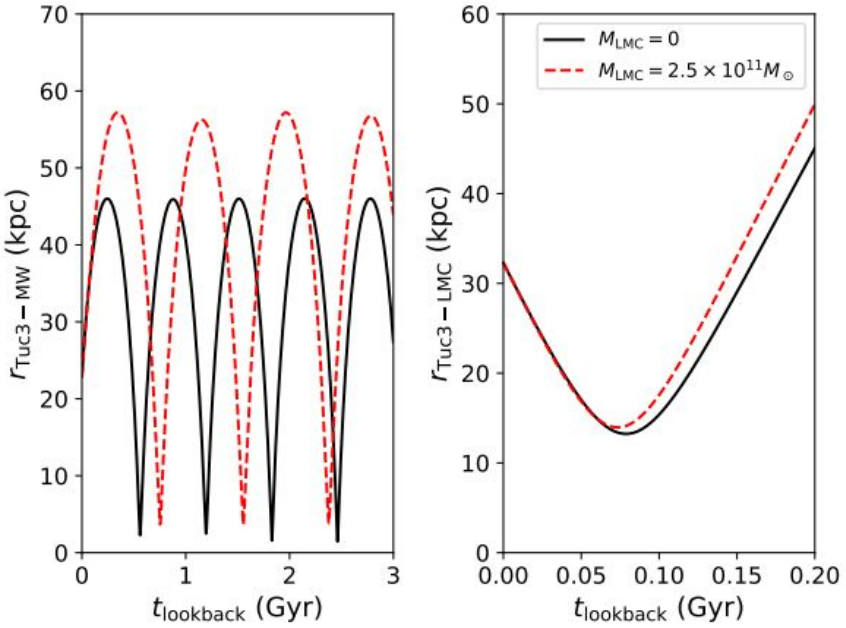
Proper motions perpendicular to the stream



Erkal, TSL et al. 2018
(DES Collaboration)

Fitting the orbit

Erkal, TSL et al. 2018
(DES Collaboration)

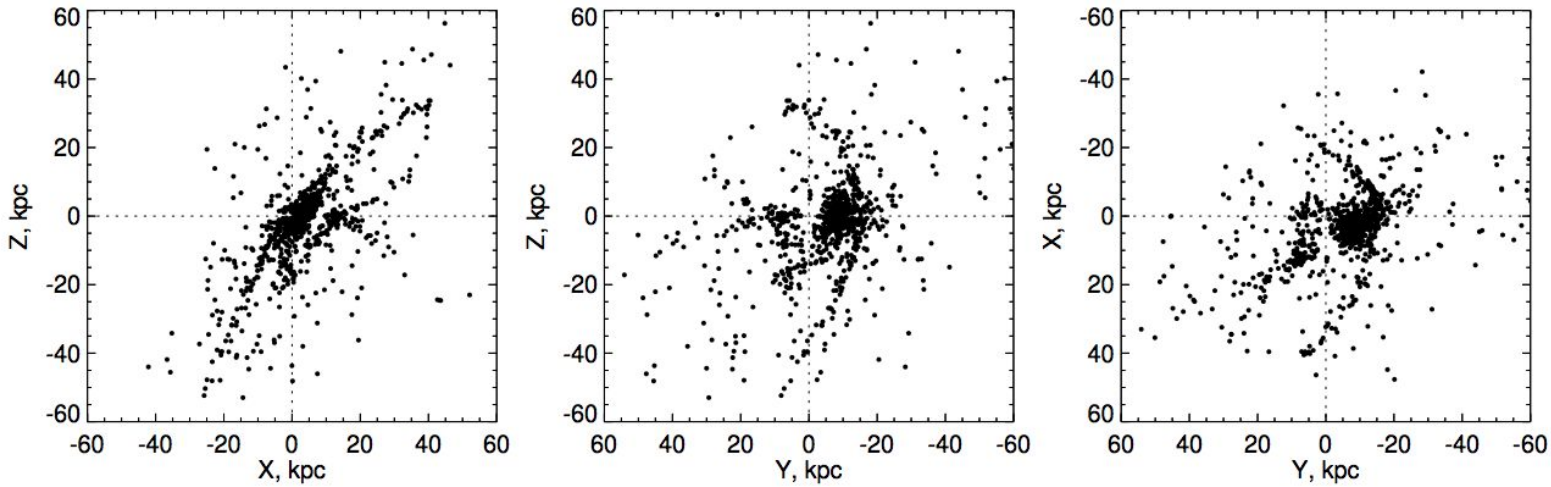


a pericenter ~ 2-3 kpc
minimum approach to LMC — ~12 kpc

LMC cannot be ignored

Orphan Stream

Orphan Stream inferred from RR Lyraes in Gaia DR2



Koposov et al. 2019, arXiv: 1812.08172
(The OATs Collaboration)

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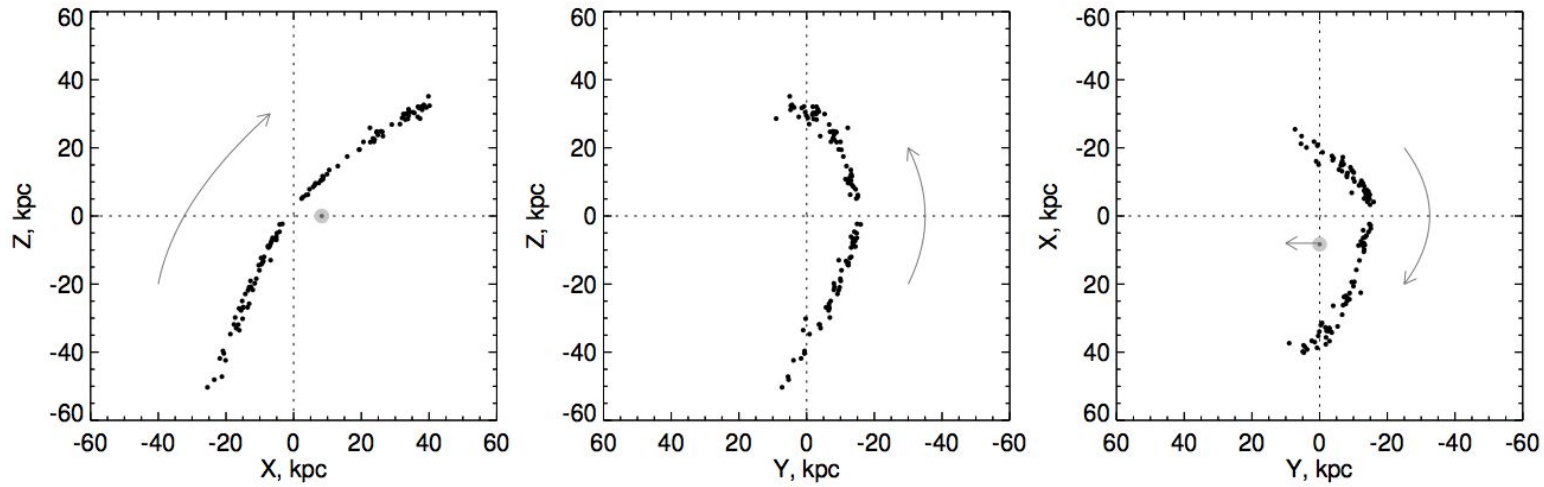

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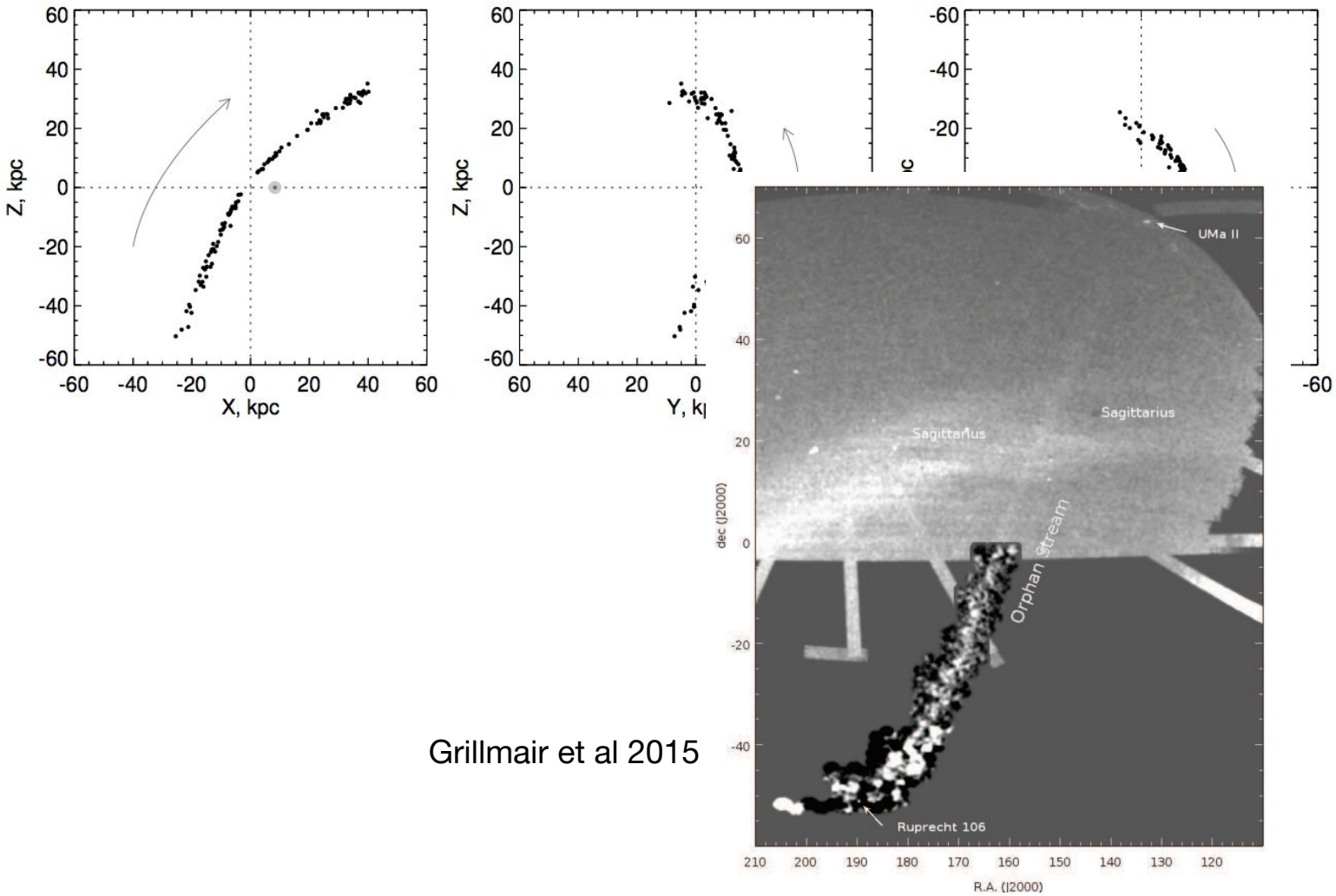
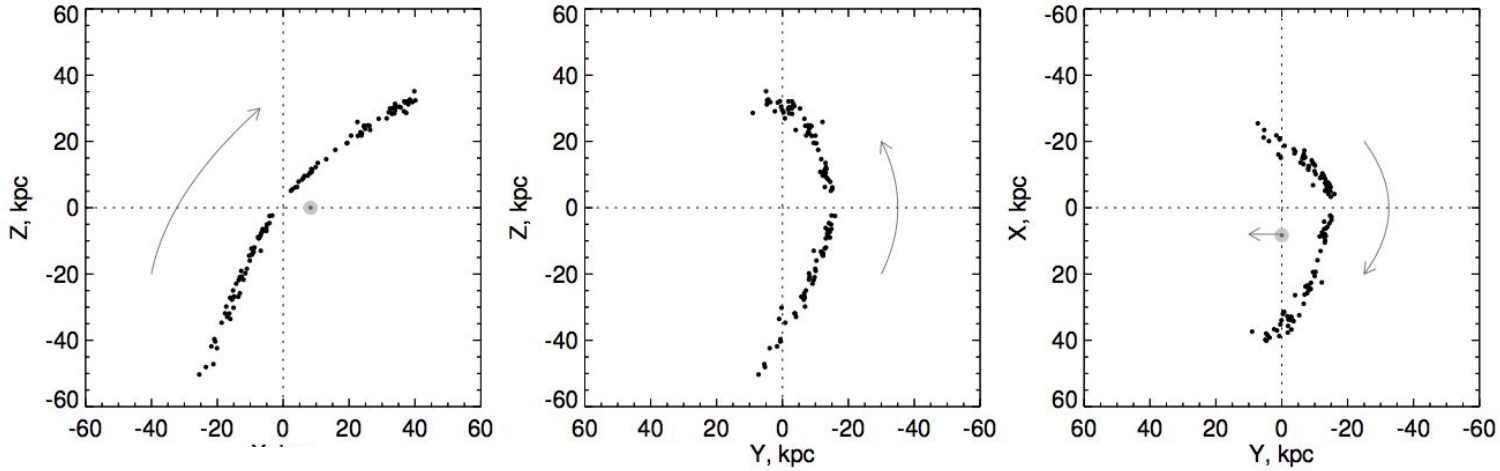
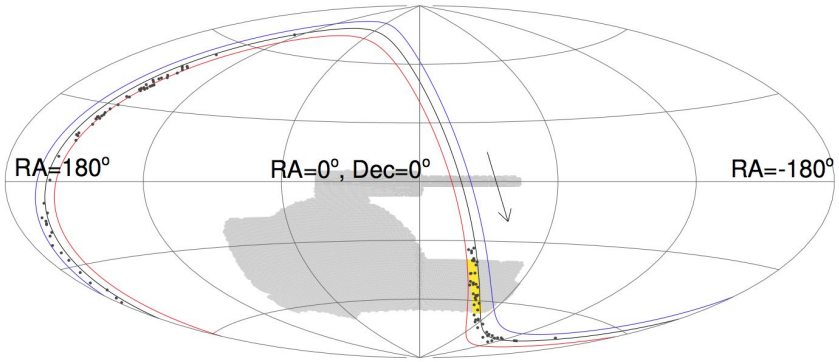


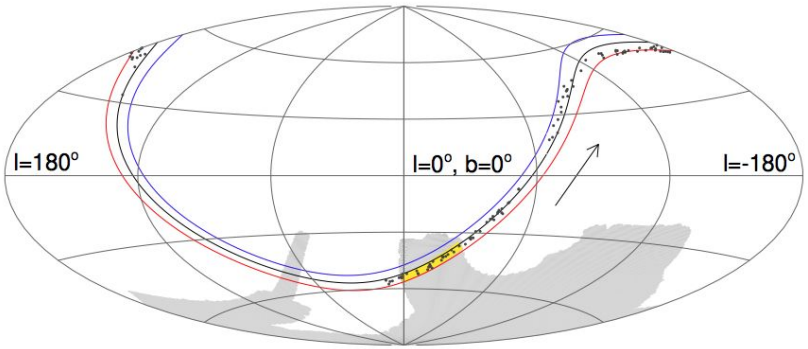
Grillmair et al 2015

Orphan Stream

Orphan Stream inferred from RR Lyraes in Gaia DR2







Koposov et al. 2019, arXiv: 1812.08172
(The OATs Collaboration)

Orphan Stream

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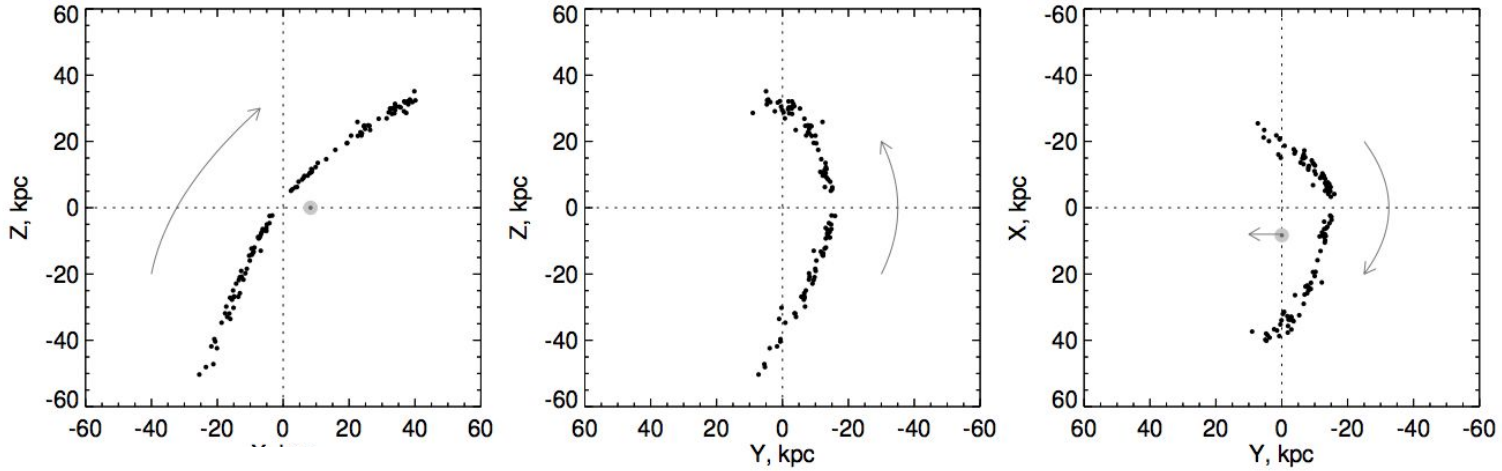
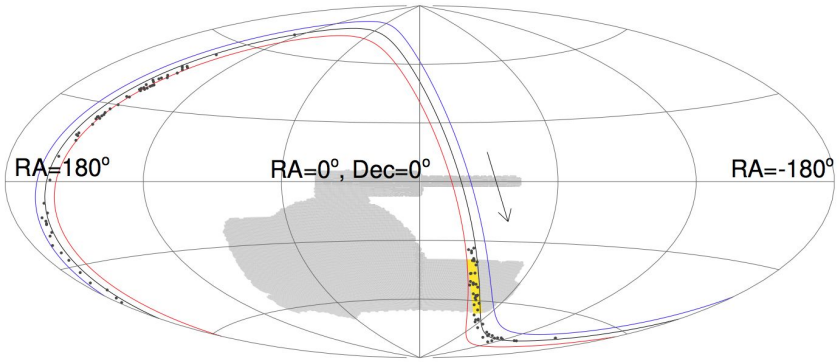
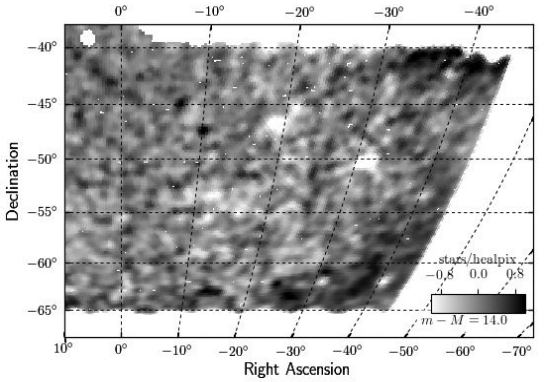




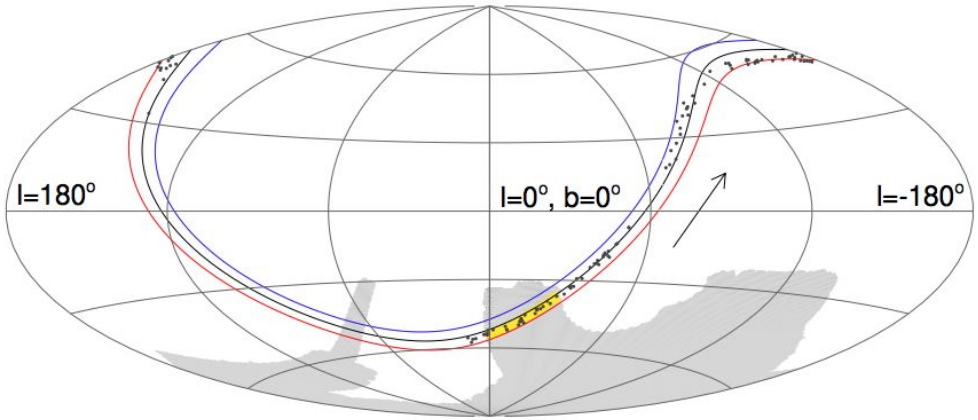


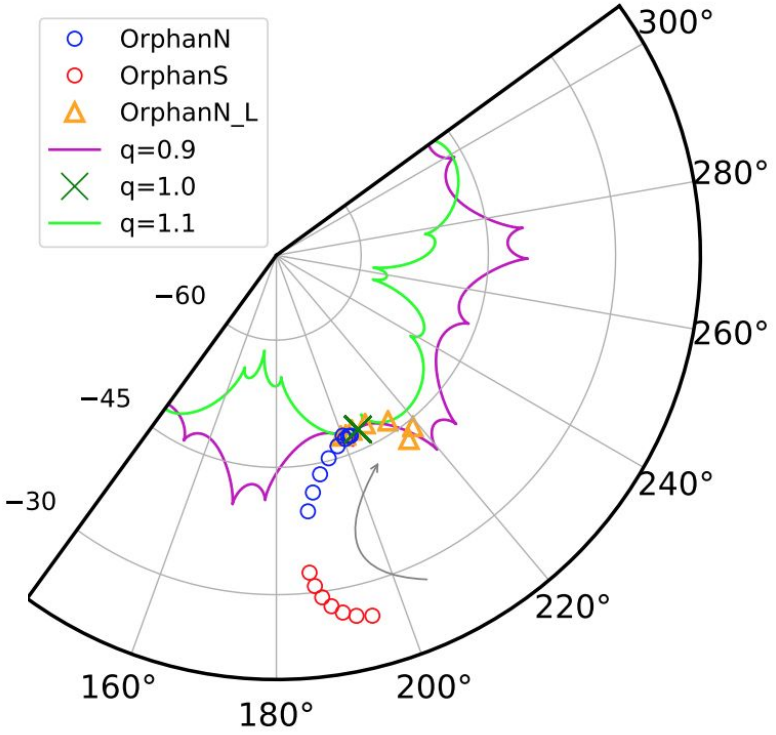
Shipp et al. 2018

Koposov et al. 2019, arXiv: 1812.08172
(The OATs Collaboration)

Orphan Stream

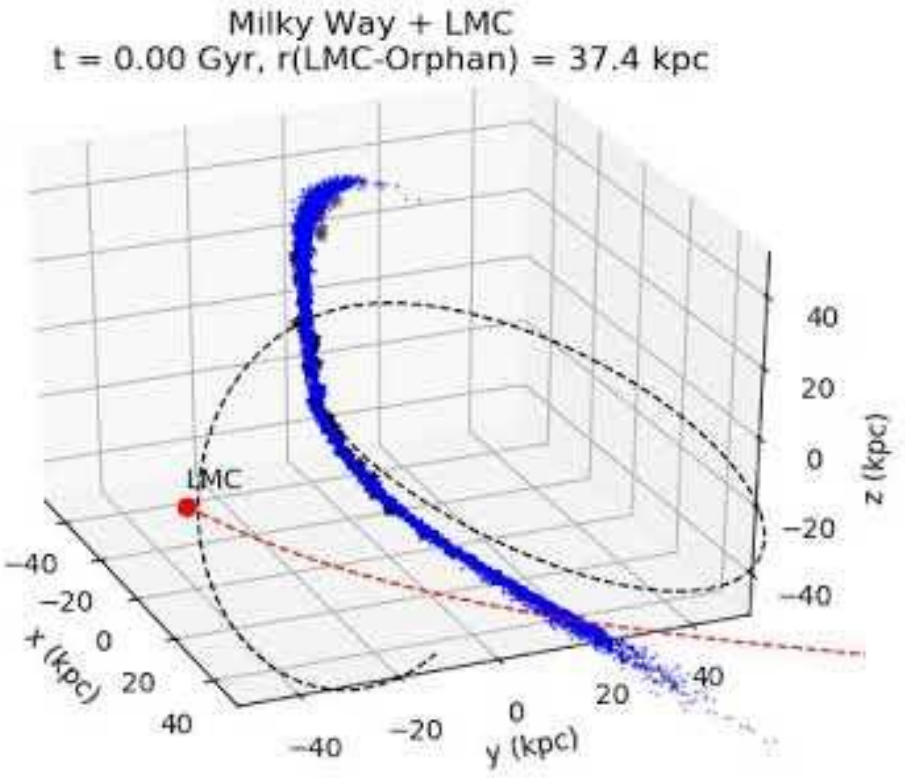
Galactocentric Pole drifts
Significantly: > 20 deg





Koposov et al. 2019, arXiv: 1812.08172
(The OATs Collaboration)

Orphan Stream is perturbed by LMC

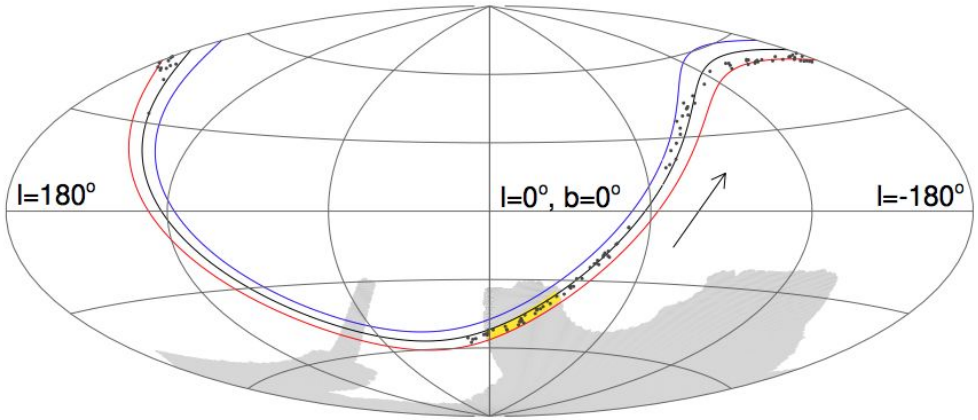


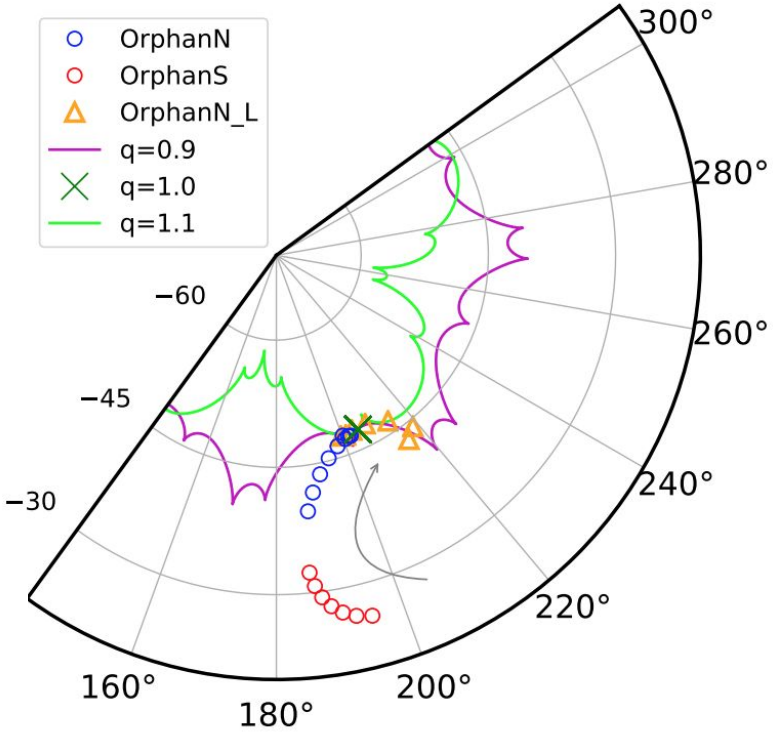
Credit: Denis Erkal

http://personal.ph.surrey.ac.uk/~de0012/files/orphan_pr/

Orphan Stream

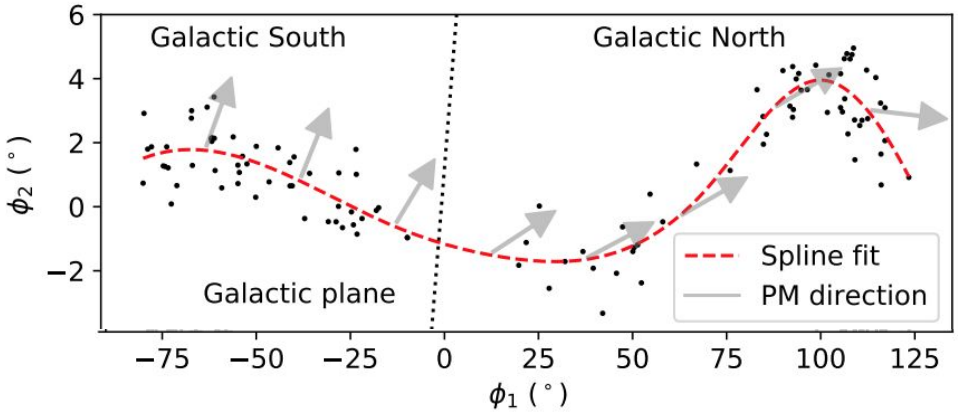
Galactocentric Pole drifts
Significantly: > 20 deg





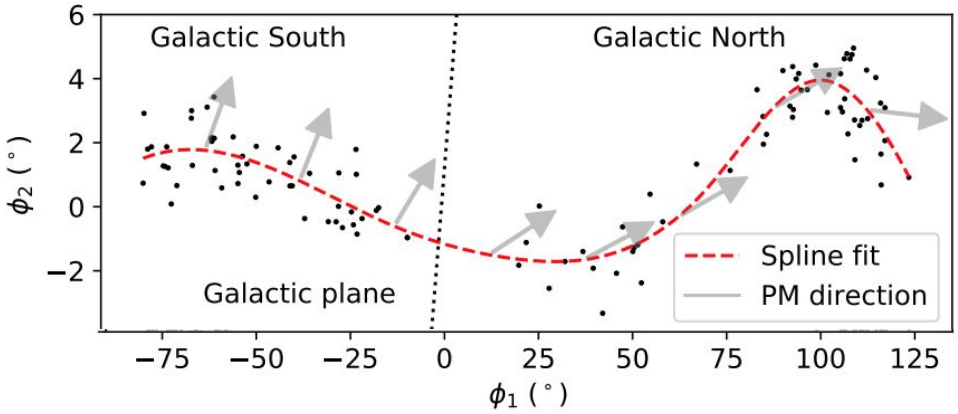
Koposov et al. 2019, arXiv: 1812.08172
(The OATs Collaboration)

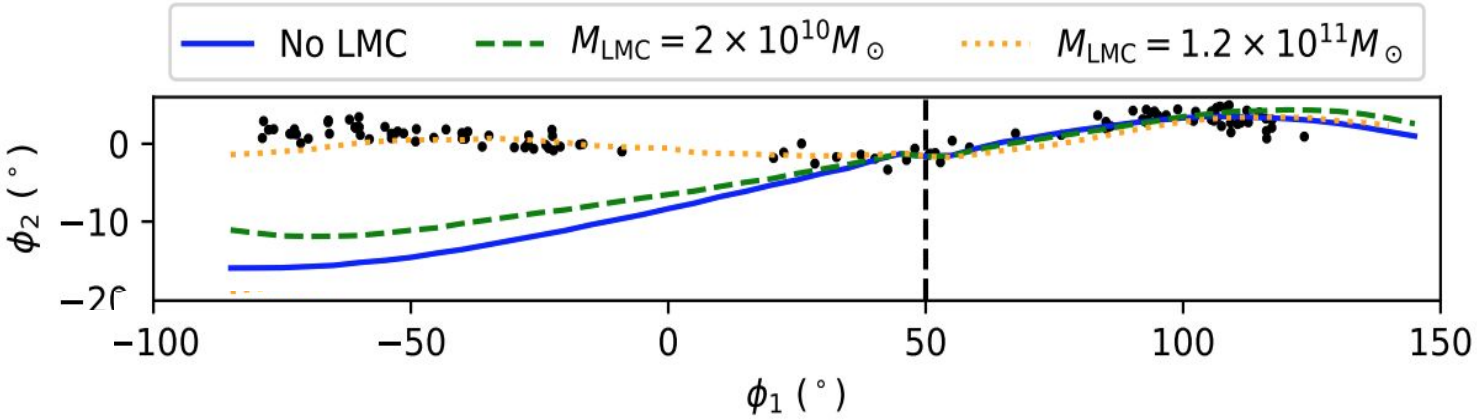
Perturbation from LMC



Erkal et al. 2019, arXiv: 1812.08192
(The OATs Collaboration)

Perturbation from LMC

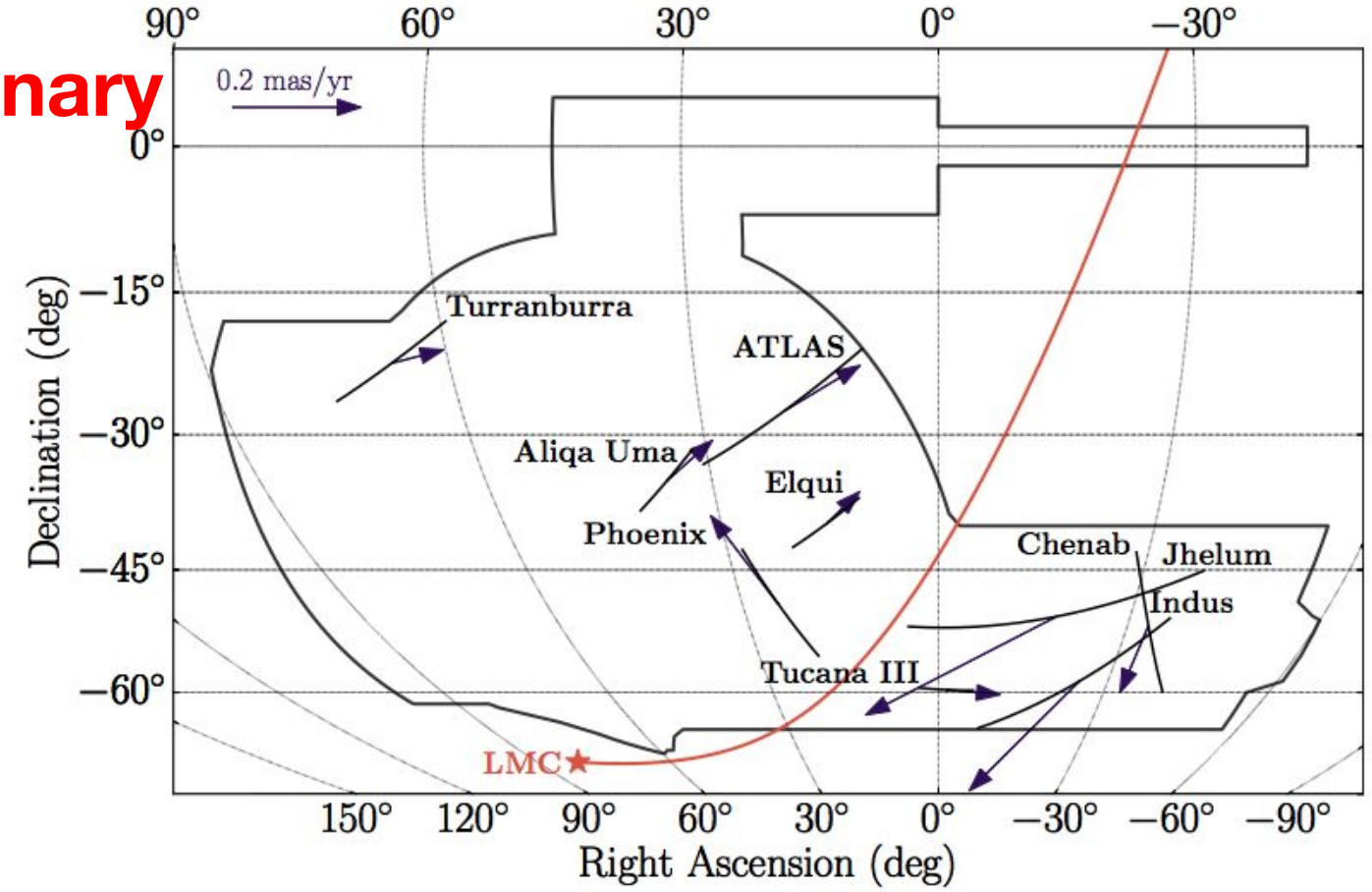




Erkal et al. 2019, arXiv: 1812.08192
(The OATs Collaboration)

Proper Motion / Track Misalignment

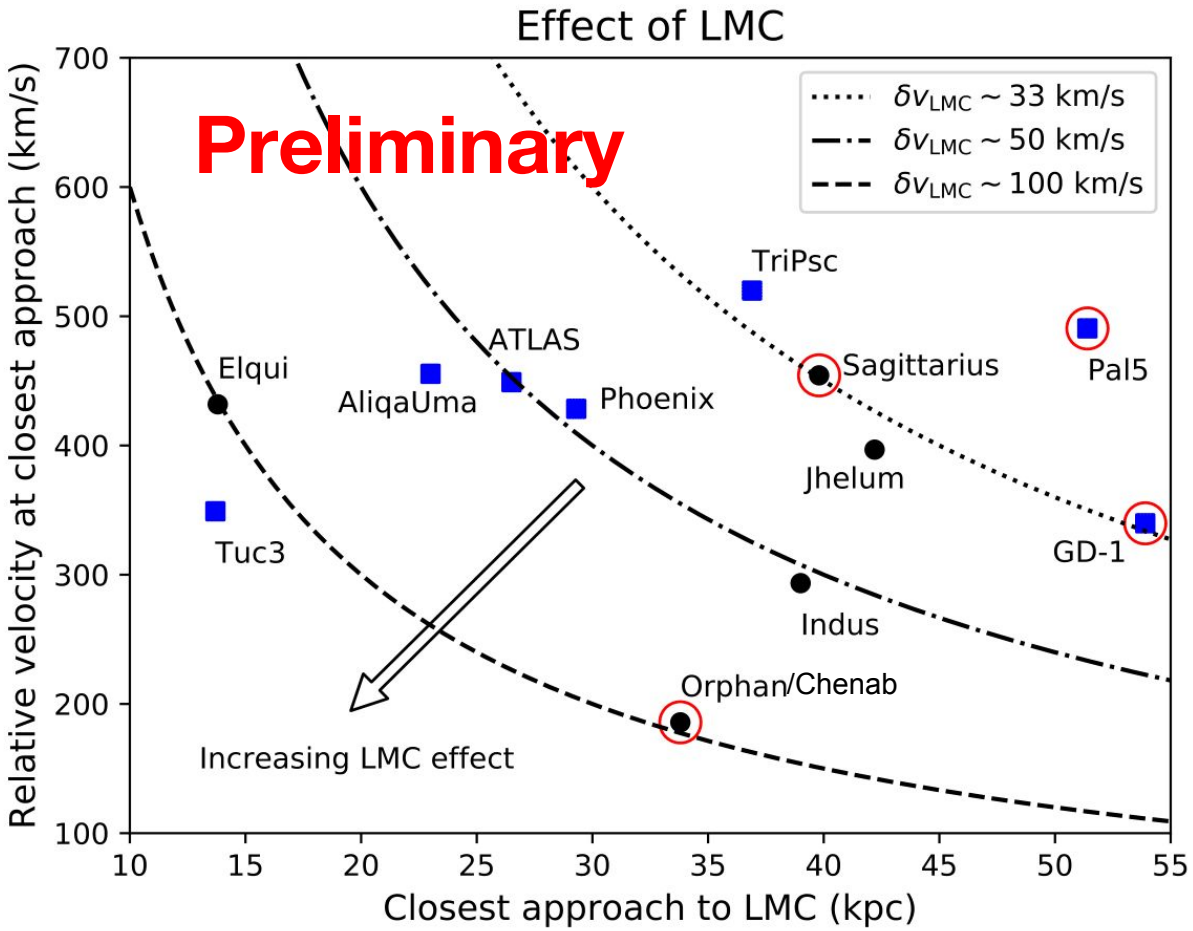
Preliminary



Shipp et al. in prep

Most Southern Streams were affected by LMC

Perturbation from LMC



Globular cluster stream

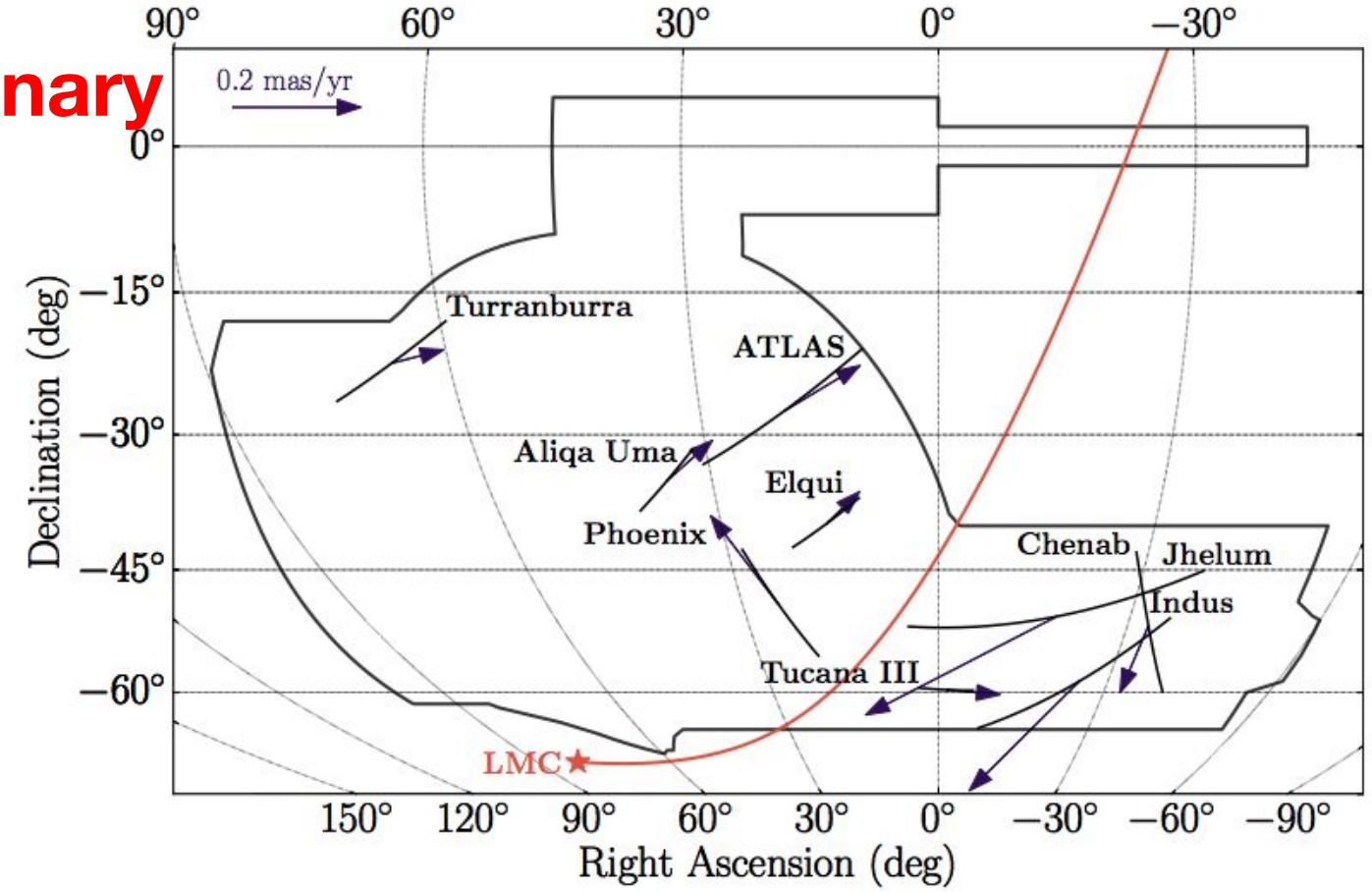
Dwarf galaxy stream

Stream has been fit

Simultaneous fit with multiple streams can infer the 3D profile of LMC

Proper Motion / Track Misalignment

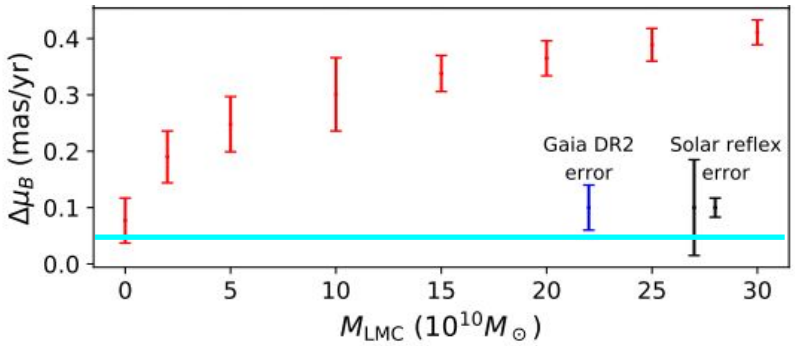
Preliminary



Shipp et al. in prep

Prediction for the Proper Motion

Proper motions perpendicular to the stream

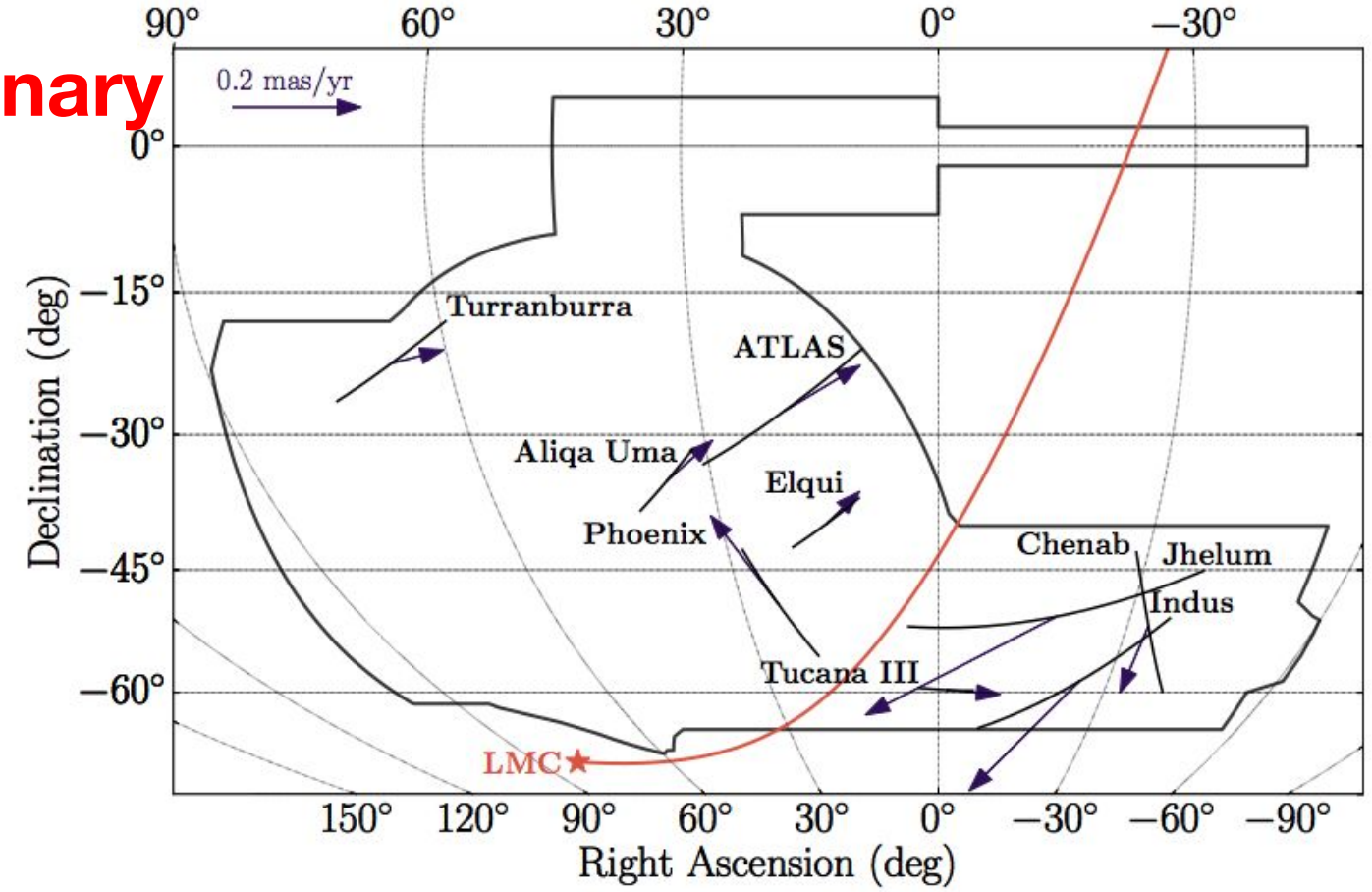


Erkal, TSL et al. 2018
(DES Collaboration)

➢ **Milky Way's reflex motion was not considered**

Proper Motion / Track Misalignment

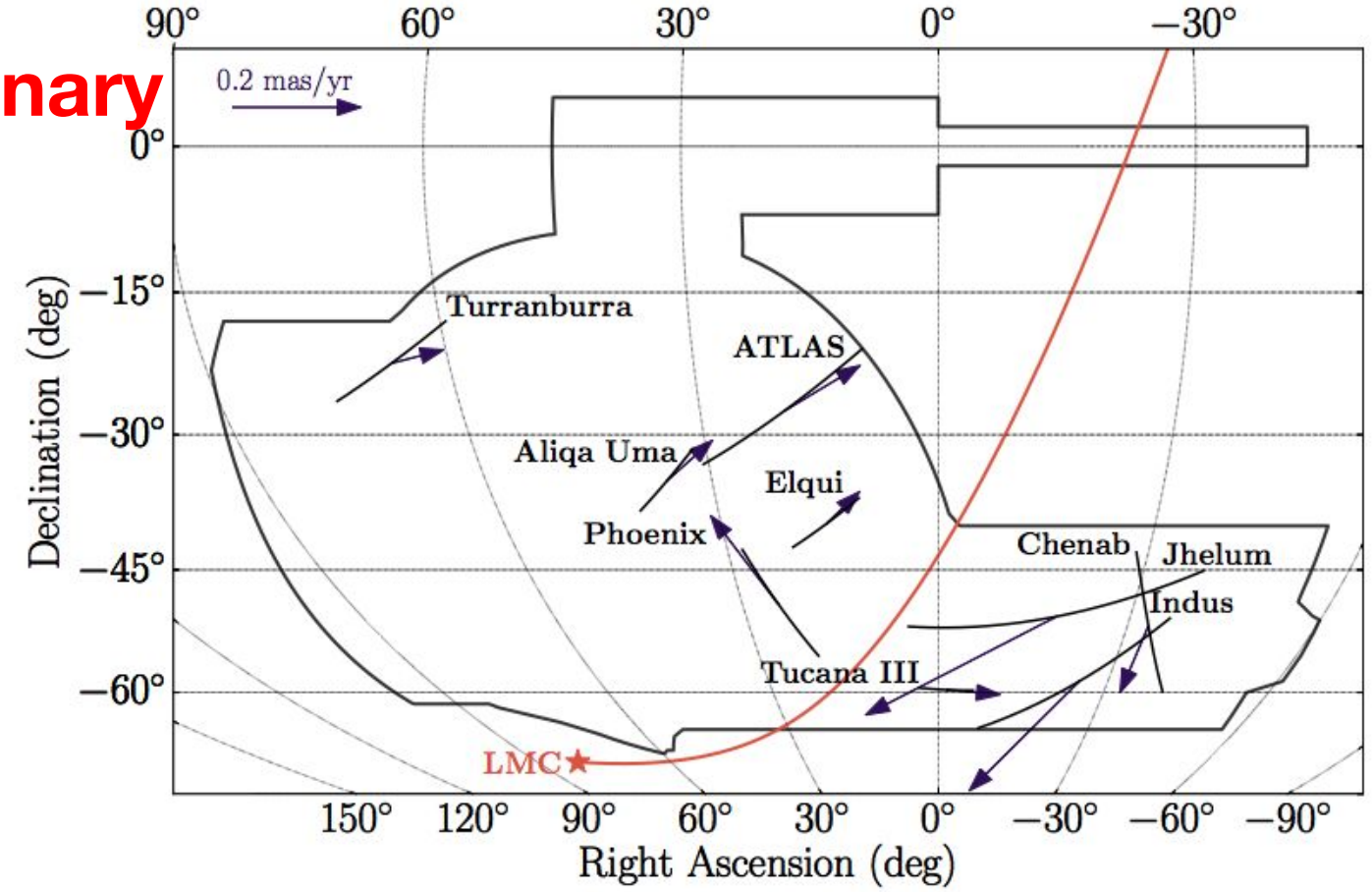
Preliminary



Shipp et al. in prep

Proper Motion / Track Misalignment

Preliminary



misalignment in distance gradient/RV

Shipp et al. in prep

Summary

- **Only ~10% of the stellar streams have been followed up spectroscopically. We know very little about the orbit/kinematics/chemistry of the streams**
- **We are at the best time to follow-up all the streams, thanks to Gaia DR2.**
- **We are in the process of obtaining 6D+1 info for the southern streams**
  - **Characterize stream progenitors**
  - **Constrain the Milky Way potential/mass**

We must account for the LMC if we want to measure MW's shape.

Simultaneous fit with multiple streams can infer the 3D profile of LMC

If a stream in the south should be followed, please let us know!