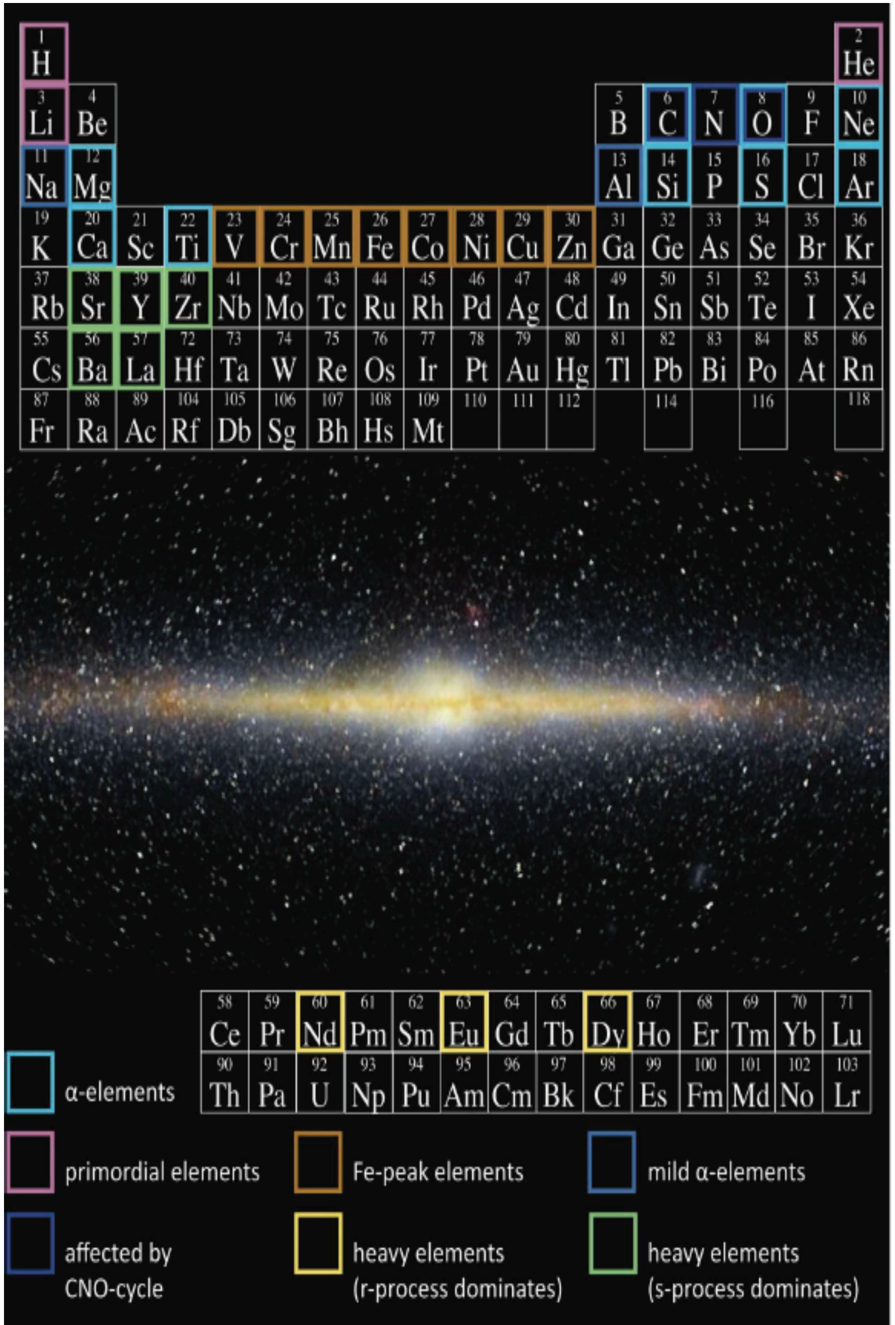

Astronomical Data

…a very biased view

Else Starkenburg

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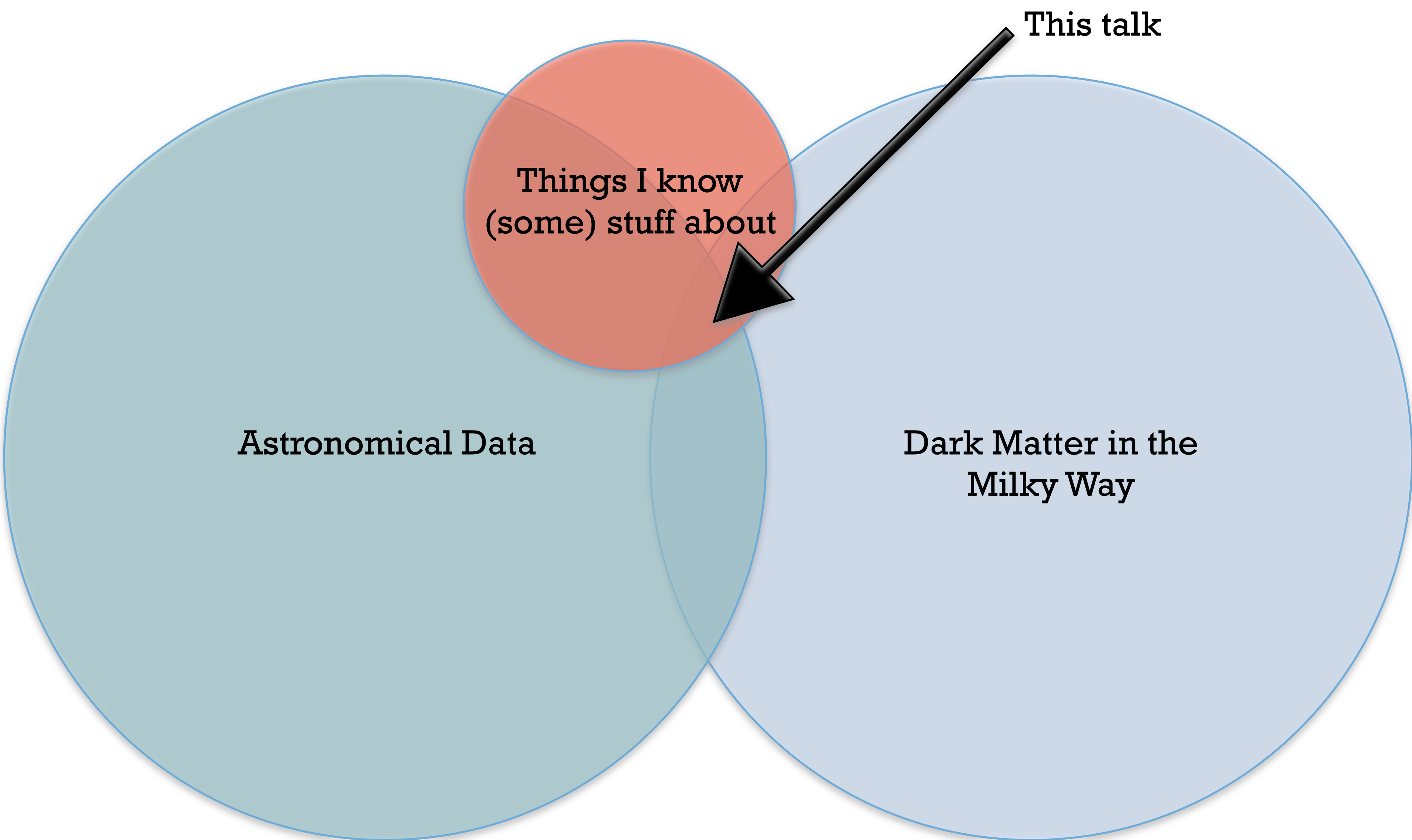
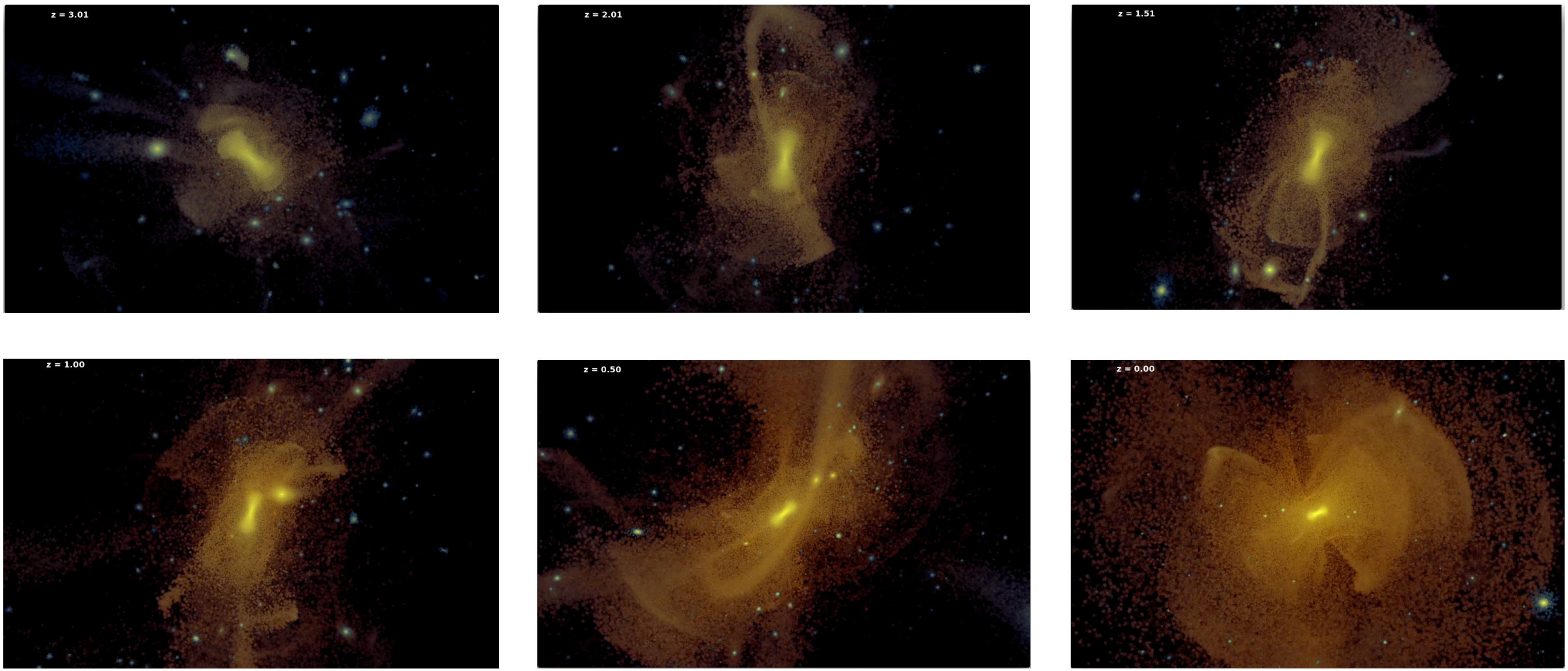
Leibniz-Institut für Astrophyisk, Potsdam

Content


This talk
Things I know (some) stuff about
Astronomical Data
Dark Matter in the Milky Way

Dark Matter in the Milky Way

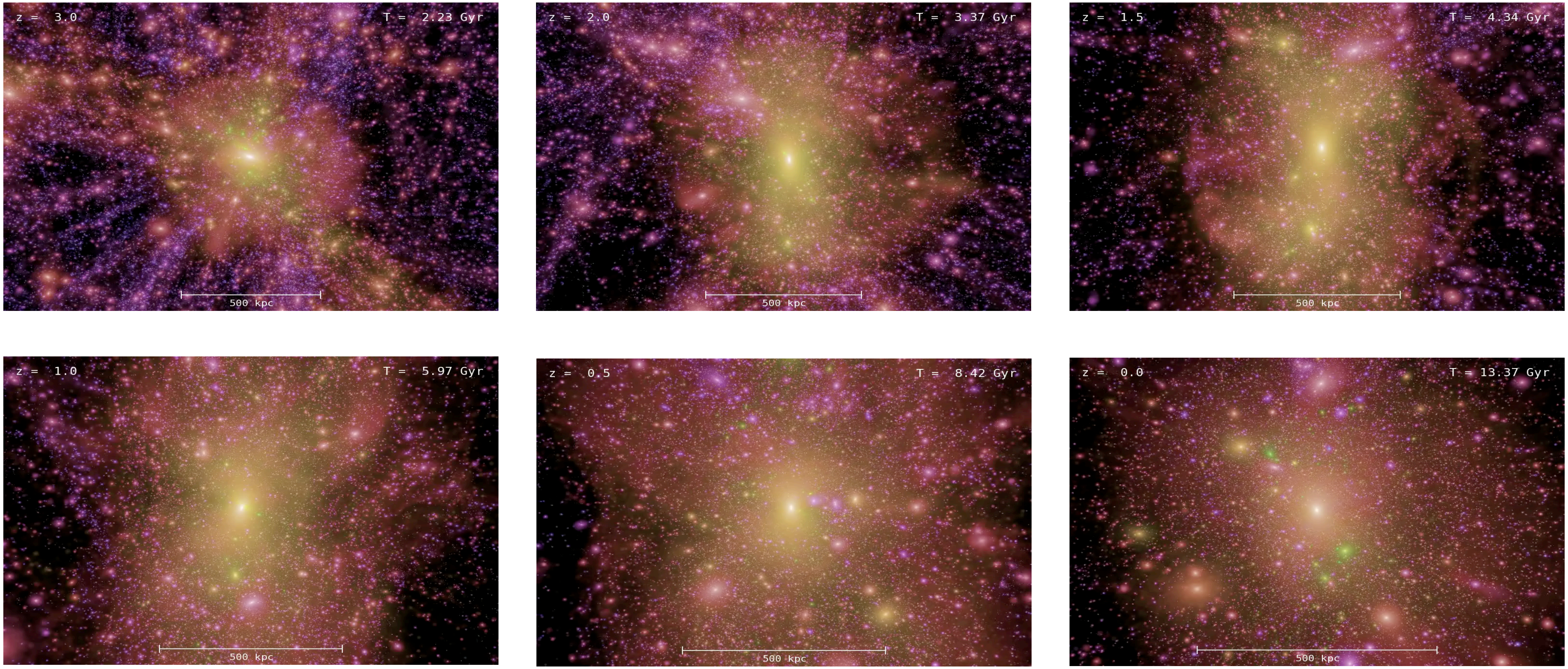
How to get from here



Credit: J. Helly, A. Cooper, S. Cole and C. Frenk (ICC), based on simulation data from The Virgo consortium and software by V. Springel

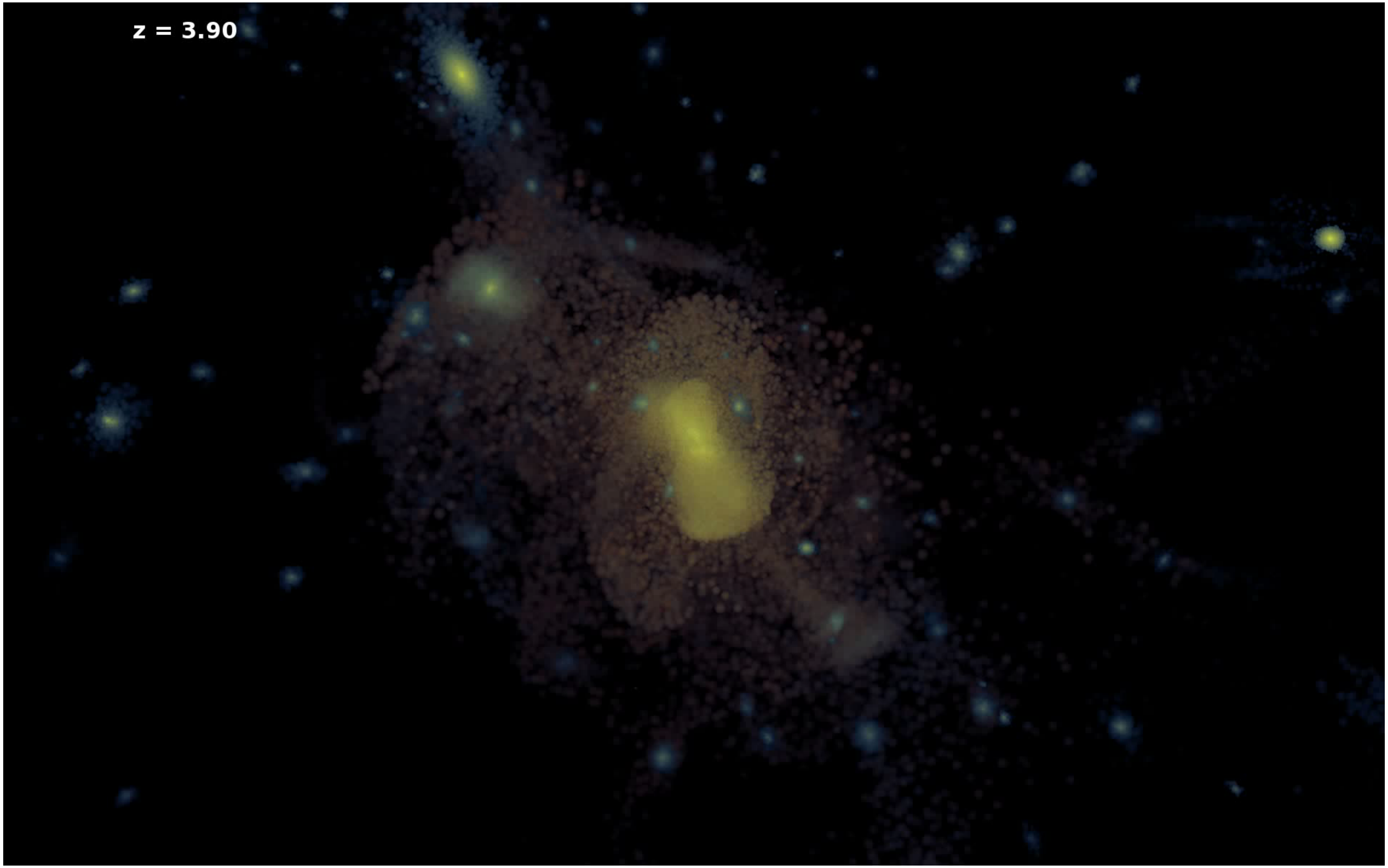
Dark Matter in the Milky Way

How to get from here…..to here



Credit: J. Helly, A. Cooper, S. Cole and C. Frenk (ICC), based on simulation data from The Virgo consortium and software by V. Springel

Does this show the history of our Milky Way?



Credit: J. Helly, A. Cooper, S. Cole and C. Frenk (ICC), based on simulation data from The Virgo consortium and software by V. Springel

Astronomical data

- Stars
  - Position
  - Luminosity
  - Radial velocity
  - Proper motions (tangential velocity)
  - Metallicity
    - Multiple chemical abundances

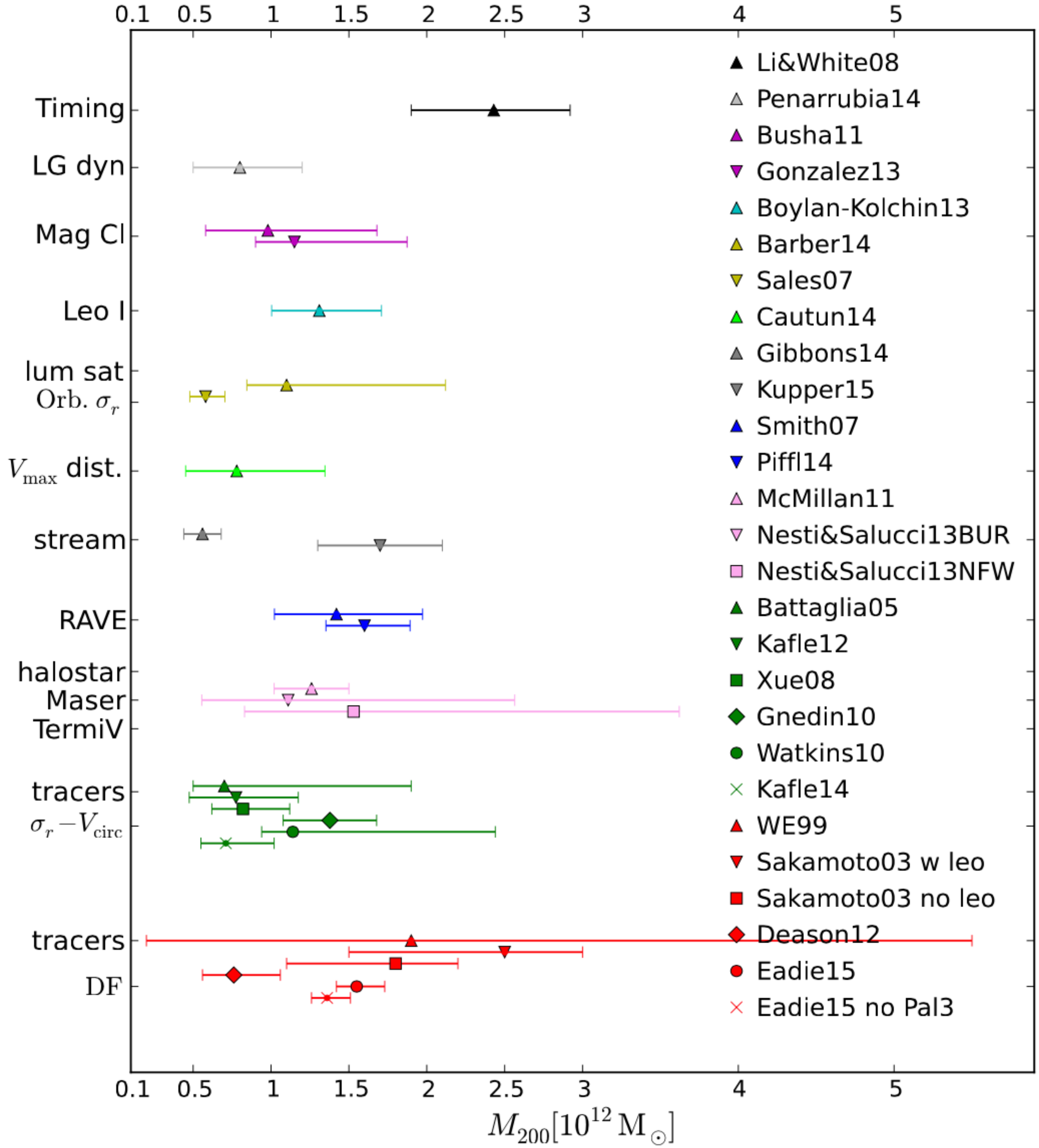
  - Stellar parameters
    - Temperature
    - Gravity
    - Turbulence

The imprint of dark matter on astronomical data

- The Milky Way and its dark matter
  - How massive is the Milky Way really?
    - Why do we care?
- The most dark matter dominated galaxies?
  - Should we look at the satellite galaxies to see dark matter annihilation signals, and if so, which?
- What other signals can we see from dark matter?
- What current and future data will help us solve these problems?

How massive is our Galaxy?

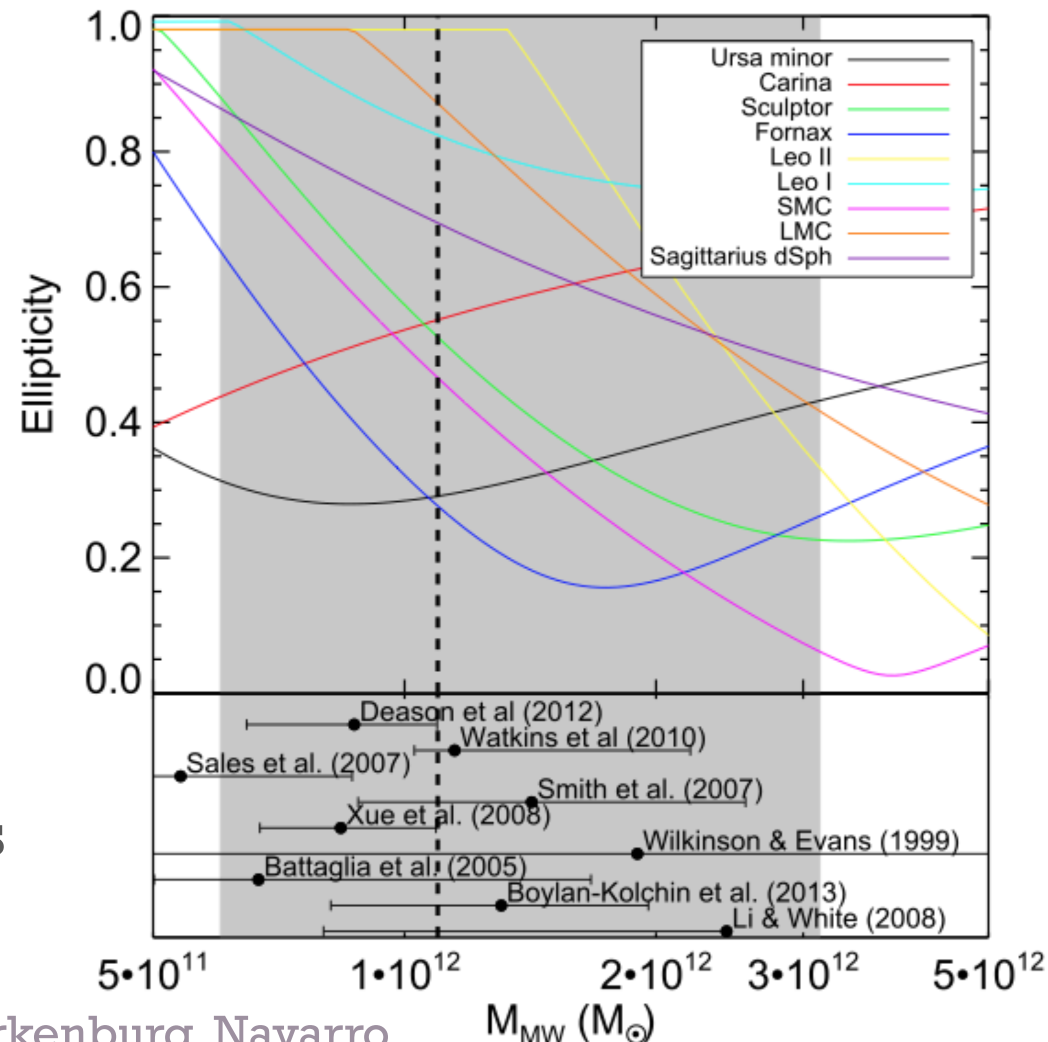
- Milky Way total mass is uncertain



Wang et al., 2015

Why do we care?

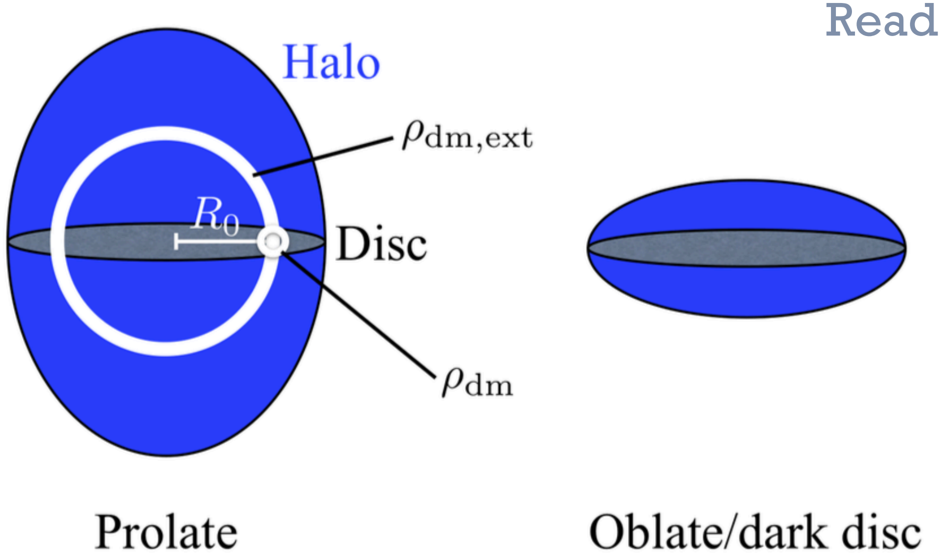
- Calibrating our simulations
- Small scale "crisis"
  - (many experts here on these topics)
  - "Too big to fail"
  - "Missing satellites"
  - Magellanic Clouds
- Derivation of orbits
- The critical observation is kinematics of tracers further out



Barber, Starkenburg, Navarro, McConnachie, Fattahi, 2014

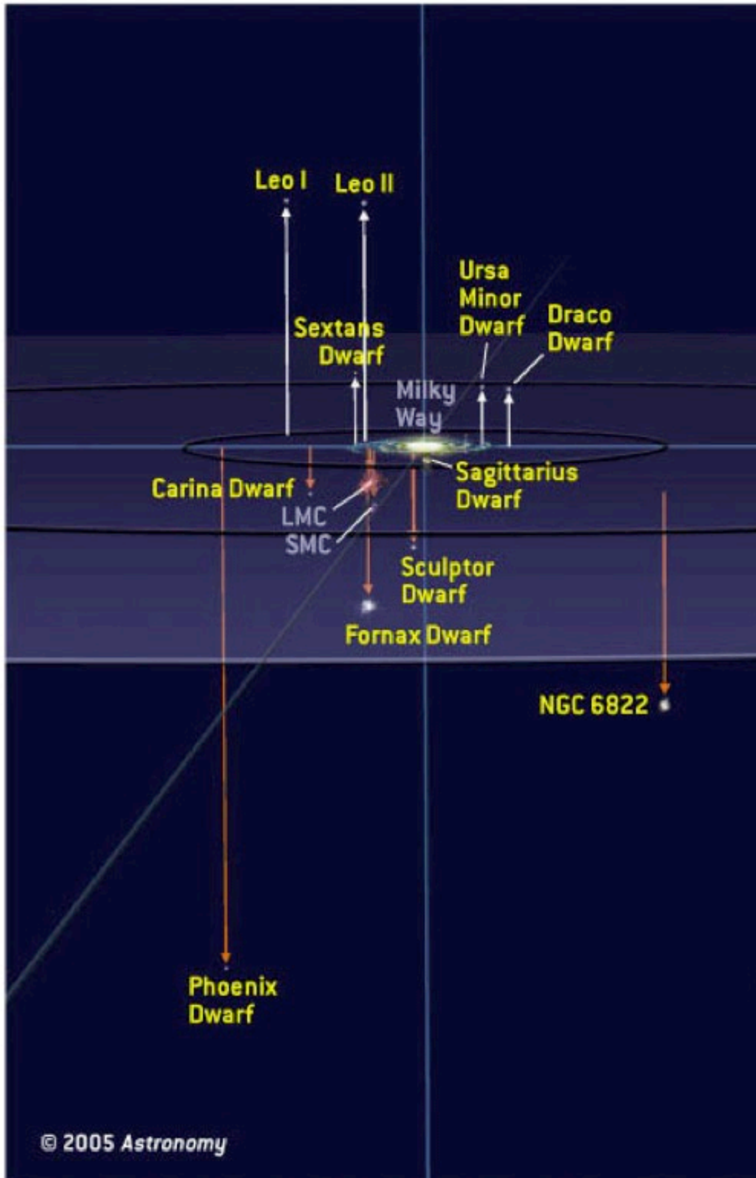
The shape of the halo

Read, 2014



- How much does the halo respond to the disk and accretion history?
  - Affects also the orbits of streams
- One way to measure this is compare local measurements of DM to global (rotation curves)
  - Read et al., 2014, Iocco et al., 2015, Silverwood et al., 2015
    - Assumption: dynamical equilibrium

The most dark matter dominated?



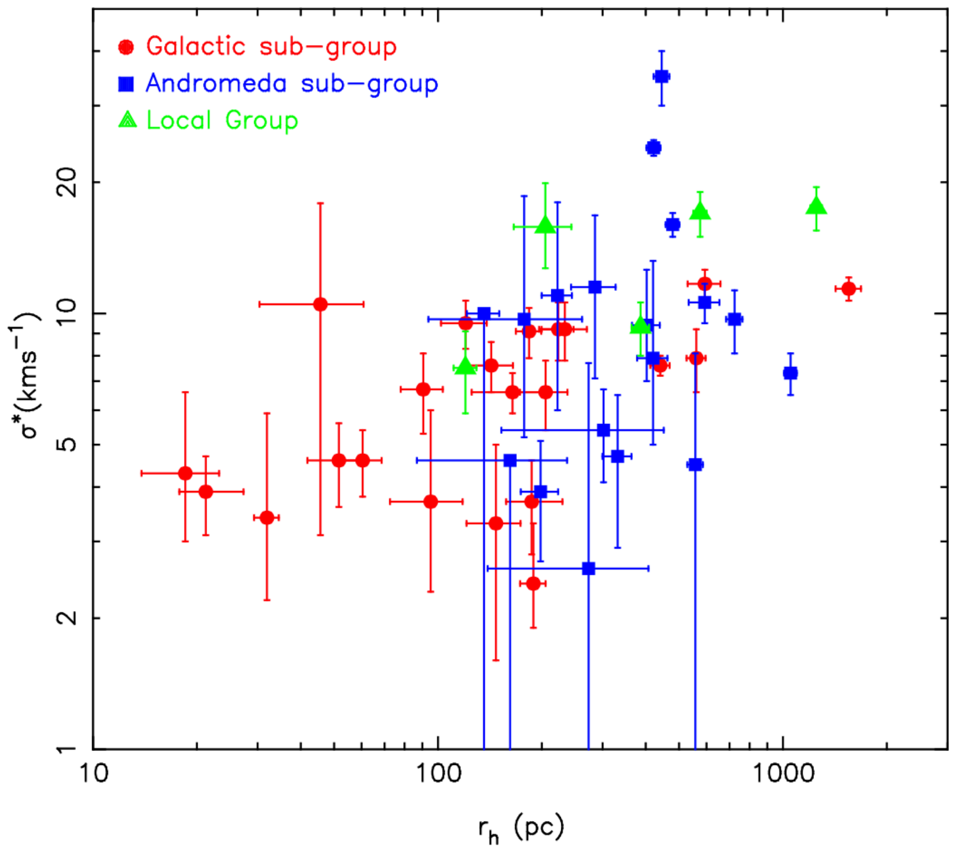
- Many satellite galaxies around the Milky Way are a unique opportunity to study galaxy formation at a different mass scale
  - And they seem to be very dark matter dominated!

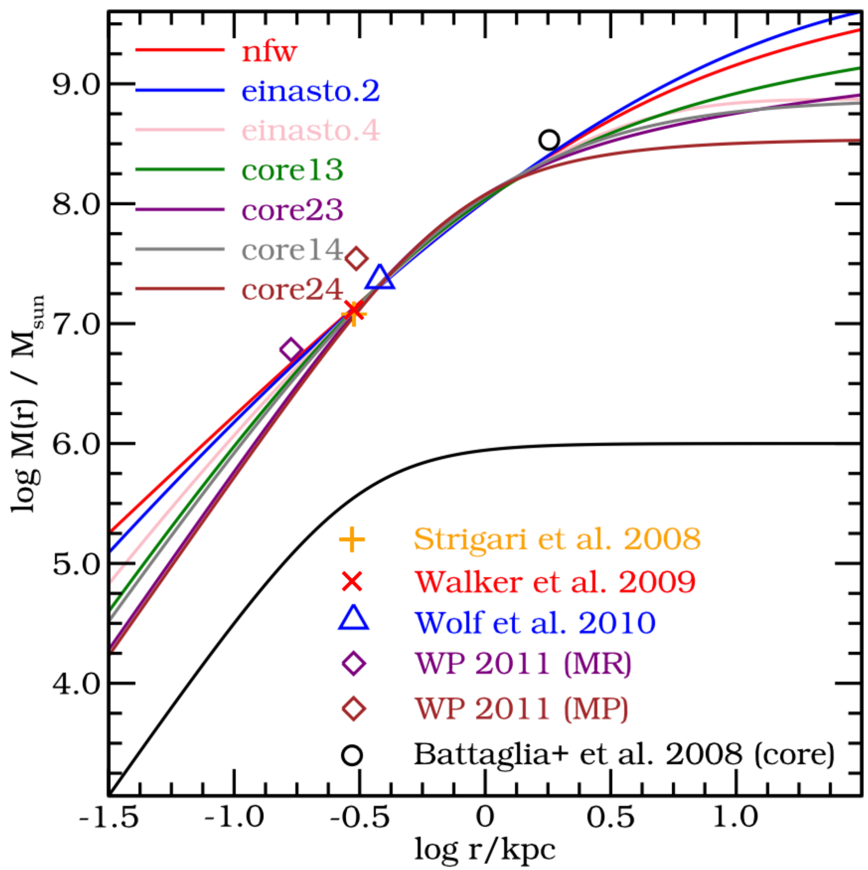
- Some reviews:
  - Walker 2012
  - Battaglia et al., 2013

The most dark matter dominated?

- Luminosity – velocity dispersion relation

Breddels & Helmi 2013

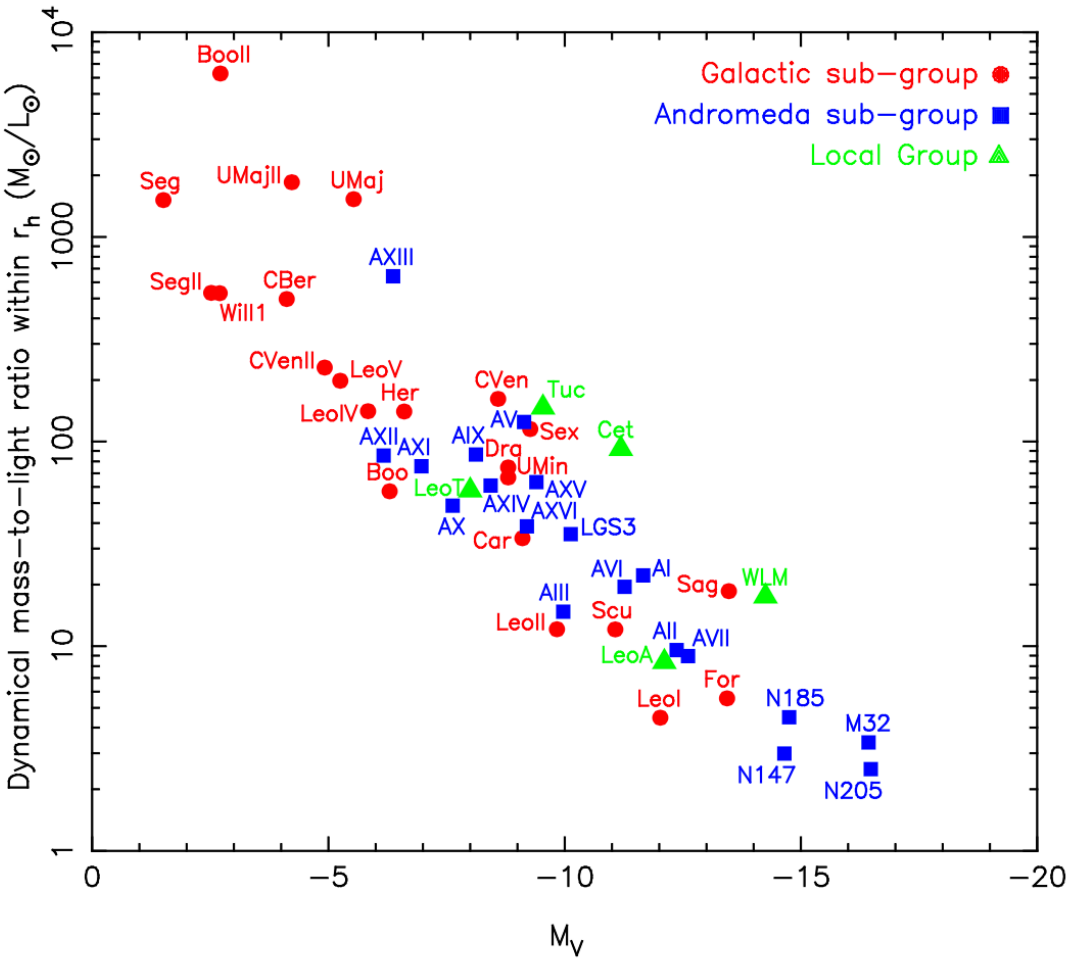




McConnachie et al., 2012

The most dark matter dominated?

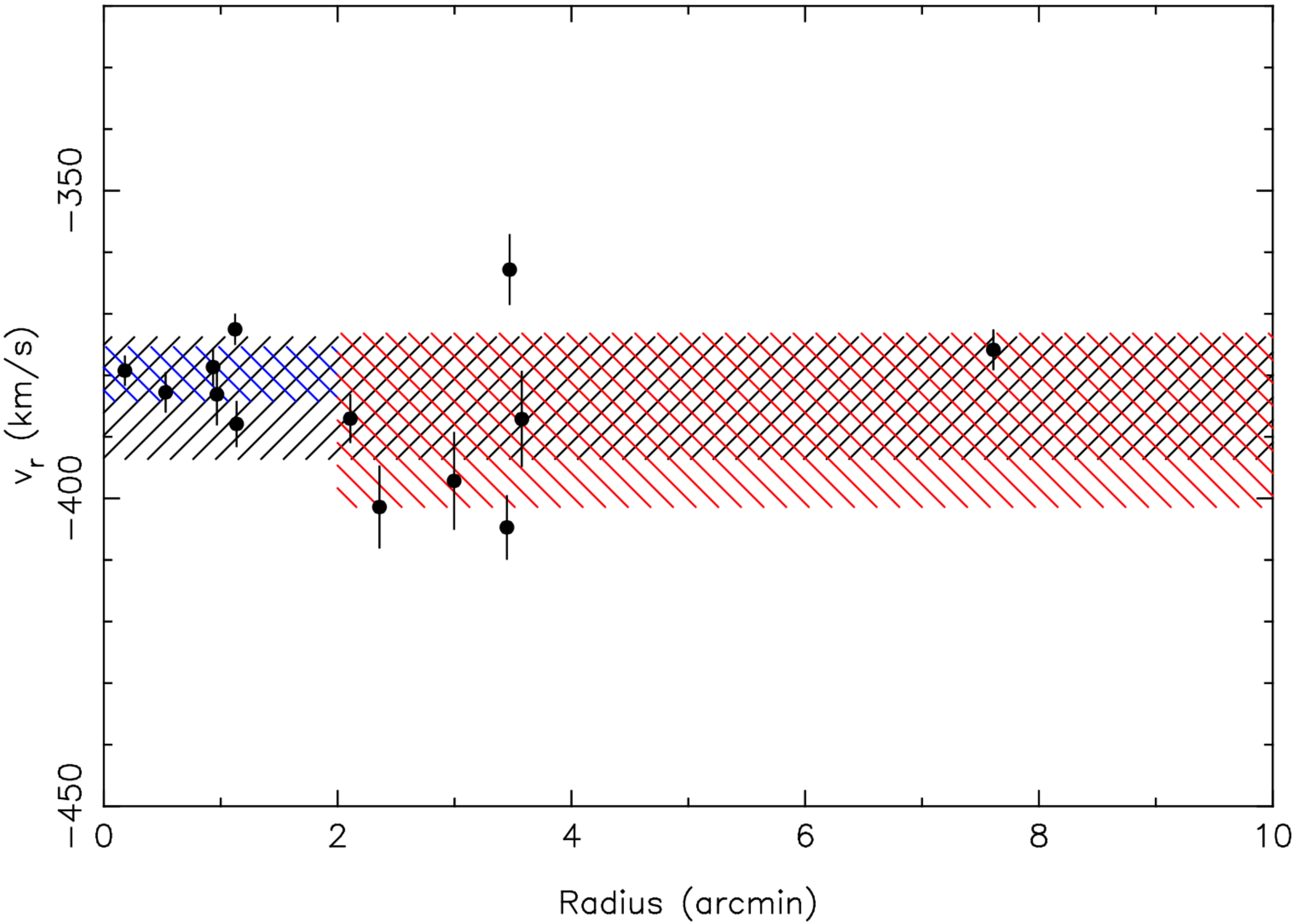
- Luminosity – velocity dispersion relation



The most dark matter dominated?

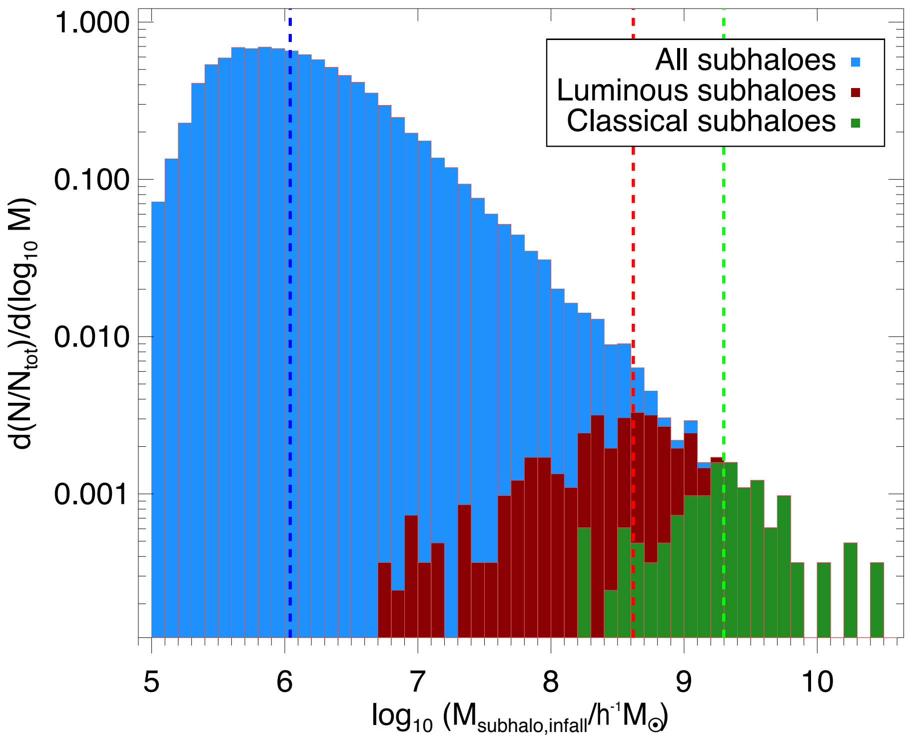
- Dark matter masses are uncertain – in particular in the smaller systems - due to:
- Foreground contamination
- Binaries
  - Can the velocity dispersion for the smallest galaxies
  - McConnachie & Cote, 2010: binaries cannot account for observed dispersions much in excess of ~4.5 km/s
  - Munoz et al., 2010: if the measured velocity dispersion of a dSph ranges between 4 and 10 km/s , the inflation from binaries should not be more than 30%
- Are they spherically symmetrical?
- Are they in dynamical equilibrium?

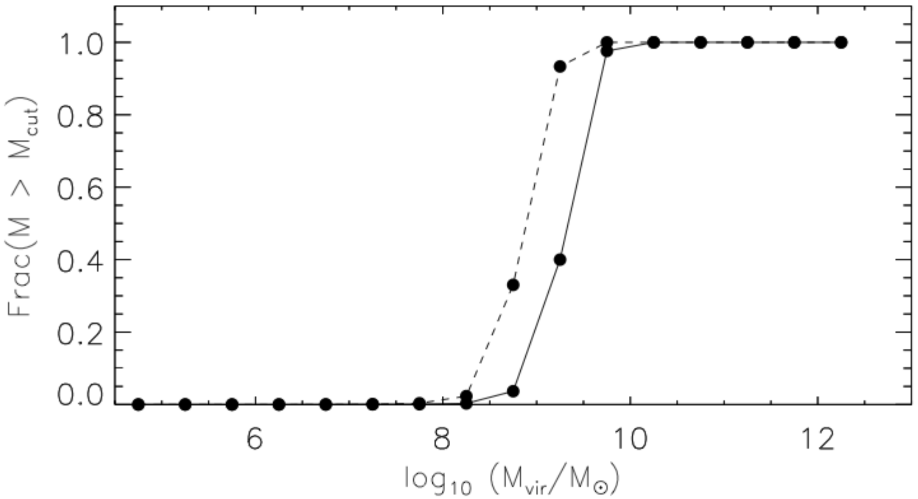
A recent example: Triangulum II



Martin et al., 2016

Who lives in which halo?





Barber, Starkenburg, Navarro et al., 2014

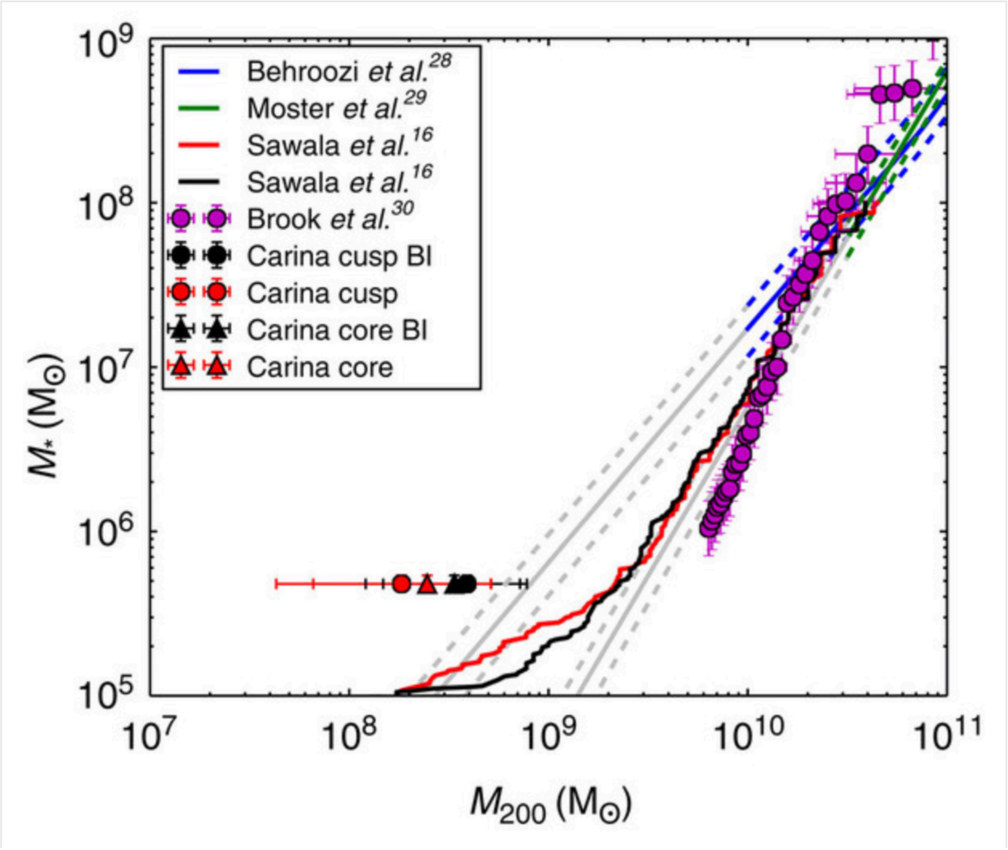
Yaryura, Helmi, Abadi & Starkenburg, 2016

Abundance matching is likely to break down at low masses

How can we make progress?

- Careful modelling taking into account all these effects
- Time-dependent observations to correct for binaries
  - e.g., Koposov et al., 2011, Walker et al., 2014,
- Chemical analysis of the stars to differentiate between dwarf galaxies and globular clusters
- Focussing on more isolated dwarf galaxies
  - Although here we have faintness limits
  - Also problems with modelling the rotation curves (see work Kyle Oman)
- Find extra-tidal stars to investigate if stripping is occurring

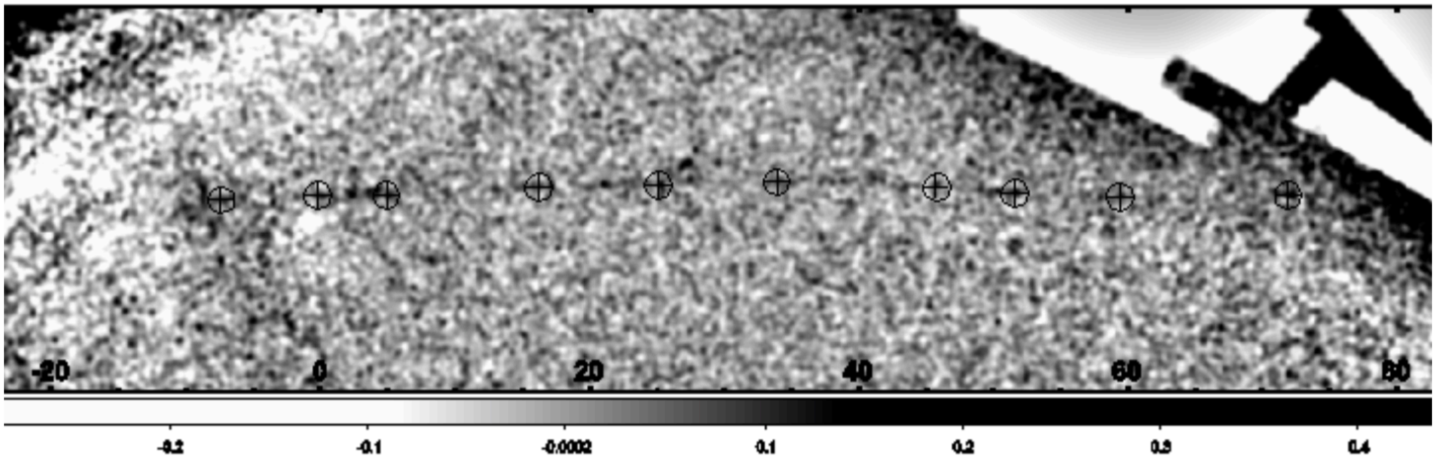
Figure 1: The estimated pre-infall mass of the Carina dwarf compared with predictions from cosmological simulations.



Ural et al., 2015

Other signatures of dark matter

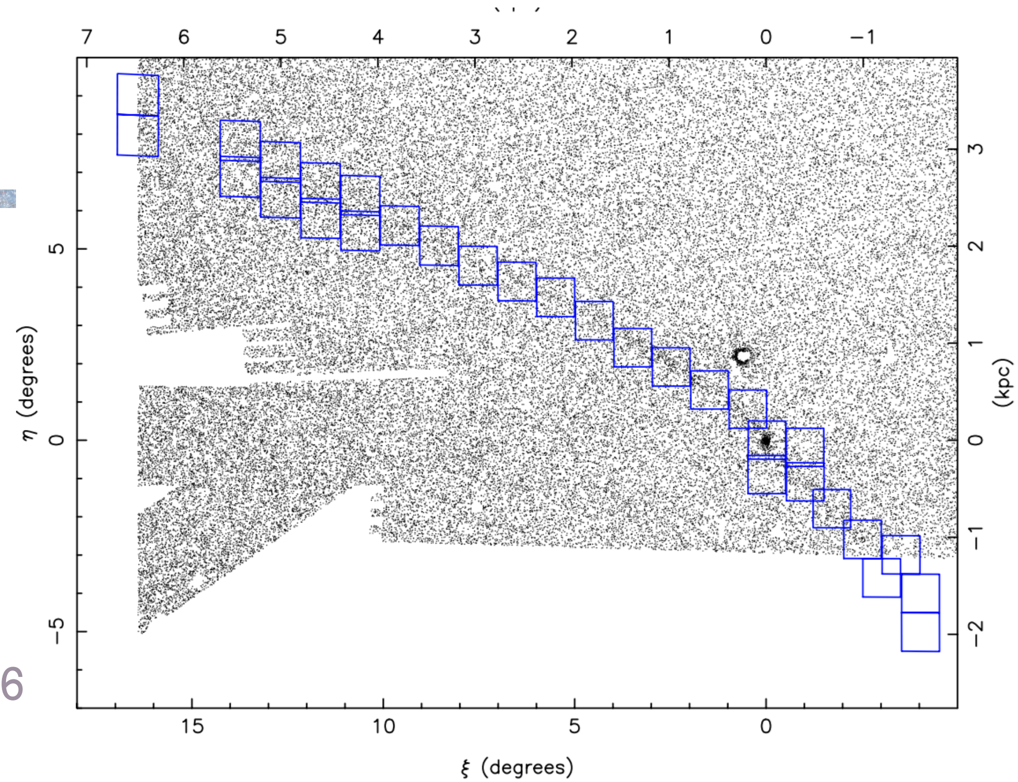
Dark matter haloes
& stellar streams



Courtesy: Ray Carlberg, GD1

- Detection of substructures with stellar streams
- Applied to a few streams today but has great potential
  - Carlberg, 2015: "Around one hundred velocity measurements per kiloparsec of stream will enable tests for the presence of a local sub-halo density as small as 0.2-0.5% of the local mass density, with about 1% predicted for 30 kiloparsec orbital radii streams."
  - See also Erkal et al., 2015

Dark matter haloes & stellar streams



Ibata et al., 2016

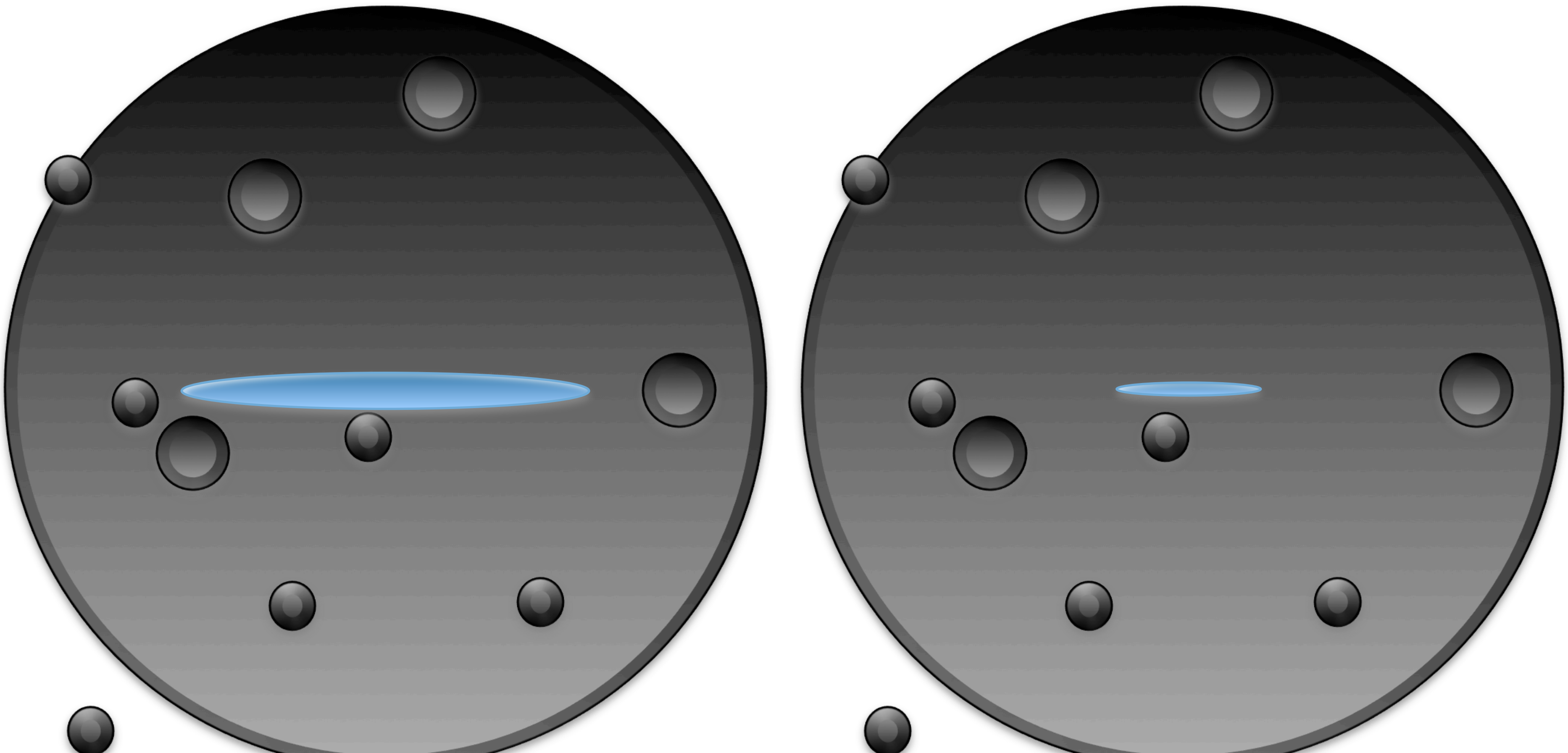
- Debate on whether this is visible on Palomar 5 stellar stream
  - Carlberg et al., 2012 sees gaps using SDSS data and a matched filter-map (giving more weight to certain types of stars)
  - Ibata et al., 2016 could not reproduce these results with narrow-band photometry from CFHT
    - They find the stream is actually very smooth

How can we make progress?

- Deeper photometry
  - S/N in GD1 is 2.3
- Adding velocities through spectroscopic data
- Add proper motions
  - Also to remove foreground

What can be the impact of dark satellites?

A. Helmi, L.V. Sales, E. Starkenburg, T.K. Starkenburg et al., ApJL, 2012

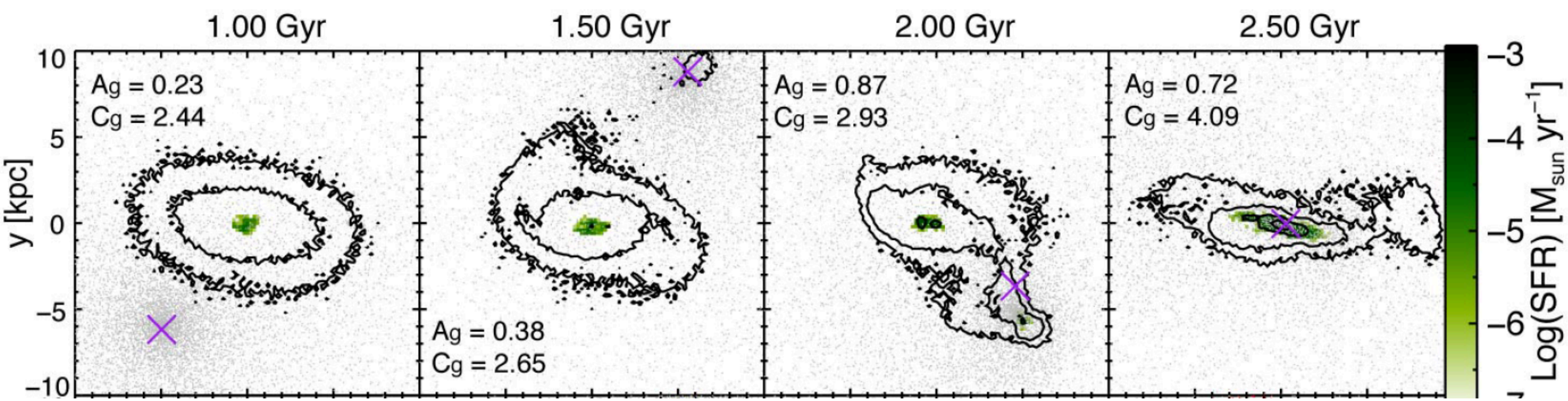


Milky Way-like:
Its disk doesn't care

Dwarf-like: has an impact with a dark halo as big as its disk ~1.5x in its life

What can be the impact of dark satellites?

Tjitske Starkenburg et al., 2016



- Small dark matter clump, not supposed to form any stars
  - Sweeps up gas and start forming stars in the merger event
  - In gas-poor mergers, the system becomes more spherical
- Avenues to progress
  - Theoretical understanding of how often this will happen and understanding unique signatures
  - Systematic observations of isolated dwarf systems

Current & future surveys

- Recap of our wish-list:
- Understanding tidal stripping, binary populations & foreground in dwarf spheroidal systems
  - Rotation curves in further away dwarf irregular systems
- Deeper photometry of the halo streams and dwarf galaxy systems
- Lots of spectroscopy to determine velocities
  - Of outer halo tracers
  - Of stellar streams & galaxies (weed out contamination)
- Proper motions

Photometry efforts:

- PanSTARRS1: SDSS-like, but a bit deeper and with 3π coverage
  - Also scans everything multiple times, so variable stars can be flagged
  - First data release "soon"!

- In the future: LSST

- Smaller targeted surveys
  - "Solo dwarfs" survey of isolated dwarf systems in the Local Group (Higgs et al., 2016)

Metallicity-sensitive surveys

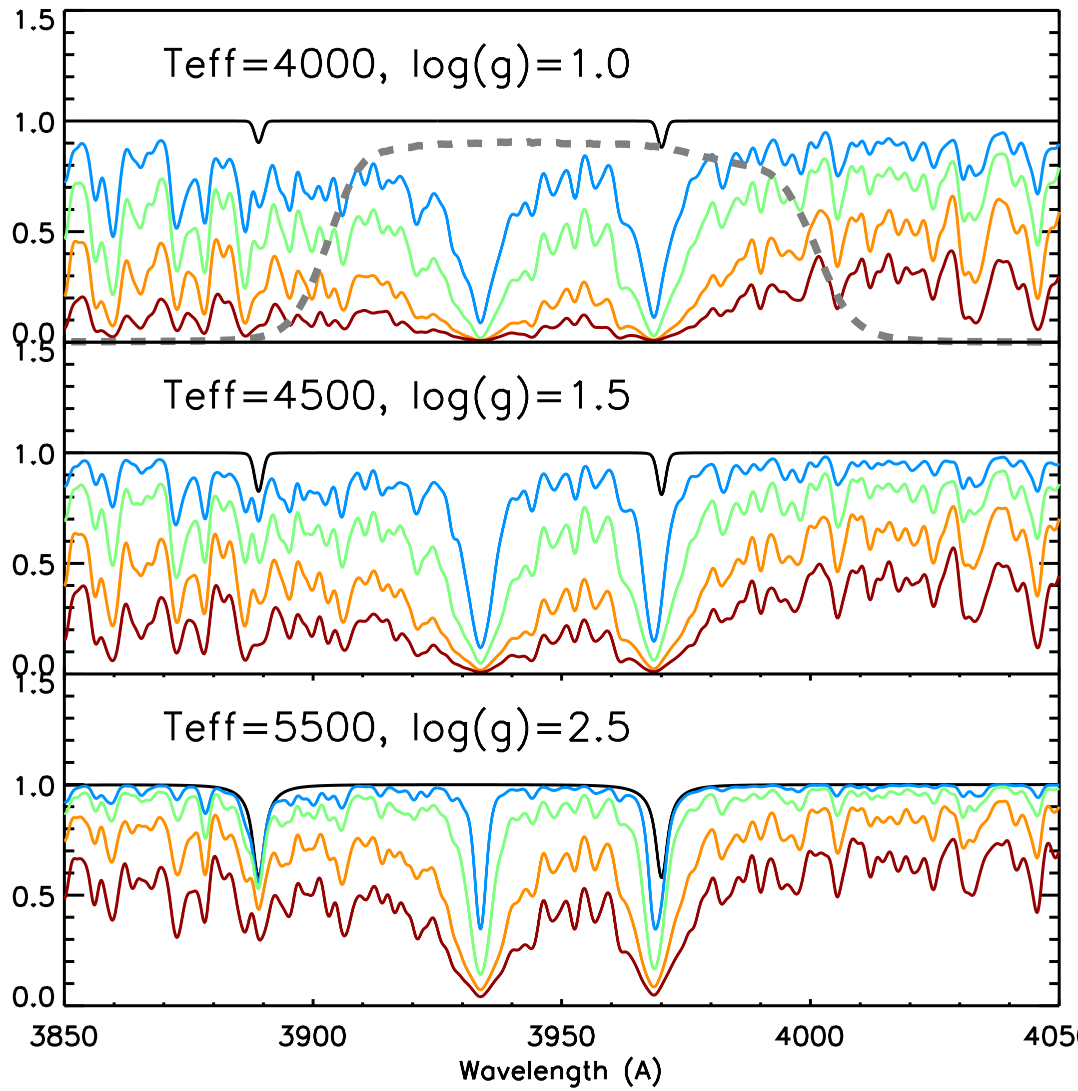
- Metallicity-sensitive photometry can really help to efficiently find stripped material from existing substructures
  - Trace the stripping of dwarf galaxies
  - Also new dimension in substructure searches

- Many planned/ongoing surveys are mapping the Galaxy
  - "Pristine" in the Northern Hemisphere
  - In the Southern Hemisphere: SkyMapper
  - Complementary in the Northern Hemisphere: the LUAU survey
    - Deep u-band photometry
  - APASS (multi-narrow-band)
  - Gaia spectrophotometry

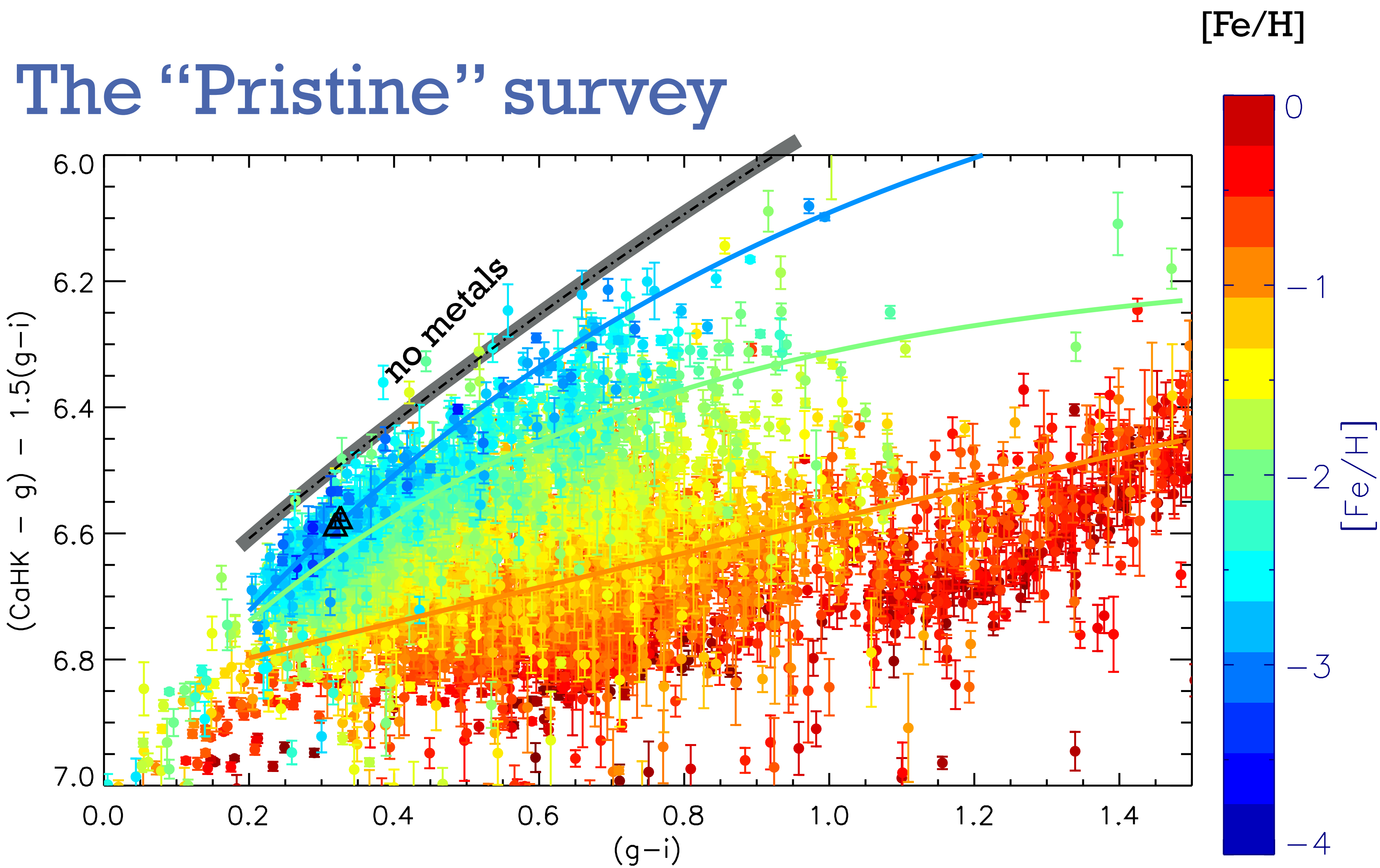
Using narrow-band photometry

- The "Pristine" survey
  - Find metal-poor stars and finally uncover statistical samples in the halo and surrounding dwarf galaxies
  - CFHT – 4m, 1° fov
  - Currently >600 deg^2
  - +1000 deg^2

[Fe/H] = –∞
[Fe/H] = –3.0
[Fe/H] = –2.0
[Fe/H] = –1.0
[Fe/H] = +0.0

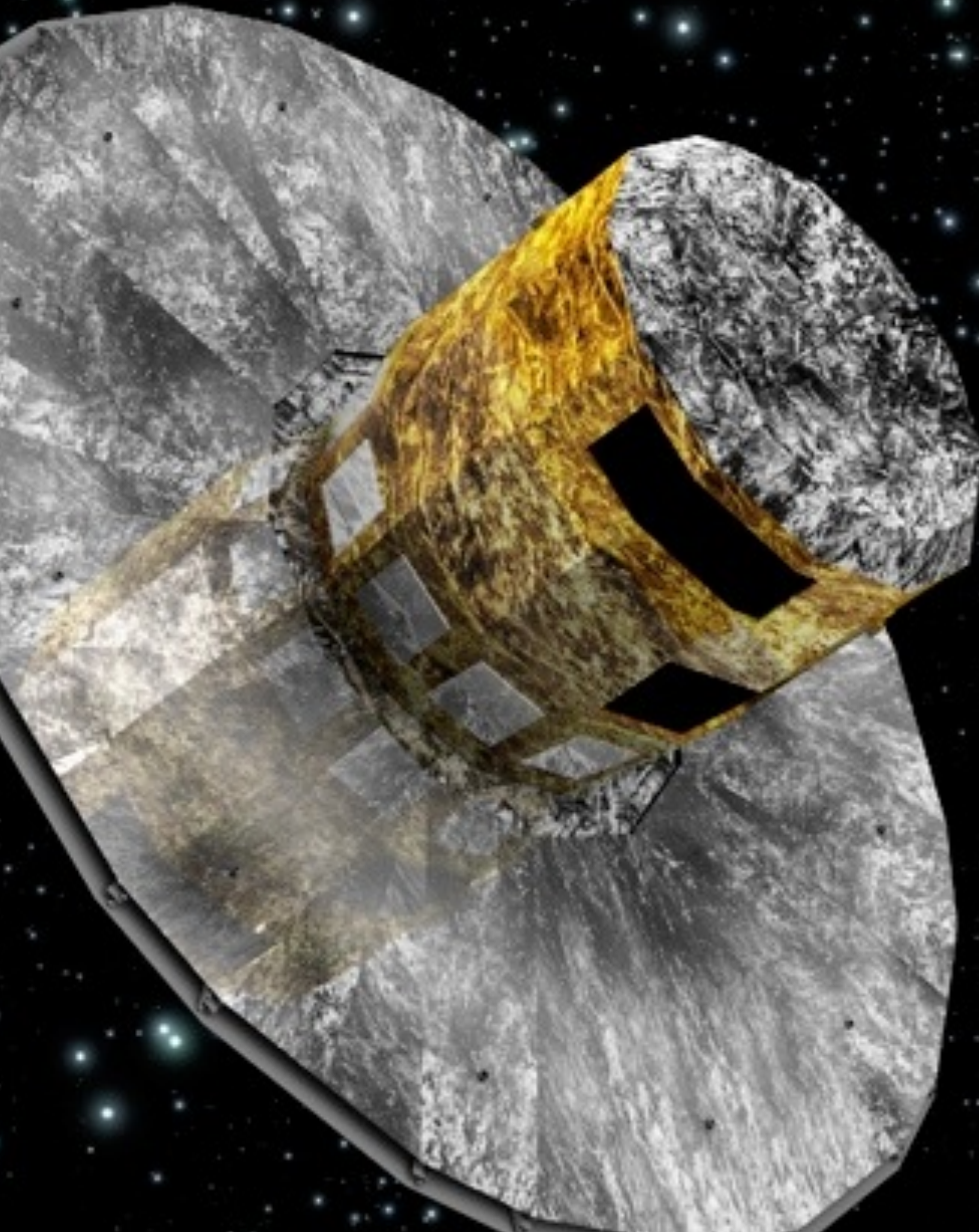


The "Pristine" survey



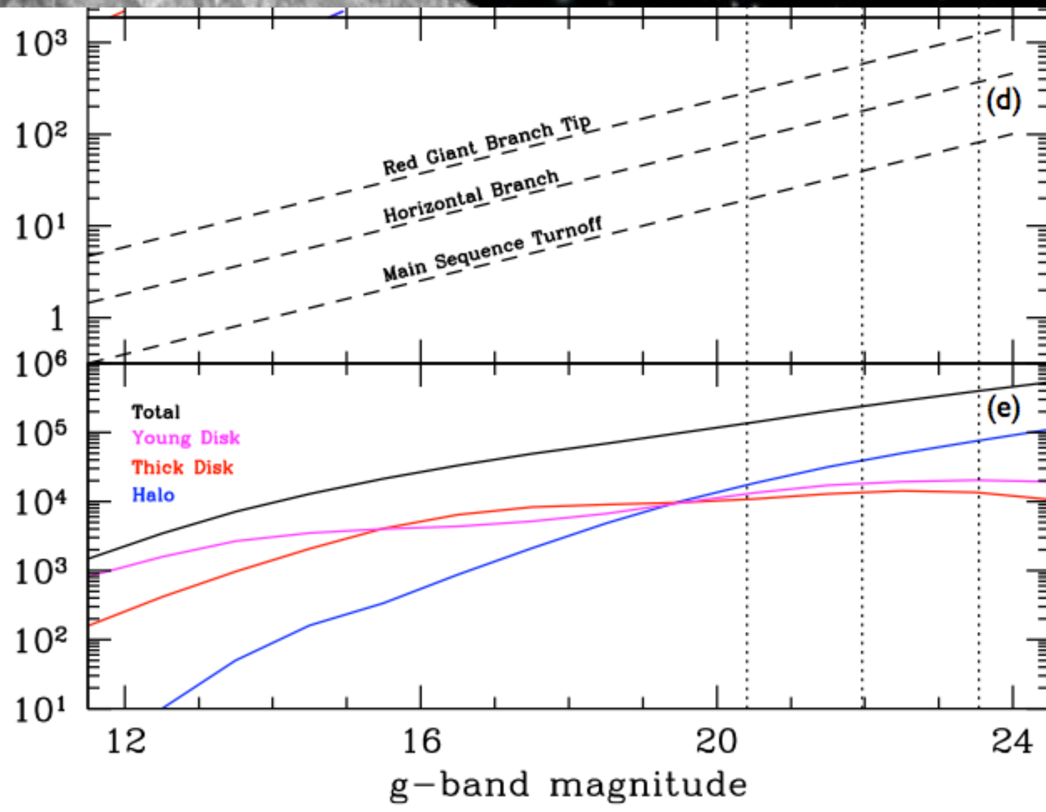
PIs: Else Starkenburg & Nicolas Martin. Co-Is: Piercarlo Bonifacio, Elisabetta Caffau, Raymond Carlberg, Patrick Cote, Patrick Francois, Stephen Gwyn, Vanessa Hill, Rodrigo Ibata, Pascale Jablonka, Julio Navarro, Alan McConnachie, Ruben Sanchez-Janssen, Kim Venn, Kris Youakim

The Future is Now



- Gaia will obtain proper motions and parallaxes for all objects to G=20, radial velocities to G~15-16, and abundances to G~12
- Multiple 4m MOS instruments will complement Gaia by obtaining radial velocities and chemical abundance information for stars in the nearby Galaxy (e.g., HERMES, WEAVE, 4MOST)

The Future is Now



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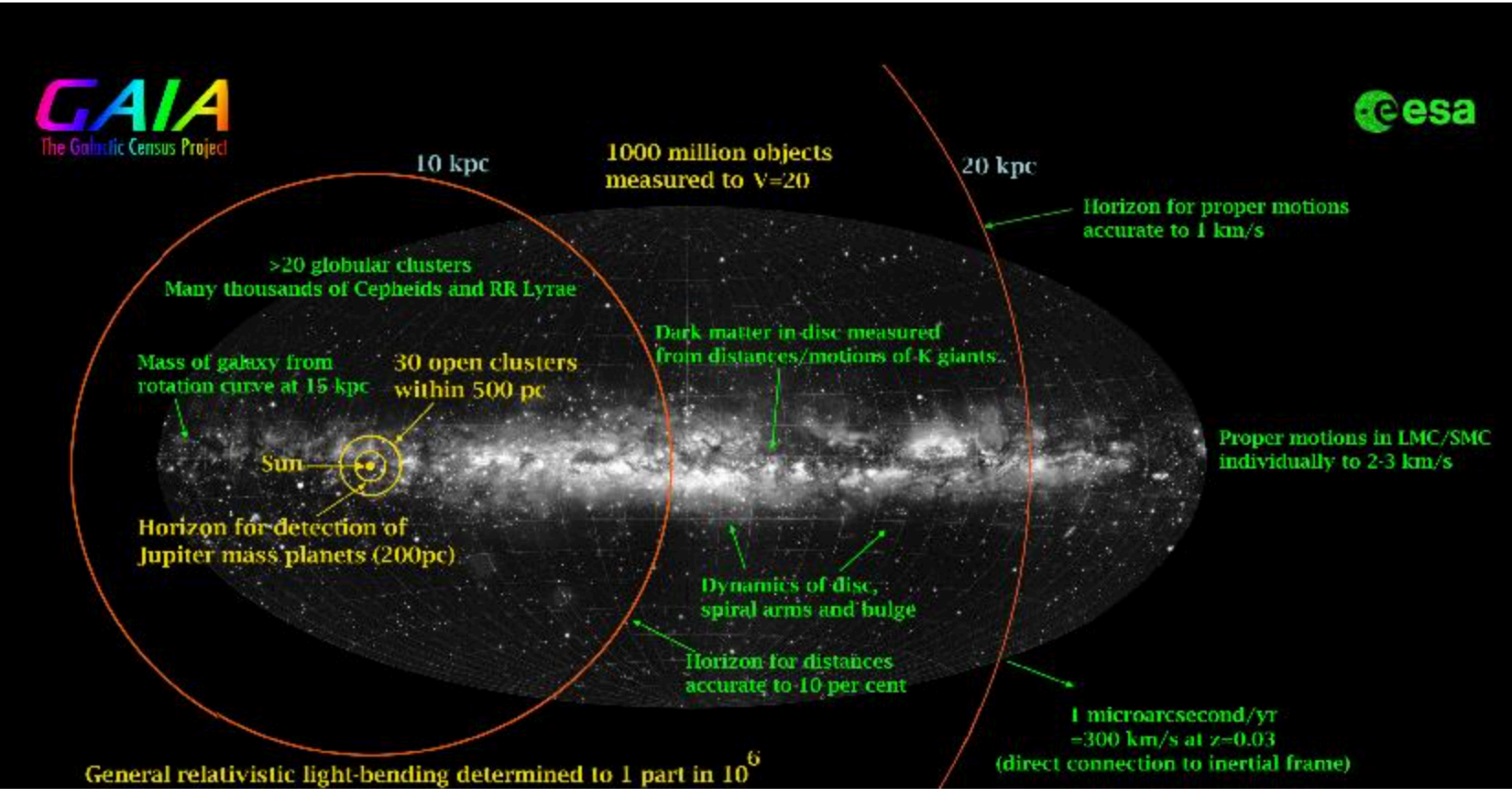
Gaia data

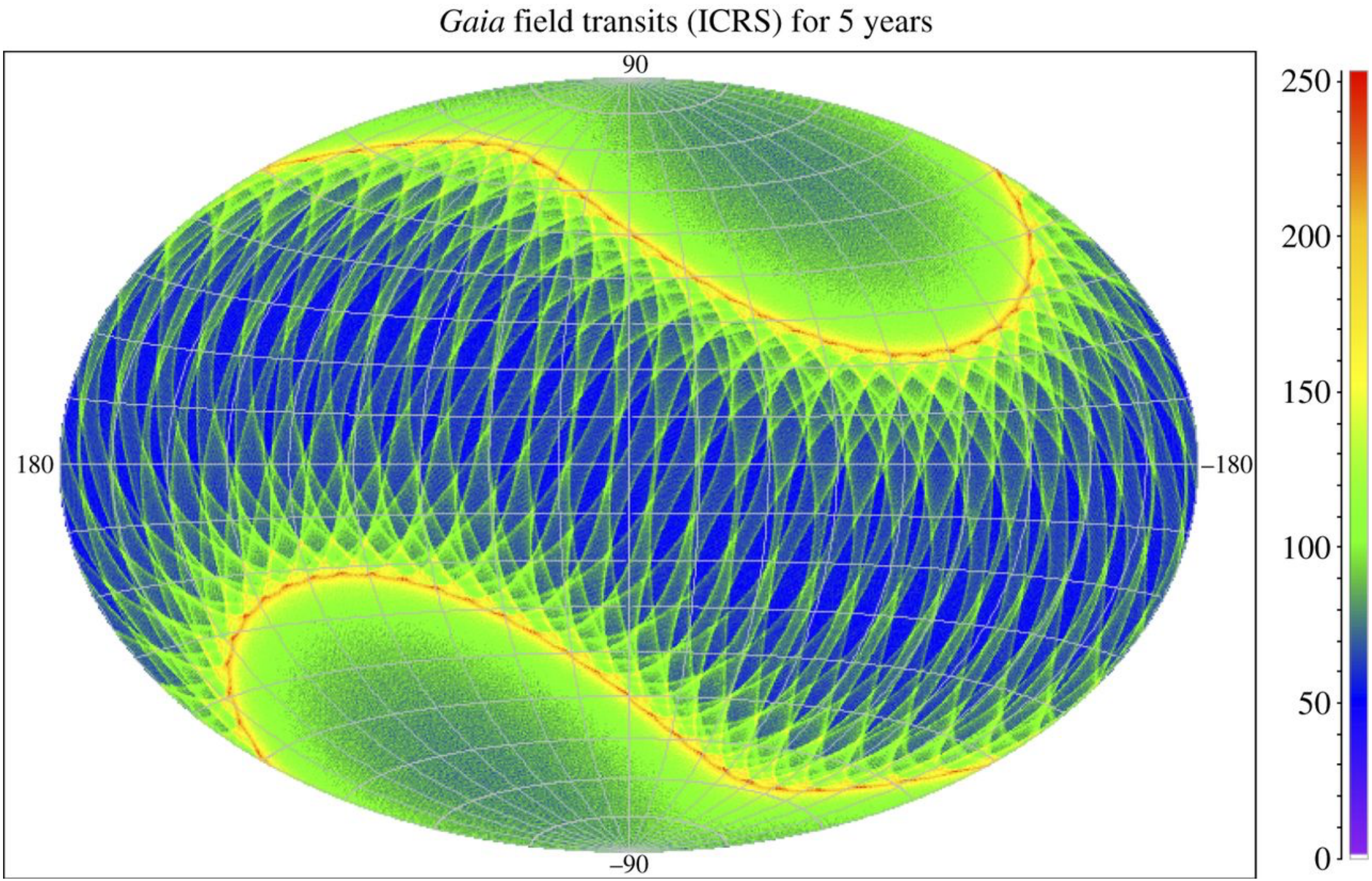

GAIA
The Galactic Census Project
esa
10 kpc
1000 million objects
measured to V=20
20 kpc
Horizon for proper motions
accurate to 1 km/s
>20 globular clusters
Many thousands of Cepheids and RR Lyrae
Dark matter in disc measured
from distances/motions of K giants
Mass of galaxy from
rotation curve at 15 kpc
30 open clusters
within 500 pc
Sun
Proper motions in LMC/SMC
individually to 2-3 km/s
Horizon for detection of
Jupiter mass planets (200pc)
Dynamics of disc,
spiral arms and bulge
Horizon for distances
accurate to 10 per cent
1 microarcsecond/yr
=300 km/s at z=0.03
(direct connection to inertial frame)
General relativistic light-bending determined to 1 part in 10^6

Gaia time line

- "End of summer"
  - First public data release
  - Positions and (G)magnitudes for all single stars
  - Proper motions and parallaxes for selected bright stars overlapping with the Tycho catalogue
  - Variables in some special fields

- Spring/summer 2017
  - First data release containing proper motions for all stars
  - Updated until end of mission after 5 years

Gaia scanning



Spectroscopy in the future

- Follow-up for Gaia:
  - The missing radial velocity component
  - Chemistry
- Many projects with hundreds of fibers:
- WEAVE – on the 4m William Herschel Telescope on La Palma (Spain)
  - Surveys to begin 2018
    - Resolving power: ~5000 & ~20,000
    - Kinematics & chemistry
- HERMES:
  - Already started
  - Mainly focussing on the disc of the Galaxy
  - Bright & high-resolution
- PSF:
  - On Subaru
  - Only medium-resolution mode

Spectroscopy in the future

- 4MOST – 4 Metre Multi-Object Spectroscopic Telescope (on ESO's VISTA)
  - 4 Galactic surveys to begin 2021
  - + 4 extra-galactic surveys
    - My role: co-PI of the low-resolution bulge & disk survey
    - Largest follow-up survey of Gaia (2400 fibers)
    - Resolving power: ~5000 & ~20,000
    - Kinematics, but many elemental abundances too

- Maunakea Spectroscopic Explorer

- Transforming CFHT on Mauna Kea into 10-meter class wide-field *dedicated* spectrograph by 2025
  - Project office funded/studies underway

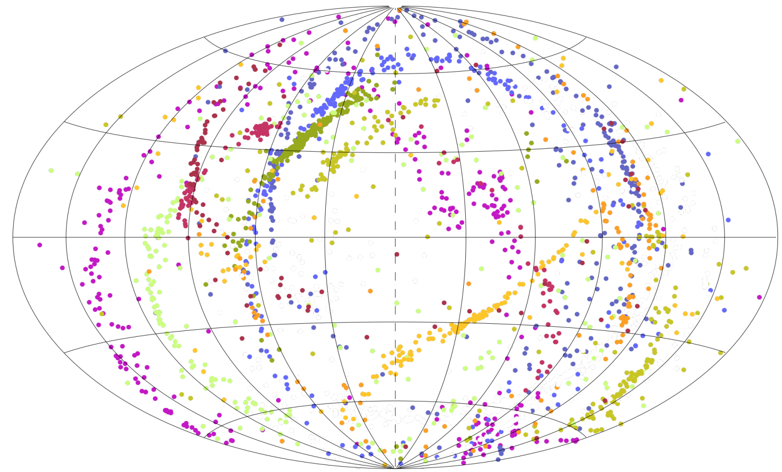
Spectroscopy in the future

- MOONS
  - Near-infrared (Apt to study the inner Galaxy)
  - 2019 on ESO-VLT
  - High-resolution and medium resolution mode
  - ~1000 fibers

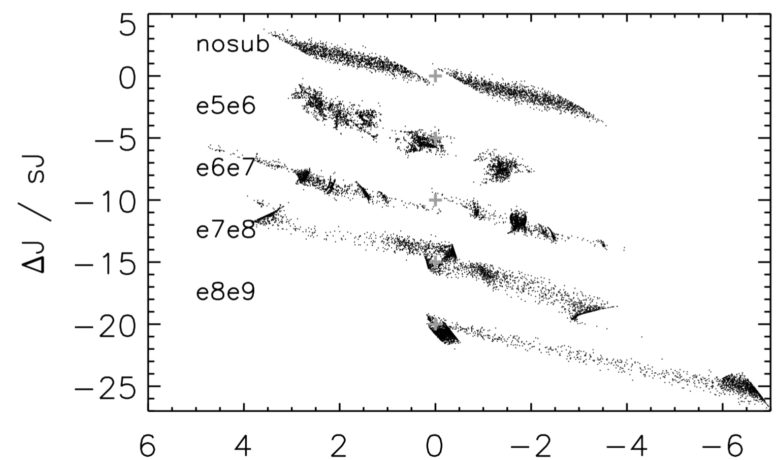
http://www.roe.ac.uk/~ciras/MOONS/VLT-MOONS.html

Goals: Milky Way dynamics

- Determine the Milky Way 3D potential from local streams up to ~100kpc
  - How is DM reacting to baryons:
    - has there been significant adiabatic contraction?
    - is there a disk-like DM component?
    - does the DM respond to the bar?
  - Determine the mass spectrum of Dark Matter 10^3–10^5 $M_\odot$ halo substructure by the kinematic effects on cold stellar streams



Cooper+ (2010)



Yoon+ (2011)

Conclusions

- Exciting times!
- ESA-Gaia is a game-changer
- The follow-up spectroscopy surveys are underway
  - We will have a 6D view on our Galaxy like never before – opening up many new possibilities
    - 7-D or more, with metallicity information, or chemical abundances