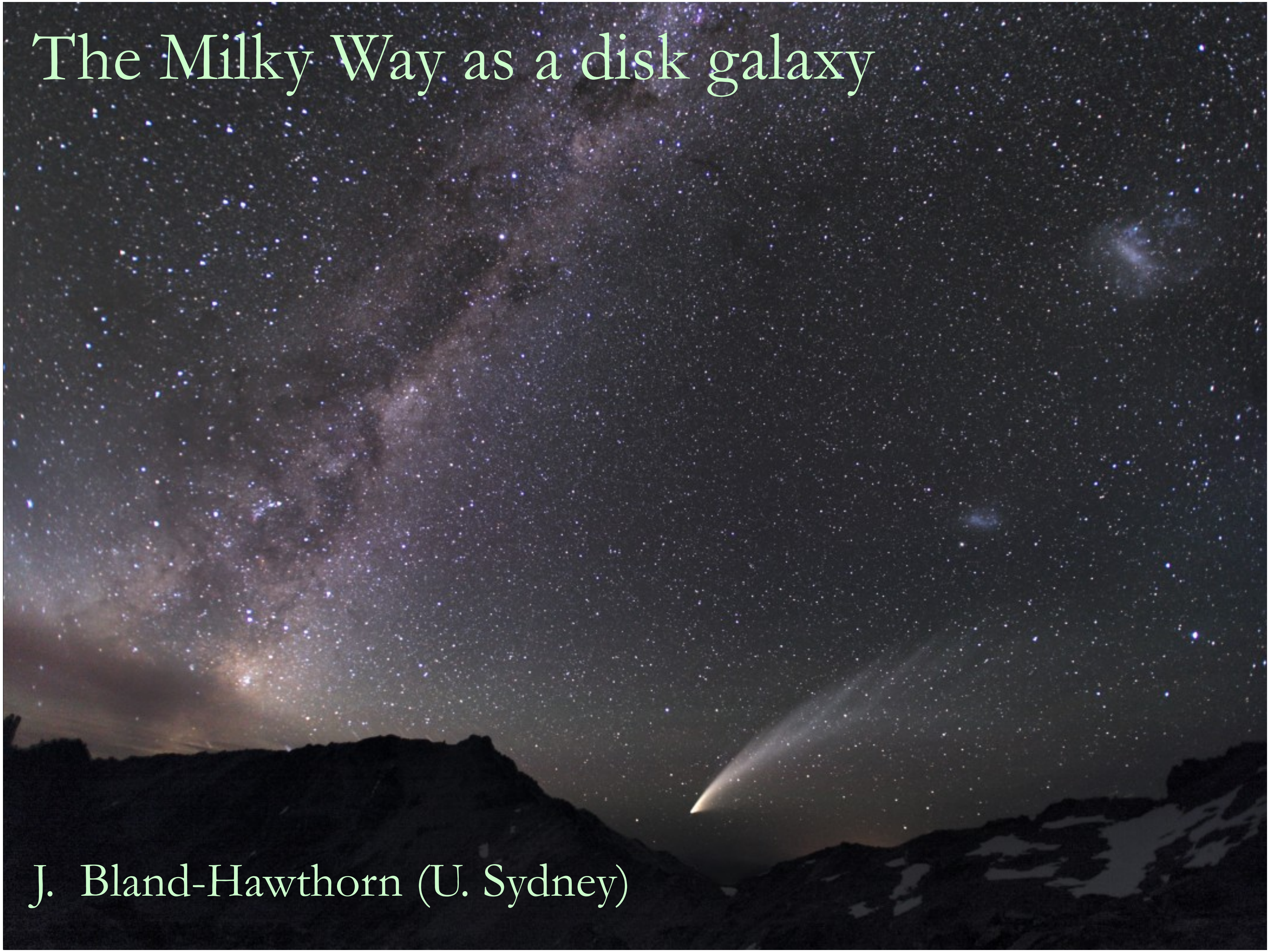
The Milky Way as a disk galaxy



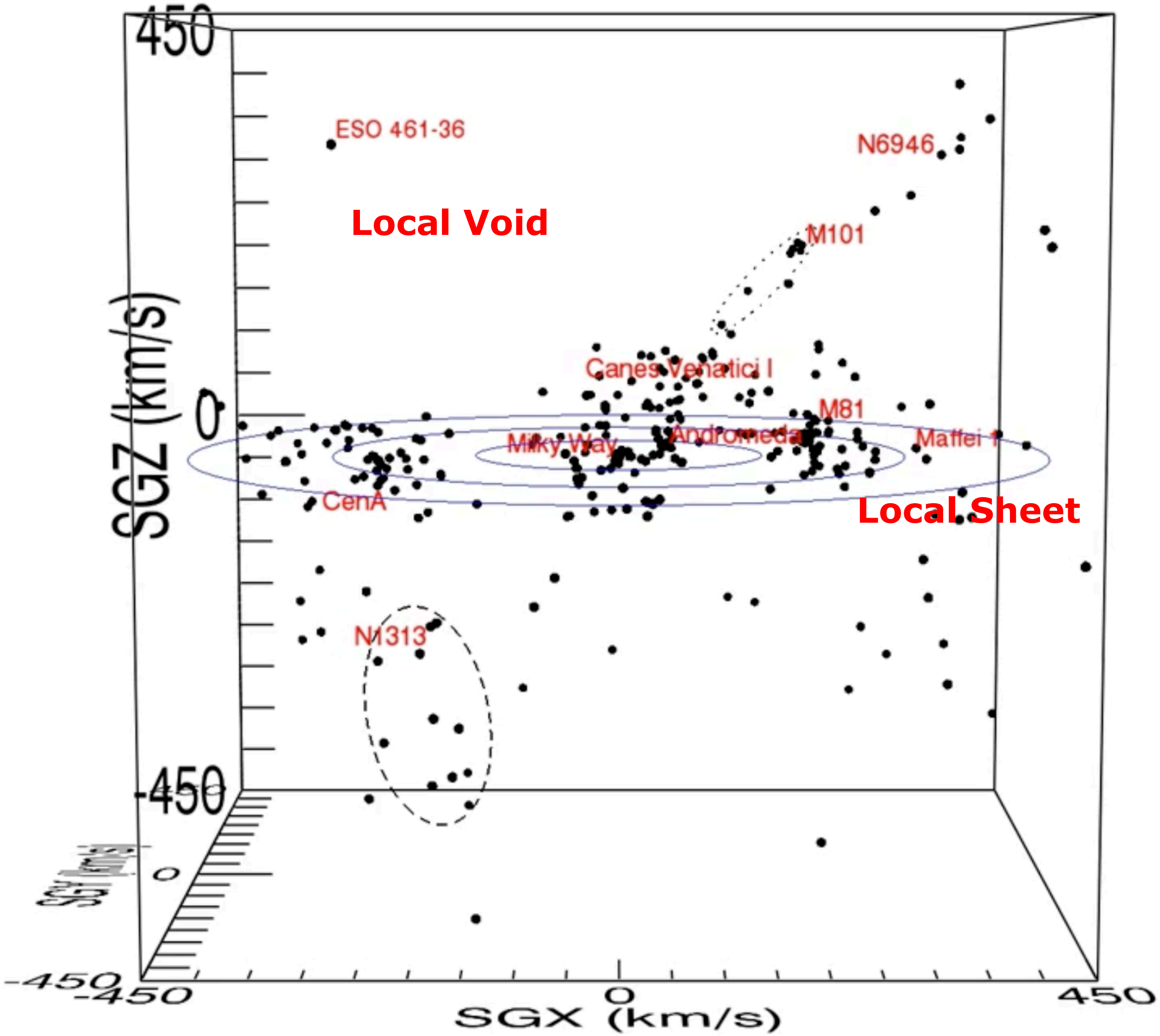
J. Bland-Hawthorn (U. Sydney)

The Milky Way in context

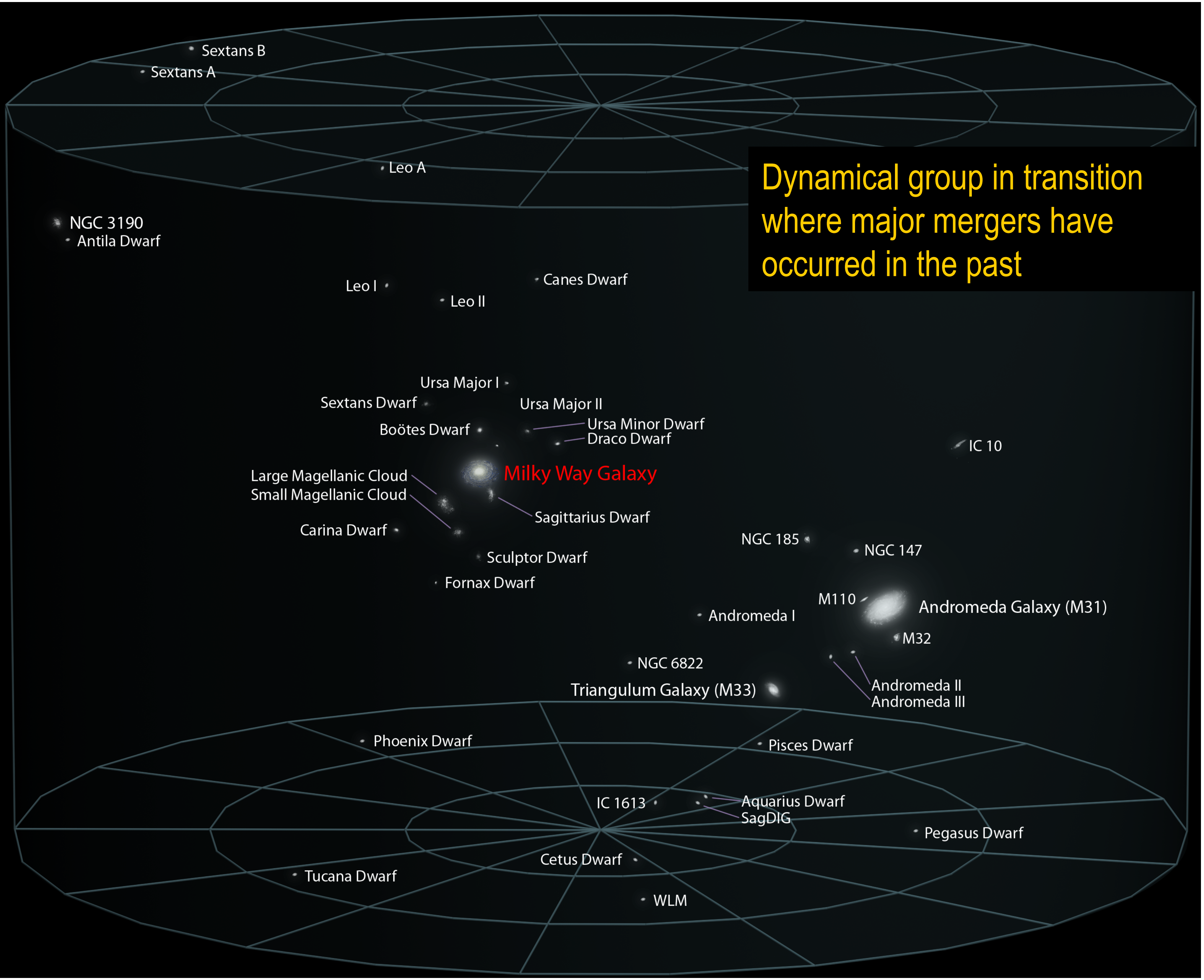
Cosmicflows-2

Tully+ 2008 ff

Group concentrations are the norm, often dominated by a pair of ≥ $L_\star$ galaxies.



A still taken from:
vimeo.com/66641648

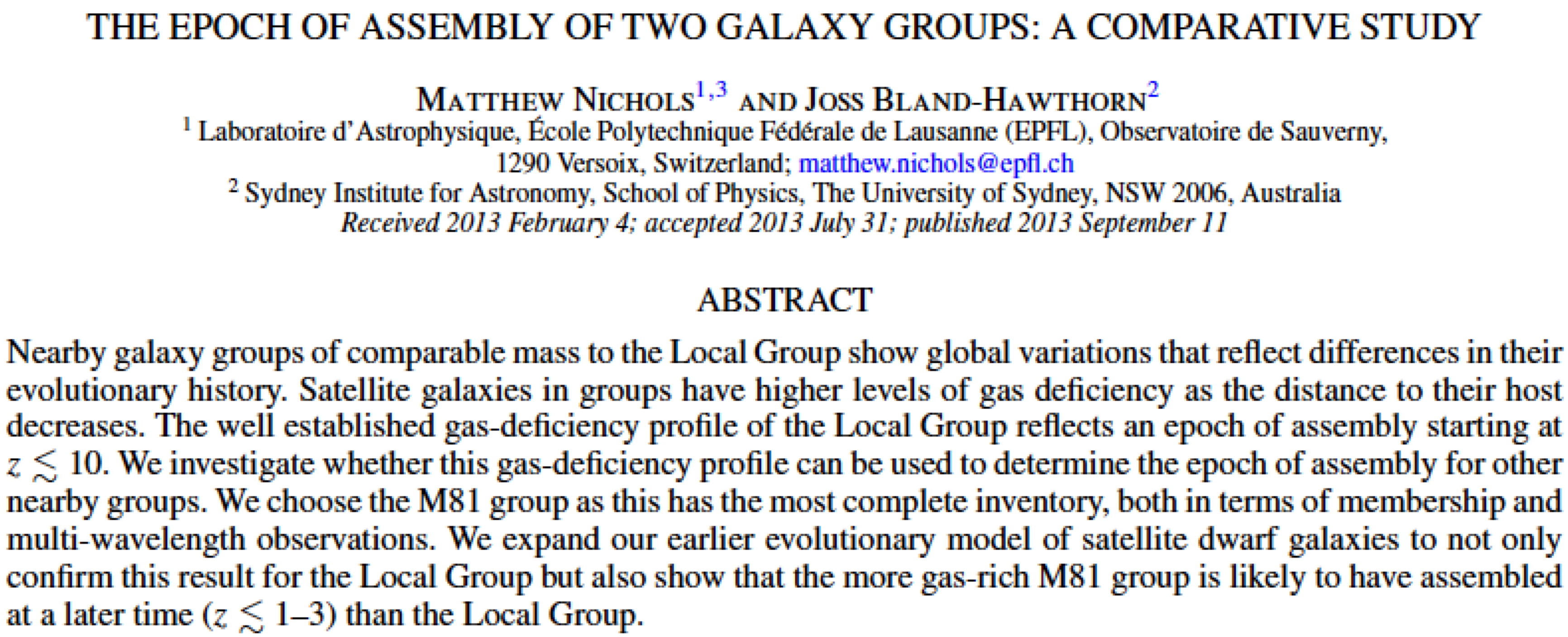


Dynamical group in transition where major mergers have occurred in the past

LG and M81 group – comparison

These have by far the most complete multiband inventories down to 10^8 $M_\odot$.

The M81 group appears to be "younger" than the Local Group from its total gas content and its weaker gas deficiency profile.



THE EPOCH OF ASSEMBLY OF TWO GALAXY GROUPS: A COMPARATIVE STUDY

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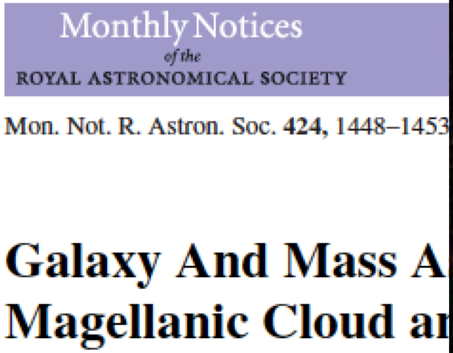
ABSTRACT

Nearby galaxy groups of comparable mass to the Local Group show global variations that reflect differences in their evolutionary history. Satellite galaxies in groups have higher levels of gas deficiency as the distance to their host decreases. The well established gas-deficiency profile of the Local Group reflects an epoch of assembly starting at $z \lesssim 10$. We investigate whether this gas-deficiency profile can be used to determine the epoch of assembly for other nearby groups. We choose the M81 group as this has the most complete inventory, both in terms of membership and multi-wavelength observations. We expand our earlier evolutionary model of satellite dwarf galaxies to not only confirm this result for the Local Group but also show that the more gas-rich M81 group is likely to have assembled at a later time ($z \lesssim 1$–3) than the Local Group.



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

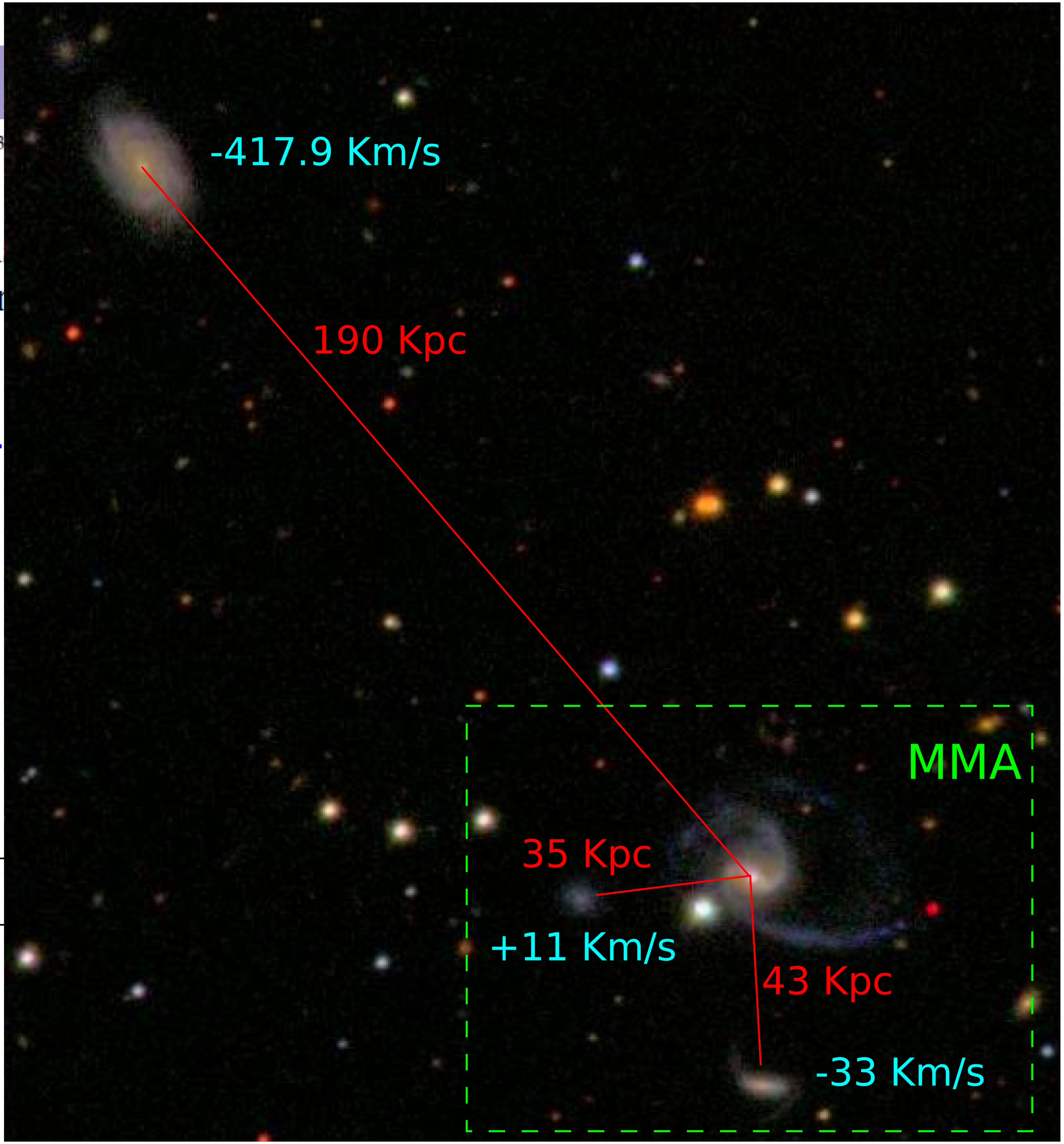
Mon. Not. R. Astron. Soc. 424, 1448–1453

Galaxy And Mass A
Magellanic Cloud a

How common are MW-

MW+LMC
MW+LMC+SMC
MW+LMC+SMC, all

The image that follows



Milky Way and M31 are galaxies in transition – “green valley”

M31 and Milky Way – comparison

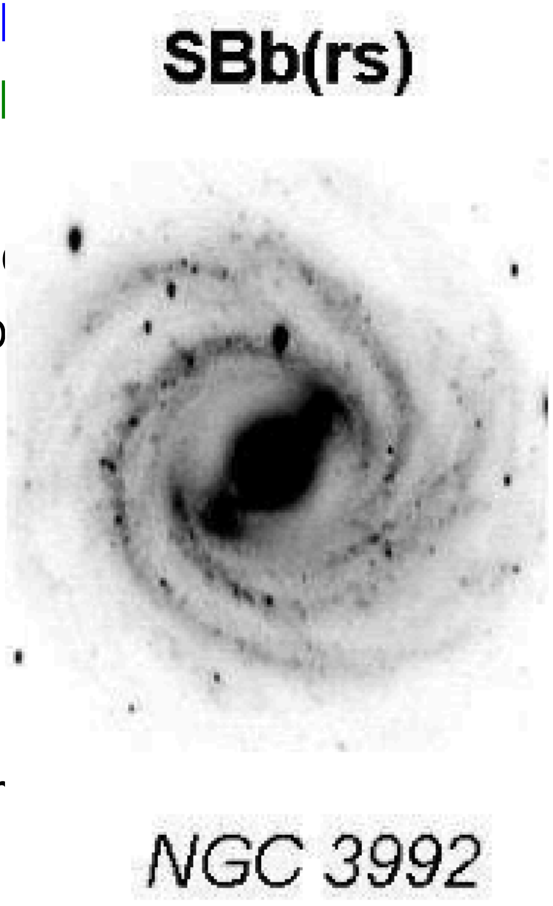
- **Milky Way** total mass (<300 kpc) ~ 1.1 x 10^{12} $M_\odot$ (Kafle+ 2013), f_b ~ 4% (7% < 200 kpc)
- M31 more massive ~ 1.4 x 10^{12} $M_\odot$ (Watkins+ 2010; Corbelli+ 2010), f_b ~ 12%

- **Milky Way** thick disk ~ 5 x 10^{9} $M_\odot$ (Arnadottir+ 2010), h ~ 1
- **M31** thick disk ~ 3 x 10^{10} $M_\odot$ (Collins+ 2011), h ~ 3 kpc, [Fe/

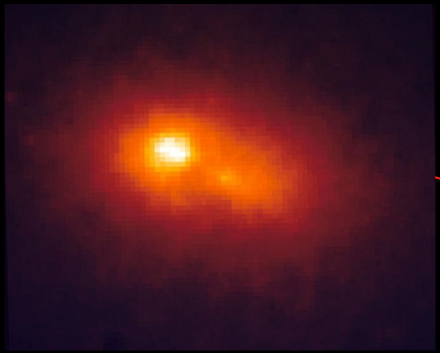
- **Milky Way** has central bar, small bulge (1.0 x 10^{10} $M_\odot$) form
- M31 has huge box/bar bulge (5 x 10^{10} $M_\odot$?) formed by majo

- **Milky Way** black hole ~ 4.4 x 10^{6} $M_\odot$ (active 2 Myr ago)
- M31 black hole ~ 1.7 x 10^{8} $M_\odot$ (quiet; double nucleus)

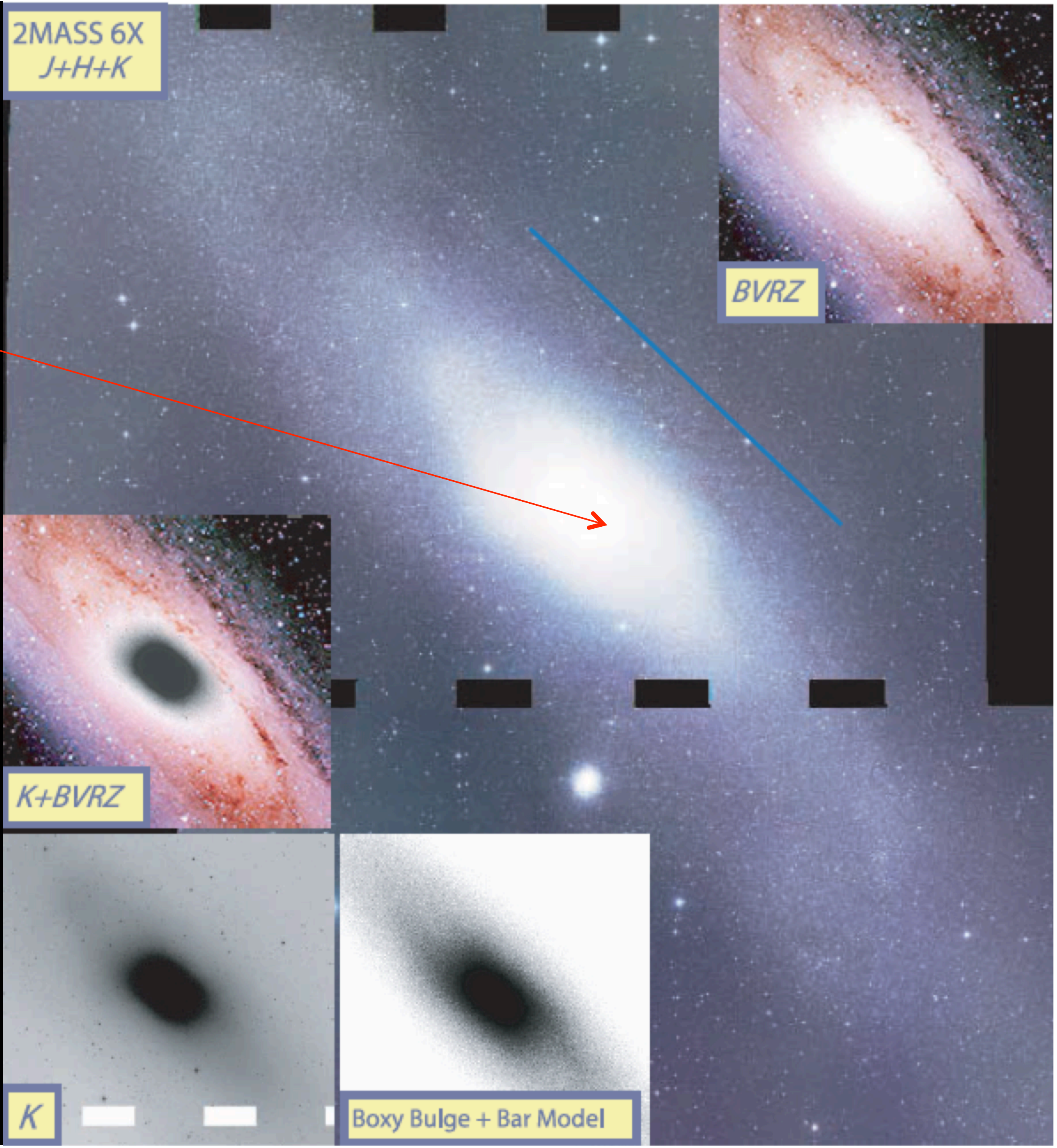
- M31 dwarfs structurally different from **Milky Way** dwarfs
- M31 and **Milky Way** converging, will collide in ~ 4 Gyr to for



M31 Bulge



double nucleus



M31/MW black hole mass ratio consistent with a rapid dependence on **bulge mass**

(e.g. Scott+ 2013)

This may not be physically meaningful given the different origins of the bulges.

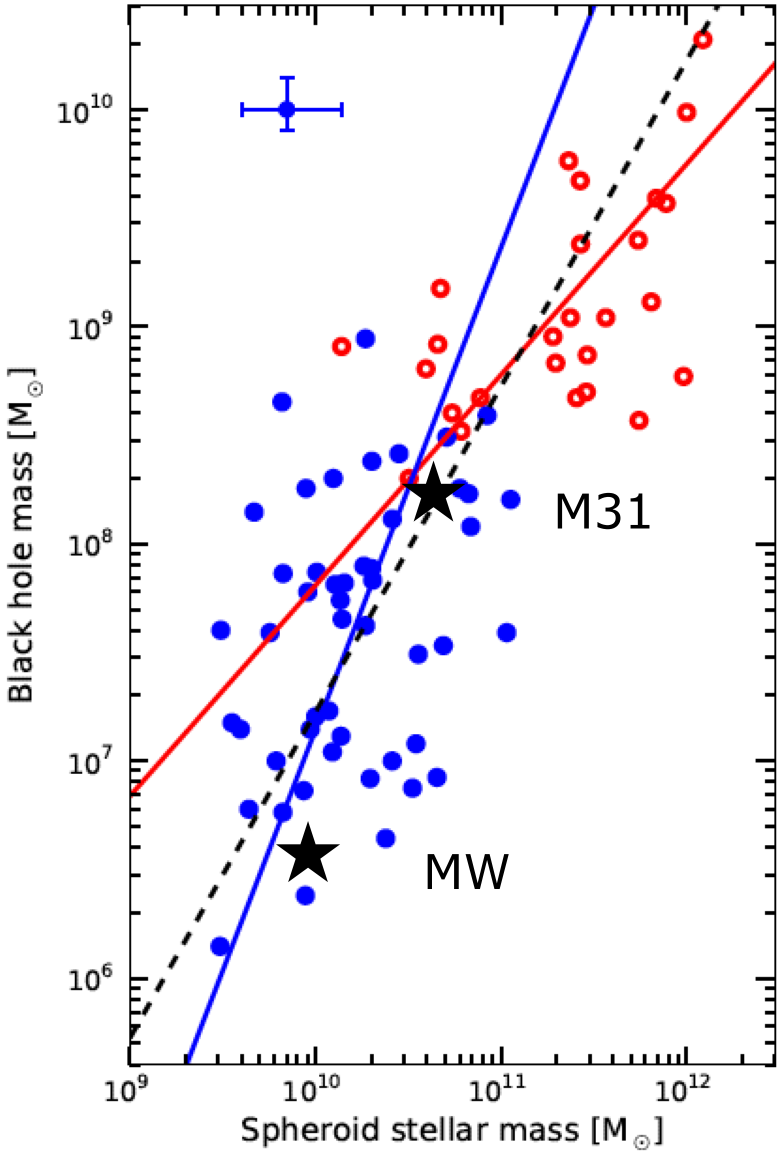
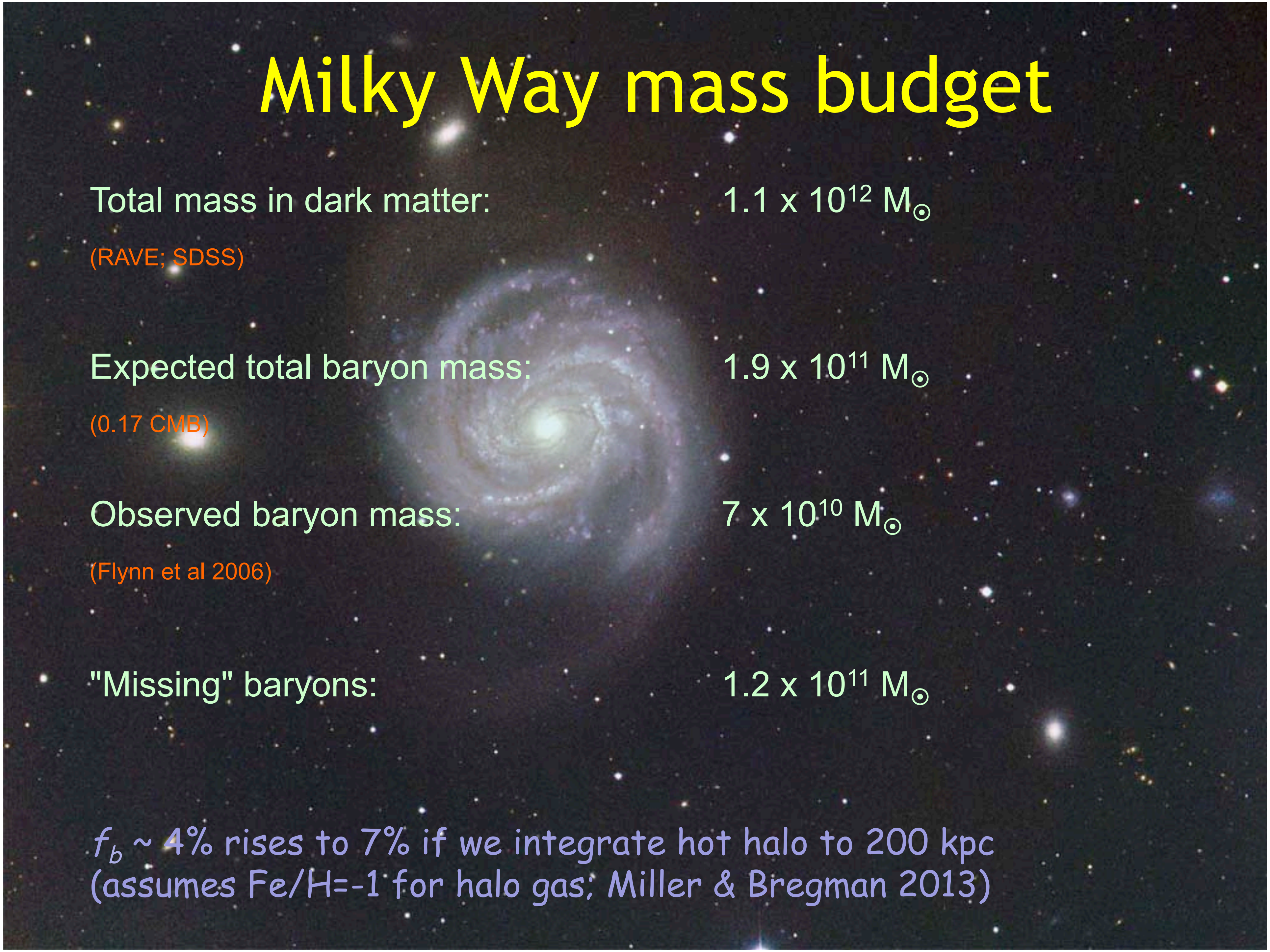


Figure 3. Supermassive black hole mass vs. spheroid stellar mass for core-Sérsic (open red symbols) and Sérsic (filled blue symbols) galaxies. The best-fitting linear relations to the two samples are, given by Eqns. (3) and (4) shown as the solid lines. For comparison, the best-fitting linear regression for the full sample is shown as the dashed line and is dependent on the sample selection. A representative error bar is shown in the upper left corner.

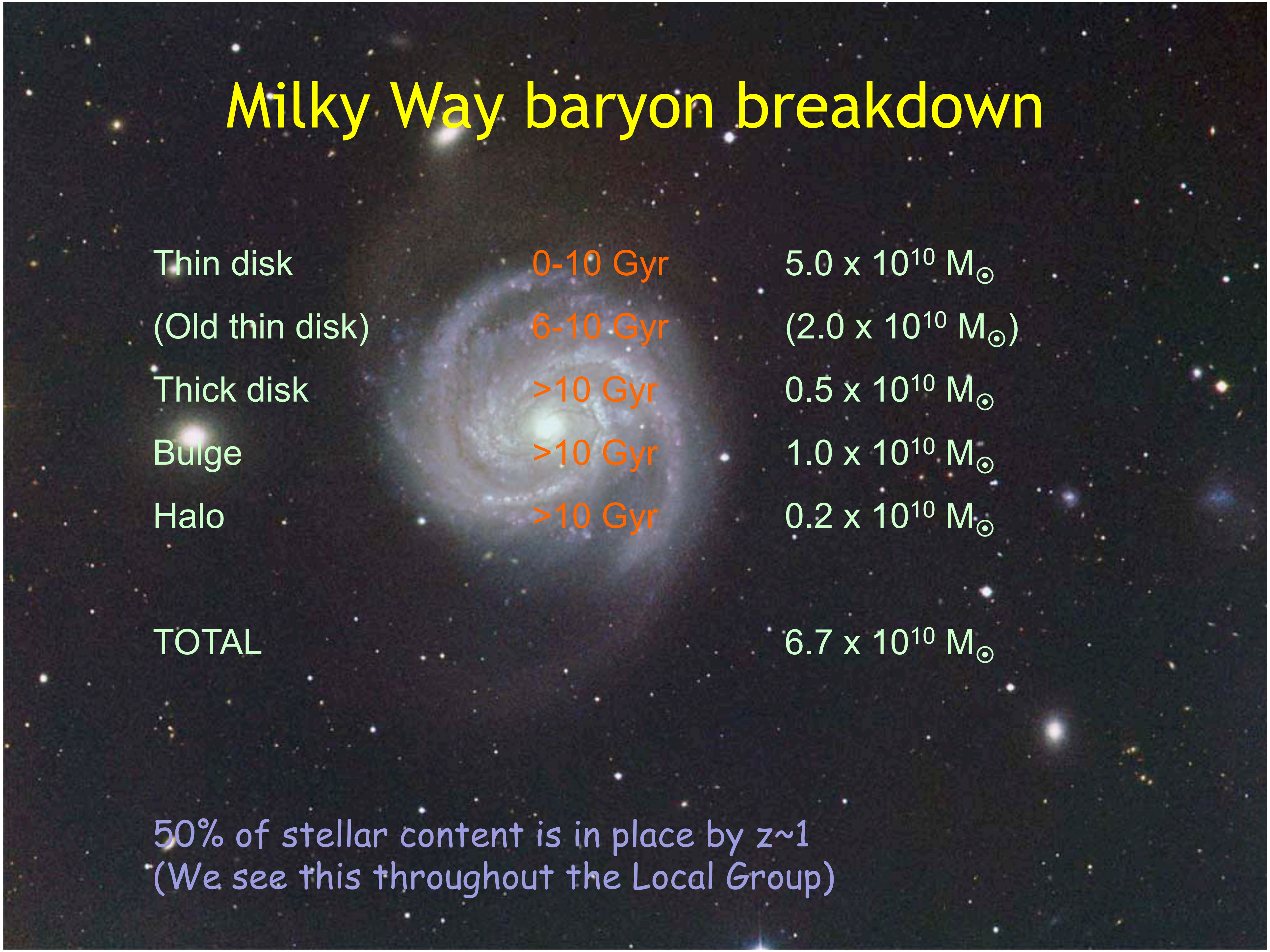
Milky Way mass budget



Total mass in dark matter: (RAVE; SDSS)	1.1 x 10^{12} $M_\odot$
Expected total baryon mass: (0.17 CMB)	1.9 x 10^{11} $M_\odot$
Observed baryon mass: (Flynn et al 2006)	7 x 10^{10} $M_\odot$
"Missing" baryons:	1.2 x 10^{11} $M_\odot$

f_b ~ 4% rises to 7% if we integrate hot halo to 200 kpc
(assumes Fe/H=-1 for halo gas; Miller & Bregman 2013)

Milky Way baryon breakdown

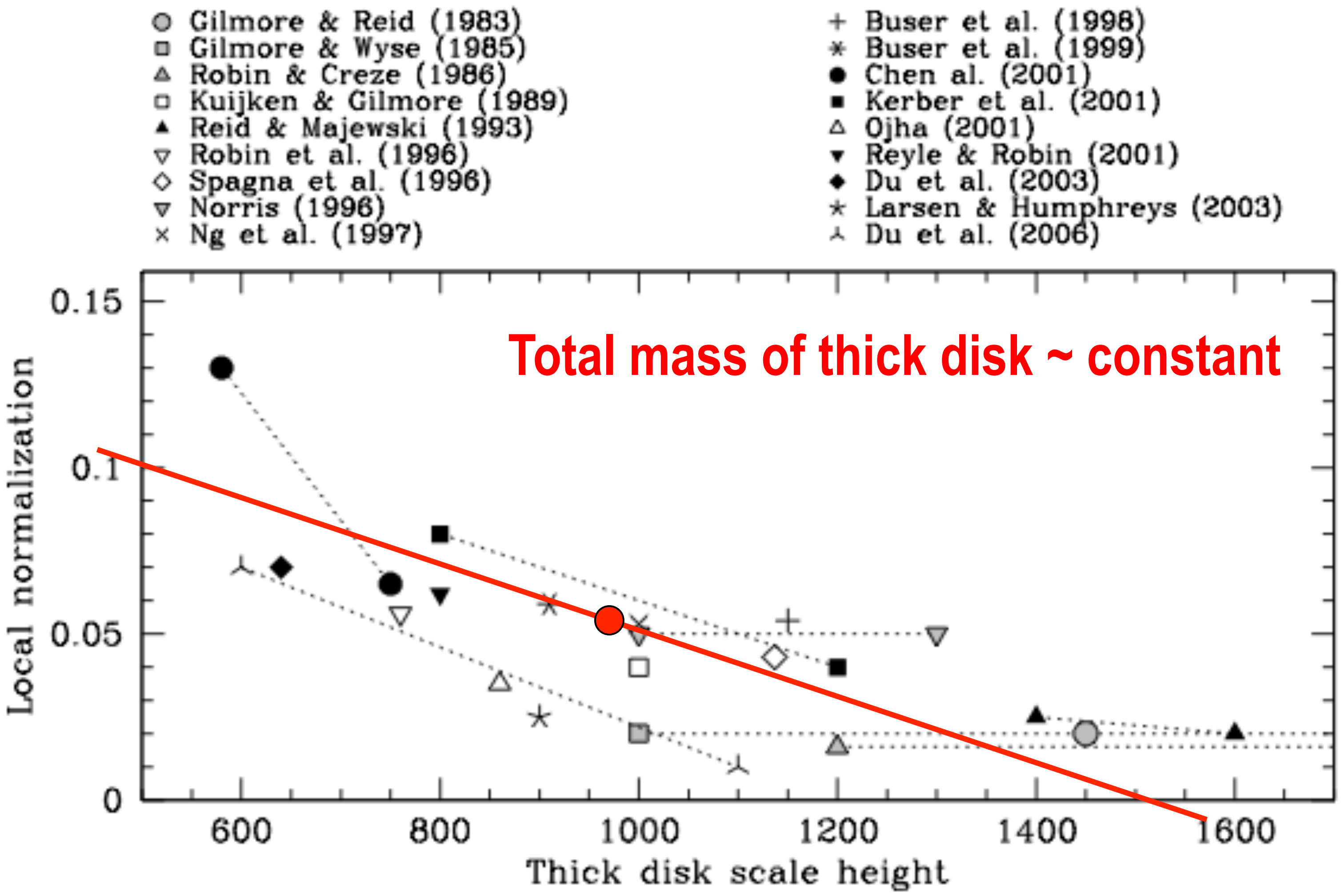


Thin disk	0-10 Gyr	$5.0 \times 10^{10}\ M_\odot$
(Old thin disk)	6-10 Gyr	$(2.0 \times 10^{10}\ M_\odot)$
Thick disk	>10 Gyr	$0.5 \times 10^{10}\ M_\odot$
Bulge	>10 Gyr	$1.0 \times 10^{10}\ M_\odot$
Halo	>10 Gyr	$0.2 \times 10^{10}\ M_\odot$
TOTAL		$6.7 \times 10^{10}\ M_\odot$

50% of stellar content is in place by z~1
(We see this throughout the Local Group)

MW Thick Disk

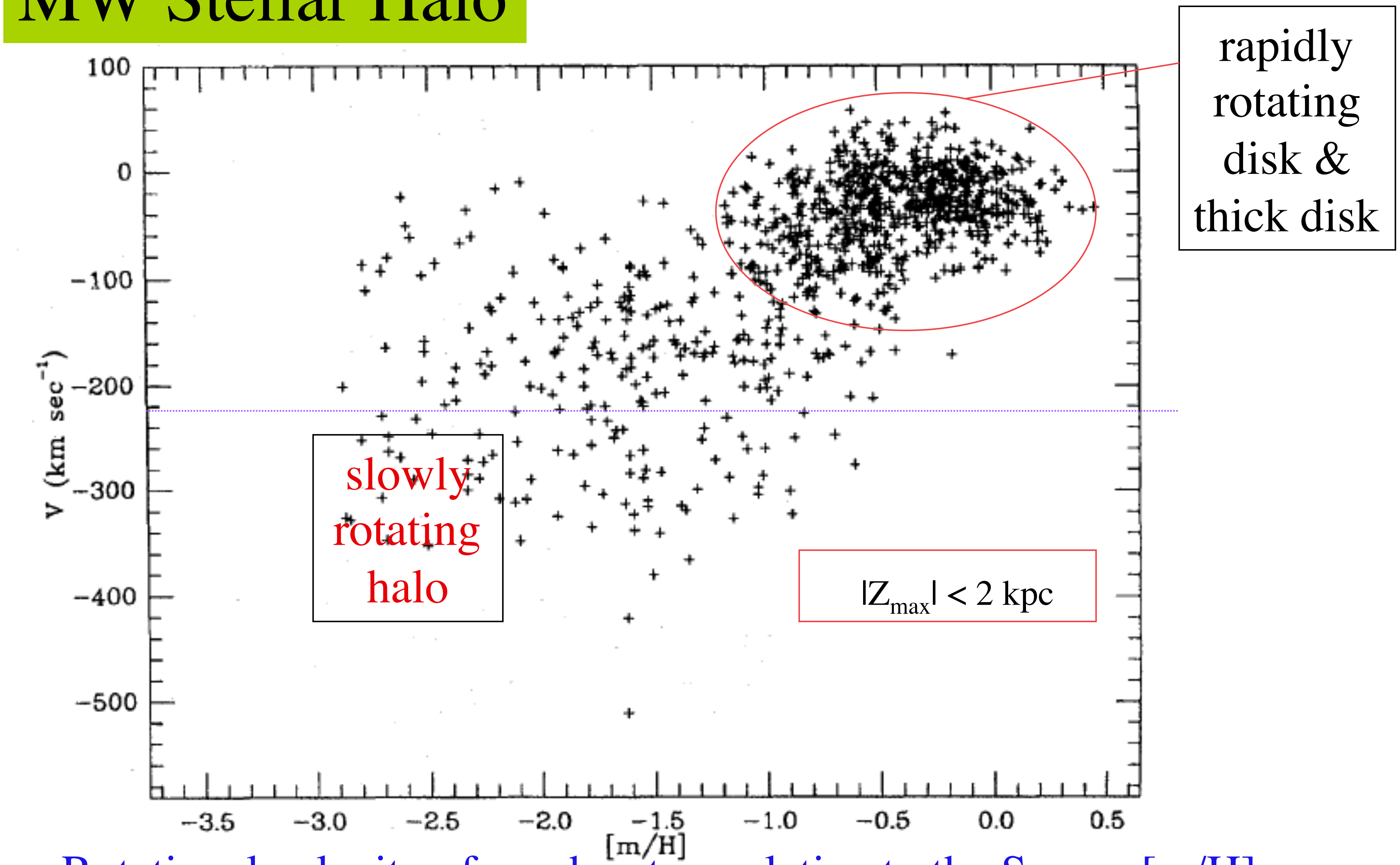
óttir, Sofia Feltzing & Ingemar Lundström



Total mass of thick disk ~ constant

Figure 3. The local normalisation is plotted against the thick disk scale height for a compiled list of values from the literature. References are given above the Figure. When a study gives a range of values, the extremes are plotted and connected with a dotted line.

MW Stellar Halo



rapidly rotating disk & thick disk

slowly rotating halo

$|Z_{max}| < 2$ kpc

Rotational velocity of nearby stars relative to the Sun vs [m/H]

(V = -232 km/s corresponds to zero angular momentum)

(Carney et al 1990)

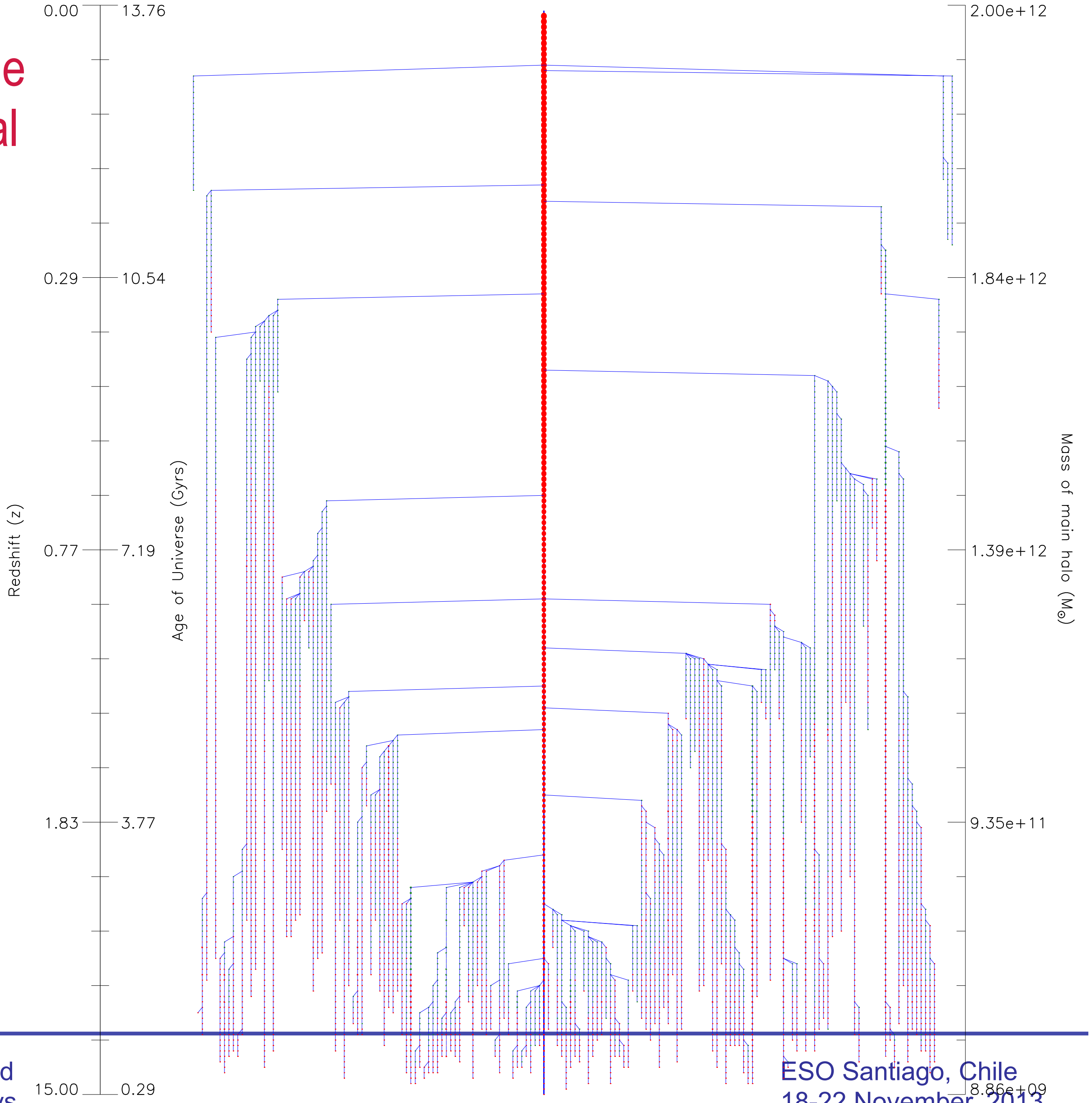
Near-field cosmology

We can consider the Galaxy as our “universe” and probe back to shortly after the Big Bang.

Half of all stars in the Galaxy (and the Local Group) were formed before z ~ 1

The oldest components are the halo, bulge and thick disk (z~2-4).

We struggle to identify the counterparts in the Hubble Deep Field.



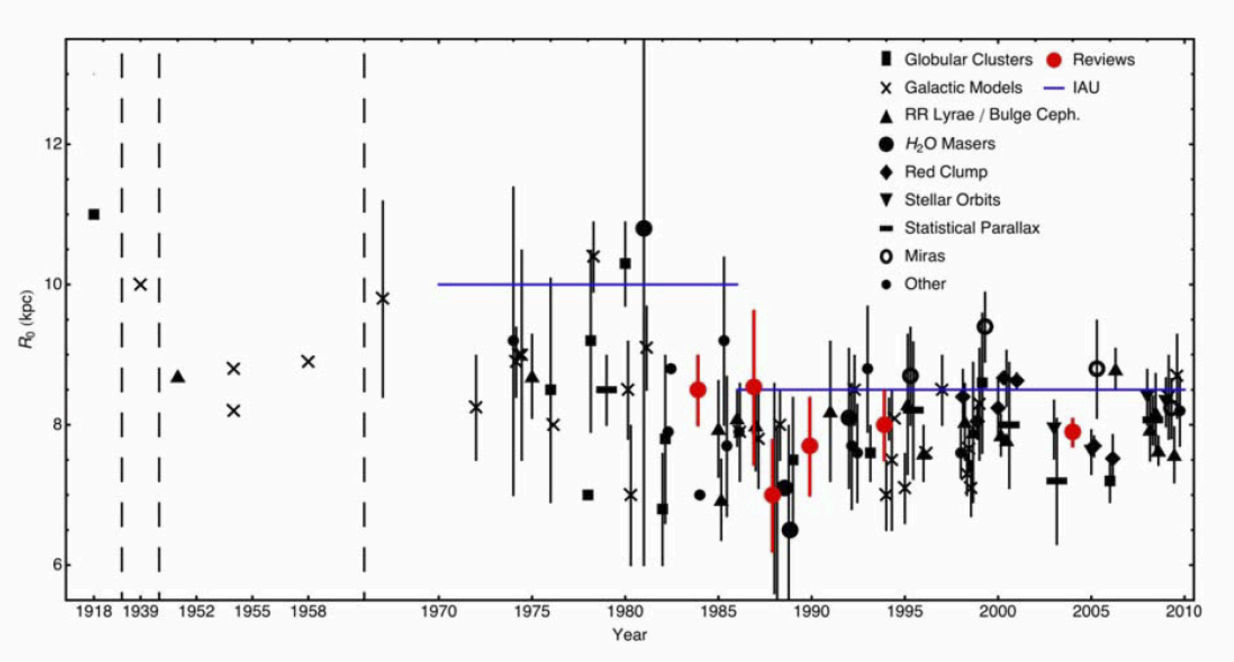
All cosmologies have fundamental parameters

The only thing known with high certainty is the proper motion of Sgr A*

$$(V_{circ}+V_{sun})/R_{sun} = 30.24 \pm 0.11 \text{ km s}^{-1} \text{ kpc}$$

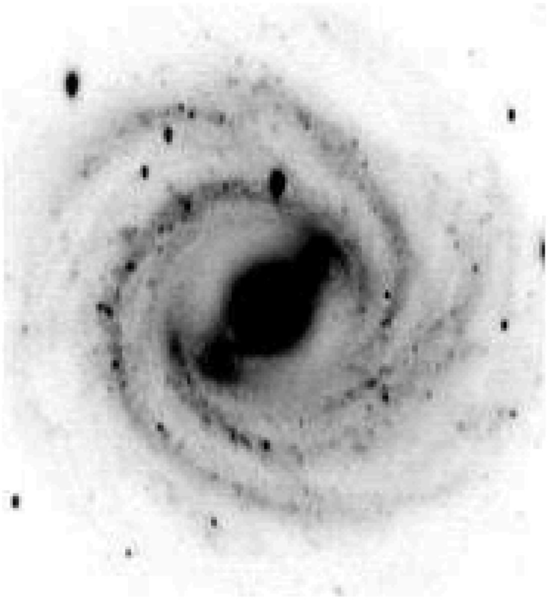
(Reid & Bruntháler 2004; McMillan & Binney 2010)

R_{sun} = 7.5-8.0 kpc



V_{circ} allows us to get ~bolometric quantities like total magnitude through the TF relation.

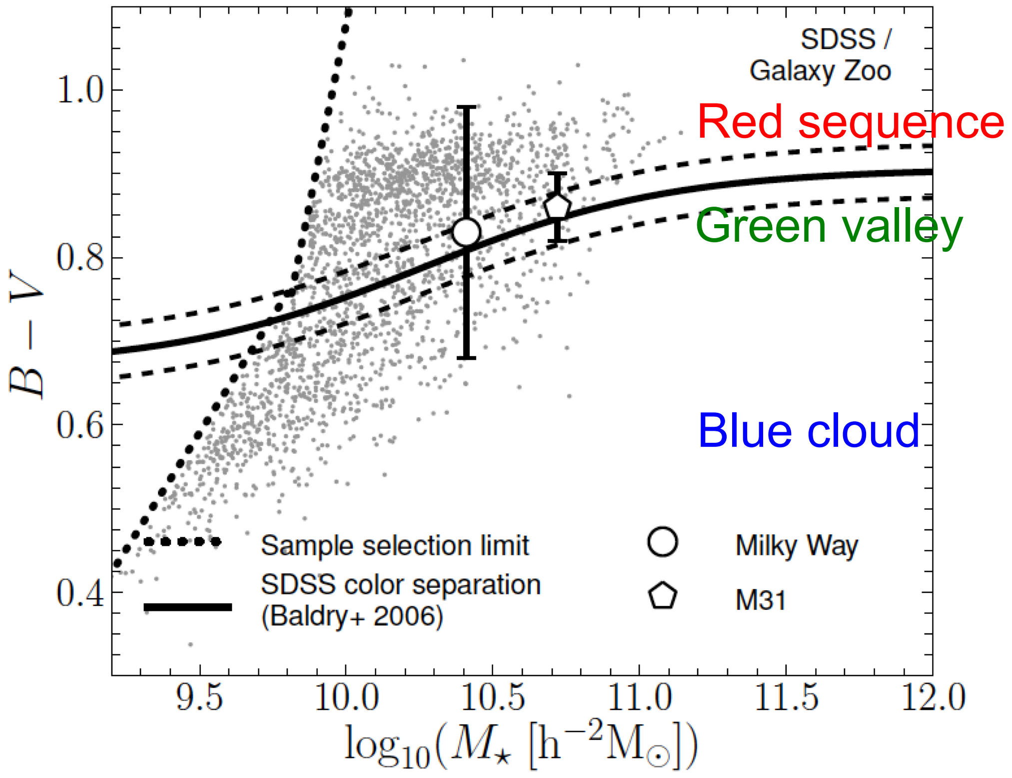
SBb(rs)



NGC 3992

The best analogue
of the Galaxy

Mutch, Croton & Poole 2013



Big surveys in the near field

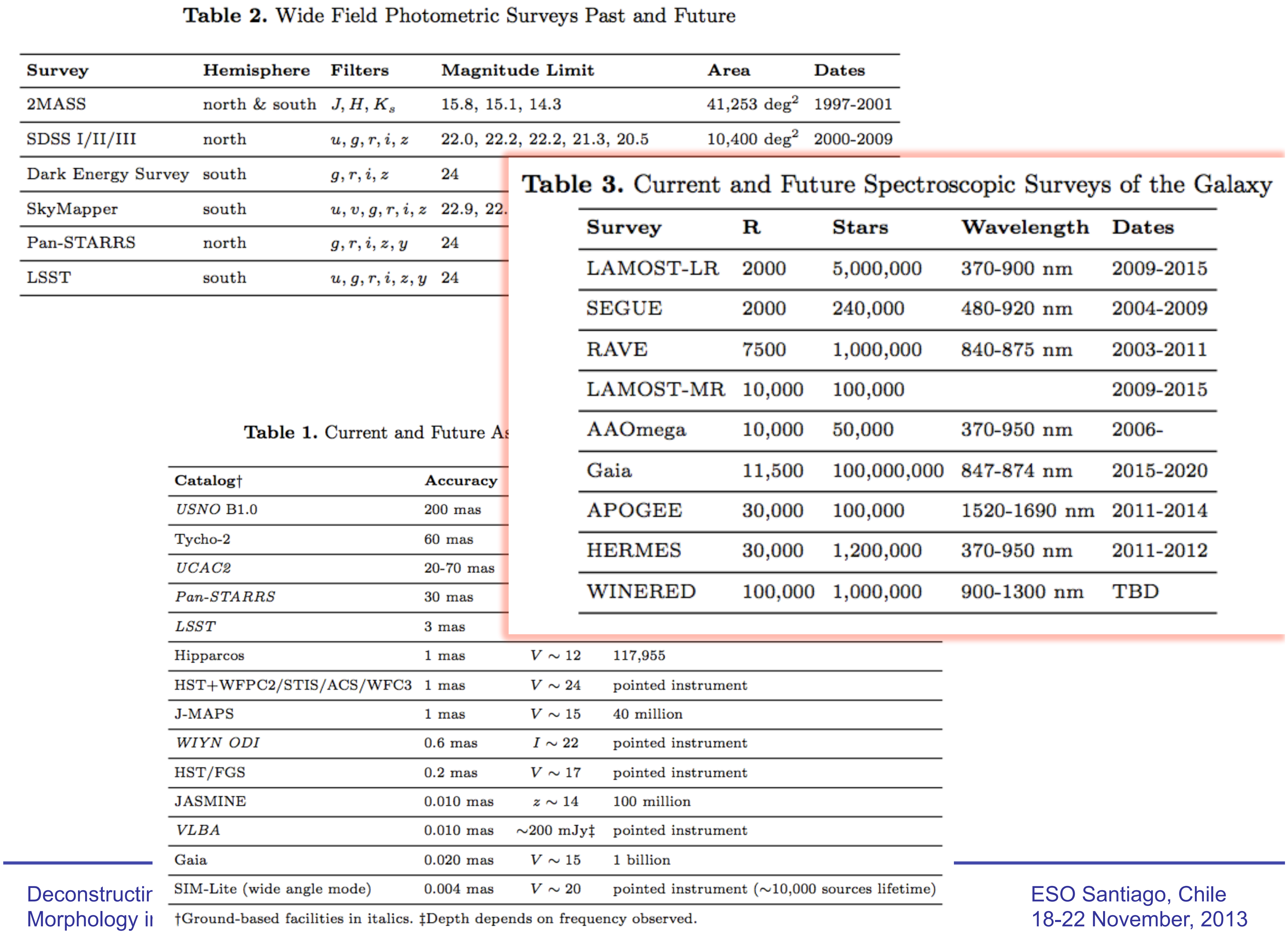


Table 2. Wide Field Photometric Surveys Past and Future

Survey	**Hemisphere**	**Filters**	**Magnitude Limit**	**Area**	**Dates**
2MASS	north & south	J, H, K_s	15.8, 15.1, 14.3	41,253 deg^2	1997-2001
SDSS I/II/III	north	u, g, r, i, z	22.0, 22.2, 22.2, 21.3, 20.5	10,400 deg^2	2000-2009
Dark Energy Survey	south	g, r, i, z	24		
SkyMapper	south	u, v, g, r, i, z	22.9, 22.		
Pan-STARRS	north	g, r, i, z, y	24		
LSST	south	u, g, r, i, z, y	24		

Table 3. Current and Future Spectroscopic Surveys of the Galaxy

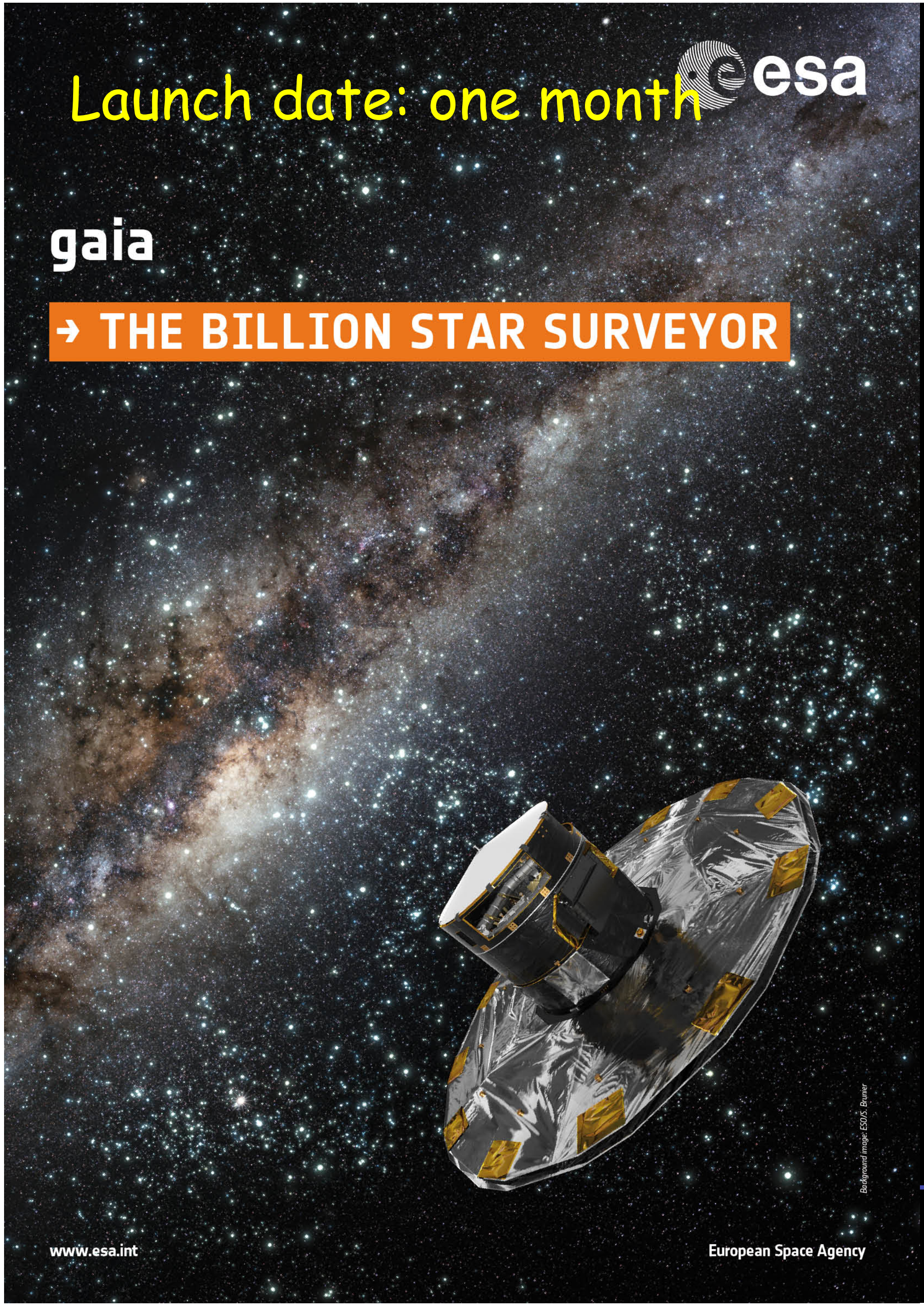
Survey	**R**	**Stars**	**Wavelength**	**Dates**
LAMOST-LR	2000	5,000,000	370-900 nm	2009-2015
SEGUE	2000	240,000	480-920 nm	2004-2009
RAVE	7500	1,000,000	840-875 nm	2003-2011
LAMOST-MR	10,000	100,000		2009-2015
AAOmega	10,000	50,000	370-950 nm	2006-
Gaia	11,500	100,000,000	847-874 nm	2015-2020
APOGEE	30,000	100,000	1520-1690 nm	2011-2014
HERMES	30,000	1,200,000	370-950 nm	2011-2012
WINERED	100,000	1,000,000	900-1300 nm	TBD

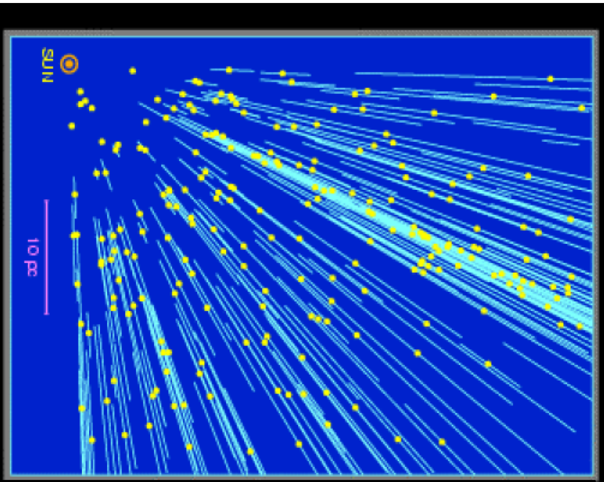
Table 1. Current and Future As

Catalog†	**Accuracy**		
USNO B1.0	200 mas		
Tycho-2	60 mas		
UCAC2	20-70 mas		
Pan-STARRS	30 mas		
LSST	3 mas		
Hipparcos	1 mas	$V \sim 12$	117,955
HST+WFPC2/STIS/ACS/WFC3	1 mas	$V \sim 24$	pointed instrument
J-MAPS	1 mas	$V \sim 15$	40 million
WIYN ODI	0.6 mas	$I \sim 22$	pointed instrument
HST/FGS	0.2 mas	$V \sim 17$	pointed instrument
JASMINE	0.010 mas	$z \sim 14$	100 million
VLBA	0.010 mas	∼200 mJy‡	pointed instrument
Gaia	0.020 mas	$V \sim 15$	1 billion
SIM-Lite (wide angle mode)	0.004 mas	$V \sim 20$	pointed instrument (∼10,000 sources lifetime)

†Ground-based facilities in italics. ‡Depth depends on frequency observed.

Launch date: one month



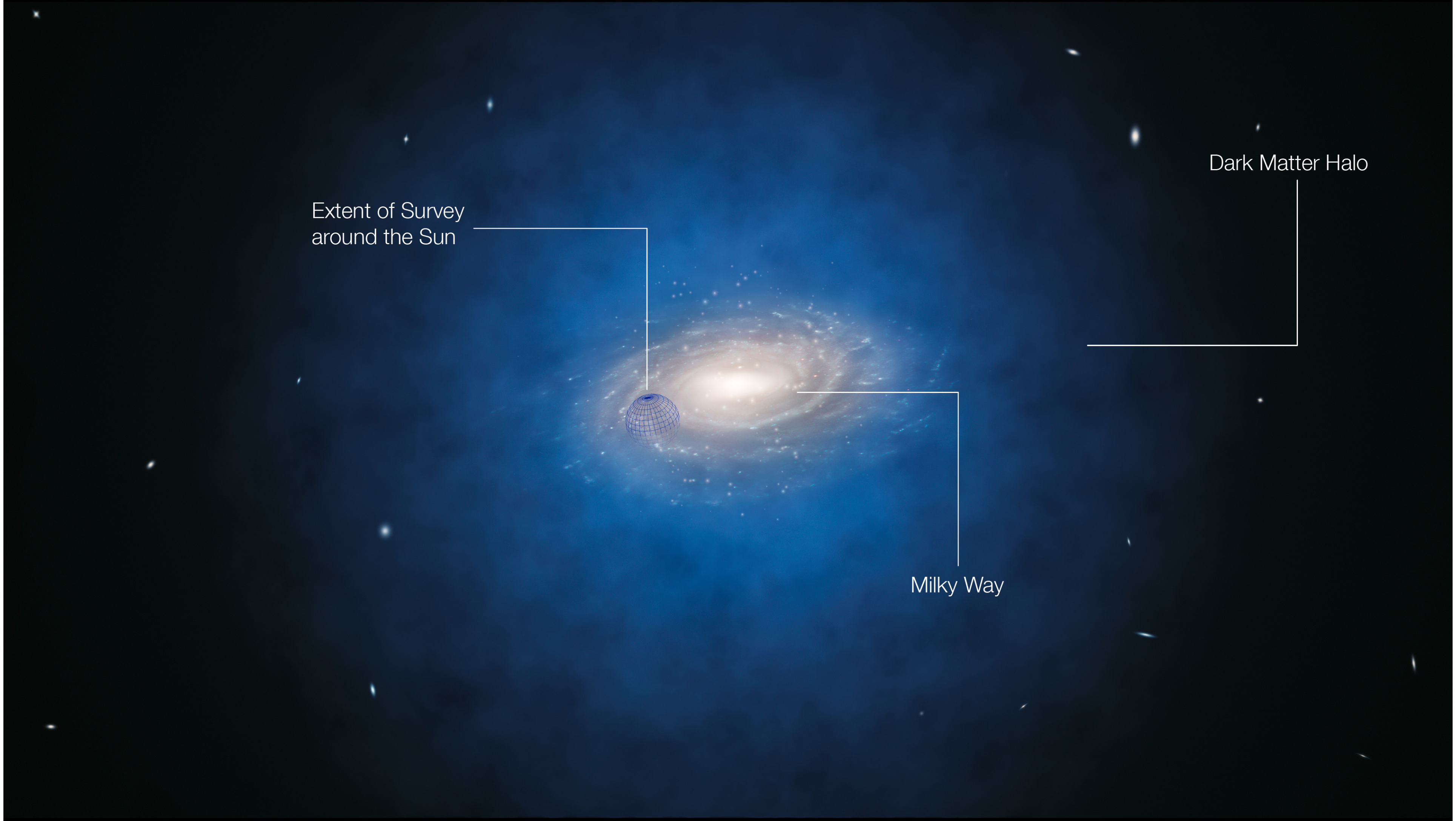


Ground

Hipparcos

GAIA

Most of stellar astrophysics is based on local samples



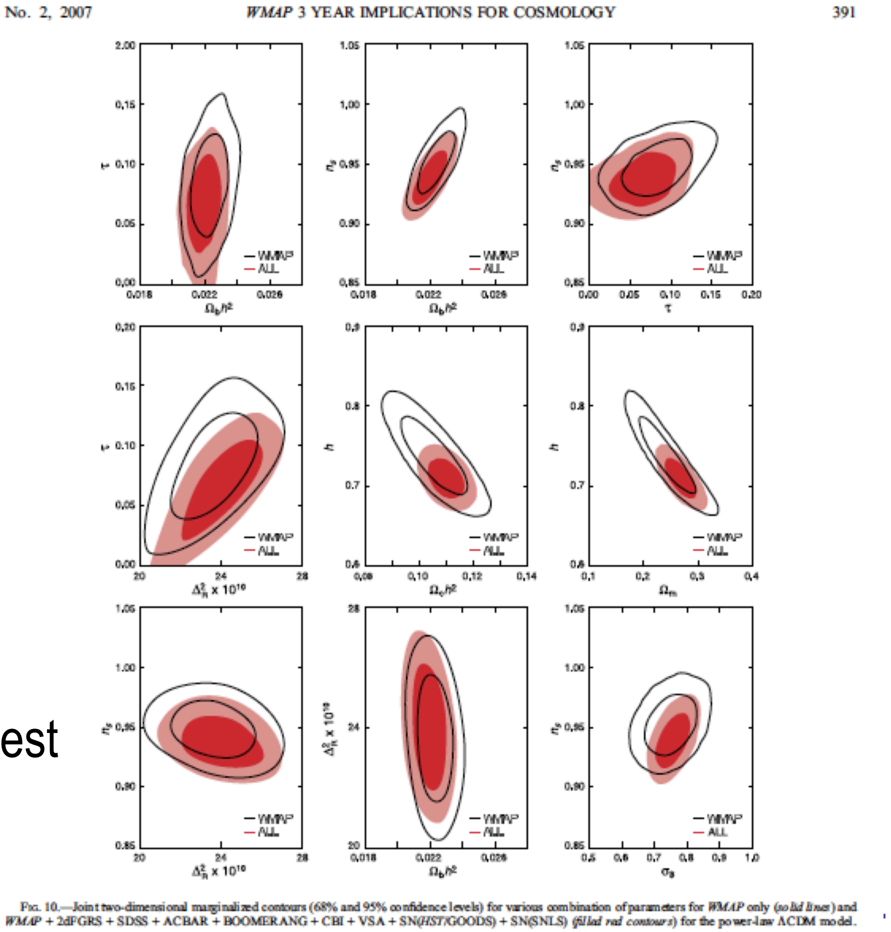
What near-field studies must learn from the far field

Far-field cosmologists have a "concordance model" for cleaning and comparing redshift surveys (W(α,δ); completeness; sampling; bias…)

To test a hypothesis, we must understand:

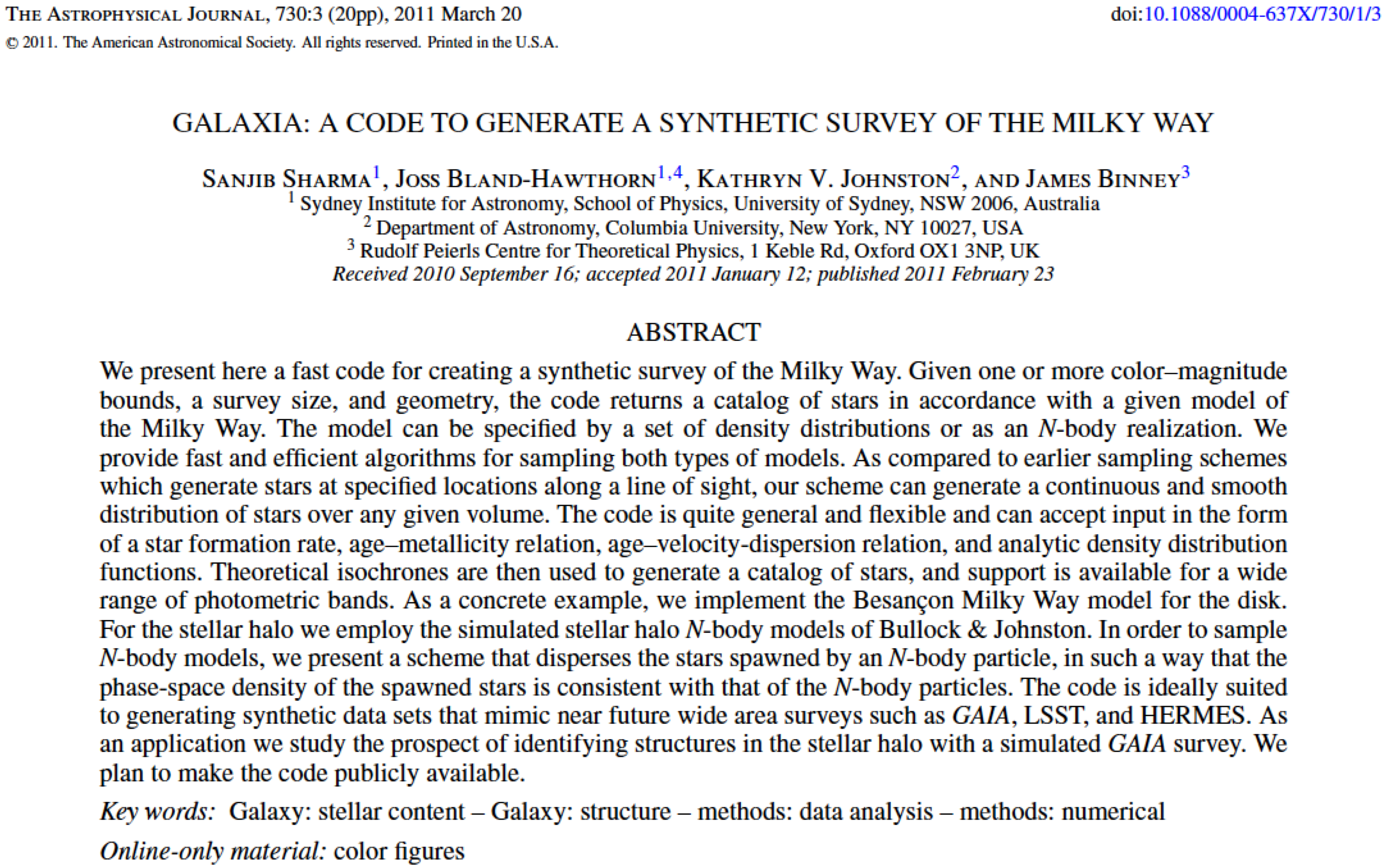
1. Our selection function
2. Consequences of our selection function
3. Uncertainties from statistical realizations

In the **near field**, there is no consistent Galactic framework for comparing surveys, so how do we test any hypothesis?



No. 2, 2007 *WMAP* 3 YEAR IMPLICATIONS FOR COSMOLOGY 391

Fig. 10.—Joint two-dimensional marginalized contours (68% and 95% confidence levels) for various combination of parameters for *WMAP* only (*solid lines*) and *WMAP* + 2dFGRS + SDSS + ACBAR + BOOMERANG + CBI + VSA + SN(*HST*/GOODS) + SN(SNLS) (*filled red contours*) for the power-law ΛCDM model.



THE ASTROPHYSICAL JOURNAL, 730:3 (20pp), 2011 March 20
doi:10.1088/0004-637X/730/1/3

GALAXIA: A CODE TO GENERATE A SYNTHETIC SURVEY OF THE MILKY WAY

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ABSTRACT

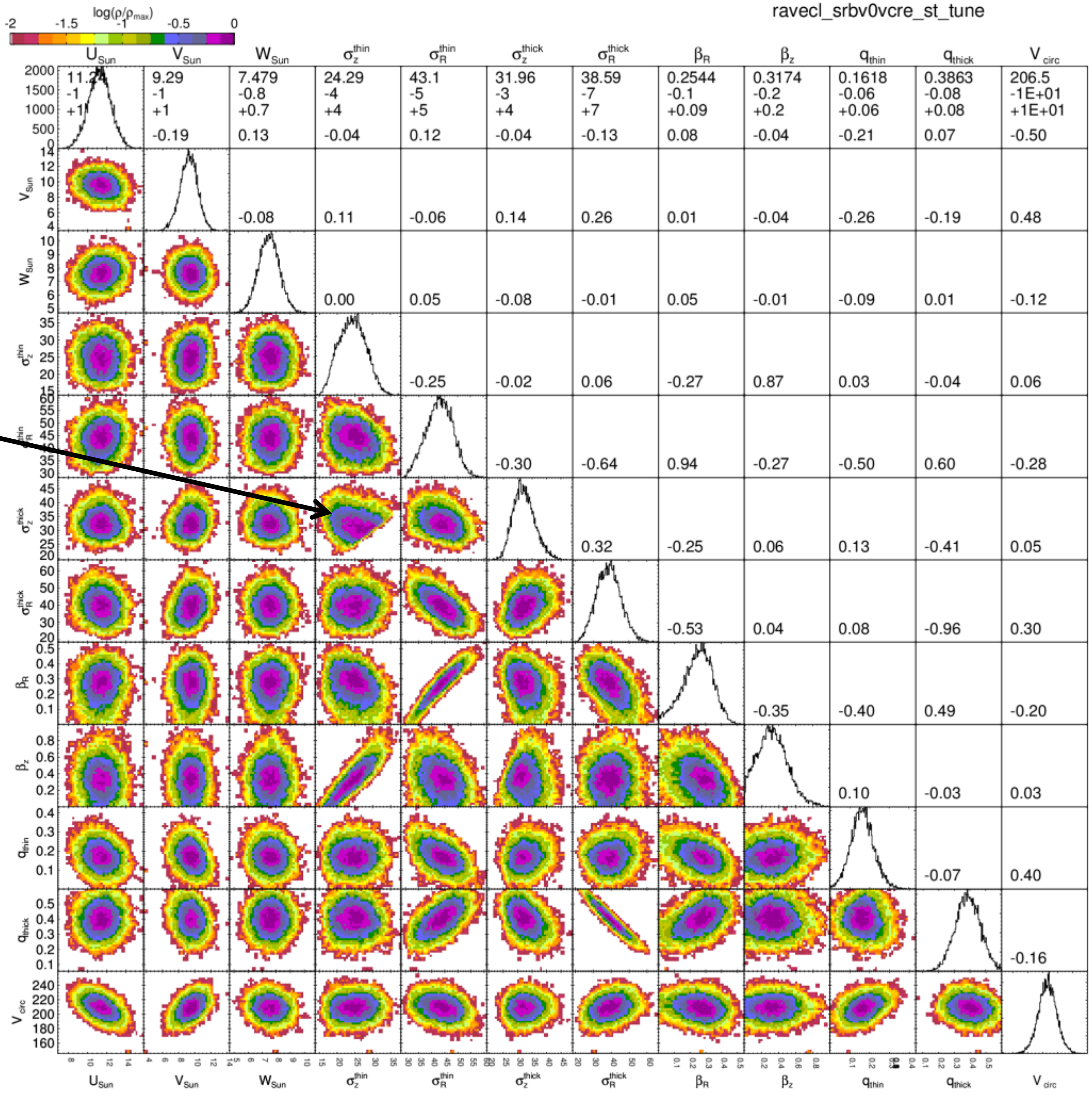
We present here a fast code for creating a synthetic survey of the Milky Way. Given one or more color–magnitude bounds, a survey size, and geometry, the code returns a catalog of stars in accordance with a given model of the Milky Way. The model can be specified by a set of density distributions or as an *N*-body realization. We provide fast and efficient algorithms for sampling both types of models. As compared to earlier sampling schemes which generate stars at specified locations along a line of sight, our scheme can generate a continuous and smooth distribution of stars over any given volume. The code is quite general and flexible and can accept input in the form of a star formation rate, age–metallicity relation, age–velocity-dispersion relation, and analytic density distribution functions. Theoretical isochrones are then used to generate a catalog of stars, and support is available for a wide range of photometric bands. As a concrete example, we implement the Besançon Milky Way model for the disk. For the stellar halo we employ the simulated stellar halo *N*-body models of Bullock & Johnston. In order to sample *N*-body models, we present a scheme that disperses the stars spawned by an *N*-body particle, in such a way that the phase-space density of the spawned stars is consistent with that of the *N*-body particles. The code is ideally suited to generating synthetic data sets that mimic near future wide area surveys such as *GAIA*, LSST, and HERMES. As an application we study the prospect of identifying structures in the stellar halo with a simulated *GAIA* survey. We plan to make the code publicly available.

Key words: Galaxy: stellar content – Galaxy: structure – methods: data analysis – methods: numerical

Online-only material: color figures

A publicly available fast code: http://galaxia.sourceforge.net
This is the basis for the RAVE & HERMES surveys.

RAVE-SHU



Note impact
of “extra prior”

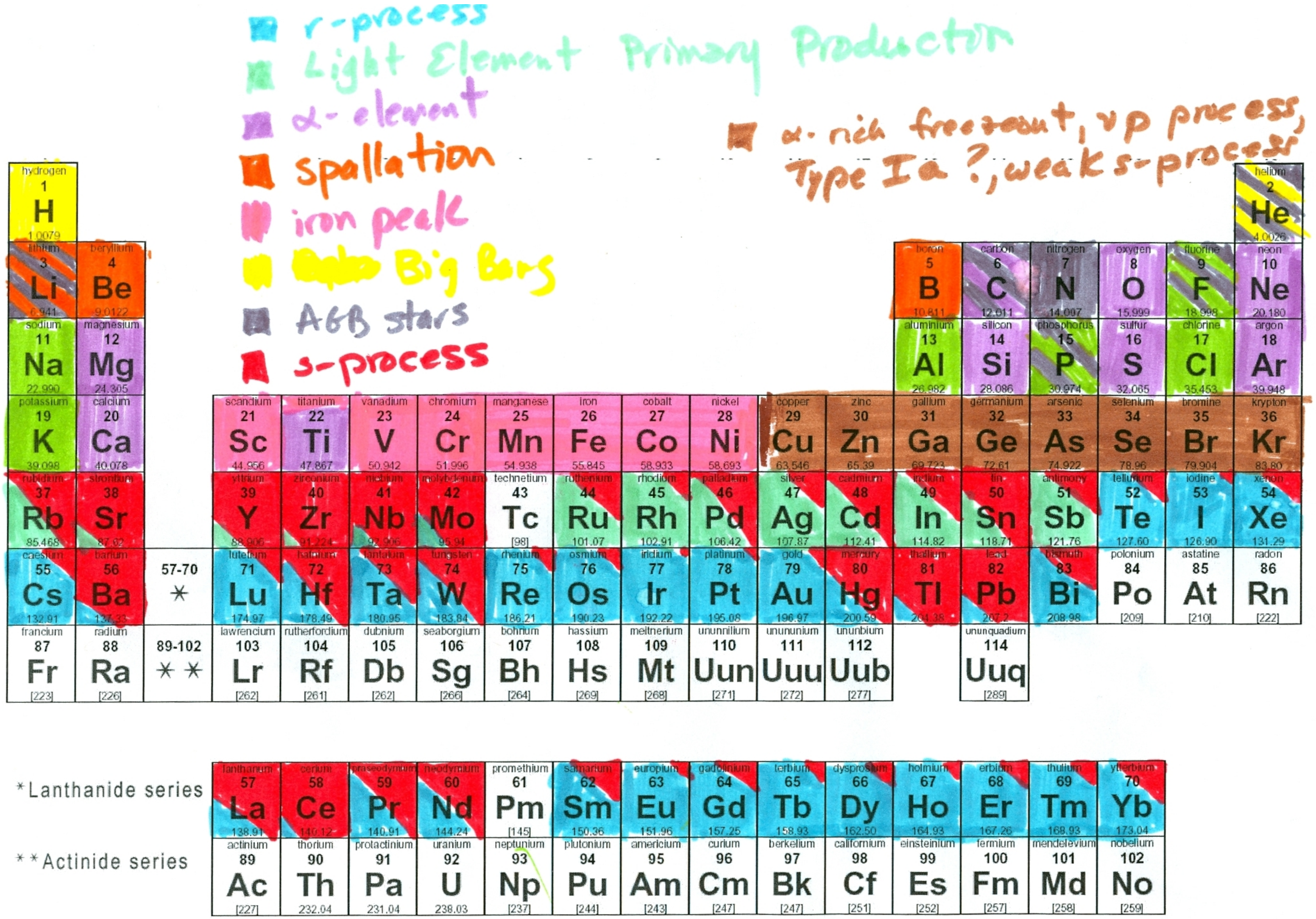
RAVE volume
big enough to
fit for V_{circ}

A fundamental limitation of Galactic studies are accurate **stellar ages** for **individual** stars, one of the great unsolved problems of astrophysics.

Gaia or asteroseismology may ultimately get us to within 10-30% errors for solar-type stars.

How can we proceed?

Cosmic chemistry – the ultimate puzzle

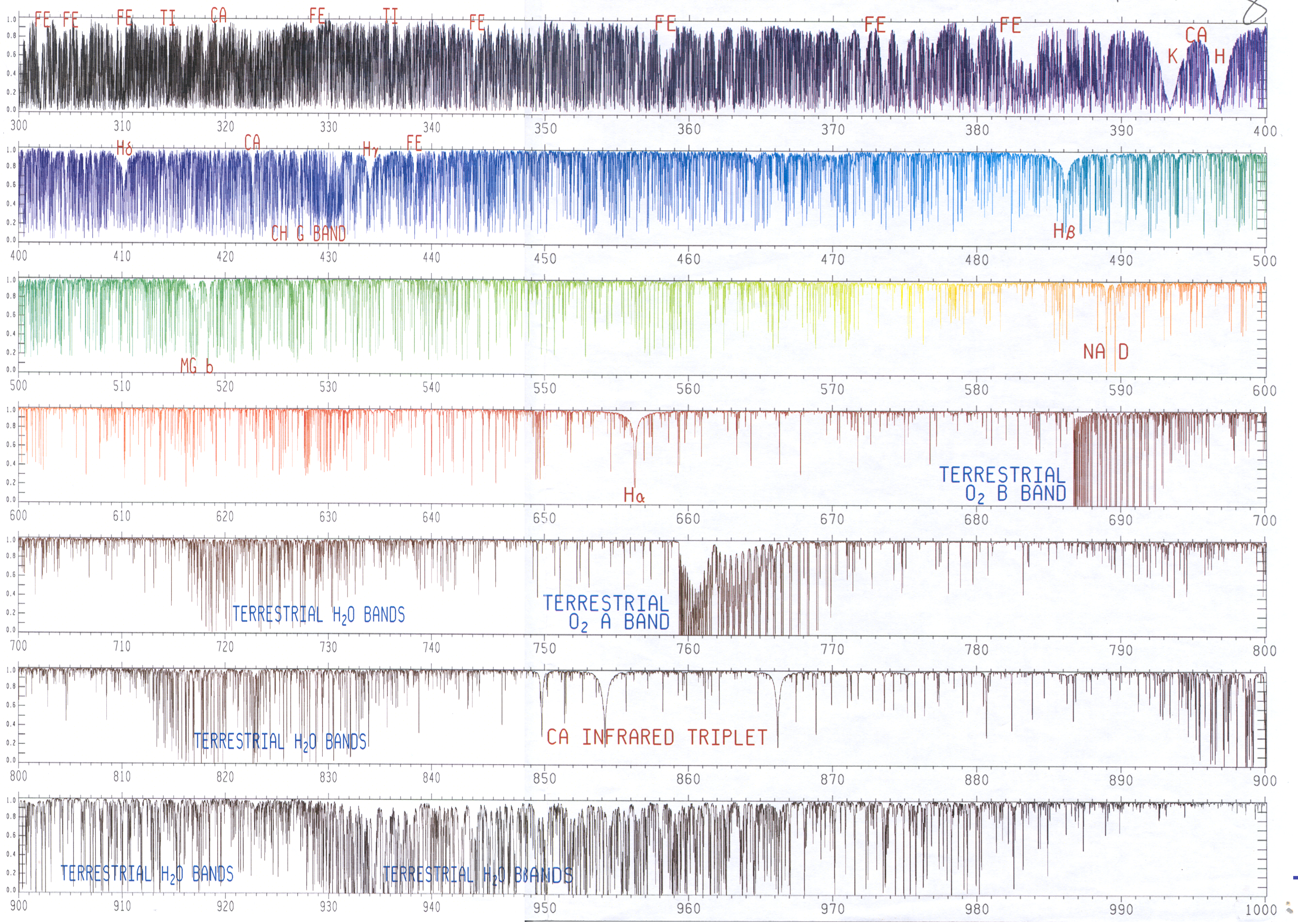


- 🟦 r-process
- 🟩 Light Element Primary Production
- 🟪 α-element
- 🟧 spallation
- ▨ iron peak
- 🟨 Big Bang
- ⬛ AGB stars
- 🟥 s-process
- 🟫 α-rich freezeout, νp process, Type Ia ?, weak s-process

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

KITT PEAK SOLAR FLUX ATLAS (KURUCZ, FURENLID, BRAULT, AND TESTERMAN 1984)



Can we detect specific signatures of the first stellar generations today?

We don’t know yet since our “**first star” models** produce chemical signatures that we can’t easily relate to the most metal poor stars (in our Galaxy) or to the most metal poor clouds at the highest redshifts.

Are we looking in the wrong place?

Metal poor star, [Fe/H] < -5

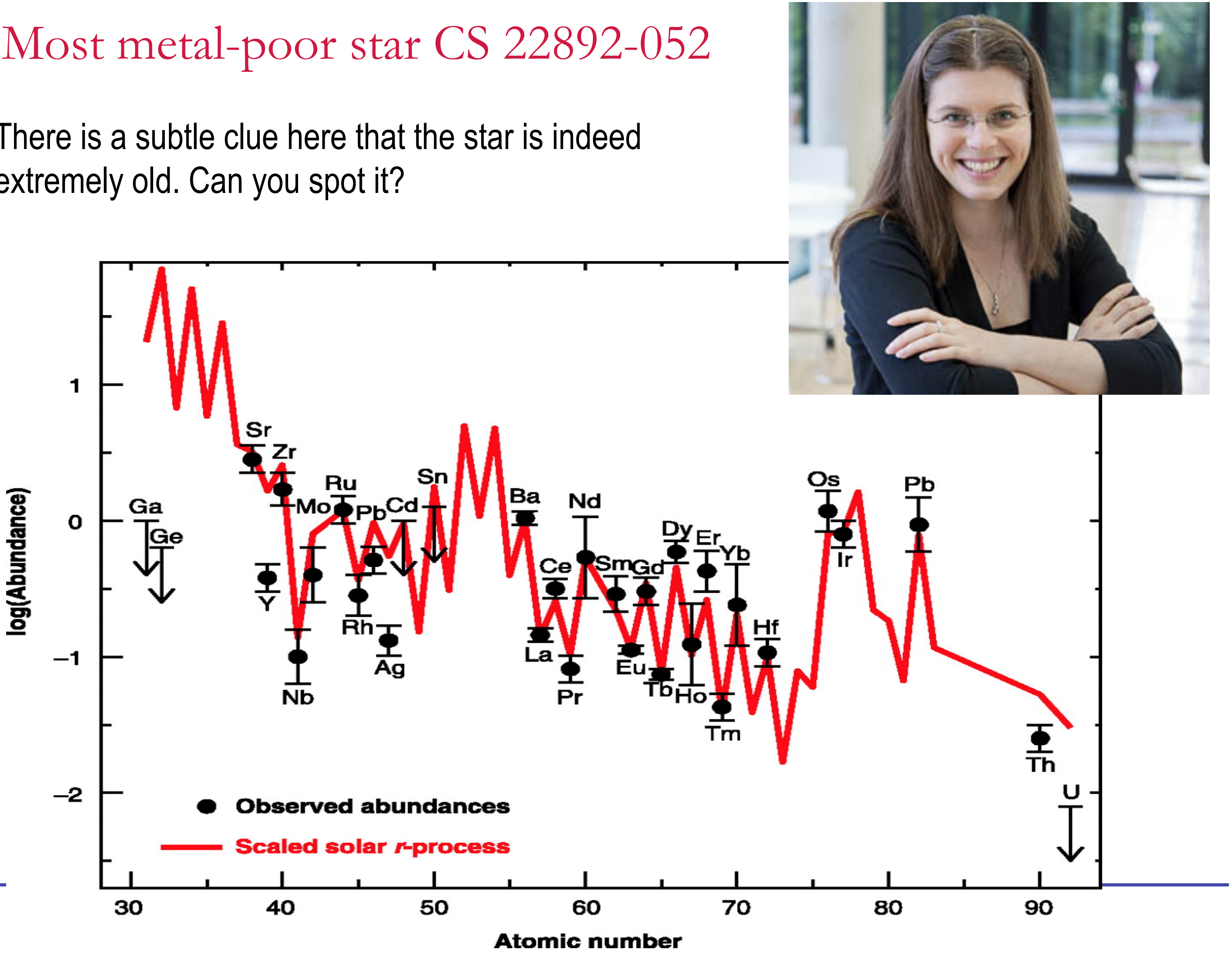
Faint dwarf

Globular cluster:

These are a puzzle. [Fe/H] = -1.5 but many are >12 Gyr old!

Most metal-poor star CS 22892-052

There is a subtle clue here that the star is indeed extremely old. Can you spot it?



HERMES @ AAT (first light 2013B)

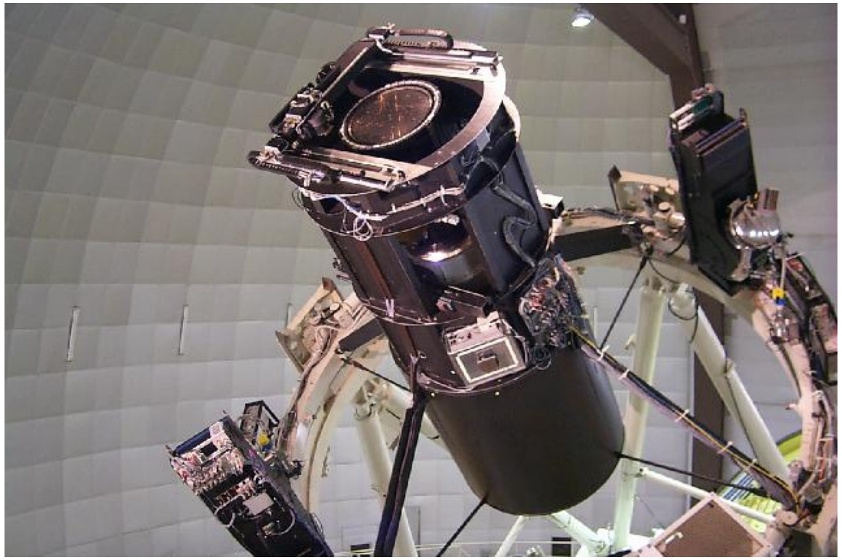
First of a new generation of Galactic Archaeology machines (e.g. Gaia, 4MOST)

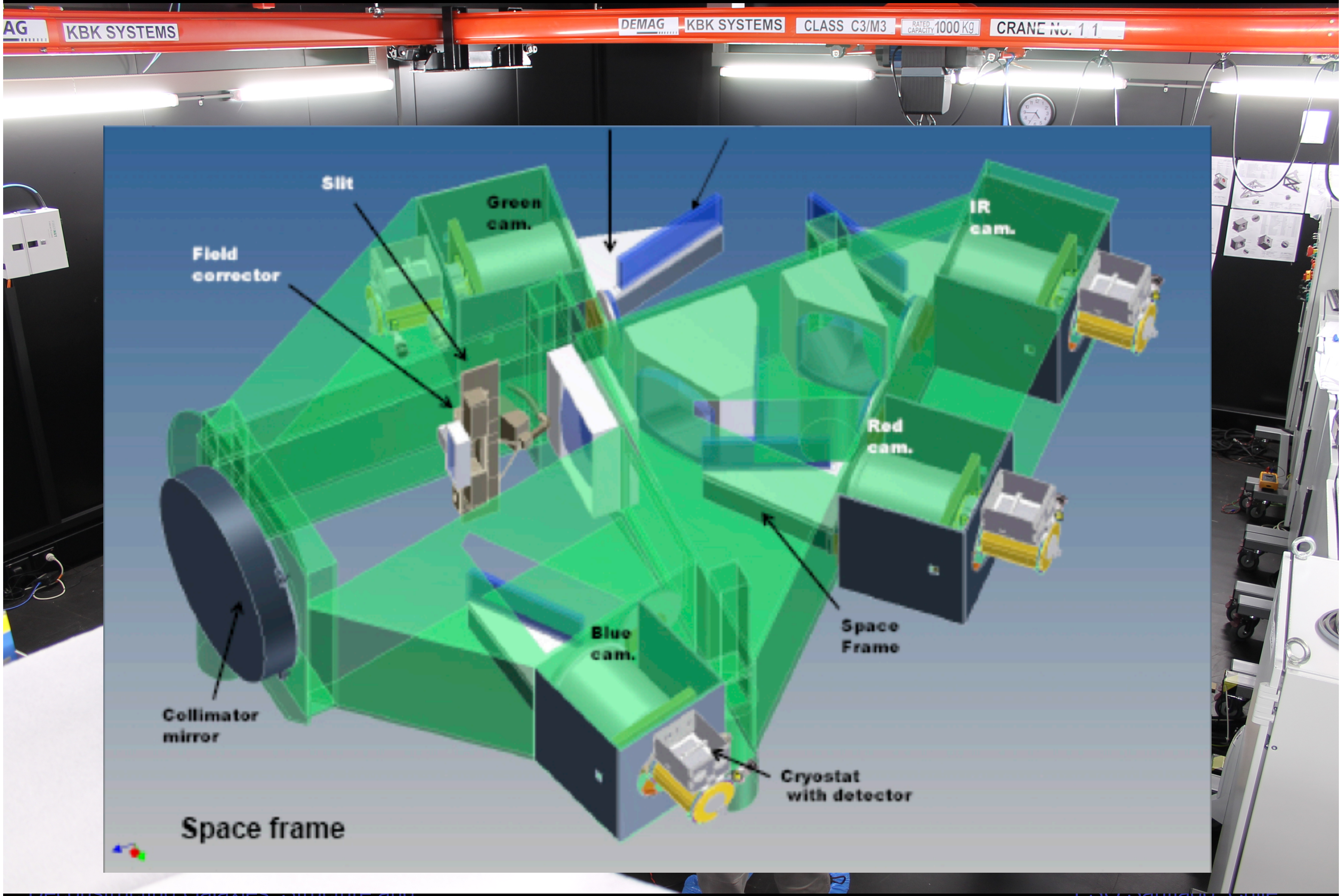
\$10M investment up front: 400 fibres over 2° field

New \$12M 4-arm spectrograph, R=28000, 1000A in 4 bands across *bvri*

Team of about 40 (~Australian) astronomers

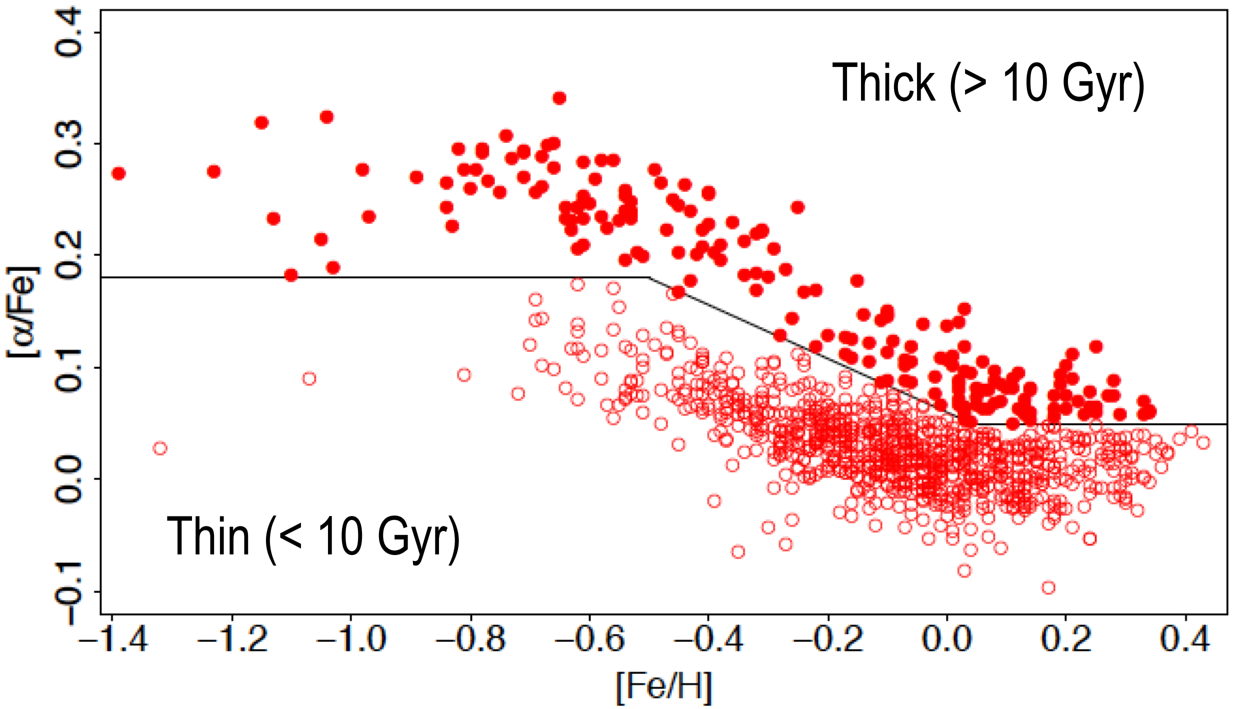
Will measure 30 chemical elements in 1-2 million stars over the next 5-10 yrs

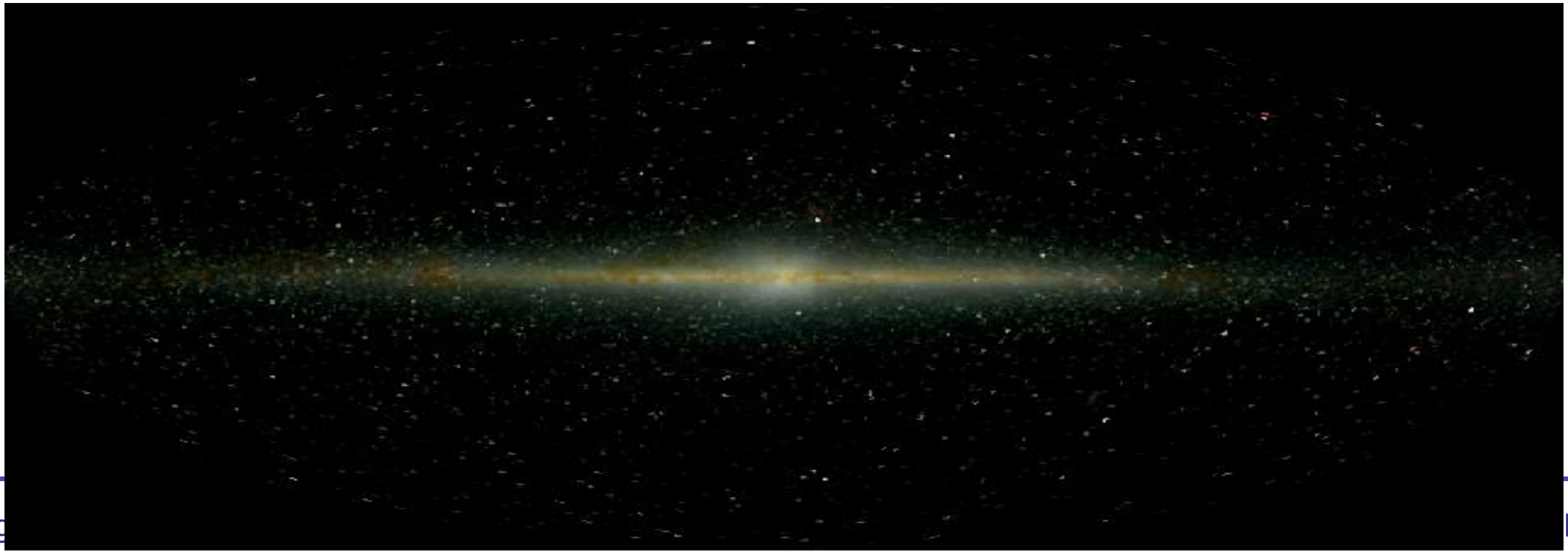



AG
KBK SYSTEMS
DEMAG
KBK SYSTEMS
CLASS C3/M3
RATED CAPACITY 1000 Kg
CRANE No. 1 1
Slit
Green cam.
Field corrector
IR cam.
Red cam.
Space Frame
Blue cam.
Collimator mirror
Cryostat with detector
Space frame

Thick disk:

Nice example of where age and chemistry are intimately coupled





Summary

- The Galaxy will always be the essential underpinning to astrophysics because of its proximity:
  - Chemistry of the First Stars
  - Stellar astrophysics, ages
  - Star formation, molecular astrophysics
  - Black hole evolution
  - Feedback & accretion processes
  - Secular processes

$$\Theta_0 = 234 \pm 13 \text{ km s}^{-1}.$$ (A

Traditionally, one invokes the Oort model to infer the circular speed, but Olling & Dehnen (2003) find that the current best res depends substantially on the stellar populations used in the analysis.

The circular velocity yields an estimate of the optical luminosity of the Milky Way via the Tully-Fisher relation. To convert optically measured maximum rotation velocity $V_{\rm rot}$ to the 20% line width of H I measurements W_{20}, we use the relation

$$W_{20}/2 = (0.93 \pm 0.02)V_{\rm rot} + 27 \pm 1.5 \text{ km s}^{-1},$$ (A

derived from the data given by Mathewson & Ford (1996). From the Galactic rotation curve from H I and CO terminal velocit (using Fig. 9.17 of Binney & Merrifield 1998), we estimate that the maximum rotation velocity of the Milky Way is $V_{\rm max}$ $1.03\Theta_0 = 241 \pm 13$ km s^{-1}. Identifying $V_{\rm max} = V_{\rm rot}$, we find

$$W_{20}(\text{MW}) = 502 \pm 30 \text{ km s}^{-1}.$$ (A

From the *COBE* DIRBE integrated light for the Milky Way in the near infrared (J, K, L) wavelength bands, Malhotra et al. (19 showed that the Milky Way is on the standard Tully-Fisher relation in these wavelength bands, slightly on the brighter side within the dispersion around the relation. Assuming that the Milky Way has the standard color of spiral galaxies, we may expect the luminosity in the B band also satisfies the Tully-Fisher relation for the B band. Using the Sakai et al. (2000) local calibrati

$$M_{B_T^c} = -19.80 - 7.97(\log W_{20} - 2.5),$$ (A

we find

$$L_{B^c}(\text{MW}) = 10^{10.74 \pm 0.19}\ L_\odot,$$ (A

where we use $B_\odot = 5.46$ and the error is dominated by the intrinsic dispersion (0.43 mag) of the B-band Tully-Fisher relation. T superscript c stands for extinction-free quantities.

An alternative estimate of the B-band luminosity uses the color transformation applied to the DIRBE integrated K-band lu nosity of the Milky Way. A comparison of the samples of Malhotra et al. (1996) and Sakai et al. (2000) indicates $B_T^c - K^c$ 2.84 ± 0.10 for typical Sbc galaxies. Thus, $K^c(\text{MW}) = -23.95 \pm 0.25$ yields $B_T^c = -21.1 \pm 0.3$, or

$$L_{B^c}(\text{MW}) = 10^{10.63 \pm 0.13}\ L_\odot.$$ (A

Combining the two, our recommended value is

$$L_{B^c}(\text{MW}) = (4.6 \pm 1.4) \times 10^{10}\ L_\odot.$$ (A