2.2 Local Kinematics

OVERVIEW

- Aim of the following classes

- Solar neighborhood & disk structure
- Distance measurements
- Velocities of nearby stars
- Frames of reference
- Local kinematics

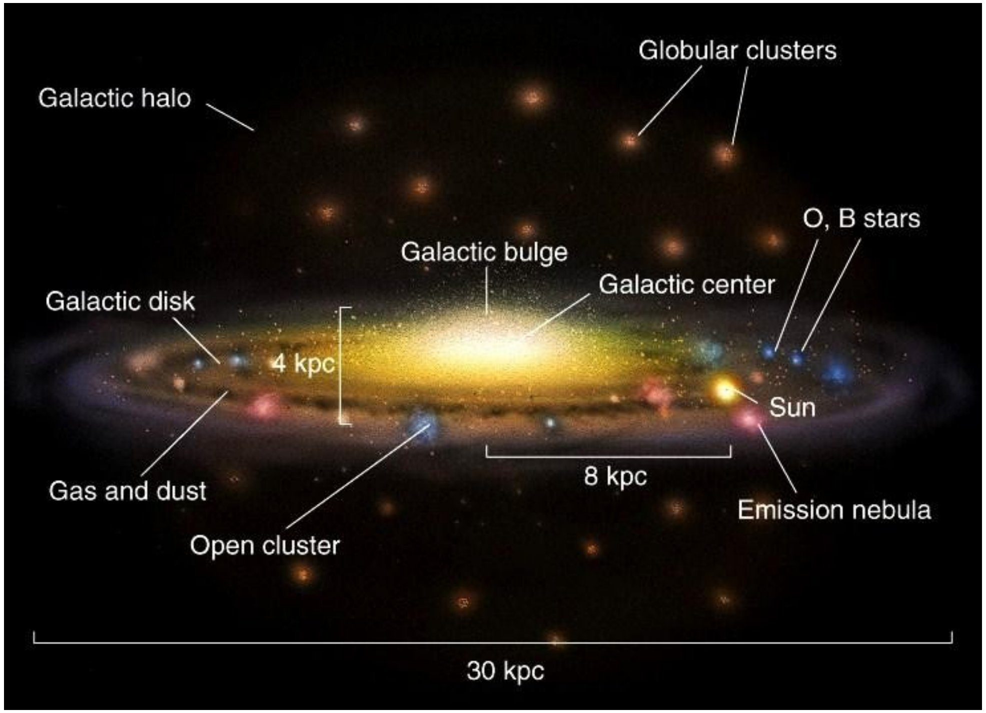
AIM

- Going from the small scale to the large scale of the Galaxy
- Acquire observational data to build the picture of the formation of the Galaxy (not give it for granted)

NOTE: In astronomy, **Galaxy**, with "G" always refers to the Milky Way, while **galaxy** refers to a general galaxy
(the title of this class is ambiguous!)

1 - SOLAR NEIGHBORHOOD AND DISK STRUCTURE

- "Neighborhood" vary according to the context (~200-300 pc, where the dust limits observations)
- Components of the Milky Way (see previous classes):



THE SOLAR NEIGHBORHOOD – MASS CONTENT

- Stars

  differences:

  - Initial Mass Function (IMF)

  - stellar evolution

Tipo	Densidad [$M_\odot$ pc^{-3}]
Estrellas de SP O-F	0.014
Estrellas de SP G-M	0.036
Estrellas del halo	0.0001
Enanas blancas	0.005
Total	**0.055**

- Interstellar medium (ISM) ~ 0.04 M_sun/pc^3

  (gas and dust)

- Dark matter ~ 0.01 M_sun/pc^3

=> TOTAL ~ 0.1 M_sun/pc^3

THE SOLAR NEIGHBORHOOD – VERTICAL DISTRIBUTION

- Stars
  - exponential
  - depends on stellar class

$$n(z) = n_0 e^{-|z|/z_0}.$$

Tipo	z_0 (pc)
O-B	50
A	120
F	190
dG	340
dK	350
dM	350

- Interstellar medium (ISM) - thin disk (gas and dust)

- Dark matter – spherical halo

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Tipo	z_0 (pc)
O-B	50
A	120
F	190
dG	340
dK	350
dM	350

- Interstellar medium (ISM) – h ~50 pc (gas and dust)

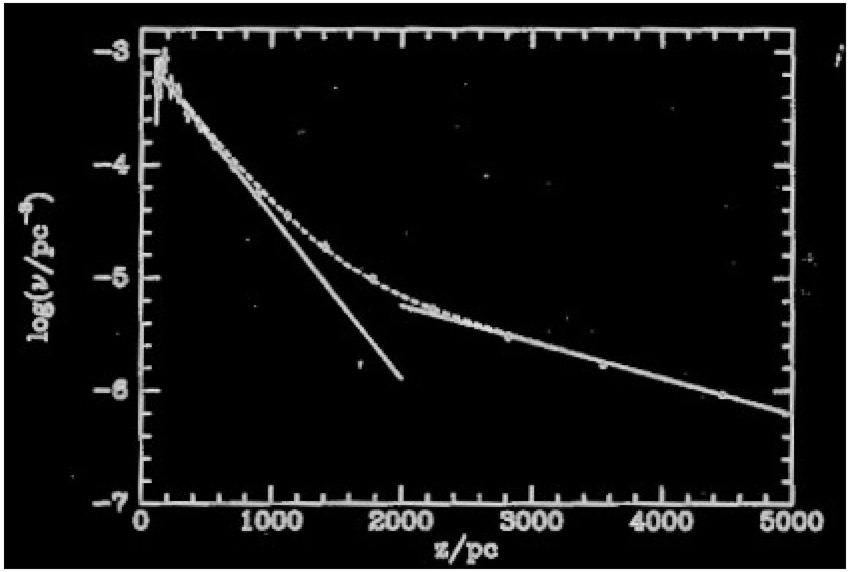
- Dark matter – spherical halo

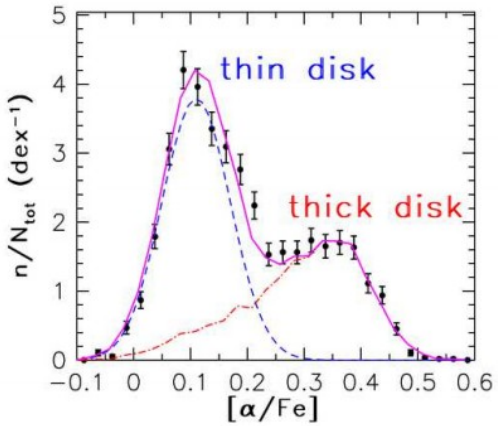
INDICATION FOR EVOLUTION ?

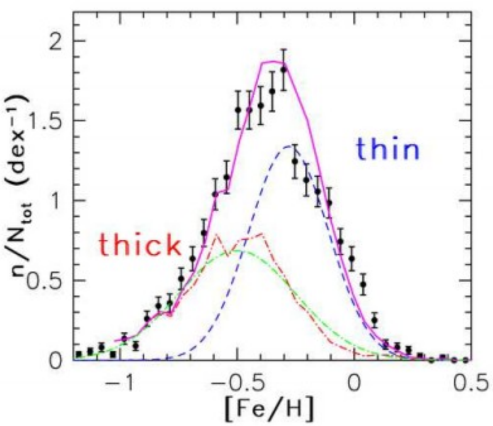
THE SOLAR NEIGHBORHOOD – DISK (VERTICAL SCALE)

More hints about disk evolution:

- The double profile of the disk
  - *thin* disk (h~250 pc) (95% of stars)
  - **thick** disk (h~1000 pc)
- Metallicity:
  - *thin* disk <[Fe/H]> ~ -0.3
  - **thick** disk <[Fe/H]> ~ -0.6







Ivezić (2012, ARA&A, 50, 251)

thin disk:

- hosts younger stars
- Same h as the gas
- narrower (as the name says)
- metal richer

THE SOLAR NEIGHBORHOOD – DISK EVOLUTION

Possible disk evolution:

- Stars are born in the same place (where is the gas), but their obits evolve in via interactions with gas clouds and spiral arms

→ interactions not sufficient to "puff-up" **thick** disk to 1 kpc (?)

- Old galaxy interaction "heated" ALL the *thin* disk, and later the gas fell back to the plane, where young stars now form

→ gas relaxes faster than stars because of viscosity

THE SOLAR NEIGHBORHOOD – CAVEATS ABOUT DISK EVOLUTION

Keep in mind:

- thick/thin disks are commonly found in spiral galaxies
  e.g. Yoachim (2005; arXiv:astro-ph/0508460v1)

- the separation thick/thin might be artificial:
  it could be a series of components
  e.g. Bovy (2012, ApJ, 753, 148)

2 – DISTANCE MEASUREMENTS

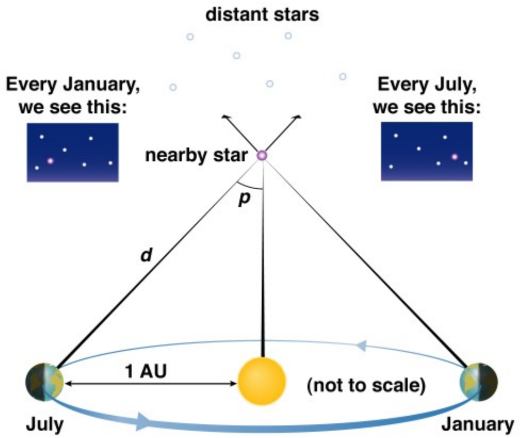
Distance measurement for the local stars

- Parallax (trigonometric):

$$d(pc) = \frac{1AU}{\pi('')}$$

Hipparchos (1989 – 1993)

Gaia (first data release 2017)

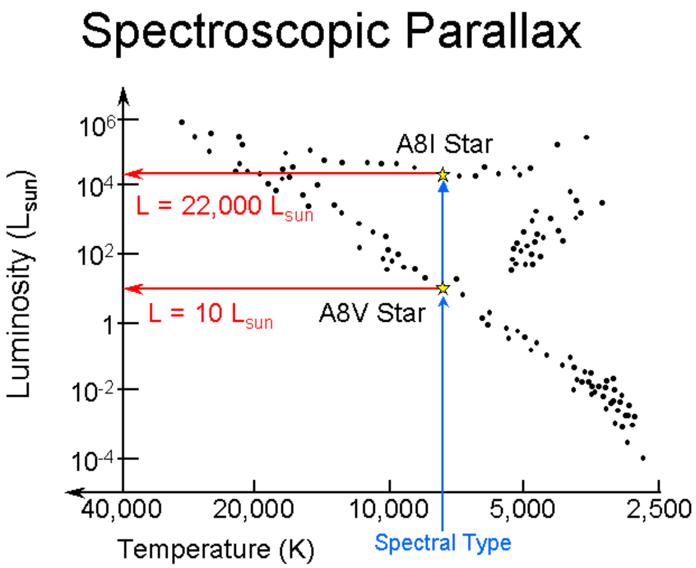


	Hipparchos	*Gaia*
mag limit (V)	12	20
Effective distance	1 kpc	10 Mpc
Observed objects	~10^5	~10^9
Distance accuracy	~5-10%	<1%

SPECTROSCOPIC PARALLAX

- Parallax (spectroscopic):
  - for a given spectral class we know L
  - compare L (model) VS F (observed)
  - → find distance:

$$L = 4\pi\ d^2\ F$$



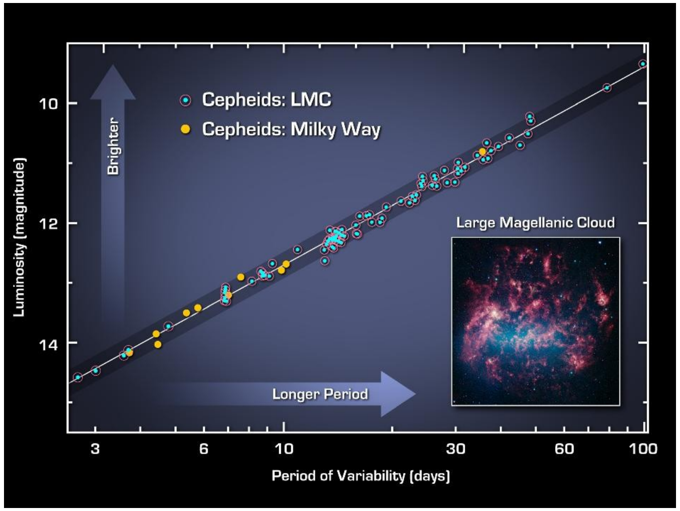
- Features:
  - less accurate than trigonometric parallax
  - valid up to larger (pre-Gaia era) distances (~100 kpc)
  - affected by dust absorption
  - luminosity class difficult to disentangle for distant stars

OTHER STELLAR DISTANCE MEASUREMENTS

- Stellar peculiar characteristics:

  - Cepheids (supergiants):
    L – Period

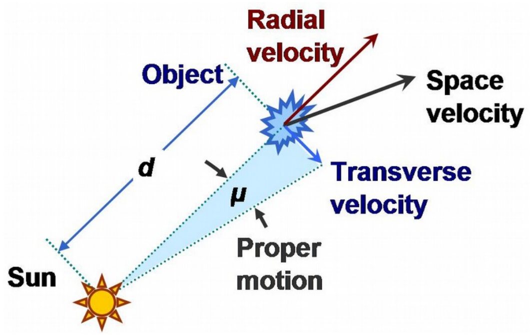
  - RR Lyrae (horizontal branch)
    spectroscopic parallax
    (they have an extremely constant L)



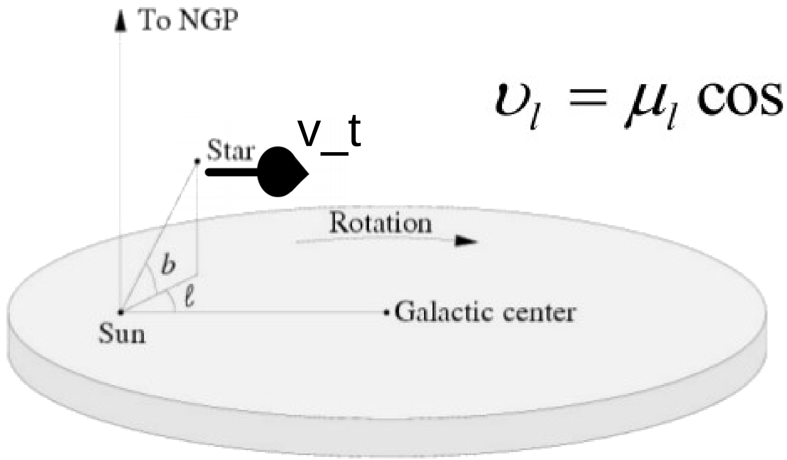
3 – VELOCITIES OF NEARBY STARS

- **Proper motion** μ [rad/sec] = motion of an object in the sky
- ... but 3D velocity v has more components:
  - *tangential* component (proper motion) $\upsilon_t = \mu\ d$
  - *radial* component (doppler) υ_r

[cm/sec]



- In galactic coordinates, v_t can be further projected as:



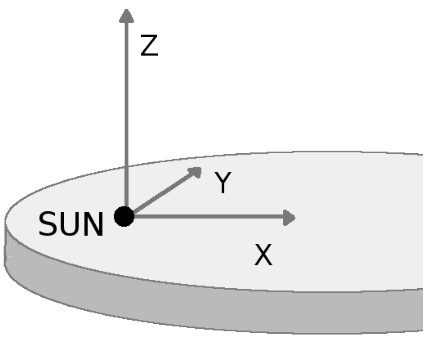
$$\upsilon_l = \mu_l \cos b\ d; \qquad \upsilon_b = \mu_b\ d$$

$$\mu_b = db/dt$$

$$\mu_l = dl/dt$$

VELOCITIES OF NEARBY STARS - HELIOCENTRIC CARTESIAN SYSTEM

- Switching to the "comfortable" heliocentric Cartesian system:



$$x = r\cos b\cos l$$
$$y = r\cos b\sin l$$
$$z = r\sin b$$

star velocity:

$$U = \frac{dx}{dt} = \dot{r}\cos b\cos l - r\dot{b}\sin b\cos l - r\dot{l}\cos b\sin l$$

$$V = \frac{dy}{dt} = \dot{r}\cos b\sin l - r\dot{b}\sin b\sin l + r\dot{l}\cos b\cos l$$

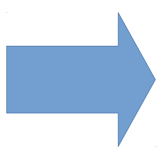
$$W = \frac{dz}{dt} = \dot{r}\sin b + r\dot{b}\cos b$$

From previous slide:

$$\dot{r} = \upsilon_r$$

$$r\dot{l}\cos b = \upsilon_l$$

$$r\dot{b} = \upsilon_b$$



$$U = \upsilon_r\cos b\cos l - \upsilon_b\sin b\cos l - \upsilon_l\sin l$$
$$V = \upsilon_r\cos b\sin l - \upsilon_b\sin b\sin l + \upsilon_l\cos l$$
$$W = \upsilon_r\sin b + \upsilon_b\cos b$$

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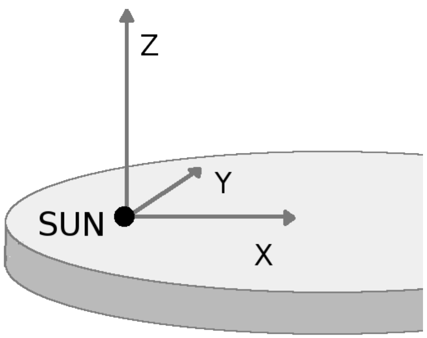

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$$W = \frac{dz}{dt} = \dot{r}\sin b + r\dot{b}\cos b$$

Measurable:
- v_r → *spectroscopy*
- v_b, v_l → *proper motion*

From previous slide:

$$\dot{r} = \upsilon_r$$

$$r\dot{l}\cos b = \upsilon_l$$

$$r\dot{b} = \upsilon_b$$

$$U = \upsilon_r \cos b \cos l - \upsilon_b \sin b \cos l - \upsilon_l \sin l$$
$$V = \upsilon_r \cos b \sin l - \upsilon_b \sin b \sin l + \upsilon_l \cos l$$
$$W = \upsilon_r \sin b + \upsilon_b \cos b$$

VELOCITIES OF NEARBY STARS - HELIOCENTRIC CARTESIAN SYSTEM

$$\upsilon_r = U\cos b\cos l + V\cos b\sin l + W\sin b$$
$$\upsilon_b = -U\sin b\cos l - V\sin b\sin l + W\cos b$$
$$\upsilon_l = U\sin l + V\cos l$$

Reverse

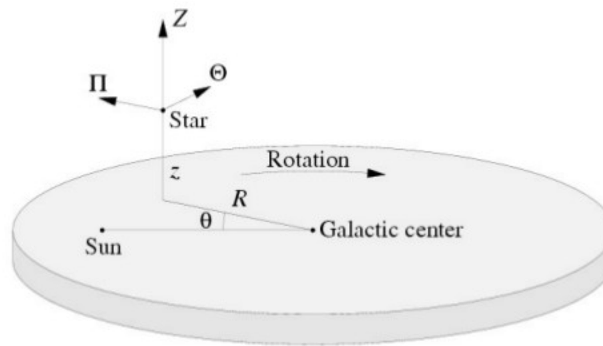
(we will need them later)

$$U = \upsilon_r\cos b\cos l - \upsilon_b\sin b\cos l - \upsilon_l\sin l$$
$$V = \upsilon_r\cos b\sin l - \upsilon_b\sin b\sin l + \upsilon_l\cos l$$
$$W = \upsilon_r\sin b + \upsilon_b\cos b$$

4 – FRAMES OF REFERENCE

- **Galacto-centic** system is the natural system (!= galactic coordinates!):

$\Pi \equiv dR/dt$
$\Theta \equiv R\, d\theta/dt$
$Z \equiv dz/dt$



Fundamental Frame of Reference (SFR)

- However, to study the Sun's neighborhood is more convenient to adopt a "local" frame of reference:

Local Standard of Rest (LSR)

Kinematic LSR

heliocentric, rotates at the average velocity of local stars (no assumptions on why)

Dynamic LSR

defined at any point, rotates on circular orbit with a velocity Θ_0 imposed by axisymmetric potential

4 – FRAMES OF REFERENCE

IF stars were really on perfectly circular orbits

Local Standard of Rest (LSR)

Kinematic LSR

heliocentric, rotates at the average velocity of local stars (no assumptions on why)

=

Dynamic LSR

defined at any point, rotates on circular orbit with a velocity Θ_0 imposed by axisymmetric potential

PECULIAR VELOCITY

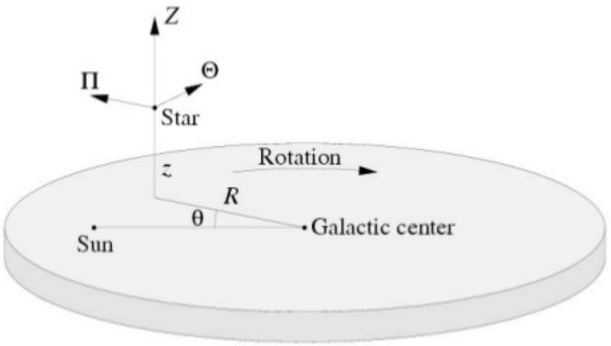
- **Peculiar velocity** = velocity (u,v,w) of a star w/r to its dyn. LSR (LSR*)

Variable	Descripción
X,Y,Z	Coordenadas de un objeto en el SFR
Π,Θ,Z	Velocidad de un objeto en el SFR
$(0,\Theta_0,0)$	Velocidad del LSR en el SFR
u,v,w	Velocidad peculiar, i.e., velocidad de una estrella respecto a sus SLR.
U,V,W	Velocidad de un objeto respecto al Sol
v_Θ'	Velocidad acimutal del Sol respecto al LSR cinemático
v_Θ	Velocidad acimutal del Sol respecto al LSR dinámico
υ_r	Velocidad de un objeto respecto al Sol, a lo largo de la visual
υ_l , υ_b	Velocidad de un ojbeto respecto al Sol, en dirección *l*, *b*, respectivamente

$\Pi \equiv dR/dt$

$\Theta \equiv R\, d\theta/dt$

$Z \equiv dz/dt$



$$u_* = \Pi_* - \Pi_{SLR} = \Pi$$

$$v_* = \Theta_* - \Theta_{LSR} = \Theta - \Theta_0$$

$$w_* = Z_* - Z_{LSR} = Z$$

Peculiar velocity

- To convert this to heliocentric coordinates we need to:

→ find the peculiar velocity of Sun w/r to its LSR (LSR_sun)

→ find the differential velocity between LSR_sun and LSR*

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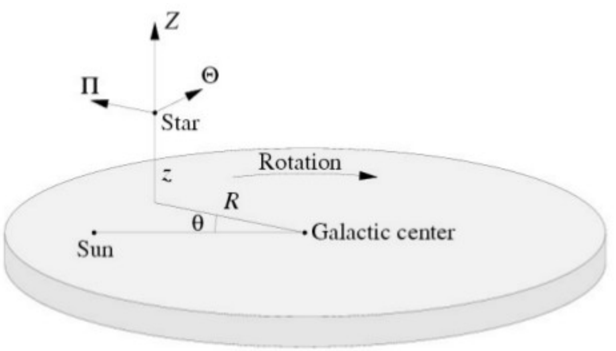


$$u_* = \Pi_* - \Pi_{SLR} = \Pi$$

$$v_* = \Theta_* - \Theta_{LSR} = \Theta - \Theta_0$$

$$w_* = Z_* - Z_{LSR} = Z$$

Peculiar velocity

- To convert this to heliocentric coordinates we need to:

→ find the peculiar velocity of Sun w/r to its LSR (LSR_sun)

→ ~~find the differential velocity between LSR_sun and LSR*~~

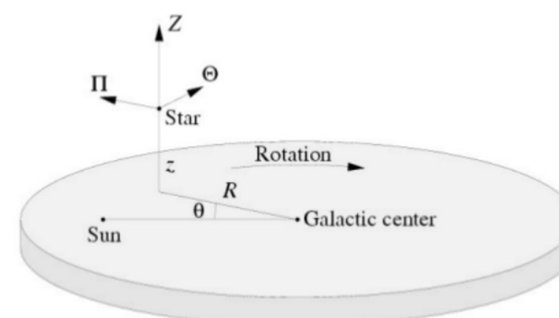
(we ignore this assuming no differential rotation – nearby stars)

PECULIAR VELOCITY – HELIOCENTRIC COORDINATES

- Velocity of a star w/r to the Sun:

$$U_* = u_* - u_\Theta - (\Pi_{LSR*} - \Pi_{LSR\Theta})$$
$$V_* = v_* - v_\Theta - (\Theta_{LSR*} - \Theta_{LSR\Theta})$$
$$W_* = w_* - w_\Theta - (Z_{LSR*} - Z_{LSR\Theta})$$

assuming no differential rotation



$$U_* = u_* - u_\Theta = \Pi_* - \Pi_\Theta$$
$$V_* = v_* - v_\Theta = \Theta_* - \Theta_\Theta$$
$$W_* = w_* - w_\Theta = Z_* - Z_\Theta$$

NOTE: u v *w* ↔ LSR**

$u_\Theta\, v_\Theta\, w_\Theta$ ↔ LSR_sun

- Adopting a sample of nearby stars, we can say:

$$\langle U_* \rangle = \underbrace{\langle u_* \rangle}_{=0} - u_\Theta = -u_\Theta$$
$$\langle W_* \rangle = \langle w_* \rangle - w_\Theta = -w_\Theta$$

- But we *cannot* say: $\langle v_* \rangle = 0$

  - that is true in the *kinematic* LSR (actually it's the definition)

  - ... but now we are using the *dynamic* LSR

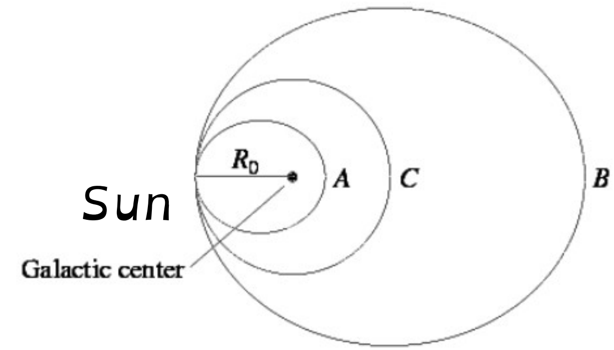
ESTIMATING <v*>

- A = Sun's orbit

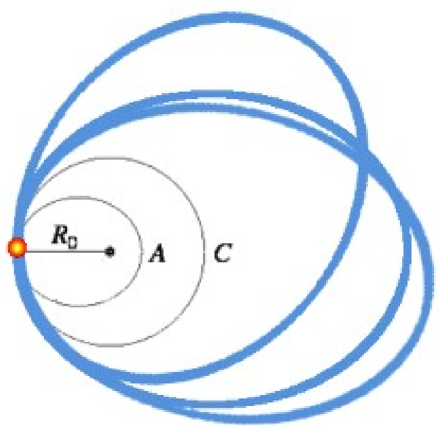
  B = random star orbit

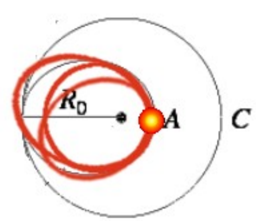
  C = circle around Galaxy center

  (where LSR is defined)



- Consider that stars passing near the Sun when it is at the apocenter:





  - are slower
  - come from the outskirts of the Galaxy

    (where density is lower)

→ on average stars are slower than the Sun!

Asymmetric drift → <v*> < 0

We will therefore write: $\langle V_* \rangle = \langle v_* \rangle - v_\Theta$

and define the velocity of Sun w/r to the *kinematic* LSR v_Θ': $v'_\Theta = -\langle V_* \rangle$

FORMULATION OF PECULIAR MOTION OF THE SUN

- Finally, the **peculiar motion ($u_\odot$, $v_\odot$, $w_\odot$) of the Sun** (in dyn. LSR_sun) is:

$$u_\Theta = -\langle U_* \rangle$$

$$v_\Theta = -\langle V_* \rangle + \langle v_* \rangle = v'_\Theta + \langle v_* \rangle$$

$$w_\Theta = -\langle W_* \rangle$$

- while **($u_\odot$, $v'_\odot$, $w_\odot$)** defines the **motion of the Sun** in the kin. LSR
- Let's now see how to *measure* it:

$$\upsilon_r = U \cos b \cos l + V \cos b \sin l + W \sin b$$

$$\upsilon_b = -U \sin b \cos l - V \sin b \sin l + W \cos b$$

$$\upsilon_l = U \sin l + V \cos l$$

Star velocity w/r Cartesian heliocentric (seen previously)

for each star i in a sample:

$$\upsilon_{ri} = U_i \cos l_i \cos b_i + V_i \sin l_i \cdot \cos b_i + W_i \sin b_i$$

By grouping stars in sub-samples with (l,b) ~ CONST :

$$\upsilon_{ri} = \alpha U_i + \beta V_i + \gamma W_i$$

$$\langle \upsilon_{ri} \rangle = -\alpha \cdot u_\Theta - \beta \cdot v'_\Theta - \gamma \cdot w_\Theta$$

MEASUREMENT OF PECULIAR MOTION OF THE SUN

$$\langle \upsilon_{ri} \rangle = -\alpha \cdot u_{\Theta} - \beta \cdot v'_{\Theta} - \gamma \cdot w_{\Theta}$$

- This equation holds for each sub-sample (l,b) ~ CONST

  → for *M* sub-samples (*j* = 1 … *M*), we have *M* equations of the type:

$$\alpha_j u_{\Theta} + \beta_j v'_{\Theta} + \gamma_j w_{\Theta} = k_j$$

- Solving the equations (3 sub-samples are sufficient)

  → we obtain the **(u_{Θ}, v'_{Θ}, w_{Θ}) motion of the Sun** in the *kinematic* LSR

WE USED ONLY THE RADIAL VELOCITIES !

→ we can now obtain the motion of any star

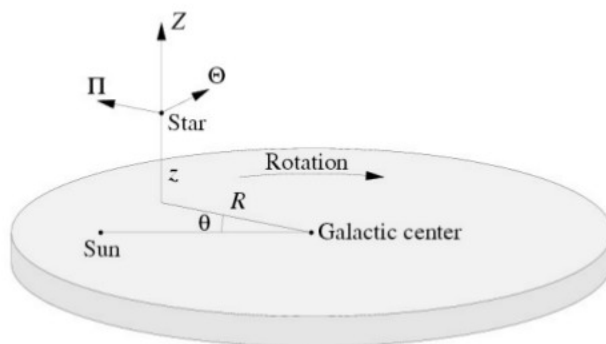
Values measured:
Sun is moving north and inward, faster than LSR_sun

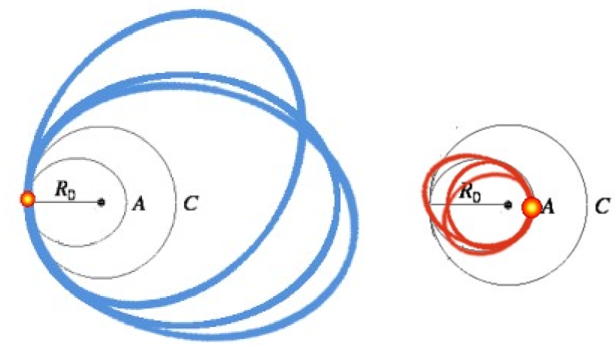
$$u_{\Theta} = 10.0 \quad km \cdot s^{-1}$$
$$v'_{\Theta} = 5.2 \quad km \cdot s^{-1}$$
$$w_{\Theta} = 7.2 \quad km \cdot s^{-1}$$

MEASUREMENT OF PECULIAR MOTION OF THE SUN

- Let's switch to the **(u_{Θ}, v_{Θ}, w_{Θ}) motion of the Sun** in the *dynamic* **LSR** *(i.e., let's find v_{Θ})*

$\Pi \equiv dR/dt$
$\Theta \equiv R\, d\theta/dt$
$Z \equiv dz/dt$



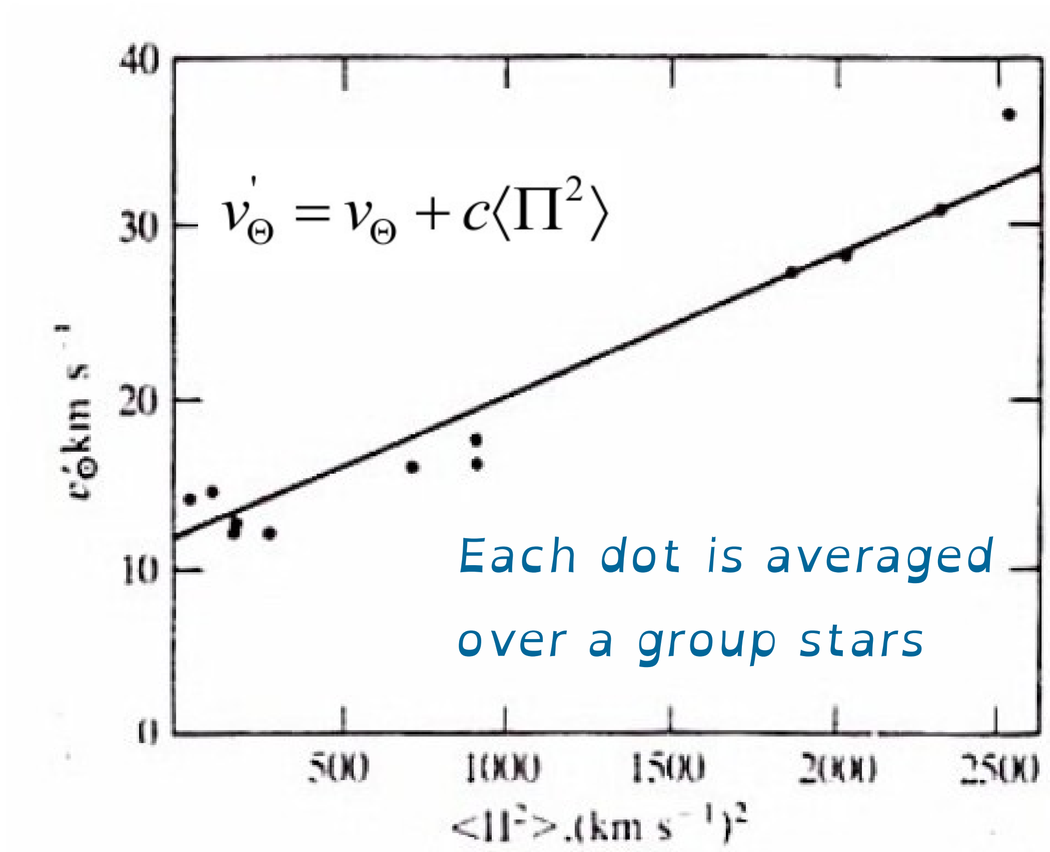


- We can assume that v_{Θ} depends on how many elliptical obits there are Observationally, this is given by the dispersion on radial velocities Π:

$$\langle v_* \rangle \sim \langle \Pi^2 \rangle$$

$$v_{\Theta} = -\langle V_* \rangle + \langle v_* \rangle = v'_{\Theta} + \langle v_* \rangle \quad \Rightarrow \quad v'_{\Theta} = v_{\Theta} + c\langle \Pi^2 \rangle$$

MEASUREMENT OF PECULIAR MOTION OF THE SUN



$$v'_{\Theta} = v_{\Theta} + c\langle \Pi^2 \rangle$$

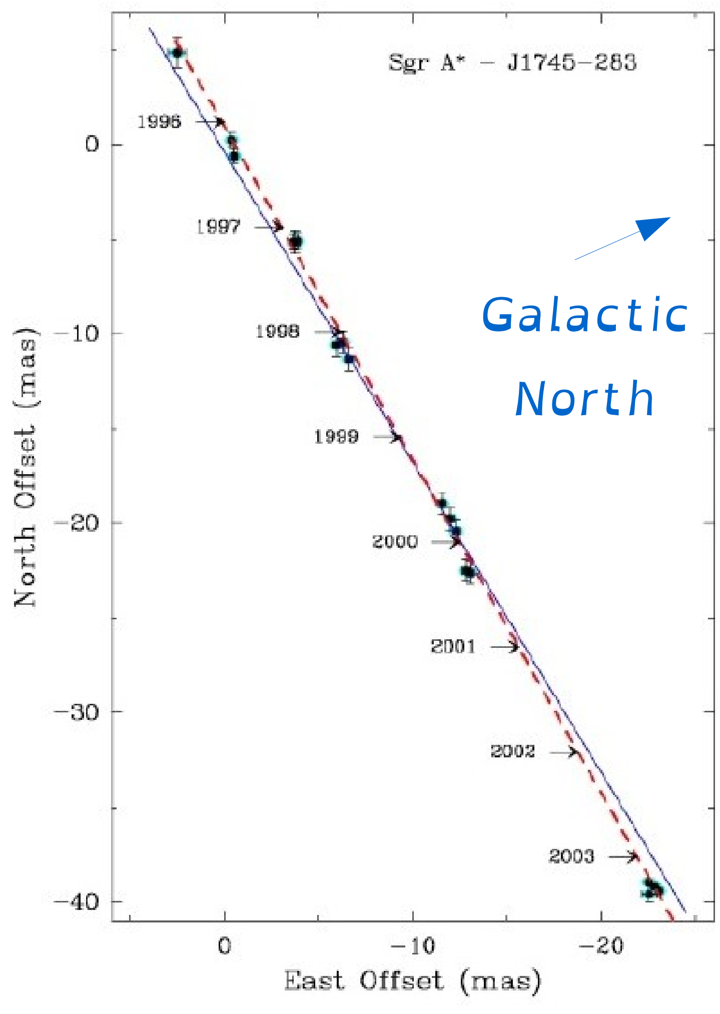
Each dot is averaged over a group stars

$$v_{\Theta} = 12.0 \quad km \cdot s^{-1}$$

!= 0 → Sun moves also w/r to dynamic LSR

MOTION OF THE LSR_sun IN THE GALAXY (SFR)

- We can use the apparent movement of the radio source SgrA* (AGN)
- Radio interferometry (e.g. VLBI) can achieve high (μarcsec) resolution
- Assuming R_0 = 8.5 kpc
  → relative velocity $\Theta_0 \sim 235$ km/sec
- Can repeat with any non-rotating object:
  - halo GCs → $\Theta_0 \sim$ 220 km/sec
  - other galaxies (big uncertainties)



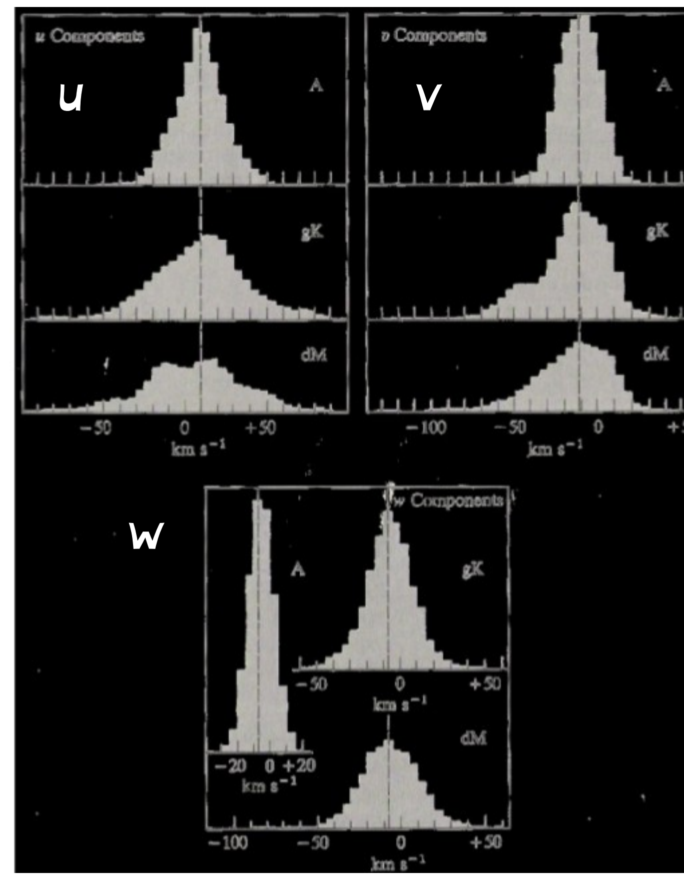
5 – LOCAL KINEMATICS - DISK

- Distribution of stellar velocity around u, v, w ~ Gaussian
- The distribution changes with:

  - the axis u, v, w

  - the stellar type

Tipo	$\langle u^2\rangle^{0.5}$	$\langle v^2\rangle^{0.5}$	$\langle w^2\rangle^{0.5}$	l_v (°)
Enanas				
B0	10	9	6	-50
A0	15	9	9	15
F0	24	13	10	19
G0	26	18	15	21
K0	28	16	11	2
M0	32	21	10	3
Gigantes				
A	22	13	9	27
F	28	15	9	14
G	26	18	15	12
K0	31	21	16	14
Súpergigantes				
Cefeidas	13	9	5	-
O-B5	12	11	9	36



LOCAL DISK KINEMATICS - VELOCITY DISTRIBUTIONS

- We observe:
  - distribution is tighter for more massive (younger) stars
  - later stellar types along M-S include stars of a wider range of ages *(hence their distributions are intrinsically wider)*

Tipo	$\langle u^2\rangle^{0.5}$	$\langle v^2\rangle^{0.5}$	$\langle w^2\rangle^{0.5}$	l_v (°)
Enanas				
B0	10	9	6	-50
A0	15	9	9	15
F0	24	13	10	19
G0	26	18	15	21
K0	28	16	11	2
M0	32	21	10	3
Gigantes				
A	22	13	9	27
F	28	15	9	14
G	26	18	15	12
K0	31	21	16	14
Súpergigantes				
Cefeidas	13	9	5	-
O-B5	12	11	9	36

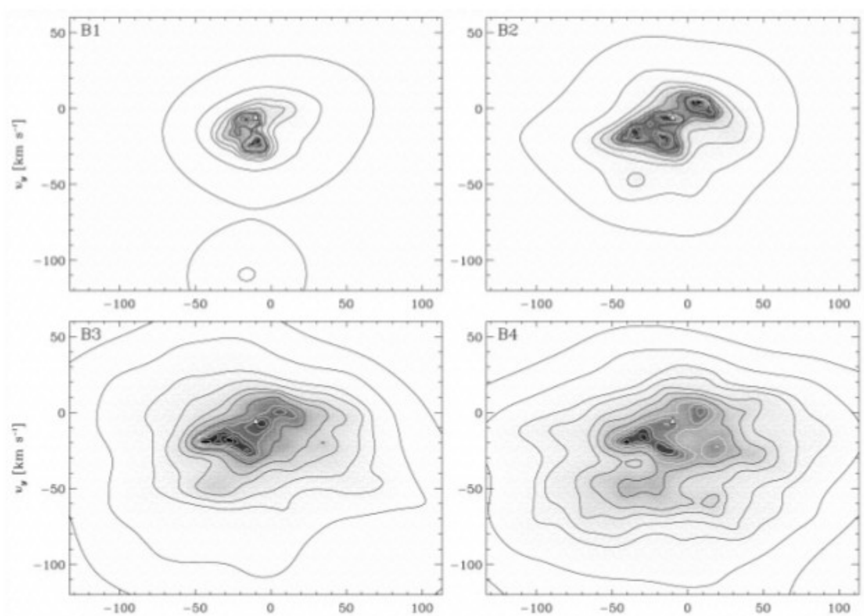
- Consistent with the picture that stars form in the gas disk, with:
  - small vertical separation
  - similar peculiar velocities

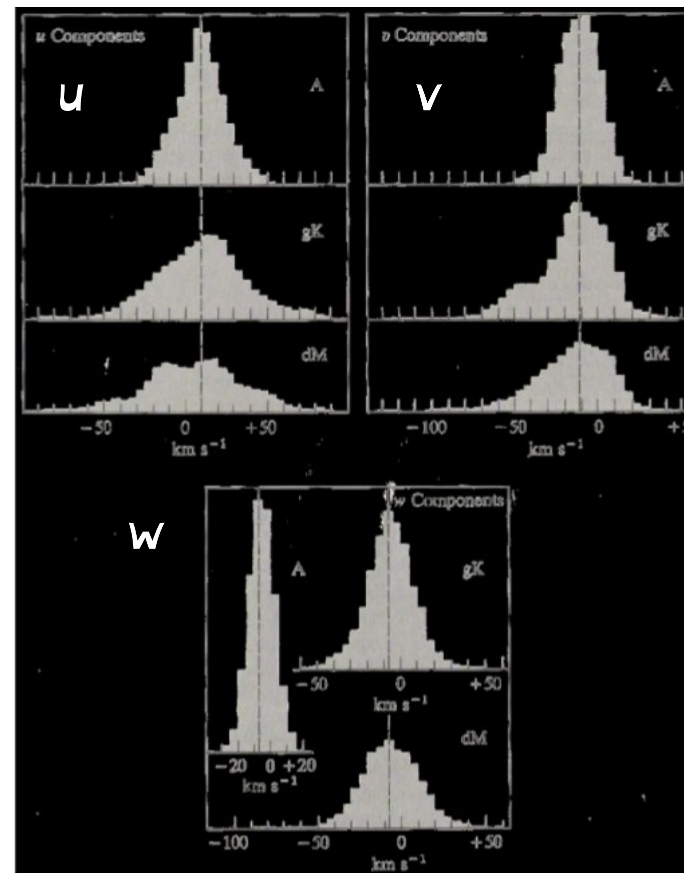
- … and their obits evolve by interactions with molecular clouds and spiral arms

NOTE: still not enough to create thick disk!

LOCAL DISK KINEMATICS - VELOCITY DISTRIBUTIONS 2D

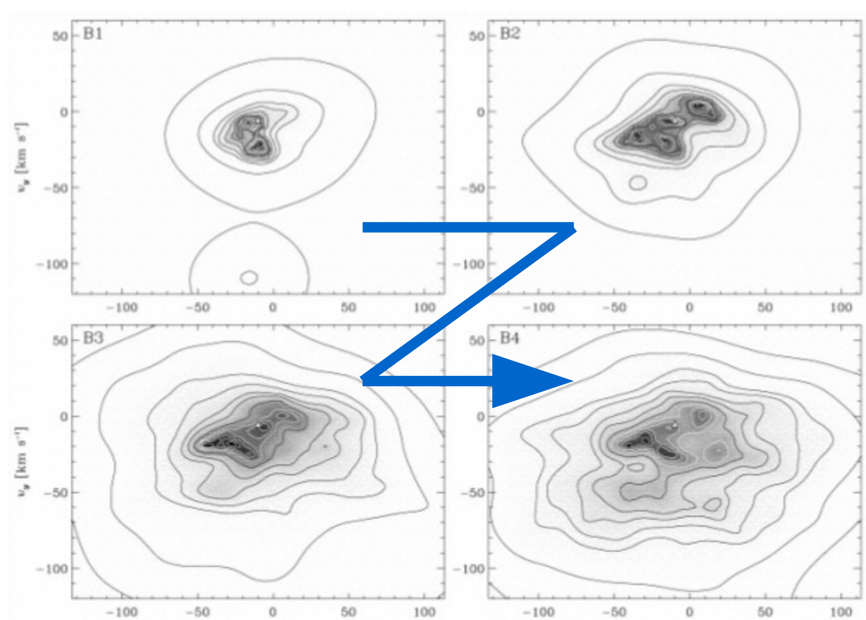
- Distribution around u, w ~ symmetric
- Distribution around v !~ symmetric
  and <v> < 0 (asymmetric drift)
- Alternative view:





LOCAL DISK KINEMATICS - VELOCITY DISTRIBUTIONS 2D

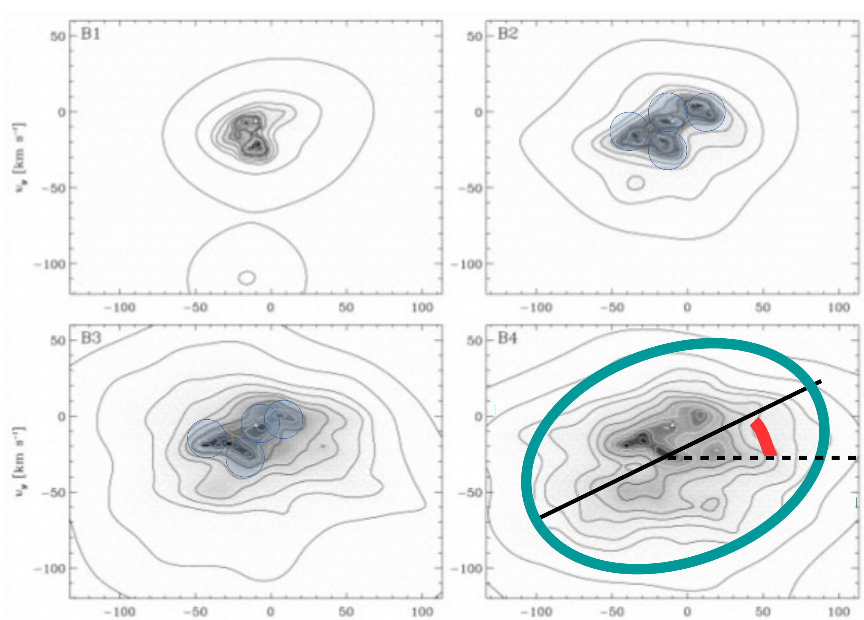
- dispersion u > dispersion v > dispersion w *(why? under debate)*
- smaller mass ↔ higher dispersion
- dispersion v asymmetric, <v> < 0



Decreasing mass

LOCAL DISK KINEMATICS - VELOCITY ELLIPSOID

- Co-moving groups
  - can be identified on the u, v, w hyperplane *(see e.g. work of A. Binks)*
  - mostly composed by massive (young) stars
    (they get dispersed by interactions)



Examples:

Pleiads, Hyades, Sirio group

- We define:
  - the velocity ellipsoid (it's 3D)
  - the vertex deviation (angle l_v)

LOCAL DISK KINEMATICS - VELOCITY ELLIPSOID

- How to write the velocity Probability distribution Function P(V)?

  If the distributions were independent & symmetric Gaussians:

$$P(\bar{V}) = P_u(u)P_v(v)P_w(w)$$
$$= \frac{1}{(2\pi)^{1.5}\sigma_u\sigma_v\sigma_w}\exp\left[-\left(\frac{u^2}{2\sigma_u^2}+\frac{v^2}{2\sigma_v^2}+\frac{w^2}{2\sigma_w^2}\right)\right]$$

  ... but the only symmetric Gaussian is w, while u and v are correlated !

- We choose new axis set:
  - **u_1** ← *rotating u, v by l_v*
  - **v_2**
  - **w** ← *we keep this axis*

$$\frac{1}{(2\pi)^{1.5}\sigma_1\sigma_2\sigma_w}\exp\left[-\left(\frac{u_1^2}{2\sigma_1^2}+\frac{v_2^2}{2\sigma_2^2}+\frac{w^2}{2\sigma_w^2}\right)\right]$$

Schwarzschild distribution

(somebody call this "velocity ellipsoid")

LOCAL DISK KINEMATICS - VERTEX DEVIATION

- Considerations on vertex deviation:

  1- is more significant for younger stars

  2- in an axi-symmetric system, u would be a principal axis

Tipo	$\langle u^2 \rangle^{0.5}$	$\langle v^2 \rangle^{0.5}$	$\langle w^2 \rangle^{0.5}$	l_v (°)
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K0	31	21	16	14
Súpergigantes				
Cefeidas	13	9	5	-
O-B5	12	11	9	36

- Possible origins of vertex deviation:

  1- initial formation condition

  few nearby co-moving groups strongly influence the (u,v) distribution (stochastic occurrence)

  2- local potential is **not** axi-symmetric

  attraction by e.g. spiral arms

LOCAL HALO KINEMATICS

- Characteristics of halo stars:

  - large peculiar velocities (i.e. velocity w/r to their LSR)

    → a.k.a. *high-velocity stars*

  - large asymmetric drift (i.e. <v*>)

    → large difference w/r to a circular orbit

    (halo is a sphere with almost no rotation)

- For halo, better use the Galcto-centric (SFR) velocities (Π, Θ, Z)

  (Θ_0 = velocity of LSR_sun in the SFR) ~ 220 km/sec

Tipo	$\langle\Theta\rangle-\Theta_0$	$\langle\Theta\rangle$	σ_Π	σ_Θ	σ_Z
Cúmulos globulares	-165	55	145	-	-
Sub-enanas	-185	35	170	90	65
RR Lyraes	-220	0	210	120	90

LSR_sun → $\langle\Theta\rangle-\Theta_0$

Galacto-centric (SFR) → $\langle\Theta\rangle$

LOCAL HALO KINEMATICS

- Additionally:
  - large velocity dispersions (σ_Π, σ_Θ, σ_Z)
  - milder rotation than disk ($<\Theta>$)

    inner halo → prograde 0÷60 km/sec

    outer halo → retrograde -40÷-70 km/sec

    Frank & White (1980), Carollo (2007, Nature, 450, 1020)

- We will also see that halo stars are:
  - old
  - metal poor

Tipo	$<\Theta>-\Theta_0$	$<\Theta>$	σ_Π	σ_Θ	σ_Z
Cúmulos globulares	-165	55	145	-	-
Sub-enanas	-185	35	170	90	65
RR Lyraes	-220	0	210	120	90

KINEMATICS – BIG PICTURE