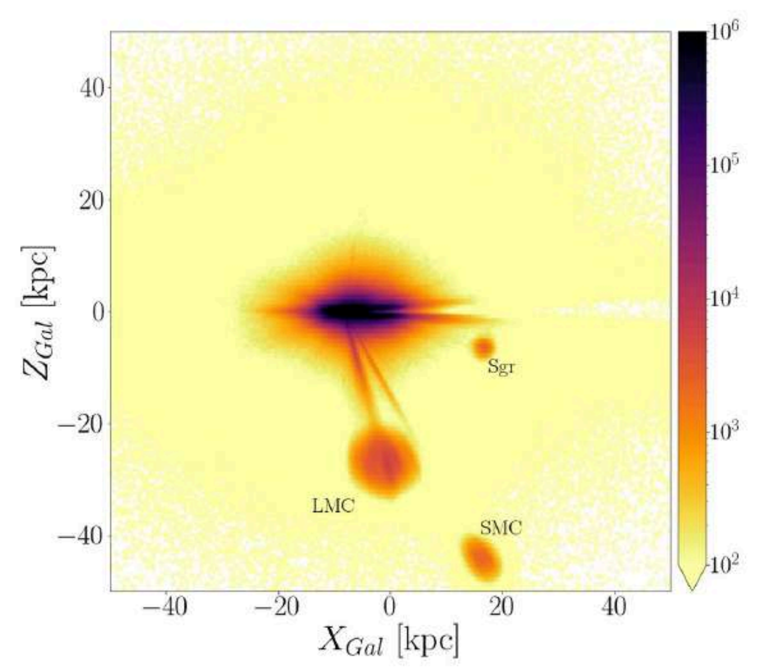
Leibniz-Institut für Astrophysik Potsdam

Constraints on the mass of and the mass distribution in the Milky Way system based on Gaia and massive spectroscopy



Matthias Steinmetz

Leibniz-Institut für Astrophysik Potsdam (AIP)

Discussion points

- Dark mass distribution in Milky Way before Gaia
- Dark mass distribution in Milky Way after Gaia
- Dealing with the frisky Milky Way disk
- Mass distribution in the Milky Way satellites with Gaia and MUSE
- Bounds on ALP dark matter from MUSE

Dark mass distribution in Milky Way before Gaia

@concelice

The simple (simplistic?) model

- Two main observational constraints:
  - Circular velocity at the solar circle: 220-240 km/s
  - Flat, at large radii DM dominated rotation curve (assuming the MW behaves like other galaxies)
- Simple model: characteristic timescale: $\tau_{\rm dyn} = \frac{2\pi r_{\rm vir}}{v_{\rm circ}} = \tau_{\rm Hubble} = \zeta H^{-1}$

$$
\begin{aligned}
r_{\rm vir} &= \frac{v_c H^{-1}}{2\pi}\zeta \\
&= 106 h^{-1}\mathrm{kpc}\left(\frac{v_c}{100\mathrm{km/s}}\right)\left(\frac{H_0}{H(z)}\right)\left(\frac{3\zeta}{2}\right) \\
M_{\rm vir} &= \frac{1}{G} v_c^2\, r_{vir} = \frac{\zeta}{2\pi G\, H} v_c^3 \\
&= 2.47\times 10^{11} h^{-1}\,\mathrm{M}_\odot \left(\frac{v_c}{100\mathrm{km/s}}\right)^3\left(\frac{H_0}{H(z)}\right)\left(\frac{3\zeta}{2}\right)
\end{aligned}
$$

Where we come from ...

For the reasons discussed above, we consider our most precise and robust estimate for the distribution of B_{200} to be that obtained for host galaxies with $150\,\mathrm{km\,s^{-1}} \leqslant V_{max}(\mathrm{host}) < 300\,\mathrm{km\,s^{-1}}$ and with no morphology cut. The median of this distribution then gives our best estimate of the true halo mass of the Milky Way:

$$M_{200,MW} = 2.43 \times 10^{12}\,\mathrm{M_\odot}\,, \qquad (9)$$

or $\log M_{200}/M_\odot = 12.39$. The quartiles of the distribution imply $[12.25, 12.49]$ for the most probable range of this quantity, while the 5% point implies a lower limit of 11.90 at 95% confidence. Thus the implied mass of the Milky Way is roughly half that of the Local Group as a whole, as might be expected on the basis of the similarity of the two giant galaxies. It is quite similar to other recent estimates based on applying equilibrium dynamics to the system of distant Milky Way satellites and halo stars (e.g. Wilkinson & Evans 1999; Sakamoto, Chiba & Beers 2003). A significantly smaller estimate came from the analysis of the high-velocity tail of the local stellar population by Smith et al. (2007), but we note that such analyses, in reality, only place a lower limit on the mass of the halo, since the distribution of solar neighbourhood stars may well be truncated at energies significantly below the escape energy.

- Until ~2010: A total mass of $2-2.5\times10^{12}\mathrm{M_\odot}$ was a commonly adopted value for the Galaxy + halo.
- Navarro & MS 2001, Abadi et al 2010: Such high halo mass may be difficult to bring into agreement with the local dynamics of the Milky Way disk, in particular if adiabatic contraction is of relevance ⇒ rotation speed at the solar circle would be too high

Li & White (2008)

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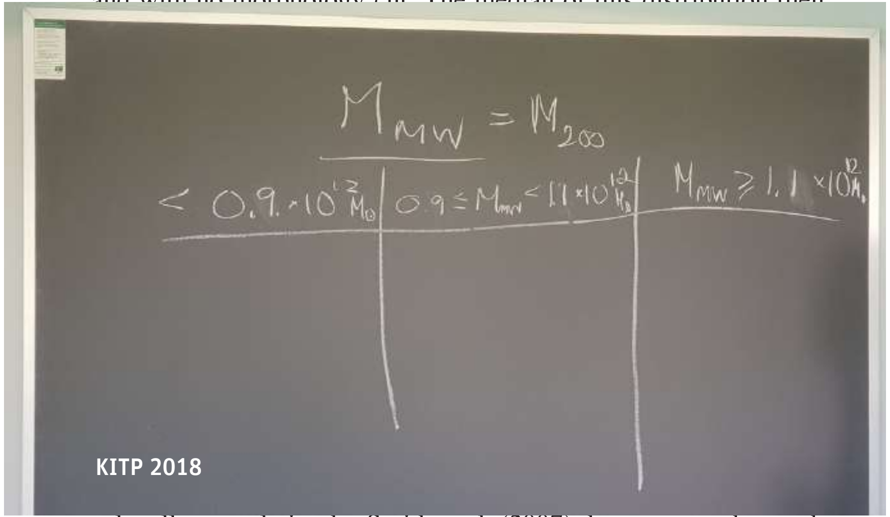

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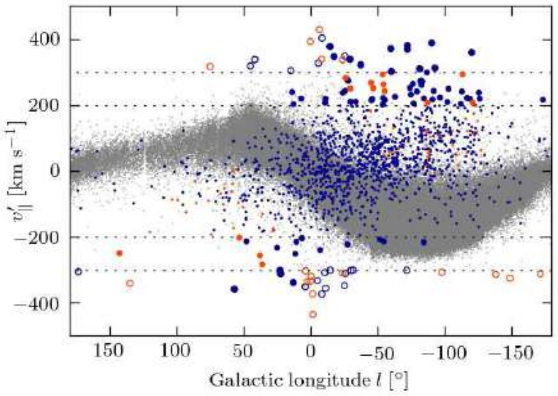
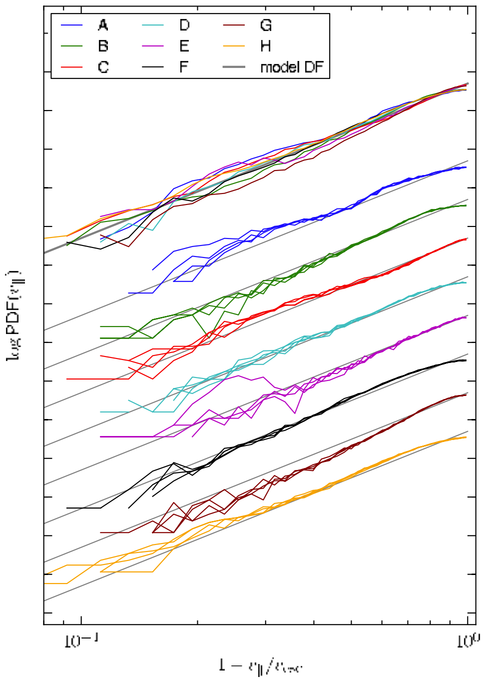
Li & White (2008)

Escape speed of the Milky Way at the Solar Circle

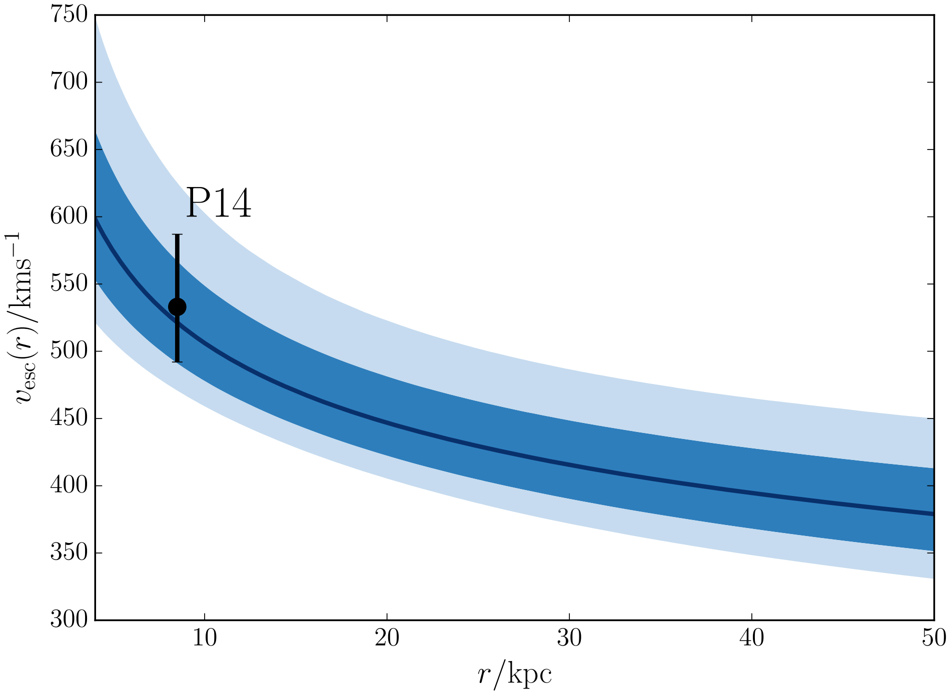
- Leonard & Tremaine (1990):
  - consider distribution function f(E)
  - f → 0 as E → $\Phi(r_{vir}) \Rightarrow n(v) \propto (v_{esc}-v)^k$
- k-dependence verified via simulations
- Measure distribution $n(v_{\parallel})$ for high-velocity RAVE stars on counterrotating orbits
- note: strictly only a lower limit on M_{vir}
- Smith + RAVE (2007): 498km/s < v_{esc} < 608km/s
  $1.1\times10^{12} M_\odot$ < Mvir < $2.1\times10^{12} M_\odot$
- Piffl + RAVE (2014): 492km/s < v_{esc} < 587km/s
  $1.2\times10^{12} M_\odot$ < Mvir < $2.1\times10^{12} M_\odot$





Escape velocity out to 50kpc using SDSS

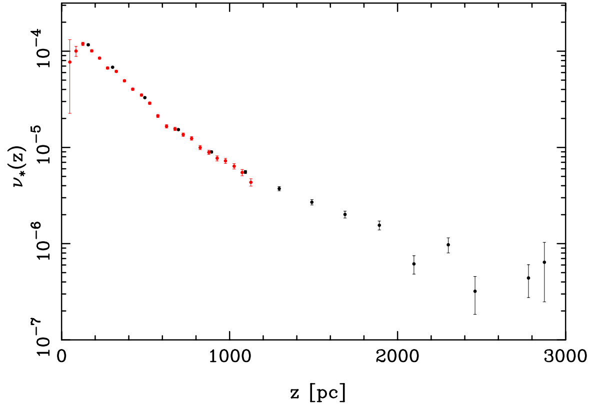
- fairly rapid decline to 376km/s at 50kpc

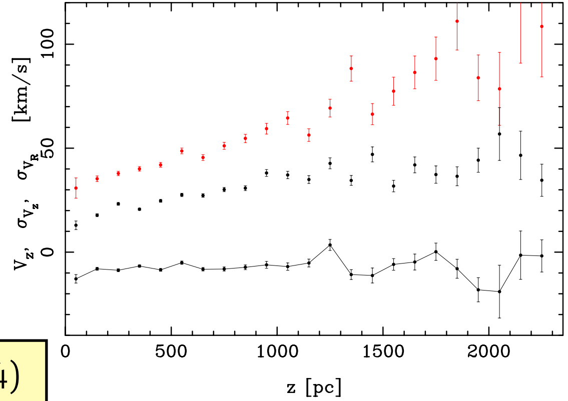


Williams et al. (2017)

Determining the local density by the K_z force

- basically following the idea of Oort in the 1930s
- Take a sample of stars in a towards the Galactic Poles up to a certain distance from the Galactic Plane.
- subset of red clump stars gives good distances.
- Change in kinematics with vertical distances gives total vertical force (in simplest approximation proportional to surface density)
- number counts of stars gives baryonic mass distribution



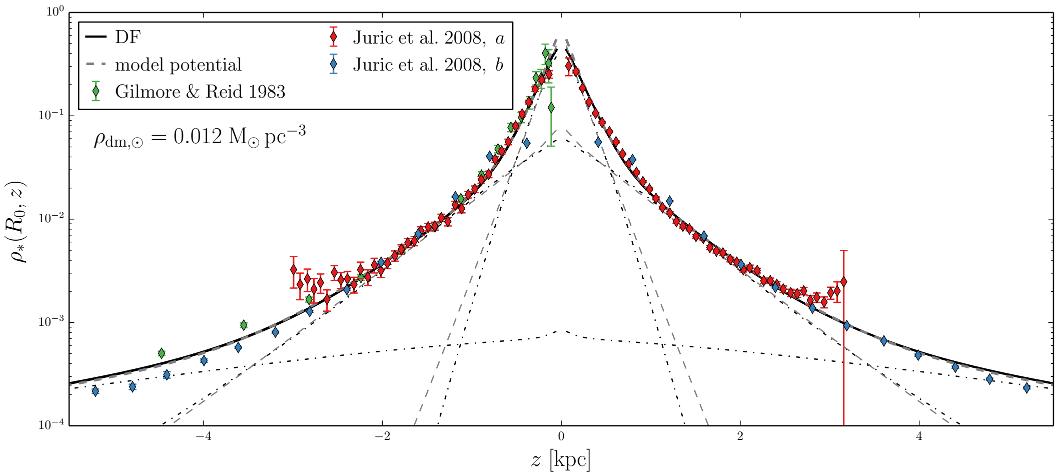


$$\varrho_{\rm DM} \approx 0.54\,\mathrm{GeV\,cm^{-3}}$$

Bienaymé et al. (2014)

Parameters from Galaxy models

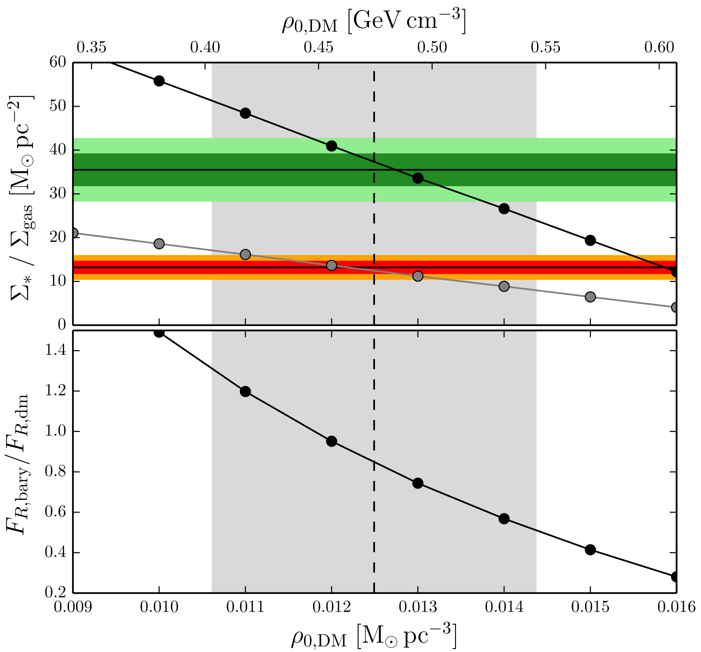
- Mass Model:
  - three exponential disks
  - flattened bulge
  - NFW dark matter halo

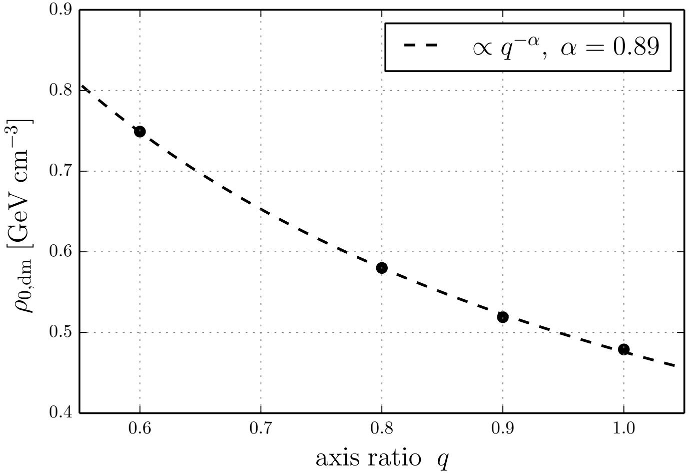


- Binney 2012 model for kinematics (incl. stellar halo)
- Model fit to vertical RAVE data
- see e.g. Bovy & Rix 2013, Piffl et al 2014, McMillan 2016

Parameters from Galaxy models

Piffl et al. (2014)





$$\varrho_{\mathrm{DM}} = 0.0126 \times q^{-0.89} \mathrm{M}_\odot \, \mathrm{pc}^{-3} \pm 10\%$$

$$\Sigma_{\mathrm{tot}}(< 0.9\mathrm{kpc}) = 69 \pm 10 \, \mathrm{M}_\odot \, \mathrm{pc}^{-2}$$

$$M_{\mathrm{DM}}(< R_0) = (6.0 \pm 0.9) \times 10^{10} \, \mathrm{M}_\odot$$

$$M_{\mathrm{vir}} = (1.3 \pm 0.1) \times 10^{12} \, \mathrm{M}_\odot$$

- 46% of the radial force acting on the Sun provided by baryons

Local mass densities in solar neighborhood (pre Gaia)

- Total surface density within z=±1kpc:

$$\Sigma_{tot} = 70\,\mathrm{M_\odot\,pc^{-2}} \pm 10\,\%$$

- Most studies find for the (3D) local DM density:

$$\varrho_{DM} \approx 0.01\mathrm{M_\odot\,pc^{-3}} \approx 0.38\,\mathrm{GeV\,cm^{-3}}$$

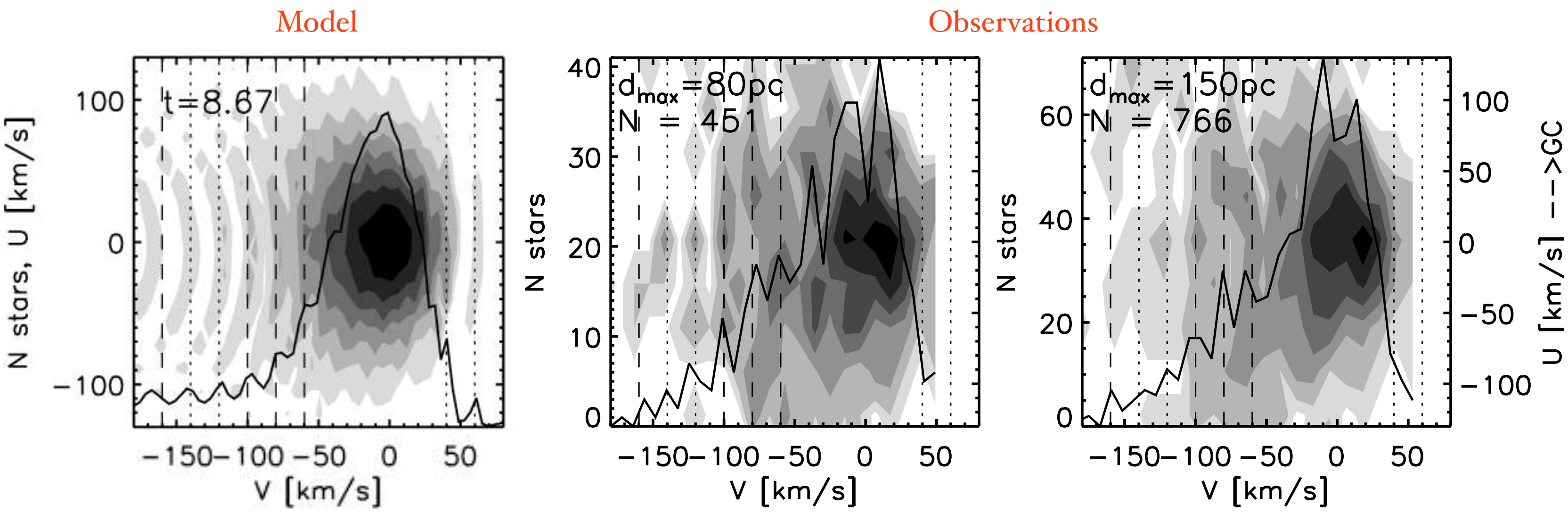
(e.g. Bovy & Rix 2013, Piffl et al 2014, McMillan 2016), also consistent with rotation curve analysis (McGaugh 2016))

- Bienaymé et al (2014) with RAVE find somewhat higher values:

$$\varrho_{DM} \approx 0.54\,\mathrm{GeV\,cm^{-3}}$$

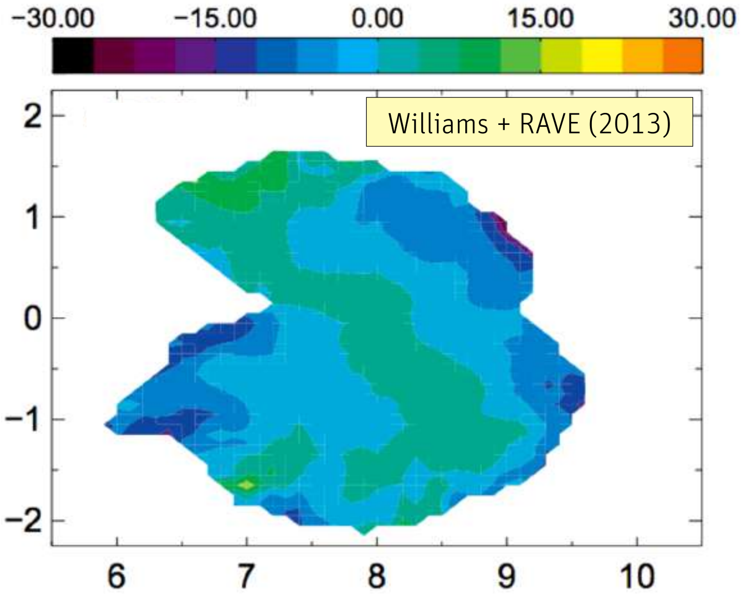
- DM contribution depends on the assumption for the local stellar distribution.

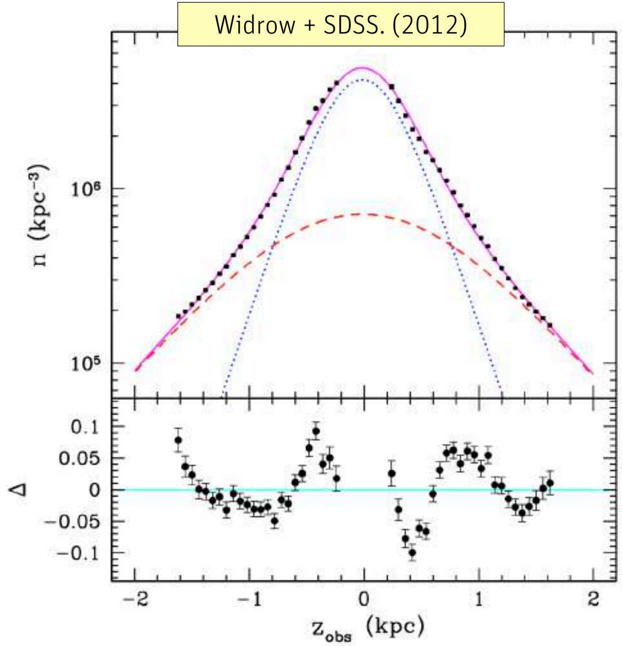
Is the Milky Way ringing?



- Michev et al. (2009): Prediction for a merger 1.9 Gyr ago

Vertical Waves in the disk found in RAVE+SDSS data





- possible origin: interaction with dwarf galaxy (Sagittarius dwarf)

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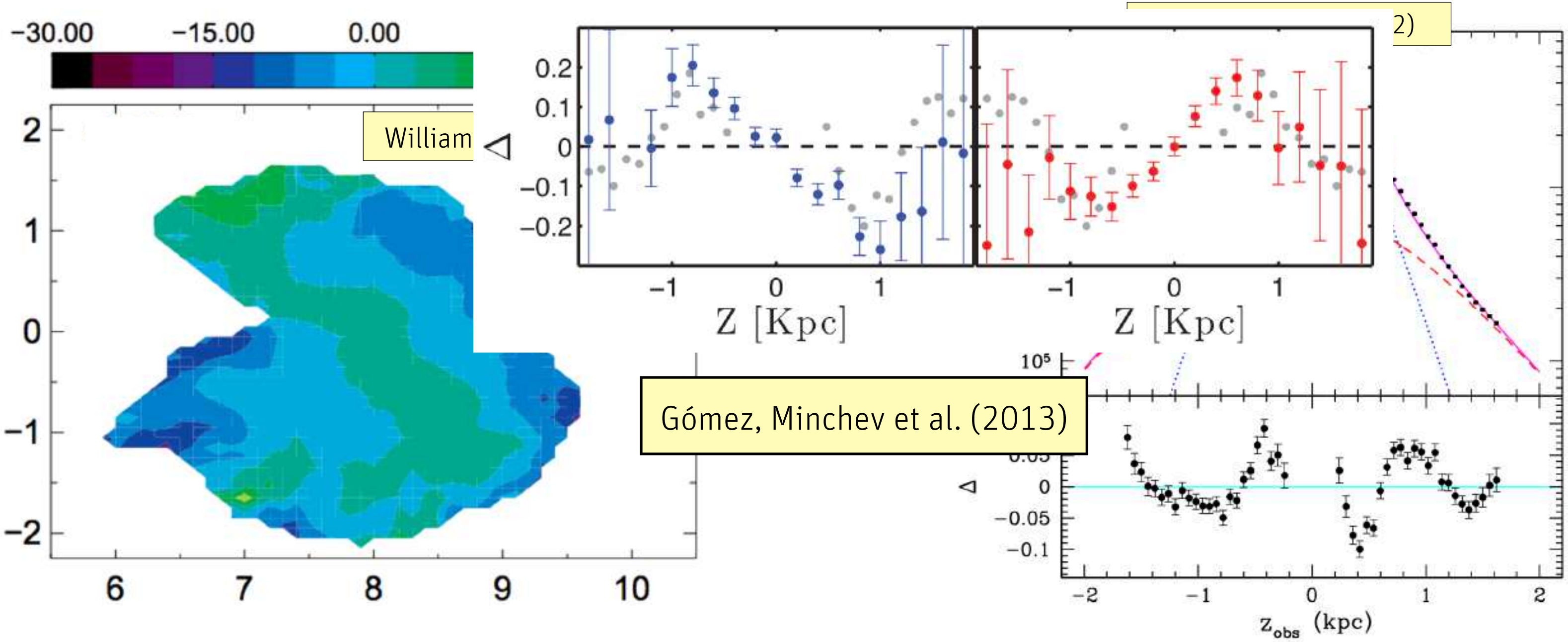

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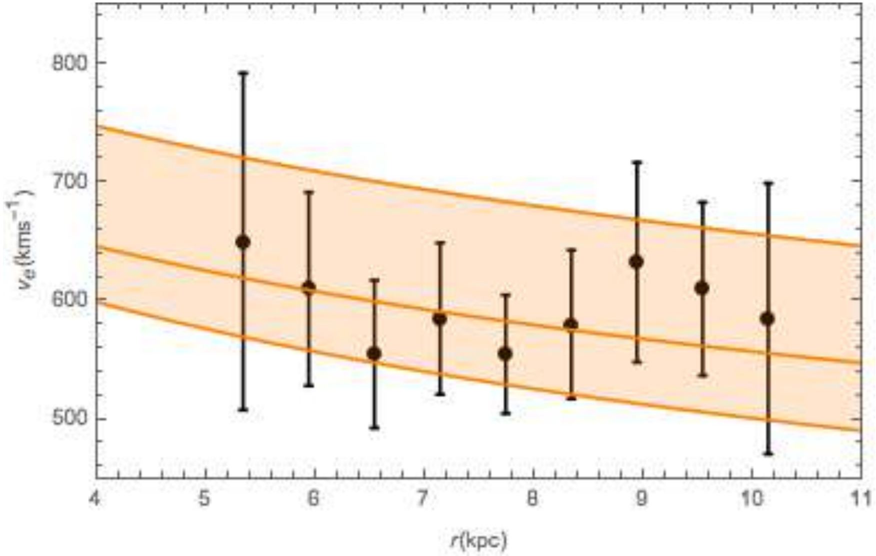
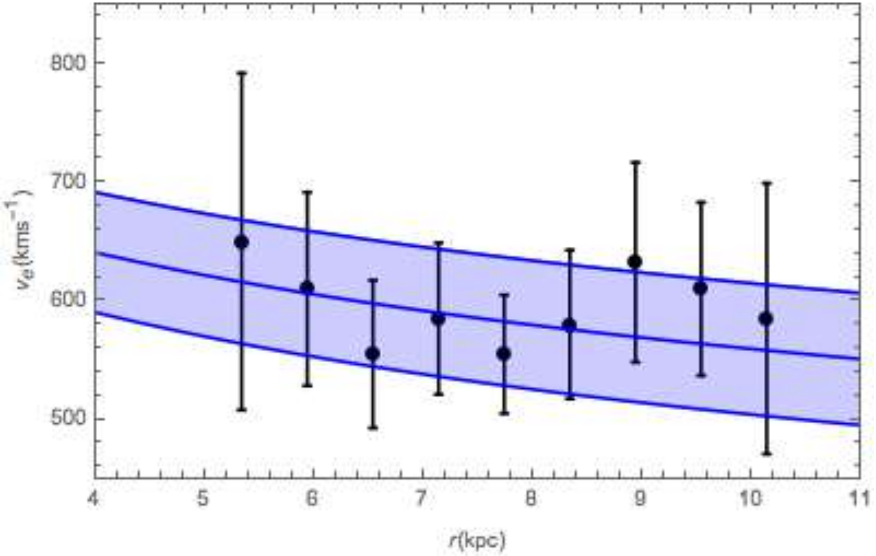
Dark mass distribution in Milky Way after Gaia

Escape velocity with Gaia DR2

Monari et al. (2018)





$v_c = 240\,\mathrm{km/s}$

$$M_{\mathrm{MW}} = 1.28^{+0.68}_{-0.50} \times 10^{12}\,\mathrm{M}_\odot$$

$v_c = 228\,\mathrm{km/s}$

$$M_{\mathrm{MW}} = 1.55^{+0.64}_{-0.51} \times 10^{12}\,\mathrm{M}_\odot$$

Local mass densities in solar neighborhood

- Hagen & Helmi (2018) with RAVE+TGAS find somewhat higher values for local DM density $\varrho_{\rm DM} \approx 0.69$ GeV cm^{-3} but use a smaller scale height for the thin disk of 0.27kpc (with 0.31kpc as in McMillan they would get 0.46 GeV pc^{-3})
- Eilers et al (2019) with APOGEE + GaiaDR2 find somewhat lower values: $\varrho_{\rm DM} \approx 0.30$ GeV cm^{-3}, non-local model
- Eilers results are indicative of a comparably low total DM mass ($\approx 7.5 \times 10^{11} M_\odot$)

Milky Way mass from 3D orbits of MW satellites

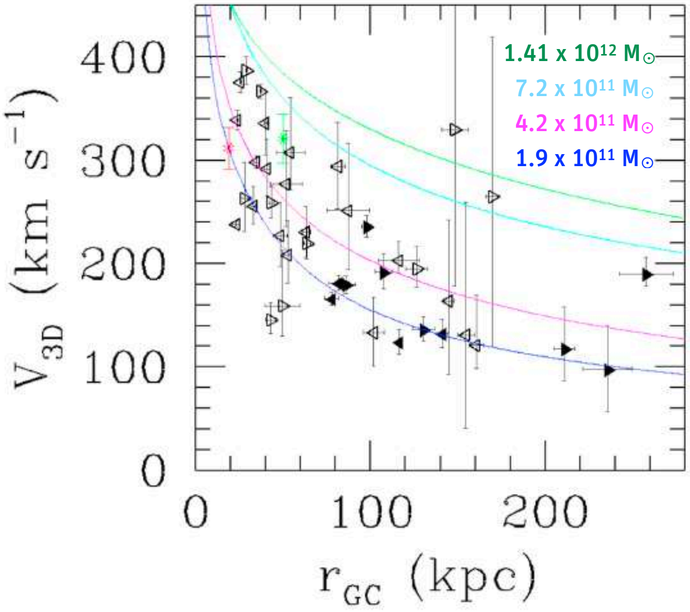
- proper motions from HST, VISTA, and (of course) Gaia DR2
- Patel et al (2018) find
  - $M_{MW} = (0.85 \pm 0.25) \times 10^{12}\ M_\odot$ (Sag Dwarf included)
  - $M_{MW} = (0.96 \pm 0.3) \times 10^{12}\ M_\odot$ (Sag Dwarf excluded)
  - high speed satellites set lower mass limit, low speed satellites higher upper mass limit
- However, HST proper motion of globular clusters (Sohn et al 2018, Watkins et al 2018) lead to a fairly high mass
  - $M_{MW} = (1.87\ \text{-}\ 0.5/\text{+}0.7) \times 10^{12}\ M_\odot$ based on HST PM
  - $M_{MW} = (1.41\ \text{-}\ 0.5/\text{+}2$[!]$) \times 10^{12}\ M_\odot$ based on GaiaDR2 PM
  - $M_{MW} = (1.67\ \text{-}\ 0.5/\text{+}0.8) \times 10^{12}\ M_\odot$ based on GaiaDR2 + HST PM
- mass estimates from local group timing also came down considerably (e.g. van der Marel, Peñarrubia)
- Mass estimates in general considerably smaller than 10 yrs ago, but M_* remained basically unchanged!
- Kafle et al 2018: compare mass estimates derived from sims: difficult to get better than 15%

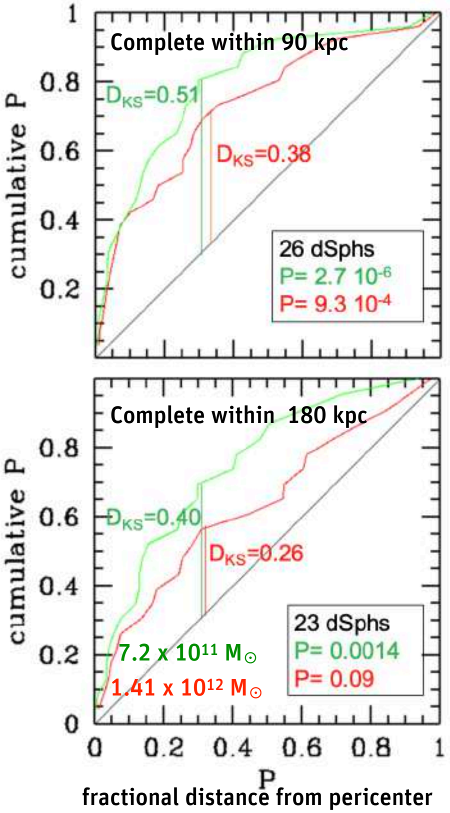
Milky Way Satellites: Mass and Orbits

Gaia EDR3 proper motions for ~50 nearby dwarfs

Li et al. (2021, ApJ, 916, 8), but see also Battaglia et al. (2021), McConnachie & Venn (2020).

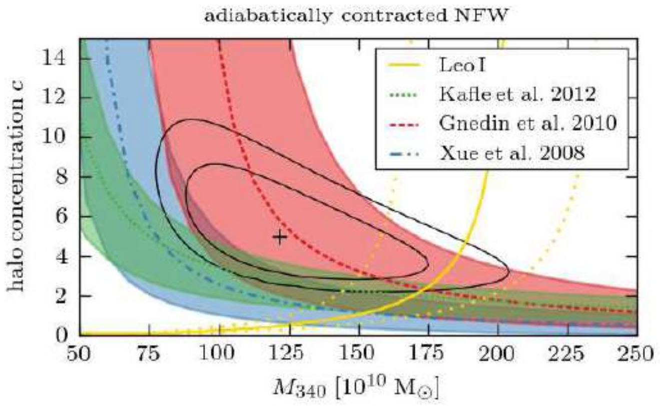
- Requiring most satellites to be bound to MW implies its DM halo is consistent with relatively low mass (~ 7 x 10^{11} $M_\odot$).
- Too many dwarfs are close to their pericenters, would expect the opposite (see also Fritz et al. 2018 for Gaia DR2).

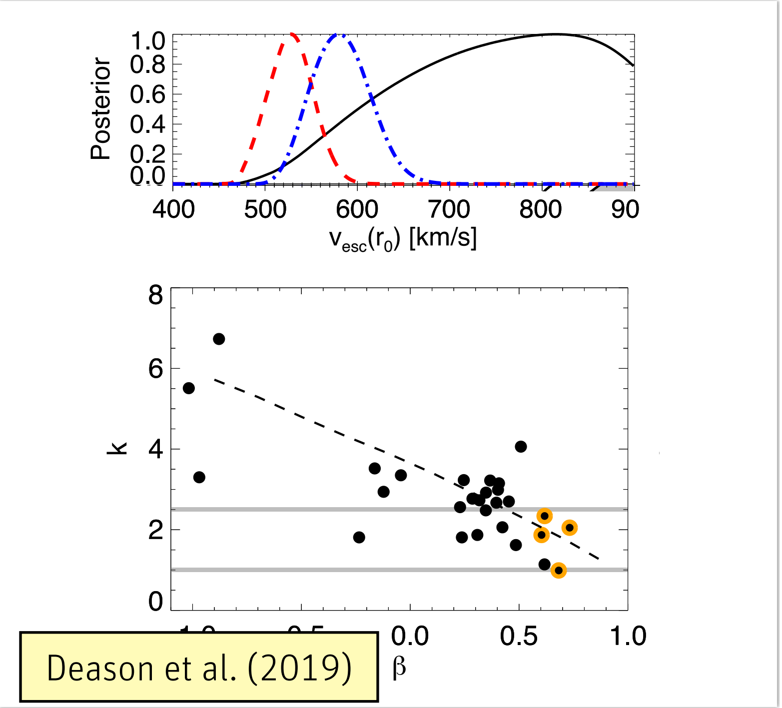




Milky Way may be considerably less massive

- recent Gaia data taking into account the local velocity distribution reveals considerable anisotropy





Deason et al. (2019)

Milky Way may be considerably less massive

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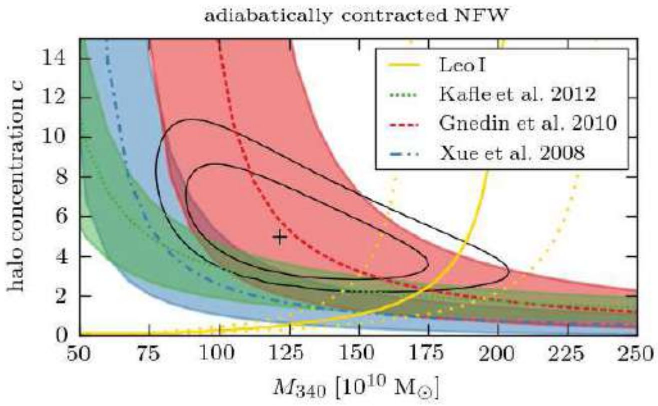
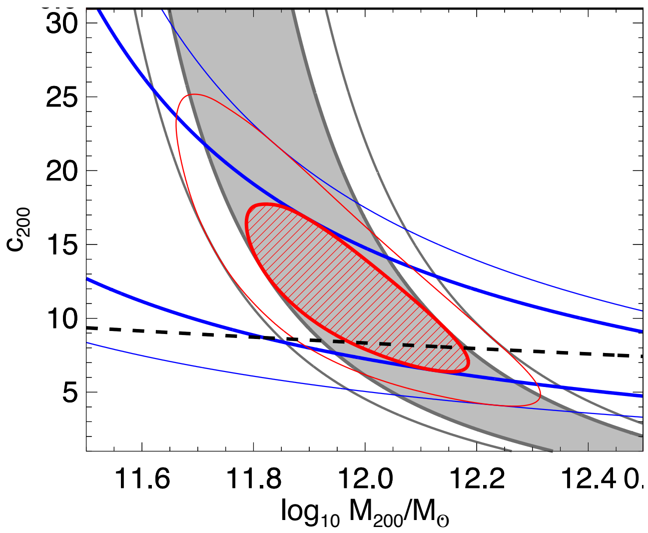
  $\Longrightarrow M_{MW} \approx 10^{12}\ M_\odot$

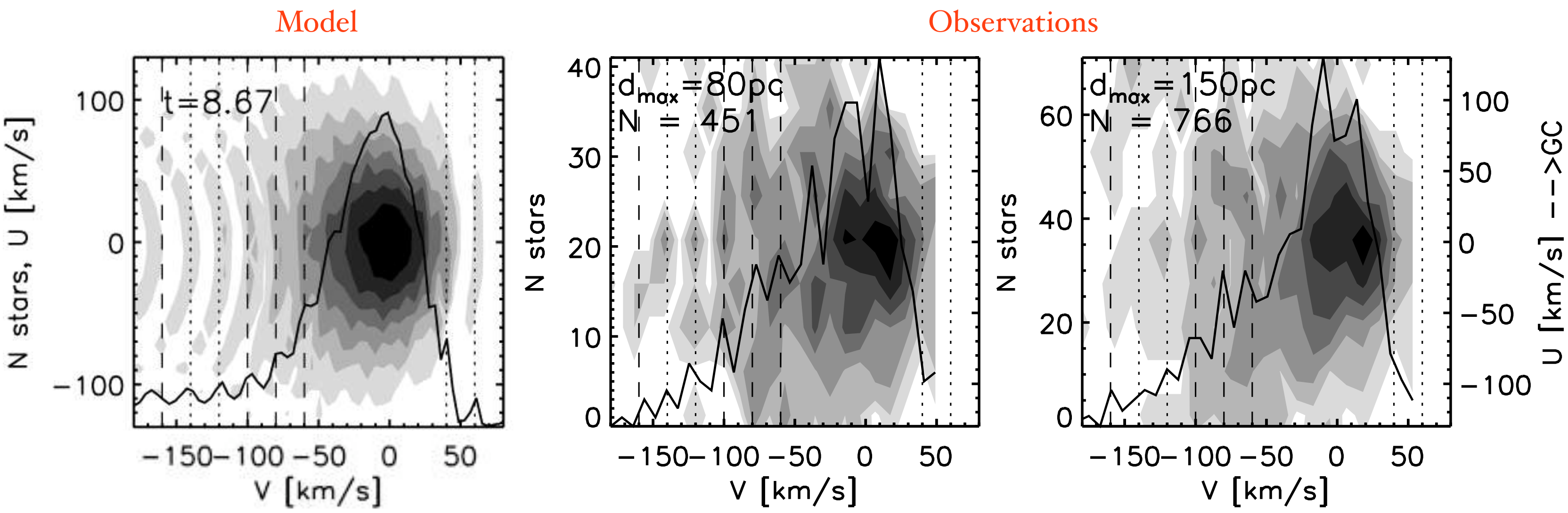




Deason et al. (2019)

Dealing with the frisky Milky Way disk

Is the Milky Way ringing? - yes it is!



- Michev et al. (2009): Prediction for a merger 1.9 Gyr ago

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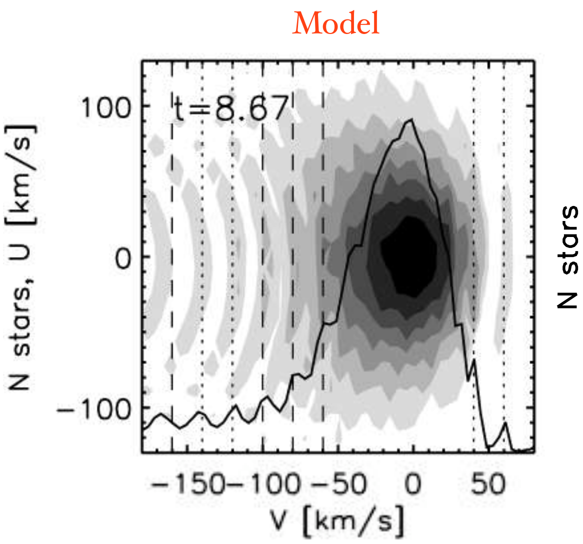
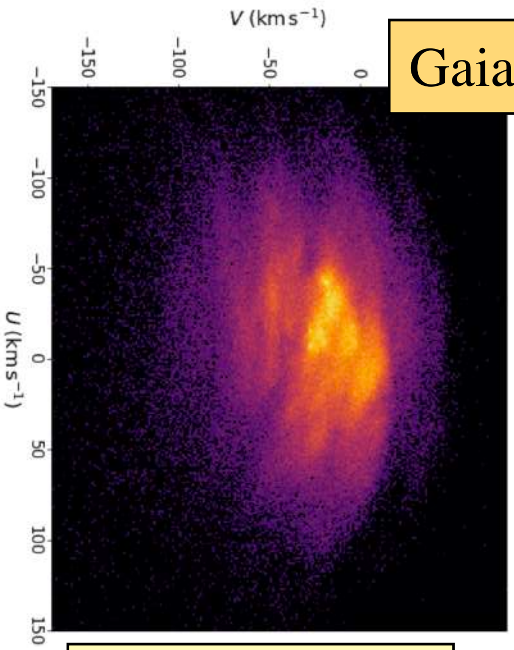
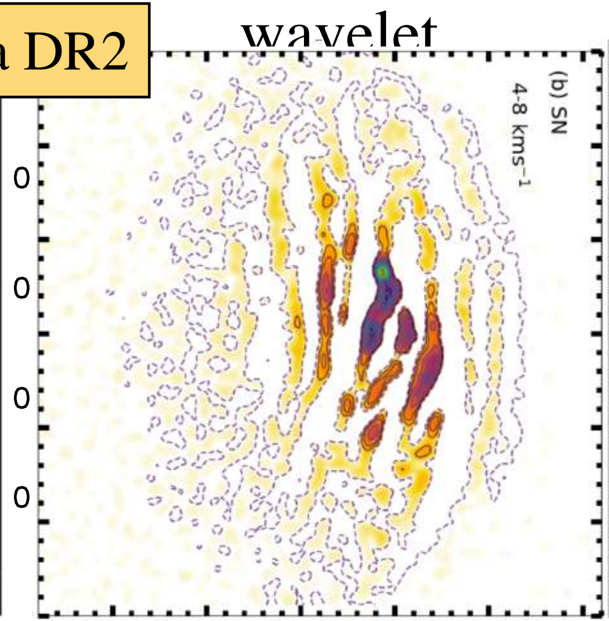




Katz et al. (2018)



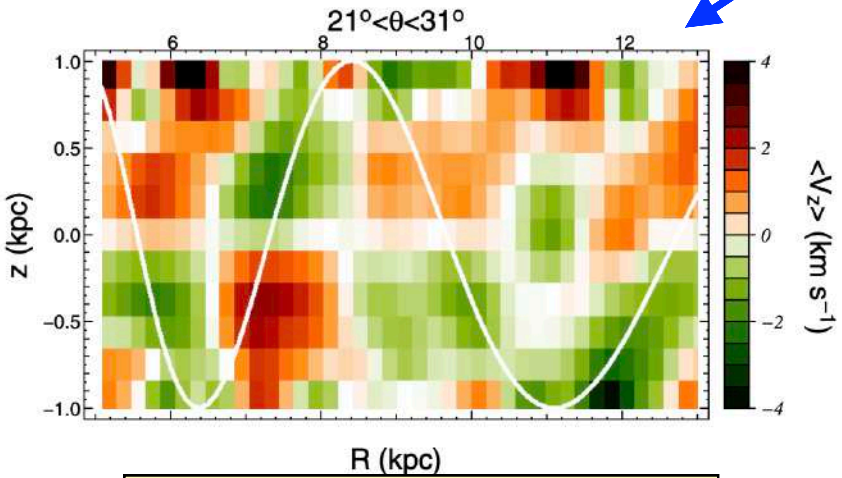
Ramos et al. (2018)

- Michev et al. (2009): Prediction for a merger 1.9 Gyr ago

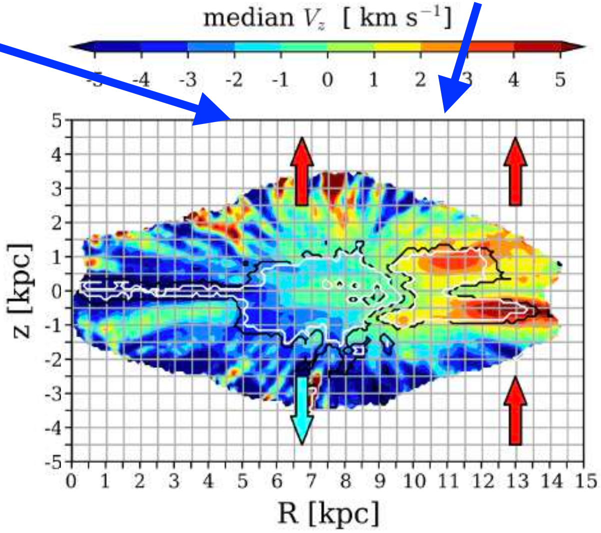
Gaia DR2 data: disk structure a combination of bending and breathing modes

Breathing mode from **spiral arms** or external

Bending mode possibly from Sgr

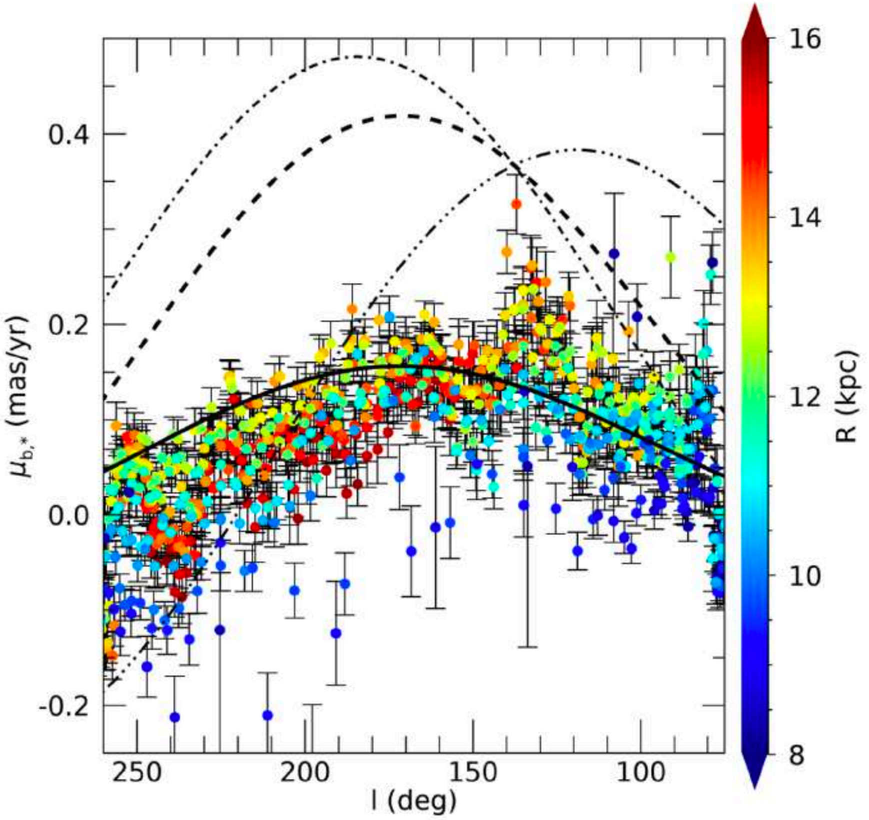


Faure, Siebert, and Famaey (2014)



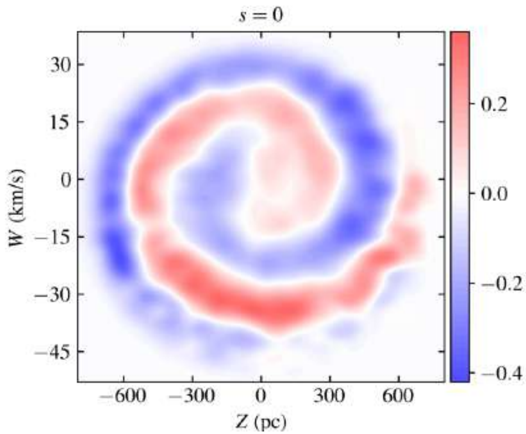
Carrillo, Minchev, MS et al. (2019)

Gaia DR2: clear sign of Milky Way Warp



Poggio et al. (2021)

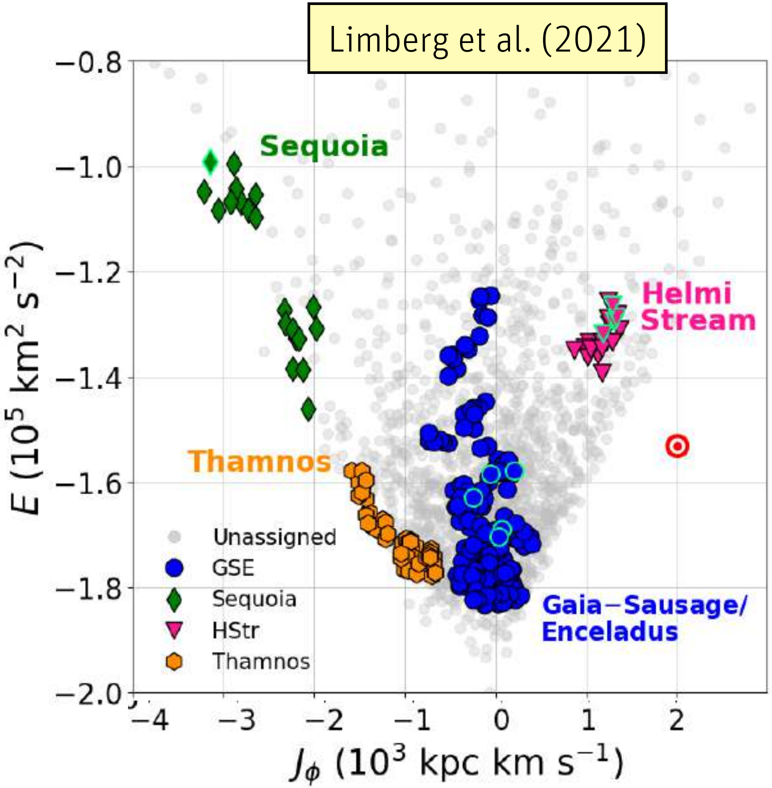
Non-equilibrium - it is not a bug, it is a feature!

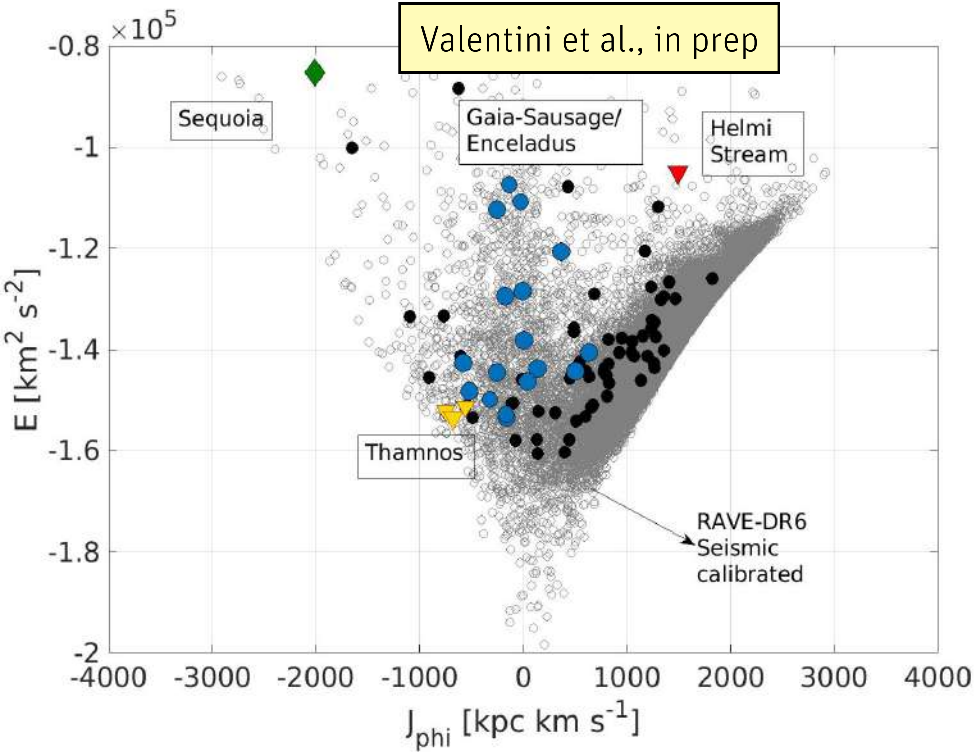


- Widmark, Laporte et al (2021): First measurement of the local dark matter density using non-equilibrium dynamics with Gaia eDR3 + spectroscopic surveys (SDSS, LAMOST, RAVE ...).
- Model background phase-space density distribution of the equilibrium distribution to isolate the perturbation (i.e. phase-space spiral, used to infer potential). Together with a baryonic model, one can then extract a local DM density.

Local DM density: $\varrho_{\mathrm{DM}} = 0.32 \pm 0.15$ GeV cm^3

Galactic Archaeology: the Halo





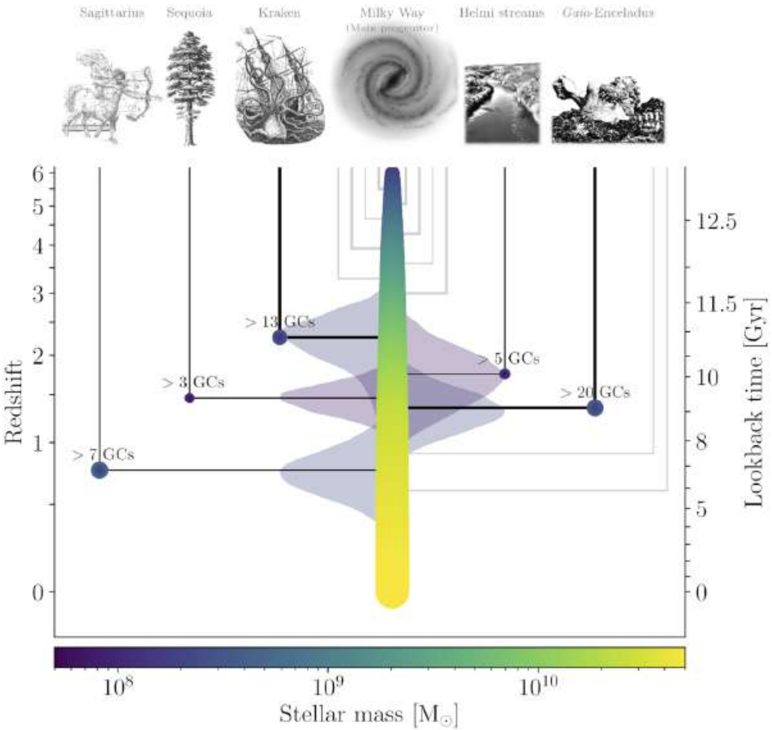
Galactic Archaeology: the Halo

Preliminary results:

Age GSE (3 stars) = 11.1 Gyr σ= 2.4 Gyr
Age Sequoia (1 star) = 13.5 Gyr σ= 3 Gyr
Age Thamnos (2 stars) = 9.2 Gyr σ= 2.5 Gyr

Statistics will improve!

Chemistry will allow a better characterization of the progenitor!



Kruijssen et al. (2020)
Galaxy merger tree

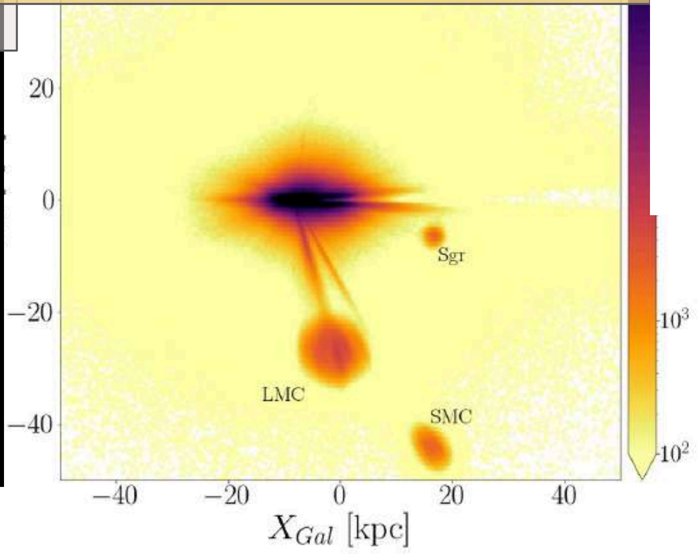
StarHorse → Bayesian approach, achieving precise distances, extinctions by combining Parallax, photometry and spectroscopy (when available)

- Allow us to direct detect of the Galactic bar in density maps;
- Bayesian approaches are fundamental to study distances where Gaia parallaxes are imprecise (e.g Bulge, LMC/SMC);

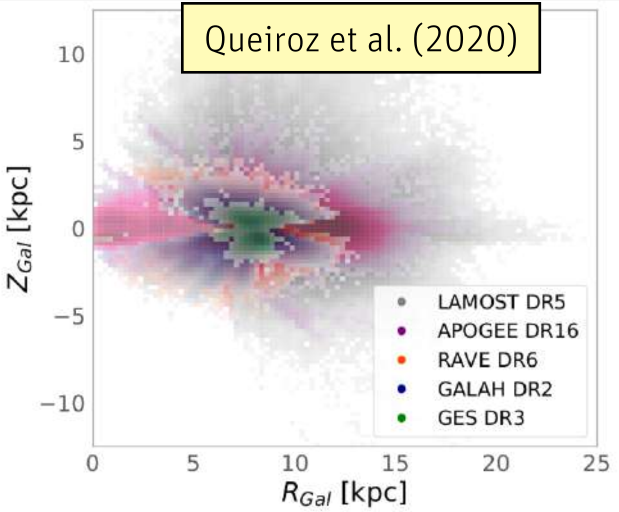
Almost as if we can see our Galaxy from above!

Credit: Data: ESA/Gaia/DPAC, A. Khalatyan (AIP) & StarHorse team; Galaxy map: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Now with EDR3 (~ 360 million stars)



Queiroz et al. (2020)



- With spectroscopic input + GDR2 ~ 6 million stars
- More precise astrophysical parameters → detail studies of chemo-kinematics

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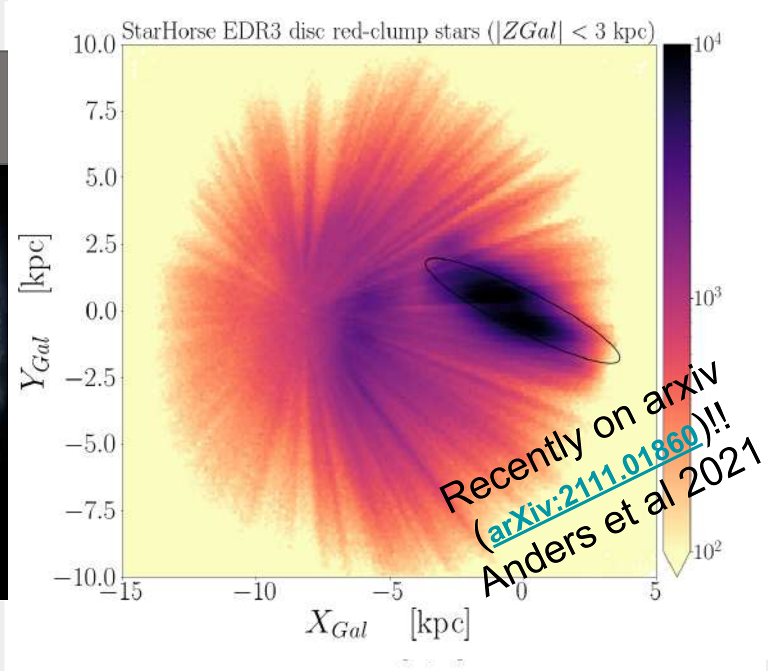

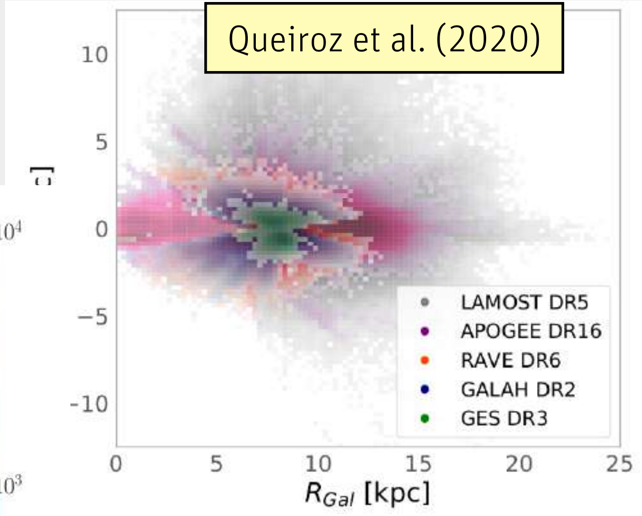

- With spectroscopic input + GDR2 ~ 6 million stars
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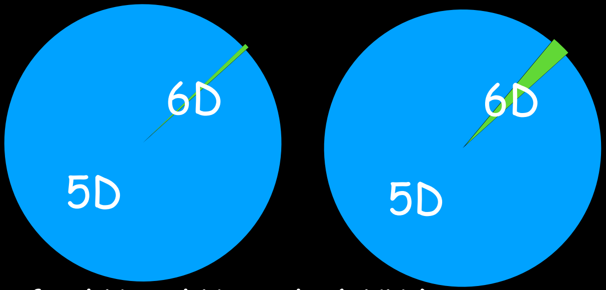
Augmented reality for Gaia with artificial neural networks

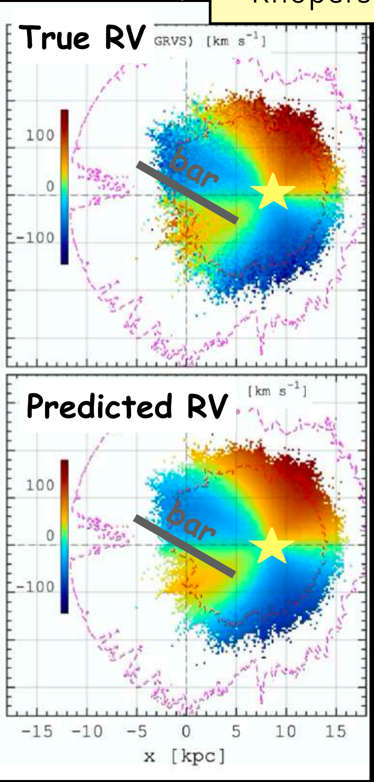
Gaia EDR3(2020) Gaia DR3 (2022)



5D: ra,dec,pmra,pmdec,parallax

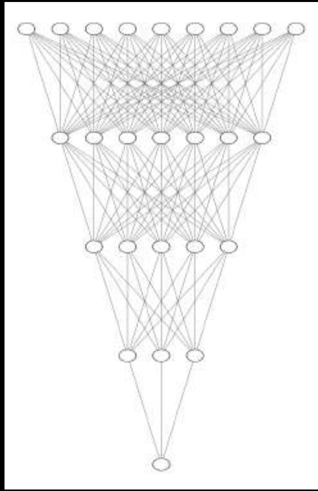
6D: 5D, LOS radial velocity

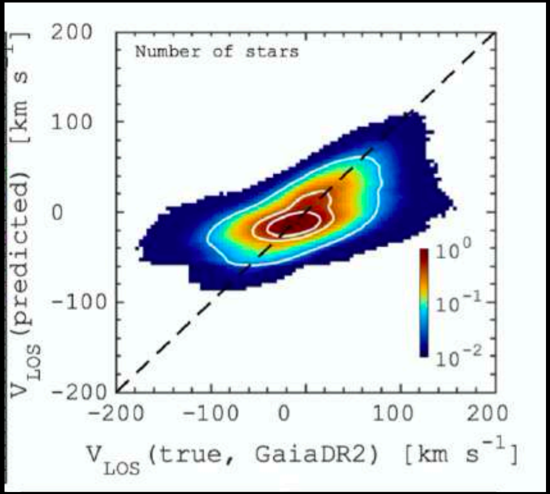
Khoperskov et al., 2021



Artificial Neural Networks (ANNs)

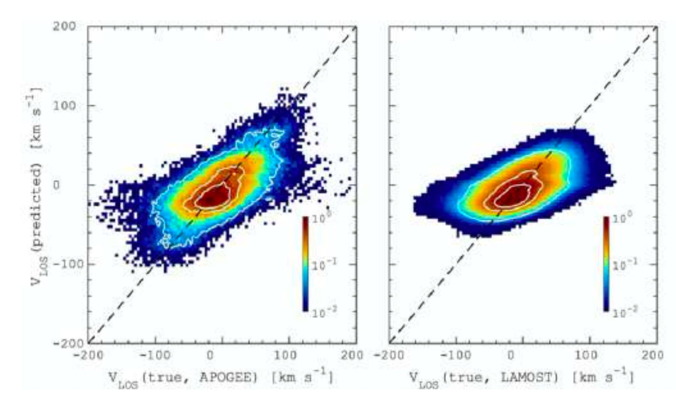
Input: 5D information





Output: LOS radial velocity

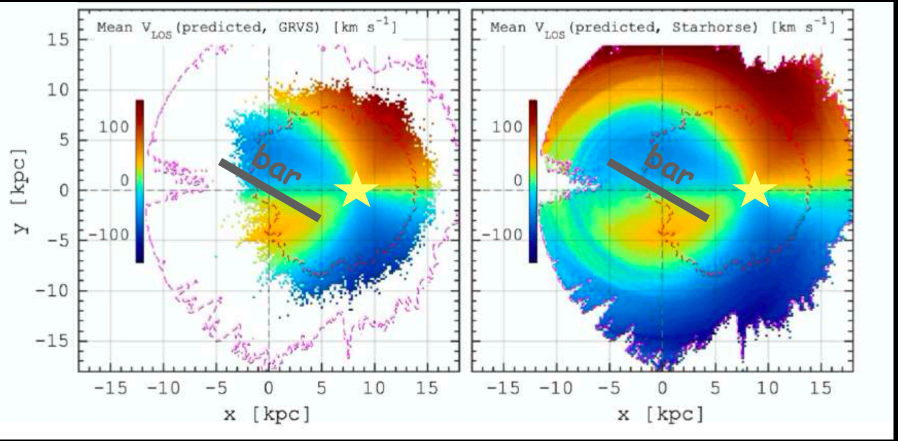
Augmented kinematics of the Milky Way disk



Comparison with APOGEE (left) and LAMOST (right) LOS velocities which are not used in the ANNs training

Left: Gaia DR2 LOS velocity map for ~6M stars

Right: LOS velocity map for ~130M stars from Starhorse



Khoperskov, Guiglion, Minchev et al (submitted)

Galactic disks are frisky:they bend, wiggle, wobble, ring, and mix

- **Time-dependent phenomena very important to consider - Milky Way is not in equilibrium:**
  - interaction with other galaxies — disk ringing, bending, and warping
  - resonances with spiral arms and central bar — resonant moving groups
  - redistribution of angular momentum in the disk — radial migration
- **Detailed modelling needed to interpret observations:**
  - dynamics typically too complicated to solve analytically
  - numerical simulations in the cosmological context needed
- **Age information is crucial for understanding the Milky Way disk structure and evolution**
  - great expectations from PLATO and TESS in the near future
- **Gaia + spectroscopic follow-up surveys (e.g., WEAVE, 4MOST) data will revolutionize further our understanding of the Milky Way!**

Bounds on ALP dark matter from Leo T observations with MUSE

MUSE-faint GTO programme on the dynamics of dwarf galaxies

- MUSE: integral field spectrograph
  - 90000 spectra over 1'x1' field with a 0.2'' sampling
    - extrem good sampling of area between stars ⇒ sky substraction
  - 470 nm - 935 nm at a sampling of 0.125 nm
  - GLAO via 4 laser guide stars (590 nm)
  - 15 x 900s exposures of the Leo T dwarf spheroidal galaxy

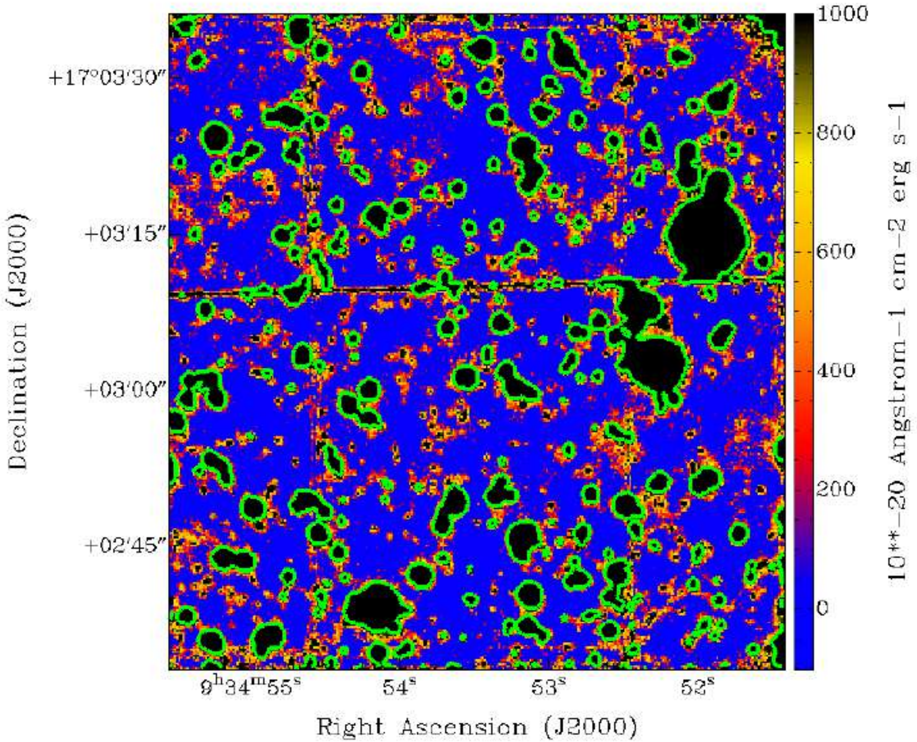
Astrophysical limits on axions and ALPs

- Coupling to EM → axions decay into photons
- Primakoff effect: inverse reaction: creation of axions from thermal photons in in the fluctuating field of stellar plasma, basis of most axion searches
    - Direct detection of the Sun's axion flux
- Primakoff effect can result in a considerable energy drain, shortening life time of certain phases of stellar evolution
    - Life time of the horizontal branch phase (He burning) of stars. $g_{10} = 1$ would lower the HB phase by ~30%
    - Globular cluster exclude such high values base on the ratio of HB stars to red giants

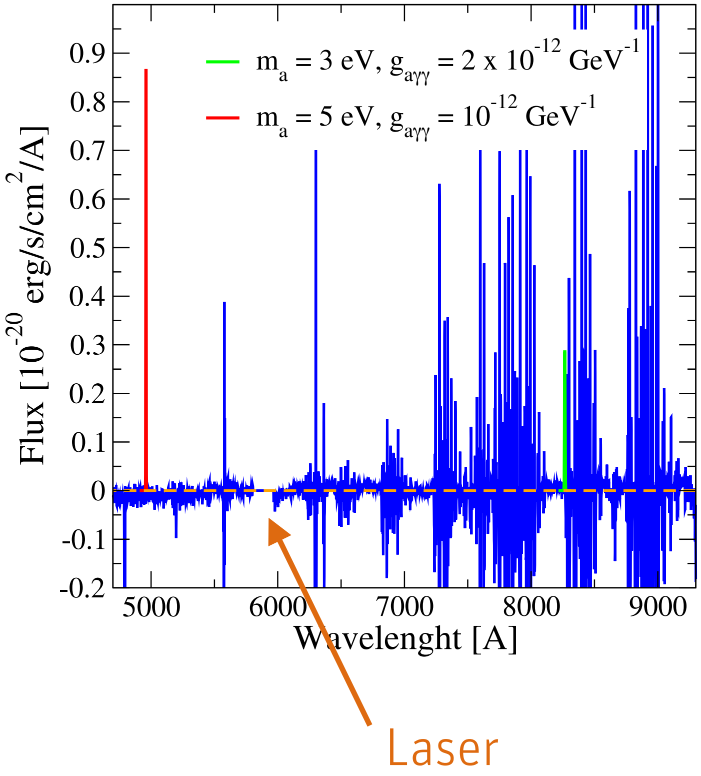
Astrophysical limits on axions and ALPs

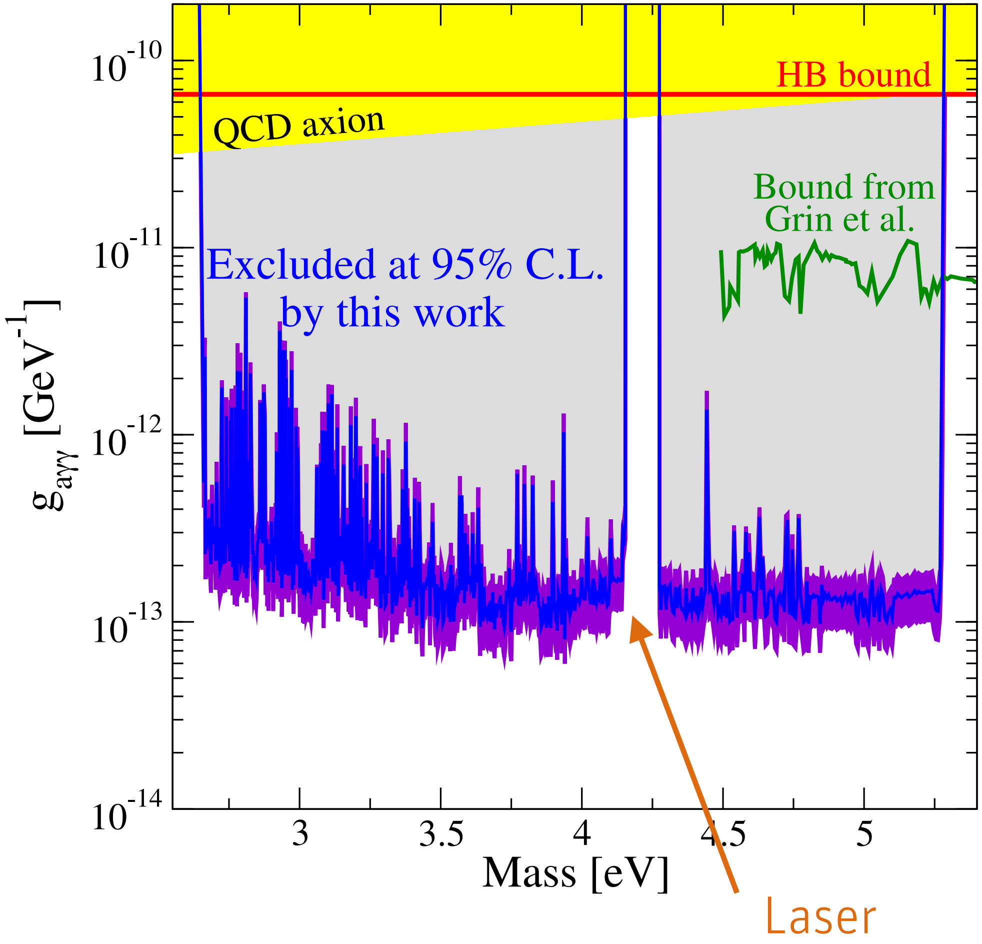
- direct constraint on the ALP decay rate:
  - has been done for Galaxy clusters Abell 2667 and 2390 with VIMOS (Grin et al, 2007)
- MUSE-Faint GTO:
  - After subtraction of Leo T stars, foreground stars, other faint sources (background galaxies) and sky background, can we measure or constrain the extended emission of the DM decay into photons (assuming the DM is ALPs)?

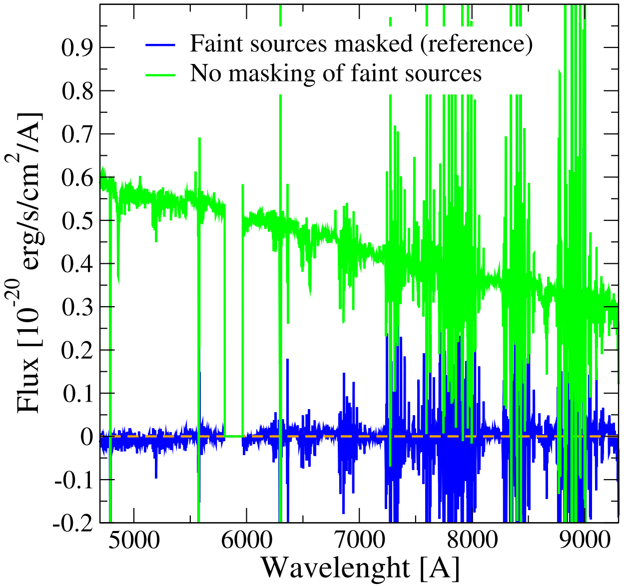
Regis et al., 2021

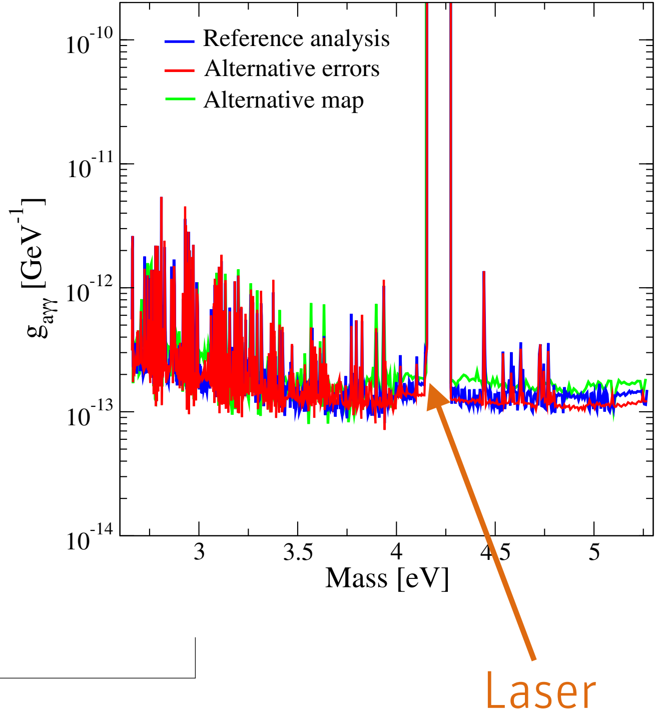


average flux




HB bound
QCD axion
Bound from
Grin et al.
Excluded at 95% C.L.
by this work
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
3
3.5
4
4.5
5
Mass [eV]
Laser


Faint sources masked (reference)
No masking of faint sources
Flux [10^{-20} erg/s/cm^2/A]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
5000
6000
7000
8000
9000
Wavelenght [A]


Reference analysis
Alternative errors
Alternative map
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
3
3.5
4
4.5
5
Mass [eV]
Laser

Summary

- Dynamical models of the Milky Way and its satellite system:
  - Total mass: $M_{\text{tot}} \approx 10^{12}\,\mathrm{M}_\odot$
  - Local DM density: $\varrho_{\text{DM}} \approx 0.3\,\text{GeV cm}^{-3} \approx 0.0085\,\mathrm{M}_\odot\,\text{pc}^{-3}$
- Modeling of LMC and ultra faint dwarfs (Gaia, MUSE) appear to be more consistent with a steep inner density profile (cusp)
- Main challenge: regarding Milky Way modelling, we went from a data starved to a data-driven situation.
  - Advanced modelling of non-equilibrium (perturbed equilibrium) required
  - use chemistry age information in baryonic component for dating dynamical events
  - role of simulations (qualitative $\Rightarrow$ quantitative tool)