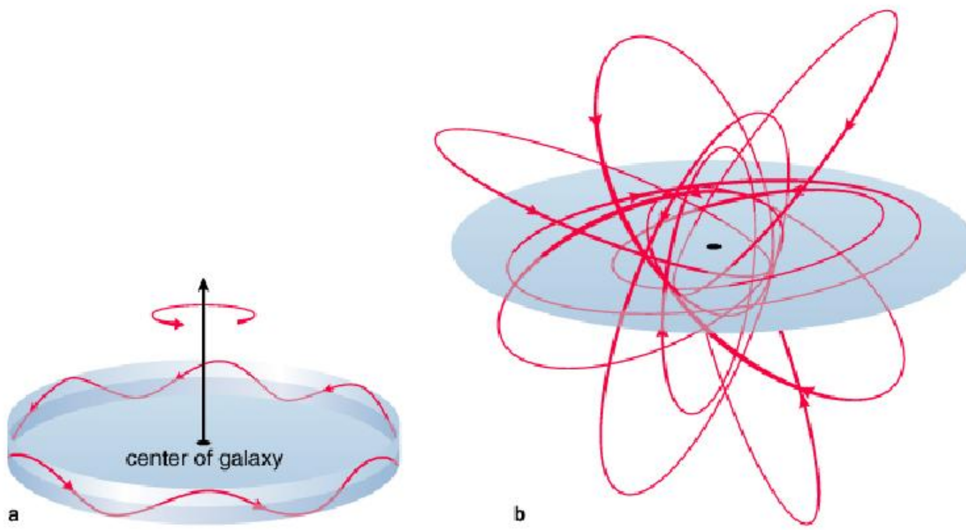
Zeroth Order Dynamics

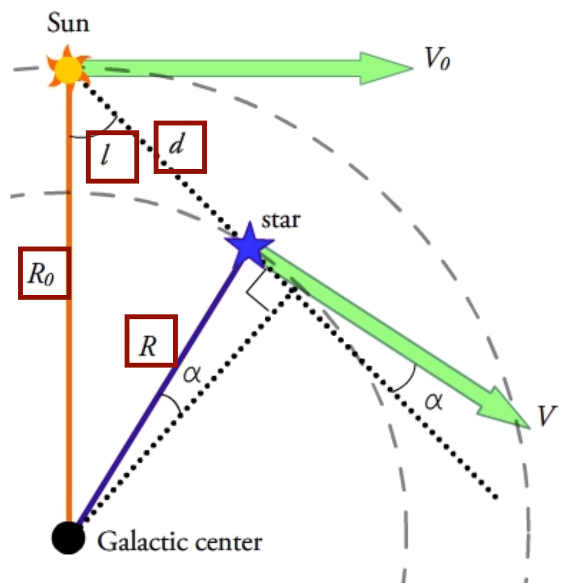
- Stars in disk have mostly rotational velocity- very little random or r or z components
- Stars in bulge and halo mostly random orbits, but some rotation.
- Need to use different techniques to estimate the mass of these '2' components



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
- $V_{observered, radial}=V(\cos\alpha)-V_0\sin(\ell)$
- $V_{observered ,tang}=V(\sin\alpha)-V_0\cos(\ell)$
- using the law of sines
- $\sin\ell/R \sim \cos\alpha/R_0$

Much more later

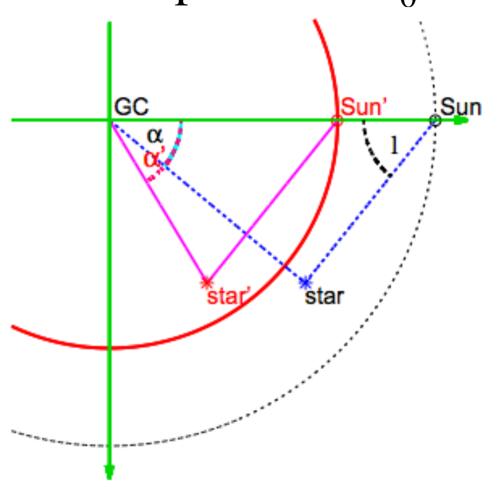


wikipedia

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



effect of changing R_0

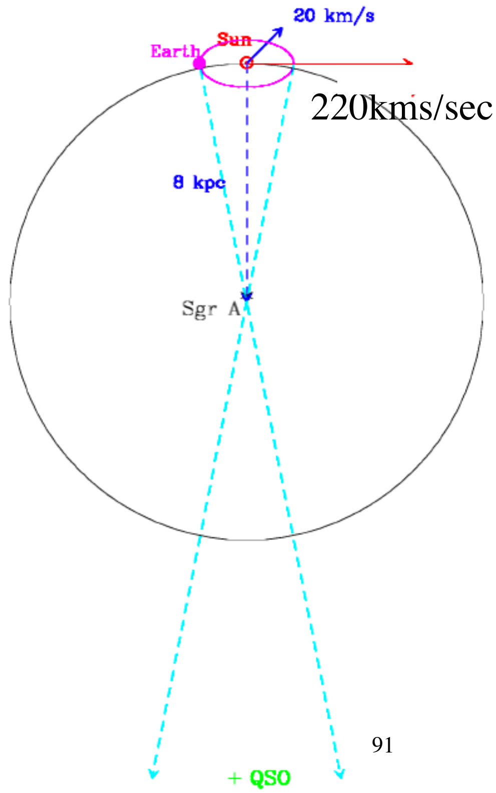
R. Schonrich

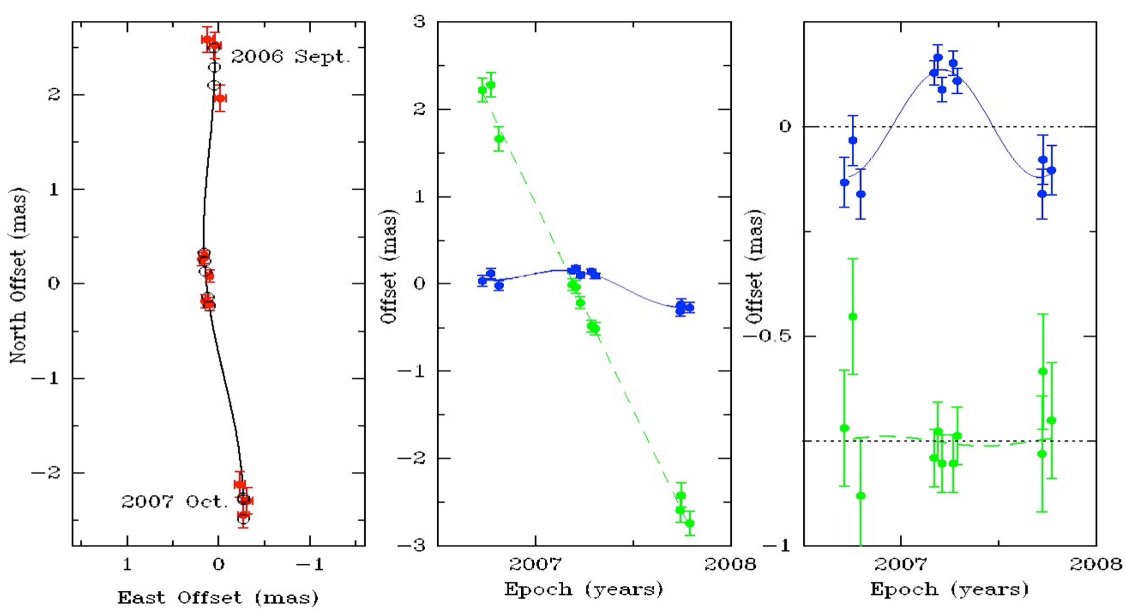
Distances From Motions https://www.cfa.harvard.edu/~reid/trigpar.html

- Distance to the galactic center (R_0) by measuring the **proper motion+parallax** of SgrA* caused by the velocity of the sun – shift is ~0.1milli-arcsecs* (~5x10^{-10} rads)
- East is blue, north in green -right panel has proper motion removed. left panel motion on sky

M. Reid
ARA&A 31,345
ApJ 2009 705,1548

*

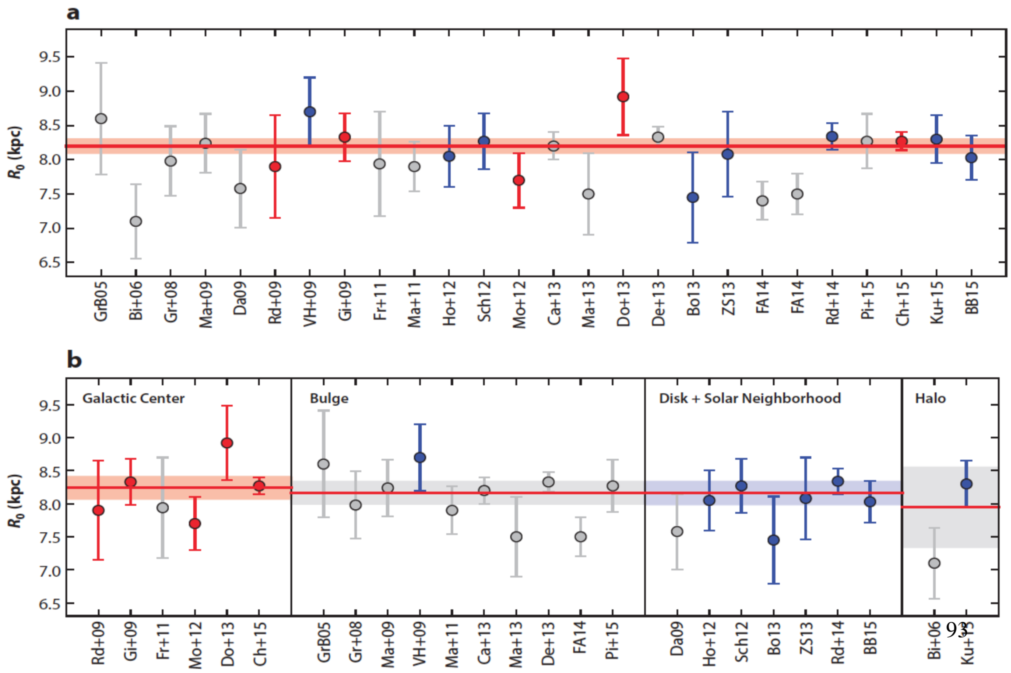




- Left panel- position on the sky vs time
- Middle Panel: East (filled blue circles and solid line) and North (open green circles and dashed line) position offsets and best fit parallax and proper motions fit versus time
- the best fit proper motion has been removed, showing only the parallax

Distance to Galactic Center- Lots of Techniques

- Bland-Hawthorn and Gerhard 2016 R_0=8.2+/- 0.1 kpc. This value is significantly lower than the IAU standard (R_0=8.5 kpc).



93

Galactic structure from trigonometric parallaxes of star-forming regions

- Mark J. Reid Proceedings IAU Symposium No. 289, 2012

Surprisingly , the nature of the spiral structure of the Milky Way remains largely unknown after nearly a century of intense observational studies.

The primary reasons are

- that dust obscures most of the Galaxy's disk from view optically
- distances are exceedingly great and difficult to measure.

The discovery of the 21 cm spectral line of atomic hydrogen, and later millimeter-wave lines of molecular carbon monoxide (CO) gas, gave hope that one could map the Milky Way, because these radio lines were not affected by interstellar dust and their observed velocities could be used to estimate (kinematic) distances.

- However, kinematic distances are plagued by both ambiguities for sources observed inside the 'Solar Circle' and large uncertain ties from unknown non-circular motions.

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)]

(lets do the math)

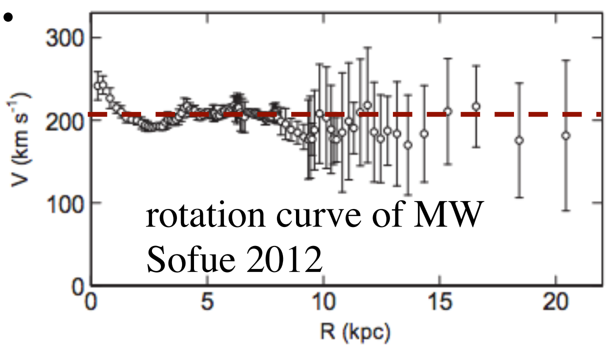
- sun's distance from enter R_0~8kpc and rotational velocity ~220km/sec

  $M=9\times10^{10}\,M_\odot$ - corresponds to a density of ~$4\times10^{-3} M_\odot/pc^3$ (uniform sphere) - mass within 8kpc; if extend to 350kpc (virial radius) get $4\times10^{12}\,M_\odot$ since rotation curve is flat; 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 ~2.7×10^5 at solar circle and 600 at viral radius (using above simple formula) (150 using a *more* correct mass estimator).
  - In CDM theories the size of a virialized system is when the overdensity is >200
- Near the sun detailed measurements show that

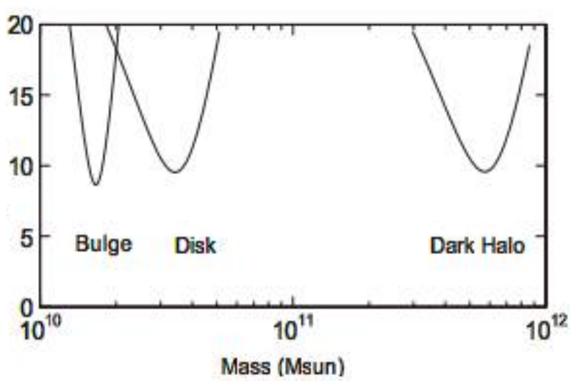
the surface density of *baryons* $\Sigma \approx 47$+/-3 $M_\odot\,pc^{-2}$ comprising
brown dwarfs (1.2 $M_\odot\,pc^{-2}$),
white dwarfs (4.9 $M_\odot\,pc^{-2}$),
ISM gas (13.7 $M_\odot\,pc^{-2}$), and
main sequence and giant stars (27.0 $M_\odot\,pc^{-2}$).
baryons + dark matter $\Sigma = 70+/-5\,M_\odot\,pc^{-2}$ integrating over +/-1.1kpc

Accurate 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 (see next slides)
- Stellar mass of MW is ~$6\times10^{10} M_\odot$
- DM mass is 1-$2\times10^{12} M_\odot$; M/L~30
-



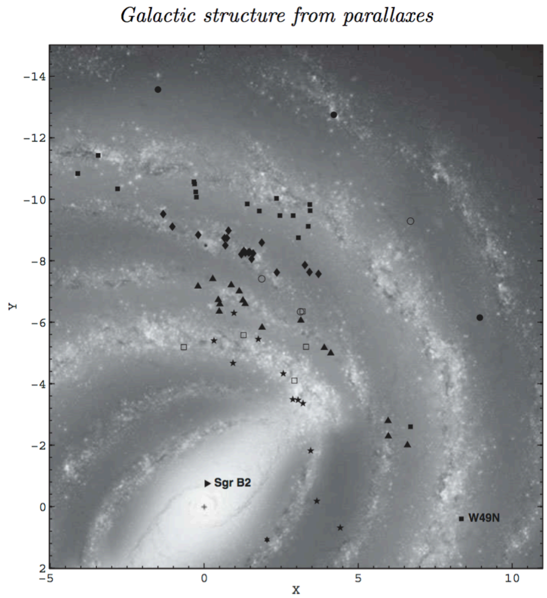
rotation curve of MW
Sofue 2012



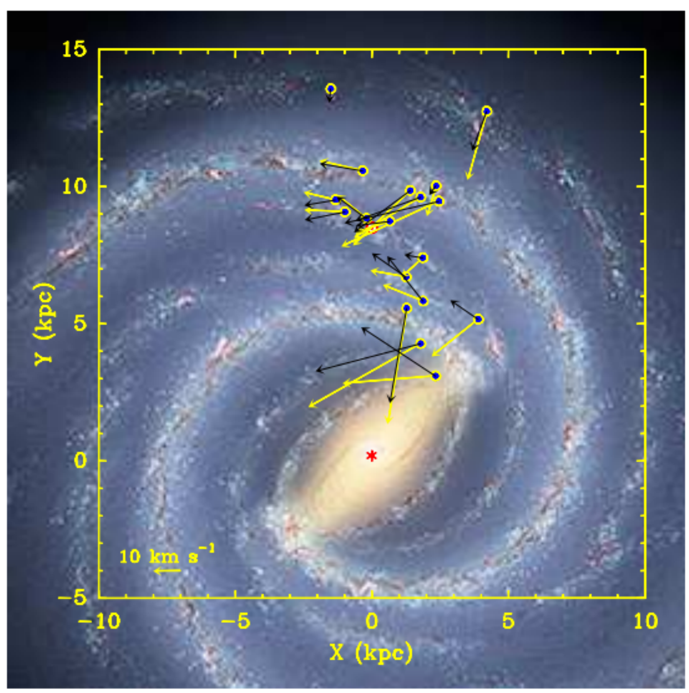
Range of allowed values

VLBI Data

- Using parallaxes and proper motions of a large number of high-mass star-forming regions, have full 3D locations and velocity vectors
- Get better galactic model
  - Preliminary results show that the Milky Way has four major, gas-rich spiral arms, and some minor arms in its inner region near the bar.
  - and best estimates
- $R_0 = 8.38 \pm 0.18$ kpc,
- $\Theta_0 = 243 \pm 7 \text{km s}^{-1}$
- $\partial\Theta / \partial R = -0.4 \pm 0.7 \text{kms}^{-1} \text{kpc}^{-1}$.



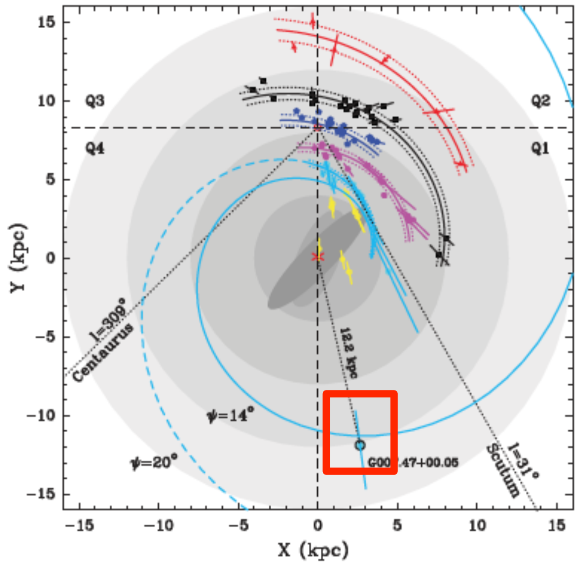
- The light (yellow) arrows are for IAU standard values of R_0 = 8.5 kpc and V_r = 220 km /s and a flat rotation curve, black arrows for V_r= 254 km/s
- high mass star forming regions orbit the Galaxy slower than the Galaxy rotates!



ˈig. 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

Hot New Paper

- New data for triangular region extending ~10° to either side of the Galactic center where the MW is rotating ~perpendicularly to our line of sight, so radial velocities are degenerate at values around zero
- VLBA, which has been measuring trigonometric parallaxes and proper motions) of masers associated with hundreds of high-mass star–forming regions in the Galaxy
- change in position with time of the masers, with respect to an extragalactic continuum source is the sum parallax (i.e., a sinusoid), due to motion of Earth around the Sun, plus motion of the maser in the earth frame.
- For a distant maser derive parallax of 0.049+/-0.006 mas (!) =20.4 kpc



Mapping spiral structure on the far side of the Milky Way- Sanna et al Science 358,227 2017

Comparison to Kinetic Model of MW

- Need priors for the Galactic rotation curve, $\Theta(R)$, and Θ_0 at R_0. Paper uses

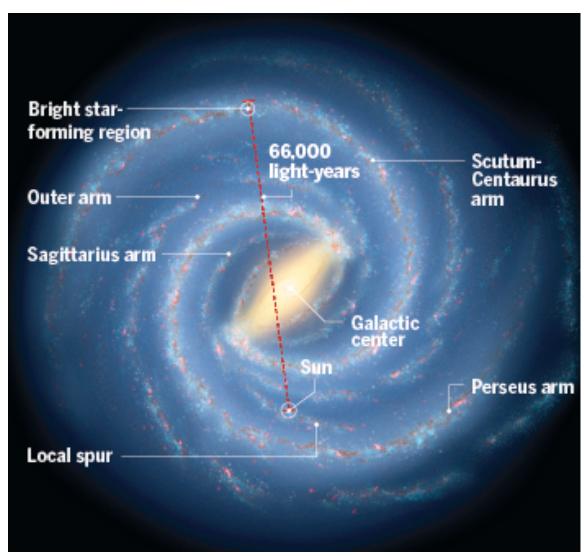
Θ_0=241+/-8, R_0± 8 8.34 ± 0.16

Get agreement between parallax and the kinematic

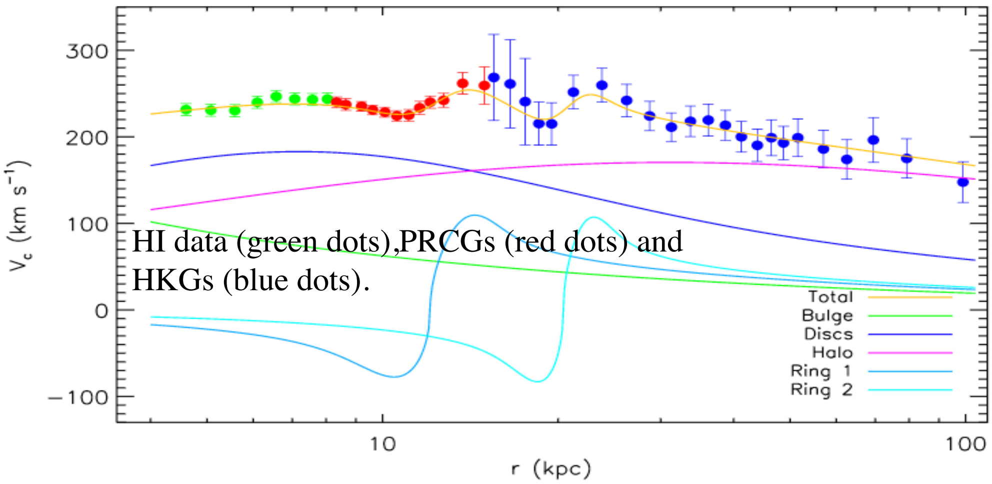
distances so approximation of circular motions holds at Galactocentric radii near 12 kpc in the far outer Galaxy but a single logarithmic spiral cannot describe the full complexity

of the Scutum-Centaurus-OSC arm (more later)

With radio parallax can now map spiral structure throughout the Galaxy.



Precise Rotation Curve

- Using 16,000 RG stars (Huang et al 2016) fitted with a detailed model of the MW
- M_{bulge}=8.9x$10^9 M_\odot$, $M_{disk,gas}$=5.5x10^9 $M_\odot$; M_{disks}=43x10^9 $M_\odot$
- $M_{DM\ Halo}$=9x$10^{11}M_\odot$
- M_{total}=9.7x$10^{11}M_\odot$ 7% baryons (Planck 18% of **matter** is baryonic, 4.9% of closure density)
- 

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.

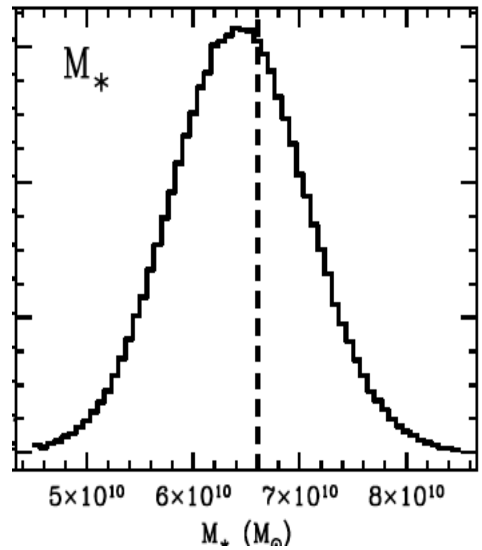
- it remains unclear whether there is any need for a substantial amount of dark matter in the disk itself (Binney et al 2012)
  - But, a major obstacle is that the uncertainty in the amount of baryonic matter in the disk makes it hard to determine the relative contributions from dark and baryonic matter 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.

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



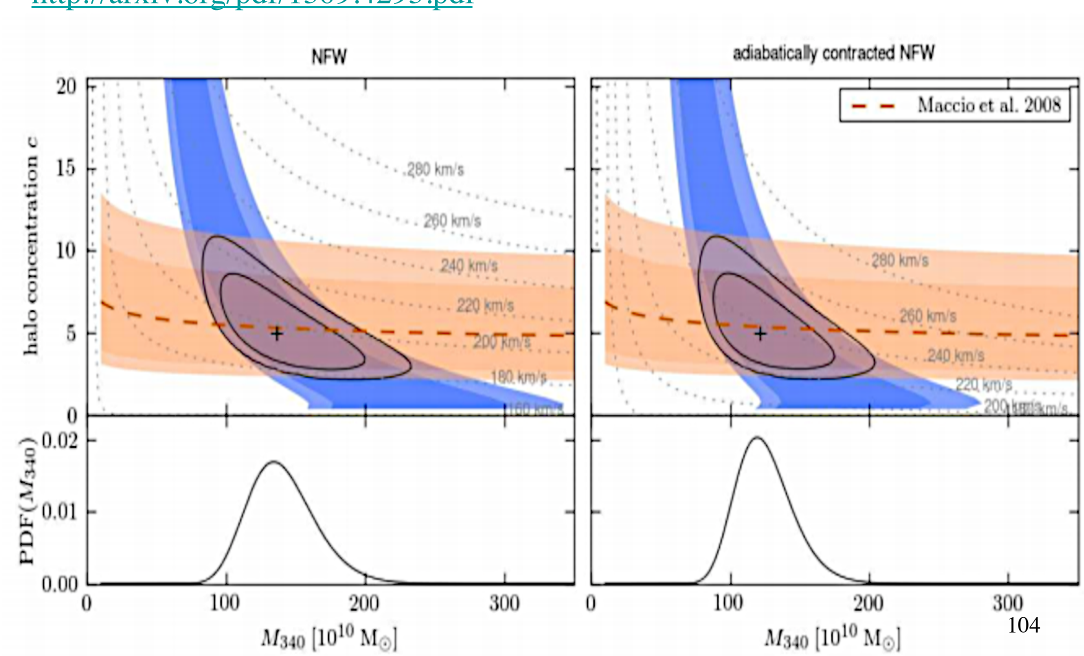
Probability of stellar mass
McMillian 2012

Best fit parameters

- at sun, thin disk has 90% of the mass and thick disk 10%
- 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 = 8.9x 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 $M_\odot/pc^3$)

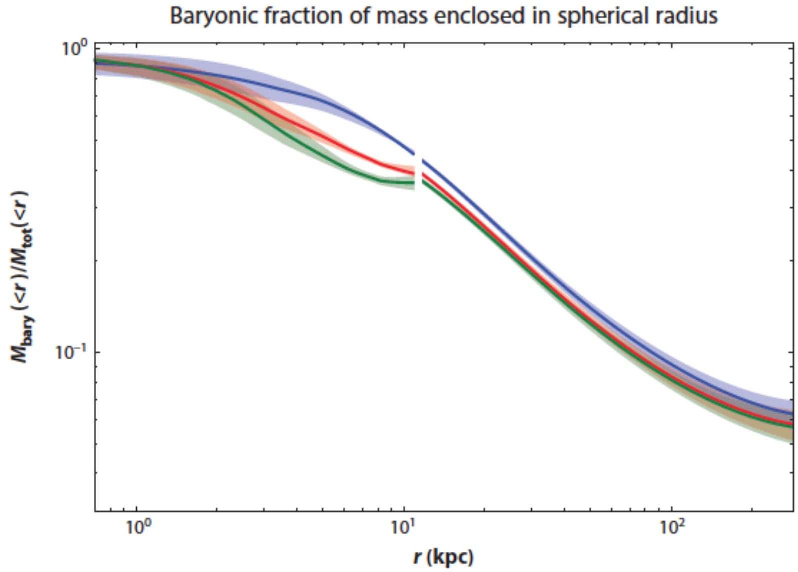
How does mass depend on shape of potential and circular velocity.

- Another detailed analysis of the MW mass (Binney et al 2013. Piffl 2013; http://arxiv.org/pdf/1309.4293.pdf



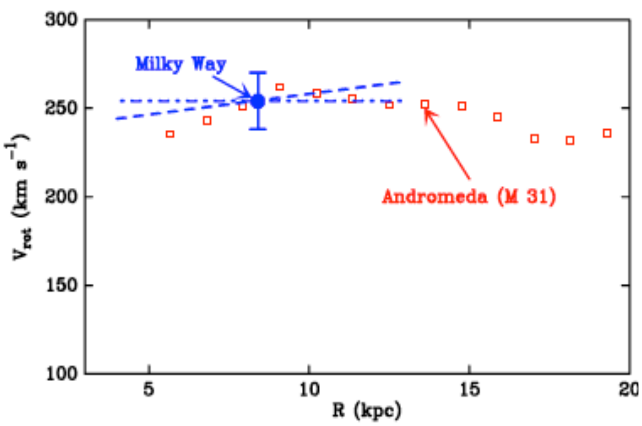
Dark Matter

- Using best estimates of all the baryons
- the fraction of the gravitational mass that is baryonic varies from ~95 % near the galactic center, ~50% near the sun down to ~7% at the virial radius compared to 16% for the universe as a whole



Bland-Hawthorn and Gerhard 2016

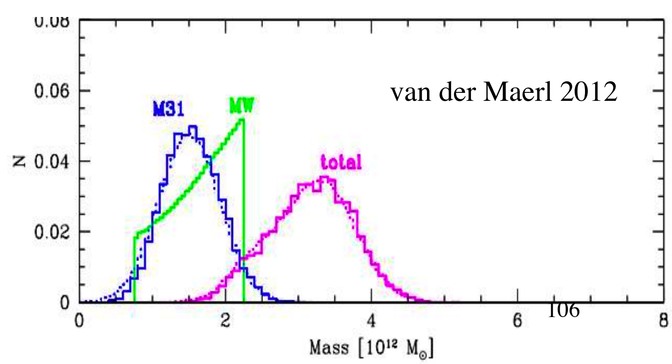
Comparison with M31



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

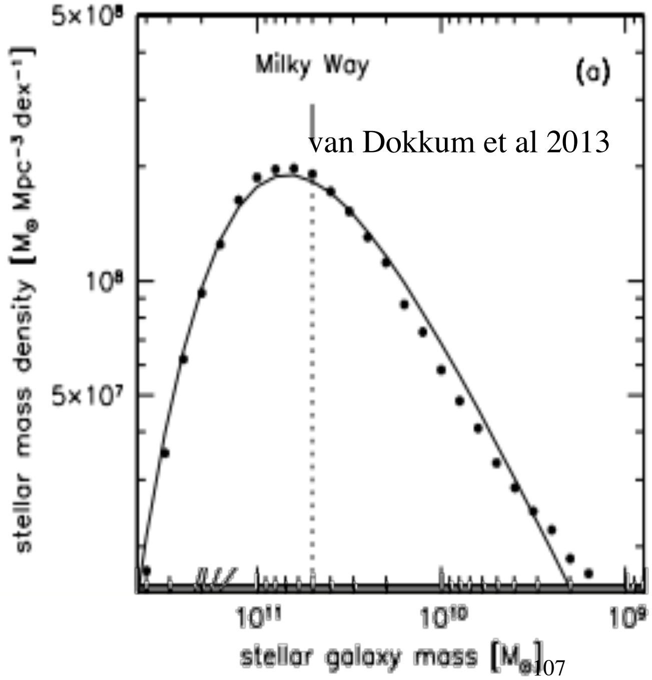
Probability that M31 and MW have a given mass and for the sum

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



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)

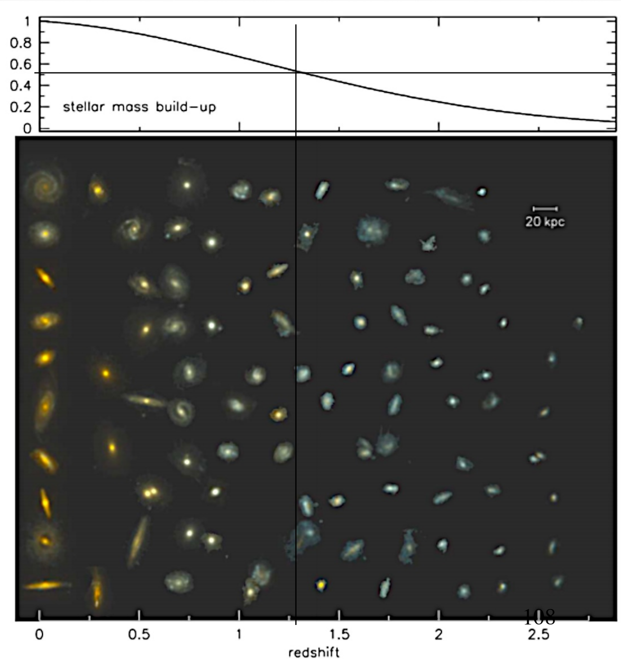


107

Progenitors of the MW

- What did the progenitors of the MW look like- **van Dokkum et al** [2013ApJ...771L..35V] (please read) 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.



108

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

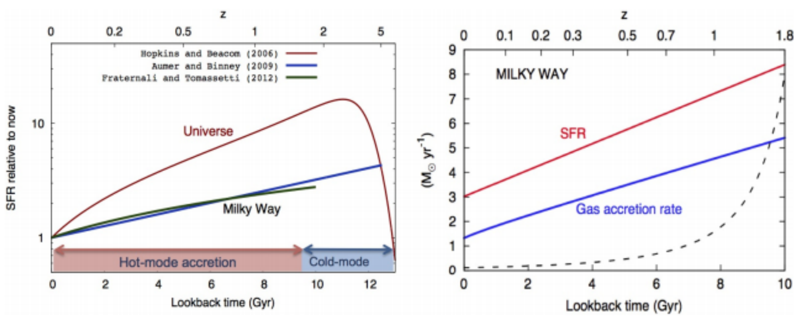


Figure 1. *Left:* comparison between two determinations of the SFH of the Milky Way (Aumer & Binney 2009; Fraternali & Tomassetti 2012) and the average star formation rate density of the Universe (Hopkins & Beacom 2006). The three distributions are normalized at the current time. *Right:* reconstruction 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.

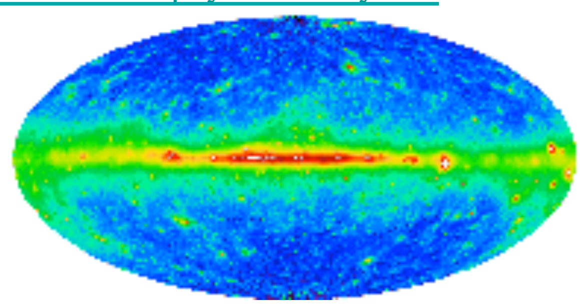
SF history of MW (Fraternali 2013) MW SFR does not match that of the universe as a whole (but it shouldn't- at high z elliptical galaxies dominate)

Cosmic Rays-100th Anniversary of their Discovery in 2012

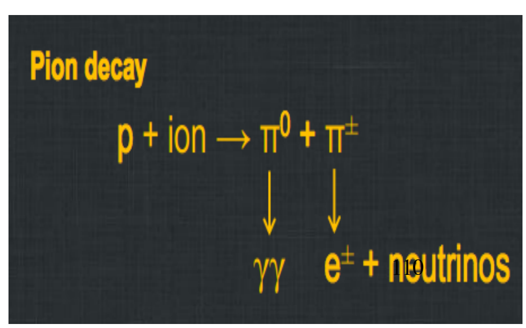
http://www.aps.org/publications/apsnews/201004/physicshistory.cfm

- 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
  - Direct measurements at earth
- 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

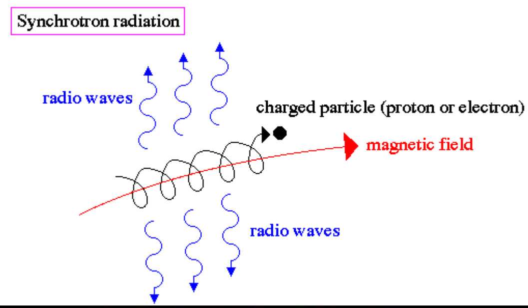


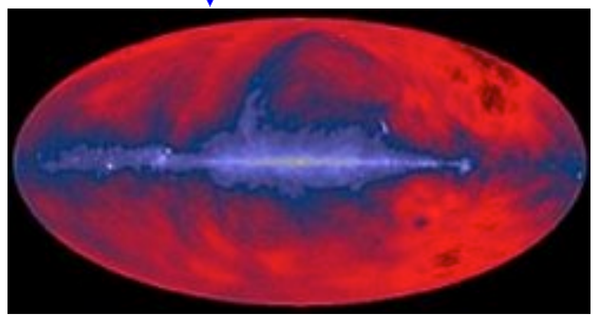
Radio Continuum Emission

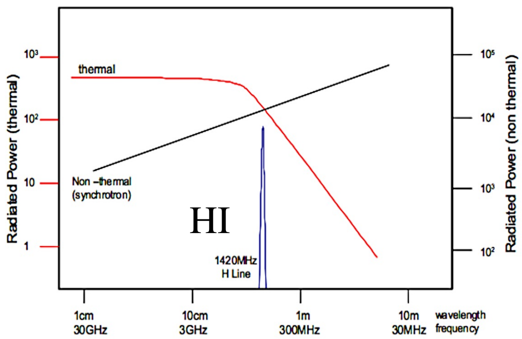
- Synchrotron emission: convolution of particle spectrum and magnetic field-power law spectrum-power law spectrum $F_\nu \sim A\nu^{-\alpha}$

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.





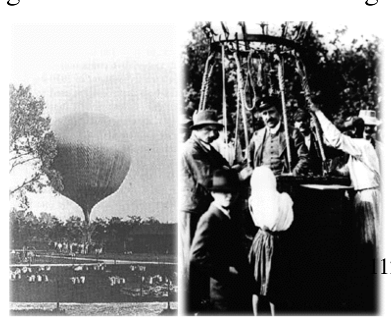


radio continuum image of MW

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

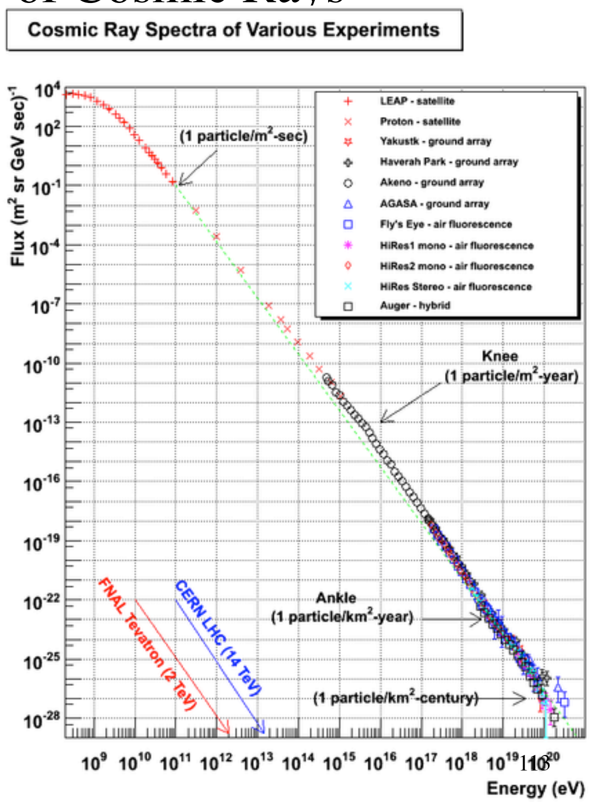
- scientists had been puzzled by the levels of ionizing radiation measured on the earth and in the atmosphere.
- The assumption was that the radiation from the earth and would decrease as one went away from the surface.
- Hess greatly increasing the precision of the electroscopes*and then by personally 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



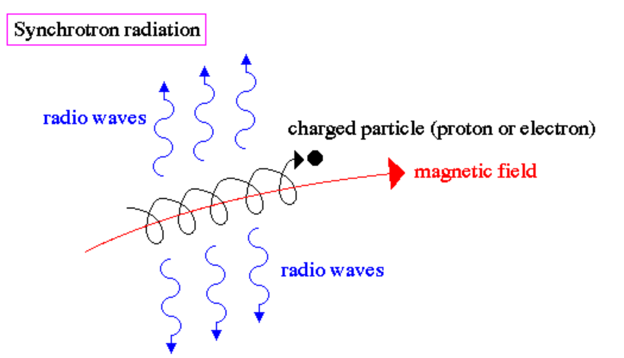
105 Years of Cosmic Rays

- 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

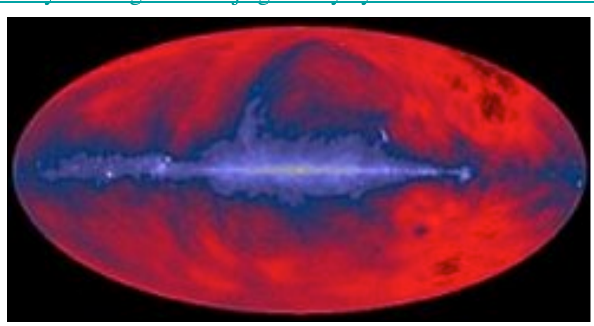


Cosmic Rays

- Have appreciable energy density ~1 eV/cm^3
- **Synchrotron emission intensity is convolution of particle spectrum and magnetic field-**
  - emission is due to relativistic electrons
- 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= $m_e c(\mathrm{sqrt}(\gamma^2-1)/eB$; 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

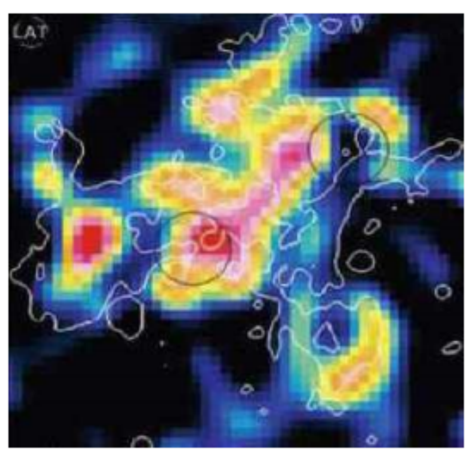


Fig. 2 ~100 pc Cygnus Superbubble in 10-100 Gev γ-Rays from Fermi [11]

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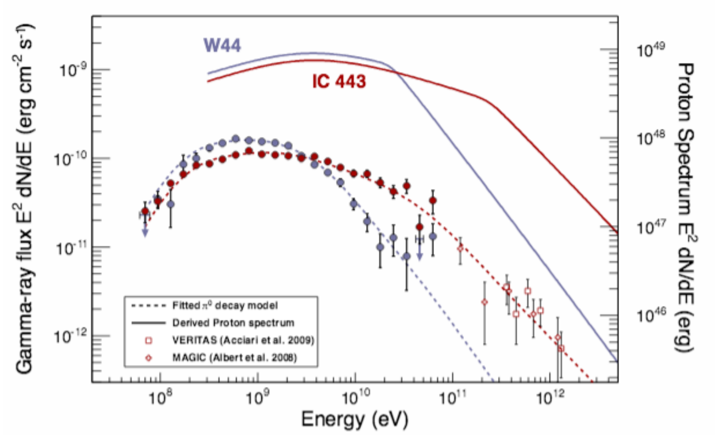

Figure 5. Proton and gamma-ray spectra determined for IC 443 and W44 from [55].

- The gamma ray emission traces the gas distribution (times the CR distribution)
- Fermi detection of π_0 decay in 2 SNR- **proof** that some CRs are produced in SNR

ISM

$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

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 dynamics...***