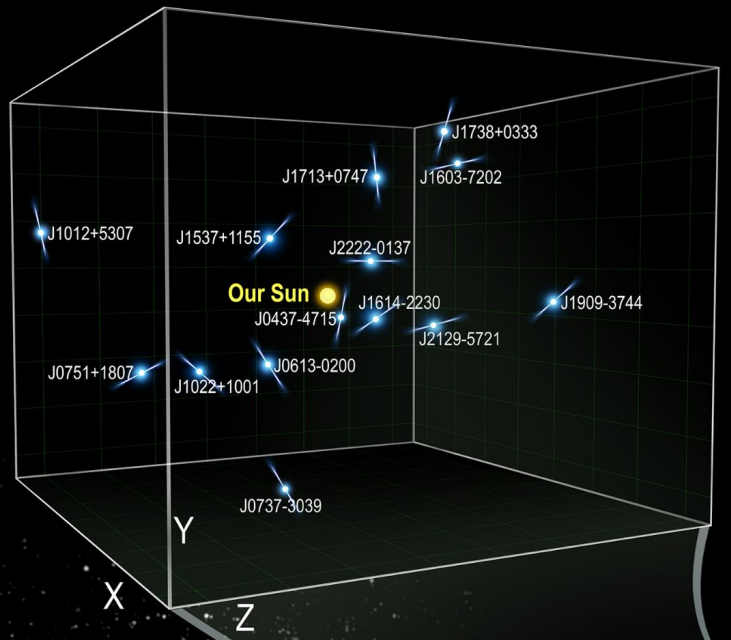

The Value of Direct Acceleration Measurements

Thomas Donlon II

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Collaborators:

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Michael T. Lam

Lawrence M. Widrow

Alice Quillen

Philip Chang

Scott Ransom

Enrico Ramirez-Ruiz

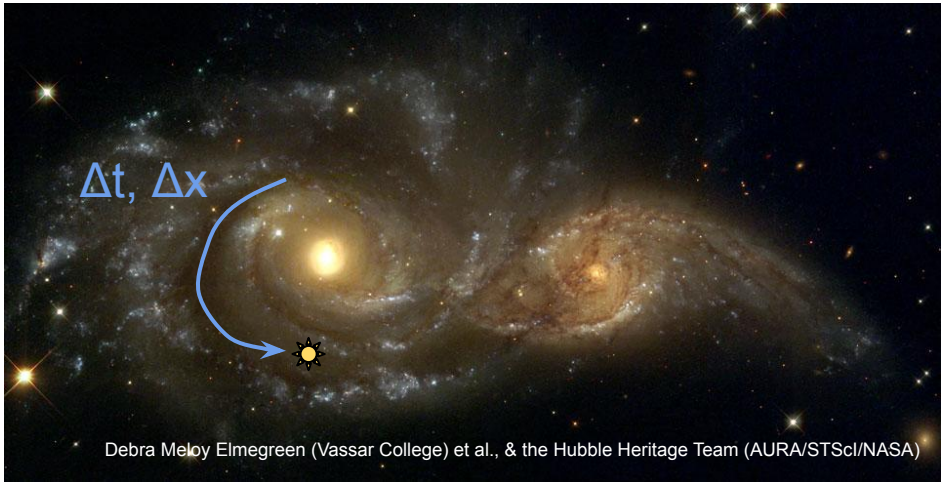
Sophia Vanderwaal

Why Care About Direct Accelerations?

Most of our tools for studying Galactic structure *estimate* accelerations.

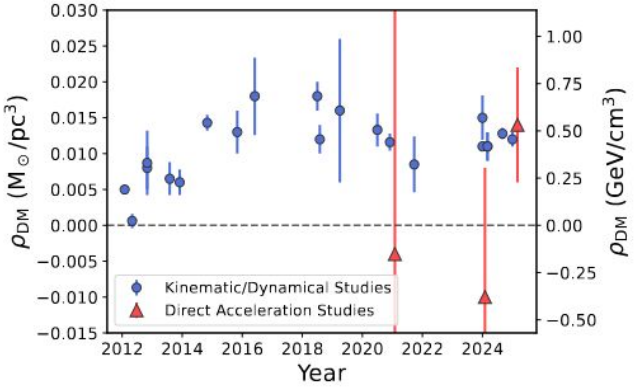
This often requires assumptions such as dynamical equilibrium (time-static DF or potential), axisymmetry, etc.

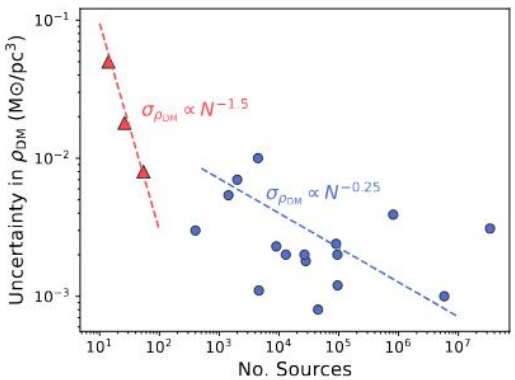
These tools produce results that are temporally and spatially averaged (for example, different populations give different values).

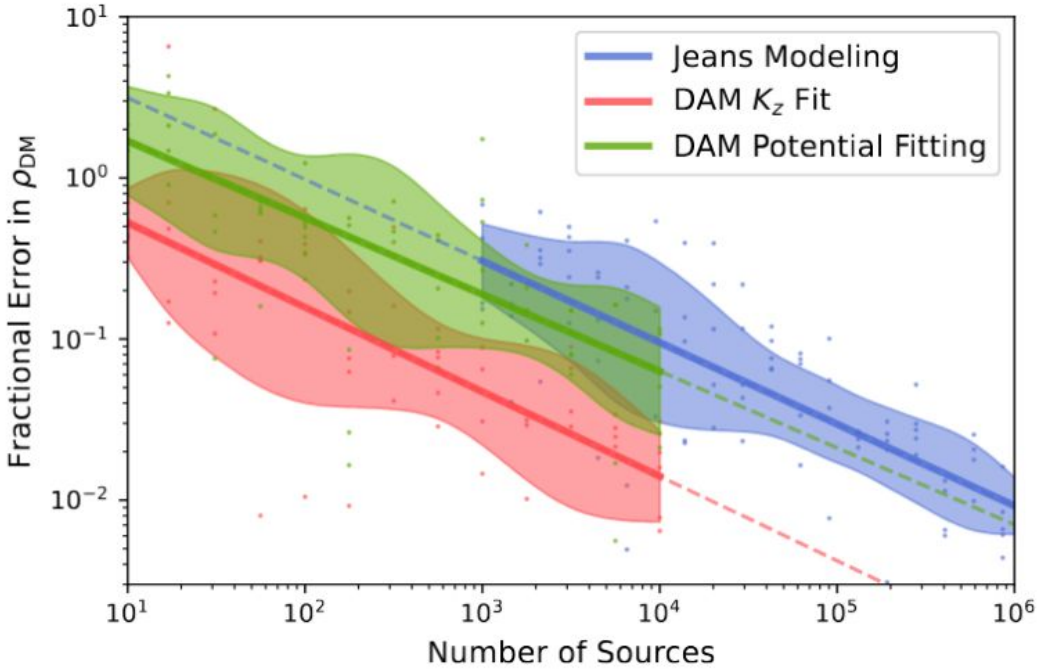


We are now entering an era where we can directly observe the instantaneous acceleration field at specific points without relying on these assumptions!

Dark Matter From Accelerations







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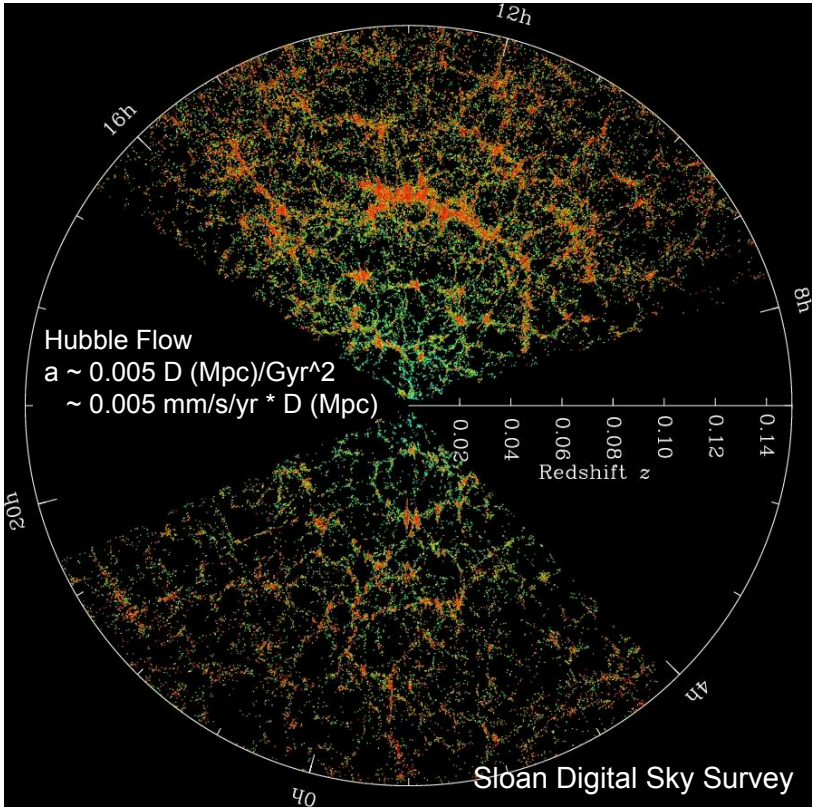
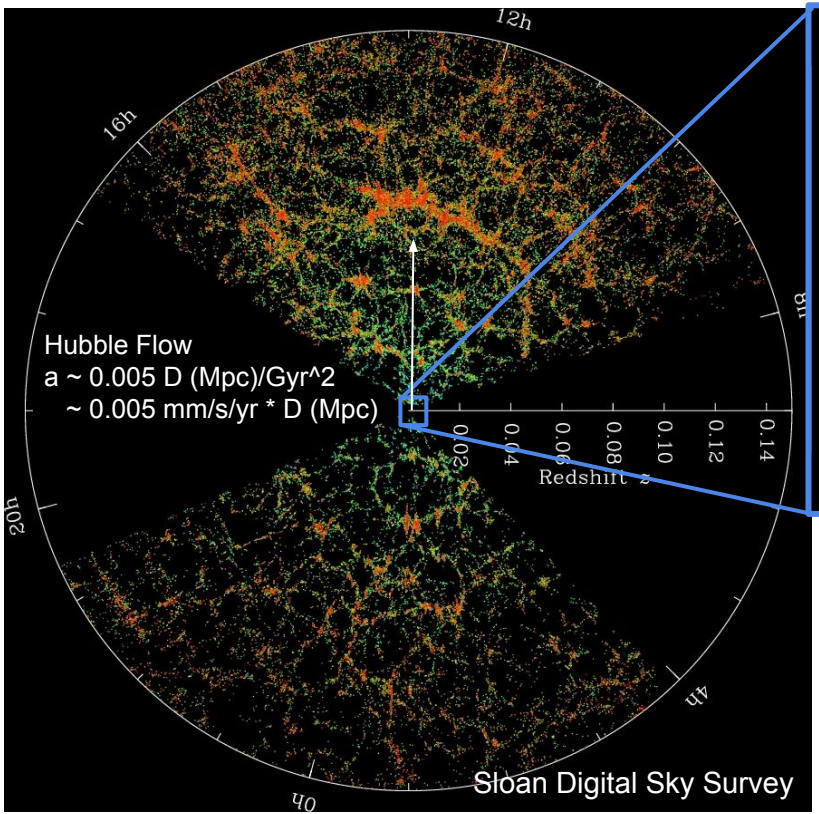
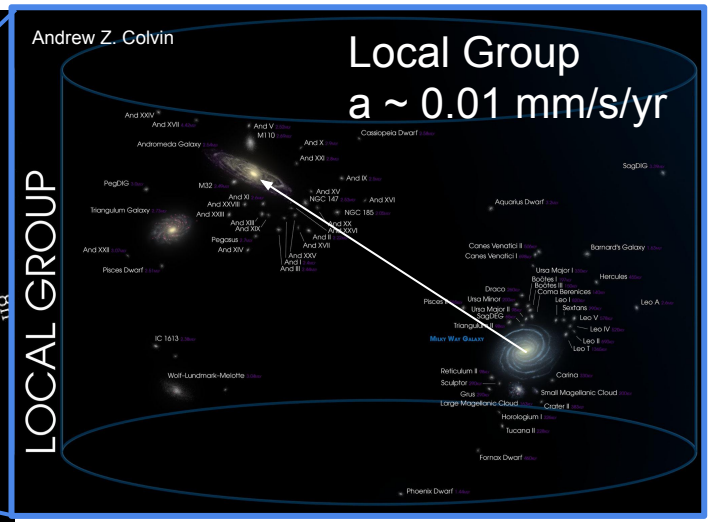
The Scale of Accelerations



The Scale of Accelerations





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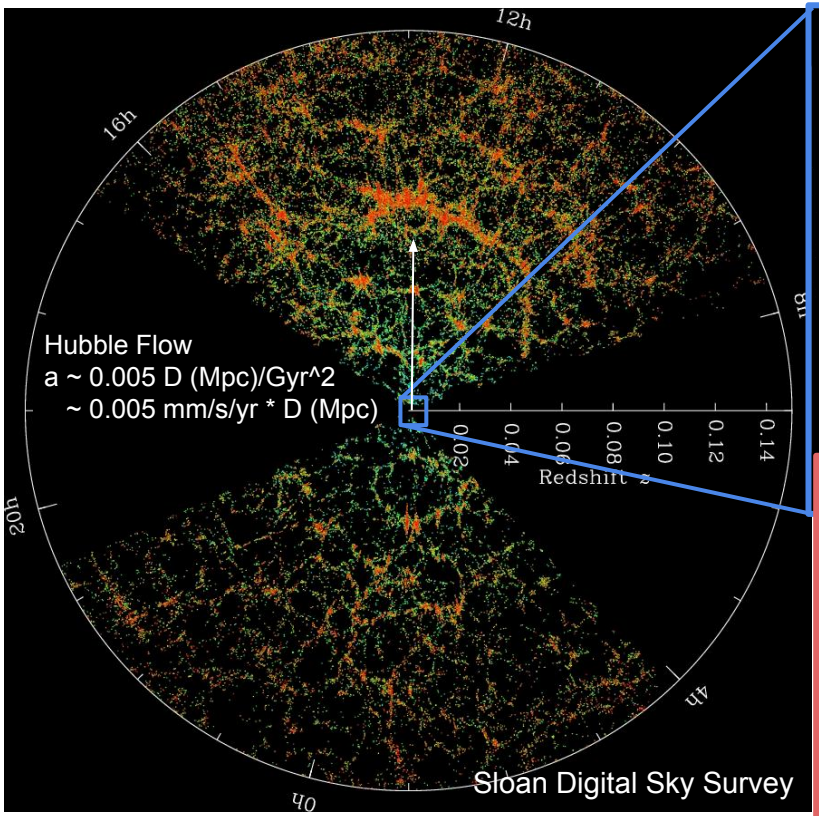

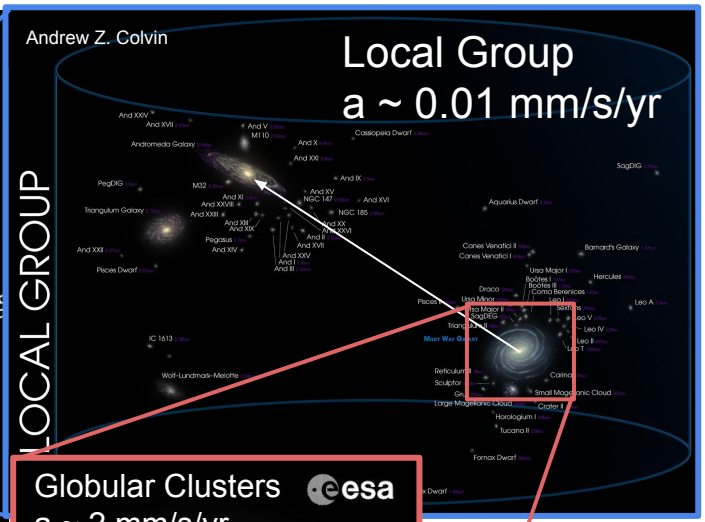

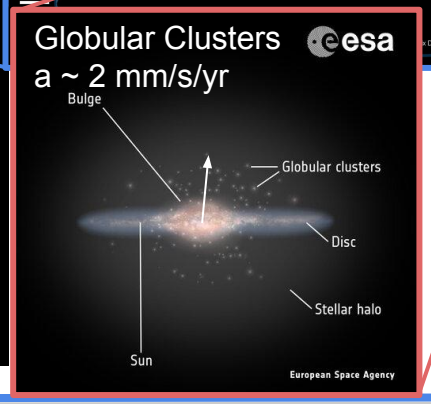

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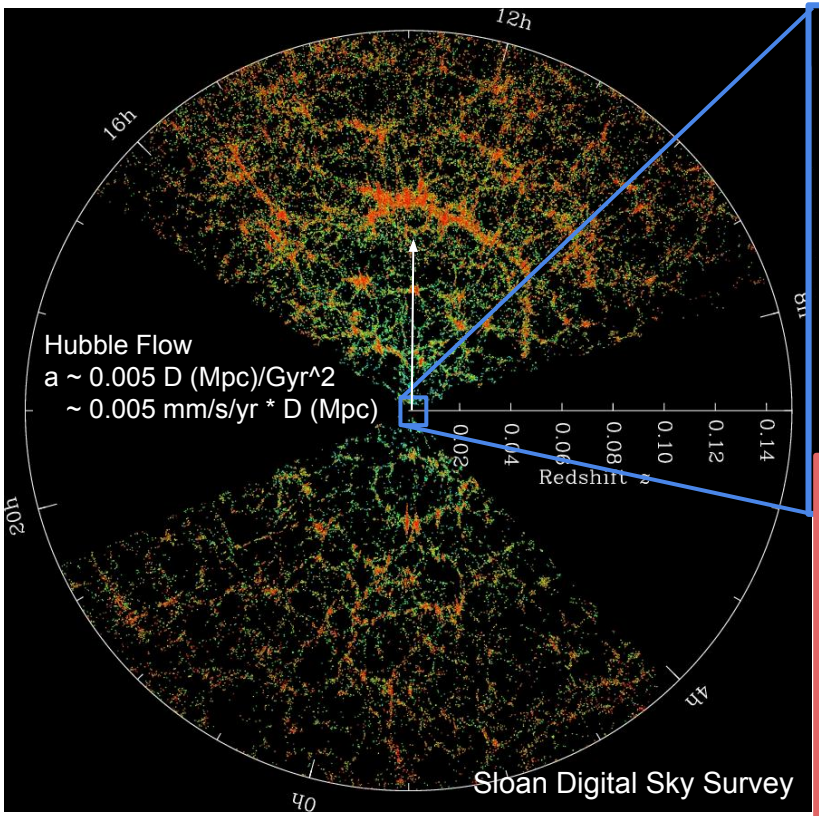

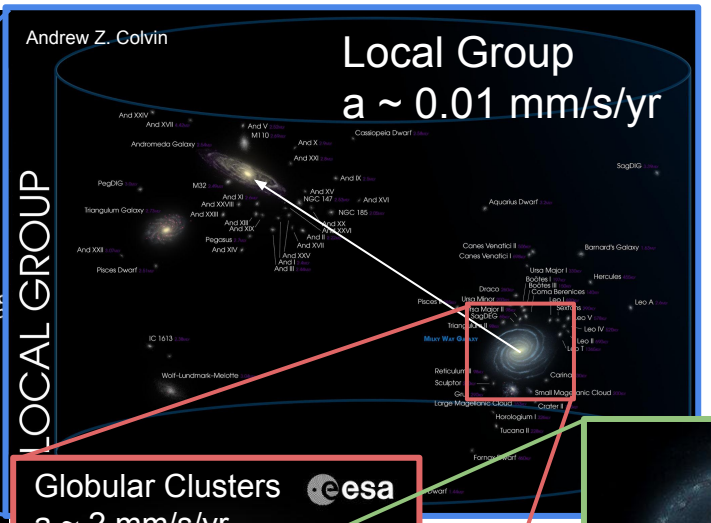

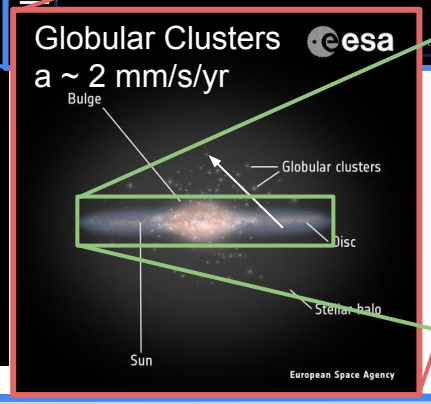

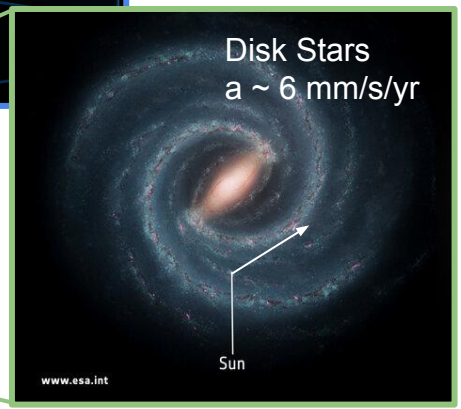

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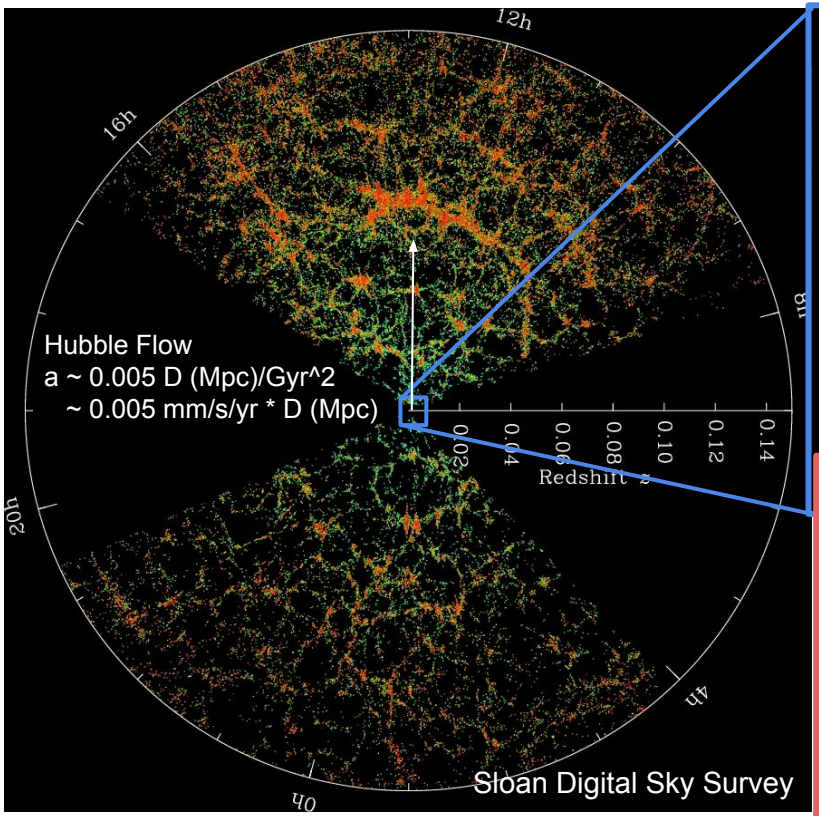

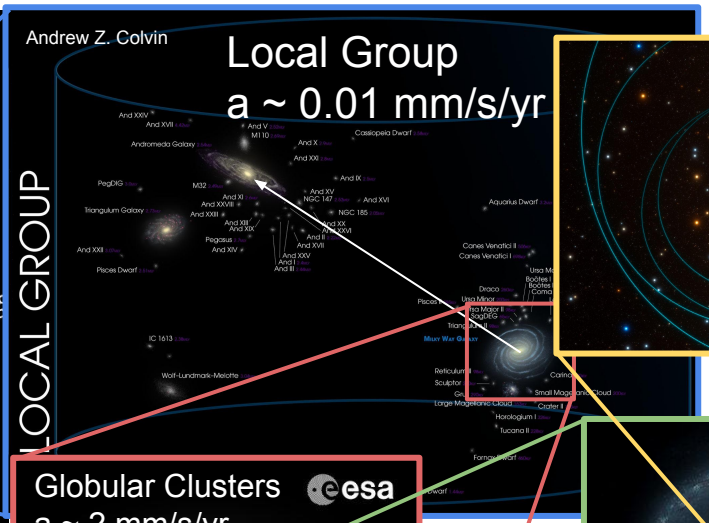

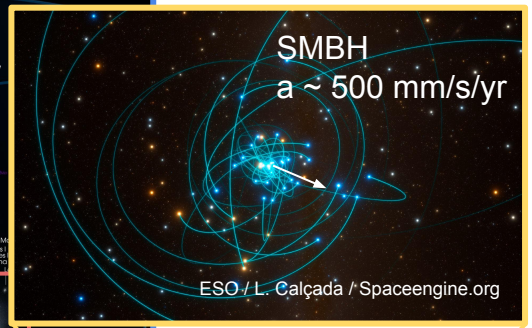

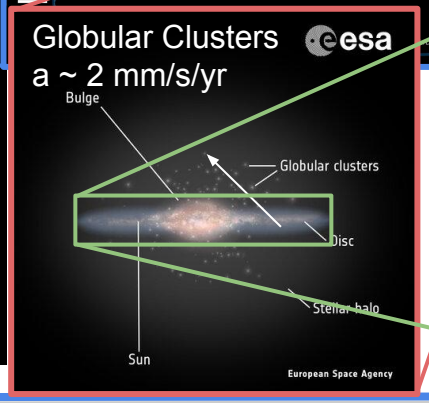

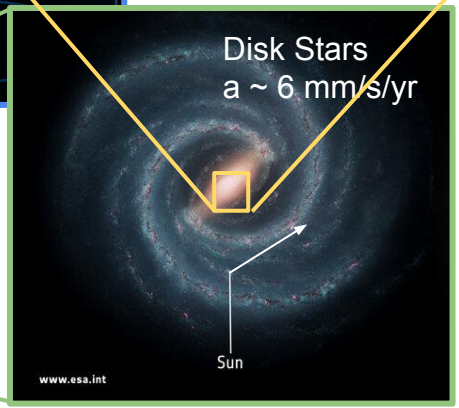

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1. Accelerations in LISA

2. Observed Direct Acceleration Measurements

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Accelerations in LISA

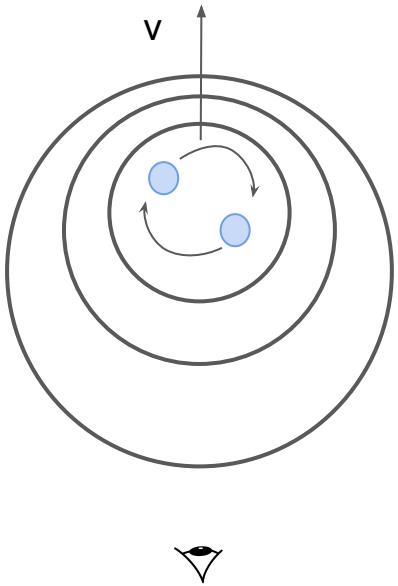
Doppler Shift

Observed frequency

$$f = \left(1 + \frac{\Delta v}{c}\right) f_0$$

Change in frequency

$$\Delta f = \frac{\Delta v}{c} f_0$$



See frequency drift due to GW (Ebadi et al. 2024)

$$f_s(\tau) = f_{s0} + \dot{f}_{s0}\tau + \ddot{f}_{s0}\tau^2/2 + \dots .$$

$$\dot{f}_{s0} = \frac{3}{8}\frac{f_{s0}}{\tau_c}, \quad \ddot{f}_{s0} = \frac{33}{64}\frac{f_{s0}}{\tau_c^2}, \quad \dots .$$

But you also see additional frequency drift due to change in velocity = acceleration

What kind of accelerations can LISA measure?

Disclaimer: Judgments made from literature that I am not an expert in

- Cosmological (Hubble flow)
- Intergalactic
- Intra-galactic (dwarf galaxies, globular clusters)
- Galactic
- Hierarchical Triples

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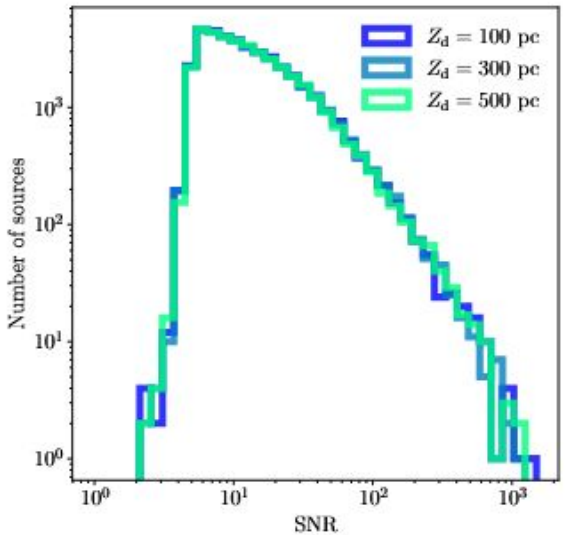
- Cosmological (Hubble flow) Probably not.
- Intergalactic Probably not.
- Intra-galactic (dwarf galaxies, globular clusters) Probably not, but maybe?
- Galactic Maybe?*
- Hierarchical Triples Likely, but probably only a few sources.
  (ex. SOBH binaries in AGN disks, nuclear star clusters, etc.)

Double White Dwarf Binaries in LISA

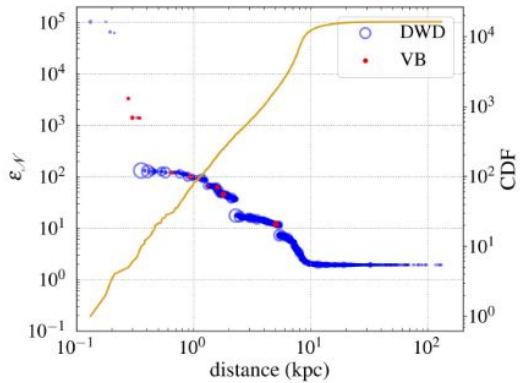
LISA is expected to individually resolve O(10^4) DWD systems in the Milky Way.



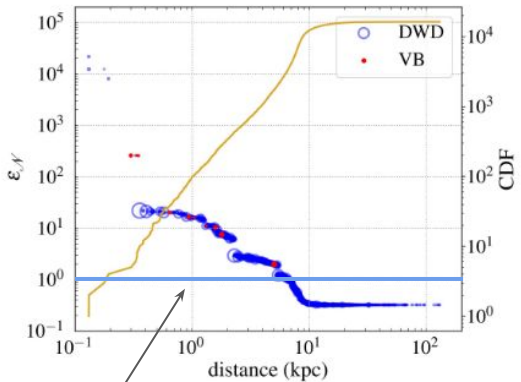
Georgousi et al. (2022)

It *may* be possible to constrain the Galactic potential directly from 10 years of LISA DWD data.

(without EM data)



(with EM data)



Ebadi et al. (2024)

(Below 10^0 = constraint)

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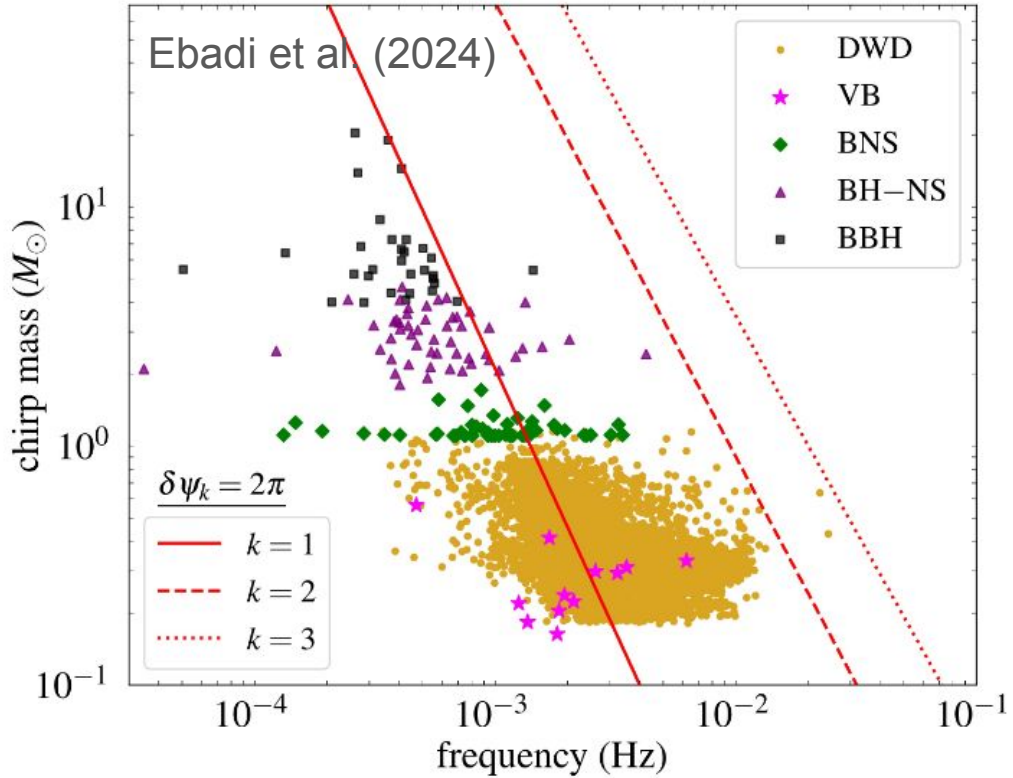
Double White Dwarf Binaries in LISA

Problem: (“Challenge”!)

In order to directly obtain acceleration for a *single* DWD, one must measure the first and second derivative (k=1,2) for that system.

That is probably only going to be the case for a few sources in LISA (T ~ 10 years)



1. Accelerations in LISA

2. Observed Direct Acceleration Measurements

Measuring Pulsar Accelerations

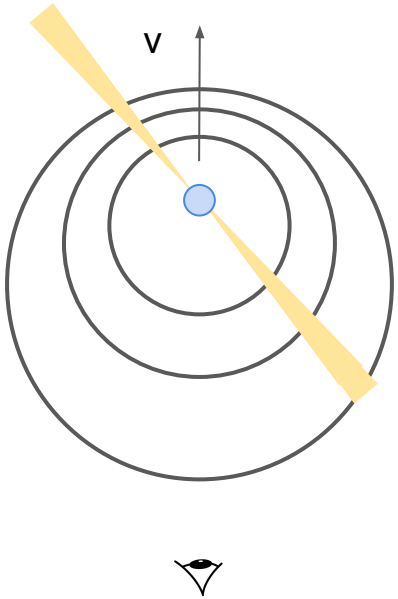
Doppler Shift

Observed frequency

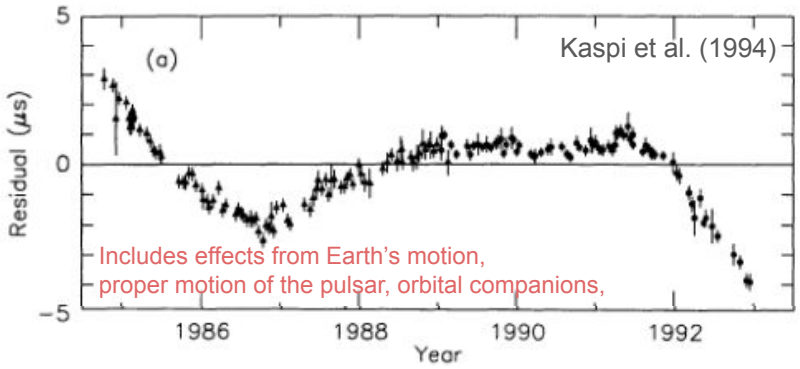
$$f = \left(1 + \frac{\Delta v}{c}\right) f_0$$

Change in frequency

$$\Delta f = \frac{\Delta v}{c} f_0$$



Can obtain P, Pdot from *very* precise pulsar timing



Rewriting as derivatives…

$$\frac{\dot{P}}{P} = \frac{a_{\rm los}}{c},$$

(Soon there will be other tracers that can be used to obtain accelerations…!)

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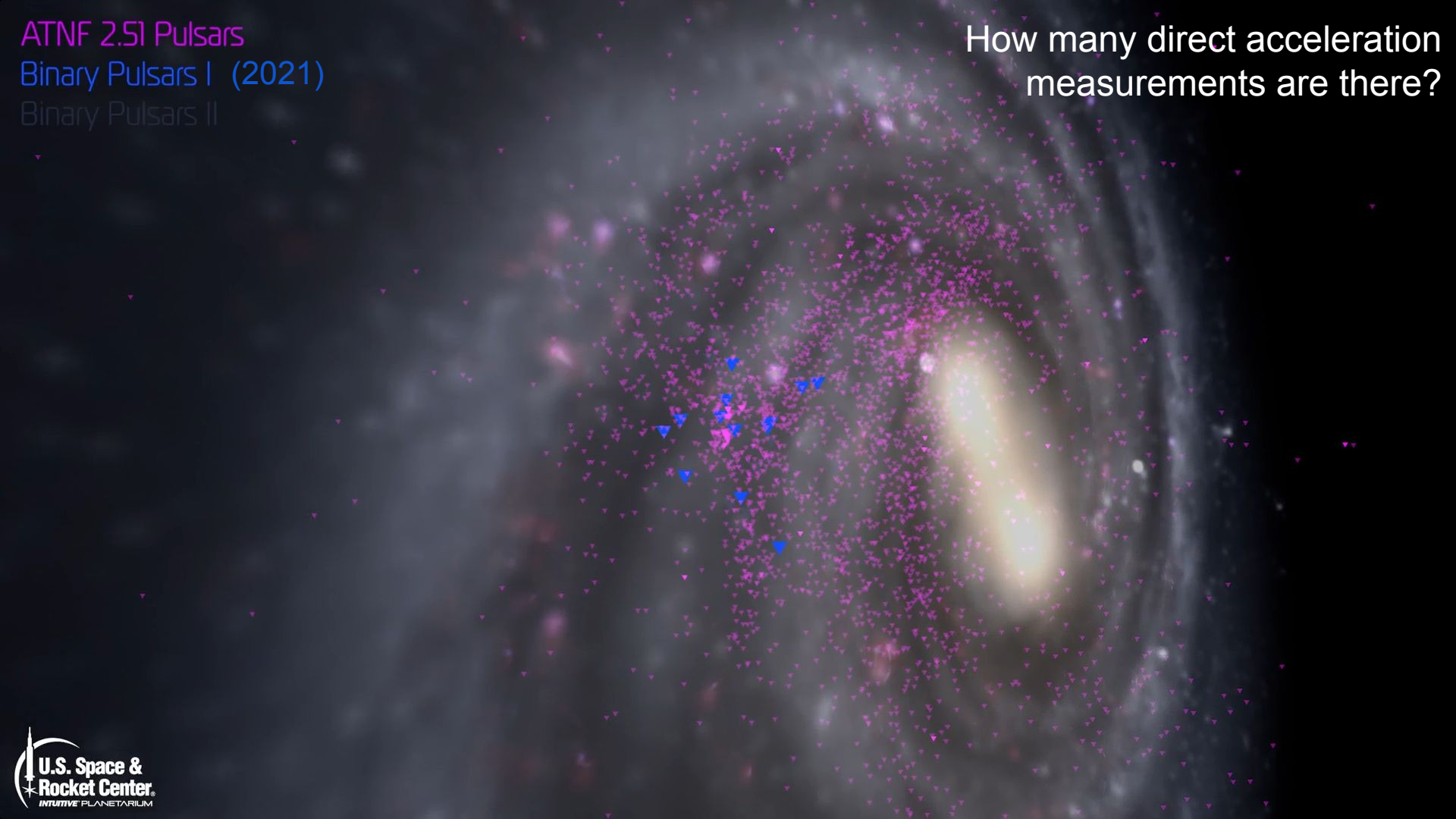
ATNF 2.51 Pulsars
Binary Pulsars I (2021)
Binary Pulsars II
How many direct acceleration measurements are there?
U.S. Space & Rocket Center
INTUITIVE PLANETARIUM


ATNF 2.51 Pulsars
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Binary Pulsars II (2024)
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INTUITIVE PLANETARIUM


ATNF 2.51 Pulsars
Binary Pulsars I (2021)
Binary Pulsars II (2024)
Single Pulsars (2025)
How many direct acceleration measurements are there?
U.S. Space & Rocket Center
INTUITIVE PLANETARIUM

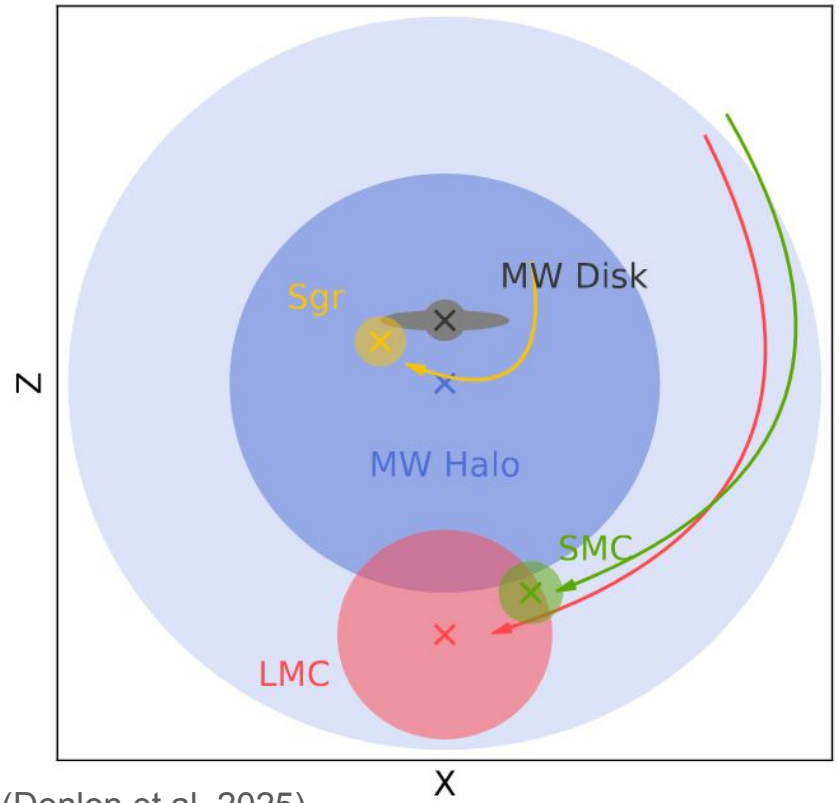
How many direct acceleration measurements are there?

Currently, we only have O(50) direct acceleration measurements (although the number of sources is increasing rapidly).

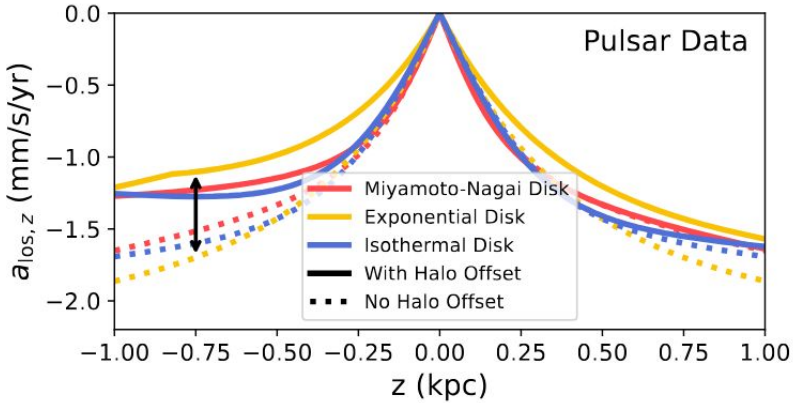
LISA could expand that to over 10,000 sources!

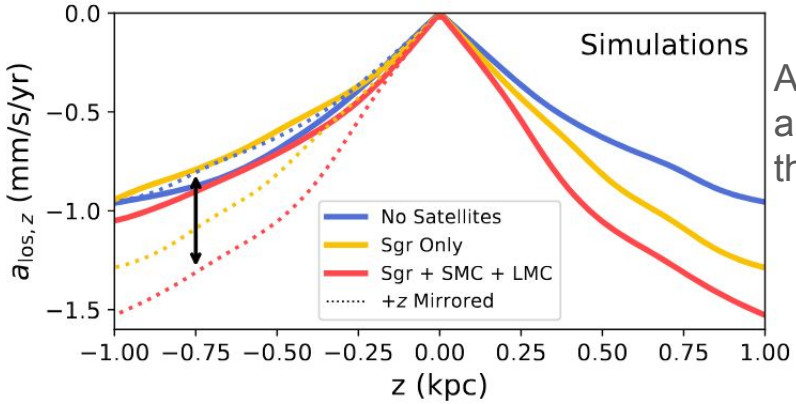
U.S. Space & Rocket Center
INTUITIVE PLANETARIUM

Halo Disequilibrium from Satellite Galaxies



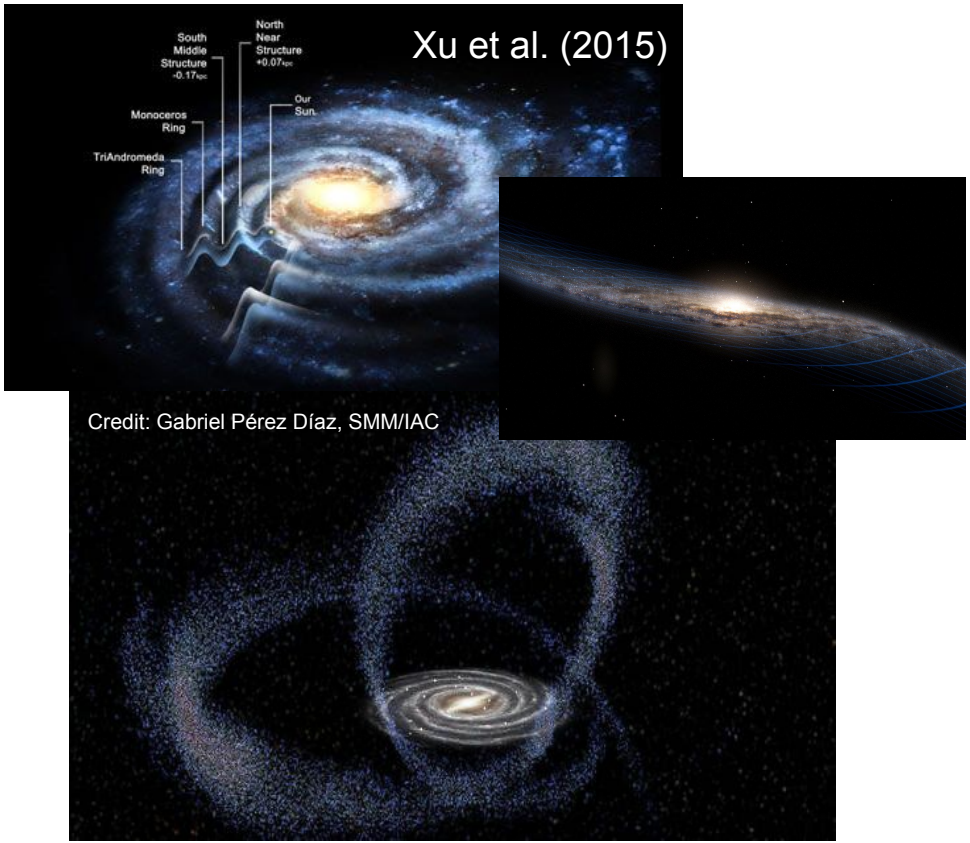
(Donlon et al. 2025)

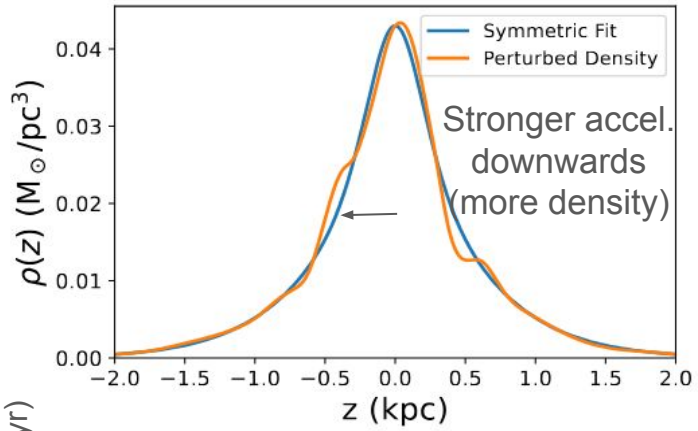


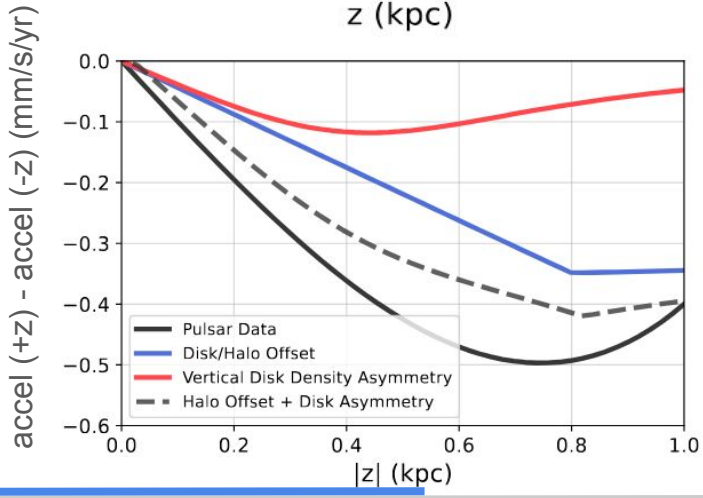


Accel. stronger above the disk than below it!

Disk Disequilibrium from Satellite Galaxies







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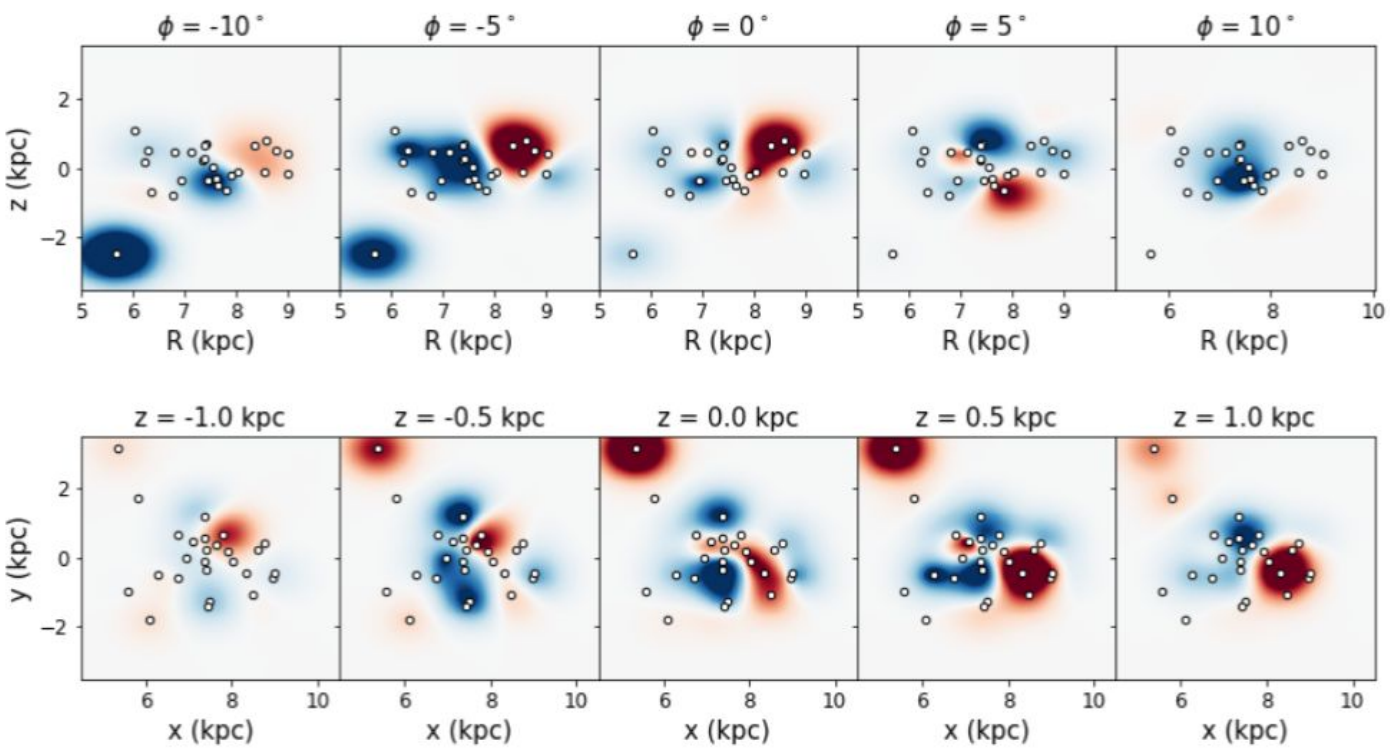
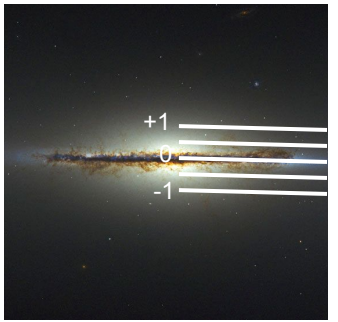
3D Maps of the Galaxy's Acceleration

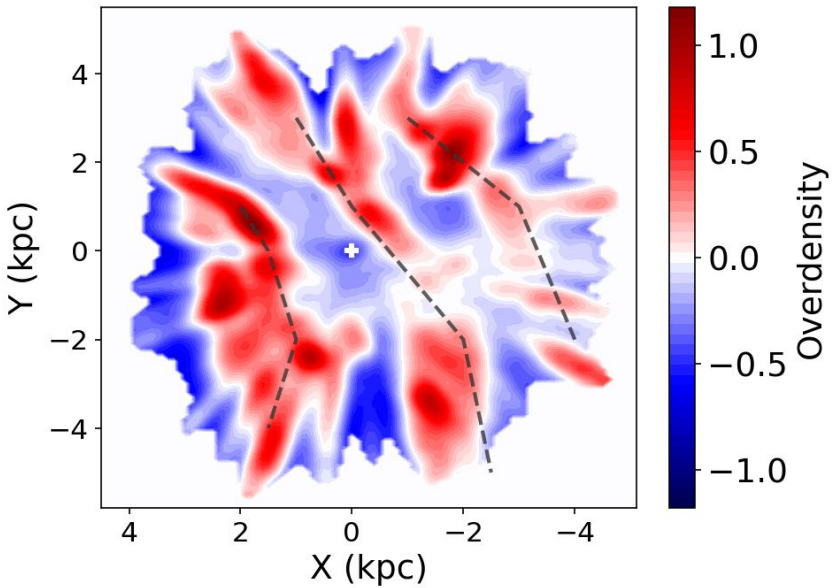




Equilibrium is symmetric in +/- phi and +/- Z… Things are substantially out of equilibrium!

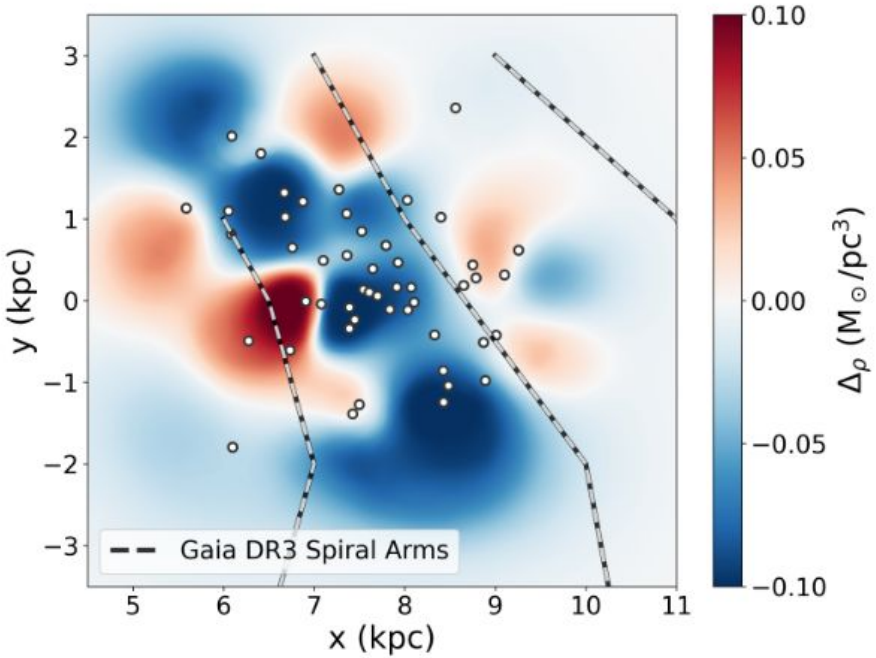
Accelerations Due to Spiral Arms

O-B star density



Poggio et al. (2021)

Pulsar accelerations

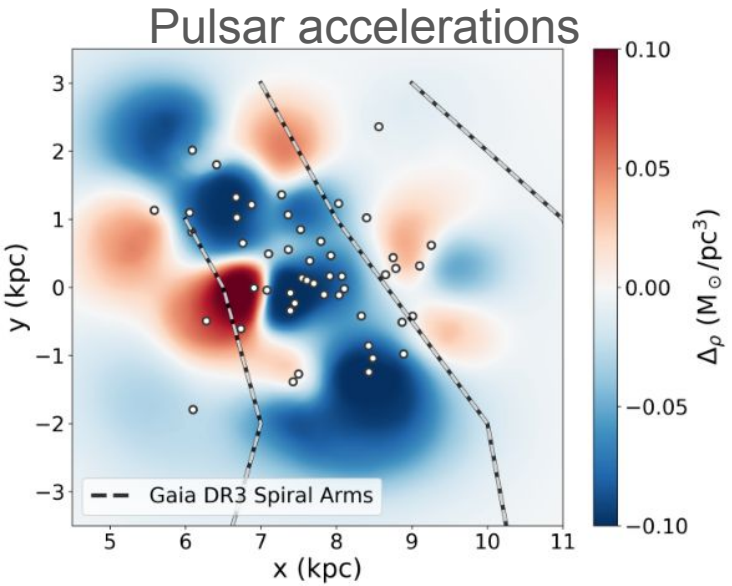


Validation of LISA Accelerations

Two ways of validating LISA data:

1. Direct comparison for EM and LISA accelerations of a given source (we expect to directly measure DWD accelerations soon!)

2. Maps of LISA accelerations and other sources should agree.



If we can make a similar map from other sources, they should agree with the pulsar data.

If they don't, we can calibrate the sources against each other!

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Takeaways

- Direct acceleration measurements are quickly becoming a viable way to probe the instantaneous acceleration field of the Galaxy
- These accelerations are valuable dynamically because they enable novel study of dark matter substructure and satellite interactions
- This field is growing (fast!) – we've already done cool things, more cool things are hopefully coming. In <5 years we've quadrupled the number of accelerations!
- LISA potentially promises a 2-3 order of magnitude increase in the number of Galactic accelerometers. How can we use these to do Galactic science?