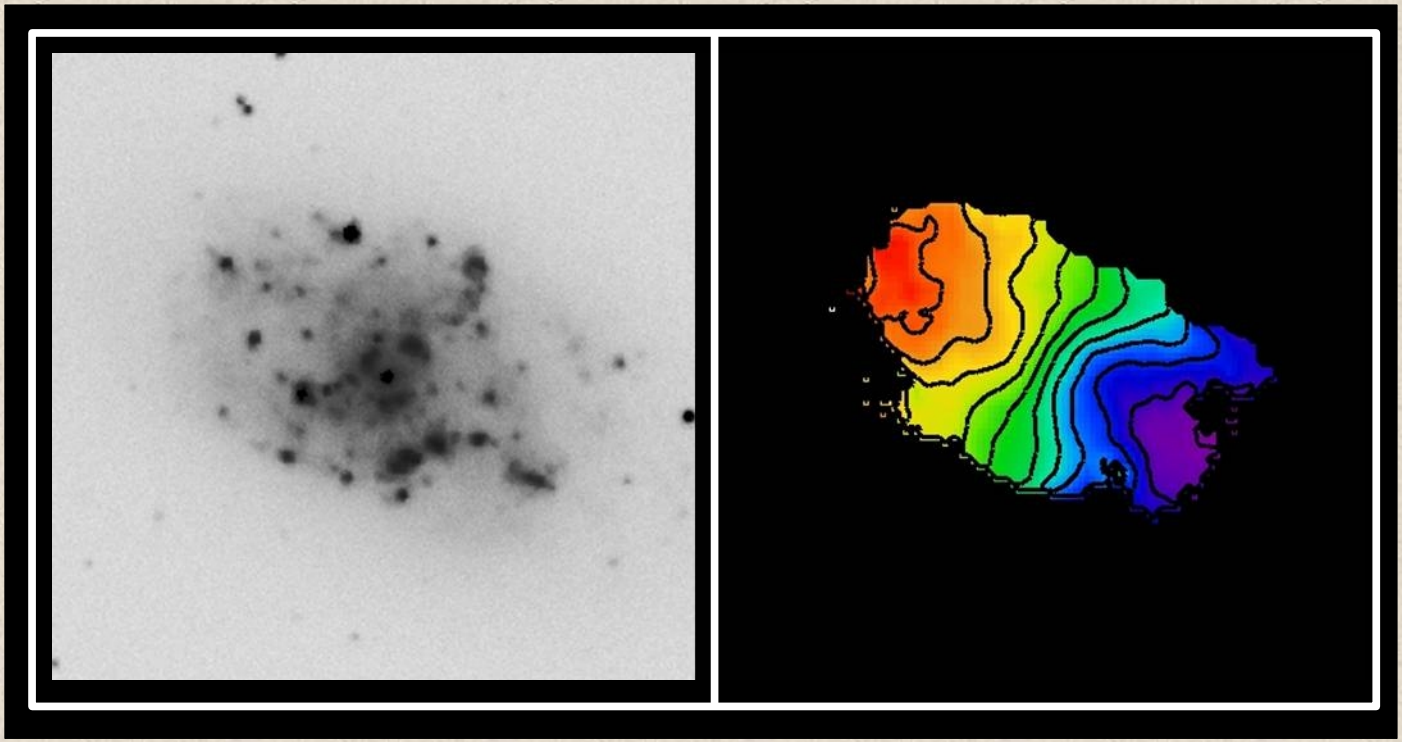
The Dark Matter Halos of LSB Galaxies



Rachel Kuzio de Naray
NSF Postdoctoral Fellow
UC Irvine

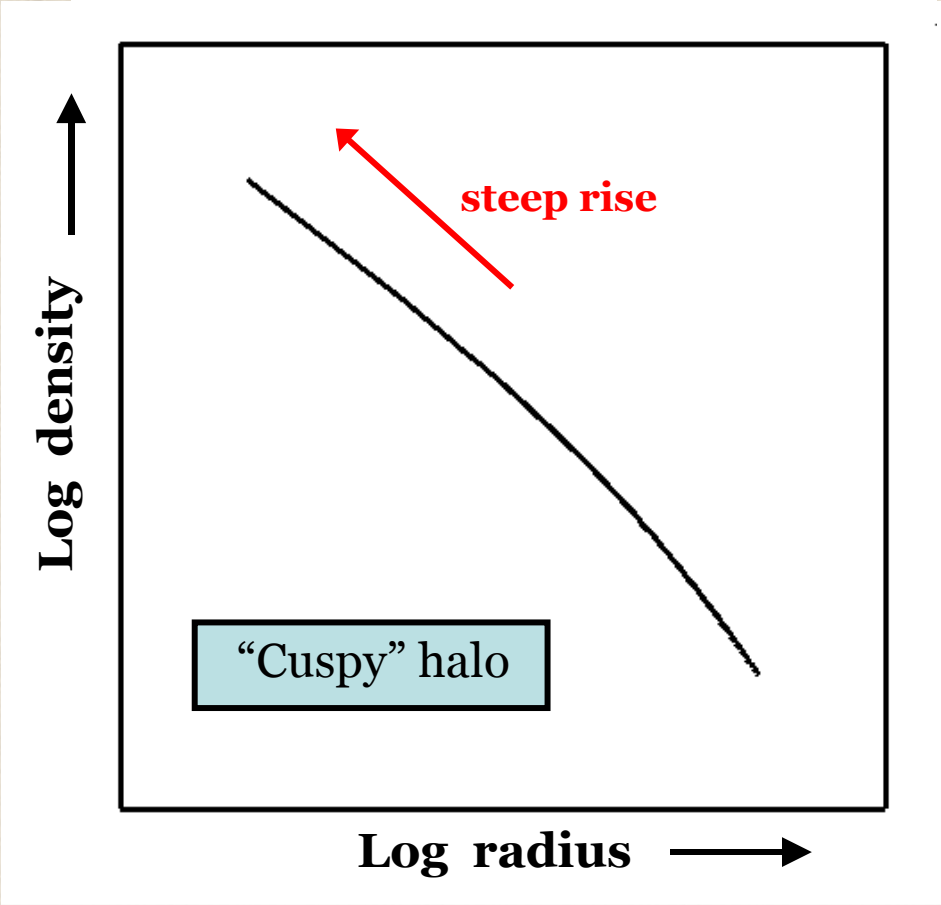
The Dark Matter Halos of LSB Galaxies:

The Cusp-Core Problem

Expectations

Expectations from Simulations of Cold Dark Matter

CDM halos are "cuspy": steeply rising density profiles



$$\rho \sim r^{\alpha}$$

α = **-1** NFW (1996, 1997)

-1.5 Moore et al. (1999)

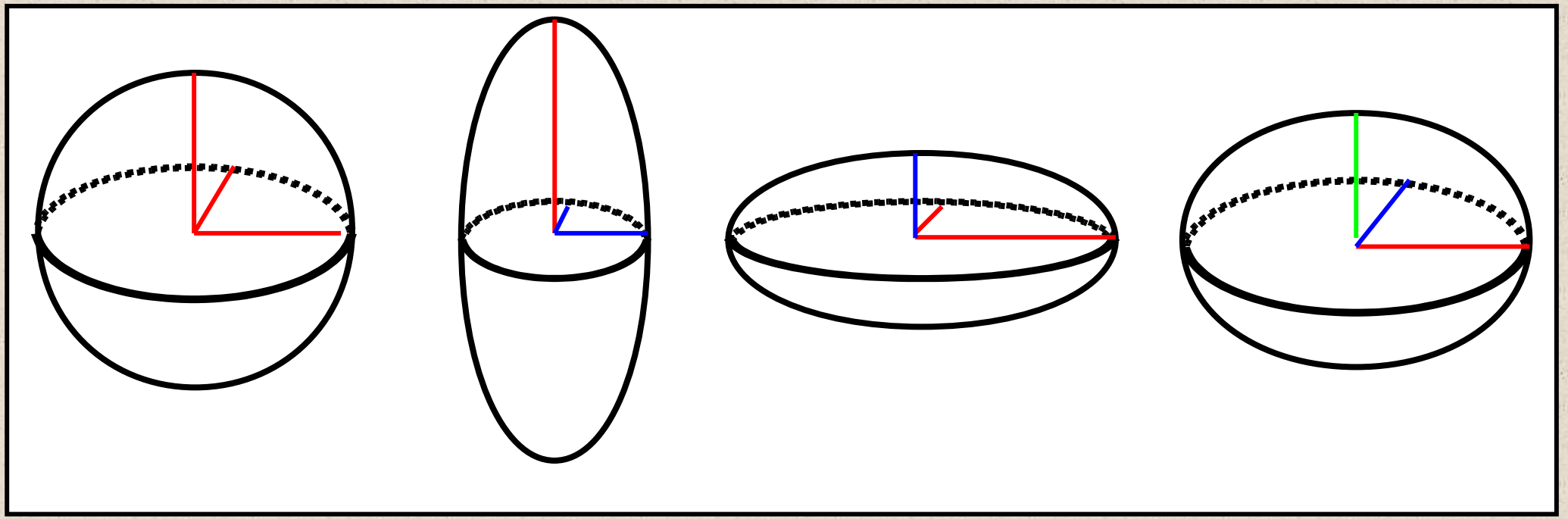
Mass dependent (Reed et al. 2003)

Radius dependent (Navarro et al. 2004)

little less than -1 (Navarro et al. 2008)

+ others ...

Shapes of CDM Halos

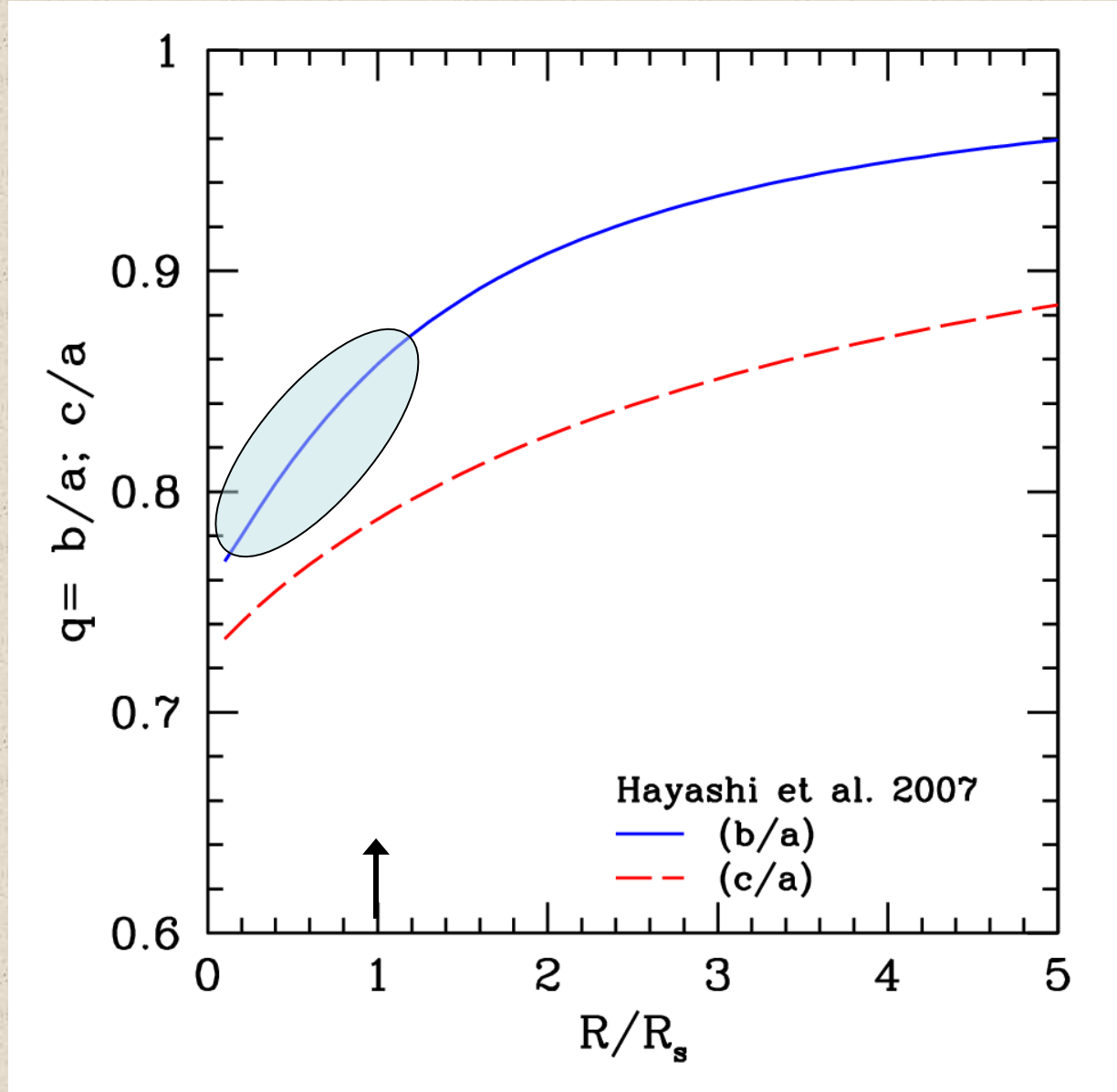


Spherical	Prolate	Oblate	Triaxial
a = b = c	a > b = c	a = b > c	a > b > c
all three equal	one long axis	one short axis	three different
	football	frisbee	

Shapes of CDM Halos

CDM halos are triaxial and more often prolate than oblate
(e.g. Allgood et al. 2006)

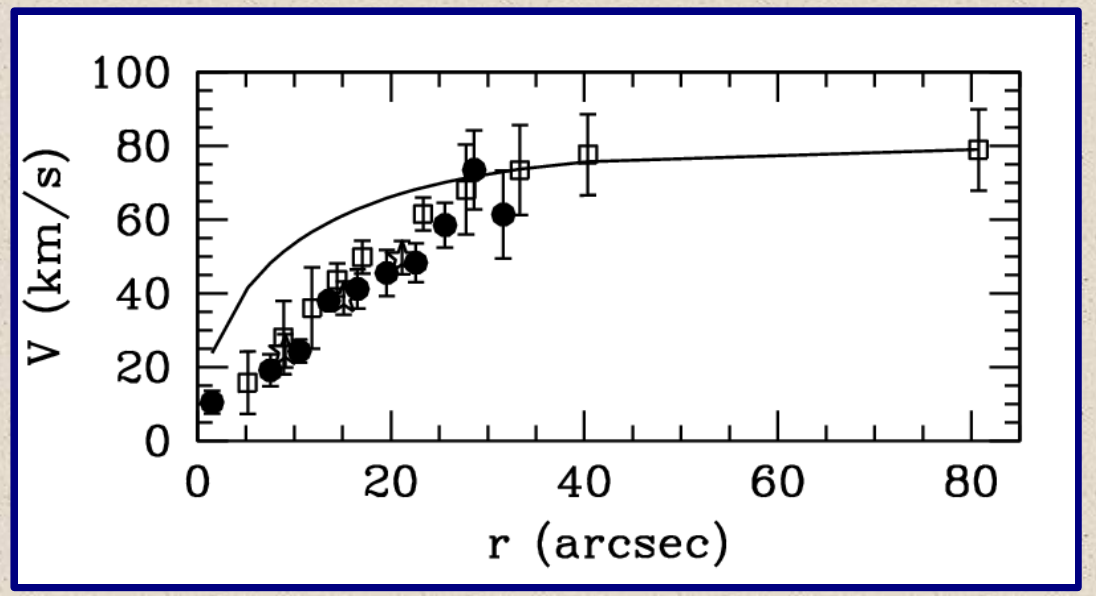
CDM halos have axis ratios that change with radius; triaxial at the center, spherical near the edge
(Hayashi et al. 2007)



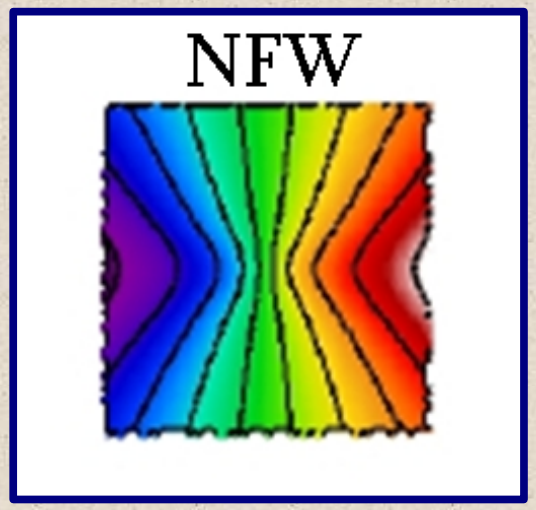
(Hayashi, Navarro & Springel 2007)

Cuspy NFW Halos

$$\Phi(R) = -\frac{G M_{200} \ln(1 + R/R_s)}{R\left[\ln(1+c) - c/(1+c)\right]}$$



fast-rising rotation curves

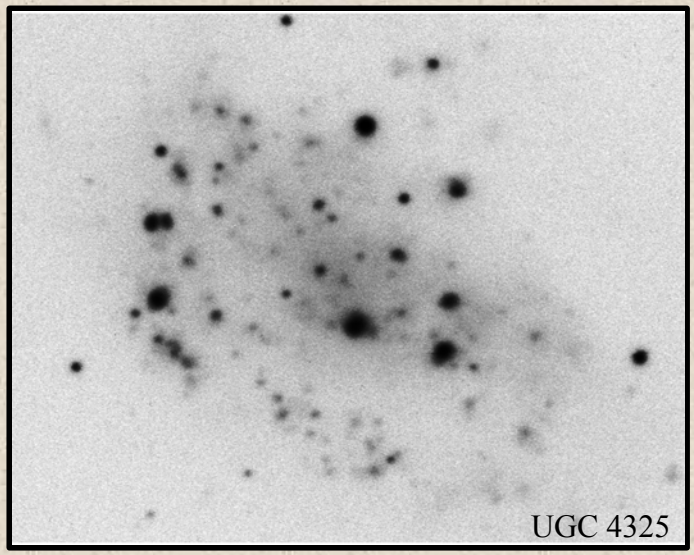


pinched velocity fields

Observations of Dark Matter-Dominated Galaxies

Observations of Dark Matter-Dominated Galaxies

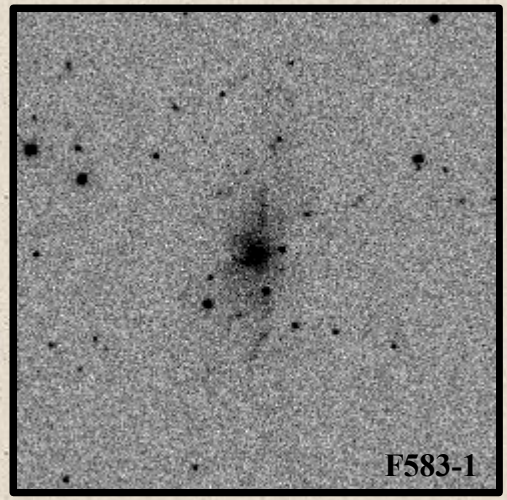
Low Surface Brightness Galaxies

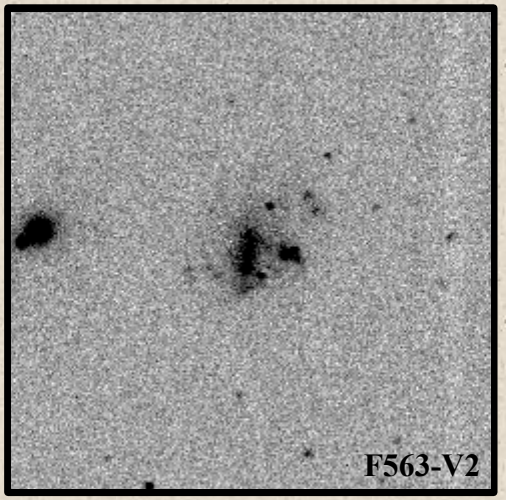


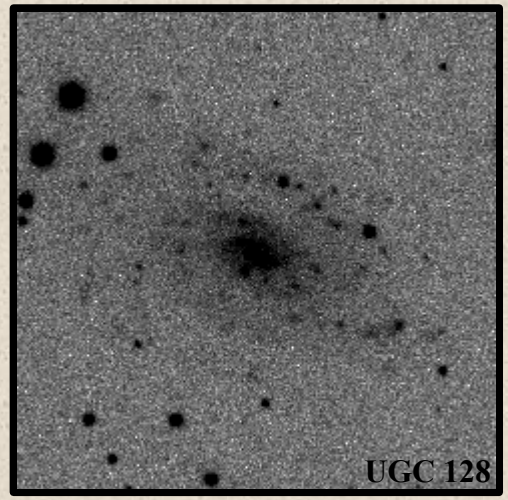
dark matter-dominated down to small radii

↓

zero/minimum disk assumption about baryonic mass



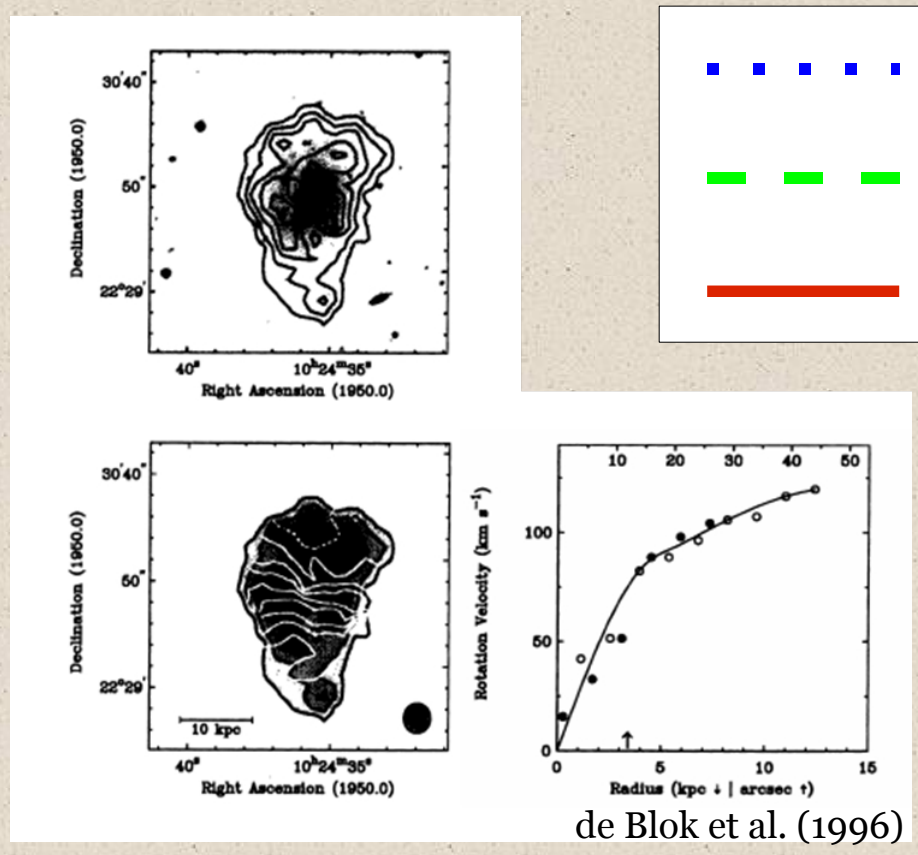




Radio Data: HI Observations

HI Velocity Fields and Rotation Curves:

Moore (1994)
Flores & Primack (1994)
de Blok, McGaugh, & van der Hulst (1996)
+ many more …

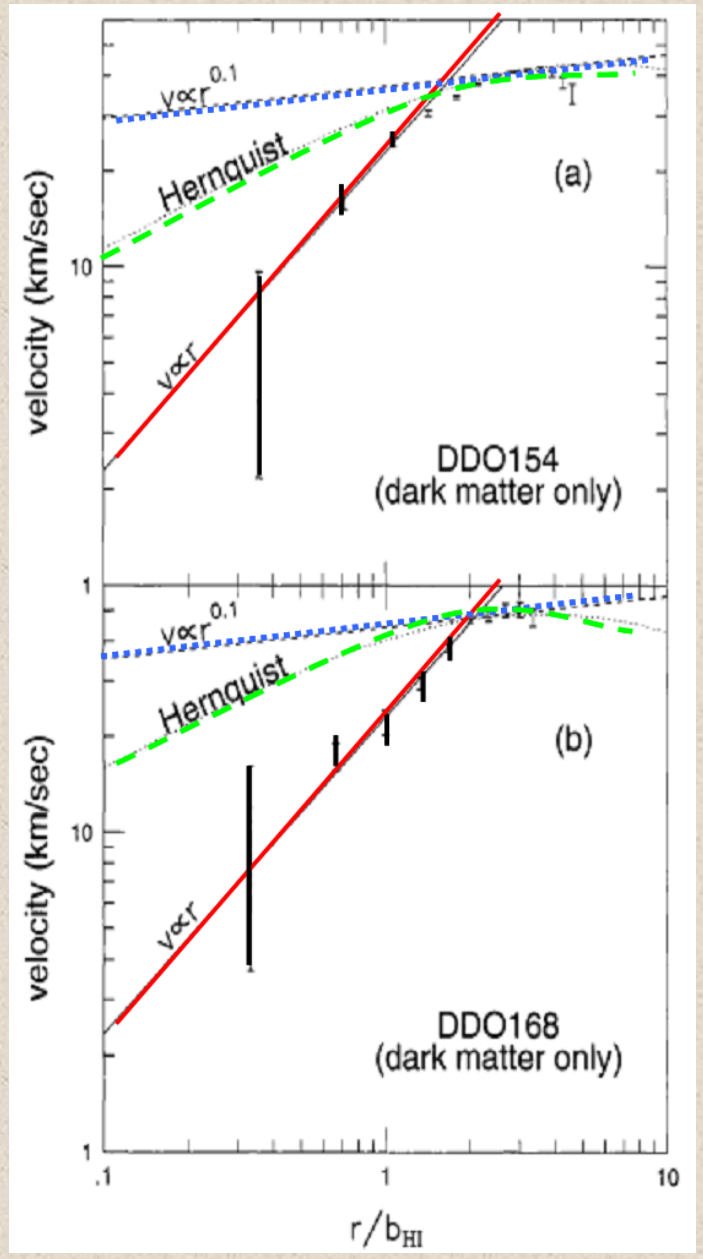


de Blok et al. (1996)

$\rho \sim r^{-1.8}$

$\rho \sim r^{-1}$

$\rho \sim r^{0}$

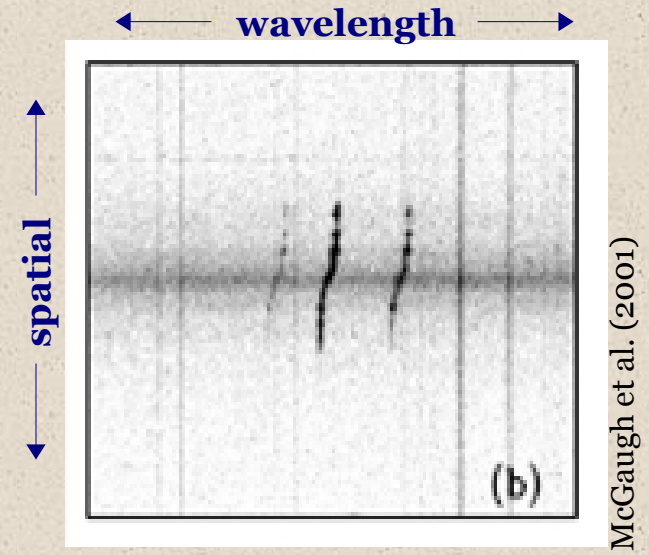


Flores & Primack (1994)

Optical Data: Long-slit Hα Observations

Long-Slit Hα Rotation Curves:

McGaugh, Rubin, & de Blok (2001)
de Blok & Bosma (2002)
Marchesini et al. (2002)
+ many more ...

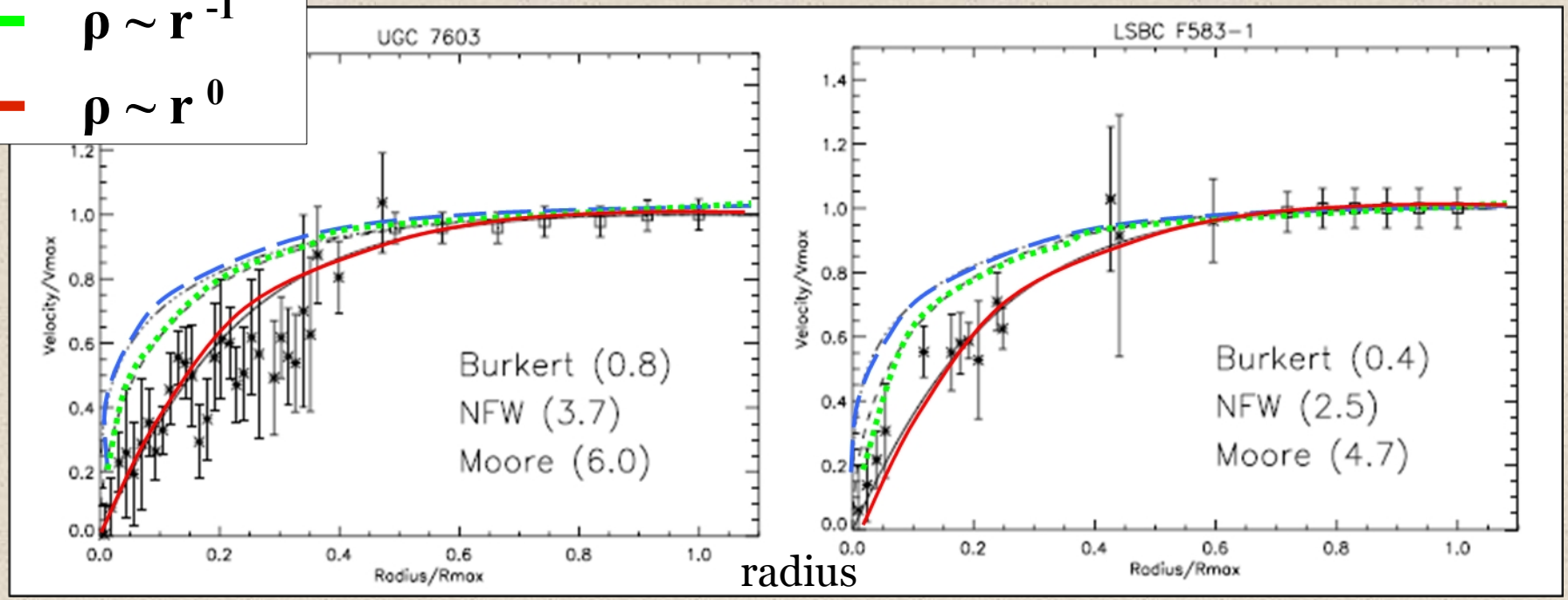


McGaugh et al. (2001)

$\rho \sim r^{-1.5}$

$\rho \sim r^{-1}$

$\rho \sim r^{0}$

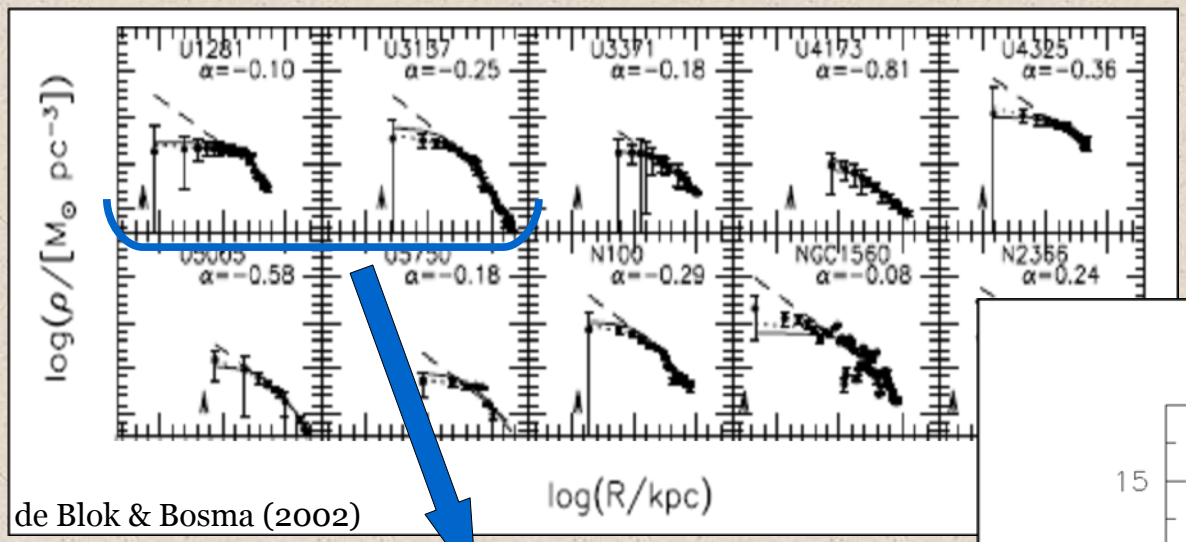


Velocity

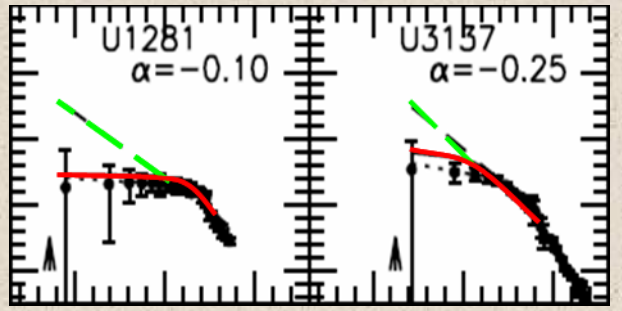
radius

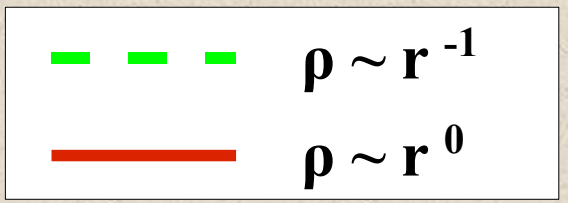
Marchesini et al. (2002)

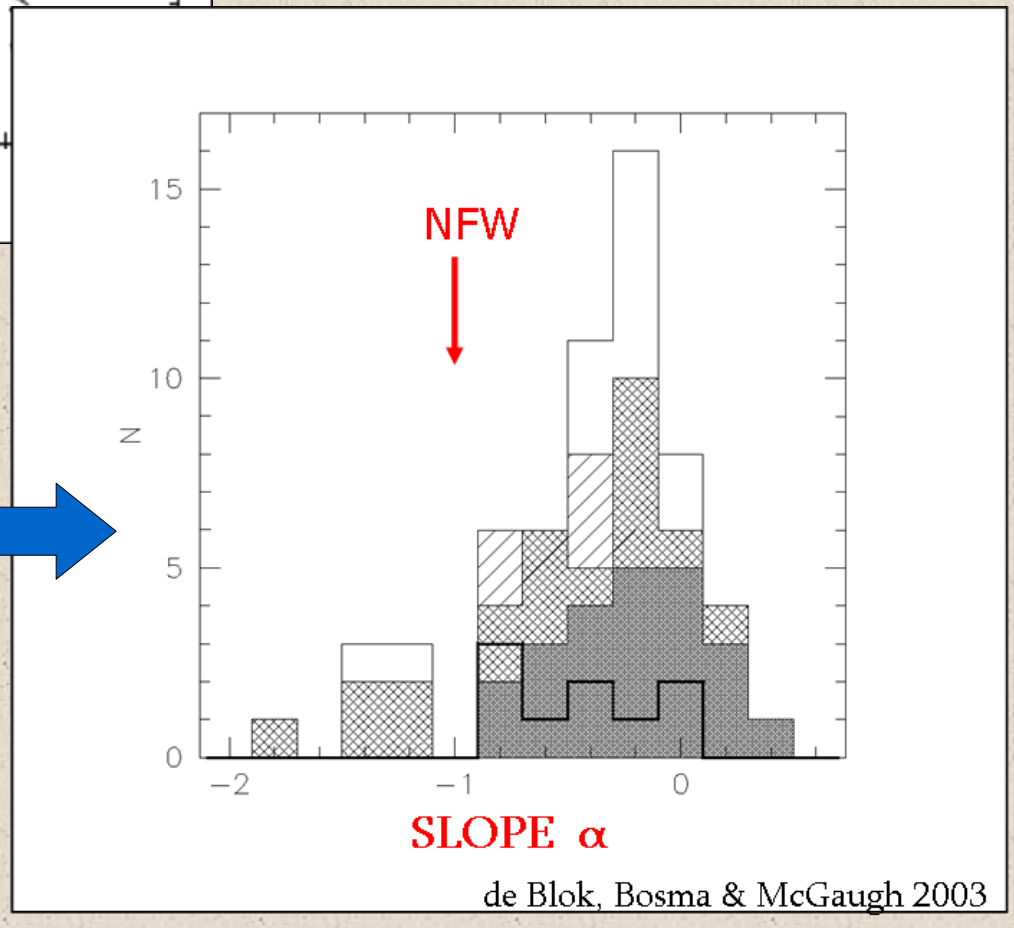
Observations of Dark Matter-Dominated Galaxies



de Blok & Bosma (2002)





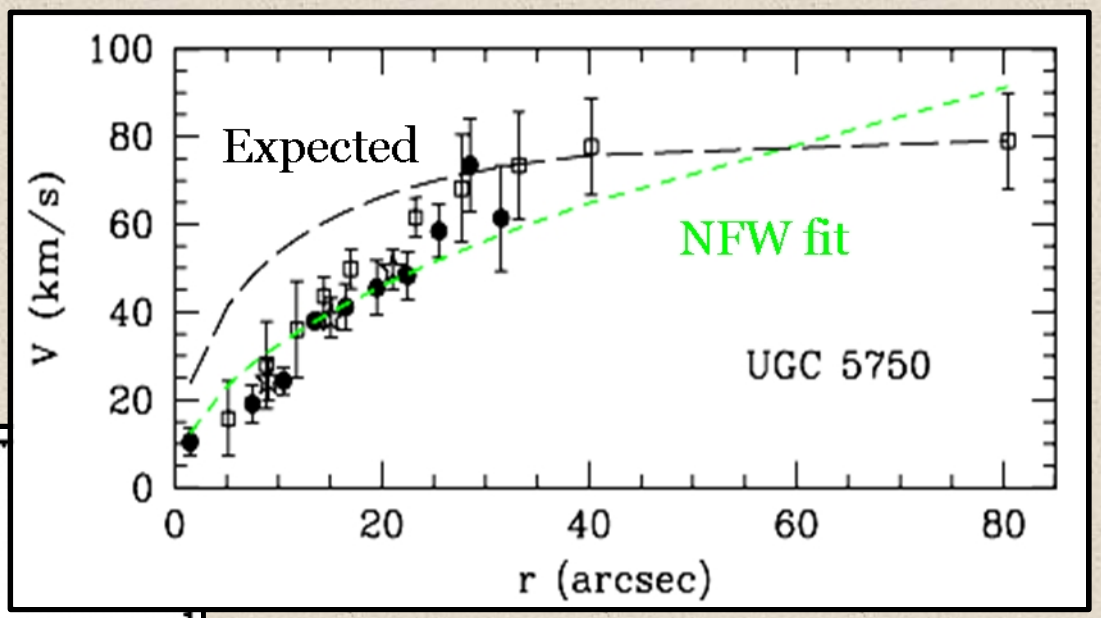


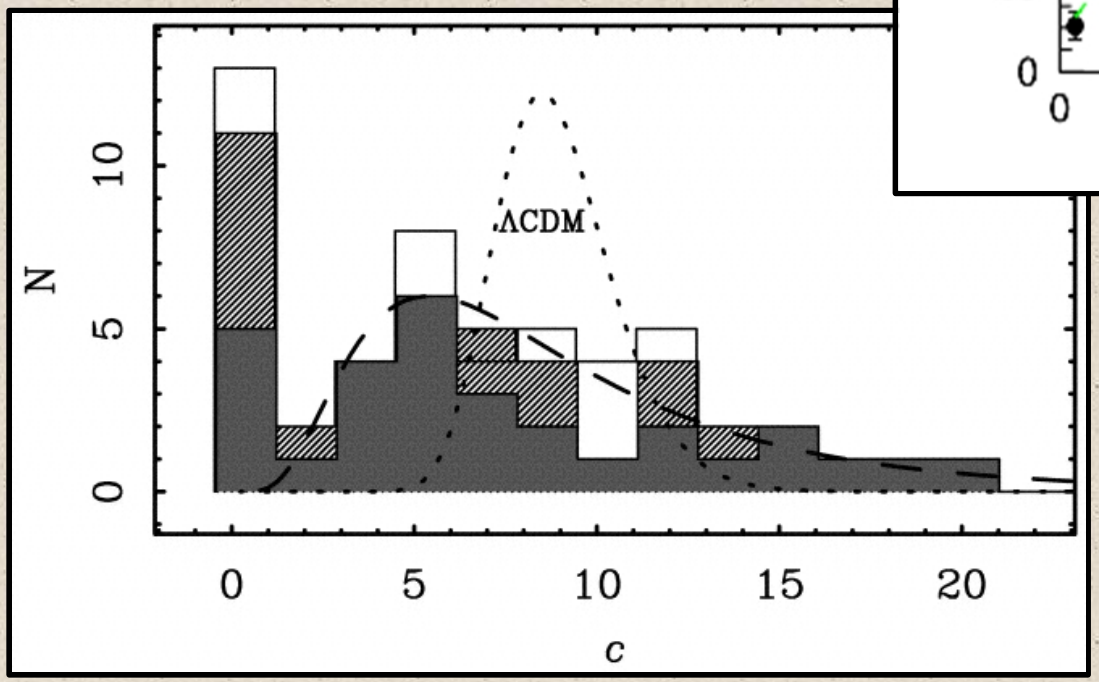
de Blok, Bosma & McGaugh 2003

Observations of Dark Matter-Dominated Galaxies

Inconsistencies:

- **Rotation curve shapes**
- **Halo parameters**
- **Cosmological parameters**





McGaugh, Barker & de Blok (2003)

The Cusp-Core Problem

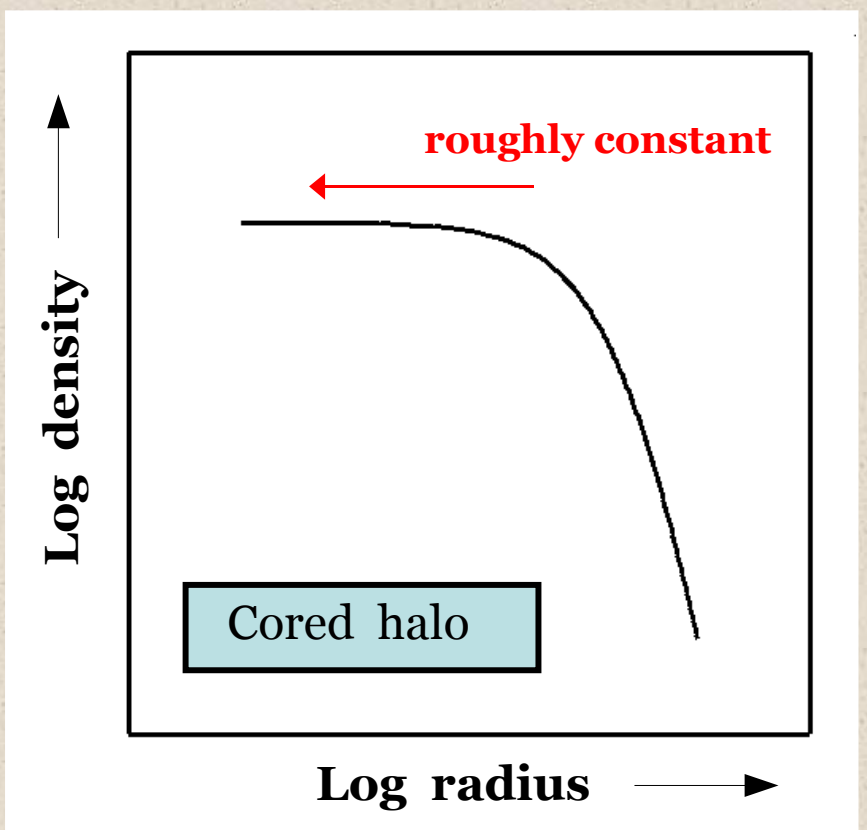
Expect *cusps*, but observe *cores*

$$\rho \sim r^{0}$$

Pseudo-Isothermal Halo

No Cosmological Motivation

No Theoretical Basis



A Problem with the Data?

HI Rotation Curves ← Low spatial resolution?

Long-Slit Hα Rotation Curves ← Slit misplacement?
Long-Slit Hα Rotation Curves ← Noncircular motions?

- New Observational Approach -

Integral Field Spectroscopy

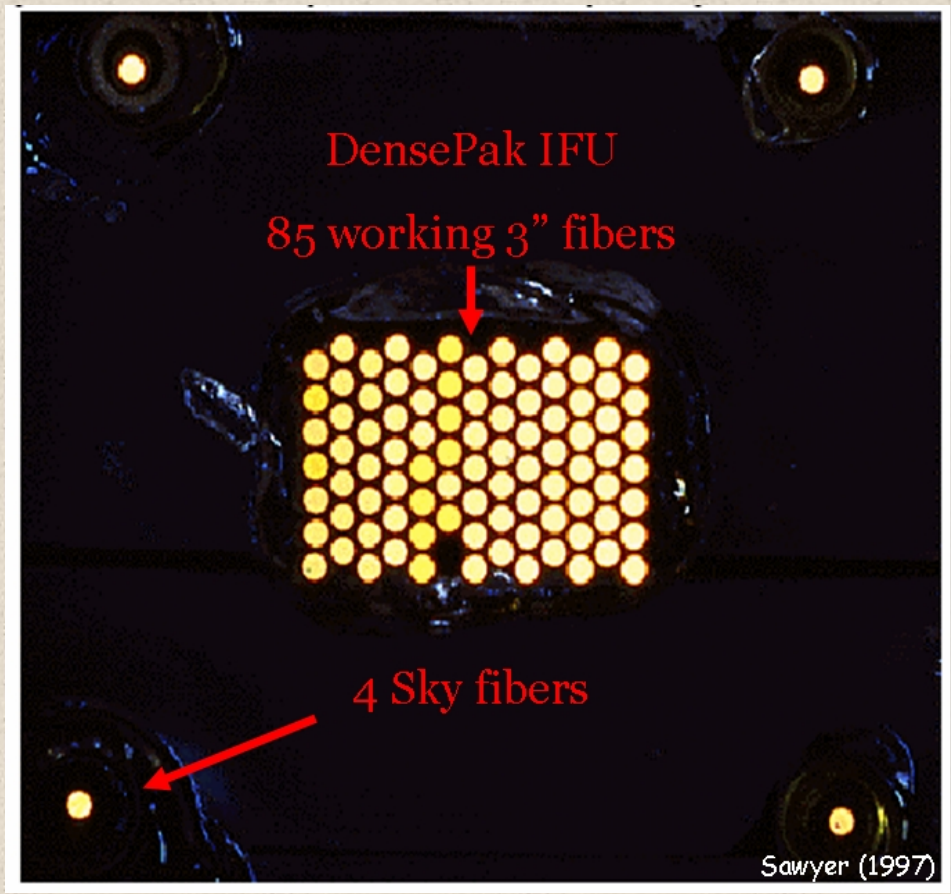
- well-resolved optical velocity fields
- sub-kiloparsec resolution
- two-dimensional data

Kuzio de Naray et al. (2006, 2008)
Chemin et al. (2004)
Swaters et al. (2003)
Simon et al. (2005)

+ others ...

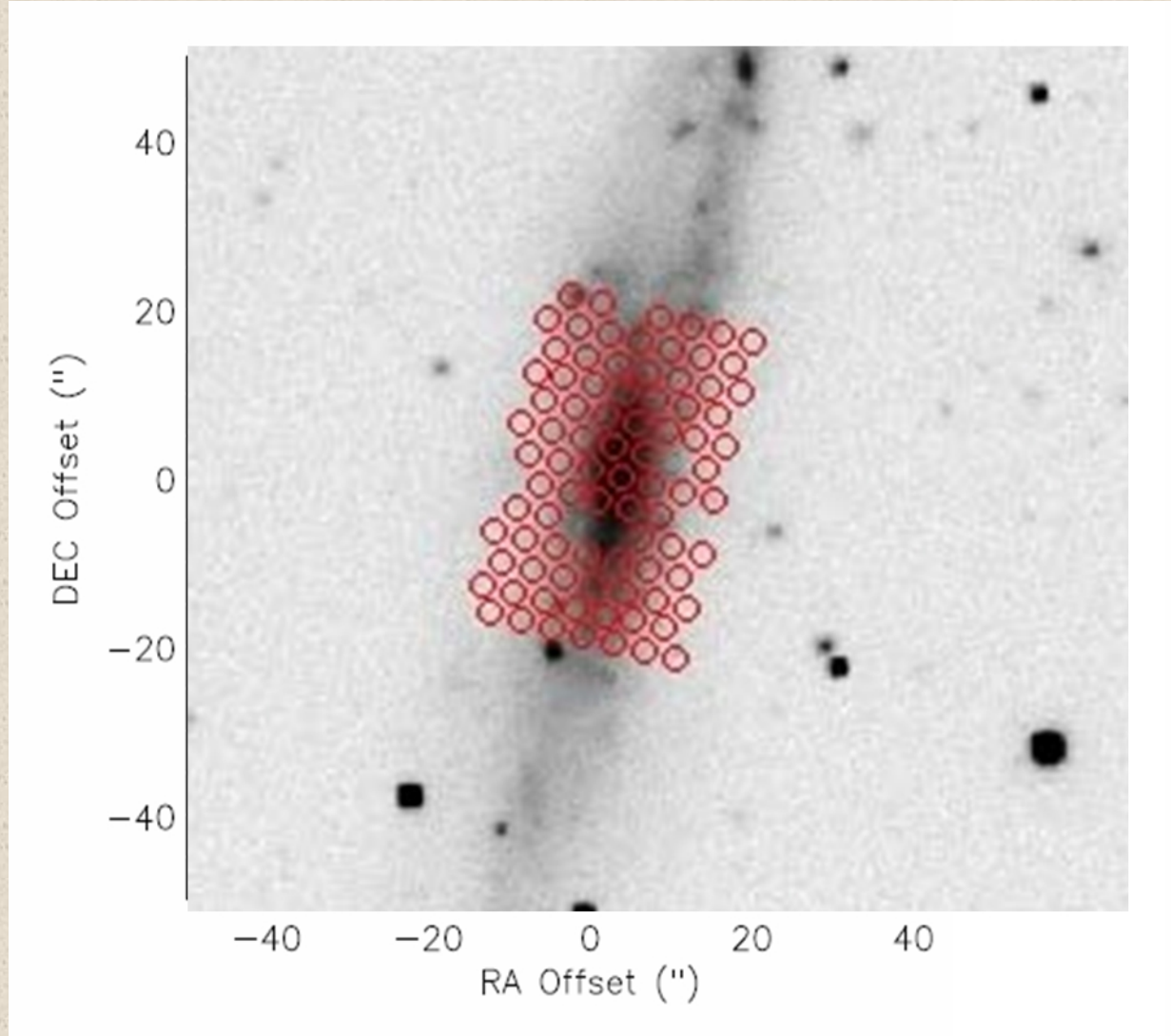
Integral Field Spectroscopy with the DensePak IFU

Observing with DensePak

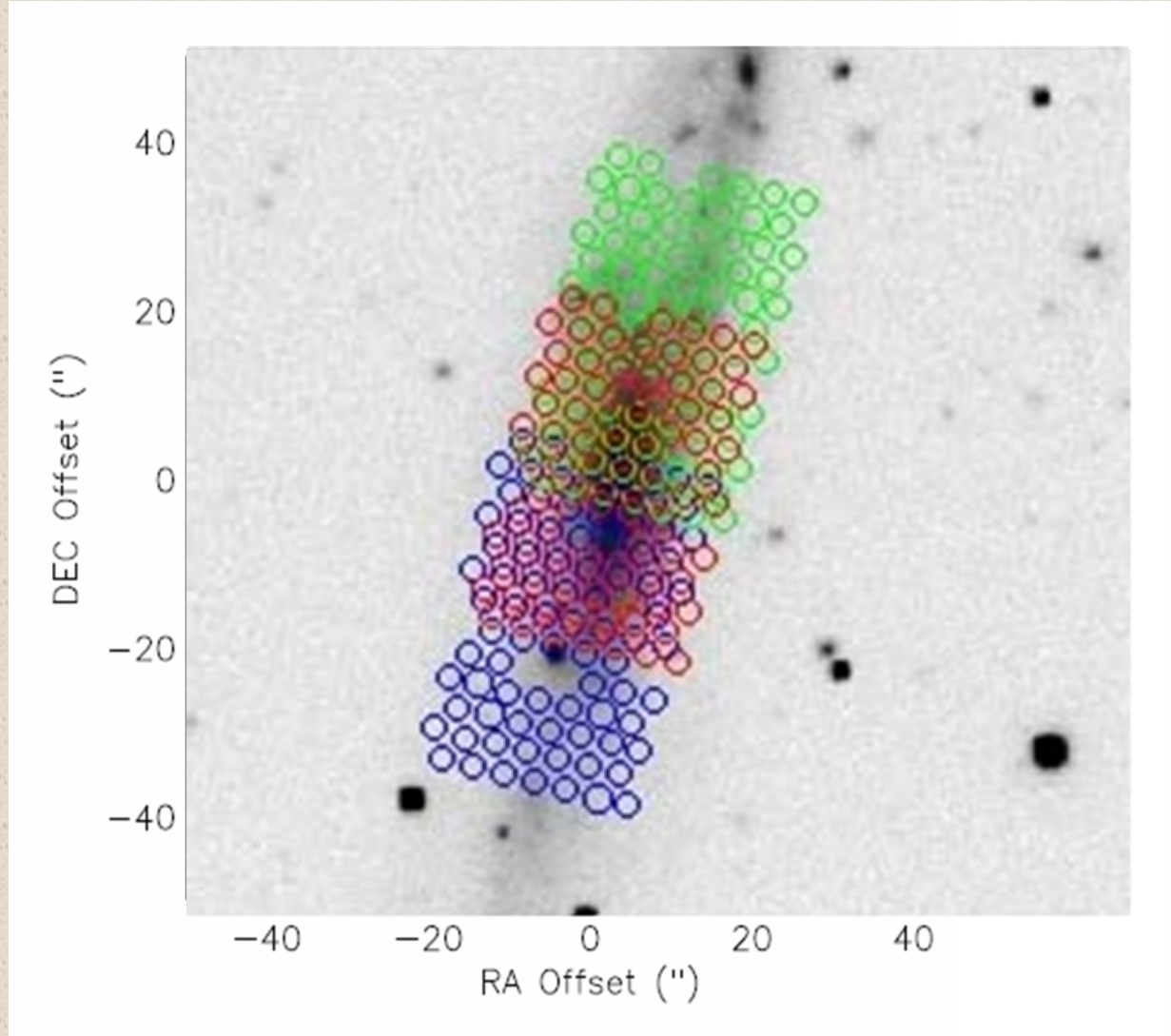


43" x 28" fixed array of 3" fibers

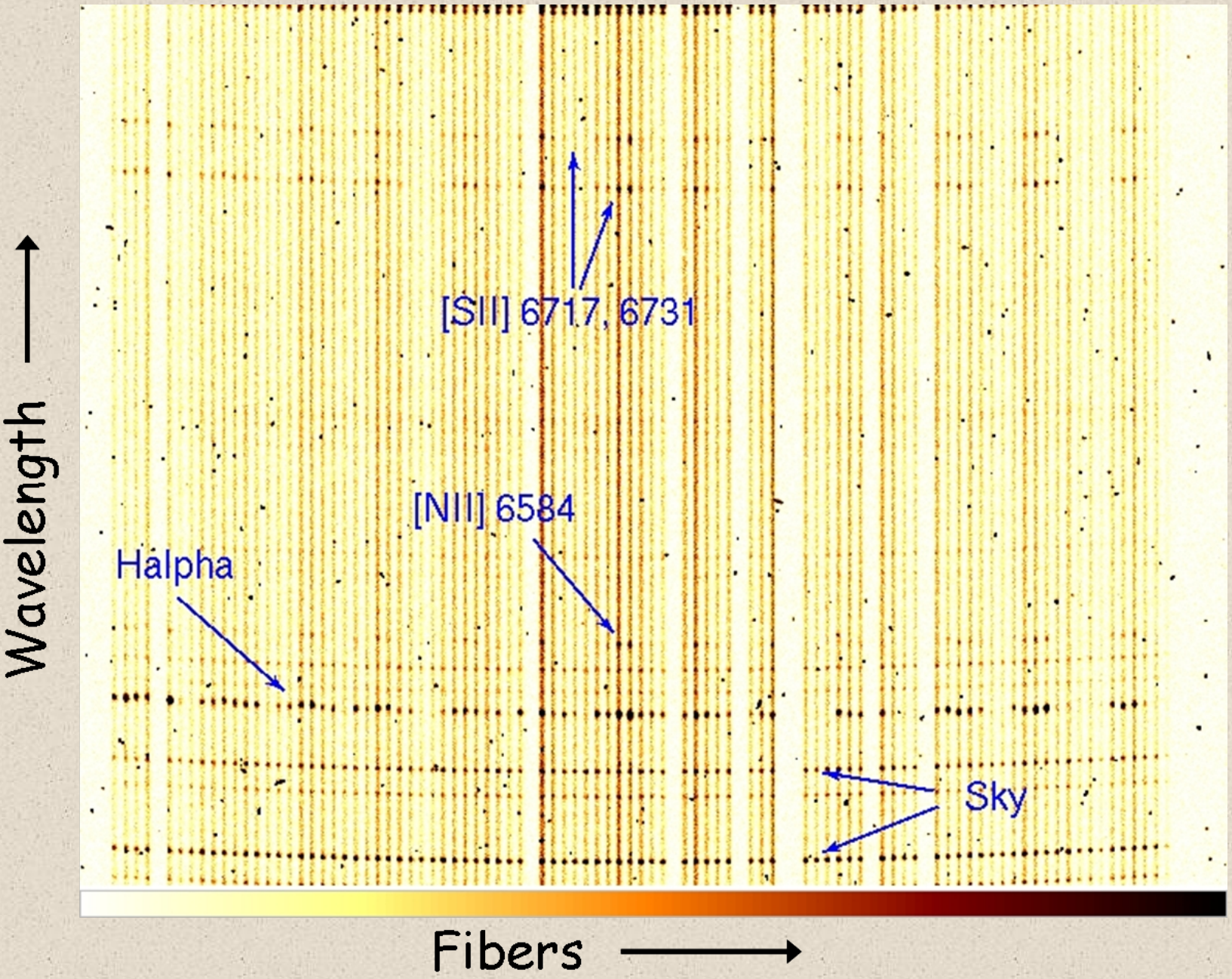
Observing with DensePak



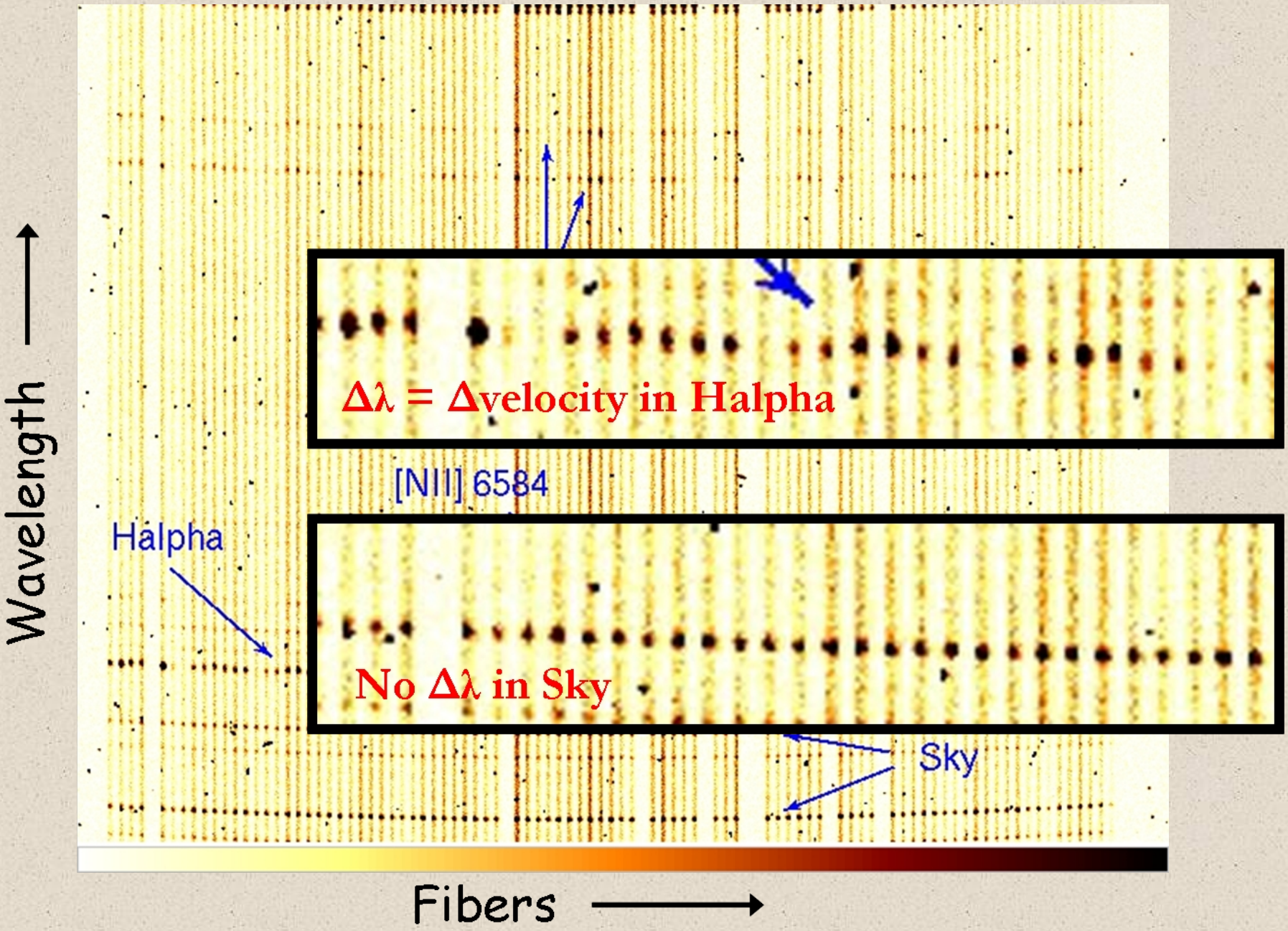
Observing with DensePak



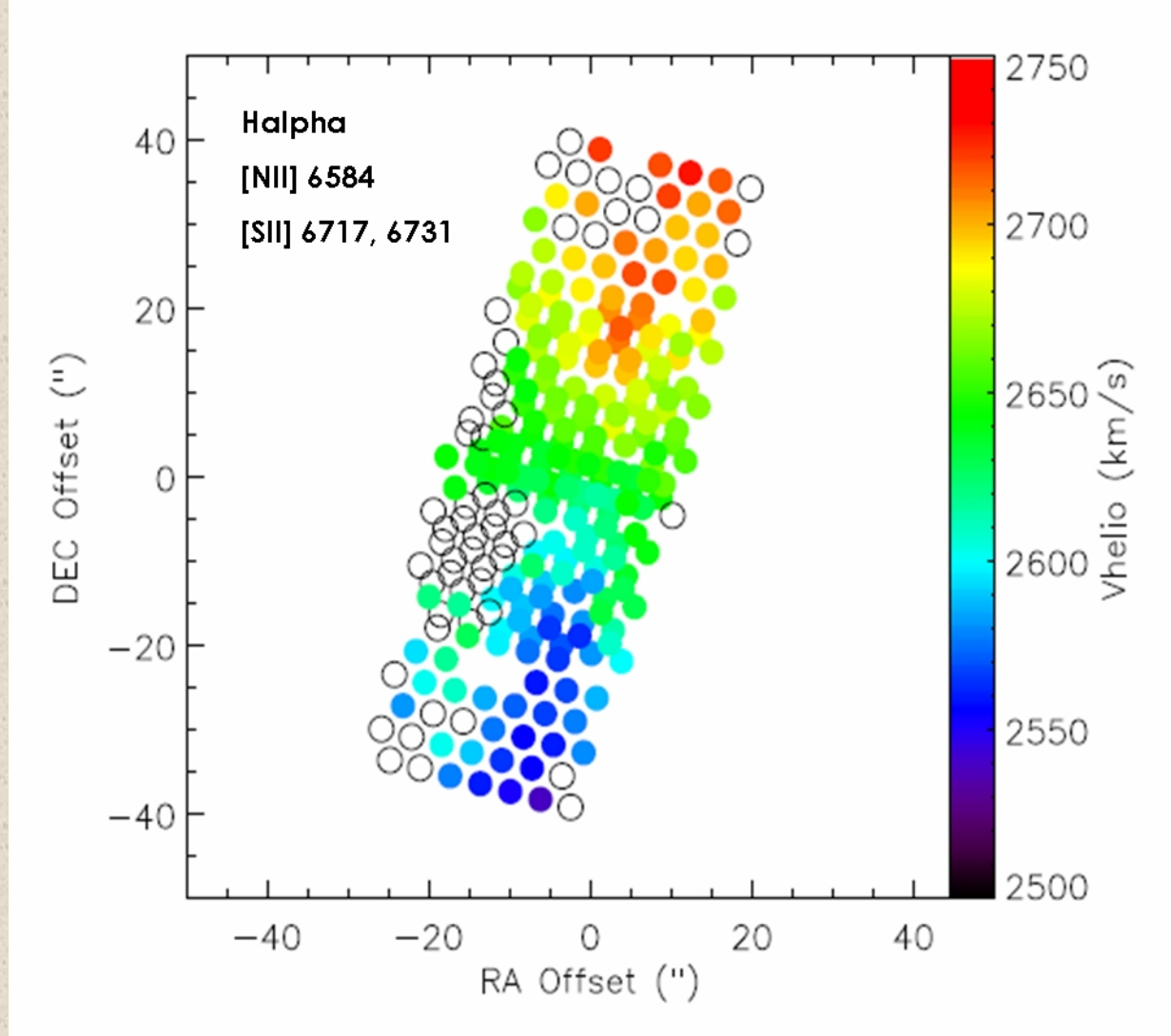
Observing with DensePak



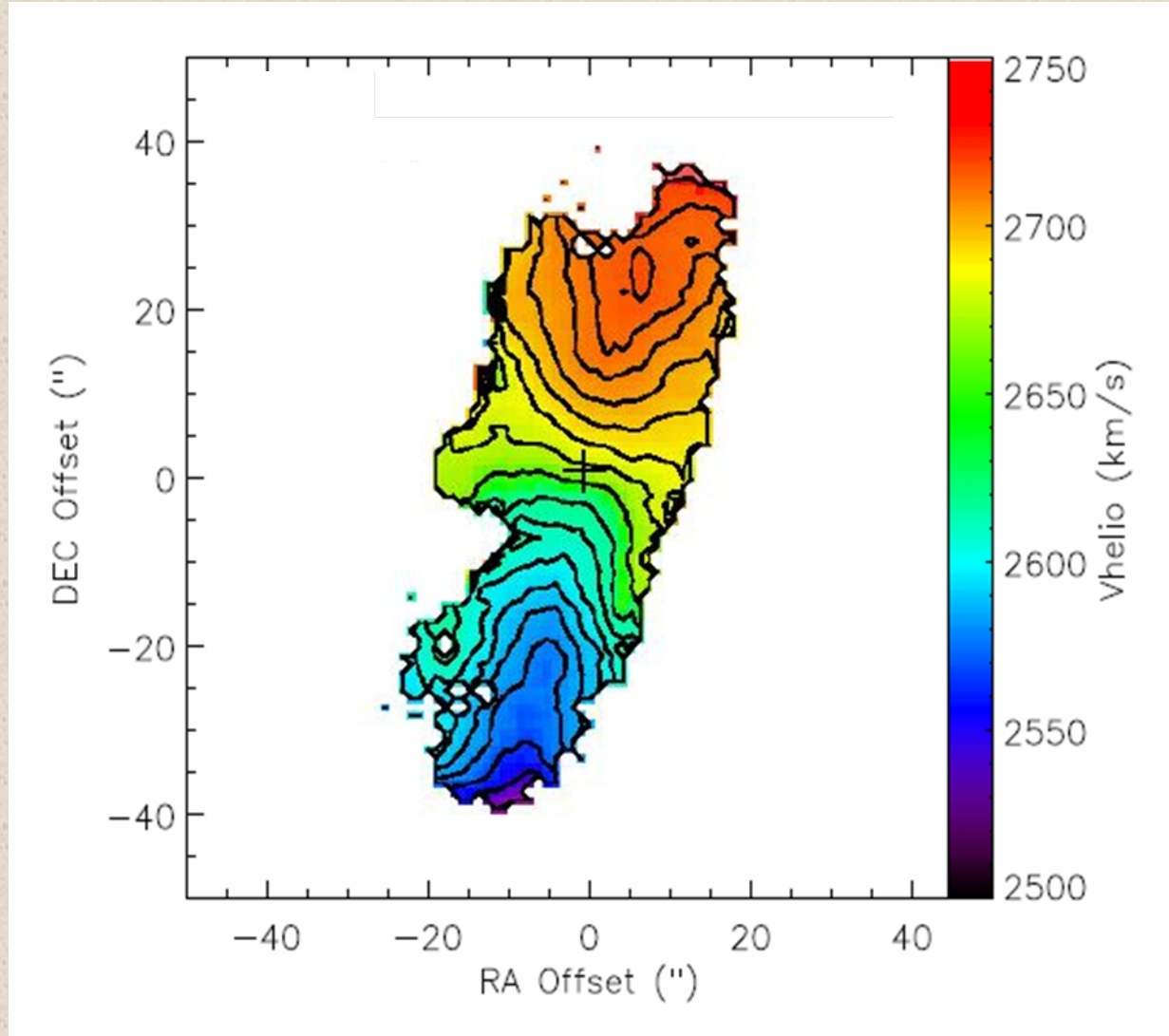
Observing with DensePak



Observing with DensePak

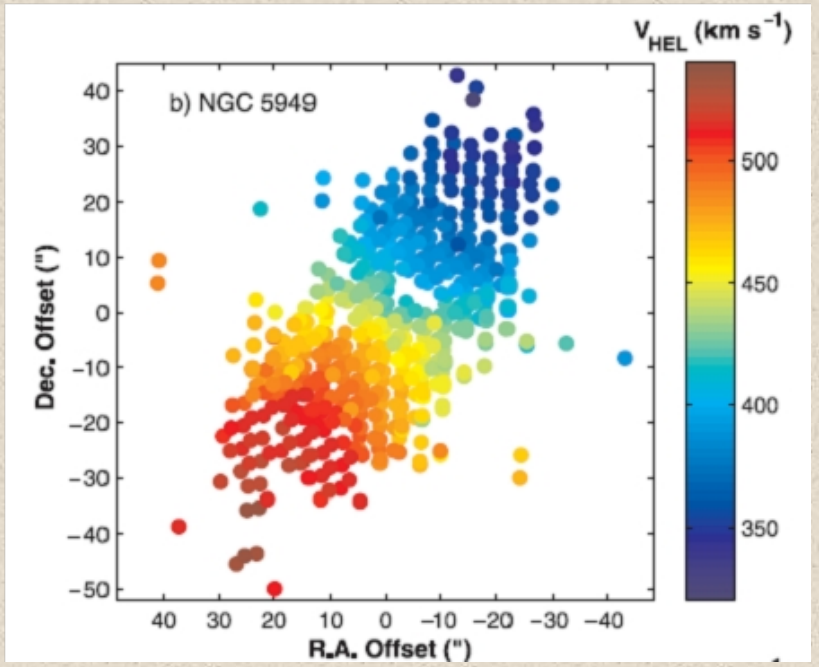


Observing with DensePak

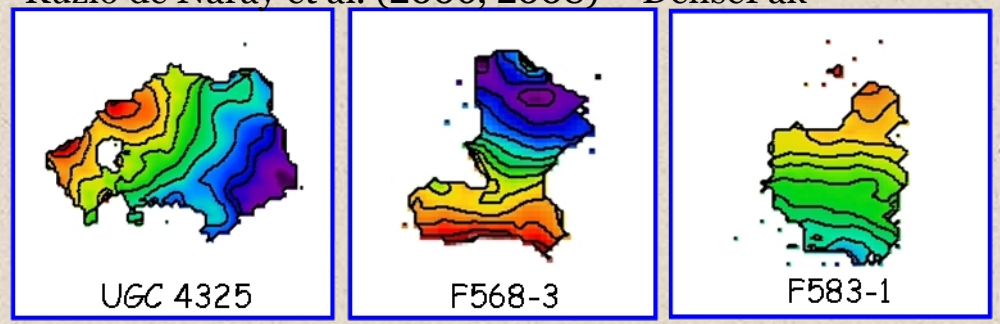


IFU Velocity Fields

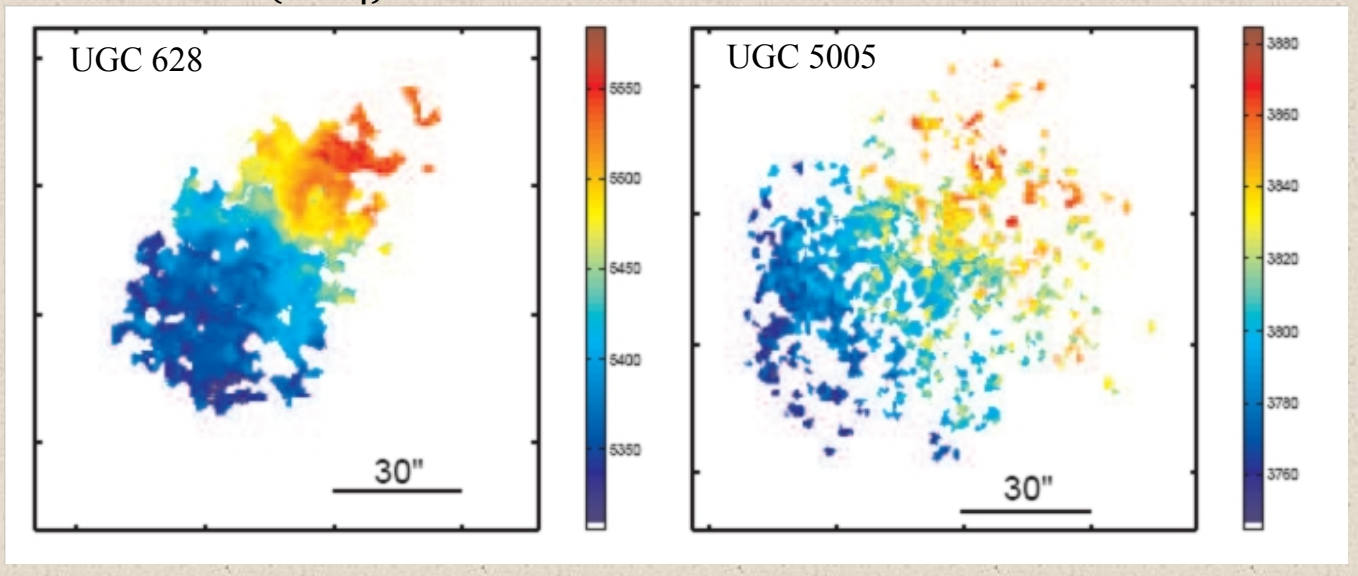
Simon et al. (2005) – DensePak



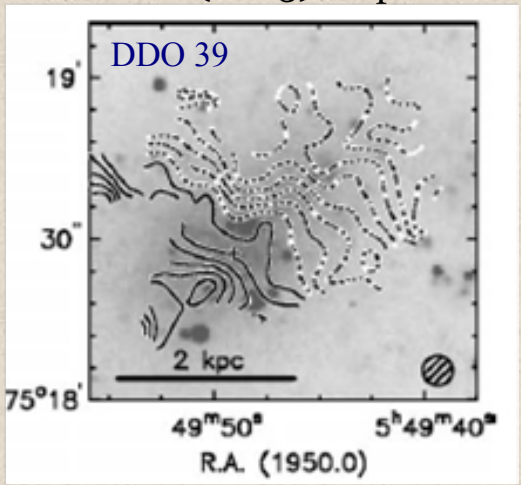
Kuzio de Naray et al. (2006, 2008) – DensePak



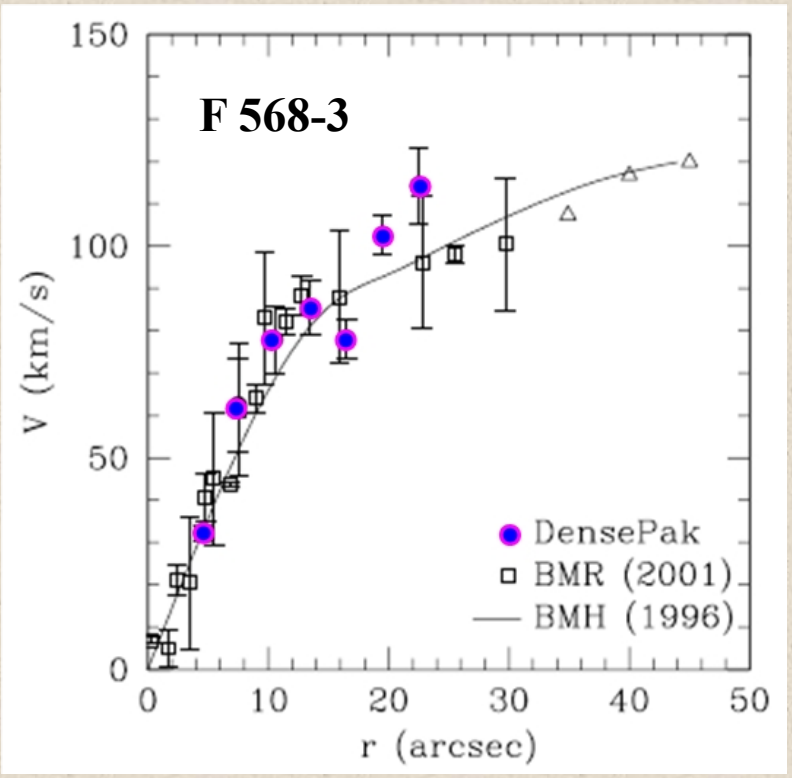
Chemin et al. (2004) – FaNTOmM

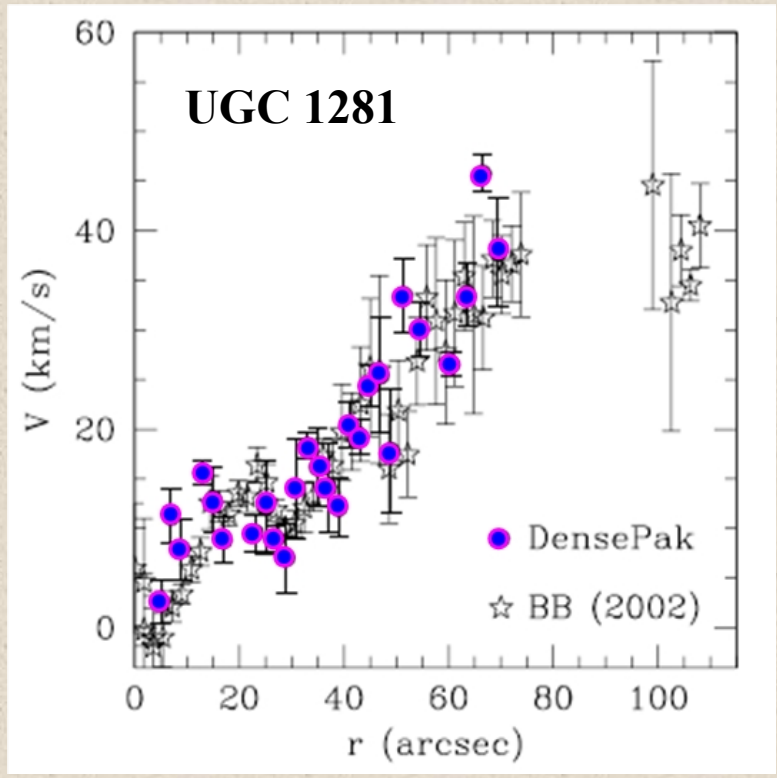


Swaters et al. (2003) – SparsePak



Comparison with Previous Observations



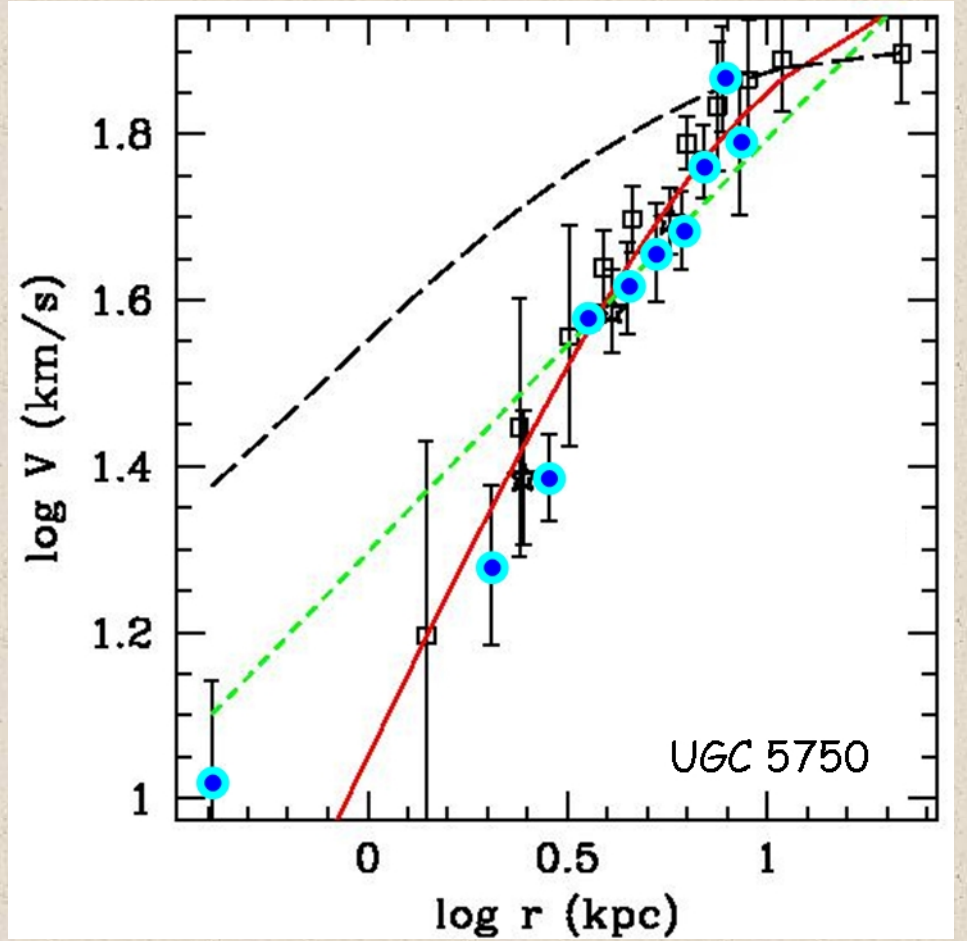


Kuzio de Naray et al. (2006)

DensePak **Long-slit** **HI**

Broad consistency with previous long-slit and HI rotation curves

Halo Fits: Cuspy NFW



For 17 galaxies in Kuzio de Naray et al. (06, 08):

No NFW fit possible or concentration too low for majority of galaxies

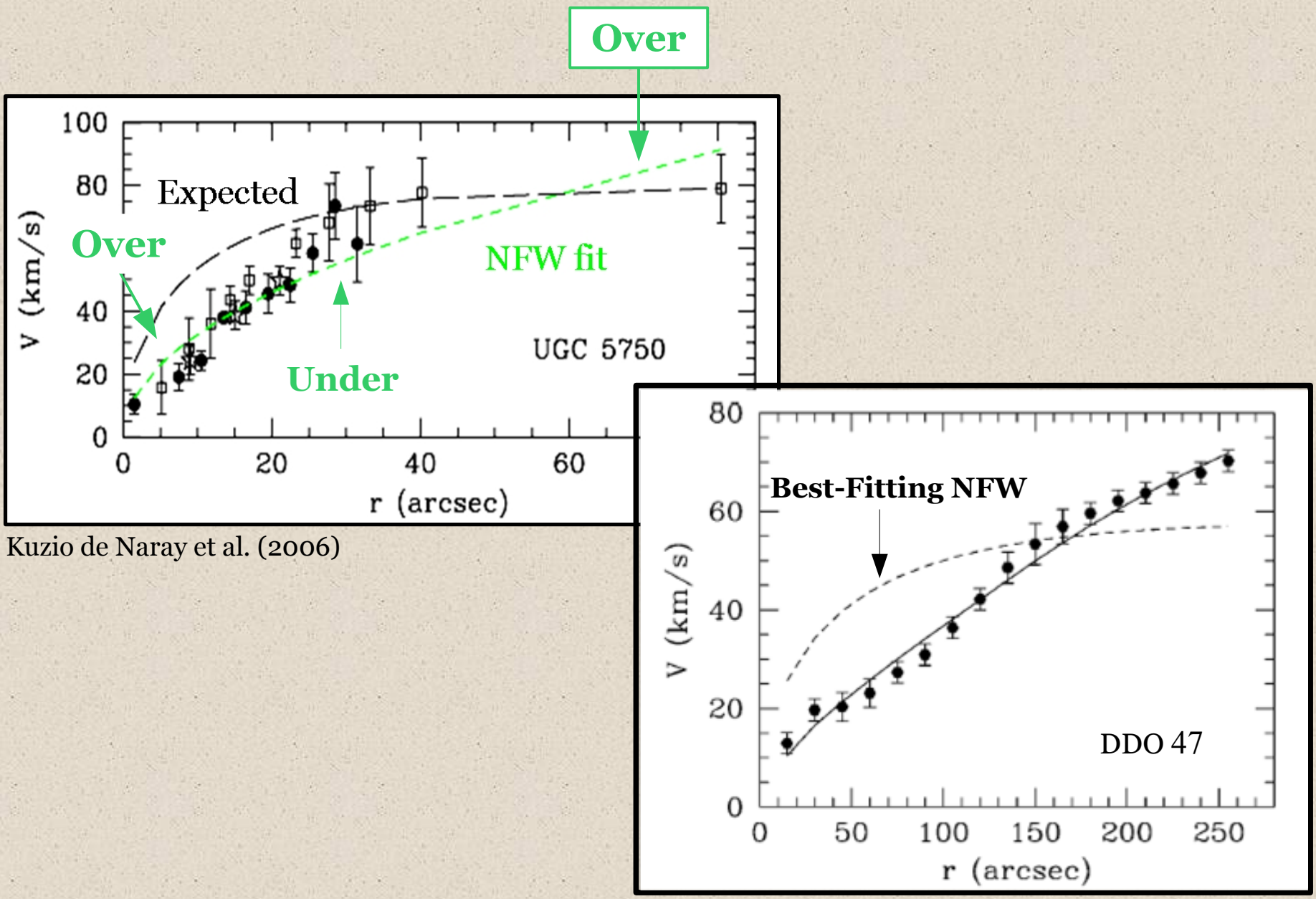
median Dpak:	**c ~ 4.5**
Tegmark 04:	**c ~ 8.2**
WMAP3:	**c ~ 6.1**

Concentrations that are ~ 2 – 2.5 σ low:

Gentile et al. (2007) – problematic
Swaters et al. (2003) – less concerned

Concentrations decrease when zero disk assumption is relaxed.

Halo Fits: Rotation Curve Shapes



Kuzio de Naray et al. (2006)

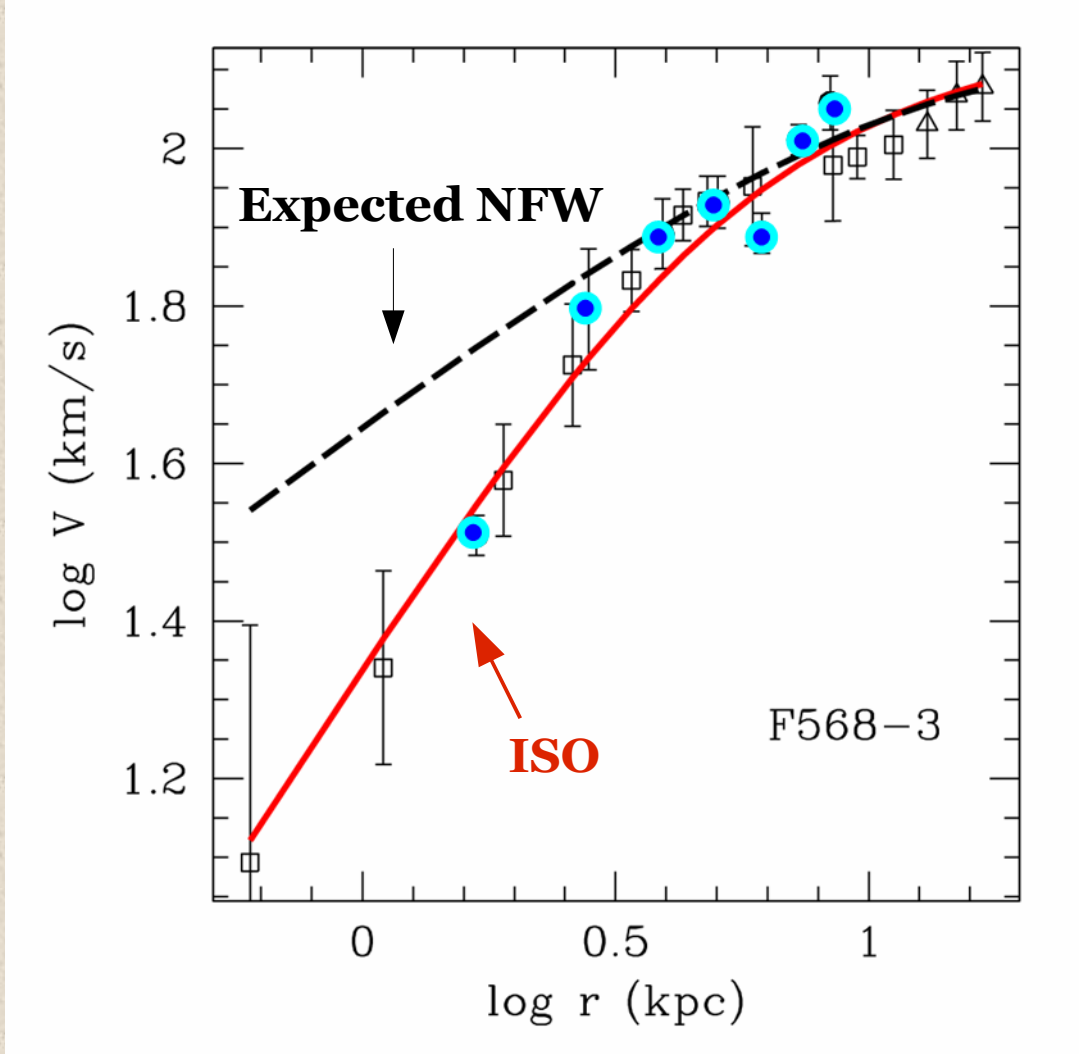
Gentile et al. (2005)

Halo Fits: Cored Profiles

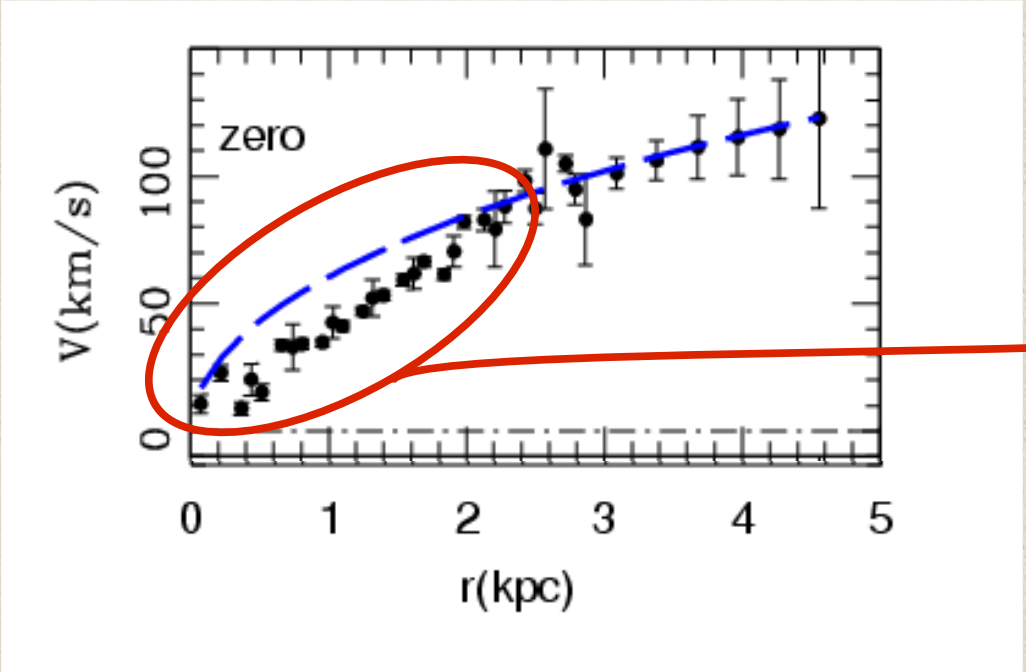
For 17 galaxies in Kuzio de Naray et al. (06, 08):

13 of 17 galaxies best-described by isothermal halos

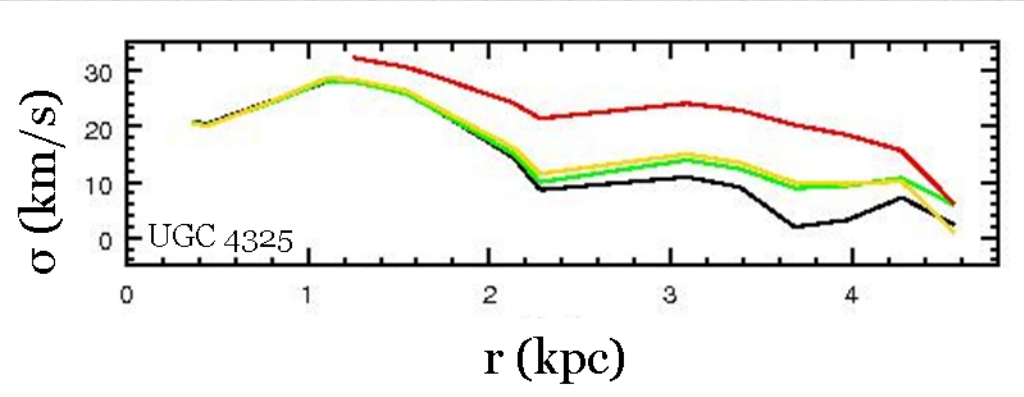
Core radius is typically a few kpc



Can Noncircular Motions Solve the Problem?



Noncircular Motions?



$$3\sigma^2 = V^2_{CDM} - V^2_{DM}$$

$$\sim 20 \text{ km/s}$$

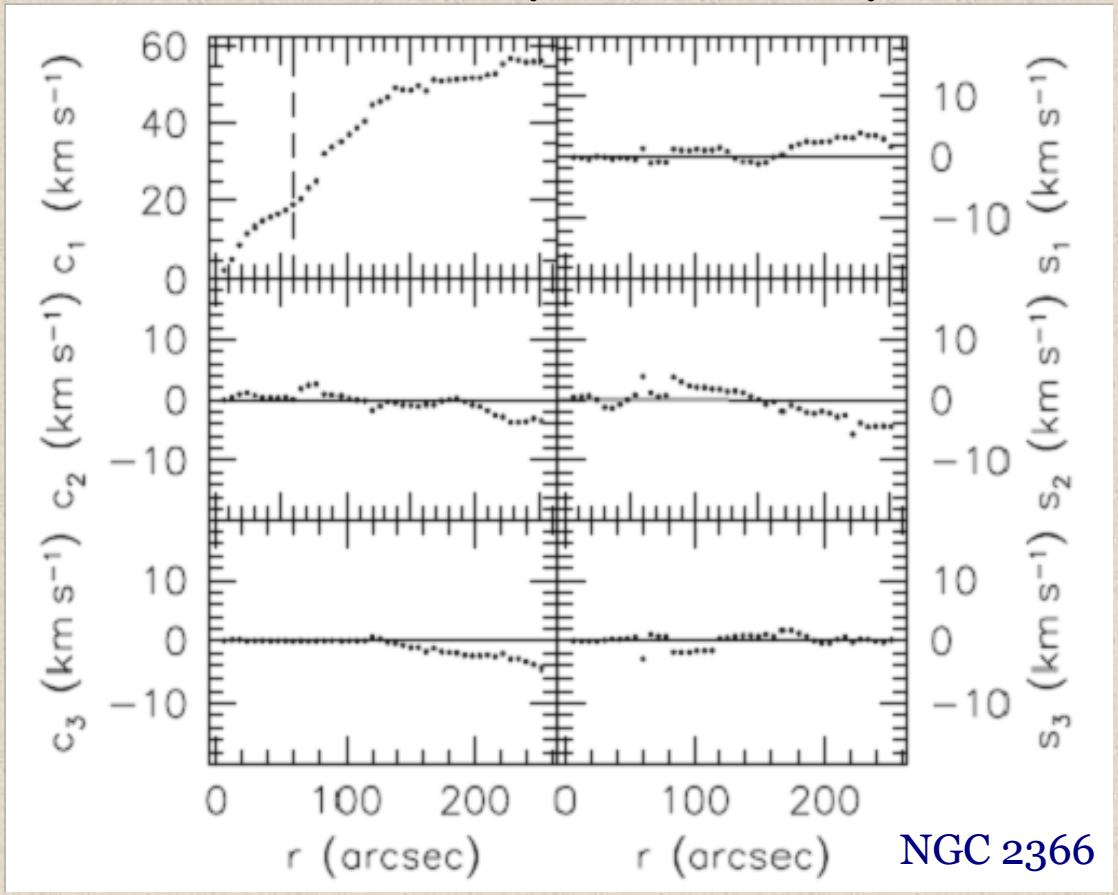
$\sigma_{observed} \sim 6 - 10$ km/s

Can Noncircular Motions Solve the Problem?

Harmonic decomposition of velocity field

$$V_{LOS} = c_0 + \sum_{m=1}^{N} [c_m \cos(m\psi) + s_m \sin(m\psi)]$$

Rotation velocity Radial velocity

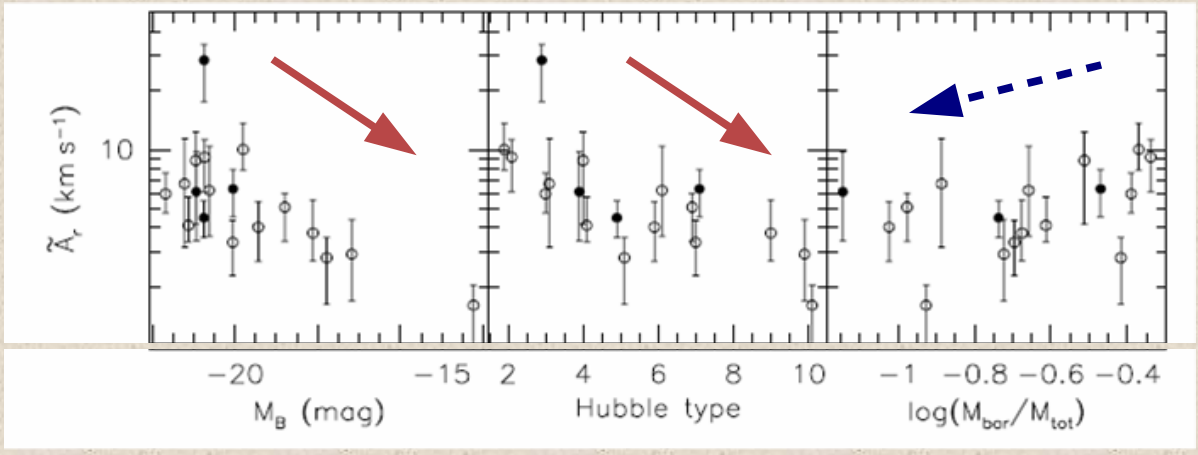


Trachternach et al. (2008)

Noncircular Motions

Noncircular motions in 19 THINGS galaxies (Trachternach et al. 2008)

Median σ (km/s)



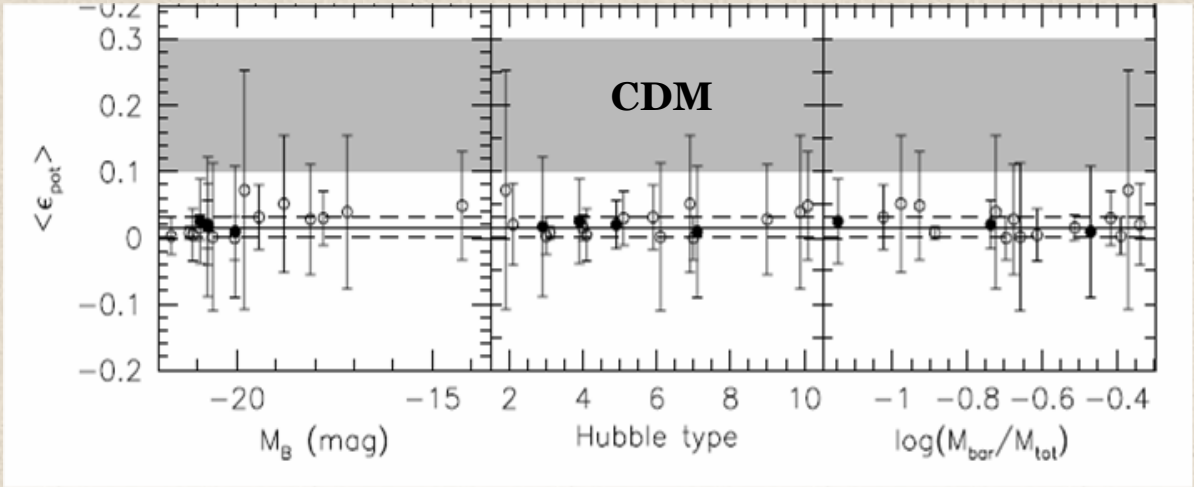
Average σ:

6.7 km/s

~90% of galaxies
σ ≤ 9 km/s

M_B Hubble Type $\log(M_{bar}/M_{tot})$

Elongation of potential



<ε $_{pot}$> = 0.017

pretty round

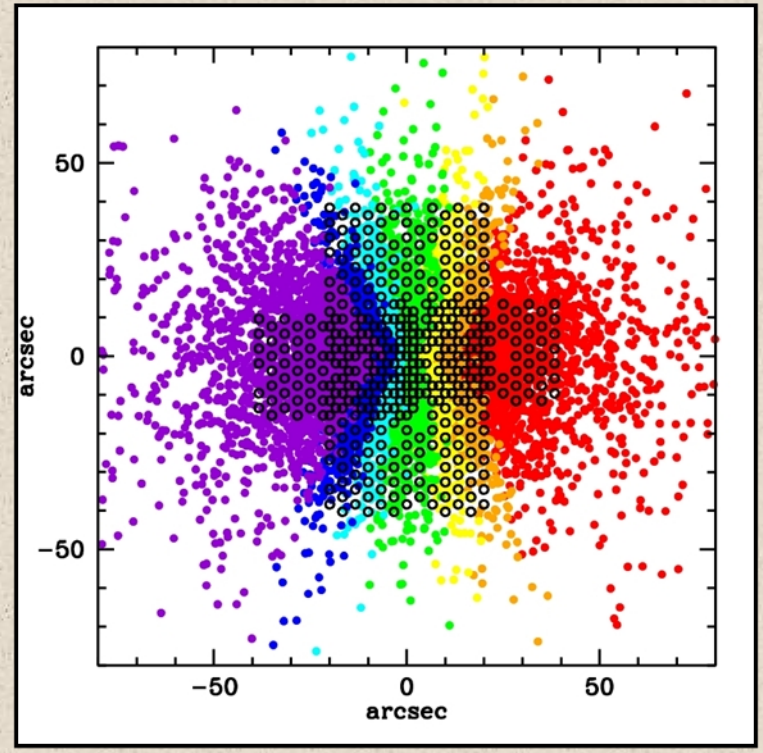
Modeling the DensePak Data

- Two-dimensional rigid analytic NFW potential

- Halo parameters consistent with the cosmological *concentration-V_{200}* relation

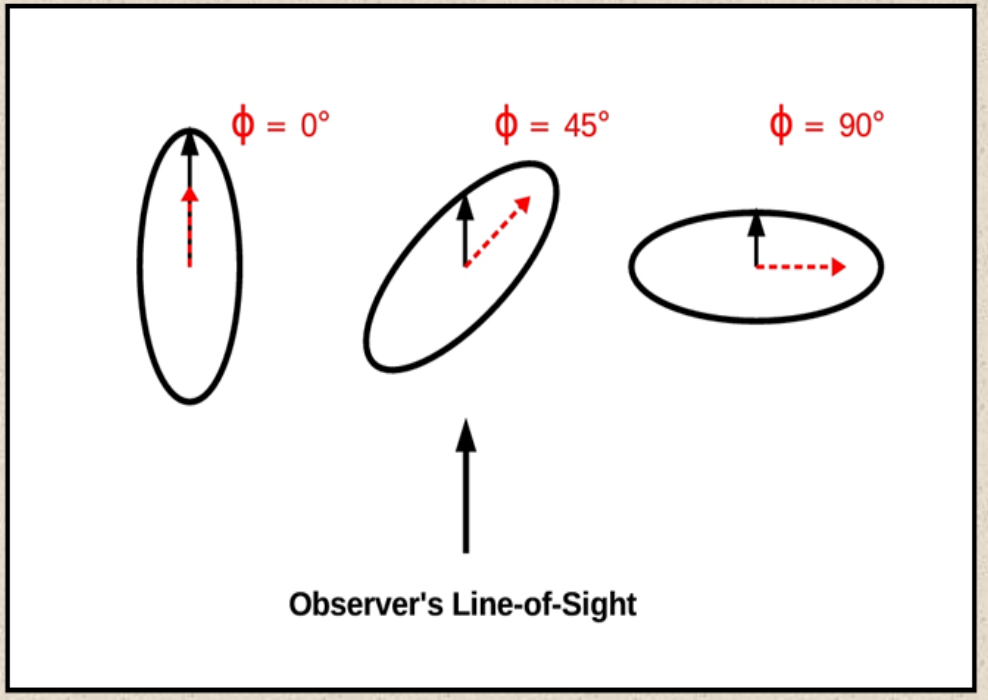
- Observed disk scale length, inclination spatial resolution, velocity dispersion

- "Observe" the simulated galaxies with the DensePak IFU



Non-Axisymmetric Potential

Noncircular Orbits



Fixed axis ratios:

[similar to Hayashi et al. (2007)]

q =	0.98	0.90
	0.96	0.88
	0.94	0.86
	0.92	0.84

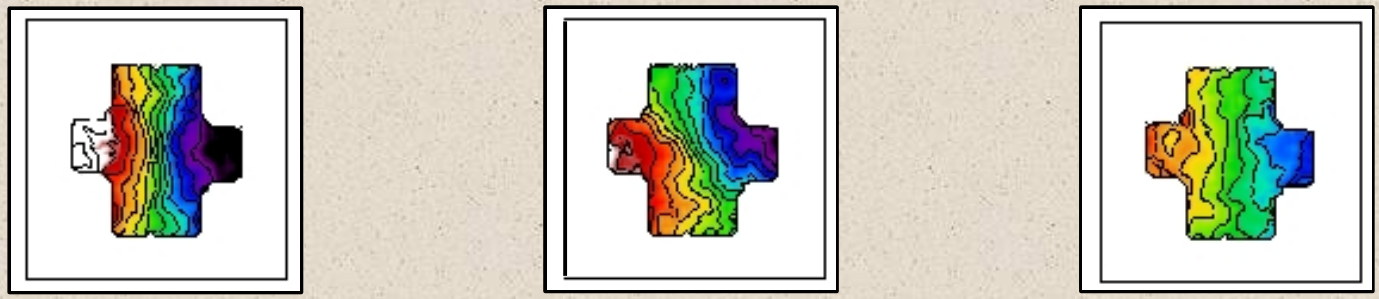
Angle between elongated axis and line-of-sight:

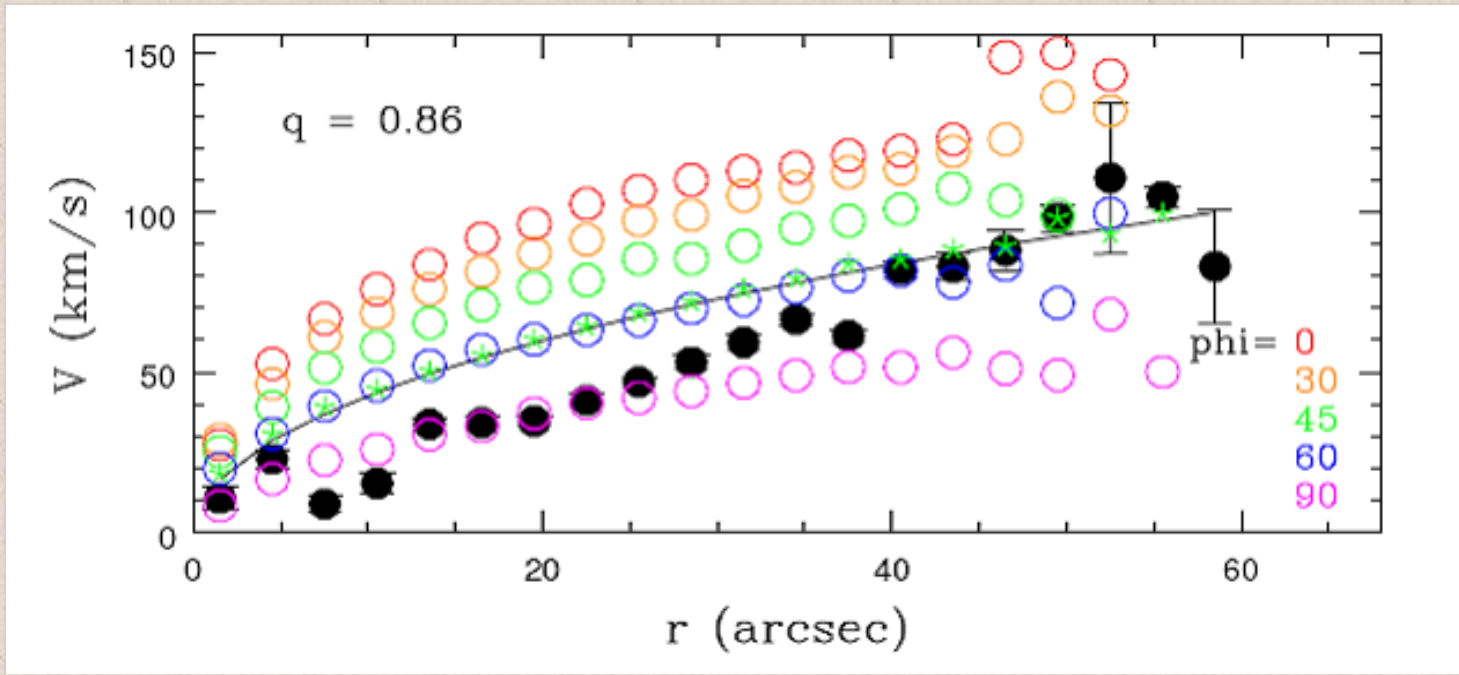
$\varphi = 0^{o}, 30^{o}, 45^{o}, 60^{o}$, and 90^{o}

These 2D potentials are equivalent to 3D **prolate** dark matter halos in which the long axis of the halo coincides with the elongated axis of the disk.

Non-Axisymmetric Potential

$\varphi = 0^{\circ}$ $\varphi = 45^{\circ}$ $\varphi = 90^{\circ}$

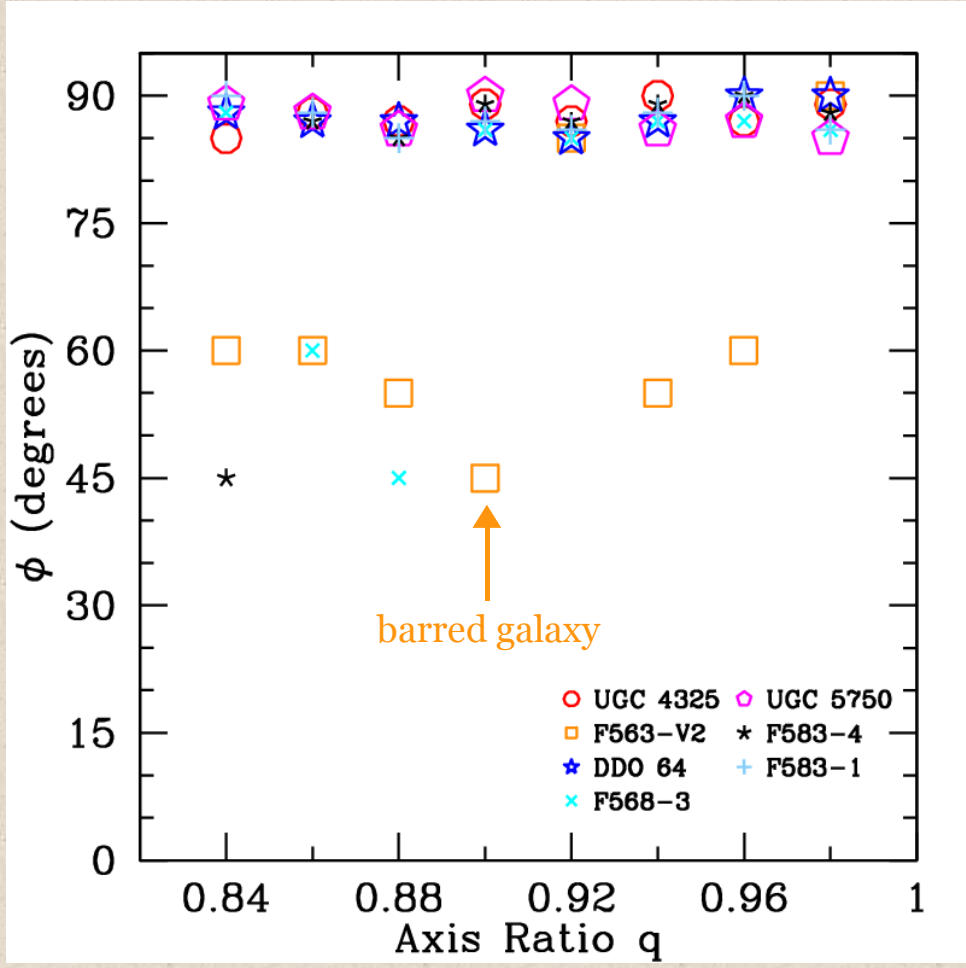


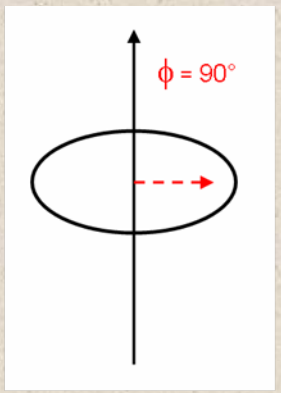


Asymmetric Halo → **Mock rotation curves both *above & below* the true circular rotation curve**

Non-Axisymmetric Potential

May need an axis ratio that changes with radius, however …



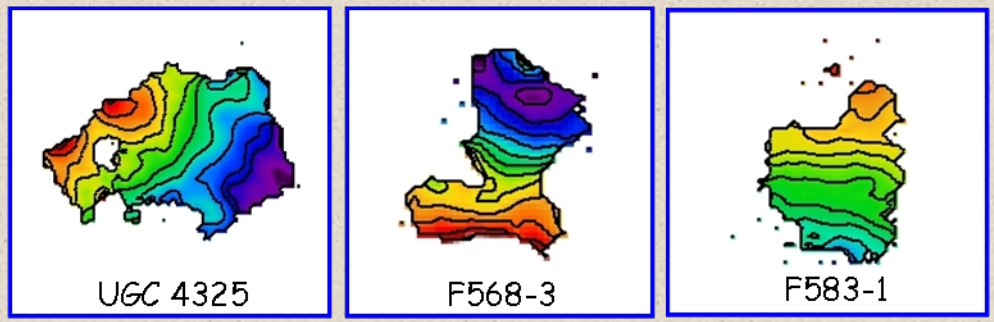


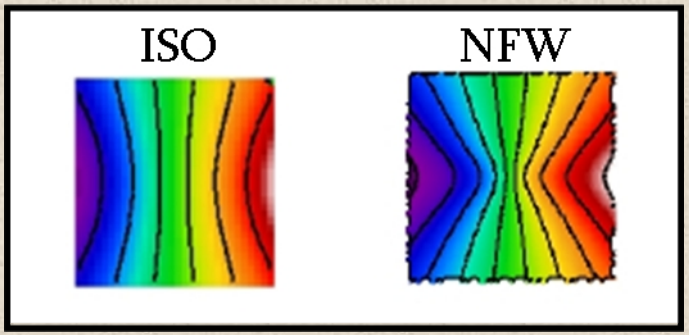
Elongated axis ⊥ to observer's LOS

Inconsistent with random distribution of halo orientations on the sky

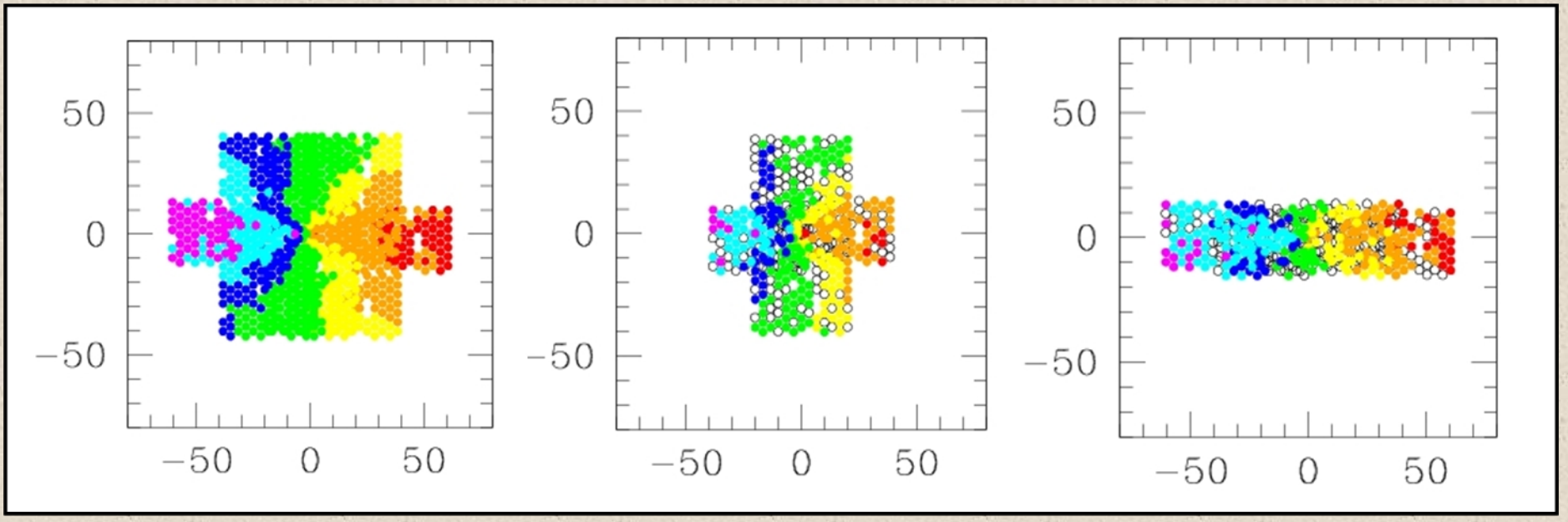
Triaxial Halo

Tobias Kaufmann (UCI): 3D simulations with gas *and* dark matter





Triaxial velocity fields show the "NFW pinch" that is not seen in observed velocity fields



Summary

- Numerical simulations predict **cuspy, prolate-triaxial** halos with **pinched velocity fields** and **fast-rising rotation curves**

- **Observed** LSB HI & long-slit rotation curves are **more consistent** with **cored** halos

- Velocity fields from **IFU spectroscopy** look **solid-body** & rotation curves are also better-described by **cored** halo profiles

- Noncircular motions typically **not large enough** to reconcile the data with cuspy halos

- **2D simulations:**
  - -may indicate the need for radially-varying axis ratio
  - -**BUT** special viewing angle required ($\varphi \longrightarrow 90^{o}$)

- **3D simulations:**
  - -Triaxial Halo $\longrightarrow$ mock DensePak velocity fields look pinched