Back to the Galaxy II

Scott Tremaine, IAS

KITP Sep 29, 2008

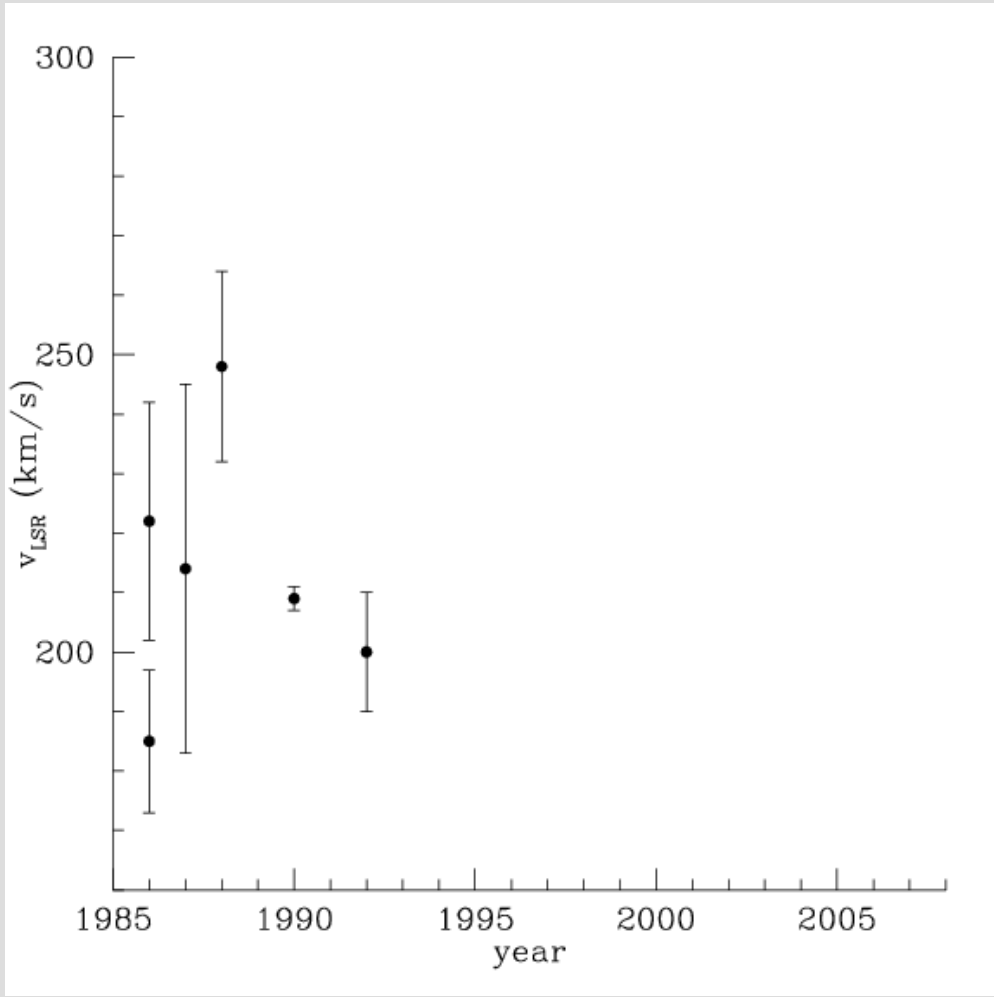
A pessimist's view of Galactic structure. II

PESSIMISM, n. A philosophy forced upon the convictions of the observer by the disheartening prevalence of the optimist with his scarecrow hope and his unsightly smile (Bierce, The Devil's Dictionary)

- focus on areas in which progress has been slow (since optimists do not)
- at the time of BTTG I there was slow progress in our understanding of
  - properties of solar neighborhood (solar radius, solar speed, local density [the Oort limit], Oort constants, etc.)
  - distribution of mass in the dark halo (total mass, outer radius, shape, local density, etc.)
  - spiral structure (amplitude, number of arms, pattern speed, morphology, etc.)
- why is understanding Galactic structure so hard?
  - Galactic disk is very responsive and the environment is noisy (molecular clouds, merging satellites, etc.)
  - triaxial stellar systems are much more complicated than axisymmetric ones (bar, halo, and perhaps bulge and disk)
  - substructure in disk and halo
  - relaxation is ineffective so Galaxy retains memory of initial conditions (nature, not nurture)
  - dark matter

The speed of the Local Standard of Rest

- Hipparcos spacecraft improved accuracies of parallaxes and proper motions by about a factor 10 (~100,000 stars with accuracy ~1 mas or 1 mas/yr)
- "I think that the improved accuracy of the Hipparcos survey will...resolve many of the puzzles and inconsistencies in our current understanding of Galactic structure"



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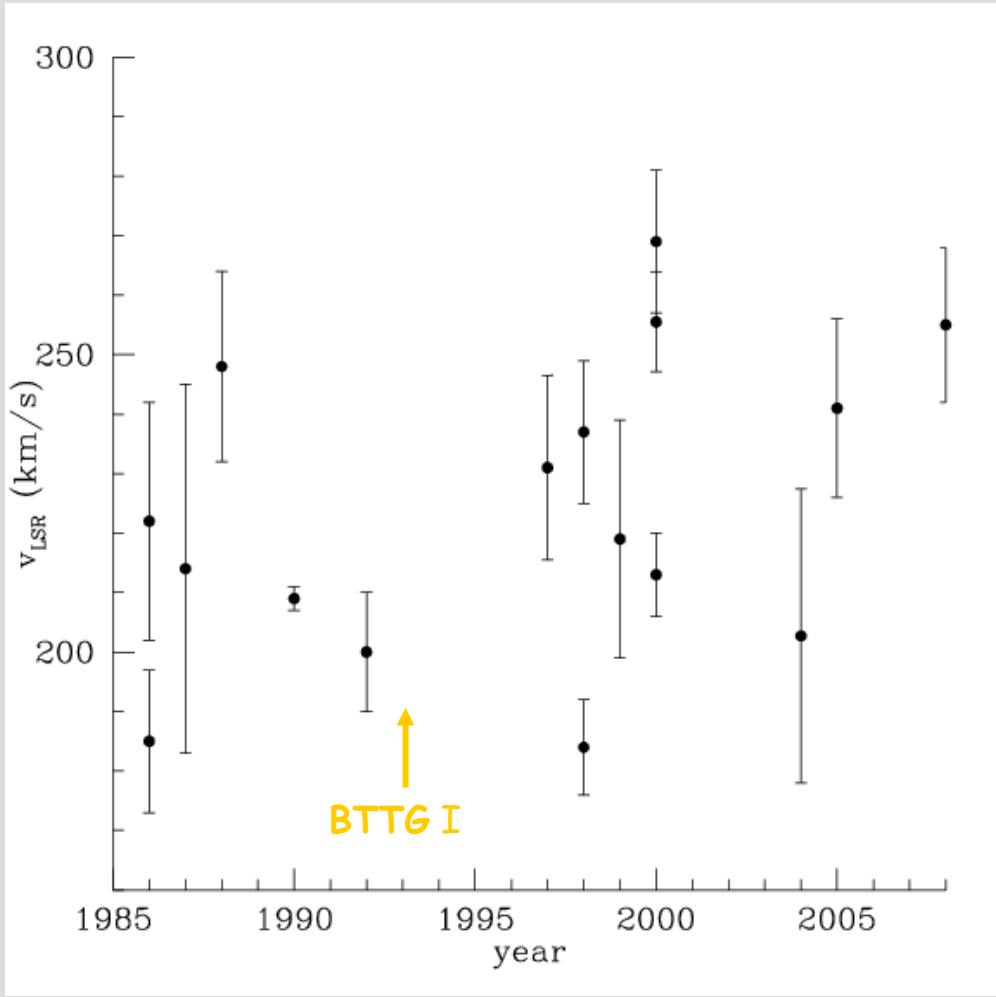
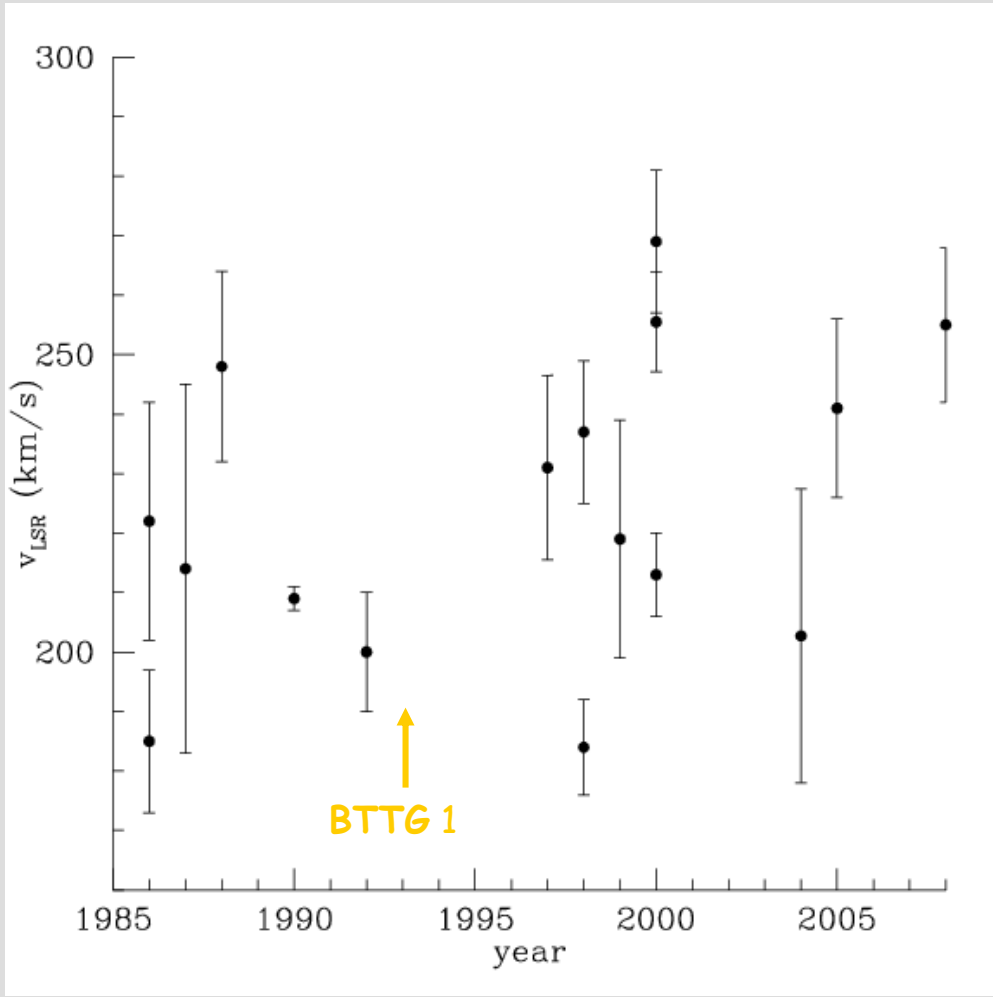
- not pessimistic enough
- accurate local measurements yield accurate global velocity field only if the field is smooth and axisymmetric



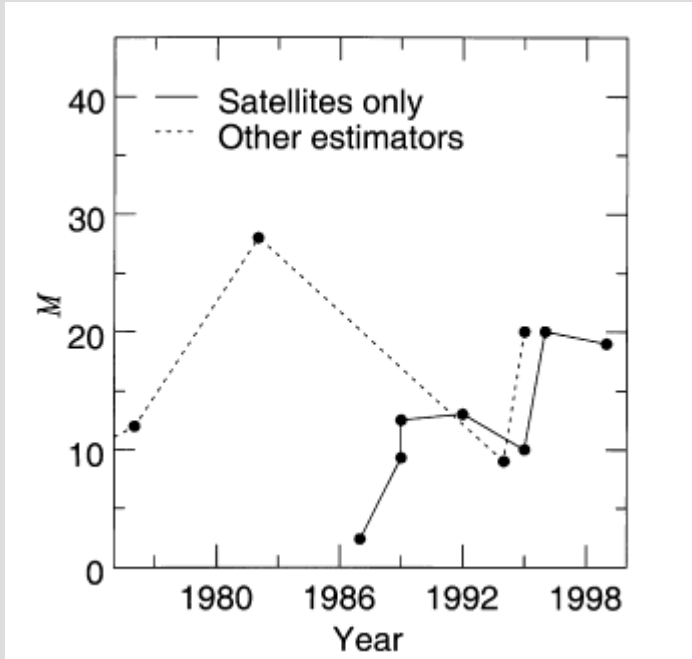
The speed of the Local Standard of Rest

- GAIA spacecraft (launch 2011) will improve accuracies of parallaxes and proper motions by about a factor 30 (~10^9 stars with accuracy ~0.03 mas or 0.03 mas/yr)
- I think that the improved accuracy of the GAIA survey will...resolve many of the puzzles and inconsistencies in our current understanding of Galactic structure



Dark matter distribution

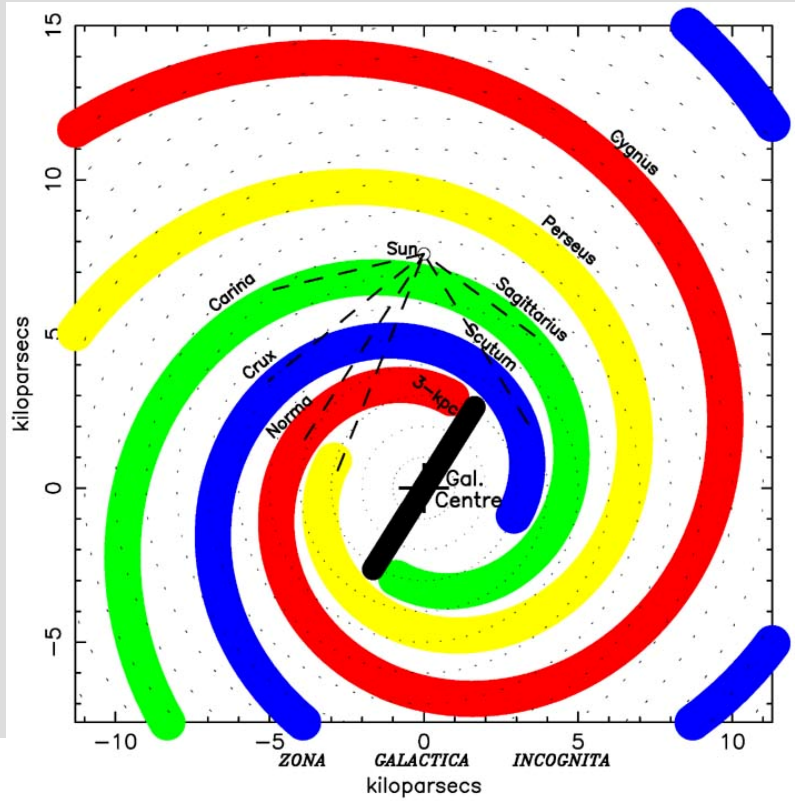
- dark matter dominates the total mass of the Galaxy
- estimates of total mass and size of Galaxy have not changed much, though evidence is now much better:
  - Ostriker, Peebles & Yahil (1974): $M \sim 10^{12}\ M_\odot$, R ~ 500 kpc
  - Wilkinson & Evans (1999): $M \sim 2 \times 10^{12}\ M_\odot$, 90% of mass inside 400 kpc
  - Battaglia et al. (2005): $M \sim 1 \times 10^{12}\ M_\odot$
- fraction of radial force at the solar radius supplied by dark matter:
  - 10 – 45 % (Sackett 1997)
  - 35 – 65 % (Binney & Tremaine 2008)
  - lower limit is non-zero *only* because halo models have monotonic density
- uncertainty arises mainly because of uncertain disk scale length (surface density $\propto$ exp(- R/h) with h between 2 and 3 kpc)
- simulations of structure formation predict strong density cusps in dark matter but observations are consistent with ***no*** dark matter at or within solar radius



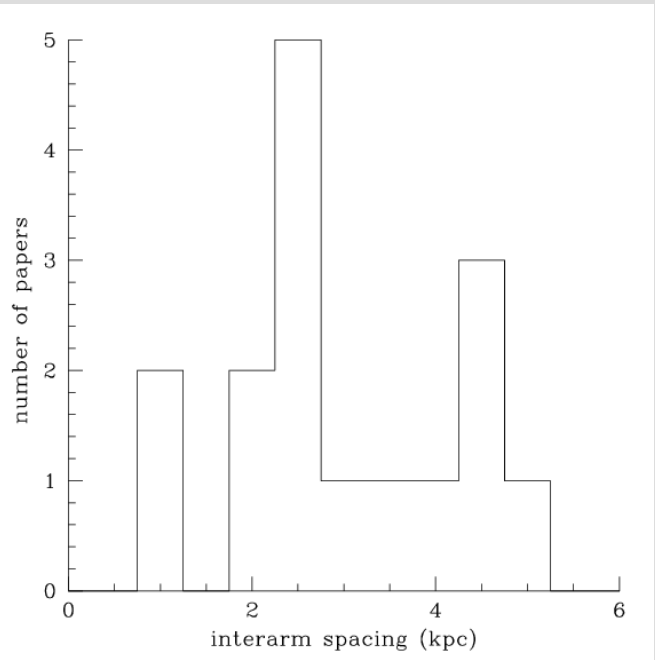
Spiral structure

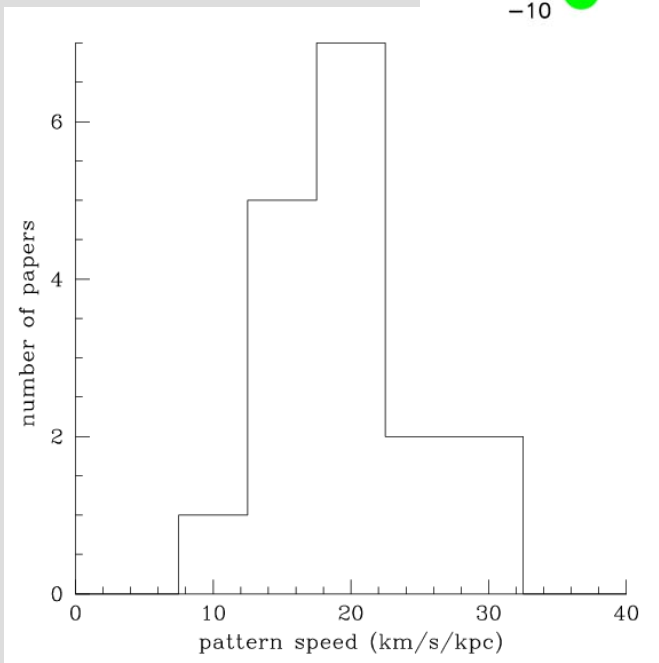
What we don't know:

- transient or steady?
- pattern speed (none? one? several?)
- number of arms (2? 3? 4?)
- amplitude
- pitch angle or interarm spacing
- morphology (grand-design or flocculent)



Vallée (2008)





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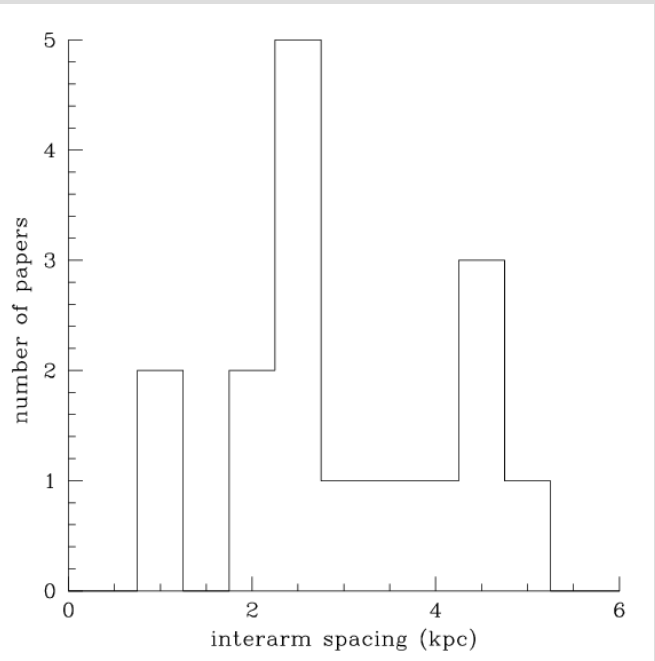

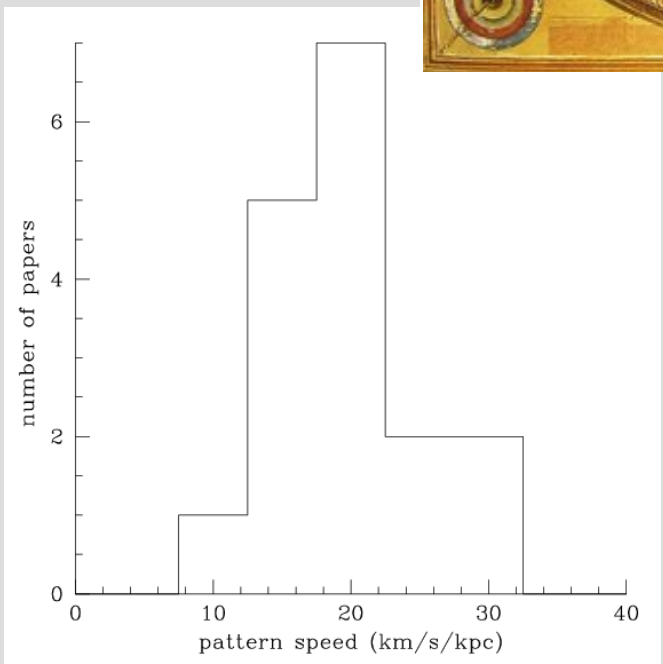

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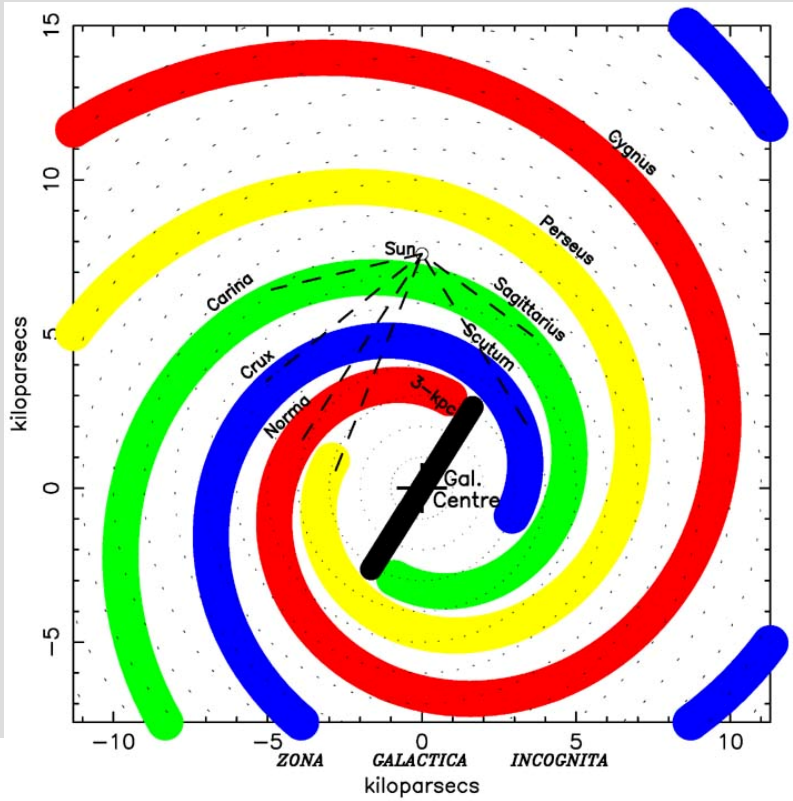

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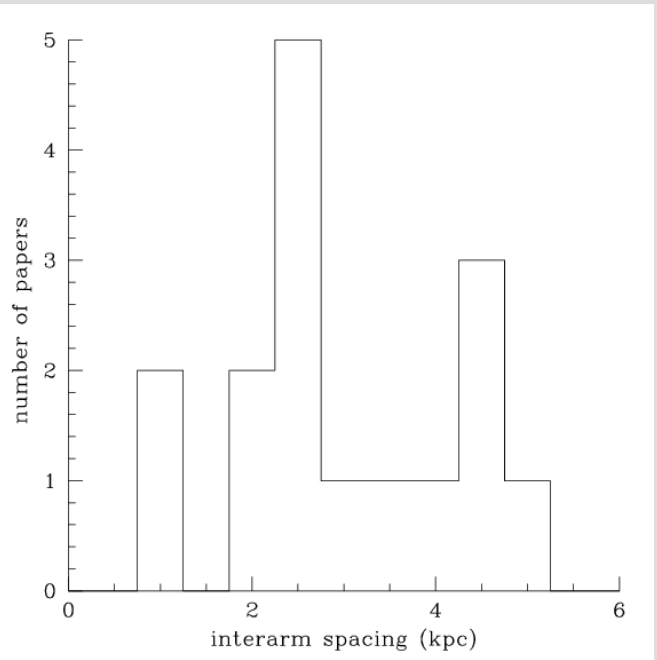
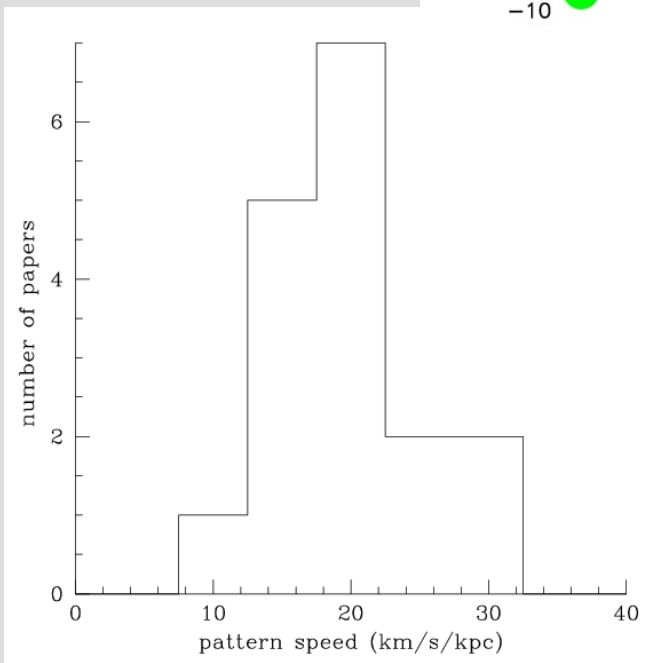
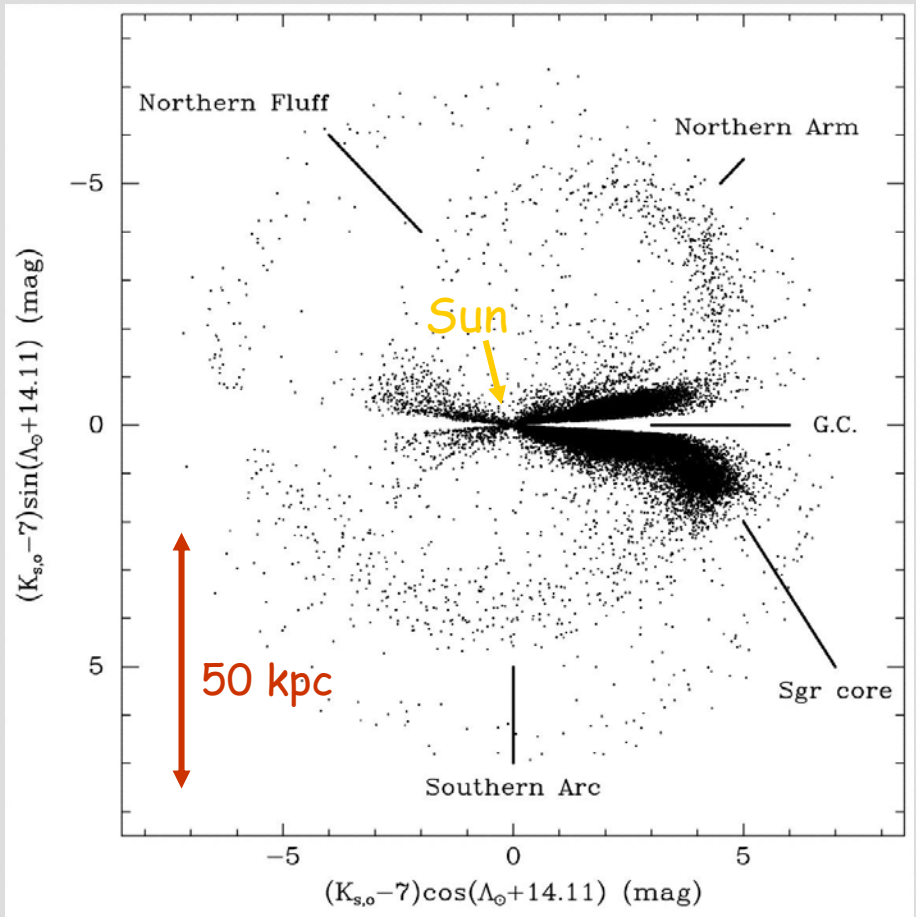




Roškar

Substructure in the stellar halo

- in the past decade many lumps, tails and other features have been discovered in the stellar halo of the Galaxy
  - Sagittarius stream
    - associated with Sagittarius dwarf galaxy
    - has been detected around 1-2 complete orbits
    - passes over Galactic poles and close to the Sun
    - provides a significant fraction of all halo stars at ~ 50 kpc

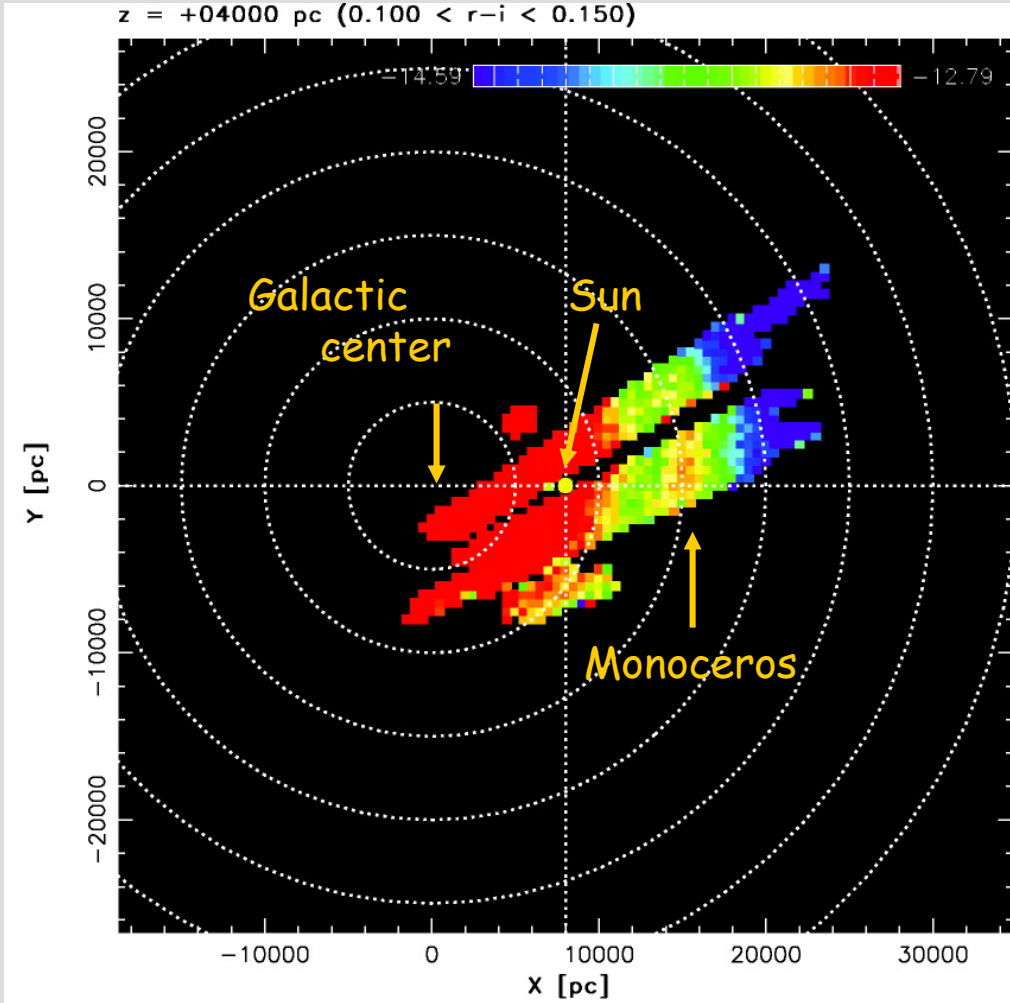


Majewski et al. (2003)

Substructure in the stellar halo

- in the past decade many lumps, tails and other features have been discovered in the stellar halo of the Galaxy
  - Sagittarius stream
  - Monoceros stream
    - approximately circular ring lying in the Galactic plane at R~16 kpc

de Jong Jurić

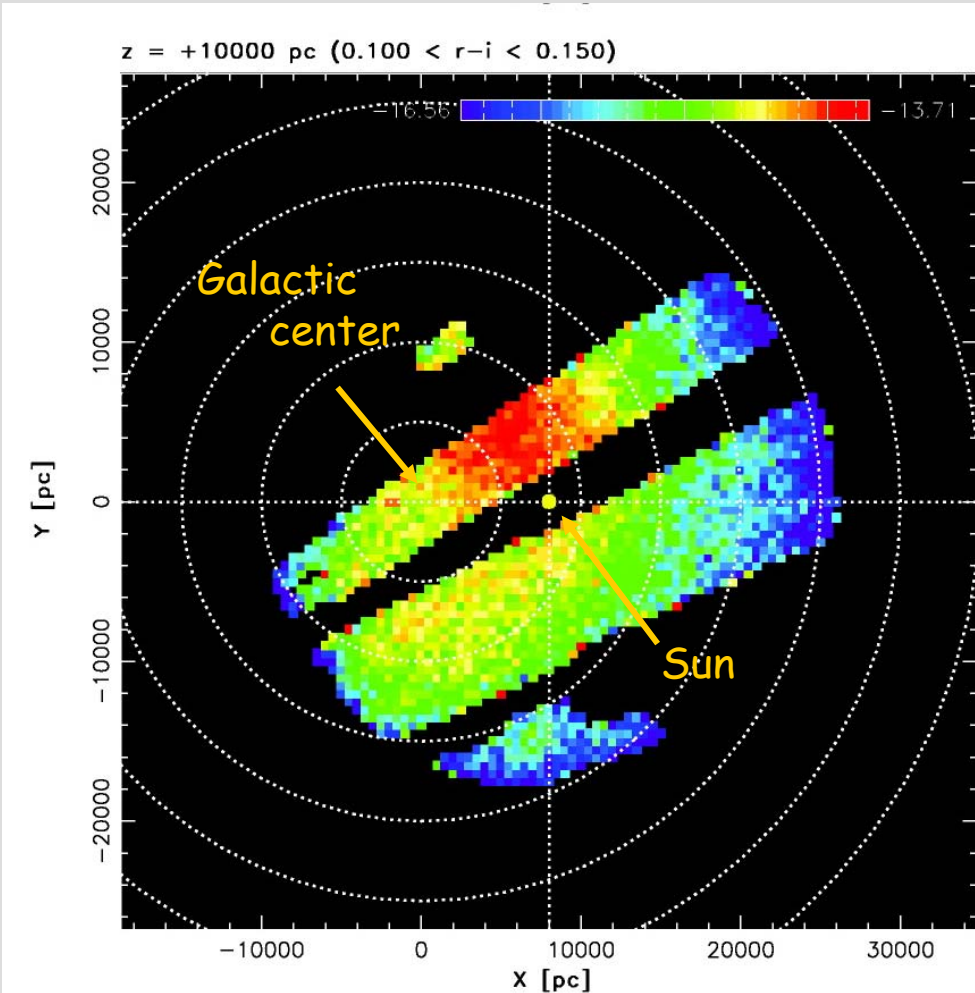


Jurić et al. (2008)

Substructure in the stellar halo

- in the past decade many lumps, tails and other features have been discovered in the stellar halo of the Galaxy
  - Sagittarius stream
  - Monoceros stream
  - Virgo overdensity
    - factor two excess

Jurić



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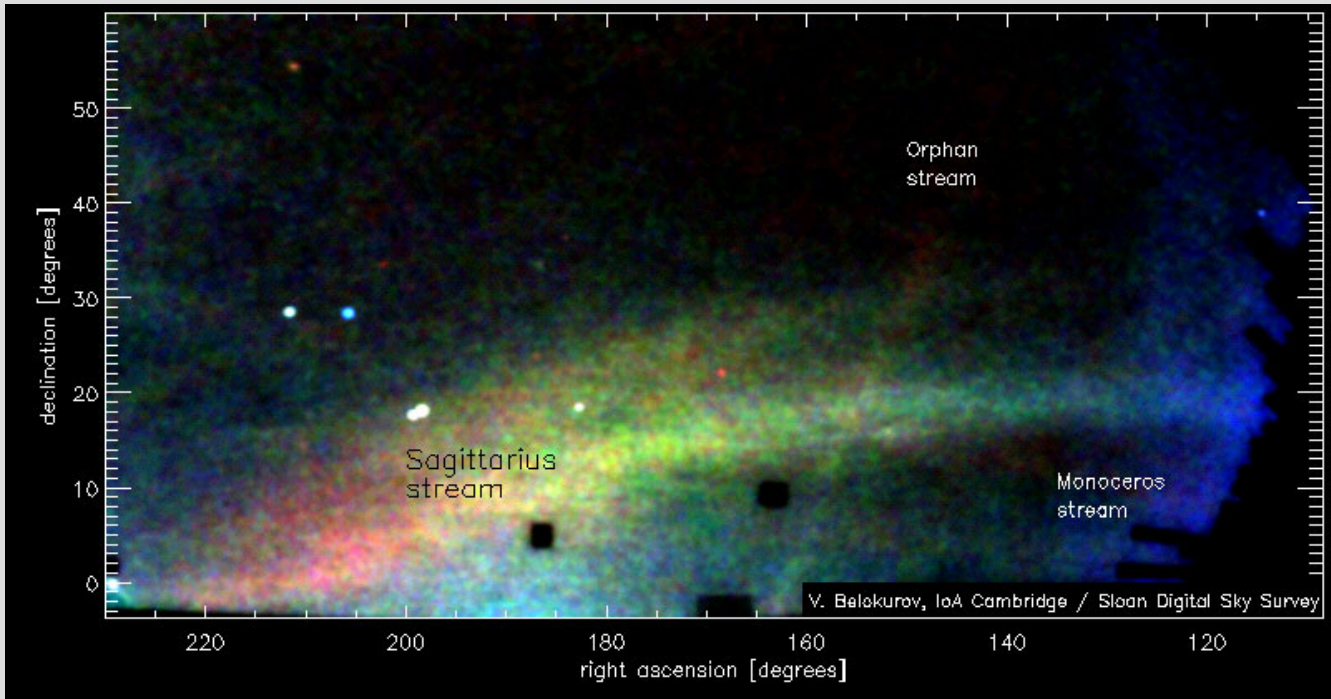
  - Virgo overdensity
  - "field of streams"

Belokurov et al. (2006)



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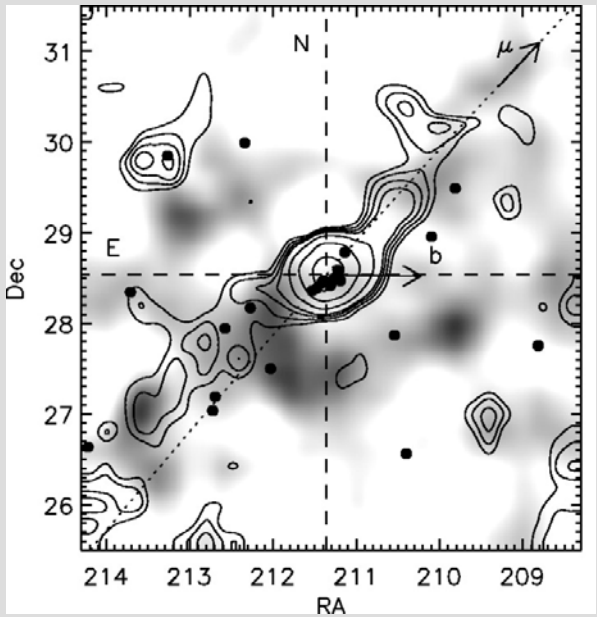
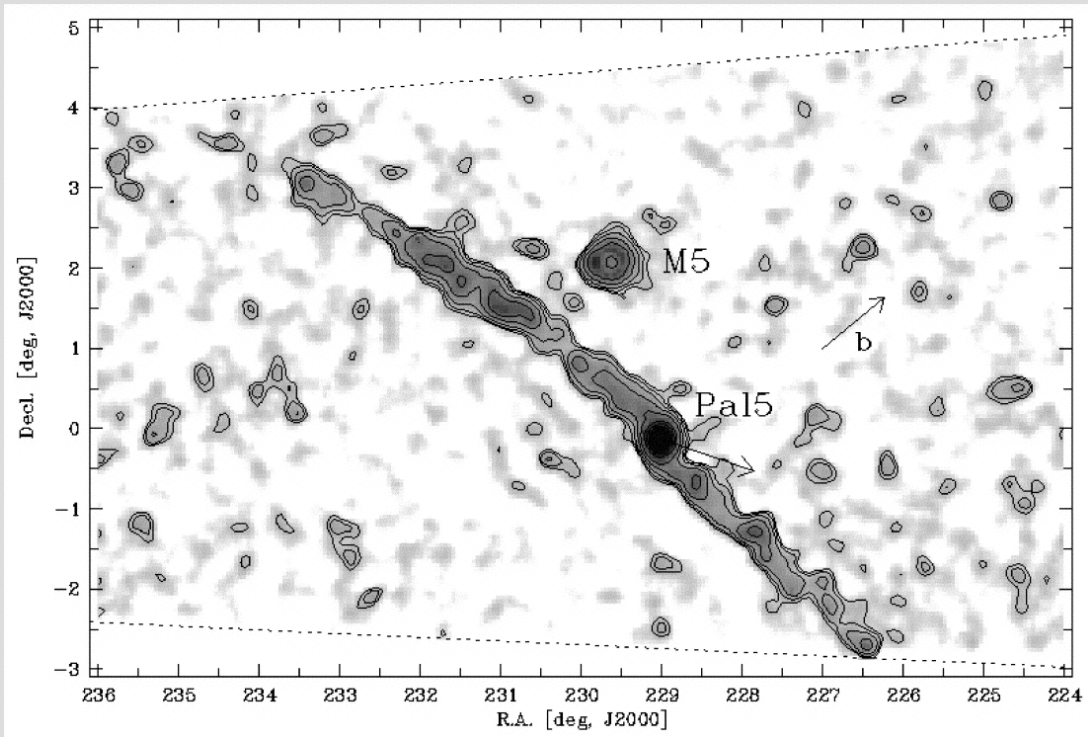
  - Virgo overdensity
  - "field of streams"
  - tidal tails from globular clusters



Belokurov et al. (2006)

Odenkirchen et al. (2003)



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  - Sagittarius stream
  - Monoceros ring
  - Virgo overdensity
  - "field of streams"
  - tidal tail from globular cluster Pal 5
  - ~10 new dwarf satellite galaxies

Bullock

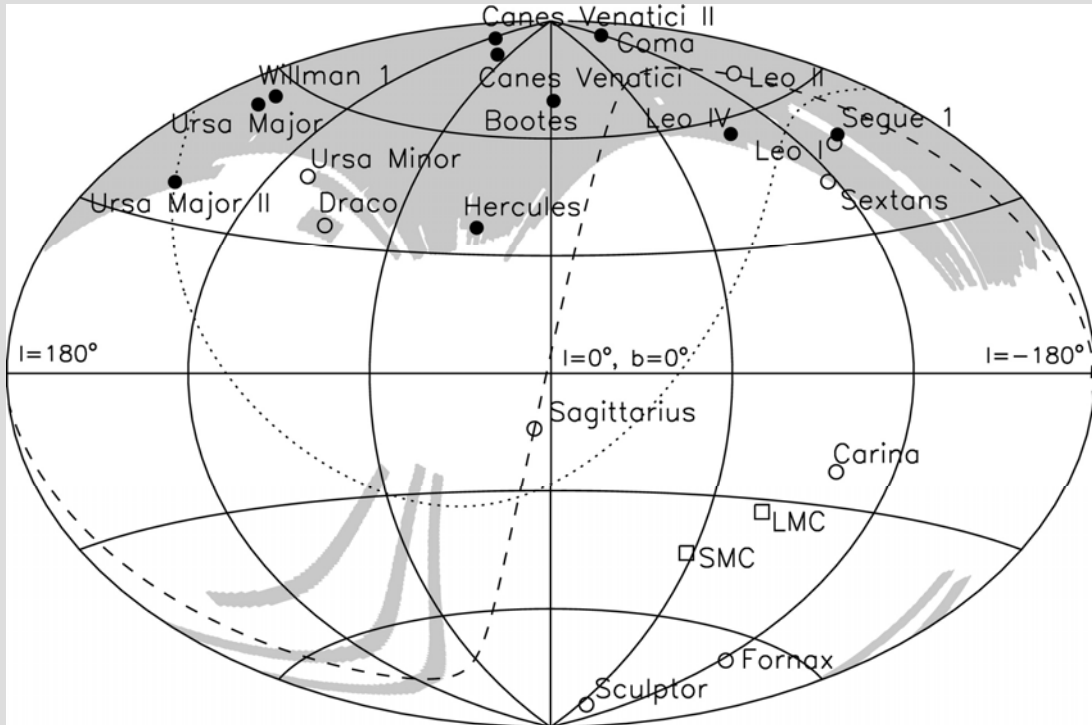
Schlaufman

Geha

Belokurov et al. (2007)

○ previously known

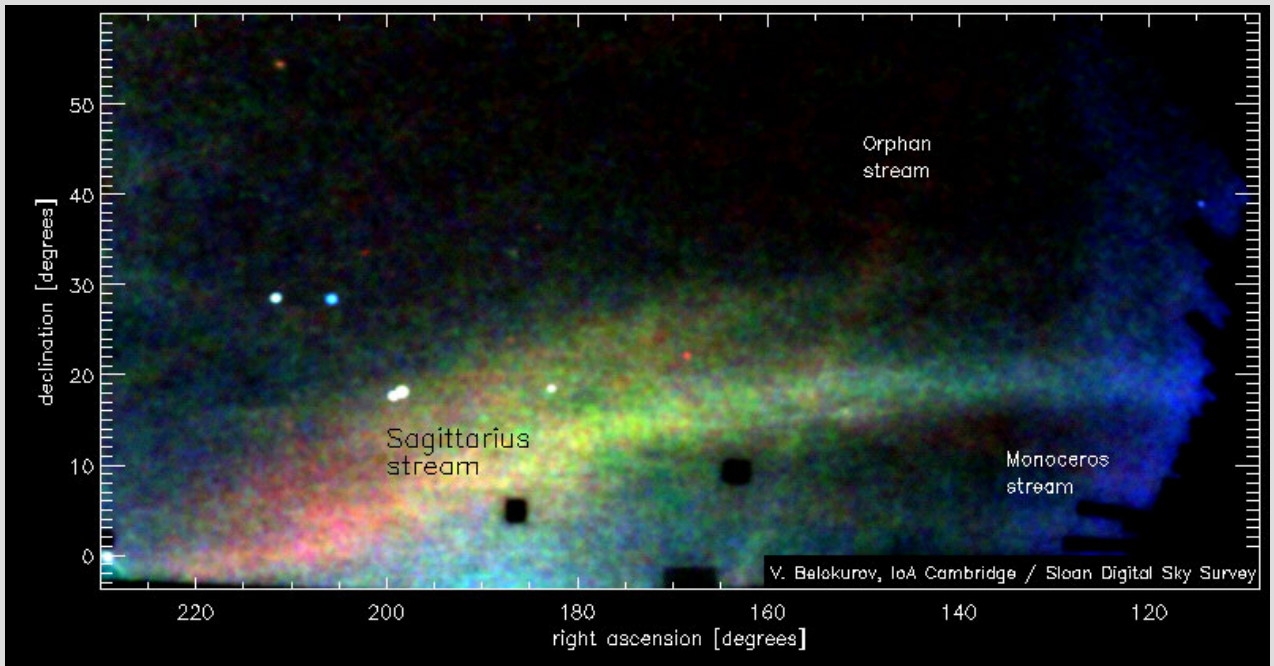
● SDSS

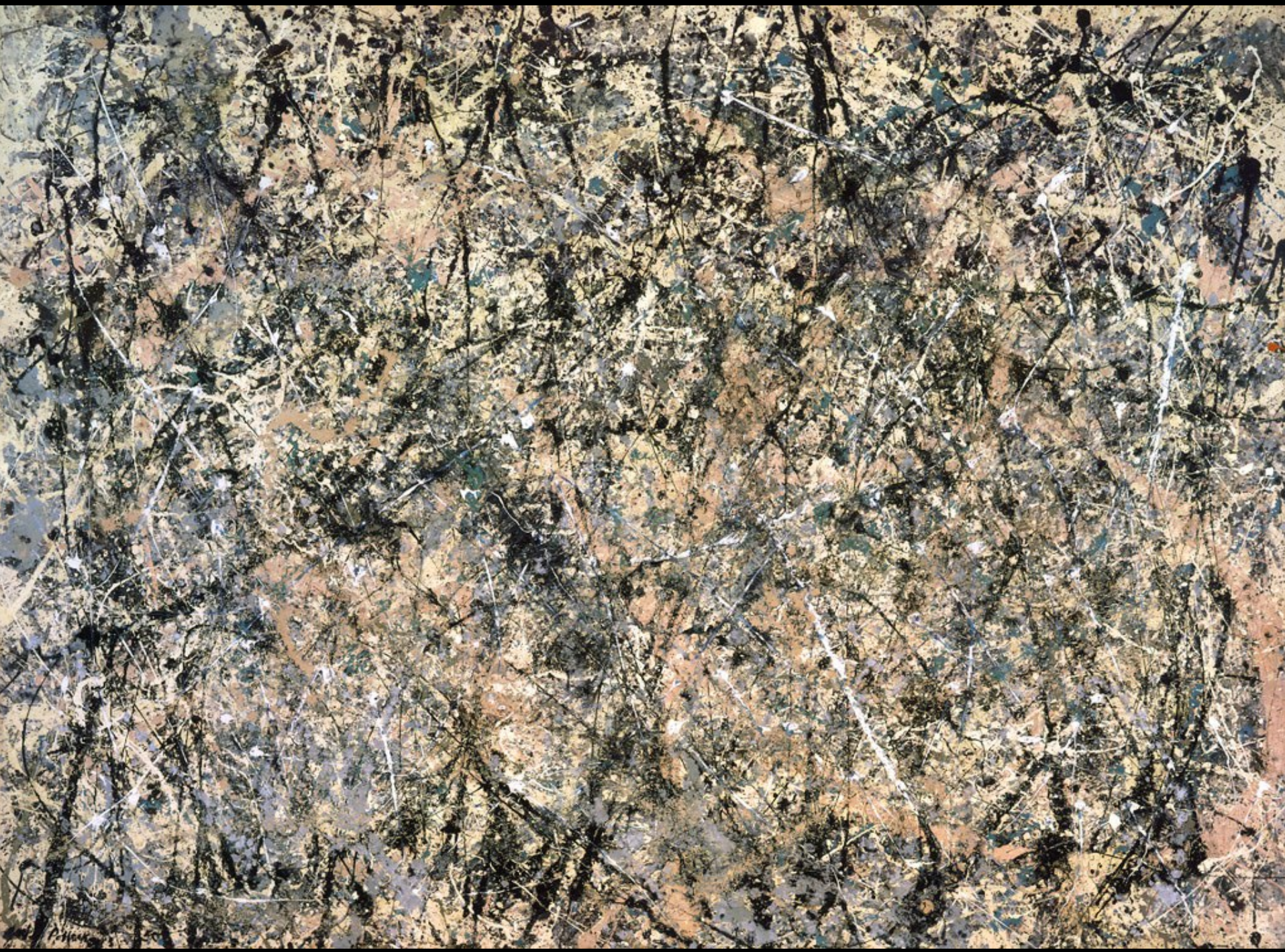


Substructure in the stellar halo

- concept of a lumpy halo dates back to Searle & Zinn (1978)
- BTTG I:

  Let us imagine how the Galaxy would look if we had a special telescope that was only sensitive to stars at r > 50 kpc. We would not see a smooth distribution of stars randomly dotted around the celestial sphere; rather, the stars would be concentrated in randomly oriented streaks of various lengths...





Substructure in the stellar halo

- Gould (2003): in the solar neighborhood, no stream has more than 5% of stars; typical stream < 0.25%; > 400 streams if equally strong. This is difficult to reconcile with the prominence of the Sagittarius stream
- "All science is either physics or stamp collecting" (Rutherford). When does mapping the substructure turn from physics into stamp collecting?

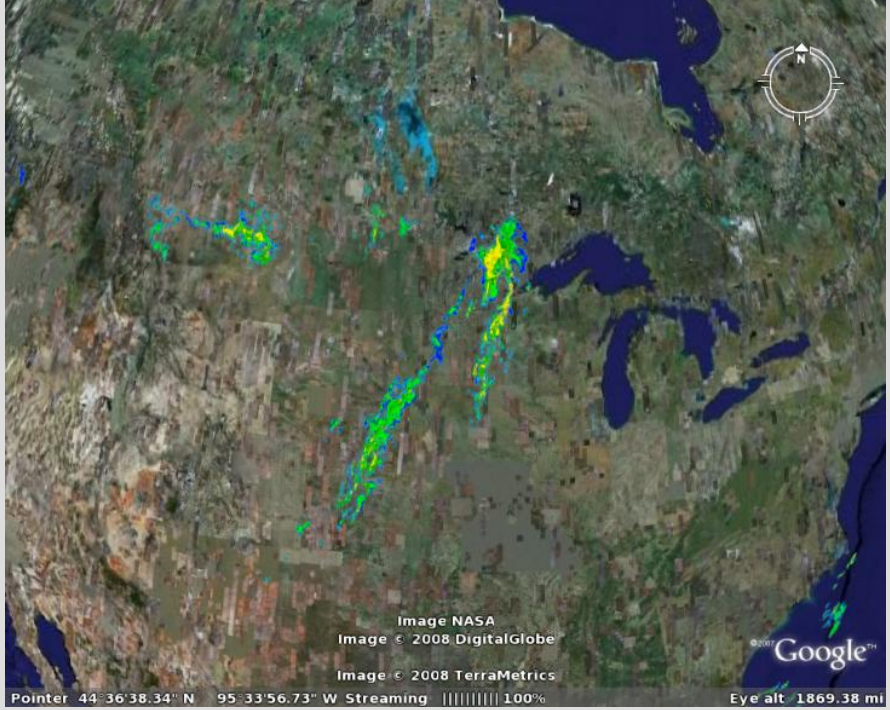


Image NASA
Image © 2008 DigitalGlobe
Image © 2008 TerraMetrics
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Pointer 44°36'38.34" N 95°33'56.73" W Streaming 100%
Eye alt 1869.38 mi

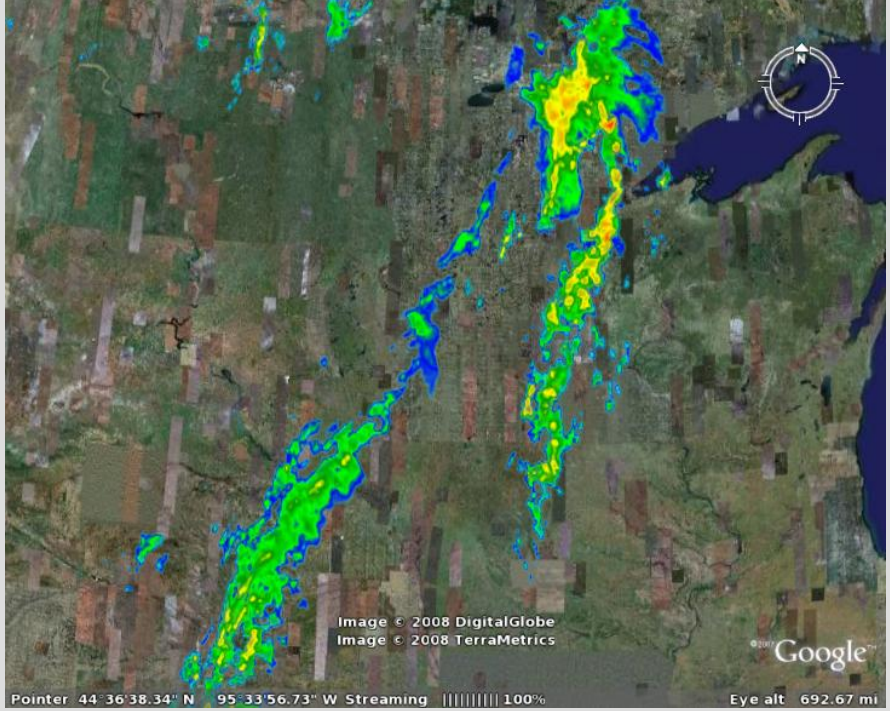
Image © 2008 DigitalGlobe
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Pointer 44°36'38.34" N 95°33'56.73" W Streaming 100%
Eye alt 692.67 mi

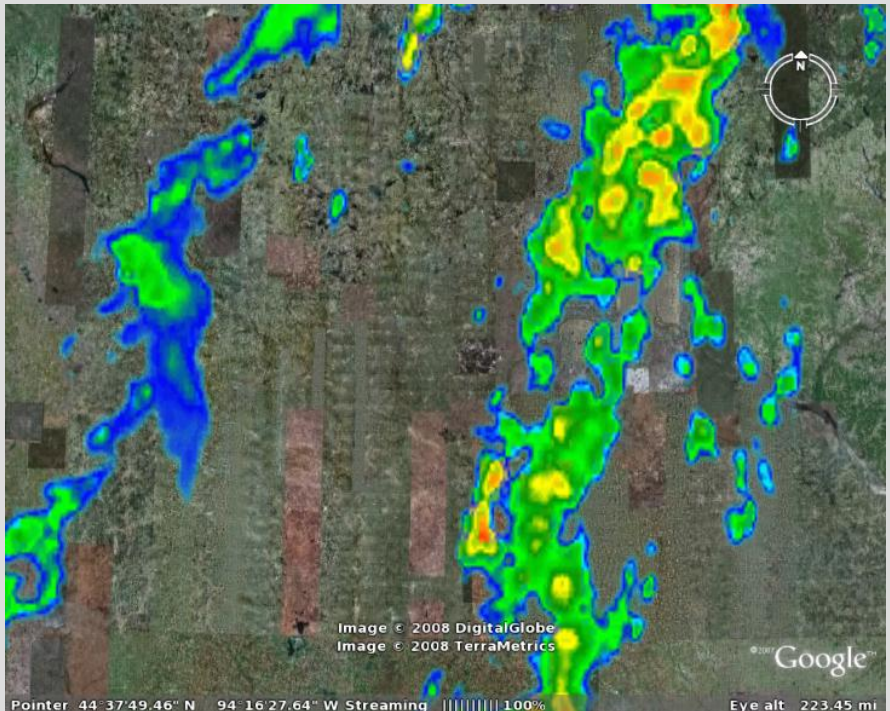


Image © 2008 DigitalGlobe
Image © 2008 TerraMetrics
Google
Pointer 44°37'49.46" N 94°16'27.64" W Streaming 100%
Eye alt 223.45 mi

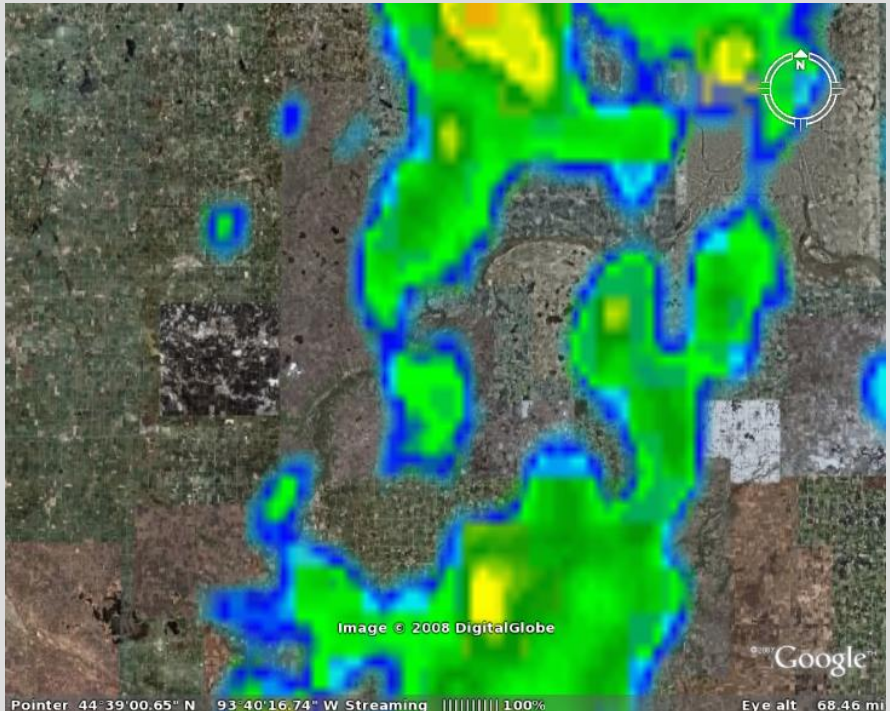
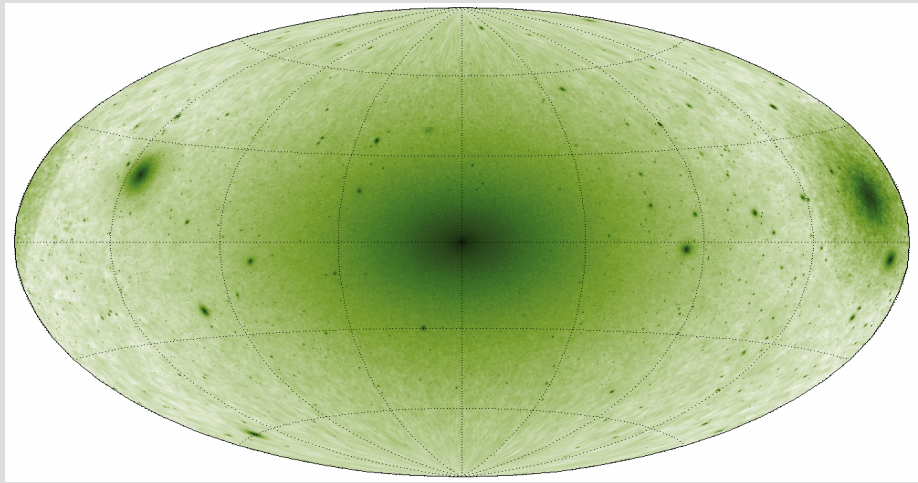


Image © 2008 DigitalGlobe
Google
Pointer 44°39'00.65" N 93°40'16.74" W Streaming 100%
Eye alt 68.46 mi

Substructure in the dark halo

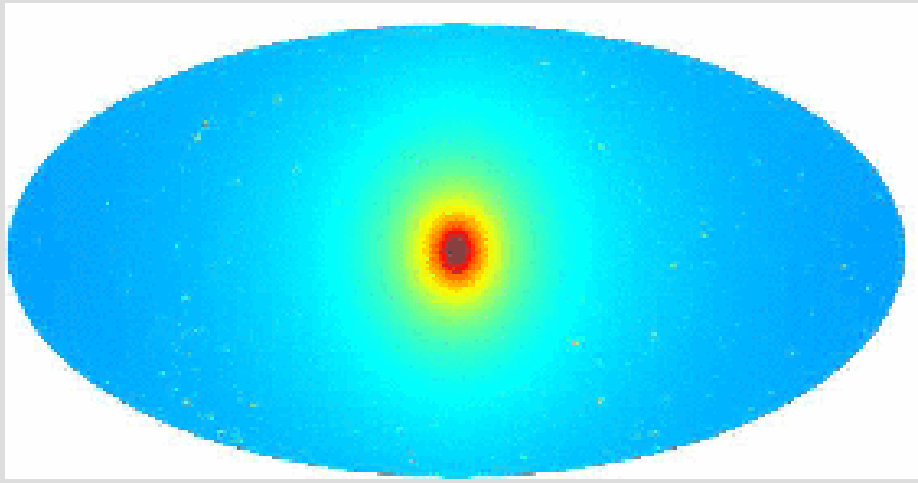
- annihilation radiation from WIMP dark matter may be observable by GLAST/Fermi



Kuhlen et al. (2008)

Kuhlen

- strongest signal from the sub-halos
- detectable sub-halos resolved by Fermi
- most prominent sub-halo typically has d ~ 20-40 kpc and M ~ 10^7-10^9 $M_\odot$



Springel et al. (2008)

Frenk

- strongest signal from the smooth main halo
- detectable sub-halos unresolved by Fermi
- most prominent sub-halo typically has d ~ 3-30 kpc and M ~ 10^6-10^7 $M_\odot$

Substructure in the dark halo

- annihilation radiation from WIMP dark matter may be observable by GLAST/Fermi
- there is room for improvement in our description of halo substructure:
  - groups and clusters (rich, poor, regular, irregular, Bautz-Morgan type, Rood-Sastry type, cD, etc.) $\Rightarrow$ statistical measures of clustering (correlation function, power spectrum, etc.)
  - primary halo, sub-halos, unresolved substructure in primary halo, substructure in sub-halos, sub-sub-halos, caustics, etc. ?
- what is the effect of the halo substructure on the Milky Way disk?
  - warp
  - non-circular motions
  - flatness (within ~0.1% inside solar circle)

Blitz

Weinberg

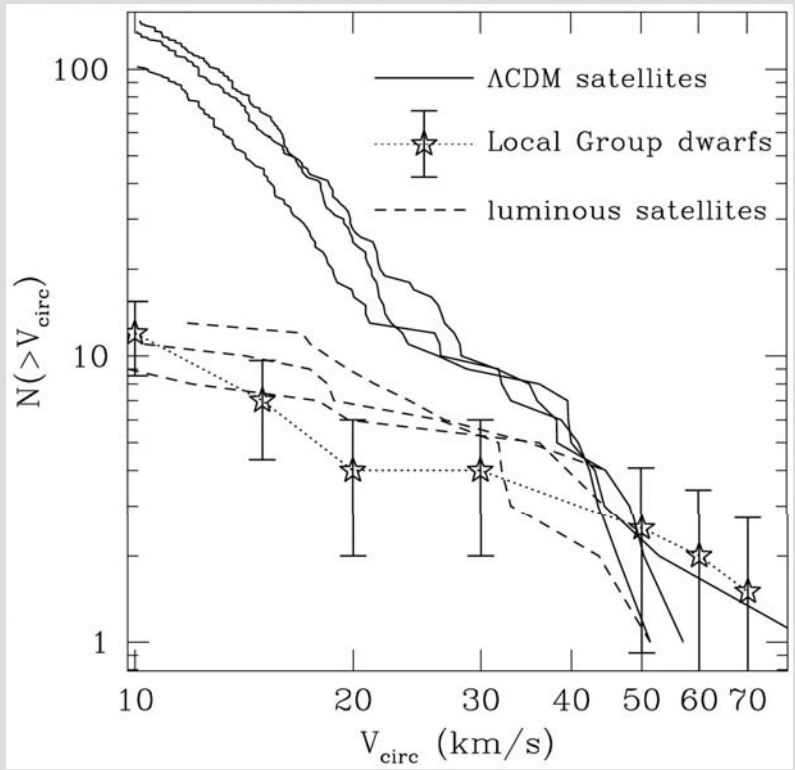
Dark matter on small scales

- standard ΛCDM model provides a comprehensive explanation for large-scale structure (> 1 Mpc) but not for small-scale structure:
  - missing satellite problem
  - dark-matter dominated dwarf galaxies appear to have cores, not cusps
    - isotropic models of stellar kinematics are fit better by cored potentials
    - survival of cold sub-systems
    - short dynamical friction timescales for globular clusters
  - relatively small dark-matter content inside the solar radius
- the Milky Way is ***the*** unique laboratory for exploring the properties of dark matter on small scales

Helmi | Bullock | Koposov | Tollerud

Chaname

Navarro



Kravtsov et al. (2004)

Substructure in the local disk

possible explanations for the substructure:

- dispersal of stars formed in small regions (but structure is present even in old stars)
- resonance trapping
- response to spiral transients

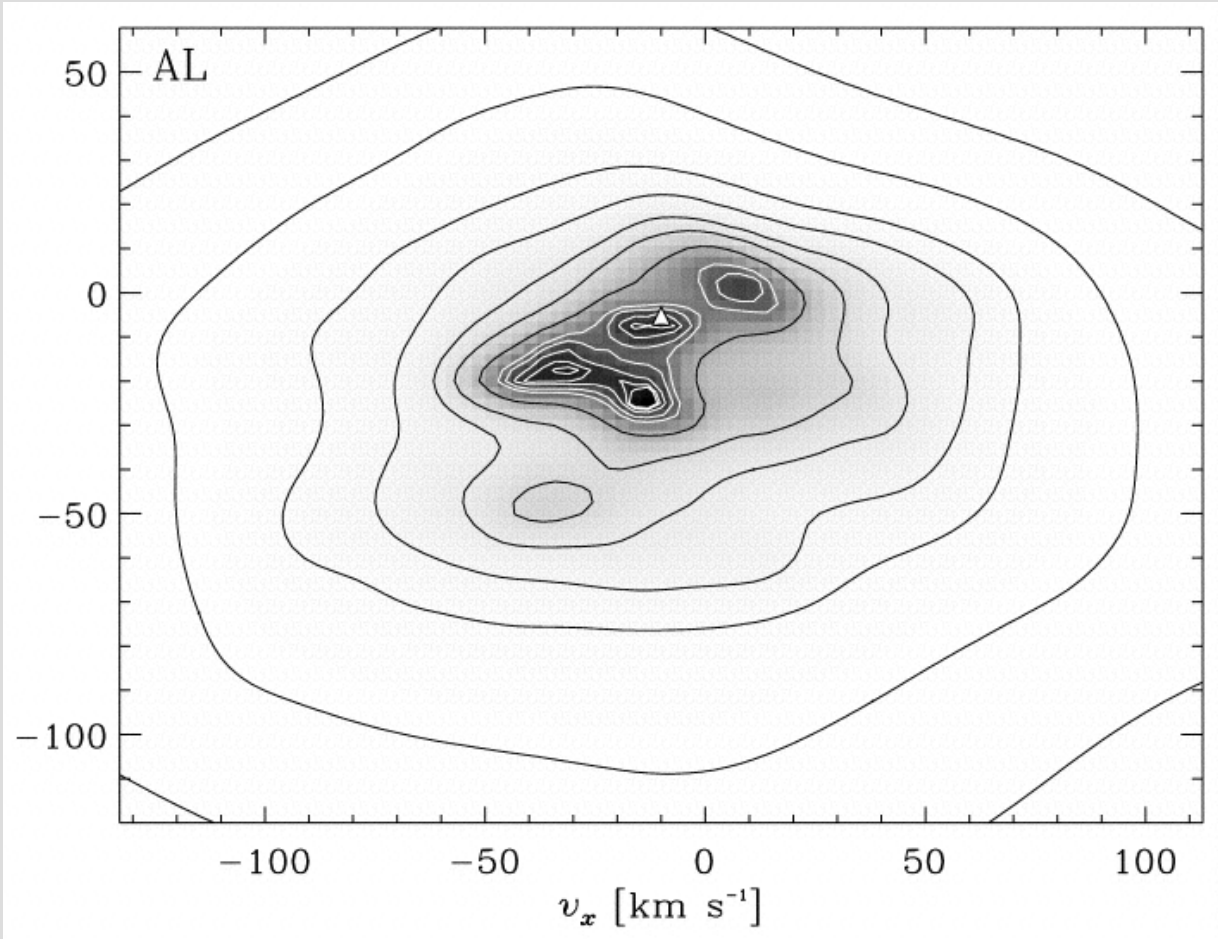
Klement

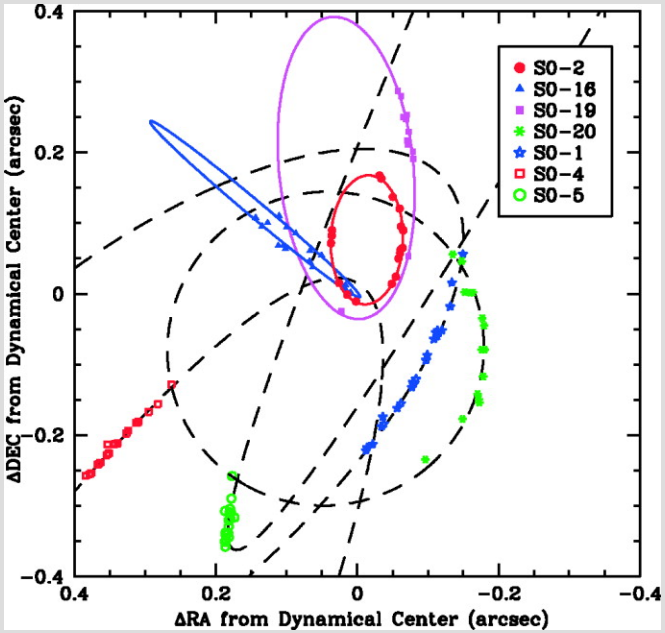
Rix

Steinmetz

Lackner

Dehnen (1998)



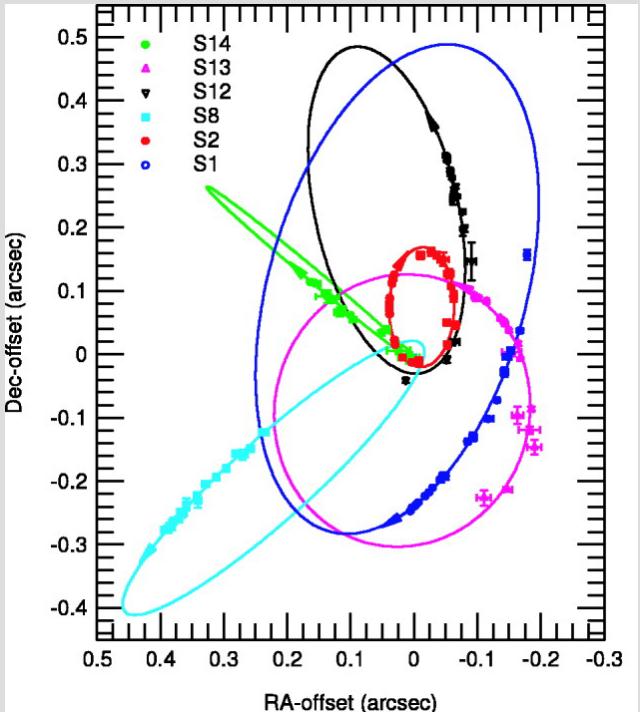


Ghez et al. (2005)

The central black hole

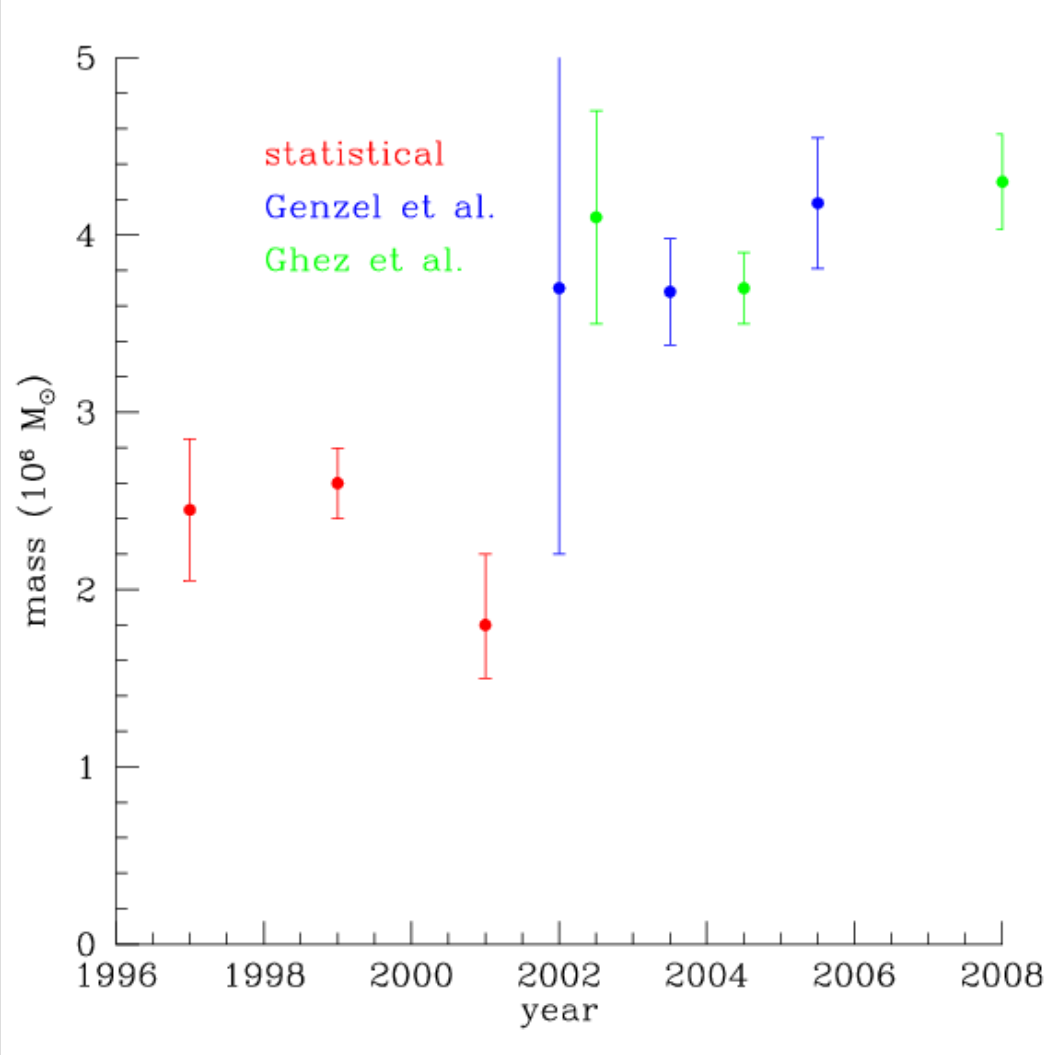
- the center of the Milky Way contains a black hole of mass ~ a few $\times 10^6$ $M_\odot$
- the black hole probably grew to its present mass either by swallowing stars or through gas accretion when the Milky Way was an active galaxy

Ghez



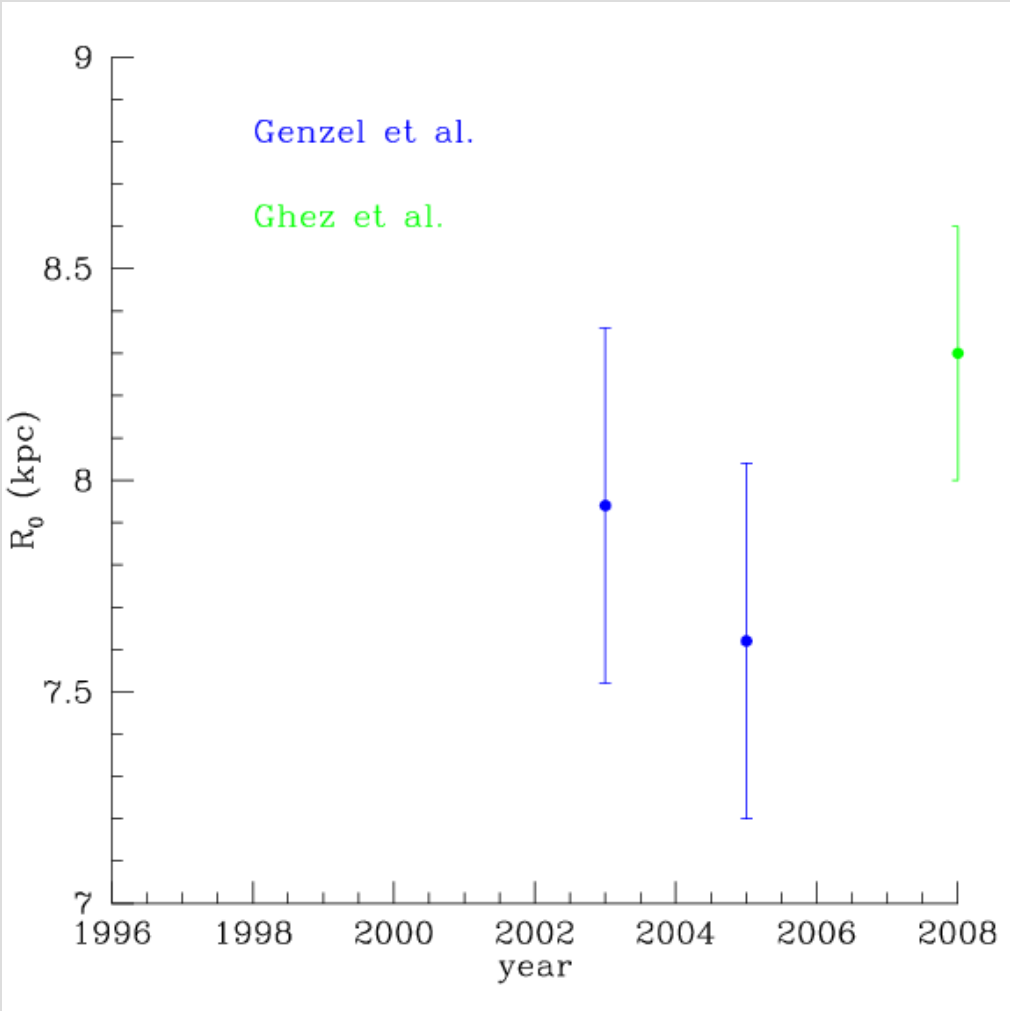
Eisenhauer et al. (2005)

The central black hole



- measurements of the black-hole mass through statistical analysis of proper motions and radial velocities of stars at ~ 0.05 pc are a factor of two lower than measurements from stellar orbits at ~ 0.001 pc

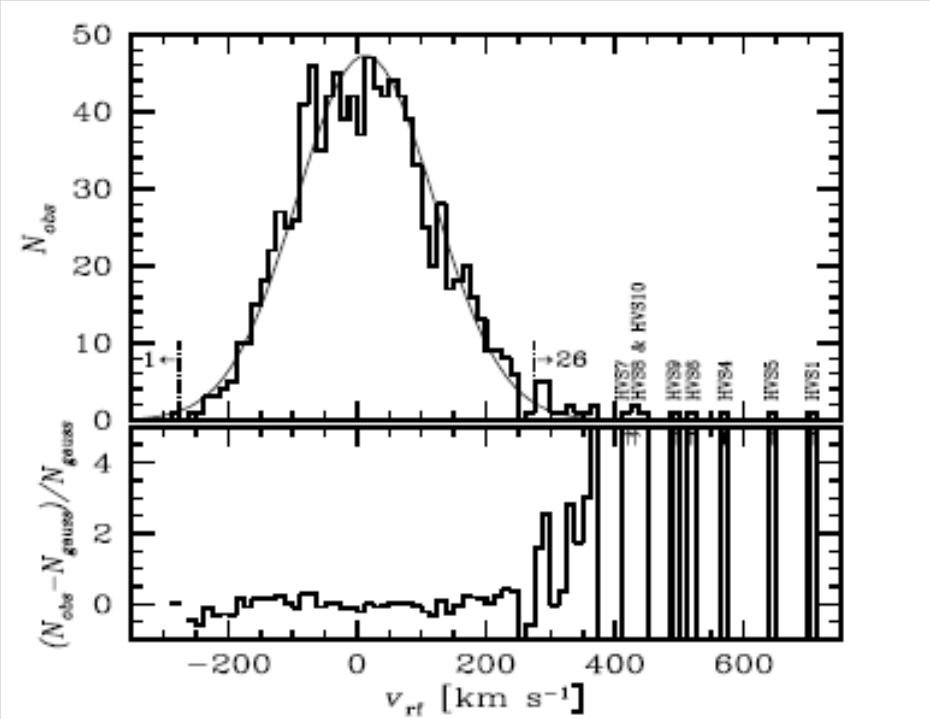
The central black hole



- measurements of the distance to the Galactic center from stellar orbits around the central black hole are improving...wait for BTTG 3

Hypervelocity stars

Brown



Brown et al. (2007)

- young, massive stars traveling outward from the Galaxy at speeds exceeding ~500 km/s
- only plausible formation mechanisms are:
  - disruption of binary stars deep in the potential well of a black hole (Hills 1988)
  - slingshot from binary black hole
- HE 0437-5439 has heliocentric velocity of 725 km/s but cannot come from the Galactic center:
  - main-sequence lifetime 35 Myr but travel time from Galactic center is 100 Myr
  - metallicity is 0.5 solar

but it is only 20 kpc from the Large Magellanic Cloud and has LMC abundances

is it a blue straggler? is there a black hole in the LMC? if so, where?

Subjects I hope to hear more about:

- spiral structure: we have no quantitative measure of spiral structure in the Galaxy that's accurate to a factor of two (number of arms, interarm spacing, amplitude, etc.) and thus have no understanding of the qualitative role of spiral structure in determining the present properties of the Galaxy
- scale length of the stellar disk: is it not remarkable that the biggest uncertainty in dynamical models of the Galaxy is the scale length of the stellar disk? Can surveys like SEGUE and RAVE fix this?
- baryonic substructure: when does mapping the substructure in the stellar halo turn from physics into stamp collecting?
- the Large Magellanic Cloud: does it have a massive black hole, and if so where is it?
- WIMP annihilation in the halo: why can't we agree on what we expect to see from GLAST/Fermi?
- star formation history and chemical evolution: of both the Milky Way and the dwarf satellite galaxies
- ΛCDM on small scales: what can we learn from the Milky Way and its satellites?