DWARF GALAXIES AND STELLAR STREAMS IN THE ERA OF GAIA AND WFIRST

Ting Li
Leon Lederman Fellow, Fermilab
KICP Associate Fellow, University of Chicago

WFIRST Science In Our Own Backyard
Caltech, June 18-20, 2019

SOC : a talk “on the topic of Galactic streams, satellites, DM and relation of WFIRST to DES and MSE.”

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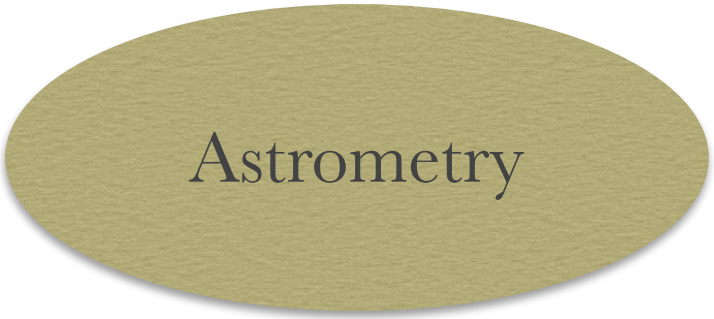
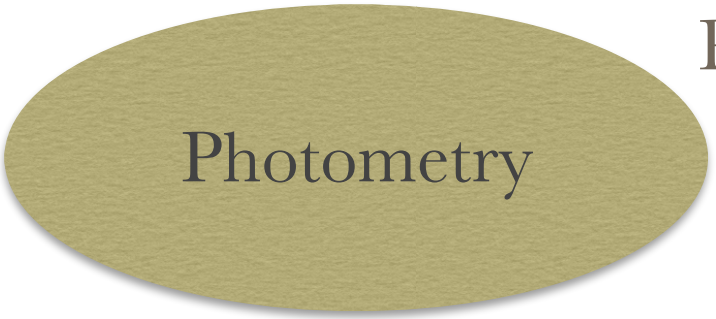
Astronomy: Science of Observations



Position
Distance (foreground removal)
Proper Motion



Brightness and color
Stellar Population (CMD)
Structure Parameters
Distance (galaxies or streams)

Line-of-sight Motion
Stellar Parameters
Chemical Composition

Where are we now?

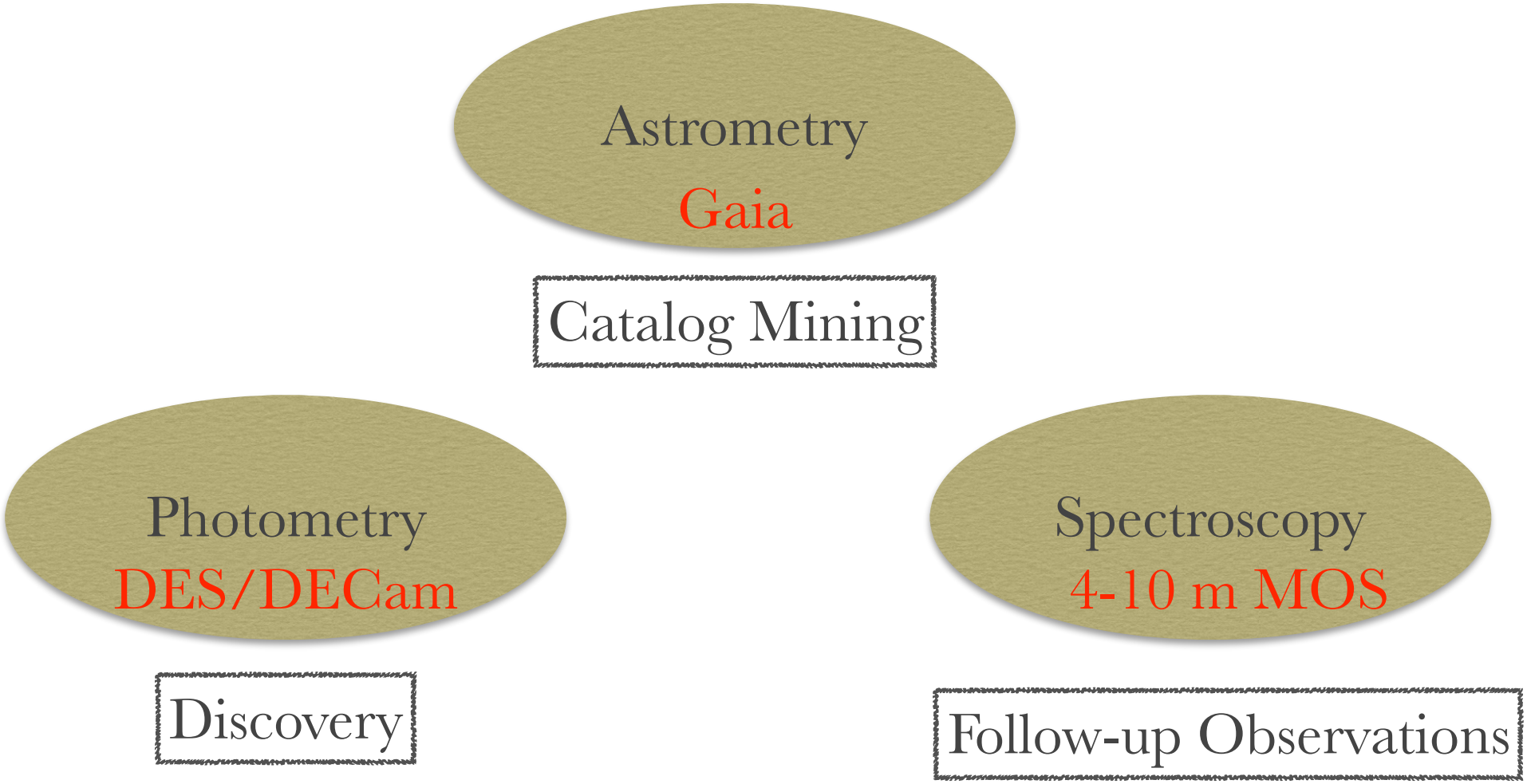
Ongoing Surveys

Astrometry
Gaia

Photometry
DES/DECam

Spectroscopy
4-10 m MOS

Ongoing Surveys

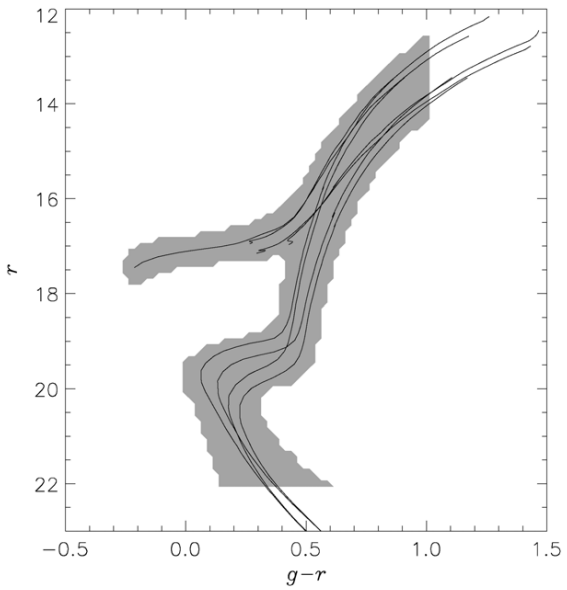


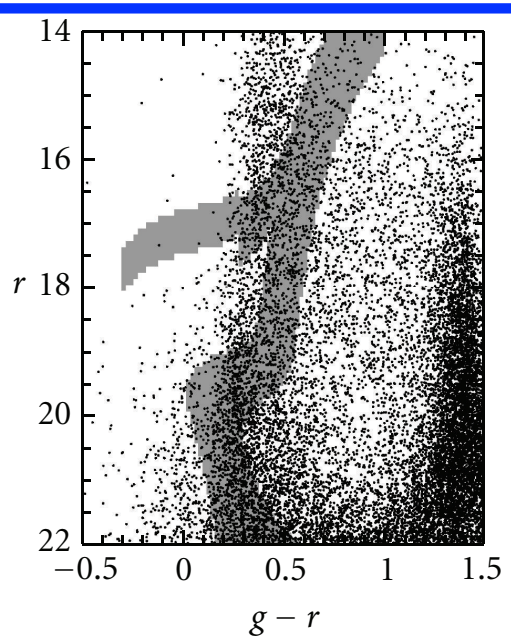

Photometry
DES/DECam
THE DARK ENERGY SURVEY
Dark Energy Survey (DES)
• optical grizY imaging survey with Blanco 4m and DECam at CTIO
• ~600 nights from 2012-2018
• 5000 sq deg sky coverage with a depth of 24-25th mag
• an international collaboration of ~400 members; 90% on cosmology
• ~10-20 active members in Milky Way WG (current conveners: Keith Bechtol and Ting Li)
• 24 papers published, 3 submitted
• ~180 papers published total in DES

Ultra-Faint Dwarf Galaxies: Discovery

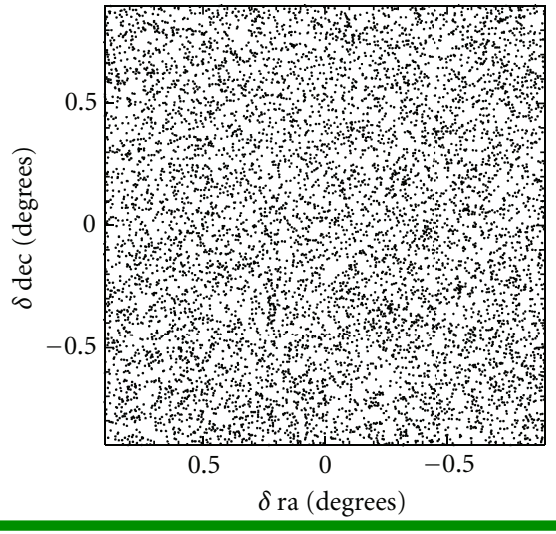
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

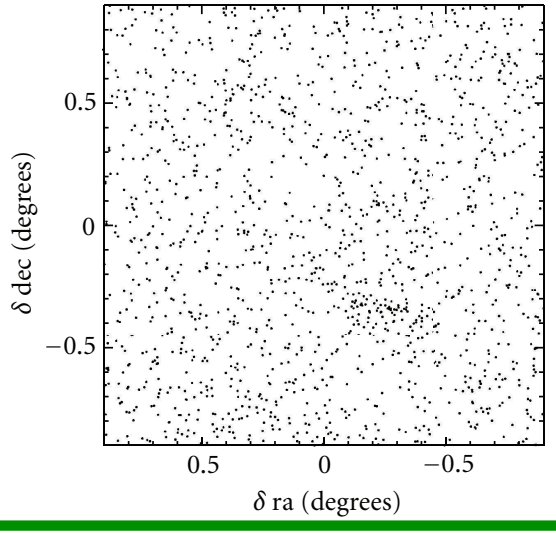
Color-Magnitude Domain

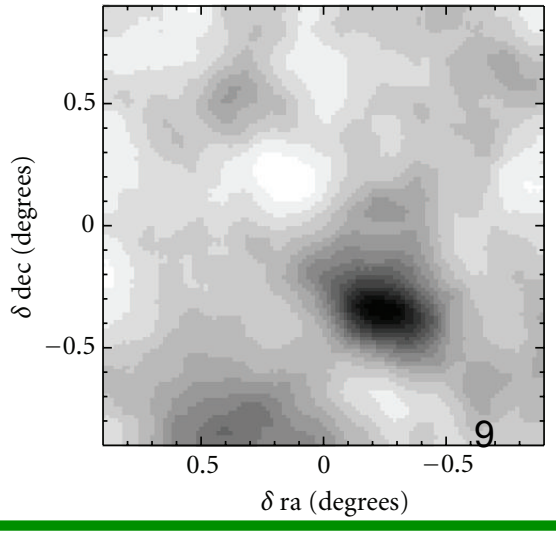




Spatial Domain

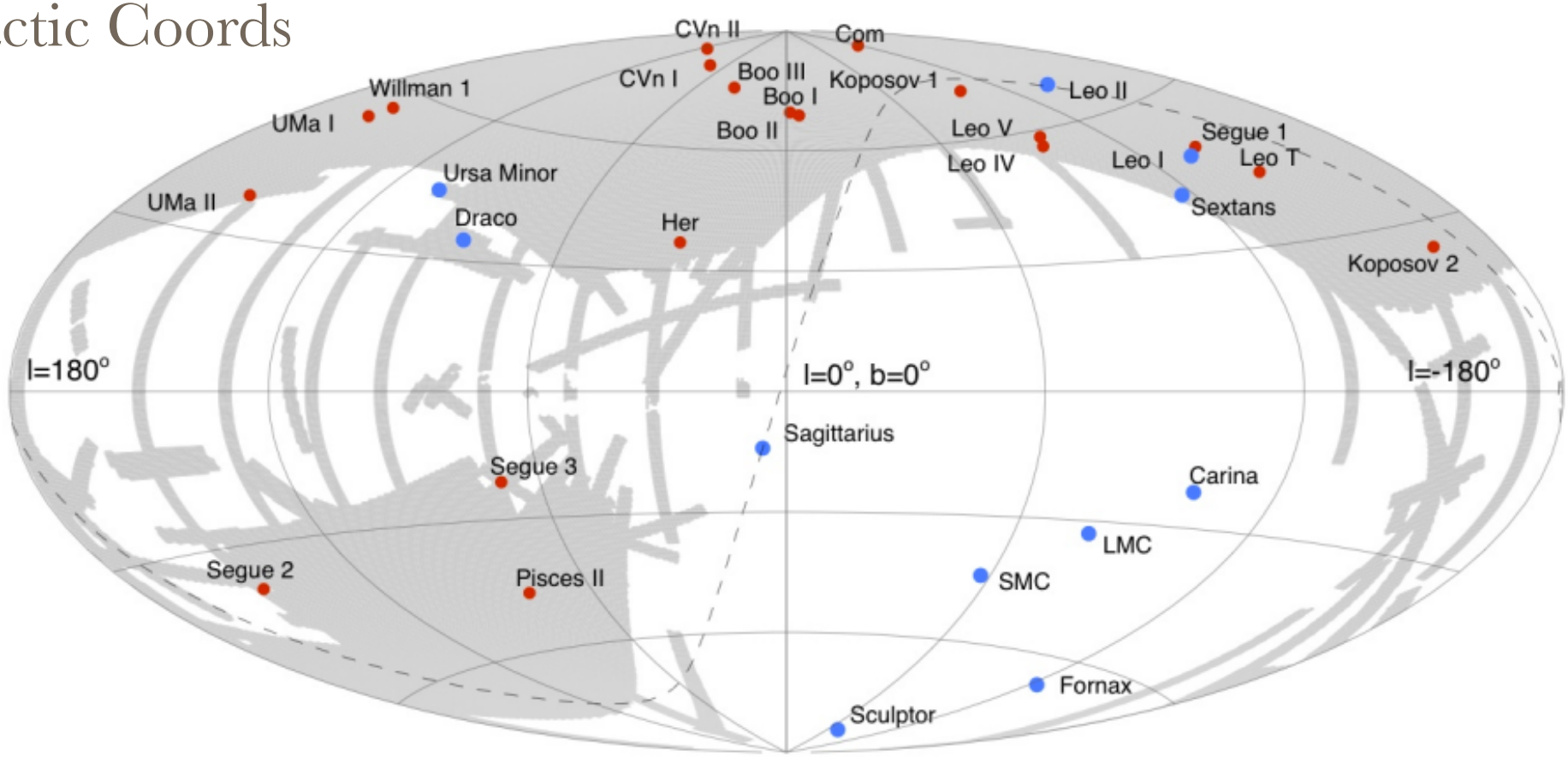






Dwarf Galaxies: Discovery

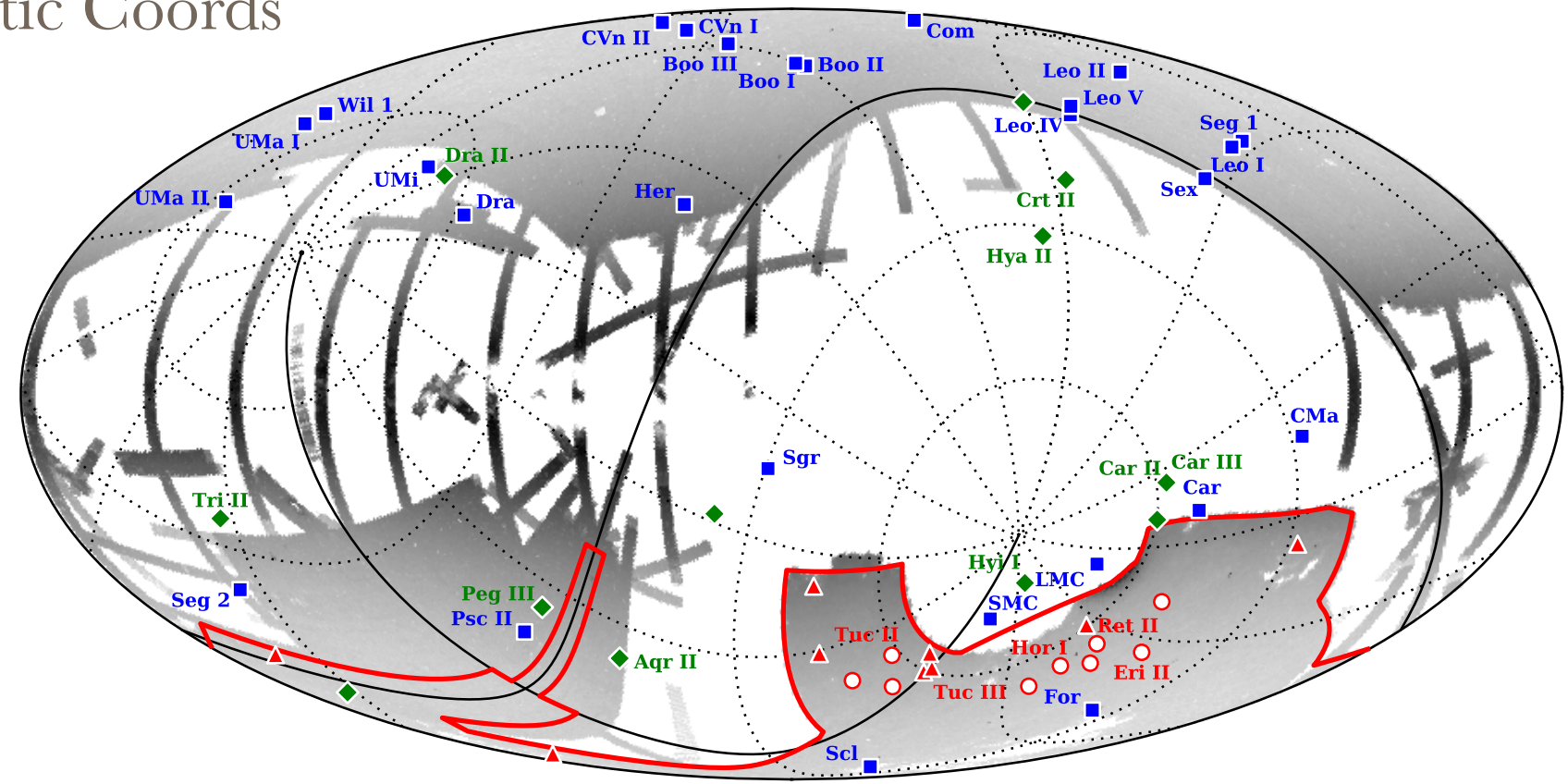
Galactic Coords



Belokurov et al. (2013)

New Ultra-Faint Dwarf Galaxies

Galactic Coords

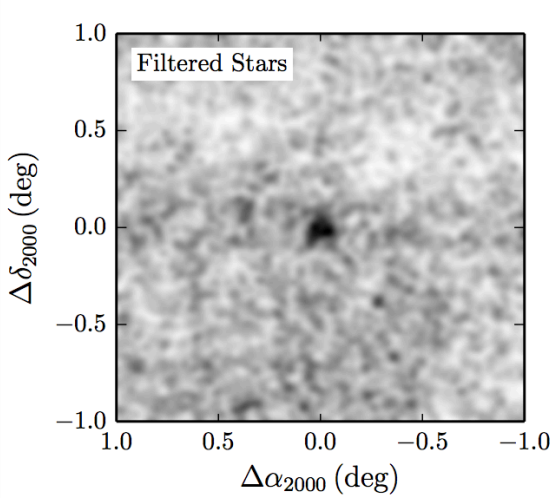


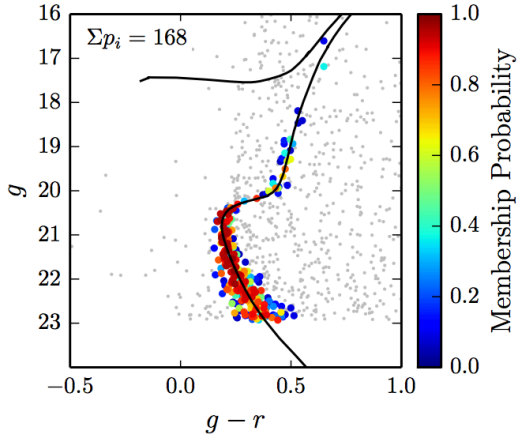
blue: prior 2015
red: 2015 - Now (DES)
green: 2015 - Now (others include DECam)

Credit: Alex Drlica-Wagner

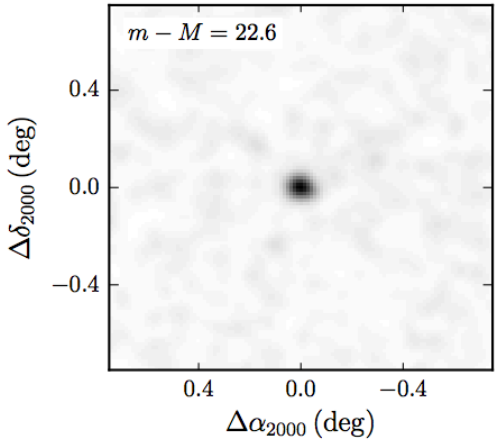
New Ultra-Faint Dwarf Galaxies

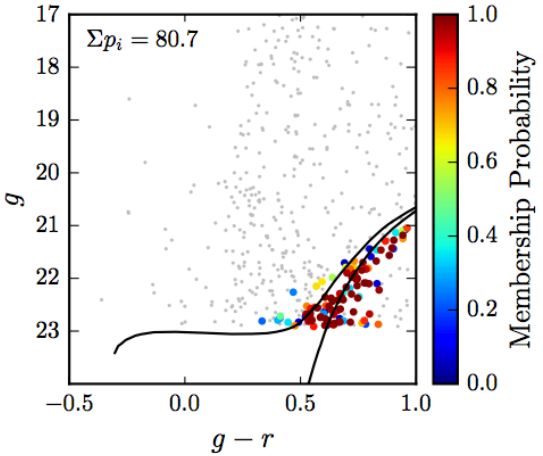
Tucana III
~25 kpc
Mv ~ -2.4





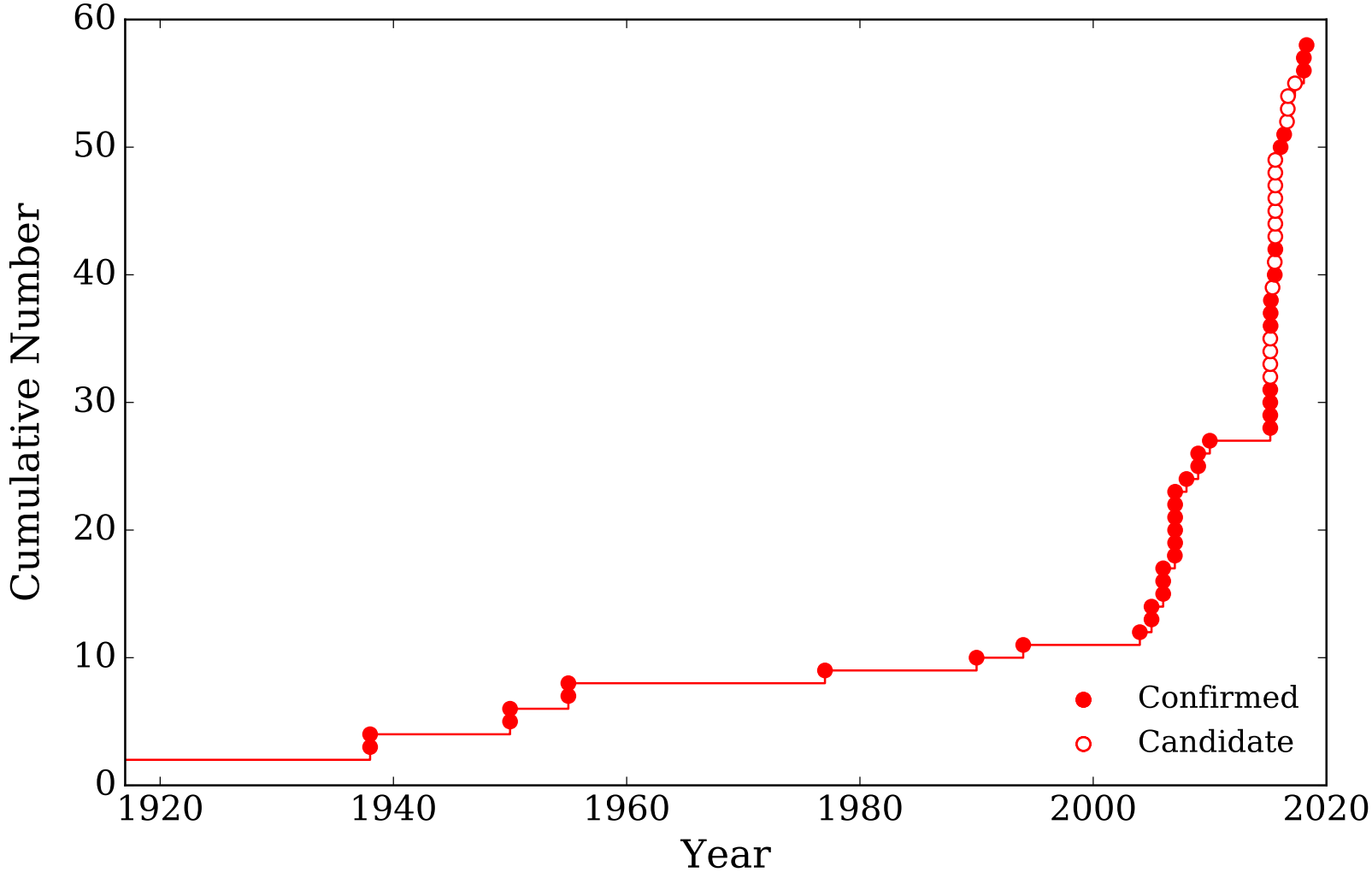
Eridanus II
~370 kpc
Mv ~ -7.4





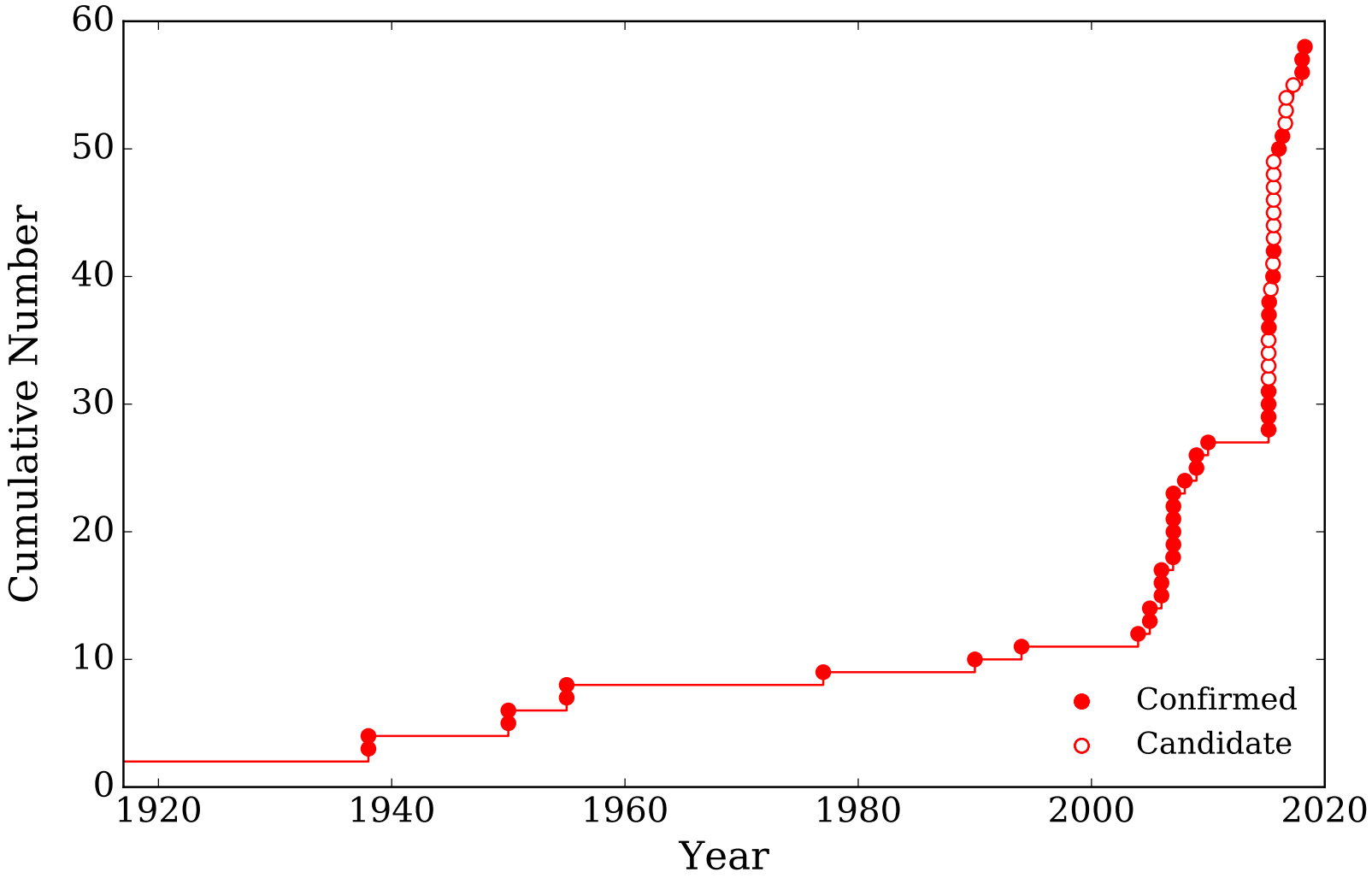
Bechtol et al. 2015
Drlica-Wagner et al. 2015

Dwarf Galaxy Discovery Timeline



Credit: Keith Bechtol

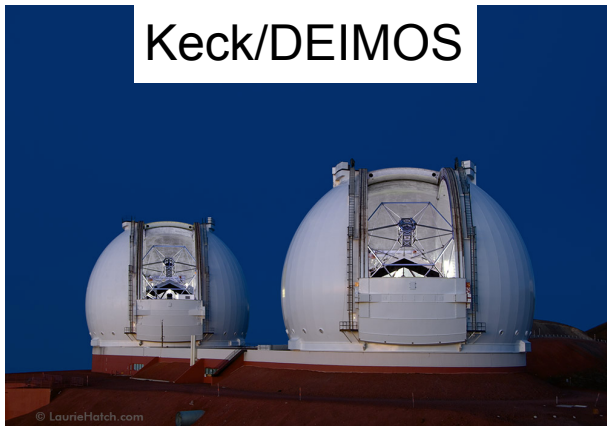
Dwarf Galaxy Discovery Timeline



Credit: Keith Bechtol

Bootes IV w/ HSC
arXiv: 1906.07332

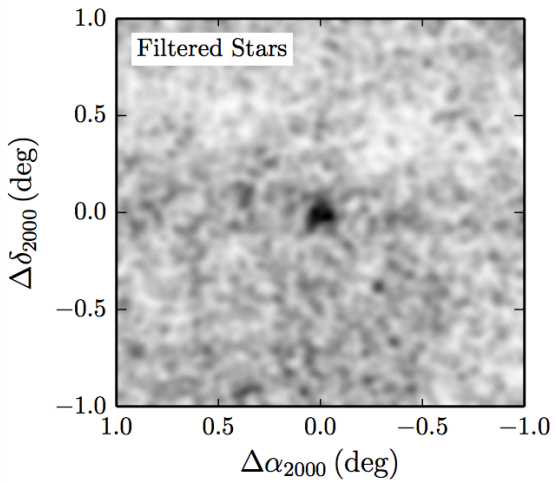
Spectroscopy
8m MOS

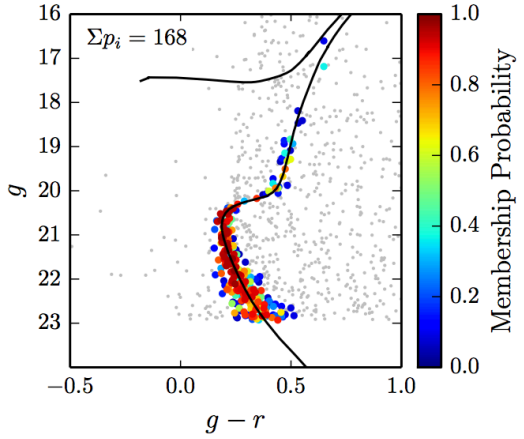


6-10m telescopes
FOV: 15-30 arcmin

Dwarf Galaxies: Discovery

Tucana III
~25 kpc
Mv ~ -2.4





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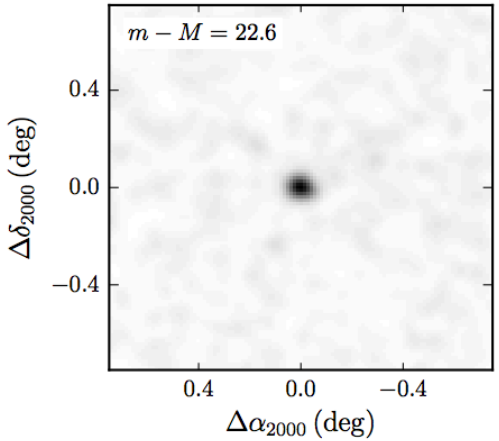
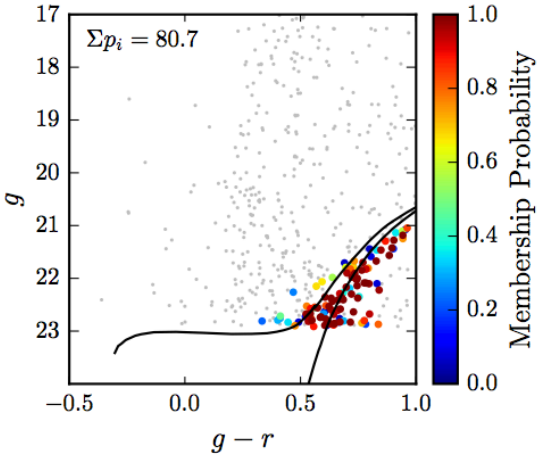
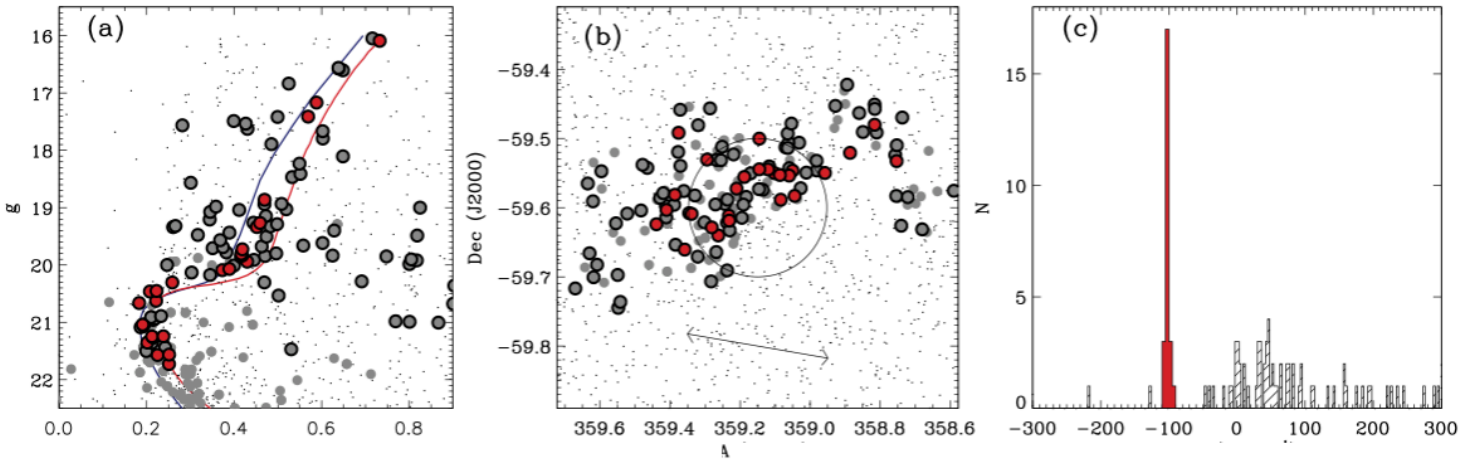


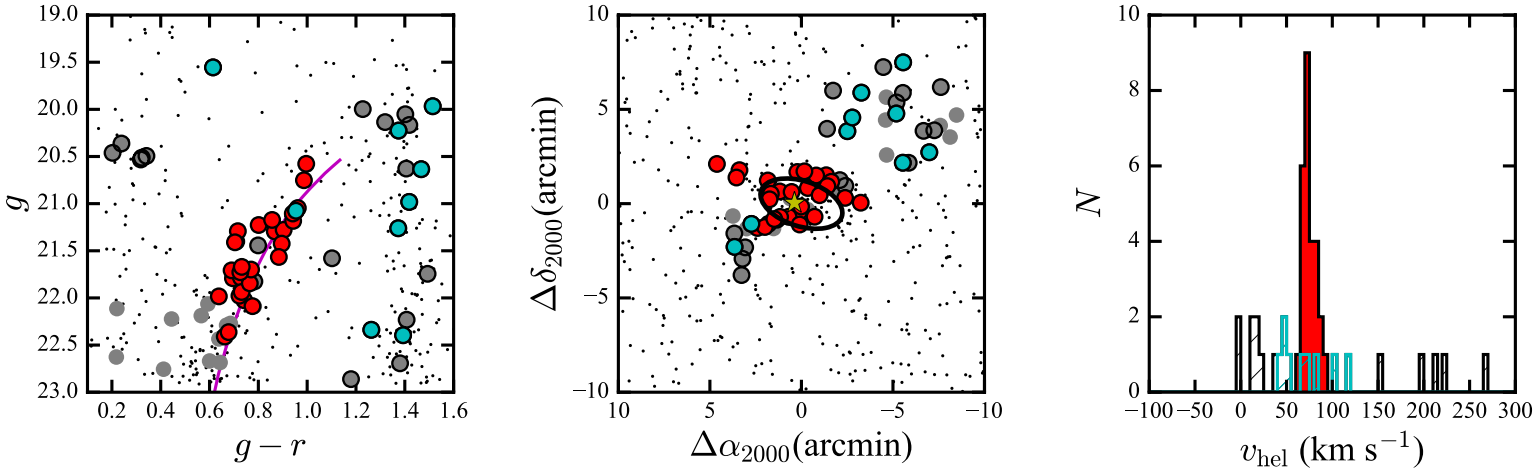


Dwarf Galaxies: Spectroscopy w/ Magellan/IMACS

Tucana III
Simon et al. 2017



Eridanus II
Li et al. 2017

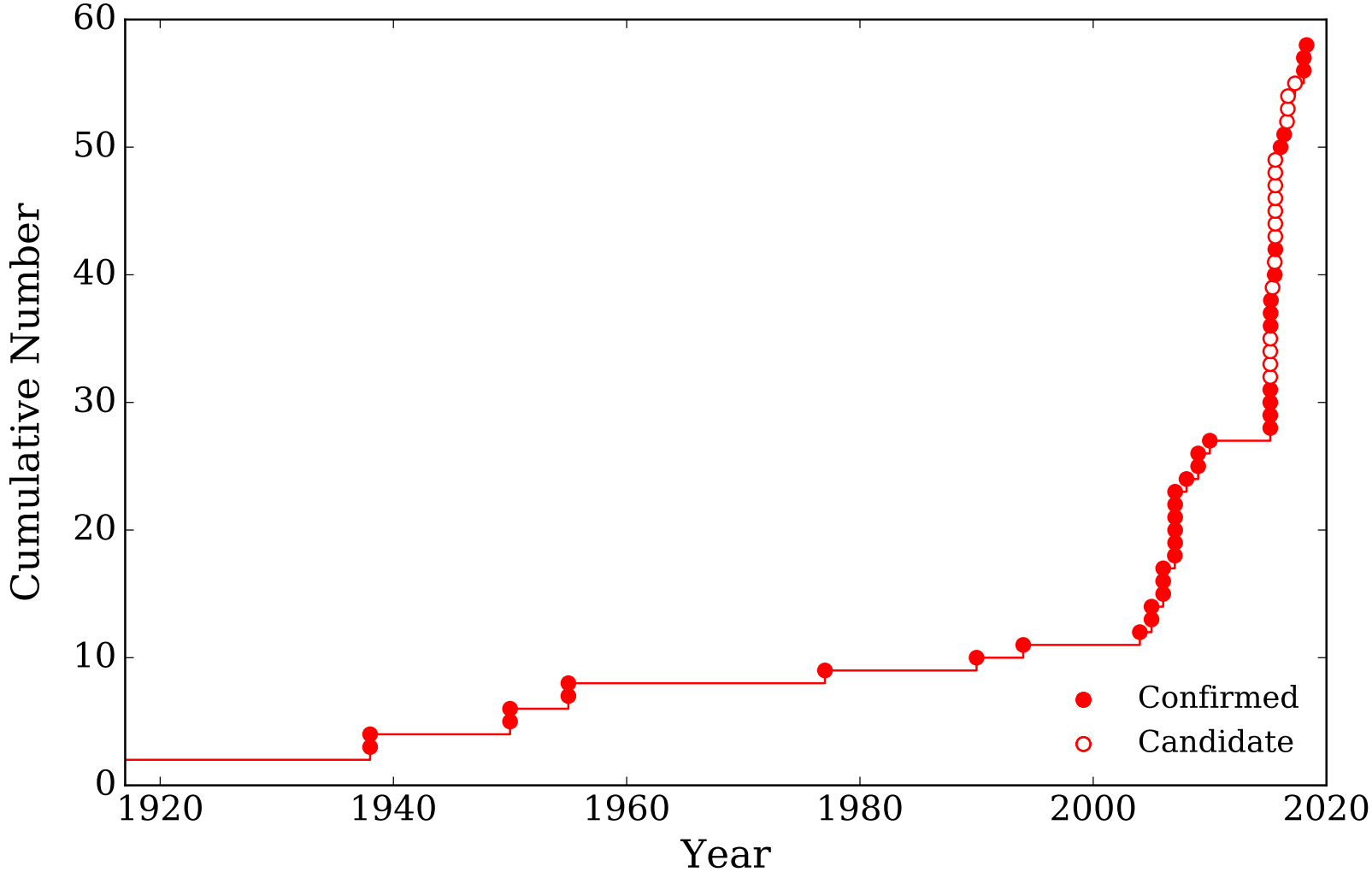


confirmation; member identification; dynamical mass

Dwarf Galaxies: Spectroscopy

As of April 2019, **44** satellite galaxies have published radial velocities.

Dwarf Galaxy Discovery Timeline



Credit: Keith Bechtol

Astrometry

Gaia

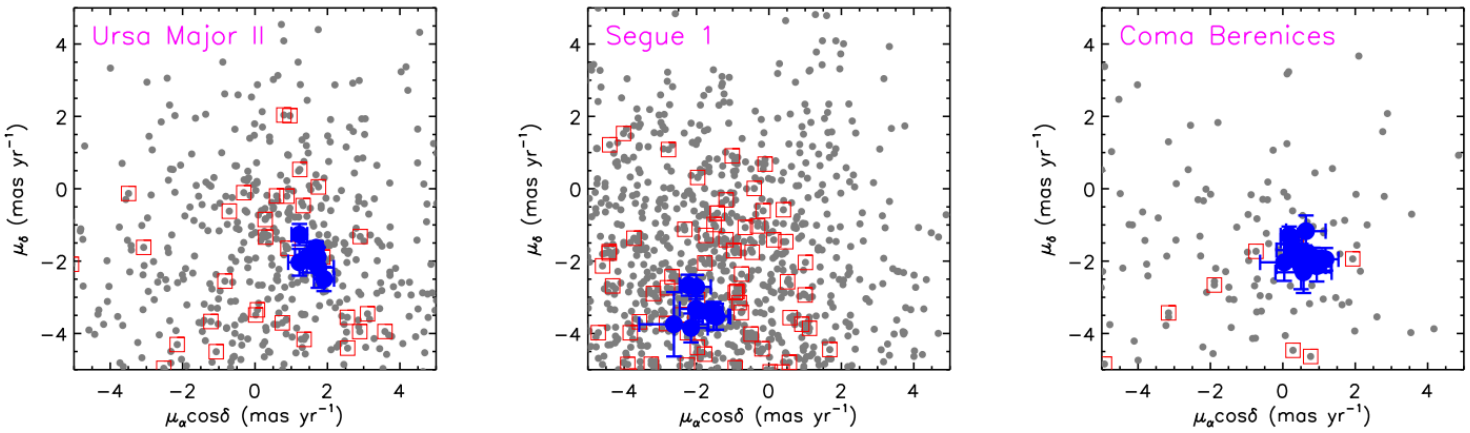
April 2018: Gaia DR2

gaia

only classical dwarf galaxies has measured
Proper Motion prior Gaia

Dwarf Galaxies: Proper Motion

PM from confirmed spectroscopic members



Simon et al. 2018
See also Fritz et al. 2018, Kallivayalil et al. 2018….

Dwarf Galaxies: Proper Motion

PM without spectroscopic members

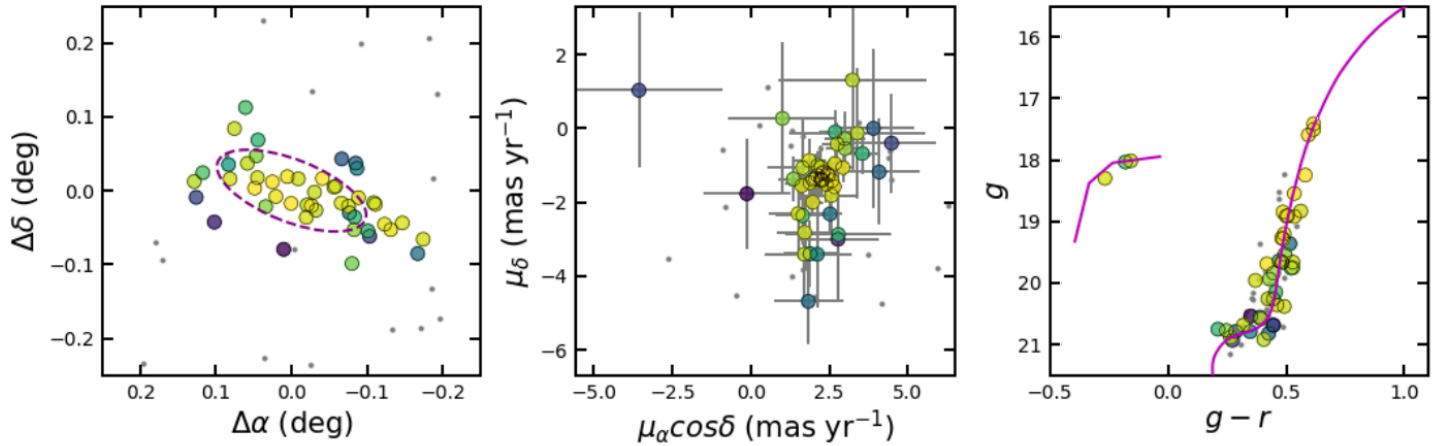
$$\mathcal{L} = (1 - f_{\rm MW})\mathcal{L}_{\rm satellite} + f_{\rm MW}\mathcal{L}_{\rm MW}$$

$$\ln \mathcal{L}_{\rm PM} = -\frac{1}{2}(\chi-\overline{\chi})^{\top} C^{-1} (\chi-\overline{\chi}) - \frac{1}{2}\ln\left(4\pi^2 \det C\right)$$

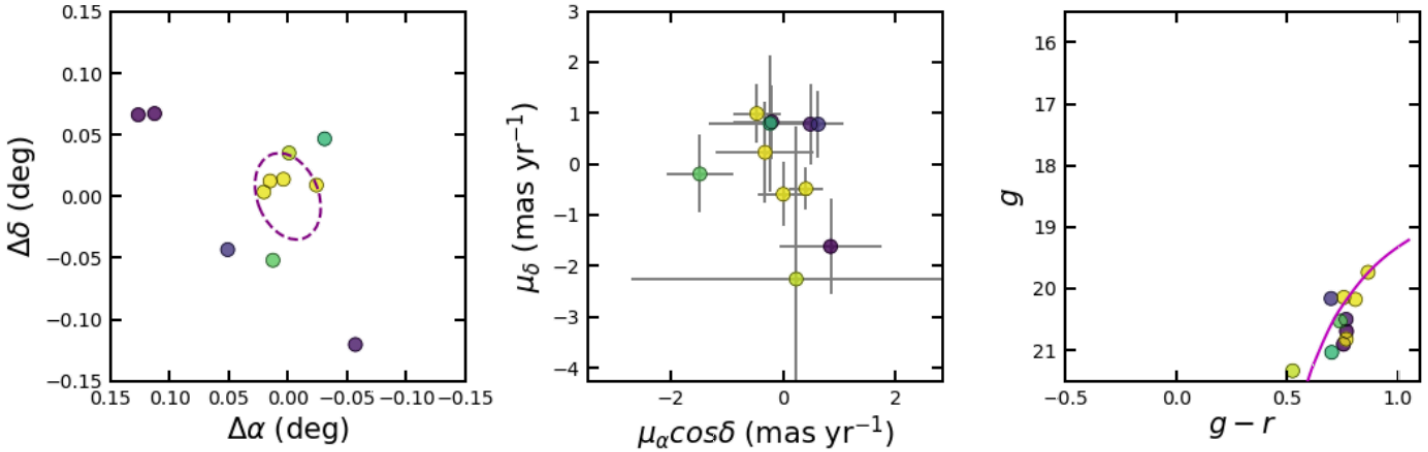
$$\chi = (\mu_\alpha \cos\delta, \mu_\delta)$$

$$C = \begin{bmatrix} \epsilon^2_{\mu_\alpha \cos\delta} + \sigma^2_{\mu_\alpha \cos\delta} & \epsilon^2_{\mu_\alpha \cos\delta \times \mu_\delta} \\ \epsilon^2_{\mu_\alpha \cos\delta \times \mu_\delta} & \epsilon^2_{\mu_\delta} + \sigma^2_{\mu_\delta} \end{bmatrix}$$

Reticulum II



Columba I



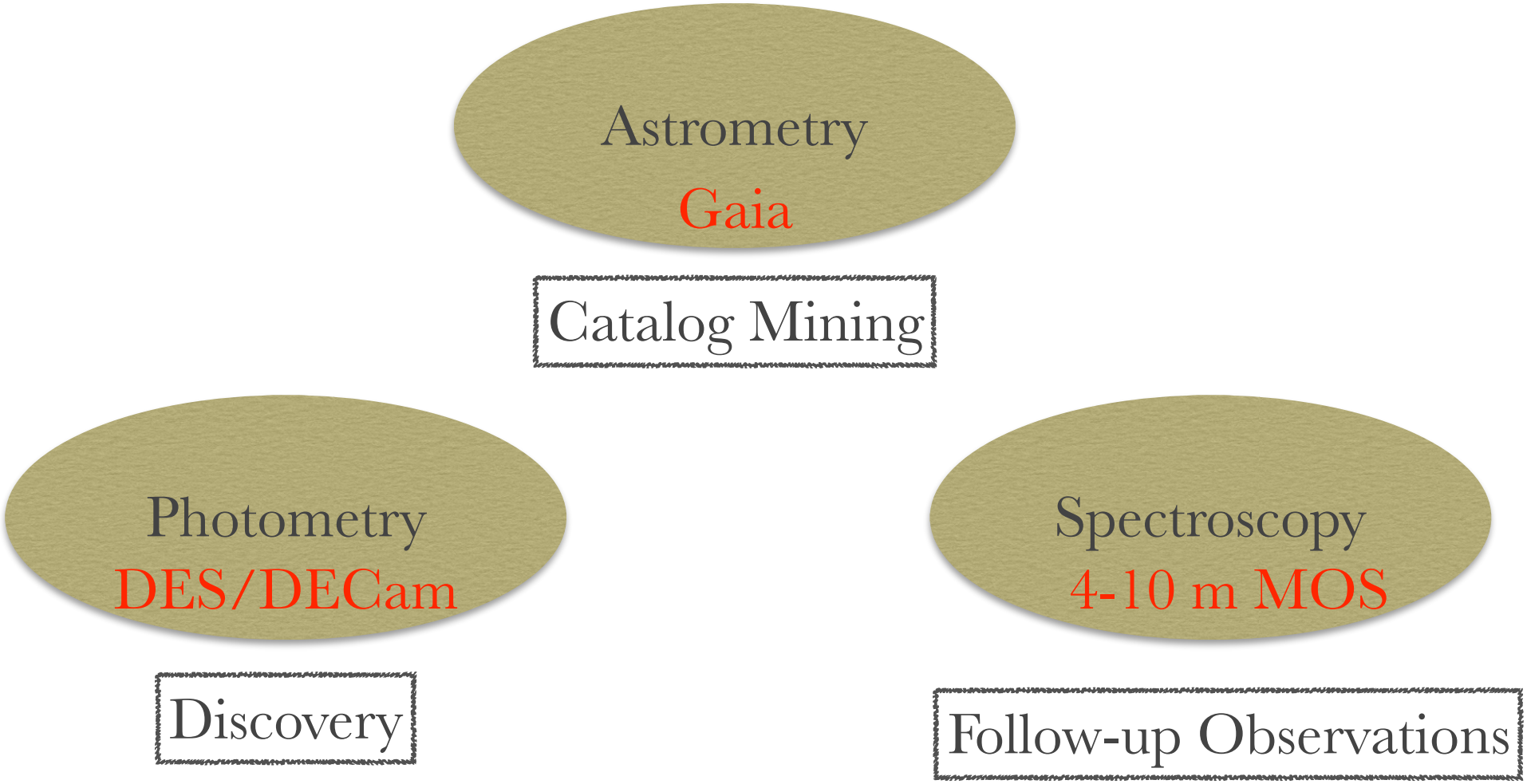
Pace & Li 2019

Dwarf Galaxies

As of April 2019, **44** satellite galaxies have published radial velocities.

As of April 2019, **46** satellite galaxies have published proper motions.

Ongoing Surveys

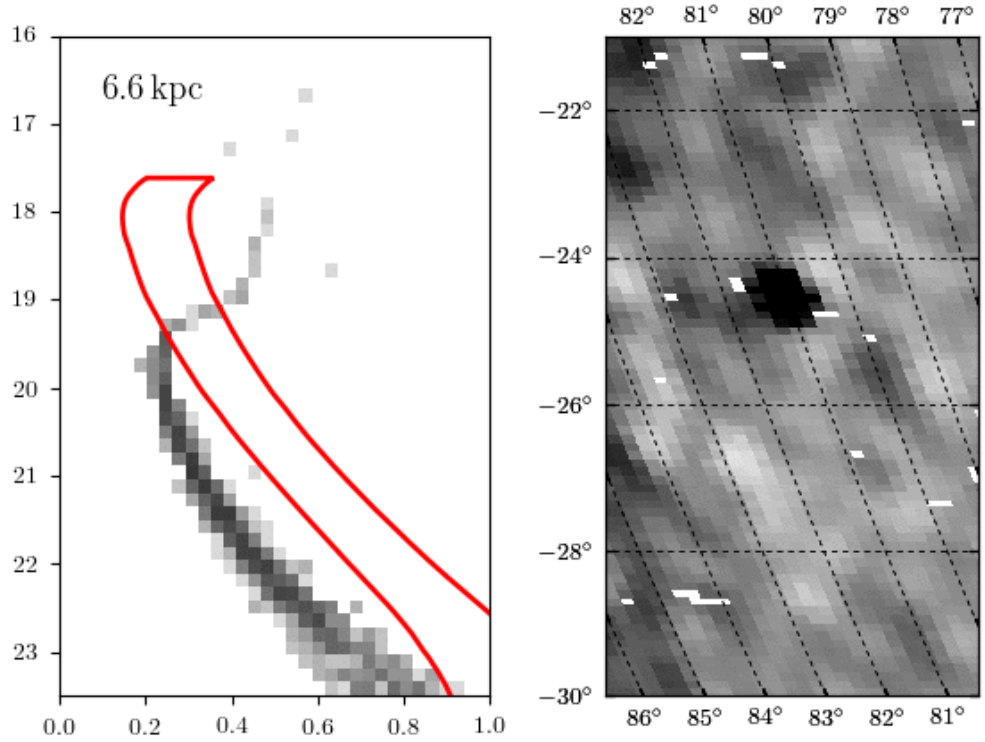


Stellar Streams : Discovery

Stellar Streams : Discovery

Credit: Alex Drlica-Wagner

NGC 1904

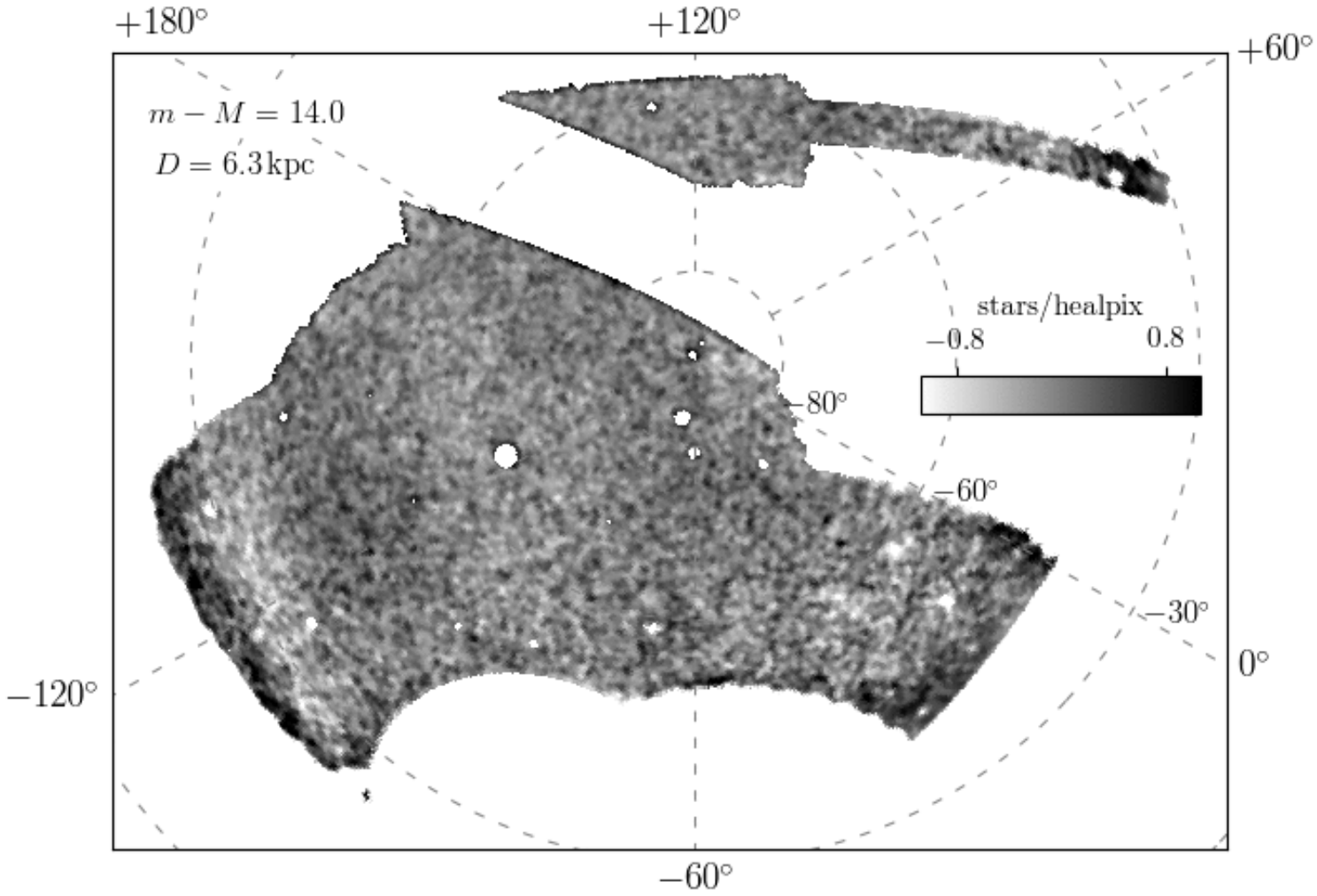


Red = selection region around isochrone; τ = 13 Gyr, Z = 0.0002, m-M = 14-19

Stellar Streams : Discovery

Nora Shipp
UChicago

Shipp et al.
2018



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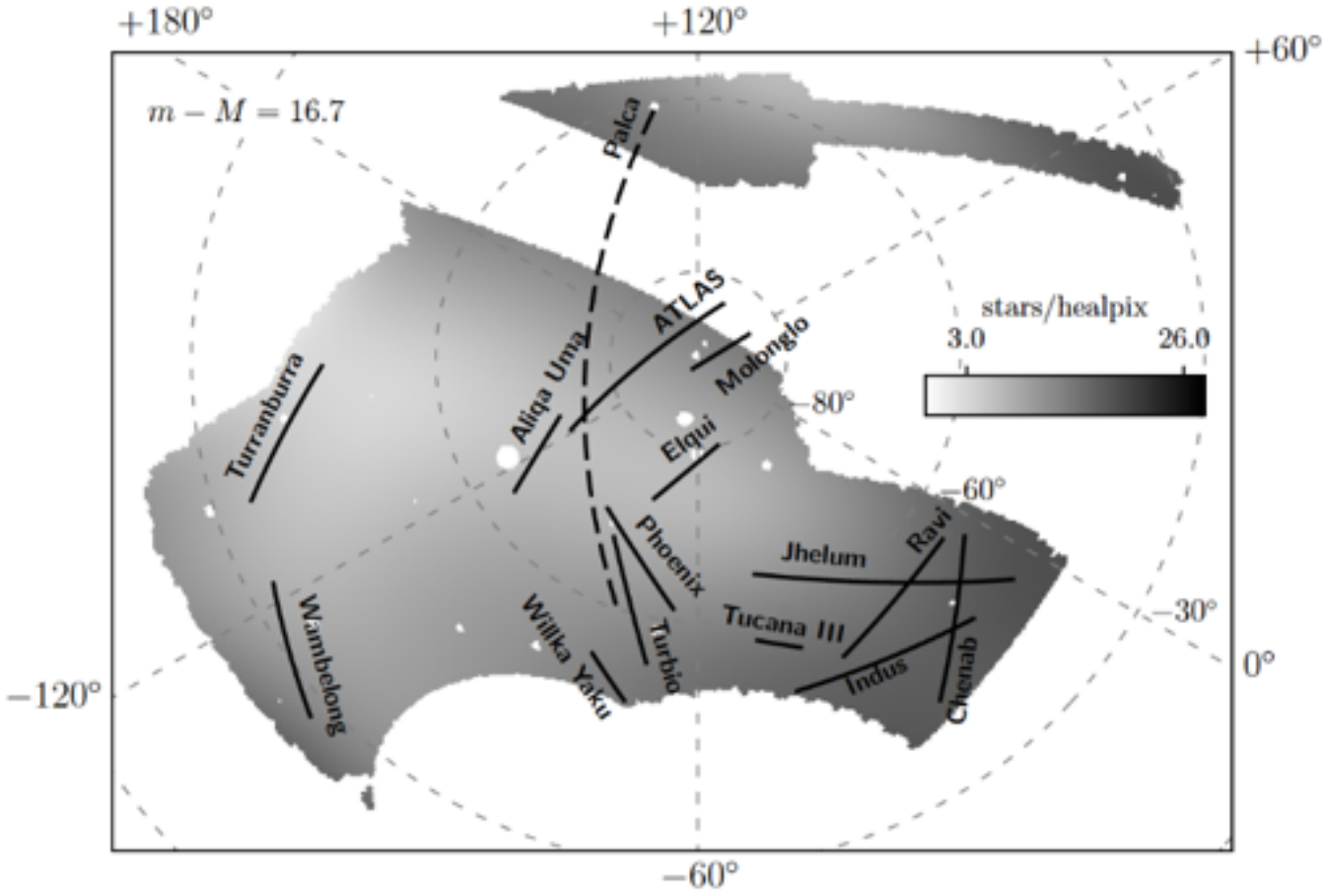
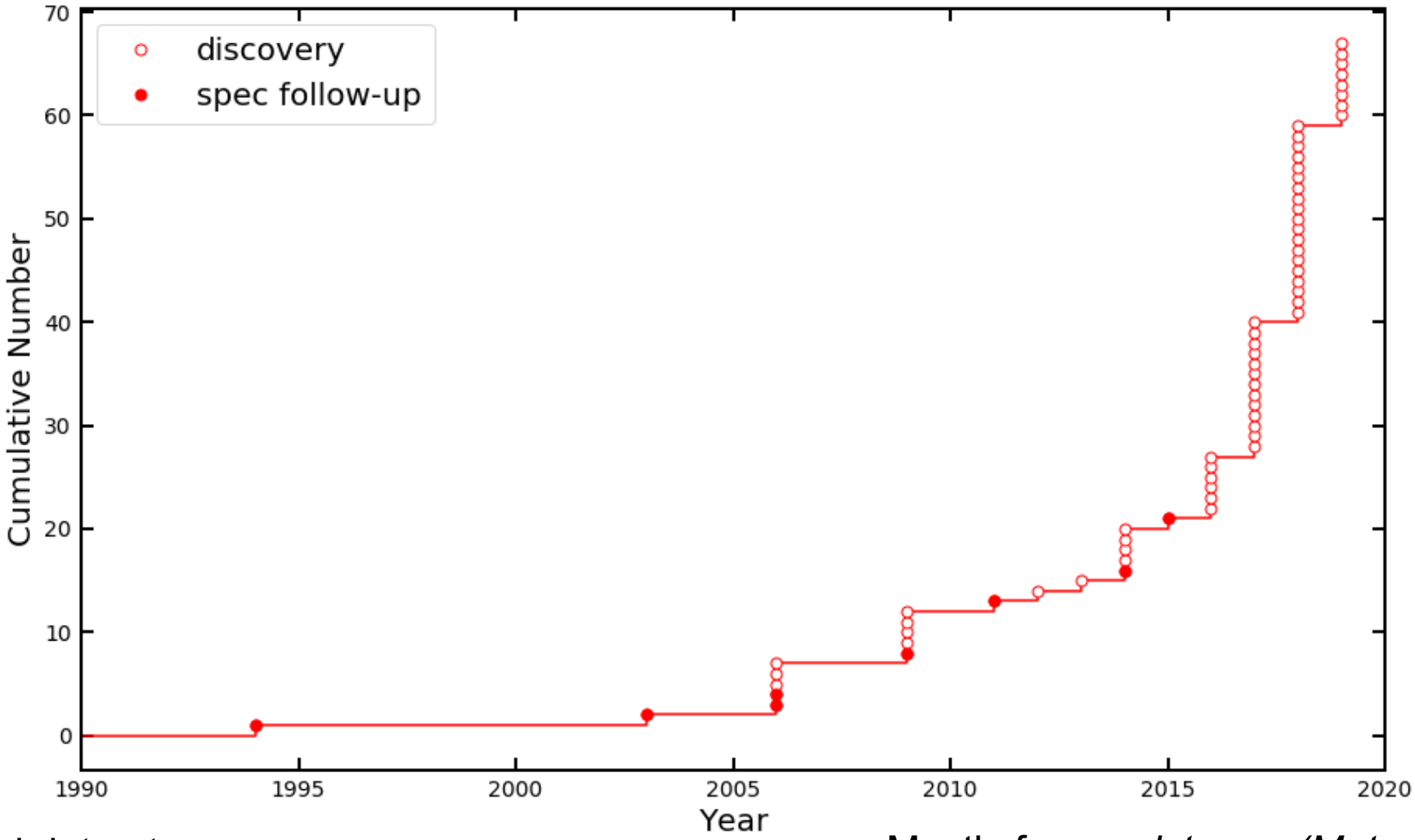


11 new stream
+ 4 previous known (including 2 from DES)

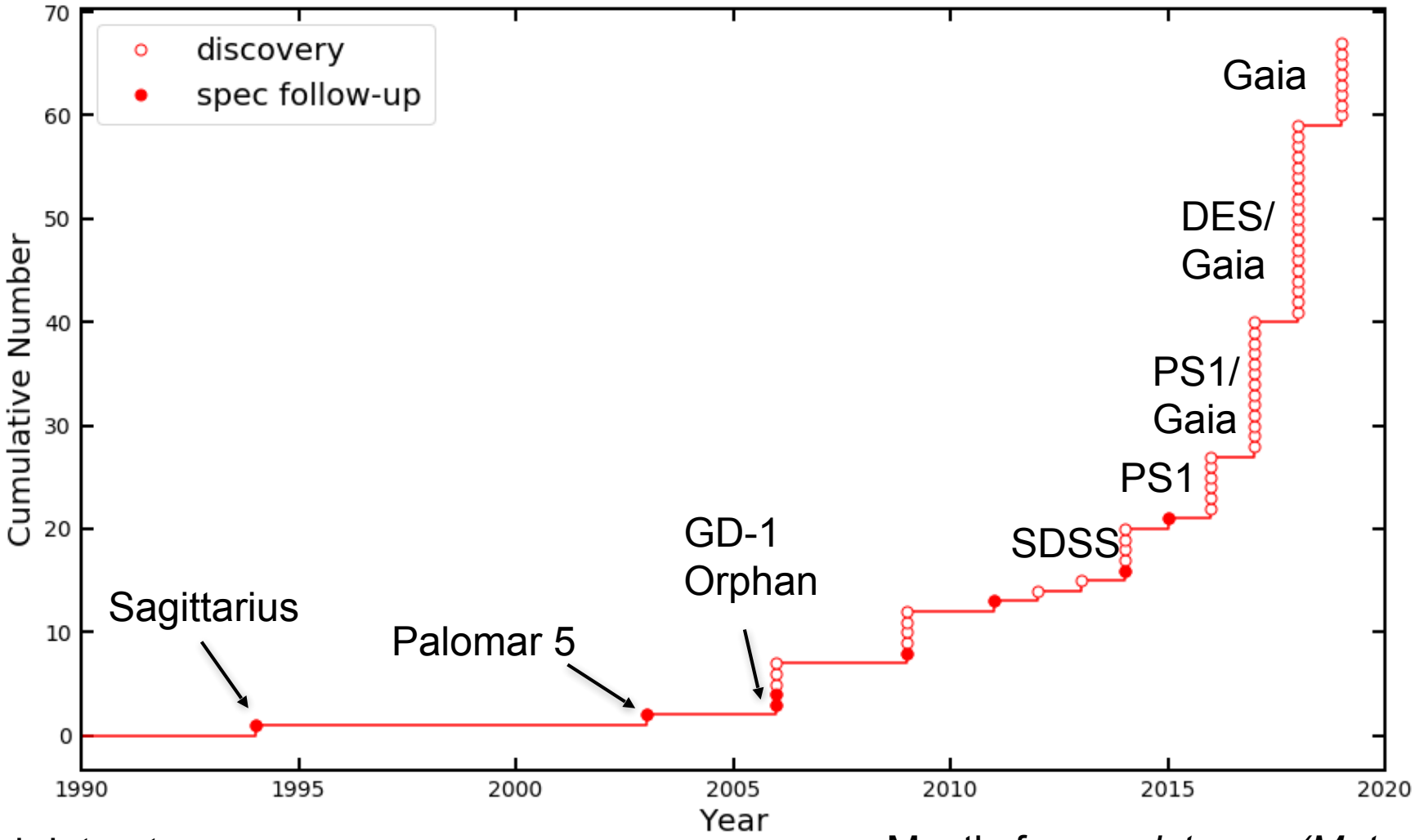
Stream Discovery Timeline



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

Mostly from *galstream (Mateu+2018)*
https://github.com/cmateu/galstreams

Stream Discovery Timeline



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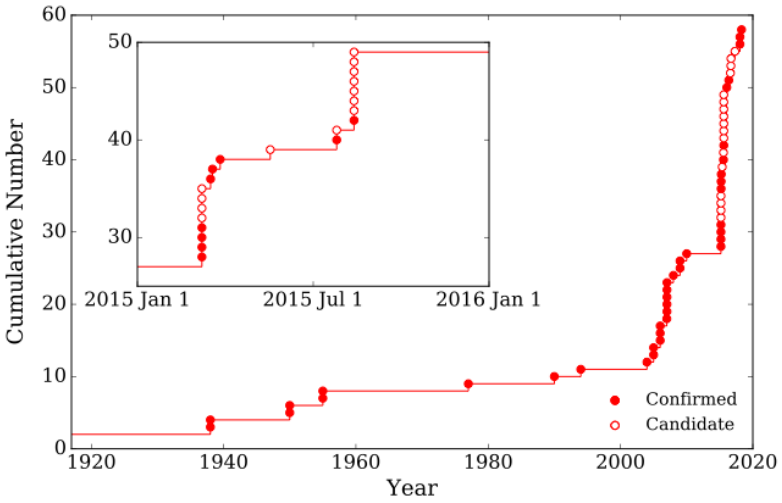
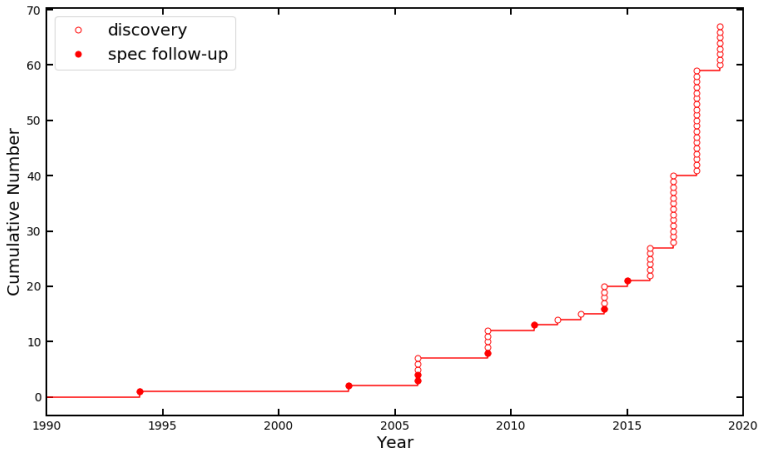
Spectroscopy: dwarfs vs streams



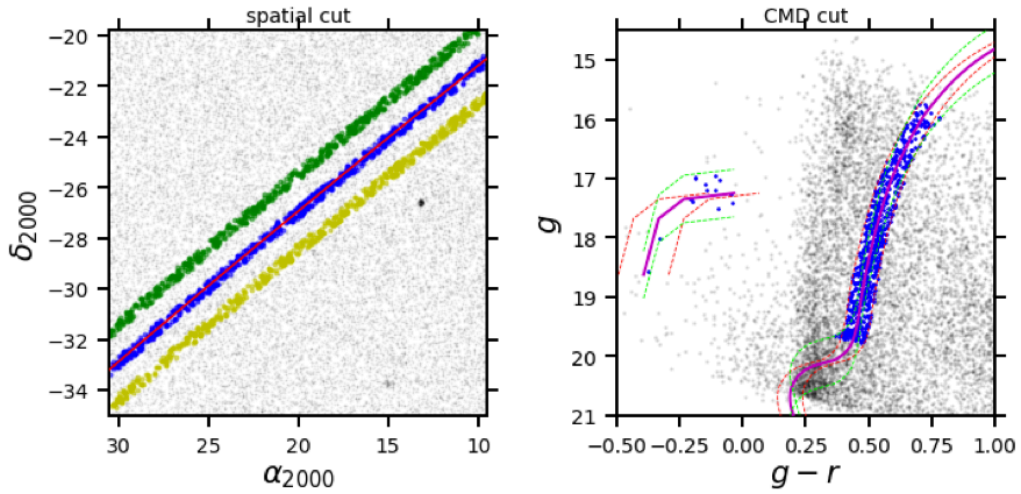
Dwarf Galaxies: > 70%

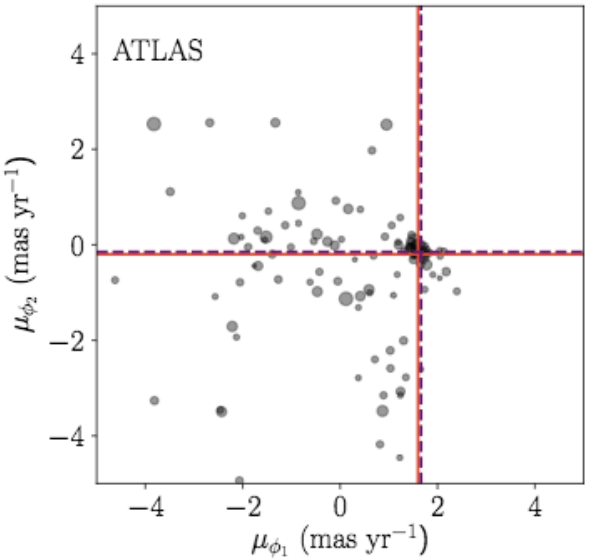
Stellar Streams: ~ 10%



Stream: more diffuse, higher background contamination

Streams : Proper Motions



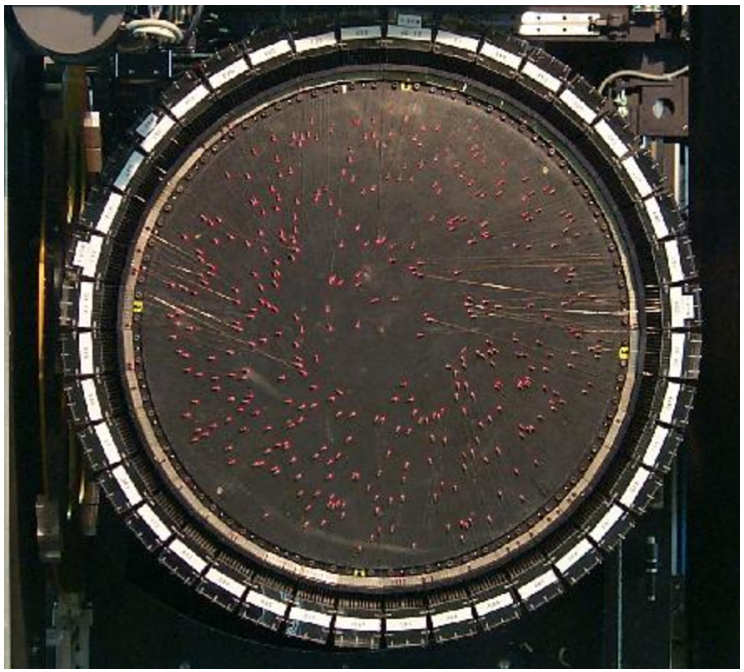


Proper Motion measurements on all DES streams

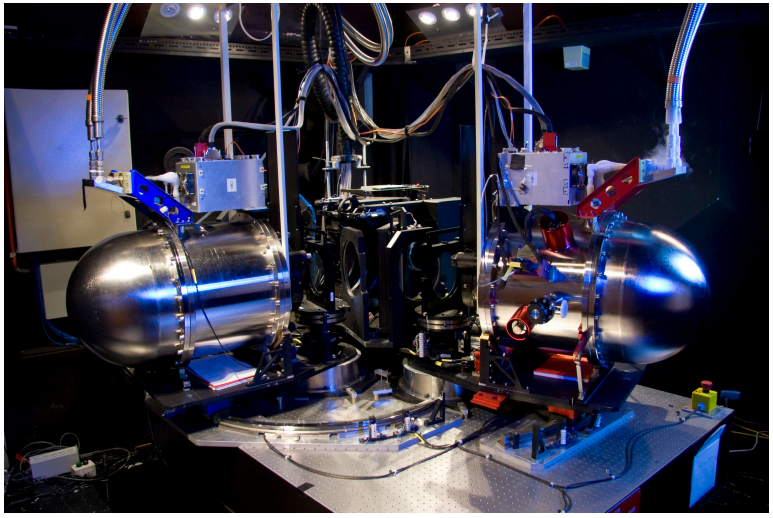
Shipp et al.
to be submitted

Stream: Spectroscopy with AAT

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



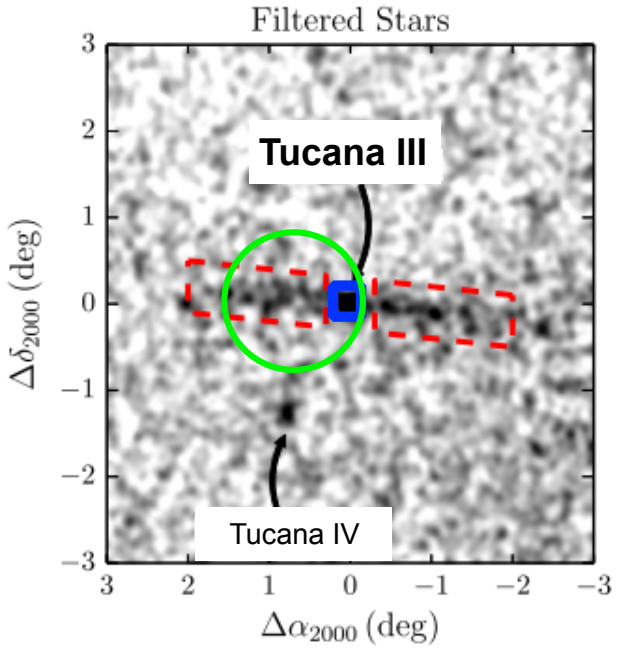
2df: 2-deg (in diameter) field fiber positioner w/ 400 fibers



AAOmega: a dual-arm optical spectrograph

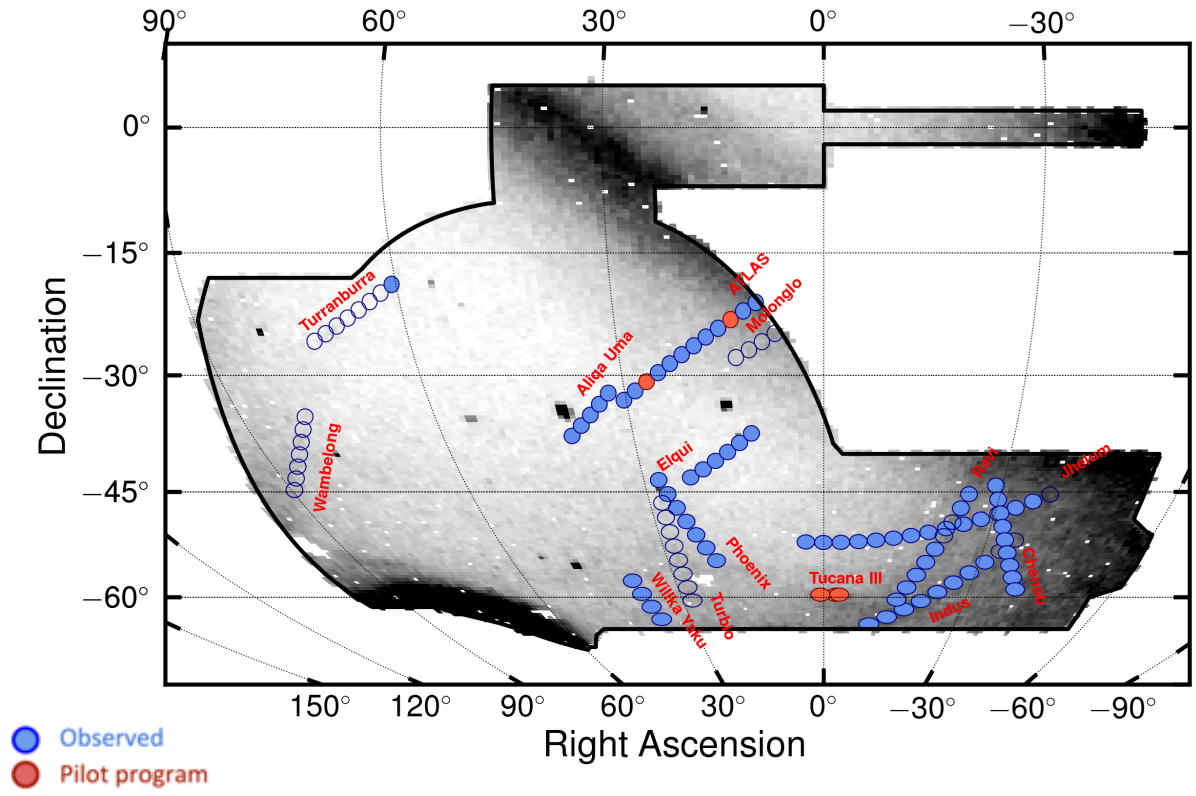
Large Field-of-View, High Multiplexity
= An Ideal Instrument for Stellar Streams

Stream: Spectroscopy with AAT



Tidal tails of Tucana III

Southern Stellar Stream Spectroscopic Survey (S^5)

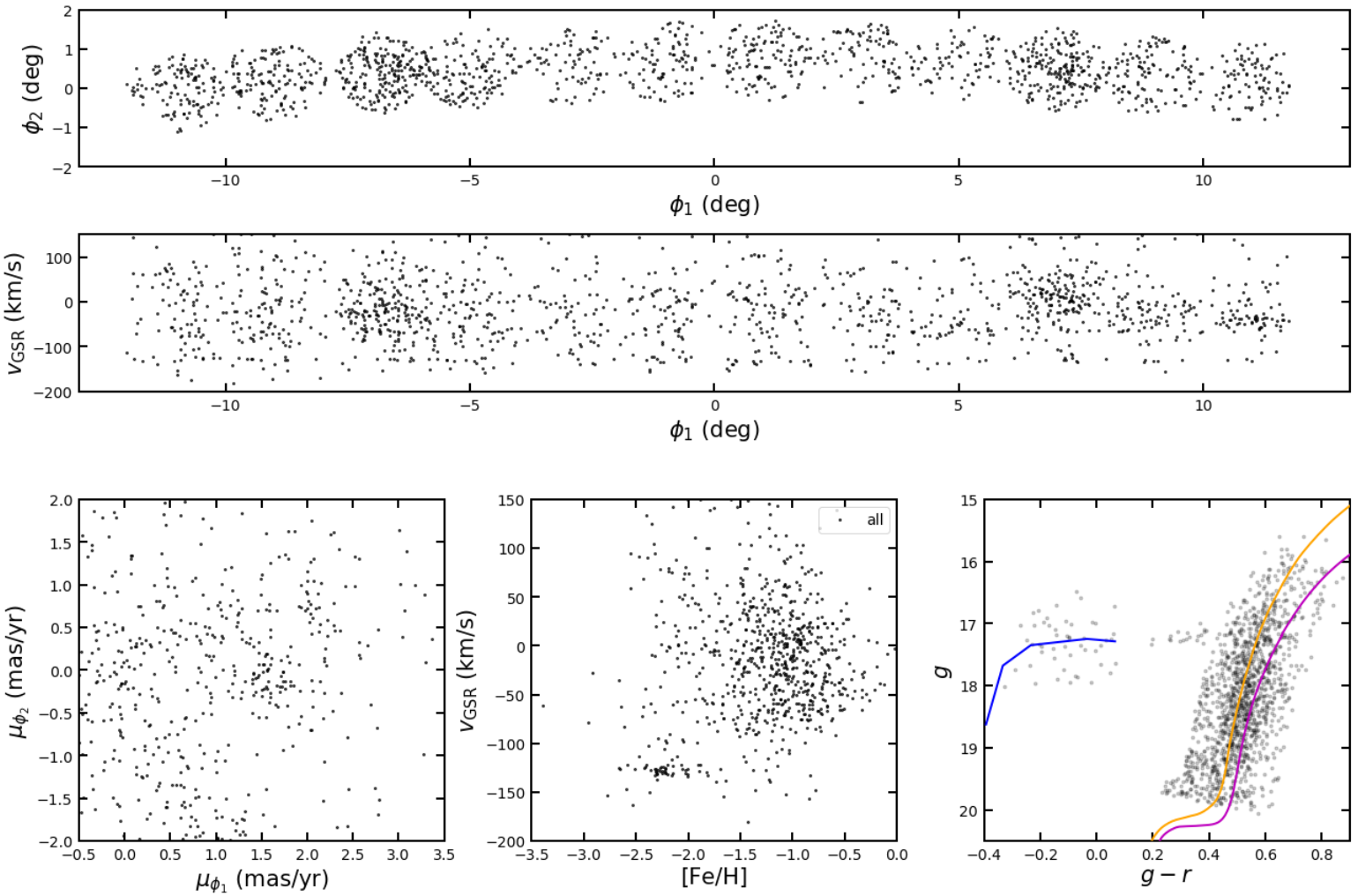


Li et al.
to be submitted

s5collab.github.io

- AAT + 2df/AAOmega
- ~30 members international collaborations
  Co-PI (Dan Zucker and Ting Li)
- Targets with 15 < g < 19.5
- RV precision ~ 1-5km/s
- Started in August 2018
- ~25 nights in 2018B
- 10 DES streams fully mapped
- 43k spectra on 38k targets
- Expand beyond DES footprint in 2019 for a total of 20 streams

Southern Stellar Stream Spectroscopic Survey (S^5)



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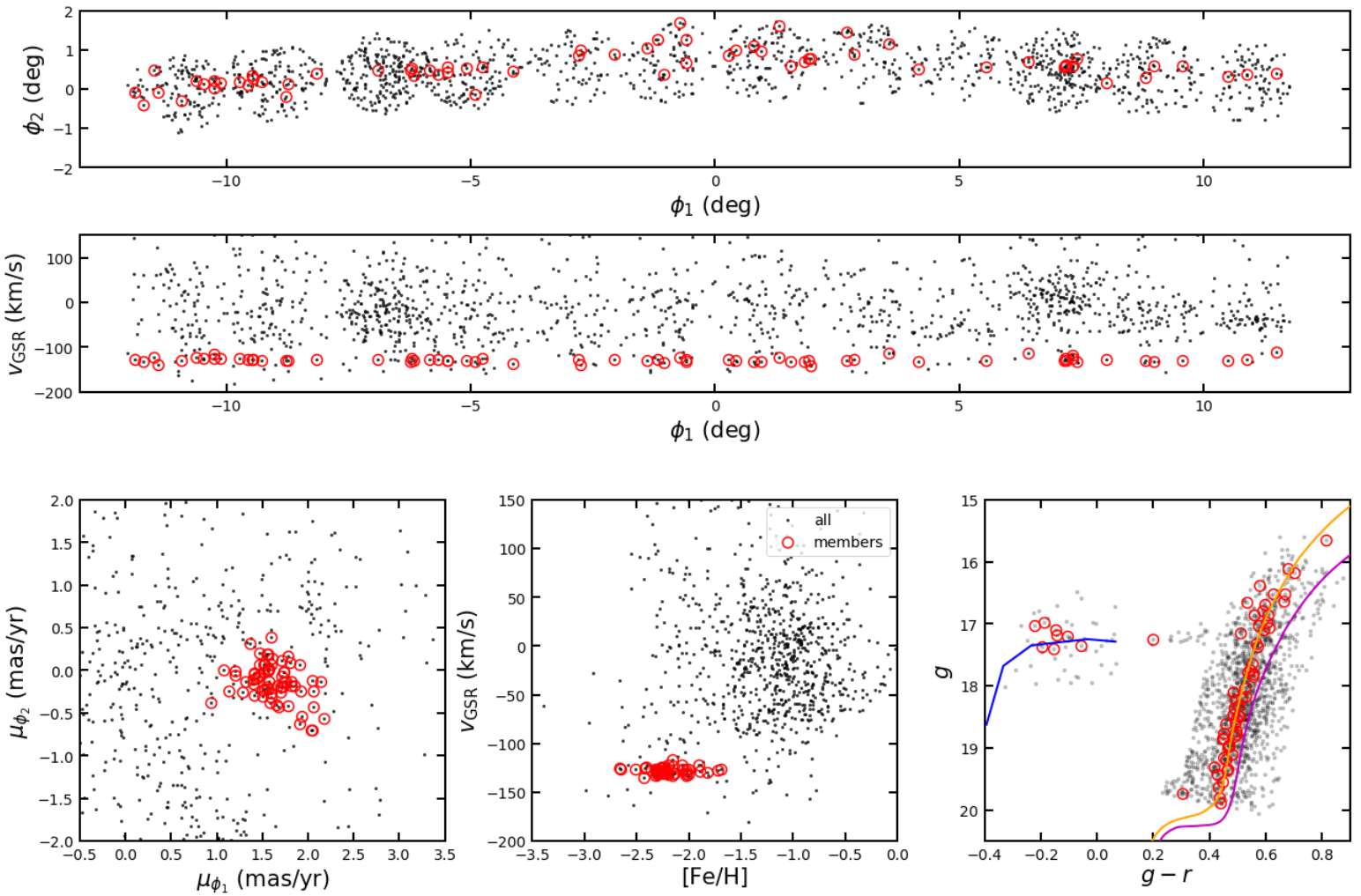


Streams : DES + Gaia + S^5

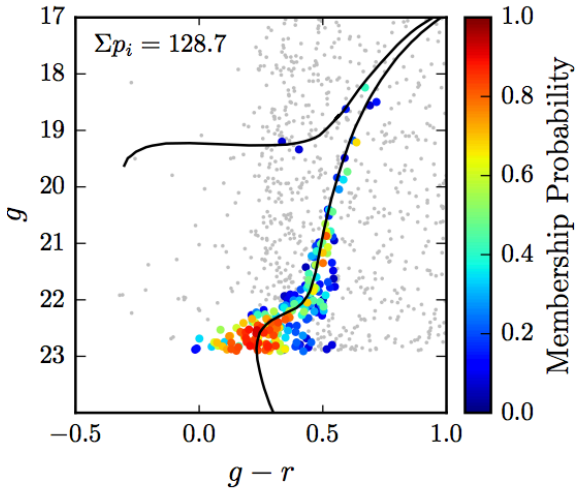
- Characterize stream progenitors
- Constrain the Milky Way potential
- Assess the influence of LMC

Where are we now?

Where will we be at in 10-20 yrs?

Ongoing Surveys

50 kpc



Astrometry
Gaia

G~20
(similar in r)

Photometry
DES

r~23.5

Spectroscopy
8m+4m

dwarf galaxies: (8m) r~21.5
stellar streams: (4m) r~19.5

Future Surveys

Astrometry
WFIRST

r~25-26

Photometry
LSST

r~27

Spectroscopy
30m + 10m

dwarf: (30m) r~24.5
streams: (10m) r~22.5

More discoveries (w/ LSST or WFIRST) at fainter luminosity, farther distance, lower surface brightness

Astrometry
WFIRST

r~25-26

Photometry
LSST

r~27

Spectroscopy
30m + 10m

dwarf: (30m) r~24.5
streams: (10m) r~22.5

Streams: Now and Future

- SDSS/DES:
  streams < 50 kpc
- Proper motions from Gaia
- Spectroscopy from S^5 and other upcoming 4m spectroscopic surveys, e.g. DESI, WEAVE, 4MOST

- LSST:
  streams > 50 kpc
- Proper motions from WFIRST
- What about spectroscopy?
  - 13 8m+ optical telescopes: Subaru, 4xVLTs, 2xKeck, 2xGemini, LBT, SALT, GTC, HET

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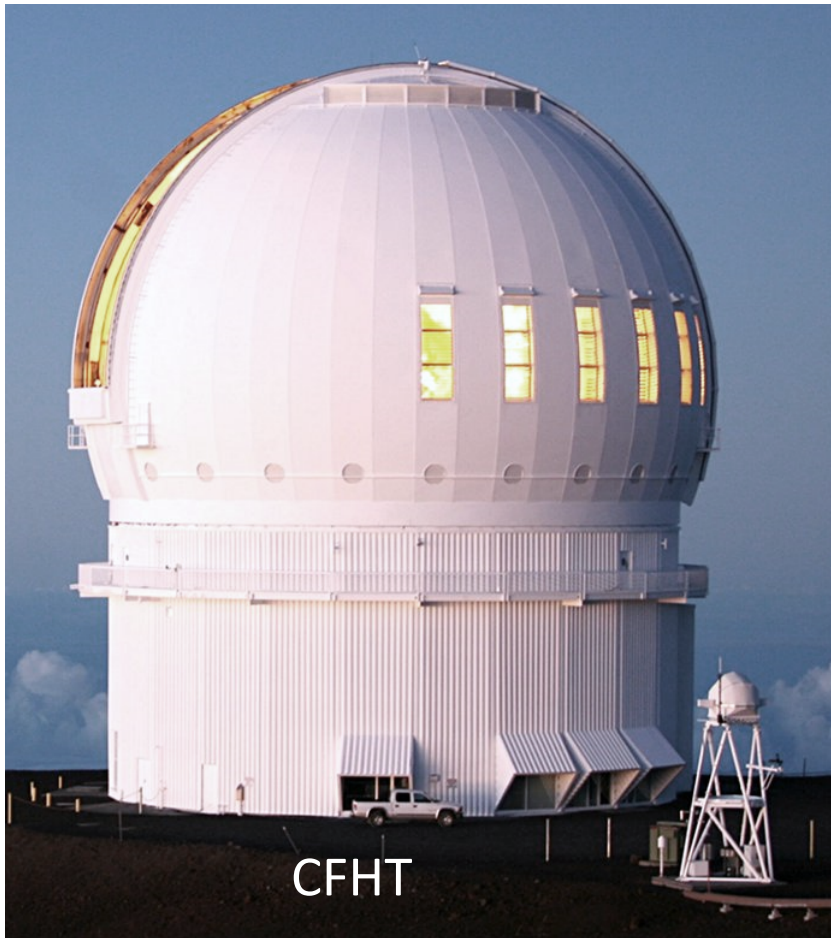
    14th telescope?

Maunakea Spectroscopic Explorer

Facility transformation



Maunakea Spectroscopic Explorer

Facility transformation

- 11.25 m mirror (in diameter)
- 1.5 deg field of view (in diameter)
- ~3200 fibers in low/med resolution (R~2k - 6k)
  ~1000 fibers in high resolution (R~20k-40k)
- Dedicated Survey Telescope

9 Science Working Group

— Exoplanets and stellar astrophysics
— Chemical nucleosynthesis
— The Milky Way and resolved stellar populations
— Galaxy formation and evolution
— Active Galactic Nuclei and Supermassive Black Holes
— **Astrophysical tests of dark matter**
— Cosmology
— Time domain astronomy and the transient Universe
— Solar System science

— Astrophysical tests of dark matter

Astrophysical Tests of Dark Matter with Maunakea Spectroscopic Explorer

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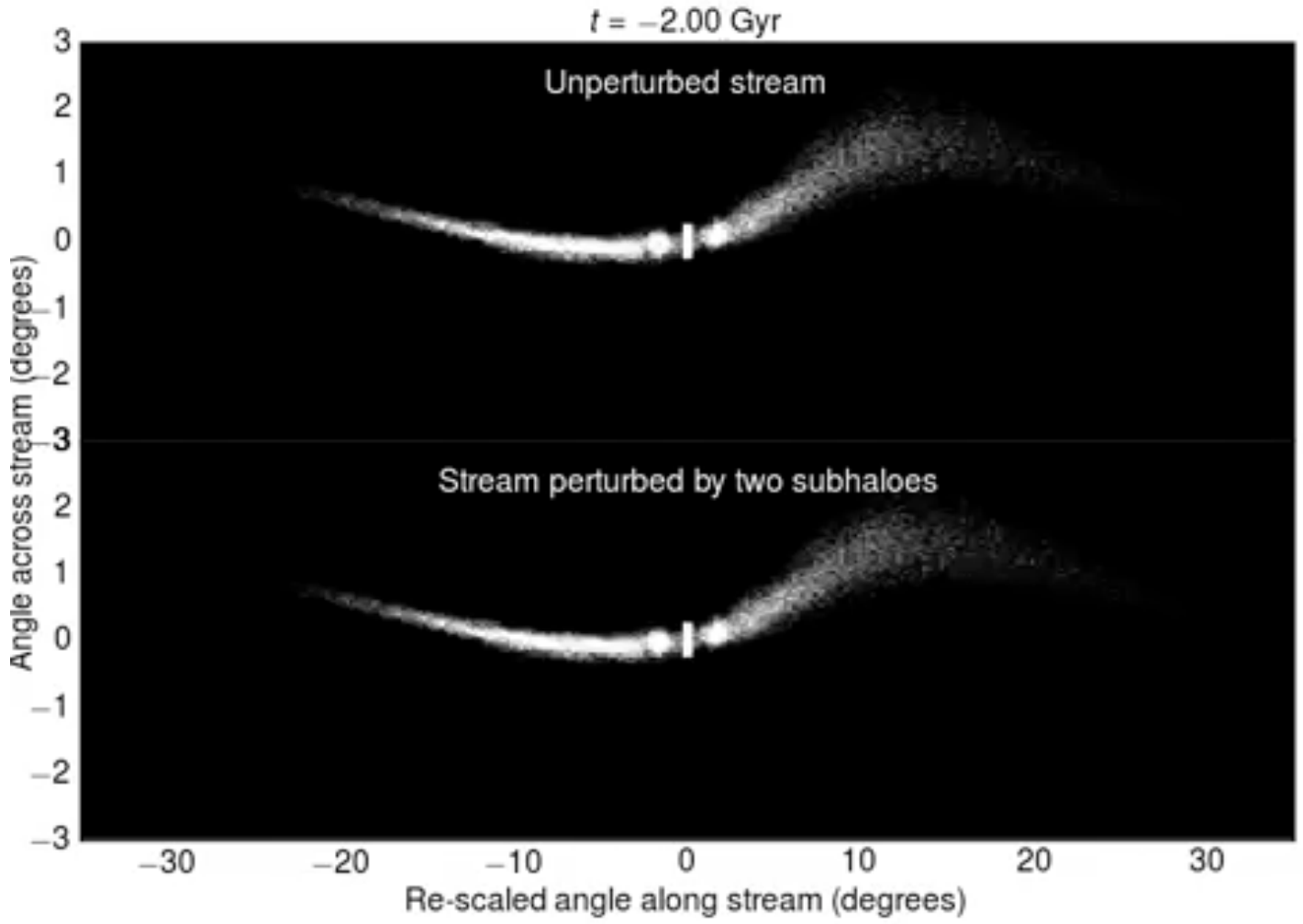
DM chapter (40 pages): 1903.03155

All Science Cases (300 pages): 1904.04907

One Science Case w/ WFIRST on Dark Matter Science

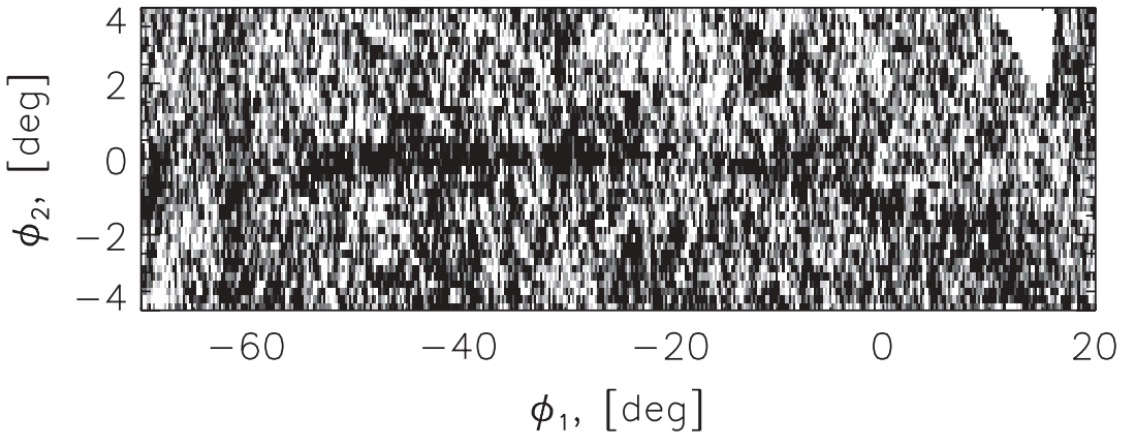
investigation on the known streams w/ WFIRST

Stellar Streams: Subhalo Perturbations



Credit: Denis Erkal

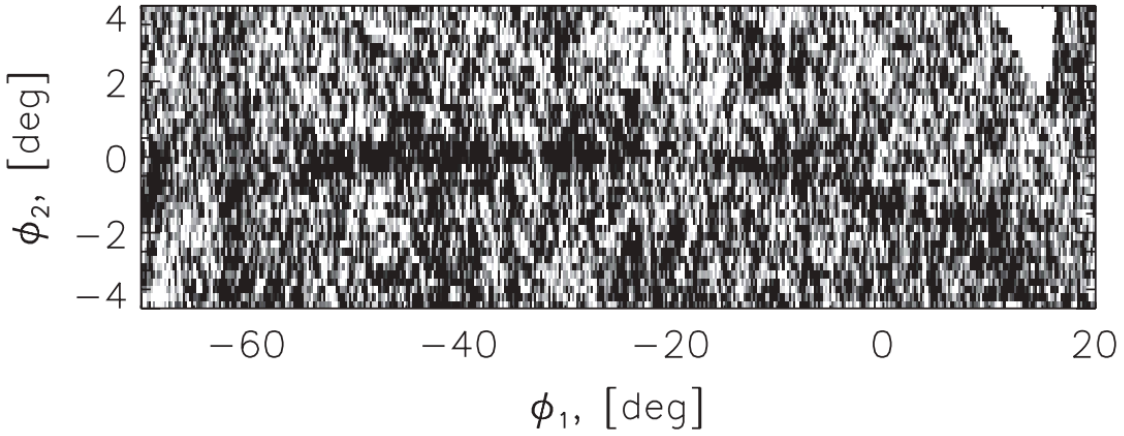
Stellar Streams: Subhalo Perturbations — GD-1

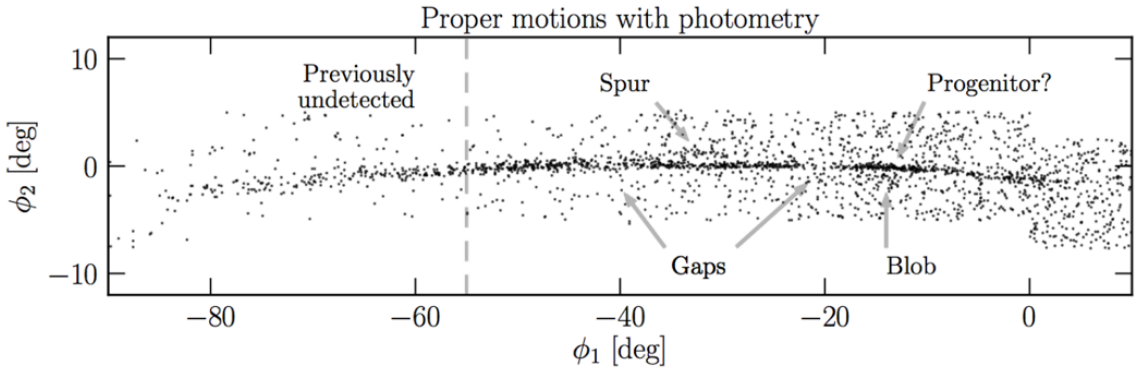


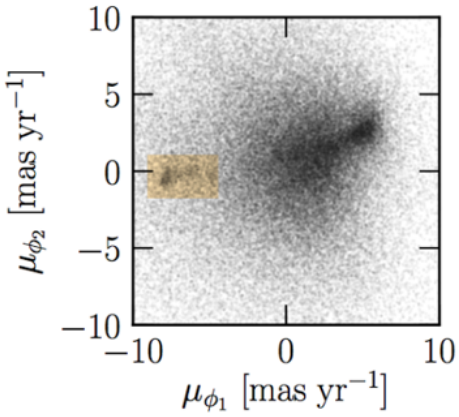
It is interesting that the stream managed to evade possible destruction by interaction with DM subhalos orbiting around MW (Carlberg 2009). Although, the clumpiness observed in the stream may be attributed to these past interactions (S. E. Koposov et al. 2010, in preparation).

Koposov et al. 2010

Stellar Streams: Subhalo Perturbations — GD-1



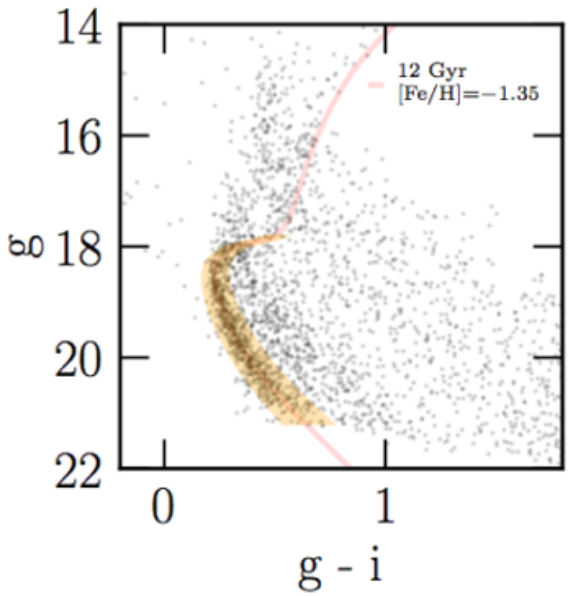




Price-Whelan & Bonaca (2018)

Stellar Streams: Subhalo Perturbations — GD-1

GD-1: 10 kpc

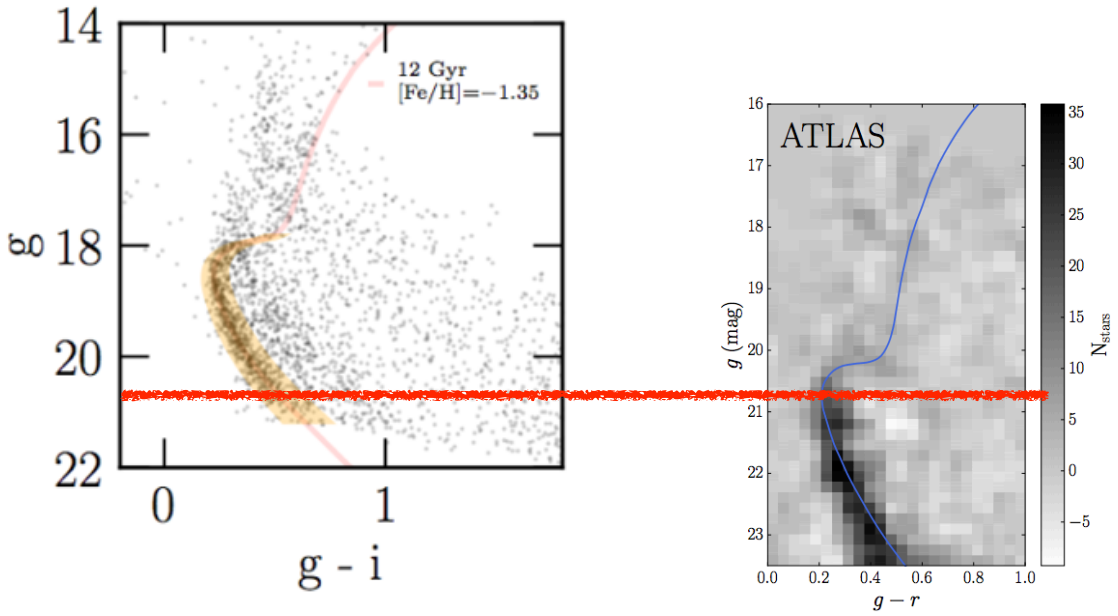


Price-Whelan & Bonaca (2018)

Stellar Streams: Subhalo Perturbations — ATLAS?

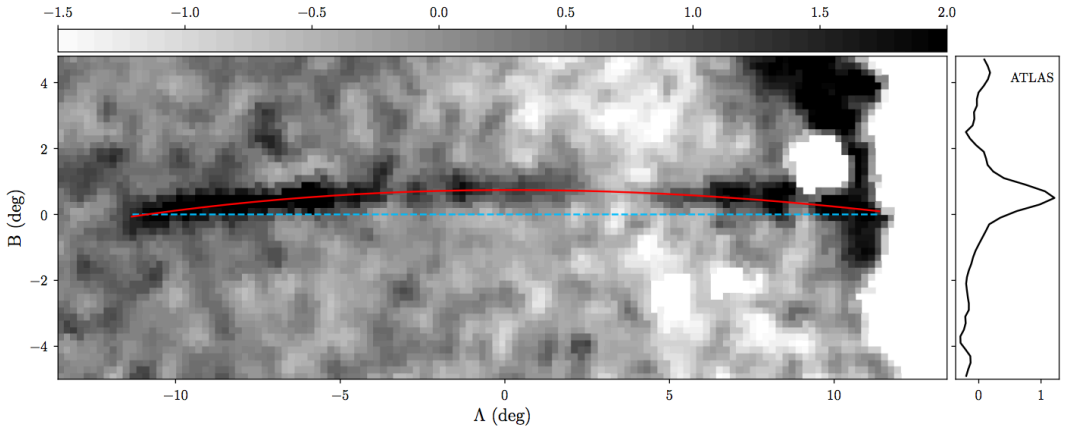
GD-1: 10 kpc

ATLAS: 25 kpc



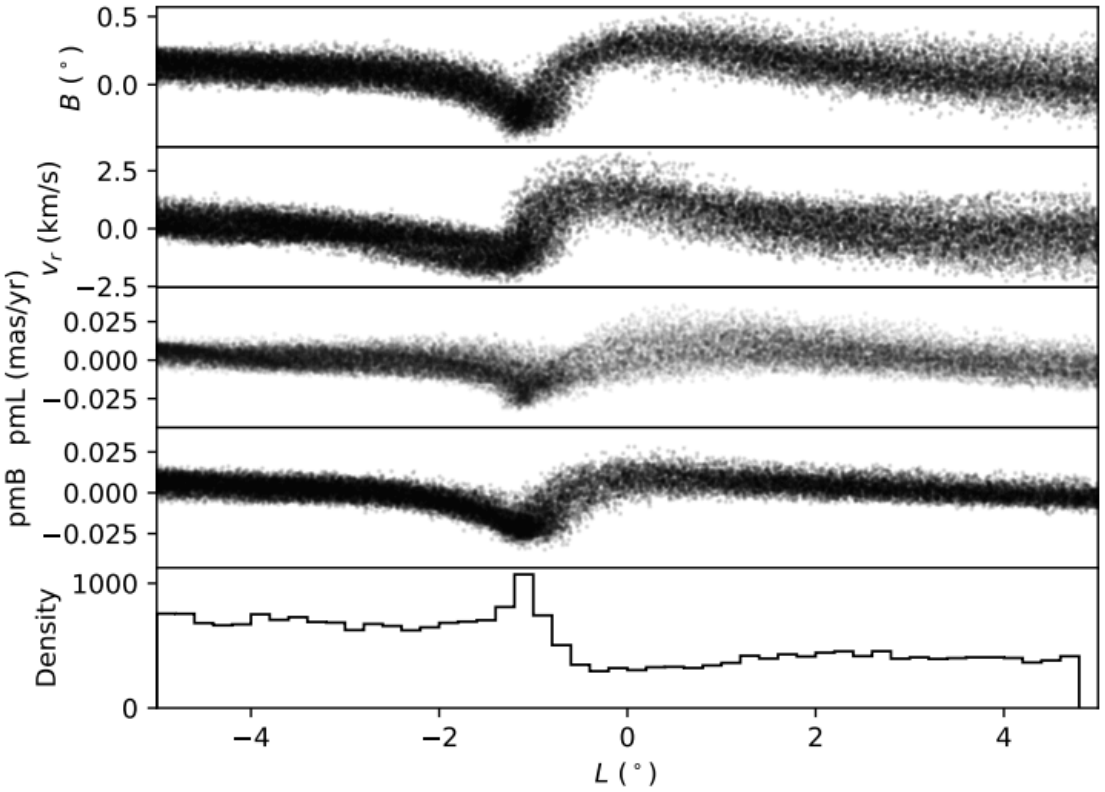
Price-Whelan & Bonaca (2018)

Shipp et al. (2018)



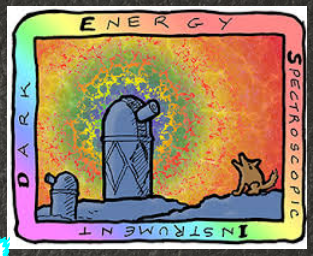
Gaps in ATLAS Stream?
Need WFIRST

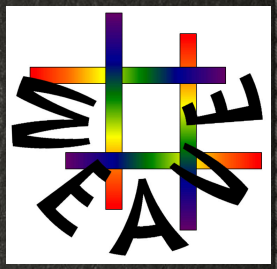
Perturbations in 6D



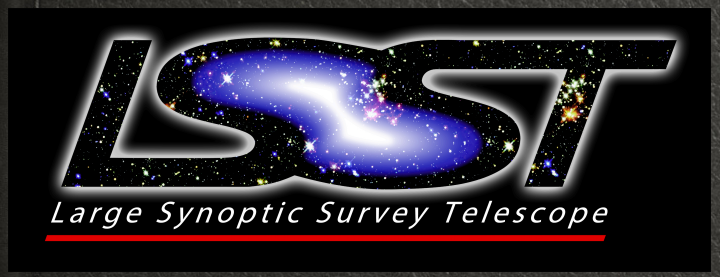
a simulated GD-1 like stream in a 10^6 Msun subhalo

MSE Science Case
DM chapter (40 pages): 1903.03155





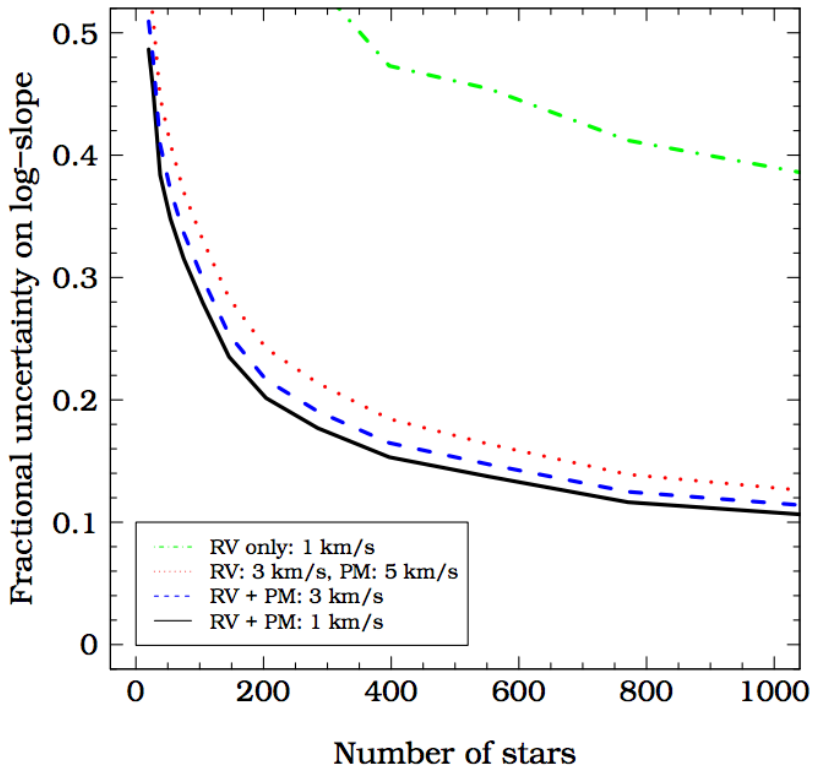
We are in the era with overwhelming amount of data



SOC : a talk “on the topic of Galactic streams, satellites, DM and relation of WFIRST to DES and MSE.”

Thanks for your attention

Dwarf Galaxies: Core vs. Cusp



Simon et al. 2019
arXiv: 1903.04742
Astro2020 White Paper

- a 5σ detection of a central density cusp
  - 3 km/s precision in RV and PM
  - 8 μas/yr at 80 kpc
  - 21 μas/yr at 30 kpc
- Achievable on Draco like dwarf galaxies with WFIRST w/ a baseline of a few years