Mass Distribution in Galaxies using Multi-wavelength 3D Spectroscopy

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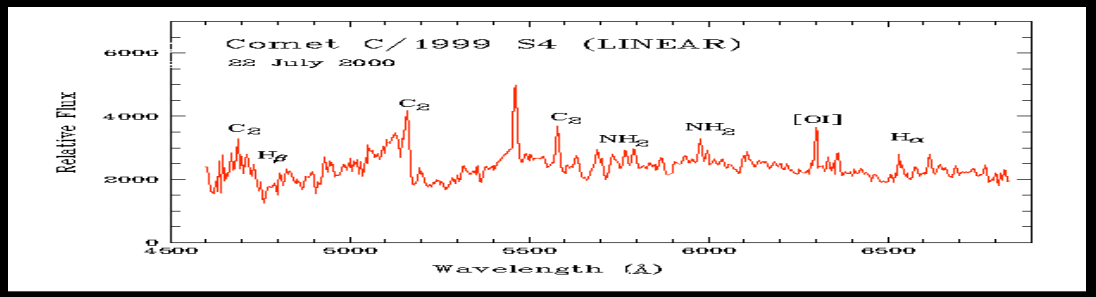
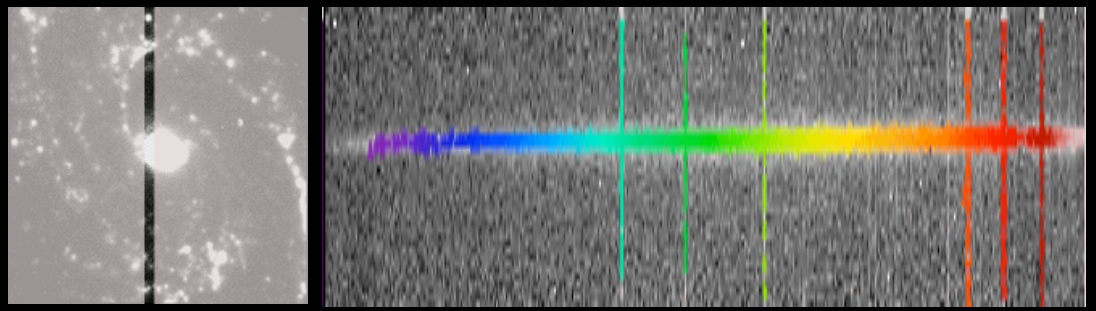
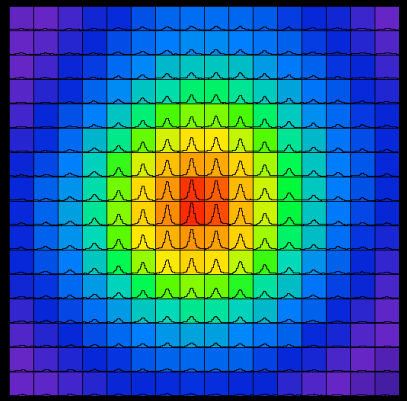
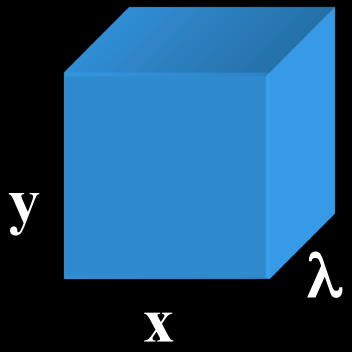
1D 2D 3D … Spectroscopy

- 1D : I(λ)
- 2D : I(λ,x)
- 3D : I(λ,x,y)









3D spectroscopy or spectroscopic imaging

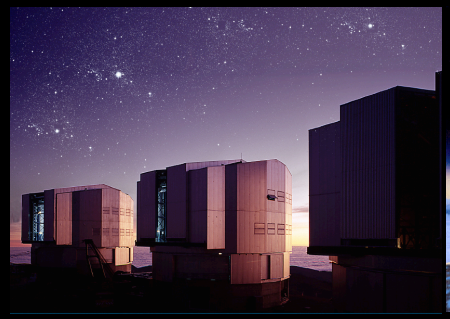
3D spectroscopy (radio λs): an essential tool for aperture synthesis instruments



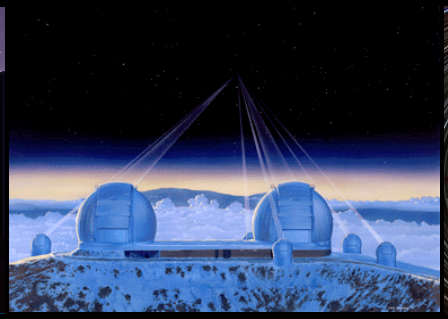

WSRT VLA ATCA ALMA

KAT7 → MeerKat → SKA

3D spectroscopy (optical λs): an essential tool for 4m, VLT, ELTs and LST



VLT

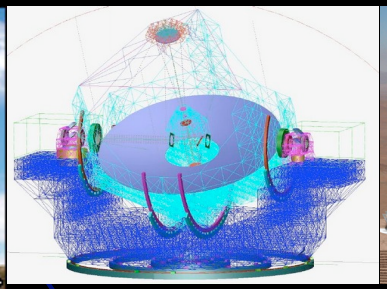


Keck

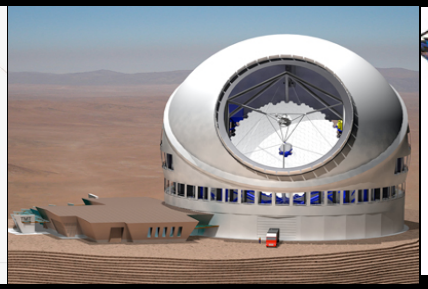
Gemini

GTC

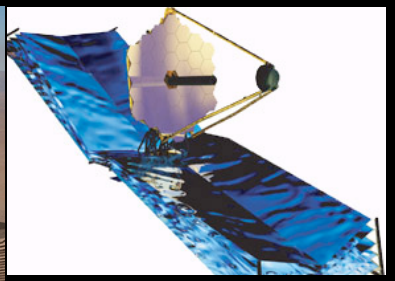
SALT



E-ELT



TMT



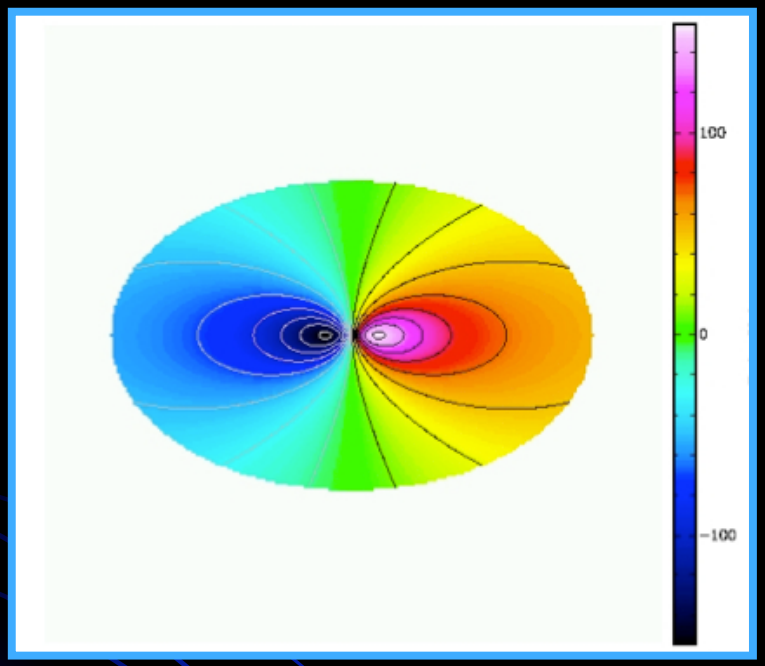
JWST

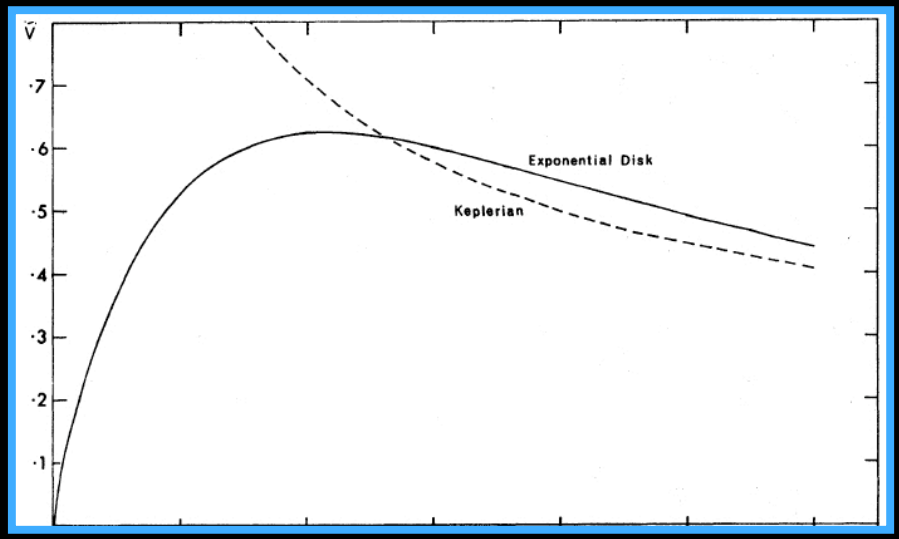
Disk Galaxy: MW & Andromeda

The Milky Way from Sutherland

M31: nearby spiral in the Local Group

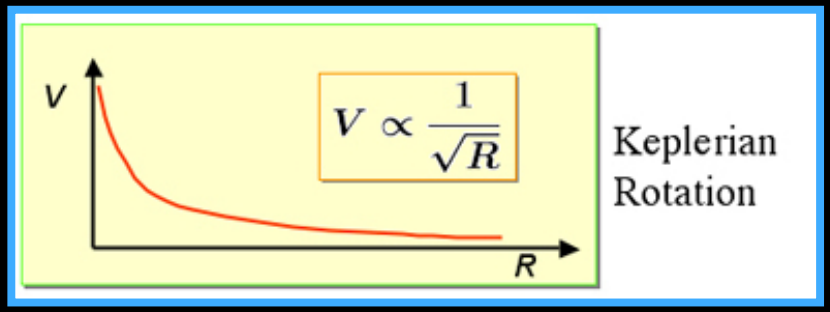
Galaxy Rotation Curve (RC)



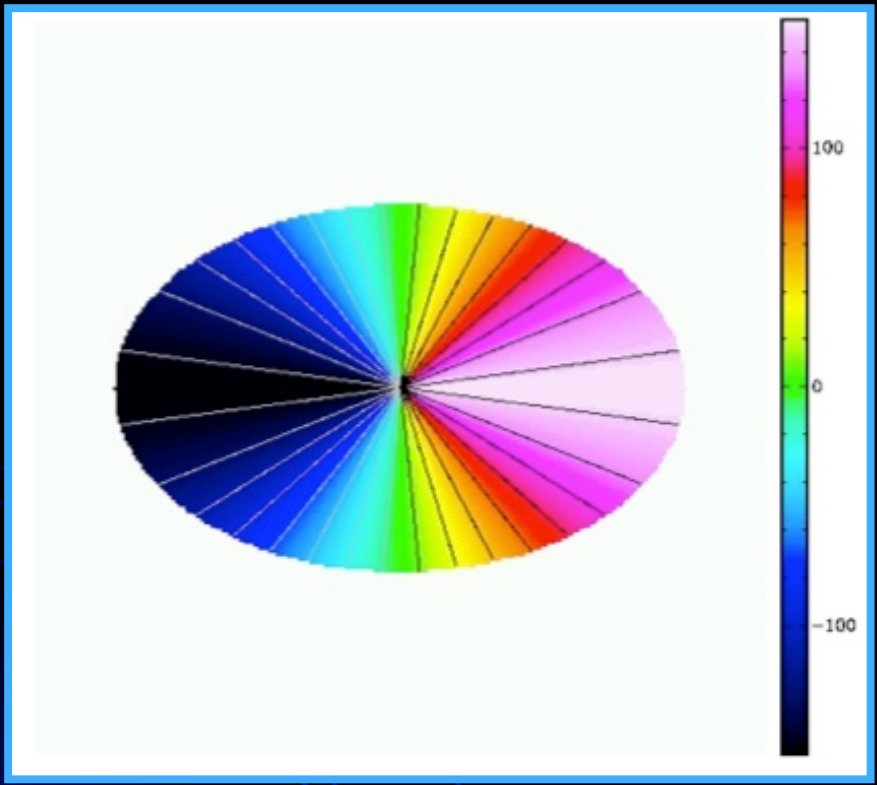


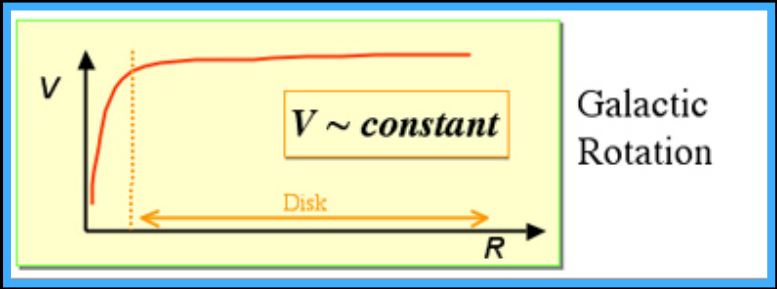
Exponential disk model

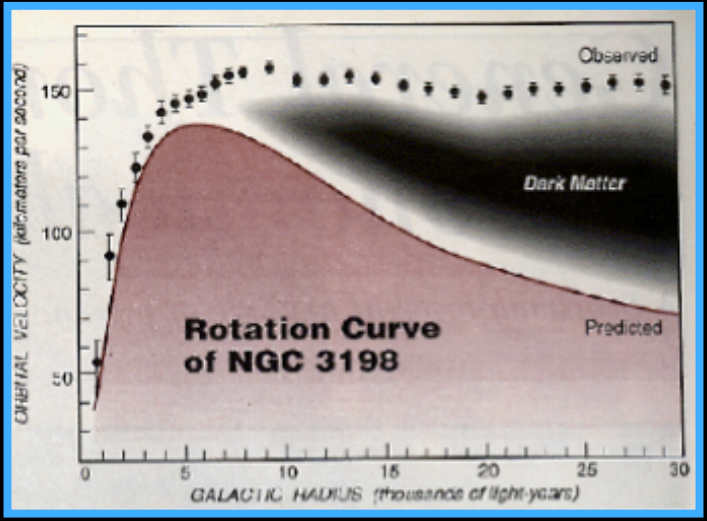
$$I(r) = I_0 e^{-\frac{r}{h_r}}$$



Galaxy Rotation Curve (RC)

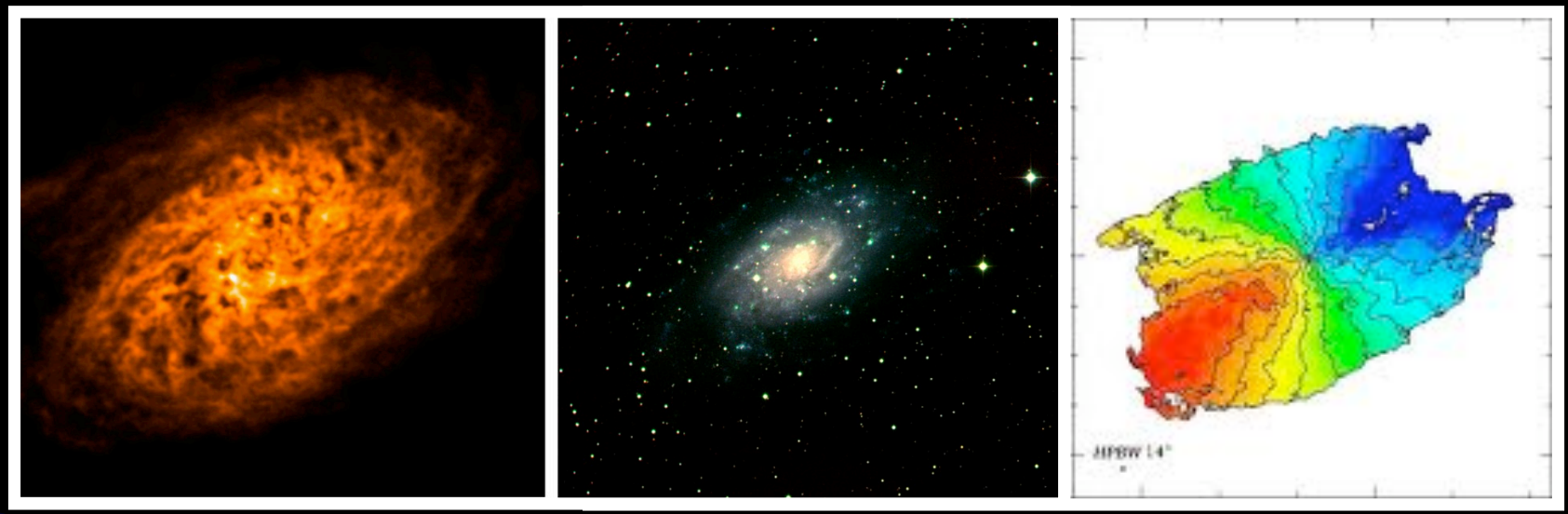






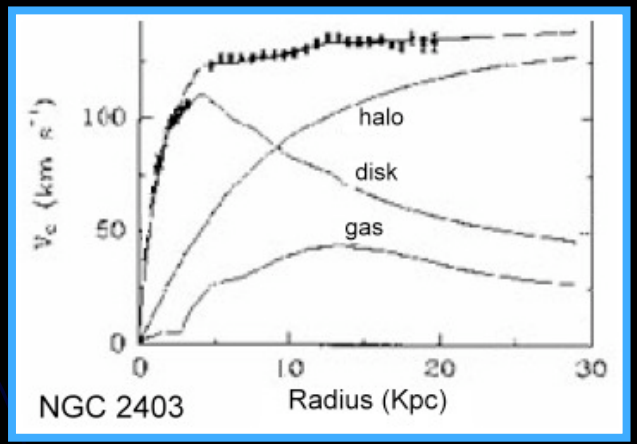
Flat Rotation Curve

NGC 2403



HI gas distribution

HI velocity field



HI Rotation Curve

NGC 2403

THE ASTRONOMICAL JOURNAL, 136:2648–2719, 2008 December doi:10.1088/0004-6256/136/6/2648

HIGH-RESOLUTION ROTATION CURVES AND GALAXY MASS MODELS FROM THINGS

W. J. G. DE BLOK[1], F. WALTER[2], E. BRINKS[3], C. TRACHTERNACH[4], S-H. OH[5], AND R. C. KENNICUTT, JR.[6]
[1] Department of Astronomy, University of Cape Town, Rondebosch 7700, South Africa; edeblok@ast.uct.ac.za

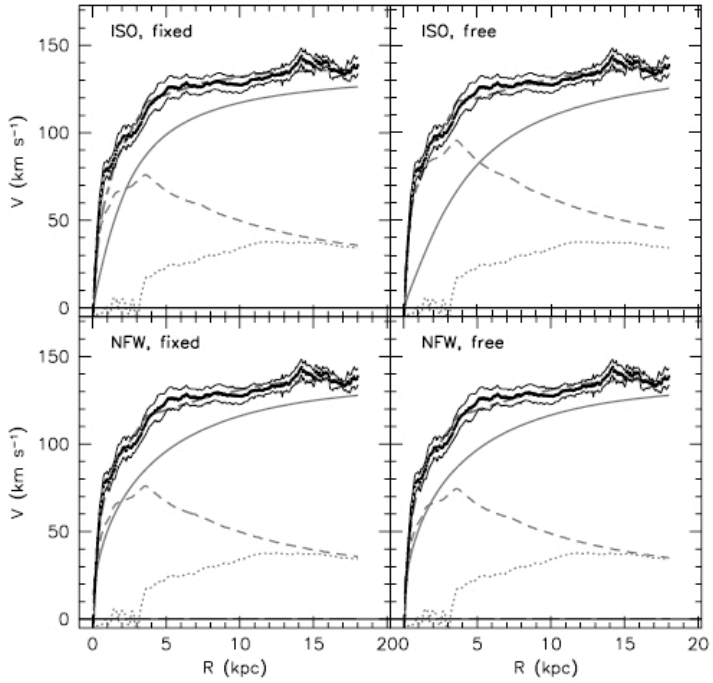
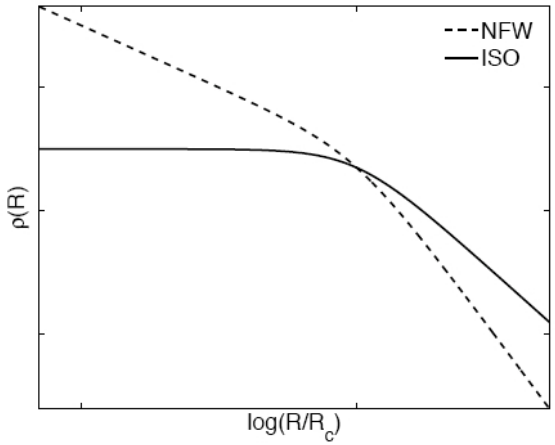


Figure 25. ISO and NFW rotation curve fits for the single-disk model of NGC 2403. Symbols and lines are as in Figure 23.

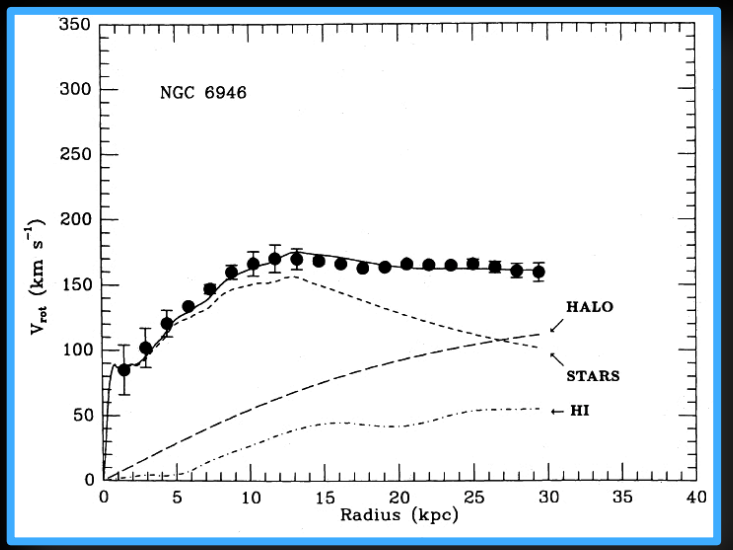
$$\rho(\mathcal{R})_{\rm NFW} = \frac{\rho_0}{(\mathcal{R}/\mathcal{R}_c)(1+(\mathcal{R}/\mathcal{R}_c)^2)}$$

$$\rho(\mathcal{R})_{\rm iso} = \frac{\rho_0}{1+(r/r_c)^2}$$



Dark Matter in Spiral Galaxies

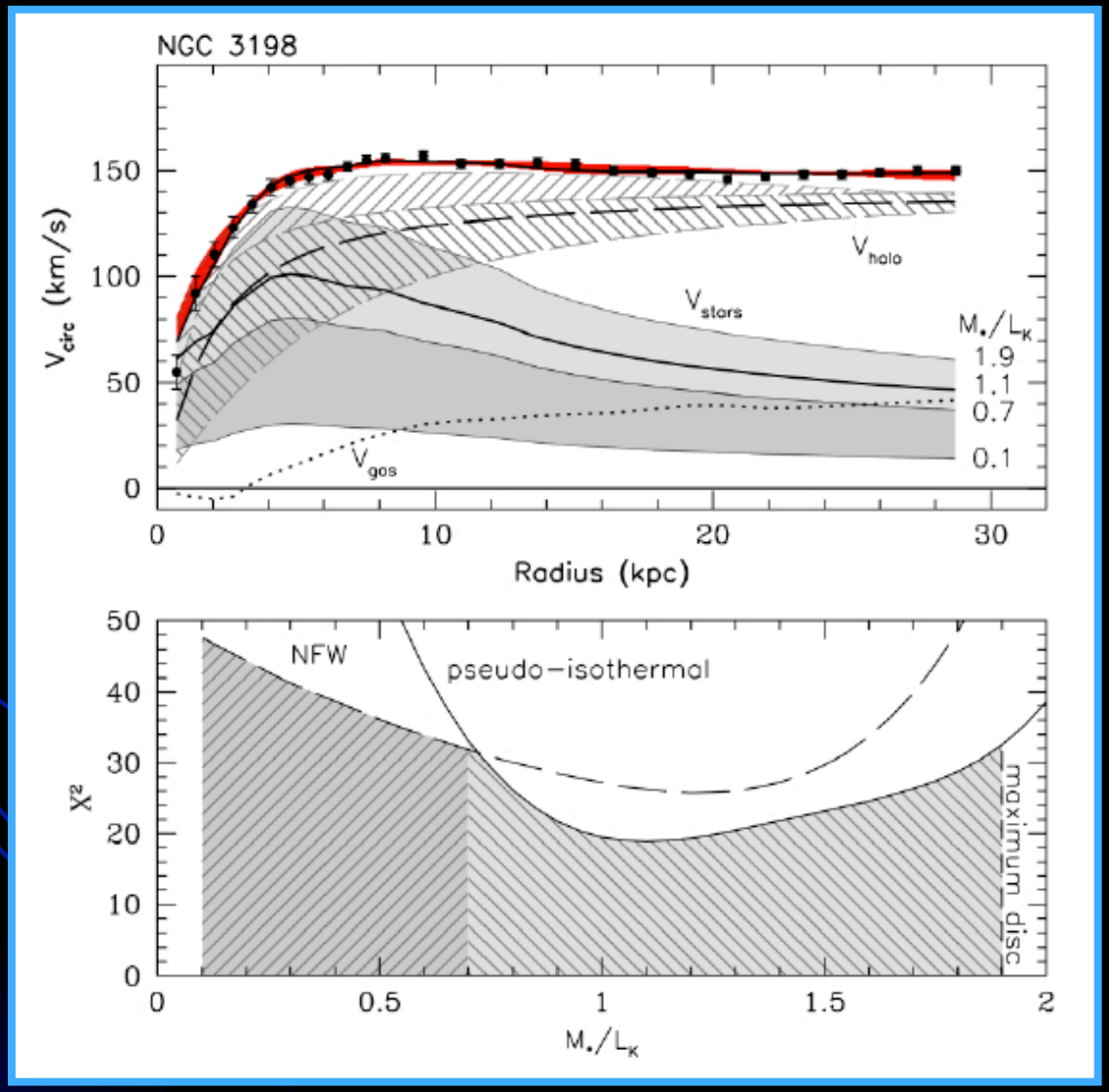
- In the inner parts, luminous matter (stars & gas) can explain the rotation velocities.
- At the end of the visible disk, dark and luminous matter contribute about equally to the observed velocities.
- In the outer parts, mass is totally dominated by dark matter



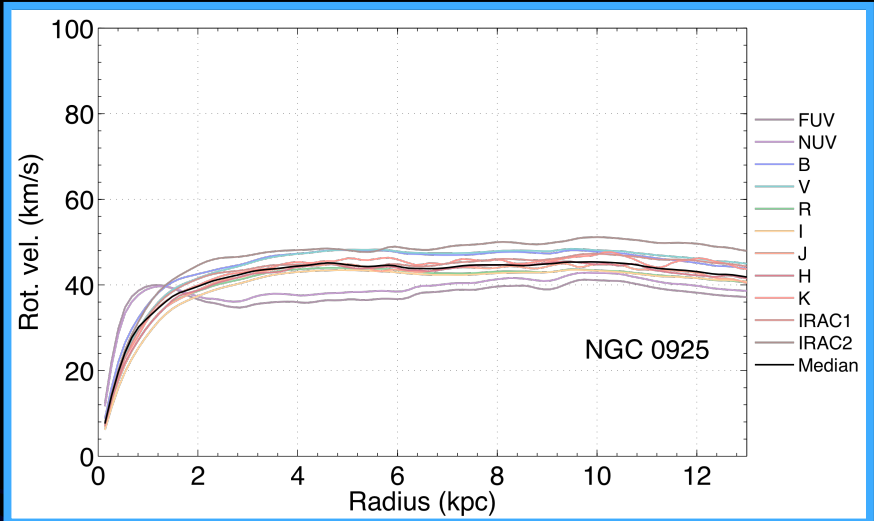
Carignan et al. 1990

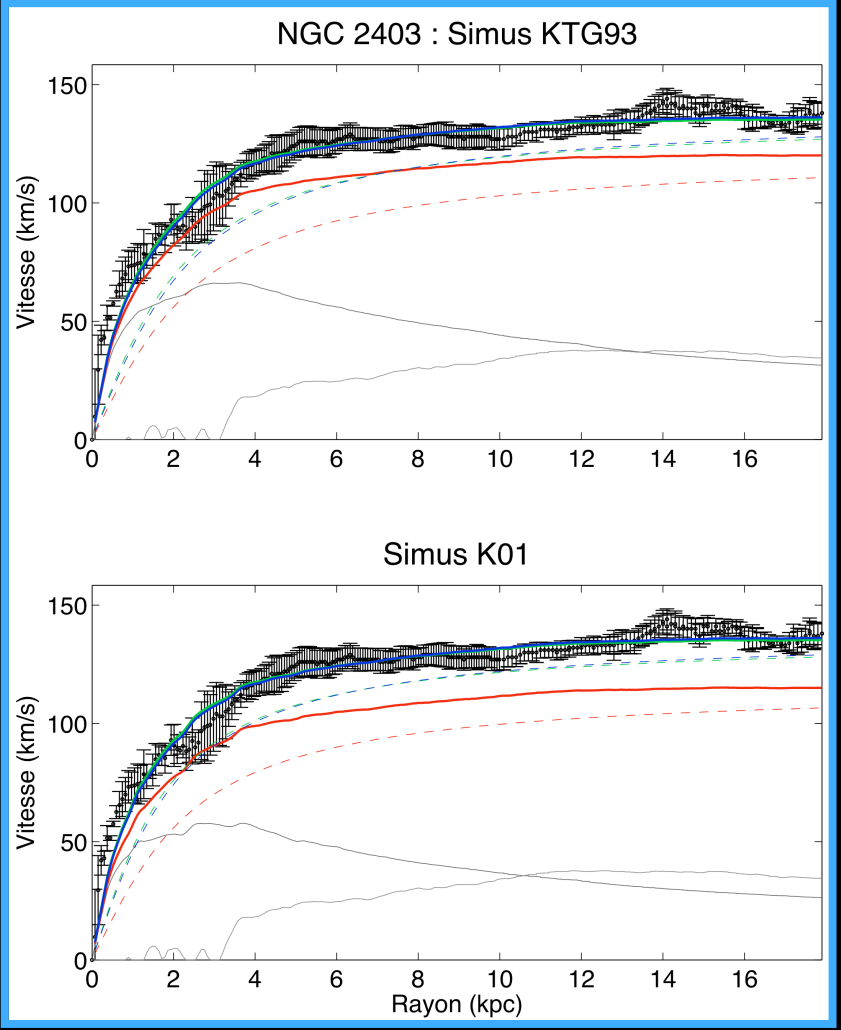
NGC 6946

NGC 3198


NGC 3198
150
100
50
0
V_{circ} (km/s)
V_{halo}
V_{stars}
V_{gas}
$M_\bullet/L_K$
1.9
1.1
0.7
0.1
0
10
20
30
Radius (kpc)
50
40
30
20
10
0
X^2
NFW
pseudo−isothermal
maximum disc
0
0.5
1
1.5
2
$M_\bullet/L_K$

Sorting out the M/L value





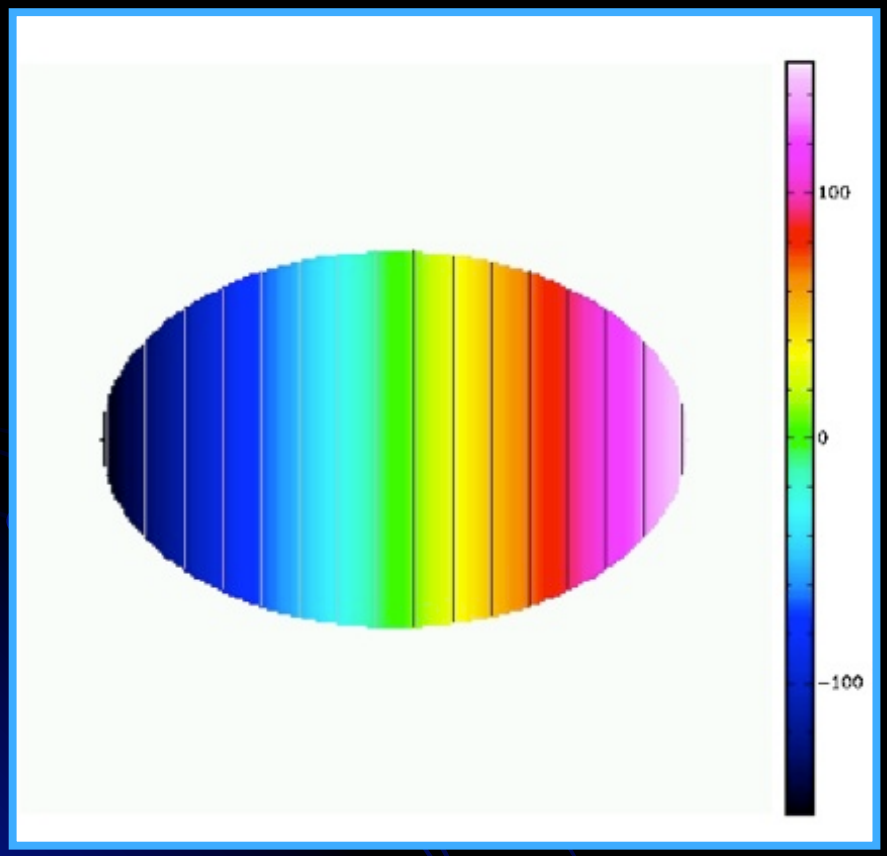
PhD thesis
Marie-Maude de Denus-Baillargeon
Université de Montréal

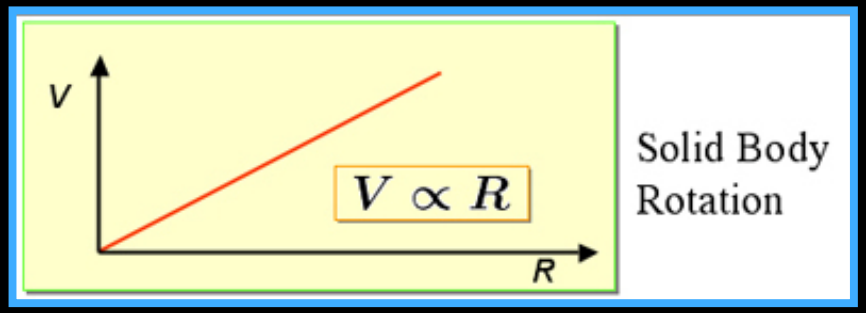
Dwarf Galaxy: Magellanic Clouds

SMC & LMC from Sutherland

SMC: Small Magellanic Cloud

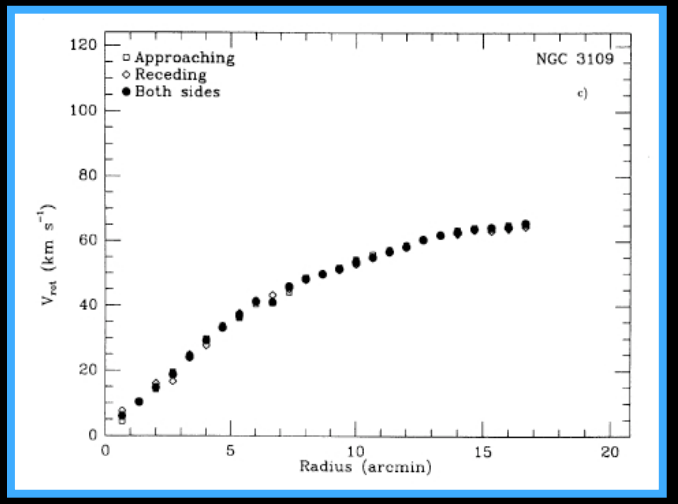
Galaxy Rotation Curve (RC)



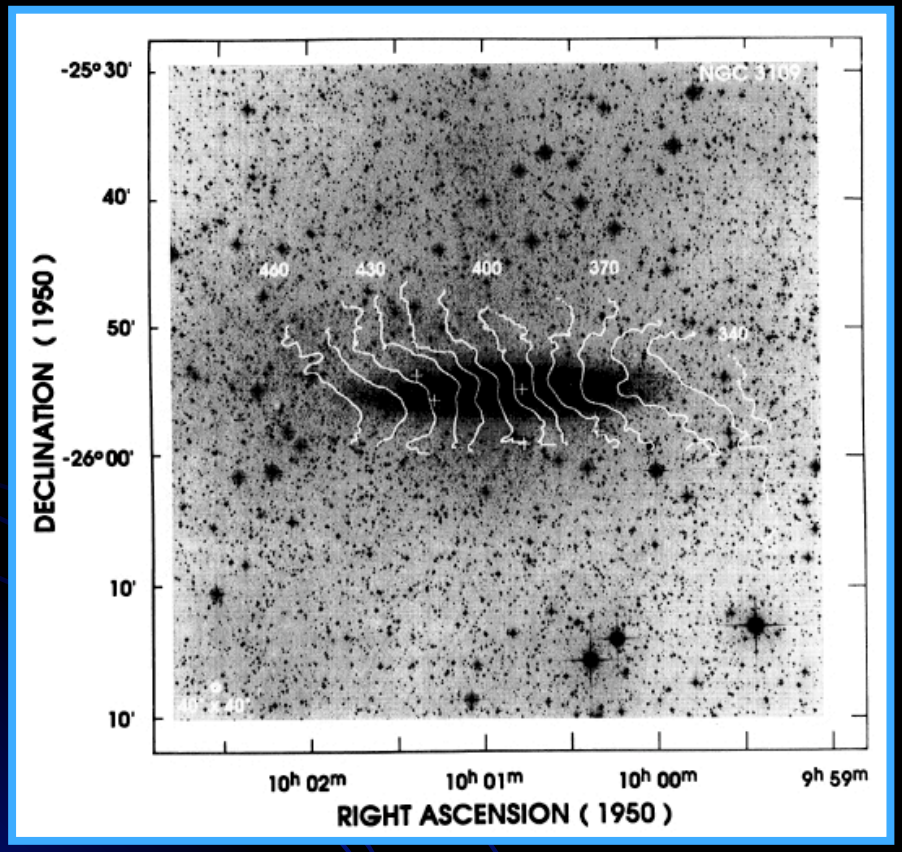


NGC 3109

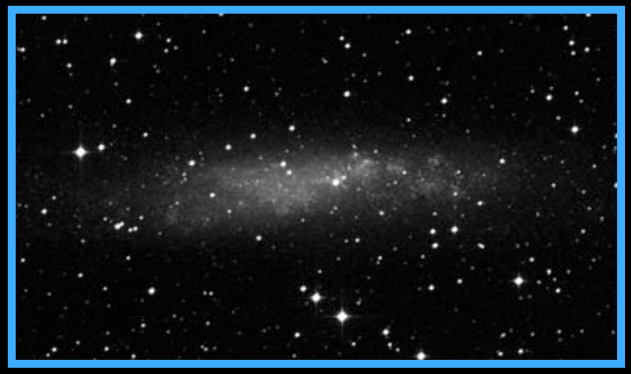
Rotation Curve



Jobin & Carignan 1990

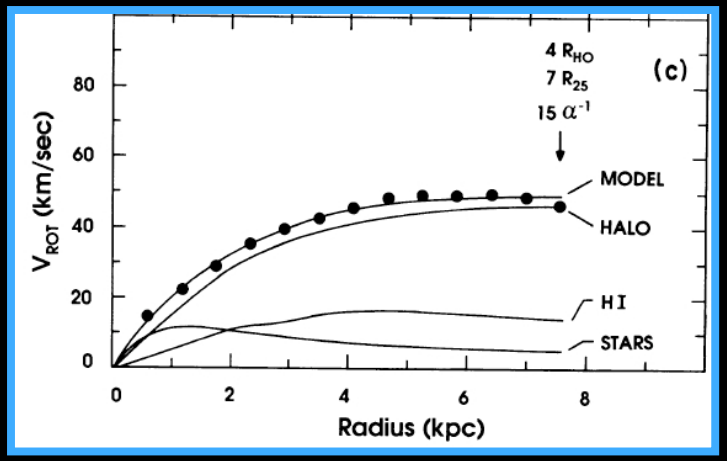


Velocity Field



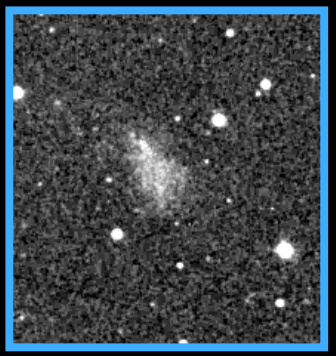
Dark Matter in dIrrs

- Dark matter halo dominates at all radii
- There is more luminous matter in gas than in *
- Dark matter constitutes 90% of the mass



Carignan & Freeman 1988

DDO 154

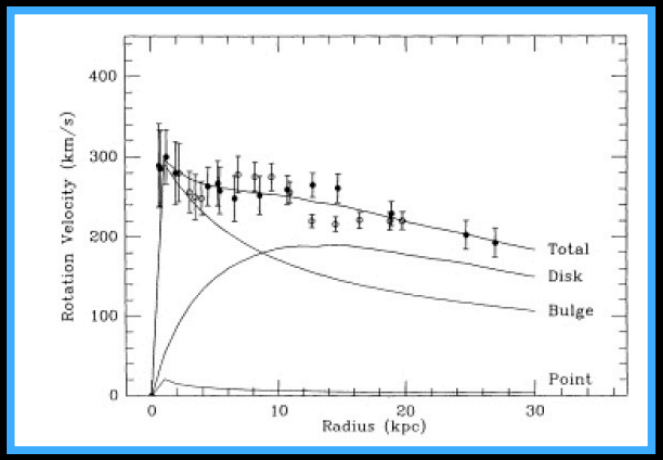


The case of M31

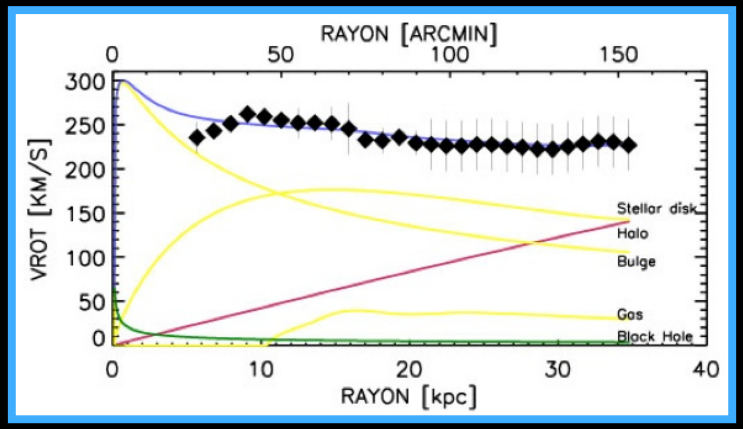
- Extensively studied at HI > 30 years ago
- Not well suited for more recent arrays (pre-EVLA) because of the problem of the lack of short spacings
- Need to be redone with smaller array

The case of M31

- Contrary to most known spiral, M31 would have a declining RC And NO dark matter !
- First, reobserve with single dish (Bonn & GBT) which showed a flat RC

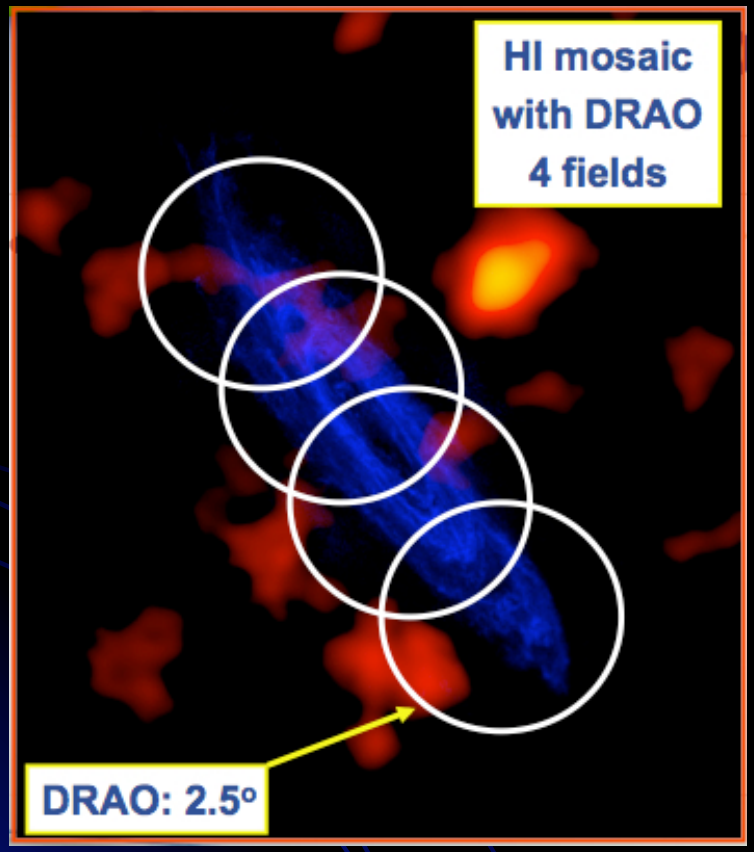


Braun 1991



Carignan et al. 2006

M31 Synthesis Observations



Superposed on Thilker et al. 2004 – GBT data

3 months of observing at DRAO – 7 x 9m

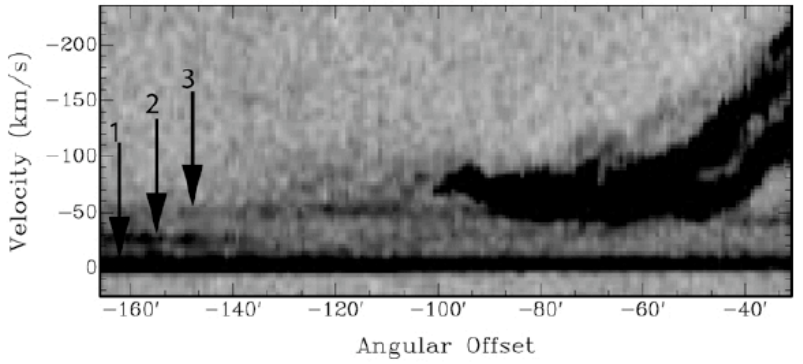


Figure 2. Contamination of the data by Galactic H I. The slice through the datacube shows three H I components from the Milky Way at (1) ~ -4 km s^{-1}, (2) ~ -20 km s^{-1}, and (3) ~ -40 km s^{-1}.

Chemin, Carignan & Foster 2009)

M31 DRAO HI Observations

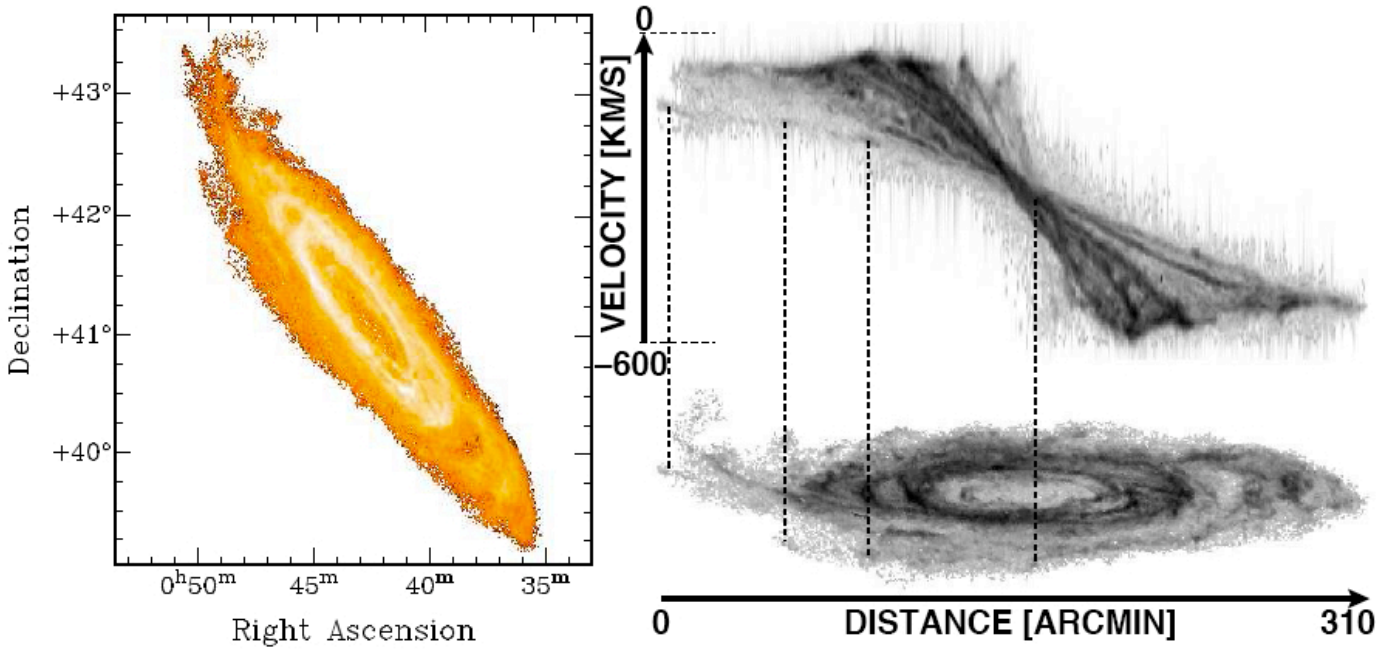


Figure 1: Left-hand panel: HI integrated emssion of Messier 31. **Right-hand panel:** 3D view of the HI datacube of M31. The top panel is the position-velocity diagram of the full datacube projected onto the photometric major axis. The bottom panel is the same map as in the right-hand panel but displayed with the major axis parallel to the horizontal axis. Dashed lines show the location of the newly discovered external arm (see text for details).

Chemin, Carignan & Foster 2009)

M31 DRAO HI Observations

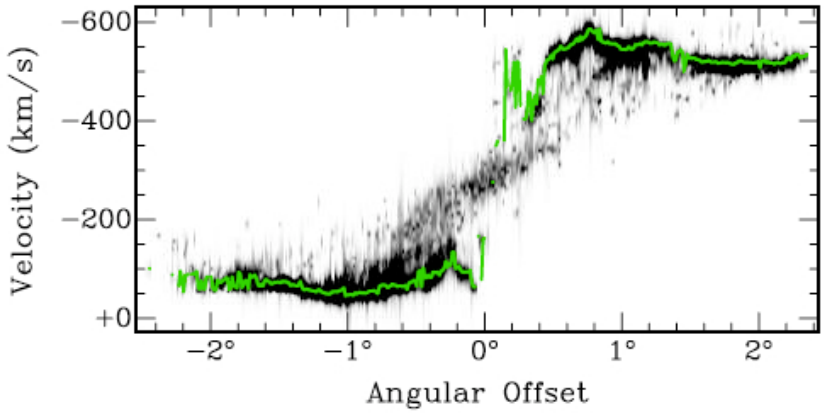


Figure 7. Position velocity plot made along the photometric major axis P.A. = 38°. A green curve represents a slice through the velocity field of the main H I component.

HI position-velocity diagram

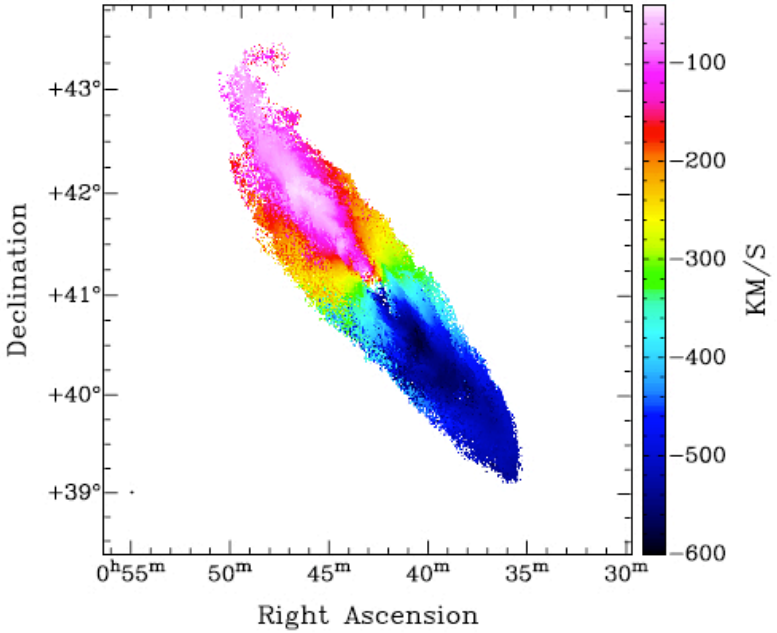


Figure 8. Velocity field of M31 used for the titled-ring model analysis.

HI velocity field

Chemin, Carignan & Foster 2009)

M31 DRAO HI Observations

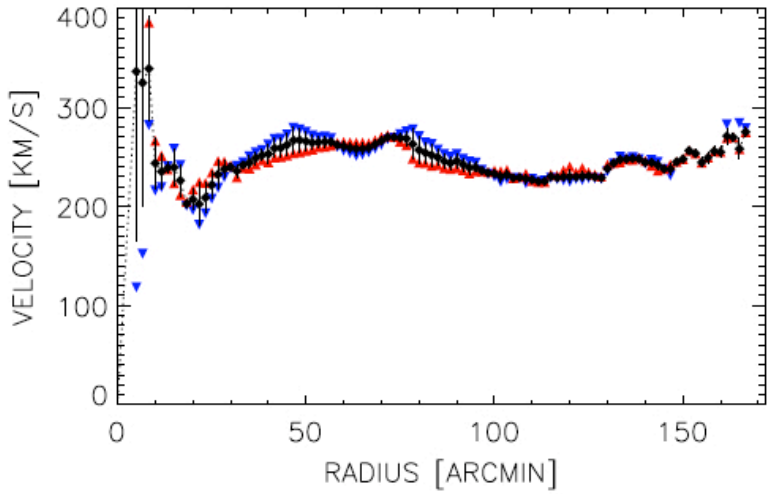


Figure 10. H I rotation curve of Messier 31. The filled diamonds are for both halves of the disk fitted simultaneously while blue downward/red upward triangles are for the approaching/receding sides fitted separately (respectively).

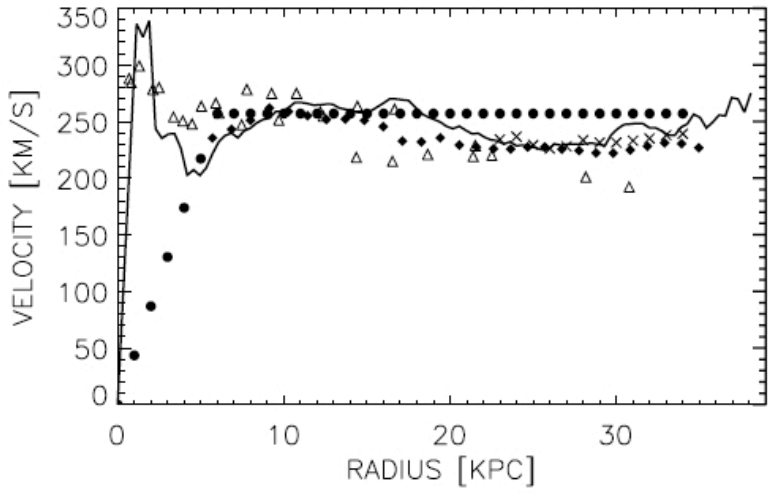


Figure 11. Comparison between H I rotation curves from Newton & Emerson (1977; crosses), Brinks & Burton (1984; filled circles), Braun (1991; open triangles), Carignan et al. (2006; filled diamonds), and our new derived rotation

Chemin, Carignan & Foster 2009)

M31 DRAO HI Observations

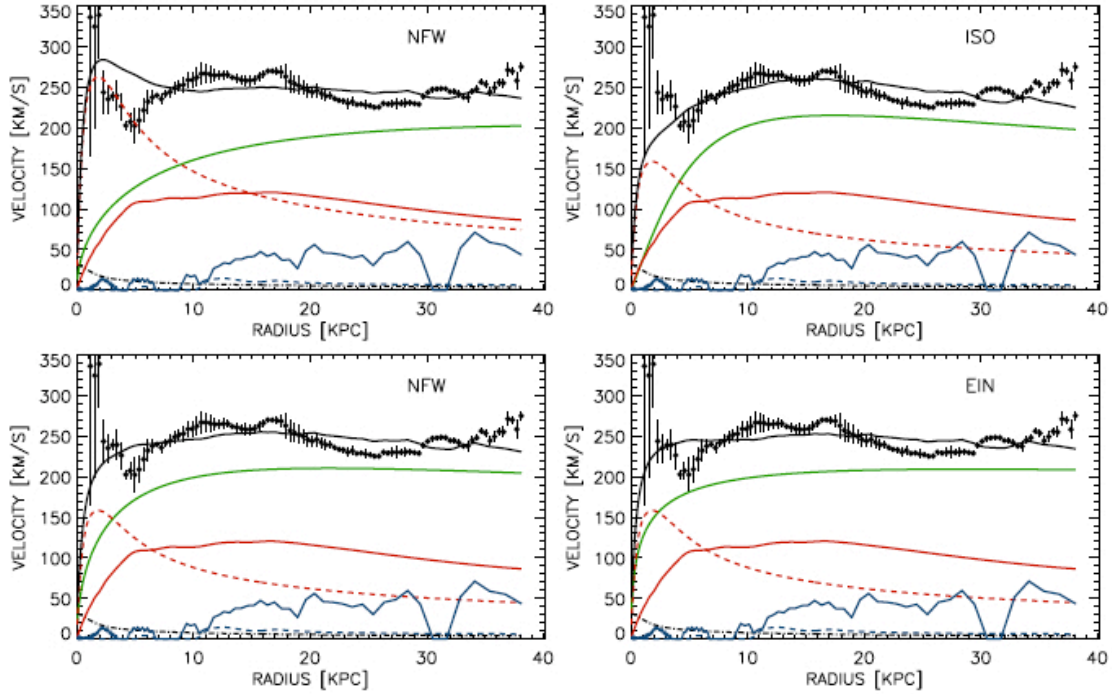
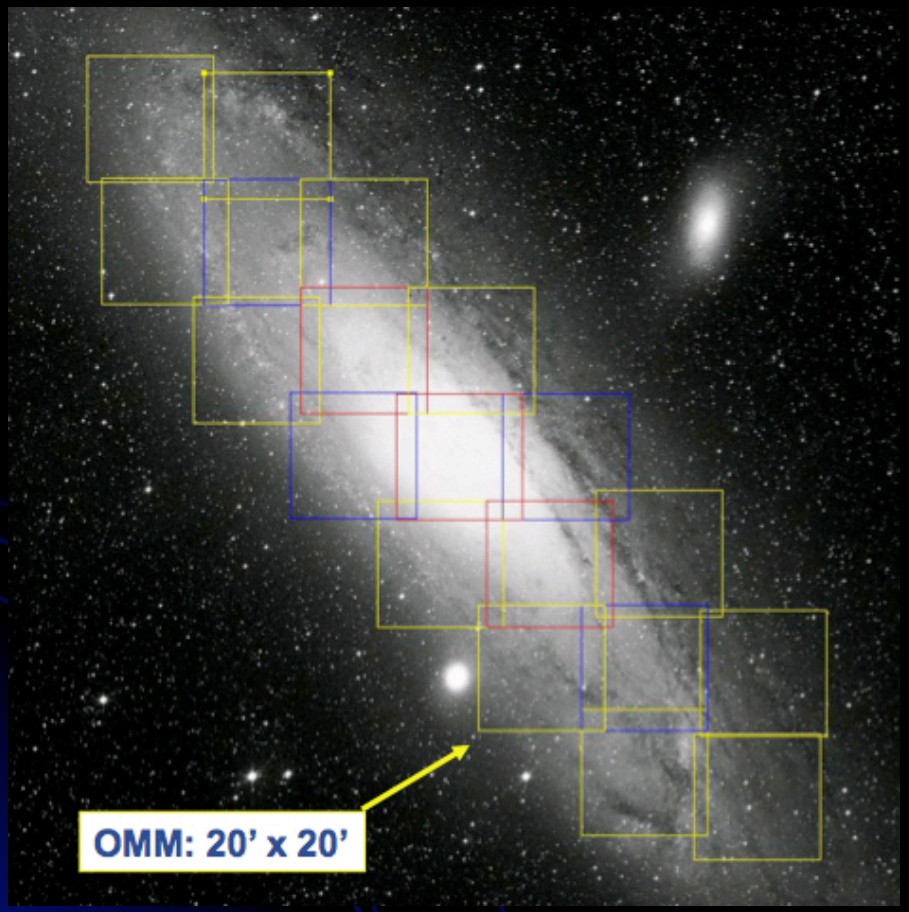


Figure 17. Mass distribution models of Messier 31. Top-left: result with bulge and disk mass-to-light ratios fixed at values $\Upsilon_{\rm Bulge} = 2.2$ and $\Upsilon_{\rm Disk} = 1.7$ (respectively) for a cuspy dark matter halo ("NFW"). Top-right: same as in the top-left panel but with $\Upsilon_{\rm Bulge} = 0.8$ for a pseudo-isothermal sphere ("ISO"). Bottom: same as in the top-right panel but for the NFW cusp (left) and Einasto ("EIN," right) halos. A black dashed–dotted line is for the black hole contribution, solid and dashed blue lines for the neutral and molecular gaseous disks, solid and dashed red lines for the stellar disk and bulge, a green line for the dark matter halo and a solid black line for the overall model.

Chemin, Carignan & Foster 2009)

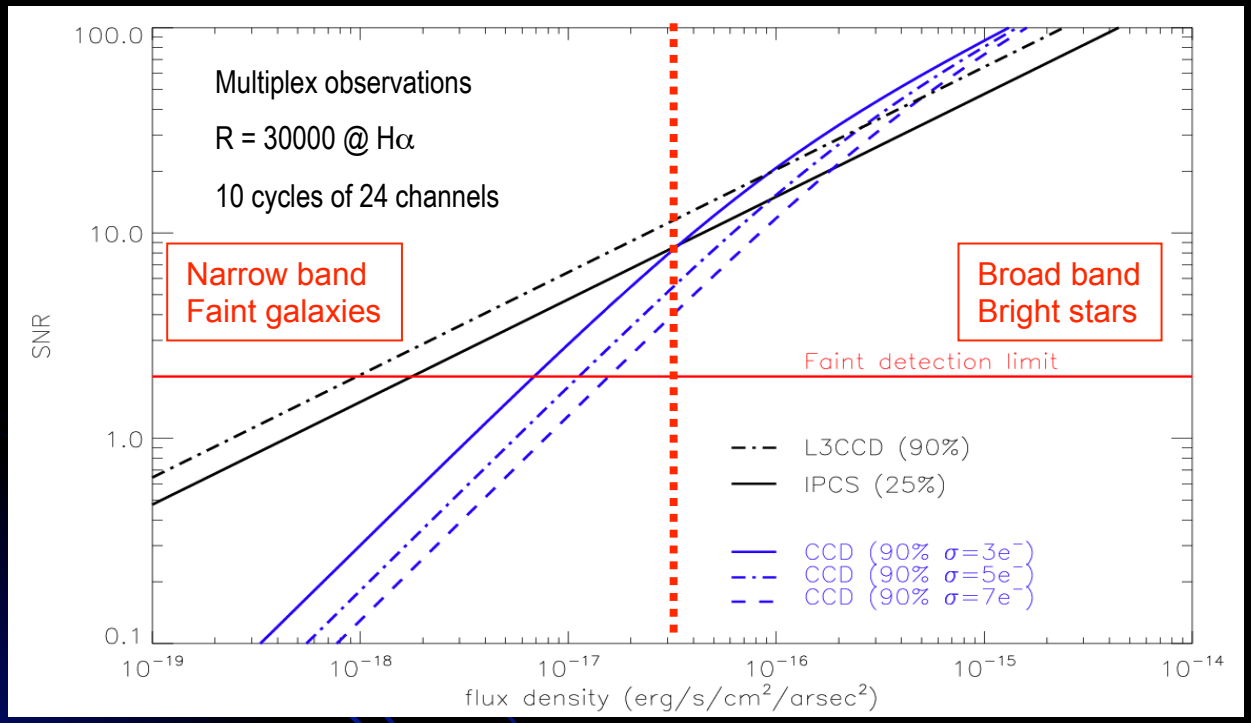
M31 OMM Hα FP Observations



20 fields
~ 10 nights
on 1.6m
telescope

Kam Sié, PhD project in Montréal

Principles behind Photon Counting



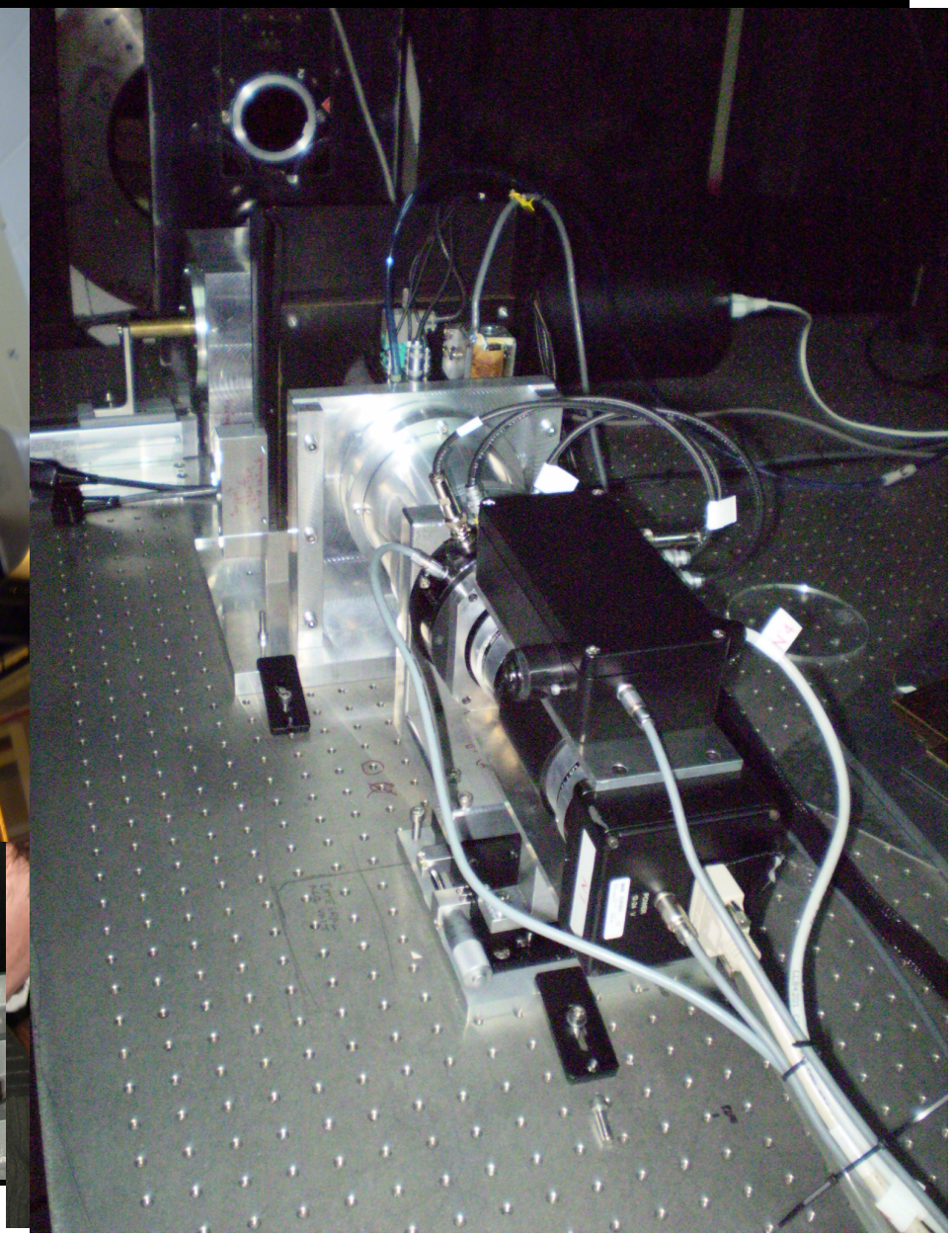
- *Avantages*
- no readout noise
- fast readout of CCD
- easy OH removing
- faint fluxes observations

- *Disadvantages*
- bright fluxes
- QE 20-25 %

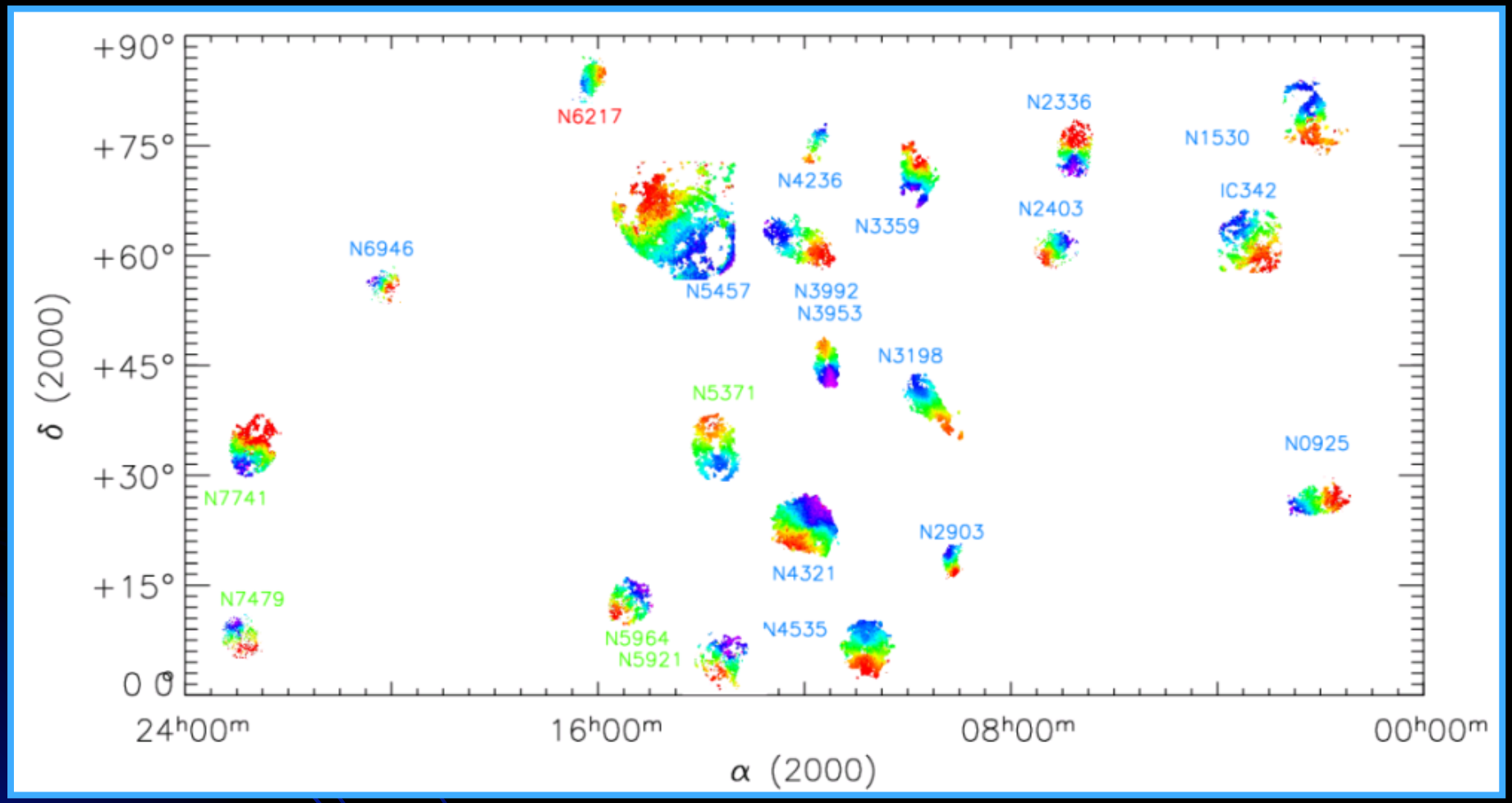
http://www.astro.umontreal.ca/fantomm/

IPCS + Focal Reducer + FP = GHαFaS

WHT
La Palma

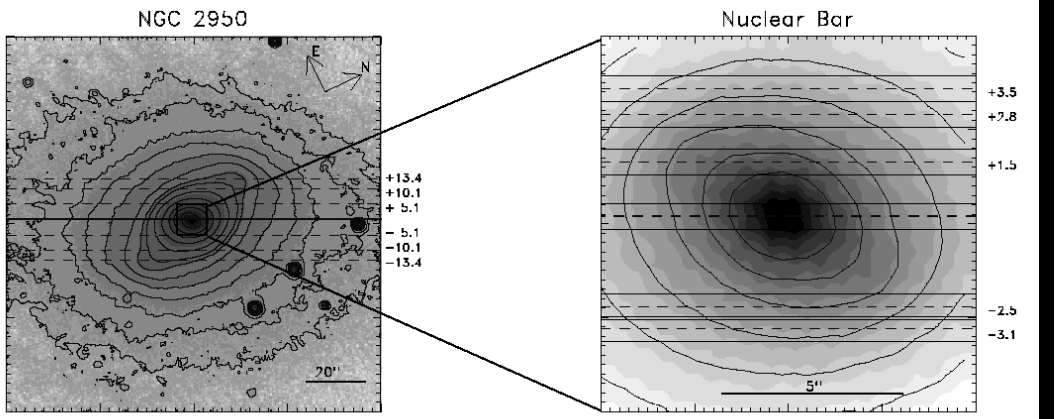


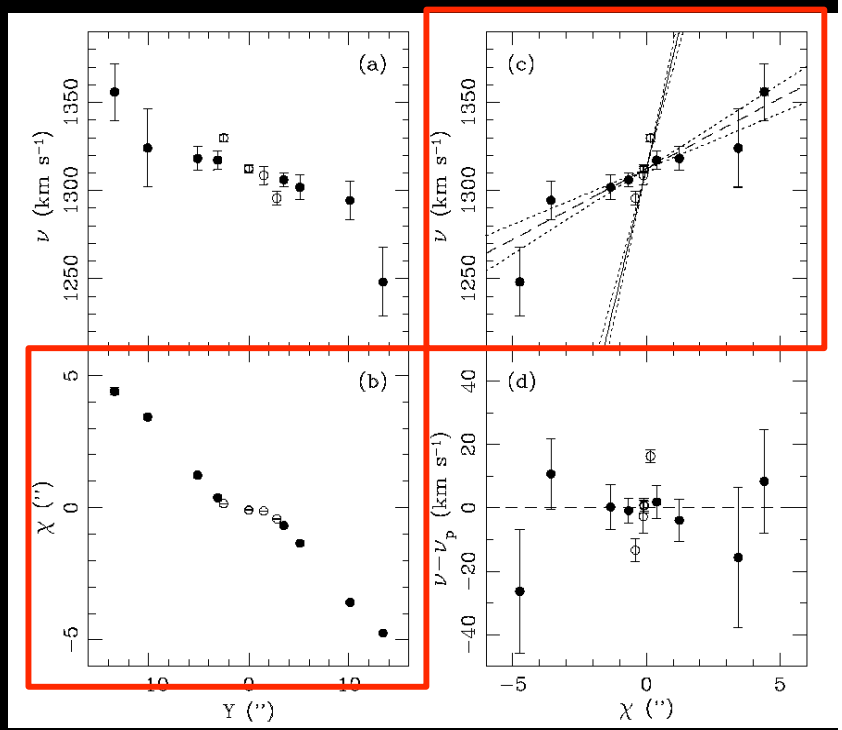
BHaBar (Hernandez 2005)



- Blue = Observatoire du mont Mégantic (Québec, Canada) - OmM
- Green = Canada-France-Hawaii Telescope (Hawaii) - CFHT
- Red = Observatoire de Haute Provence (France) - OHP

Tremaine Weinberg method : multiple pattern speed determination





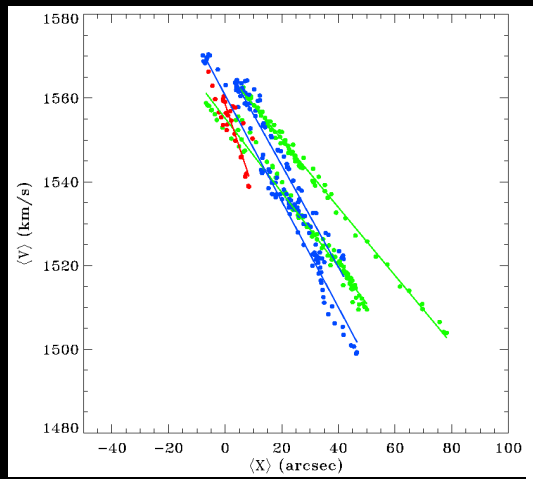
Corsini, E. M., Debattista, V. P., & Aguerri, J. A. L. 2003, ApJL, 599, L29

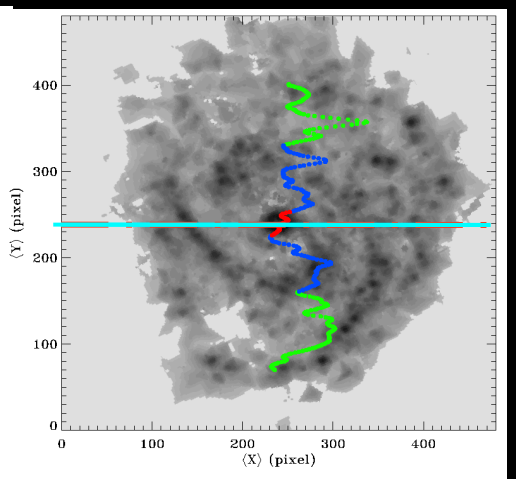
Apply to Hα velocity field

Thèse O. Hernandez

Hernandez et al. (2005)

NGC 4321

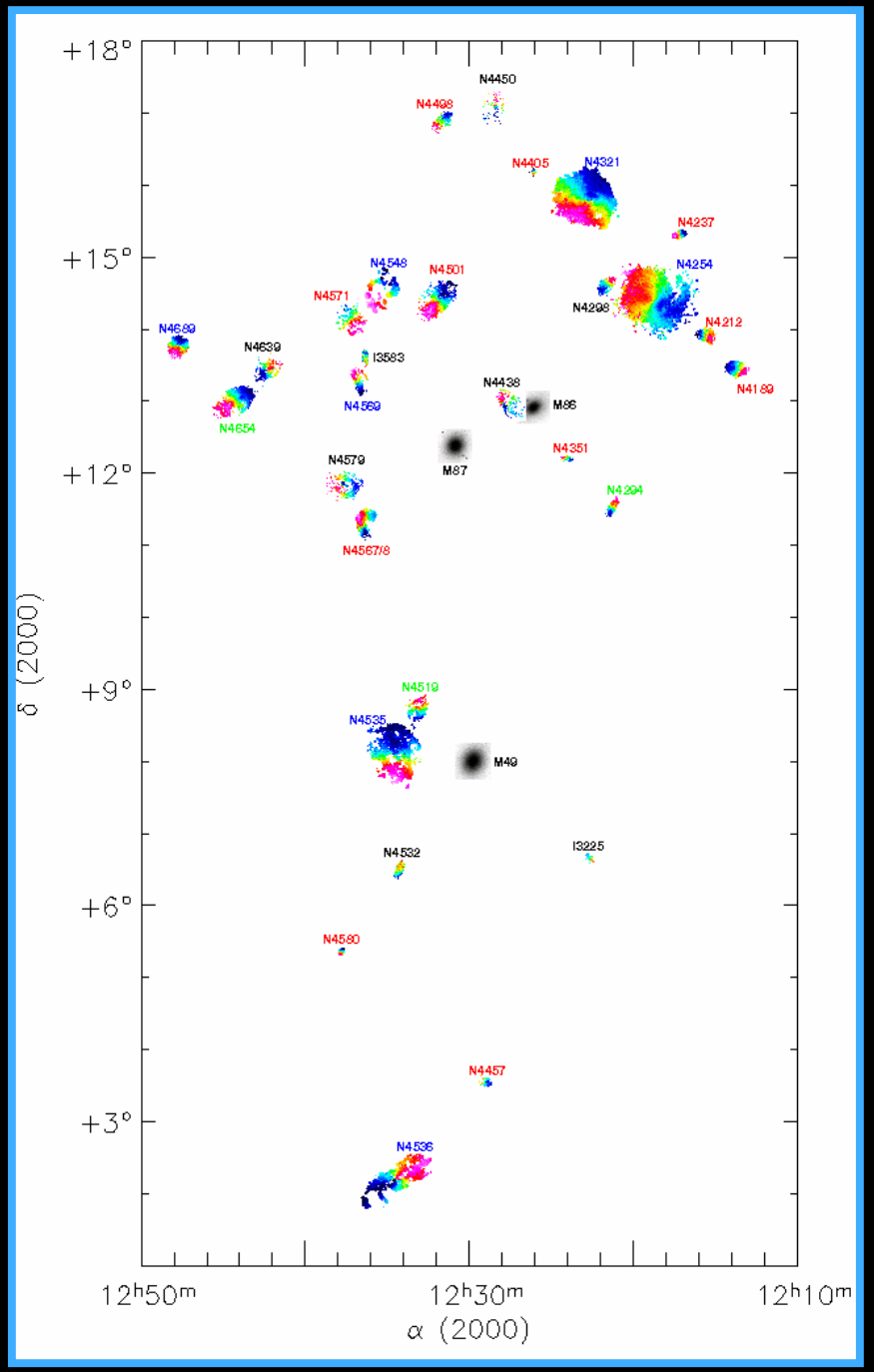




VIRGO

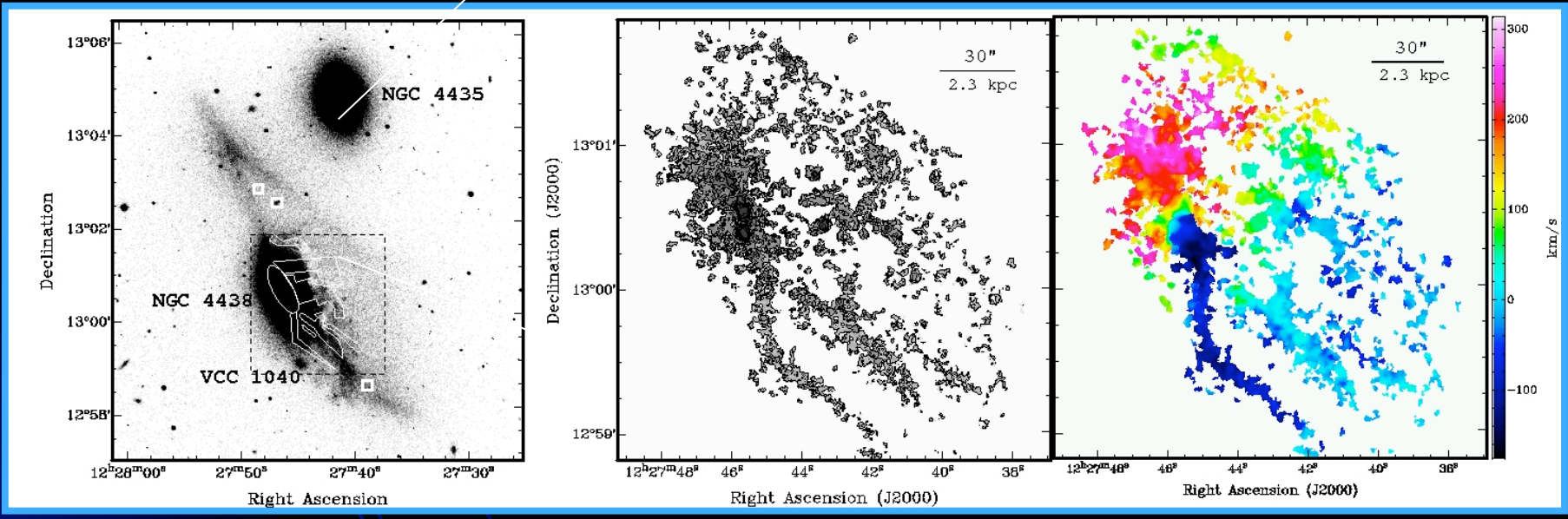
(Chemin et al. 2006)

Blue = Observatoire du mont Mégantic (Québec, Canada) - OmM
Green = Canada France Hawaii Telescope (Hawaii) - CFHT
Red = Observatoire de Haute Provence (France) - OHP
Black = ESO - La Silla 3.6m

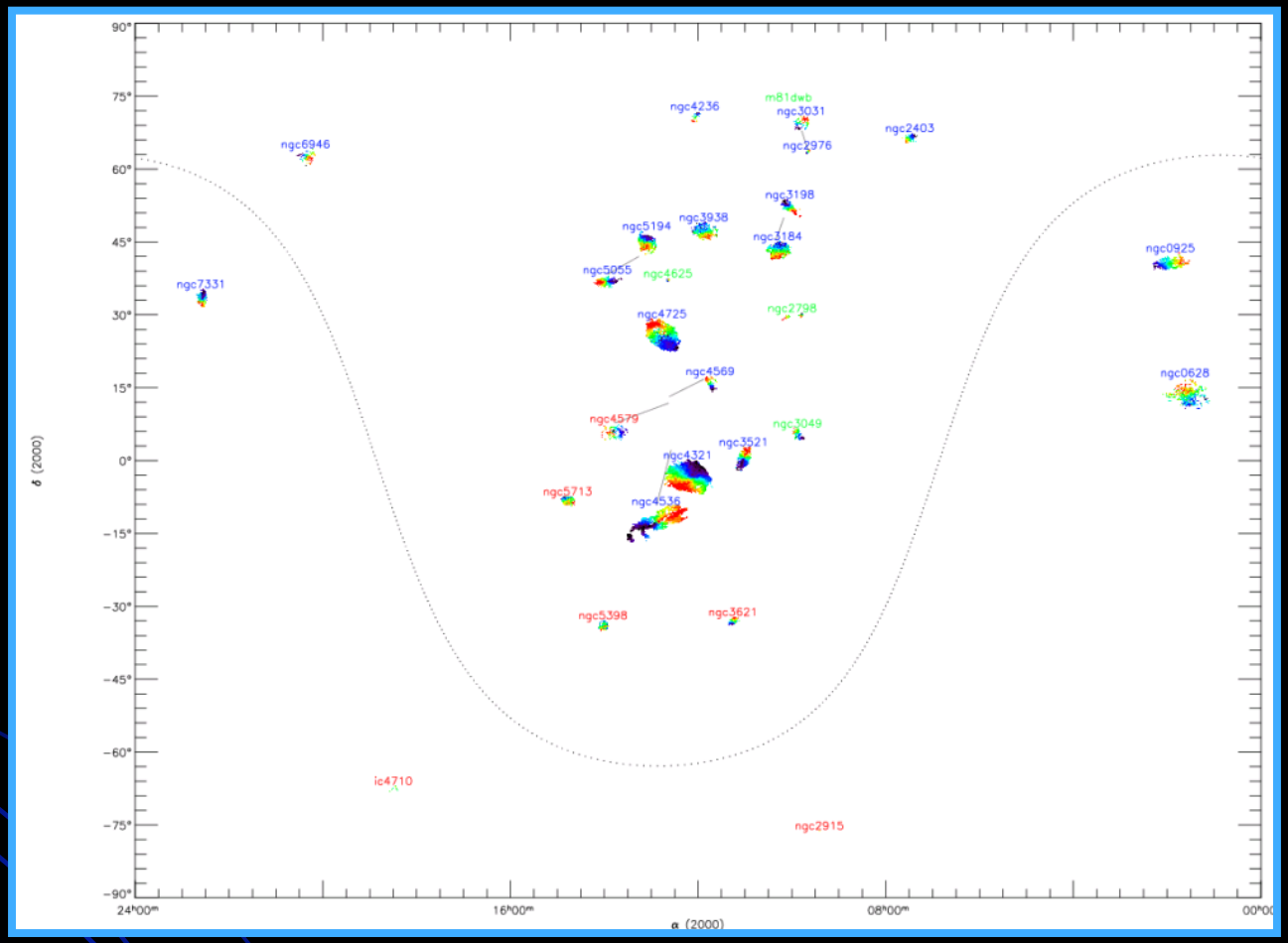


High Resolution Hα FP: Virgo Cluster
(Chemin et al, 2005)

NGC 4438 = Prototype of a galaxy interacting with ram pressure stripping and companion



SINGS (Daigle et al. 2006 & Dicaire et al. 2008)



- Blue = Observatoire du mont Mégantic (Québec, Canada) - OmM
- Green = Canada-France-Hawaii Telescope (Hawaii) - CFHT
- Red = ESO - La Silla 3.6m (Chili)

SINGS: Spitzer IR Nearby Galaxy Sample

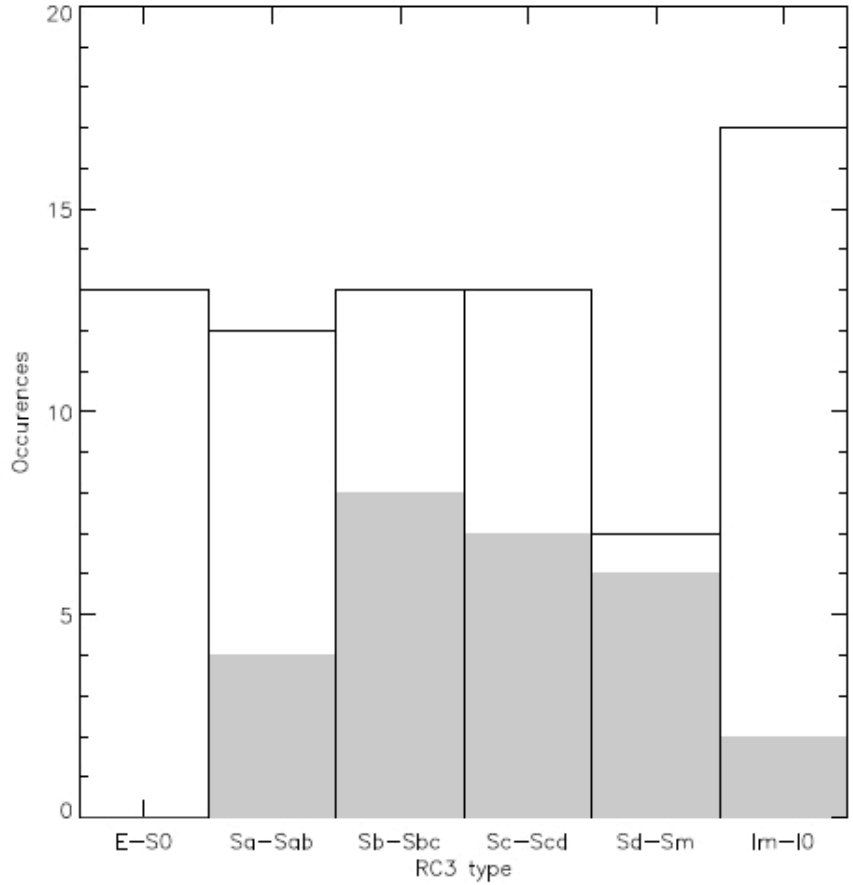
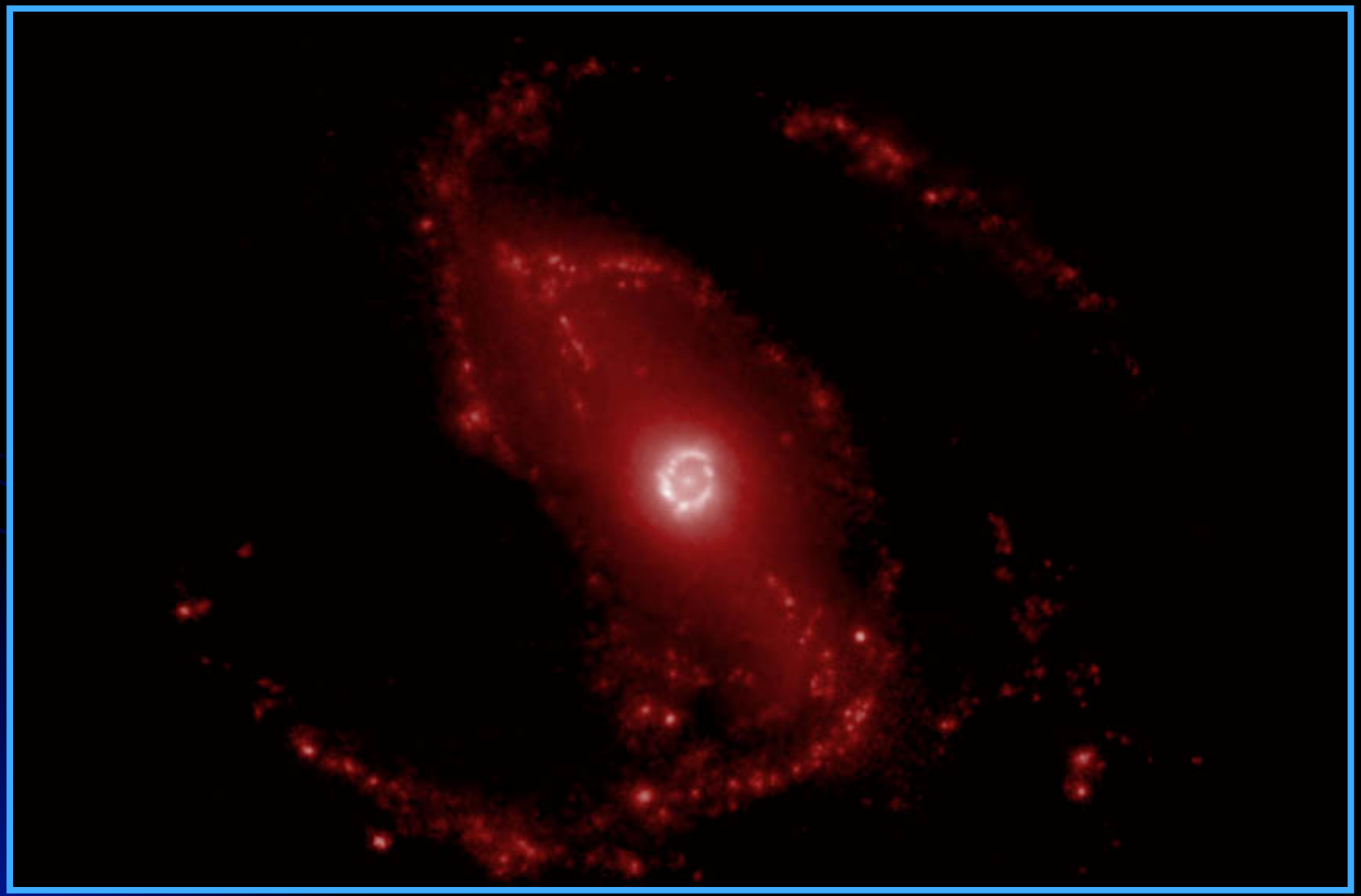


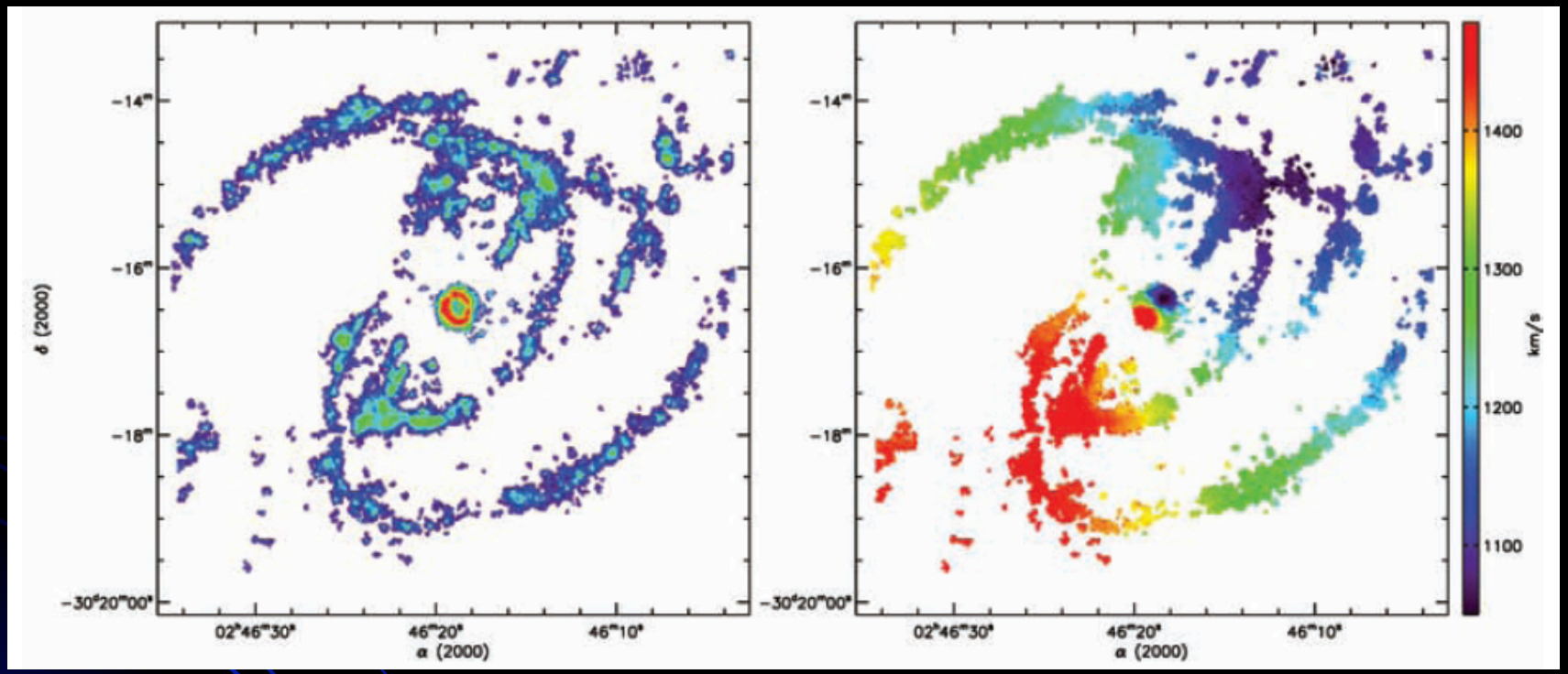
Figure 1. The SINGS RC3 galaxy type distribution. The grey area shows the galaxies presented in this paper.

SINGS
Kennicutt et al. 2003

SINGS: NGC 1097 (mosaic of 4 fields)



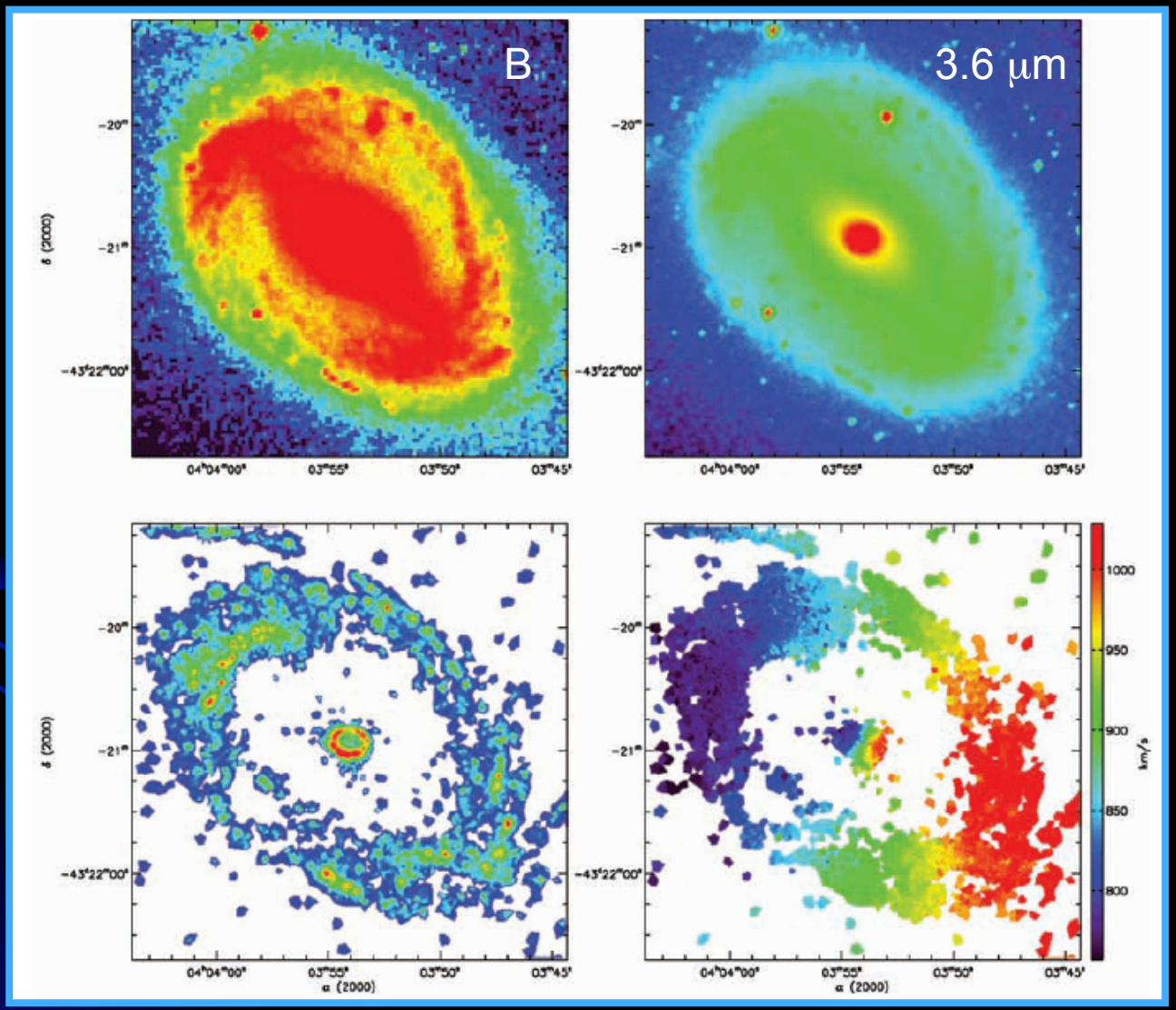
SINGS: NGC 1097 (mosaic of 4 fields)



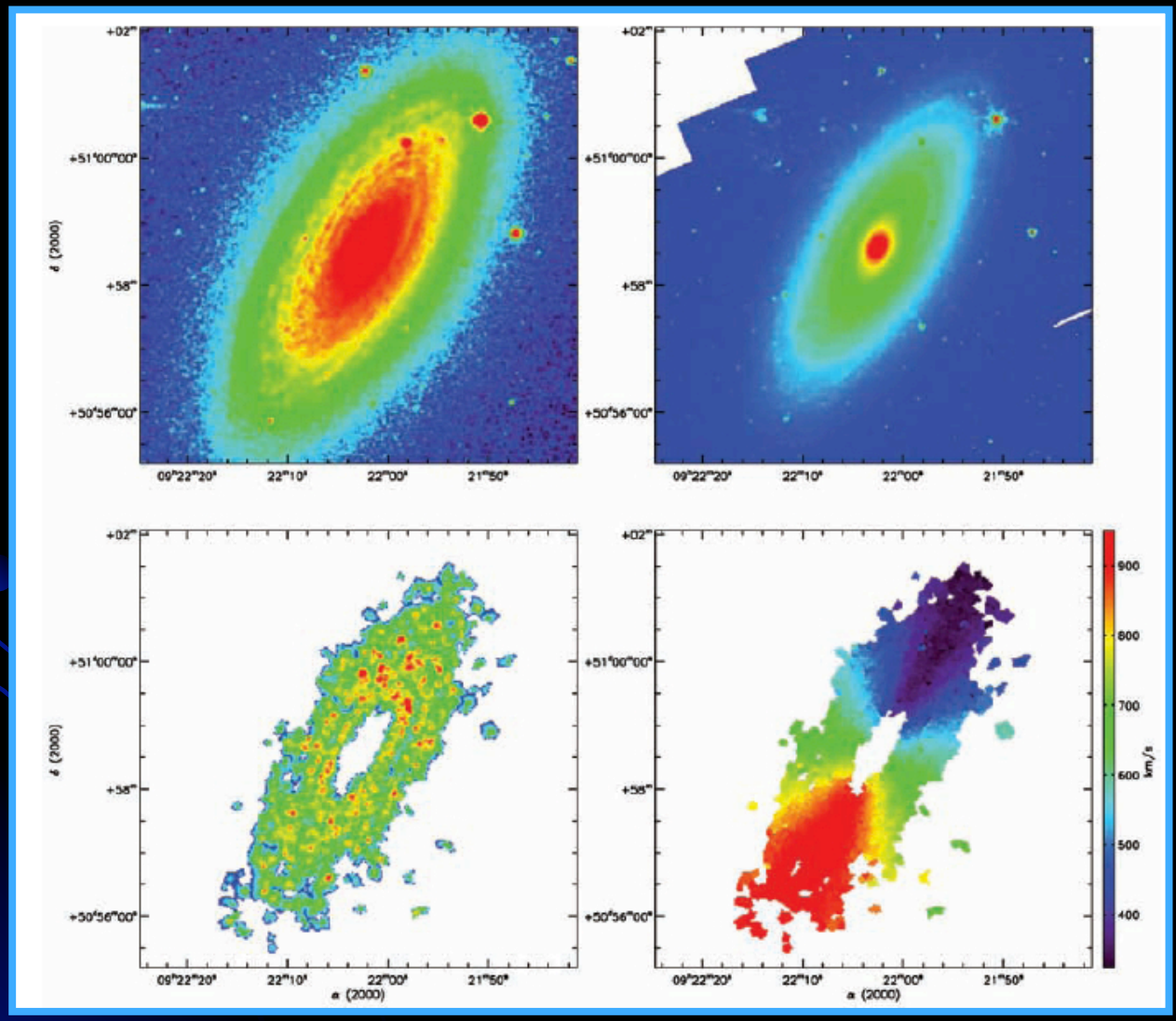
Hα distribution

Hα velocity field

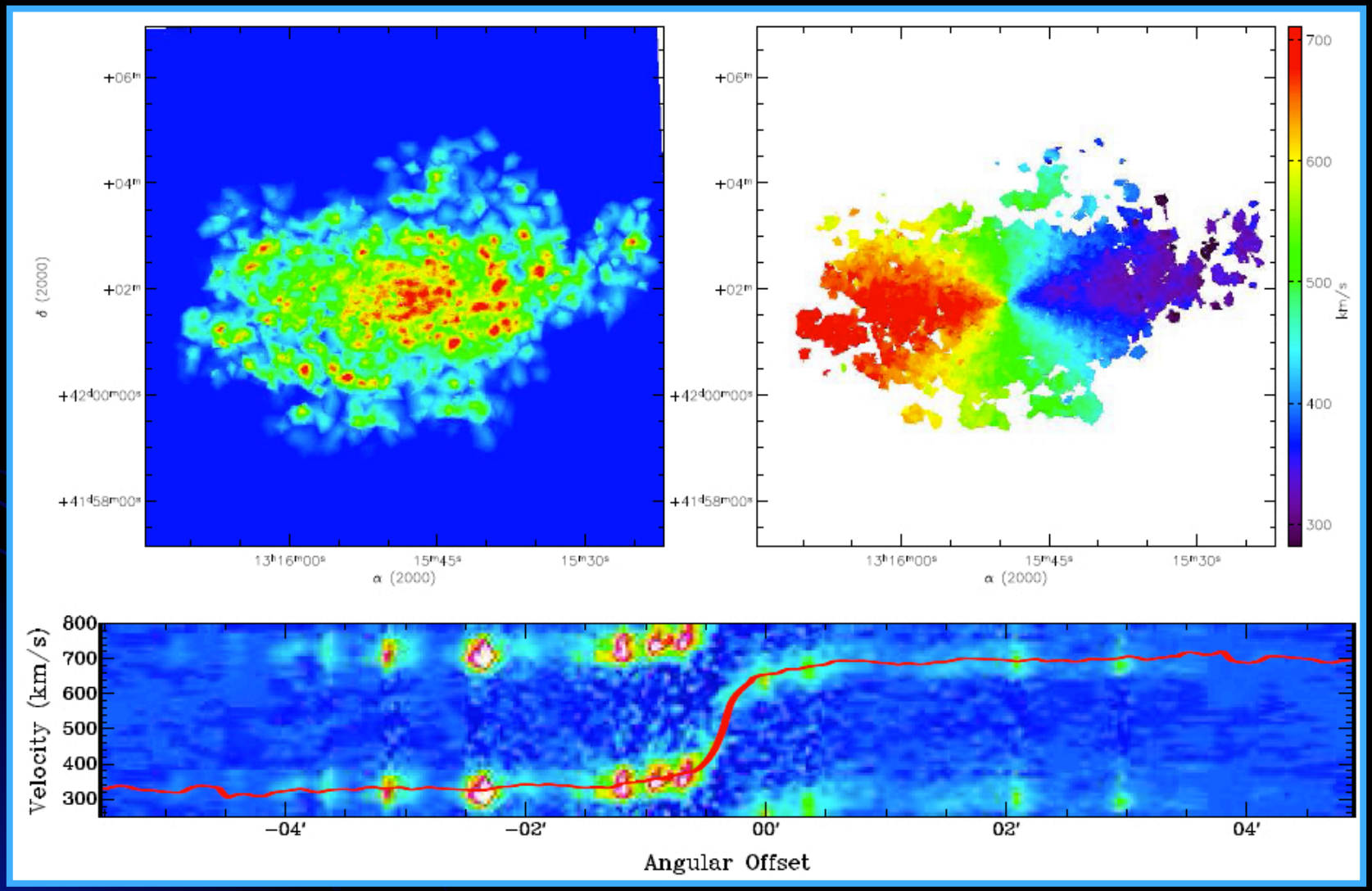
SINGS: NGC 1512 SBab (barred)



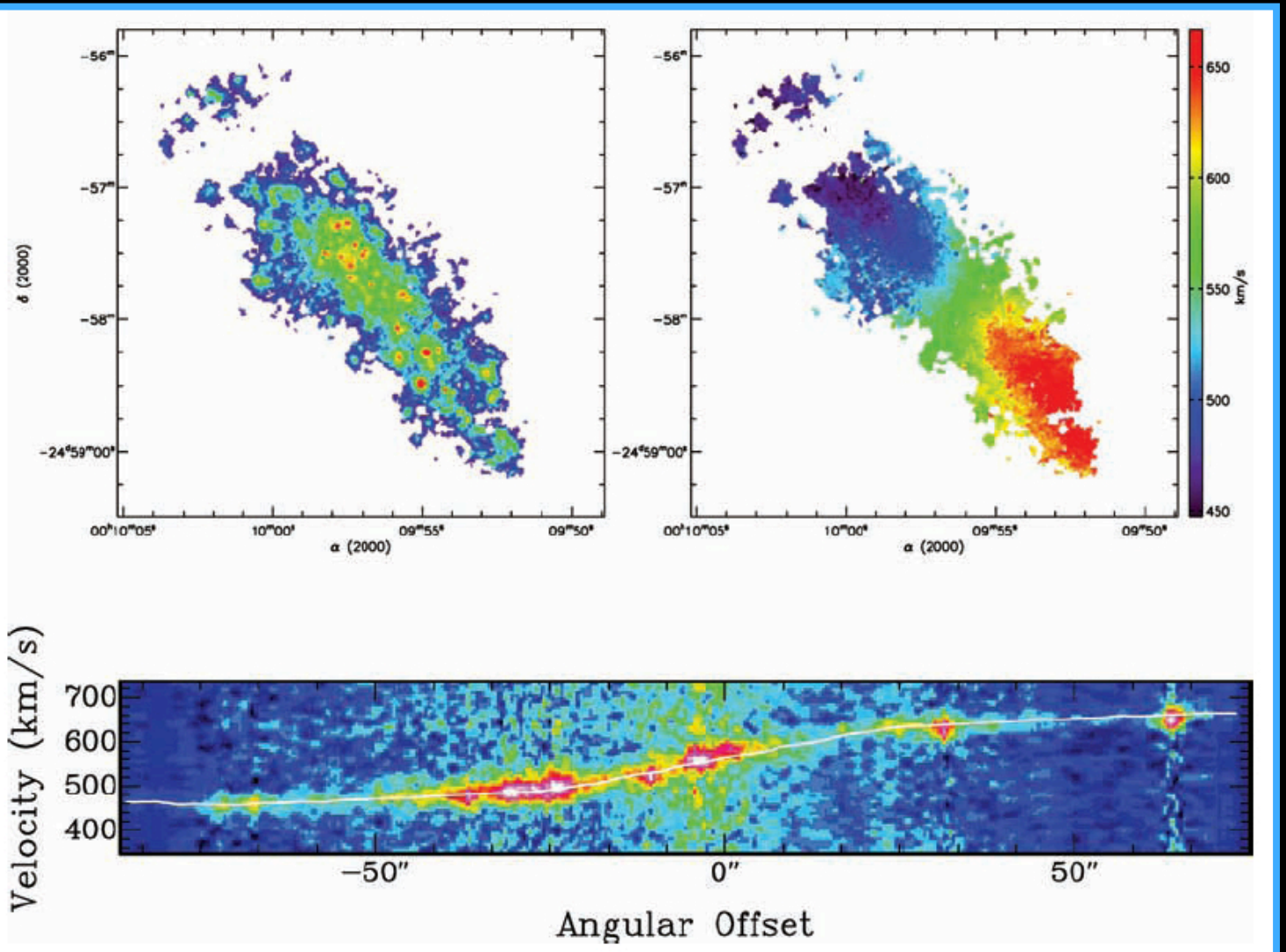
SINGS: NGC 2841 SAb (non-barred)



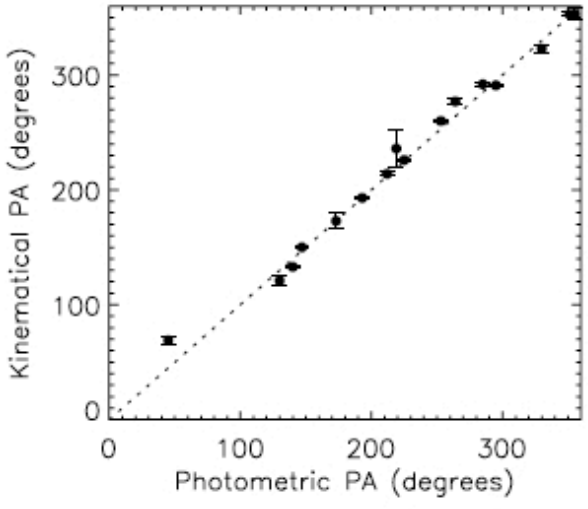
SINGS: NGC 5055 SAbc



SINGS: NGC 24 SAc



SINGS (photometric vs kinematical parameters)



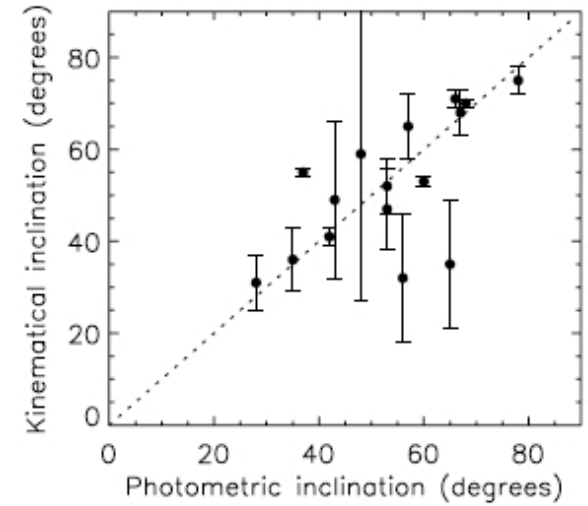
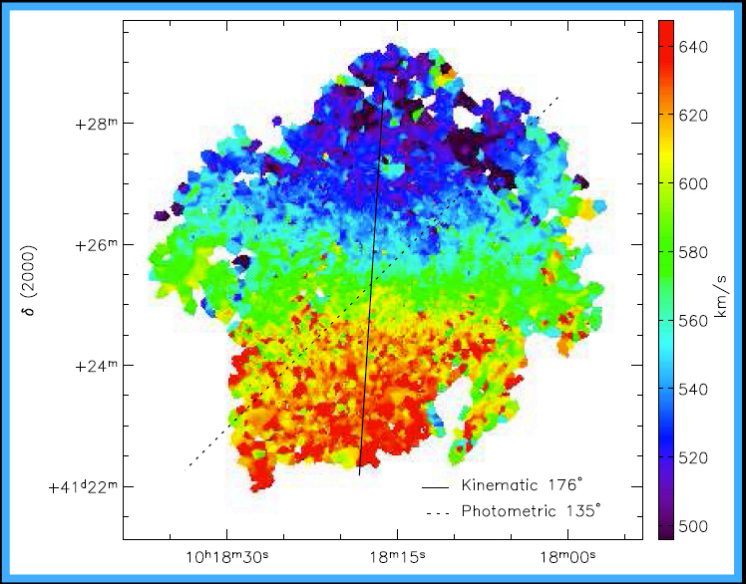
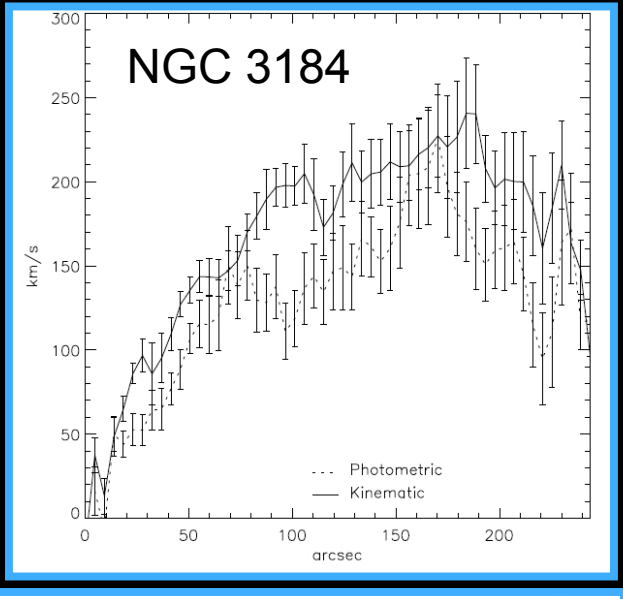
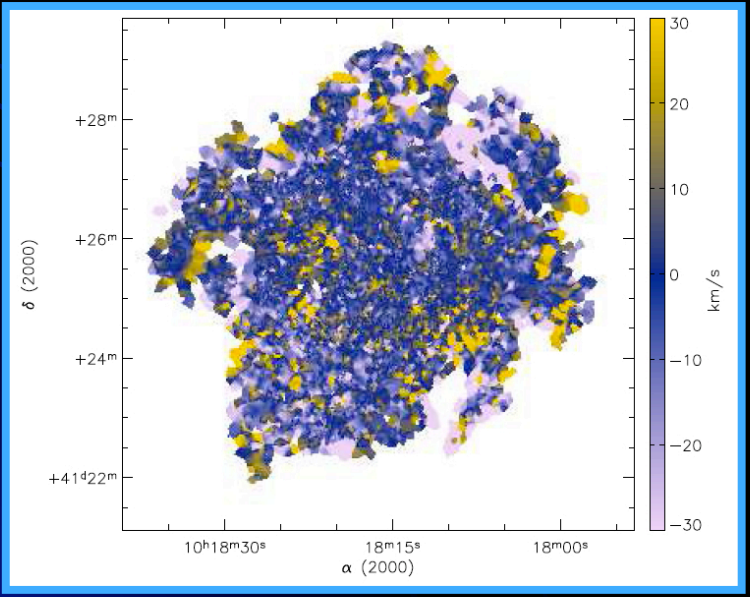


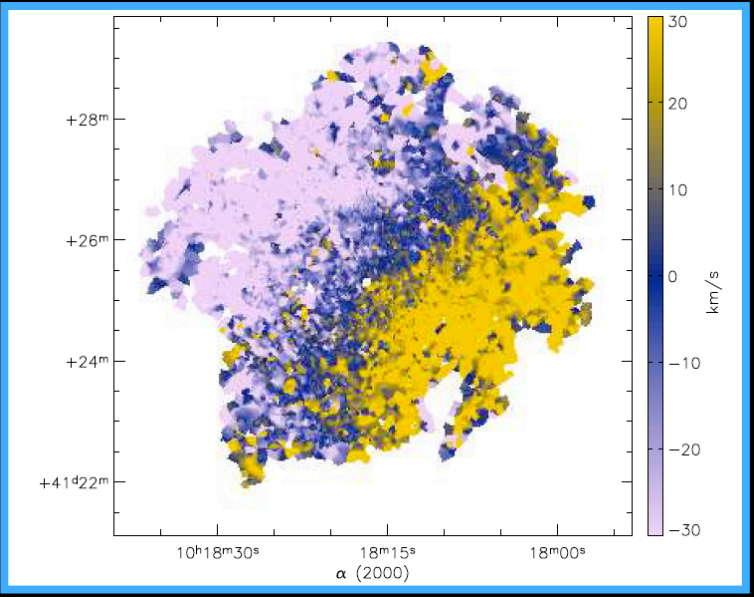
Figure 1. Comparison between photometric and kinematical parameters. Top: PA. Bottom: inclination. The dotted line represents agreeing parameters.

SINGS (photometric vs kinematical parameters)









SINGS (Hα data to correct for beam smearing)

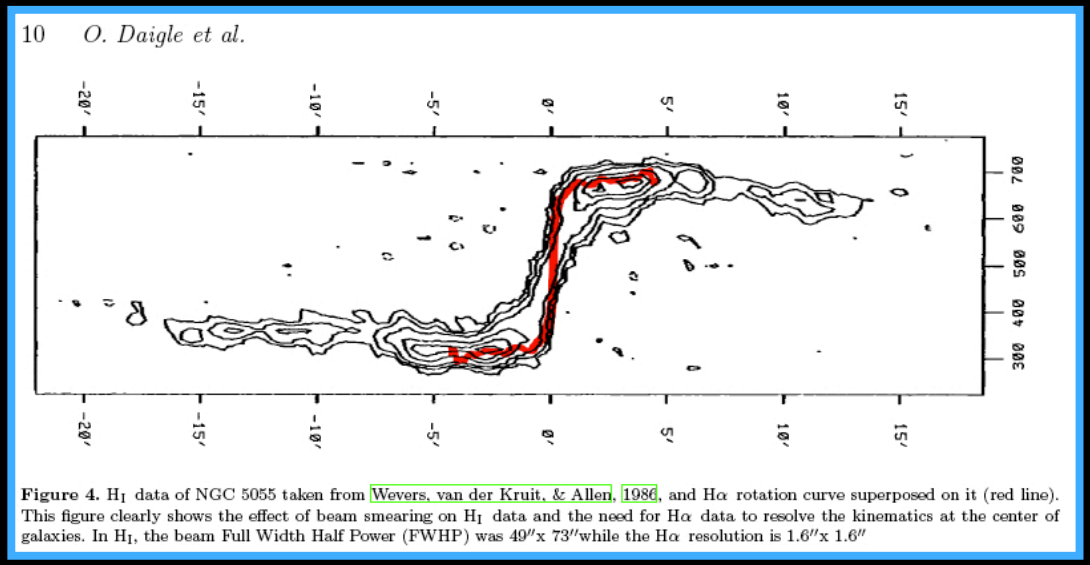
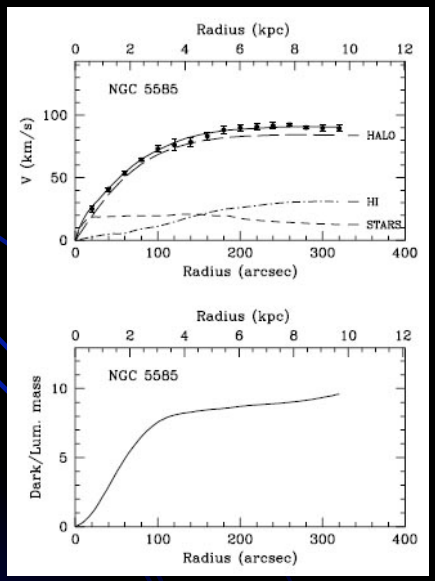
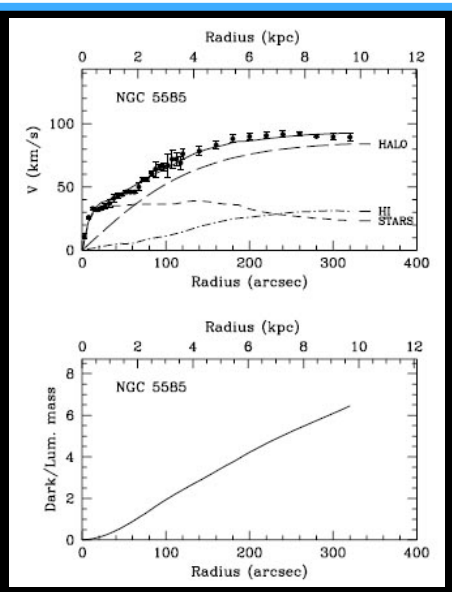


Figure 4. H_I data of NGC 5055 taken from Wevers, van der Kruit, & Allen, 1986, and Hα rotation curve superposed on it (red line). This figure clearly shows the effect of beam smearing on H_I data and the need for Hα data to resolve the kinematics at the center of galaxies. In H_I, the beam Full Width Half Power (FWHP) was 49″x 73″while the Hα resolution is 1.6″x 1.6″



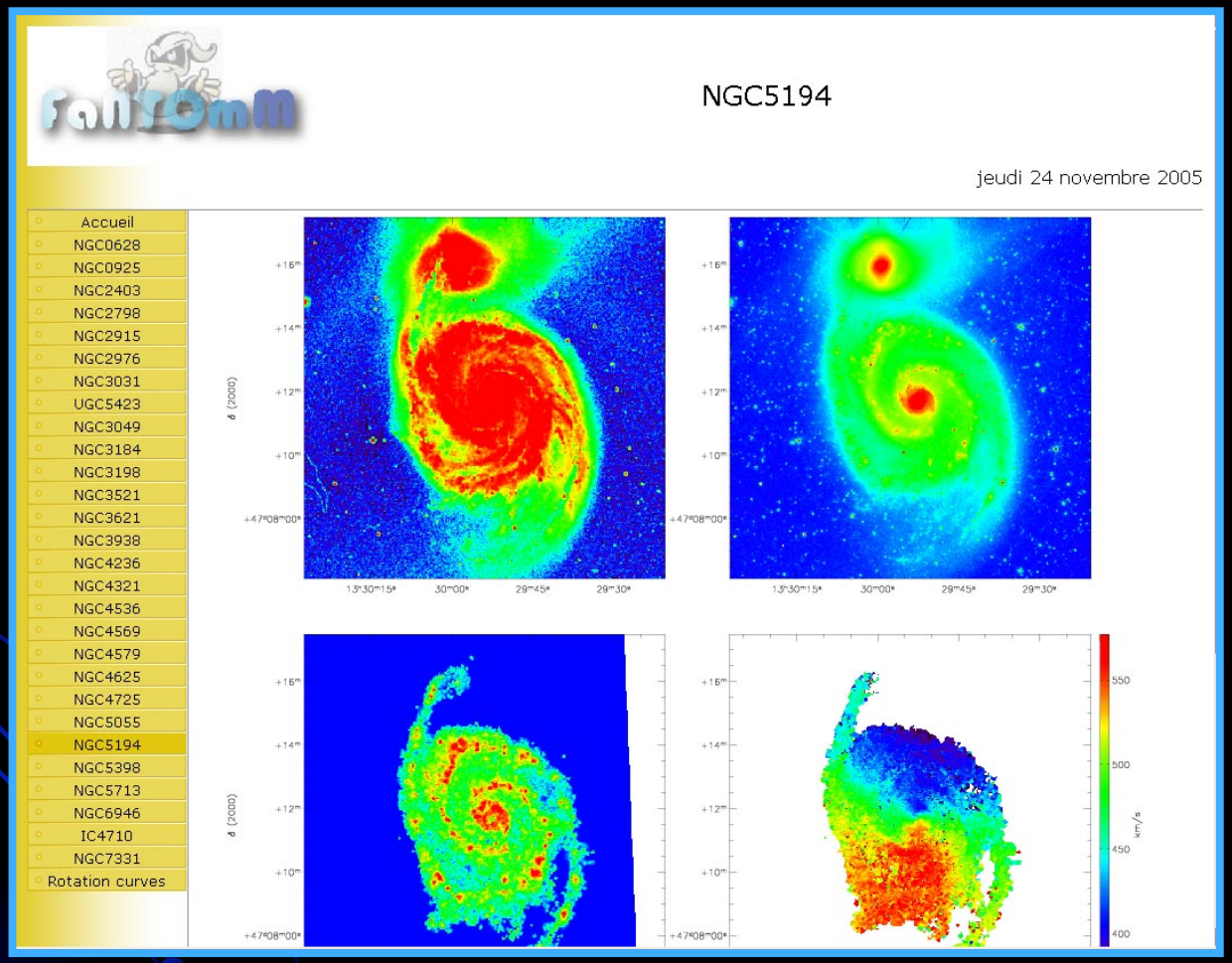


Blais-Ouellette et al. 1999

M_{dark}/M_{lum} ~ 8.7

M_{dark}/M_{lum} ~ 4.6

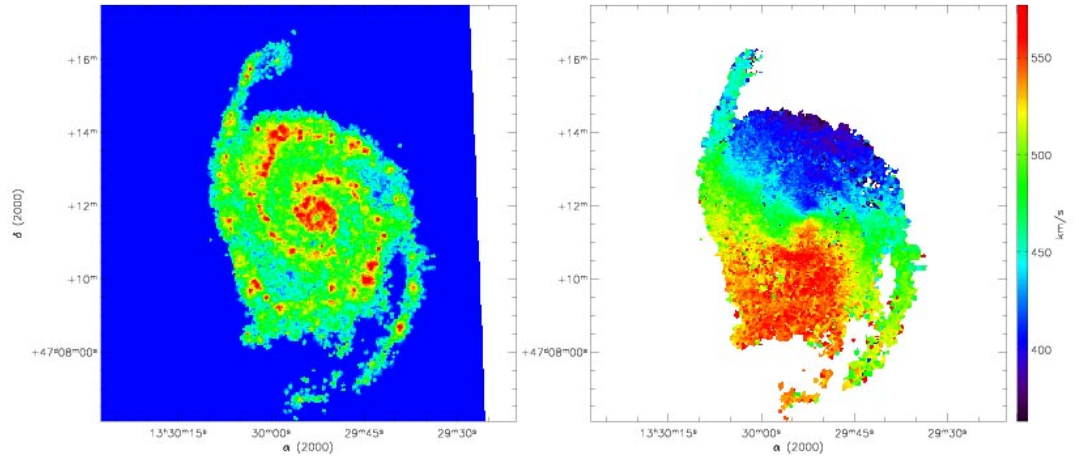
Get the data available quickly to the community



http://www.astro.umontreal.ca/fantomm/sings/

Make the reduced data available quickly

- NGC4569
- NGC4579
- NGC4625
- NGC4725
- NGC5055
- NGC5194
- NGC5398
- NGC5713
- NGC6946
- IC4710
- NGC7331
- Rotation curves



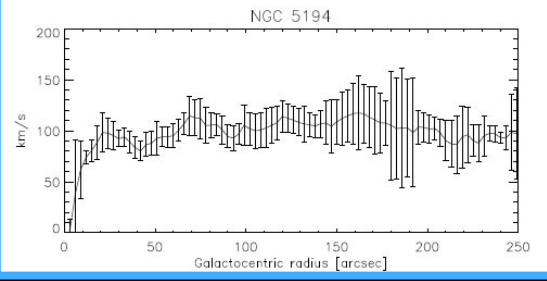
Accueil | NGC0628 | NGC0925 | NGC2403 | NGC2798 | NGC2915 | NGC2976 | NGC3031 | UGC5423 | NGC3049 | NGC3184 | NGC3198 | NGC3521 | NGC3621 | NGC3938 | NGC4236 | NGC4321 | NGC4536 | NGC4569 | NGC4579 | NGC4625 | NGC4725 | NGC5055 | NGC5194 | NGC5398 | NGC5713 | NGC6946 | IC4710 | NGC7331 | Rotation curves

Cliquez sur le nom de fichier pour le récupérer - Click on the file name to download it.

NGC 0628	NGC 0925	NGC 2403	NGC 2798	NGC 2915	NGC 2976	NGC 3031
UGC 5423	NGC 3049	NGC 3184	NGC 3198	NGC 3521	NGC 3621	NGC 3938
NGC 4236	NGC 4321	NGC 4536	NGC 4569	NGC 4579	NGC 4625	NGC 4725
NGC 5055	NGC 5194	NGC 5398	NGC 5713	NGC 6946	IC 4710	NGC 7331

Pour un fichier de l'ensemble des courbes de rotation, cliquez ici.

For the complete package of the rotation curves, click here.



THINGS

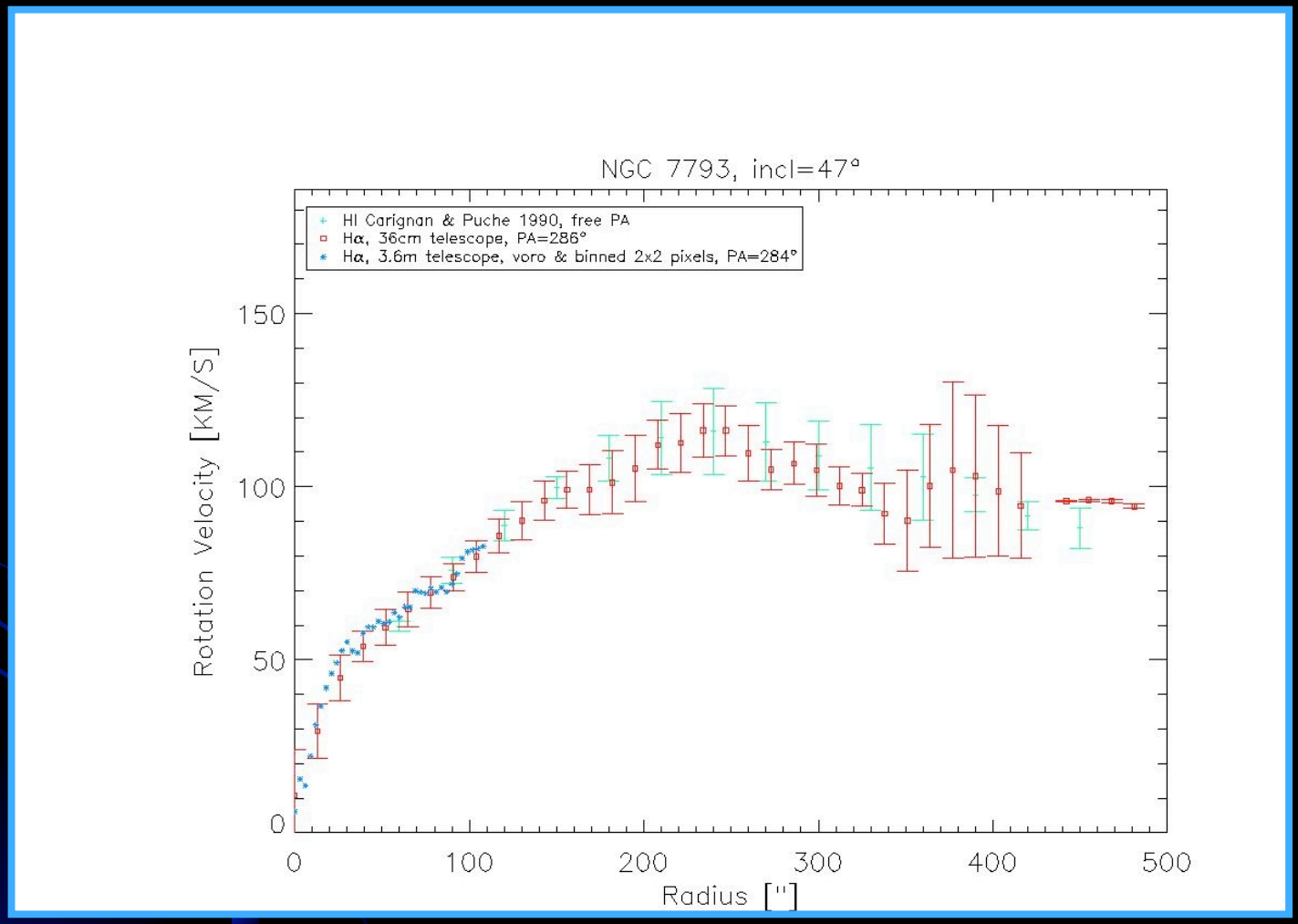
The HI Nearby Galaxy Survey

	moment 0		moment 1		moment 2		data cube	
DDO 53	na	ro	na	ro	na	ro	na	ro
DDO 154	na	ro	na	ro	na	ro	na	ro
Holmberg I	na	ro	na	ro	na	ro	na	ro
Holmberg II	na	ro	na	ro	na	ro	na	ro
M81 dwarf A	na	ro	na	ro	na	ro	na	ro
M 81 dwarf B	na	ro	na	ro	na	ro	na	ro
NGC 628	na	ro	na	ro	na	ro	na	ro
NGC 925	na	ro	na	ro	na	ro	na	ro
NGC 1569	na	ro	na	ro	na	ro	na	ro
NGC 2366	na	ro	na	ro	na	ro	na	ro
NGC 2403	na	ro	na	ro	na	ro	na	ro

http://www.mpia.de/THINGS/

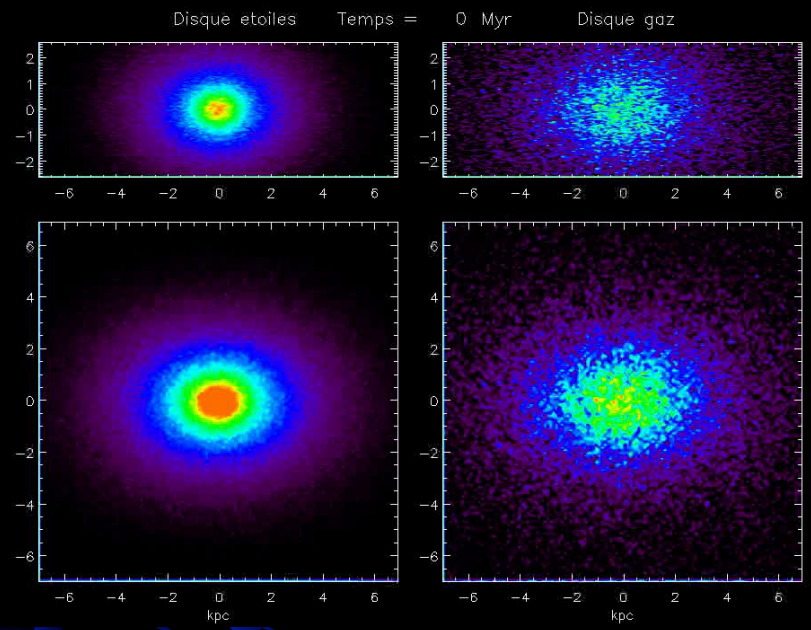
FaNTOmM

Hα kinematics with a 36cm !

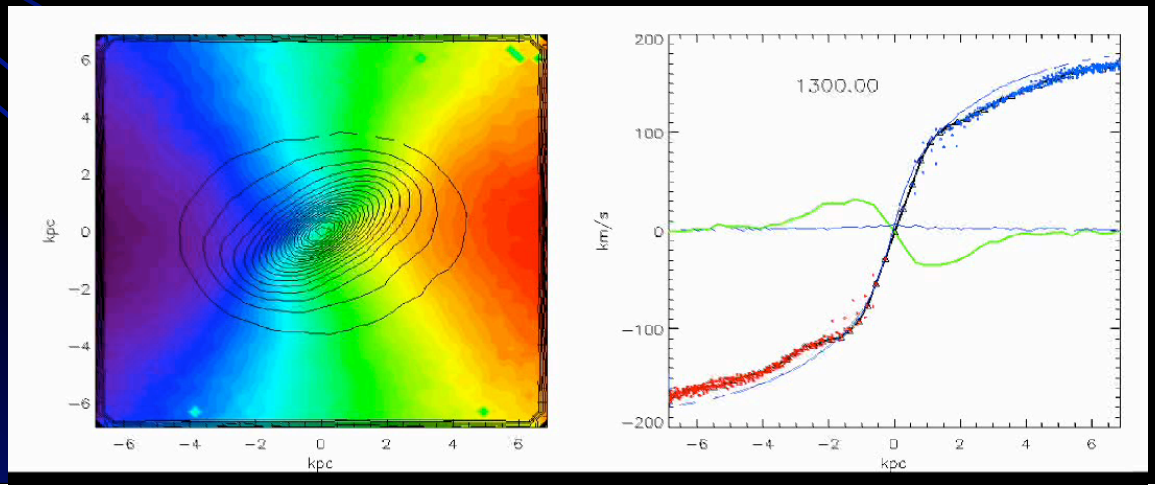


Pixel size ~4.5” for a FOV ~40’ same system than on the 3,6m

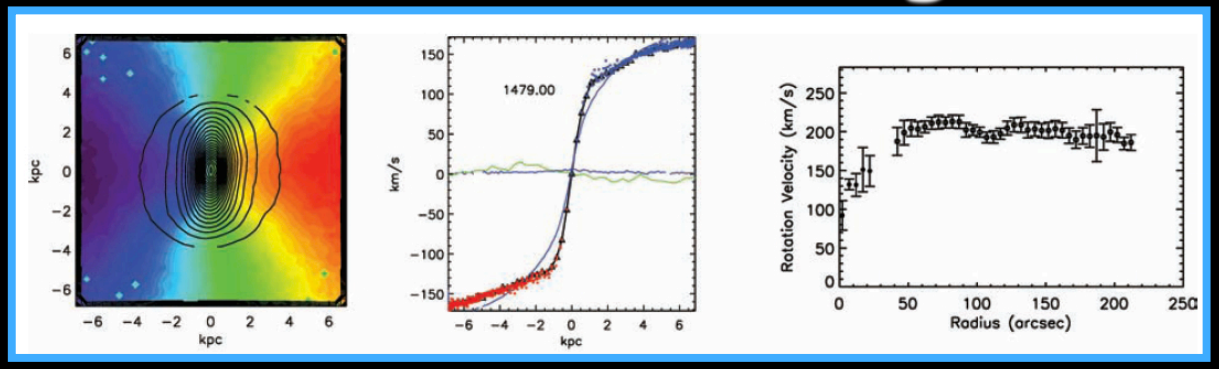
Science behind 3D FP data (ex.: barred galaxies)



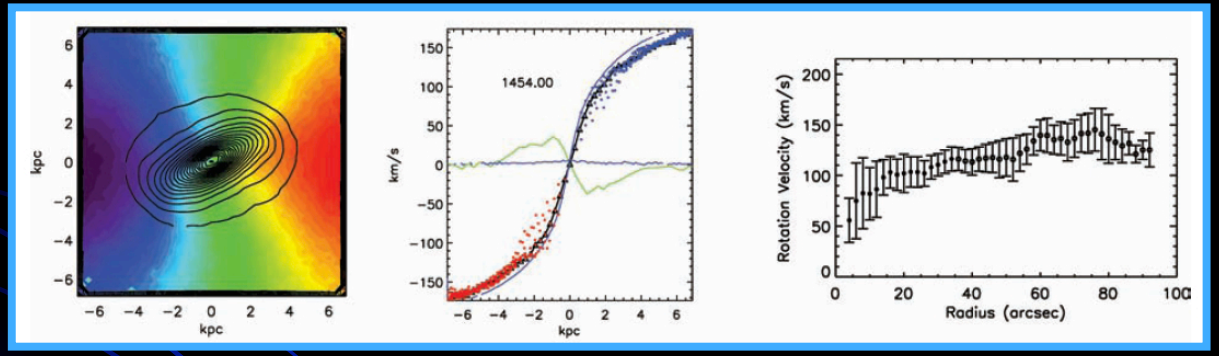
N-body + SPH simulations – GADGET code (Hernandez et al. 2005)



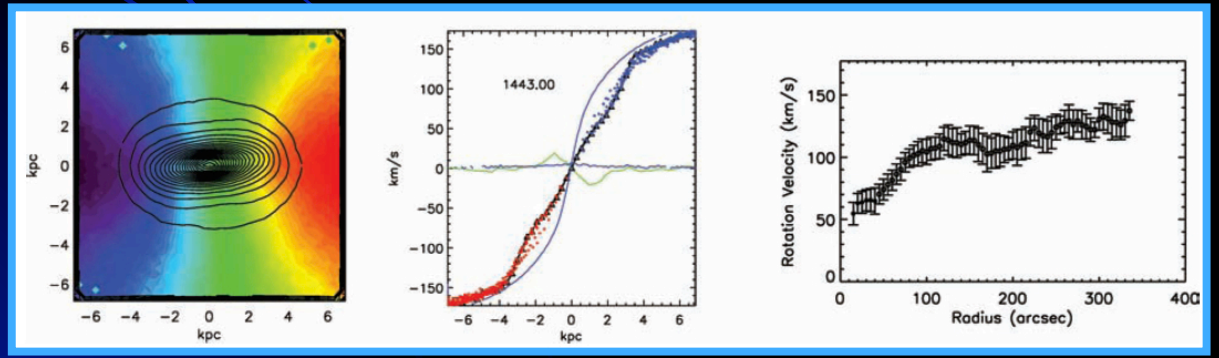
Science behind 3D FP data (ex.: barred galaxies)



NGC 3351

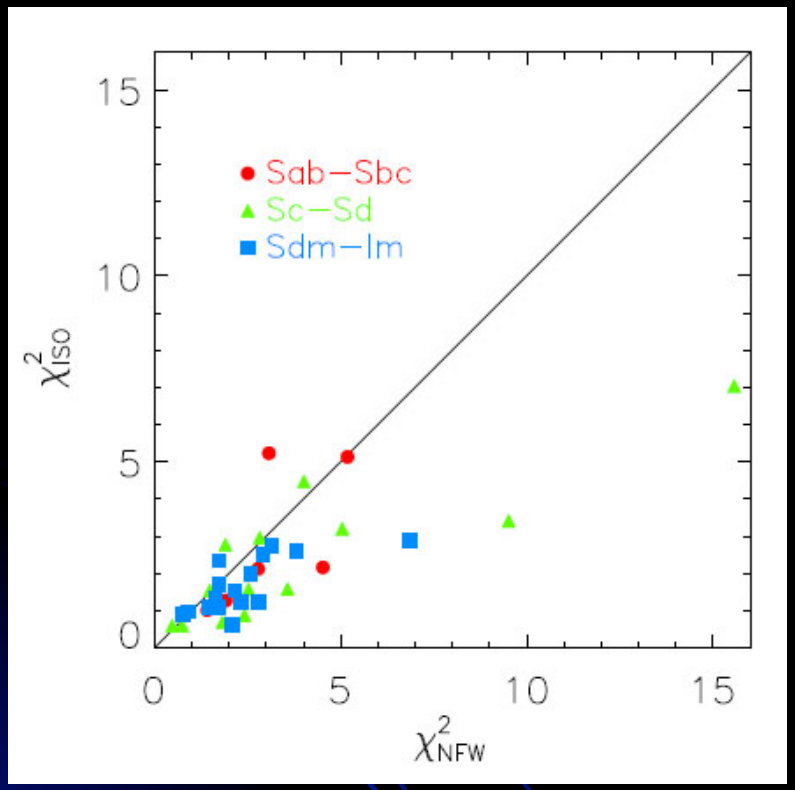


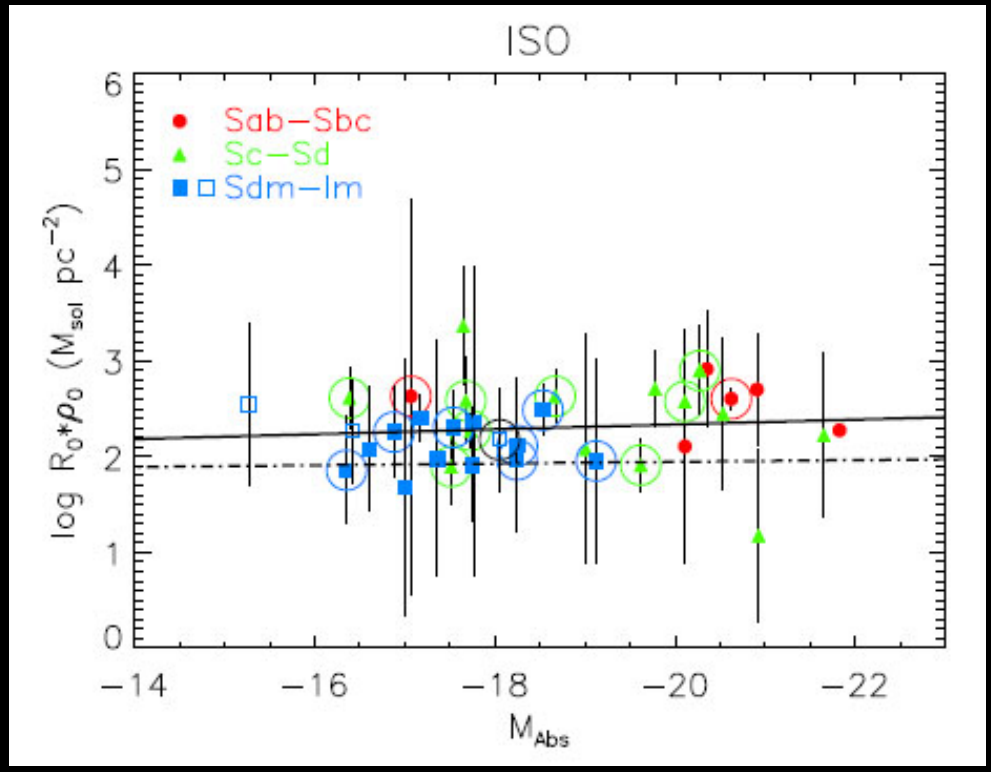
NGC 337



NGC 4559

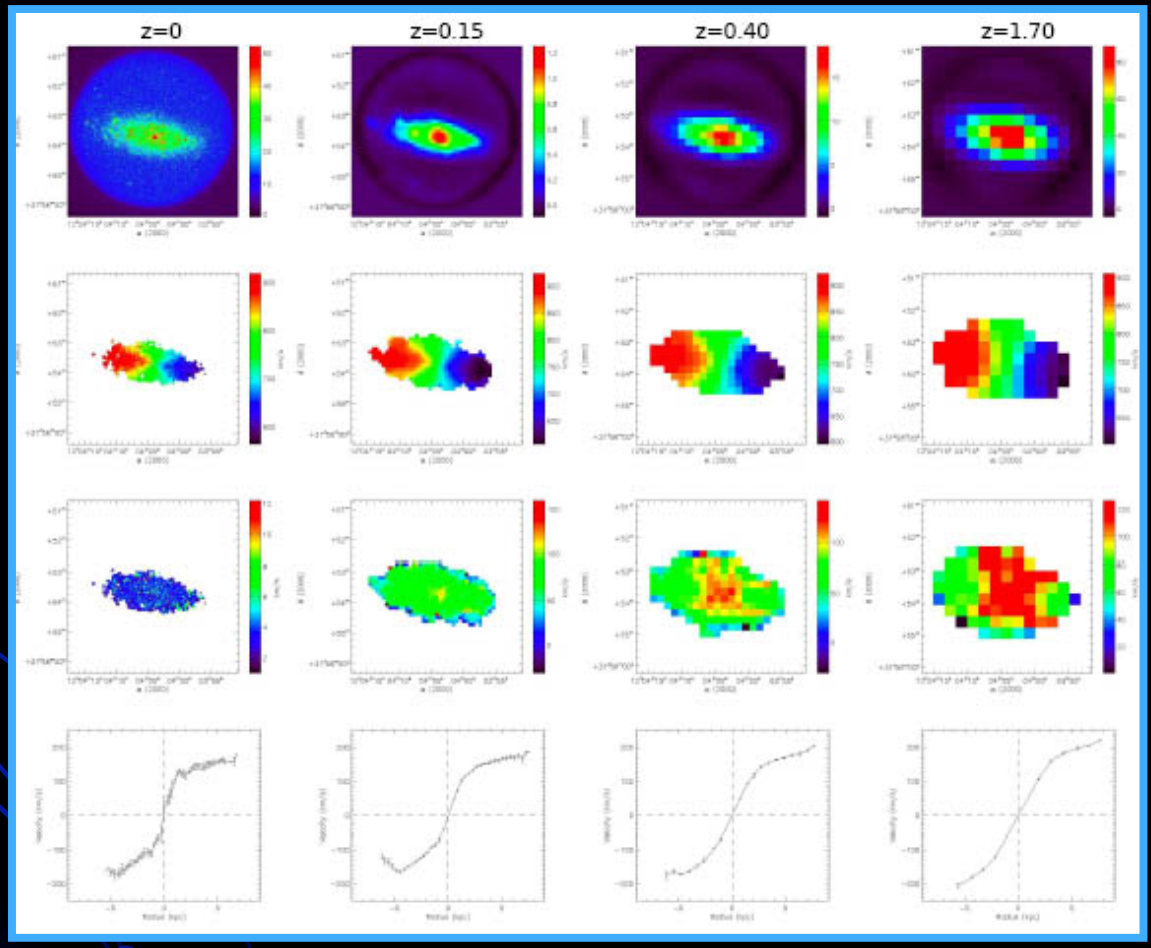
Science behind 3D FP data (ex.: dark halo profile)





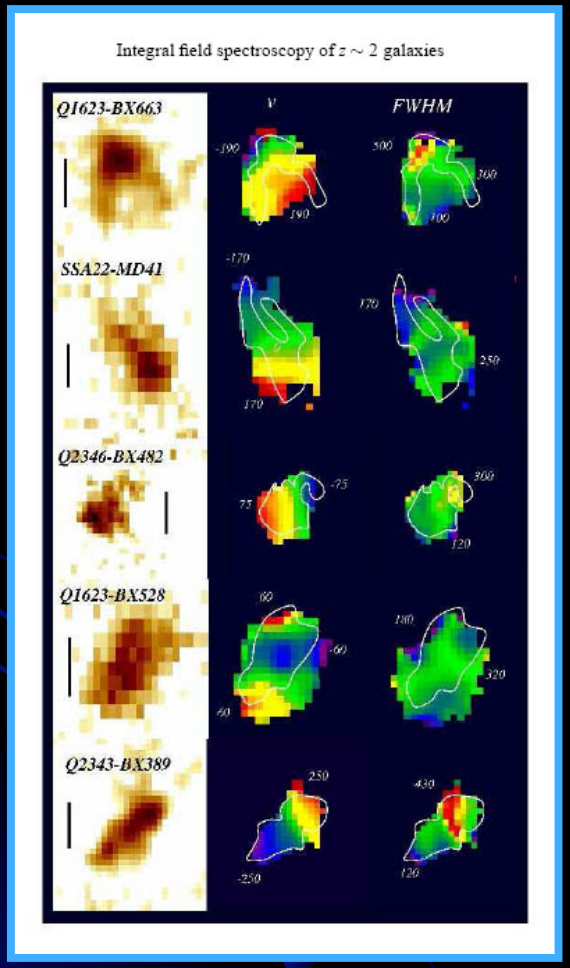
Spano et al. 2006, GHASP sample

SINGS Hα Kinematics: local sample to understand high z galaxies

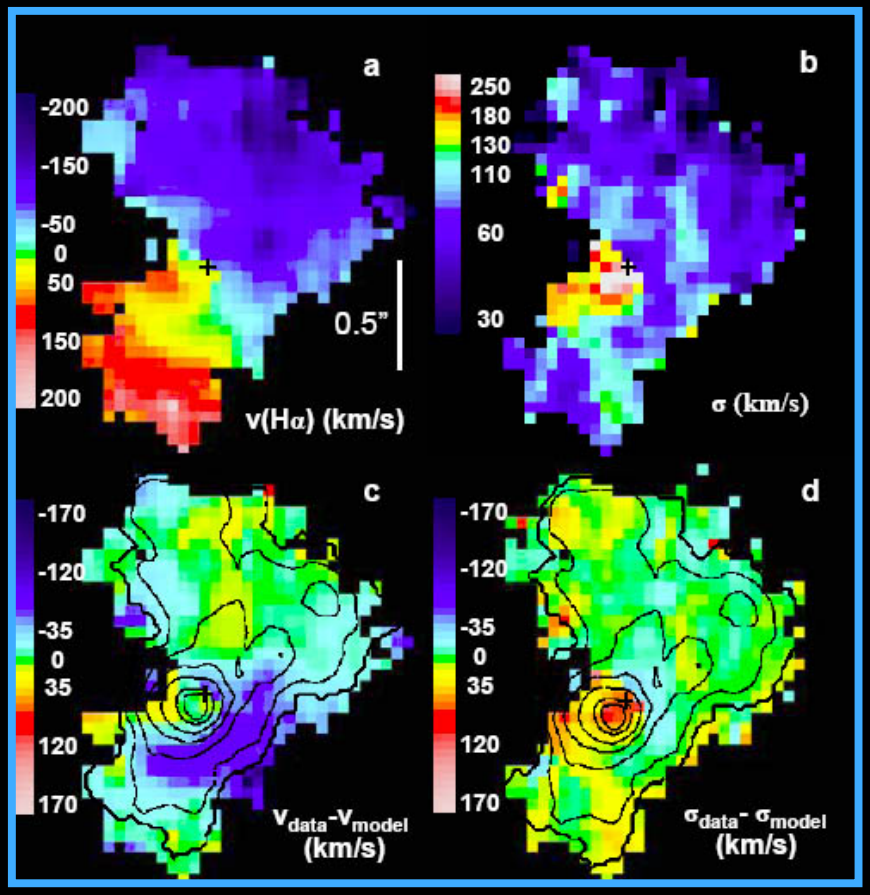


Épinat et al. 2006

SINGS Hα Kinematics: local sample to understand high z galaxies



Fôrster-Schreiber et al. 2006



Gernzel et al. 2006 z=2.4

SINGS Hα Kinematics: local sample to understand high z galaxies

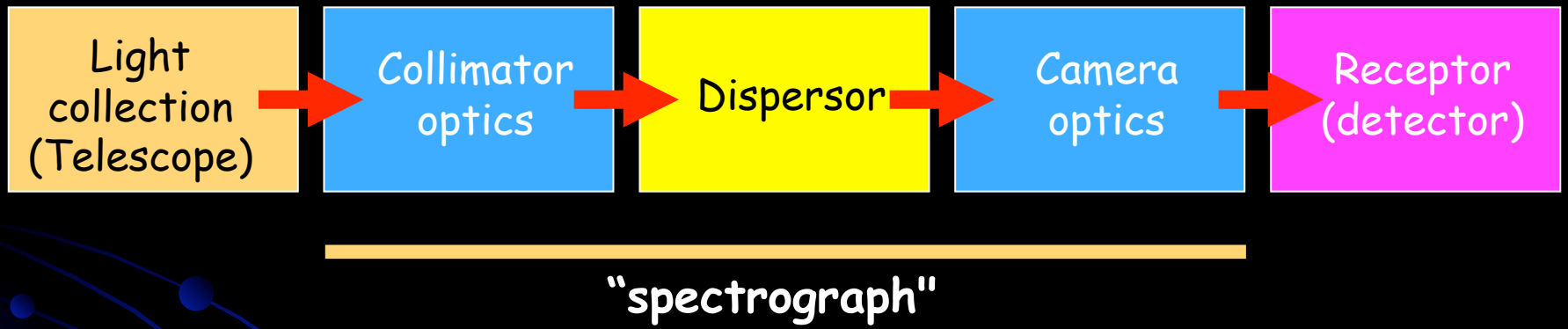
- **Disentangle the distance from evolution effects**: morphological and kinematical evolution through the age.
- B = galactic radius / the seeing (Beam parameter)
- 1-100 Mpc ➔ B = [hundreds - few tens]
- 0.15 < z < re-ionization epoque

➔ B = [~ ten to a few units or less …]

SINGS Hα Kinematics: local sample to understand high z galaxies

- **Rotation curves need B ≥10**. Otherwise:
- under-estimation of R_{max} and V_{max}
- "solid-body*fication*" of the rotation curves (controversy CORE vs CUSPY halo density profile)
- (fine) structures attenuated/erased: bars, rings, spiral arms, bubbles, …
- shift of the kinematical parameters (PA, centre, inclination, V_{sys})

Spectroscopy, does not involve only a spectrograph…



The detector : 3 major elements to consider for 3D spectroscopy

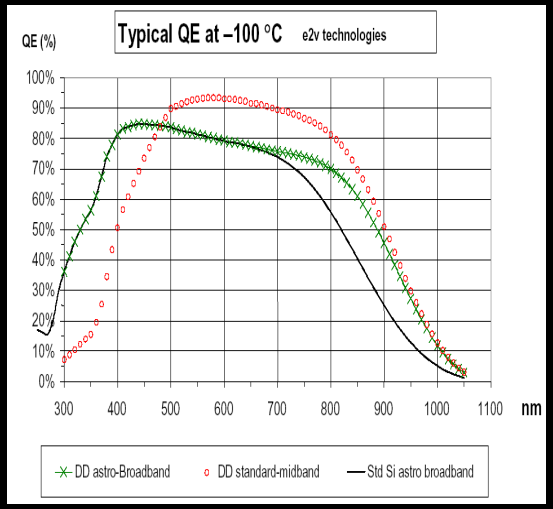
Besides the basic characteristics (DQE, $\Delta\lambda$) :

- The pixel size ⟷ Sampling of the « seeing »
- The intrinsic noise or read-out noise ⟷ σ of the minimum detectable signal (limiting magnitude)
- The time resolution ⟷ Counting or integration ? Simple image or multiplex ?

integration

CCD's

- DQE → 98% ~ 6000 Å (back-illuminated + anti-reflection coating)
- → 4kx4k pix 12µm
- → read-out noise ~ $2e^-$
- Mosaic of CCDs (ex.:Megacam 40 * 2kx4.6k [25x30 cm ; 377 Mpix])

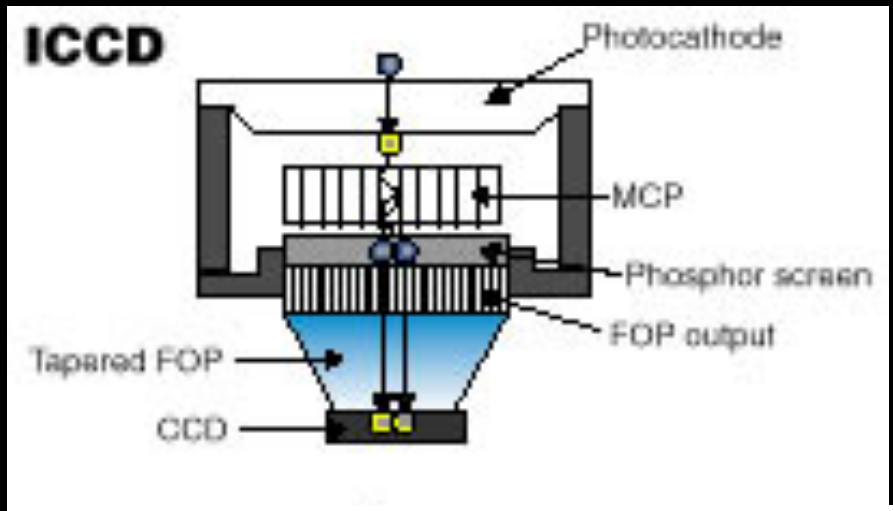


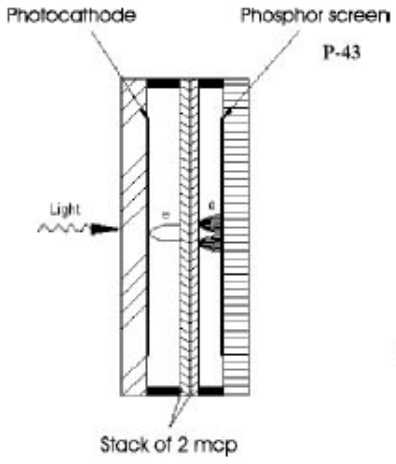
E2V 44-90

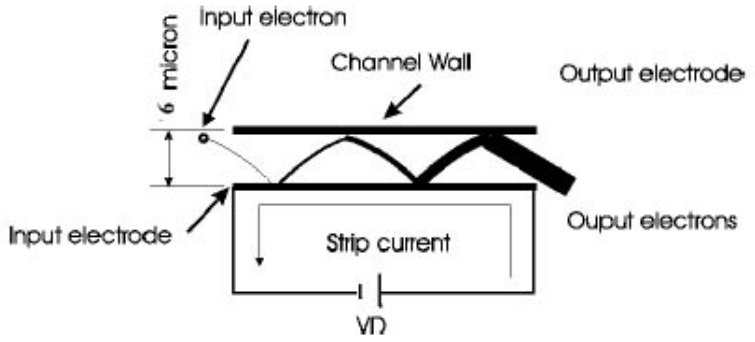
counting

Photon counting intensified CCD's

LAM + LAE

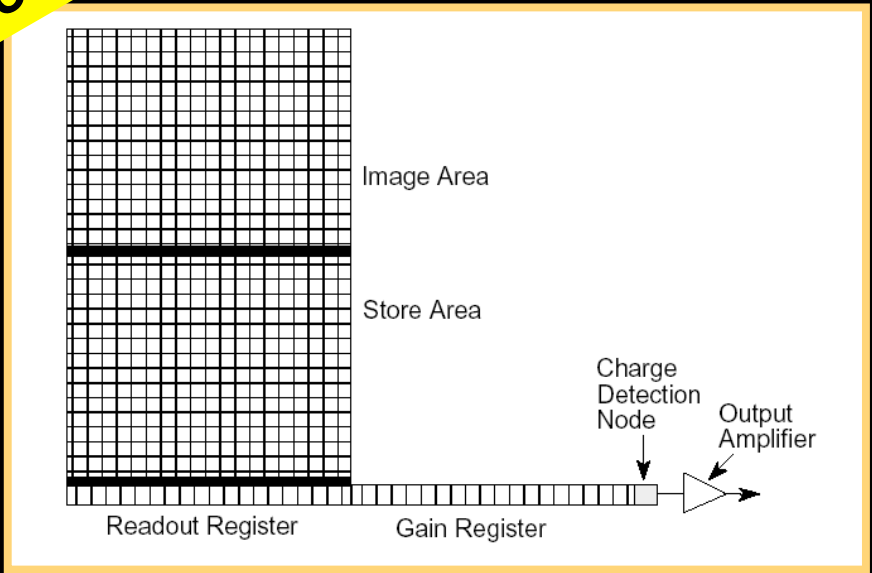






Counting

EMCCD (L3CCD/e2v)



Pixel 10-20 μ

T° < 170 K

Visible (0.4 μ - 1.1 μ)

DQE > 90%

Size 1Kx1K (CCD097)

(in fact: FT 1Kx2K)

SAAO just bought one

→ Classical CCD's with on-chip intensification electronics (into the registers)
[EMCCD: Electron Multiplying CCD; LLLCCD: Low Light Level CCD]

→ Read-out noise < photon noise (limiting factor / CIC: Clock Induced charge

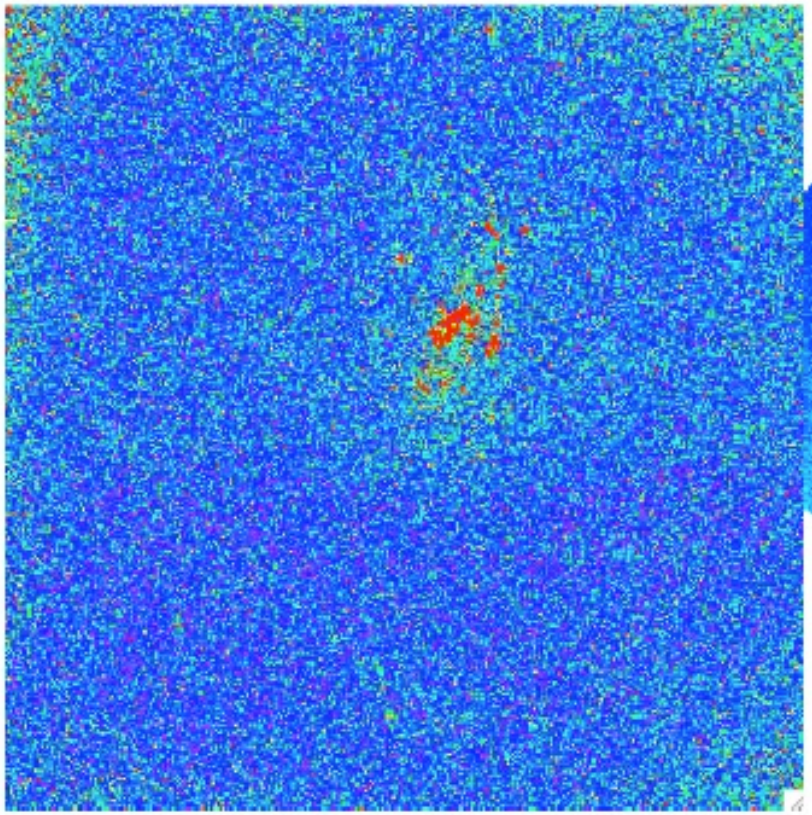
→ in integration (DQE ~ 45%) and photon counting (DQE ~ 90%)

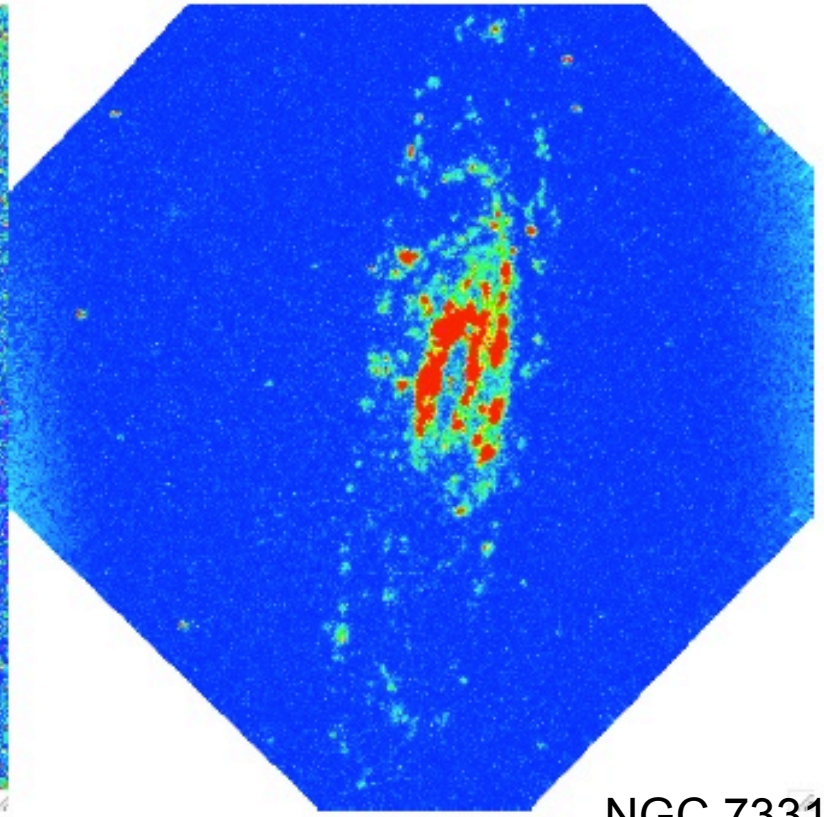
→Developments (LAE/UCT - LAM)

→Development e2V/LAE/LAM/UCT: 4Kx8K FT EMCCDs

CCCP: **C**CD **C**ontroler for
Counting **P**hotons
CIC < 0.0001 photon/pixel/image
Daigle PhD thesis
Started his company: NüVü

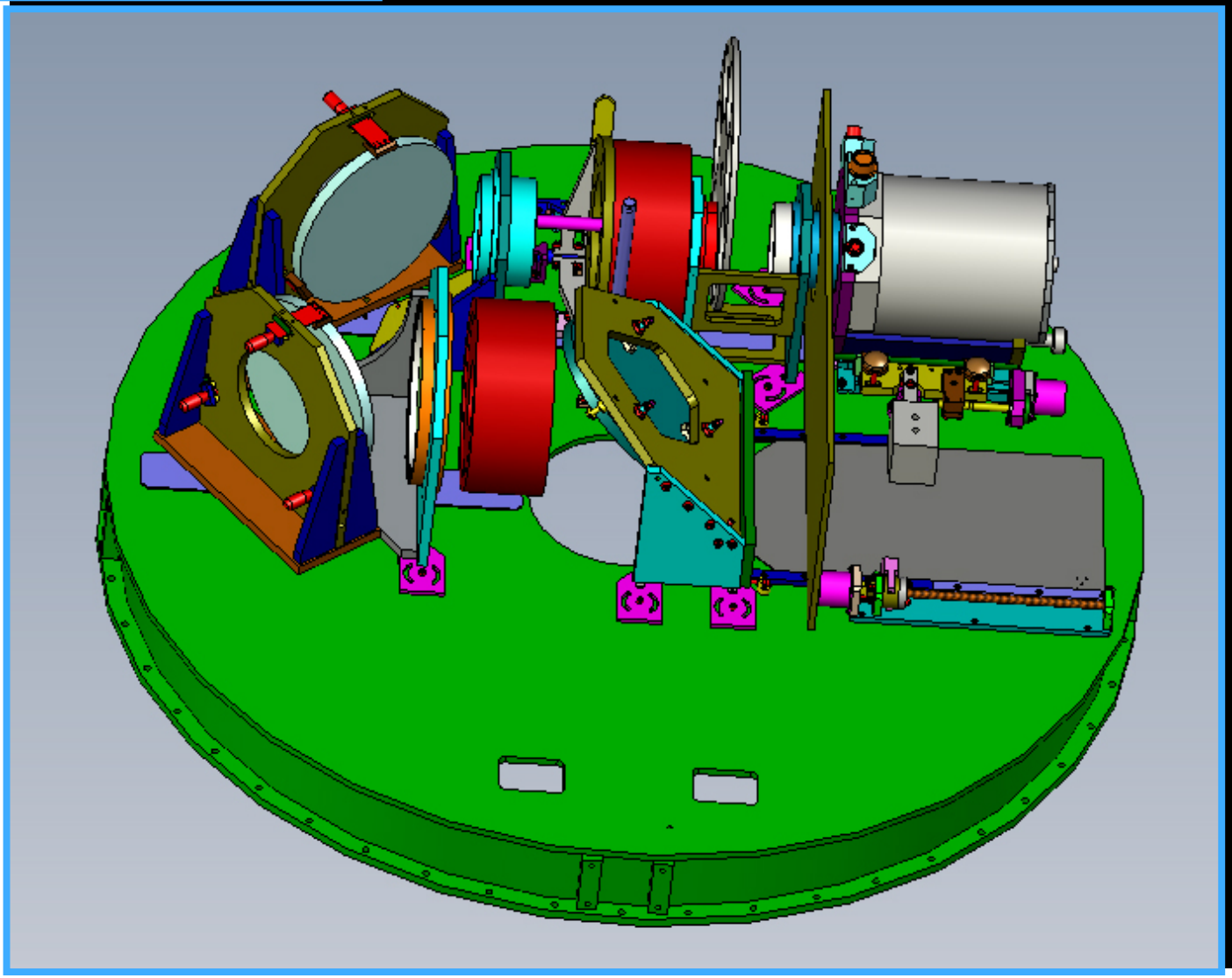
CCD207 + CCCP = FaNTOmM II

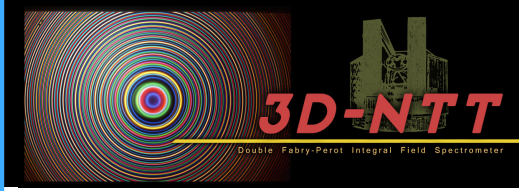




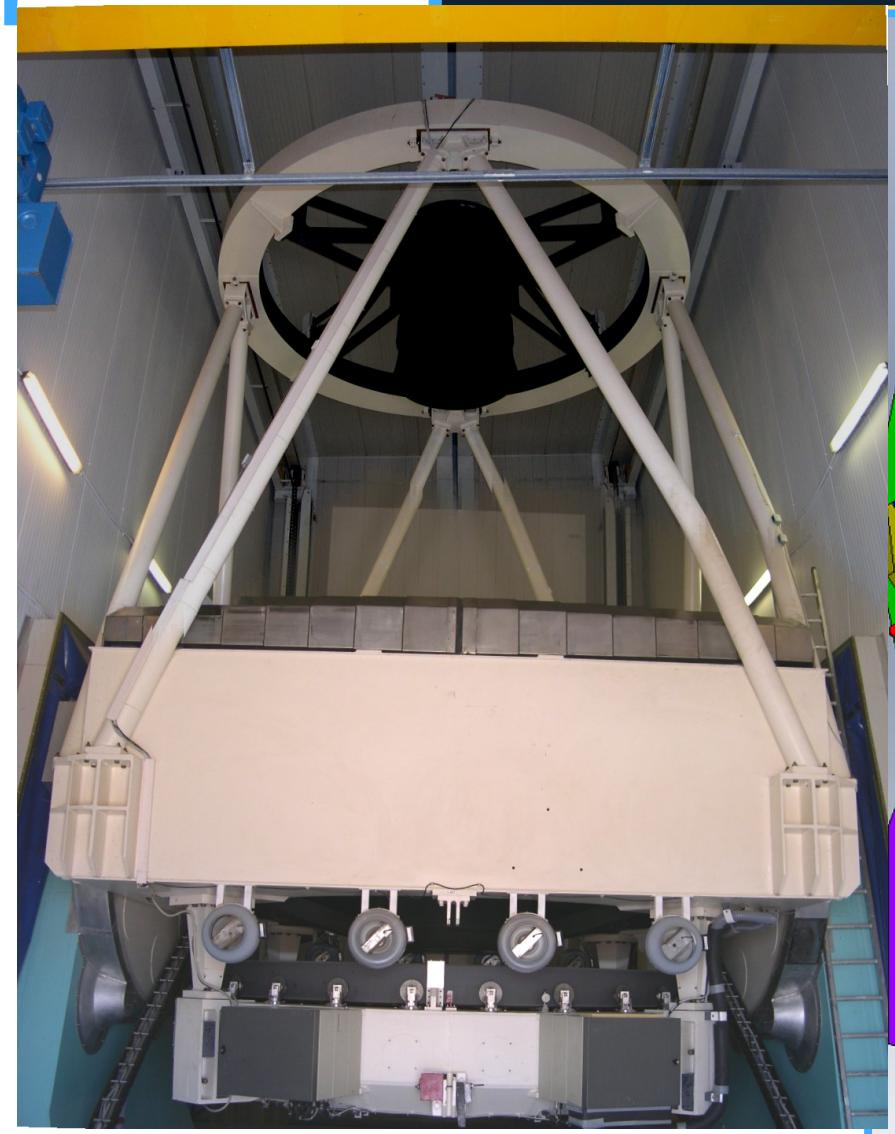
NGC 7331

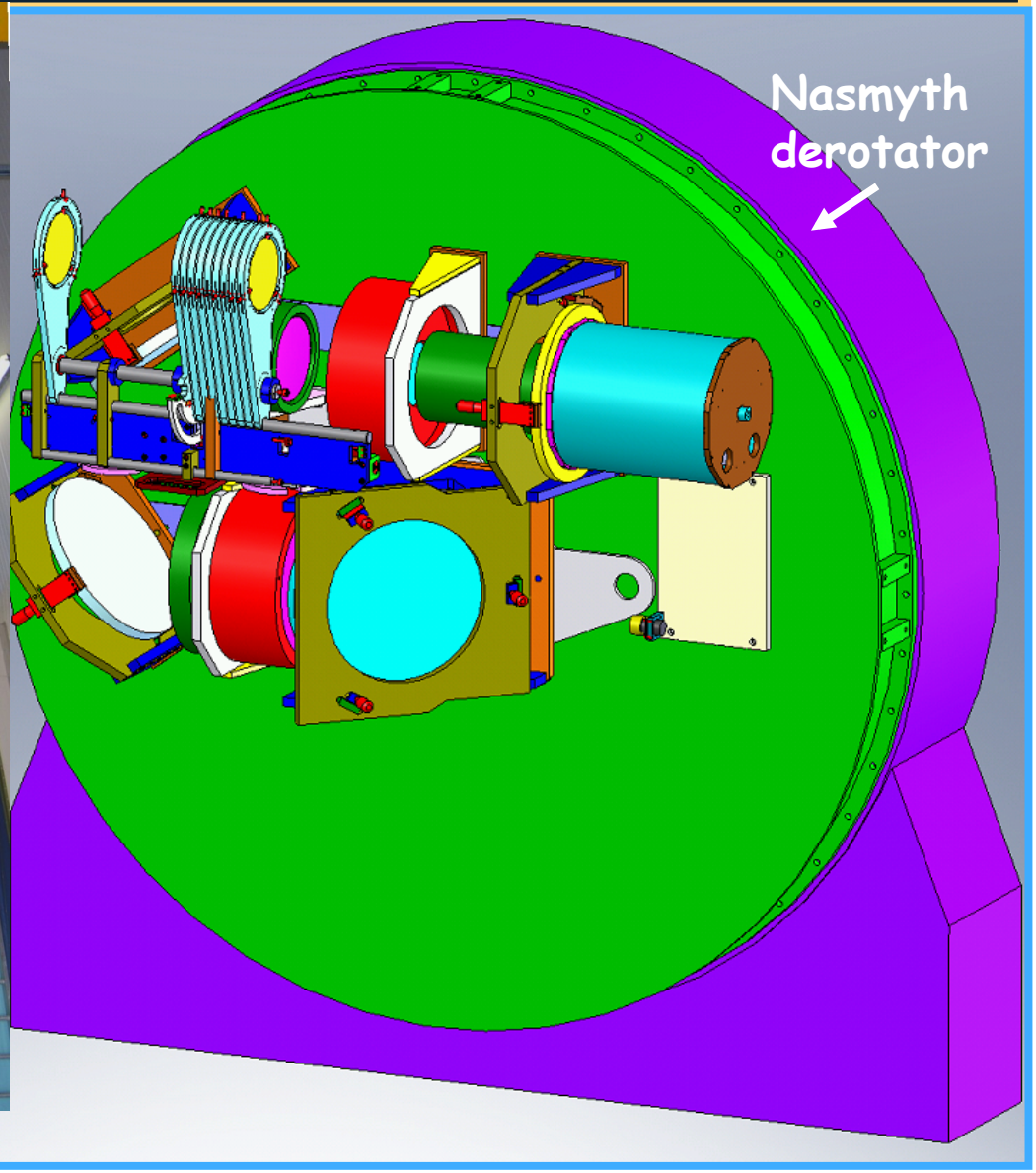
Double Fabry-Perot Integral Field Spectrometer





Double Fabry-Perot Integral Field Spectrometer

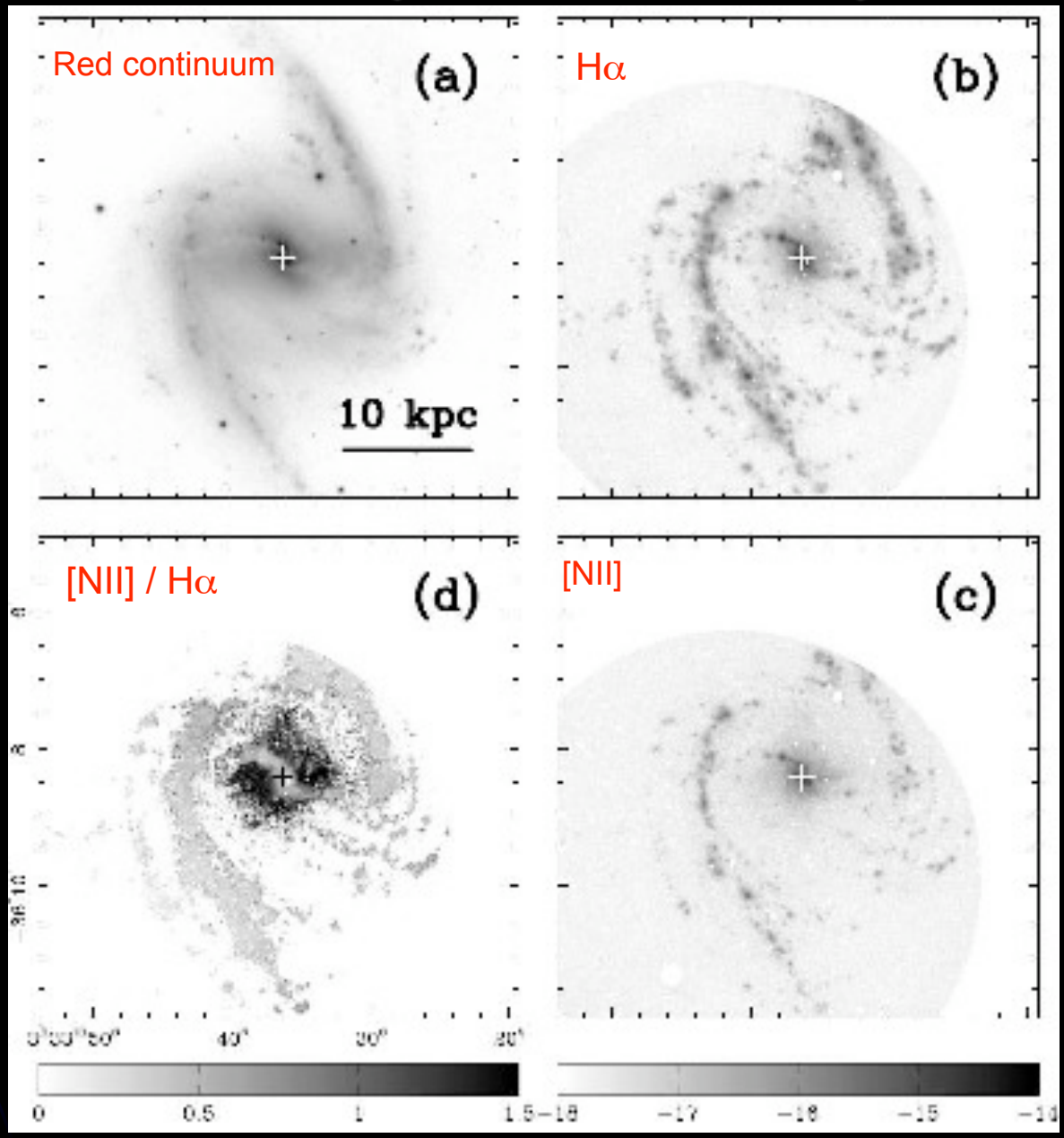




Low Resolution Mode (Tunable Filter)

Example of metal abundance map obtained with a Tunable Filter

NGC1365 observed with the TTF on the AAT (Veilleux et al. 2003)



Toward new challenges

FaNTOmM is a resident instrument:
- 1.6m OMM
- 1.93m OHP

FaNTOmM is a visiting instrument on:
- 3.6m CFHT
- 3.6m ESO/La Silla

GHaFaS is a resident instrument: :
- 4.3m WHT

Short term :
- RSS (double etalons) on SALT
- New EMCCD at Sutherland

Medium term :
- NTT : 3D-NTT

Long term :
- Collaboration with OSIRIS
- New detector
  - 4Kx4K FT EMCCD with LAM
  - QE ~ 90% with low CIC
- New FP controller (PhD project of a PhD student from Burkina Faso in coll. with LAM
- New FP etalon with LAM

Conclusion

- In the last 10 years, new Photon counting cameras combined with Fabry-Perot Interferometry have been very successful at studying the kinematics of Local Galaxies
- New instrumentation such as the 3DNTT, the RSSFP on SALT and eventually OSIRIS on Grantecan should allow to make the link with higher redshift objects

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oDAUo

Université de Montréal

Cet observatoire d'Astrophysique à été inauguré
le 26 novembre 2007 par
S.E.M. Tertus ZONGO,
Premier Ministre, Chef du Gouvernement
du Burkina Faso

The End

Thank's to UNISA