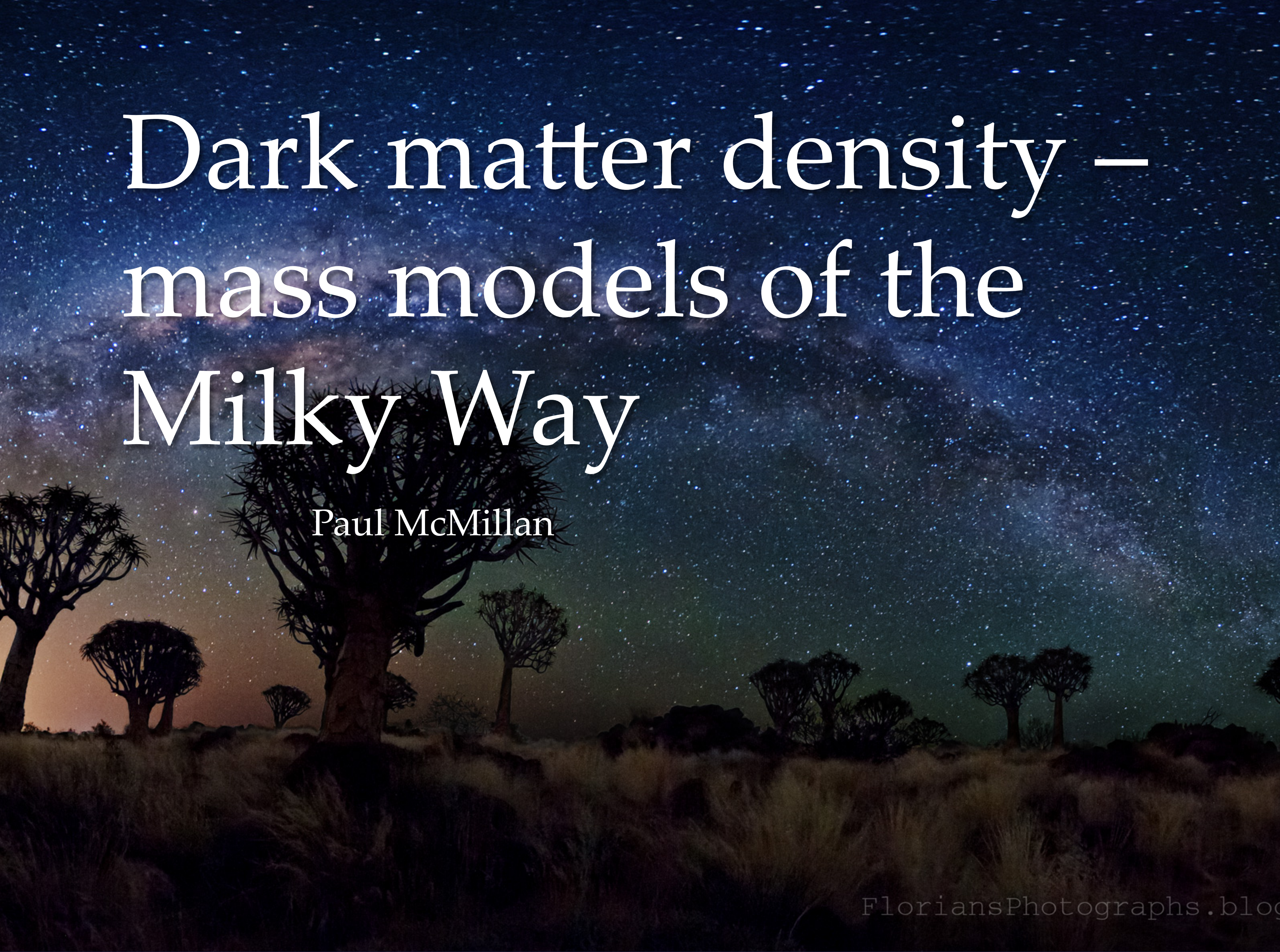
Dark matter density – mass models of the Milky Way

Paul McMillan



The observational problem

The metaphor “can’t see the wood for the trees” unusually valid.

We’re in the middle of the Galaxy – hard to tell its shape.

Much in the Galaxy is shrouded in dust

Hard to tell a nearby dwarf from a distant giant (or know distance to gas clouds)

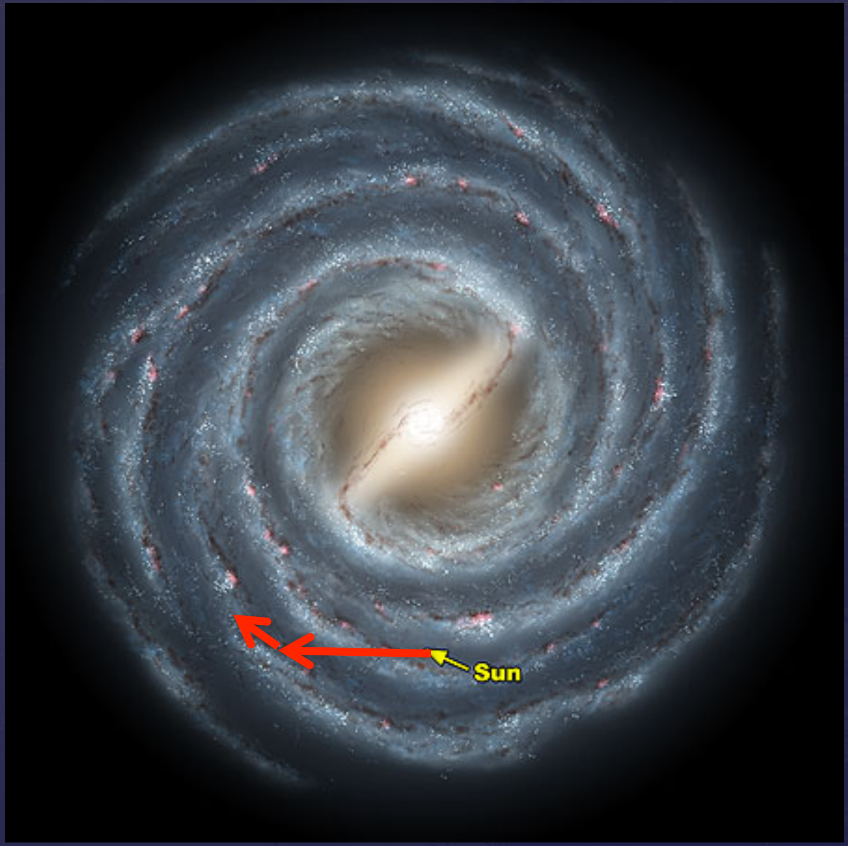
We’re orbiting the Galactic Centre along with everything else

The Sun's velocity in the Galaxy

Break into two parts:

Circular speed at the Sun, v_c
(tells us $d\Phi/dR$ at R_0)

Peculiar velocity of the Sun
$\mathbf{v}_{\odot} = (U_{\odot}, V_{\odot}, W_{\odot})$



Credit: NASA/JPL-Caltech/R. Hurt (SSC)

(N.B. this is not a photo)

Peculiar velocity of the Sun

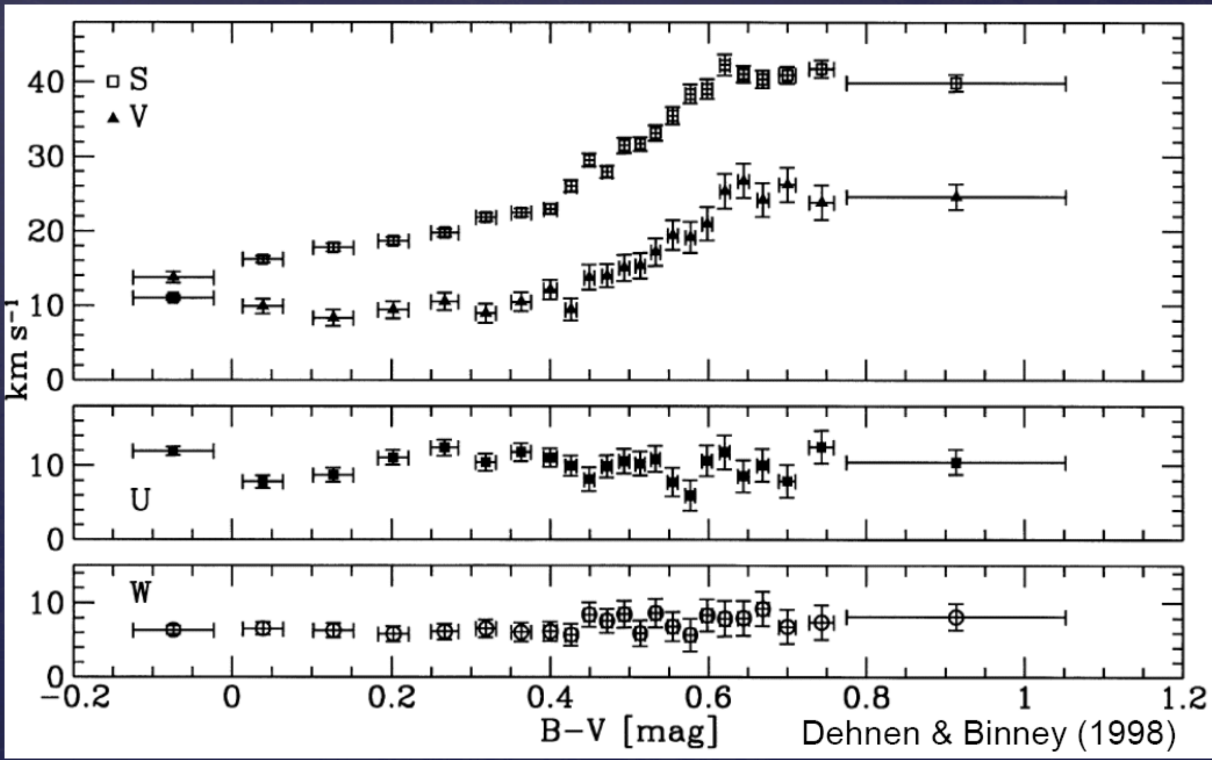
Stars in the Solar neighbourhood

Binned in colour (used as a proxy for age, and thus velocity dispersion)

U (Radial) and W (out of the plane) velocities should average to zero – difference is Sun's peculiar velocity

V doesn't – asymmetric drift (more stars visiting from inner Galaxy than outer)

Only recently realised that extrapolating for V not straightforward (Schönrich, Binney & Dehnen 2010)



$$v_c(R_0) = v_\phi - V_\odot$$

Best way to find v_ϕ is to look at the ~ fixed black hole (Sgr A*) at the Galactic centre and determine our velocity with respect to that.

"Proper motion" v_ϕ/R_0 is
-6.379 ± 0.026 mas/yr
i.e. 30.2 ± 0.2 km/s/kpc

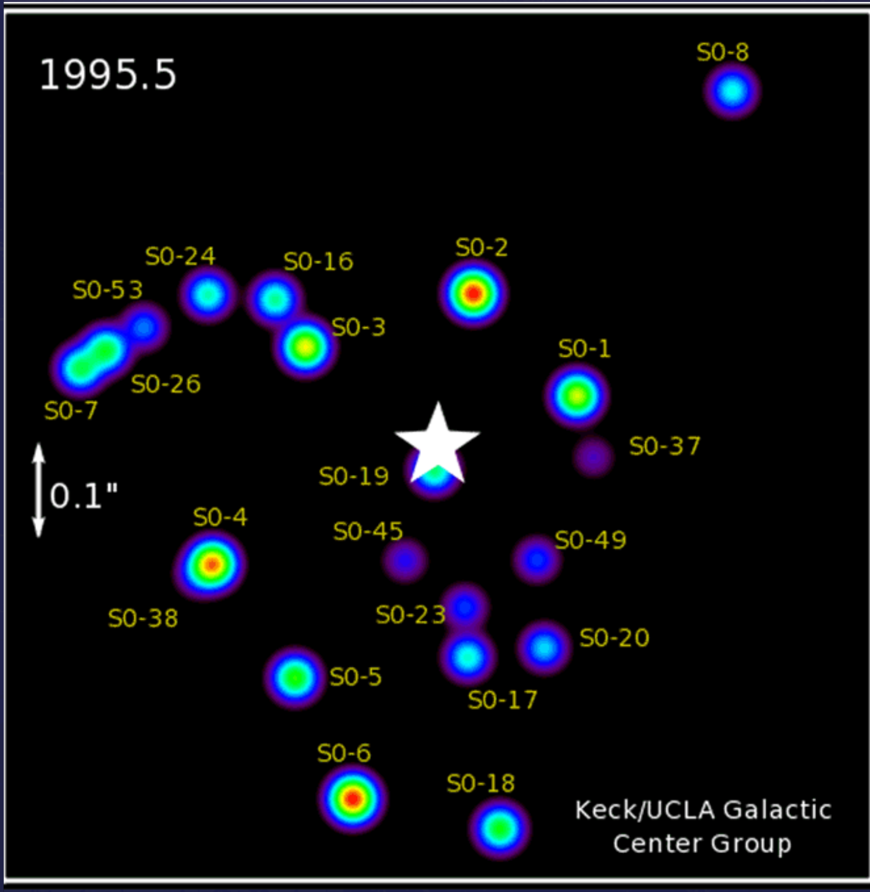
(Reid & Brunthaler 2004)

Best estimates of R_0 come from observations of stars in close orbits around Sgr A* - estimates are ~ 8.3 ± 0.3 kpc

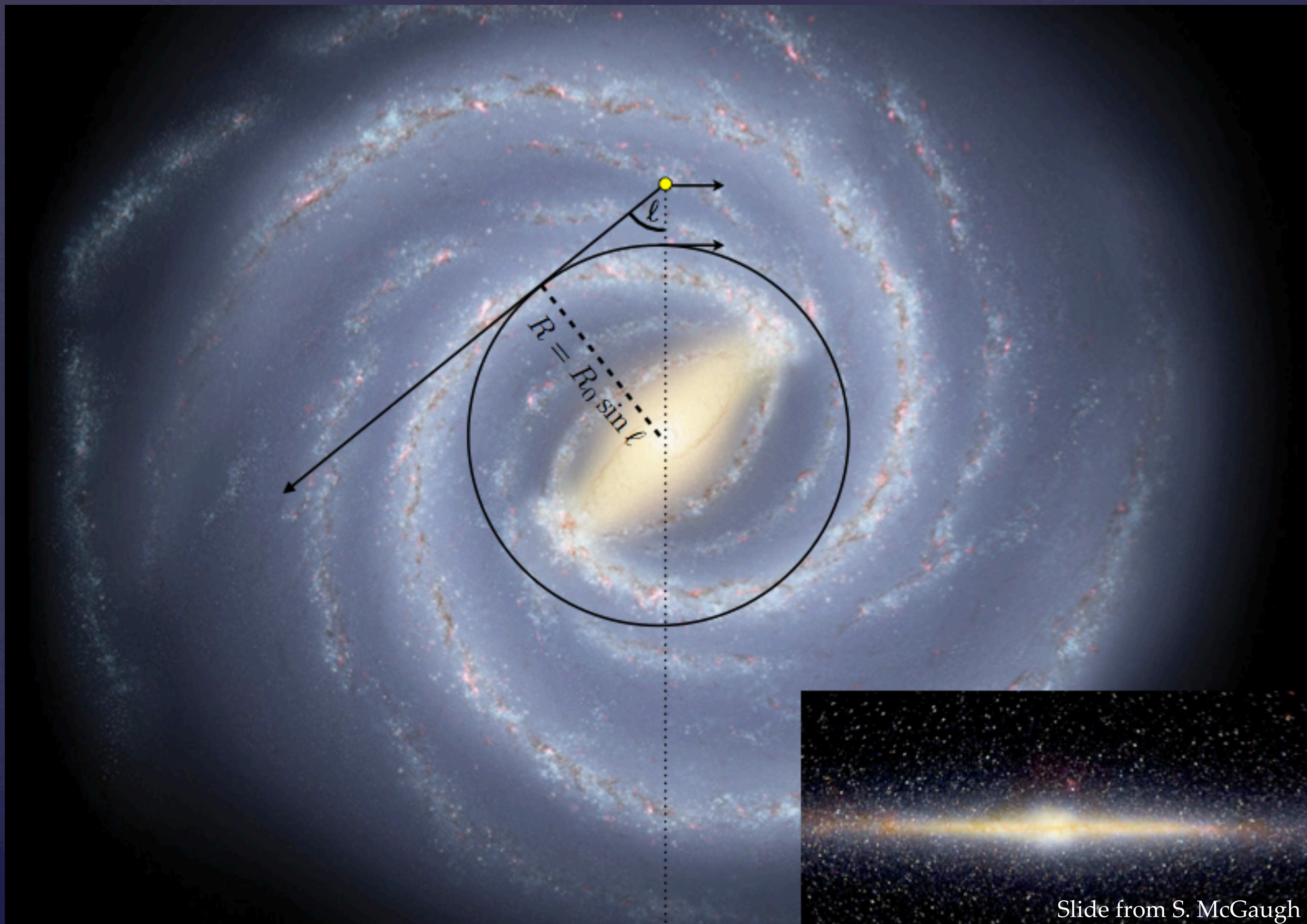
(Ghez et al 2008, Gillessen et al 2009)

So $v_c = 240 \pm 10$ km/s

(Also efforts with wide star samples e.g. Schönrich 2012)



For gas on circular orbits, maximum velocity towards Sun is at tangent point



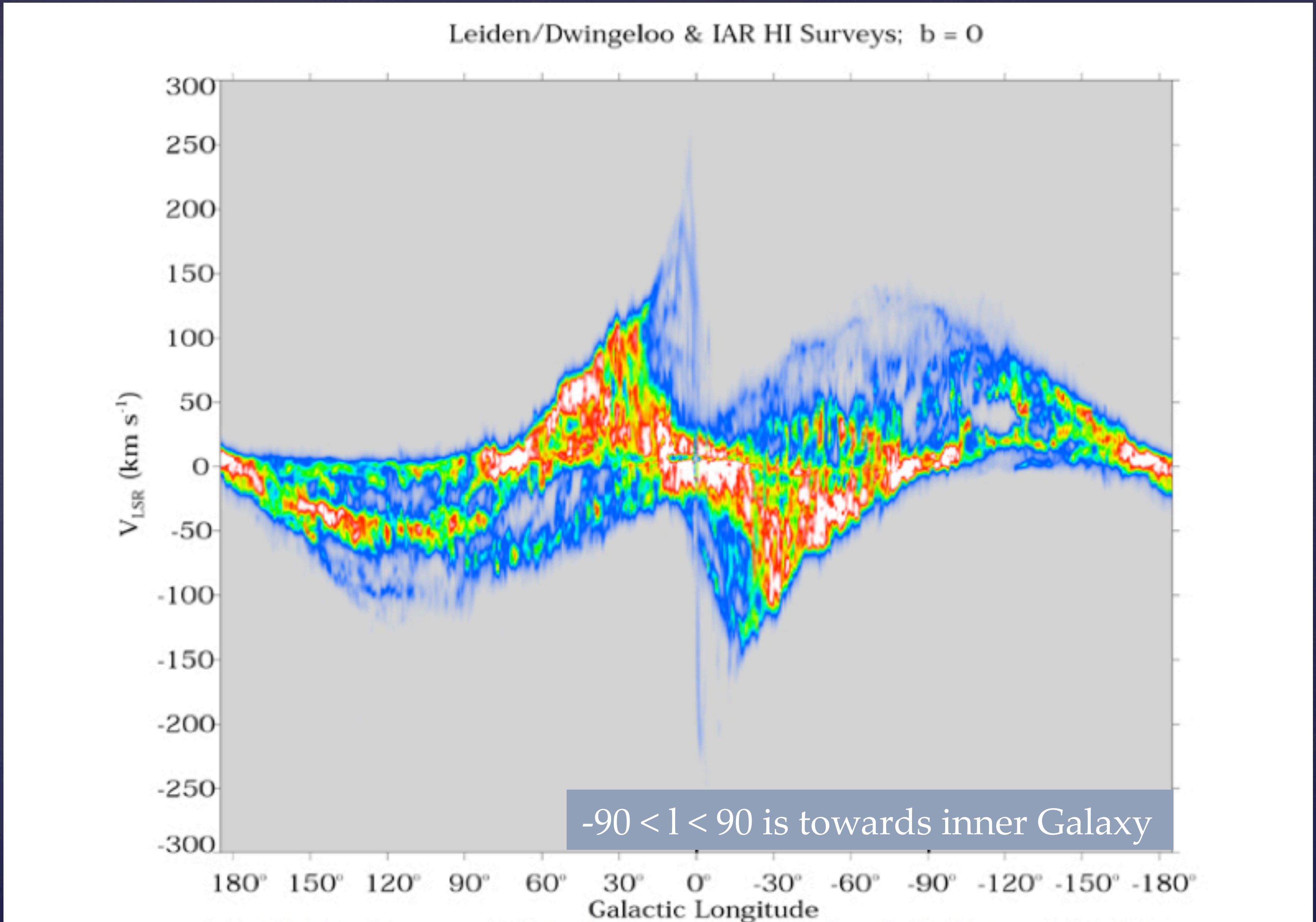
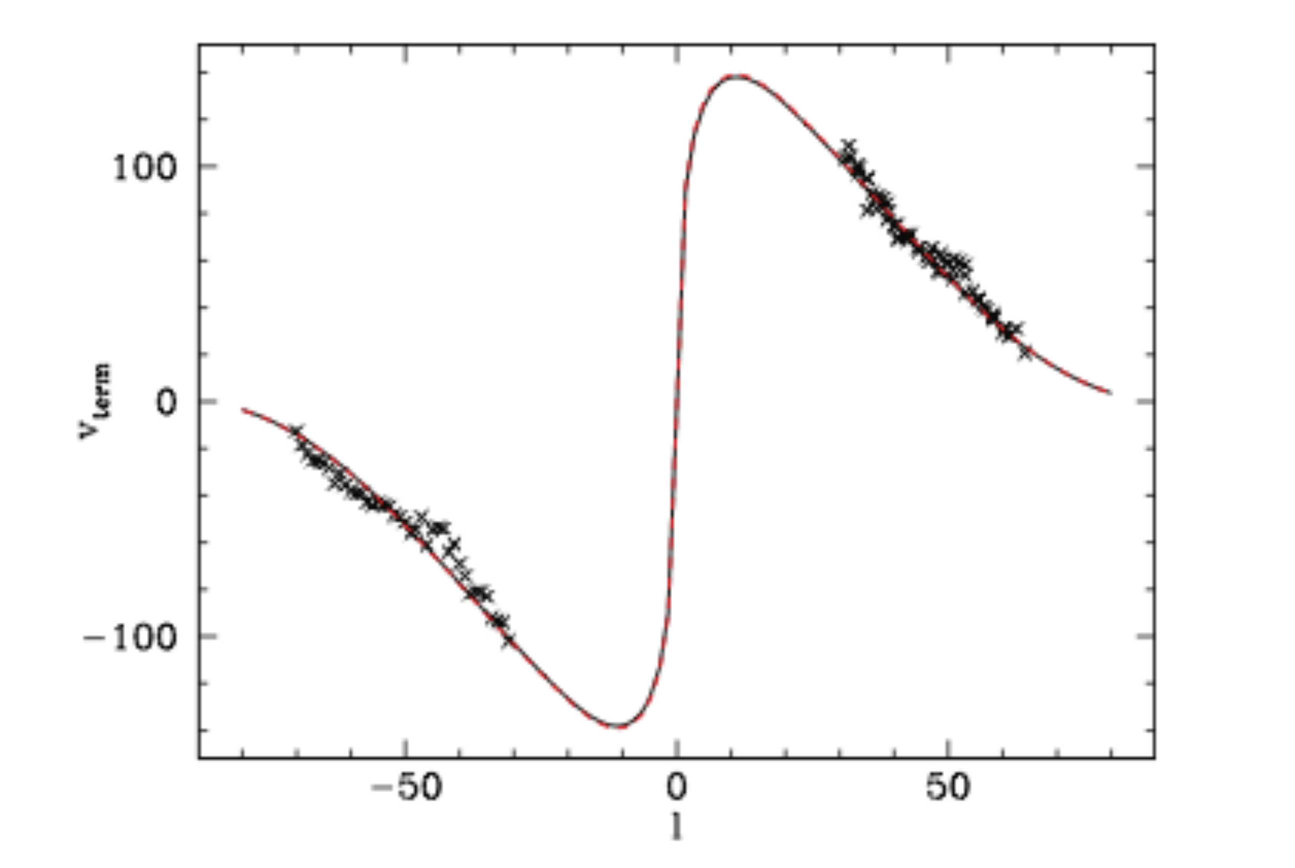


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Take just the peak “terminal velocities” and you get the crosses below.

A good model (the lines below) should have a circular velocity that lies close to these crosses at the point $R = R_0 \sin l$



Masers

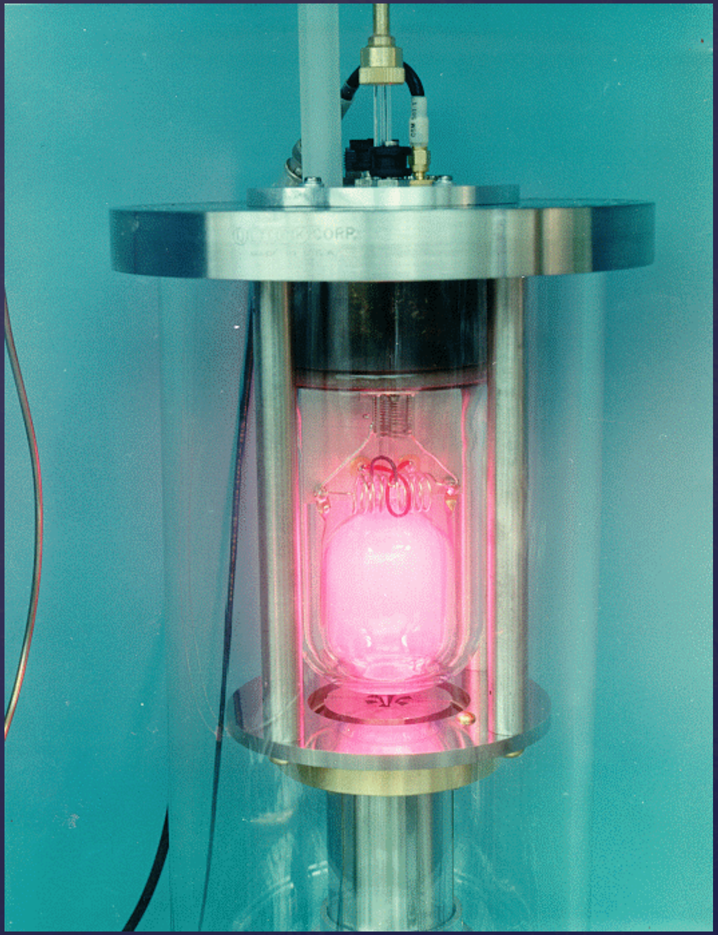
Microwave (or Molecular) Amplification by Stimulated Emission of Radiation

Occur in gas excited by nearby young stars

Associated with star forming regions, which come from cold gas – near circular orbits.

Emission has a high surface brightness, narrow frequency range and is at radio wavelengths.

Ideal for very long baseline interferometry, allowing extraordinary precision in position measurements and therefore parallax (and therefore distance)



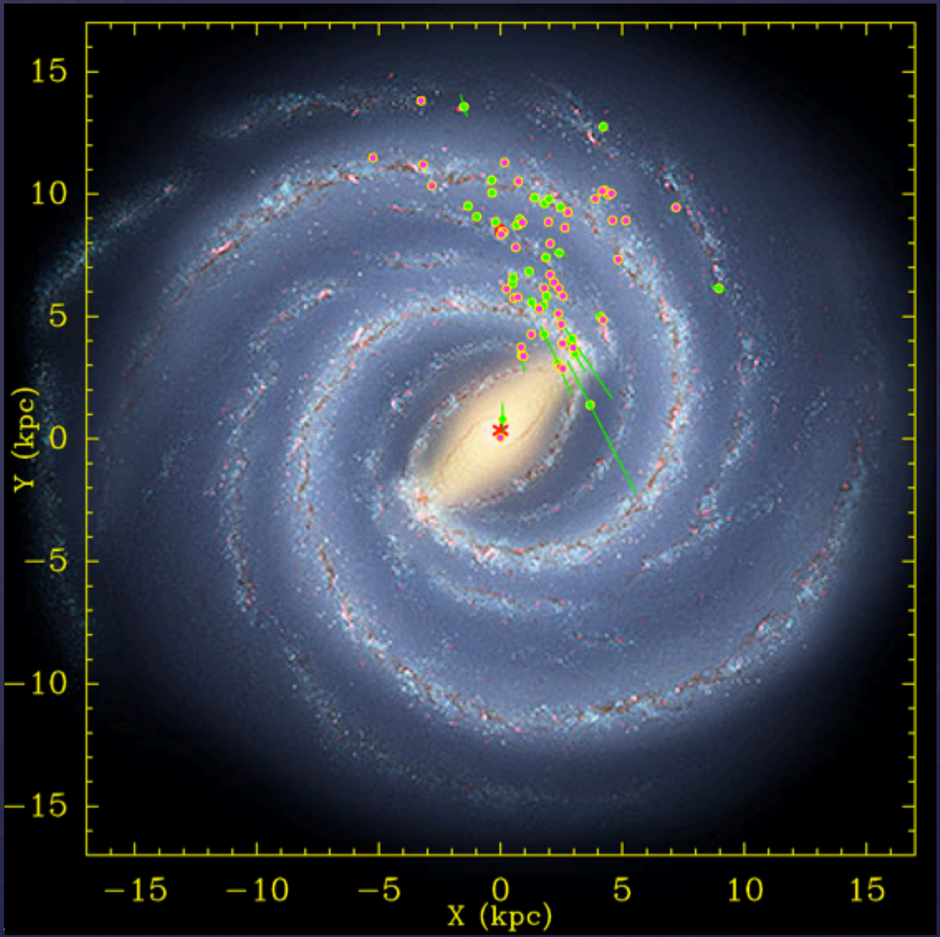
Masers

Reid et al (2009) reported impressively accurate parallax measurements for 18 maser sources.

Reid et al's treatment of these data was simplistic, so others have been back

(McMillan & Binney 2010, Bovy, Hogg & Rix 2009, McMillan 2011)

More observations are being taken…



These give us (imperfect) information about $d\Phi/dR_{(z=0)}$

Given known force from the baryonic components we know the contribution from the dark matter and therefore the halo density profile (for some halo flattening)

<u>3 problems:</u>

1. We don't know $d\Phi/dR_{(z=0)}$
2. We don't know the force from the baryonic components
3. We don't know the halo flattening

Stellar disc scalelength, surely we can all agree on that?

Reviews by Robin (1992): R_d=3.5-4.5 kpc /Sackett (1997): R_d=2.5-3.0 kpc

Optical data (solar nbhd):

2.5 kpc	Robin et al 1996	Besancon
3.2 kpc	Larsen 1996	APS-POSS
4.0 kpc	Buser et al. 1999	Basel Halo program
2.7 kpc	Zheng et al 2001	HST obs of M dwarfs
2.3 kpc	Siegel et al 2002	Kapteyn Selected Area stars
2.6 kpc	Juric et al 2008	SDSS

Infrared data:

2.5 kpc	Freudenreich 1998	COBE/DIRBE
2.3 kpc	Drimmel & Spergel 2001	COBE/DIRBE
2.3 kpc	Ruphy et al 1996	DENIS, l=217°, 239°
2.0 kpc	Reylé et al 2009	2MASS, l=90-270°
2.0 kpc	Lopez-Corredoira 2002	2MASS, l=45-315°, starcount,RG
2.4 kpc	"	Scalength of surface density
3.9 kpc	Benjamin et al 2005	GLIMPSE, |l|=30-60°

(Data compiled by Robert Benjamin)

What's the density normalisation?

Locally:

Component	$\Sigma_i\,[\mathrm{M}_\odot\,\mathrm{pc}^{-2}]$	Reference
Σ_{HI}	12.0 ± 4.0	Kalberla & Dedes (2008)
$\Sigma_{\mathrm{H_2}}$	3.0 ± 1.5	Flynn et al. (2006)
$\Sigma_{\mathrm{Warm\ gas}}$	2.0 ± 1	Flynn et al. (2006)
Σ_*	30 ± 1	Bovy et al. (2012)
$\Sigma_\bullet$	7.2 ± 0.7	Flynn et al. (2006)
Σ_b	54.2 ± 4.9	This compilation

(Taken from J. Read review, in prep)

What else can we do? : The outer Galaxy.

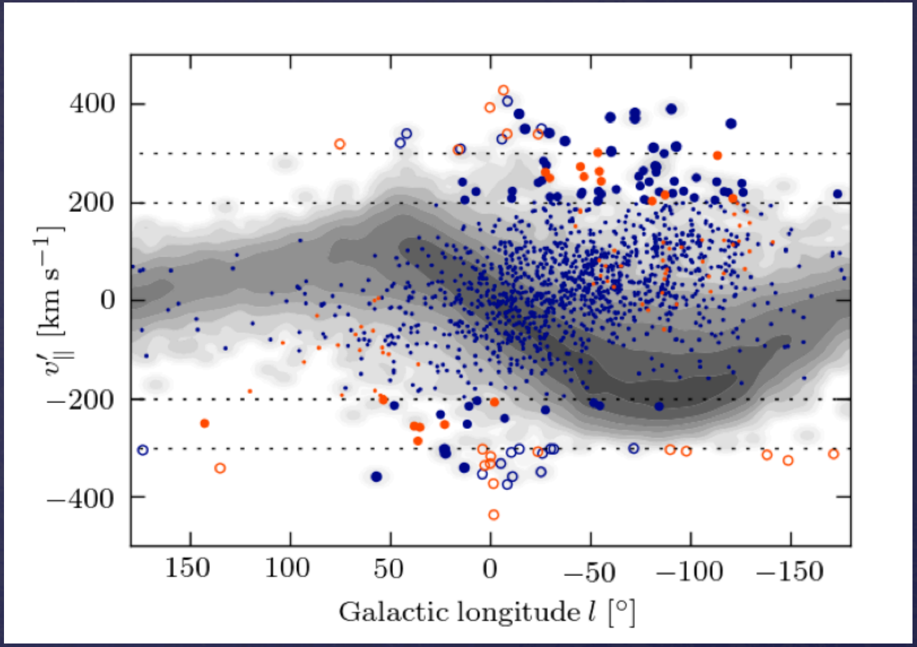
Escape velocity

Look at the highest velocity stars near the Sun

"Expect" number to fall off like $(v_{esc}\text{-}v)^k$

From RAVE survey Smith et al (2007) and Piffl et al (2013) have done this

$v_{esc} = 533\ ^{+54}_{-41}$ km/s



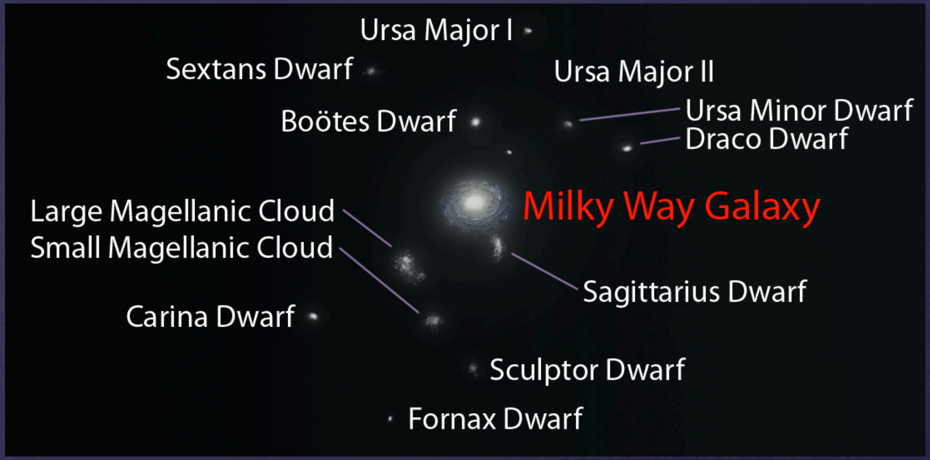
What else can we do? : The outer Galaxy.

Halo tracers

Bright stars or dwarf galaxies in the Milky Way can used as 'tracer' populations assumed to be in equilibrium.

Then can use Jeans' equations

BUT hard to get velocity except along l.o.s., so we ~ only know v_r for the objects, have to guess (based on simulations) on tangential v



(e.g. Stars: Xue et al 2008, Gnedin et al 2010; Stars with proper motion: Kafle et al 2012; Stars & galaxies: Watkins, Evans & An 2010; Galaxies: Wilkinson & Evans 1999)

What else can we do? : The outer Galaxy.

Streams?

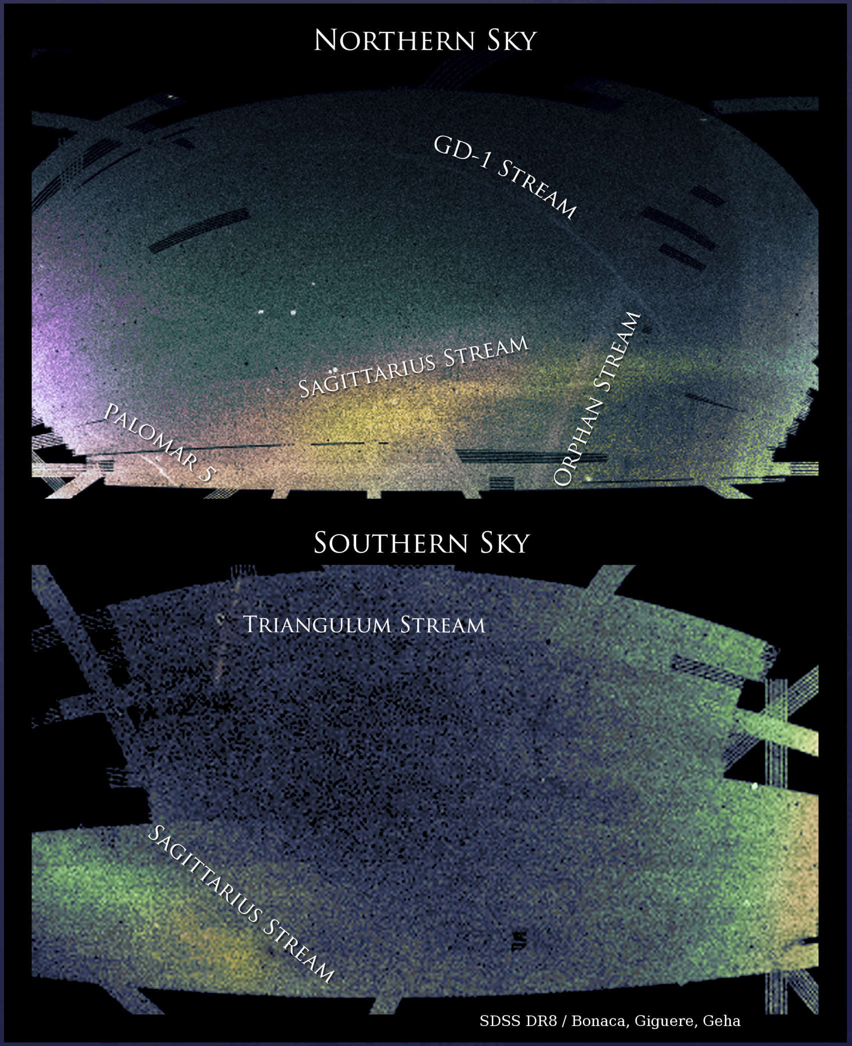
Milky Way halo has many "streams" of stars coming from disrupted star clusters/galaxies.

They all came from ~same place, so we know something about their orbits,. Use this to lean about Φ.

N.B. stars in the stream not all on the same orbit

Open area of work:

(~~Koposov et al 2010,~~ Sanders & Binney 2013, Price-Whelan & Johnson 2013)



What else can we do? : Locally.

A very common approach is to look at stars close to the Sun in R, but above the Galactic plane.

One can then apply one of Jean's equations:

$$\frac{1}{R}\frac{\partial\left(R\nu\sigma_{Rz}\right)}{\partial R} + \frac{\partial}{\partial z}\left(\nu\sigma_z^2\right) + \nu\frac{\partial\Phi}{\partial z} = 0$$

Or say that since this is in equilibrium we approximate $f(z,v_z) = f(E_z)$

where $E_z = ½v_z + [\ \Phi(R,z) - \Phi(R,0)\ ]$

What else can we do? : Locally.

This is not that simple – distances are hard to determine in astronomy, and if a ‘biased’ subset of stars are observed, this causes errors

Here the most common approach is to limit to stars of a certain colour and then use the colour to determine possible range of absolute brightness, and therefore distance (given observed brightness)

Velocities a bit easier – looking directly up so it’s ~just the radial velocity (doppler shift)

Even then, one has to make further assumptions to find Φ, and to get from that to ϱ …

What else can we do? : Locally.

The classic papers on this are by Kuijken & Gilmore (3 papers in 1989 & 1 in 1991)

THE GALACTIC DISK SURFACE MASS DENSITY AND THE GALACTIC FORCE K_z AT $z = 1.1$ KILOPARSECS

KONRAD KUIJKEN
Canadian Institute for Theoretical Astrophysics, McLennan Laboratories, 60 St. George Street, Toronto, Ontario, Canada M5S 1A1
AND
GERARD GILMORE
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, U.K.; and Canadian Institute for Theoretical Astrophysics
Received 1990 March 26; accepted 1990 November 6

($K_z(1.1\text{kpc}) = 2\pi G \times 71\pm6\ M_\odot/\text{pc}^2$)

These data were reanalysed by Garbari et al (2012) with similar results.

More complicated to model data has been looked at by Smith et al 2012 & Zhang et al 2013 – smaller statistical error bars, but systematics?

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We also have Moni-Bidin et al 2012

KINEMATICAL AND CHEMICAL VERTICAL STRUCTURE OF THE GALACTIC THICK DISK. II. A LACK OF DARK MATTER IN THE SOLAR NEIGHBORHOOD*,†

C. MONI BIDIN[1], G. CARRARO[2,4], R. A. MÉNDEZ[3], AND R. SMITH[1]

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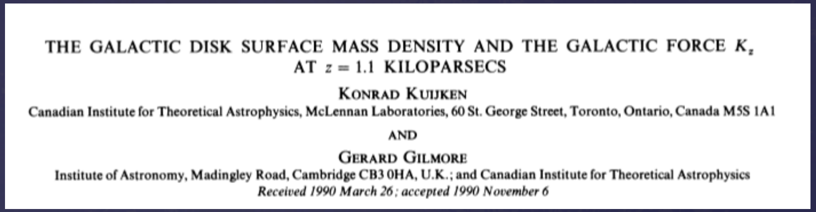
ON THE LOCAL DARK MATTER DENSITY

JO BOVY[1] AND SCOTT TREMAINE
Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA
Received 2012 May 20; accepted 2012 June 28; published 2012 August 20

What else can we do? : Locally.

The classic papers on this are by Kuijken & Gilmore (3 papers in 1989 & 1 in 1991)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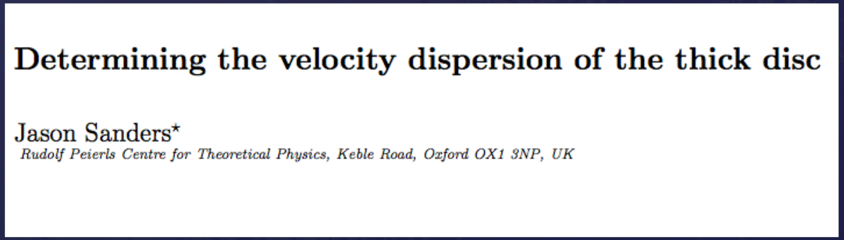
~~Bovy & Tremaine 2012~~
OK, forget it


Determining the velocity dispersion of the thick disc

Jason Sanders*
Rudolf Peierls Centre for Theoretical Physics, Keble Road, Oxford OX1 3NP, UK

Model assumptions matter. Errors propagate.

Putting it all together

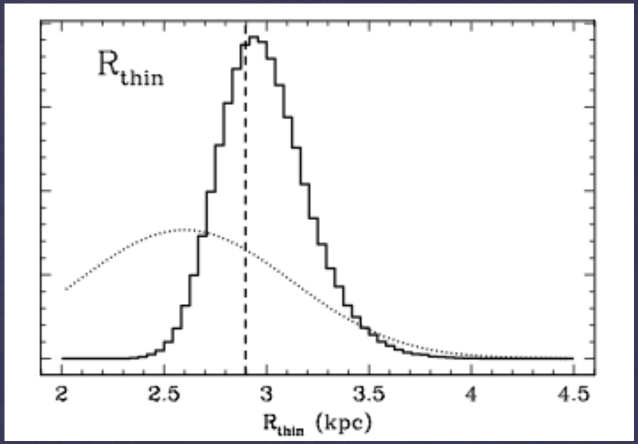
All of these separate lines of attack should yield a single Galactic potential

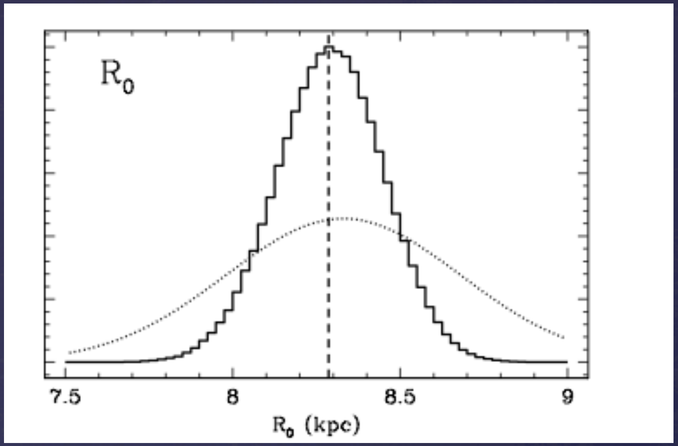
One can try to put many of these constraints together, and get out a model that (tries) to fit everything…

Property constrained	Constraint	Section described	Source
Bulge profile	See equation (1)	2.1	Bissantz & Gerhard (2002)
M_b	$(8.9 \pm 0.89) \times 10^9\ M_\odot$	2.1	Bissantz & Gerhard (2002)
Disc profile	Double exponential	2.2	–
$z_{d,thin}$	0.3 kpc	2.2	Jurić et al. (2008)
$z_{d,thick}$	0.9 kpc	2.2	Jurić et al. (2008)
$R_{d,thin}$	2.6 ± 0.52 kpc	2.2	Jurić et al. (2008)
$R_{d,thick}$	3.6 ± 0.72 kpc	2.2	Jurić et al. (2008)
$f_{d,\odot}$	0.12 ± 0.012	2.2	Jurić et al. (2008)
Halo profile	NFW profile	2.3	Navarro et al. (1996)
M_*/M_v	See equation (5)	2.3	Li & White (2009)
$\ln c_v$	2.256 ± 0.272	2.3	Boylan-Kolchin et al. (2010)
R_0	8.33 ± 0.35 kpc	3.1	Gillessen et al. (2009)
μ_{SgrA^*}	$-6.379 \pm 0.026\ \mathrm{mas\ yr^{-1}}$	3.1	Reid & Brunthaler (2004)
$K_{z,1.1}$	$2\pi G \times (71 \pm 6)\ M_\odot\ \mathrm{pc}^{-2}$	3.4	Kuijken & Gilmore (1991)
M_{50}	$\lesssim 5.4 \times 10^{11}\ M_\odot$, see equation (12)	3.5	Wilkinson & Evans (1999)
	Kinematic data	Section described	Source
	Terminal velocities	3.2	Malhotra (1994, 1995)
	Maser observations	3.3	Reid et al. (2009); Rygl et al. (2010); Sato et al. (2010)

Table of constraints used by McMillan 2011

Putting it all together





Combining these constraints gives additional information (under stated assumptions)

So, e.g. the high value of R_{thin} is related to the cusped r^{-1} density of the NFW DM density.

A cored DM profile would imply a lower value of R_{thin}

Putting it all together

	v_0	M_b	M_*	M_v
Best	239.1	8.97	66.1	1400
Convenient	244.5	8.84	65.1	1340
Mean	239.2	8.96	64.3	1260
Std. dev.	4.8	0.65	6.3	240

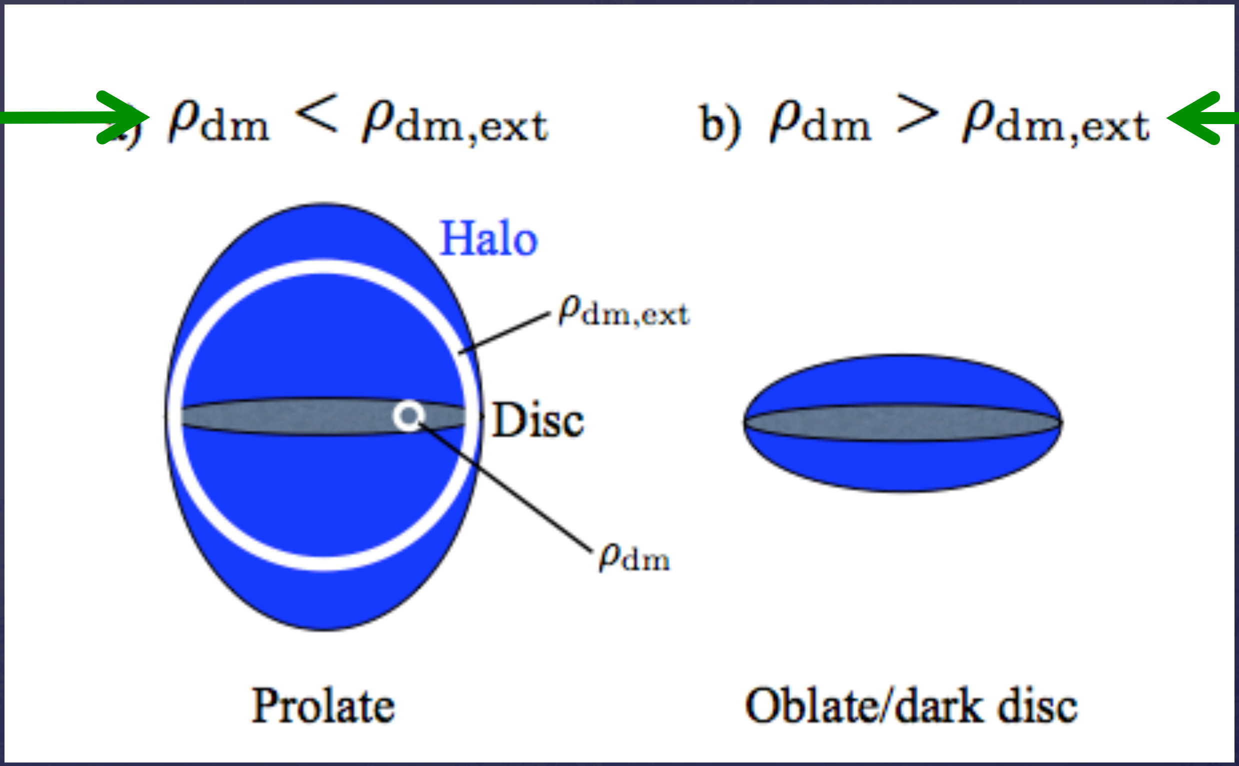
$K_{z,1.1}$	$\Sigma_{d,\odot}$	$\rho_{*,\odot}$	$\rho_{h,\odot}$	$f_{d,\odot}$
77.7	63.9	0.087	0.0104	0.122
75.4	60.3	0.083	0.0111	0.121
76.5	62.0	0.085	0.0106	0.120
5.3	7.6	0.010	0.0010	0.012

$M_\odot/pc^3$

Translates to 0.4 ± 0.04 GeV/cm^3

Can compare constraints found locally to those looking at global properties

Found locally



Found globally

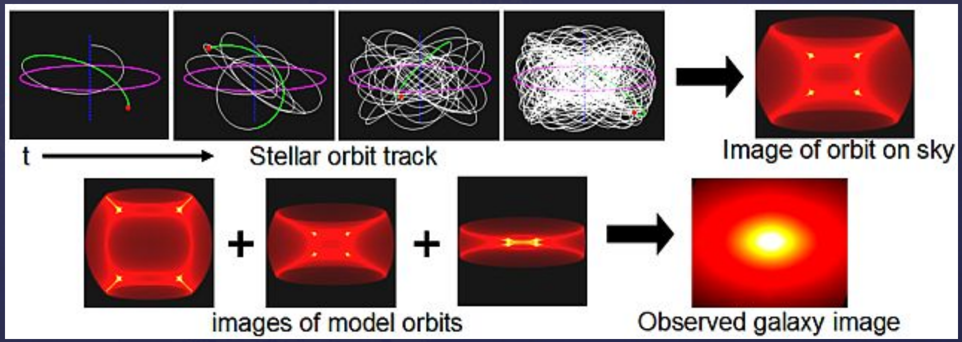
Currently uncertain, but leaning towards the former (unexpectedly)

A new approach

A df in equilibrium is of the the form f(J), where J are constants of orbital motion.

The problem is it's not easy to find these "integrals of motion" for axisymmetric potentials. $f(E,L_z)$ isn't good enough.

Usual approach (for other galaxies) is to represent as a weighted sum of phase mixed orbits (f(J) implicitly) – Schwarzchild modelling.

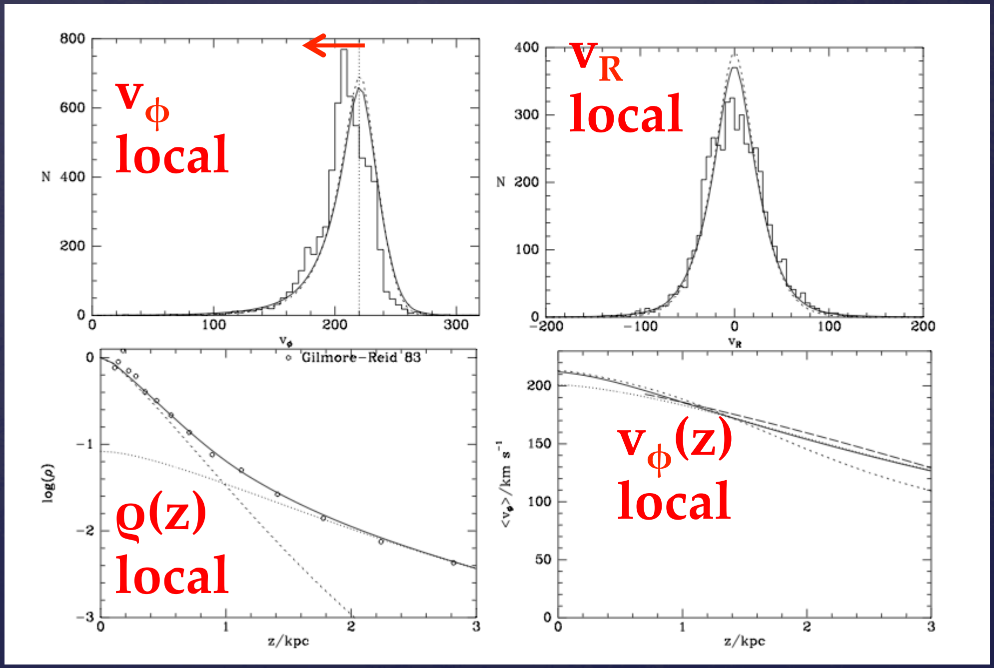


Not going to work for Milky Way – data is to good, orbit library would have to be huge. (McM & Binney 2013)

A new approach

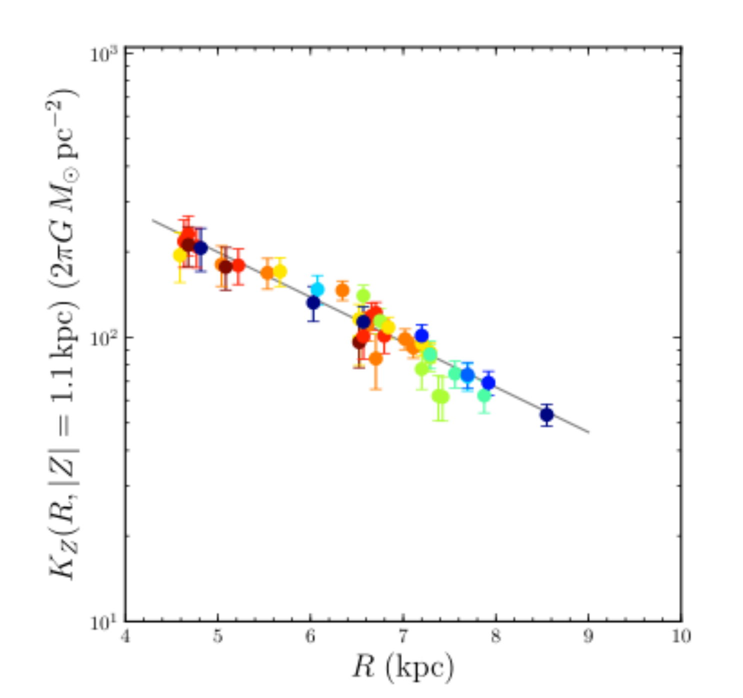
Much work has gone into getting methods for finding "action-angle coordinates" in plausible Galactic potentials, and using these to put together plausible forms for f(J) (McM & Binney 2008, 2012, Binney & McM 2011, Binney 2012)

We can then ask for new data, what Φ allows us to fit these data with f(J)?



A new approach

This approach has been shown to work for models (McM & Binney 2013, Ting et al 2013, "Gaia challenge")



It has also been applied (with a a lot of additional assumptions) to real data from the SDSS Segue (Bovy & Rix 2013).

Work is ongoing to apply to other surveys already available, and those yet to launch (Gaia).

Velocity distribution

No observational constraints.

From theory?

Anisotropic dark matter distribution functions and impact on WIMP direct detection

Nassim Bozorgnia,[a] Riccardo Catena[b] and Thomas Schwetz[a,c]

(arXiv:1310.0468)

Two points I'd make:

1)

They parameterise anisotropy through β, then produce their df as sum $f_1 + f_2$ where:

f_1 has low(ish) β throughout
f_2 has high β in outer parts

Sum has low(ish) β in inner parts, high (ish) β in outer parts, like simulated haloes.

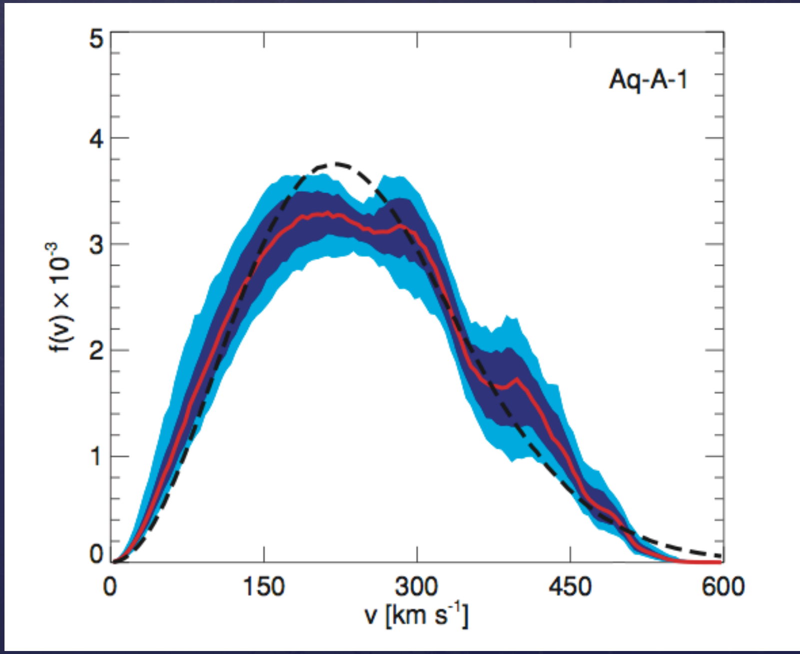
BUT:

Shape of the df will be weird.

Single parameter doesn't tell you everything

2)

Description with equilibrium df, but the least bound (highest v) particles are not phase mixed, **not in equilibrium**!



(Vogelsberger et al 2009 DM only simulations)