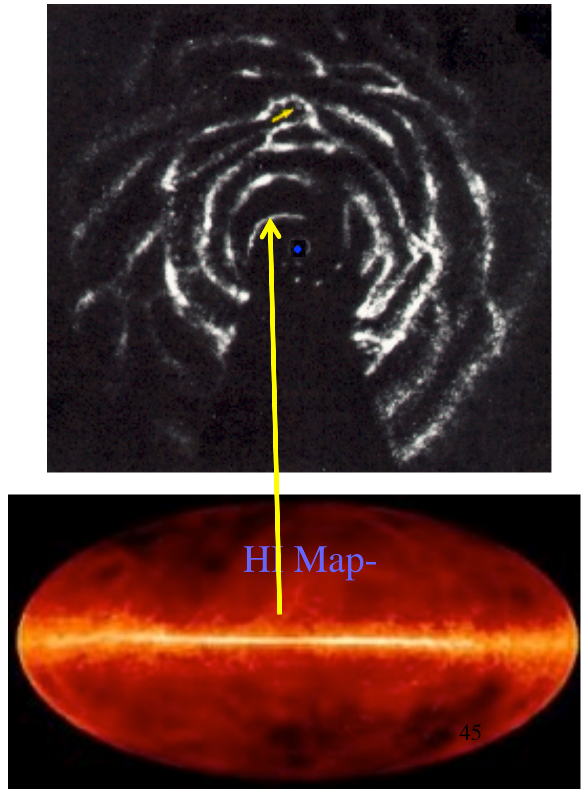
HI Maps- Major Way to Trace MW Velocity Field

- HI lies primarily in the plane- maps have velocity data associated with them- allows dynamics to be determined
  - deproject HI velocity and intensity map to show total structure of the galaxy
- Not affected by dust- shows detailed structures.
- see review article by Kalbela and J. Kerp on the web page
- Neutral atomic hydrogen (HI) traces the interstellar medium (ISM) over a broad range of physical conditions.
- 21-cm emission line is a key probe of the structure and dynamics of the Milky Way Galaxy.



Velocity of HI

- In the plane of the disk the velocity and intensity of HI gas (Sparke and Gallagher fig 2.20)
- The distribution of HI and CO emission in the longitude-velocity plane yield a characteristic maximum ("terminal") velocity for each line of sight (e.g. Binney & Merrifield 1998§9.1.1). The terminal velocities are related to the circular speed $v_c(R)$ by $v_{term}(l) = (\sin l)\, v_c(R) - v_c(R_0))\sin l$

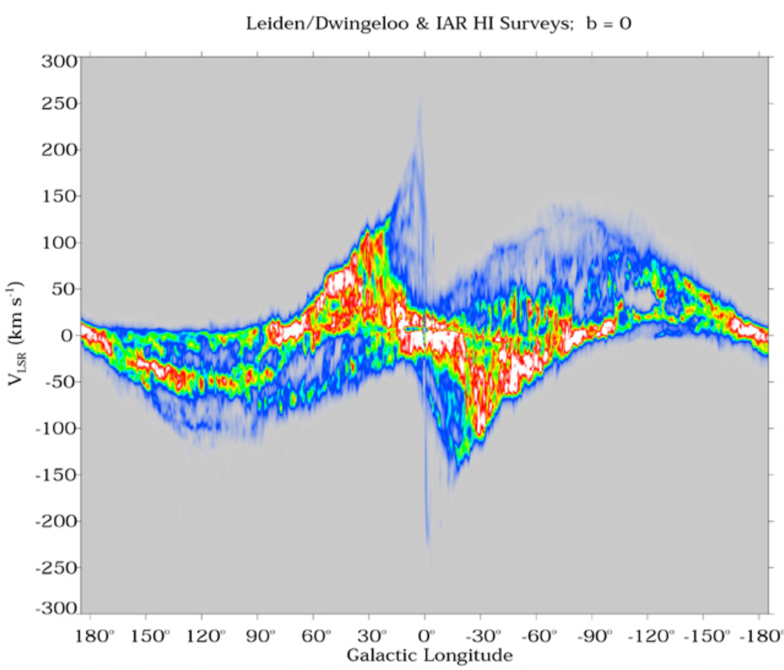


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Galactic Rotation- S+G sec 2.3, B&T sec 3.2

- Consider a star in the midplane of the Galactic disk with Galactic longitude, l, at a distance d, from the Sun. Assume circular orbits radii of R and R_0 from the galactic center and rotational velocities of V and , V_0

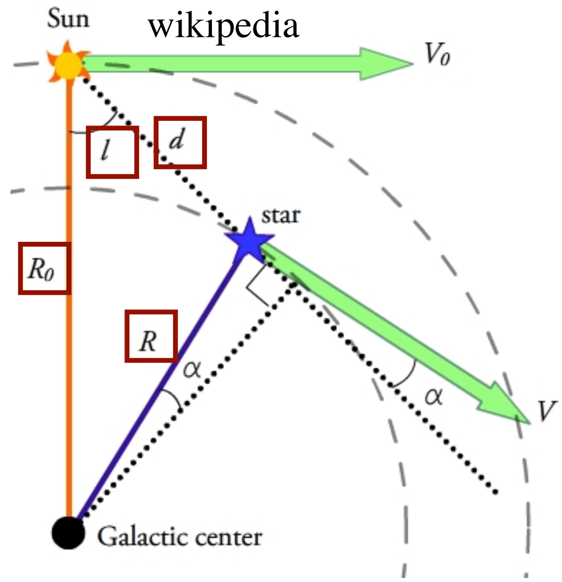
- The 2 components of velocity- radial and transverse are then for circular motion
- $V_{\text{observered, radial}} = V(\cos\alpha) - V_0 \sin(l)$
- $V_{\text{observered ,tang}} = V(\sin\alpha) - V_0 \cos(l)$
- using the law of sines

$\sin l/R \sim \cos\alpha/R_0$

which gives

$V_{\text{observered, radial}} = R_0 \sin(l)[(V/R) - (V_0/R_0)]$
S&G 2.11

Much more later



Since we have 'poor' idea of distance rely on tangent point
at 0<l<90 radial velocity is highest at the tangent point where los passes closest to galactic center

HI Observables- How to 'De-project'

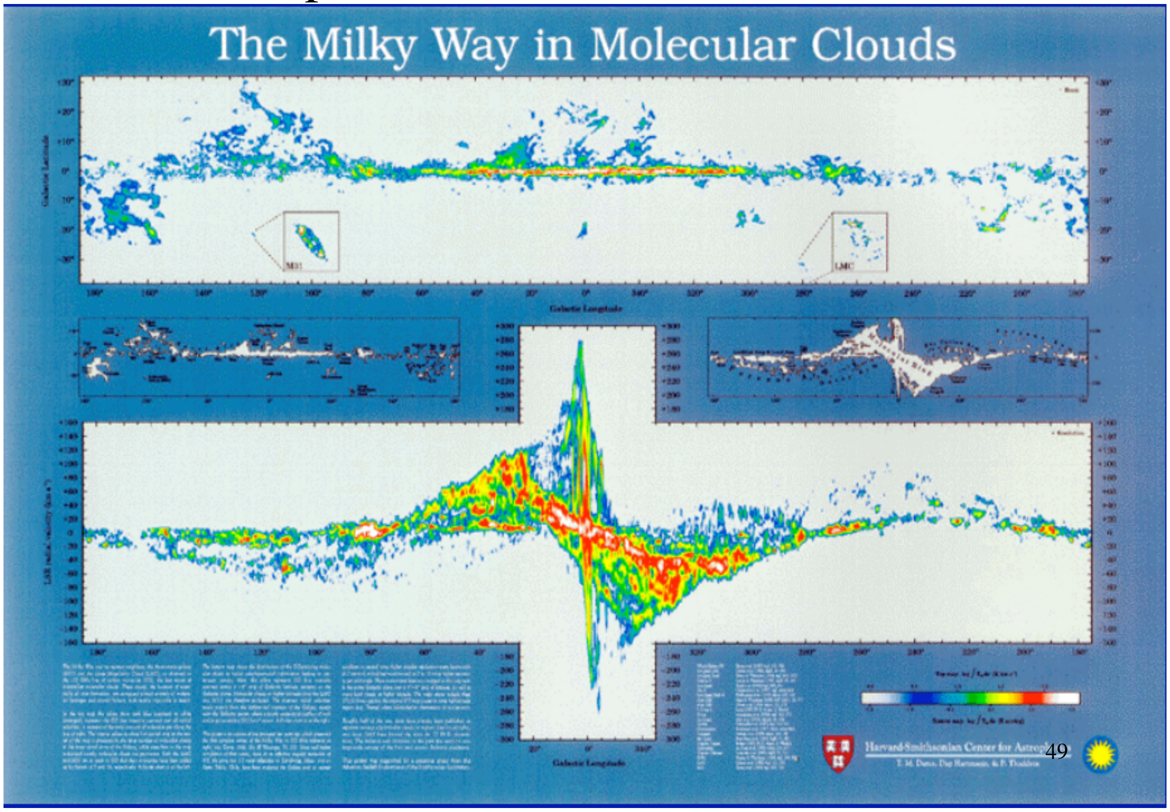
- Observed intensity $T_B(l, b, v)$ observed in Galactic coordinates longitude l and latitude b need to be converted into volume densities n(R, z) (Burton & te Lintel Hekkert 1986, Diplas & Savage 1991).
- Assuming that most of the gas follows an axisymmetric circular rotation yields a relation for the differential rotation velocity (e.g., Burton1988)

  $v(R, z) = [(R_\odot/R)\,\Theta(R, z) - \Theta_\odot]\sin l$ -cos b where v is the radial velocity along a line of sight(directly measurable); and Θ is the tangential velocity (

- for $R < R_\odot$, distances are ambiguous,
- for $R > R_\odot$, one needs to know the Galactic constants $R_\odot$ and $\Theta_\odot$ and the form of $\Theta(R, z)$ e.g. the rotation curve shape.
- See S&G pg 92-94.

$R_\odot$ is the distance of the sun from the galactic center and $\Theta_\odot$ is the velocity of rotation at the sun (a lot more later)

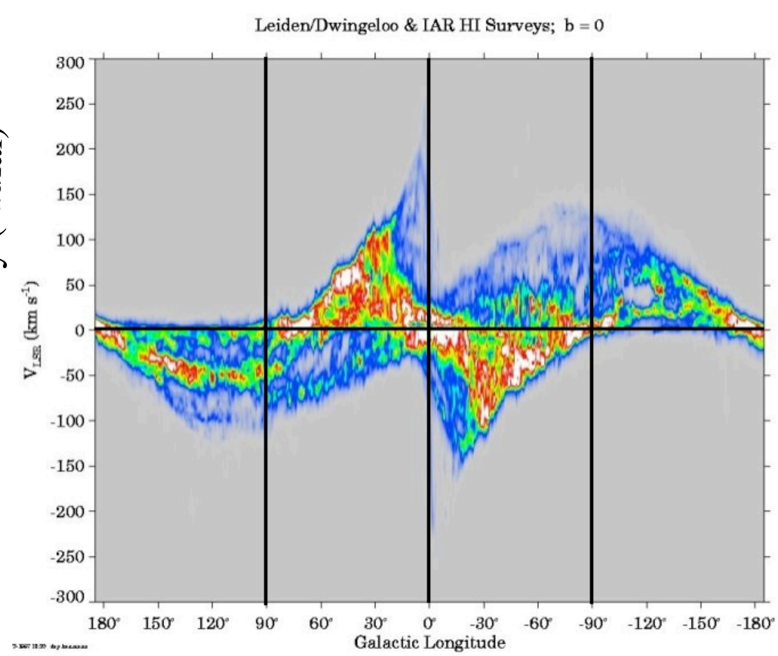
CO Maps-Tracer of Dense Molecular Gas



Galactic Rotation Curve HI data

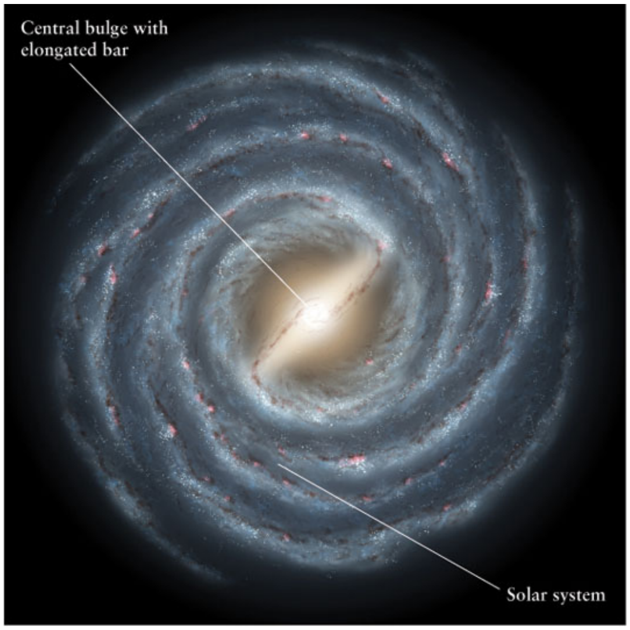
- Velocity, longitude, intensity graph of HI in the MW fig 2.20 in S+G
- The HI probes very large scales and **so many of the approximations in the derivation of the Oort constants (S+G pg 92-93) (see next lectures) are not correct and one must use the full up equations.**

Velocity (radial)

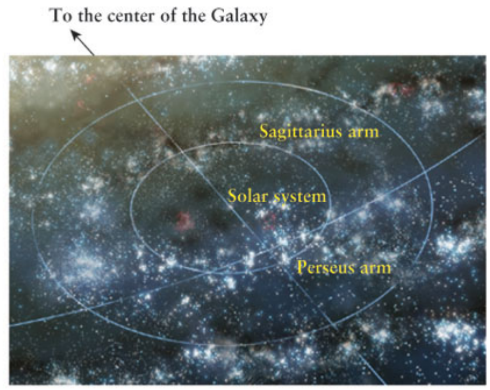


Galactic Longitude

MW is a Barred Galaxy



(a) The structure of the Milky Way's disk



(b) Closeup of the Sun's galactic neighborhood

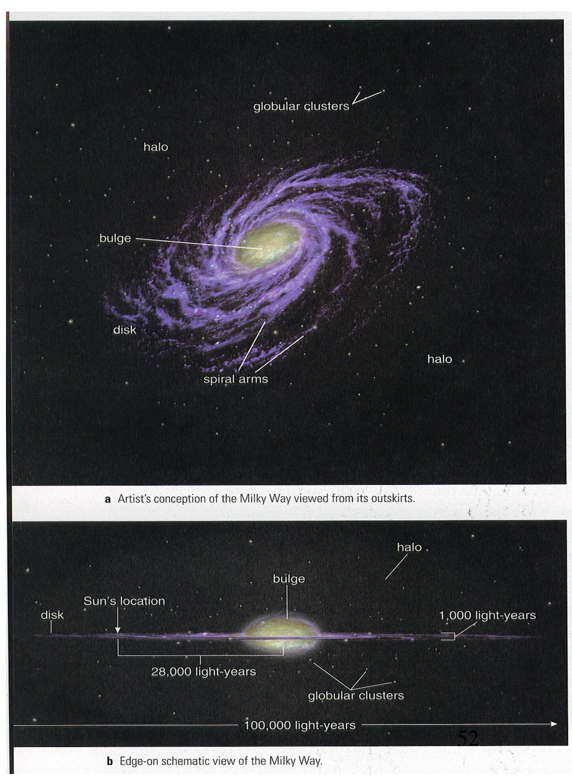
The MW bar, consists of relatively old red stars,
roughly 9 kpc in length
oriented at about a 45-degree angle relative to a line joining the sun and the center of the galaxy

Basic Properties of MW

Diameter ~23Kpc (ill defined)
at sun orbital period ~$2.5\text{x}10^8$ yrs
Mass ~$2\text{x}10^{11}\ M_\odot$ (details later)
M/L_V~10-15 (on average including DM)
Official distance of sun from GC is 8.5kpc, $v_{circular}$~220km/sec
the Milky Way is a barred galaxy

Perpendicular to the disk the stellar distribution(s) can each be 'well' described as
n(z)~exp(-z/h); h=scale height
The disk is NOT simple and has at least 2 components

1) thin disk has the largest fraction of gas and dust in the Galaxy, and star formation is taking place ; h~100pc, σ_z~20km/sec
2) thick disk h~1.5kpc older, lower metallcity population, less gas- only makes up 2% of mass density **at z~0**.

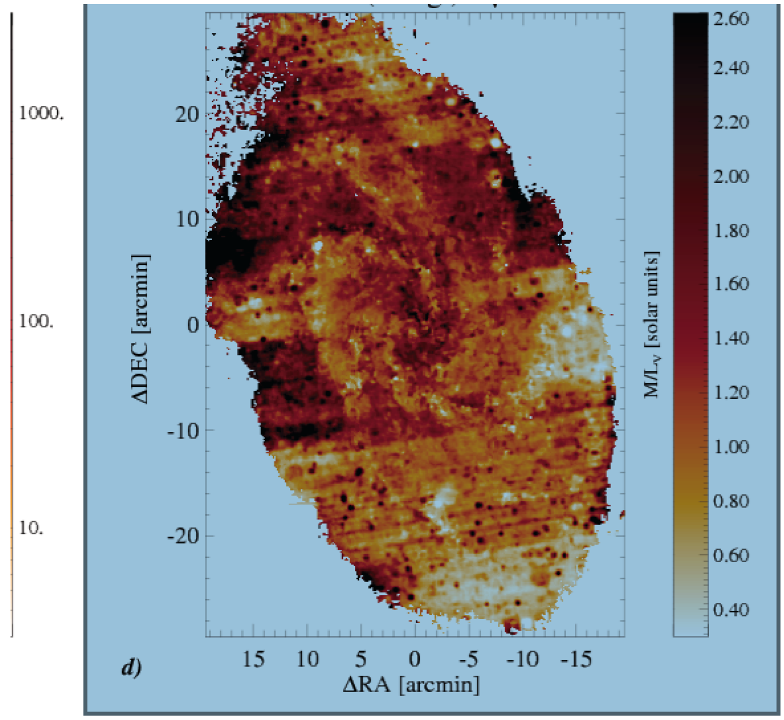


a Artist's conception of the Milky Way viewed from its outskirts.

b Edge-on schematic view of the Milky Way.

M/L_V in Nearby Galaxy M33

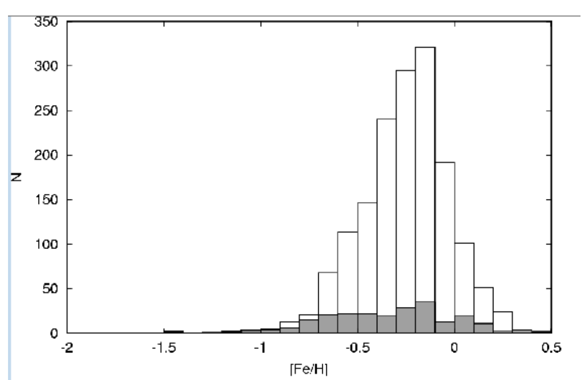
- M/L_V of the stars



Thin and Thick Disk -Details Composition

- Each of the 'components' of the MW has a 'different' (but overlapping) chemical composition (Metallicity)
- stars in the thin disk have a higher metallicity and M/L (~3). than those in the thick disk, high M/L~15 (age and metallicity effect)
- Thin disk M_{stars}~ 6×10^{10} $M_\odot$; M_{gas}~$0.5\times10^{10} M_\odot$. Stellar luminosity $L_B \approx 1.8\times10^{10} L_\odot$
- Thick disk has low mass and luminosity $M \sim 3\times10^9\ M_\odot$ and $L_B \approx 2\times10^8 L_\odot$
- the metallicity of stars in the Galactic halo and in the bulge is even lower. - in the older literature one has 'PopI' and 'Pop II'
- PopI is the component which dominates the disk O,B stars, open clusters, dust HII regions
- Pop II - bulge; old relatively metal poor

thin disk-open
thick disk shaded



[Fe/H]

Distribution of Light in Disk (S+G eq 2.8)

the thin disk and the thick disk has a similar form but different scale height and density of stars

Radial scale length of a spiral disk

$\Sigma(r)=\Sigma_0 \exp(-R/R_d)$**;** integrate over r to get total mass $M_d=2\pi\Sigma_0 R^2_d$

Vertical density distribution is also an exponential $\exp(-z/z_0)$ so total distribution is product of the two

$\rho(R,z)=\rho_0 \exp(-R/R_d)\exp(-z/z_0)$

while we may know the scale length of the stars, that of the dark matter is not known.

Also the nature of the dark matter halo is not known:- disk/halo degeneracy

Somewhat more precisely the luminosity distribution is $L(R,z)=L_0\exp(-R/h)/\cosh2(z/z_0)$ with $L_0=0.05L_\odot/pc^3$

Even more detail

Each spectral type can be characterized by a scale height, a possible indicator of age. The older the star, the more dynamical interactions it has had (Spitzer and Schwarzschild 1951).

The result is an increase in the spatial velocity of older stars (particularly along the vertical axis of the disk).

M dwarfs have relatively large scale heights, ~ 300 pc, in contrast to the younger A-type stars with ~ 100 pc (see table 2.1 in S+G)

Components of MW

HII scale height: 1 kpc

CO scale height: 50-75 pc

HI scale height: 130-400 pc

Stellar scale height: 100 pc in spiral arm, 500 pc in disk

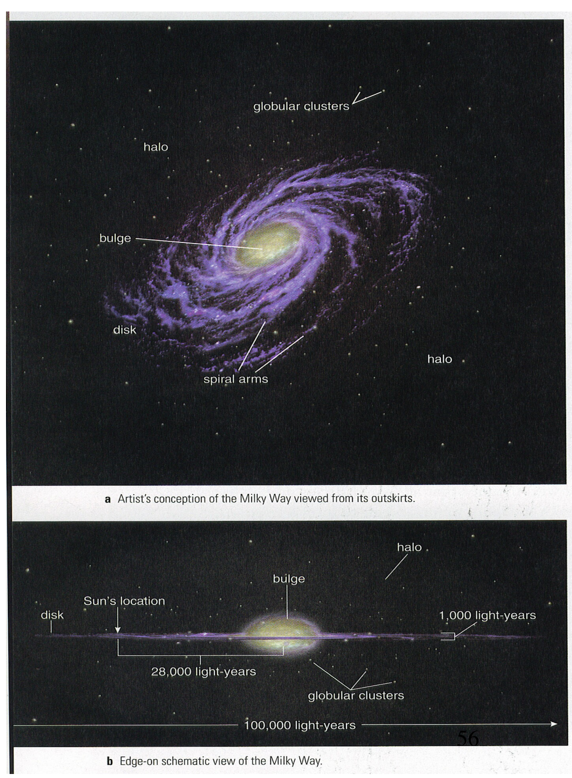
Stellar mass: $\sim 5\times10^{10}\, M_\odot$

HI mass: $\sim 3\times10^9 M_\odot$

H_2 mass (inferred from CO mass): $\sim 0.8\times10^9 M_\odot$

Total MW mass within viral radius is $\sim 8\times10^{11} M_\odot$: Mostly DM

The mass values depend on the radius within which they are estimated



a Artist's conception of the Milky Way viewed from its outskirts.

b Edge-on schematic view of the Milky Way.

Mass Distribution near Sun

- The (surface) density distributions can be derived from dynamical studies (much more later in class)
- The total surface mass density of all gravitating matter within 1.1 kpc of the centerline of the disk at the position of the sun is 67 +/-6 $M_{\odot}pc^{-2}$ and that of all identified matter (stars and gas) is 42+/-5 $M_{\odot}pc^{-2}$
- The local density of **dark matter** is 0.0075+/-0.0023 $M_{\odot}pc^{-3}$ (Zhang et al 2012) (see next lecture for how this is done)
- This dark matter density is consistent with fits to the MW halo models
- However this is very technically challenging and the total amount of dark matter is rather uncertain.
- This analysis is done using the vertical distribution of stars and their velocities (more later)

RESULTS FOR GALACTIC PARAMETERS A

Parameter	Flat rotation curve
$V_c(R_0)$ [km s^{-1}]	218±6
A [km s^{-1} kpc^{-1}]	$13.5^{+0.2}_{-1.7}$
B [km s^{-1} kpc^{-1}]	$-13.5^{+1.7}_{-0.2}$
$(B^2 - A^2)/(2\pi G)$ [$M_{\odot}$ pc^{-3}]	...
Ω_0 [km s^{-1} kpc^{-1}]	$27.0^{+0.3}_{-3.5}$
R_0 [kpc]	$8.1^{+1.2}_{-0.1}$
$V_{R,\odot}$ [km s^{-1}]	$-10.5^{+0.5}_{-0.8}$
$V_{\phi,\odot}$ [km s^{-1}]	242^{+10}_{-3}
$V_{\phi,\odot} - V_c$ [km s^{-1}]	$23.9^{+5.1}_{-0.5}$
$\mu_{Sgr\ A^*}$ [mas yr^{-1}]	$6.32^{+0.07}_{-0.70}$
$\sigma_R(R_0)$ [km s^{-1}]	$31.4^{+0.1}_{-3.2}$
R_0/h_σ	$0.03^{+0.01}_{-0.27}$
$X^2 \equiv \sigma_\phi^2/\sigma_R^2$	$0.70^{+0.30}_{-0.01}$

"The Formation and Evolution of the Milky Way," by Cristina Chiappini; 2001

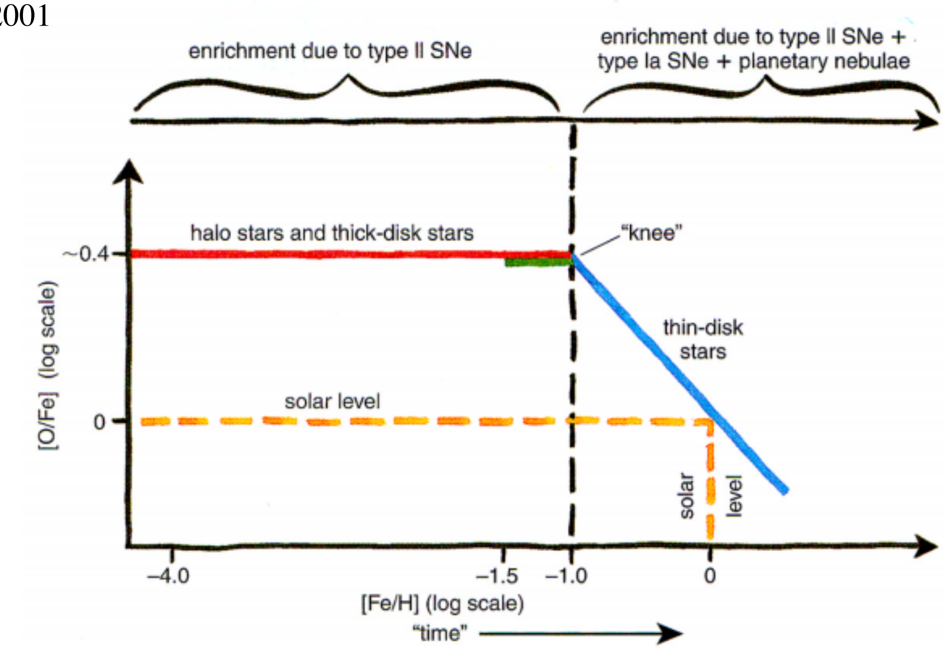
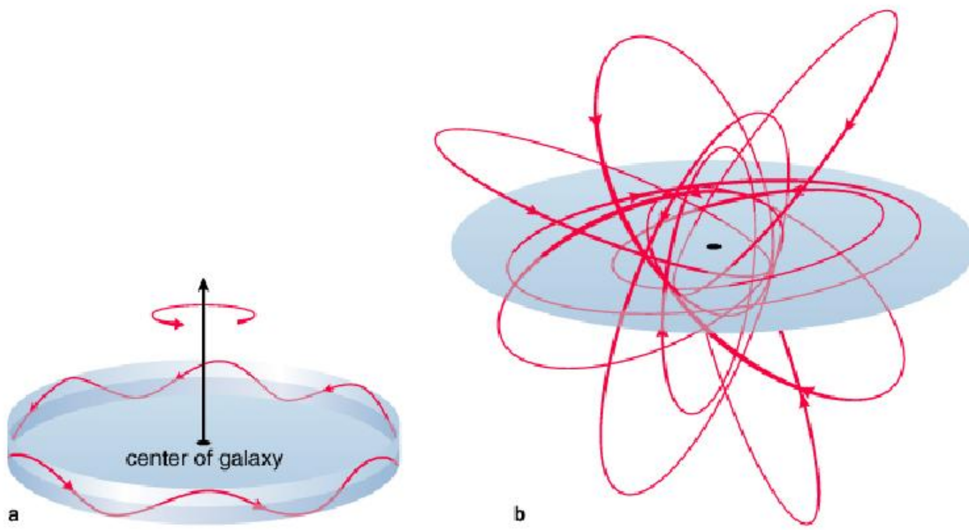


Figure 5. The general metallicity of the Galaxy—as measured by the abundance of iron (Fe), compared with hydrogen (H)—increases with time *(abscissa)* and so serves as a basis for comparing the relative abundances of two elements (such as oxygen (O) and iron; *ordinate*) that are created on different timescales. A plot of these quantities reveals a "plateau" of metal-poor stars (metallicity less than -1) that drops at a "knee" as the relative proportion of iron in the Galaxy increases. Since type Ia supernovae (SNe) are the primary source of iron, astronomers believe that the "knee" occurred about one billion years after the Galaxy began to form *(see Figure 4)*. The halo stars *(red line)* and some of the thick-disk stars *(green line)* tend to occupy the "plateau," whereas thin-disk stars *(blue line)* occupy the descending slope. These observations suggest that the halo, and part of the thick disk were formed in the first billion years of the Galaxy's evolution, and the think disk formed later.

Zeroth Order Dynamics

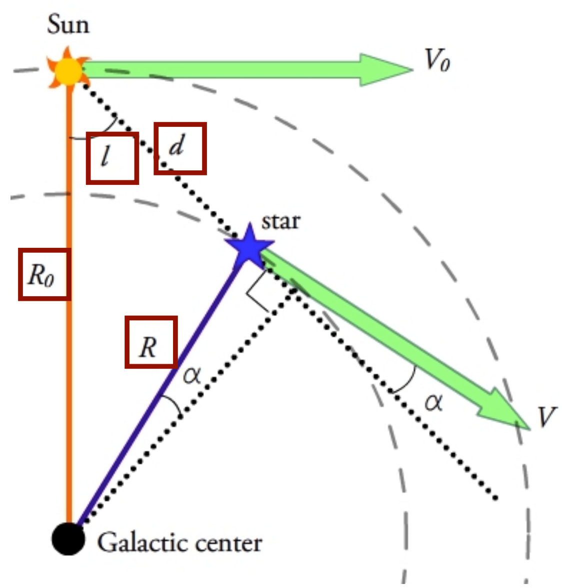
- Stars in disk have mostly rotational velocity- very little random or r or z components
- Stars in bulge and halo mostly random orbits, but some rotation.
- Need to use different techniques to estimate the mass of these '2' components



Galactic Rotation- S+G sec 2.3, B&T sec 3.2

- Consider a star in the midplane of the Galactic disk with Galactic longitude, l, at a distance d, from the Sun. Assume circular orbits radii of R and R_0 from the galactic center and rotational velocities of V and , V_0

- The 2 components of velocity- radial and transverse are then for circular motion
- $V_{observered, radial}$=V(cos α)-V_0sin(l)
- $V_{observered ,tang}$=V(sin α)-V_0 cos(l)
- using the law of sines
- sinl/R~ cosα/R_0



Much more later

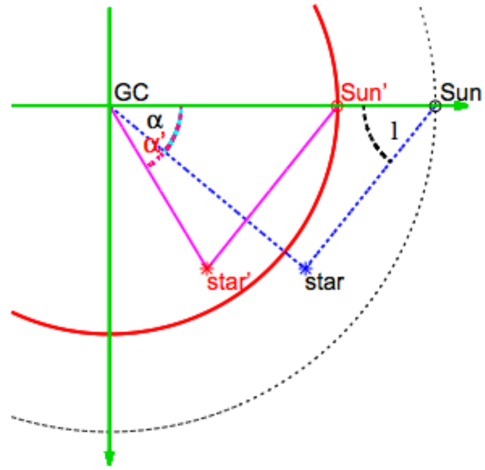
wikipedia

Why Rotation Curves for MW Depend on R_0

Changing R_0's effect on determination of the rotation curve

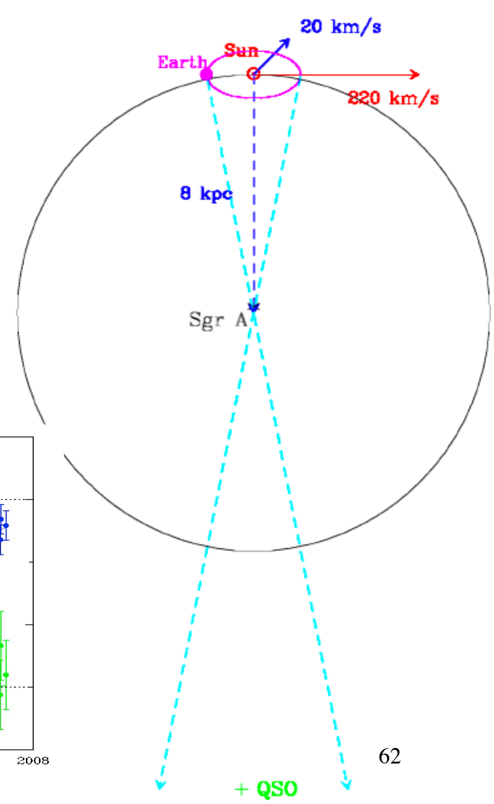
- Since the galactic longitude of the data source (star, gas) does not change, the angle, α, must grow as R_0 lessens
- This reduces the rotation speed estimated from the sources radial velocity

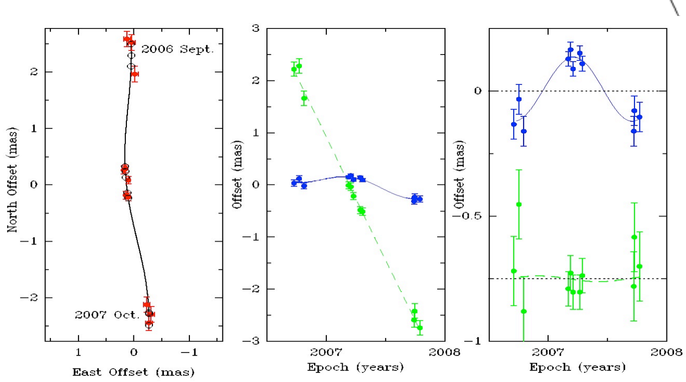
R. Schonrich



Distances From Motions

- Distance to the galactic center (R_0) is rather important; in problem 2.6 (S&G) discusses one way to use the observed positions and velocities of stars in orbit around the galactic center to get the distance
- Another way of doing this: measure the proper motion+parallax of SgrA* caused by the velocity of the sun
- East in blue, north in green -right panel has proper motion removed. left panel motion on sky





Cosmic Rays-101th Anniversary of their Discovery

http://www.aps.org/publications/apsnews/201004/physicshistory.cfm

- These are very hard to study in other galaxies
  - they are visible by the synchrotron emission emitted by electrons spiraling in the magnetic field

  γ-rays emitted by relativistic particles hitting gas
- MW

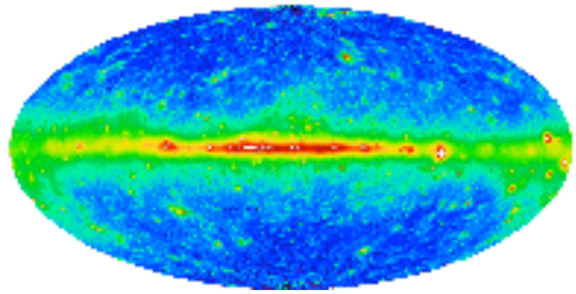
  direct measures of CRs e.g. in situ

  detailed γ-ray maps of MW

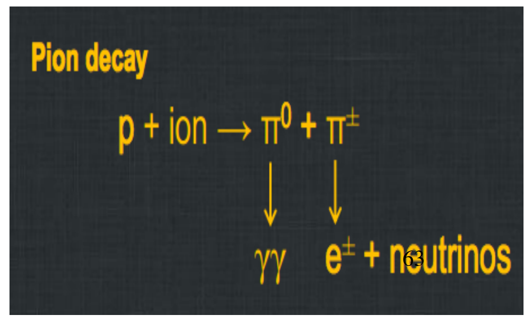
  convolution of cosmic ray energy spectrum and intensity with target (gas) density

  Very detailed radio maps

Origin: acceleration of particles in supernova shocks via first order Fermi process - total power ~10^{41} ergs/sec~10% of SN shock energy



Fermi map of MW

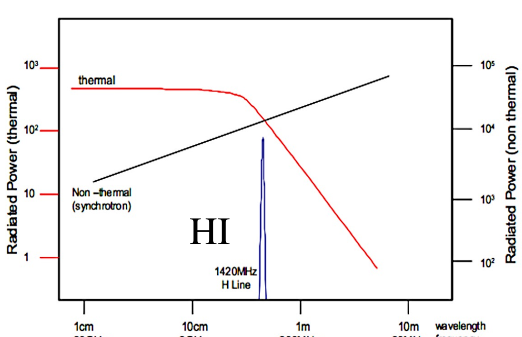


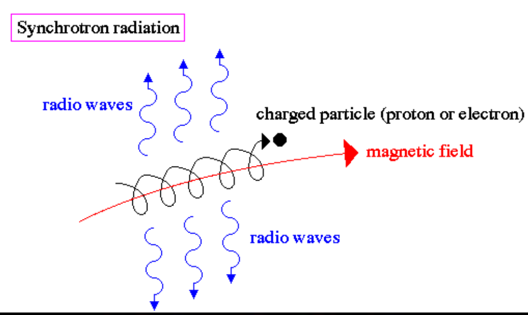
Radio Continuum Emission

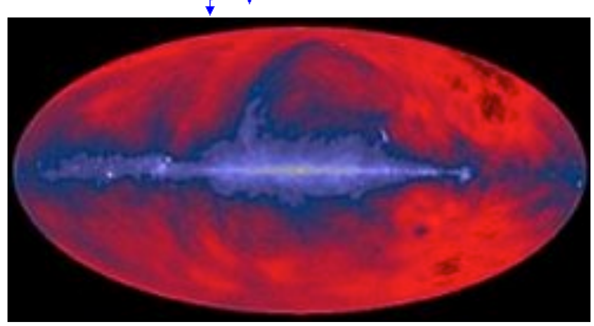
- Synchrotron emission: convolution of particle spectrum and magnetic field-power law spectrum-power law spectrum $F_\nu \sim A\nu^{-\alpha}$

slope, α depends on spectrum of CRs and intensity of magnetic field

- Thermal bremmstrahlung: fast, non-relativistic particles running by gas (breaking radiation)-exponential spectrum
- Relative intensity of the two components changes greatly with position.





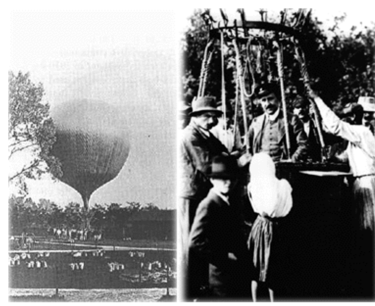


radio continuum image of MW

Cosmic Rays-100th Anniversary of their Discovery
Why Did Hess do This

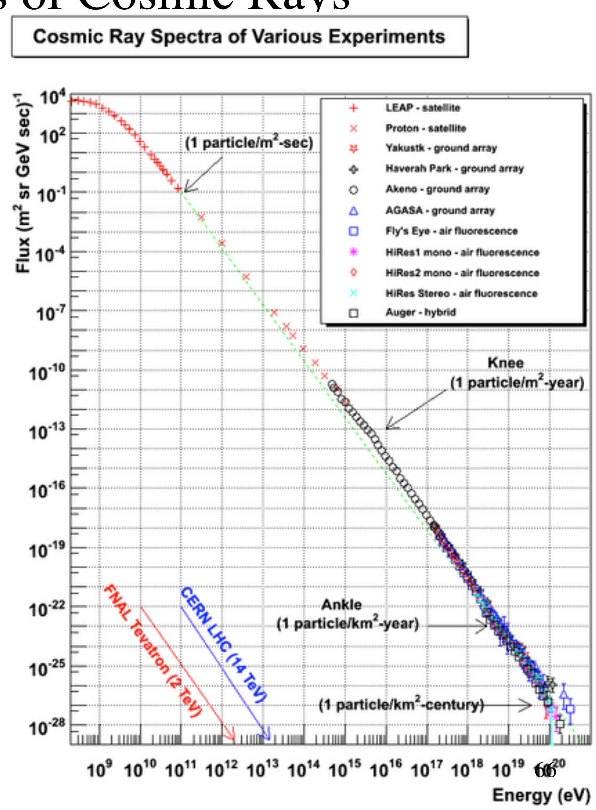
- scientists had been puzzled by the levels of ionizing radiation measured on the earth and in the atmosphere.
- The assumption was that the radiation from the earth and would decrease as one went away from the surface.
- Hess greatly increasing the precision of the electroscopes*and then by personally taking the equipment aloft in a balloon. He measured the radiation at altitudes up to 5.3 km during 1911-12 without oxygen. The daring flights were made both at day and during the night, at significant risk to himself and showed that the level of radiation increased as one went higher-observed during an eclipse and showed sun was not the origin.
- *He concluded that there was radiation coming from outer space ! (Nobel prize 1936)*

*they spontaneously discharge in the presence of ionizing radiation. The rate of discharge of an electroscope is then used as a measure of the level of radiation



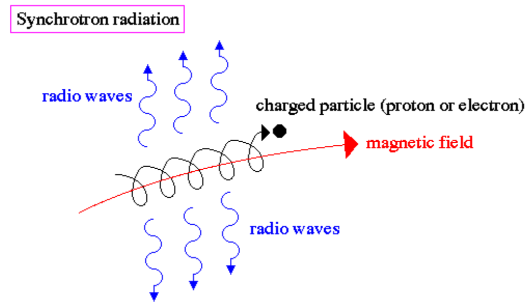
100 Years of Cosmic Rays

- In August 1912, the Austrian physicist Victor Hess flew in a balloon to altitudes of 5.3 km, measuring the flux of particles in the sky. The expectation was that the flux would decrease with altitude, precisely the opposite of what Hess found. The shocking conclusion was that particles were raining down on Earth from space.
- http://www.npr.org/blogs/13.7/2012/07/25/157286520/cosmic-rays-100-years-of-mystery



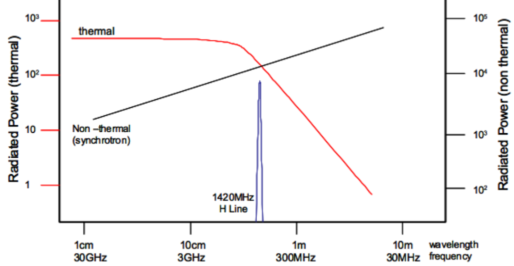
Cosmic Rays

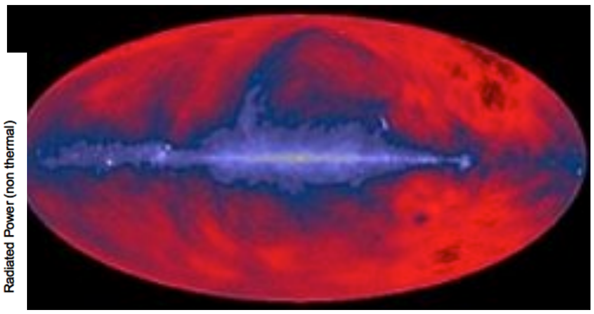
- Have appreciable energy density ~1 eV/cm^3
- Synchrotron emission is convolution of particle spectrum and magnetic field- also emission from 'non-thermal' bremmstrahlung
- Can ionize deeply into molecular clouds



http://abyss.uoregon.edu/~js/glossary/synchrotron_radiation.html

radio emission from galaxy





Cosmic Rays

- Accelerated particles propagate through the Galaxy where, due to the magnetic field, they move along complicated helical tracks.
- Therefore, the direction from which a particle arrives at Earth cannot be identified with the direction to its source of origin (Larmor radius, r= $m_e c(\text{sqrt}(\gamma^2-1)/eB$; 3.3×10^6km for 1μG, 100Mev))
- The magnetic field is also the reason why particles do not leave the Milky Way along a straight path, but instead are stored for a long time (~ 10^7 yr) before they eventually diffuse out, an effect called confinement

γ-ray Imaging of Star Forming Regions

- Fermi has imaged the γ-rays coming from star forming regions and γ-ray spectra show that this is due to cosmic rays interacting with dense gas (Lingenfelter 2012) in superbubbles (places of high massive star formation rate and thus high S/N rate).

  γ-rays come from the interaction of CRs and dense gas- Fermi has imaged sites of CR creation !

Fig. 1 Typical ~1pc Star Forming Region Shown by Bright O & B Stars

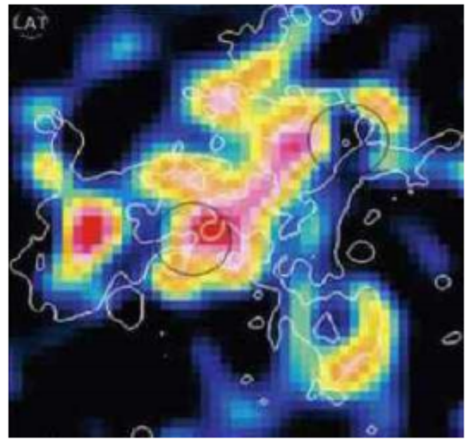


Fig. 2 ~100 pc Cygnus Superbubble in 10-100 Gev γ-Rays from Fermi [11]

Timescales

- crossing time $t_c=2R/\sigma$
- dynamical time $t_d=\mathrm{sqrt}(3\pi/16G\rho)$- related to the orbital time; assumption homogenous sphere of density ρ
- relaxation time- the time for a system to 'forget' its initial conditions

$t_r \sim Nt_c/48f^2$: N objects carrying fraction ,f, of total mass :

S+G gives $t_r=V^3/8\pi G^2 m^2 n \ln\Lambda \sim 2\times10^9 \mathrm{yrs}/[(V/10)^3 (m_\odot)^{-2} (n/10^3 \mathrm{pc}^{-3})^{-1}$

major uncertain is in $\ln\Lambda$− numerical simulations

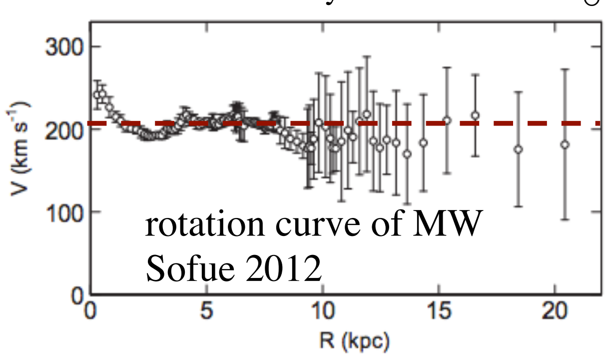
Simple Estimate of Mass of Milky Way

- If we follow problem S&G 2.18 and use $M \sim RV^2/G$- of course this is for a sphere ... ignore the details (discuss later what is correct for a disk+sphere)

- sun's distance from enter $R_0 \sim 8$kpc and rotational velocity ~220km/sec
  $M=9\times10^{10}\,M_\odot$ - corresponds to a density of $\sim 4\times10^{-3} M_\odot/pc^3$ (uniform sphere) - mass within 8kpc; if extend to 350kpc (virial radius) get $4\times10^{12}\,M_\odot$; factor of 2-4 too high but right 'order'
- critical density of universe today $\rho_{crit}=3H_0^2/8\pi G \sim 1.45\times10^{-7}\,M_\odot/pc^3$
- So the MW is 'overdense' by $\sim 2.7\times10^5$ at solar circle and 600 at viral radius (using above simple formula) and 150 using a more correct mass.
  - In CDM theories the size of a virialized system is when the overdensity is >200

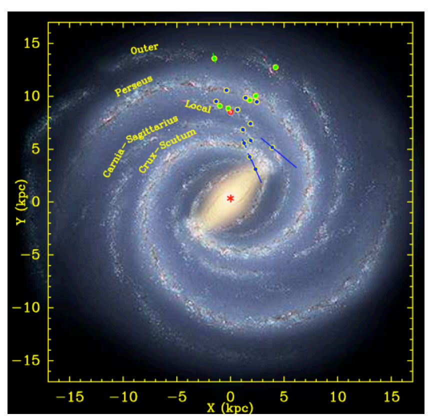
Mass of Milky Way

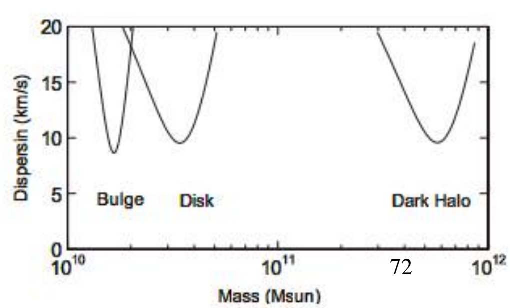
- This turns out to be rather hard to determine- there is a degeneracy between velocity and distance- use rotation curve fitting and 'proper' potentials
- New data allows absolute distance to be determined for several star forming regions (Reid et al 2009)
- Stellar mass of MW is $\sim 6\times10^{10} M_\odot$
- DM mass is $1\text{-}2\times10^{12} M_\odot$; M/L~30
- DM inside overdensity of 200 $1\text{-}2\times10^{12} M_\odot$



rotation curve of MW
Sofue 2012

Locations of star-forming regions (dots) artist's Milky Way.



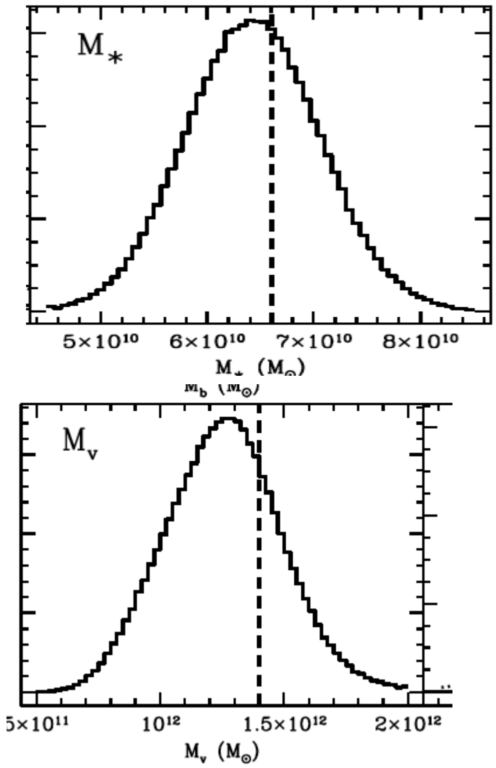


Mass of Milky Way

- The majority of the mass of the Galaxy is expected to lie in the CDM halo, which is only observable through its gravitational effect on luminous components of the Galaxy

McMillian 2012 find

- disc scale lengths of 3.00 ± 0.22 kpc and 3.29 ± 0.56 kpc for the thin and thick discs respectively;
- at sun thin disk has 90% of the mass and thick disk 10%
- R_0 Solar radius of 8.29 ± 0.16 kpc
- a circular speed at the Sun of 239 ± 5 km/s
- total stellar mass of 6.43 ± 0.63x $10^{10}M_\odot$
- bulge mass M_b = 8.9 10^9 $M_\odot$
- virial mass of 1.26 ± 0.24 x$10^{12}M_\odot$
- **a local** dark matter density of 0.40 ± 0.04GeVcm^{-3} (or in more normal units 0.01 $M_\odot/pc^3$)



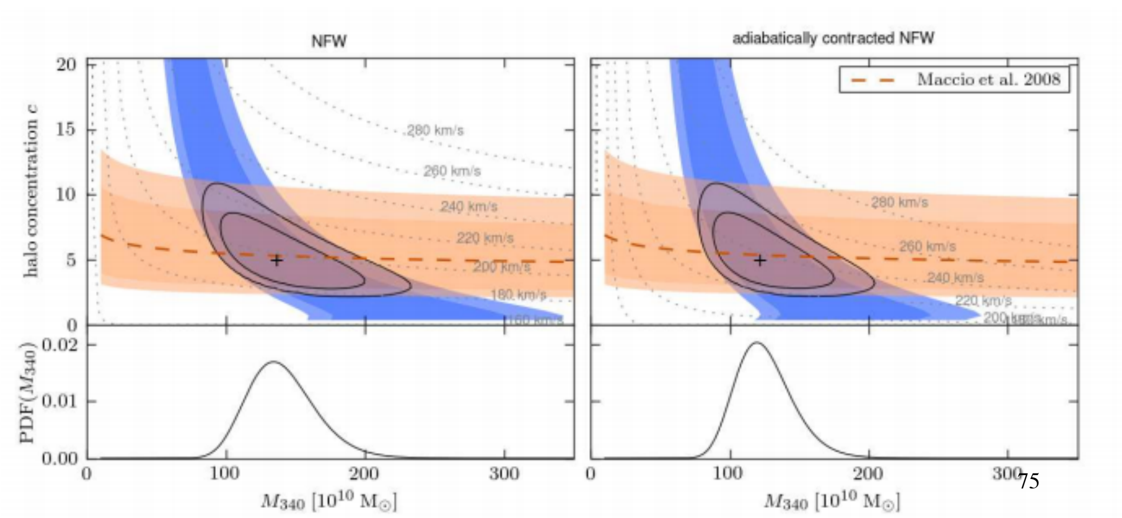
distribution functions of parameters
McMillian 2012

Mass of MW (Bovy and Tremaine 2012)

- The flatness of the Milky Way's circular-velocity curve at < 20 kpc (e.g., Xue et al. 2008) shows that the visible Galactic disk is embedded in a massive dark halo.
- The disk is composed of gas and stars (baryons), while the dark halo is believed to be dominated by dark matter.
- it remains unclear whether there is any need for a substantial amount of dark matter in the disk itself (Binney et al 2012)
- One way to determine the local density of dark matter is through a determination of the dependence of the gravitational potential on distance above the mid-plane of the disk ("height"), from measuring the kinematics of stars (e.g., Kapteyn 1922; Oort 1932; Bahcall 1984) - a lot more later.
- But, a major obstacle is that the uncertainty in the amount of baryonic matter in the disk makes it hard to determine the relative contributions from dark and baryonic matter to the density near the mid-plane.
- The contributions from baryonic and dark matter can be disentangled by measuring the gravitational potential out to larger heights. At heights of several times the disk thickness, the dark halo and the baryonic disk contributions to the potential have a different vertical dependence (e.g., Kuijken & Gilmore 1989; Garbari et al. 2011).

RAVE Sample

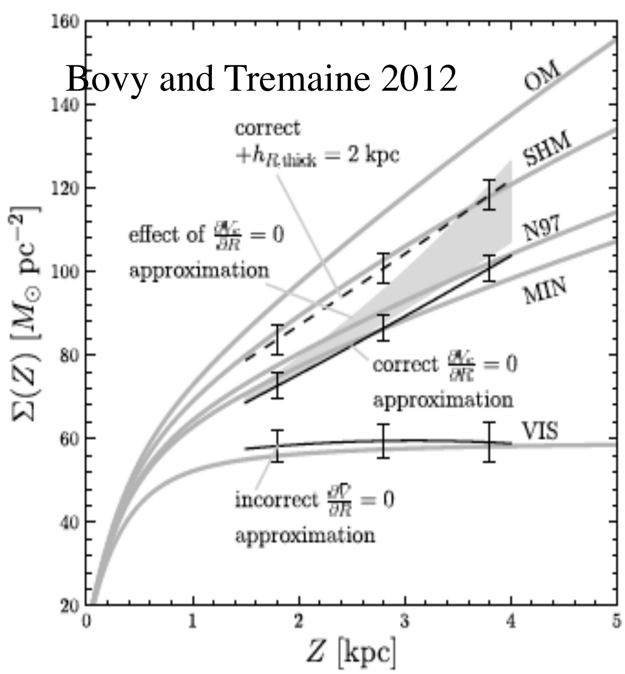
- In September 2013 another detailed analysis of the MW mass was determined (Binney et al 2013. Piffl 2013; http://arxiv.org/pdf/1309.4293.pdf)



Mass Density of MW Perpendicular to the Disk

- The breakdown of the assumptions made in this simple, “model-independent” Jeans analysis are such that the measurement has a systematic uncertainty reaching 10 to 20% at |Z| = 4 kpc.
- Therefore, a precise determination of the local dark matter density from observations at large Z using a Jeans analysis requires data that span a wide range in R such that the radial gradient of the velocity moments, can be determined.
- The Gaia mission (Perryman et al. 2001) will provide such measurements

Bovy and Tremaine 2012



•The line labeled VIS is the mass density of 'visible material'

The grey lines are including the effects of different dark matter halo models

Thin Disk- Thick Disk

- There are a variety of stellar populations in the disk.
- There is a strong tendency for age, metallicity, velocity dispersion and scale height to be correlated.
- It used to be that this was parameterized as a 'thin' and 'thick' disk.
- Of course things are more complex (Bovy et al 2013) and there seems to be a more continuous distribution.

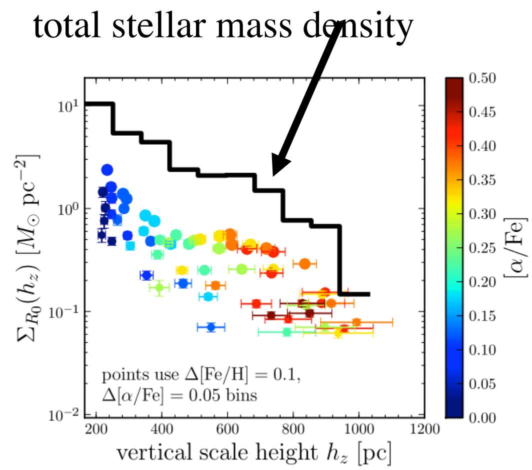
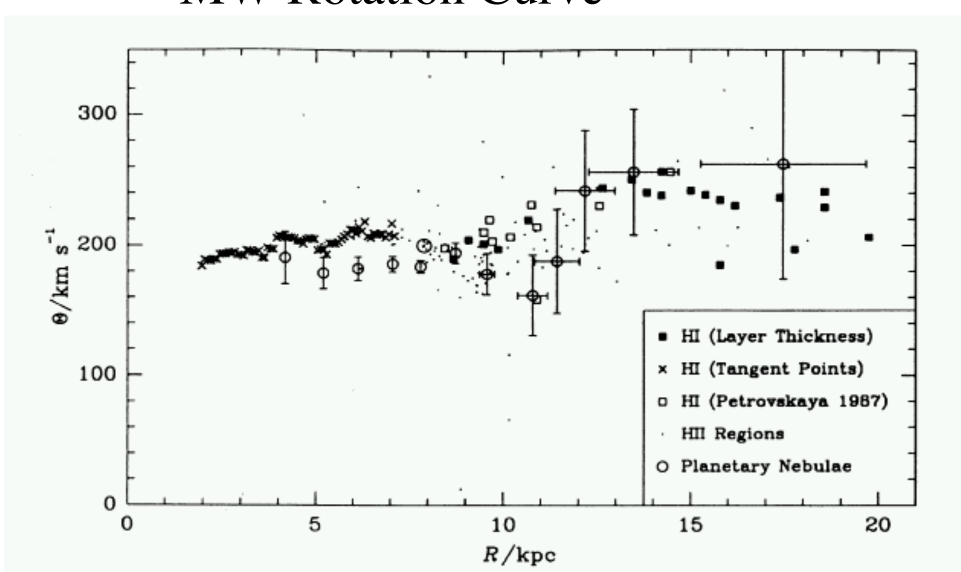


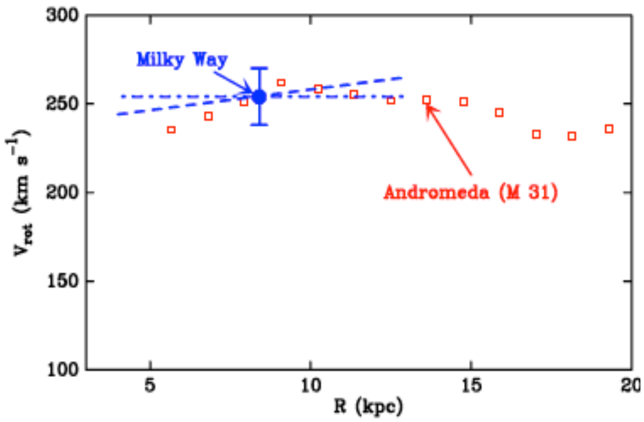
FIG. 2.— Distribution of stellar surface-mass density at the Solar radius $\Sigma_{R_0}(h_z)$ as a function of vertical scale height h_z. The thick black histogram shows the total stellar surface-mass density in bins in h_z, calculated by summing the total stellar masses of sub-populations in bins in [α/Fe] and [Fe/H]. The stellar surface-mass densities of the individual elemental-abundance bins in [Fe/H] and [α/Fe] are shown as dots, with values for Σ_{R_0}([Fe/H], [α/Fe]) on the y-axis. The points are color-coded by the value of [α/Fe] in each bin and the size of the points is proportional to the square root of the number of data points that the density fits are based on. Some of the errorbars are smaller than the points. Elemental abundance bins have a width of 0.1 in [Fe/H] and 0.05 in [α/Fe].

MW Rotation Curve



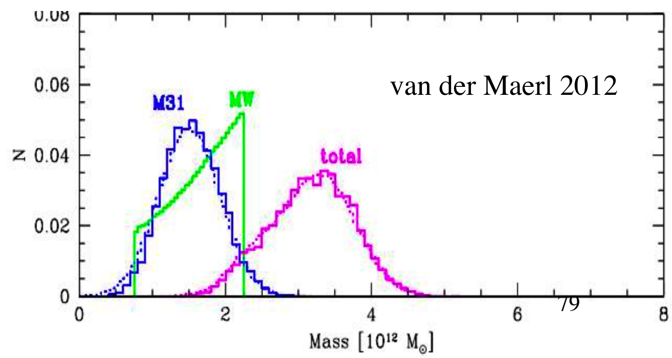
- Flynn, Sommer-Larsen , Christensen 196

Comparison with M31



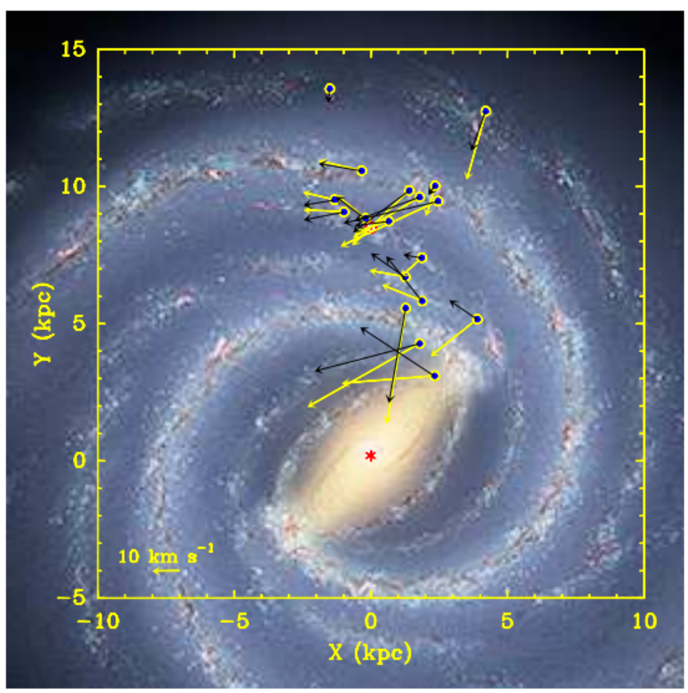
Blue line is from Reid 2009
notice it disagrees with previous figure-
this is due to difficulties in assigning accurate distances to different tracers
and correcting for non-circular motions

Probability that M31 and MW have a given mass and for the sum



the Milky Way has a significantly higher rotational speed (or, equivalently, lower baryonic mass) than the Tully-Fisher relation predicts- more later

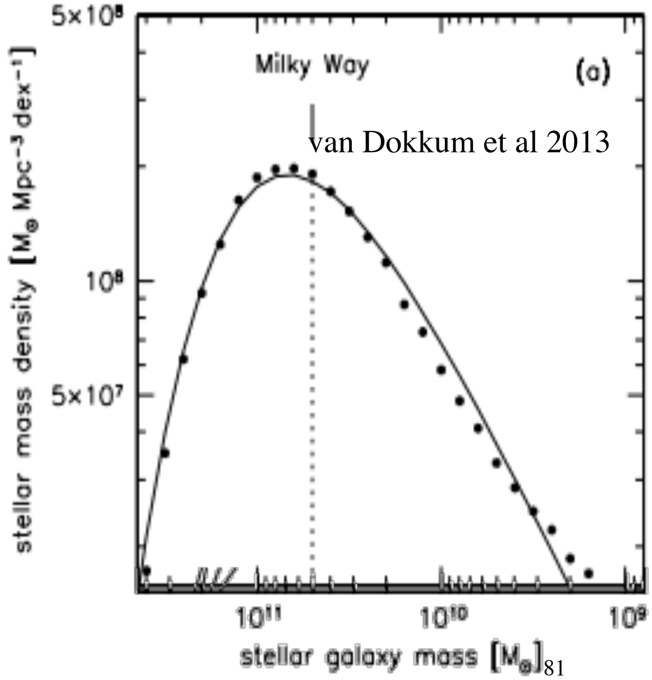
- The light (yellow) arrows are for IAU standard values of R_0 = 8.5 kpc and V_r = 220 km /s and a flat rotation curve, black arrows for V_r= 254 km/s
- high mass star forming regions orbit the Galaxy slower than the Galaxy rotates!



'ig. 3.— Peculiar motion vectors of high mass star forming regions (superposed on an artist onception) projected on the Galactic plane after transforming to a reference frame rotating with he Galaxy. A 10 km s^{-1} motion scale is in the lower left. The Galaxy is viewed from the north

Stellar Mass of MW compared to Local Galaxy Mass Function

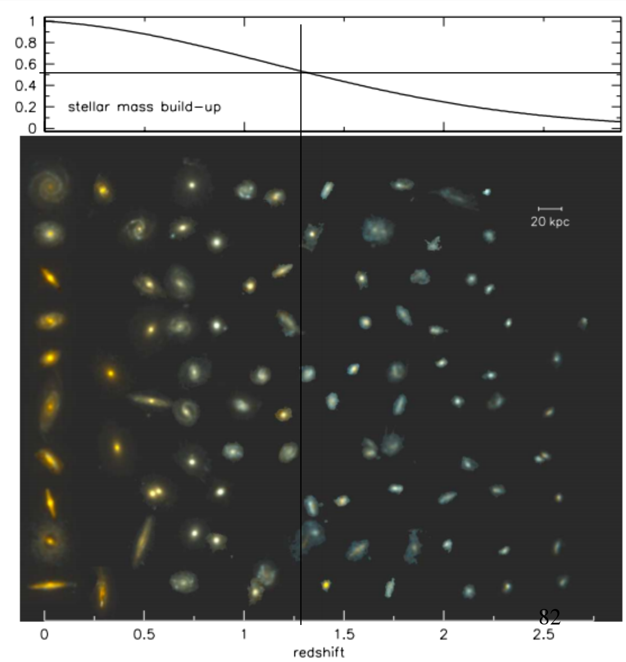
- The stellar mass of the MW is near the peak of the local galaxy mass function (not number density). (notice mass scale runs backwards....astronomers)



Progenitors of the MW

- What did the progenitors of the MW look like- van Dokkum et al 2013 present images of galaxies with the same mass density of the MW at a variety of redshifts using the average stellar mass buildup as a guide

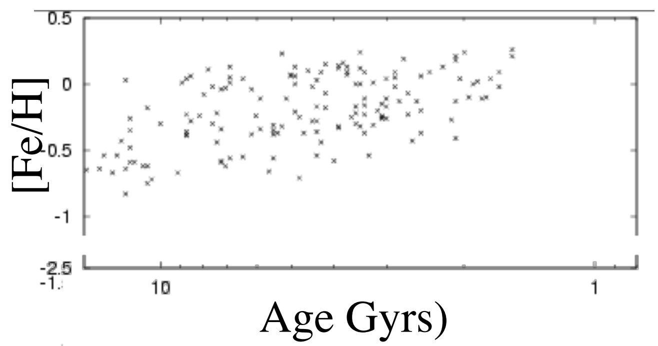
Notice that organized spirals appear only at z<1 and that at higher redshift galaxies had a very different surface brightness profile Galaxies also become redder with time (general drop of SF with redshift) and mergers are not required to explain the mass evolution of large spiral galaxies.



Age Metallicity

- Older stars **tend** to be metal poor: only in the MW and local group can this be studied with great detail (SG 4.3.2)
- However the metallicity history of the MW is very hard to unfold
- Older stars (in the MW) tend to be metal poor
  - logic is that metals are created in SN over cosmic time, next generation of stars if formed from this enriched gas, so more metal rich

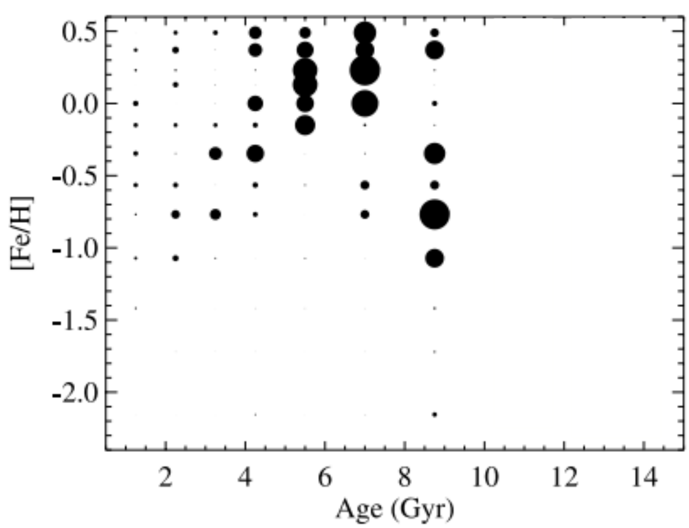
•Actually much more complex;
- –galaxy is not a closed box, gas flows in and out
  - galaxy mergers can mix things up
- –Two types of SN (type I produces mostly Fe, type II mostly O)
- –stars can move a long way from their regions of birth
- –star formation rate is not constant



Huge scatter- see http://arxiv.org/pdf/1308.5744.pdf
8.2Gyr old sun like star with Fe/H= -0.013 ± 0.004 and a solar abundance pattern

Age Metallicity

- Now can do this in M31 with HST data (!)
- Pattern seems to be more variance at younger ages rather than a trend.
- In M31 spheroid things are very different than in MW; 40% of the stars are metal-rich and younger than 10 Gyr ! (M31 has undergone a major merger MW has not)
- Lesson: MW may not be representative of spirals



Size of symbol is ~ # of stars in box; Brown et al 2006

MW as Model for Other Galaxies

- the Milky Way experienced very few minor mergers and no major merger during the last ~10Gyrs- unexpected in a cosmological scenario
- The old stellar content of the thick disk indicates a possible a merger origin at an early epoch.
- The Milky Way is presently absorbing the Sagittarius dwarf though this is a very tiny event (<1% of the Milky Way mass)

How can star formation be sustained? 3

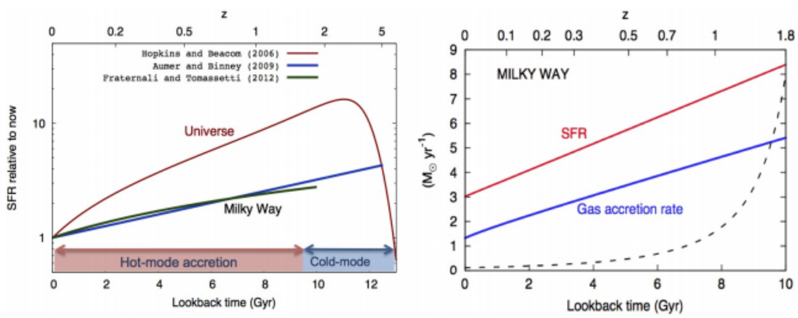


Figure 1. *Left:* comparison between two determinations of the SFH of the Milky Way (Aumer & Binney 2009; Fraternali & Tomassetti 2012) and the average star formation rate density of the Universe (Hopkins & Beacom 2006). The three distributions are normalized at the current time. *Right*: reconstruction of the SFH of the Milky Way's disc and the gas accretion rate required by the Kennicutt-Schmidt law (see Fraternali & Tomassetti 2012); the dashed line shows the evolution of a closed-box galaxy starting with the same initial amount of gas.

SF history of MW (Fraternali 2013) MW SFR does not match that of the universe as a whole (but it shouldn't- at high z elliptical galaxies dominate)

How Typical is the MW??

- the Milky Way is systematically offset by ~1σ showing a significant deficiency in stellar mass, angular momentum, disk radius, and [Fe/H] at a given V_{rot}
- The Milky Way had an exceptionally quiet formation history having escaped any major merger during the last 10 Gyr;
- Milky Way like galaxies correspond to only 7% of local spirals, - so onto the rest of the universe!
- But first, some detailed dyanamics...