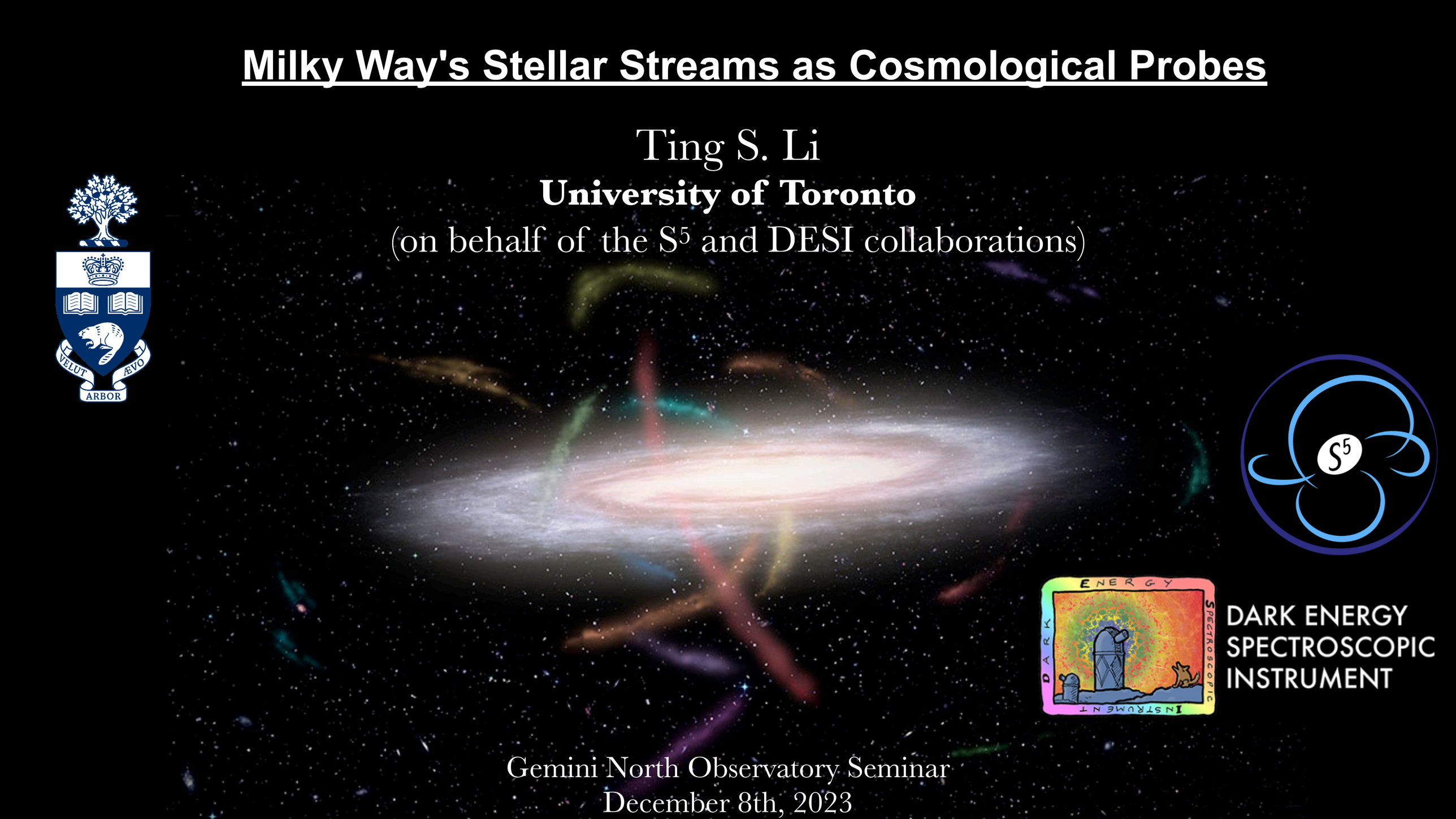
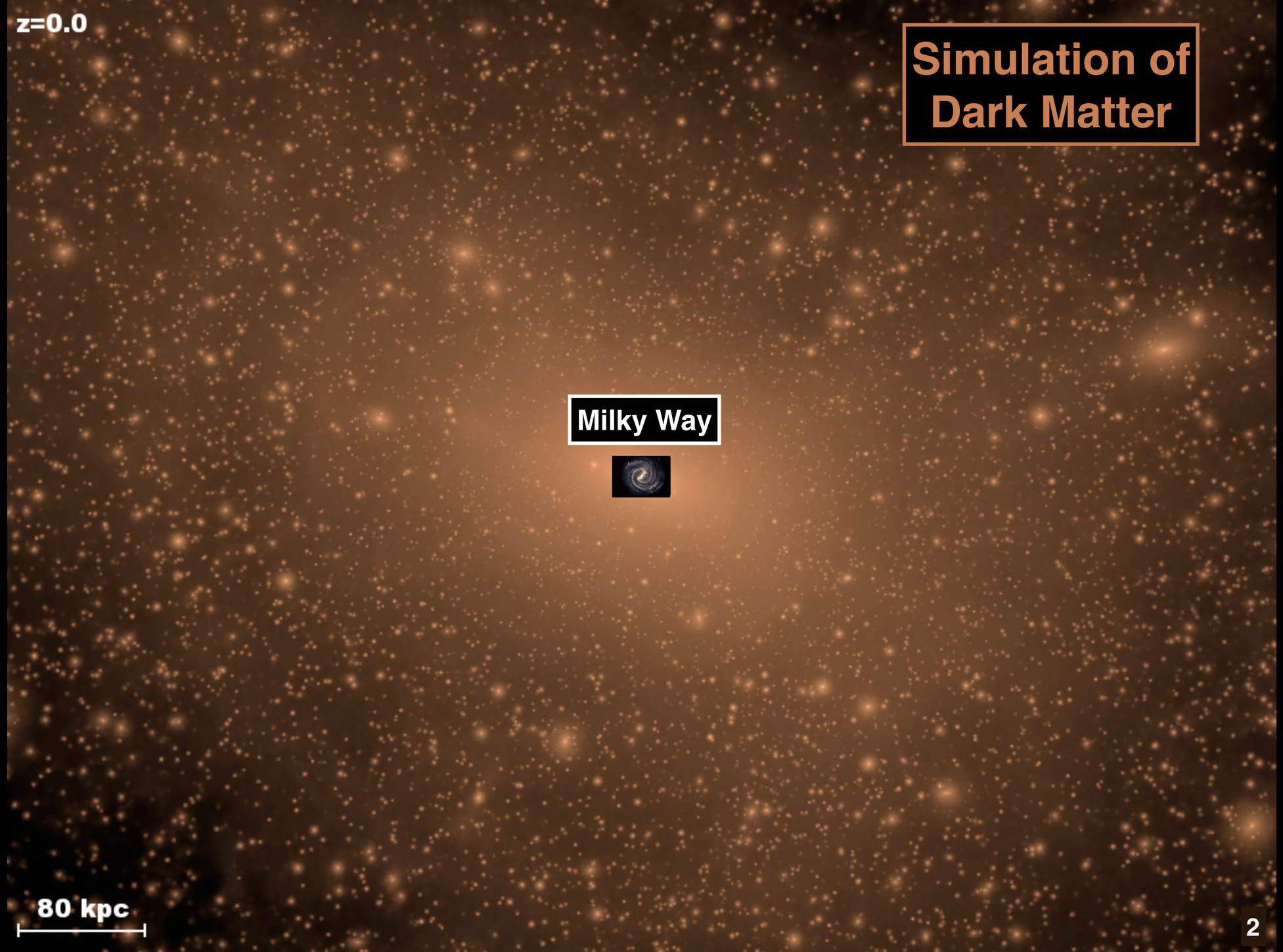
Milky Way's Stellar Streams as Cosmological Probes

Ting S. Li
University of Toronto
(on behalf of the S^5 and DESI collaborations)



Gemini North Observatory Seminar
December 8th, 2023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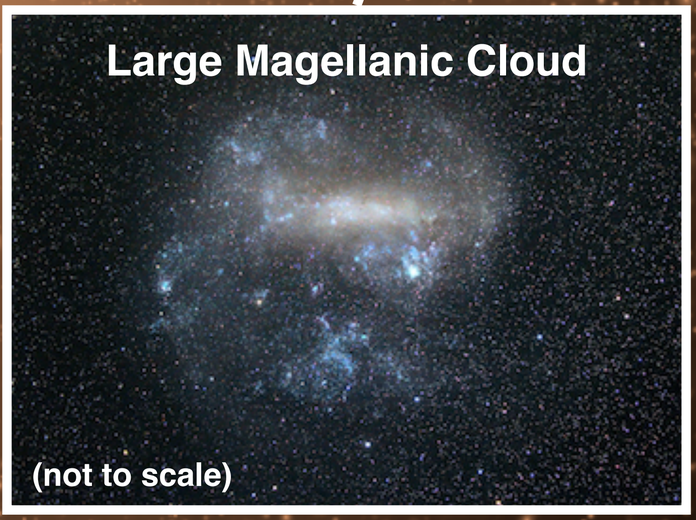
Simulation of Dark Matter
Milky Way
80 kpc

z=0.0

Simulation of Dark Matter

Milky Way

Large Magellanic Cloud



(not to scale)

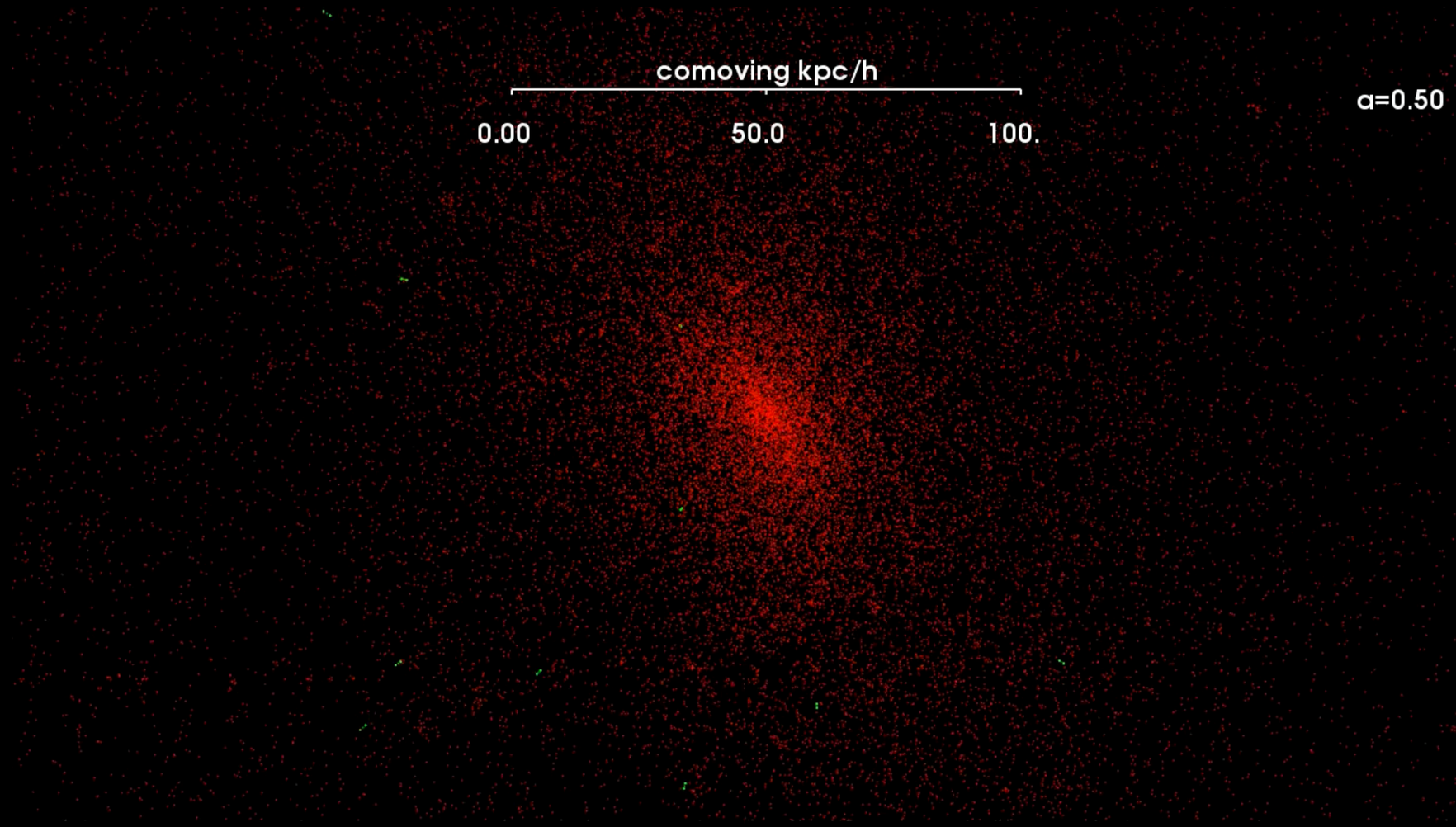
80 kpc


Large Magellanic Cloud
Small Magellanic Cloud

Large Magellanic Cloud

Small Magellanic Cloud

Milky Way's Stellar Streams



Milky Way like galaxies are assembled by accretion and disruption of many smaller systems

Stellar Streams:

- tidally disrupted
  - dwarf galaxies
  - globular clusters
- but not fully mixed

Credit: Denis Erkal

Science with Stellar Streams

Formation of Milky Way's Stellar Halo

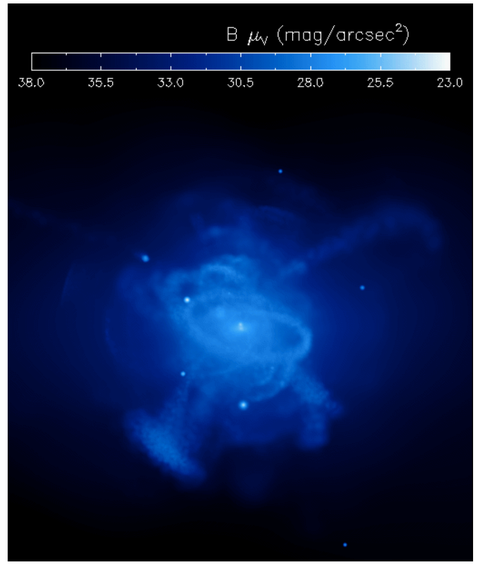
Milky Way Mass & Potential

Dark Matter Subhalos Mass Function

Science with Stellar Streams

Formation of Milky Way's Stellar Halo

- *What are the building blocks of Milky Way's stellar halo?*
- *Where do the most metal-poor stars come from?*



Bullock & Johnston (2005)

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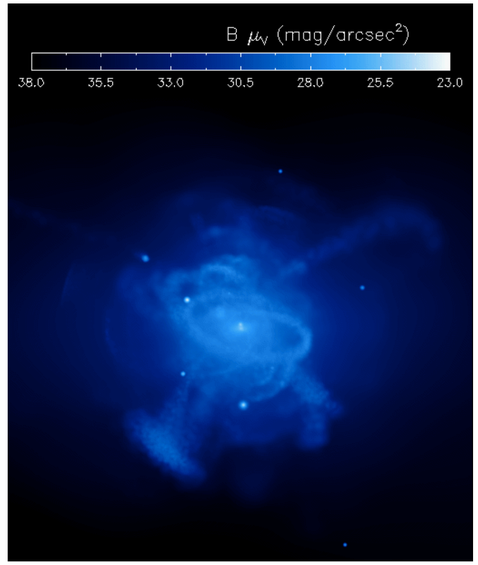

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- *Is Milky Way's virial mass 0.8 or 1.6 x 10^{12} Msun?*
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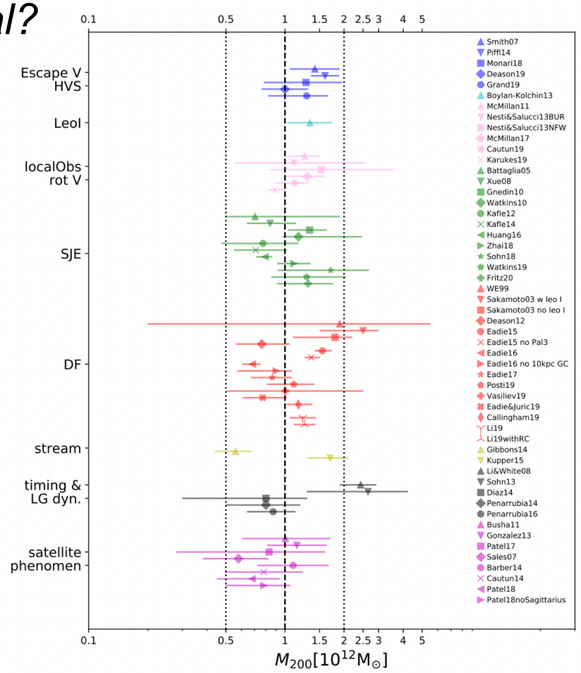

Wenting Wang et al. (2020)

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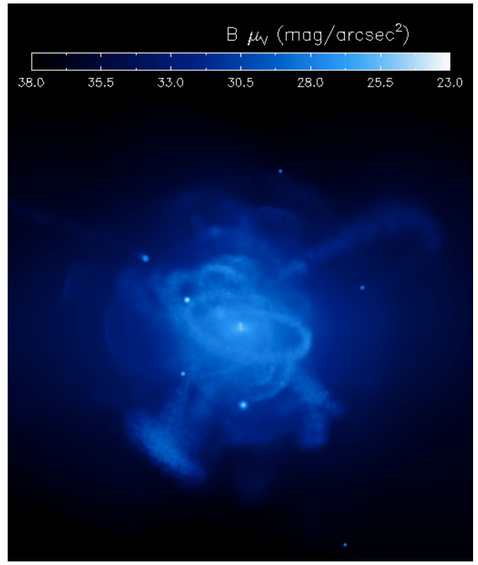

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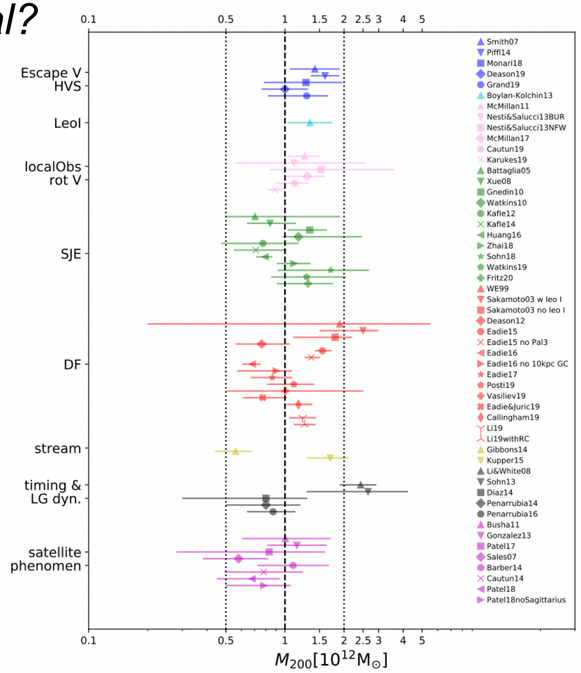

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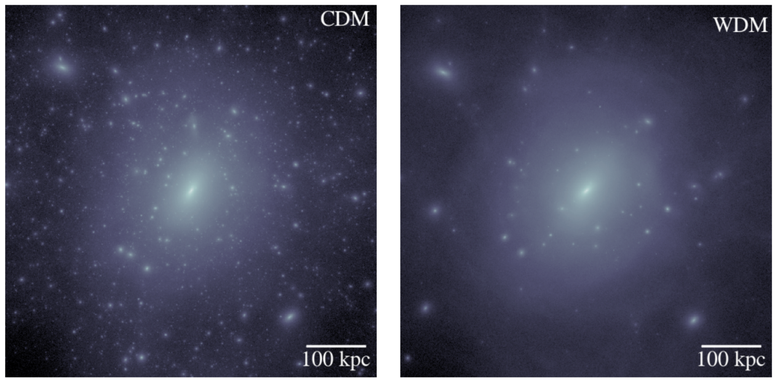
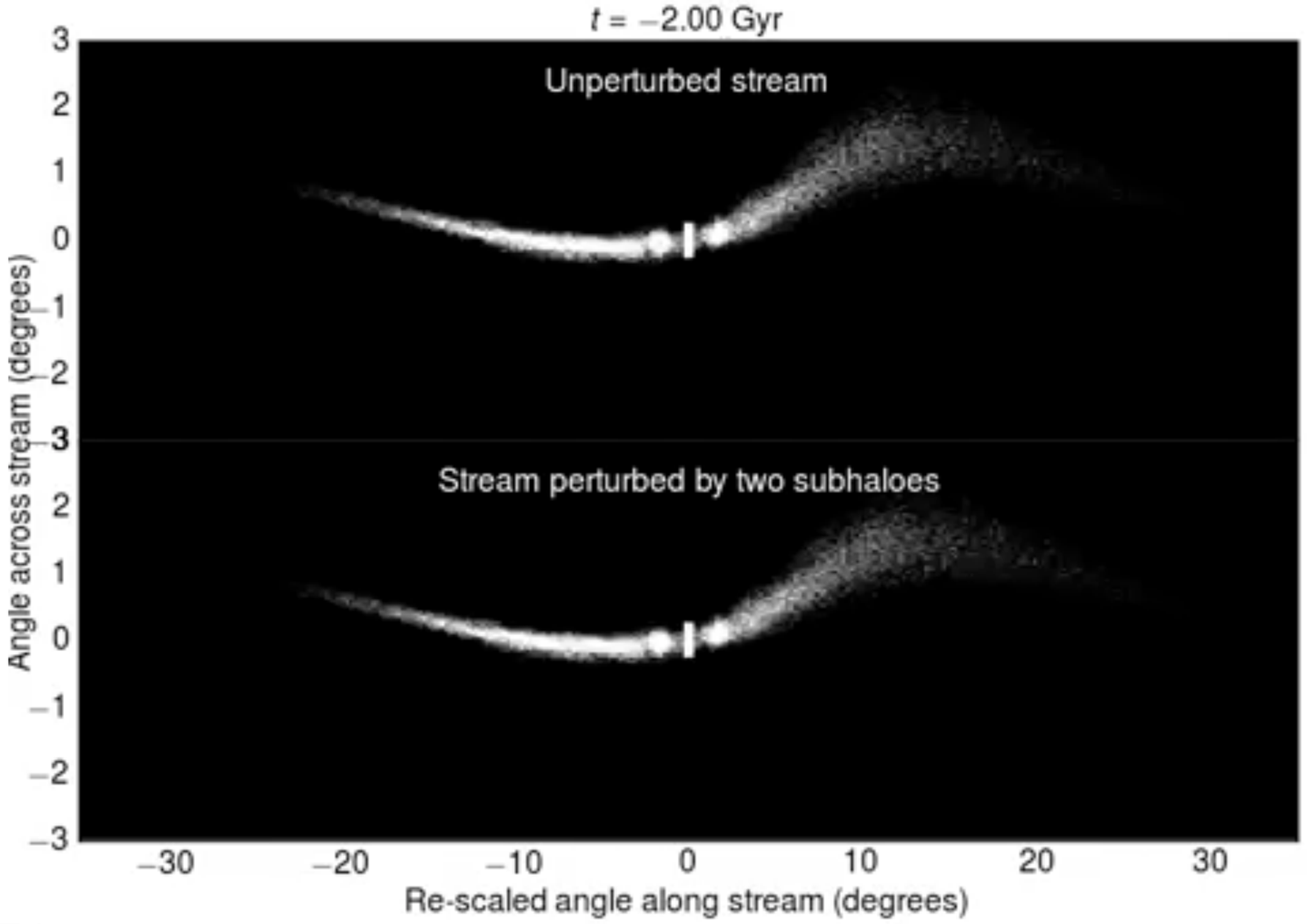


Bullock & Boylan-Kolchin (2017)

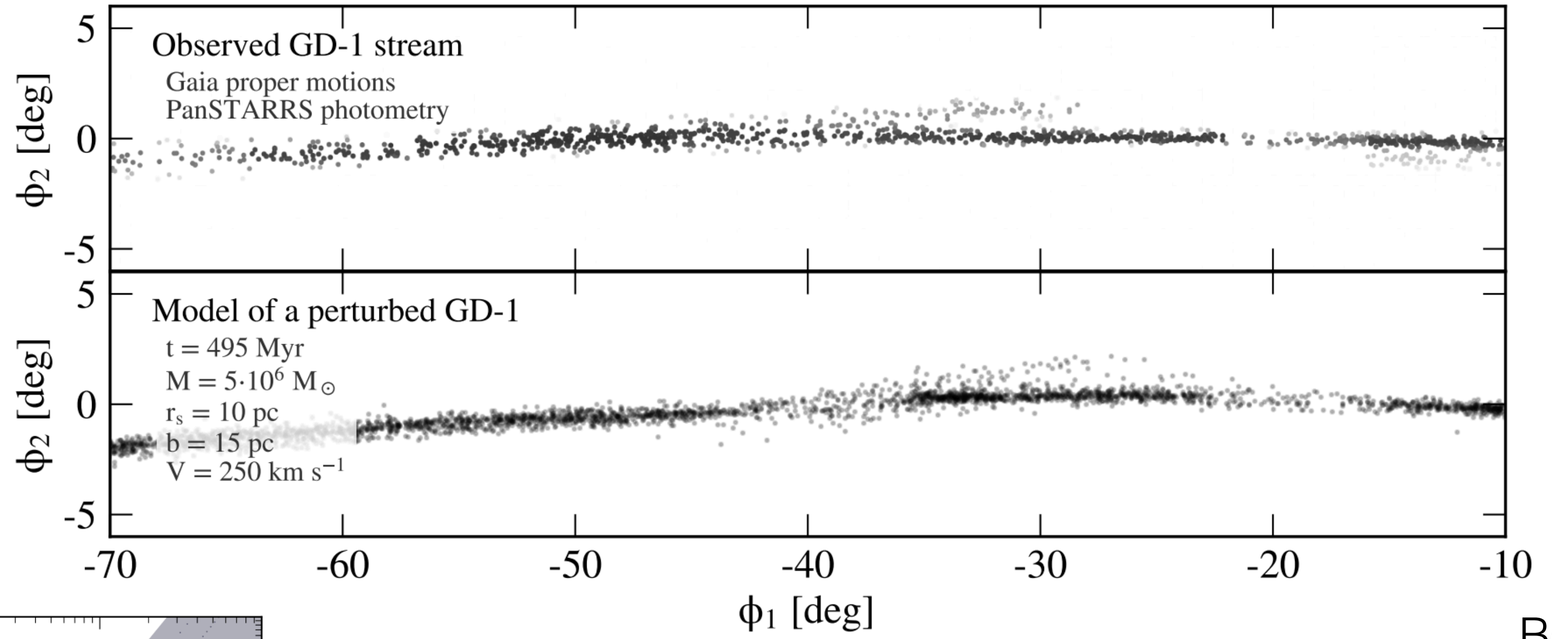
Science with Stellar Streams



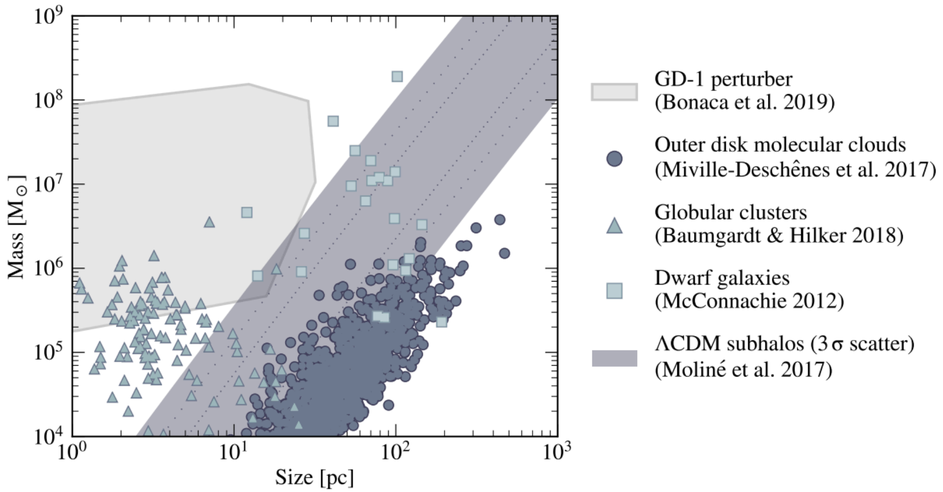
Cold streams may be perturbed by subhalo flyby

Credit: Denis Erkal

Science with Stellar Streams



Bonaca et al. (2019)



- Spur come from a compact perturber?
- However, de Boer et al (2019) shows that the spur might caused by an interaction with Sagittarius dwarf galaxy.

Science with Stellar Streams

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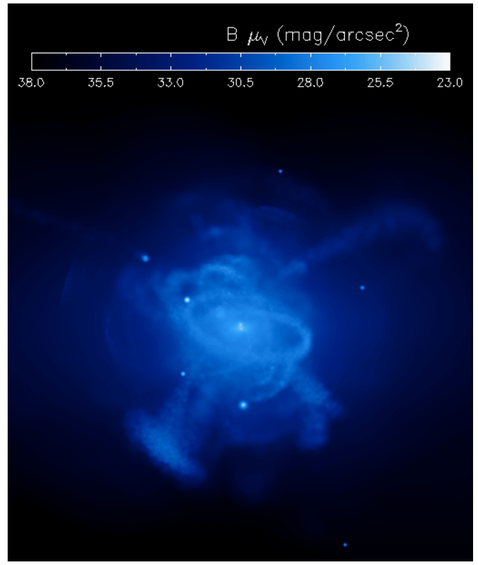

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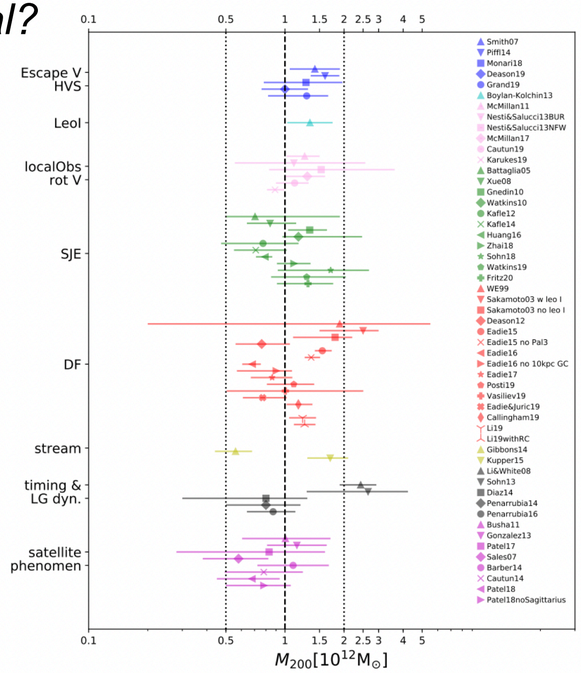

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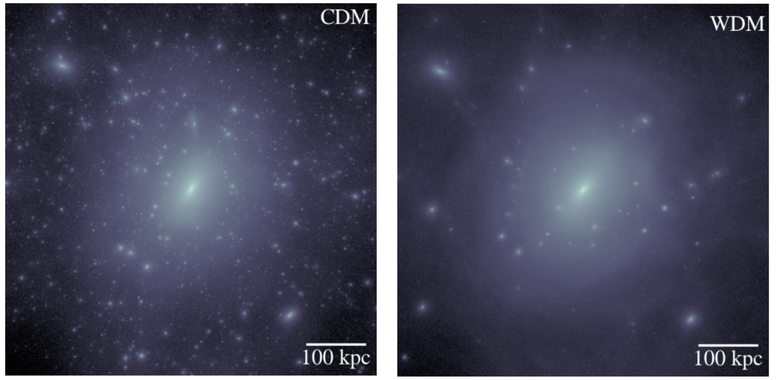
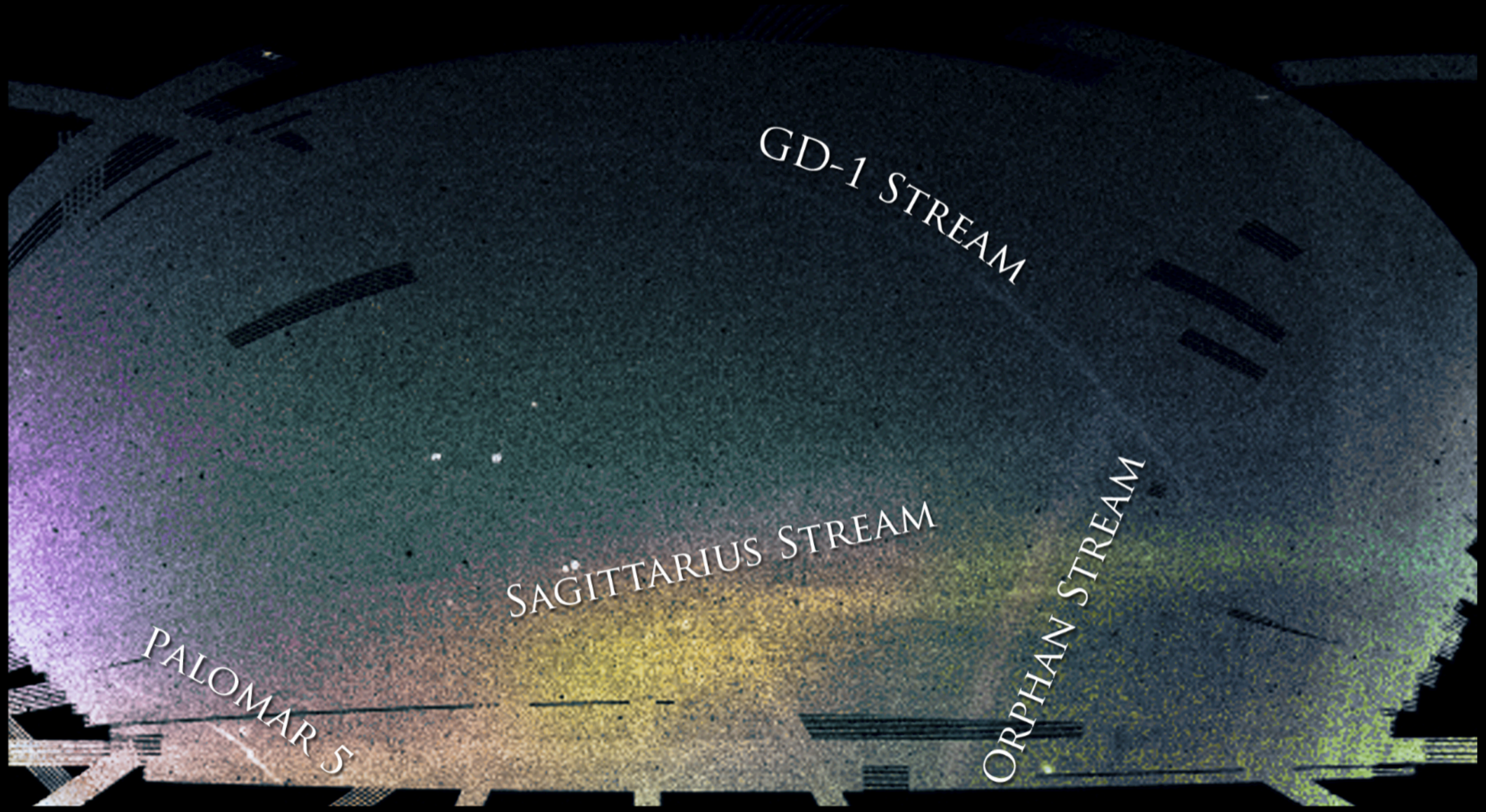


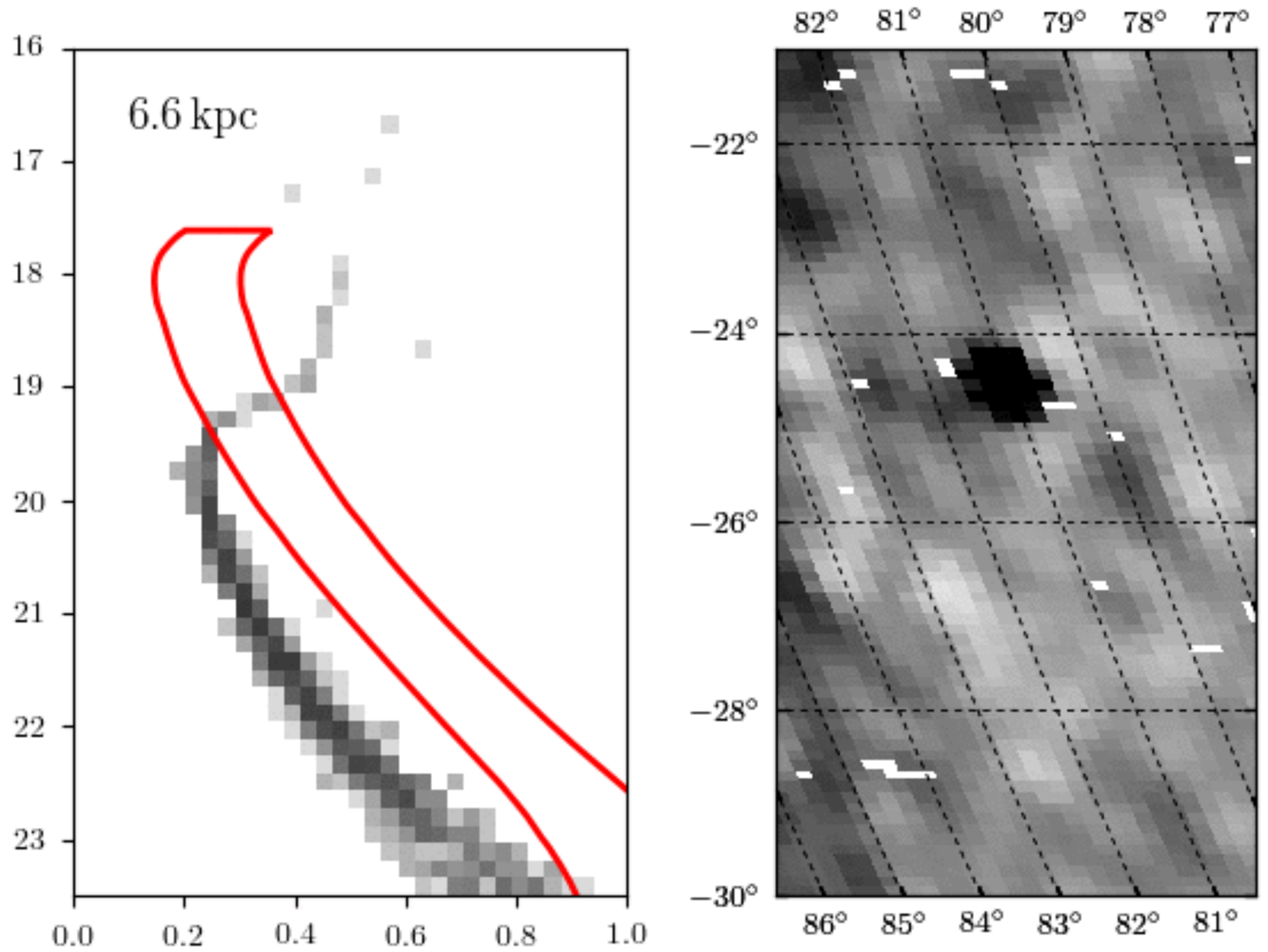
Bullock & Boylan-Kolchin (2017)

NORTHERN SKY



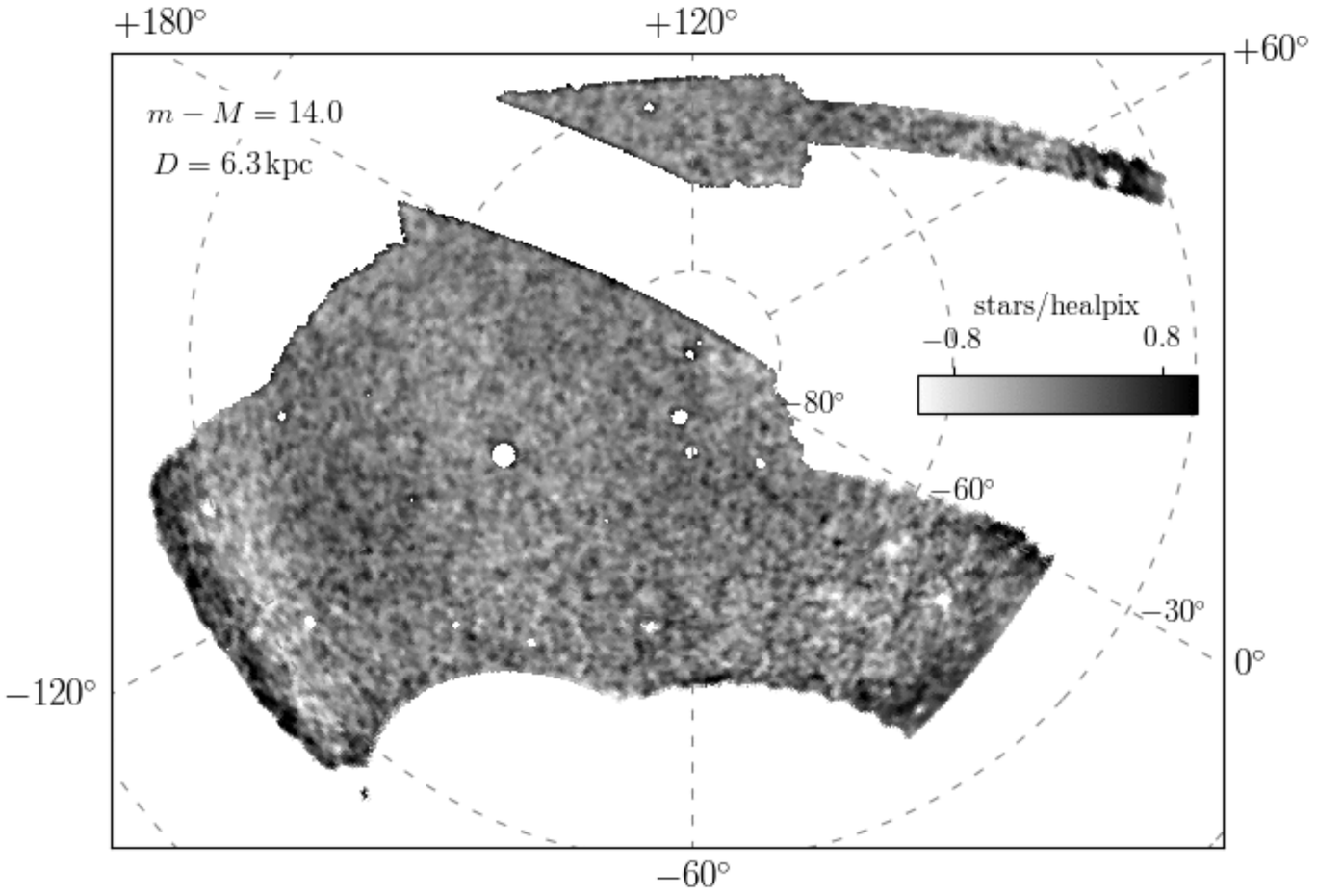
Sloan Digital Sky Survey SDSS DR8 / Bonaca, Giguere, Geha

Isochrones Scanning through in distance



Credit: Alex Drlica-Wagner

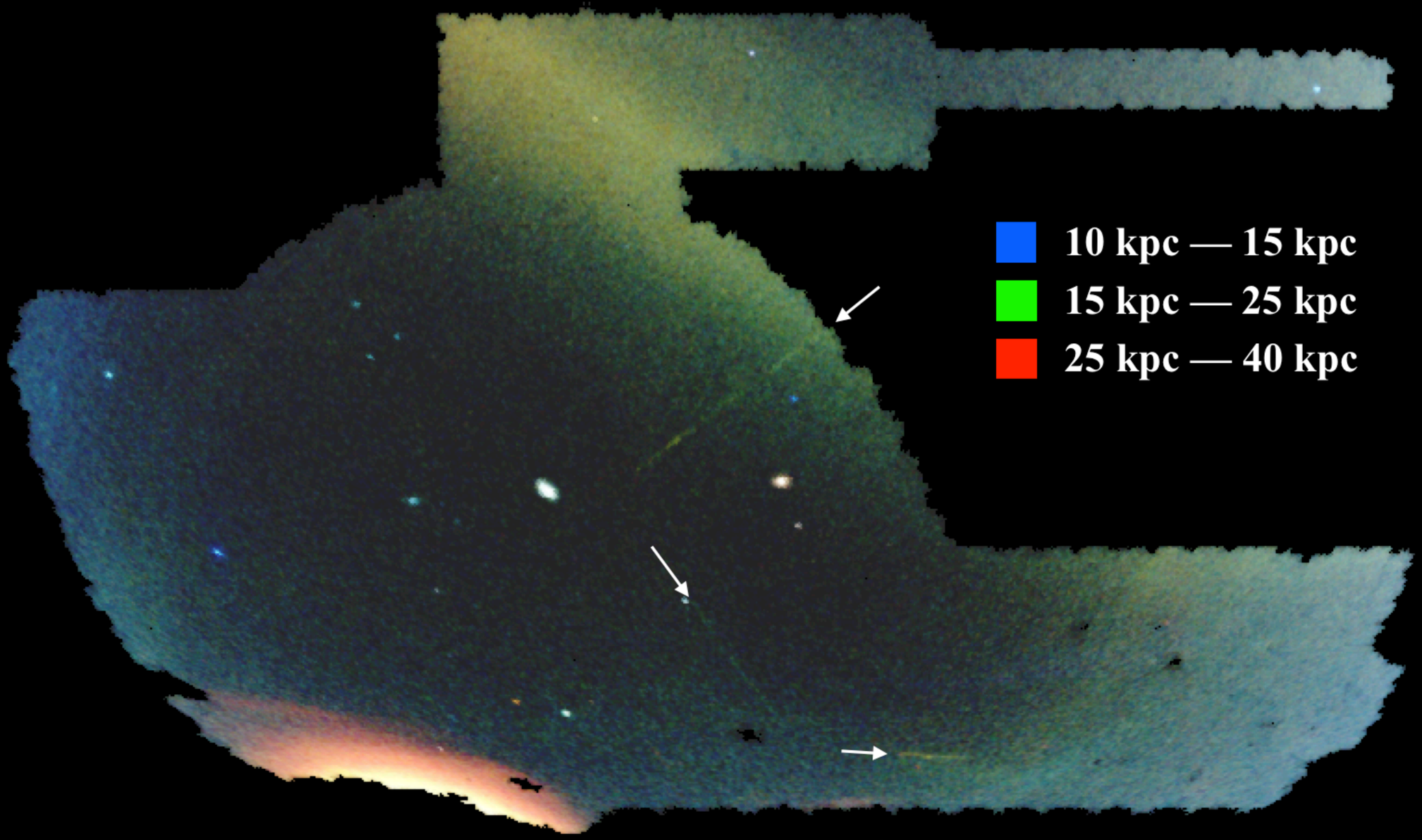
Streams in the Dark Energy Survey



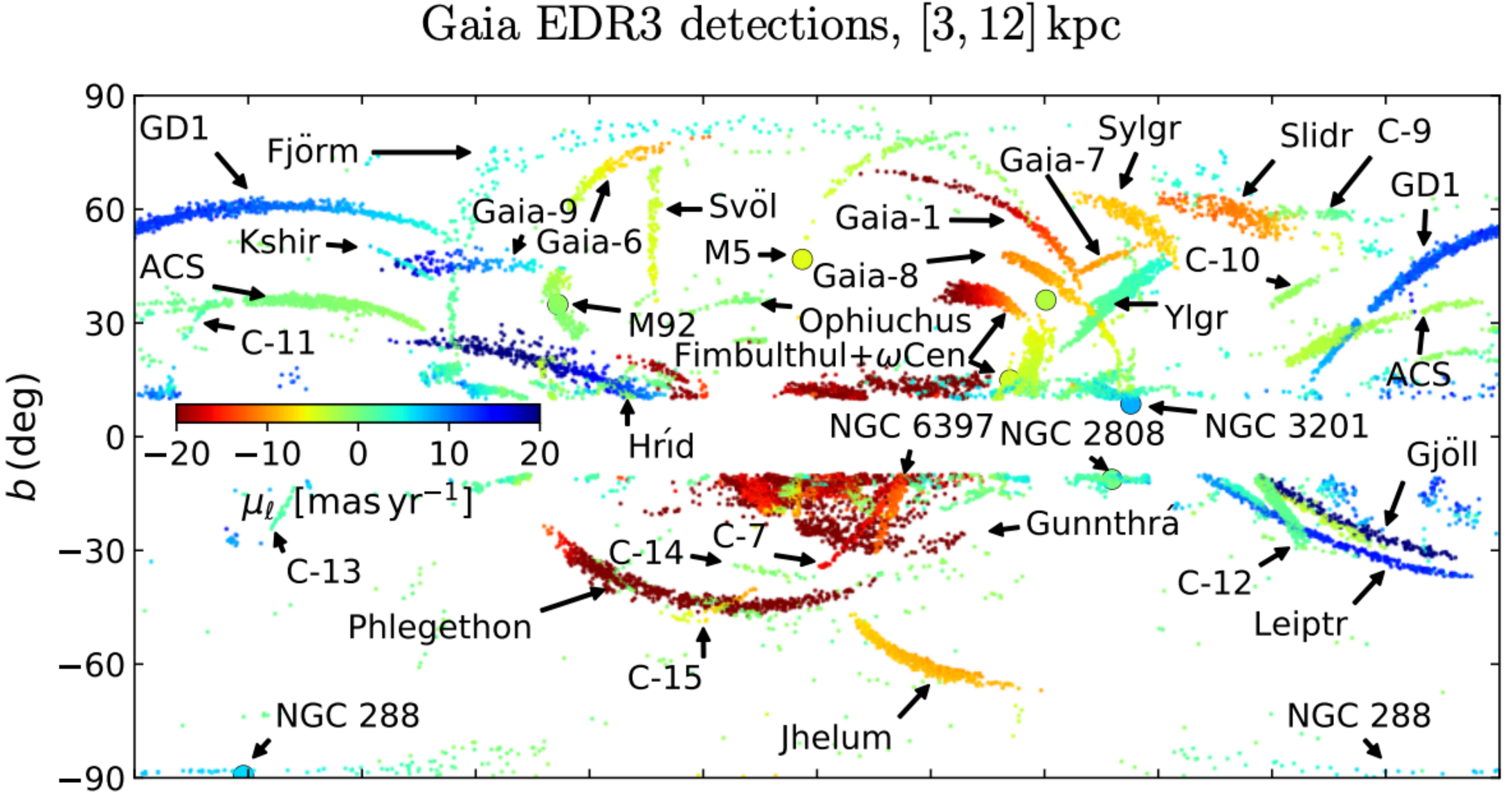
Shipp et al. 2018
(DES Collaboration)

13 new streams from DES + 2 previous known

SOUTHERN SKY

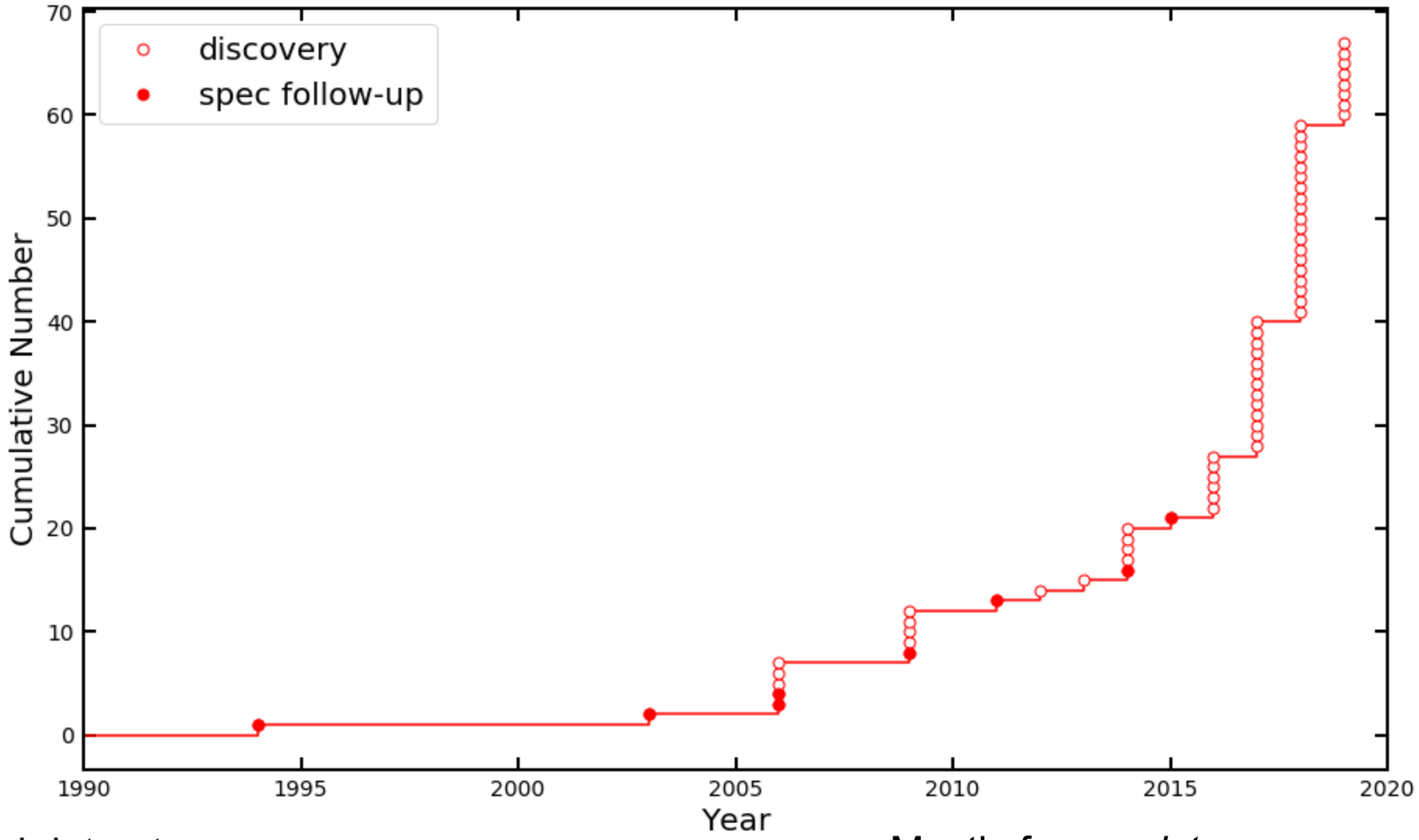


Dark Energy Survey DES / Shipp, Drlica-Wagner et al. 2018



Gaia EDR3 / Ibata et al. 2021

Milky Way Stellar Stream Discovery Timeline



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

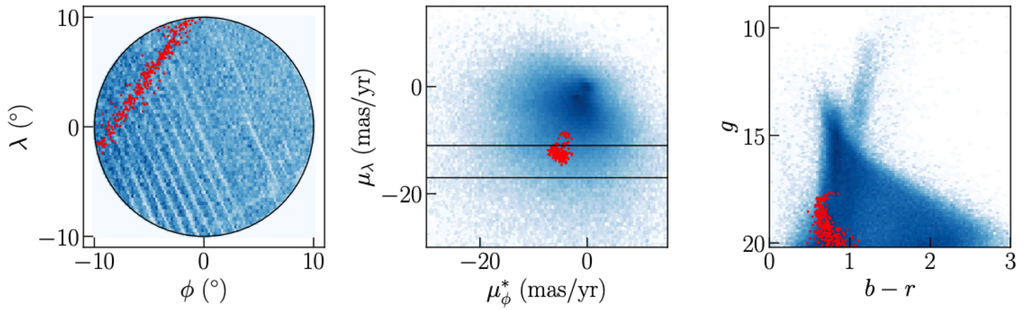
Mostly from *galstream*
https://github.com/cmateu/galstreams

Stream Search w/ Machine Learning

Via Machinae: Searching for Stellar Streams using Unsupervised Machine Learning

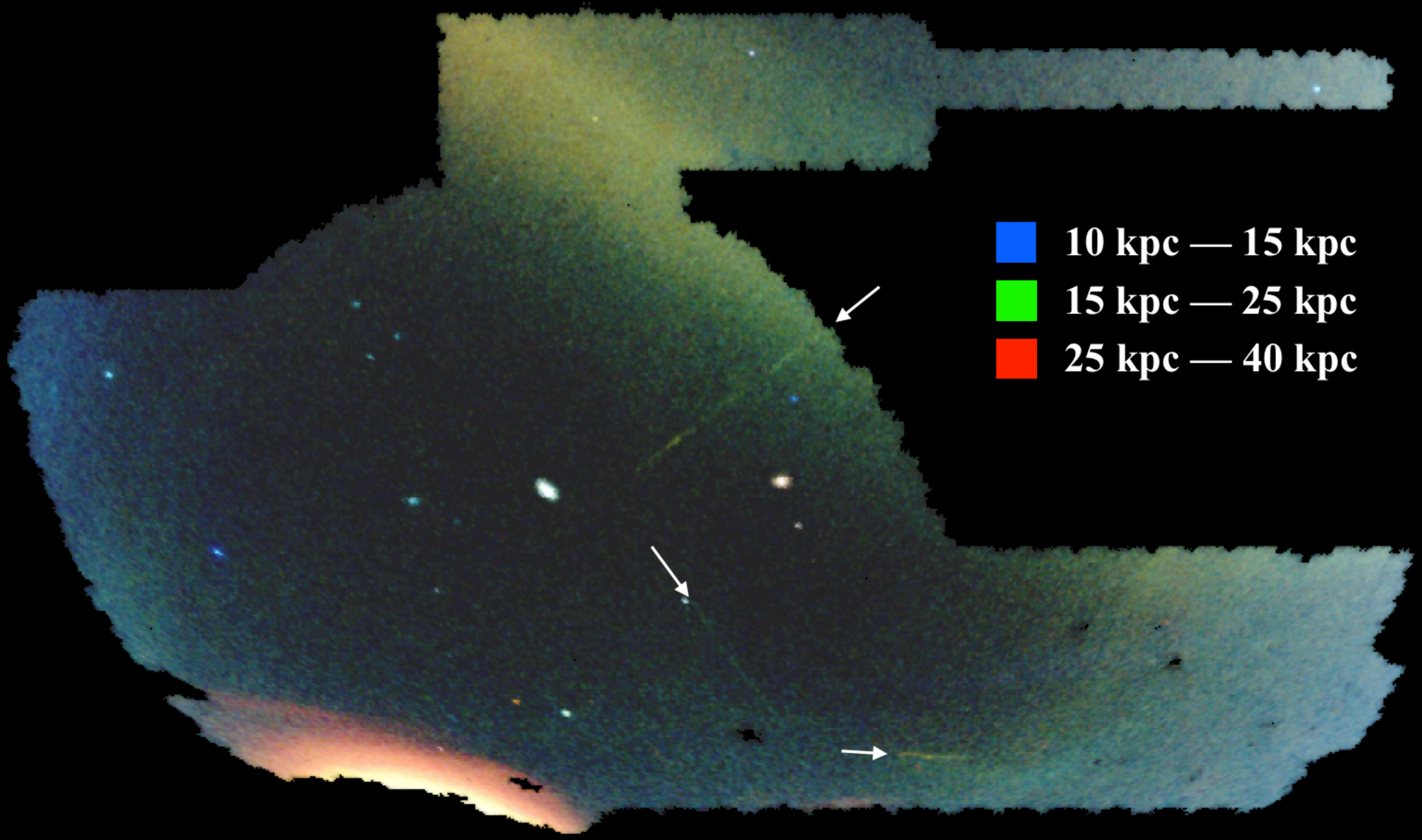
David Shih,[1]★ Matthew R. Buckley,[1] Lina Necib,[2,3,4] and John Tamanas[5]
[1]*NHETC, Dept. of Physics and Astronomy, Rutgers, Piscataway, NJ 08854, USA*
[2]*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*
[3]*Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*
[4]*Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA*
[5]*Department of Physics, University of California Santa Cruz, 1156 High Street, Santa Cruz, California 95064, USA*

based on the deep learning anomaly detector ANODE 90 new streams discovered?



Shih et al. 2021, 2023

SOUTHERN SKY



Dark Energy Survey DES / Shipp, Drlica-Wagner et al. 2018

Southern Stellar Stream Spectroscopic Survey (S^5)
Key Members of S5 Team

https://s5collab.github.io/

Ting Li

Daniel Zucker

Geraint Lewis

Kyler Kuehn

Alex Ji

Sergey Koposov

Denis Erkal

Andrew Pace

Nora Shipp

Clara Martinez-Vazquez

Sophia Lilleengen

Lara Cullinane

Sarah Martell

and Joss Bland-Hawthorn, Gary Da Costa, Dougal Mackey, Eduardo Balbinot, Andrew Casey, Gayandhi De Silva, Alex Drlica-Wagner, Marla Geha, Terese Hansen, Jennifer Marshall, Jeremy Mould, Sanjib Sharma, Kathy Vivas and many more …

S⁵: DES+Gaia

Since Summer 2018

Efficient Target Selection w/

DES DR1 photometry Gaia DR2 proper motions

DARK ENERGY SURVEY

gaia

S^5: DES+Gaia+AAT

Since Summer 2018

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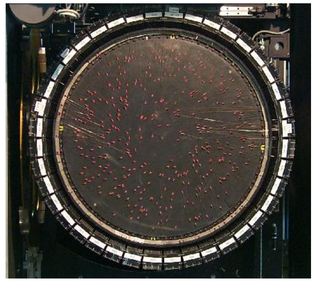
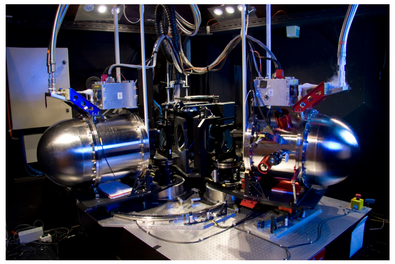


2-degree-Field (2df) fibre positioned



AAOmega spectrograph

Efficient Target Selection w/

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DARK ENERGY SURVEY

gaia

The Southern Stellar Stream Spectroscopic Survey (S5): Overview, Target Selection, Data Reduction, Validation, and Early Science
TSL et al. 2019, arXiv:1907.09481

S⁵: DES+Gaia+AAT+Magellan

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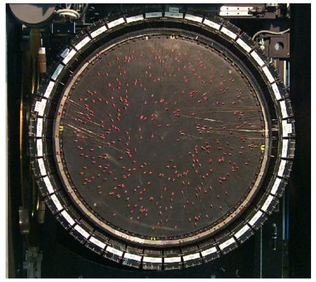

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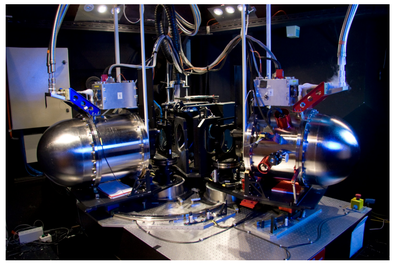

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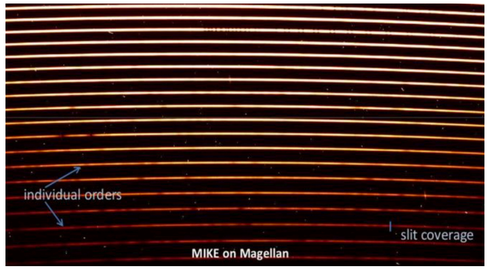
DARK ENERGY SURVEY

gaia

6.5-m Magellan Telescope

MIKE spectrograph



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Ji, TSL et al (2020), arXiv: 2008.07568

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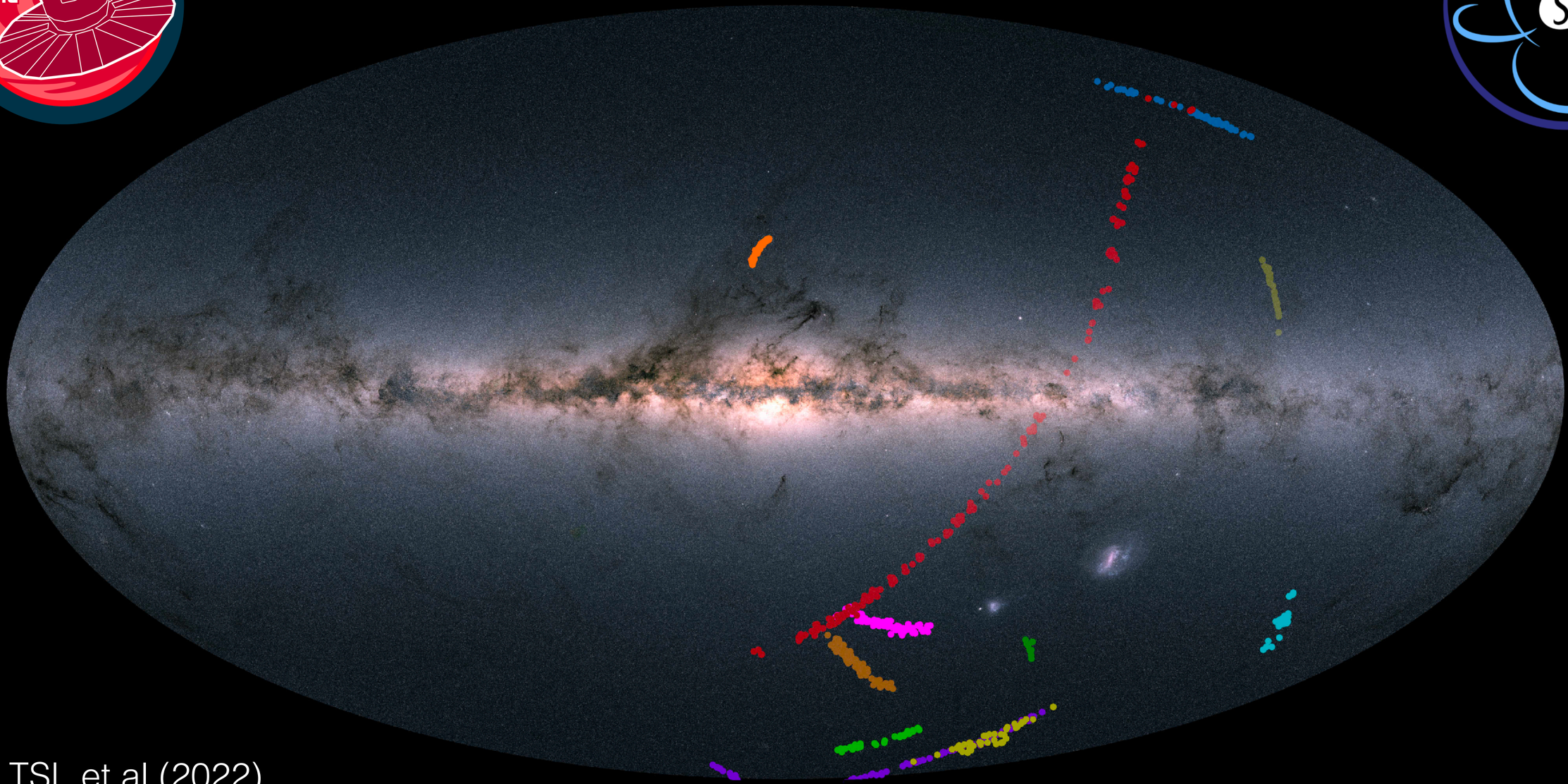
- Streams on FIRE: Populations of Detectable Stellar Streams in the Milky Way and FIRE
  Shipp, Nora *et al.* (2022) arXiv (arXiv:2208.02255)
- The effect of the deforming dark matter haloes of the Milky Way and the Large Magellanic Cloud on the Orphan-Chenab stream
  Lilleengen, Sophia *et al.* (2022) arXiv (arXiv:2205.01688)
- S⁵: The Orbital and Chemical Properties of One Dozen Stellar Streams
  Li, Ting S. *et al.* (2022) ApJ 928 30 (doi:10.3847/1538-4357/ac46d3, arXiv:2110.06950)
- Measuring the Mass of the Large Magellanic Cloud with Stellar Streams Observed by S⁵
  Shipp, Nora *et al.* (2021) ApJ 923 149 (doi:10.3847/1538-4357/ac2e93, arXiv:2107.13004)
- Signature of a Massive Rotating Metal-poor Star Imprinted in the Phoenix Stellar Stream
  Casey, Andrew R. *et al.* (2021) ApJ 921 67 (doi:10.3847/1538-4357/ac1346, arXiv:2109.03948)
- Kinematics of Antlia 2 and Crater 2 from the Southern Stellar Stream Spectroscopic Survey (S⁵)
  Ji, Alexander P. *et al.* (2021) ApJ 921 32 (doi:10.3847/1538-4357/ac1869, arXiv:2106.12656)

s5collab.github.io

S^5: DES+Gaia+AAT+Magellan

- S^5: The Destruction of a Bright Dwarf Galaxy as Revealed by the Chemistry of the Indus Stellar Stream
  Hansen, Terese T. *et al.* (2021) ApJ 915 103 (doi:10.3847/1538-4357/abfc54, arXiv:2104.13883)
- Broken into Pieces: ATLAS and Aliqa Uma as One Single Stream
  Li, Ting S. *et al.* (2021) ApJ 911 149 (doi:10.3847/1538-4357/abeb18, arXiv:2006.10763)
- The Southern Stellar Stream Spectroscopic Survey (S^5): Chemical Abundances of Seven Stellar Streams
  Ji, Alexander P. *et al.* (2020) AJ 160 181 (doi:10.3847/1538-3881/abacb6, arXiv:2008.07568)
- The tidal remnant of an unusually metal-poor globular cluster
  Wan, Zhen *et al.* (2020) Nature 583 768 (doi:10.1038/s41586-020-2483-6, arXiv:2007.14577)
- Discovery of a nearby 1700 km s^{-1} star ejected from the Milky Way by Sgr A*
  Koposov, Sergey E. *et al.* (2020) MNRAS 491 2465 (doi:10.1093/mnras/stz3081, arXiv:1907.11725)
- The southern stellar stream spectroscopic survey (S^5): Overview, target selection, data reduction, validation, and early science
  Li, T. S. *et al.* (2019) MNRAS 490 3508 (doi:10.1093/mnras/stz2731, arXiv:1907.09481)
- Proper Motions of Stellar Streams Discovered in the Dark Energy Survey
  Shipp, N. *et al.* (2019) ApJ 885 3 (doi:10.3847/1538-4357/ab44bf, arXiv:1907.09488)

s5collab.github.io



TSL et al (2022)
(S^5 Collaboration)

Credit: Gaia + S5

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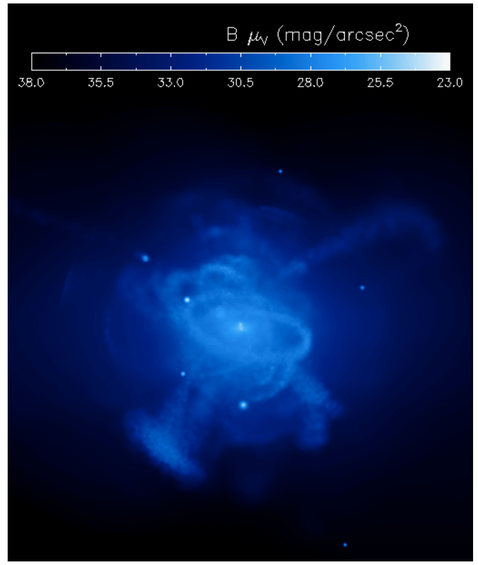

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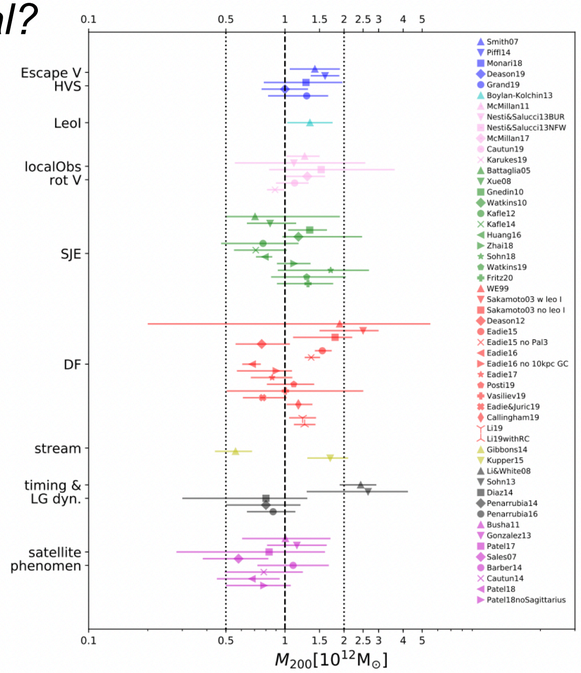

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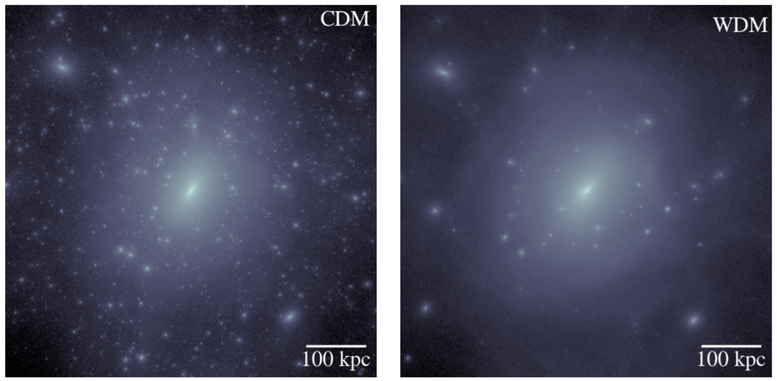
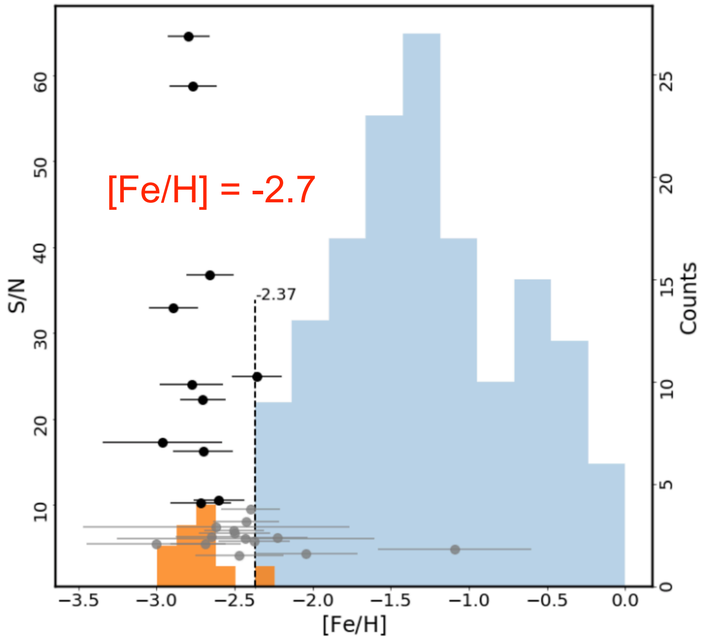


Bullock & Boylan-Kolchin (2017)

S⁵: Highlights on Stream Science w/ AAT

Phoenix Stream: more metal-poor than any known globular cluster



Cyan: globular cluster in Milky Way
Orange: stars in Phoenix Stream

Wan, Lewis, TSL et al. (2020) Nature

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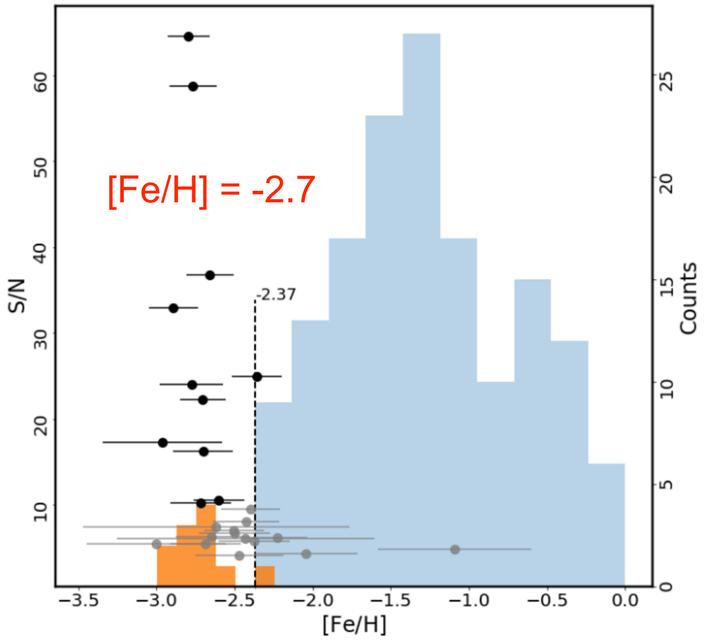

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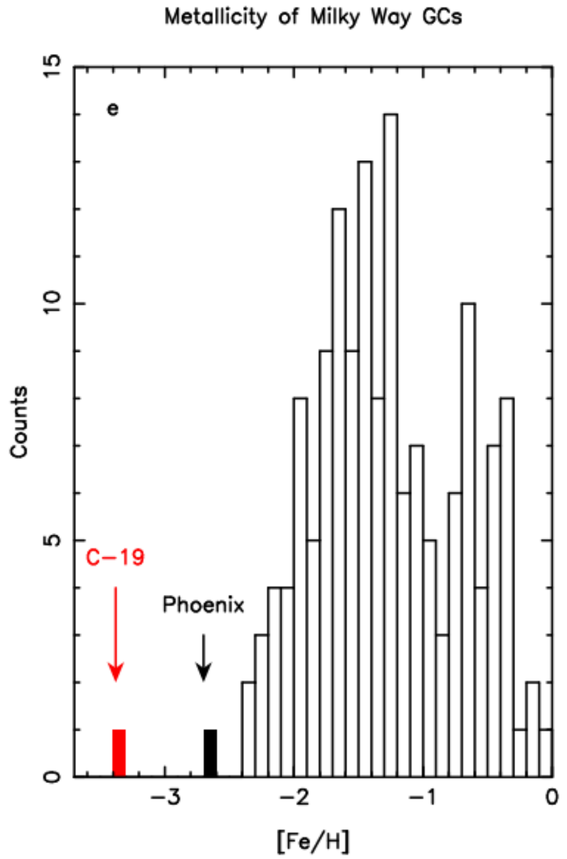
Wan, Lewis, TSL et al. (2020) Nature

C-19 Stream — [Fe/H] = -3.4!



Martin et al. (2022) Nature

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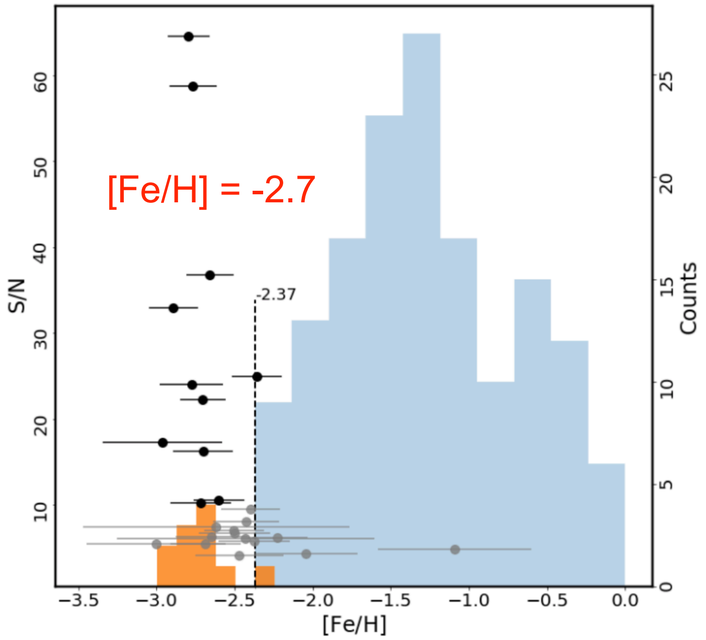

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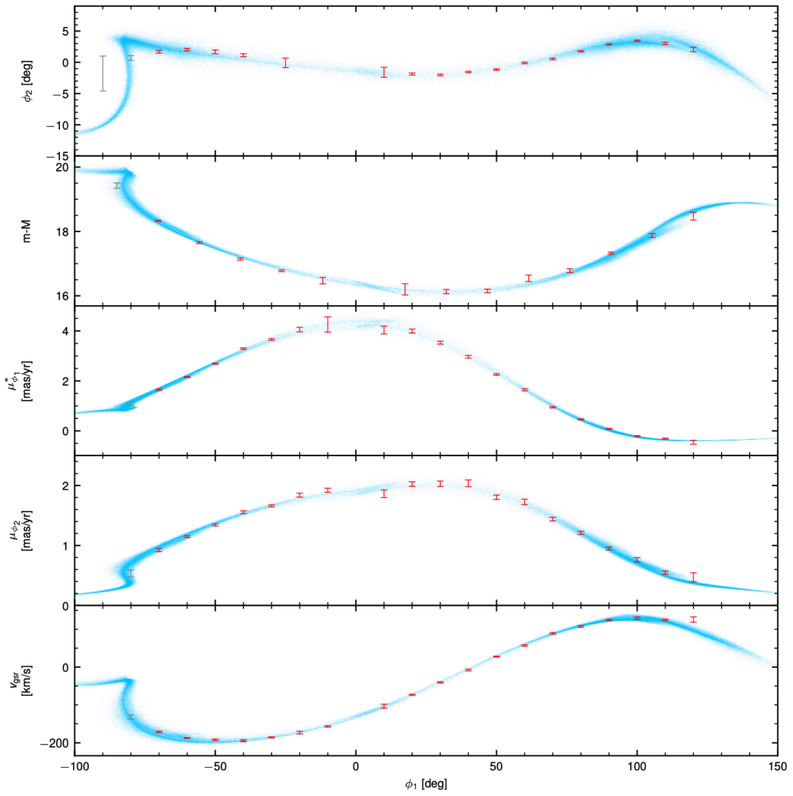
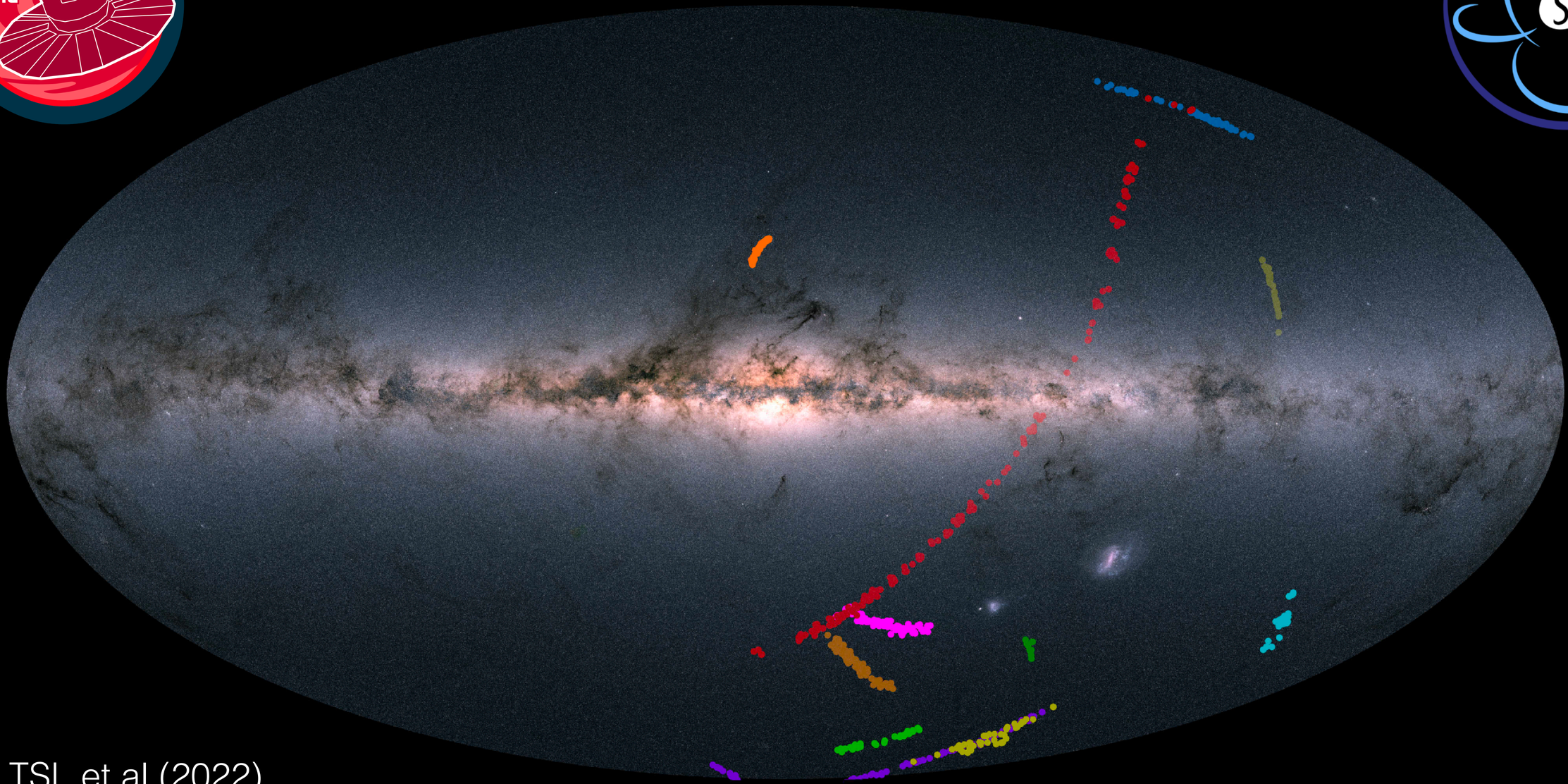
Wan, Lewis, TSL et al. (2020) Nature

Constraint on mass of the Milky Way and LMC



Koposov, Erkal, TSL et al. (2023)

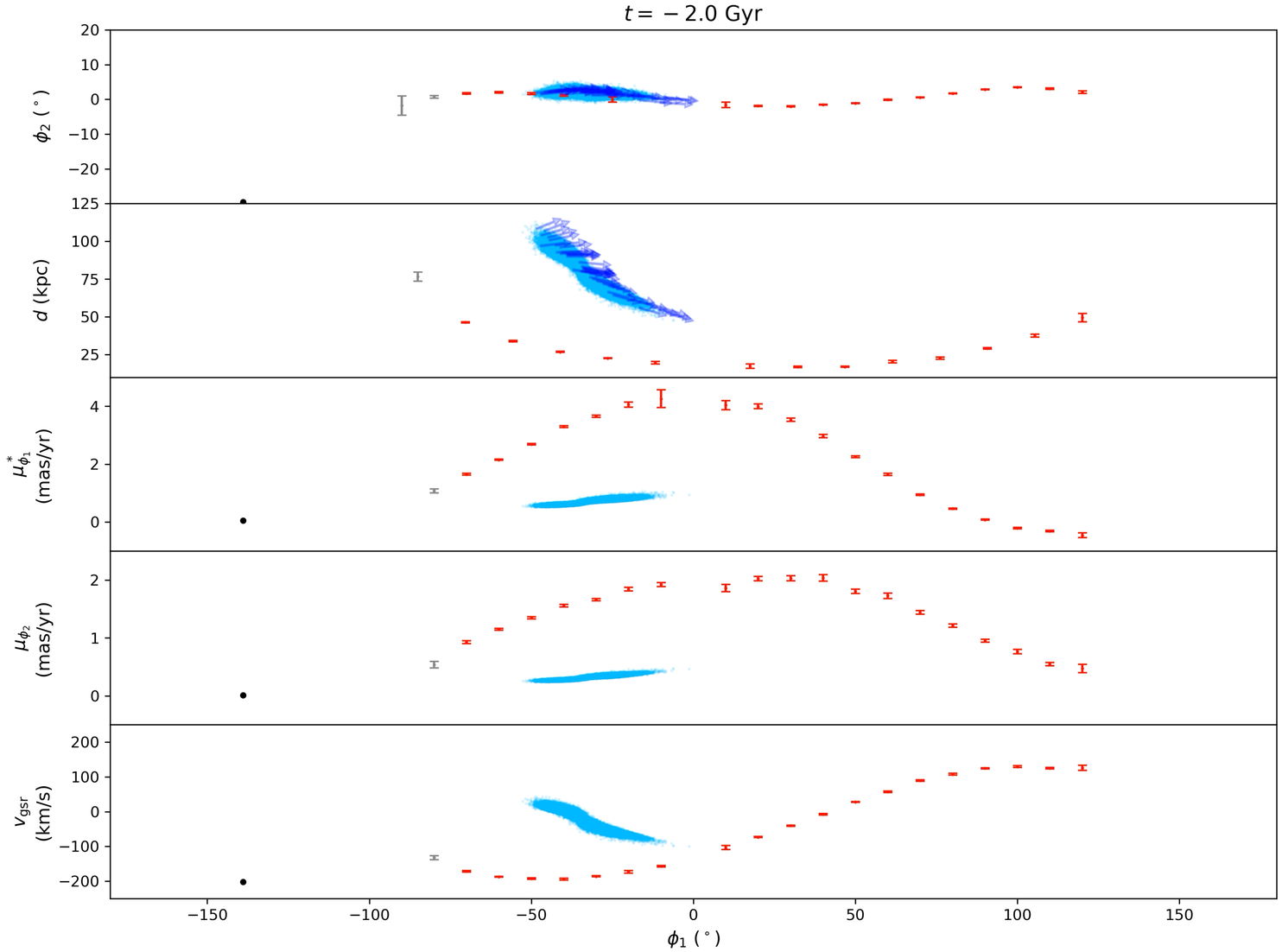

Large Magellanic Cloud
Small Magellanic Cloud



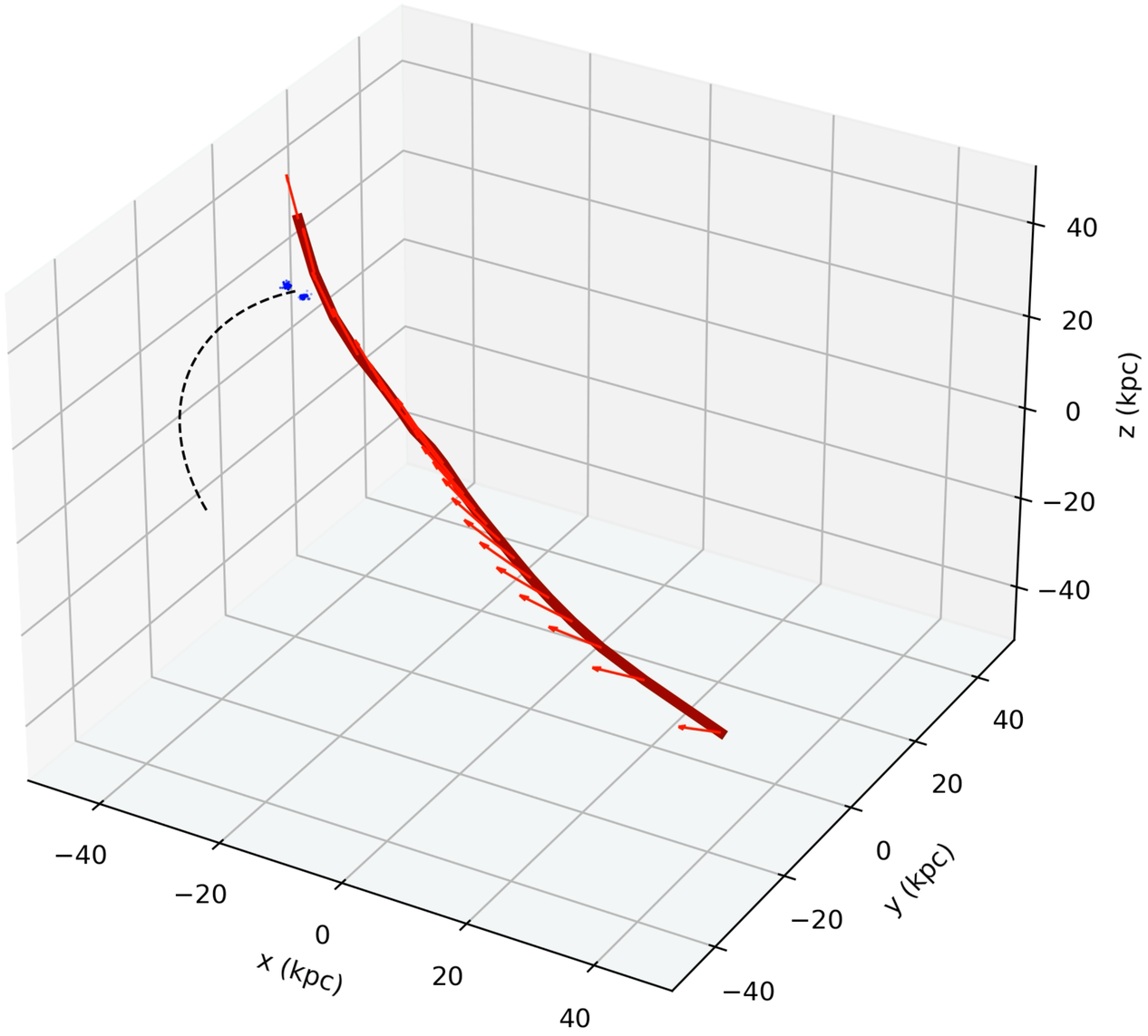
TSL et al (2022)
(S^5 Collaboration)

Credit: Gaia + S5

Orphan-Chenab Stream: fitting w/ full 6D

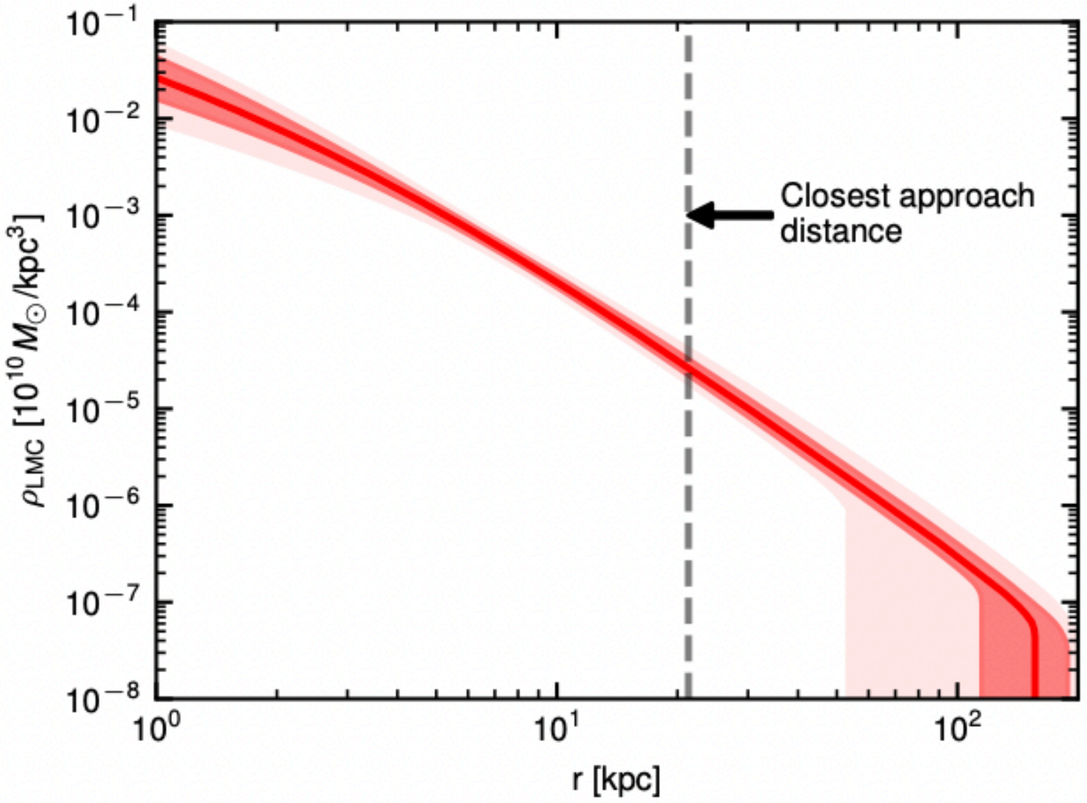


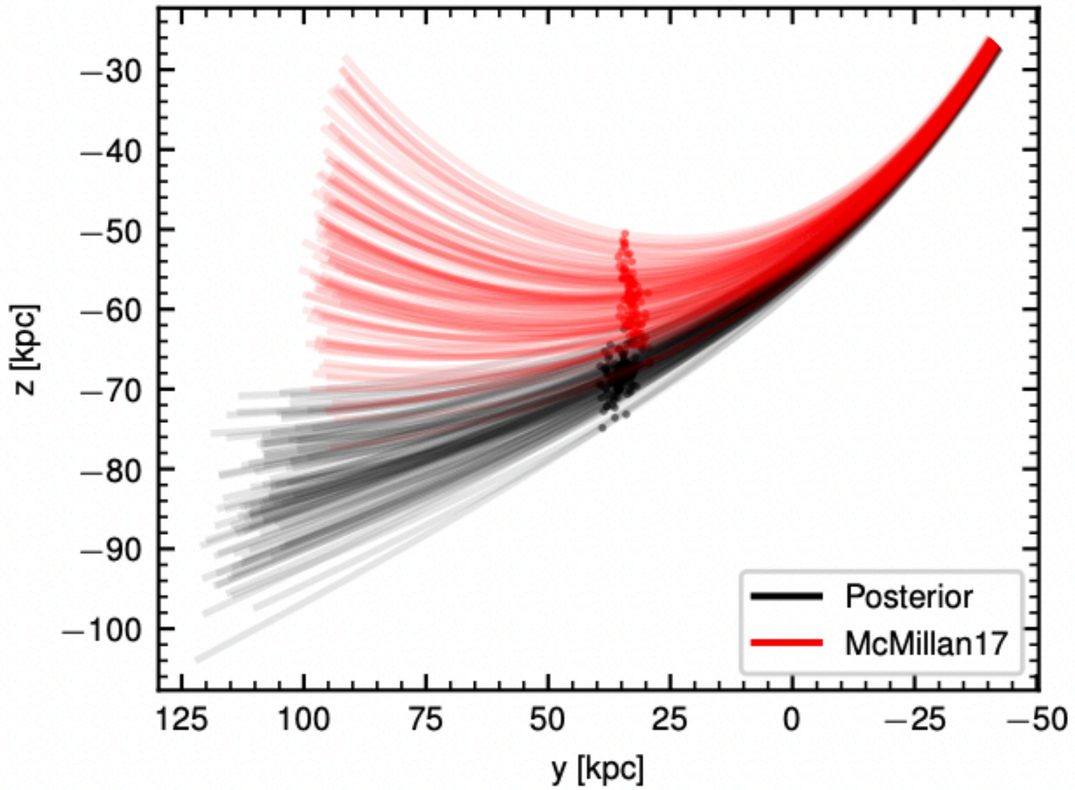
Koposov, Erkal, TSL et al. (2023)



Credit: Denis Erkal

Constraints on LMC mass profile and orbits

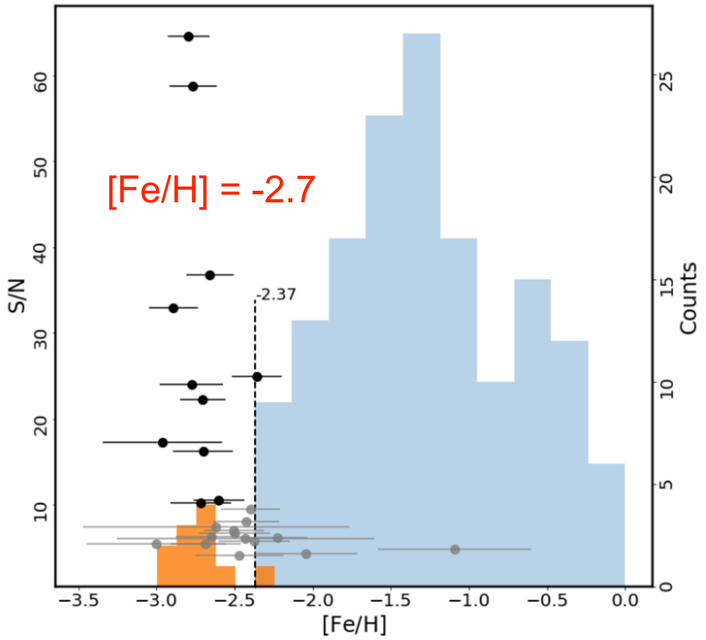




Koposov, Erkal,
TSL et al. (2023)

S⁵: Highlights on Stream Science w/ AAT

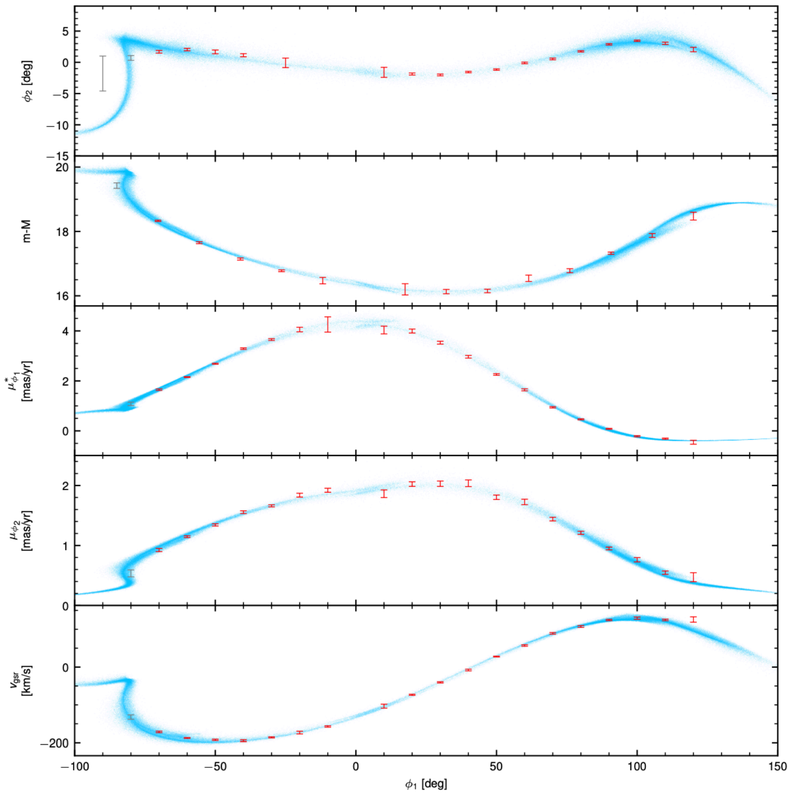
Phoenix Stream: more metal-poor than any known globular cluster



Cyan: globular cluster in Milky Way
Orange: stars in Phoenix Stream

Wan, Lewis, TSL et al. (2020) Nature

Constraint on mass of the Milky Way and LMC



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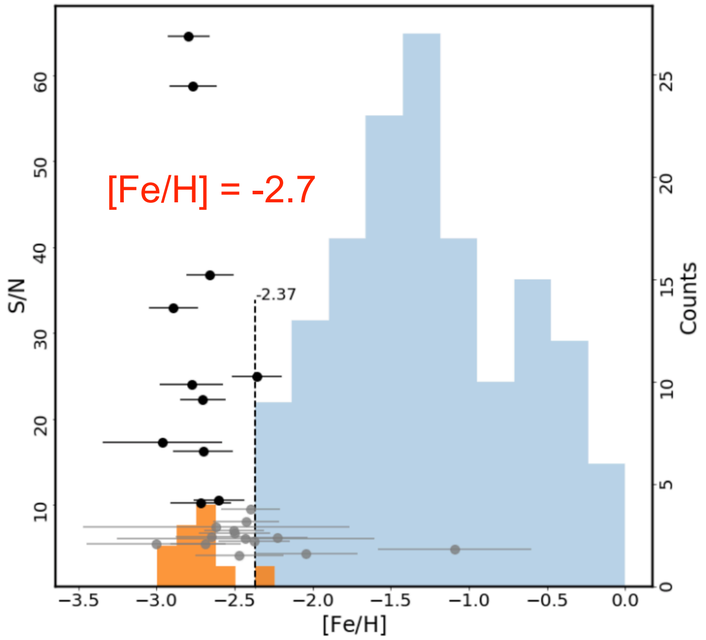

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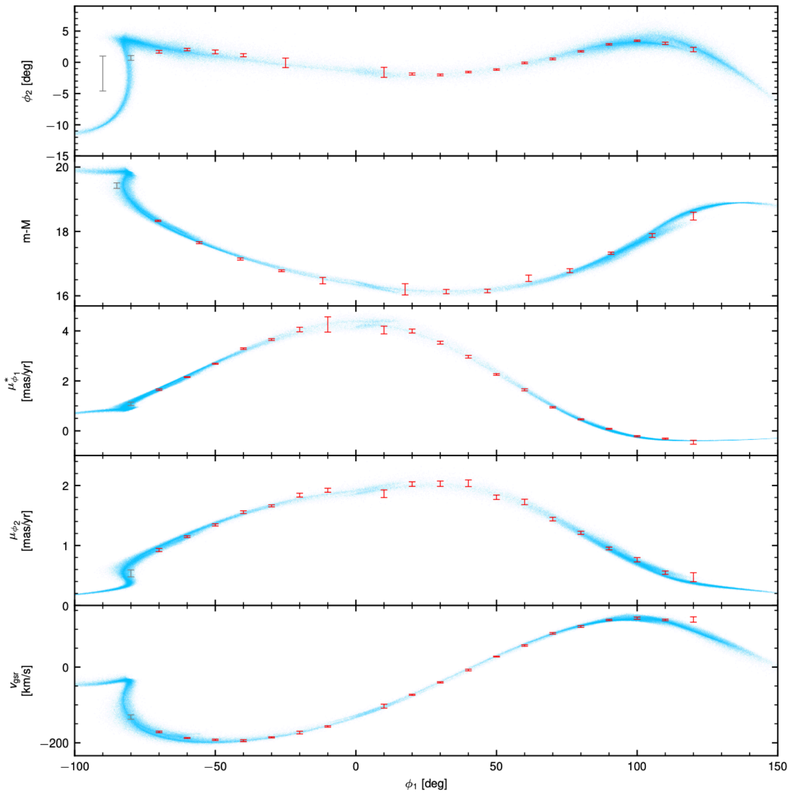
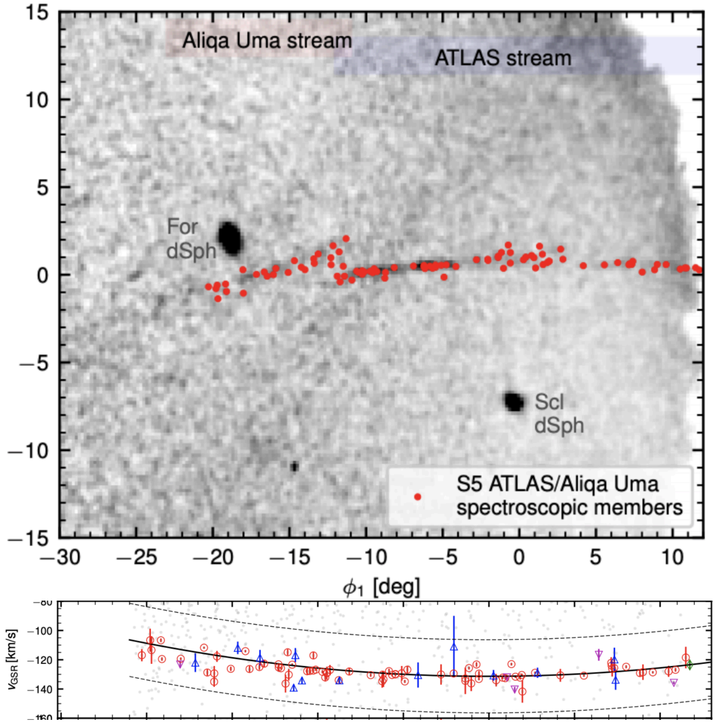


Koposov, Erkal, TSL et al. (2023)

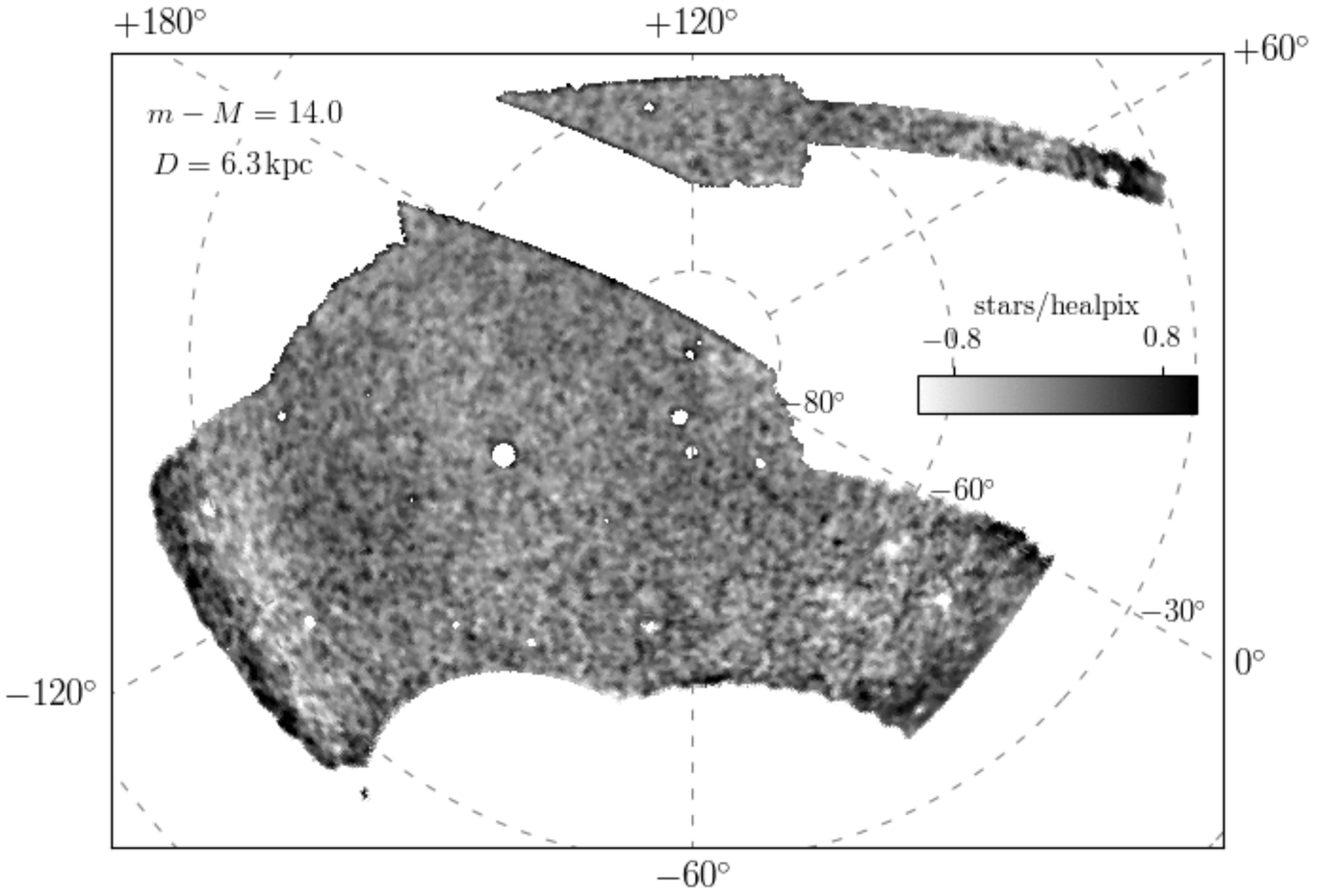
Broken stream perturbed by dark matter subhalo?



Another GD-1 like stream?

TSL et al. (2021)

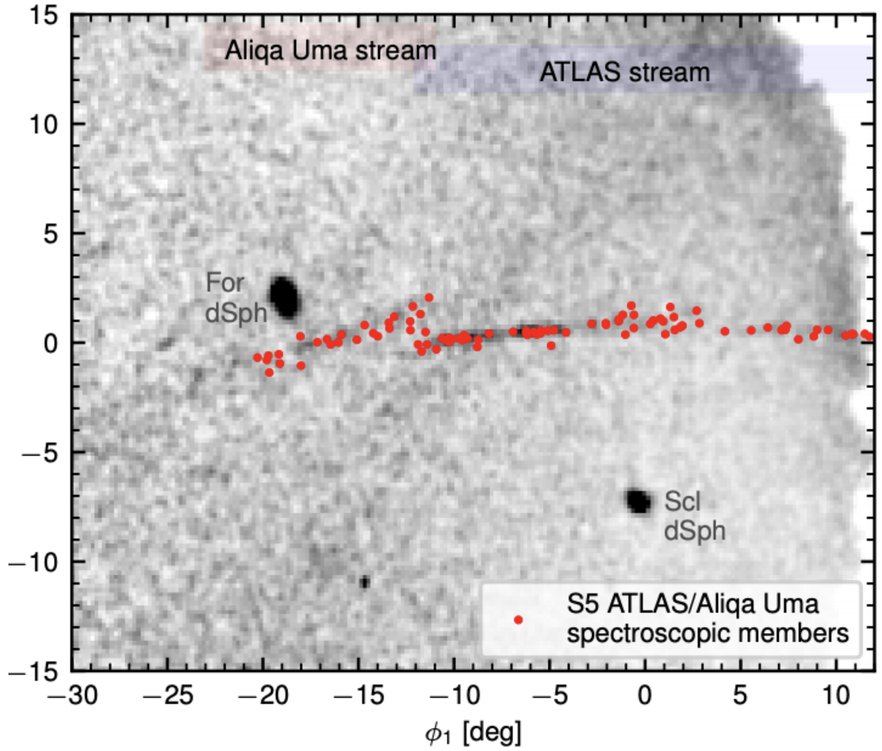
Streams in the Dark Energy Survey

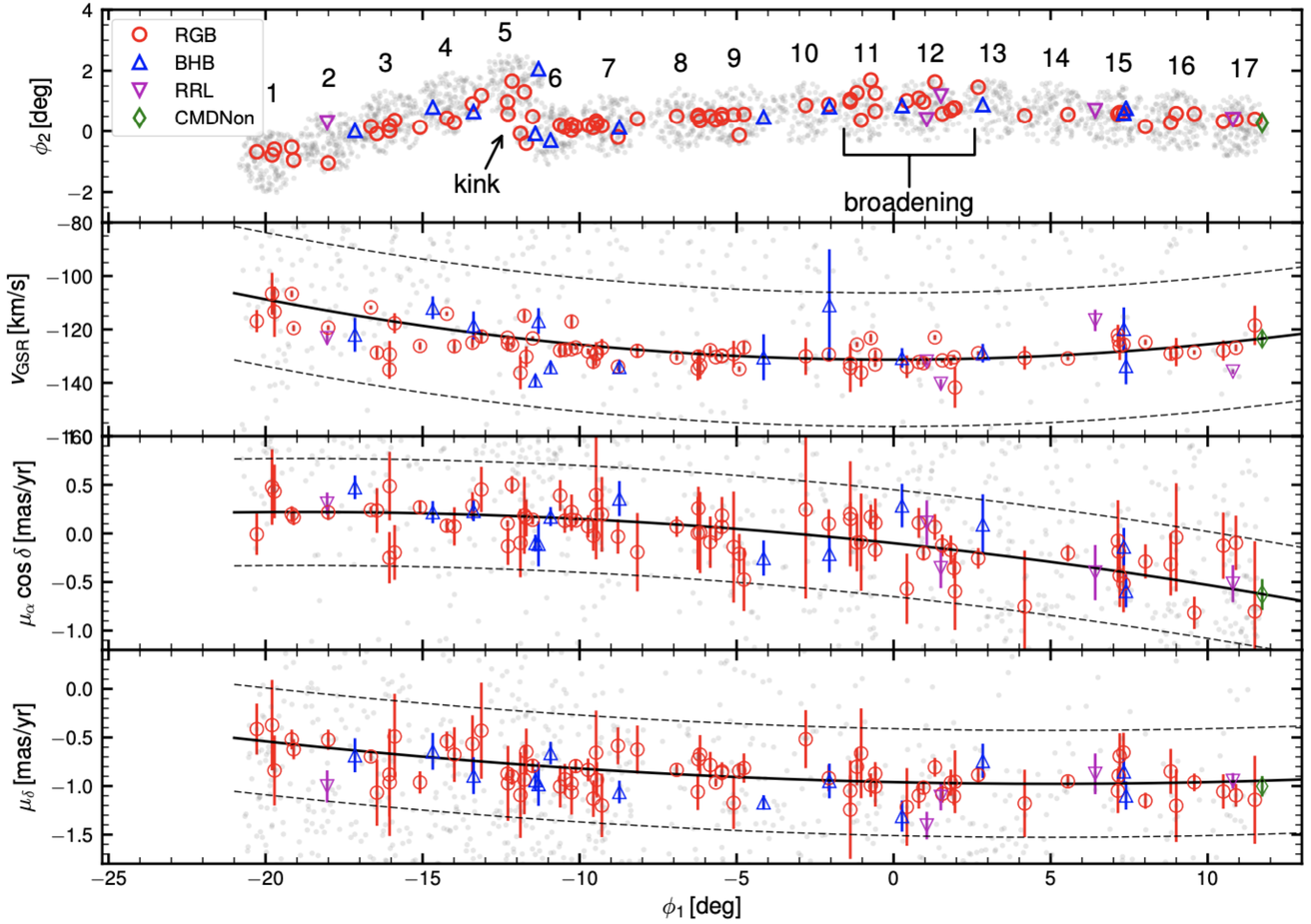


Shipp et al. 2018
(DES Collaboration)

13 new streams from DES + 2 previous known

Broken stream perturbed by dark matter subhalo?





TSL et al (2021)

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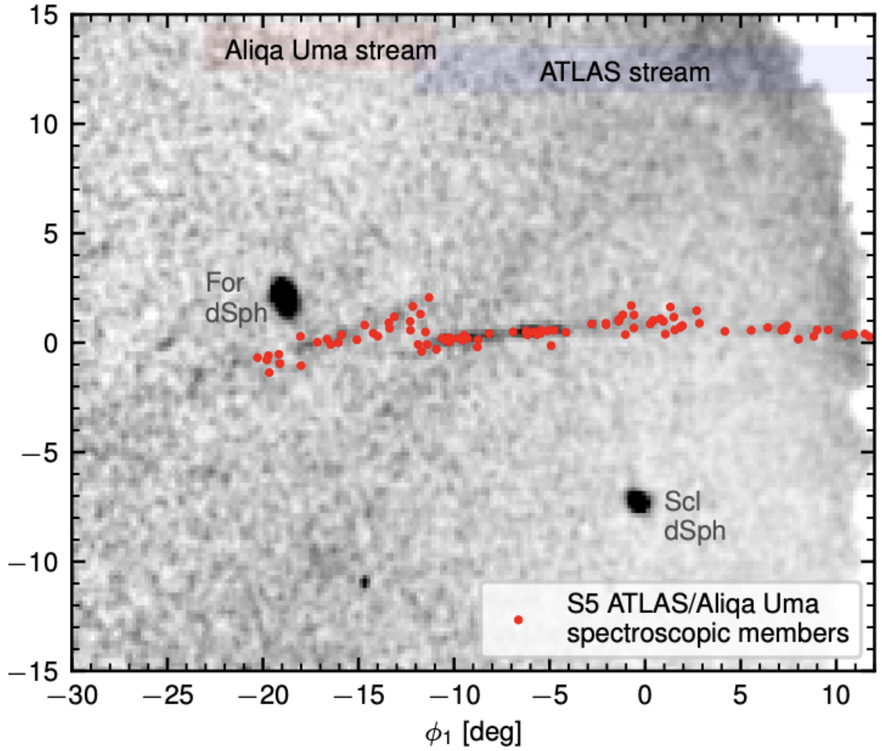
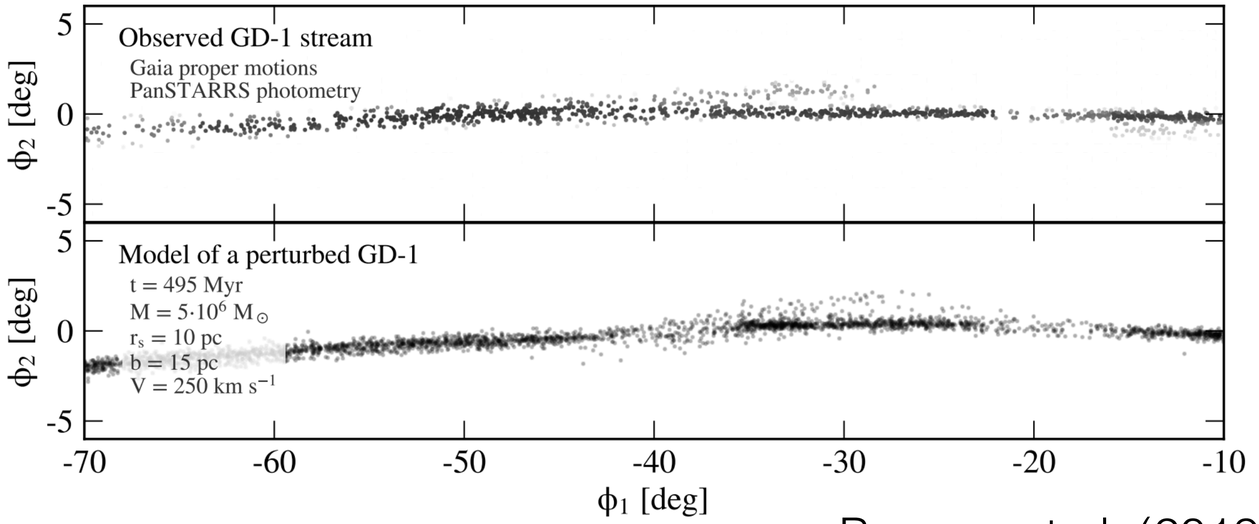
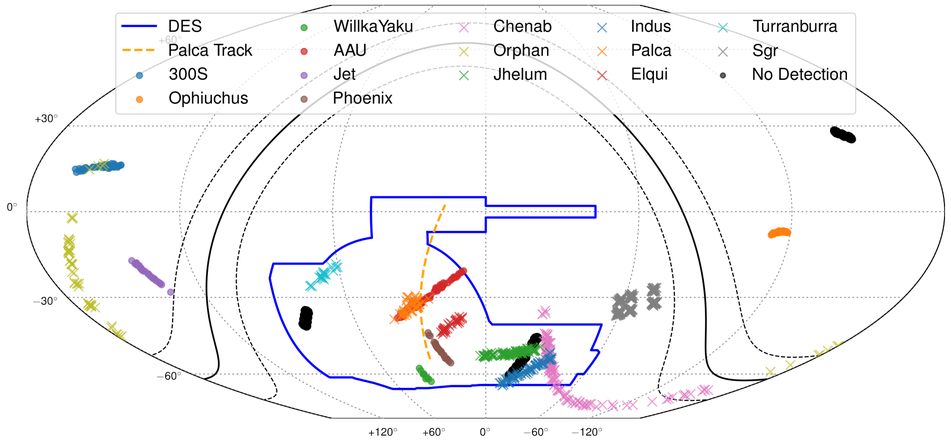




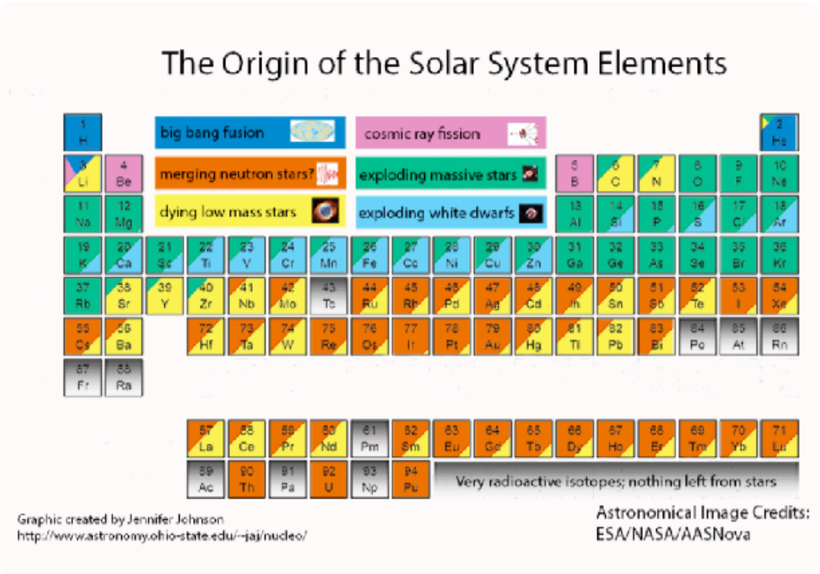
Bonaca et al. (2019)

Another GD-1 like stream?

TSL et al (2021)



S5 - STREAMS



S5 - HIRES

S5 - HALO

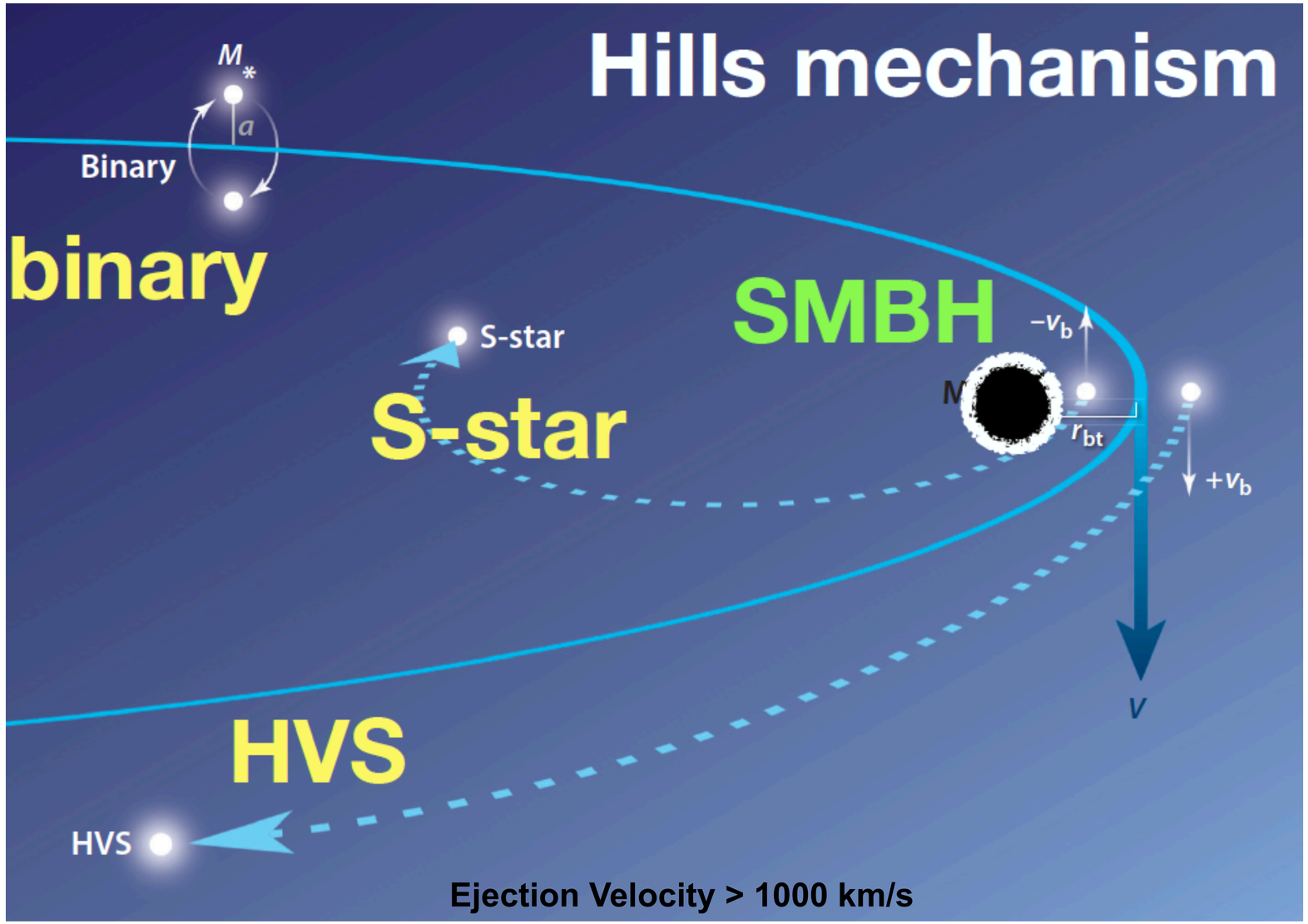
S5 - LOWZ

Discovery of Hypervelocity star S5-HVS1

S^5 - HALO *Observing Milky Way halo stars with spare fibers on AAT*

S5-HVS1 ~ 1700 km/s

Formation of Hyper Velocity Stars



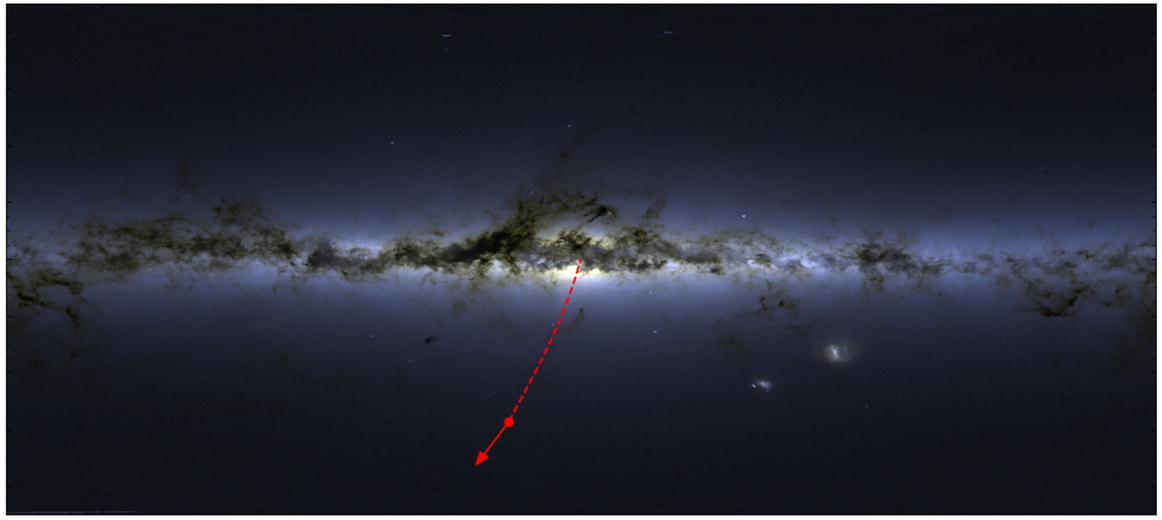
Hills (1988) Nature

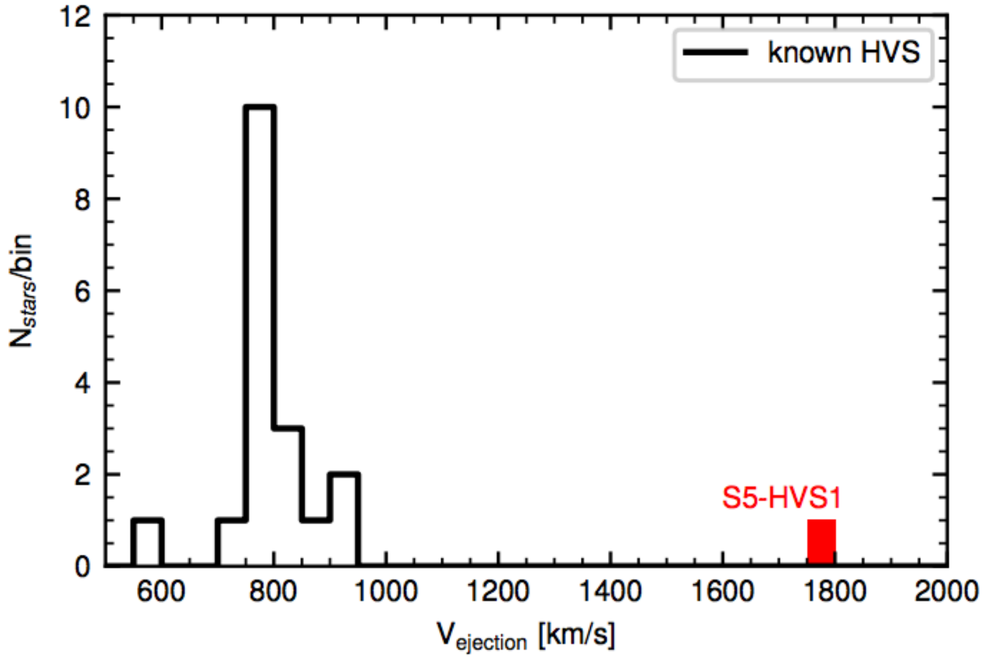
Discovery of Hypervelocity star S5-HVS1

S^5 - HALO *Observing Milky Way halo stars with spare fibers on AAT*

S5-HVS1 ~ 1700 km/s

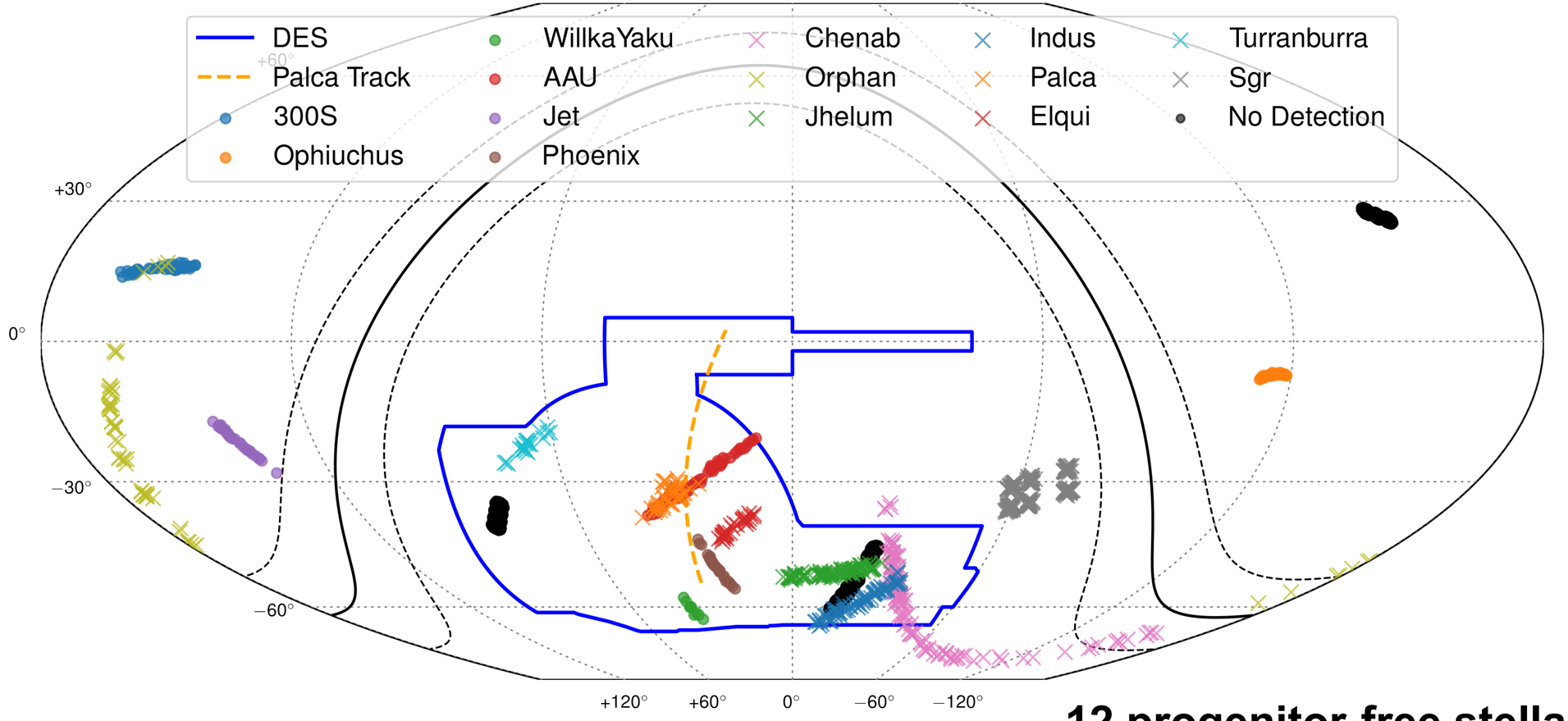
Fastest main sequence star ejected from the Galactic Center





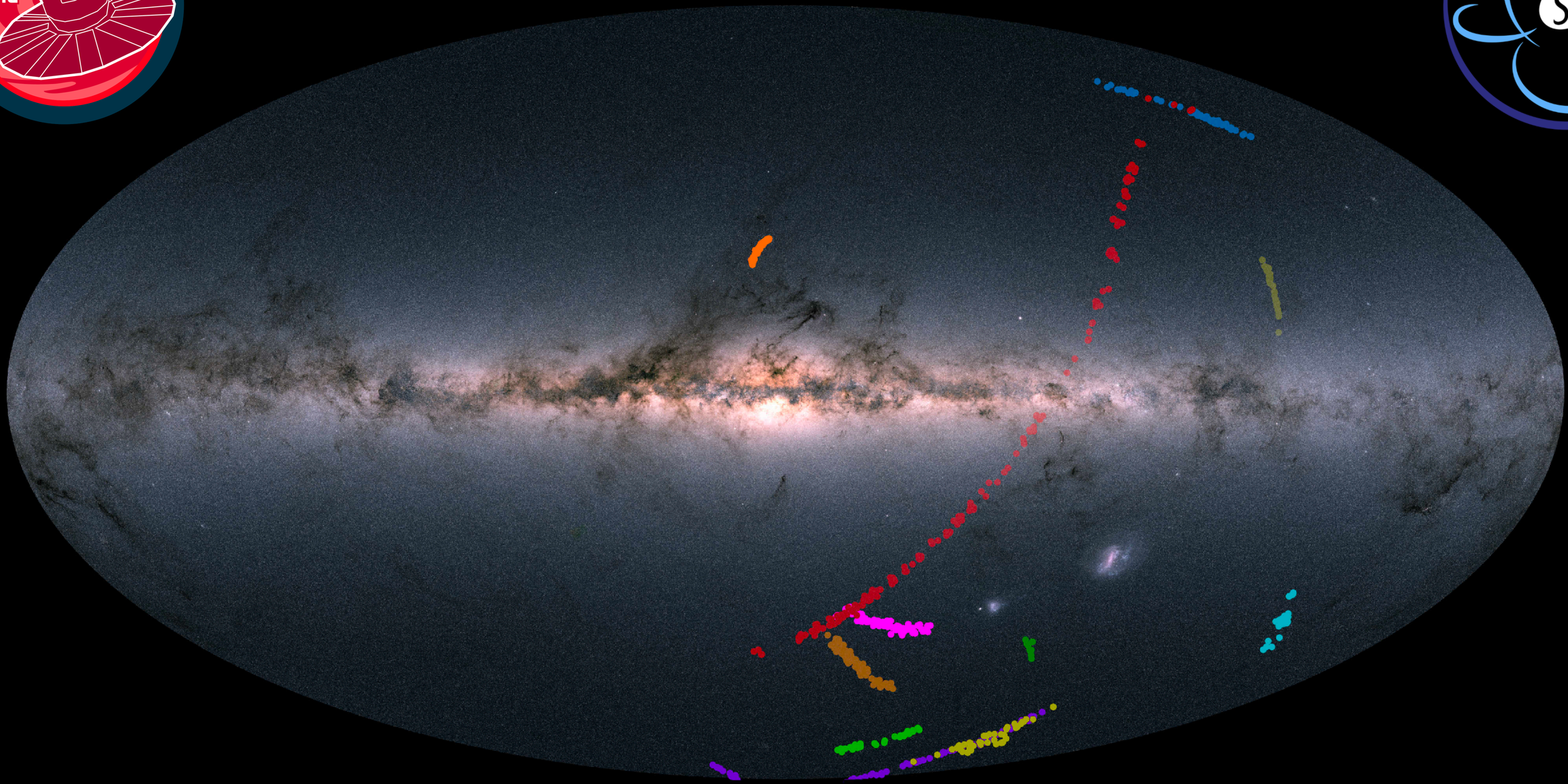
Koposov, Boubert, TSL et al. (2020)

Orbital and Chemical Properties of Stellar Streams



S5: The Orbital and Chemical Properties of One Dozen Stellar Streams
TSL et al (2022), arXiv: 2110.06950

12 progenitor-free stellar streams at ~10-50 kpc observed in 2018-2020



Credit: Gaia + S5

DESI — Dark Energy Spectroscopic Instrument

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

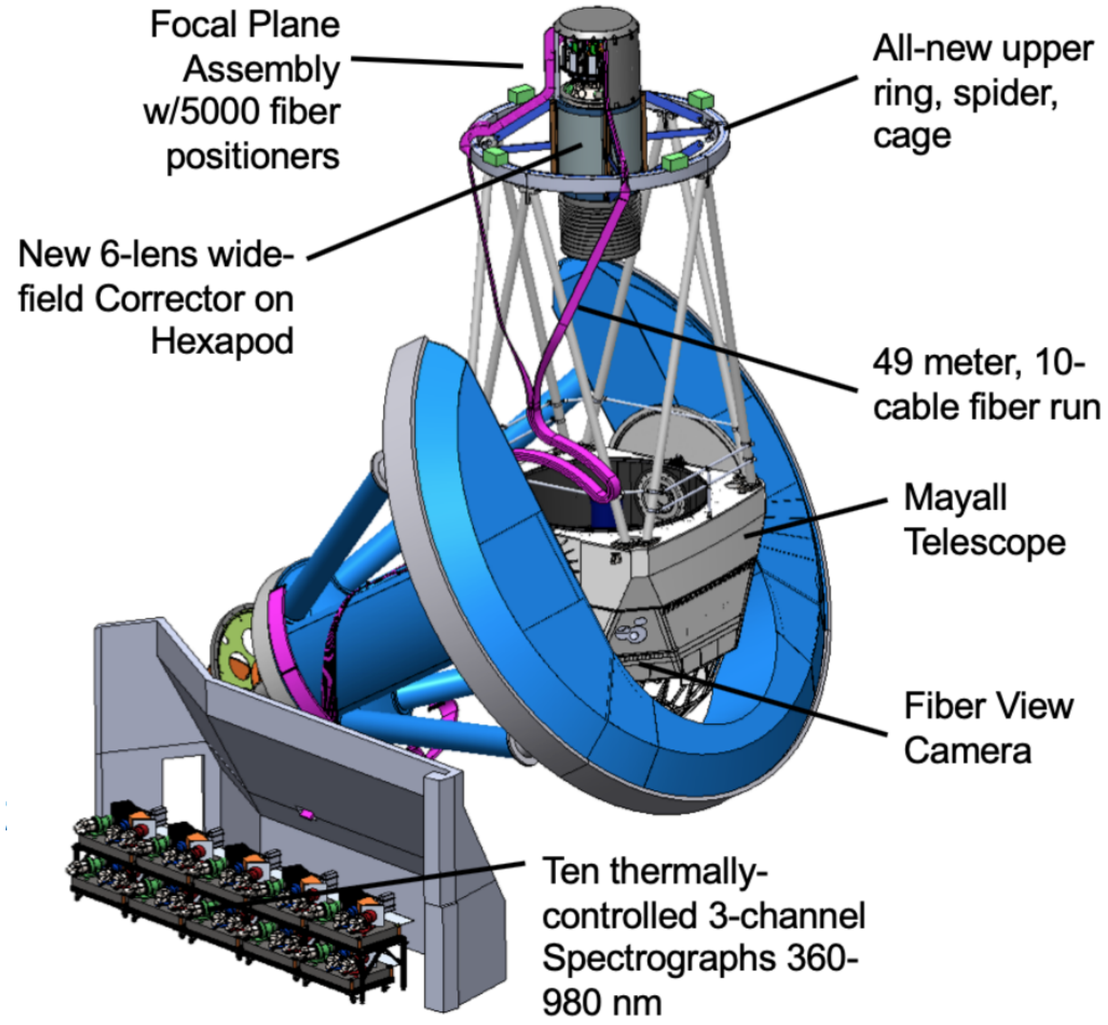
MWS — Milky Way Survey

Co-chairs: Leandro Beraldo e Silva (U Arizona)
Ting Li (U of Toronto)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI, the instrument in a nutshell



- 4-m Mayall Telescope at KPNO
- 6-Len Wide-field Corrector
- 5000 Robotic Fibers
- 10 3-Channel Spectrograph

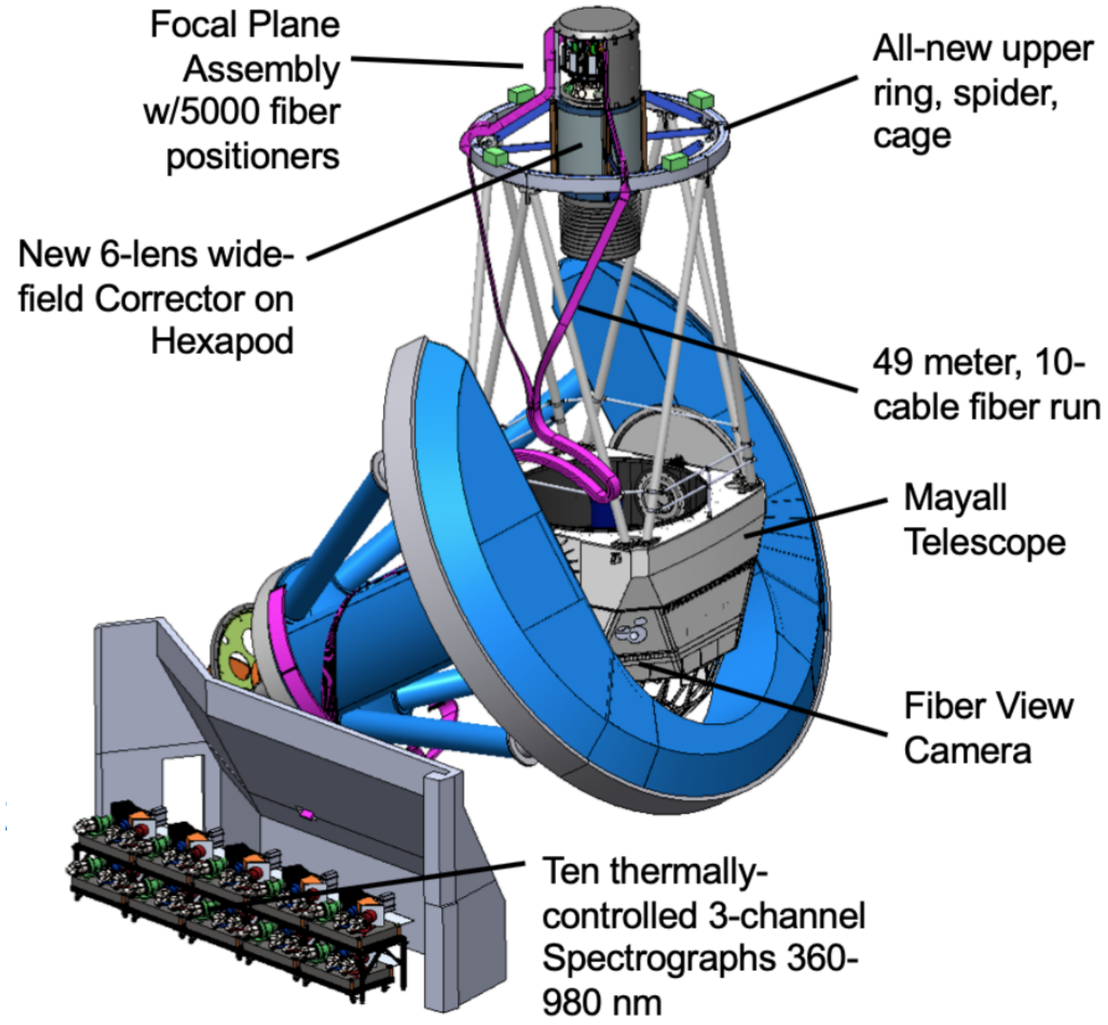
Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument

DESI Collaboration et al. 2022, arXiv:2205.10939

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI, the instrument in a nutshell



- 4-m Mayall Telescope at KPNO
- 6-Len Wide-field Corrector
- 5000 Robotic Fibers
- 10 3-Channel Spectrograph

- Dec 2020 - May 2021: Commissioning and Science Verification
  - Early Data Release in June 2023
- May 2021: Main Survey (5 yr)
  - Year 1: May 2021 - June 2022

Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument

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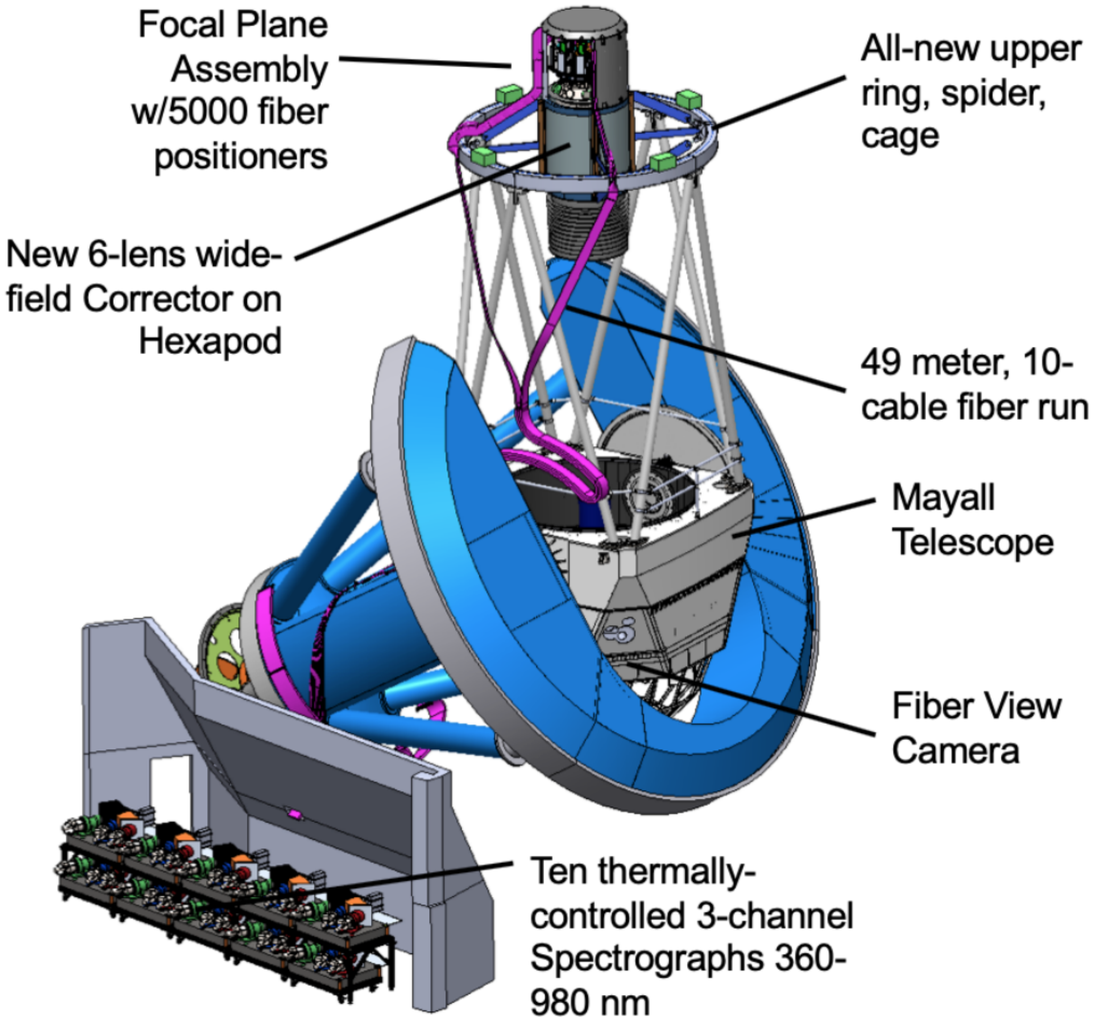

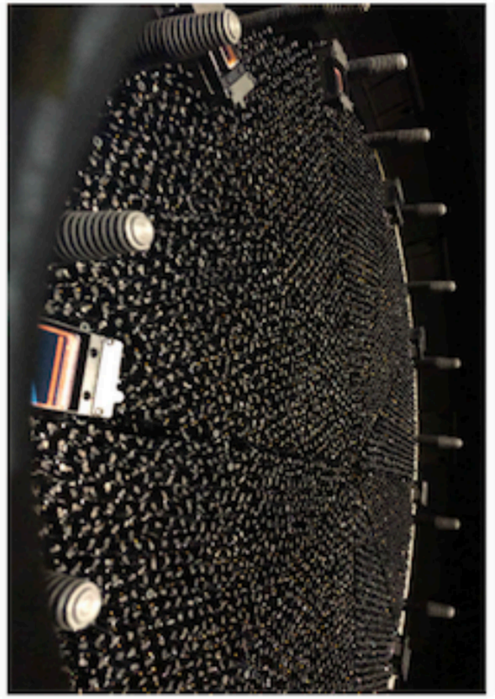

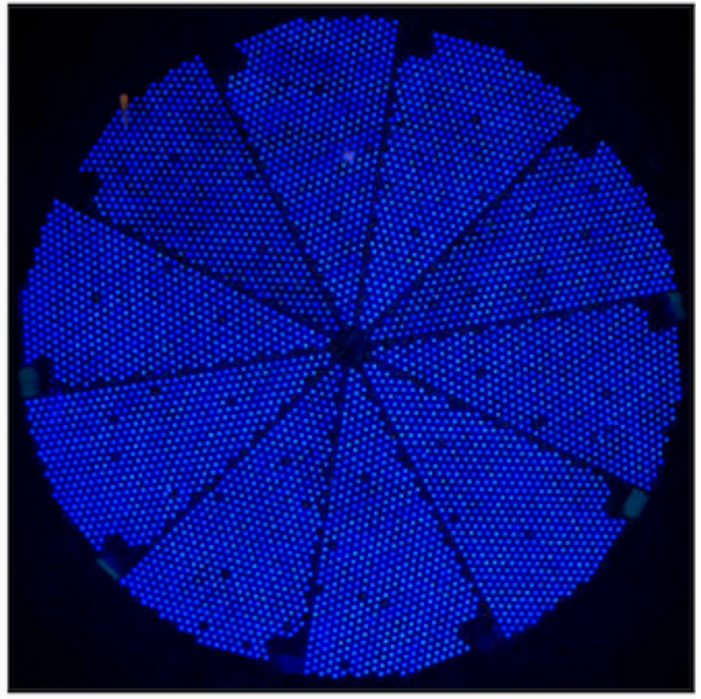

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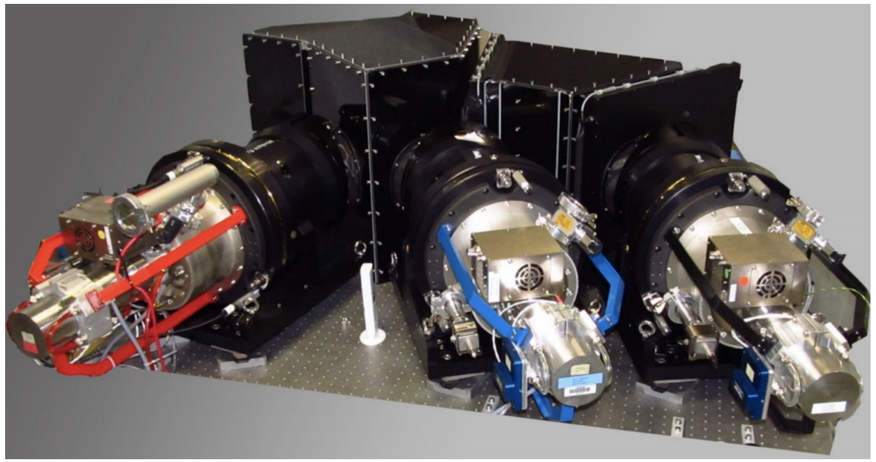
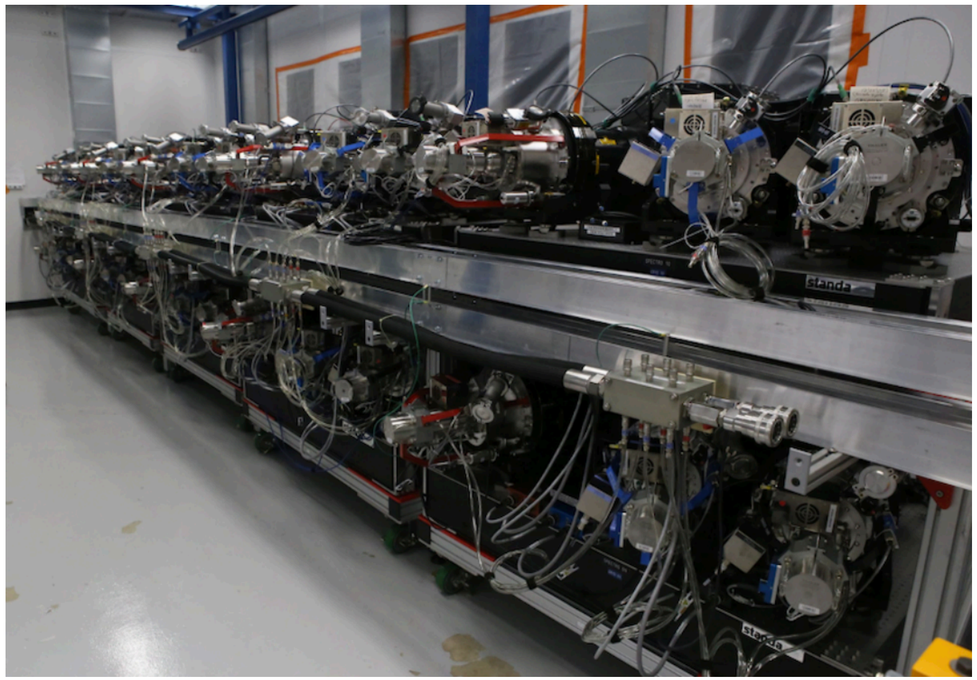
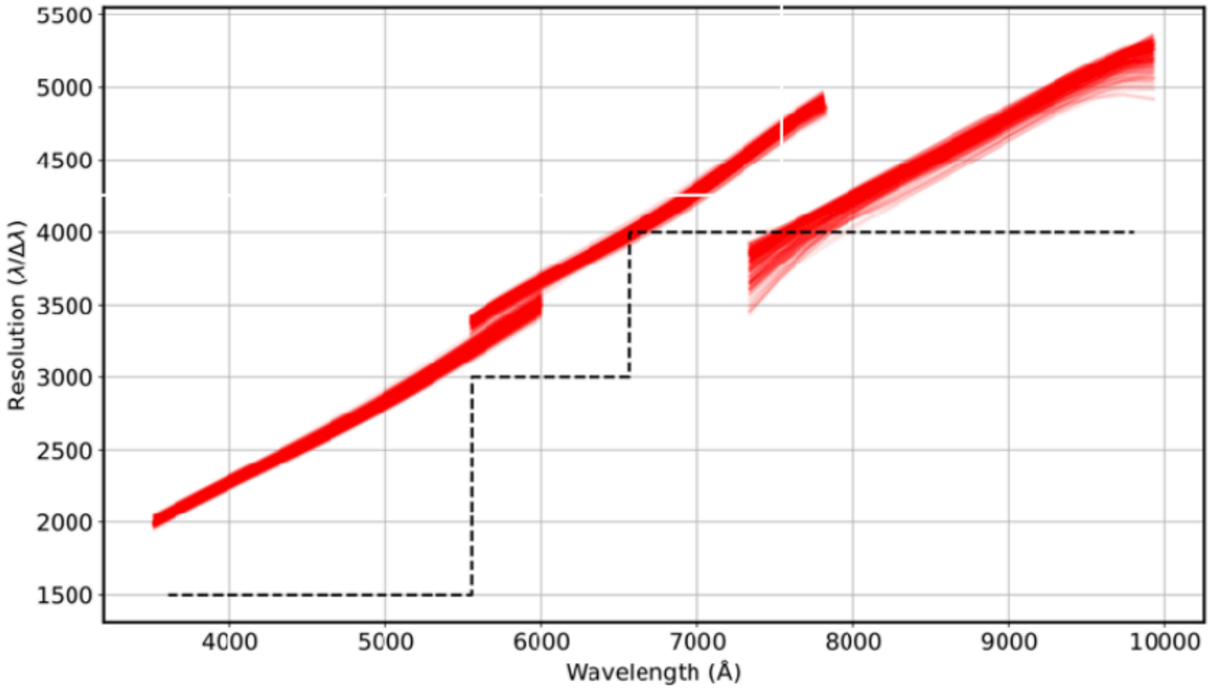
10 3-channel Spectrographs





Spectral Resolution: R~2500-5000



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U.S. Department of Energy Office of Science

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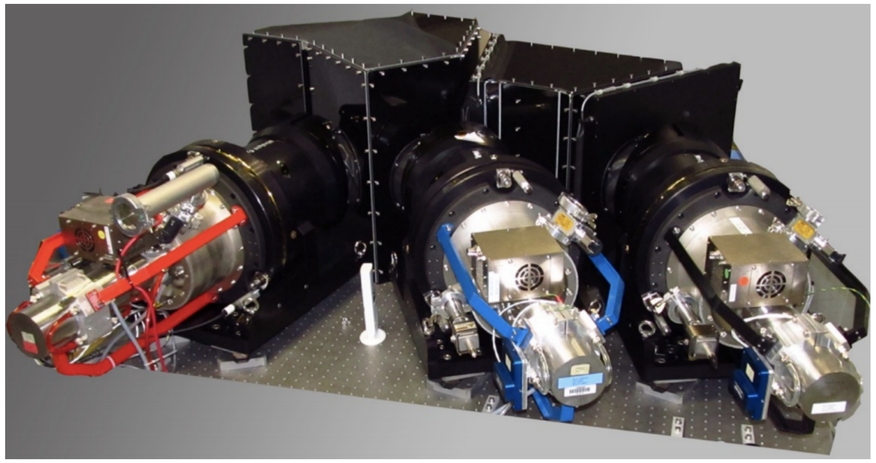
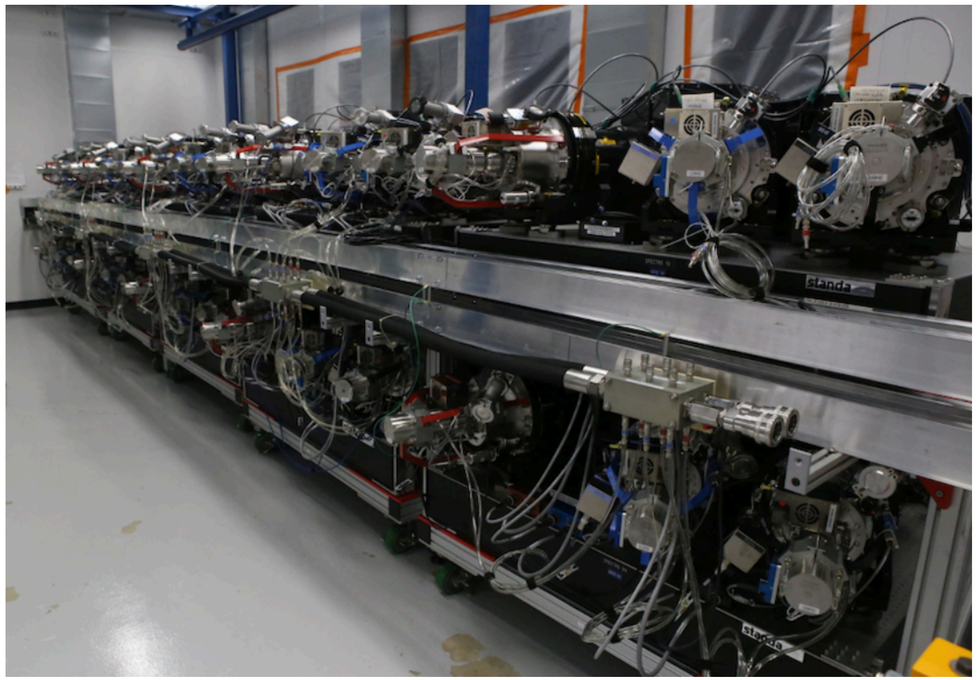
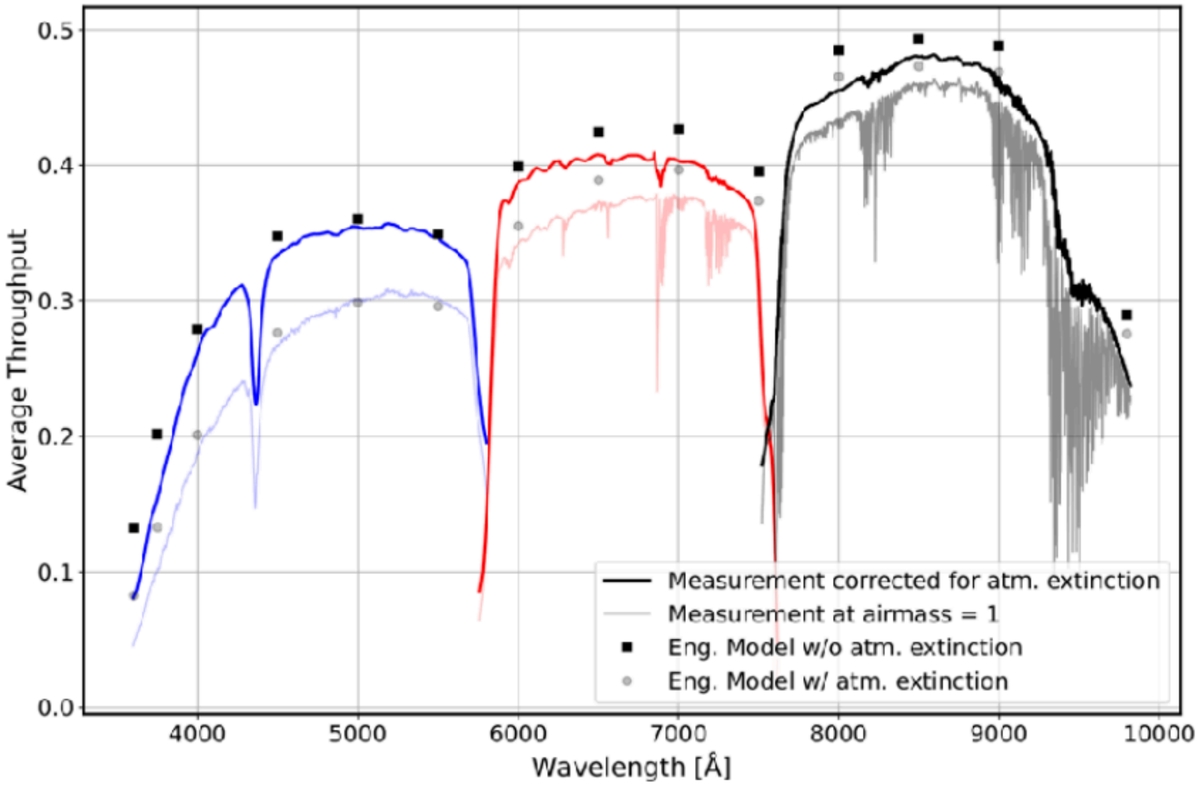




Throughput: 30-50%



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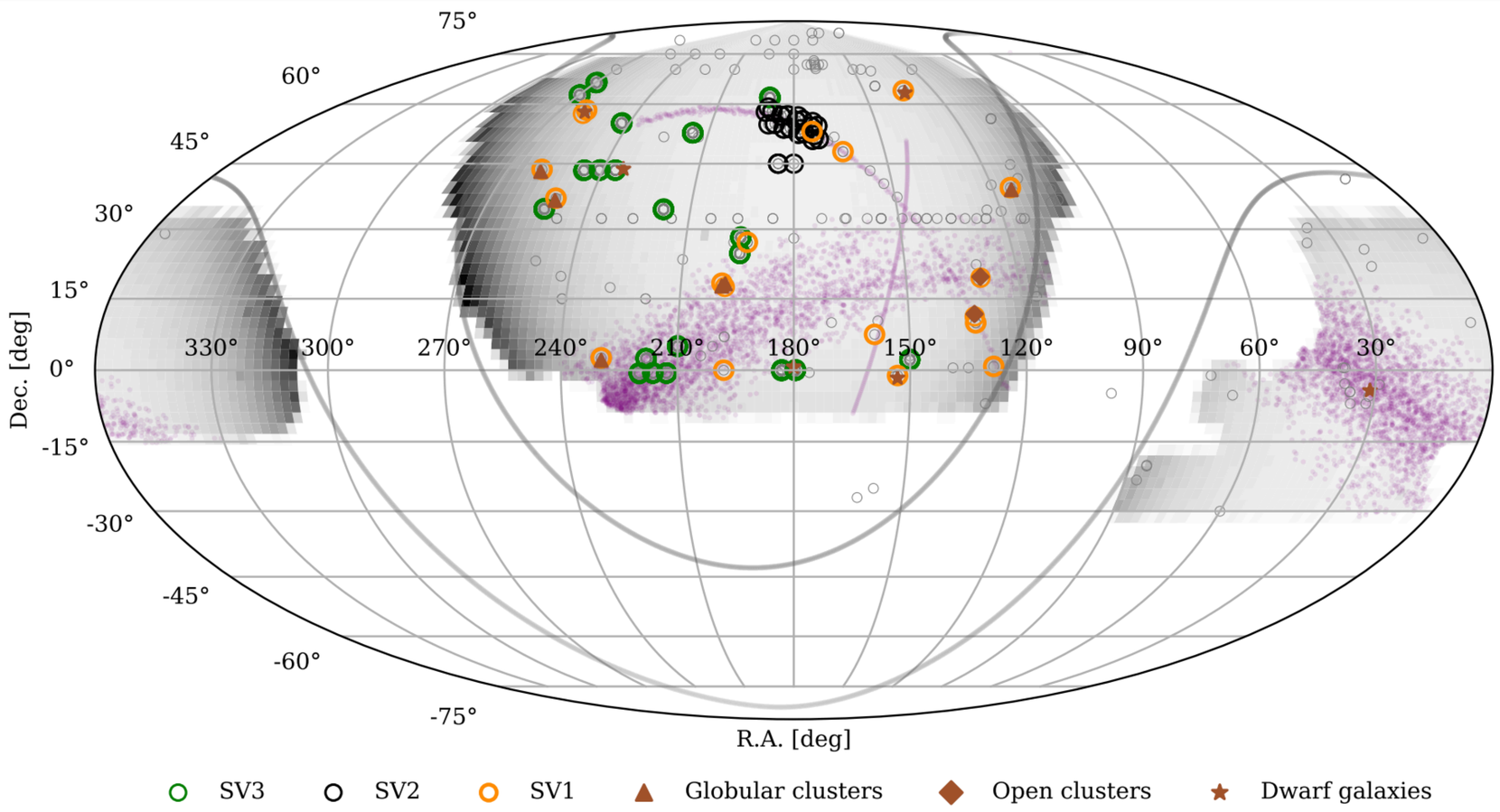
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Milky Way Survey in a nutshell



- DESI Bright Time Survey
- ~180s effective exposure time
- Goal: stars at |b|>20
  - 7M Main 16<r<19
  - 0.6M Faint
  - 6M Backup

Overview of the DESI Milky Way Survey
Cooper et al. 2023 arXiv:2208.08514
(DESI Collaboration et al)

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U.S. Department of Energy Office of Science

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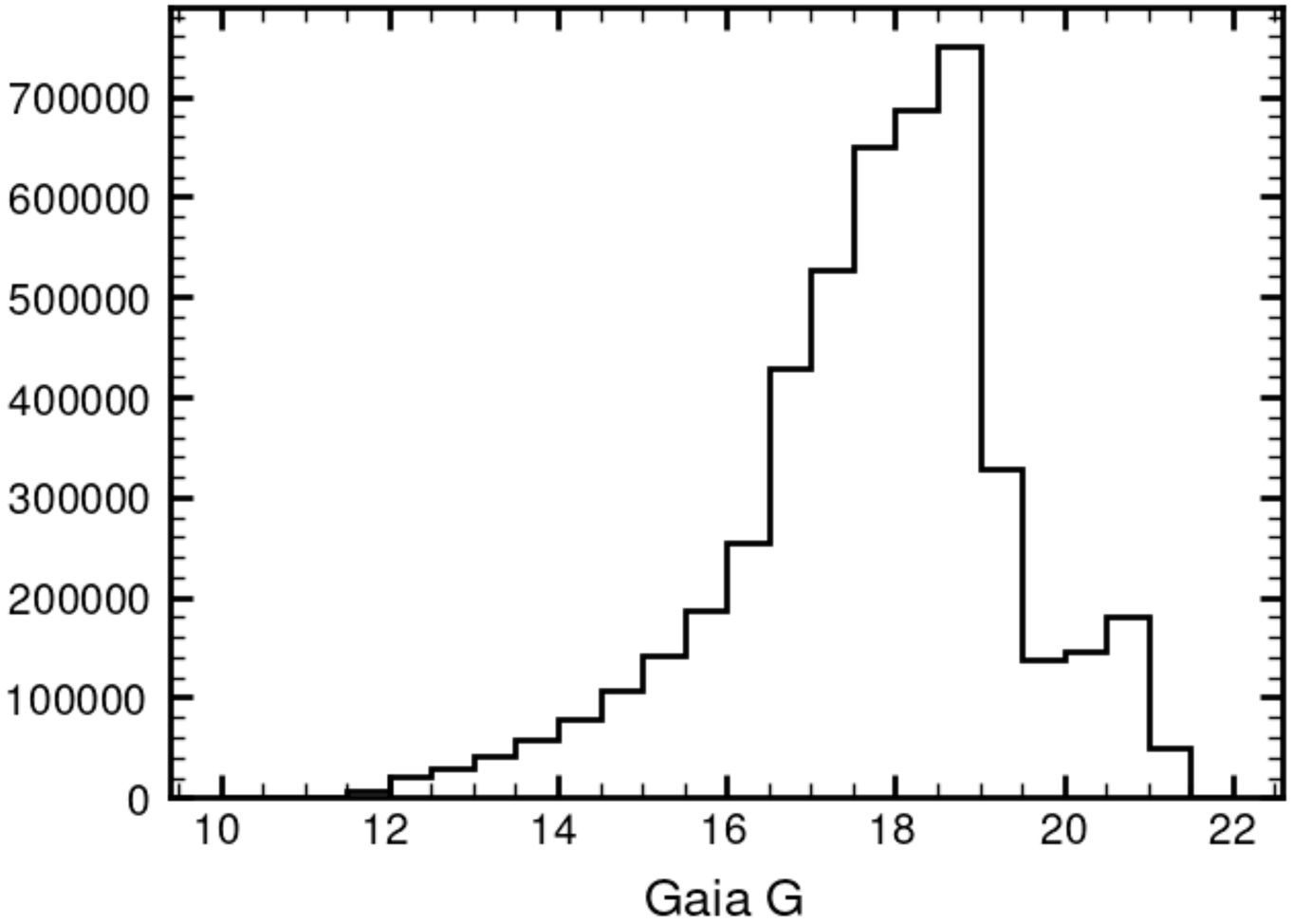

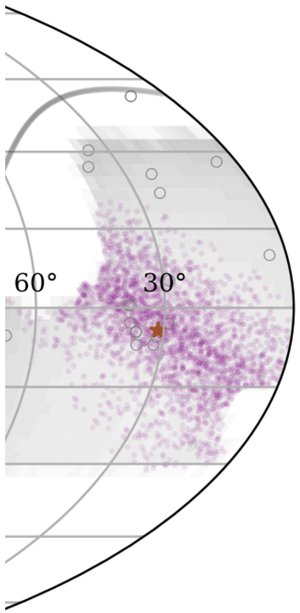

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  - 0.6M Faint
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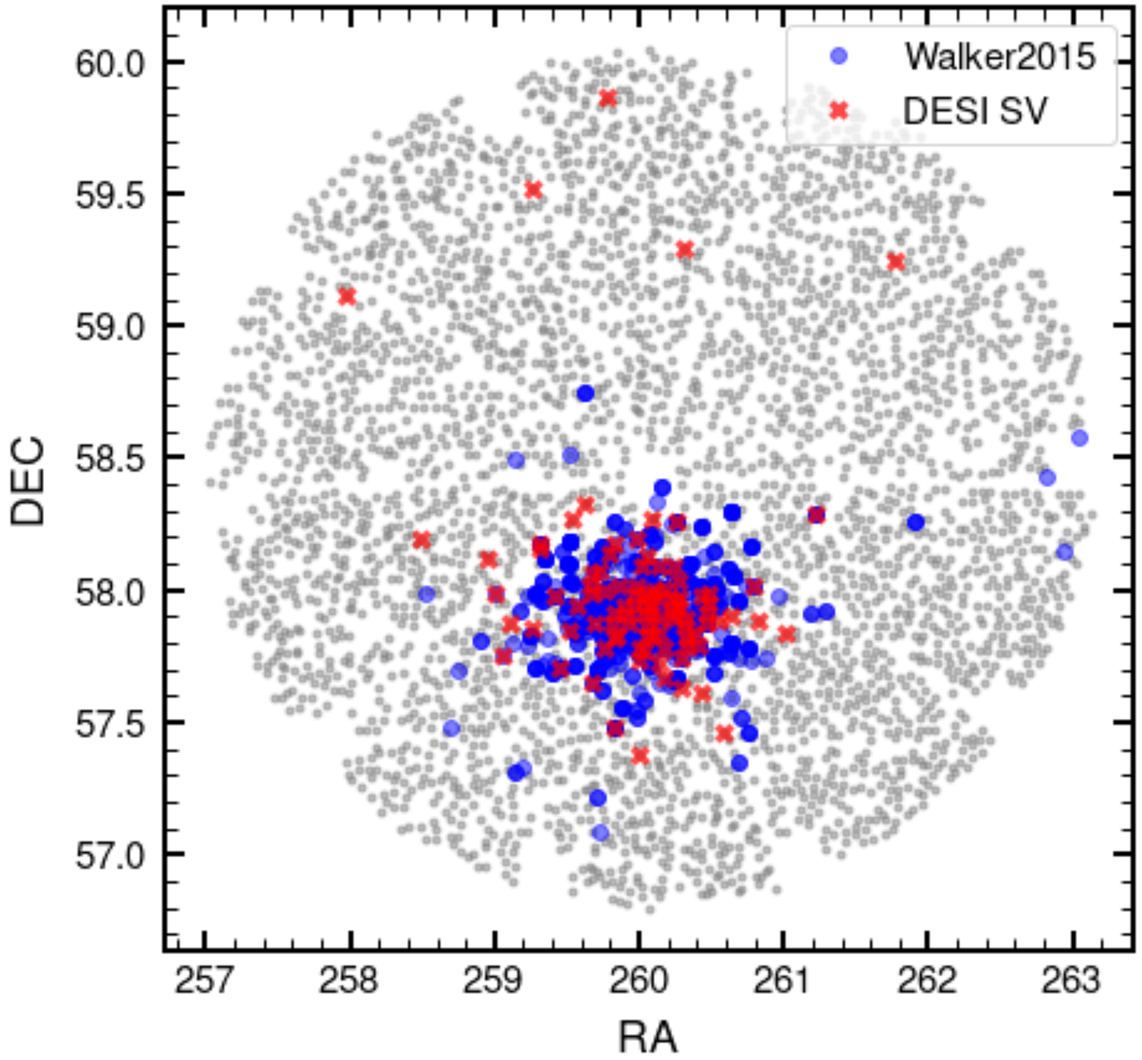
- SV+Year1: >4M star w/ RVerr<10 km/s

Overview of the DESI Milky Way Survey
Cooper et al. 2023 arXiv:2208.08514
(DESI Collaboration et al)

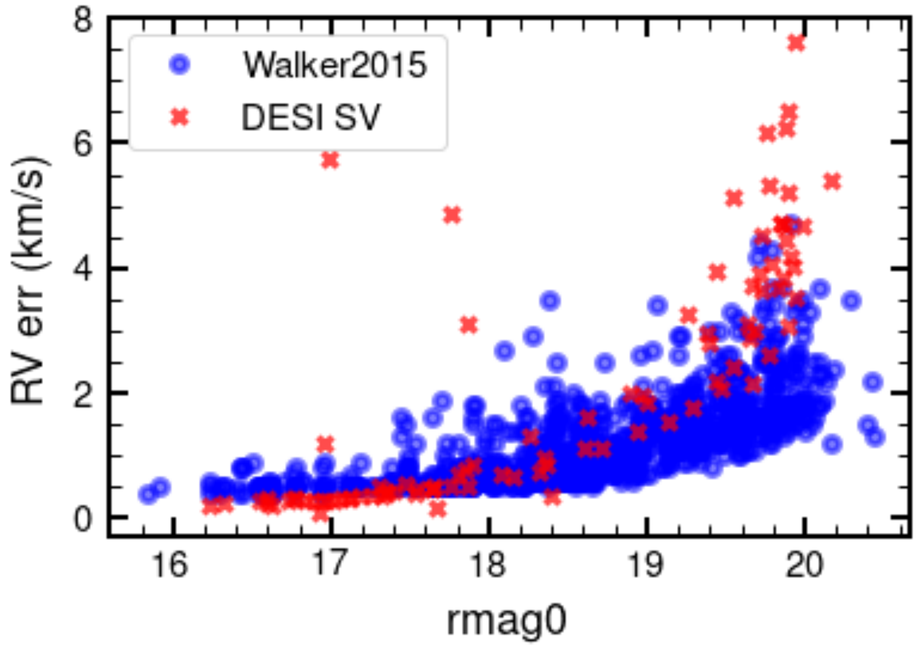
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Observation on Draco (45 min Dark Time in SV)



- Walker et al. 2015: ~500 members
- ~200 members in one DESI pointing

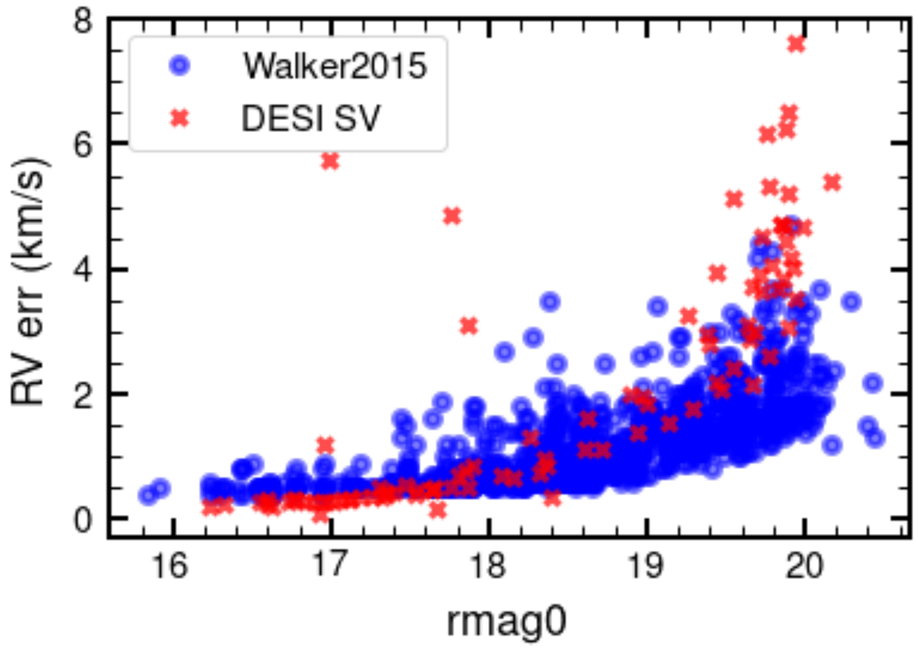


rvation on Draco
ark Time in SV)

Table 1. Log of Hectochelle Observations of Draco fields

Field	α_{2000} [a] [hh:mm:ss]	δ_{2000} [a] [°:′:″]	UT Date [dd/mm/yyyy]	HJD [b] [days]	N_{exp} [c]	Exp. Time [d] [seconds]
Dra-01	17:20:24.65	+57:53:06.9	19/04/2006	2453844.87	4	7200
Dra-02	17:23:50.00	+57:52:12.0	25/04/2006	2453850.78	5	4846
Dra-03	17:20:24.64	+57:53:06.9	23/02/2007	2454154.98	3	5400
Dra-04	17:17:37.81	+57:46:30.2	27/02/2007	2454158.96	3	5400
			11/03/2007	2454170.89	4	7200
Dra-05	17:20:38.90	+57:28:04.3	03/03/2007	2454162.94	3	5400
			09/03/2007	2454168.90	3	5400
Dra-06	17:19:23.67	+58:28:22.4	06/03/2007	2454165.90	3	5400
Dra-07	17:14:24.40	+57:28:47.6	22/04/2007	2454212.89	3	5400
Dra-08	17:26:35.35	+58:15:25.6	23/04/2007	2454213.83	3	5400
Dra-09	17:30:06.97	+57:38:24.2	24/02/2008	2454520.94	5	6000
Dra-10	17:20:25.01	+57:53:11.7	27/02/2008	2454523.99	3	3600
Dra-11	17:11:57.01	+58:18:03.1	27/02/2008	2454523.93	3	4500
Dra-12	17:10:09.01	+57:29:41.0	20/03/2009	2454910.85	2	4096
			21/03/2009	2454911.86	3	7200
Dra-13	17:20:06.72	+57:55:32.6	21/03/2009	2454911.96	2	4800
			24/03/2009	2454914.92	4	7200
Dra-14	17:41:60.00	+56:00:00.0	23/03/2009	2454913.87	4	9600
Dra-15	17:20:15.99	+57:55:30.0	15/05/2010	2455331.74	4	6000
Dra-16	17:20:15.99	+57:55:30.0	15/05/2010	2455331.84	3	4500
Dra-17	17:15:23.52	+57:55:42.0	16/05/2010	2455332.73	2	3600
			16/05/2010	2455332.78	3	4500
Dra-18	17:20:23.58	+58:24:30.0	16/05/2010	2455332.85	3	4500
Dra-19	17:20:11.57	+57:24:54.0	16/05/2010	2455332.91	3	4500
Dra-20	17:20:15.99	+57:55:30.0	29/01/2011	2455590.99	3	3600
			25/05/2011	2455706.92	4	4500
Dra-21	17:20:15.99	+57:55:30.0	25/05/2011	2455706.77	3	5400
Dra-22	17:20:15.99	+57:55:30.0	25/05/2011	2455706.84	3	5400
Dra-23	17:22:55.93	+58:02:34.0	26/05/2011	2455707.75	3	5400
Dra-24	17:17:39.05	+57:53:14.0	26/05/2011	2455707.83	3	5400
Dra-25	17:20:46.45	+57:17:29.3	26/05/2011	2455707.91	4	4800
Dra-26	17:20:00.58	+58:37:30.6	27/05/2011	2455708.86	3	5400
Dra-27	17:20:15.99	+57:55:30.0	27/05/2011	2455708.93	3	3600
			31/05/2011	2455712.87	3	3600
Dra-28	17:20:19.72	+57:52:21.9	27/05/2011	2455708.76	4	9600
			28/05/2011	2455709.89	3	6000
Dra-29	17:19:02.64	+57:22:36.0	29/05/2011	2455710.84	3	5400
Dra-30	17:22:06.84	+58:27:53.3	29/05/2011	2455710.91	3	4500
Dra-31	17:20:17.49	+57:54:42.0	29/05/2011	2455710.76	3	5400
Dra-32	17:26:54.32	+58:29:28.6	30/05/2011	2455711.90	3	5400
			31/05/2011	2455712.93	3	3600
Dra-33	17:14:13.51	+57:40:52.9	31/05/2011	2455712.78	4	7200

- Walker et al. 2015: ~500 members
- ~200 members in one DESI pointing
- 45 min DESI vs 60+ hr on MMT



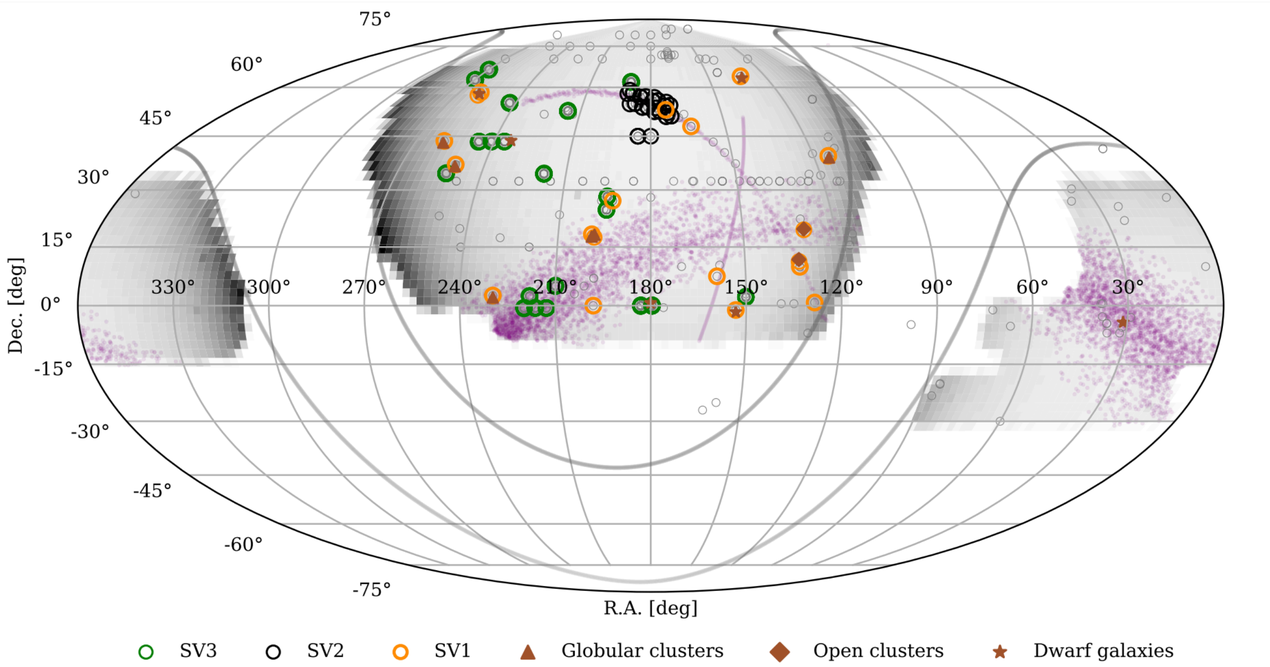
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Milky Way Survey Main Science Goal

Probing the Dark Matter and Accretion History of the Milky Way

- **The Shape and Mass of the Dark Matter Halo**
- Small-scale Substructure in the Dark Matter Halo
- The Assembly History of the Milky Way Halo
- The Formation History of the Milky Way Thick Disk
- Primordial/Metal-Poor Stars in the Milky Way

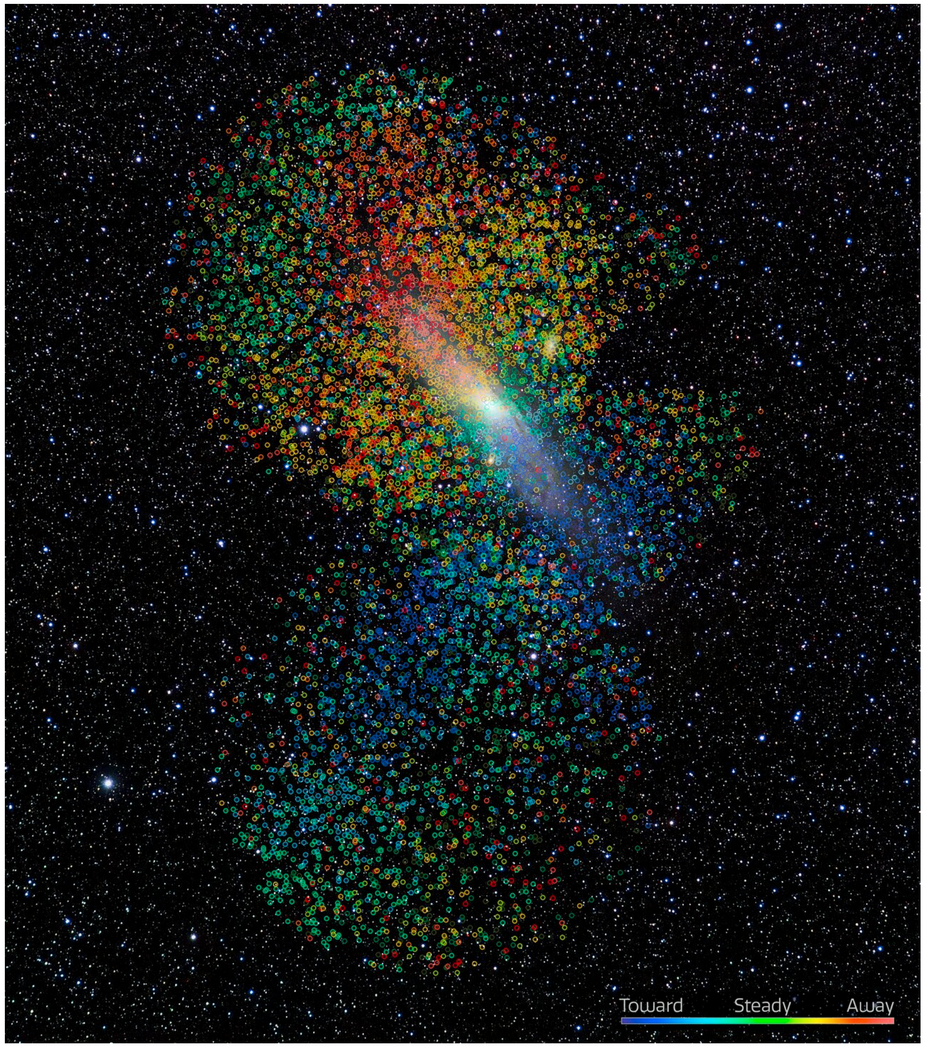


Overview of the DESI Milky Way Survey
Cooper et al. 2023 arXiv:2208.08514
(DESI Collaboration)

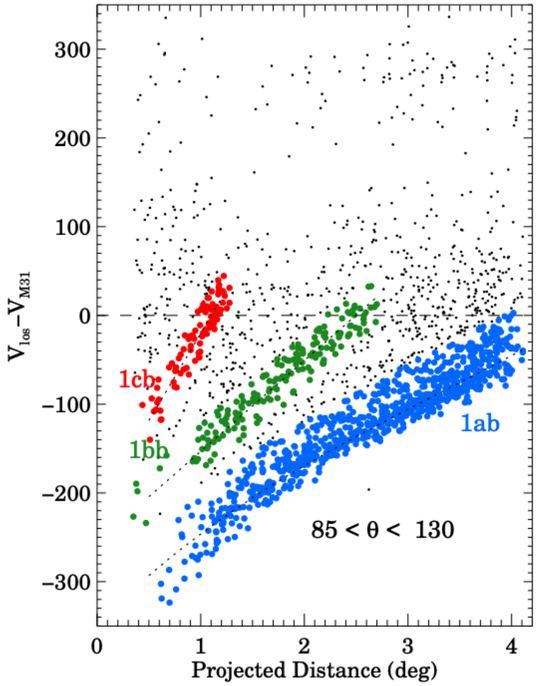
DARK ENERGY SPECTROSCOPIC INSTRUMENT

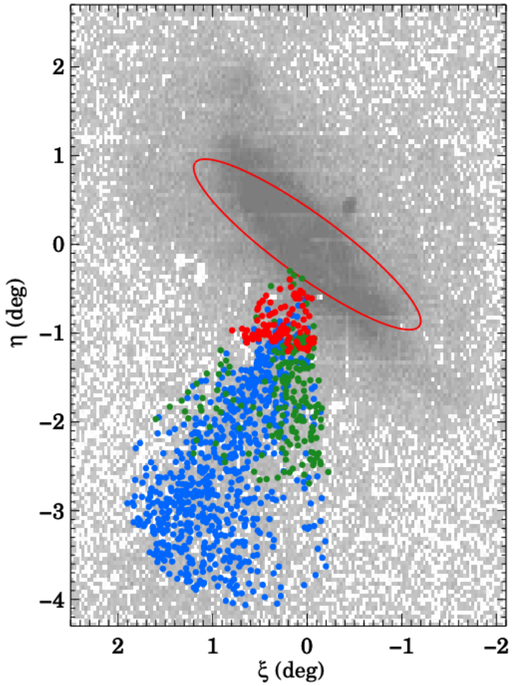
U.S. Department of Energy Office of Science

DESI's view on Andromeda and the Giant Stellar Stream



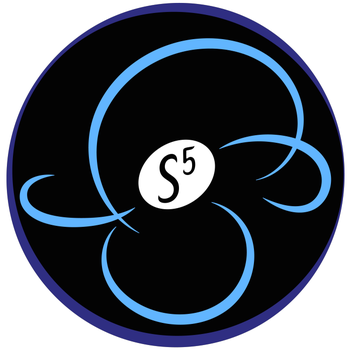
Credit: KPNO/NOIRLab/AURA/NSF/E. Slawik/D. de Martin/M. Zamani

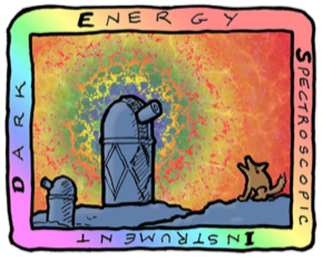




Dey, Nijita, Koposov et al. 2023 arXiv:2208.11683
(DESI Collaboration)

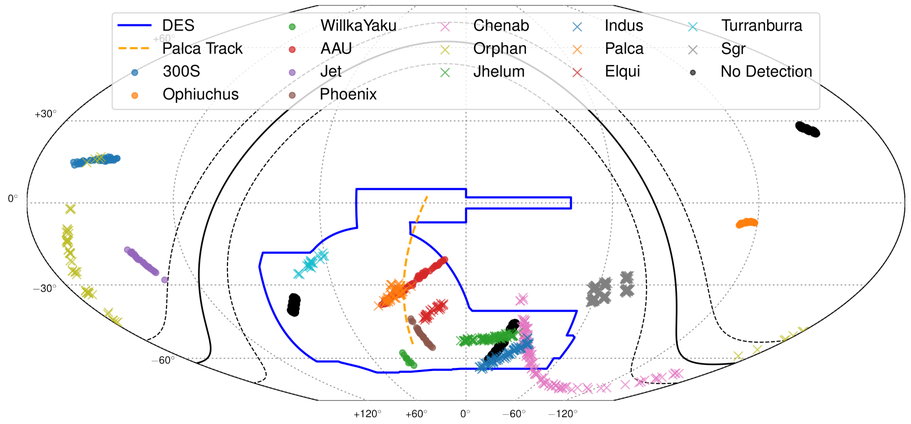
Summary

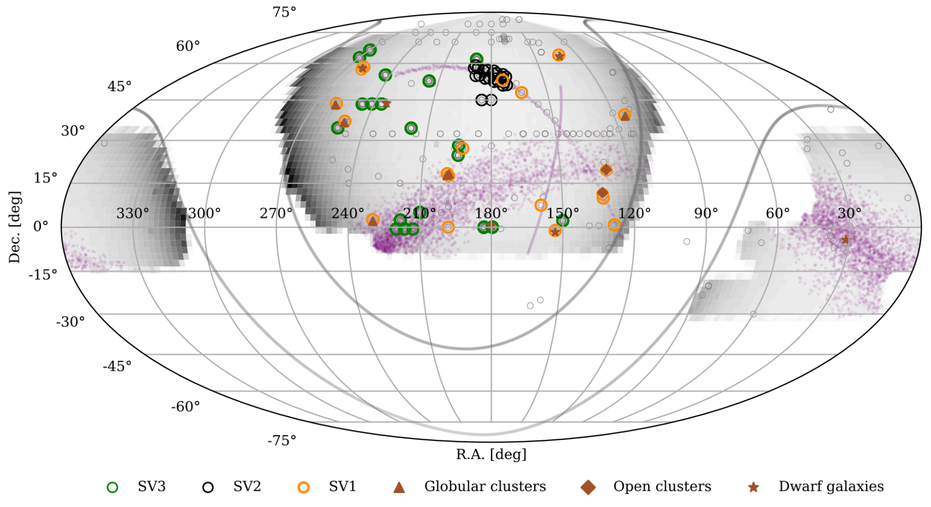




DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science





The Power of Milky Way's Stellar Streams with Full 6D+ Phase Space Data Set from S⁵ and DESI