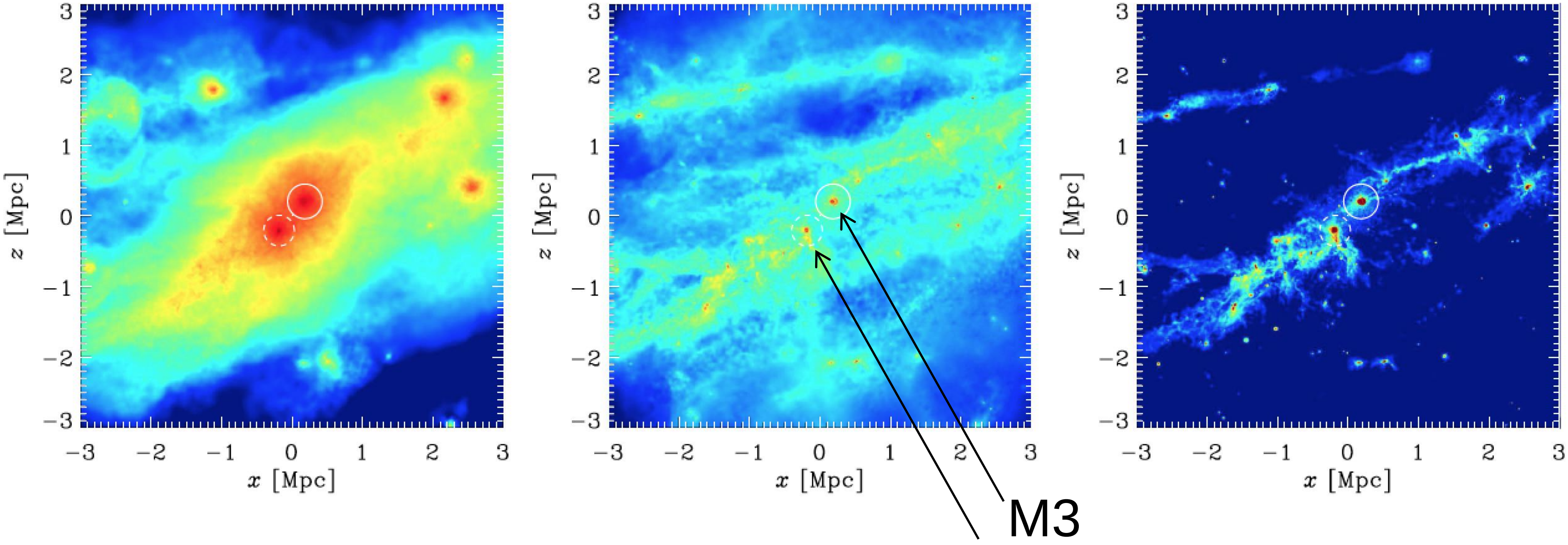
Where do galaxy disks end?

Joss Bland-Hawthorn

Galaxy formation – the grandest of all environmental sciences

Hot (>10^5 K) Warm (<10^5 K) HI (21cm)



M31

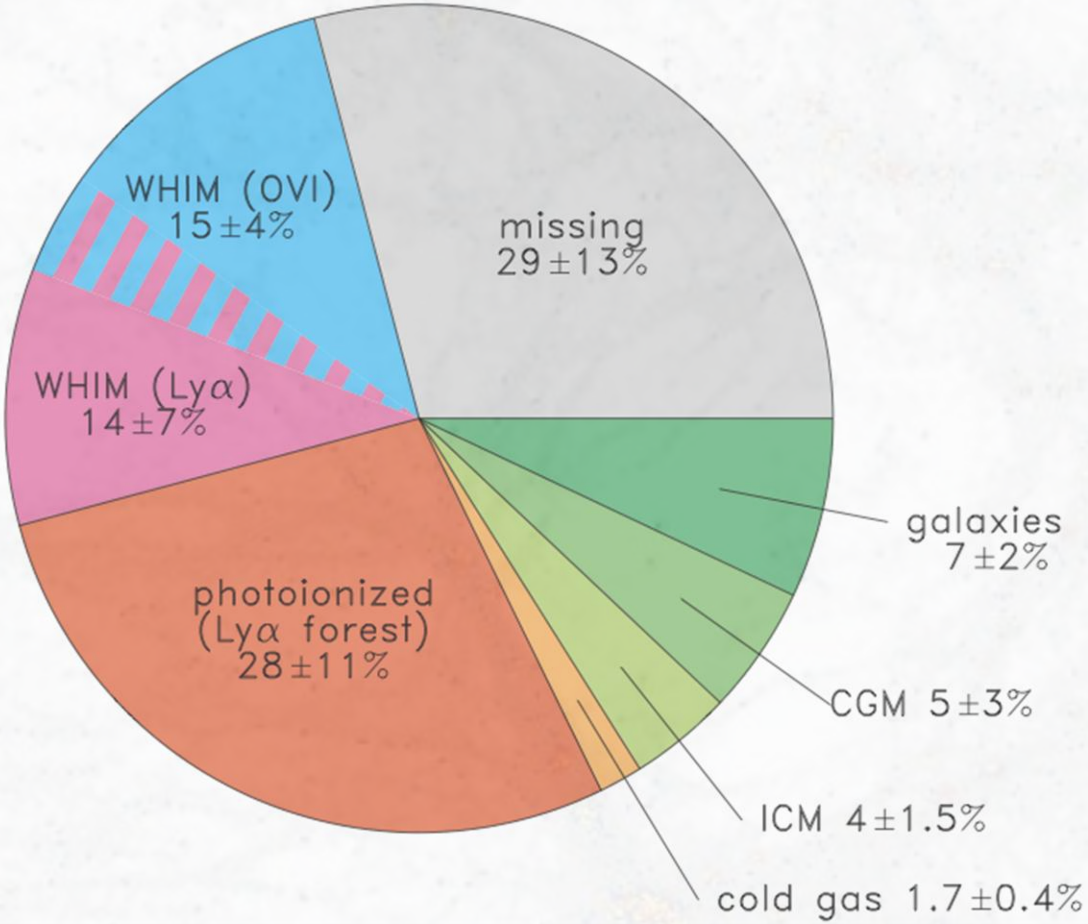
Galaxy

CLUES collaboration (Nuza+ 2014)

Baryon census (z~0)

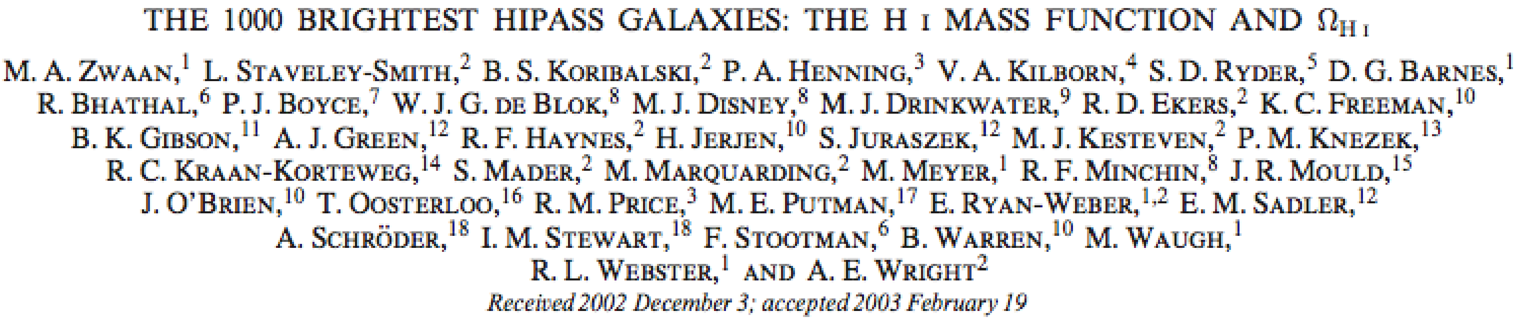
WARNING:
fixed cosmic abundances

This is a real problem since we don't know how metals vary between ISM and IGM



Most recent summary
from Shull+ 2013

COLD GAS (1.7%)



THE 1000 BRIGHTEST HIPASS GALAXIES: THE H I MASS FUNCTION AND $\Omega_{\rm H\,I}$

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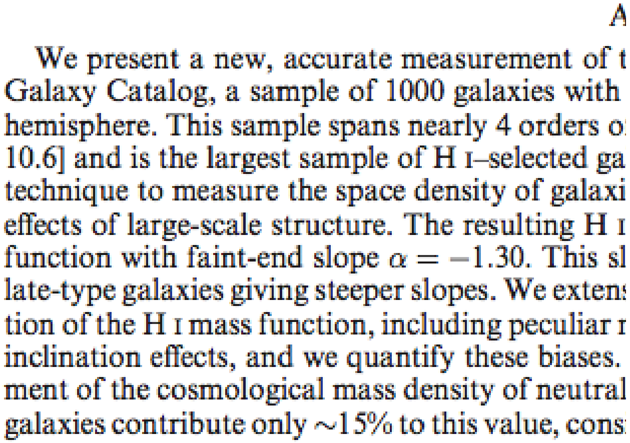
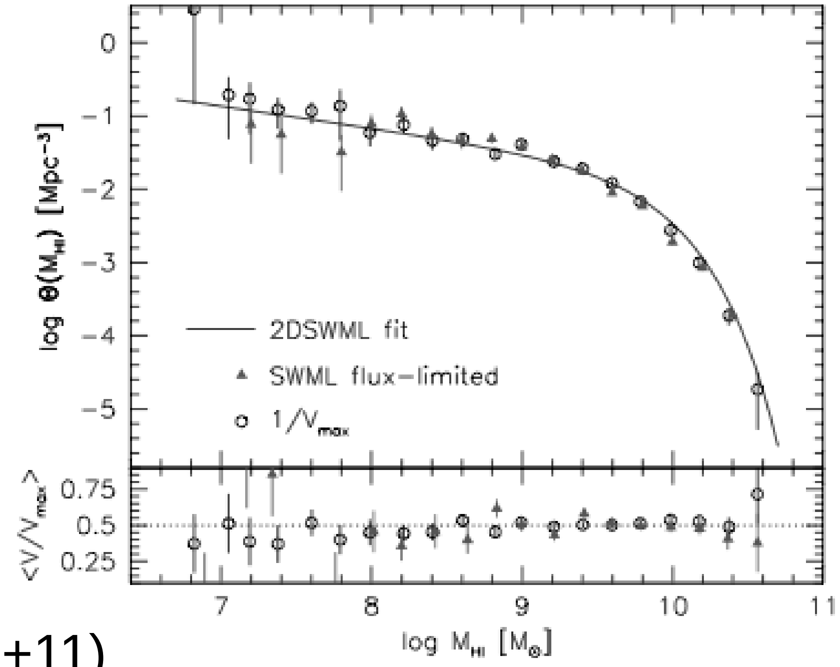
Received 2002 December 3; accepted 2003 February 19



A

We present a new, accurate measurement of t
Galaxy Catalog, a sample of 1000 galaxies with
hemisphere. This sample spans nearly 4 orders o
10.6] and is the largest sample of H I–selected ga
technique to measure the space density of galaxi
effects of large-scale structure. The resulting H I
function with faint-end slope $\alpha = -1.30$. This sl
late-type galaxies giving steeper slopes. We extens
tion of the H I mass function, including peculiar r
inclination effects, and we quantify these biases.
ment of the cosmological mass density of neutral
galaxies contribute only ∼15% to this value, cons

corrected for cold He I, H_2 (FP04)

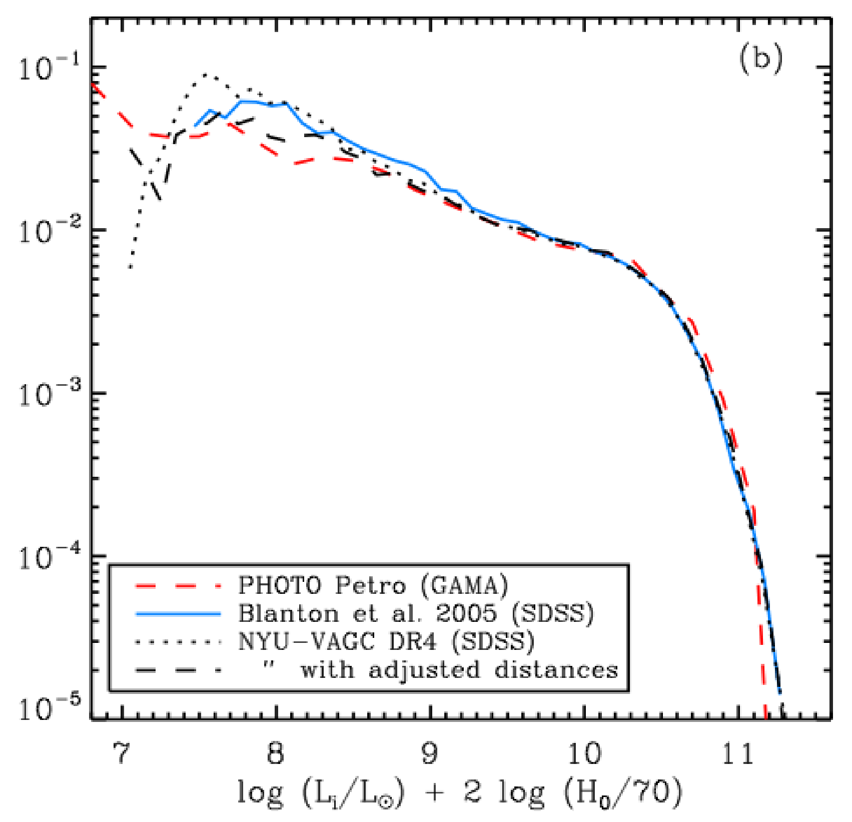


Confirmation: ALFALFA survey (Darling+11)

GALAXIES (7% + 1.7%)

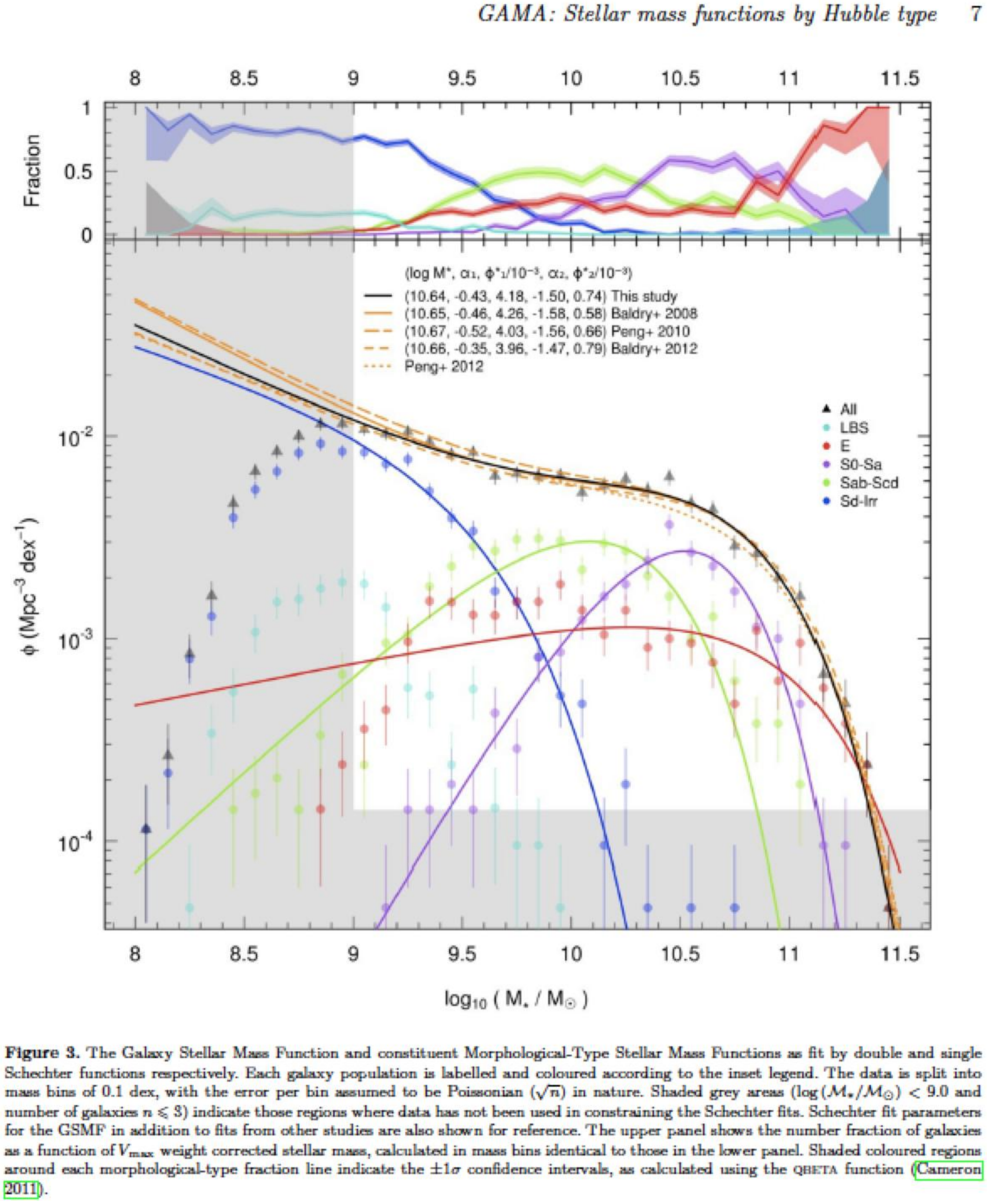
Large galaxy surveys of the local universe – 2dFGRS (Colless+ 2001), SDSS (Blanton+ 2001), GAMA (Driver+ 2012)

GF favours disks over sphero
 2:1 (Driver+ 07; cf. FHP 96)



Galaxy LFs are composites

GAMA survey (Kelvin+ 2014)



GAMA: Stellar mass functions by Hubble type 7

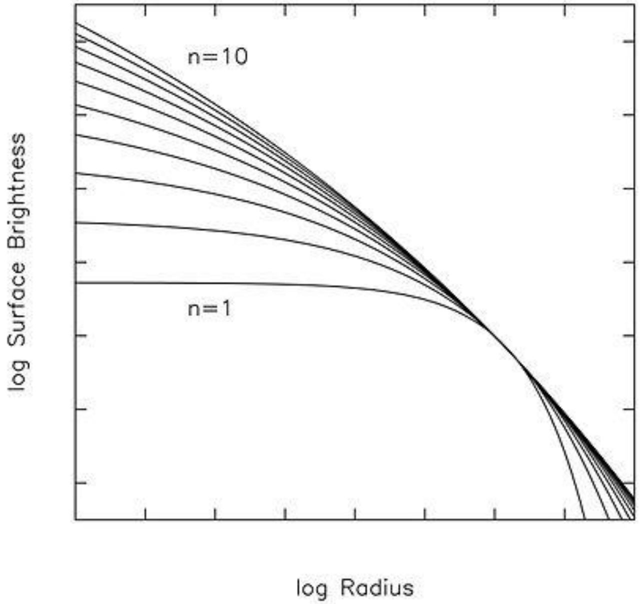
Figure 3. The Galaxy Stellar Mass Function and constituent Morphological-Type Stellar Mass Functions as fit by double and single Schechter functions respectively. Each galaxy population is labelled and coloured according to the inset legend. The data is split into mass bins of 0.1 dex, with the error per bin assumed to be Poissonian ($\sqrt{n}$) in nature. Shaded grey areas ($\log(\mathcal{M}_*/\mathcal{M}_\odot) < 9.0$ and number of galaxies $n \leqslant 3$) indicate those regions where data has not been used in constraining the Schechter fits. Schechter fit parameters for the GSMF in addition to fits from other studies are also shown for reference. The upper panel shows the number fraction of galaxies as a function of $V_{\rm max}$ weight corrected stellar mass, calculated in mass bins identical to those in the lower panel. Shaded coloured regions around each morphological-type fraction line indicate the $\pm 1\sigma$ confidence intervals, as calculated using the QBETA function (Cameron 2011).

Sersic profile (1963)

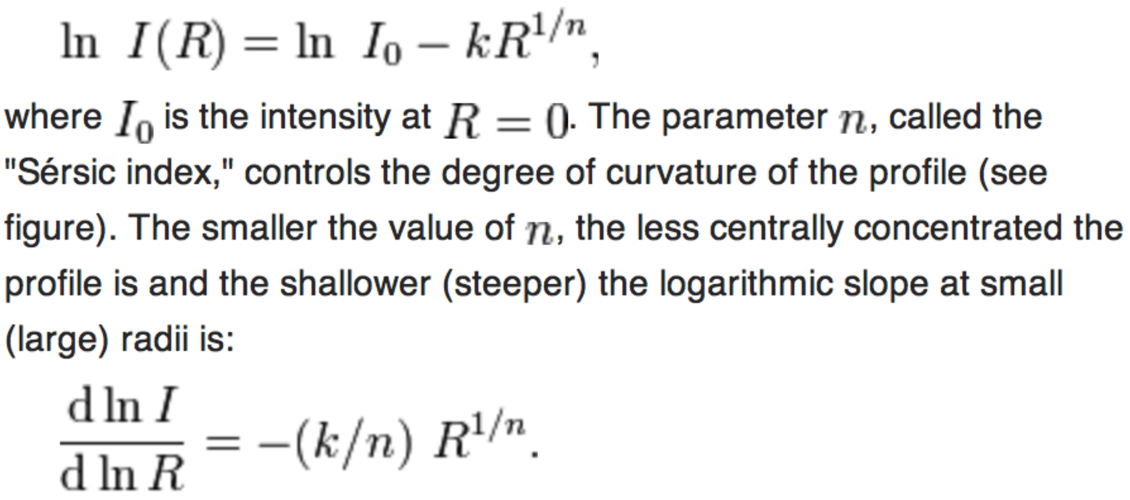
- How are we able to separate spheroids from disks for all galaxies ?

spheroid-like, n ~ 4

disk-like, n ~ 1



The Sérsic profile has the form



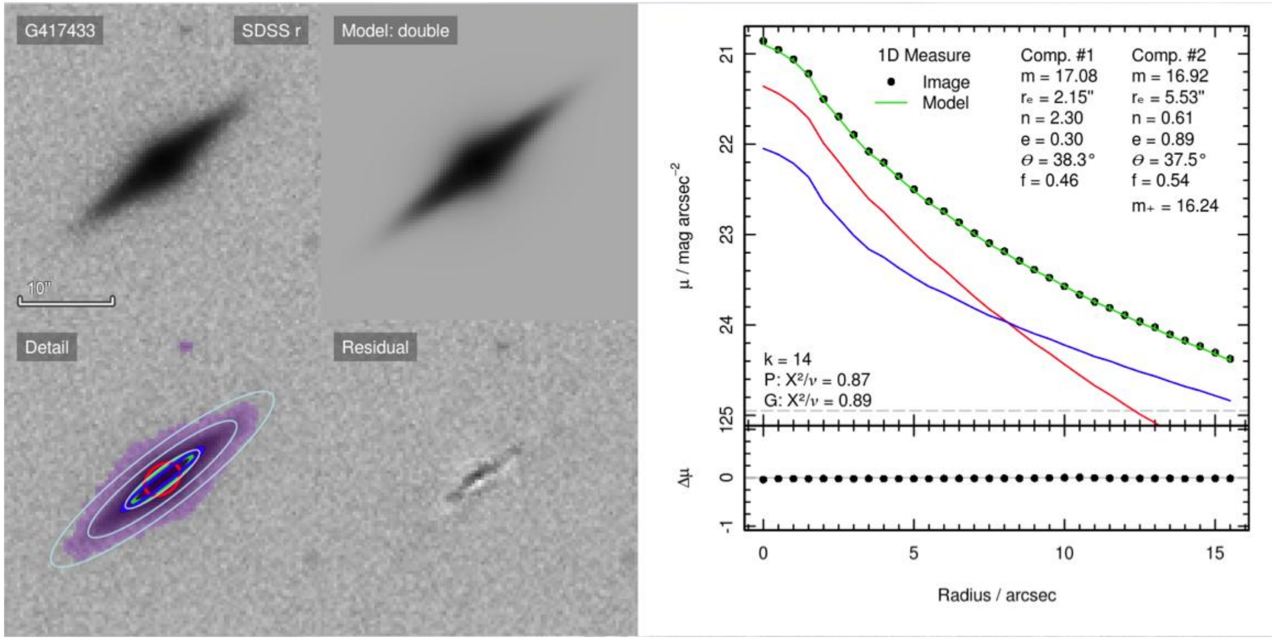
$$\ln\ I(R) = \ln\ I_0 - kR^{1/n},$$

where I_0 is the intensity at $R = 0$. The parameter n, called the "Sérsic index," controls the degree of curvature of the profile (see figure). The smaller the value of n, the less centrally concentrated the profile is and the shallower (steeper) the logarithmic slope at small (large) radii is:

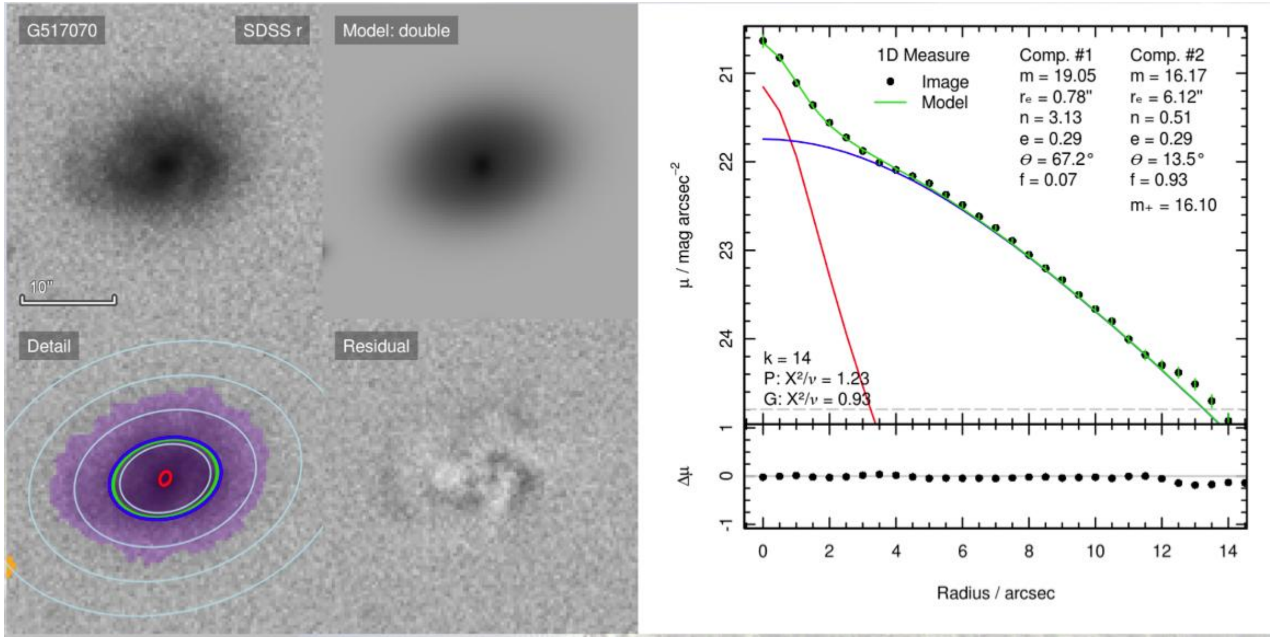
$$\frac{d\ln I}{d\ln R} = -(k/n)\ R^{1/n}.$$

What is n=½ ?

Einasto profile: mathematically identical except *I* is replaced by local density, and projected *R* is replaced by *r*, true radius.



Edge-on disk



Face-on disk

GAMA Survey
Driver+ 2015

Baryon census - overview

Collapsed baryons (18%)

Uncollapsed baryons (82%)

2013 baryon census

- Galaxies
- Cold gas
- ICM

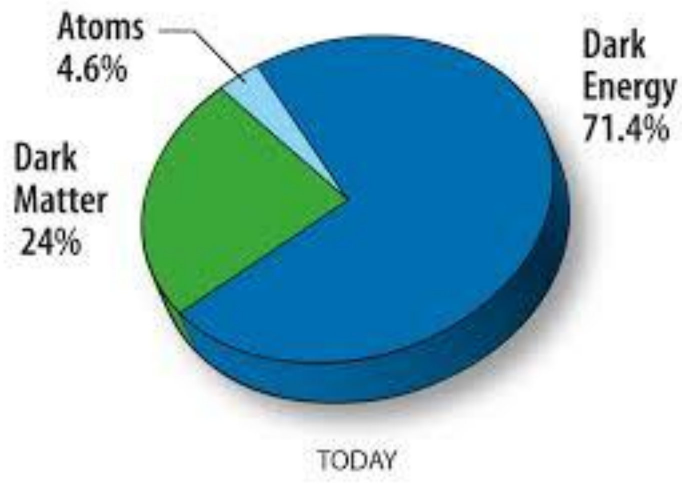
collapsed

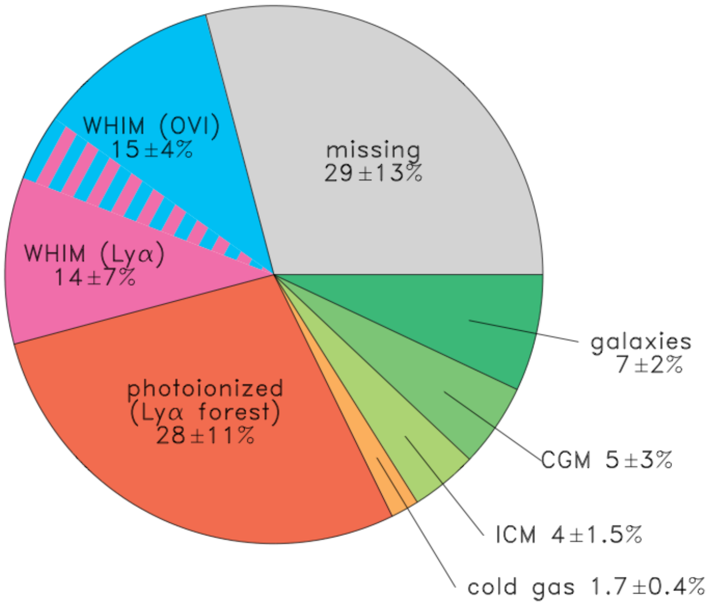
- CGM

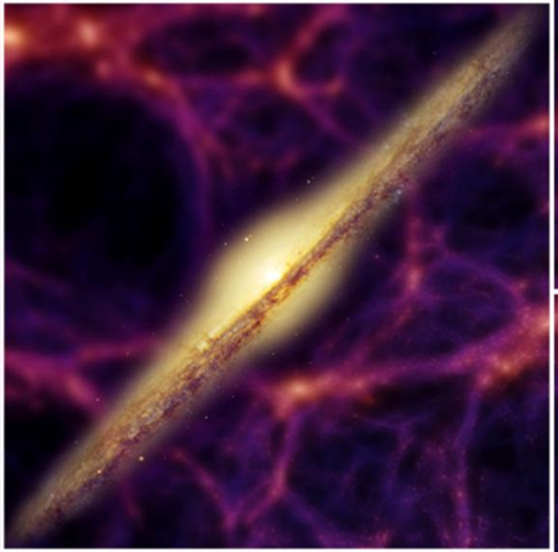
transition

- LyaF
- WHIM
- ? missing ?

uncollapsed

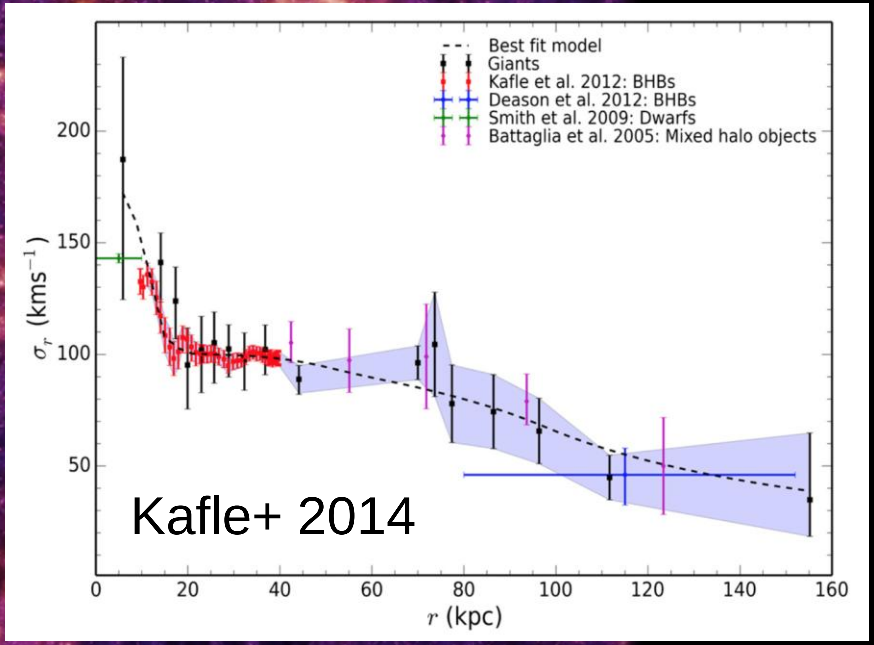






Today, the correct context for disk formation is within ΛCDM.

>95% stars in disk+bulge with trace amount in halo:

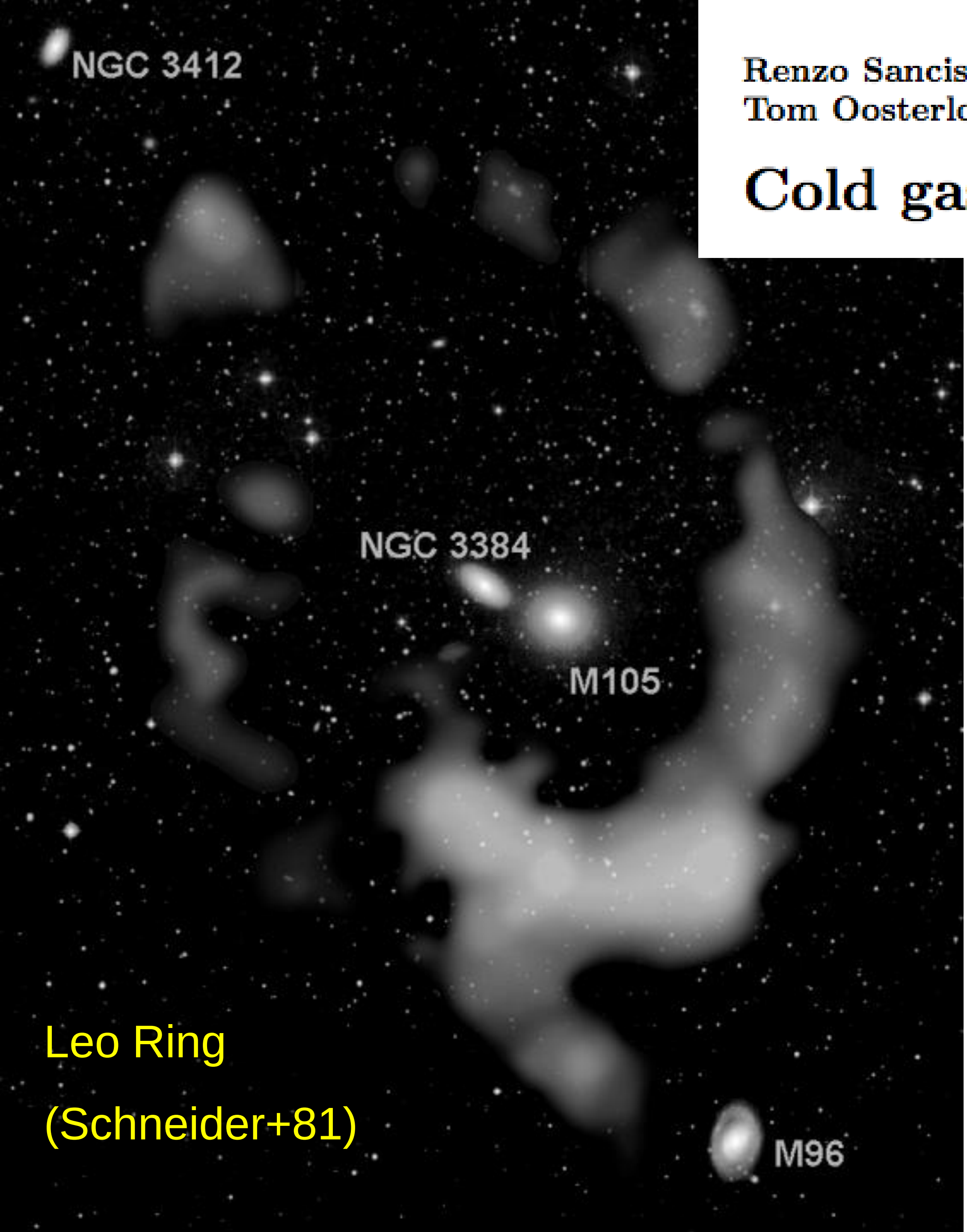


Kafle+ 2014

What about the gas?

Renzo Sancisi · Filippo Fraternali ·
Tom Oosterloo · Thijs van der Hulst

Cold gas accretion in galaxies



Leo Ring

(Schneider+81)

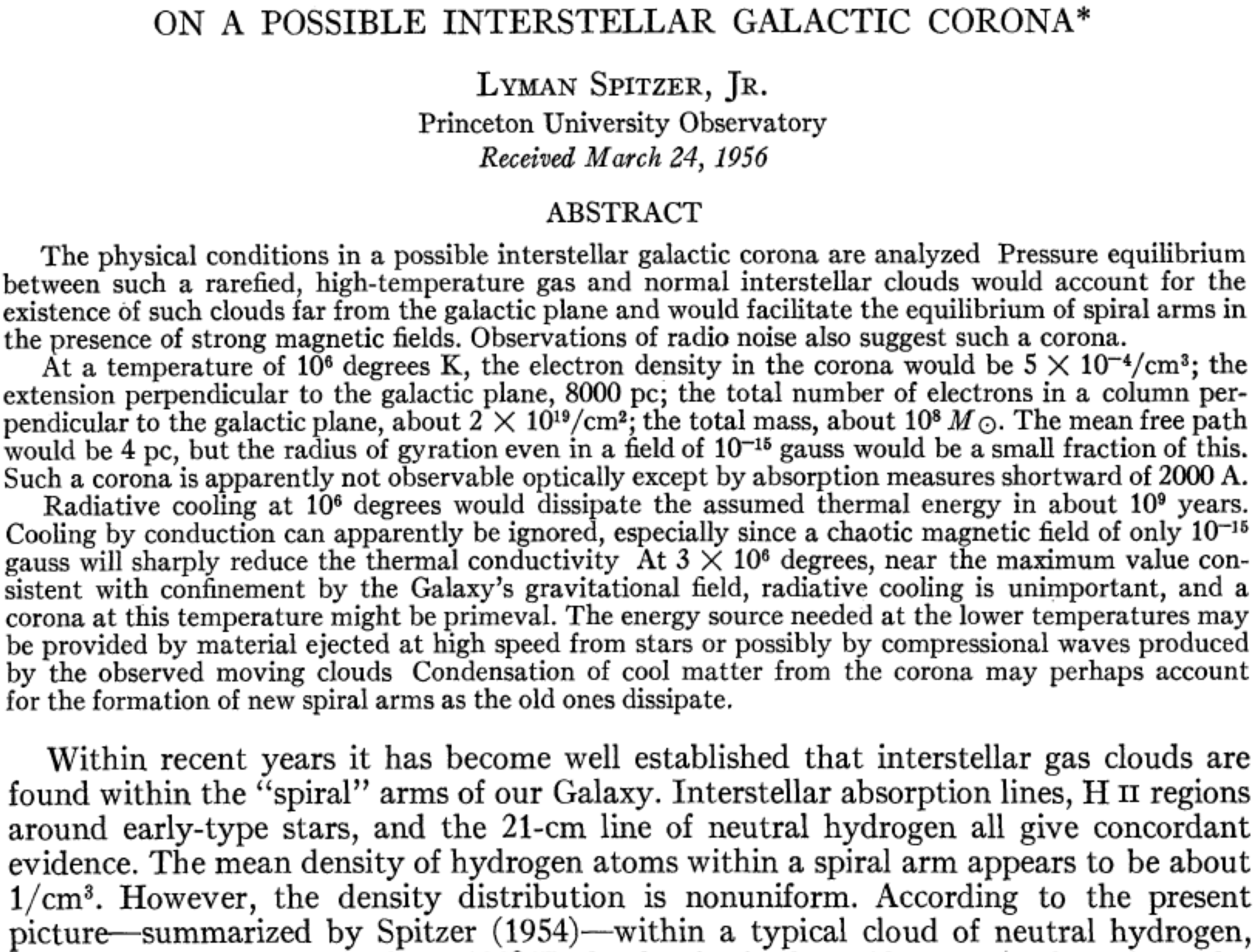
All cold gas is associated (<100 kpc) with galaxies i.e. dark matter.

e.g. tidal tails like Magellanic Stream.

If you can find a truly isolated cloud, it will be named after you!

COLD GAS (1.7%)

The Galaxy – classic paper (followed by Kahn & Woltjer 1959 for the LG)



ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

Lyman Spitzer, Jr.
Princeton University Observatory

Received March 24, 1956

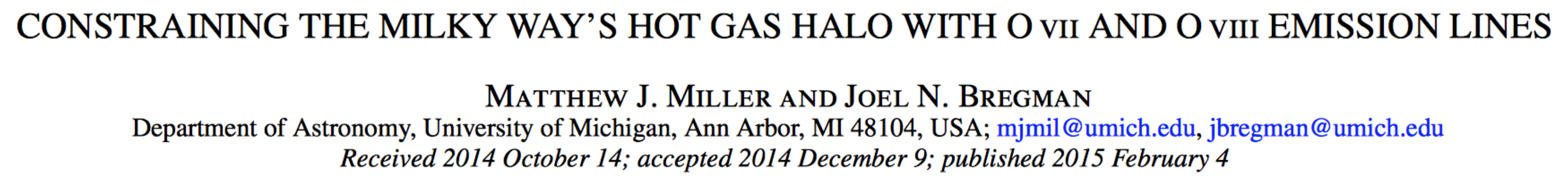
ABSTRACT

The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

At a temperature of 10^6 degrees K, the electron density in the corona would be $5 \times 10^{-4}/\mathrm{cm}^3$; the extension perpendicular to the galactic plane, 8000 pc; the total number of electrons in a column perpendicular to the galactic plane, about $2 \times 10^{19}/\mathrm{cm}^2$; the total mass, about $10^8\, M_\odot$. The mean free path would be 4 pc, but the radius of gyration even in a field of 10^{-15} gauss would be a small fraction of this. Such a corona is apparently not observable optically except by absorption measures shortward of 2000 A.

Radiative cooling at 10^6 degrees would dissipate the assumed thermal energy in about 10^9 years. Cooling by conduction can apparently be ignored, especially since a chaotic magnetic field of only 10^{-15} gauss will sharply reduce the thermal conductivity At 3×10^6 degrees, near the maximum value consistent with confinement by the Galaxy's gravitational field, radiative cooling is unimportant, and a corona at this temperature might be primeval. The energy source needed at the lower temperatures may be provided by material ejected at high speed from stars or possibly by compressional waves produced by the observed moving clouds Condensation of cool matter from the corona may perhaps account for the formation of new spiral arms as the old ones dissipate.

Within recent years it has become well established that interstellar gas clouds are found within the "spiral" arms of our Galaxy. Interstellar absorption lines, H II regions around early-type stars, and the 21-cm line of neutral hydrogen all give concordant evidence. The mean density of hydrogen atoms within a spiral arm appears to be about $1/\mathrm{cm}^3$. However, the density distribution is nonuniform. According to the present picture—summarized by Spitzer (1954)—within a typical cloud of neutral hydrogen,



CONSTRAINING THE MILKY WAY'S HOT GAS HALO WITH O VII AND O VIII EMISSION LINES

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Received 2014 October 14; accepted 2014 December 9; published 2015 February 4

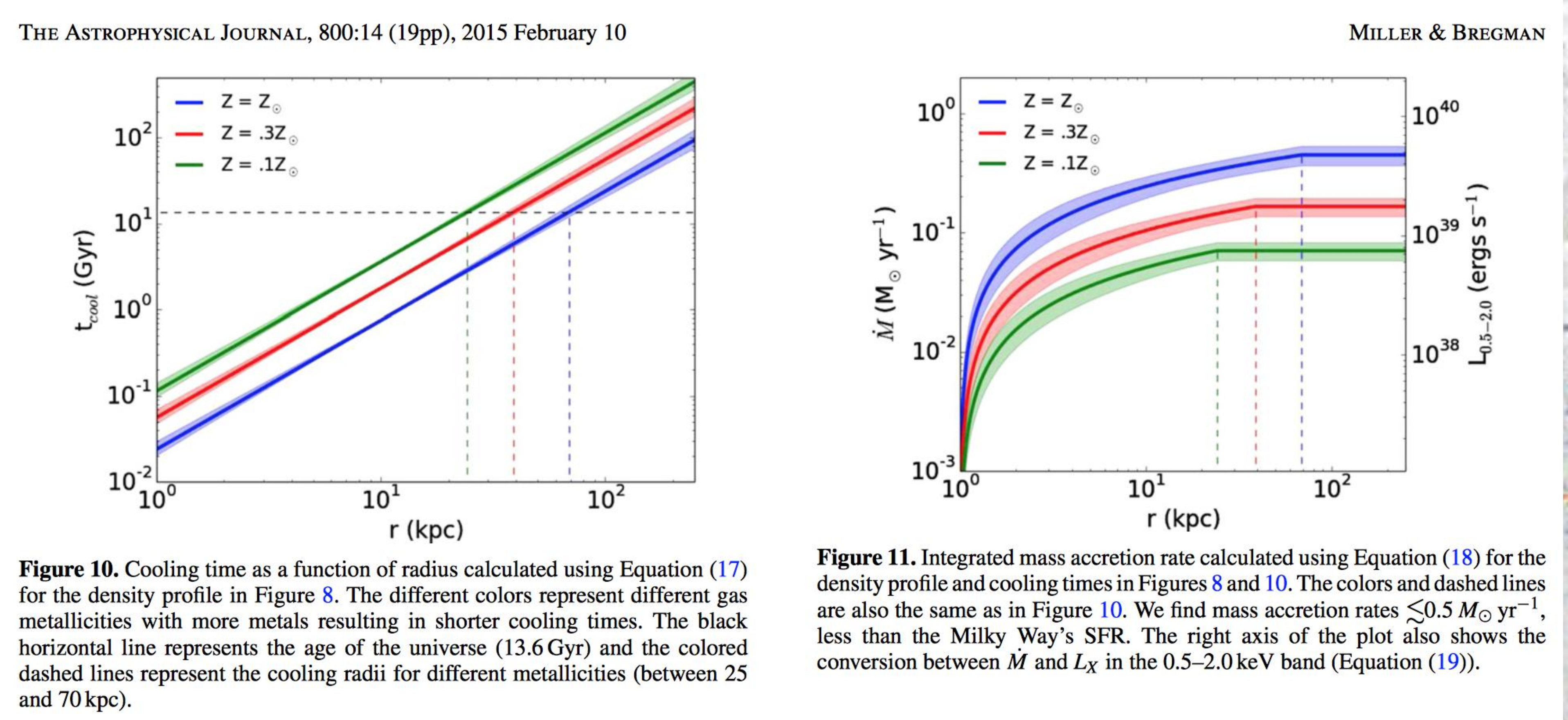
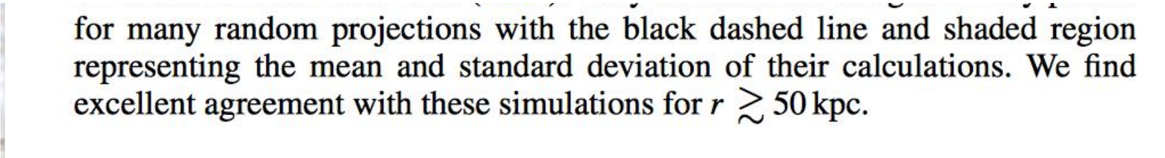


Figure 10. Cooling time as a function of radius calculated using Equation (17) for the density profile in Figure 8. The different colors represent different gas metallicities with more metals resulting in shorter cooling times. The black horizontal line represents the age of the universe (13.6 Gyr) and the colored dashed lines represent the cooling radii for different metallicities (between 25 and 70 kpc).

Figure 11. Integrated mass accretion rate calculated using Equation (18) for the density profile and cooling times in Figures 8 and 10. The colors and dashed lines are also the same as in Figure 10. We find mass accretion rates $\lesssim 0.5\ M_\odot\ \mathrm{yr}^{-1}$, less than the Milky Way's SFR. The right axis of the plot also shows the conversion between $\dot{M}$ and L_X in the 0.5–2.0 keV band (Equation (19)).

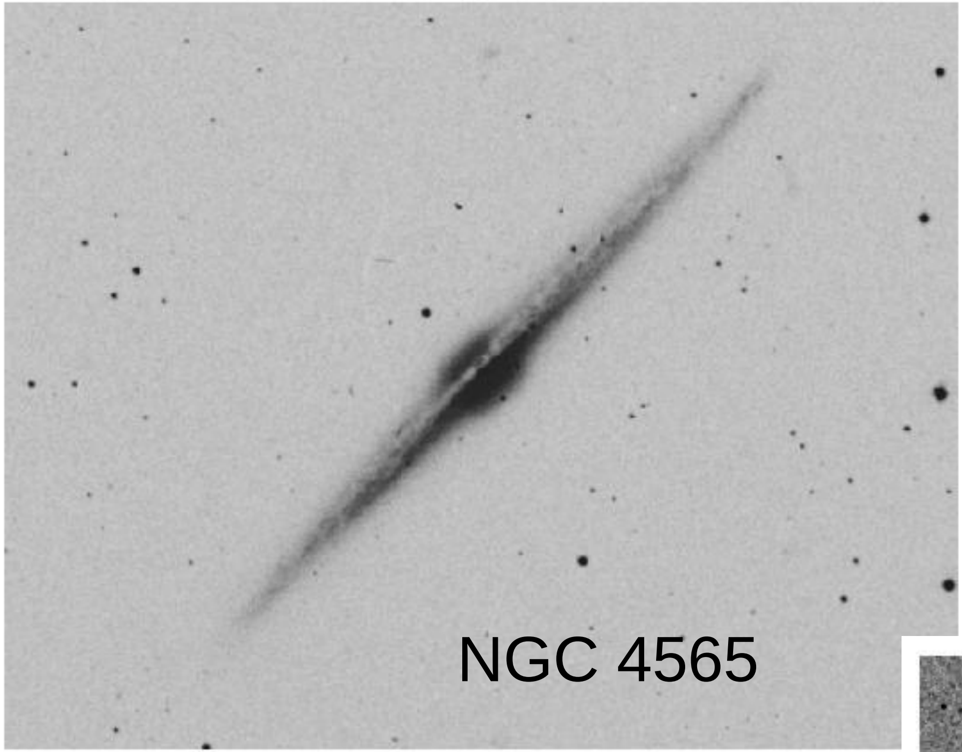


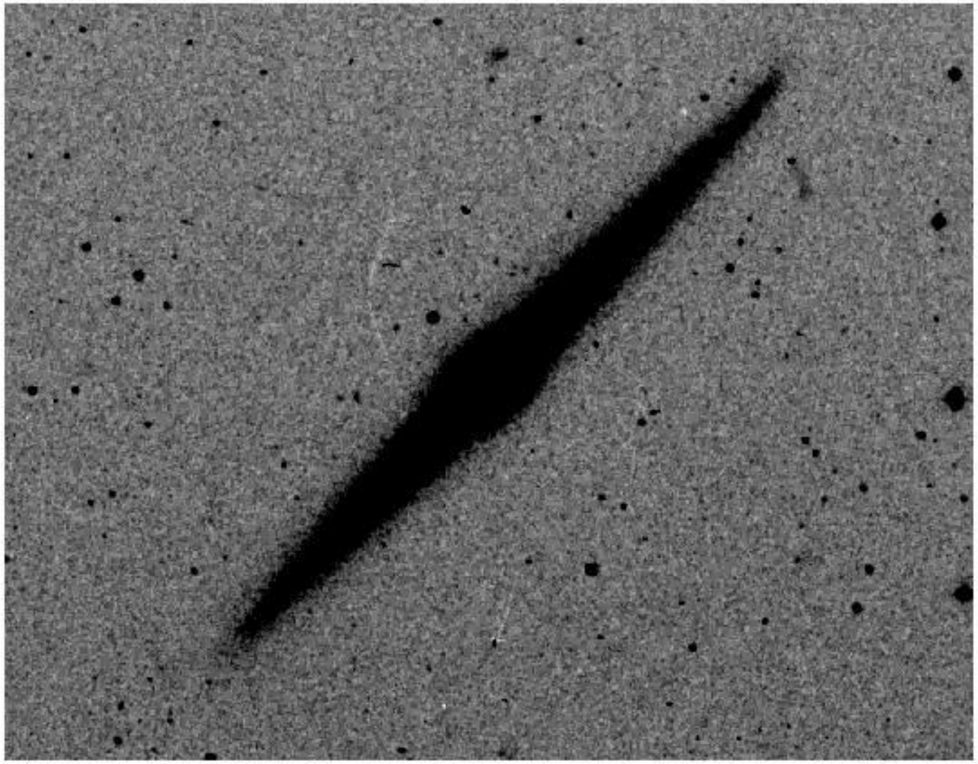
for many random projections with the black dashed line and shaded region representing the mean and standard deviation of their calculations. We find excellent agreement with these simulations for $r \gtrsim 50$ kpc.

CGM – hot gas (5%)

Cooling hot gas in the halo cannot easily account for ongoing star formation in stellar disks

Stellar disks seem to truncate but do they?





This was the general view until recently.

What does truncation mean ?

Matter moves in ~ circular orbits, and angular momentum increases outwards, so the surface brightness cut-off represents stars moving with the highest specific angular momentum ***j*** in the stellar disk.

This **may** reflect the maximum value of ***j*** for baryonic material in the original "protocloud".

That *would* be interesting.

What does truncation mean ?

e.g. say the protogalaxy is a uniform density sphere, rotating rigidly. Let $M(j)$ be the mass with specific angular momentum $< j$. Then

$$M(j)/M = 1 - (1 - j/j_{max})^{3/2}$$

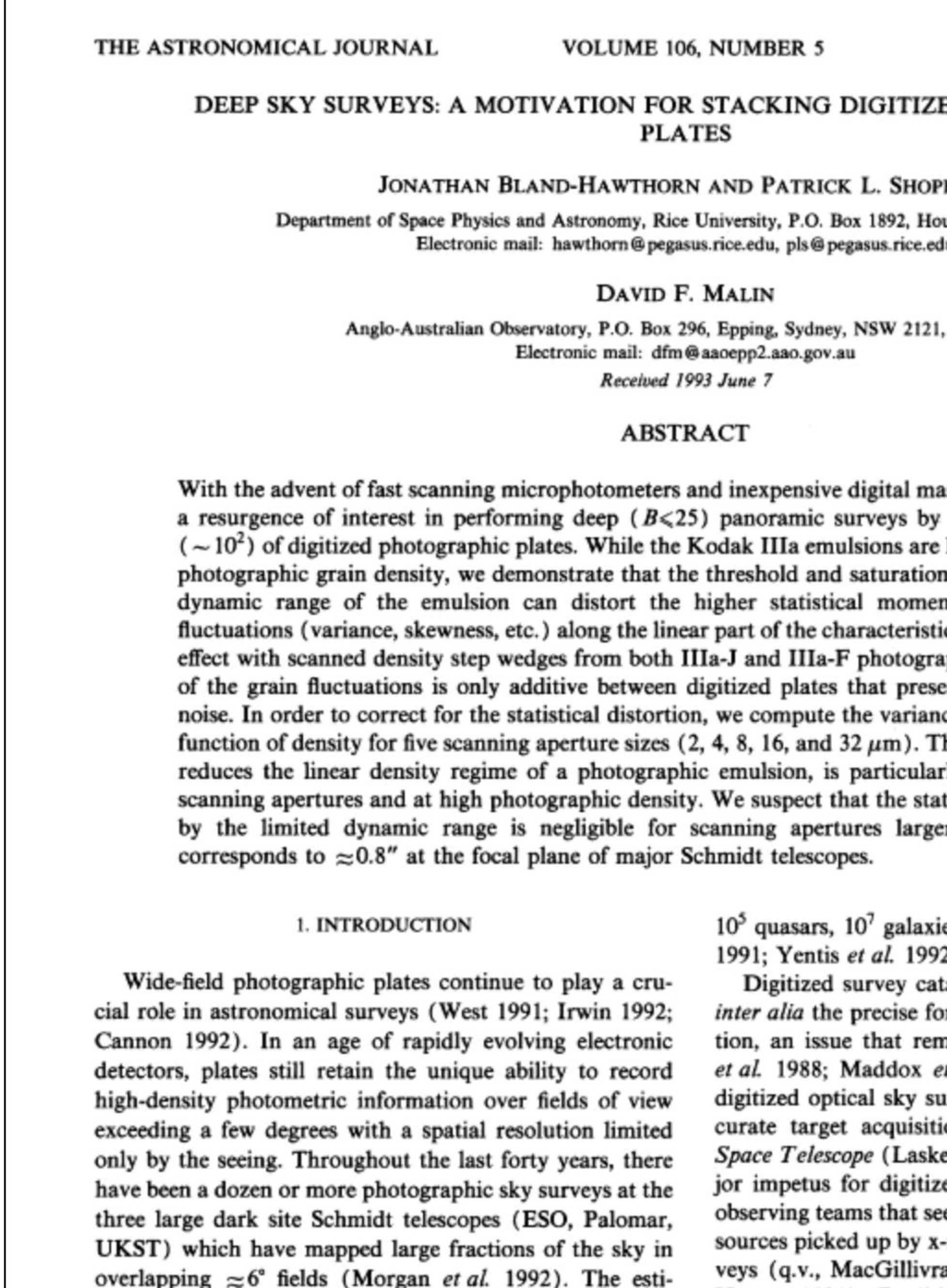
where j_{max} is the maximum specific angular momentum: i.e. the value of j at the surface of the sphere on its equator.

If this uniform sphere settles to a flat disk with a flat rotation curve $V_{rot} = V_m$, conserving $M(j)$, then this disk turns out to be close to exponential, with scale length $h = j_{max}/4.5V_m$

Then the maximum radius of the disk (where $j = j_{max}$) is $R_{max} \simeq 4.5h$, close to what is observed.

Mestel (1963); van der Kruit (2001)

1990s: stacked plates can get to fuzz @ <28 mag arcsec^{-2}



THE ASTRONOMICAL JOURNAL VOLUME 106, NUMBER 5 NOVEMBER 1993

DEEP SKY SURVEYS: A MOTIVATION FOR STACKING DIGITIZED PHOTOGRAPHIC PLATES

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Received 1993 June 7

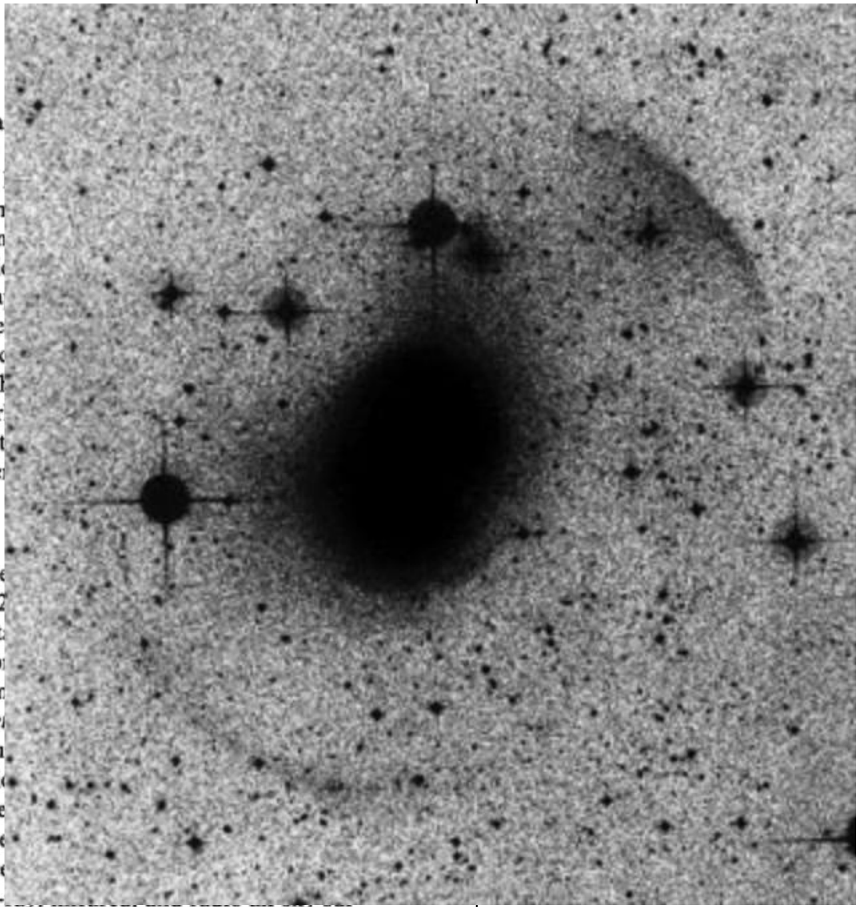
ABSTRACT

With the advent of fast scanning microphotometers and inexpensive digital ma
a resurgence of interest in performing deep ($B<25$) panoramic surveys by
($\sim 10^2$) of digitized photographic plates. While the Kodak IIIa emulsions are
photographic grain density, we demonstrate that the threshold and saturation
dynamic range of the emulsion can distort the higher statistical momen
fluctuations (variance, skewness, etc.) along the linear part of the characteristi
effect with scanned density step wedges from both IIIa-J and IIIa-F photogra
of the grain fluctuations is only additive between digitized plates that prese
noise. In order to correct for the statistical distortion, we compute the varianc
function of density for five scanning aperture sizes (2, 4, 8, 16, and 32 μm). Tl
reduces the linear density regime of a photographic emulsion, is particular
scanning apertures and at high photographic density. We suspect that the stat
by the limited dynamic range is negligible for scanning apertures large
corresponds to $\approx 0.8''$ at the focal plane of major Schmidt telescopes.

1. INTRODUCTION

Wide-field photographic plates continue to play a crucial role in astronomical surveys (West 1991; Irwin 1992; Cannon 1992). In an age of rapidly evolving electronic detectors, plates still retain the unique ability to record high-density photometric information over fields of view exceeding a few degrees with a spatial resolution limited only by the seeing. Throughout the last forty years, there have been a dozen or more photographic sky surveys at the three large dark site Schmidt telescopes (ESO, Palomar, UKST) which have mapped large fractions of the sky in overlapping $\approx 6°$ fields (Morgan *et al.* 1992). The esti-

10^5 quasars, 10^7 galaxi
1991; Yentis *et al.* 1992
Digitized survey cat
inter alia the precise fo
tion, an issue that rem
et al. 1988; Maddox *e*
digitized optical sky su
curate target acquisiti
Space Telescope (Laske
jor impetus for digitiz
observing teams that se
sources picked up by x-
veys (q.v., MacGillivray & Thomson 1992; Giovanelli &



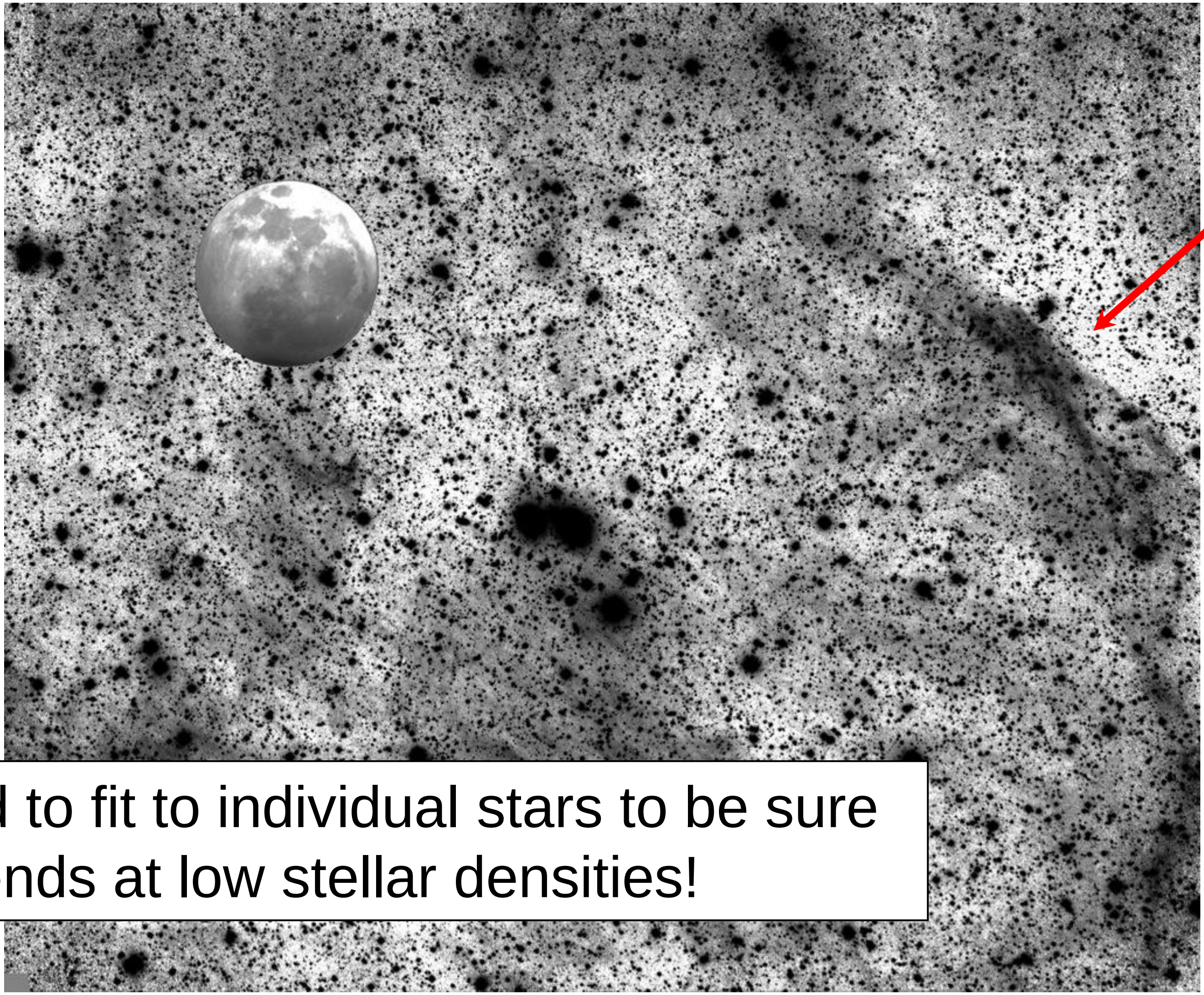
2010s:

Deep CCD imaging from CFHT

(Duc et al 2014)

Can get to fuzz @ <30 mag arcsec^{-2} but sky problem

Galactic cirrus (dust)



major problem

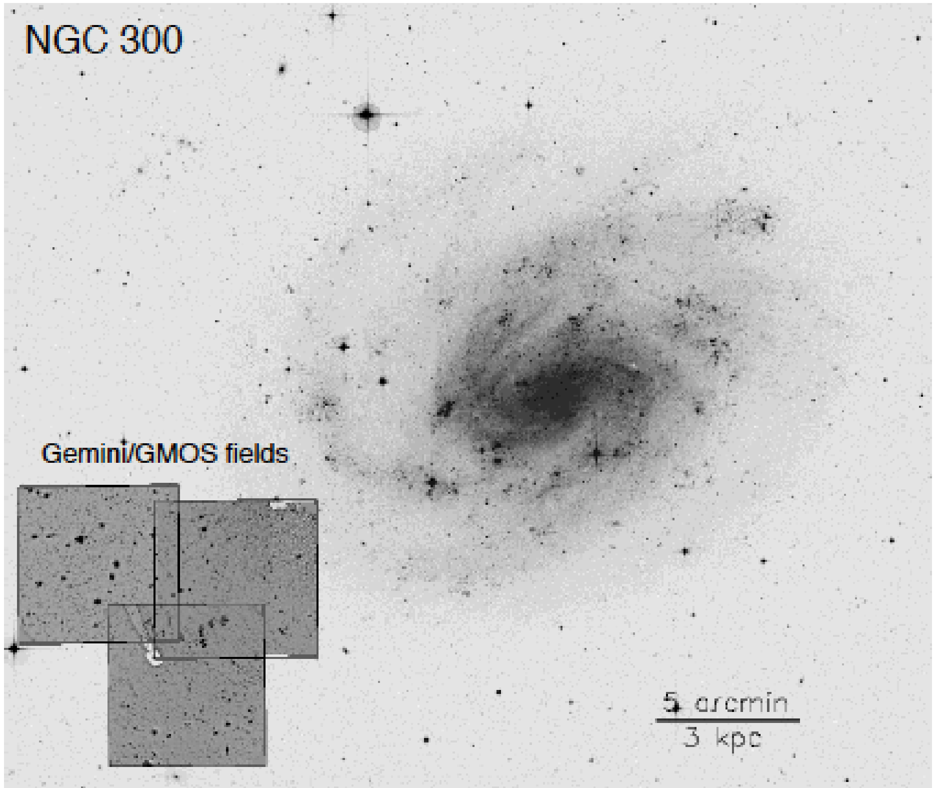
Need to fit to individual stars to be sure of trends at low stellar densities!

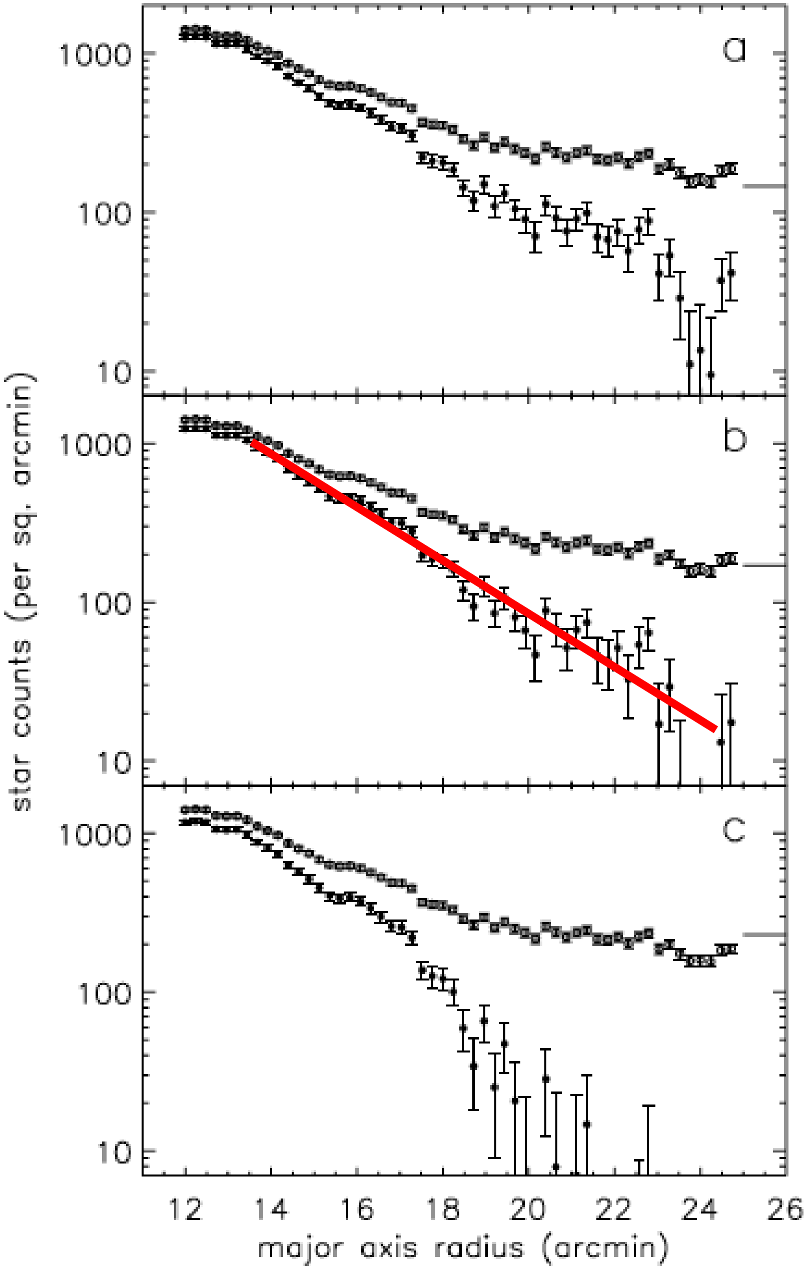
Continuously exponential disks

i.e. no sign of break !

NGC 300: JBH+ 2005 Vlajic+ 2009

NGC 7793: Vlajic+ 2011





www.aao.gov.au/astro/GalaxyCount

Ellis & JBH (2007), MNRAS, 377, 8

b = 110 +/- 20 gals arcmin^{-2}

Now includes:

Large-scale structure

All N(z) surveys to 28 mag

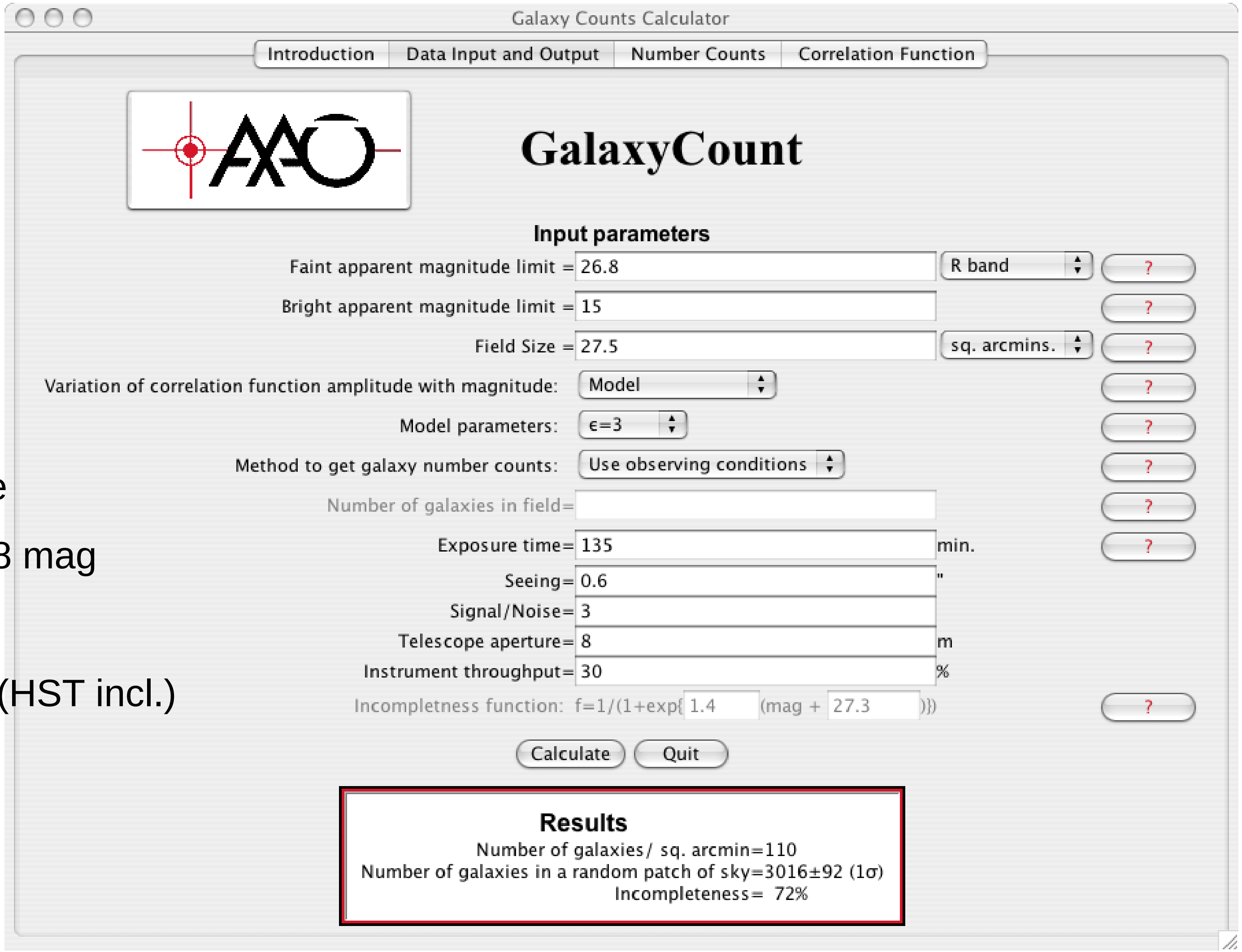
Most UV-IR filters

Different telescopes (HST incl.)

Window functions

Incompleteness

Redshift bounds



Input parameters

Faint apparent magnitude limit = 26.8 R band

Bright apparent magnitude limit = 15

Field Size = 27.5 sq. arcmins.

Variation of correlation function amplitude with magnitude: Model

Model parameters: ϵ=3

Method to get galaxy number counts: Use observing conditions

Number of galaxies in field=

Exposure time= 135 min.

Seeing= 0.6 "

Signal/Noise= 3

Telescope aperture= 8 m

Instrument throughput= 30 %

Incompletness function: f=1/(1+exp[1.4 (mag + 27.3)])

Results

Number of galaxies/ sq. arcmin=110

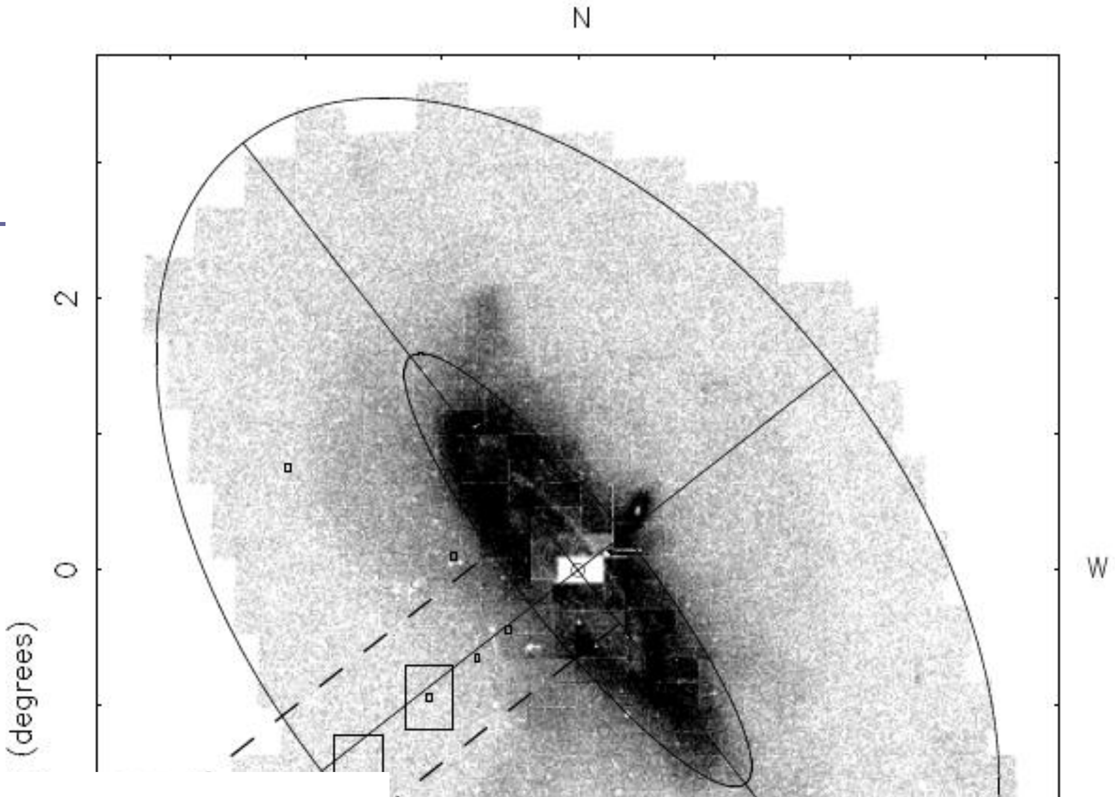
Number of galaxies in a random patch of sky=3016±92 (1σ)

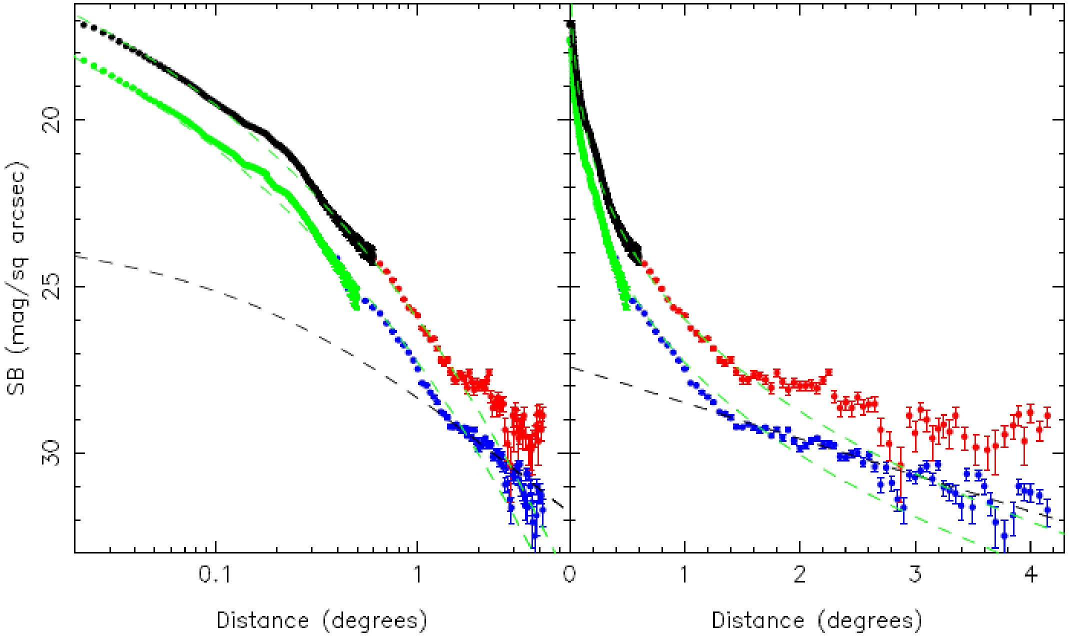
Incompleteness= 72%

Minor axis of M31

Exponential disk to > 50 kpc

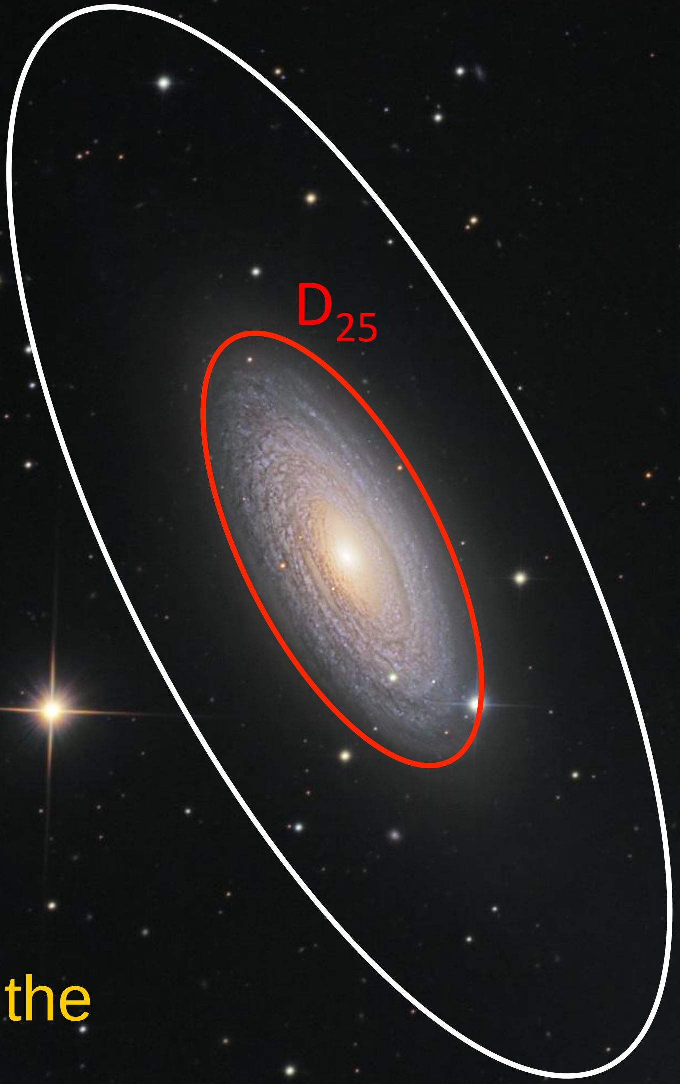
Irwin+ 2005





The traditional view was that the cold gas went at least twice as far as the stars.

NGC 2841



But you can often trace stars and faint star formation (Hα, XUV) to the edge of the HI.

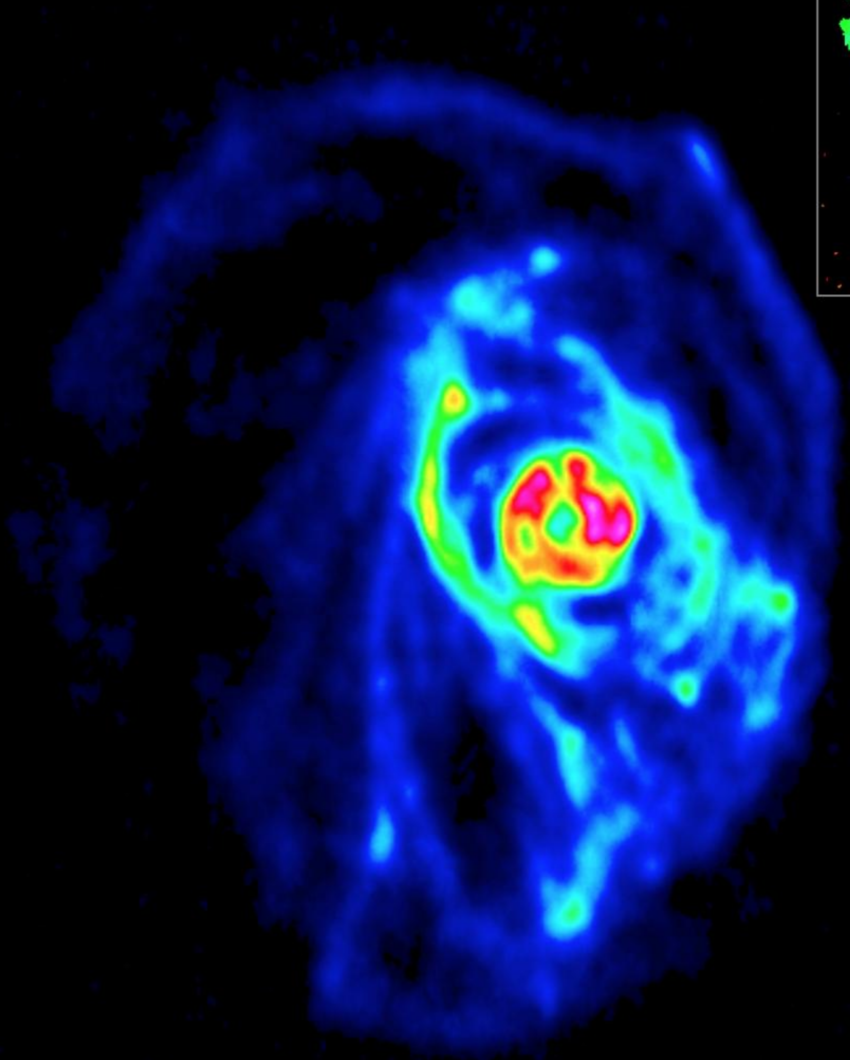
Not to be outdone, radio astronomers are now pushing much deeper than “traditional” limits of 10^{19} atoms cm^{-2} at 21 cm.

M83:

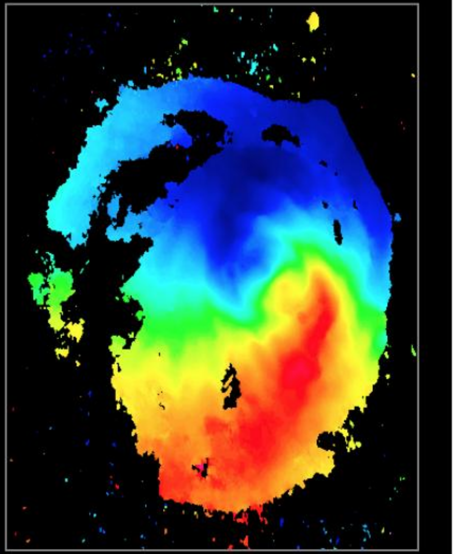
Koribalski et al, in prep.

- $D \approx 4.5$ Mpc
- HI extent > 80 kpc
- $M_{HI} = 8 \times 10^9 M_\odot$

GALEX NUV+FUV; Thilker et al.



ATCA + Parkes HI mosaic



The ASKAP PAF – a new radio camera

Front view & rear view of the ASKAP PAF

- *PAF = Phased Array Feeds (checkerboard array: 188 elements)*
- *Beamformer: creates up to 36 beams, each 1.2 degr FWHM*
- *resulting field of view is 30 square degrees (5.5 deg × 5.5 deg)*

Not to be outdone, radio astronomers are now pushing much deeper than “traditional” limits of 10^{19} atoms cm^{-2} at 21 cm.

Is there a limit to how far you can reach with cool gas ? Surely there must be.

‘Dramatic Edge’ in NGC 3198

- Disk galaxies display sharp truncation at critical column density in HI

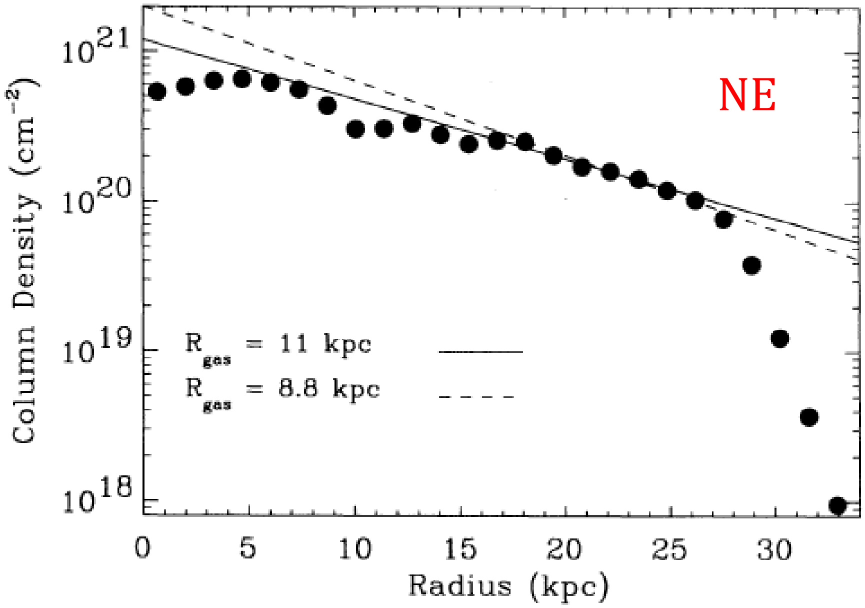


FIG. 9*a*

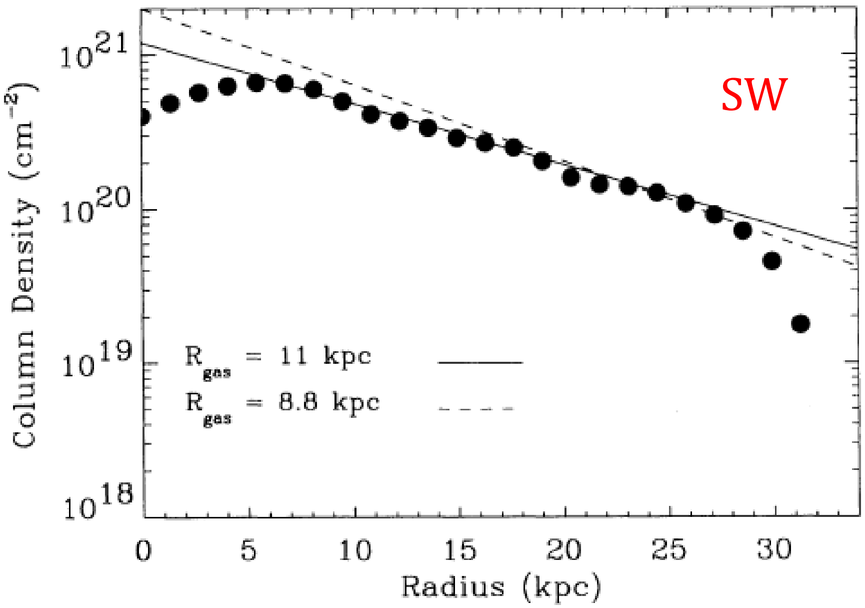
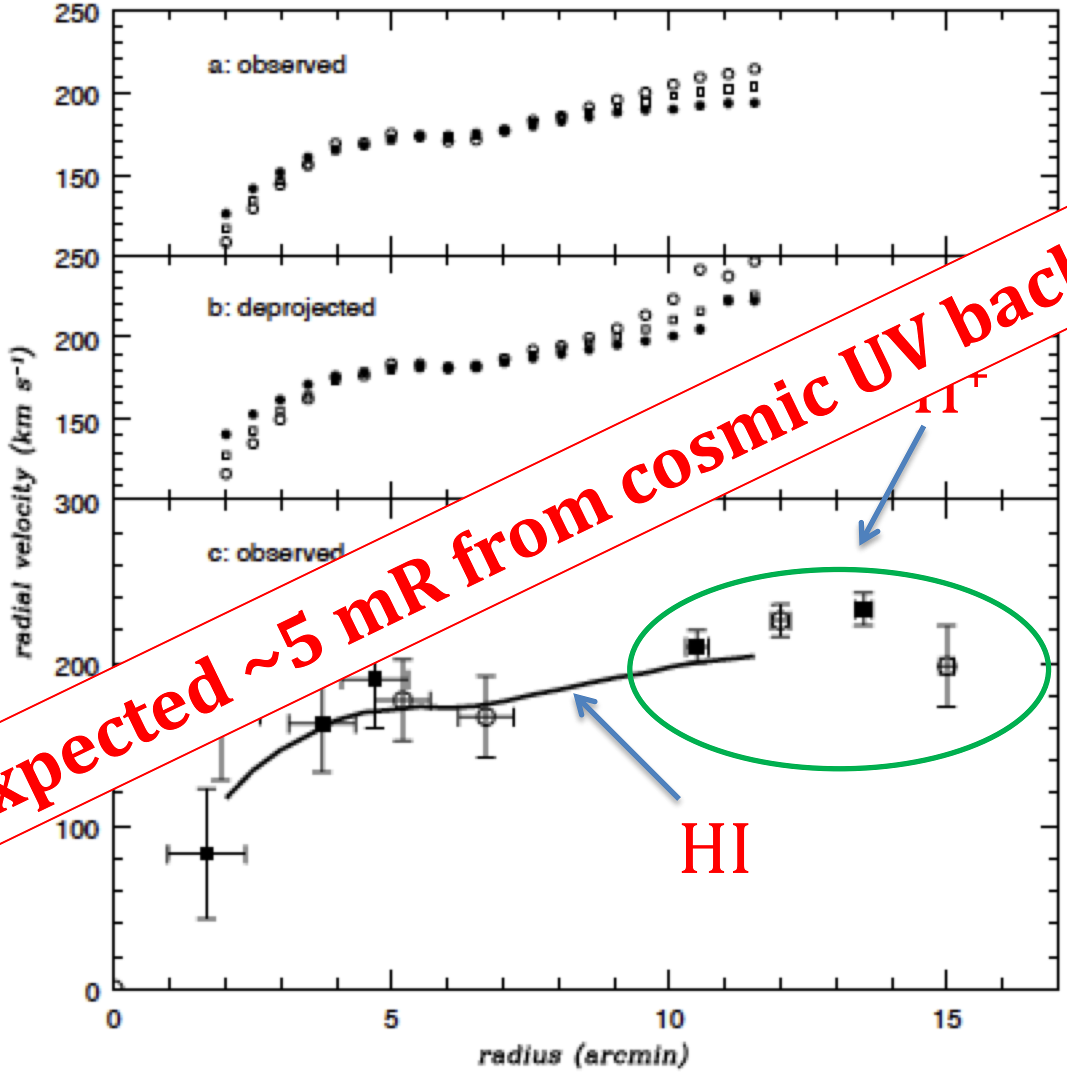


FIG. 9*b*

Maloney (1993); Dove & Shull (1994)

HI edge in NGC 253



But we expected ~5 mR from cosmic UV background

H^+

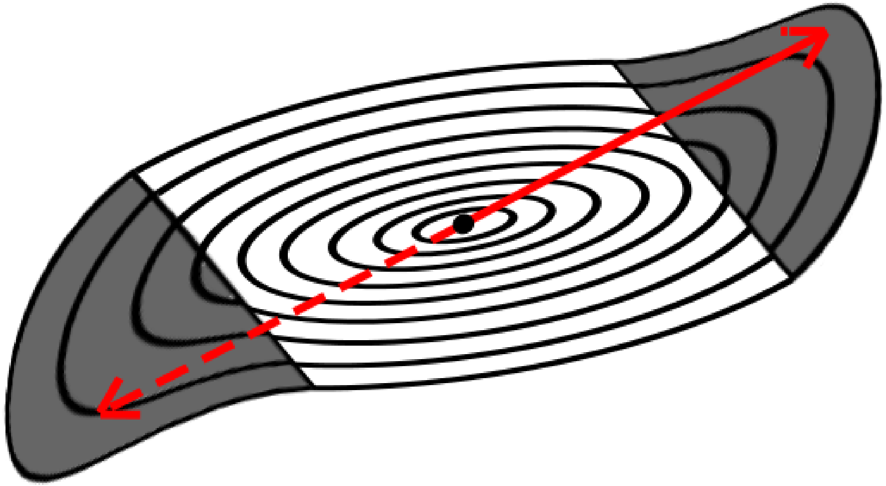
Hα detections
~70 mR

HI

JBH, Freeman & Quinn (1997)

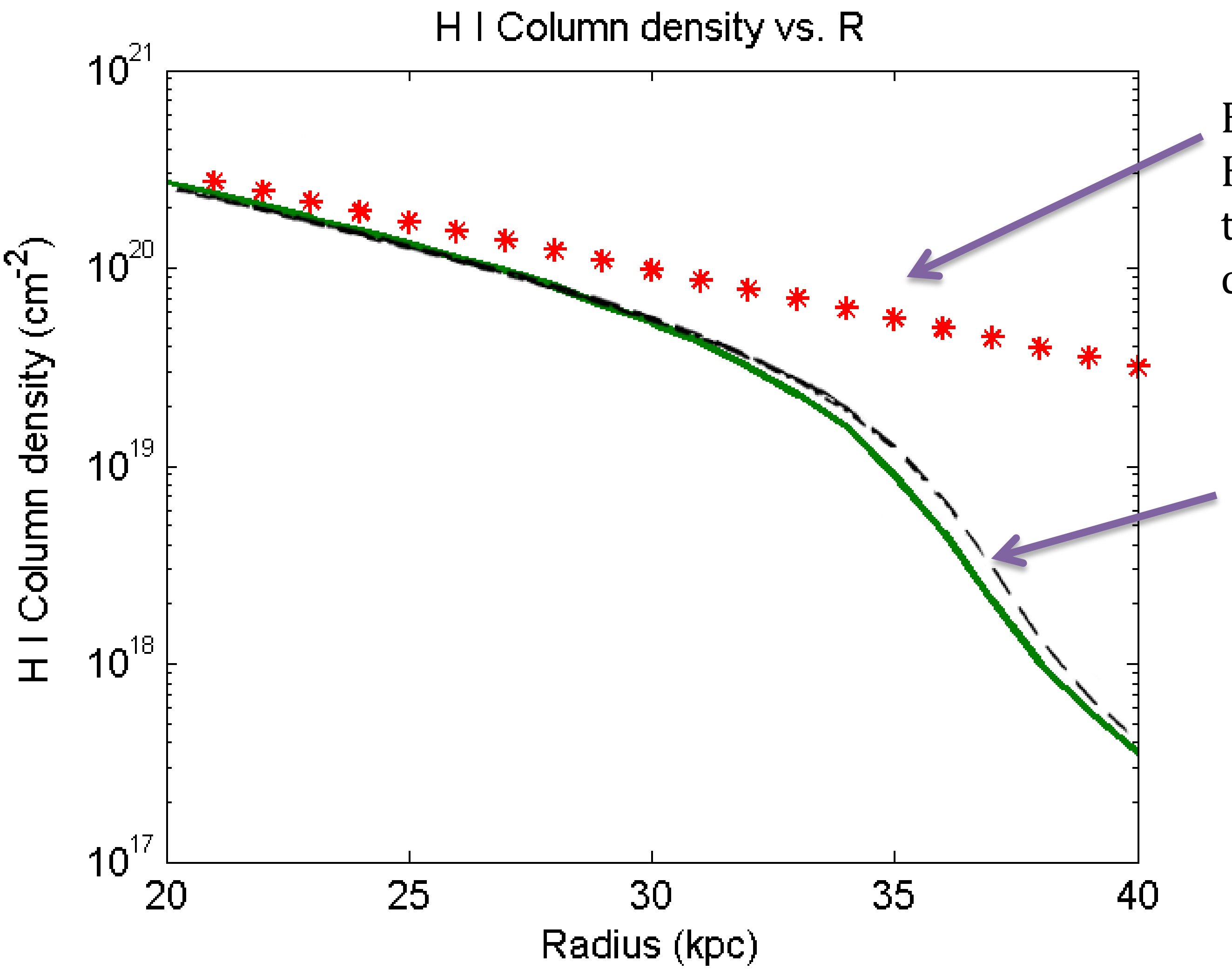
So why?

- Like all HI disks, NGC 3198 is warped beyond optical disk
- Stellar disk creates galactocentric ionizing radiation field
- Warped parts of disk ‘see’ ionizing radiation creating HI edge and weak H^+ in outer disk
- This may assist in detecting outer accreting gas in future deep observations



JBH (1998)

Warp model



Exponential HI disk (i.e. total gas column)

Self ionization: 1D vs. 3D case

JBH (1998)

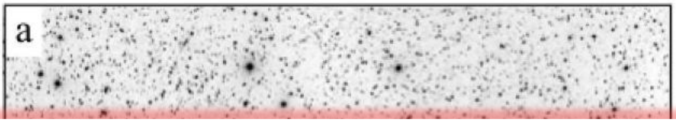
Surface photometry makes a comeback from an unexpected source thanks to arrays of high quality Canc

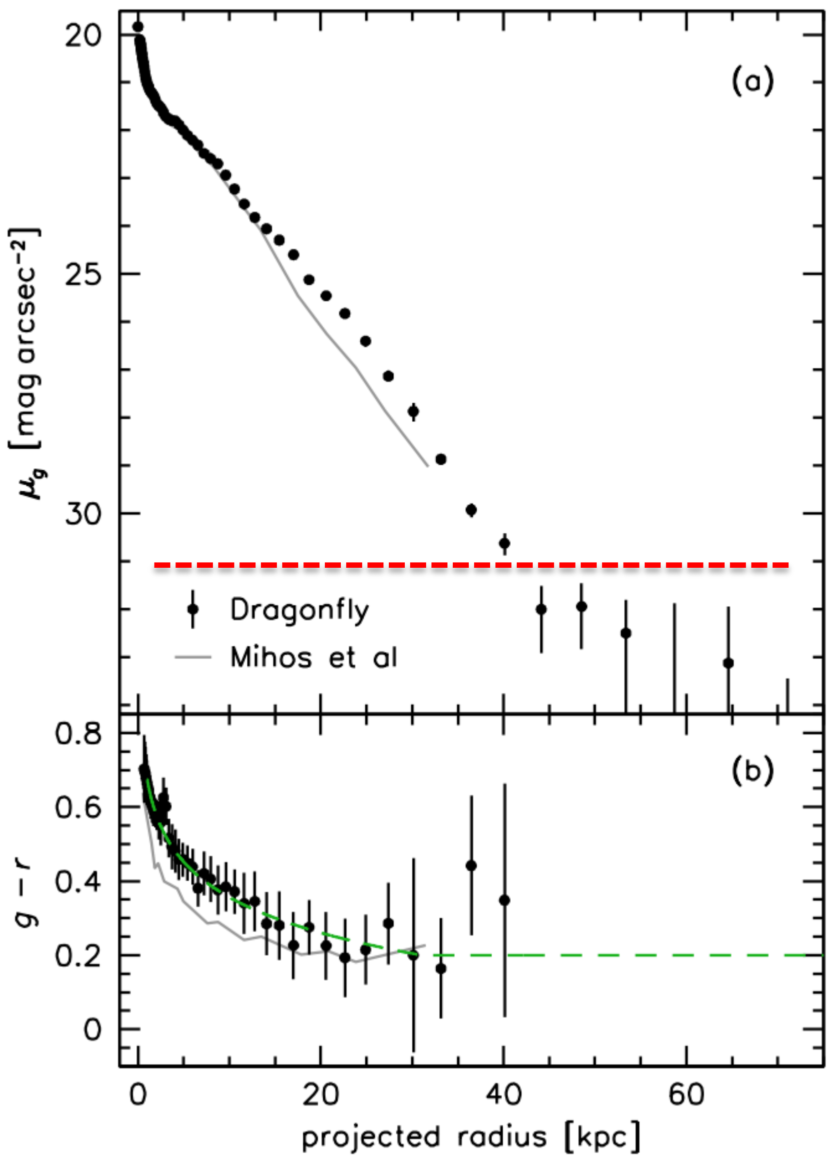
DRAGONFLY PROJECT

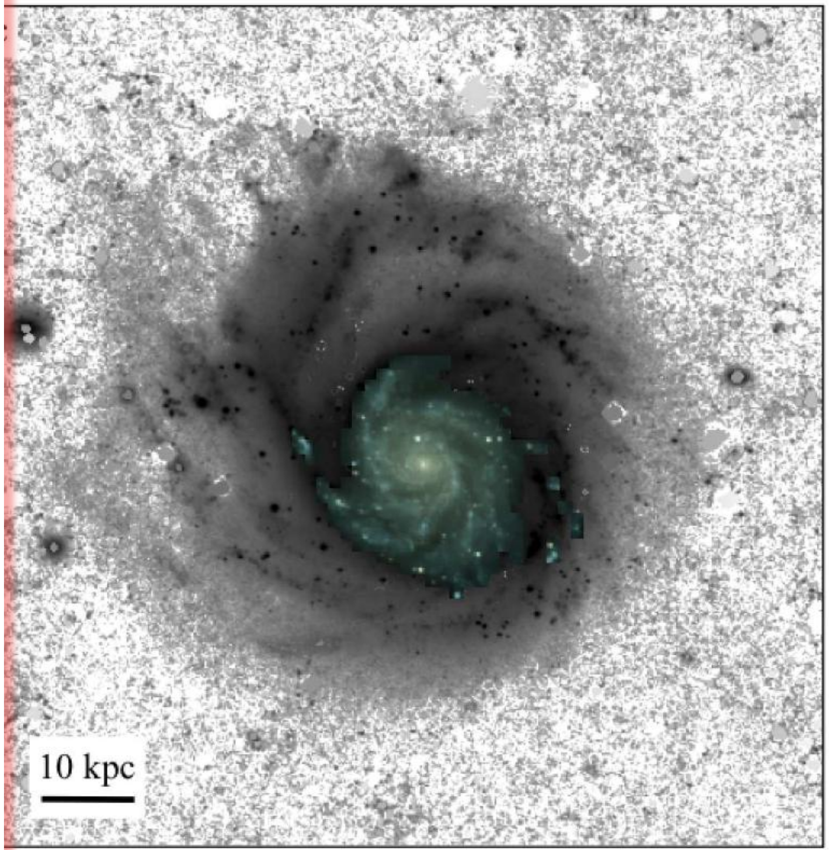
2x3 deg field of view
2.85”/pixel
Fully robotic

Dragonfly imaging of M101
(van Dokkum et al 2015)

No evidence for a break !







ered on the galaxy M101. North is up and East is to the left. *b)* The same
background structure. Owing to the excellent PSF of Dragonfly, stars as
pixels, and can be subtracted. *c)* The 44′ × 44′ area around M101 at high
. 2013) have a surface brightness of $\mu_g \sim 29$ mag arcsec^{-2}. The color image

NGC 2841

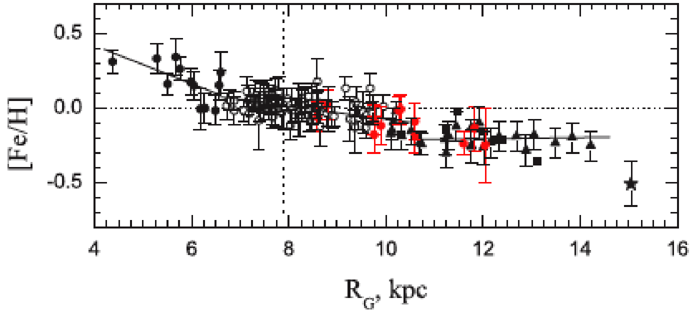
A curious effect is coming into focus at the edges of disks in the stellar abundance gradients (e.g. Vlajic+ 2009, 2011)

The archetype for the class of flocculent spirals

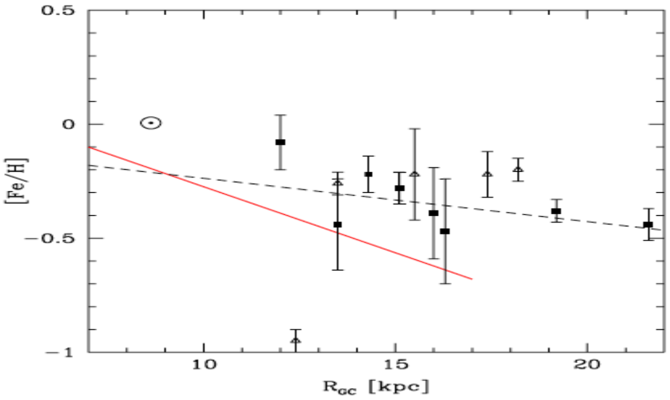
Stellar abundance gradients in outer disks:
Milky Way

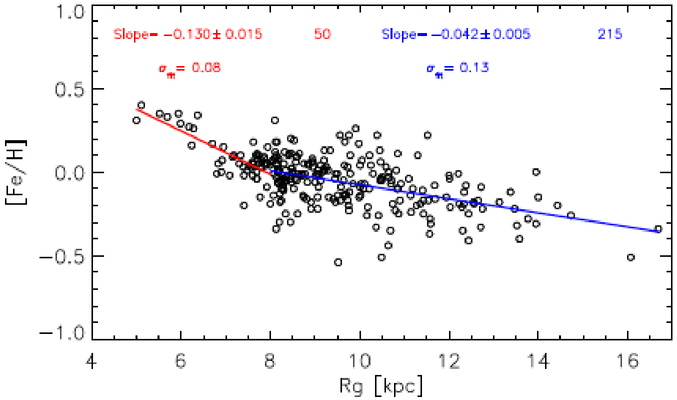
Flattening of abundance gradient observed in the Galactic outer disk

Andrievsky et al. 2004

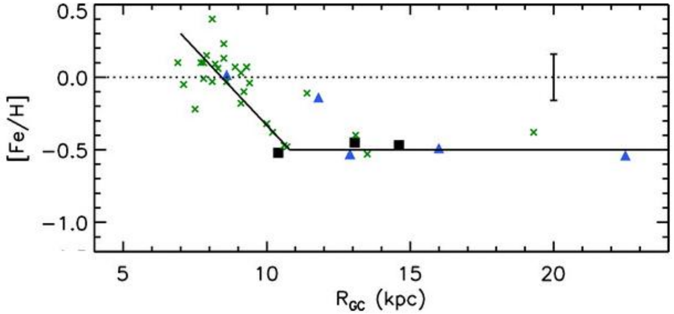


Carraro et al. 2007





Pedicelli et al. 2009



Yong et al. 2006

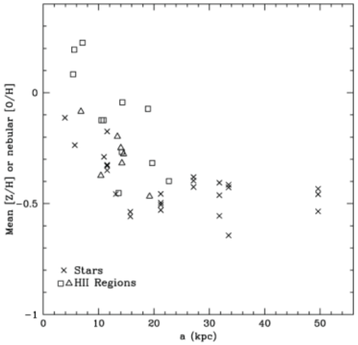
Transition at ~8 kpc

Transition at 10-12 kpc

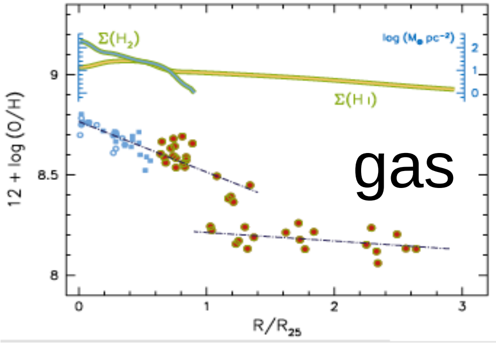
Stellar abundance gradients in outer disks:
external galaxies

Flattening of abundance gradient in external galaxies

M31: Worthey et al. 2005

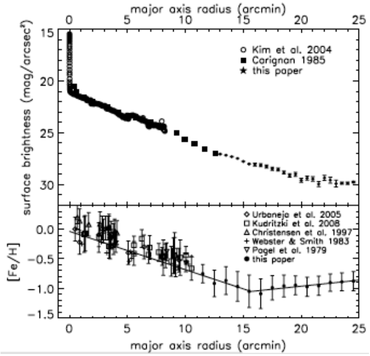


M83: Bresolin et al. 2009



gas

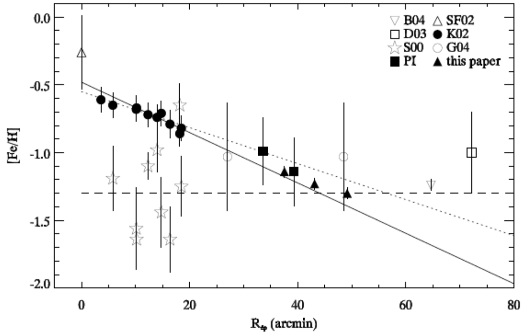
NGC 300: Vlajic et al. 2009a



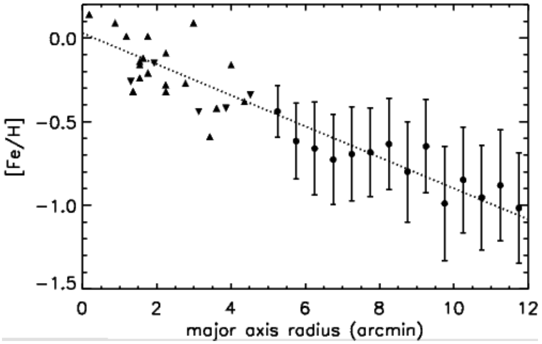
Flattening of the abundance gradient appears to be a property of (large) spiral disks

Lack of flattening in the abundance gradient

M33: Barker et al. 2007



NGC 7793: Vlajic et al. 2009b

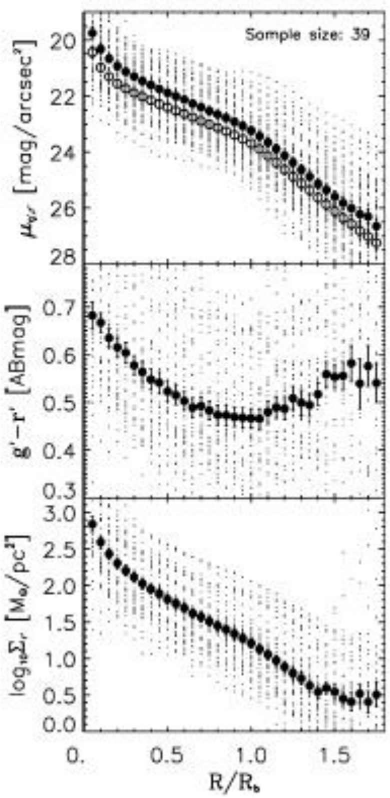


Single slope negative gradient observed in some spirals

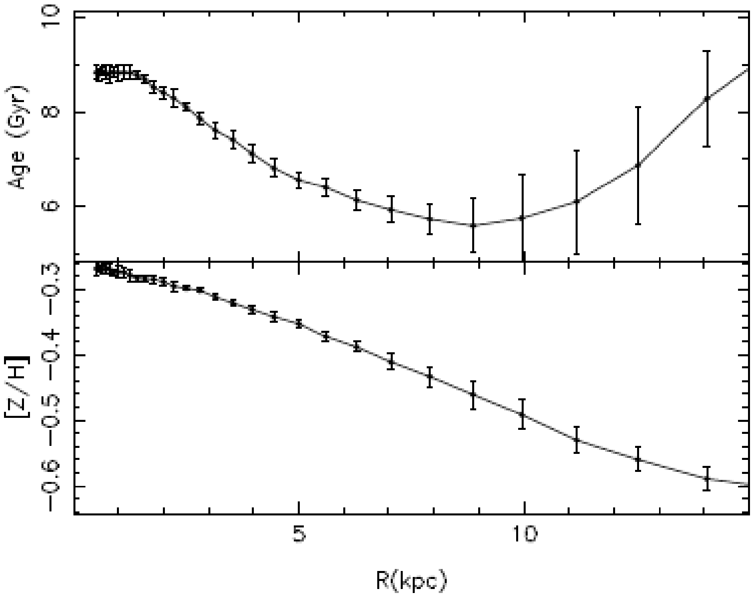
Radial migration – age gradients in outer disks

Roskar+ 2008,

Radburn-Smith+ 2012



Bakos et al. 2009



Sanchez-Blazquez et al. 2009

"U" shaped color profile observed in SDSS stacked galaxies reflects age (and not metallicity) behaviour

These models would solve the high Q problem, but not the metallicity floor?

$Q = c_s\kappa/\pi G\Sigma \leq 1$ to form stars

So how deep must we go to see outer material?

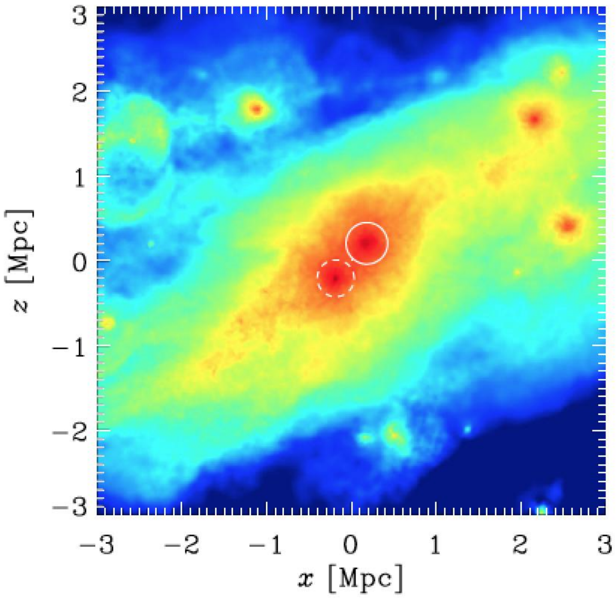
Optical: > 34 mag arcsec^{-2} (Hα, continuum; warping will help!)

Radio: < 10^{18} cm^{-2} (can survive if clumpy)

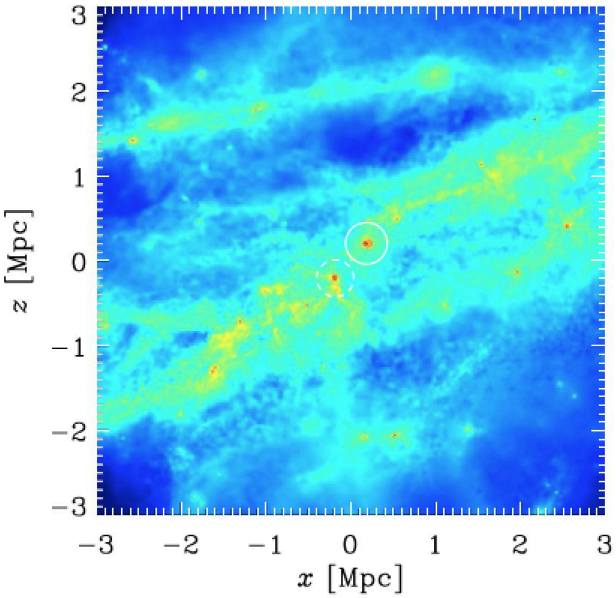
EUV: ? (currently impossible)

X-ray: ? (currently impossible beyond halo)

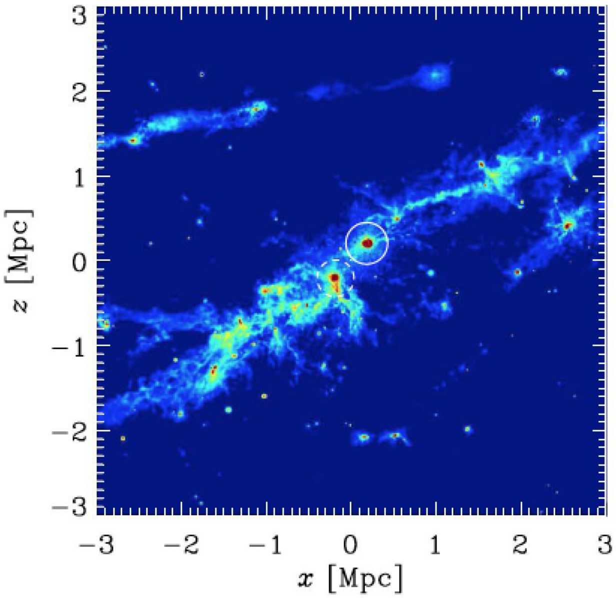
Hot (>10^5 K)



Warm (<10^5 K)



HI (21cm)



Nuza+ (2014)

Summary

There is no evidence that the collapsed baryons terminate at some critical radius.

Radial migration in the plane may be blurring the outer stellar disks (subject to dynamical evolution).

Most of what we need to understand outer disks and disk formation is below our detection levels (but there is hope for the future).