Institut d'Astrophysique de Paris
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Dissecting the Milky Way:
Report on the 2016 IAP Paris Conference on
The Milky Way and its environment
gaining insights into the drivers of galaxy formation and evolution
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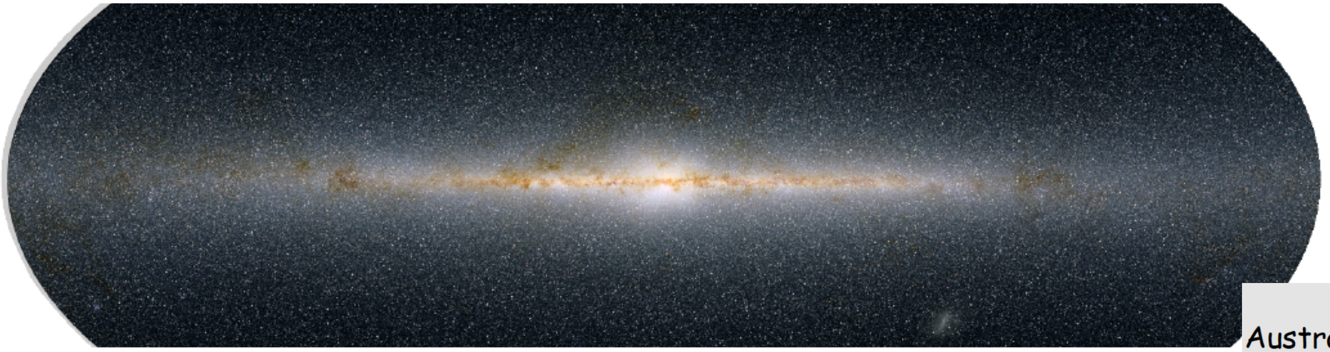
The Milky Way and its components: overview

M_B = -20.7, V_c = 238 km/s (similar to M31)

Also similar to NGC 4565



Ken Freeman
Australian National University

Masses of the components:

thin disk	4.10^{10} $M_\odot$
thick disk	5.10^{9} $M_\odot$
bulge	2.10^{10} $M_\odot$
halo	
• stellar	8.10^{8} $M_\odot$
• gas	2.10^{10} $M_\odot$
• dark	1.10^{12} $M_\odot$

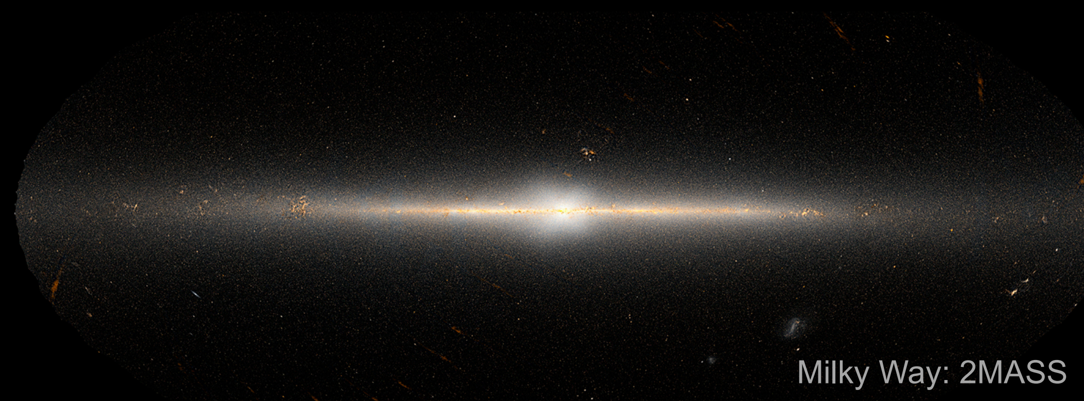
He means the boxy pseudobulge, not a classical bulge!

See Bland-Hawthorn & Gerhard ARAA 2016 for recent compilation of MW parameters

Secular Evolution of Galaxy Disks: Our Milky Way as a Case Study

John Kormendy

University of Texas at Austin
Munich University Observatory
Max-Planck-Institute for Extraterrestrial Physics



Milky Way history is dominated by gentle hierarchical clustering of fragments and by disk secular evolution & growth of 2 pseudobulges (boxy & disky).

Close analogs of the Milky Way are SB(r)b galaxies NGC 4565 and NGC 5746.

"Boxy bulge" = almost-end-on bar (note the perspective effect: left side is "taller" because it is the near side). The "box" has an exponential minor-axis profile (e. g. Launhardt et al. 2002) as bars do.

Plot boxy pseudobulge parameters = mean from Launhardt et al. 2002 and from Bland-Hawthorn & Gerhard 2016, ARA&A, 54, 520.

Plot disk parameters = mean from Portail, Gerhard et al. 2016, arXiv 1608.07954 and from Bland-Hawthorn & Gerhard 2016, ARA&A, 54, 520.

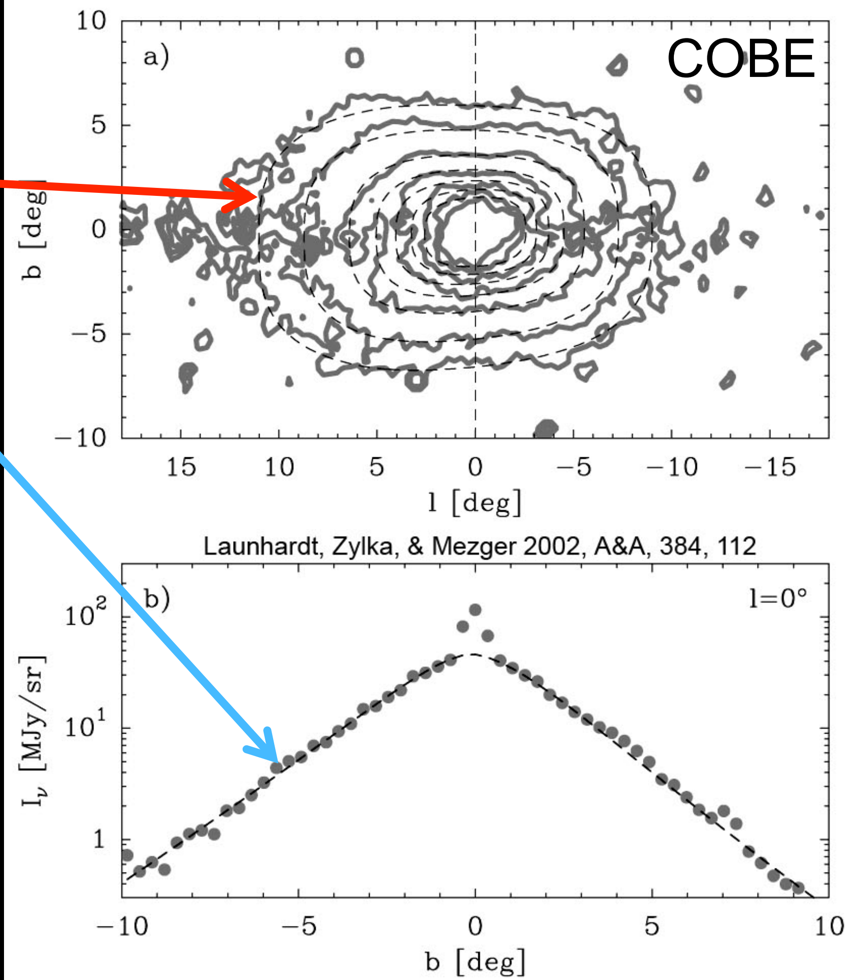


Fig. 5. 2.2 μm surface brightness distribution of the Galactic and Nuclear Bulge. In order to achieve the best signal-to-noise ratio, a weighted average of the 2.2, 3.5, and 4.9 μm maps, scaled to the 2.2 μm surface brightness, is shown. Contributions from the Galactic Disk are subtracted and the emission is dereddened for extinction by foreground dust. **a)** Contour maps of the observed dereddened (thick grey lines) and modeled (dashed lines) NIR surface brightness distribution. Levels are at 5, 10, 20, ..., 60% of modeled peak surface brightness. **b)** Latitude profile at $l = 0°$ of the observed dereddened (grey dots) and modeled (dashed line) NIR surface brightness distribution of the GB.

The Parameters of our Galaxy’s Boxy Pseudobulge are Normal

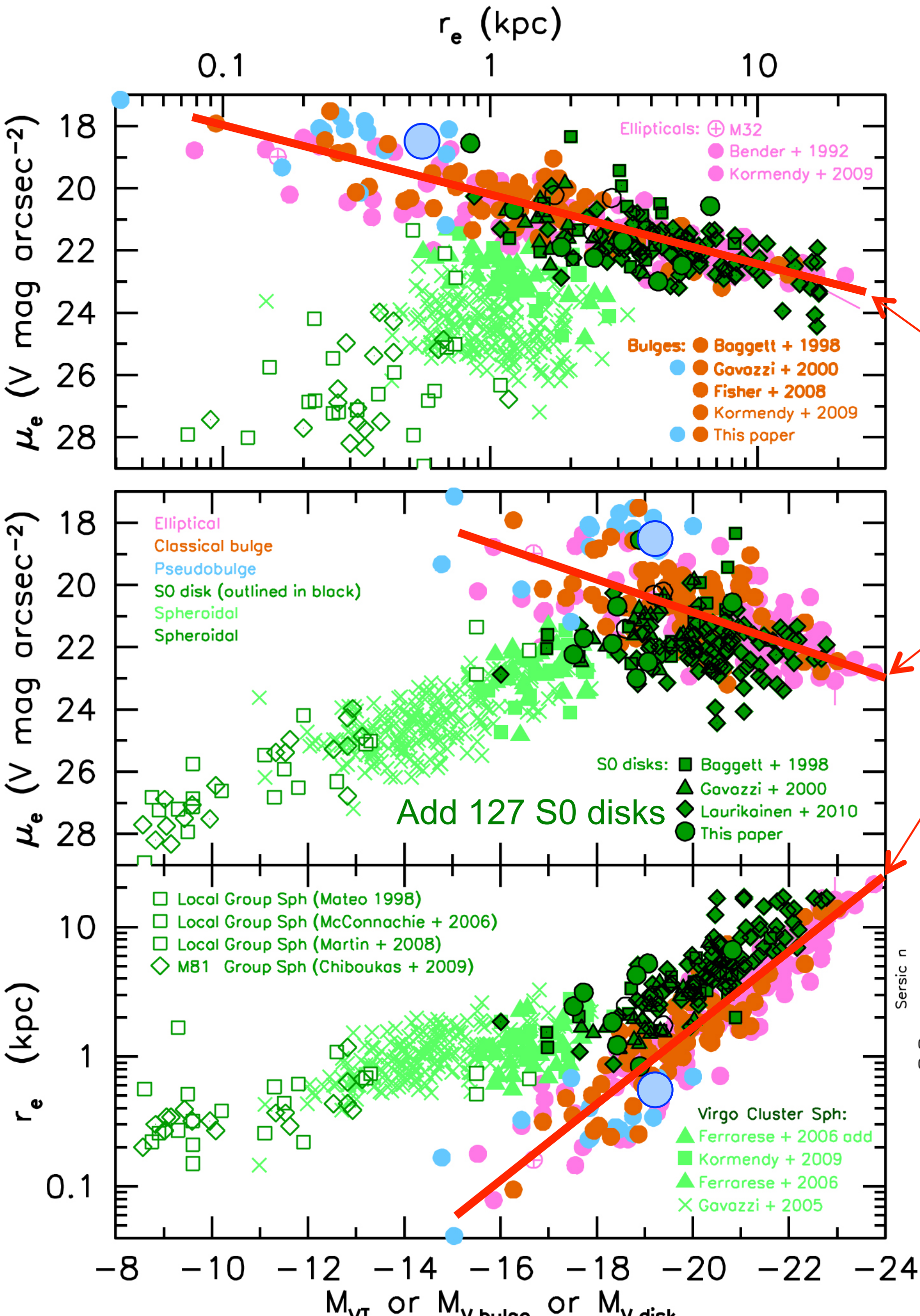
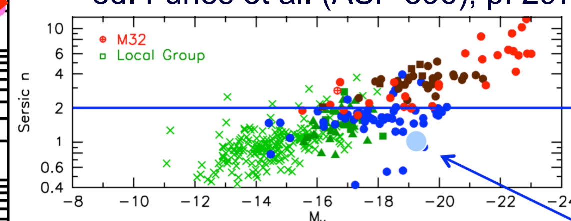


Figure:
Kormendy & Bender 2012, ApJS, 198, 2

Milky Way

Note (we will need this later):
The Fundamental Plane structural **<u>parameter correlations</u>**
define what it means to be a classical bulge or elliptical galaxy.

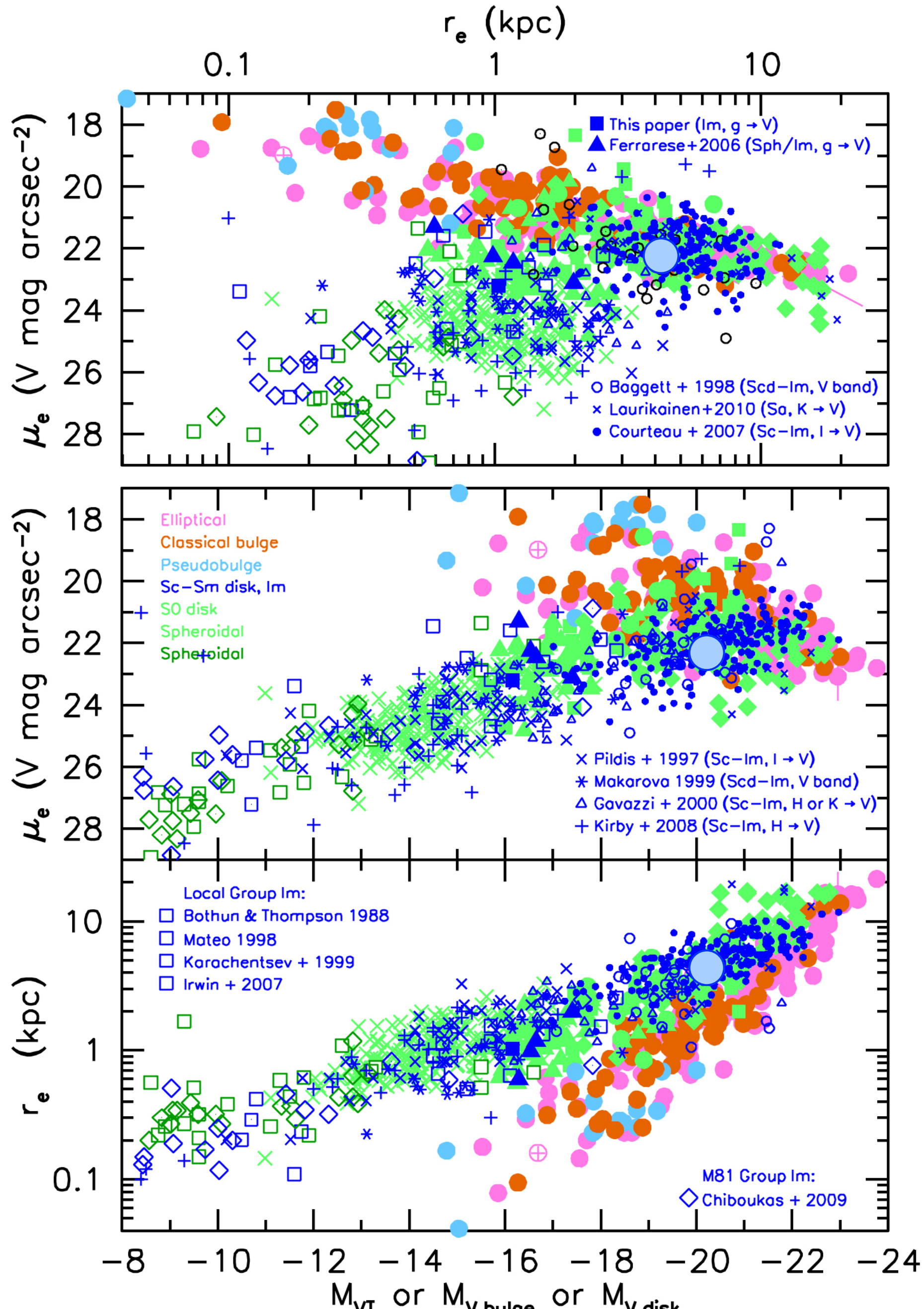
Figure: Kormendy & Fisher (2008), in Formation & Evolution of Galaxy Disks, ed. Funes et al. (ASP 396), p. 297



Classical bulges and ellipticals have n ≥ 2.
Pseudobulges have n ≤ 2.

The boxy structure = almost-end-on bar has <u>exponential</u> minor-axis profile (e. g. Launhardt et al. 2002).

The Parameters of our Galaxy's Disk are Normal



Add parameters

for 407 S+Im disks from 14 independent sources.

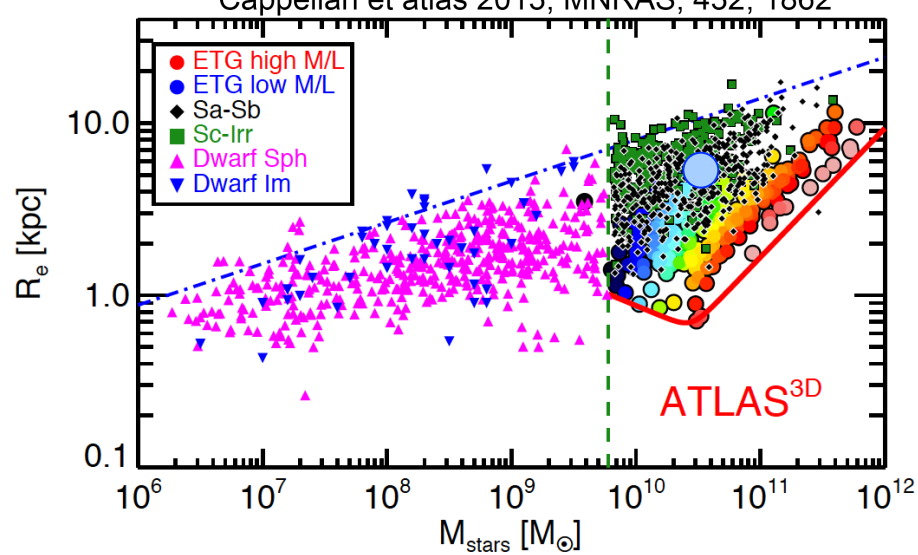
Milky Way Long bar + thin disk + thick disk

Figure:

Kormendy & Bender 2012, ApJS, 198, 2

ATLAS^{3D} team
gets closely similar results.
But, without B-D decomposition,
pure disks look continuous with pure Es.

Cappellari et atlas 2013, MNRAS, 432, 1862



Our Galaxy as similar in scale to NGC 4565
and is slightly smaller than NGC 5746.

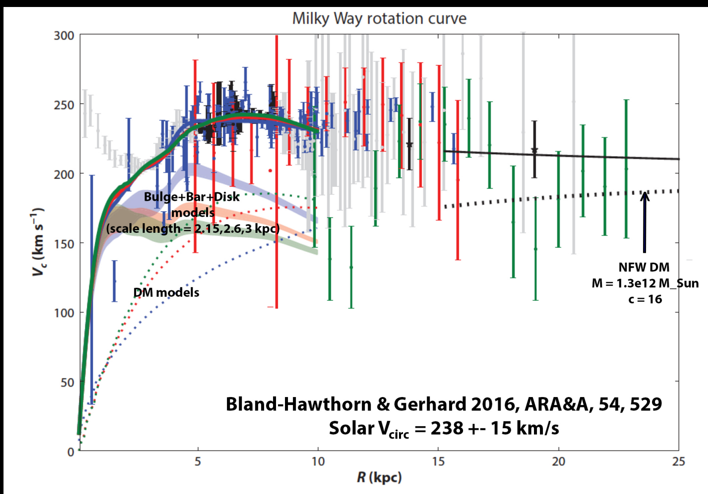
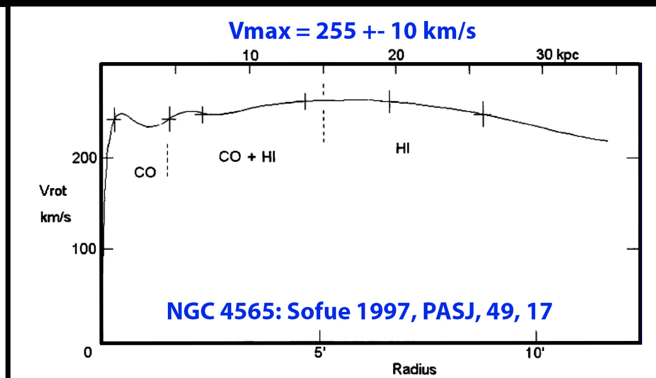
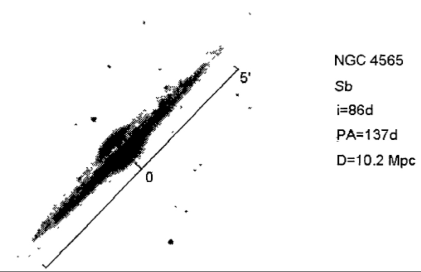


Figure 16

Galactic rotation curve. Sources for data points are: maser proper motions (PMs) and radial velocities (RVs) associated with high-mass disk stars (Reid et al. 2014, *blue*), inner Galaxy terminal velocities and outer disk velocities collected by Sofue et al. [2009, *black* (5 kpc < R < R_0) and *gray* (elsewhere)], PMs of disk red clump giants (RCGs) from López-Corredoira (2014, *red*), Jeans-equation converted RV data for blue horizontal branch (BHB) stars (Kafle et al. 2012, *green*), and stream modeling for GD-1 and Pal-5 (Koposov et al. 2010 and Küpper et al. 2015, *black stars*. All data were approximately converted to ($R_0 = 8.2$ kpc, $\Theta_0 = 238$ km s^{-1}). The colored bands show azimuthally averaged circular velocities for illustrative dynamical models with bulge, long bar, disk, and dark halo (Portail et al. 2016).

Our Galaxy





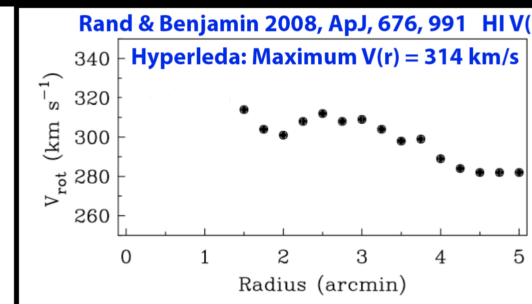
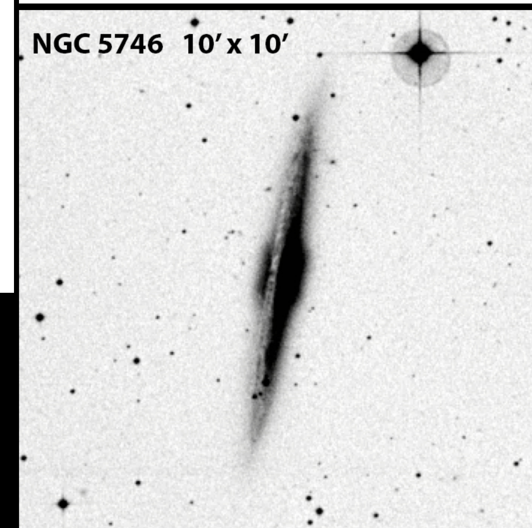
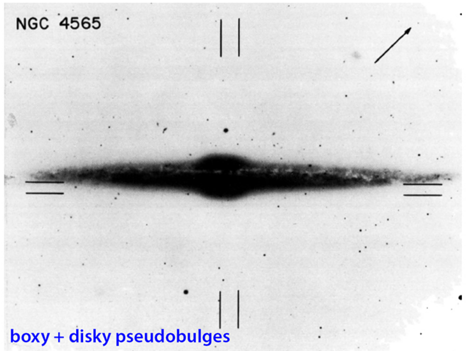


FIG. 8.—Filled circles show the rotation curve for NGC 5746 derived from envelope fitting.

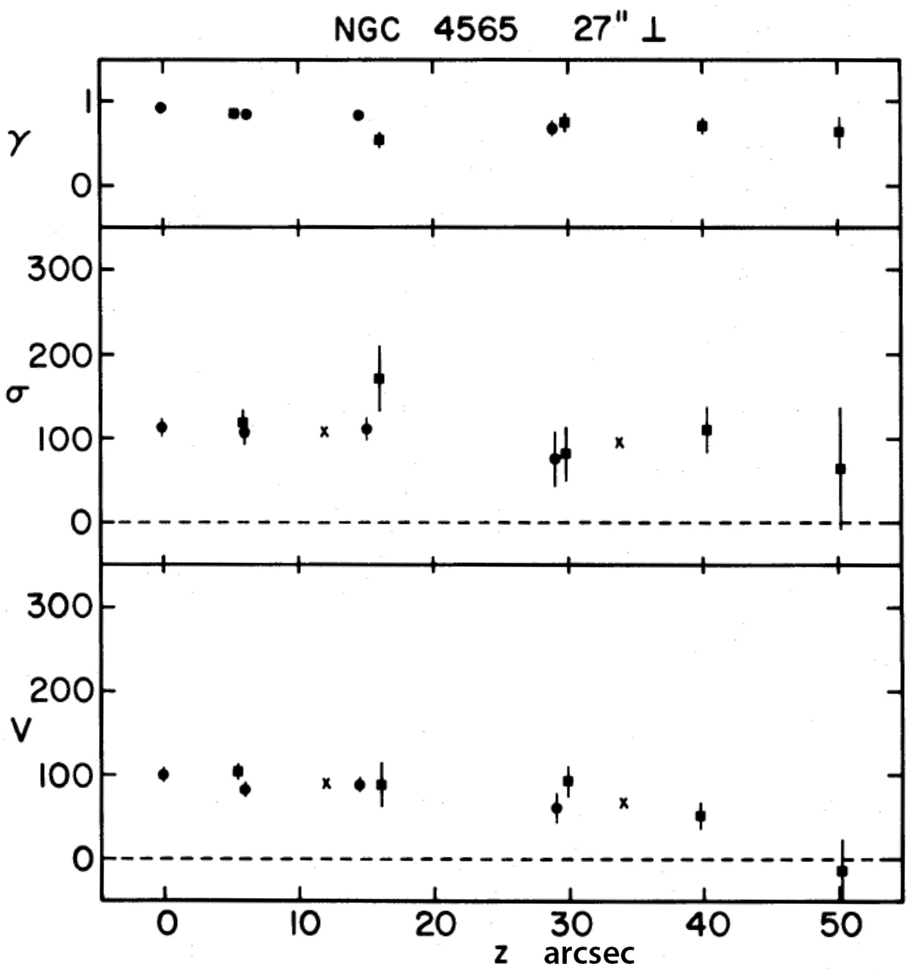




The boxy pseudobulge of NGC 4565 rotates cylindrically:

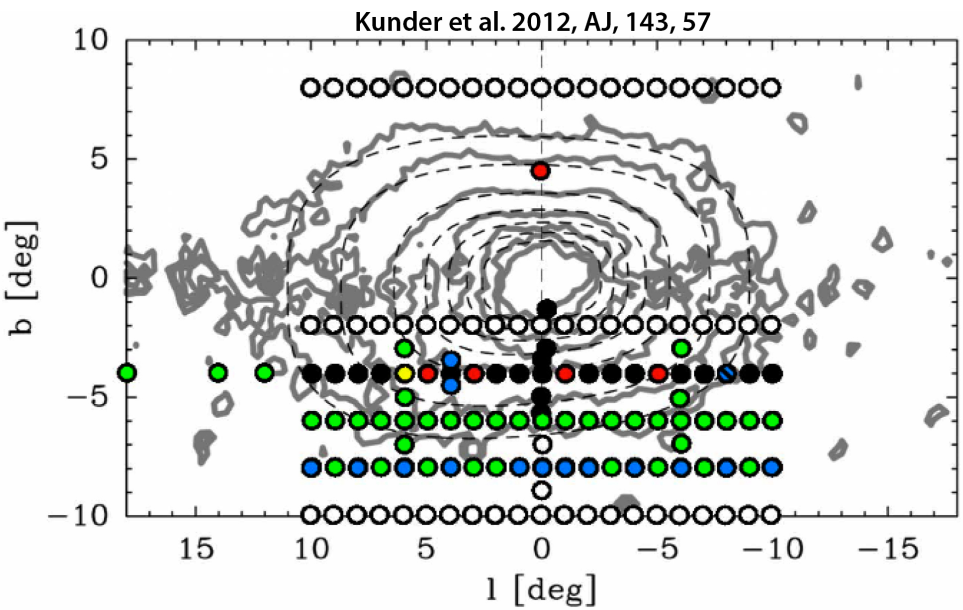
V(r) is almost constant with increasing height z above the disk plane.

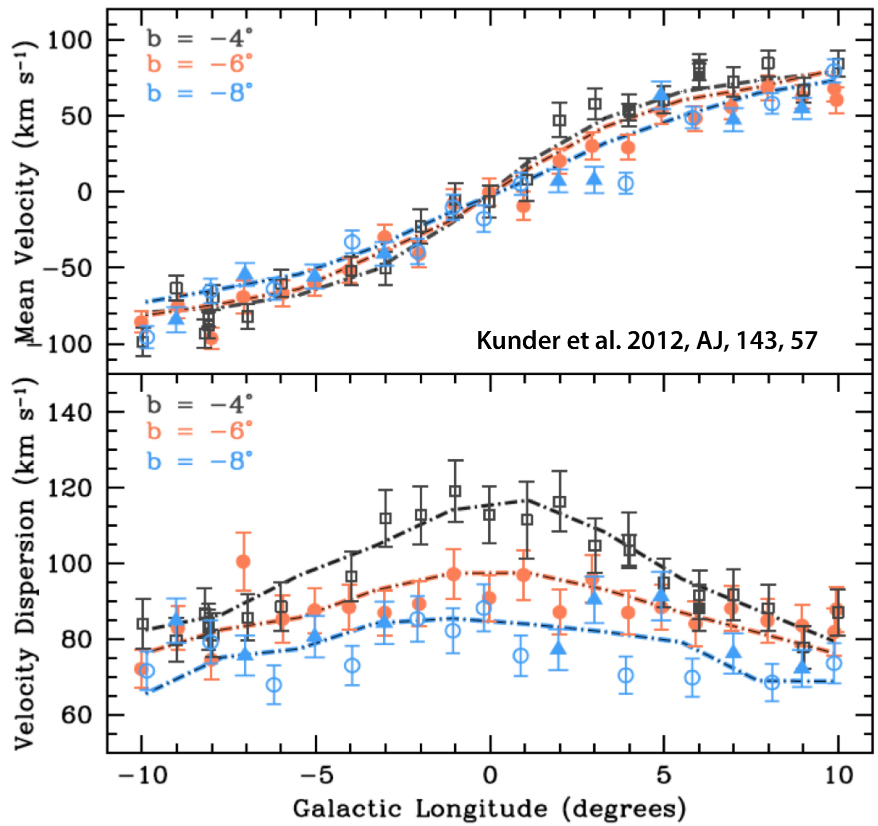
Kormendy & Illingworth 1982, ApJ, 256, 460



Like other boxy pseudobulges, the one in our Galaxy rotates cylindrically even 8 degrees = 1150 pc up from the disk plane.

Major Axis showing cylindrical rotation (Fit is Shen et al. 2010)



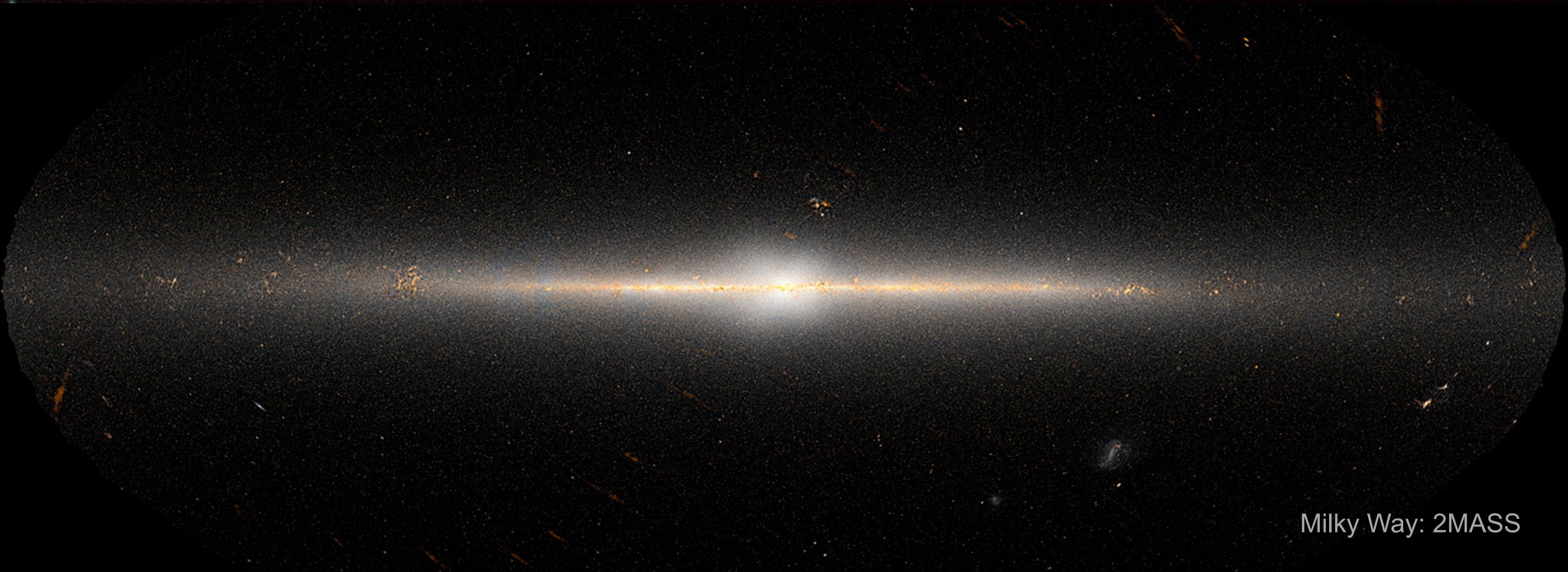


See also: **Howard et al. 2009, ApJ, 702, L153**

ARGOS: Ness, Freeman et al. 2013, MNRAS, 432, 2092 -- All 16,600 stars in "bulge region"

Our Galaxy has a boxy, edge-on bar and an outer disk.
Does it have a disky pseudobulge?

Milky Way: COBE



Milky Way: 2MASS

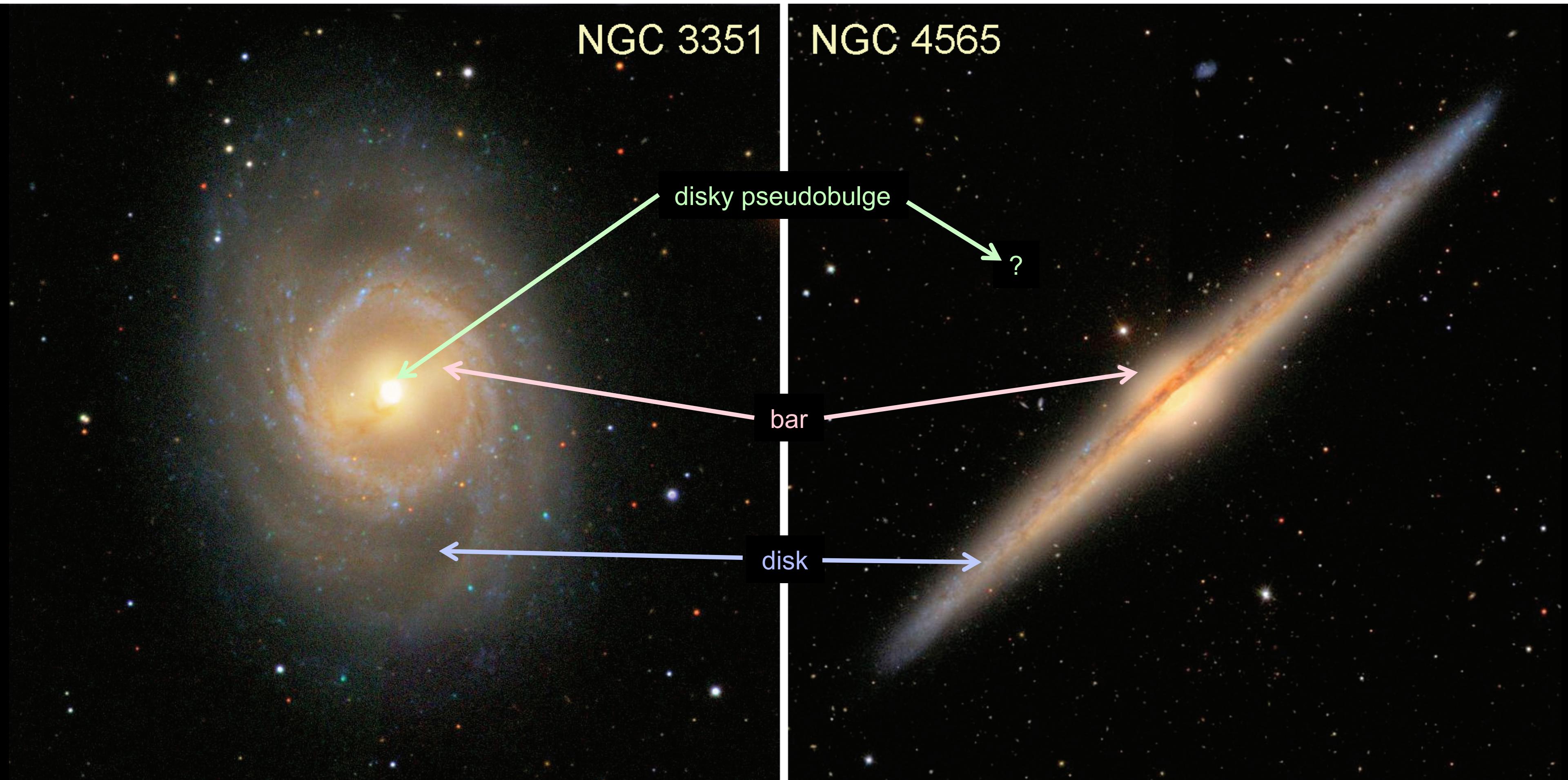
DETECTION OF A PSEUDOBULGE HIDDEN INSIDE THE "BOX-SHAPED BULGE" OF NGC 4565

JOHN KORMENDY AND JOHN C. BARENTINE

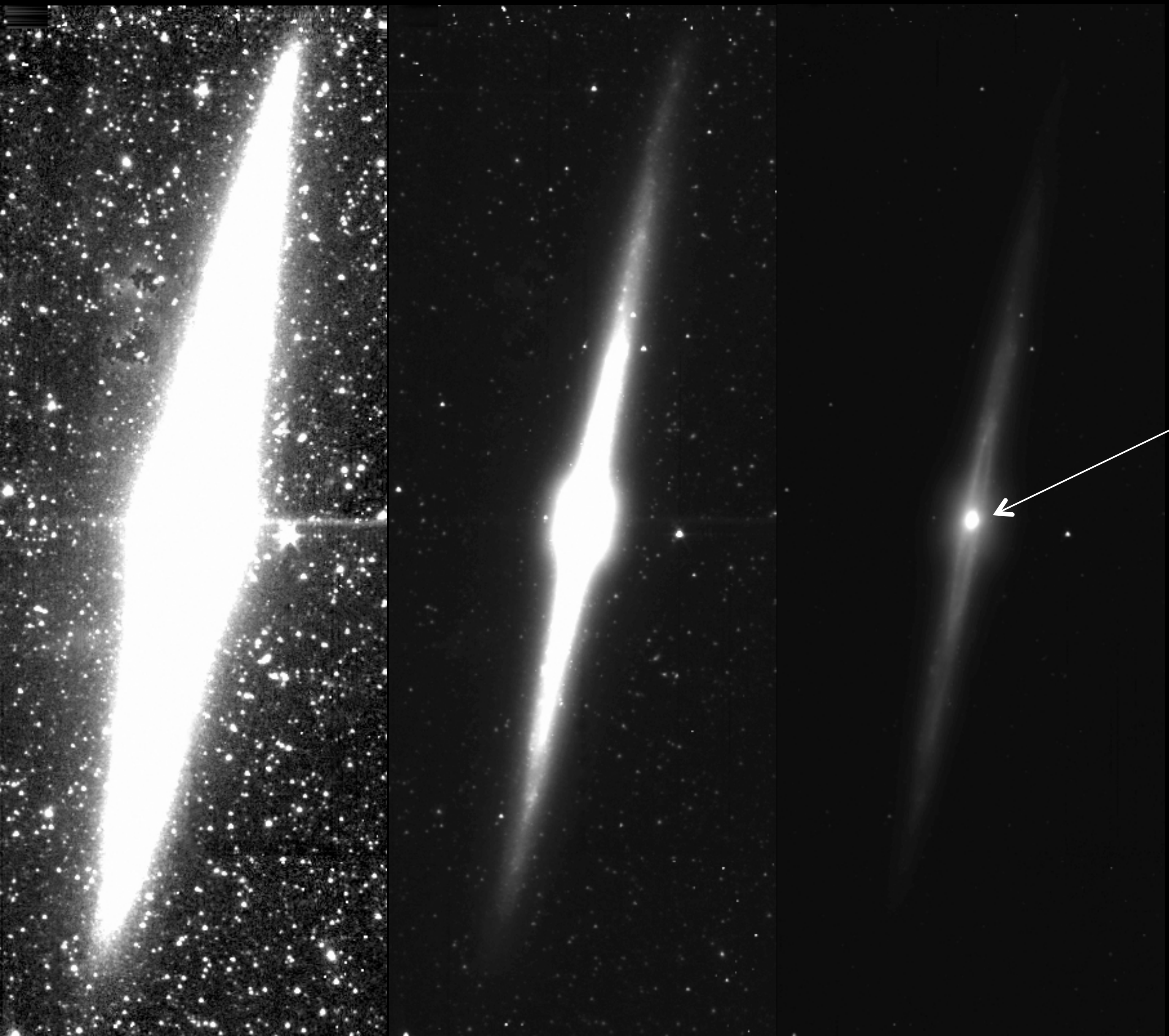
THE ASTROPHYSICAL JOURNAL LETTERS, 715:L176–L179, 2010 June 1

ABSTRACT

Numerical simulations show that box-shaped bulges of edge-on galaxies are not bulges: they are bars seen side-on. Therefore, the two components that are seen in edge-on Sb galaxies such as NGC 4565 are a disk and a bar. But face-on SBb galaxies always show a disk, a bar, and a (pseudo)bulge. Where is the (pseudo)bulge in NGC 4565?



Where is the bulge in NGC 4565?

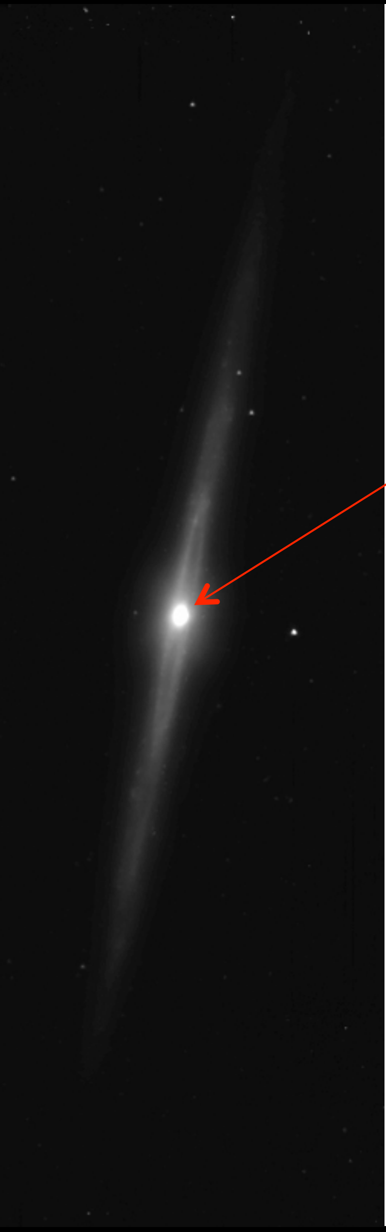


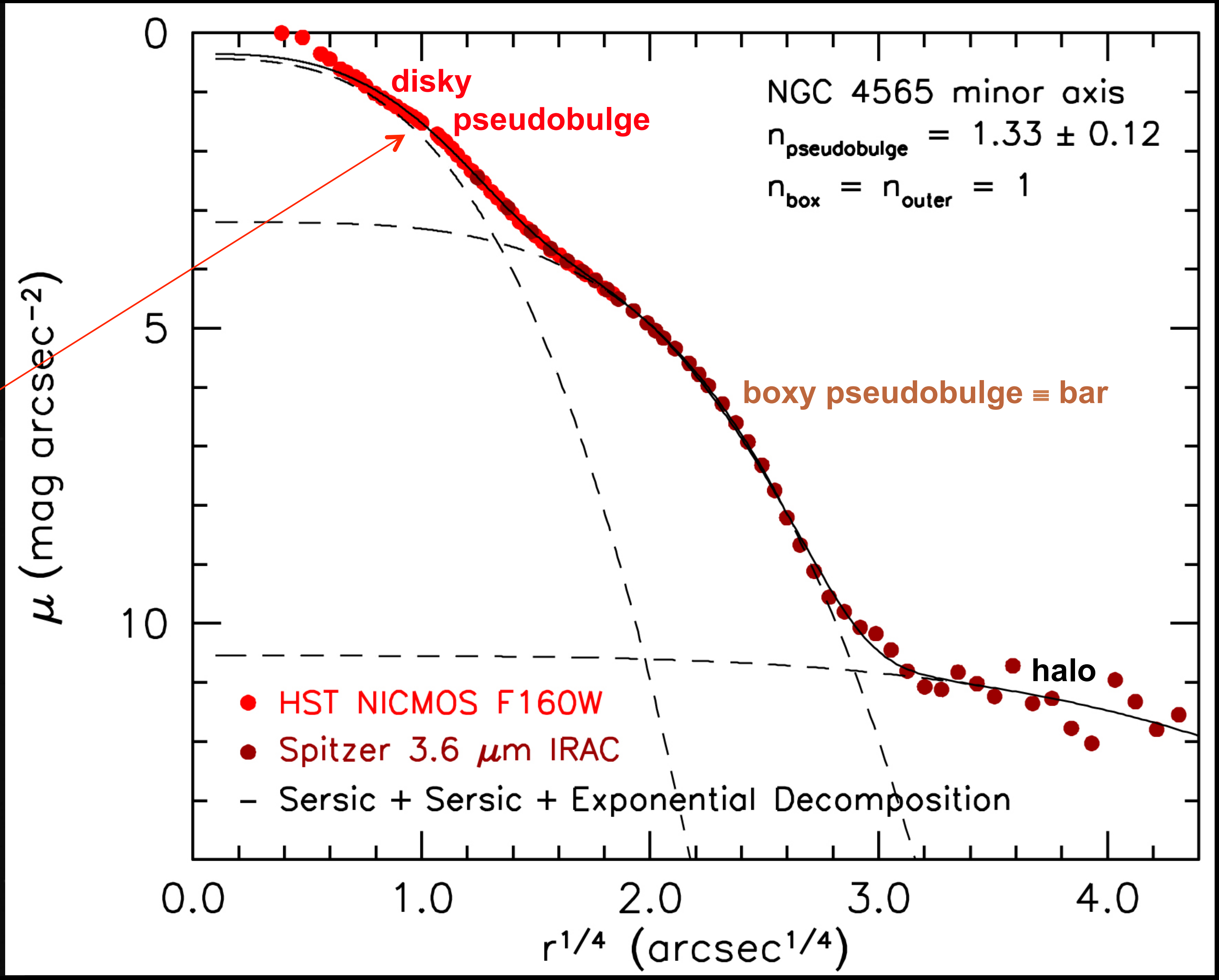
Spitzer Space Telescope
3.6 μm IRAC images
and HST NICMOS
penetrate dust but
show starlight.

⇒ clearly defined but tiny
<u>central component</u>
with B/T « 0.4,
well differentiated from
the box = bar structure
(Kormendy & Barentine
2010, ApJ, 715, L176).

This is a pseudobulge:
Sérsic n = 1.33 ± 0.12.

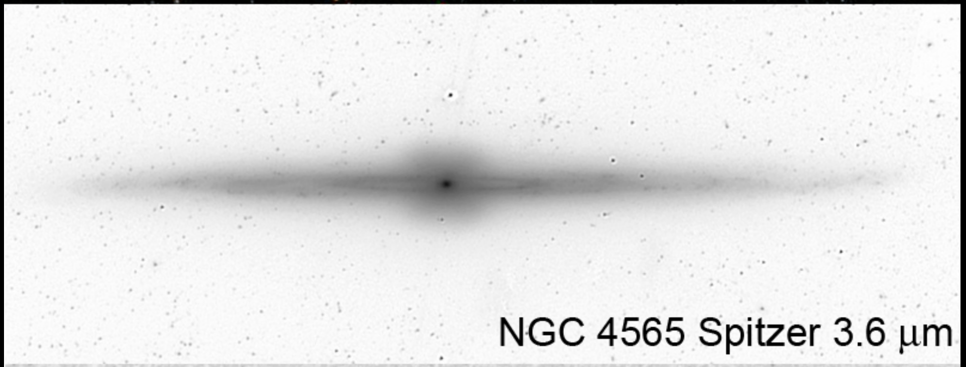
NGC 4565 contains a disky pseudobulge + ("Boxy bulge" ≡ bar)
⇒ no sign of a merger-built bulge. But V_{circ} = 255 ± 10 km s^{-1} (Rupen 1991).

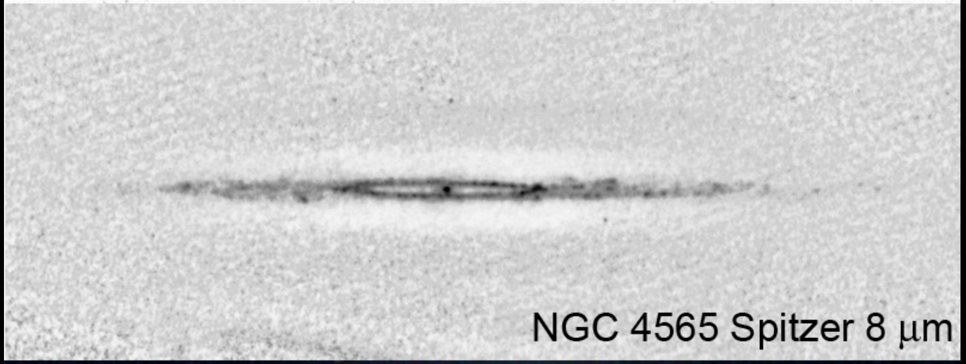


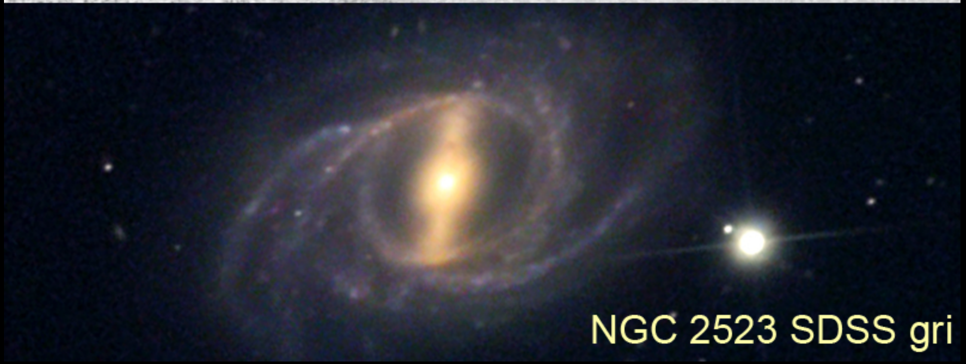


If NGC 4565 were seen face-on, it would be the most spectacular SB(r) galaxy in the sky.

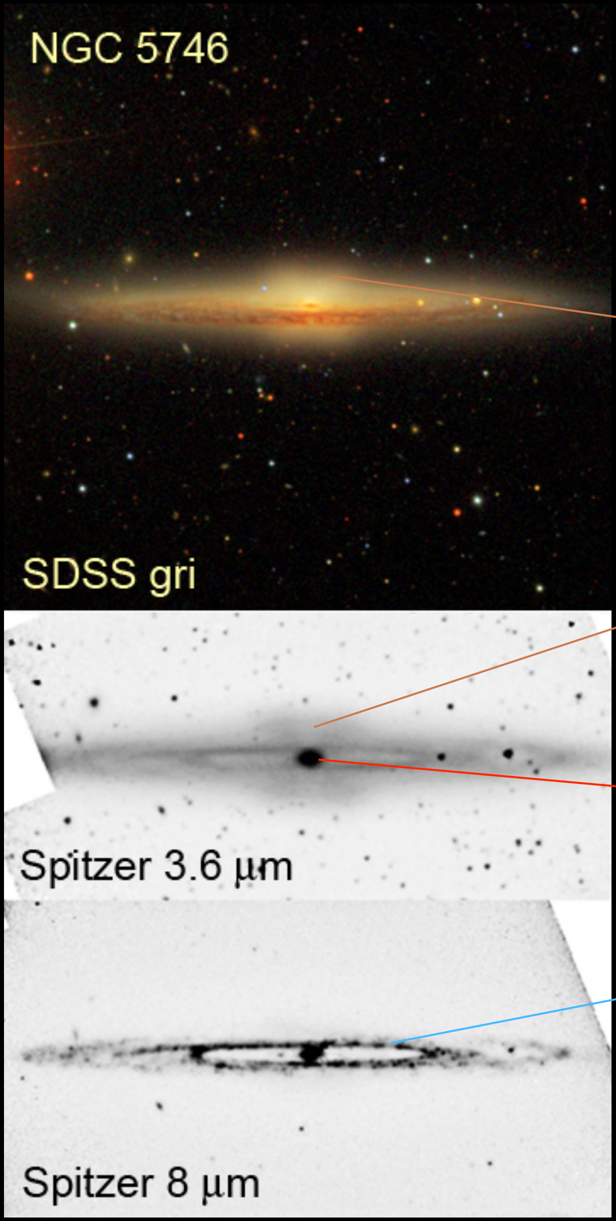
Is our Milky Way Galaxy also an SB(r)bc ?







NGC 5746 also contains a disky pseudobulge + (“Boxy bulge” ≡ bar)
⇒ no sign of merger-built bulge (Barentine & Kormendy 2012, ApJ, 754, 140).



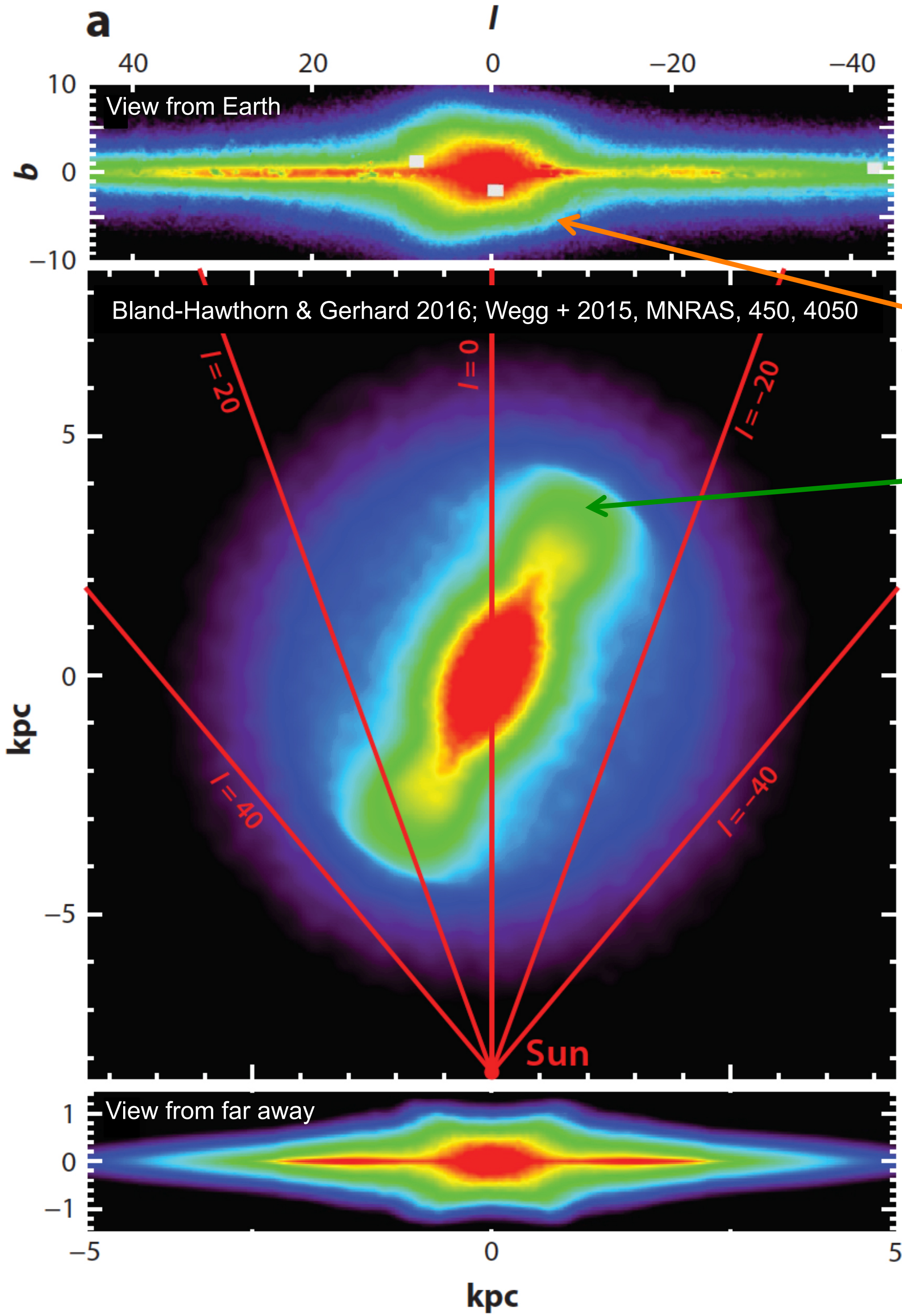
boxy pseudobulge ≡ bar

disky pseudobulge

inner ring
(star-forming;
encircles end of bar)

Our Galaxy has a boxy bulge (COBE)
that is parallelogram-shaped as seen from Earth:
This is an edge-on bar, not a classical bulge.
We call it a “pseudobulge” because it formed from the disk.

$\exists$ no sign of a classical bulge
(Freeman 2007, IAU245; this paper).



See Blitz & Spergel 1991, ApJ, 379, 631.

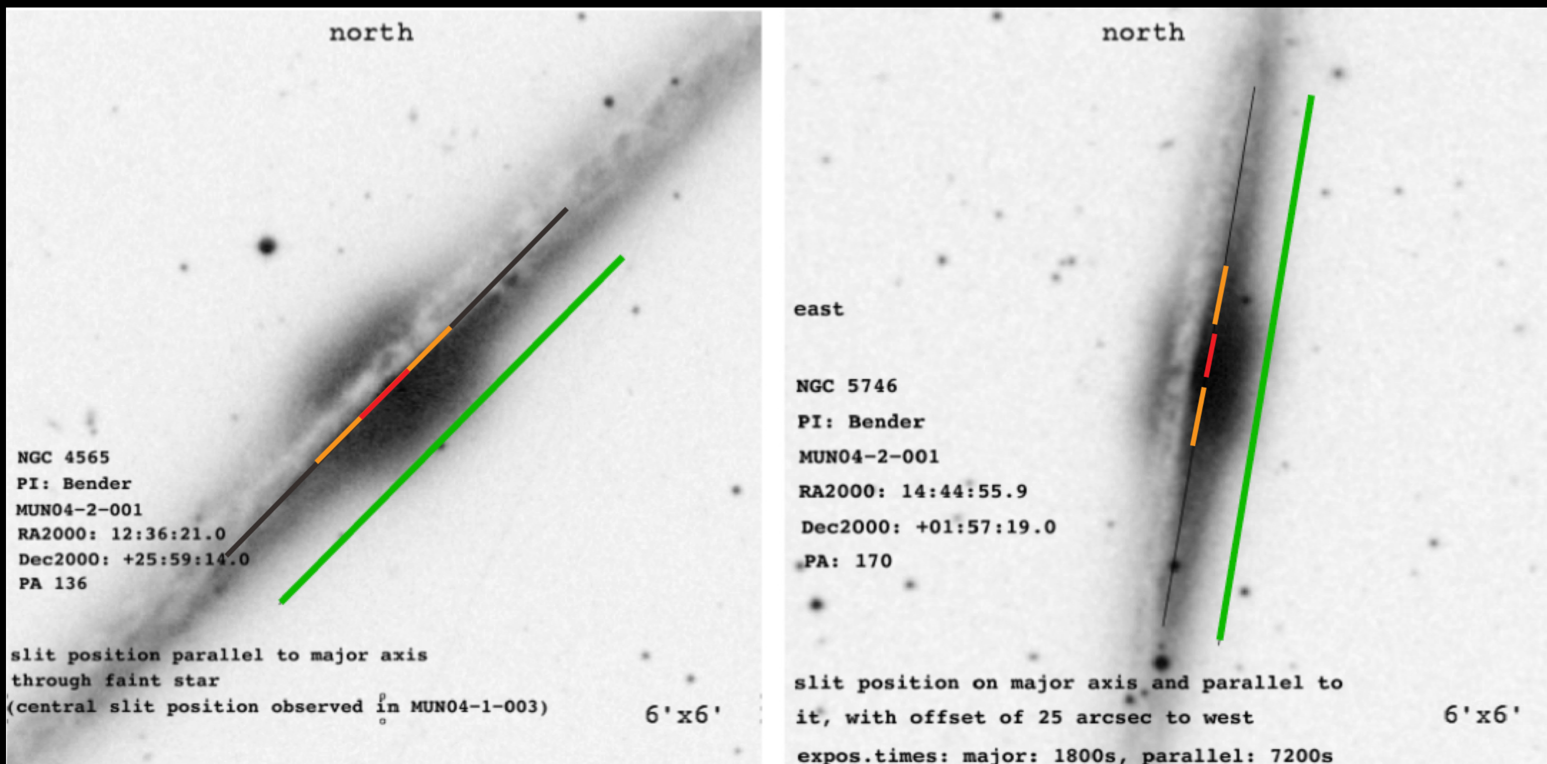
The bar consists of a thick part
(the parallelogram-shaped "boxy pseudobulge"
seen from the Earth)
and a thin bar revealed by star counts
that reaches out to $R_B \approx 5.0 \pm 0.2$ kpc.

From Portail et al. 2016, arXiv:1608.07954:
$\Omega_p \approx 39.0 \pm 3.5$ km/s/kpc,
$R_{CR} \approx 6.1 \pm 0.5$ kpc.
We are at $R_\odot \approx 8.2 \pm 0.1$ kpc.

Our Galaxy has a boxy pseudobulge (COBE),
but most of its stars are old and α-element-enhanced
(i. e., they formed during $\leq$ 1 Gyr).
Consistency with pseudobulge $\Rightarrow$ stars formed before bar.

$\exists$ no sign of a classical bulge
(Freeman 2007, IAU245; this paper).

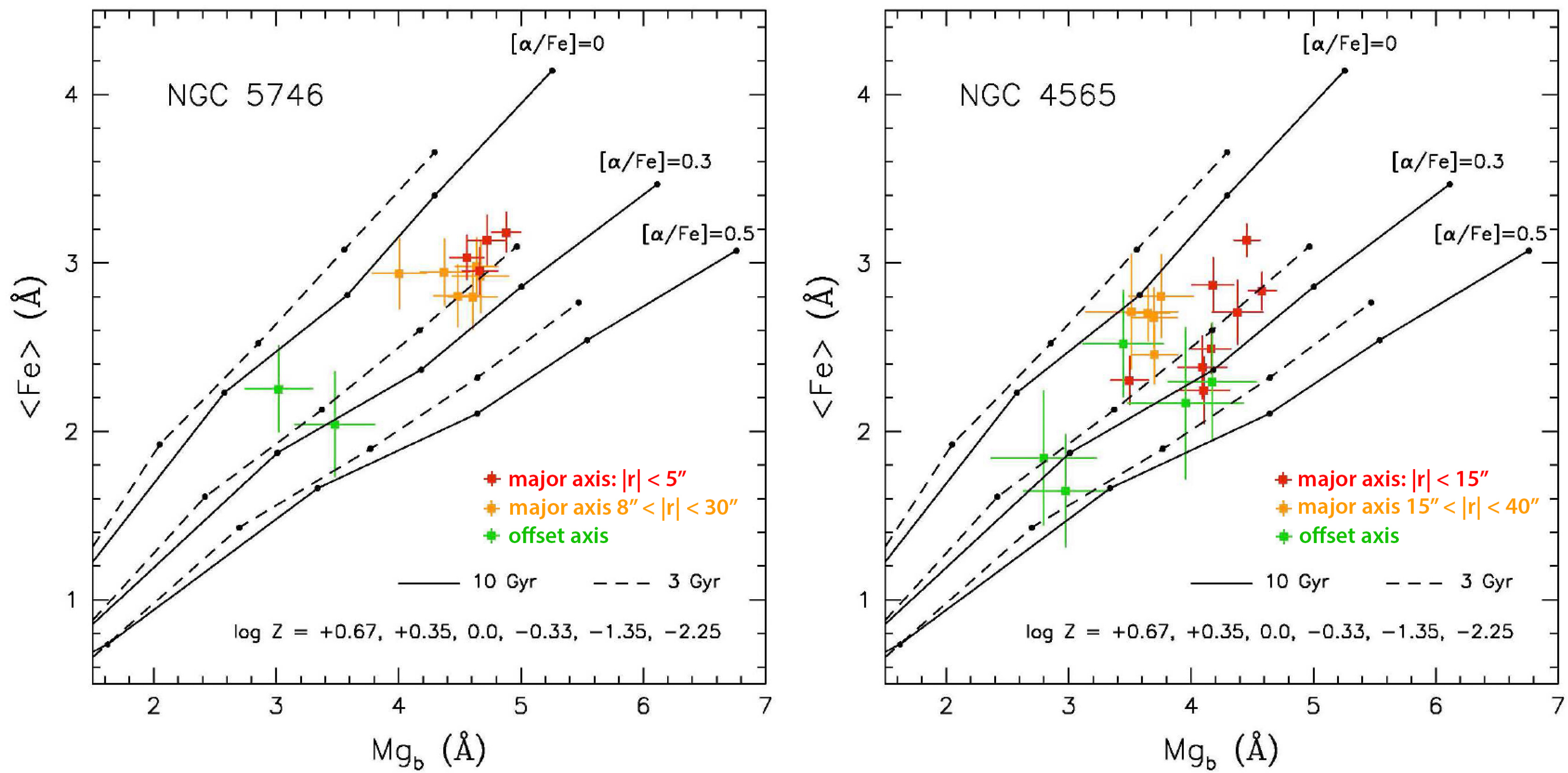
We measured [α/Fe] along the major axis and in the boxy pseudobulges of NGC 4565 and NGC 5746 using the LRS Spectrograph on the Hobby-Eberly Telescope.



NGC 4565 offset slit was at z = 35″ = 2.5 kpc @ D = 14.5 Mpc.

NGC 5746 offset slit was at z = 25″ = 3.3 kpc @ D = 27.5 Mpc.

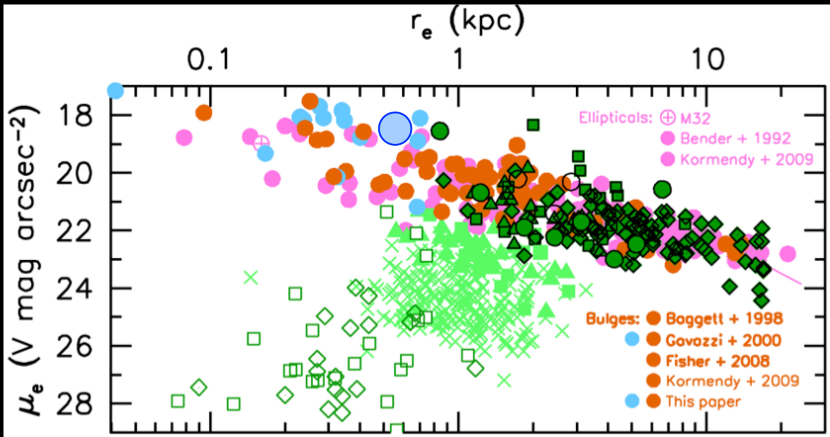
We find that [α/Fe] is enhanced with respect to Solar values in the boxy pseudobulges of NGC 4565 and NGC 5746 as it is in the boxy structure of our Galaxy .



Kormendy & Bender 2017, in preparation

FIG. 2.— The points show Fe and Mg equivalent widths as a function of galactocentric radius r using red points near $r = 0$ and bluer points farther out. For two stellar population ages (key), the lines show [α/Fe] values in log Solar units. Both box-shaped bulges are α-element enhanced, indicative of short star formation timescales (∼ 1 Gyr).

The disk of NGC 4565 has more nearly Solar [α/Fe].



The Launhardt et al. 2002
minor-axis K-band profile
allows us to check
how much classical bulge
could be hidden
in our Galaxy.

Recall: Fundamental Plane
correlations ⇒ We do not have
the freedom to tinker
classical bulge profiles
to make them easy to hide.

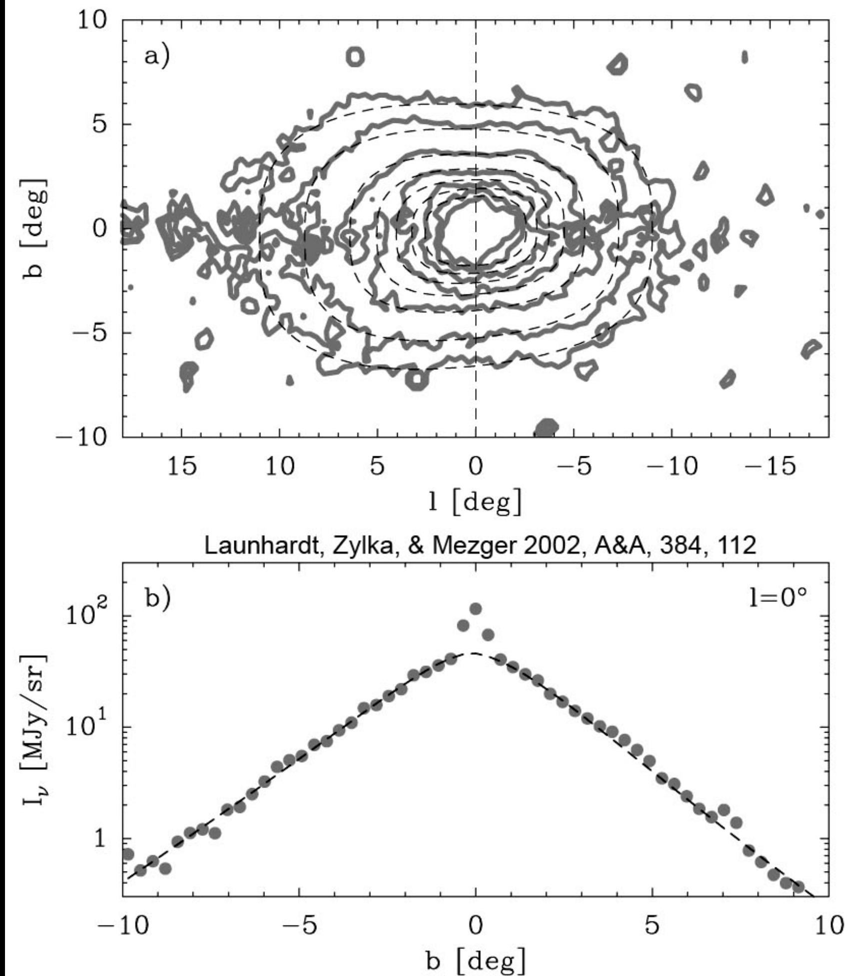
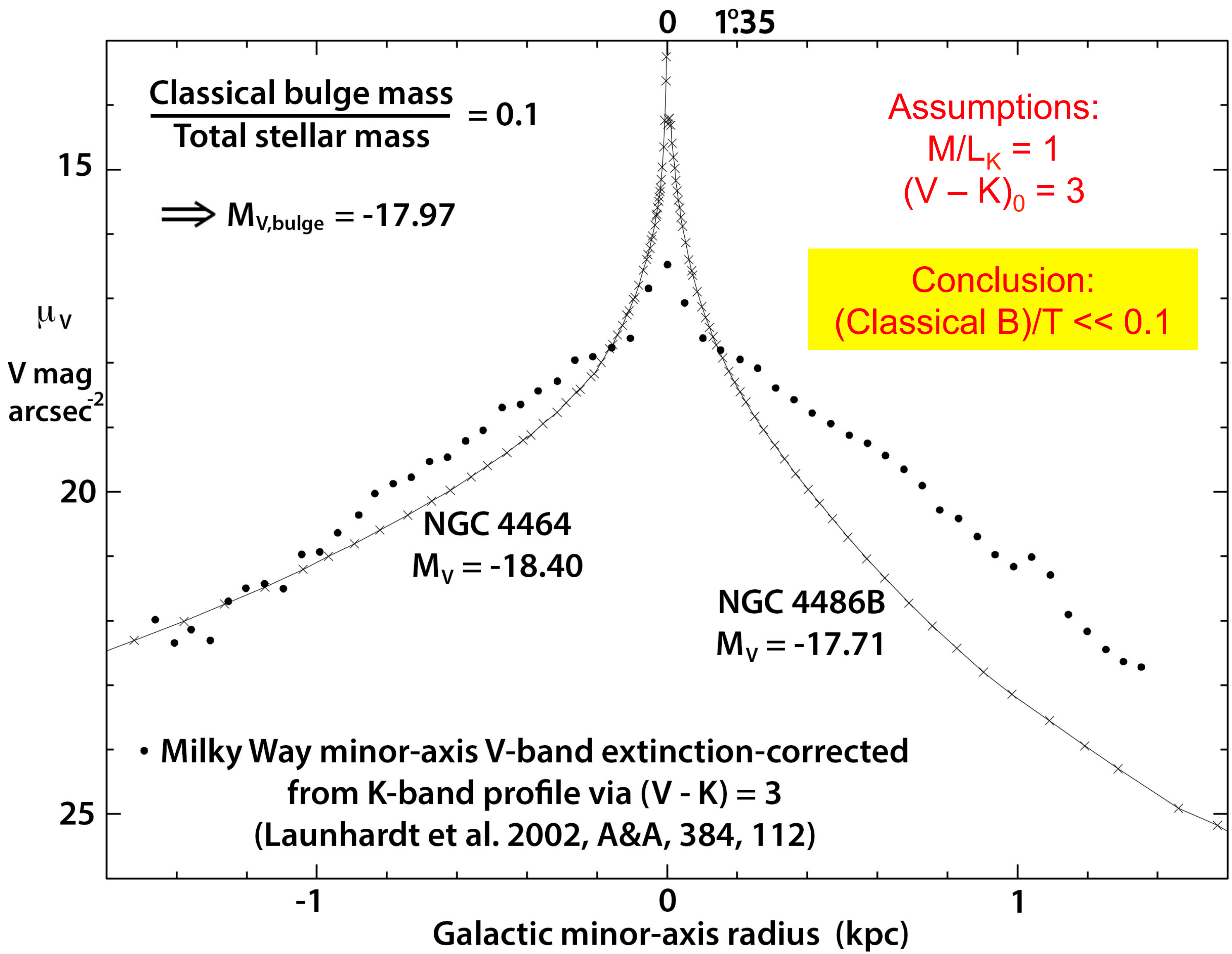


Fig. 5. 2.2 μm surface brightness distribution of the Galactic and Nuclear Bulge. In order to achieve the best signal-to-noise ratio, a weighted average of the 2.2, 3.5, and 4.9 μm maps, scaled to the 2.2 μm surface brightness, is shown. Contributions from the Galactic Disk are subtracted and the emission is dereddened for extinction by foreground dust. **a)** Contour maps of the observed dereddened (thick grey lines) and modeled (dashed lines) NIR surface brightness distribution. Levels are at 5, 10, 20, ..., 60% of modeled peak surface brightness. **b)** Latitude profile at $l = 0°$ of the observed dereddened (grey dots) and modeled (dashed line) NIR surface brightness distribution of the GB.

Could (Classical B)/T = 10 % by stellar mass?
Compare Galactic minor axis profile to 2 Virgo Es (Kormendy + 2009, ApJS, 182, 216) that bracket 10 % of the Milky Way stellar mass.



Comparison of Structural Components in Milky Way, NGC 4565, and NGC 5746

⇒ Cannot hide even a small classical bulge in our Galaxy.

(Quote: Stellar mass ratios of Milky Way, light ratios of NGC 4565 & NGC 5746)

Parameter	Milky Way	NGC 4565	NGC 5746
Nuclear cluster/T	0.00036	0.00011	…
Disky pseudobulge/T	0.04 ± 0.01	0.06 ± 0.01	0.136 ± 0.019
Box/T	0.27	~ 0.4	~ 0.4
Nuclear cluster r_e	4.2 ± 0.4 pc	unresolved	unresolved
Disky pseudobulge z_0	45 pc	90 pc	100 ± 13 pc
Boxy pseudobulge z_0	0.22 kpc	0.74 kpc	0.76 ± 0.15 kpc
Boxy pseudobulge n	~ 1	1	1.16 ± 0.18
Thin, thick disk z_0	0.30, 0.90 kpc @ $r_\odot$	0.56, 1.03 kpc	…, 1.2 kpc

Classical bulge r_e

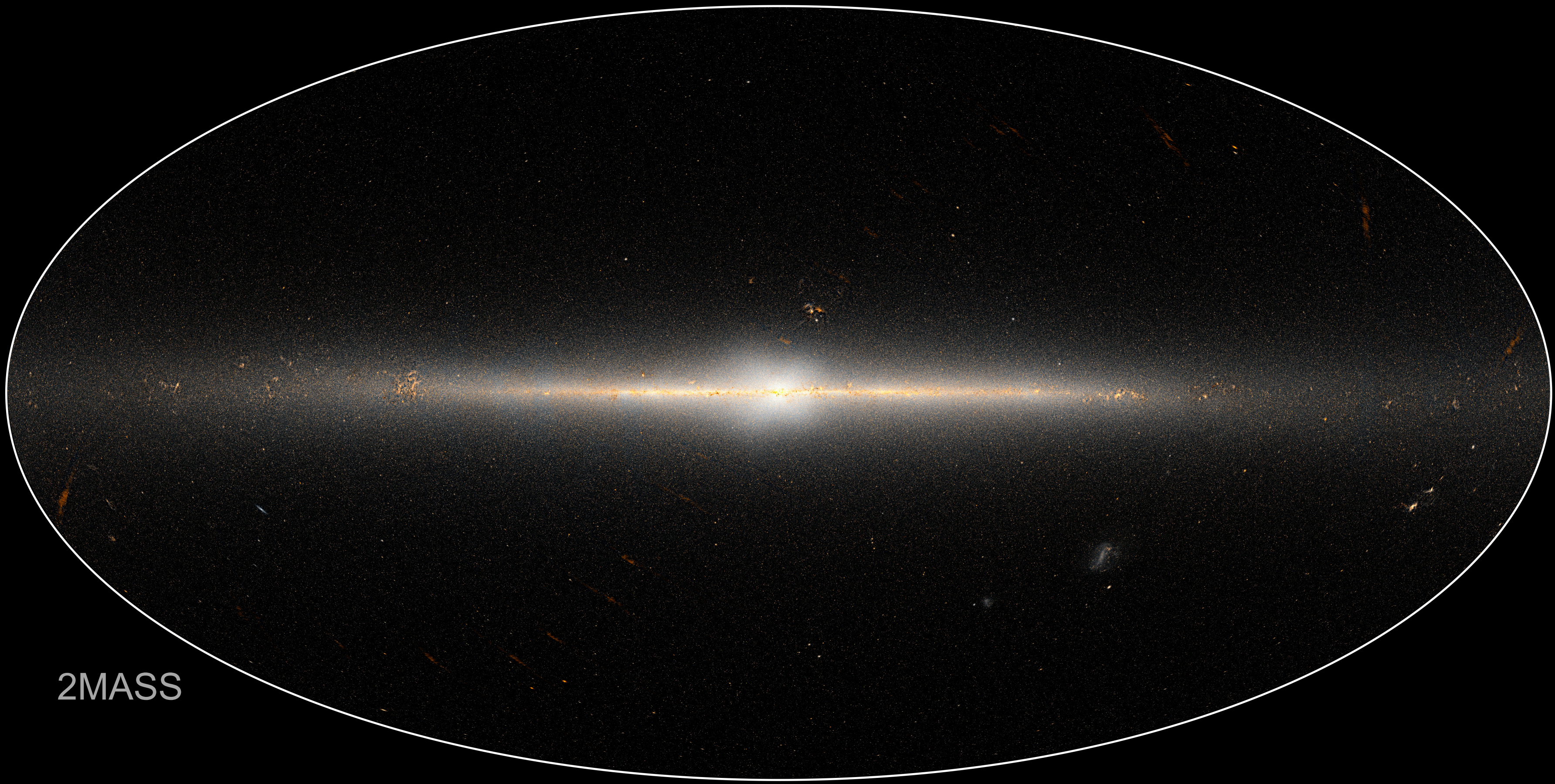
if B/T = 0.02 — 100 – 200 pc, corresponding to $M_V \approx -16.3$ (M32: -16.7)

if B/T = 0.01 — 60 – 150 pc, corresponding to the faintest Es known.

All three galaxies have B/T = 0, (Boxy PB) / T $\approx$ 0.3±0.1 and (Disky PB) / T $\lesssim$ 0.1.

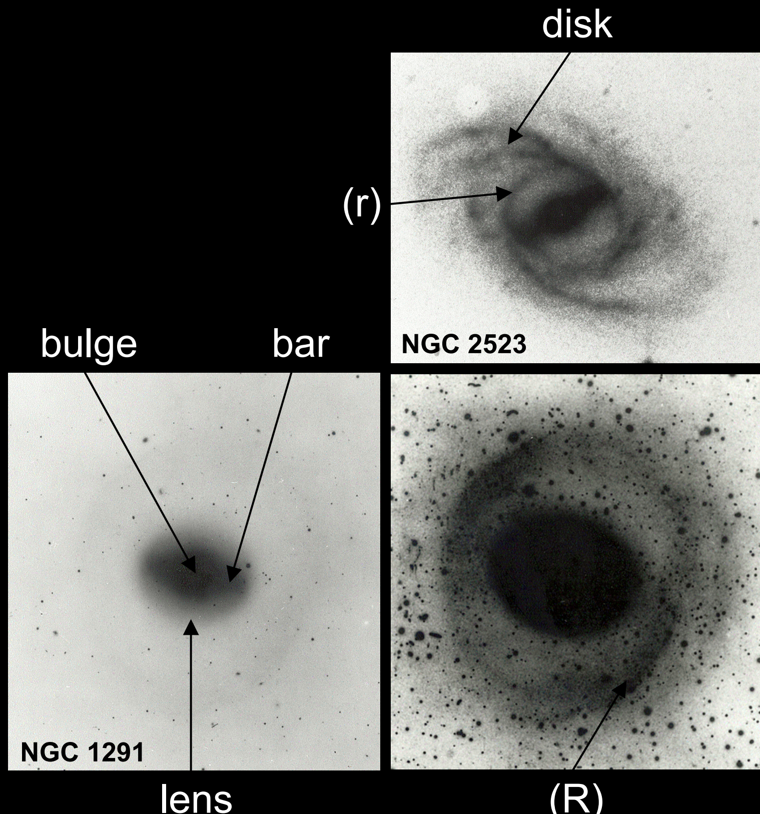
NGC 4565 & NGC 5764 are Milky Way Analogs

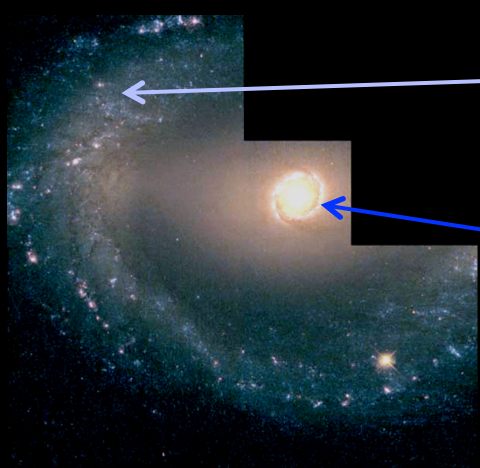
Secular Evolution of Galaxy Disks:
Our Milky Way as a Case Study



Kormendy & Kennicutt 2004, ARA&A, 42, 603;
Kormendy 2013, 23rd Canary Islands Winter School review, arXiv:1311.2609

Secular ≡ Slow Evolution of Galaxies





Evolution via angular momentum exchange between (especially) gas and nonaxisymmetric components such as bars and oval disks (timescale » dynamical time) …

… rearranges disk gas into <u>inner rings</u> (r), <u>outer rings</u> (R), and <u>pseudobulges</u>.

Duus & Freeman 1975; Simkin + 1980

Kormendy 1979; 1981; 1982; 1993; 2013, … .

Kormendy 1979; Simkin + 1980

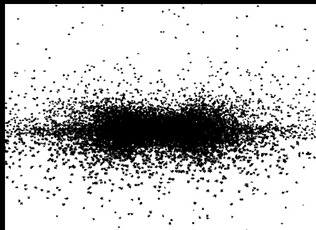
Inner rings have the same (young) stellar population as the disk, not the old stellar population of the bar.

Pseudobulges are grown slowly out of disks that are always nearly in <u>dynamical equilibrium</u>.

Secular evolution grows pseudobulges – central, dense gas+star subsystems – out of disks.

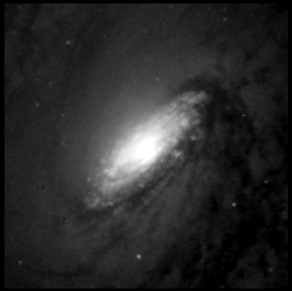
Stellar-dynamical bar formation: bars heat and buckle in the axial direction and look box-shaped when seen edge-on. Box-shaped pseudobulge = edge-on bar

(e. g., Combes & Sanders 1981, A&A, 96, 164; Combes et al. 1990, A&A, 233, 82)



Combes & Sanders 1981

Gas-dynamics: Angular momentum transport by bars drives gas to center where it starbursts and makes disky pseudobulges (see Kormendy 1993; Kormendy & Kennicutt 2004; Kormendy 2013, Canary Islands school for reviews).

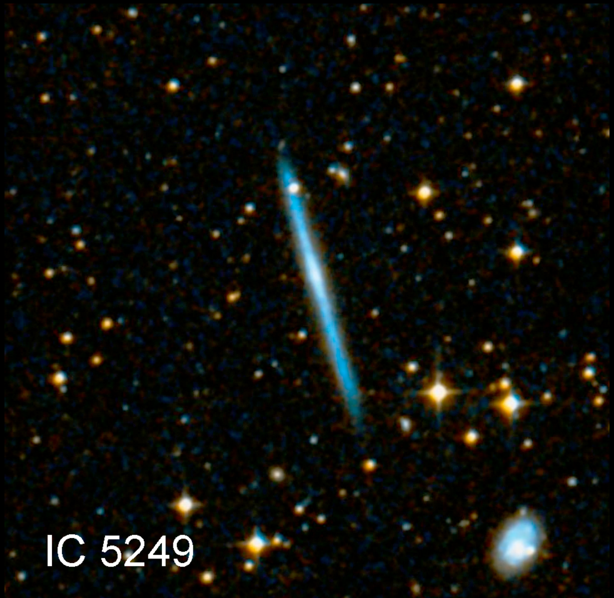


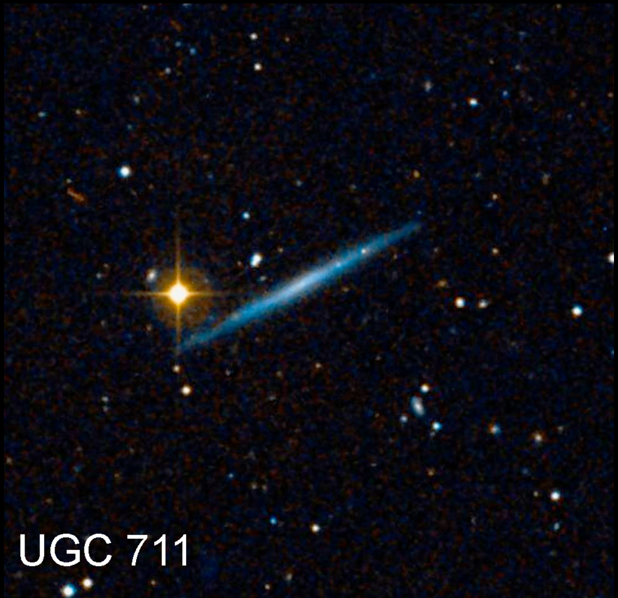
Nuclear bars – like their associated main bars – are disk phenomena ⇒ pseudobulges.

Our Milky Way has both a boxy and a disky pseudobulge … but no classical bulge.

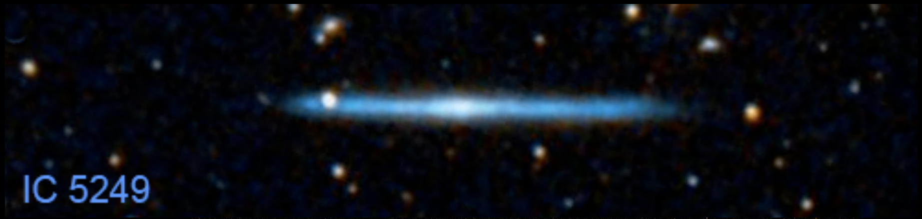
Fundamental Problem for Hierarchical Clustering:

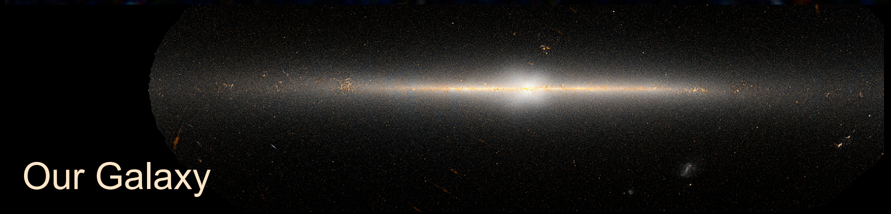
Why are there so many bulgeless disks?



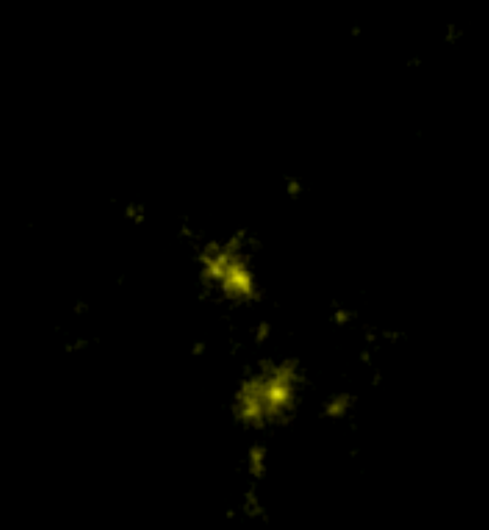


How do you make these:





… when halos grow like this?



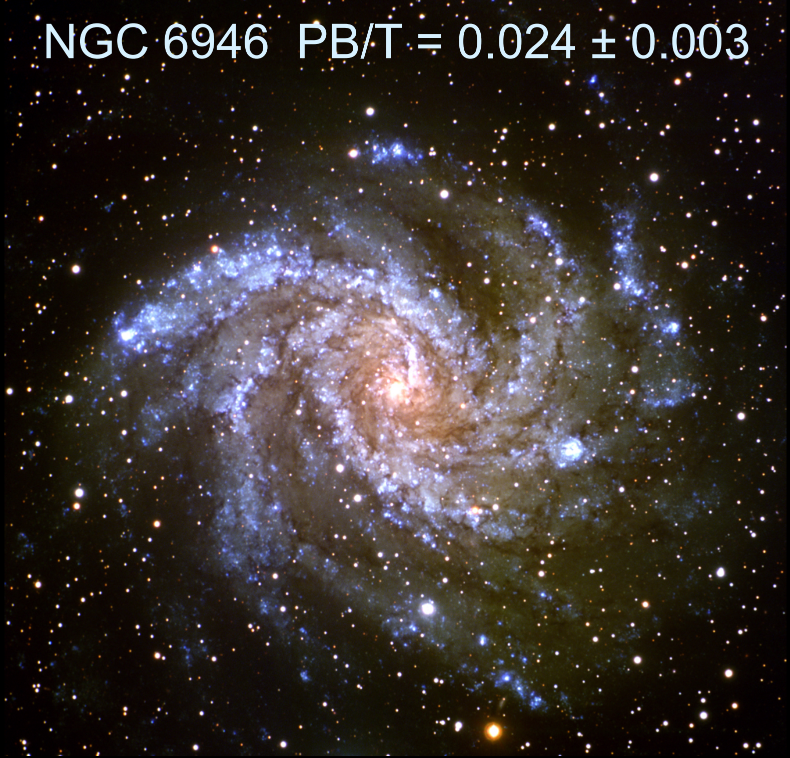
“Preventing bulge formation” is a 2-part problem:

1 – Must not let violent assembly of DM halo over-heat the cold, thin disk.

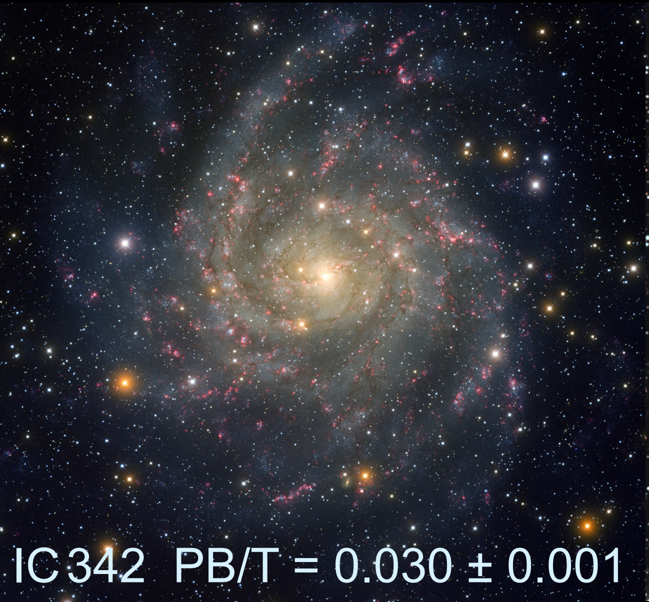
2 – Must not let violent relaxation of already-formed stars contributed by merger progenitors build a classical bulge.

M101 PB/T = 0.027 ± 0.008

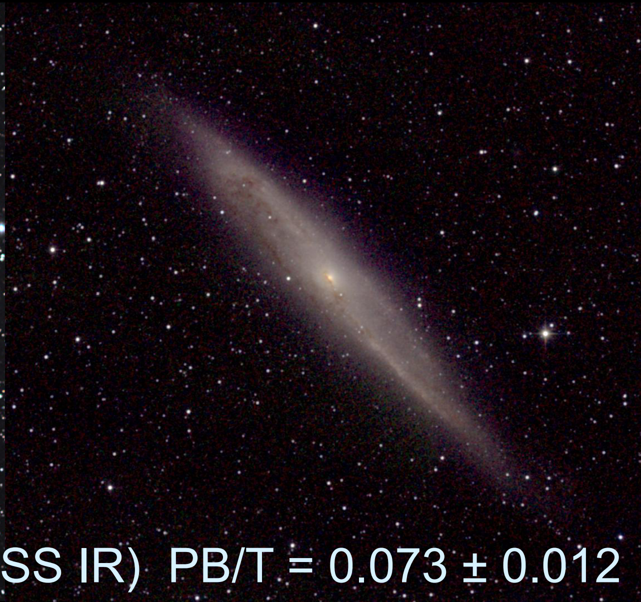
NGC 6946 PB/T = 0.024 ± 0.003



(Kormendy, Drory, Bender, & Cornell 2010, ApJ, 723, 54)



IC 342 PB/T = 0.030 ± 0.001



NGC 4945 (optical and 2MASS IR) PB/T = 0.073 ± 0.012

Giant (V_{circ} > 150 km s^{-1}) Galaxies With Distance < 8 Mpc

Kormendy, Drory, Bender, & Cornell 2010, ApJ, 723, 54

Note: 11 of 19 giant field galaxies with D < 8 Mpc have B/T = 0
(one of these is our Milky Way – it had a very gentle assembly history) ;

4 have B/T ≤ 0.12 ;

2 have B/T ~ 1/3 (M31 + M81),

and

only 2 are ellipticals (Maffei 1 + Centaurus A).

Most giant (V_{circ} > 150 km s^{-1}) galaxies in the local field contain little or no classical bulge = remnant of a major merger.
But in the Virgo cluster, > 2/3 of all stars are in bulges + ellipticals.

Fundamental Question for CDM and Hierarchical Clustering:

How did so many bulgeless disks form <u>in field environments</u>?

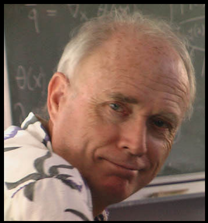
Note:

The correct trick is <u>not</u> to use feedback to delay star formation until the halo is built.

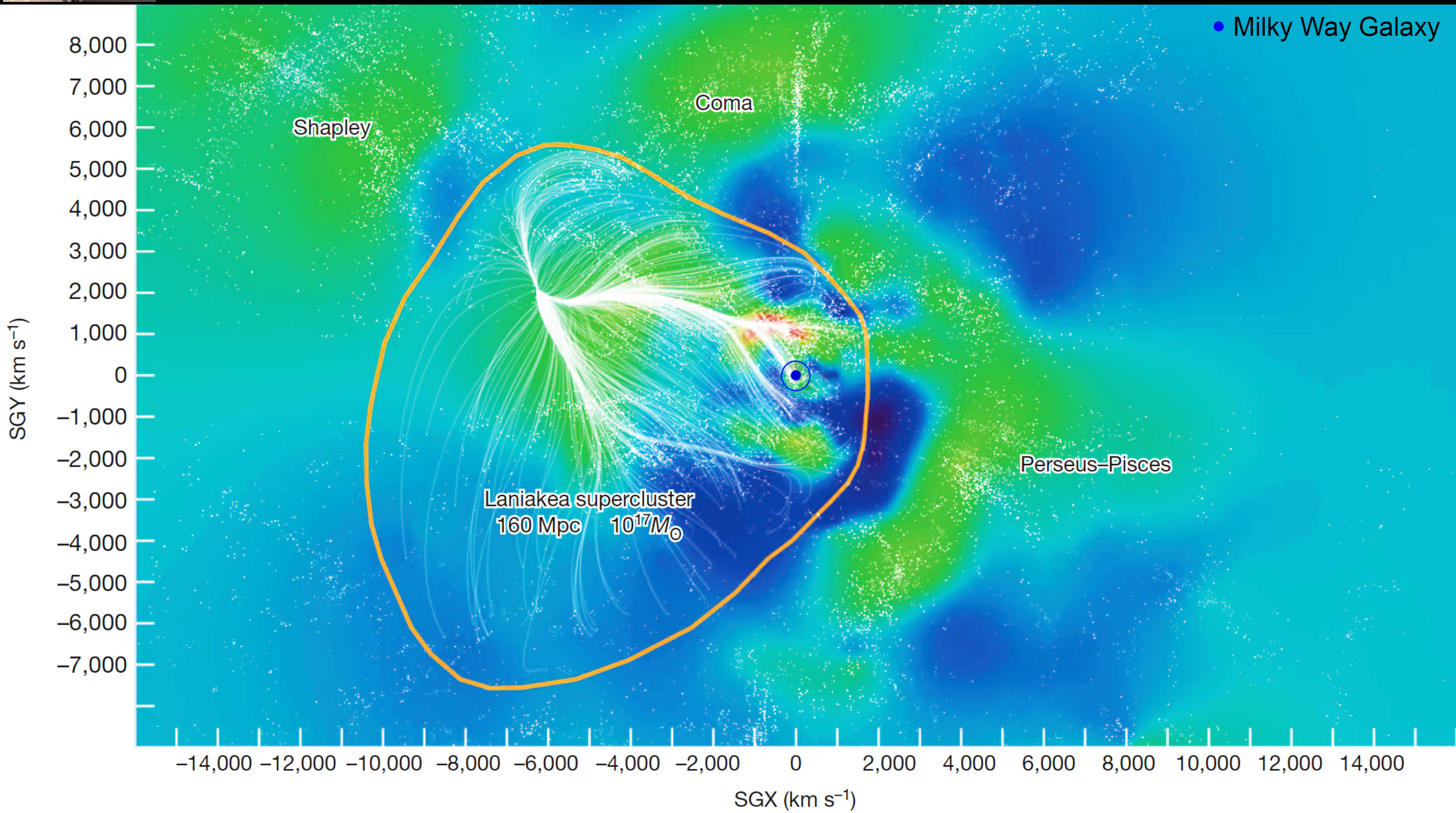
Because the <u>thin</u> disk of our Galaxy contains stars that are at least ~ 9 billion years old (from white dwarf cooling).

Correct answer must (I think) involve environment in a fundamental way. Perhaps: Difference in assembly history – <u>relatively smooth (unlumpy) accretion</u>?

This was <u>not</u> solved in talks given at the Paris meeting (e. g., Madau, Wetzel).



Tully et al. 2014, Nature, 513, 71:
Our 8-Mpc-radius volume is at the end of a cosmic web filament that belongs to the Laniakea Supercluster.



Ken Freeman also emphasized that “the Milky Way has had a quiet history of interaction with other galaxies”.

Part 2:

Stellar Populations: abundance patterns and kinematics

Warm-hot gas content

Implications for the formation history of the Milky Way and its satellites

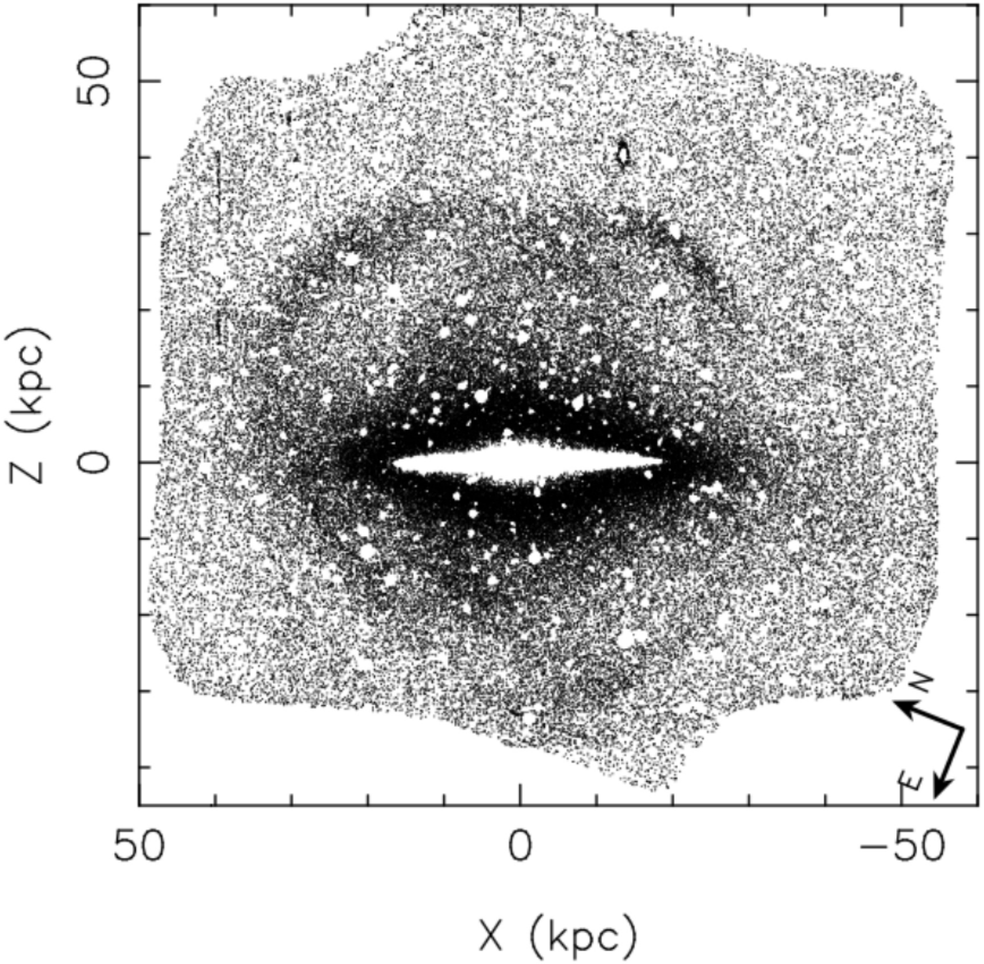
Structural Components in Milky Way

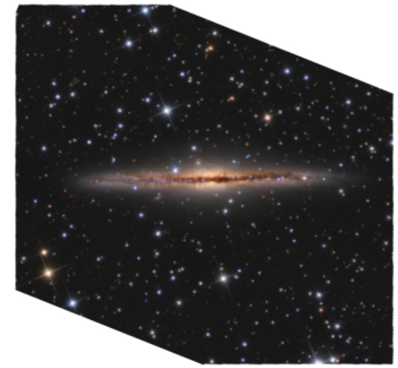
Component	$\frac{\text{Stellar mass}}{\text{Total stellar mass}}$	"Size"
Nuclear cluster	0.00036	$r_e = 4.2 \pm 0.4$ pc
Disky pseudobulge	0.04 ± 0.01	$z_0 = 45$ pc
Boxy pseudobulge	0.27	$z_0 = 0.22$ kpc
Bar = Box+thin bar	~ 0.38 (overestimated: my best guess ~ 0.3)	
Classical bulge	0 !	
Thin disk*	$\sim 0.6^{+0.05}_{-0.10}$	$z_0 = 0.30 \pm 0.05$ kpc @ $r_\odot$
Thick disk	~ 0.08	$z_0 = 0.90 \pm 0.18$ kpc @ $r_\odot$
Stellar halo	$\sim 0.014 \pm 0.005$	

Cold gas/All stars	≤ 0.15	
Warm-Hot gas/All stars	≥ 0.4	
Baryons/(Baryons+DM)	$\sim 0.07 \pm 0.01$ = less than ½ of cosmological value	

*N. B.: The thin disk flares (gets vertically thicker) at larger R; z_0 quoted at $r_\odot$.

The thick disk of NGC 891





Much discussion at the Paris conference concentrated on interpreting thin vs. thick disks.

The diamond-shaped outer isophotes of the thick disk of the Milky Way analog NGC 891, from Subaru star counts: consistent with a simple structure e.g. $\rho_L \sim \exp(-R/h_R + z/h_z)$ $\quad h_R/h_z \approx 2/1$

Also see halo substructure in NGC 891

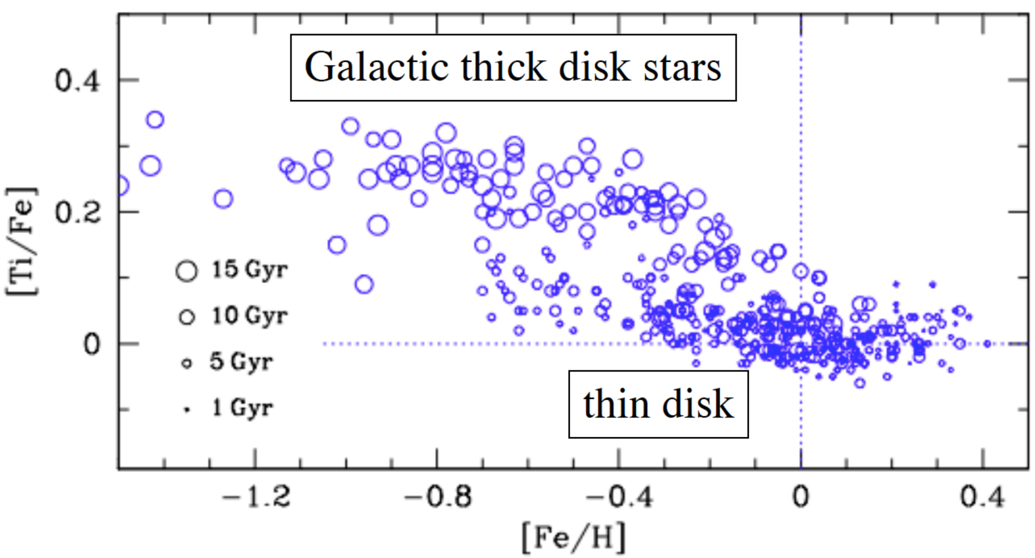
Mouhine et al 2010

Reminder: The α/Fe cosmochronometer

α/Fe ratios tell us evolutionary timescales of early **star** formation:
α elements are produced by SNe II within ~10^7 yrs after the onset of star formation;
Fe is mainly produced by SNe Ia, which only start to contribute after ~10^9 yrs
to the chemical enrichment. After that, α/Fe can never be enhanced again.

Thin and thick disk stars near the sun have different
[α/Fe] - [Fe/H] distributions
(α = Mg, Si, Ca, Ti)

α-rich means that enrichment was quick, by massive star SNII
Fe-rich means that enrichment was gradual, by white dwarf SNIa



Fuhrmann 2008, Bensby et al 2014

The Galactic thick disk: structure, kinematics, age ....

The thick disk presents a kinematically and chemically recognizable relic of the early Galactic disk going back to z ~ 2+

age believed to be older than 10 Gyr

scale height = 800 to 1200 pc (thin disk ~ 250 to 300 pc)

surface density = 5 to 20% of the local thin disk

Thin and thick disk stars near the sun have different [α/Fe] - [Fe/H] distributions
(α = Mg, Si, Ca, Ti)

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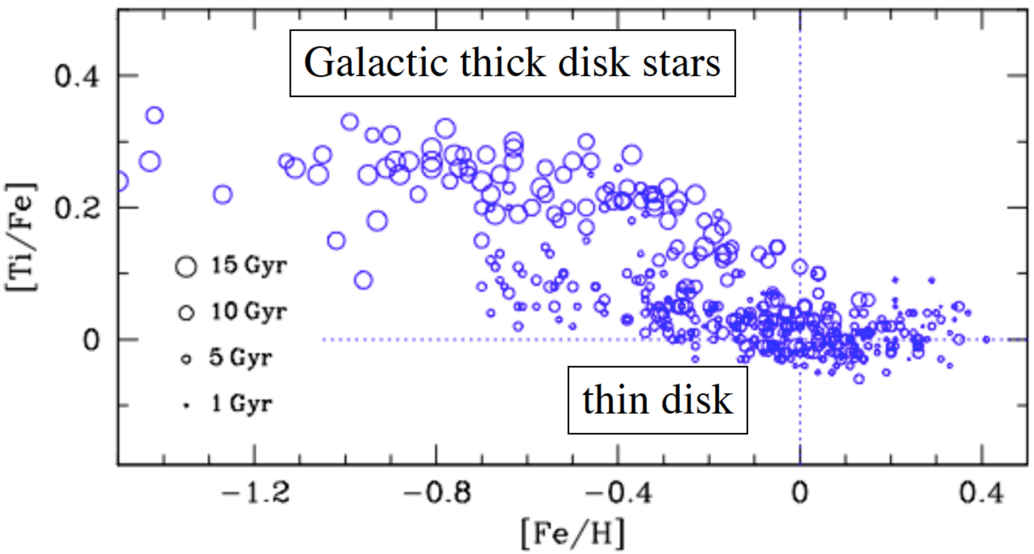


Fuhrmann 2008, Bensby et al 2014

The Paris conference was dominated by discussion of the minutiae of stellar populations and their explanations, especially: thin vs thick disks.

For example:

Hayden et al. 2015, ApJ, 808, 132
SDSS-III APOGEE measurements of 69,919 red giant stars

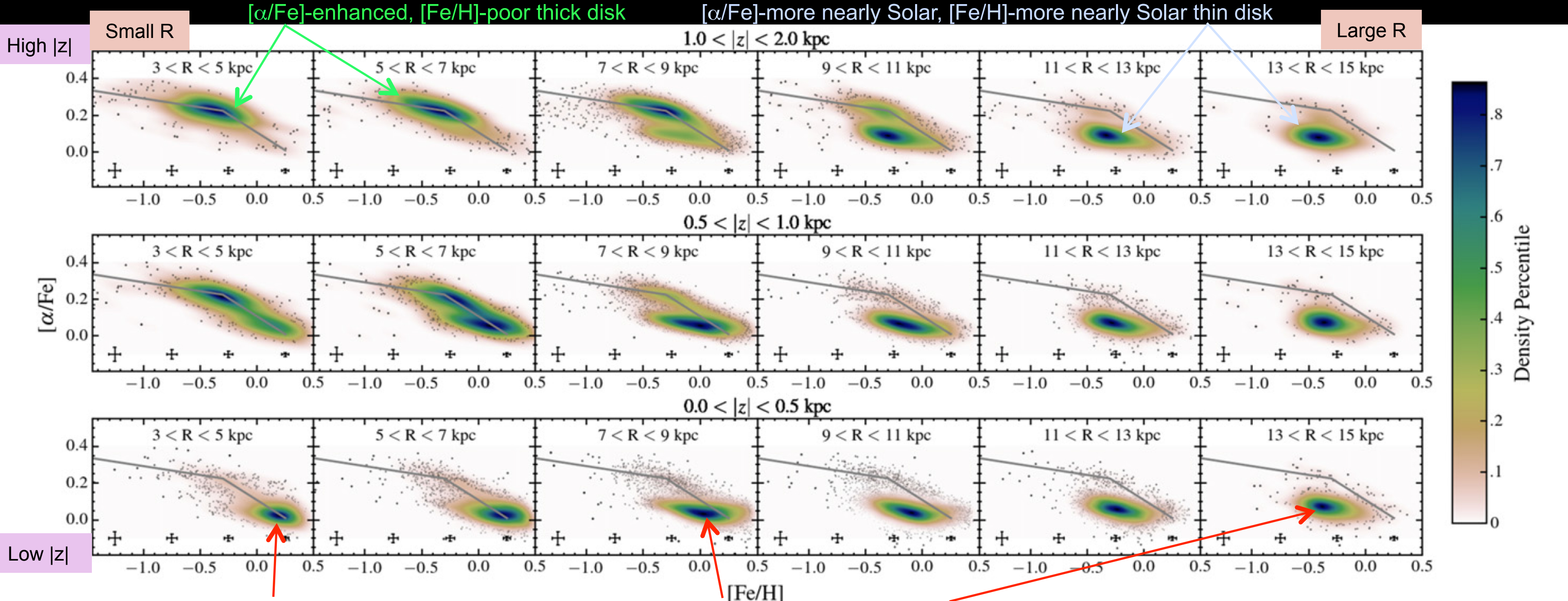


Figure 4. Stellar distribution of stars in the [α/Fe] vs. [Fe/H] plane as a function of R and $|z|$. The typical uncertainty in the abundances is shown as a function of metallicity across the bottom of each panel. The size of individual points is inversely related to the density at that location, to avoid saturation.

Notes:

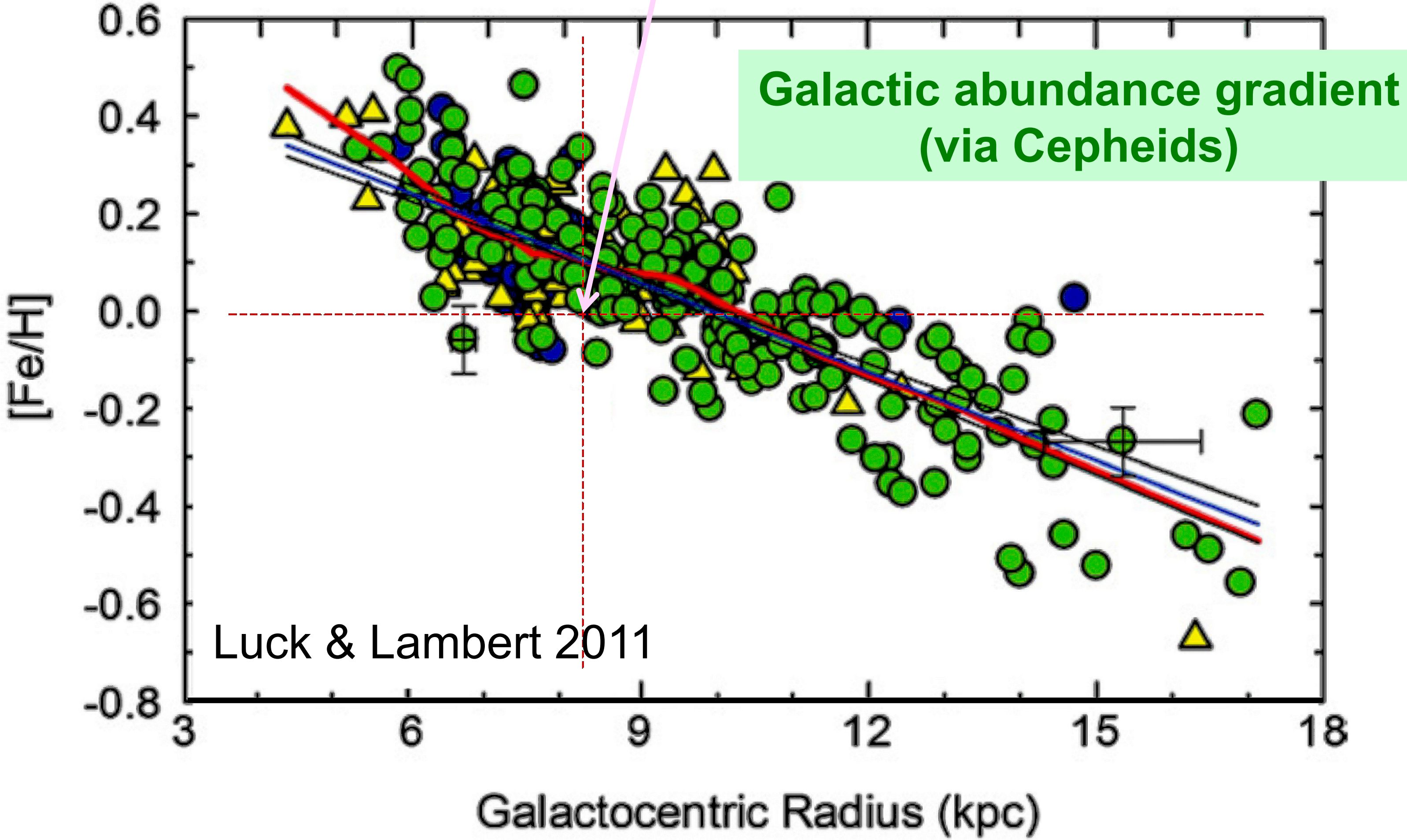
[α/Fe]-enhanced, [Fe/H]-poor thick disk is distinct from [α/Fe]- and [Fe/H]-Solar thin disk.

Shape of the thick disk [α/Fe]-[Fe/H] sequence is independent of Galactocentric radius.

The scale length of the thick disk **short**; the scale length of the thin disk is **long**.

The thin disk's metallicity distribution is skewed to smaller [Fe/H] near the center but is skewed to larger [Fe/H] at large radii. This is interpreted as an effect of radial migration.

Young stars near the Sun are typically more metal-rich than the Sun.



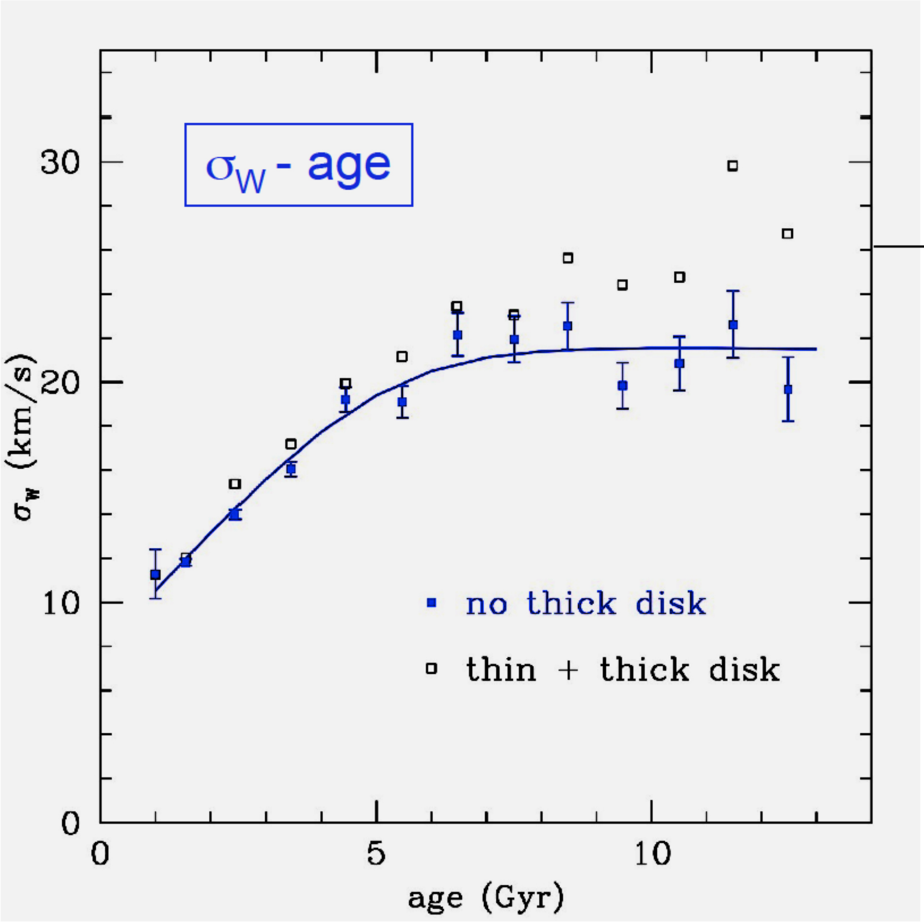
Interpretation: our Sun migrated inward from a formation site that was farther out from the Galactic center.
Or stars from smaller radii migrated outward. Or both.
There was much discussion in Paris about radial migration.

Thin Disk Heating

The dispersion is small for young stars and increases with age, for a few Gyr, due to heating processes which are not well understood.

ISM dispersion ≈ 8 km/s

Then thin disk heating for the past ~ 5 Gyr, up to $\sigma_W \approx 22$ km/s



W-dispersion vs age for GCS stars with [Fe/H] > -0.3 (*excludes most thick disk stars*).

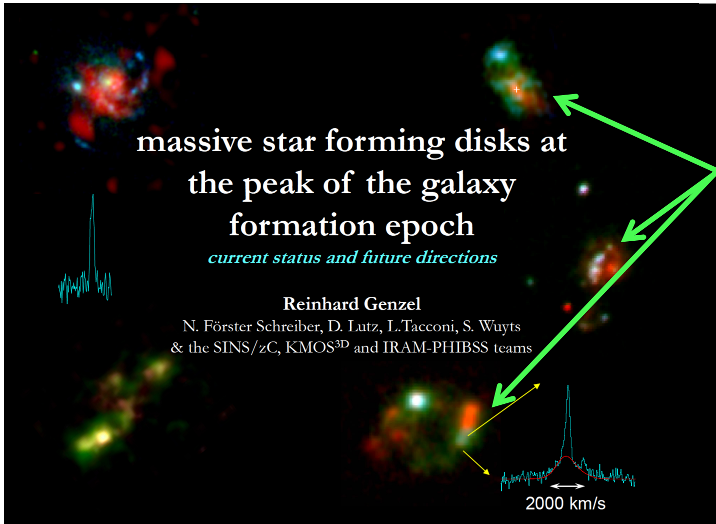
Thick disk dispersion σ_W is about 40 km/s near sun: where does that come from ?

Casagrande et al 2011

Ken Freeman emphasized that "the narrative about disk heating …
[e. g., the Spitzer-Schwarzschild 1951, ApJ, 114, 385 & 118, 106
mechanism of stellar scattering off of GMCs]
may be at least partly wrong."

Evidence from observations of
$z \approx 1$ to 3 galaxies
shows that
gas velocity dispersions were fundamentally higher than they are now.
Also, galaxies were fundamentally smaller than they are now.

Star formation would fundamentally make
thickish disks with short scale lengths,
like the thick disk of our Galaxy.

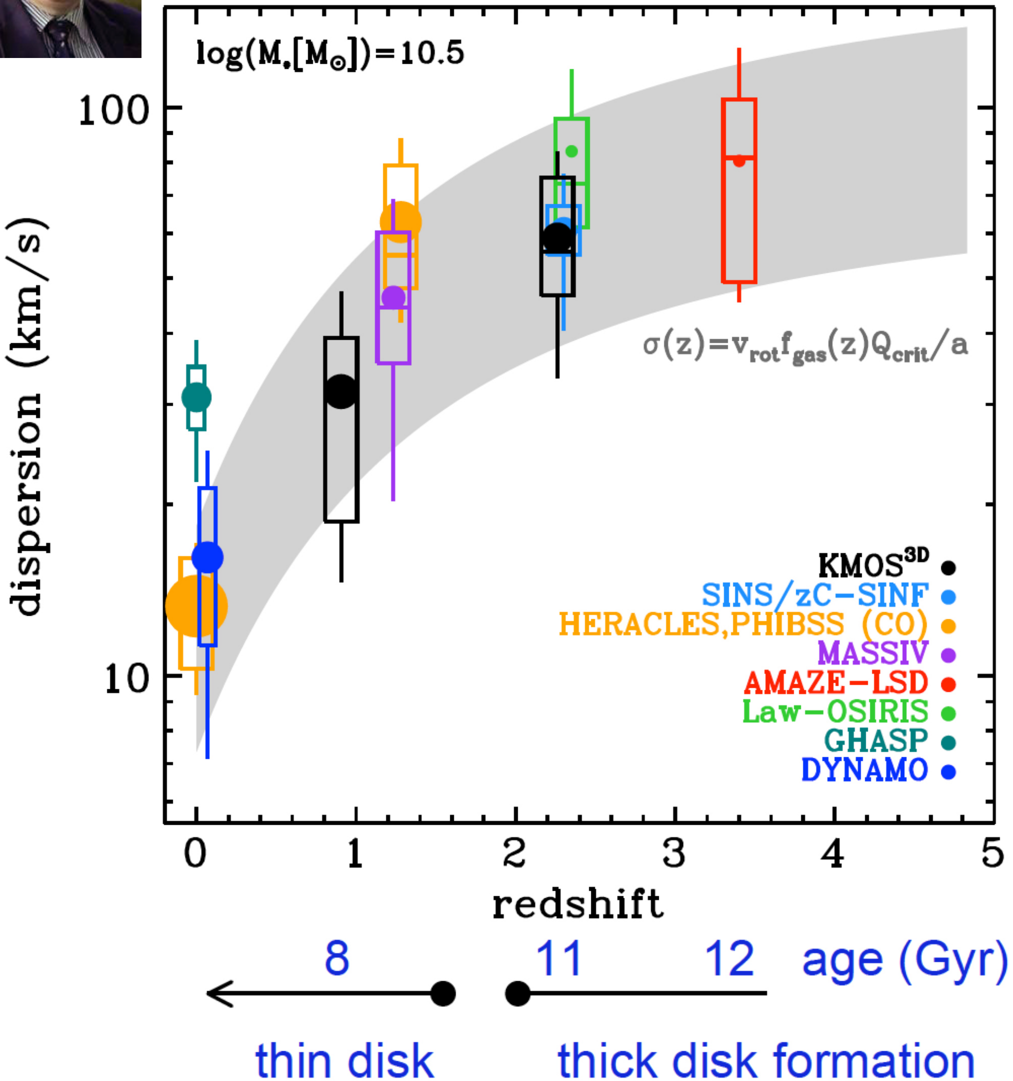


But note:
Starbursting clumps are common at $z \sim 2$
and tend to make classical bulges.

Bournaud et al. 2007, ApJ, 670, 237; Elmegreen et al. 2008, ApJ, 688, 67

We need a better solution to the problem
of pure-disk galaxies.

High disk turbulence dropping towards low z



- high-z disks are turbulent: their turbulent velocity dispersion decays from about 100 km/s at z > 3 to 30 km/s at z = 1.

- The observed decay of turbulent velocities from z ~ 3 extends into the epoch of thin disk formation 8-10 Gyr ago

- The (velocity dispersion) - age relation for the thick disk and the older thin disk stars may reflect the decaying turbulence at high-z rather than disk heating.

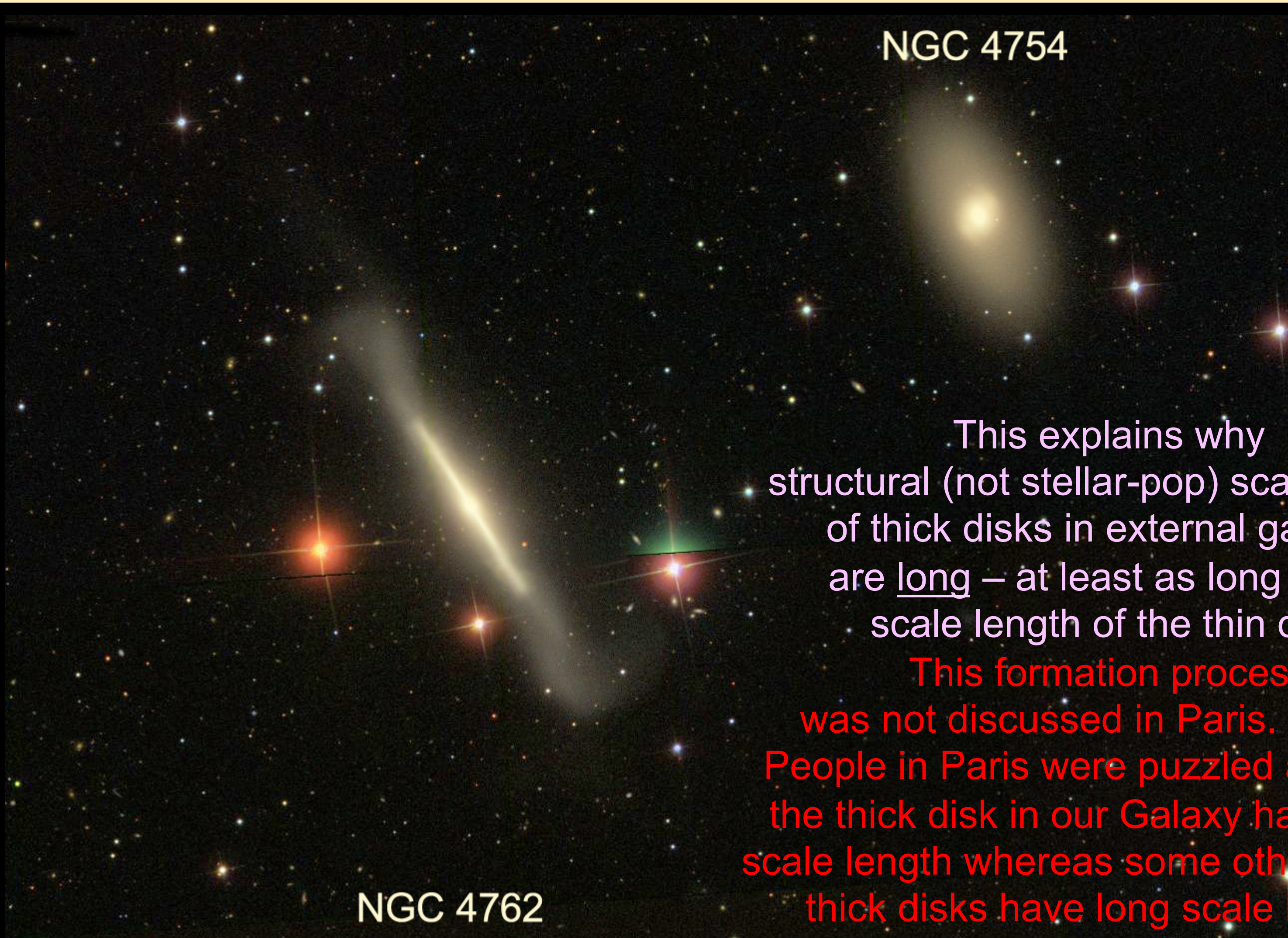
Wisnioski et al 2015

The high gas velocity dispersions
seen in starbursting, gas-dominated galaxies at $z \sim 2$
are driven by energy feedback from starbursts.
These inevitably should make
small, high-σ_z thick disks.

This is plausibly the explanation of thick disks in galaxies like the Milky Way.

But thick disks in (e. g.) Virgo cluster S0s
probably form via galaxy harassment
(Kormendy & Bender 2012, ApJS, 198, 2).

Kormendy & Bender 2012 suggest that thick disks and even Sph halos are made by dynamical heating ("harassment") in (e. g.) Virgo.
(Moore et el. 1996, 1998, 1999; Lake et al. 1998; Mayer et al. 2001a, b, 2006)



Outer disk warp ➔ vertical heating by tidal interaction with NGC 4754.
This warp will phase-wrap and become indistinguishable from a large Sph.

Upside-down disk formation (Bird et al 2013)

Idea of upside-down disk formation is not new: see Elmegreen^2 2006, Bird, Brook, Bournaud, Bershady.

The younger thin disk stars (ages < few Gyr) are likely to have formed from gas whose turbulence had decayed to the present value of around 8 km/s. Their velocity dispersions are likely to reflect disk heating...how do we observationally disentangle the contributions from a cooling gas disk and from later heating of a very thin stellar disk ?

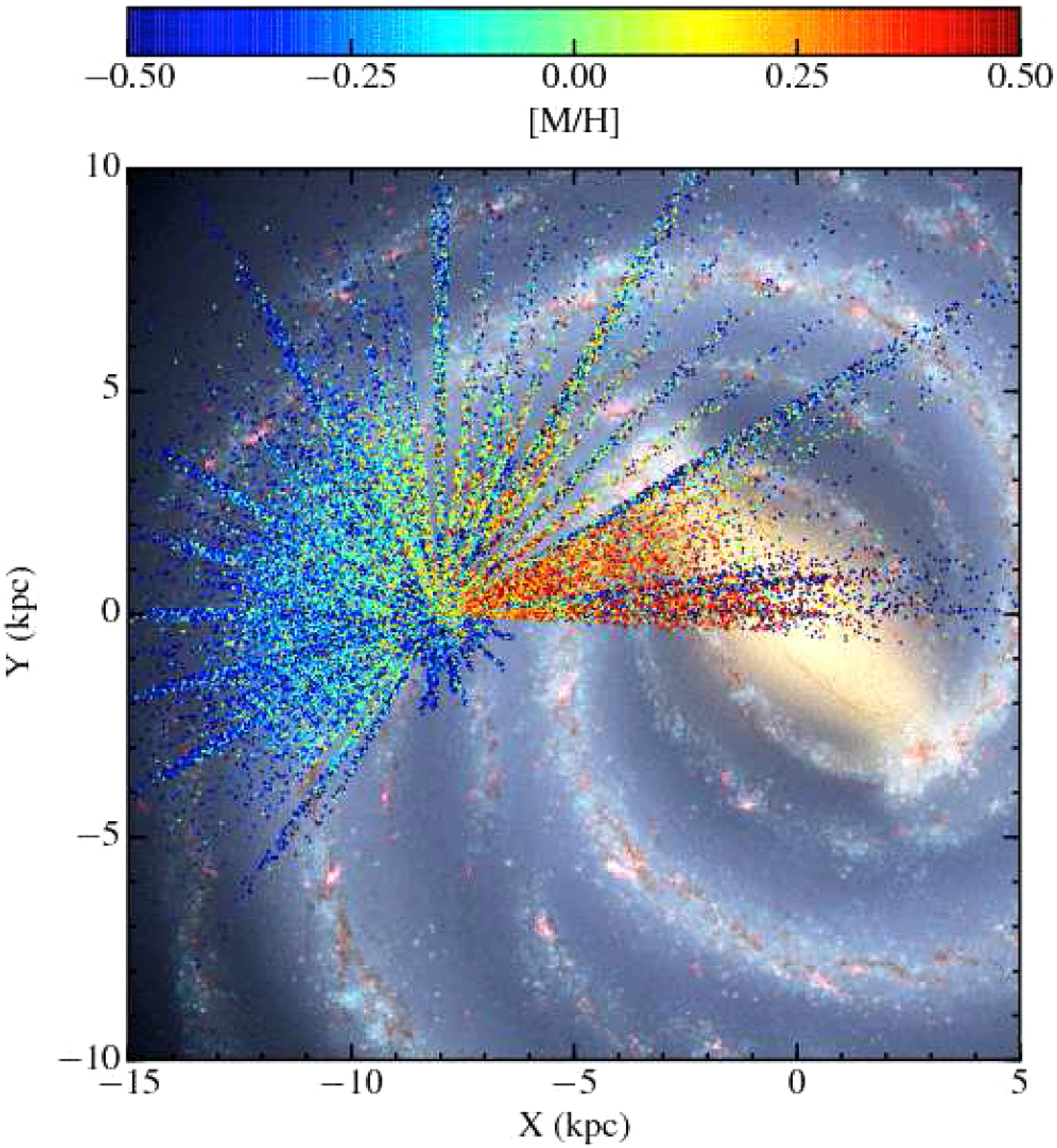
Upside-down = 2-stage disk formation:

Thick disk forms first, with σ_z determined by starburst feedback into protogalactic thick gas disk.
Bar forms from thick disk and quickly buckles.
Simulations $\Rightarrow$ that the whole bar buckles (not just some inner part that does not include a large-R “thin bar”).

Then thin disk grows slowly by accretion of cold gas from cosmic web and continued, slow star formation.
Thin disk evolves secularly, driven by the bar.

Question:
Does the whole thin bar (length ≈ 5 kpc: Bland-Hawthorn & Gerhard 2016) grow secularly from the thin disk via thick-bar-driven outward angular momentum transport $\Rightarrow$ Ω_p slowdown $\Rightarrow$ $R_{corotation}$ increase,
$\Rightarrow$ thin bar gets longer than thick bar by capturing stars from thin disk?

SDSS-III APOGEE project analyzed R ~ 22,500, S/N > 100 spectra of 146,000 stars in the IR (1.51 – 1.70 μm) so that stars can be reached and distances determinated through the Galactic center (A_H ~ 3 mag).



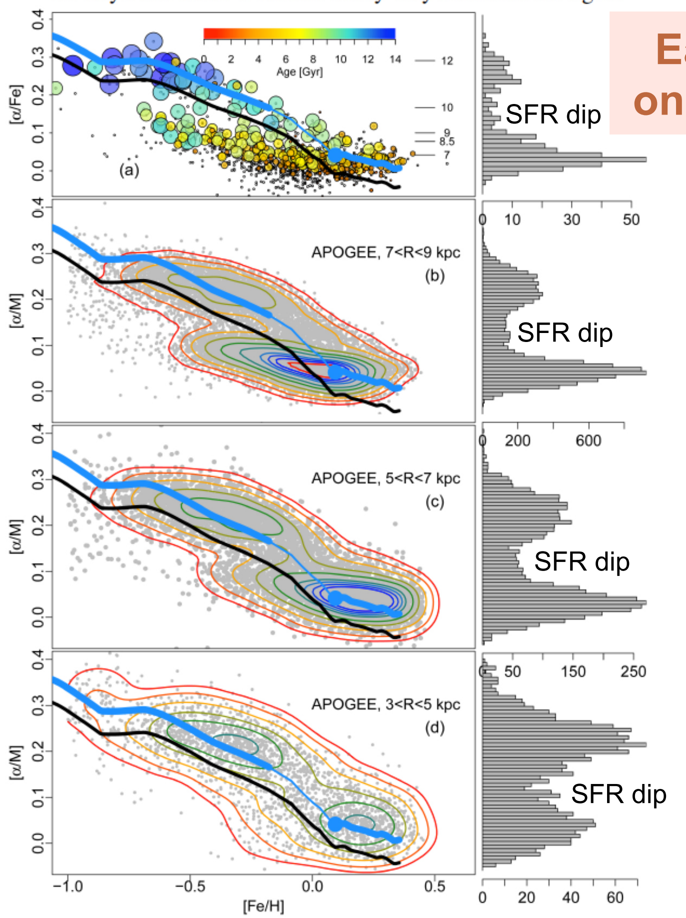
Majewski et al. 2015, arXiv:1509.05420; 2016, AN, 337, 863

Stars: Michael Hayden
Galaxy image: R. Hurt, JPL, NASA

M. Haywood et al.: When the Milky Way turned off the lights

Early temporary shutdown in Milky Way star formation was one of the most interesting suggestions at the Paris meeting.

Haywood et al. 2016, A&A, 589, A66



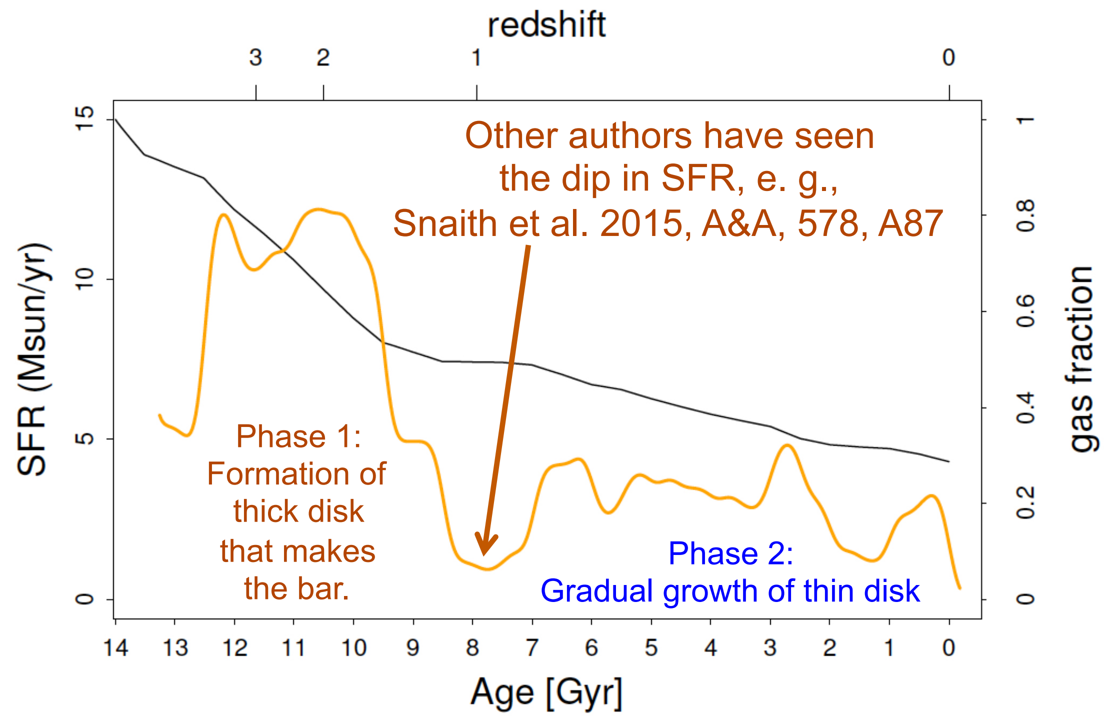
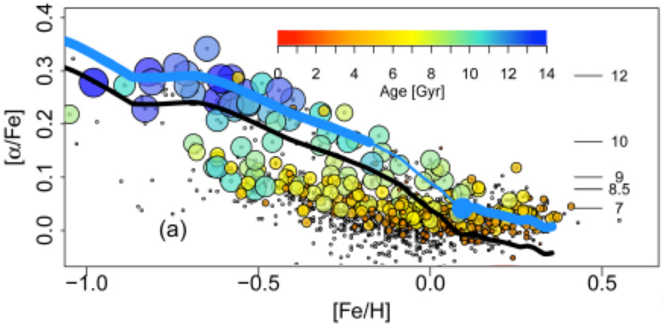


Fig. 3. **a)** Abundance distributions for stars in the solar vicinity from very high resolution spectroscopic data and **b)–d)** data from APOGEE. The inner-disk sequence (above the black line) is composed of thick-disk and metal-rich thin-disk stars and dominates the inner-disk stellar populations, as illustrated in **c)** and **d)**. The blue thick curve represents the track of our chemical evolution model, with the dot indicating the beginning of the thin-disk era at 7 Gyr. The thinner blue segment indicates the quenching phase from 10 to 7 Gyr. The black line is defined as the model −0.05 dex in [α/Fe]. We emphasize that the model (blue line) represents the evolution of the inner-disk sequence alone (stars above the black line). The outer-disk sequence (below the black line) represents a different evolution and requires a different model (see Snaith et al. 2015). The histograms count the number of stars above the black

"We emphasize that the quenching phase … could be contemporaneous with and related to the formation of the bar and the end of the thick-disk phase."

Fig. 1. Star formation history of the inner Milky Way ($R < 10$ kpc) derived from fitting the solar vicinity age-[Si/Fe] abundance with a chemical evolution model in Snaith et al. (2014; 2015; orange curve, left axis), together with the gas fraction evolution in the model (thin black curve and right axis). The SFR at ~8 Gyr is negligible (consistent with no star formation), while the gas fraction is still very high in the system, similar to the molecular gas fractions estimated in disks at redshifts ~1−3 (Daddi et al. 2010; Arevana et al. 2010; Dannerbauer et al. 2009; Tacconi et al. 2010, 2013). The SFH is normalised such that the current stellar mass of the Milky Way is $5 \times 10^{10}\ M_{\odot}$.



Suggestion: Did this sudden star formation quenching happen because bar buckling "stretched" gas vertically ⇒ volume density decreased?

SFR depends sensitively on gas density.

This 2-phase growth scenario …

(thick disk "closed box" chemical enrichment made stars in the **bar**

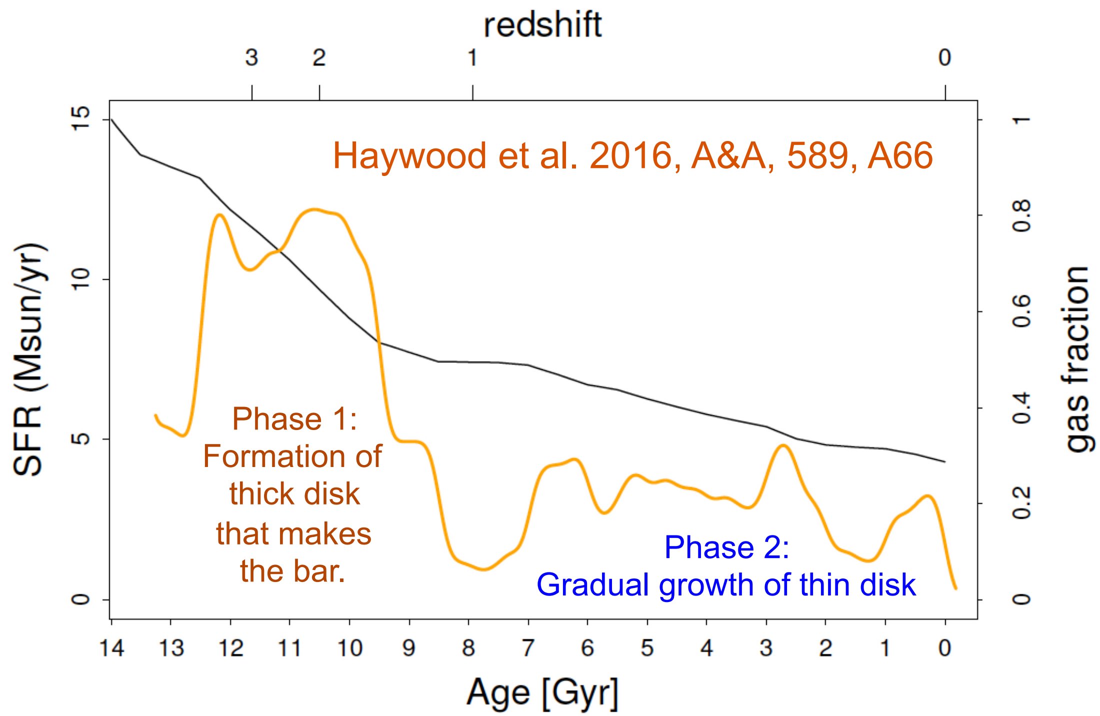
+

slow, later enrichment <u>diluted</u> by new, infalling, metal-poor gas made the stars in the **thin disk**)

… may explain why the [a/Fe] – [Fe/H] correlations show 2 distinct sequences.

The upper sequence is the thick disk + inner thin disk; the lower sequence is the outer thin disk, grown during the bar's secular evolution phase

(Haywood et al. 2016).



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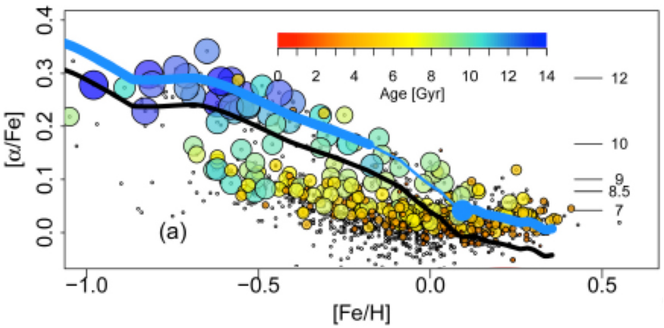
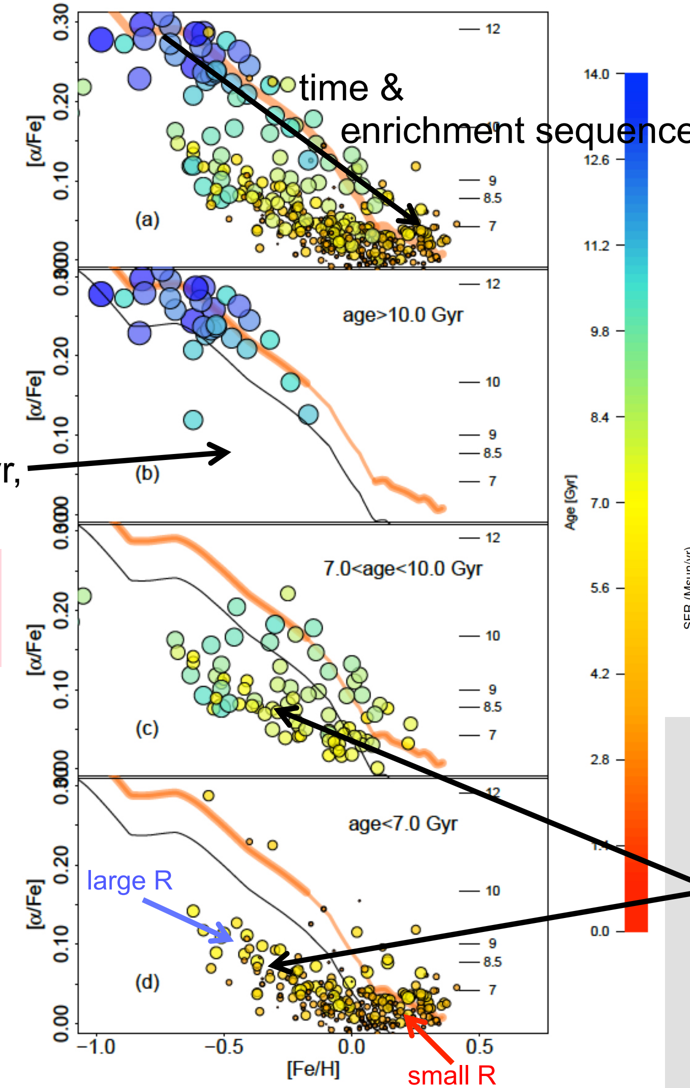
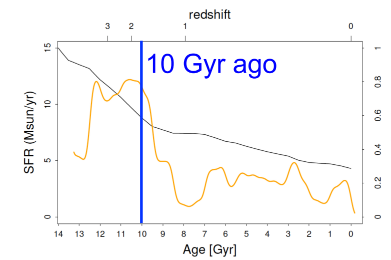




There was no thin disk at lookback time ≈ 10 Gyr,
i. e., during the first burst of star formation.

If bar buckling killed the SFR, then
the bar that buckled was made of the thick disk.



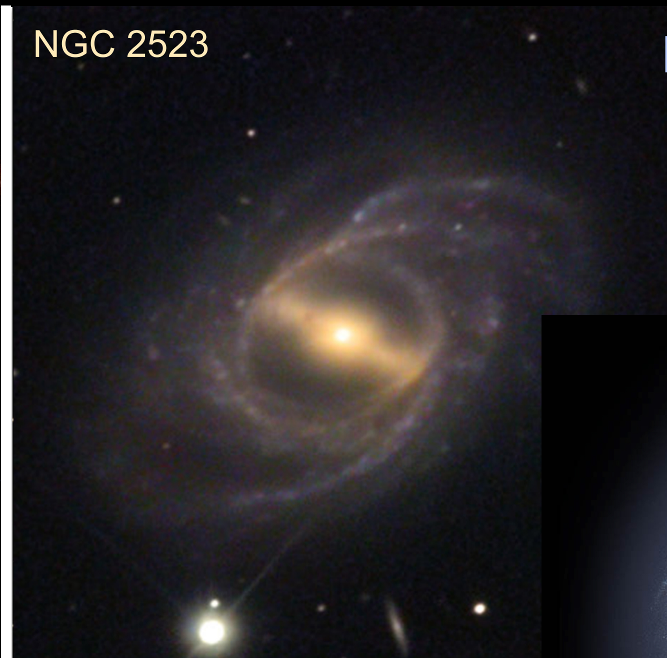
The "thin disk" grew during phase 2.

Note that the "thin disk sequence" is independent of stellar age.

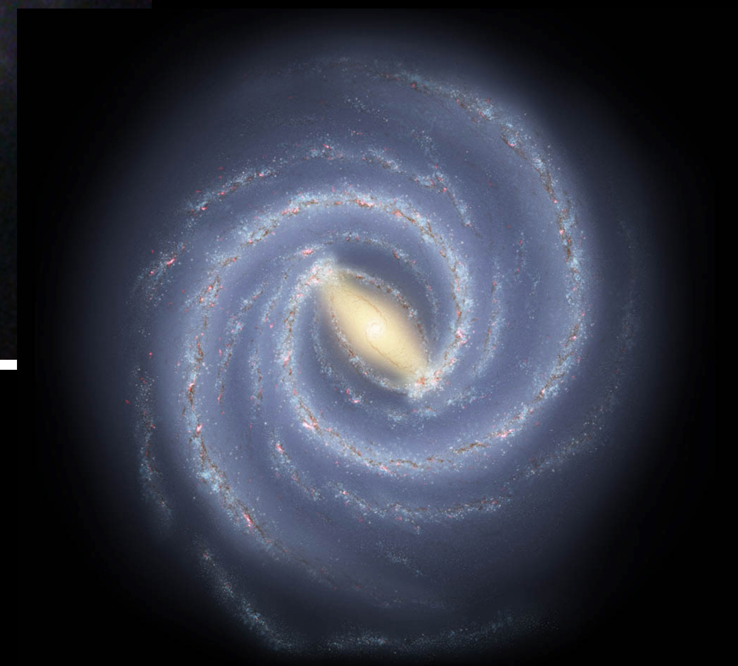
Is this a sign of dilution in the gas that made the thin disk stars by "pristine" gas that accreted from the cosmic hierarchy to grow the thin disk?

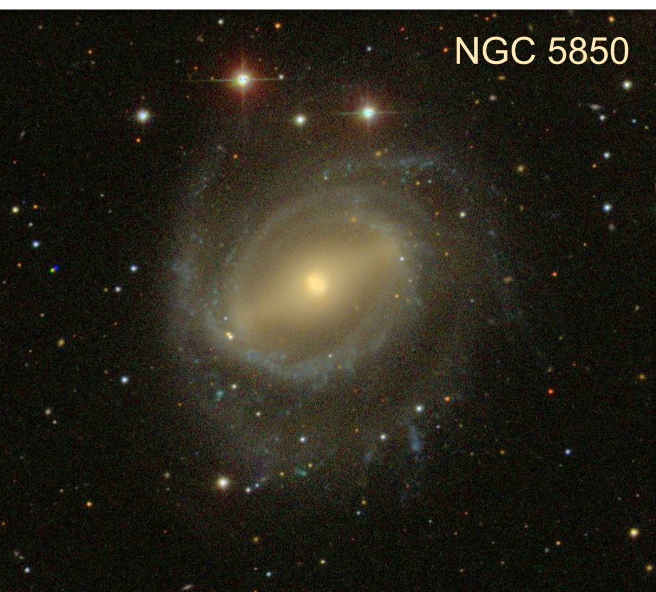
Fig. 2. [α/Fe]-[Fe/H] distribution at the solar vicinity for the sample of Adibekyan et al. (2012) with ages from Haywood et al. (2013). The colours (indicated in the legend) and size of the symbols indicate the age of the stars (larger circles imply older ages). The orange line represents the model of Snaith et al. (2015), which has the SFH of Fig. 1. The thinner segment of the line corresponds to the lull in the SFH of Fig. 1, between 10 and 7 Gyr ago. The thin black curve is the same model shifted down by −0.05 dex and is used in Sect. 3 to select inner-disk stars from the APOGEE survey. The stars below and to the left of this line are either accreted stars according to Nissen & Schuster (2010; for those objects which have [Fe/H] < −0.7 dex), or metal-poor thin-disk stars. A vertical scale within each plot indicates ages along the model from 7 to 12 Gyr.

It is very common among SB(r)b galaxies that the stellar population of the bar is old and the stellar population of the (r) and disk are young.

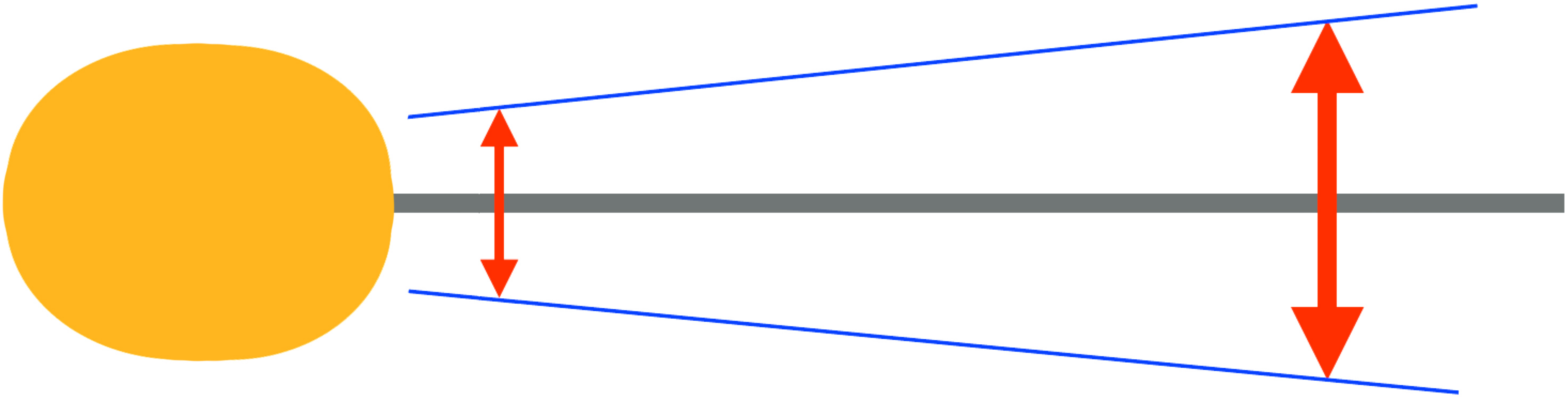


Even our Milky Way is depicted this way in the Hurt/JPL/NASA artist's conception.





RADIAL MIGRATION AND DISK FLARING



If, without changing σ_z, disk stars migrate outward to where disk density is lower and vertical restoring force is smaller, then the disk will flare outward.

We now have many explanations (all probably correct!) for thick disks:

1 – turbulent gas-dominated starbursting disks at z ~ 2 make thick stellar disks;
2 – radial migration makes thin disks flare outward;
3 – dynamical heating by GMCs, bars, and spiral structure heat disks in σ_R, σ_Φ, and σ_z,
4 – dynamical heating by gravitational tides heat disks in z, especially at large R.

This may explain why metallicity-defined “thick disk” ≠ structurally defined “thick disk”.

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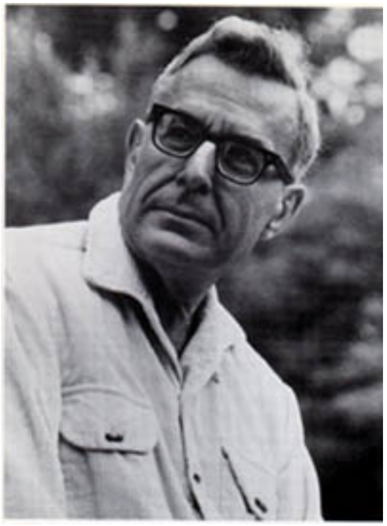
4 – dynamical heating by gravitational tides heat disks in z, especially at large R.

This may explain why metallicity-defined “thick disk” ≠ structurally defined “thick disk”.

The universe [may be] to frighteningly queer to be understood by minds like ours. It’s not a popular view. One is supposed to flourish Occam’s razor and reduce hypotheses about a complex world to human proportions. Certainly I try. Mostly I come out feeling that whatever else the universe might be, its so-called simplicity is a trick. Every now and then if we look behind us, everything has changed. It isn’t that nature tricks us. We trick ourselves with our own ingenuity. I don’t believe in simplicity.



Loren Eiseley
All The Strange Hours

Jo Bovy's talk in Paris and Bovy et al. 2016, ApJ, 823, 30 dissect the stellar populations in the Milky Way thick and thin disk.

Results broadly agree with the 2-stage (inside-out) disk formation picture.

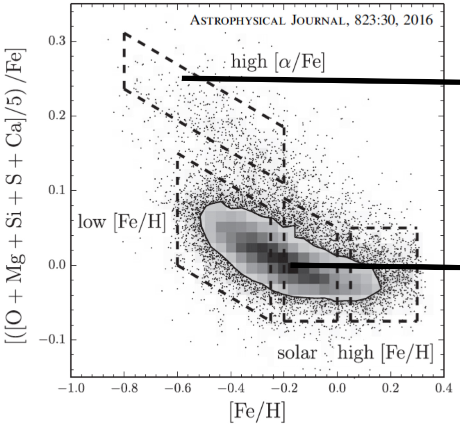
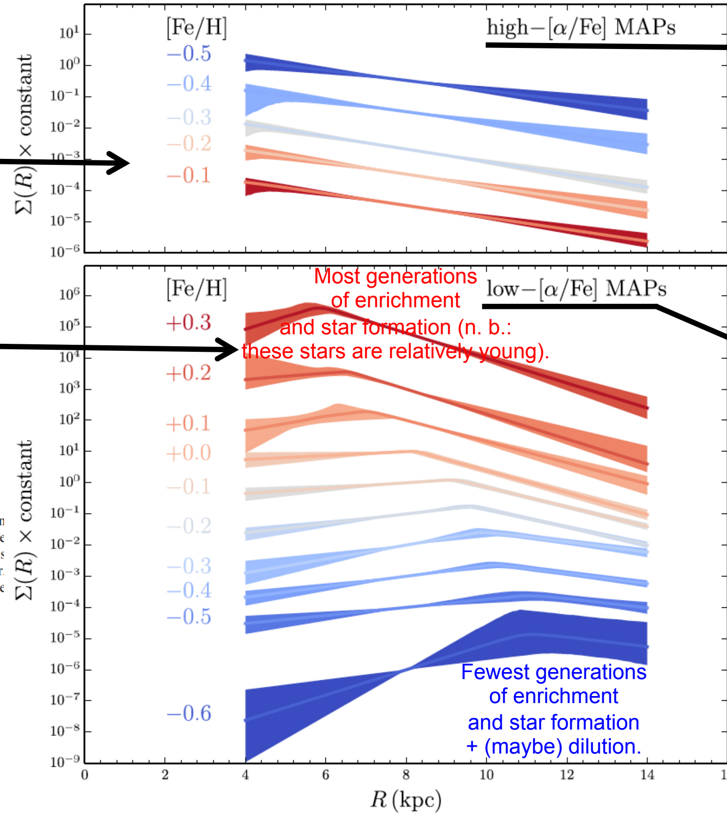


Figure 5. Distribution of the 14,699 stars in the APOGEE-RC sample used in this paper in the plane defined by the iron abundance, [Fe/H], and the average abundance of α elements (see text). A linear binned density representation is used for the 68% of the distribution that is contained within the shown contour. The dashed lines delineate the boundaries of the four broad subsamples that we study in Section 4, which we denote with the given moniker.

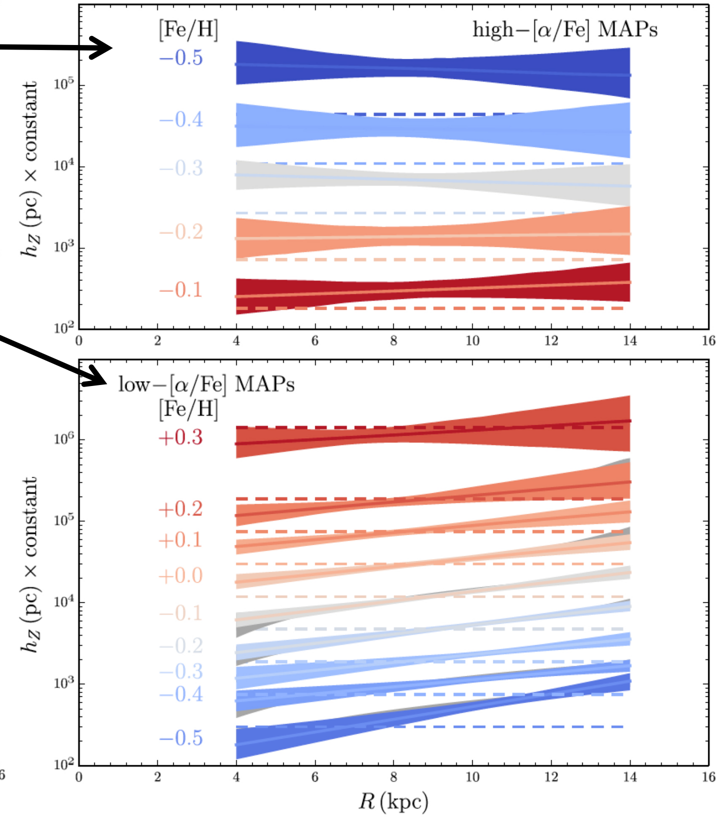
Scale lengths (middle) and scale heights (right) are shown separately for the high [α/Fe] and low [α/Fe] sequences.



Radial surface density profiles:

The high [α/Fe] sequence has radial scale length ≈ 2.2 ± 0.2 kpc for all [Fe/H]. B-H & Gerhard get 2.0 ± 0.2 kpc.

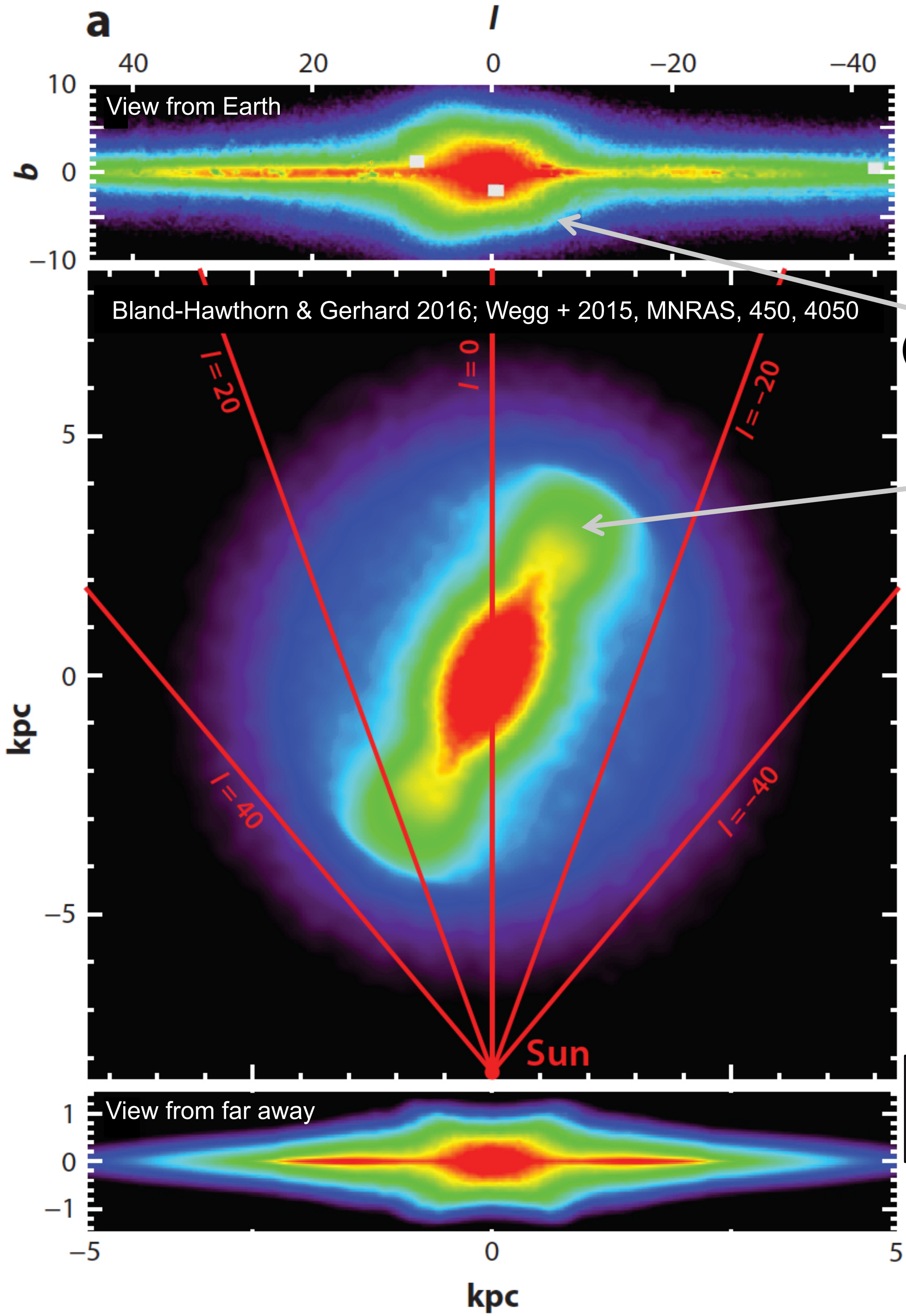
This disk has metallicity gradient (more metal-poor at larger R). Note: the metal-richest stars are youngest (consistent with gradual enrichment?) but live at smallest R. Disk grows inside→out.



Vertical scale height as function of R:

The high [α/Fe] sequence has constant radial scale height for all [Fe/H]. B-H & Gerhard get 0.90 ± 0.18 kpc at $R_\odot$.

The thin disk flares outward. Bovy argues that this is consistent with radial migration: if σ_z ≈ constant while R increases and Σ decreases, then vertical restoring force decreases and scale height increases.



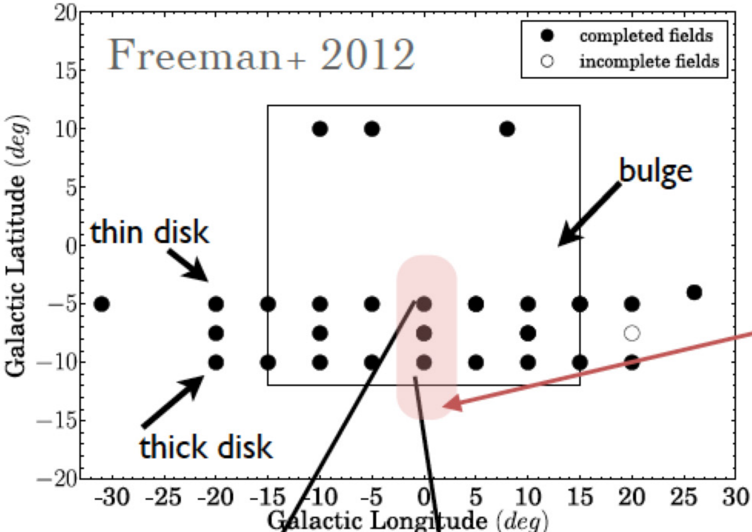
The bar consists of a thick part (the parallelogram-shaped "boxy pseudobulge" seen from the Earth) and a thin bar revealed by star counts that reaches out to $R_B \approx 5.0 \pm 0.2$ kpc.

From Portail et al. 2016, arXiv:1608.07954:
$\Omega_p \approx 39.0 \pm 3.5$ km/s/kpc,
$R_{CR} \approx 6.1 \pm 0.5$ kpc.
We are at $R_\odot \approx 8.2 \pm 0.1$ kpc.

Dissect the stellar population of the box:

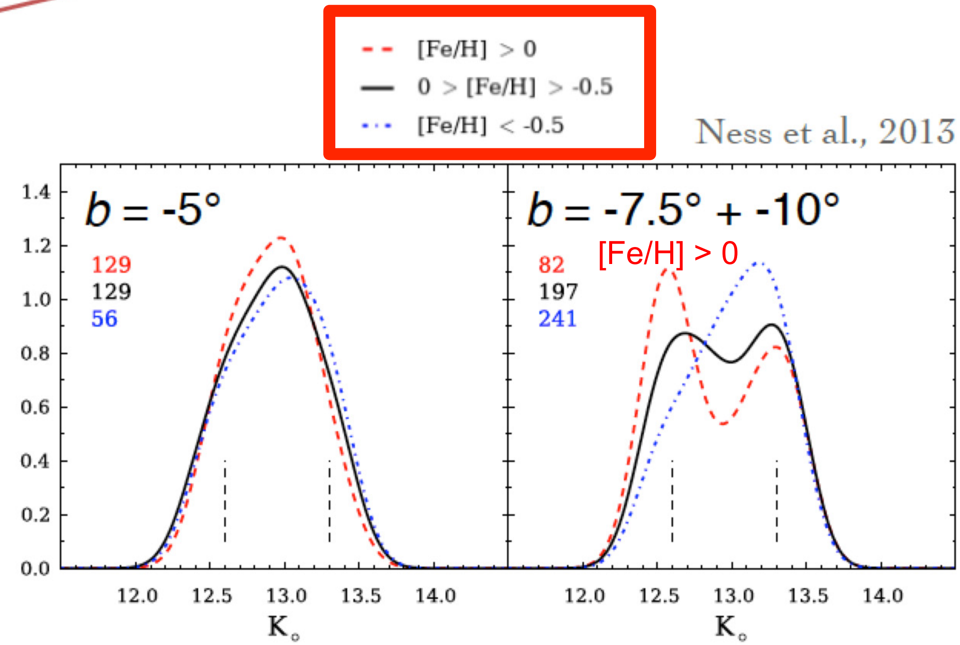
Morphology is metallicity dependent

Jonathan Bird talk (also work by Melissa Ness)



ARGOS Survey: 28,000 star survey of bulge R~ 10,000

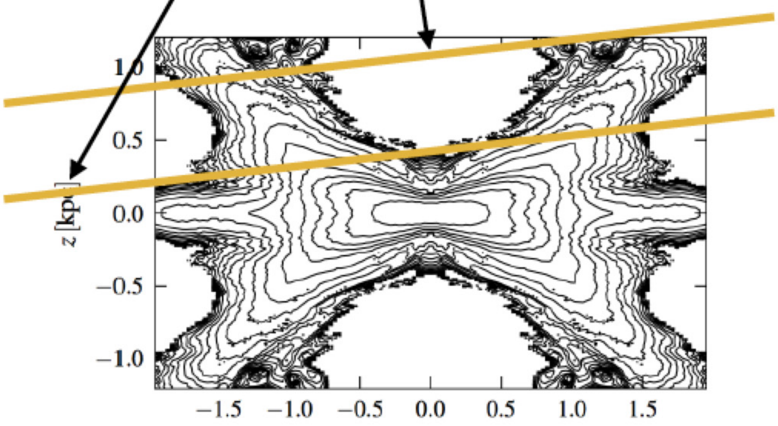
K-magnitude distribution of red clump stars ∫[Fe/H]



Ness et al., 2013

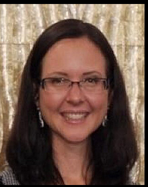
Bimodality for stars [Fe/H] > -0.5

Only the stars with [Fe/H] > -0.5 are part of the boxy/peanut



Portail et al., (2015)

This is an unsharp-masked projected density distribution of red-clump giant stars (i. e., residuals from ellipse fit: Wegg & Gerhard 2013).



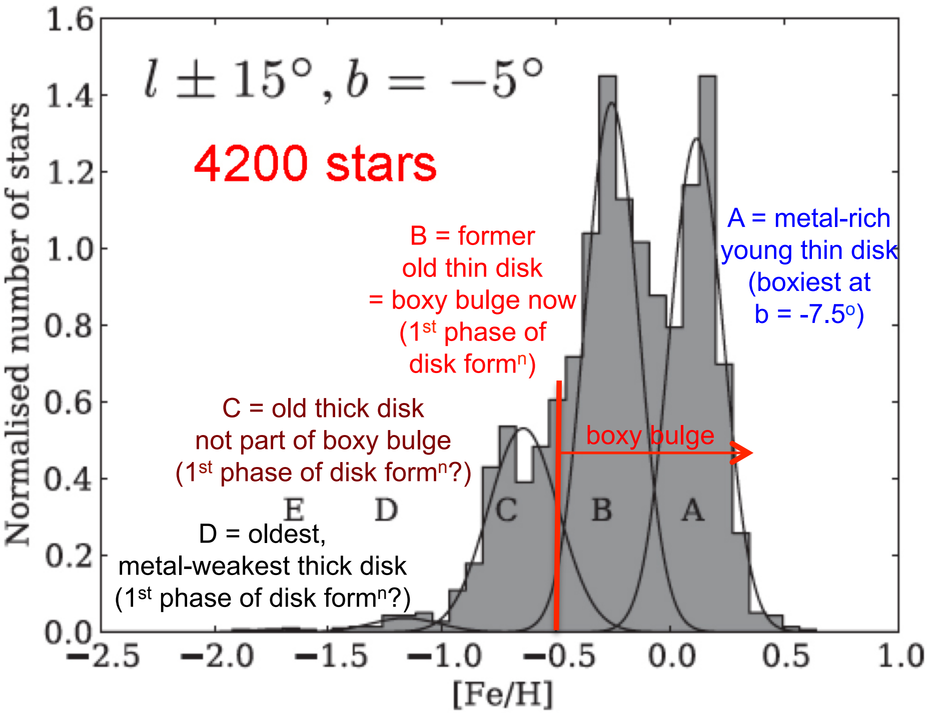
ARGOS Survey (Freeman et al. 2013, MNRAS, 428, 3660)

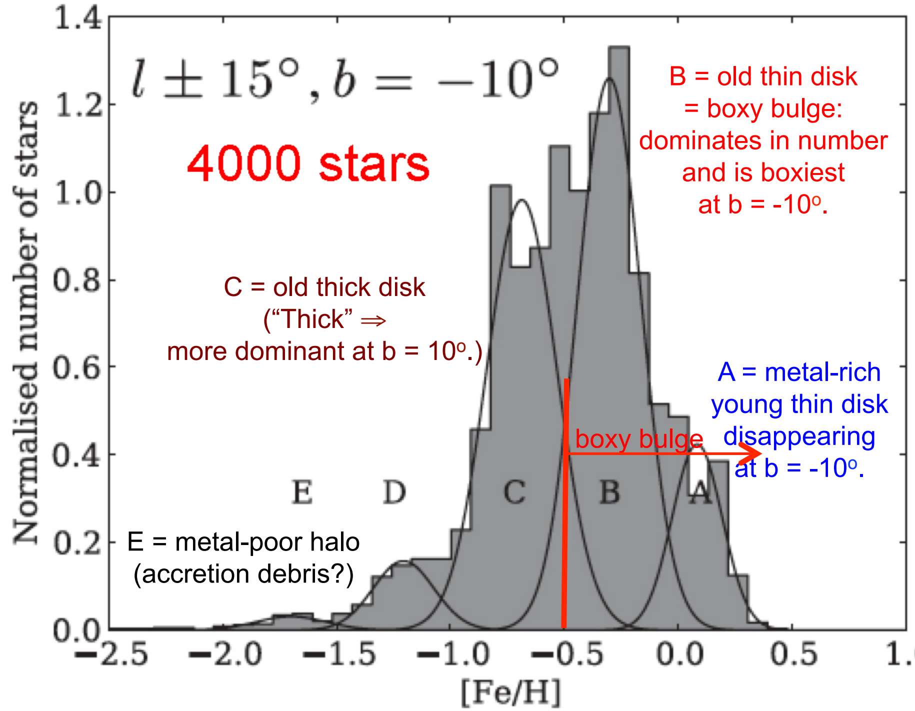
got R ≈ 11,000 AAT spectra of 28,000 stars in the bulge and inner disk at latitudes b = -5° to -10°

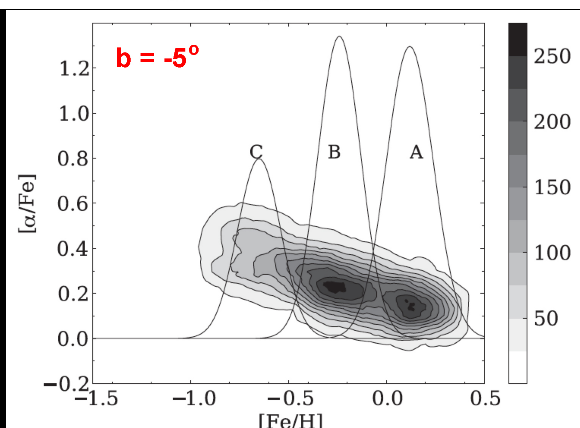
➔ abundances & distances (±1.5 kpc) to ~ 14,000 red giant stars within 3.5 kpc of Galactic Center.

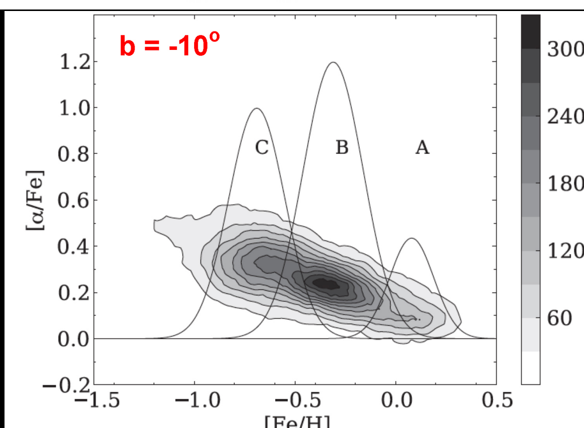
Metallicity Distribution Functions show 5 components at R ≤ 3.5 kpc:

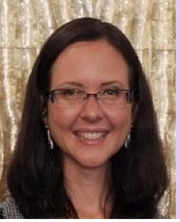
Ness et al. 2013, MNRAS, 430, 836





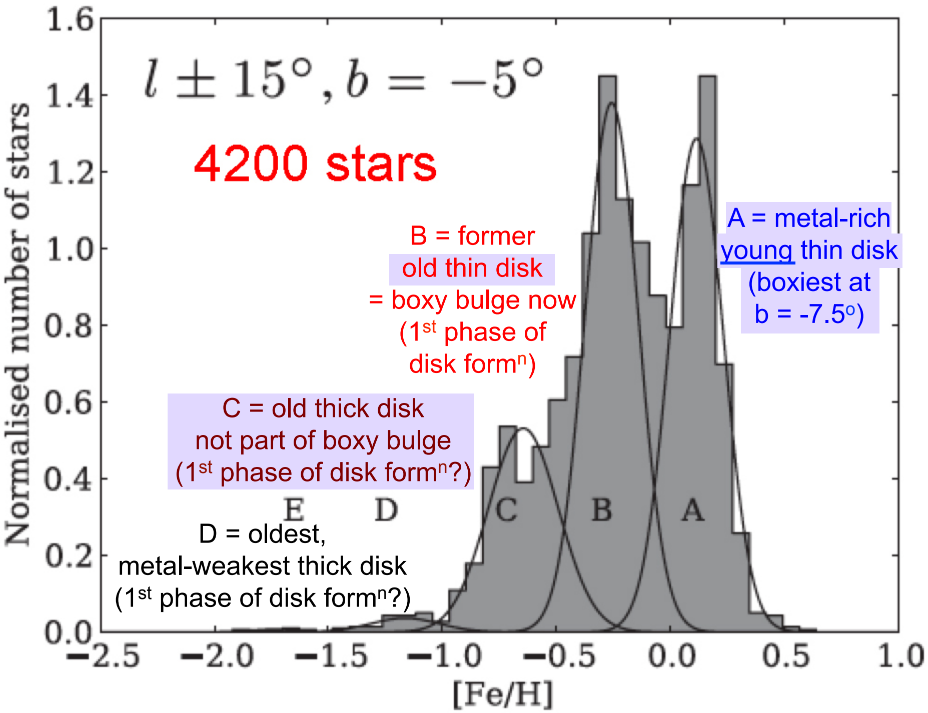


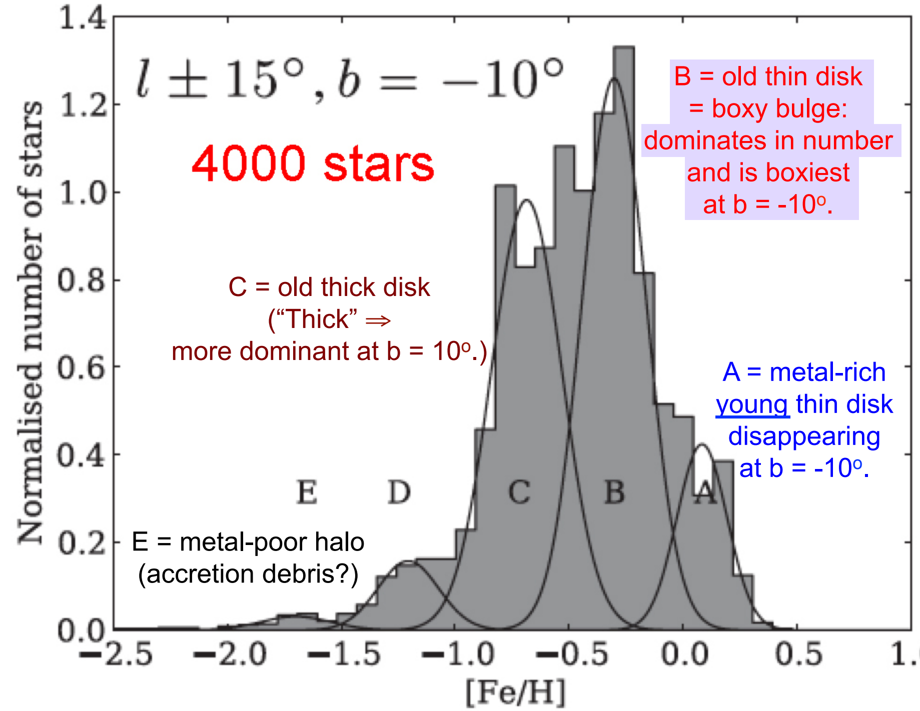


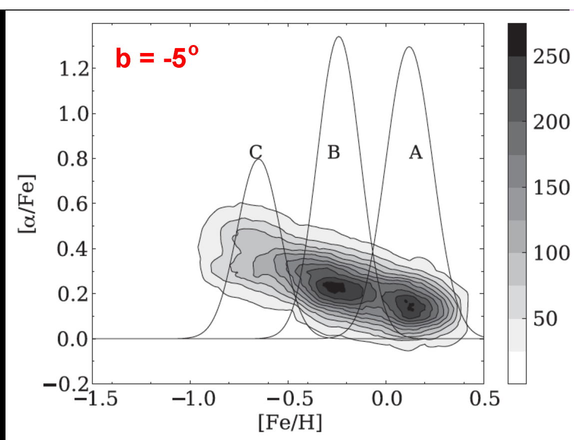


Tension ?

Ness et al. 2013, MNRAS, 430, 836







Is there tension between these results and the 2-phase formation picture in previous slides?

Why is A = "thin disk" part of the box?
That is, how can bar buckling have happened at z > 2
when all components were thick because gas σ was high?
Comp. A stars are younger than rest of bar? Did it entrain (heat) them?

Why did C = "old thick disk" not participate in buckling when
Debattista et al. 2016 find that radially-hottest stars buckle the most?

Is the contact with the 2-phase disk formation picture OK?

Emphasize: The boxy pseudobulge is not all old: Component A is relatively young (age ~ 5 to 8 Gyr), consistent with pseudobulge picture (Bensby et al. 2017, arXiv:1702.02971)

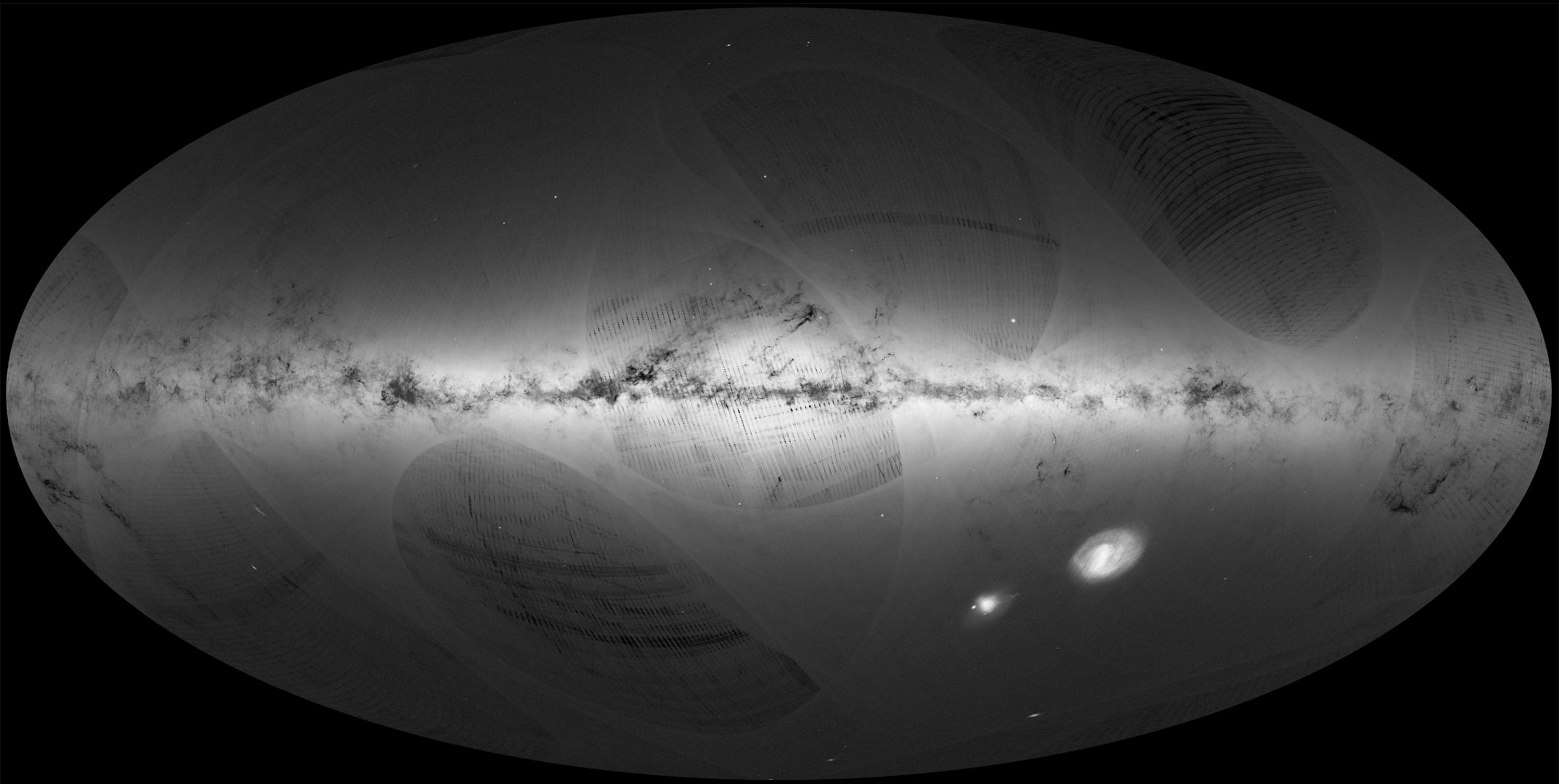
11.2. The age distribution of the Milky Way bulge *Bensby+17*

The Galactic bulge has for a long time been viewed as a genuinely old, if not the oldest, stellar population of the Milky Way. The main piece of observational evidence has been the observed red colours of the turn-off in the colour-magnitude diagrams (e.g. Terndrup 1988; Renzini 1994; Kuijken & Rich 2002; Zoccali et al. 2003; Clarkson et al. 2008; Valenti et al. 2013; Gennaro et al. 2015). As demonstrated in Bensby et al. (2013) an old turn-off will be apparent if metallicity information for the stars are lacking; old and metal-poor isochrones (10-12 Gyr and [Fe/H] ≈ -1) and intermediate-age and metal-rich isochrones (4-5 Gyr and [Fe/H] > 0) are essentially indistinguishable from each other (see also Haywood et al. 2016), and therefore the whole population will be estimated to be old. With the advent of the possibility of determining ages of individual stars in the bulge from the spectroscopic observations of microlensed dwarf, turn-off, and subgiant stars, we have seen that the bulge is not a genuinely old stellar population. While it appears to be so at metallicities below [Fe/H] ≤ -0.5, at higher metallicities there is a wide range of ages, and at super-solar metallicities the young to intermediate age stars actually seem to be in majority.

Thomas Bensby

Entrained from thin disk after bar buckling?

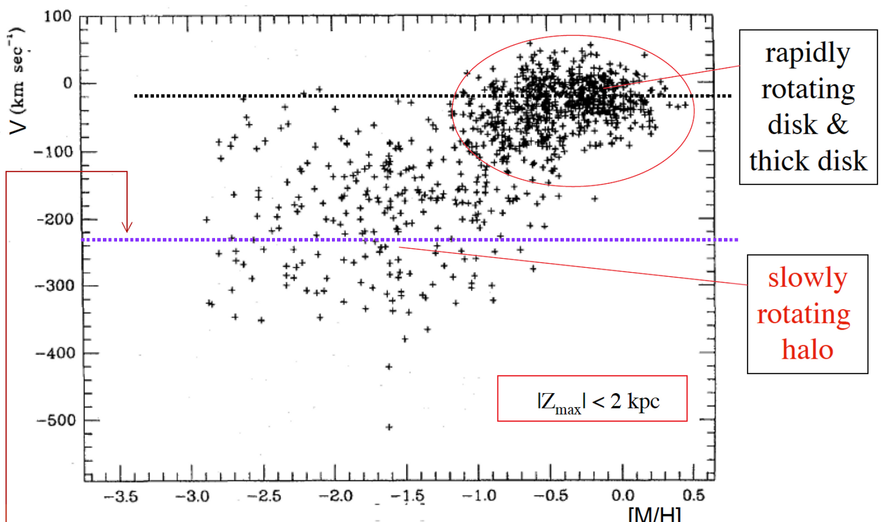
We will soon know a lot more: Gaia Data Release 1 happened during the Paris conference



Stellar halo:

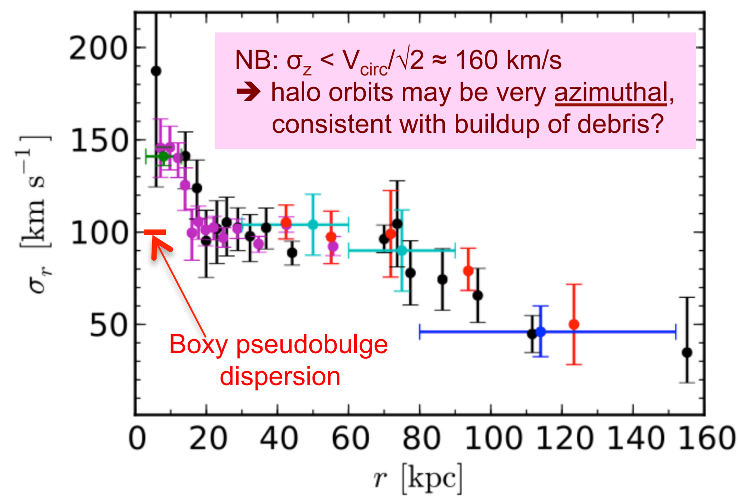
- Stars are metal-poor, with [Fe/H] from < -5 to -0.5. Only 1% of stellar mass of the MW.

- probably built up mainly from accreted small galaxies. Long dynamical time: see unmixed substructure on many scales : substructure makes up about half of the stellar halo mass.



Rotational velocity of nearby stars relative to the sun vs [M/H]
(V = -232 km/s is zero angular momentum)

(Carney et al 1990)



Velocity dispersion of MW stellar halo: metal-poor stars, GCs, satellites

- halo is supported mainly by its velocity dispersion : σ_R = 140 km/s near sun, dropping to < 50 km/s at R ~ 150 kpc. σ(R) and kinematics of halo streams are useful tracers of the total potential of the Galaxy

Bland-Hawthorn & Gerhard 2016

The metal-poor halo is mostly or entirely made of accretion debris. Witness: Stellar streams

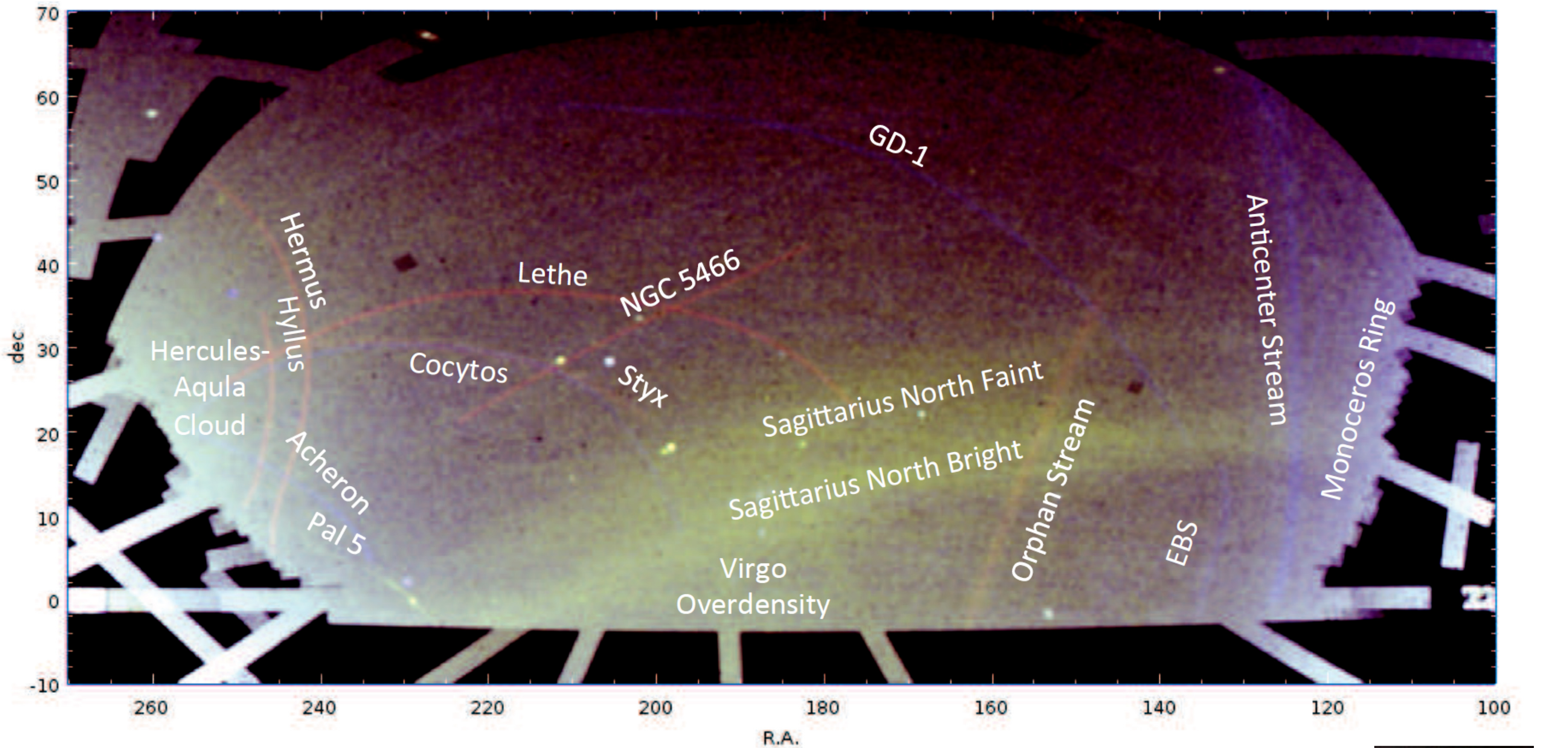


Fig. 1 A matched-filter surface density map of the northern footprint of the Sloan Digital Sky Survey. The filter used here is based on … itude distribution of the metal poor globular cluster M 13. The stretch is logarithmic and all but the Sagittarius streams have been enhanced us… caled Gaussians to make them visible at this stretch. Bluer colors correspond to more nearby stars (≤ 15 kpc) while redder colors reflect the distrib… istant stars.

Carlos Frenk suggested that we will be able
to differentiate between WDM and CDM
by looking for gaps in stellar streams that are produced only by
large numbers of small CDM halos. Present data appear to show no signs of such gaps.
The people who I talked with on this subject were skeptical that it would work.

The Gas Halo of our Milky Way

People at the Paris meeting were starting to become (still dimly!) aware of the gas halo:

Bland-Hawthorn & Gerhard 2016 estimate that
mass in cold gas = $0.7 \times 10^{10}\ M_{\odot}$;
mass in hot gas = $2.5 \times 10^{10}\ M_{\odot}$ (cf. thin disk stars = $4 \times 10^{10}\ M_{\odot}$);
Galactic baryon fraction ≈ 7 ± 1 % << Cosmic 17 %.

But: We are starting to see the hot gas in absorption against quasars, in soft X-ray background, in pulsar dispersion measures, and via ram-pressure stripping of dwarf galaxies at R < 250 kpc. Some of this gas may be cooling (helped by colder high-velocity clouds) and raining down onto the Milky Way disk.

Accreted gas is likely to be a combination of “pristine” gas from the cosmic hierarchy and recycled, metal-rich gas from a Galactic fountain.

Evidence of gas accretion?

Lehner et al. 2013

THE ASTROPHYSICAL JOURNAL, 770:138 (32pp), 2013 June 20 LEHNER ET AL.

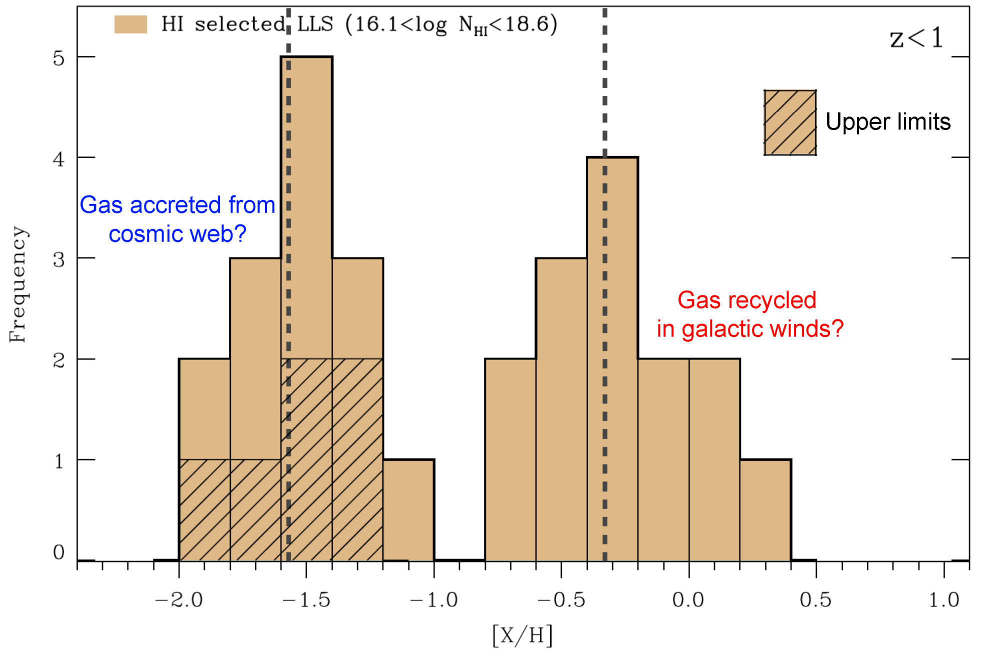
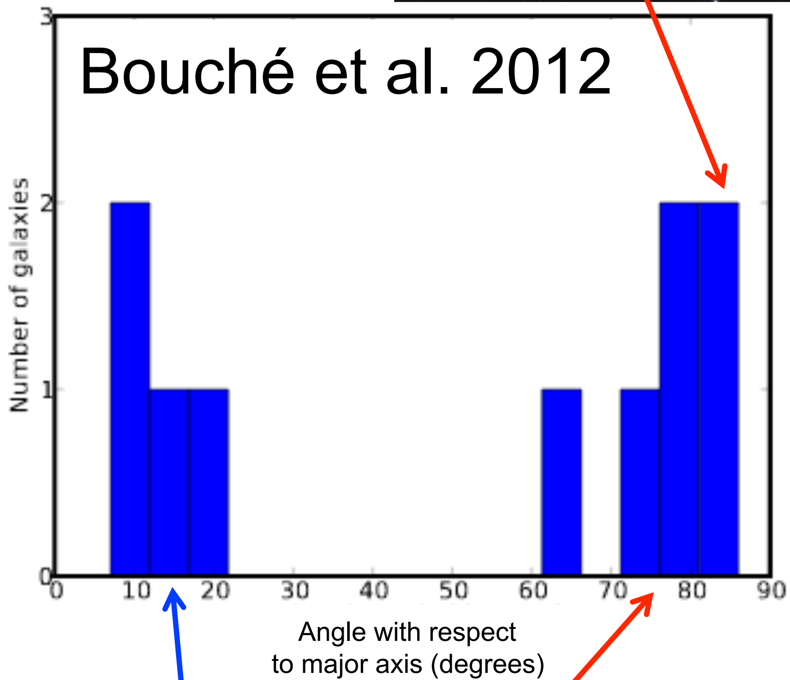


Figure 3. Metallicity distribution function of the LLS at $z \lesssim 1$. The hashed histograms highlight values that are upper limits. The metallicity distribution is bimodal where the peak values are shown by the vertical dotted lines. For the LLS with [X/H] $\leqslant -1$, the mean metallicity is an upper limit as 6/14 of the [X/H] estimates are upper limits.

X = O, Si, Mg, … measured in absorption against background quasars by HST COS in 28 Lyman limit systems (LLS) with z ~ 0.1 to 1.

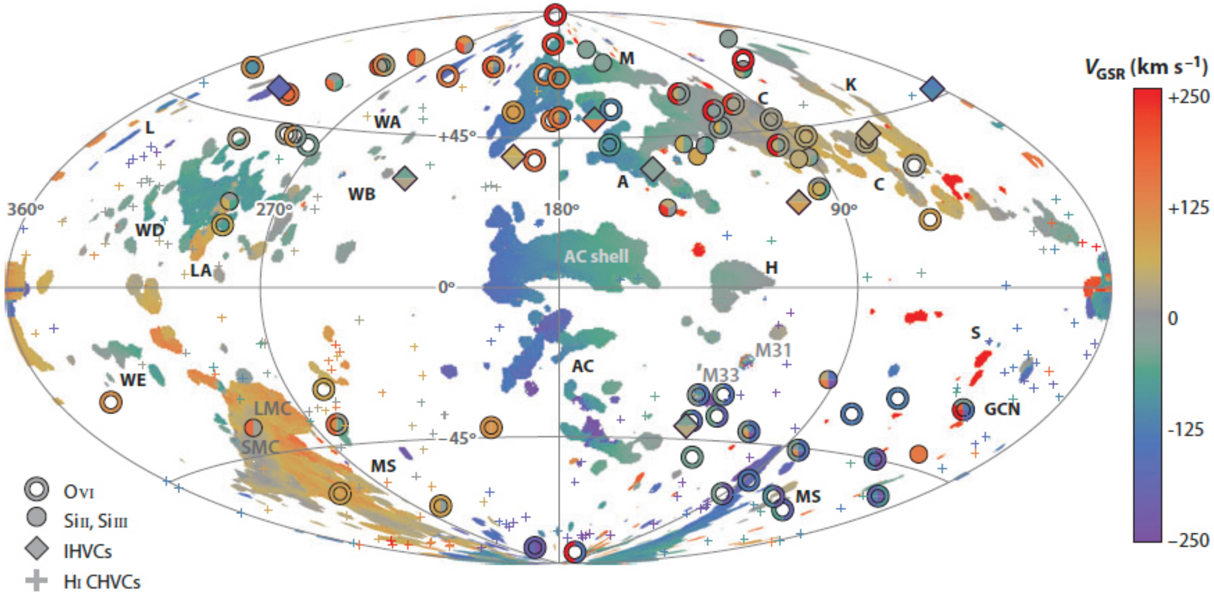


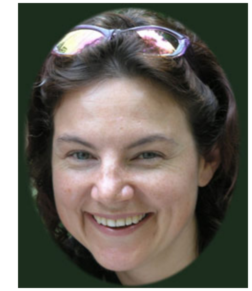
Inflow or outflow may be distinguished by the angle.

"Holy grail" of this subject:

Does low [X/H] correspond to Angle ~ 0^o and high [X/H] to Angle ~ 90^o?

Mary Putman et al. 2012, ARA&A, 50, 491





Technical problem: the distances of the clouds is measured only by their absorption against any background stars.

Nobody knows how much gas is being accreted:

Important: MW-like galaxies must accrete ~ 1 $M_\odot$ / yr
(1) to maintain SFR and
(2) to stay cold enough for spiral density waves.

Filippo Fraternali talk: only 0.1 $M_\odot$ / yr is being accreted.

Maybe this + hot halo is why Galaxy is “green valley”?

Bland-Hawthorn & Gerhard 2016: MW and 3500 MW analogs with same SFR and stellar mass (SDSS).

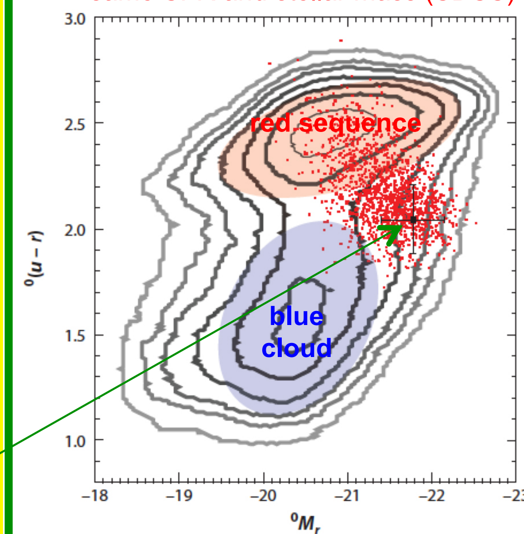


Figure 2

The distribution of H I (*shaded clouds and plus symbols*) and ionized high-velocity gas (*circles and diamonds*) on the sky with color denoting the Galactic-standard-of-rest (GSR) velocity of the detection. Otherwise this figure is the same as **Figure 1**, with the exception of showing the view from the North (*left*) and South (*right*) Galactic Poles at the bottom. Abbreviation: IHVC, ionized high-velocity cloud.

People at the Paris meeting completely forgot Davé et al. 2001, ApJ, 552, 473 !

BARYONS IN THE WARM-HOT INTERGALACTIC MEDIUM

ROMEEL DAVÉ
RENYUE CEN AND JEREMIAH P. OSTRIKER
GREG L. BRYAN
LARS HERNQUIST
NEAL KATZ
DAVID H. WEINBERG
AND
MICHAEL L. NORMAN AND BRIAN O'SHEA

THE ASTROPHYSICAL JOURNAL, 552:473–483, 2001 May 10

ABSTRACT

Approximately 30%–40% of all baryons in the present-day universe reside in a warm-hot intergalactic medium (WHIM), with temperatures in the range $10^5 < T < 10^7$ K. This is a generic prediction from six hydrodynamic simulations of currently favored structure formation models having a wide variety of numerical methods, input physics, volumes, and spatial resolutions. Most of these warm-hot baryons reside in diffuse large-scale structures with a median overdensity around 10–30, not in virialized objects such as galaxy groups or galactic halos. The evolution of the WHIM is primarily driven by shock heating from gravitational perturbations breaking on mildly nonlinear, nonequilibrium structures such as filaments. Supernova feedback energy and radiative cooling play lesser roles in its evolution. WHIM gas may be consistent with observations of the 0.25 keV X-ray background without being significantly heated by nongravitational processes because the emitting gas is very diffuse. Our results confirm and extend previous work by Cen & Ostriker and Davé et al.

These hydrodynamic simulations of structure formation indicate that baryons in the universe reside in four broad phases, defined by their overdensity $\delta \equiv \rho/\bar{\rho} - 1$ (where $\bar{\rho}$ is the mean baryonic density) and temperature T:

1. *Diffuse*: $\delta < 1000$, $T < 10^5$ K. Photoionized intergalactic gas that gives rise to Lyman alpha absorption.
2. *Condensed*: $\delta > 1000$, $T < 10^5$ K. Stars and cool galactic gas.
3. *Hot*: $T > 10^7$ K. Gas in galaxy clusters and large groups.
4. *Warm-hot*: $10^5 < T < 10^7$ K. The "warm-hot intergalactic medium" (WHIM), discussed here.

About 1/3 of the baryons in the local Universe are thought to be in the WHIM – in cosmic filaments of gas that are far away from visible galaxies.

Davé et al. 2001, ApJ, 552, 473

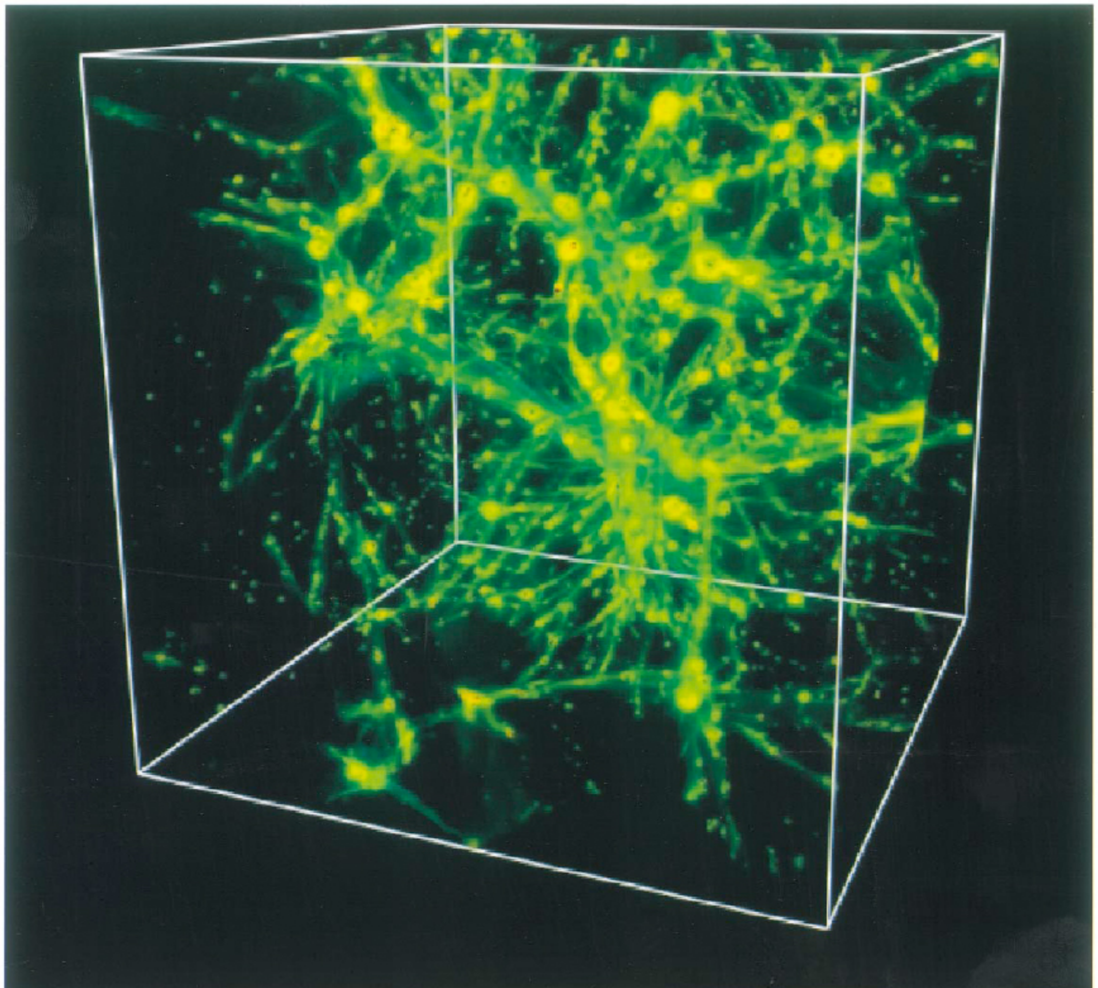


FIG. 3.—WHIM gas in simulation C2. Contours are color-coded by overdensity; green represents overdensity $\delta \sim 10$, while red shows $\delta \sim 10^4$.

6. SUMMARY

We study the warm-hot intergalactic medium (WHIM), defined as all the gas in the universe with temperature $10^5 < T < 10^7$ K, in six cosmological hydrodynamic simulations with widely varying spatial resolutions, volumes, code algorithms, and input physics. In each simulation, the WHIM contains ≈30–40% of all baryons in the present-day universe. As a rule of thumb, our simulations predict that the fractions of baryons in the warm-hot phase, the diffuse phase, and gravitationally bound systems are roughly comparable at the present epoch.

Our simulations predict that the majority of WHIM gas is far away from galaxies and clusters, residing in the diffuse IGM. A promising avenue to detect this more typical WHIM gas is via absorption, as continuing observations with STIS aboard the *Hubble Space Telescope* will detect many more O VI absorbers.

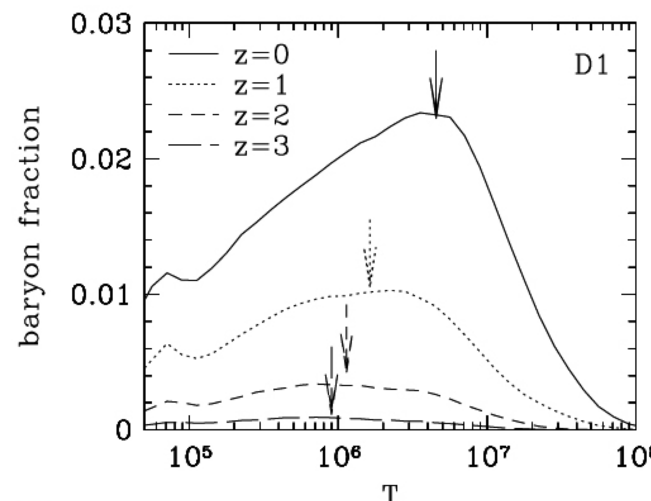


FIG. 5.—Mass fraction of baryons as a function of temperature in simulation D1, at $z = 0$ (*solid line*), $z = 1$ (*dotted line*), $z = 2$ (*short-dashed line*), and $z = 3$ (*long-dashed line*). The arrows indicate the predicted peak temperature from gravitational shock heating at various z, from eq. (2).

Kravtsov & Borgani 2012, ARA&A, 50, 353

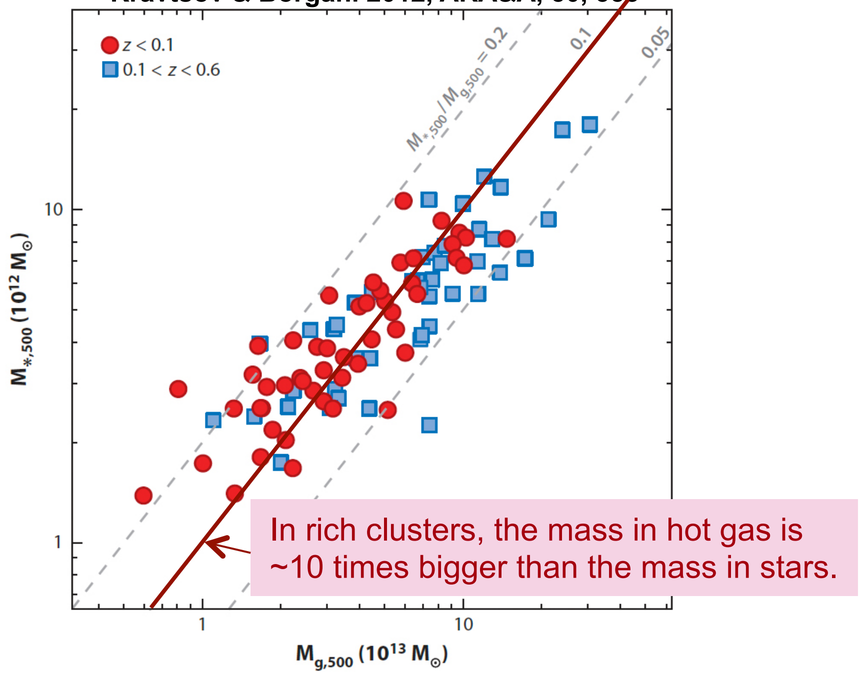


Figure 2

The mass in stars versus the mass of hot, X-ray emitting gas. Both masses are measured within the radius R_{500} estimated from the observationally calibrated $Y_X - M_{500}$ relation, assuming flat ΛCDM cosmology with $\Omega_m = 1 - \Omega_\Lambda = 0.26$ and $h = 0.71$. Red circles show local clusters located at $z < 0.1$, whereas blue squares show higher redshift clusters: $0.1 < z < 0.6$ (see Lin et al. 2012 for details). The dotted line corresponds to the constant stellar-to-gas mass ratio $M_{*,500}/M_{g,500} = 0.1$, whereas the dashed lines correspond to the values of 0.05 and 0.2 for this ratio.

Dai, Bregman, Kochanek, & Rasia 2010, ApJ, 719, 119

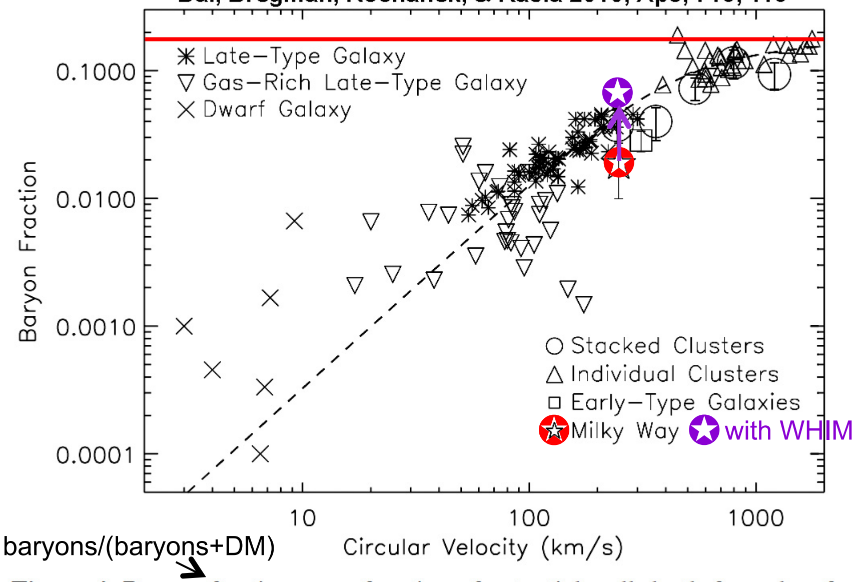
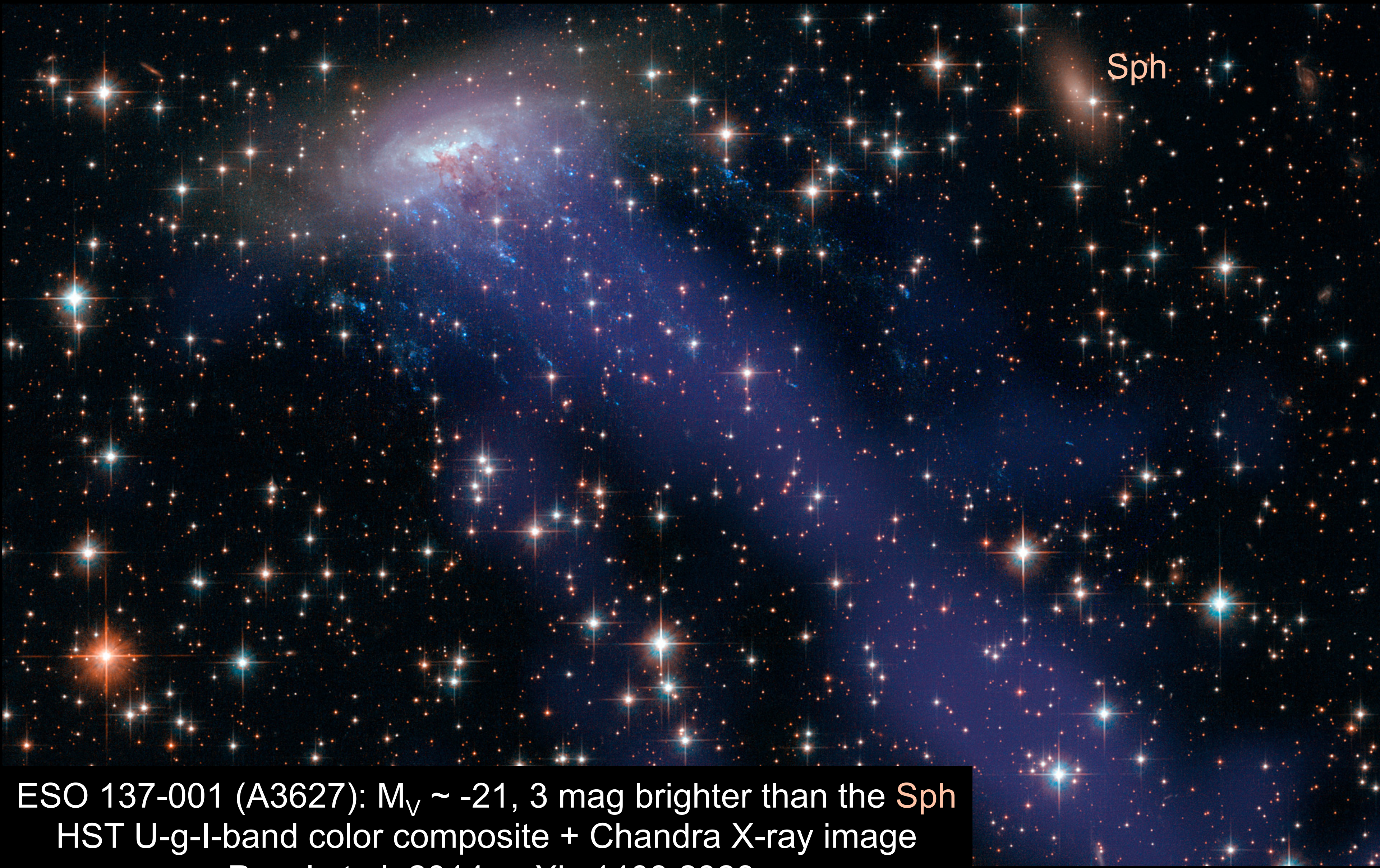


Figure 4. Baryon fractions as a function of potential well depth from dwarf galaxies to rich clusters. The circles are our stacked groups and clusters, the triangles are individual groups and clusters (Vikhlinin et al. 2006; Sun et al. 2009), the square is the ensemble of early-type lens galaxies (Gavazzi et al. 2007), asterisks are late-type galaxies (McGaugh 2005), upside-down triangles are gas-rich, late-type galaxies (Stark et al. 2009), crosses are dwarf galaxies (Walker et al. 2007), and the five-angle star is the Milky Way (Sakamoto et al. 2003; Flynn et al. 2006). The red line is the cosmic baryon fraction. The data points can be fit by a broken power-law model (dashed line) with the break at $V_c \sim 440$ km s^{-1}. The scatter of the data points around the mean relation is relatively small, which indicates that baryon fractions are largely set by the depths of a system's potential well.

Take-home message:

Probably no baryons are “missing” – they are just hard to see (especially in WHIM).

Ram-pressure stripping of cold gas by hot gas is more important than we thought.



ESO 137-001 (A3627): $M_V \sim -21$, 3 mag brighter than the Sph
HST U-g-I-band color composite + Chandra X-ray image
Pavel et al. 2014, arXiv:1403.2328

VIRGO GALAXIES WITH LONG ONE-SIDED H I TAILS

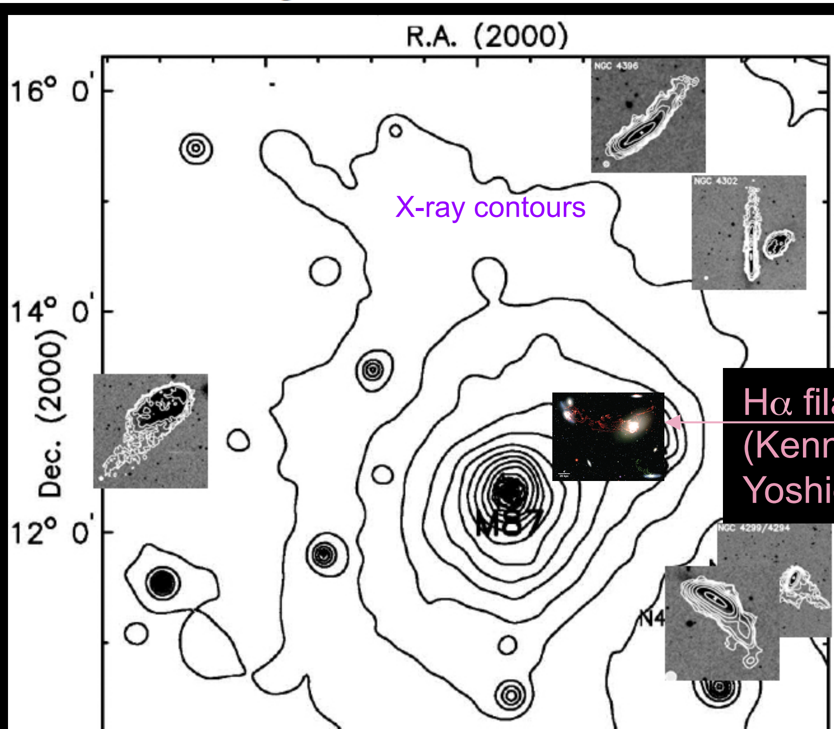
AEREE CHUNG, J. H. VAN GORKOM, JEFFREY D. P. KENNEY, AND BERND VOLLMER

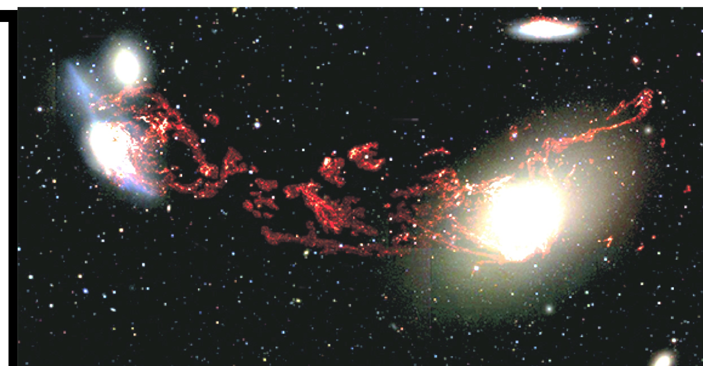
THE ASTROPHYSICAL JOURNAL, 659:L115–L119, 2007 April 20

ABSTRACT

In a new H I imaging survey of Virgo galaxies (VIVA: VLA Imaging of Virgo galaxies in Atomic gas), we find seven spiral galaxies with long H I tails. The morphology varies, but all the tails are extended well beyond the optical radii on one side. These galaxies are found in intermediate- to low-density regions (0.6–1 Mpc in projection from M87). The tails are all pointing roughly away from M87, suggesting that these tails may have been created by a global cluster mechanism. While the tidal effects of the cluster potential are too small, a rough estimate suggests that simple ram pressure stripping could have indeed formed the tails in all but two cases.

We conclude that these one-sided H I tail galaxies have recently arrived in the cluster, falling in on highly radial orbits. It appears that galaxies begin to lose their gas already at intermediate distances from the cluster center through ram pressure or turbulent viscous stripping and tidal interactions with their neighbors, or a combination of both.

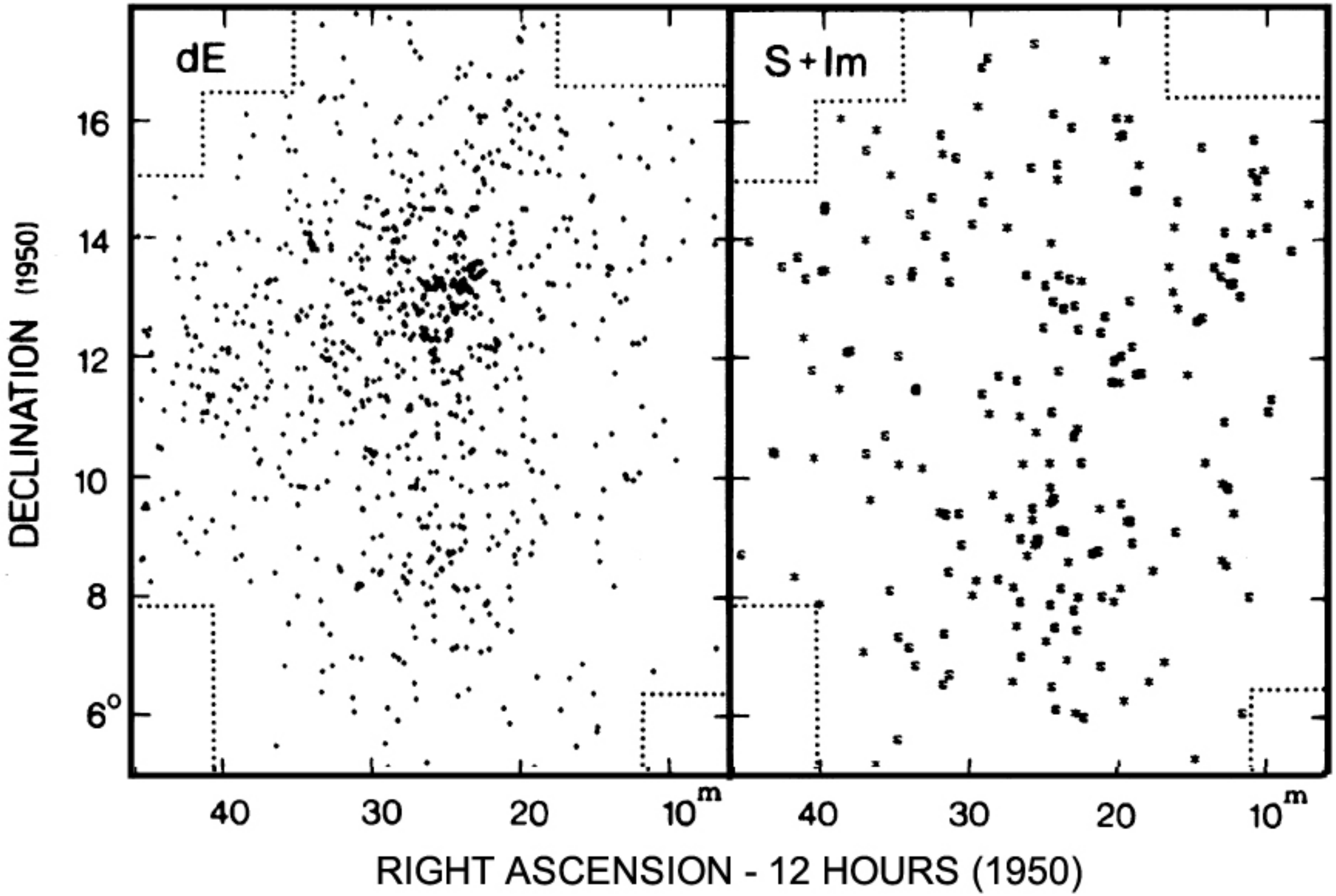




Hα filaments trail behind NGC 4438 & NGC 4388
(Kenney + 2008, ApJ, 687, L69;
Yoshida + 2004, AJ, 127, 90)

STUDIES OF THE VIRGO CLUSTER. VI. MORPHOLOGICAL AND KINEMATICAL STRUCTURE OF THE VIRGO CLUSTER

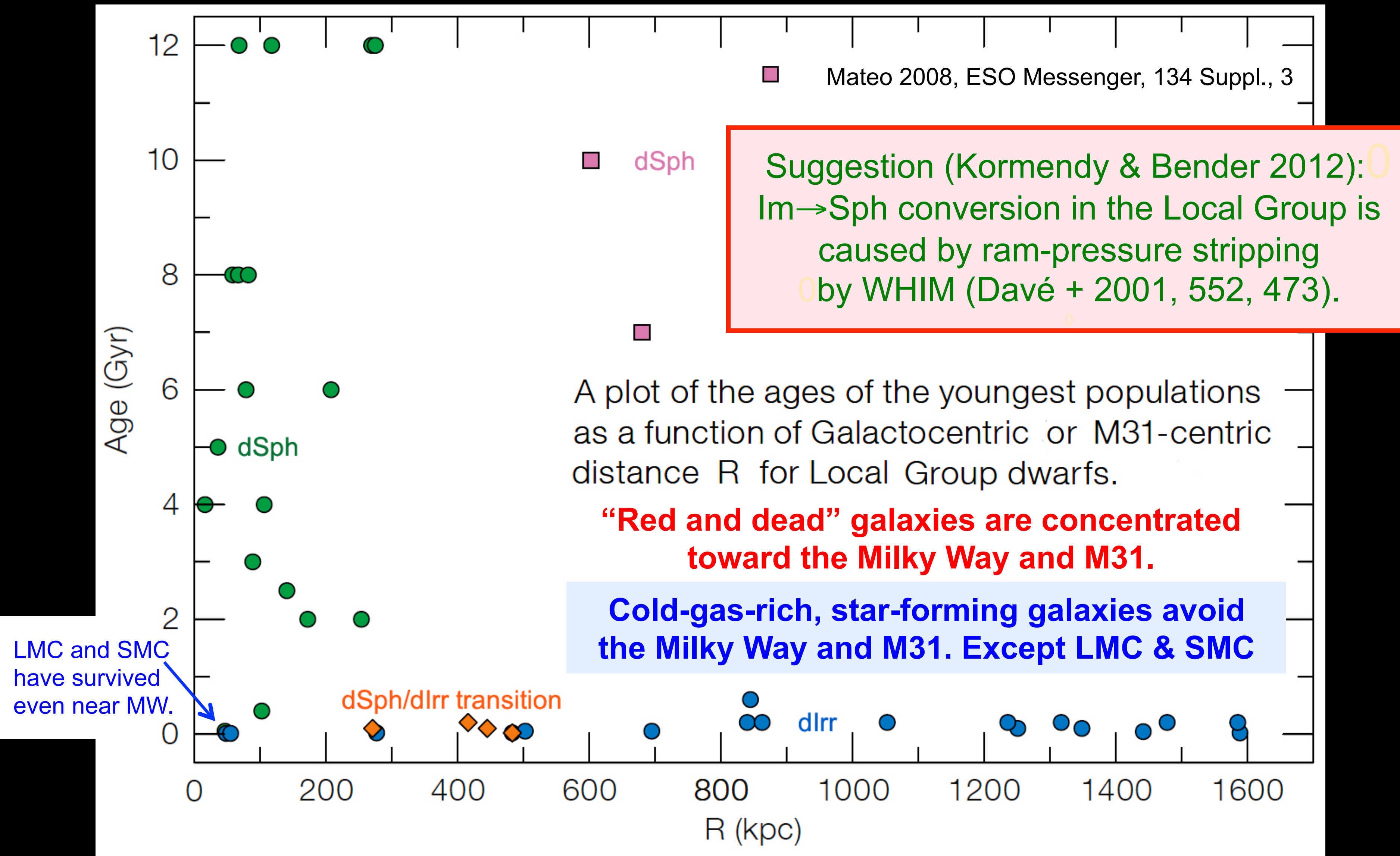
Binggeli, Tammann, & Sandage 1987, AJ, 94, 251



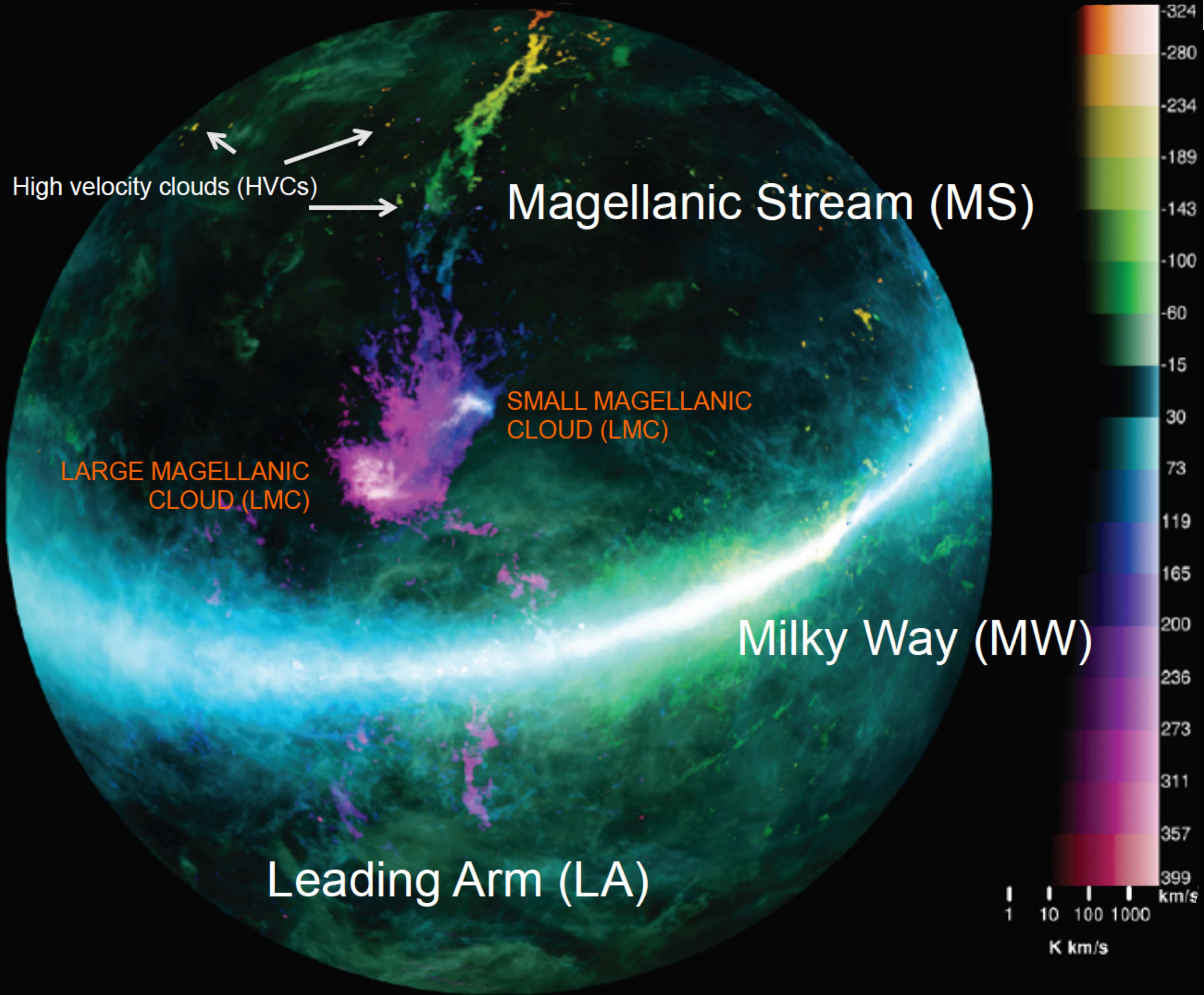
"Red and dead" galaxies are concentrated toward the center of the Virgo cluster.

Cold-gas-rich, star-forming galaxies avoid the center of the Virgo cluster.

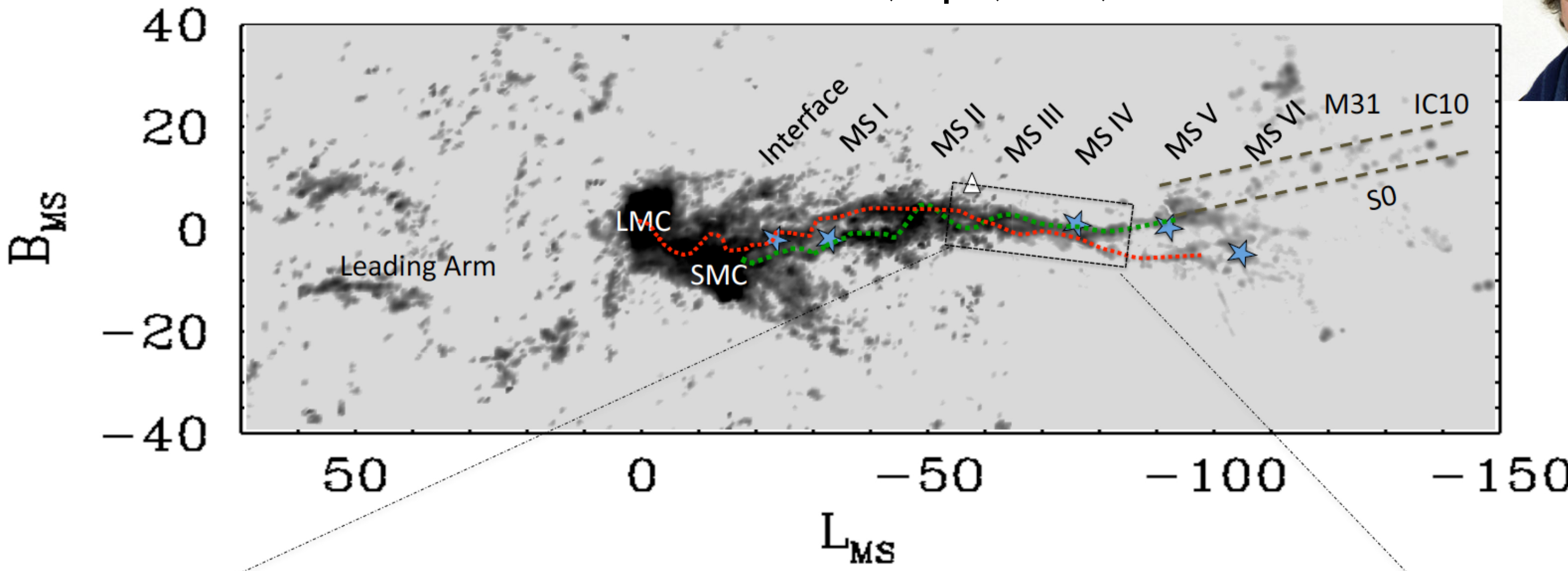
Irr → Sph transformation happens mostly near giant galaxies & in clusters of galaxies.

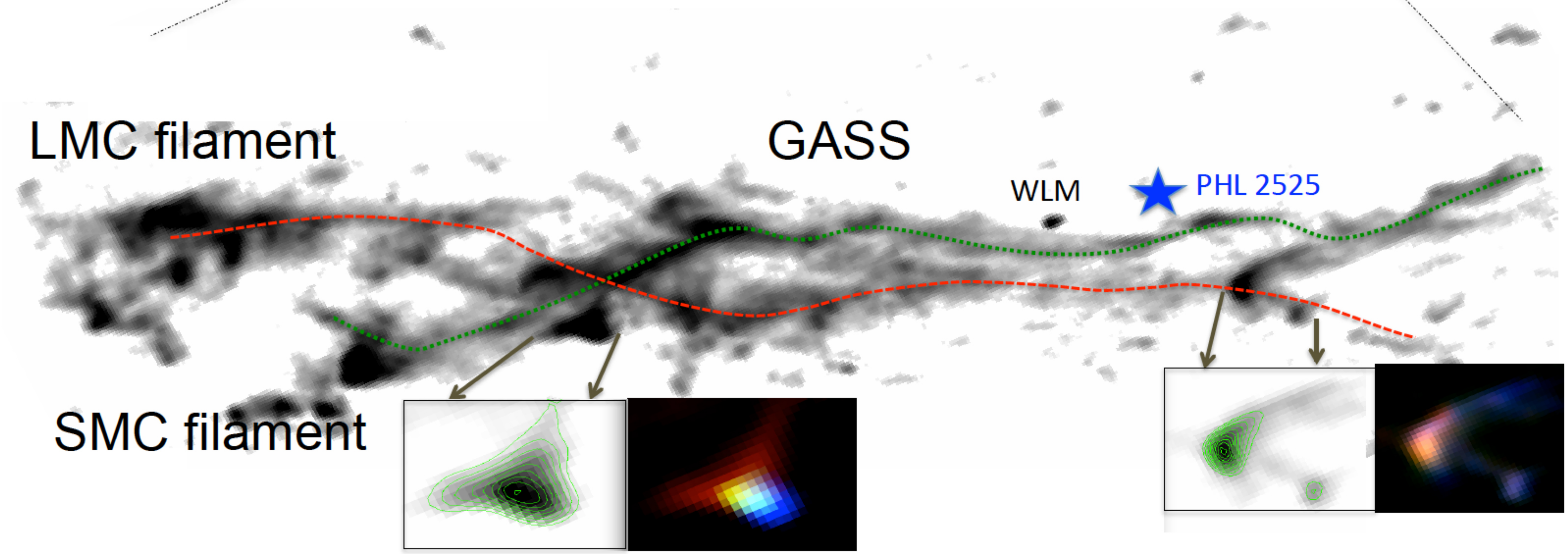


Francois Hammer presented convincing evidence that the Magellanic Clouds are being ram-pressure stripped now to form the Magellanic Stream

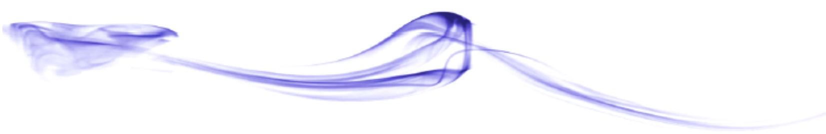


Hammer et al. 2015, ApJ, 813, 110

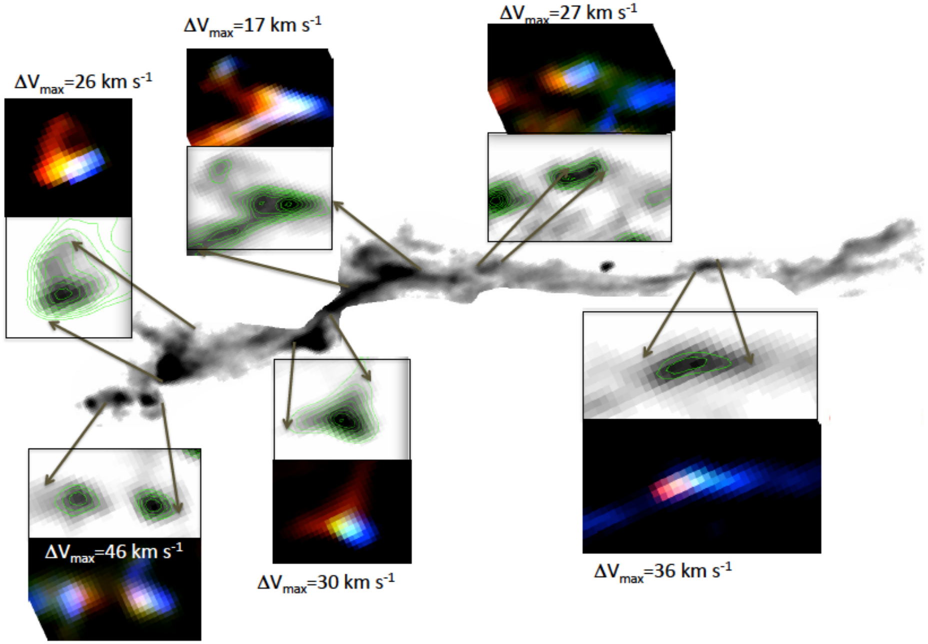


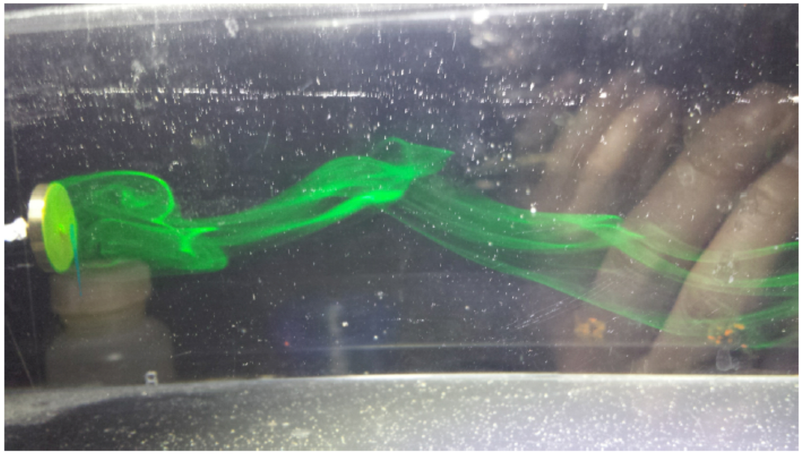


Similar behaviour than hydrodynamical flows with similar (Re, Strouhal) numbers, including vortices (or hairpin shedding)



First wake instabilities on a flow, Re=400, Wesfreid et al. 2014





The MW and its environment

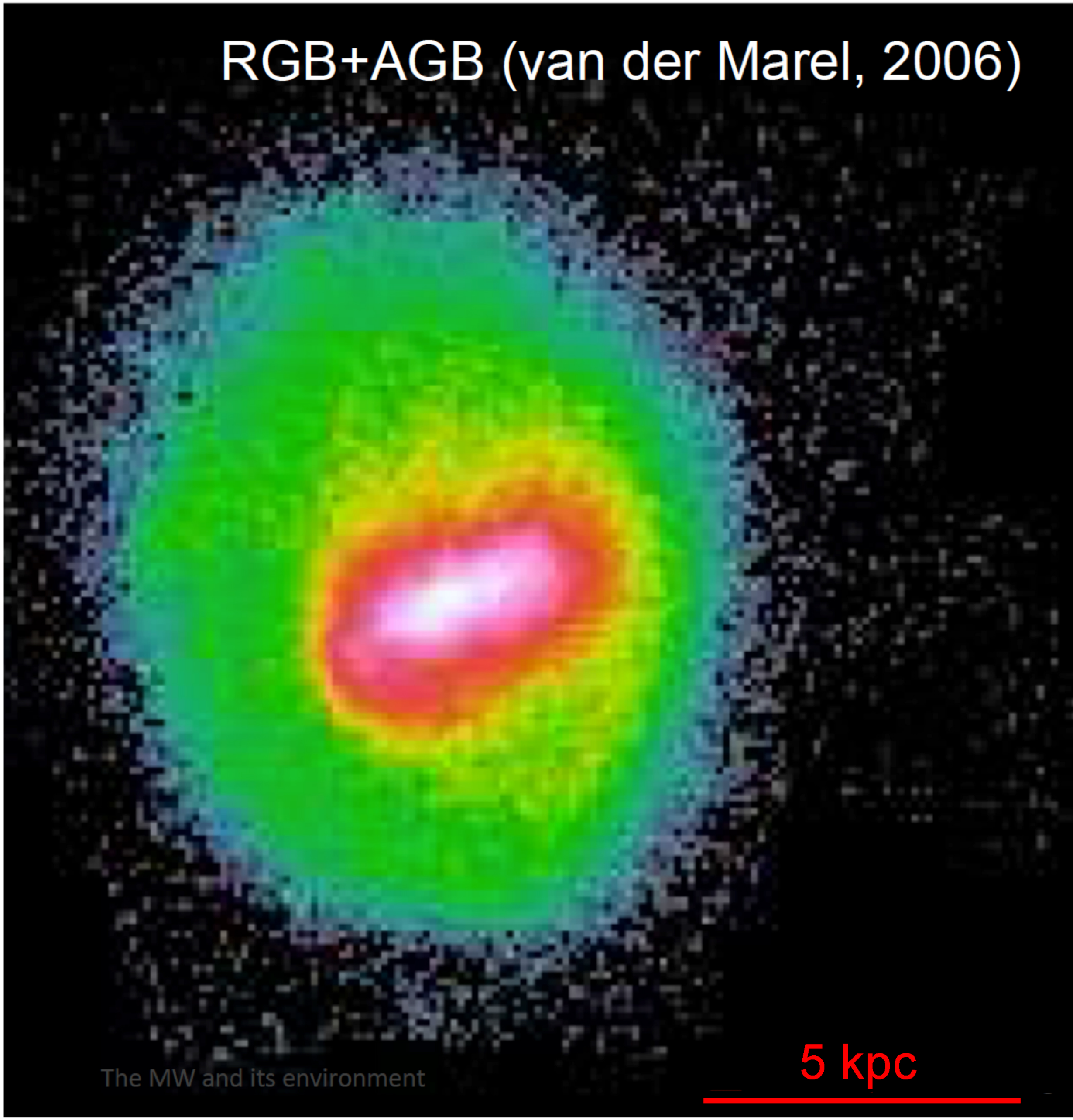
Explanation of the gigantic Magellanic System

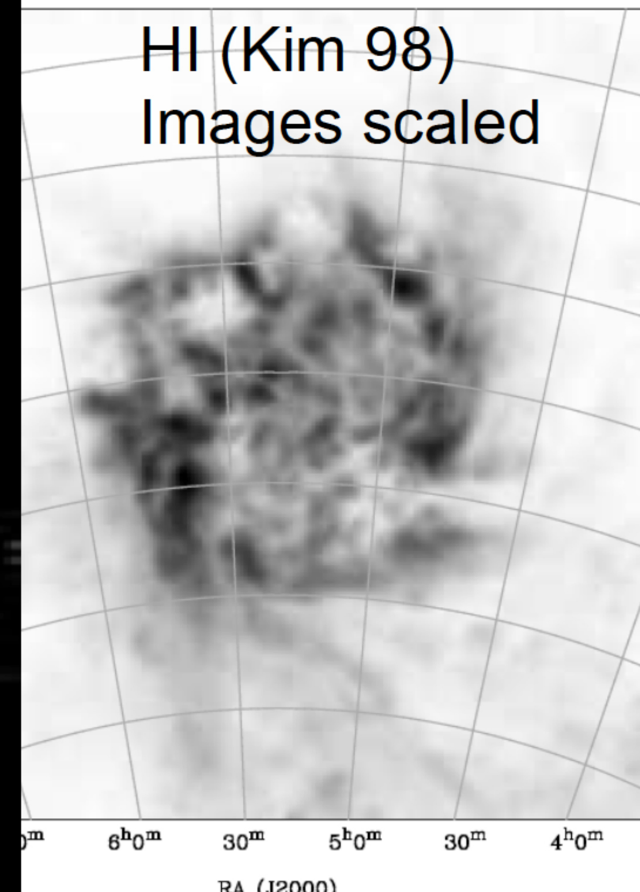
Gas of the Clouds and dSph progenitors stripped by ram-pressure exerted by the hot gas in the Milky Way halo,

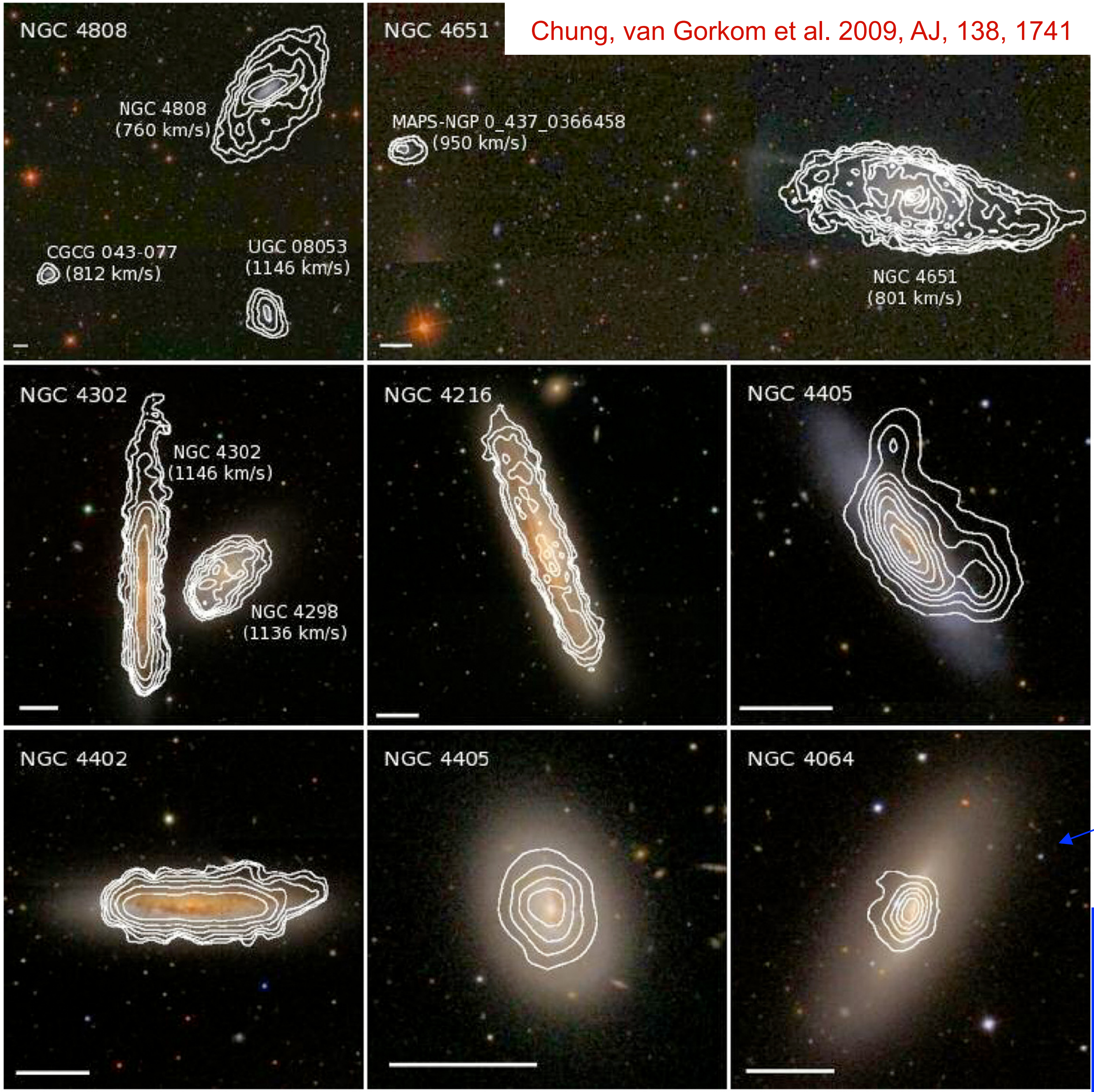
Hydro model including supersonic turbulence reproduces features of the Magellanic Stream.

Ram-pressure stripping explains why the Magellanic Stream does not contain stars.

The unusual properties of the LMC disks







Chung, van Gorkom et al. 2009, AJ, 138, 1741

"We confirm that galaxies near the [Virgo] cluster core have HI disks that are smaller compared to their stellar disks ($D_{HI}/D_{25} < 0.5$).

Most of these galaxies in the [cluster] core also show gas displaced from the disk which is either currently being stripped or falling back after a stripping event."

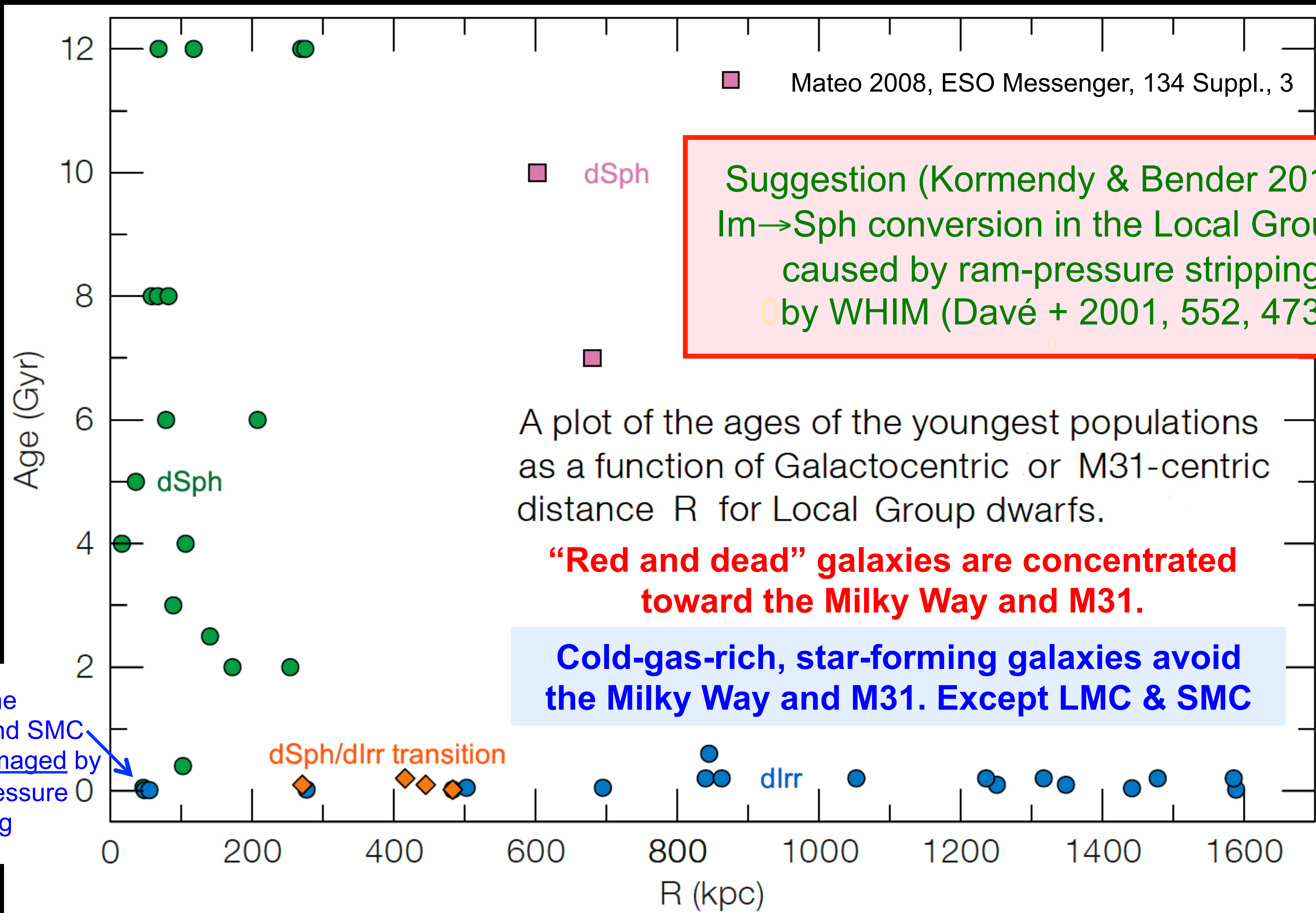
The mean absolute magnitude of NGC 4402, NGC 4405, & NGC 4064 is $M_V = -19.4 \pm 0.2$.

Virgo Sph galaxies are fainter.

If even the deep gravitational potential wells of still-spiral galaxies suffer HI stripping, then the shallow potential wells of dS+Im galaxies are more likely to be stripped.

Figure 8. Examples of the different H I morphologies found in the survey. Total H I images are shown in white contours overlaid on the SDSS images. The thick white bar in the bottom-left corner indicates 1 arcmin in each panel. The top row shows examples of gas-rich galaxies in gas rich environments in the outskirts, the middle row shows galaxies at intermediate distances, while the bottom row shows examples of severely truncated H I disks at a range of projected distances from M87.

Irr → Sph transformation happens mostly near giant galaxies & in clusters of galaxies.



Suggestion (Kormendy & Bender 2012): Im→Sph conversion in the Local Group is caused by ram-pressure stripping by WHIM (Davé + 2001, 552, 473).

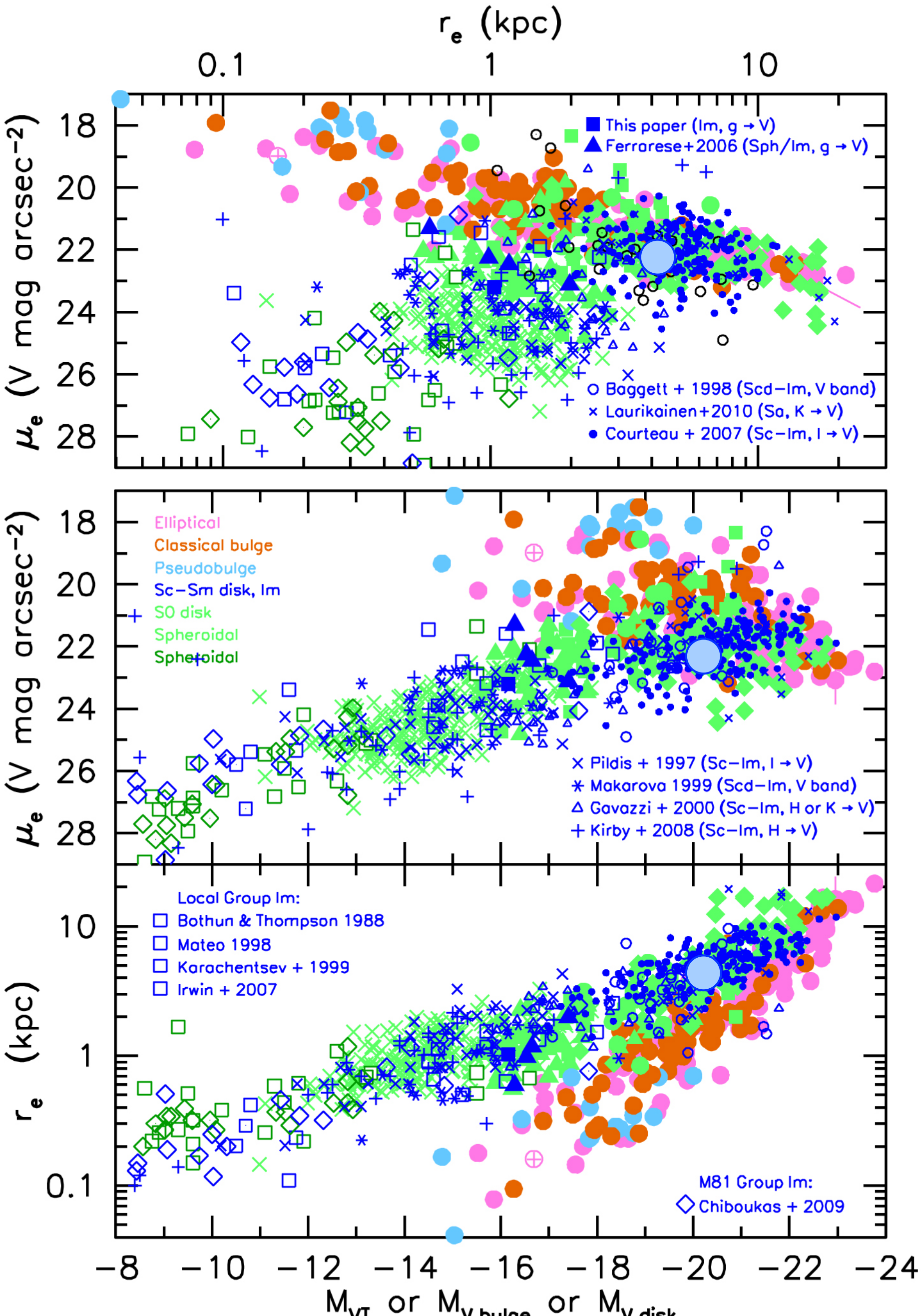
A plot of the ages of the youngest populations as a function of Galactocentric or M31-centric distance R for Local Group dwarfs.

"Red and dead" galaxies are concentrated toward the Milky Way and M31.

Cold-gas-rich, star-forming galaxies avoid the Milky Way and M31. Except LMC & SMC

Even the LMC and SMC are <u>damaged</u> by ram-pressure stripping

The Parameters of our Galaxy's Disk are Normal



Milky Way Long bar + thin disk + thick disk

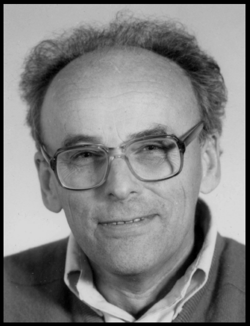
Figure:
Kormendy & Bender 2012, ApJS, 198, 2

Recall: S + Im galaxies have the same structural parameter correlations as S0 disks + Sph galaxies.

This is true at all M_V. E. g., "giant" Sph galaxies in the Local Group are NGC 147, NGC 185, and NGC 205.

This supports our suggestion that Sphs are defunct dS+Im systems.

Revised Parallel Sequence Hubble Classification



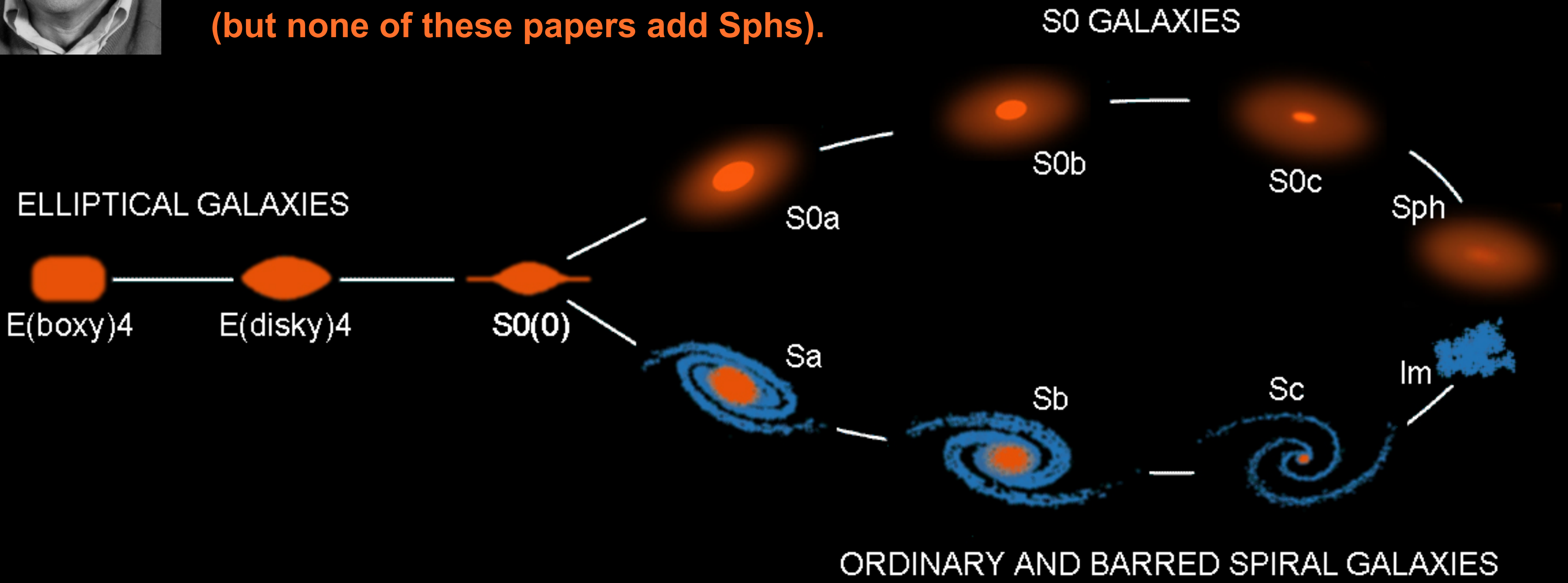
Kormendy & Bender 2012, ApJS, 198, 2;

cf: van den Bergh 1976, ApJ, 206, 883;

Laurikainen et al. 2010, MNRAS, 405, 1089;

Cappellari et al. 2011, MNRAS, 416, 1680

(but none of these papers add Sphs).



Many processes of environmental secular evolution reshape galaxies especially in rich clusters but even in the Local Group, transforming small companions of giant galaxies+clusters by converting star-forming S+Im galaxies into red and dead S0+Sph galaxies.

Sph galaxies are bulgeless S0s.