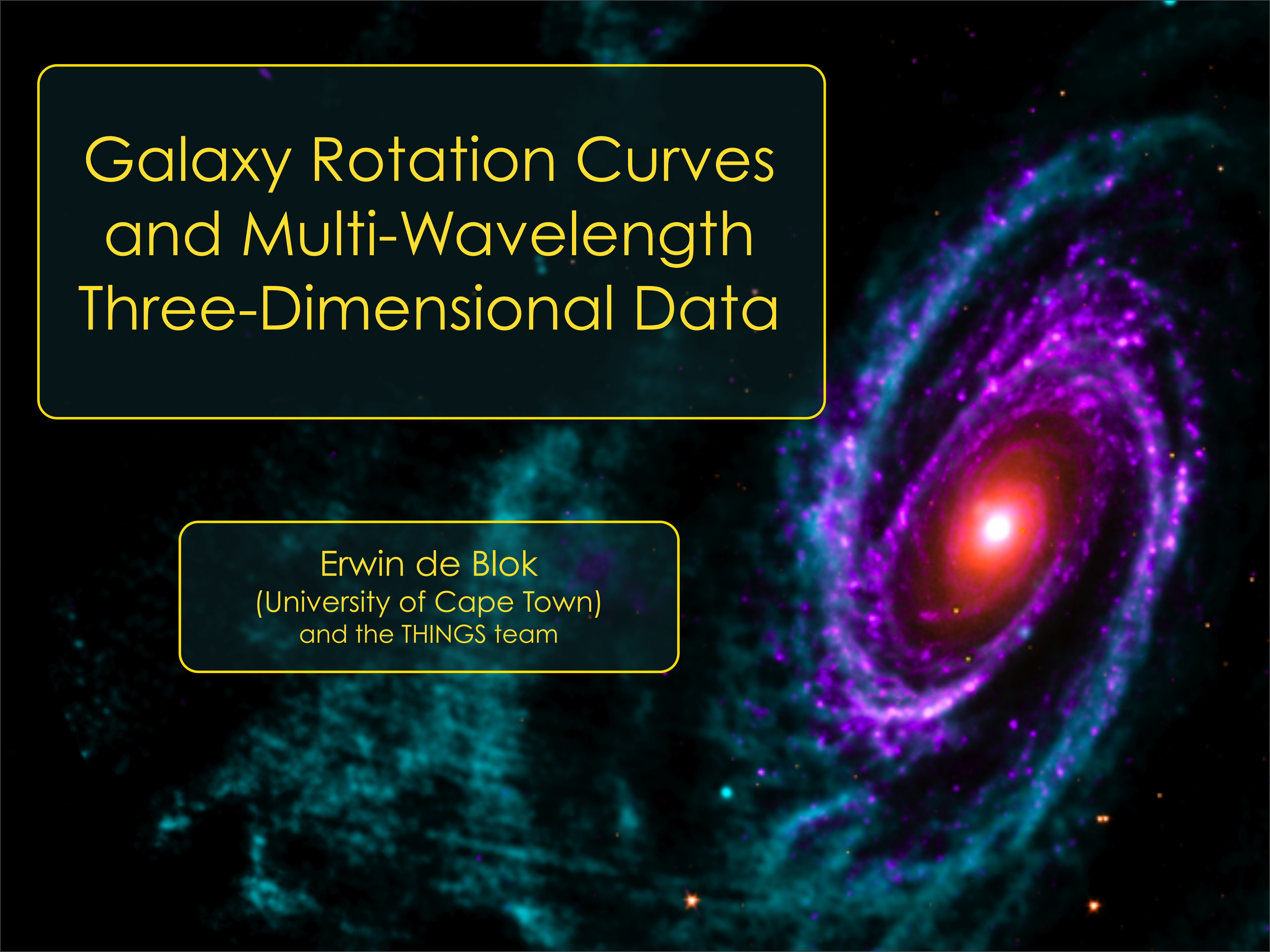
Galaxy Rotation Curves and Multi-Wavelength Three-Dimensional Data

Erwin de Blok
(University of Cape Town)
and the THINGS team



Contents

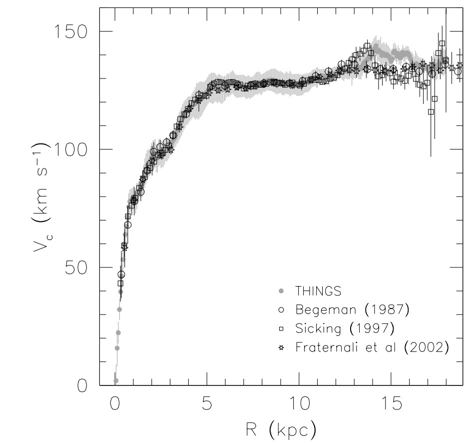
- Rotation curves
- From 3D to 2D - profile shapes velocity fields & non-circular motions
- Multi-wavelength baryons
- Back to 3D - Multi-wavelength dynamics: CO and HI

Rotation Curves

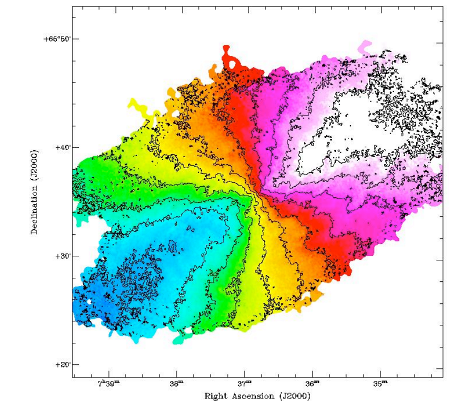
- Efficient way of describing dynamics of galaxies
- In combination with baryons: information on presence and distribution of dark matter
- Useful for studies of SF threshold
- Baseline for non-circular motions studies
- Info on geometry (warps)

Derivation steps

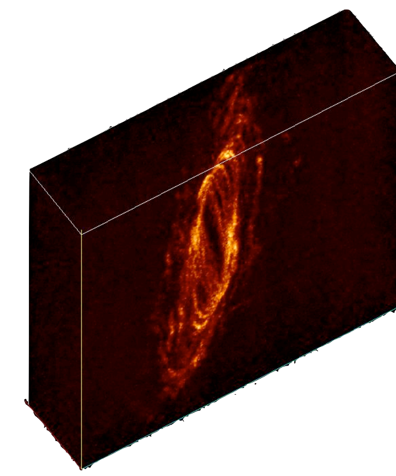
- Standard technique
- Rotation curve: $V = V(R)$
- Derived from velocity field using tilted rings
- $V(x,y) = V_{sys} + V_C(R) \sin(i) \cos(\theta)$
- Velocity field $V(x,y)$ derived from data cube $I(x,y,v)$



1D



2D



3D

THINGS: The HI Nearby Galaxy Survey

- Large NRAO VLA program (2003-2006)
- ~500 hours: B, C and D arrays
- 34 galaxies: Sa - Irr, 3-10 Mpc
- Resolution ~ 6” (100-300 pc)
- Velocity Resolution ~ 5 km s^{-1}
- Sensitivity ~ 5 x 10^{19} cm^{-2}
- total: 1 Tbyte

HI (VLA)
Star Formation (Galex UV+Spitzer 24mu)
Old Stars (Spitzer 3.6mu)

- Targets overlap SINGS *Spitzer* Legacy Survey and GALEX Nearby Galaxy Survey
- Data public later this year

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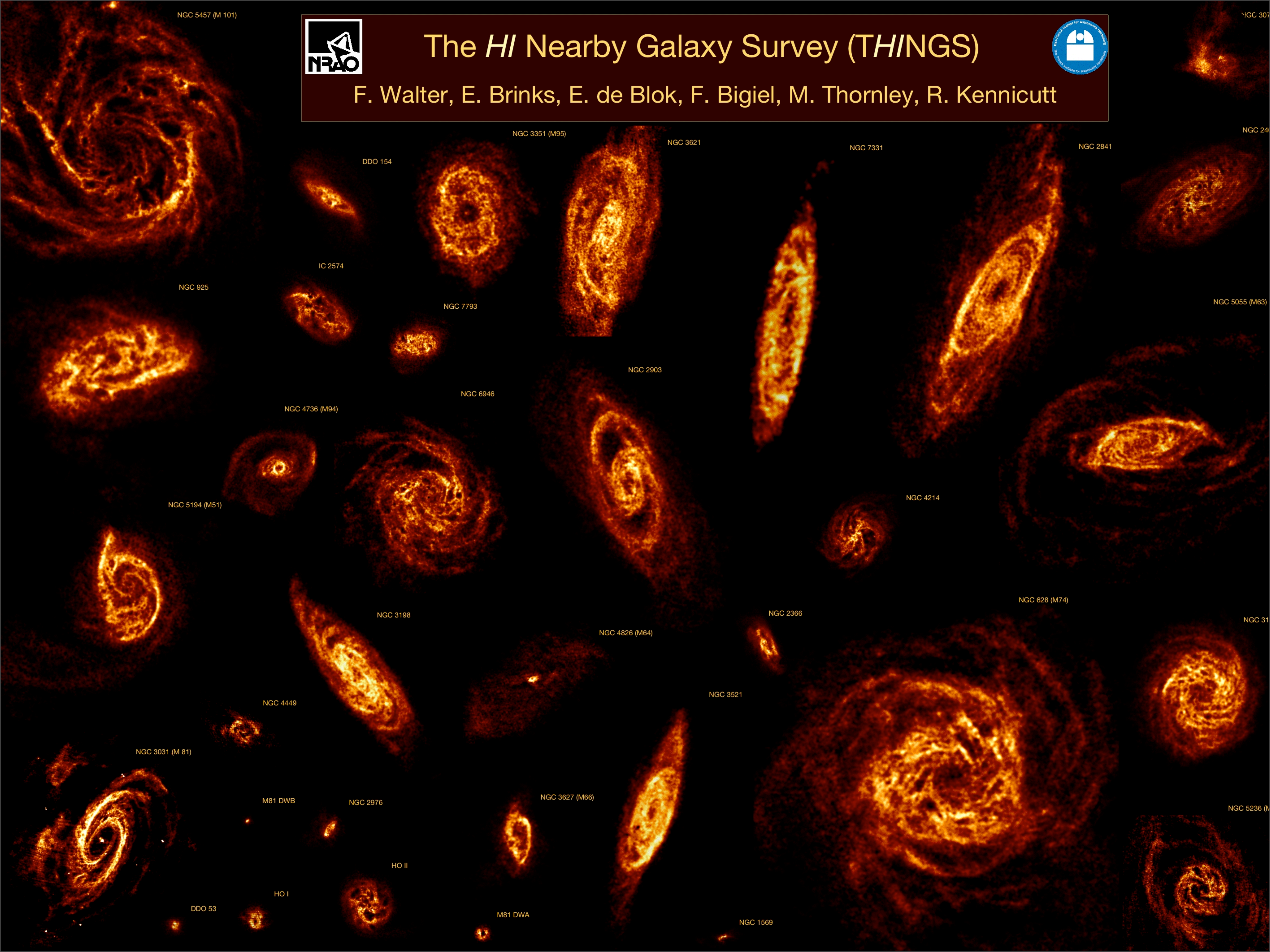
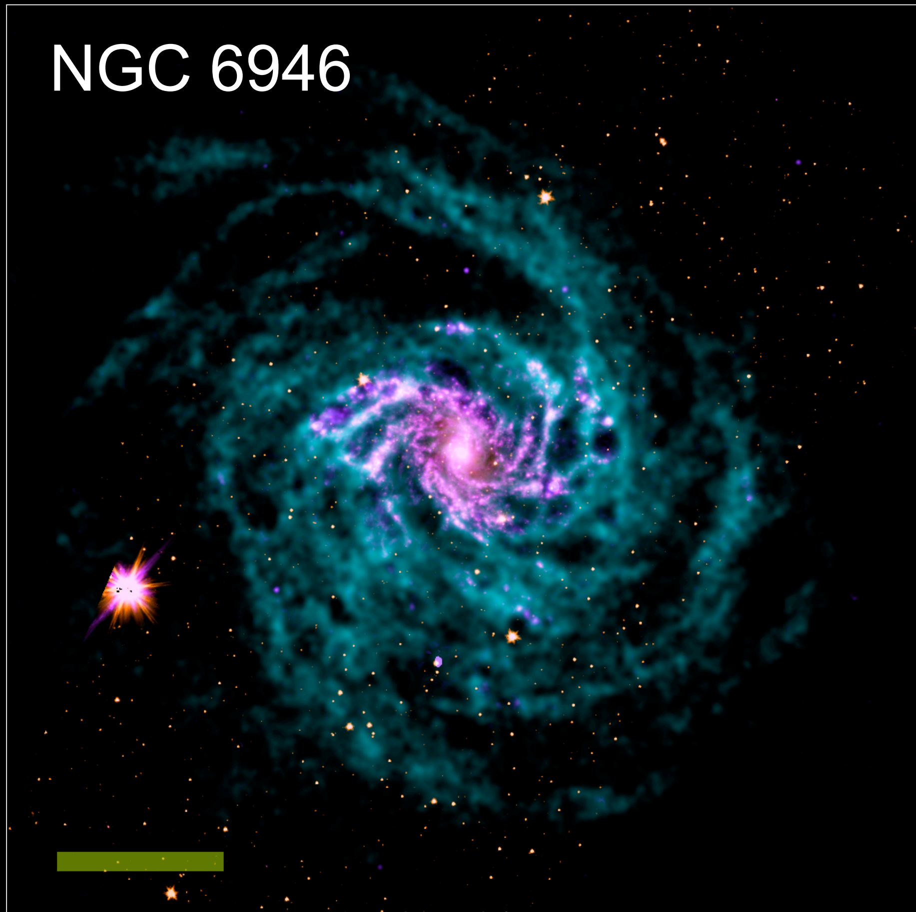
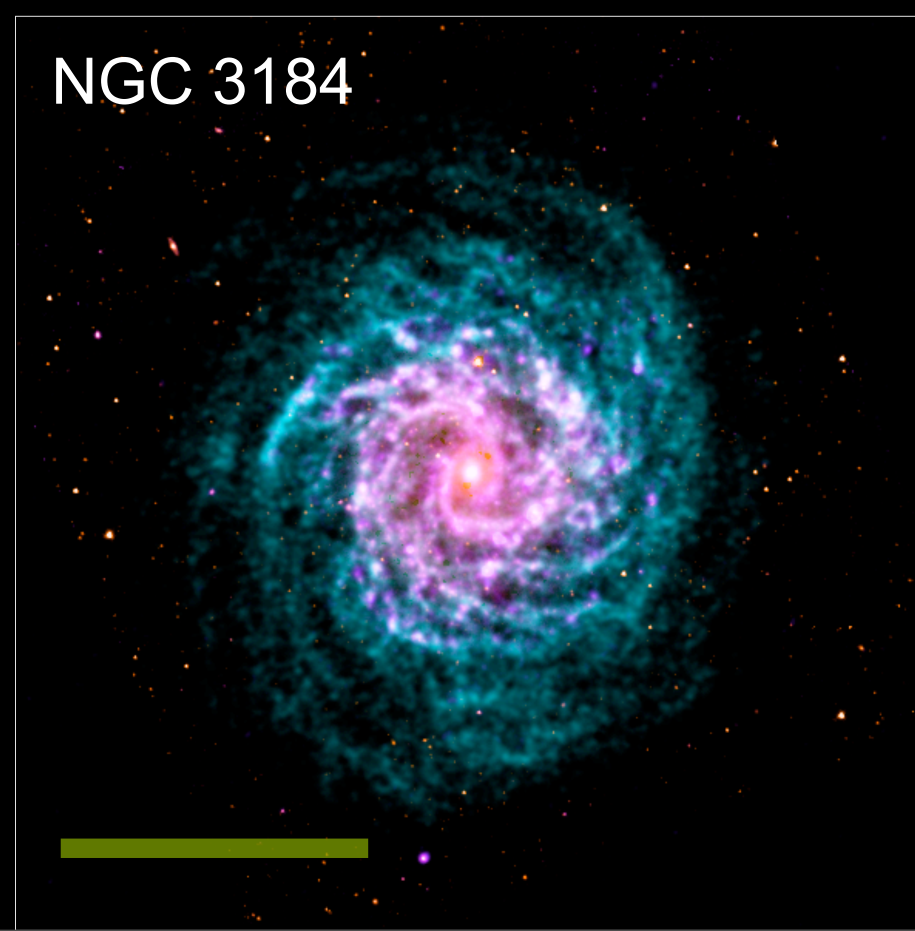


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 5457 (M 101)
DDO 154
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 24
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 4214
NGC 5194 (M51)
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 31
NGC 4826 (M64)
NGC 3521
NGC 4449
NGC 3031 (M 81)
M81 DWB
NGC 2976
NGC 3627 (M66)
NGC 5236 (M
HO II
HO I
DDO 53
M81 DWA
NGC 1569

Spiral Galaxies in T*HI*NGS — The *HI* Nearby Galaxy Survey





‘Face-on’
Spiral Galaxies
in T*HI*NGS

scale:
10 kpc
30.000 light years

Color Coding:

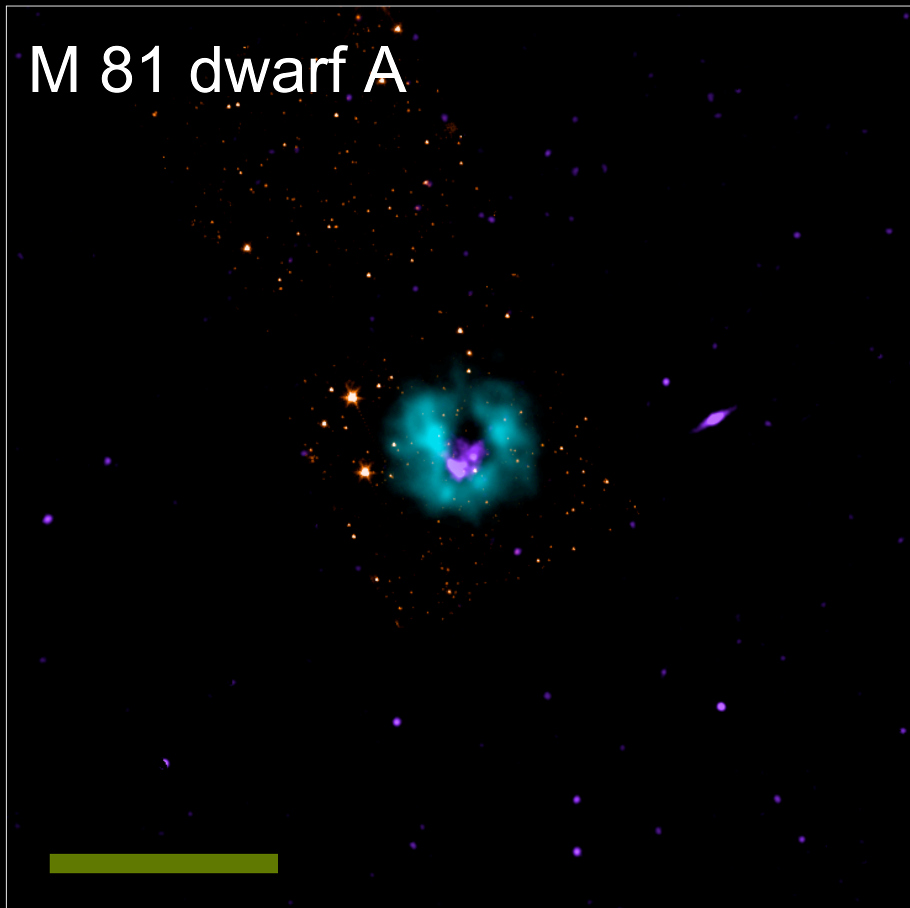
Atomic Hydrogen (HI)
(Very Large Array)

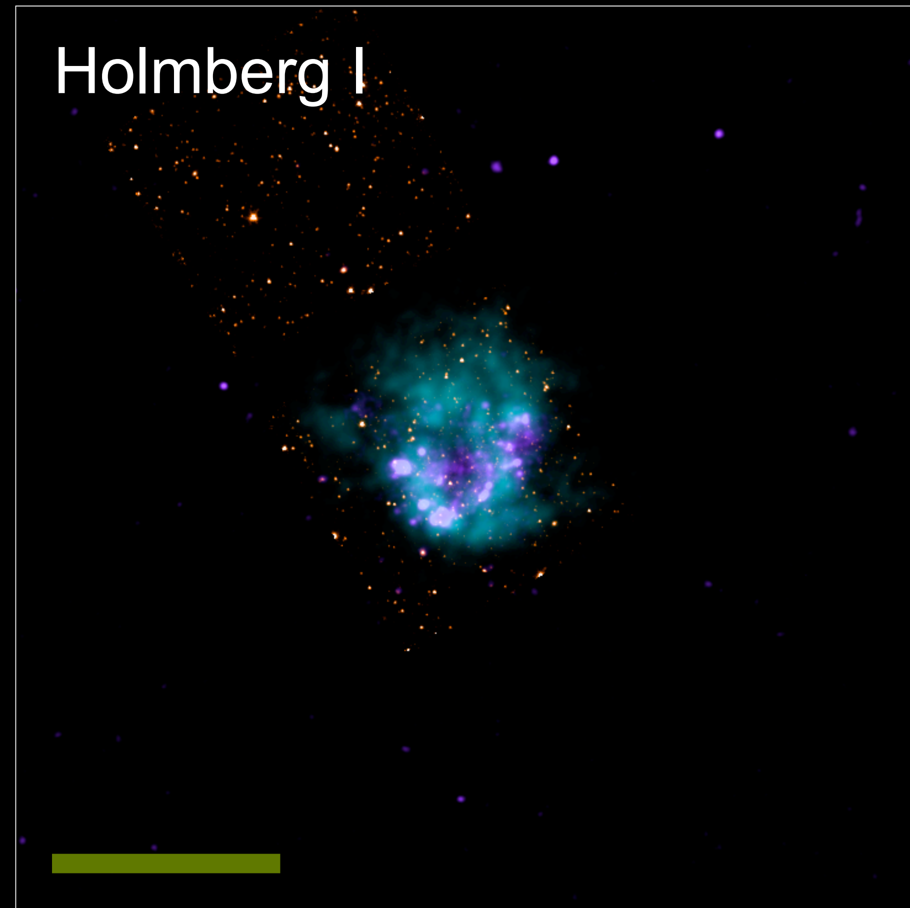
Old stars
(Spitzer)

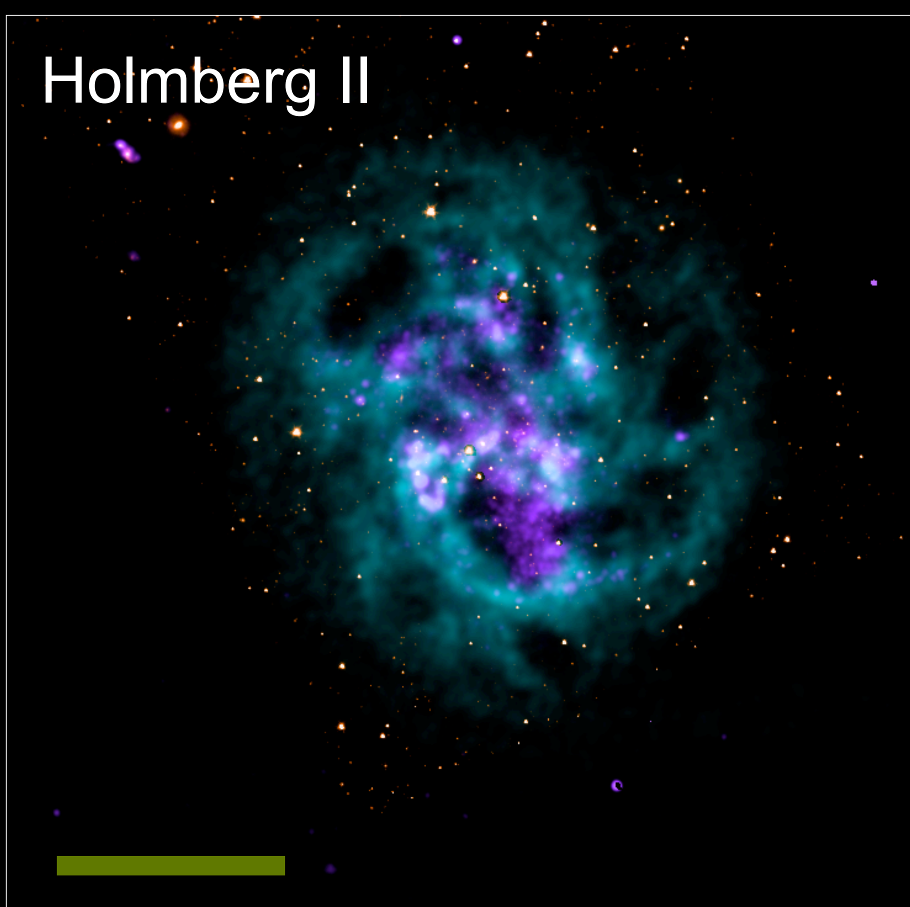
Star Formation
(Galex & Spitzer)

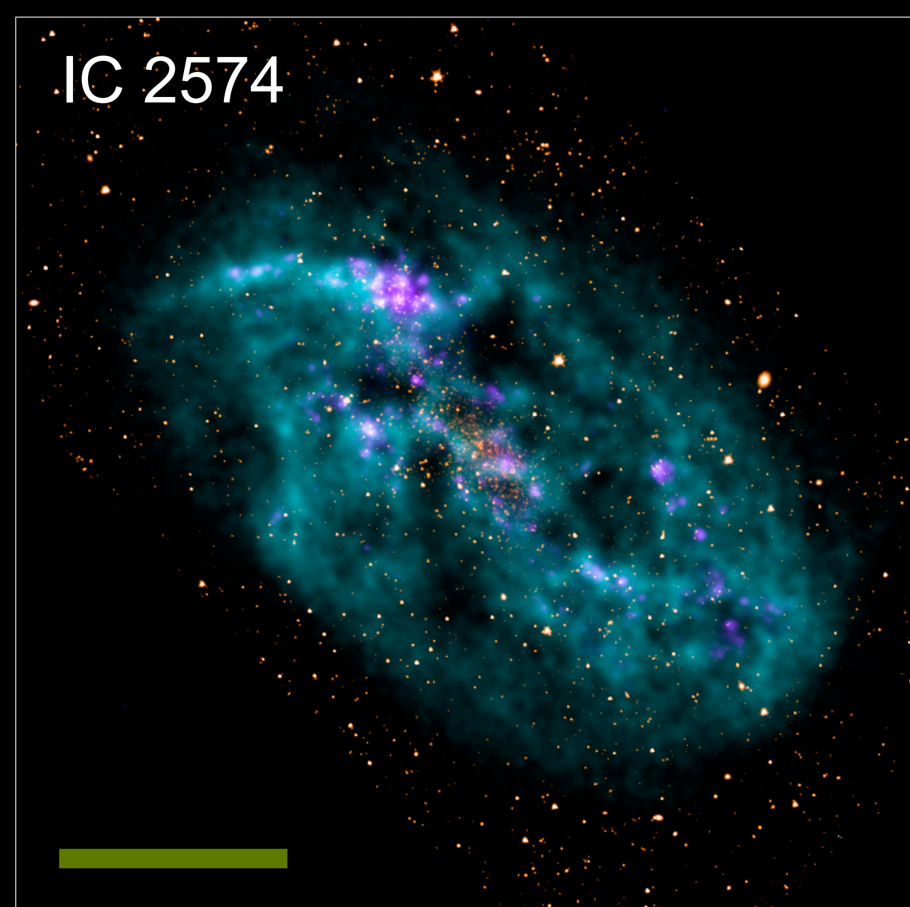
Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

Dwarf Galaxies in T*HI*NGS -- The *HI* Nearby Galaxy Survey









Dwarf Galaxies of the M81 group in T*HI*NGS

scale:
5 kpc
15.000 light years

color coding:

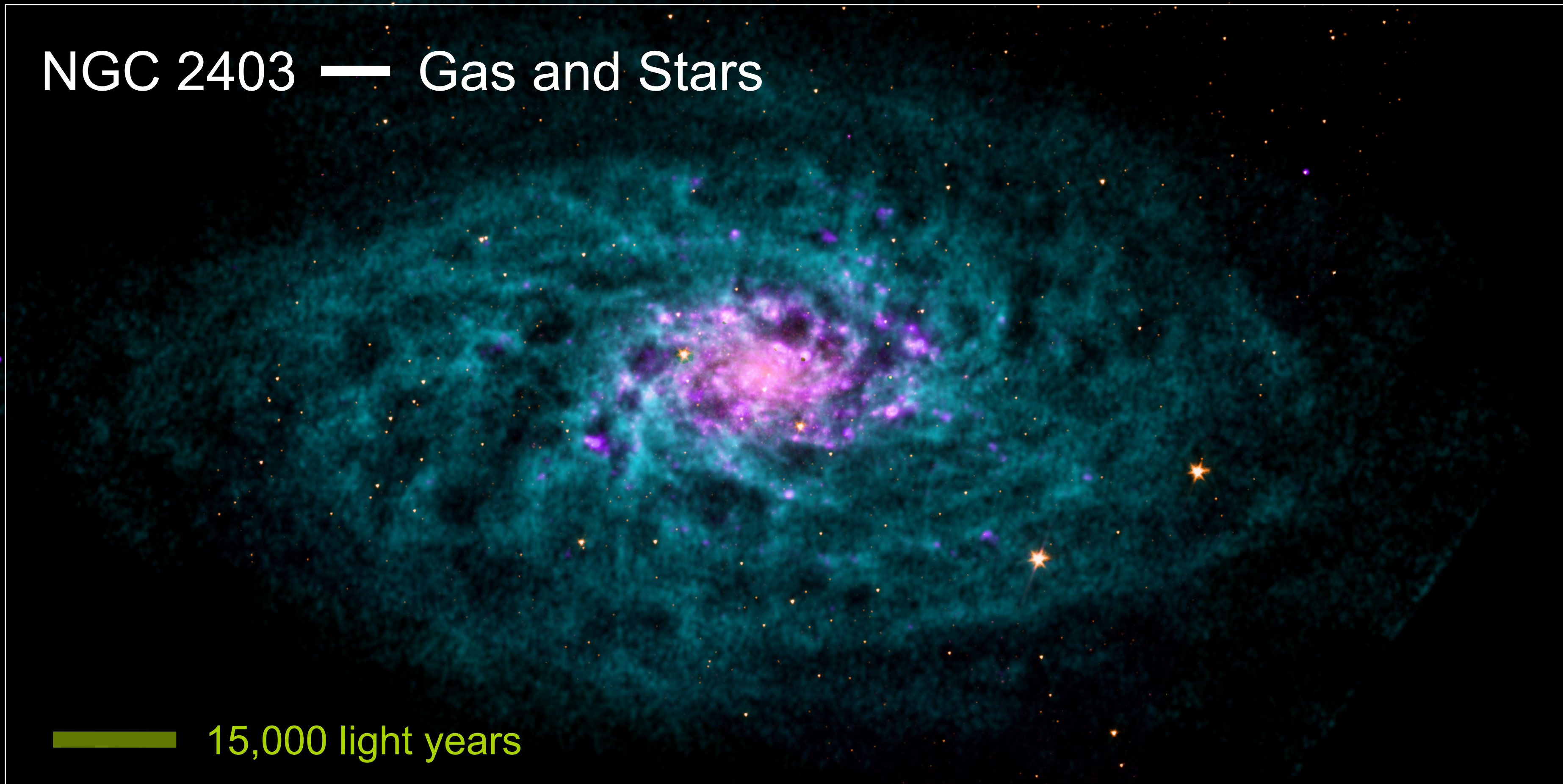
Atomic Hydrogen (HI)
(Very Large Array)

Old stars
(Spitzer)

Star Formation
(Galex & Spitzer)

Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

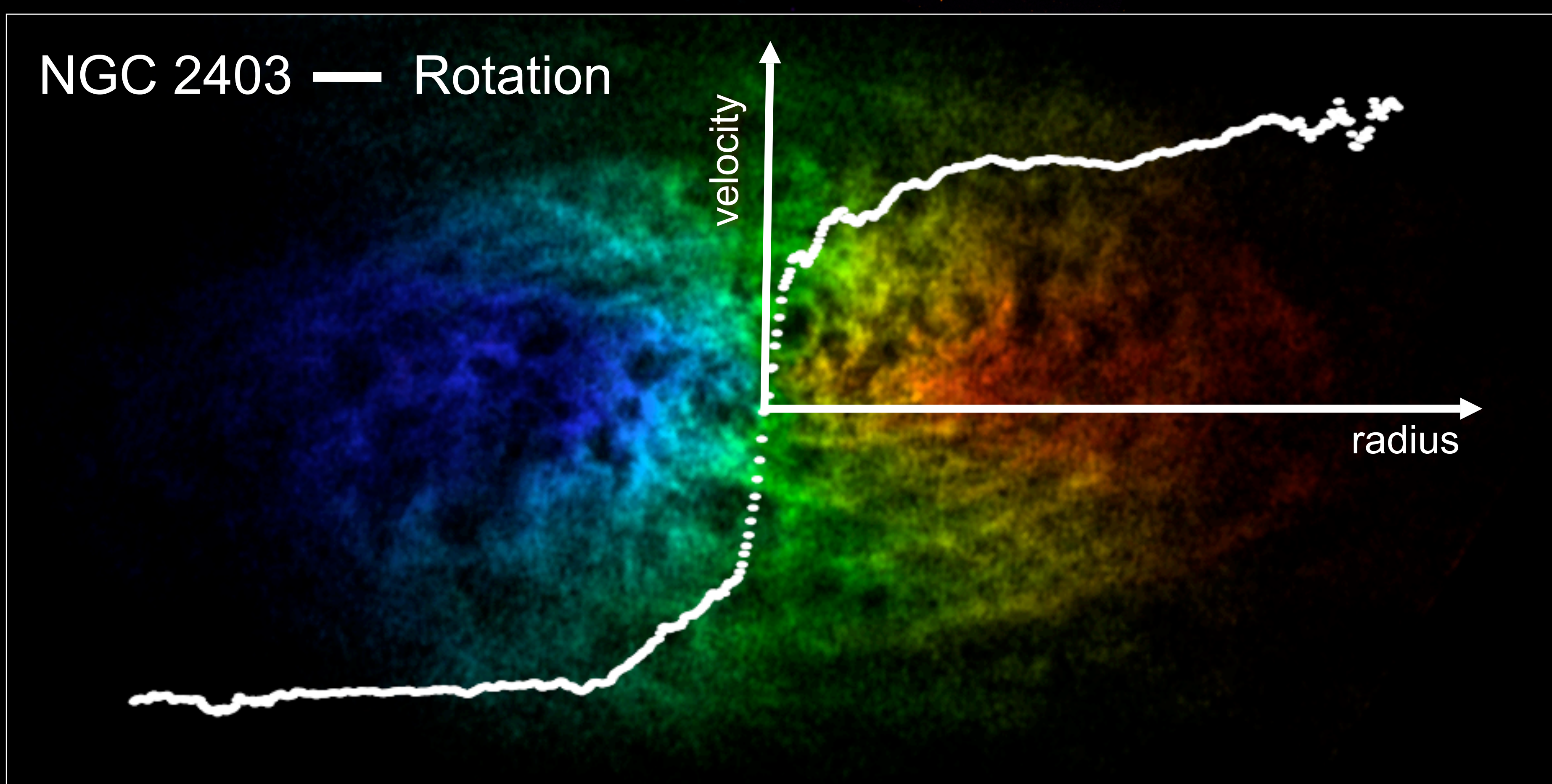
Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey



THINGS
The HI Nearby Galaxy Survey

Color Coding:

THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)



Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

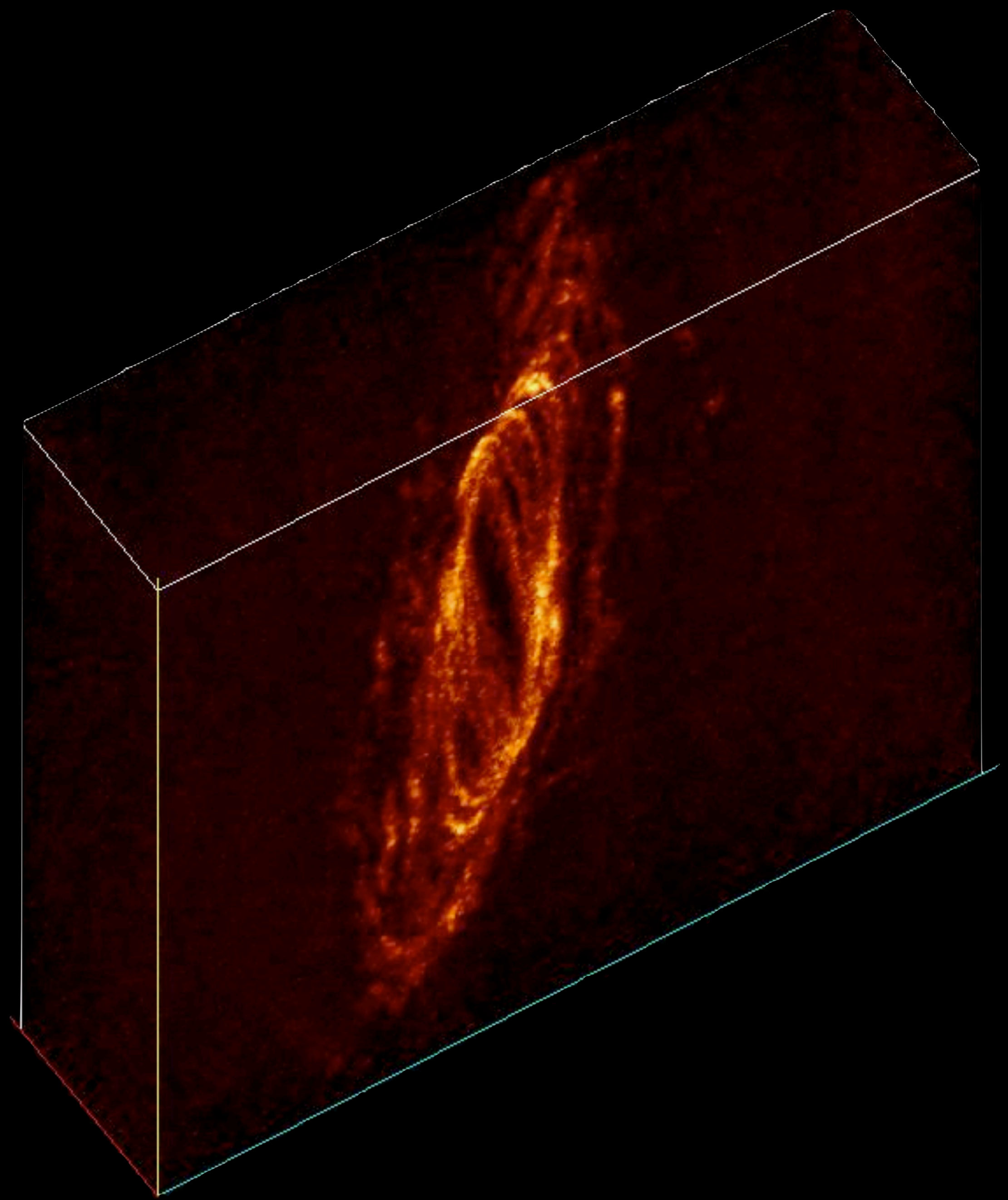
Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg

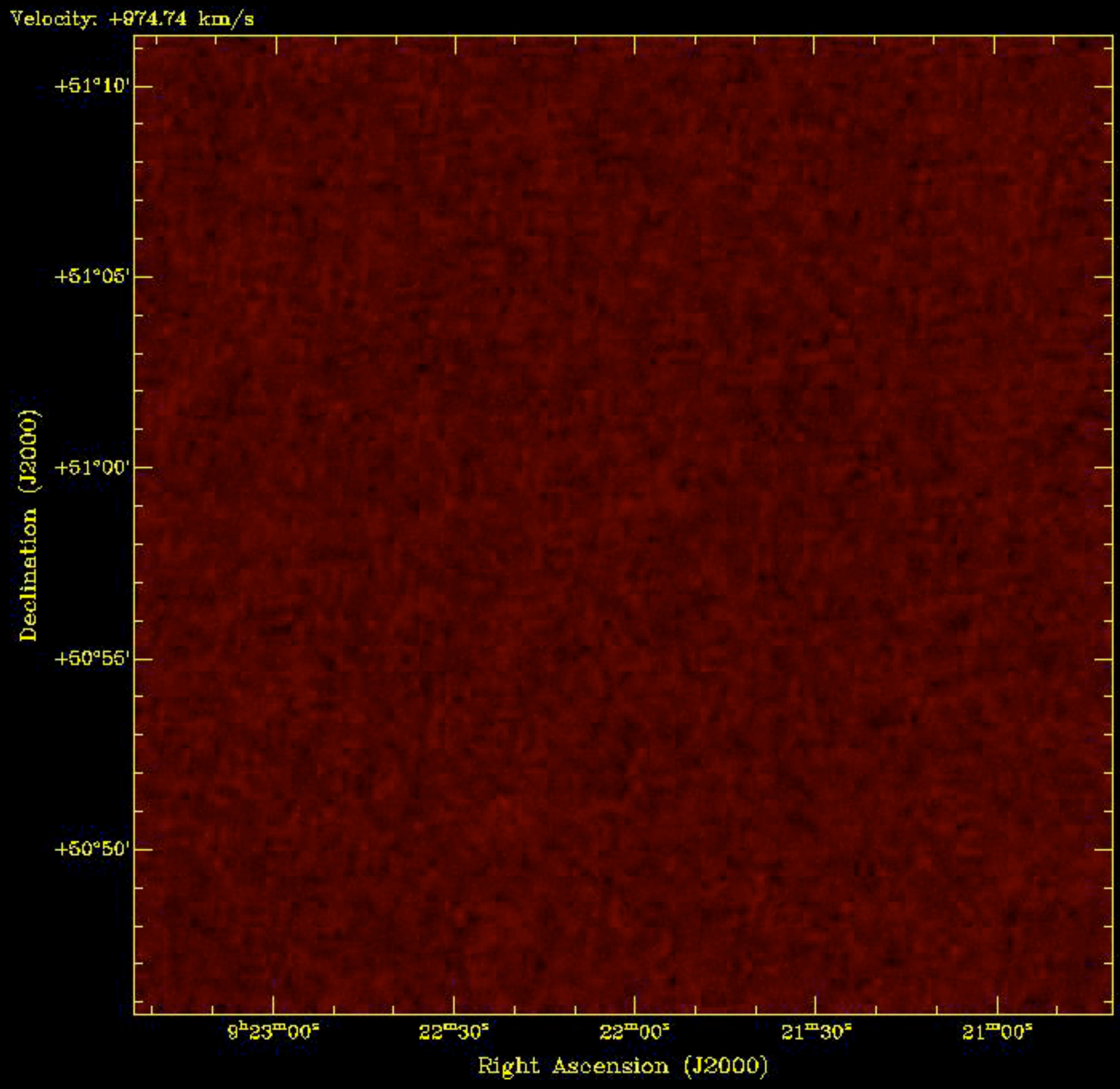
NRAO

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

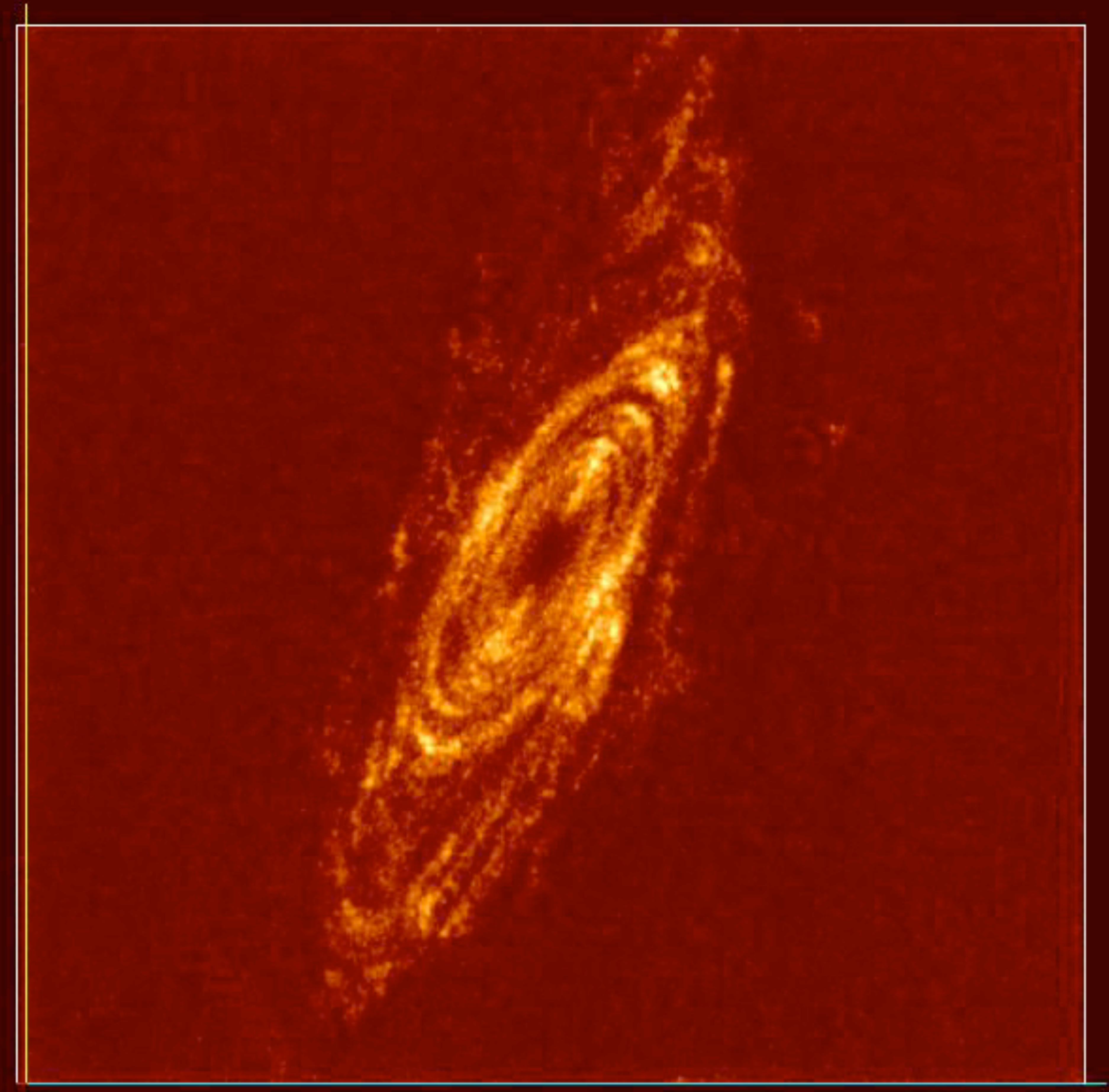
Data cubes

- HI data cube: 2 spatial axes, 1 velocity or frequency axis
- At one position signal can be present at multiple velocities
- Mission: for velocity field need to identify “typical” velocity
- Illustration: NGC 2841

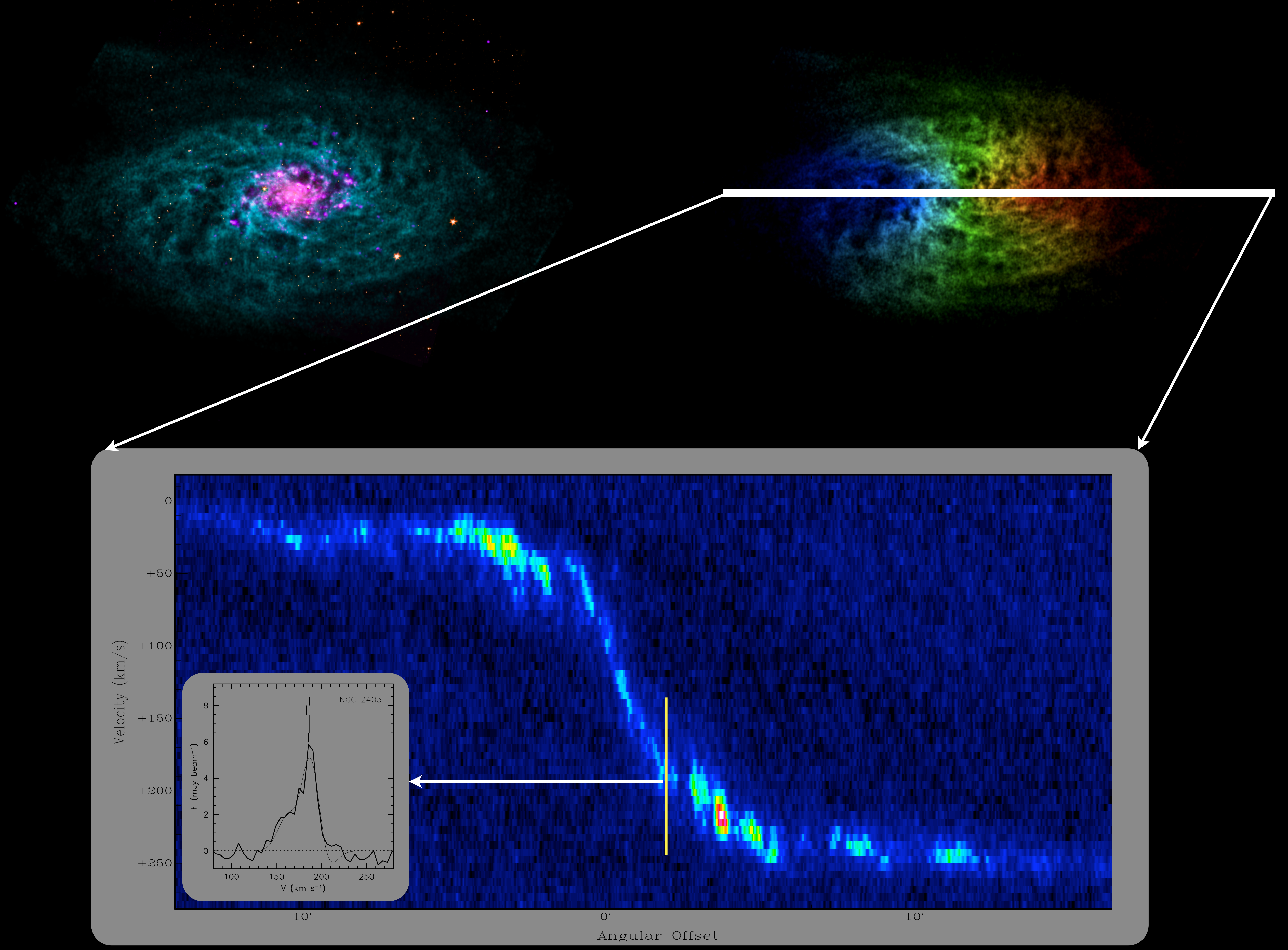




NGC 2841 THINGS
natural weighted data cube

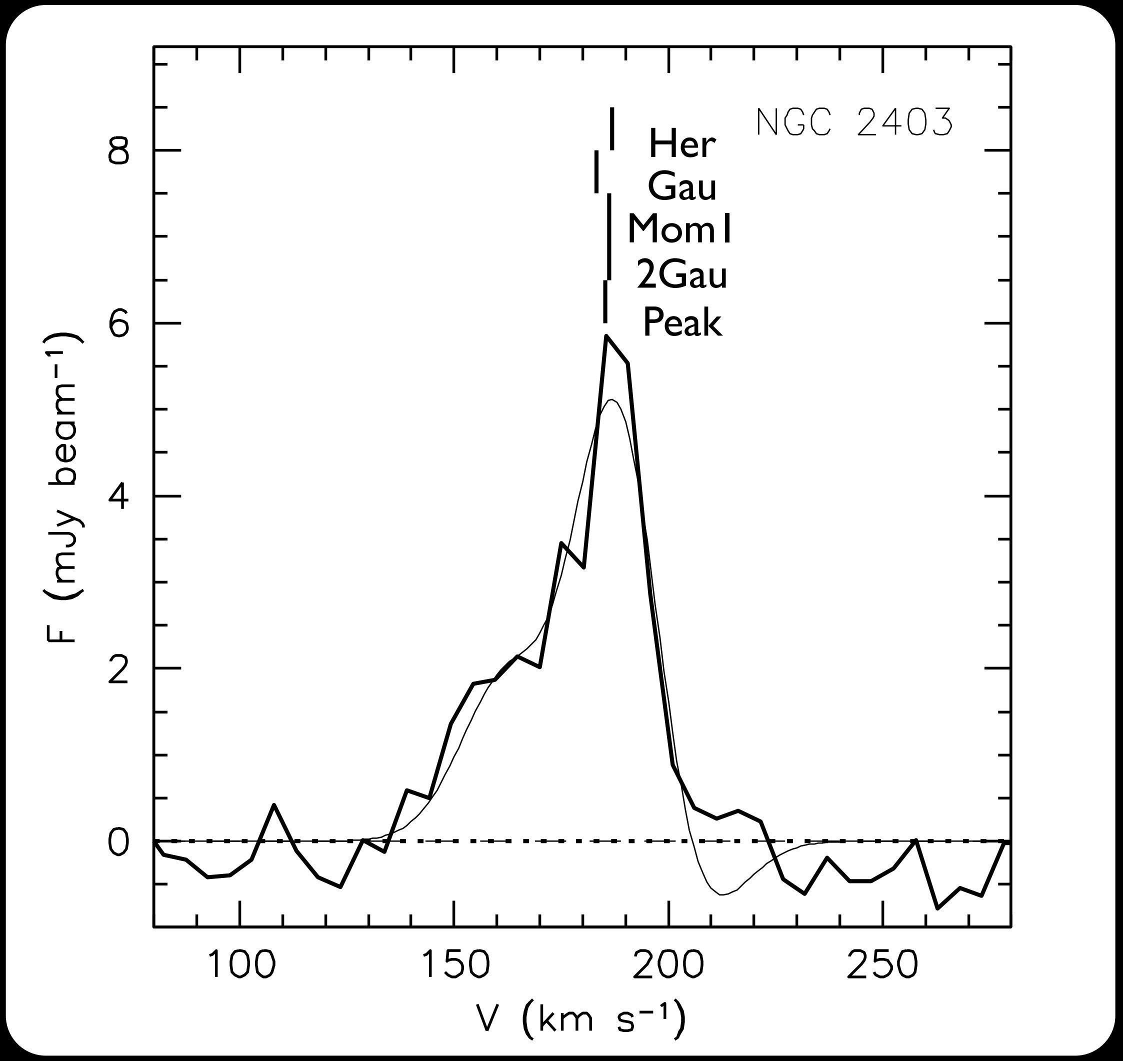


major axis position velocity diagram of NGC 2403



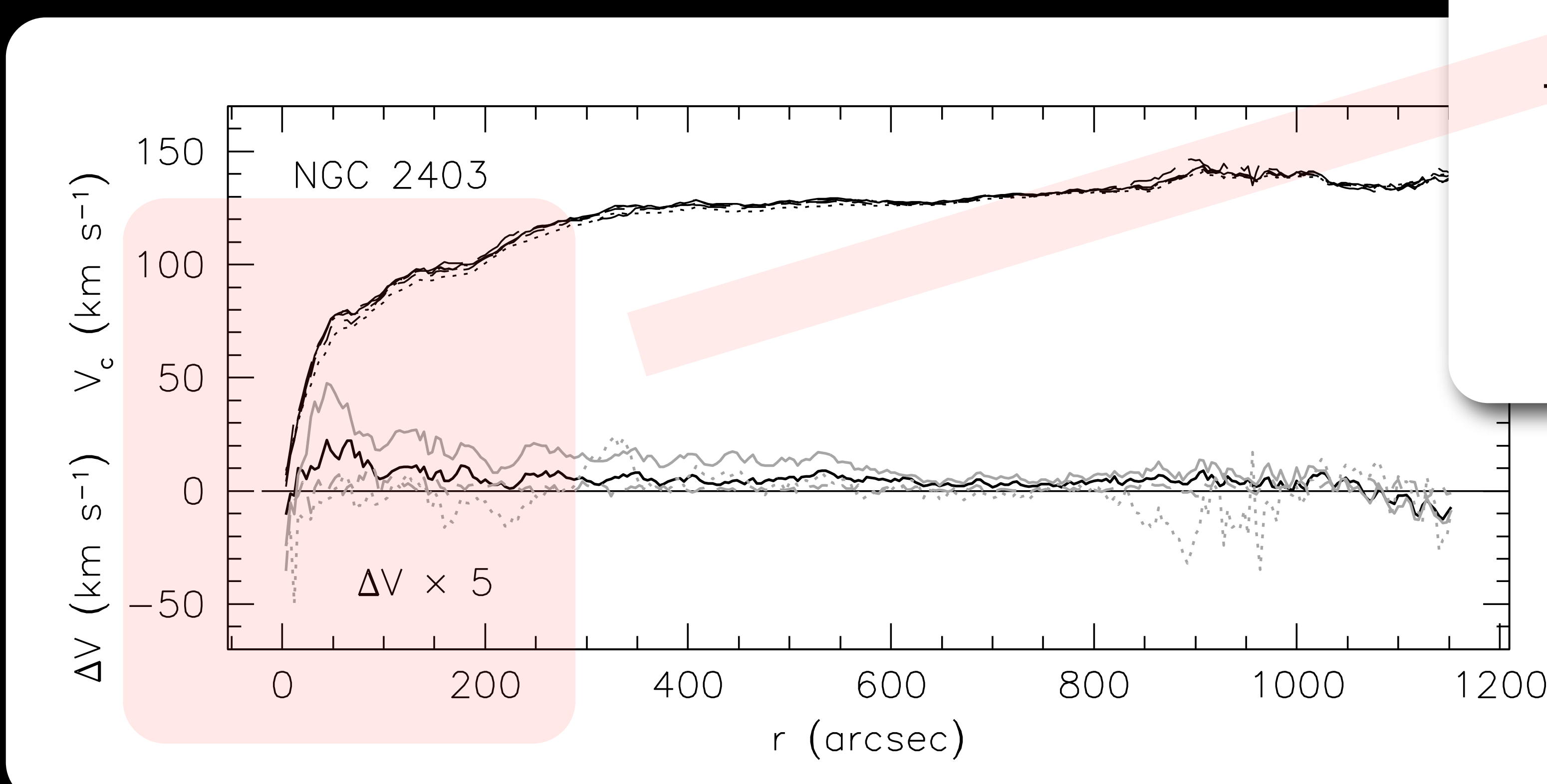
From 3D to 2D

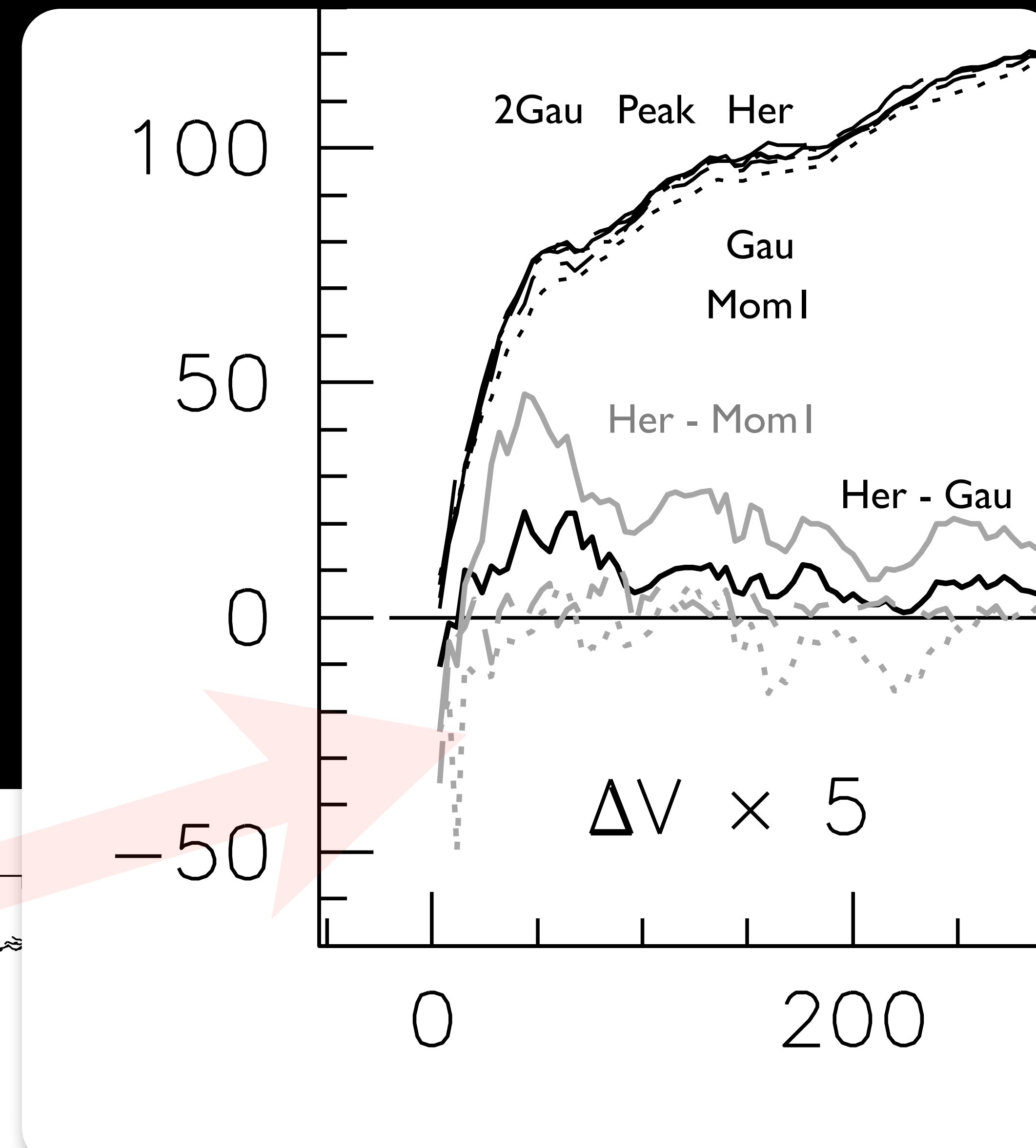
- Not all profiles symmetrical
- Need to define a “typical” velocity
- Choice has impact on velocity field
- Consider:
  - first-moment
  - single gaussian
  - double gaussian
  - peak velocity
  - third-order hermite polynomial



From 3D to 2D

- Rotation curves using different velocity fields
- First moment and Gaussian underestimate velocity
- Hermite, Double Gaussian, Peak velocity agree
- Hermite most stable





THINGS Rotation Curves

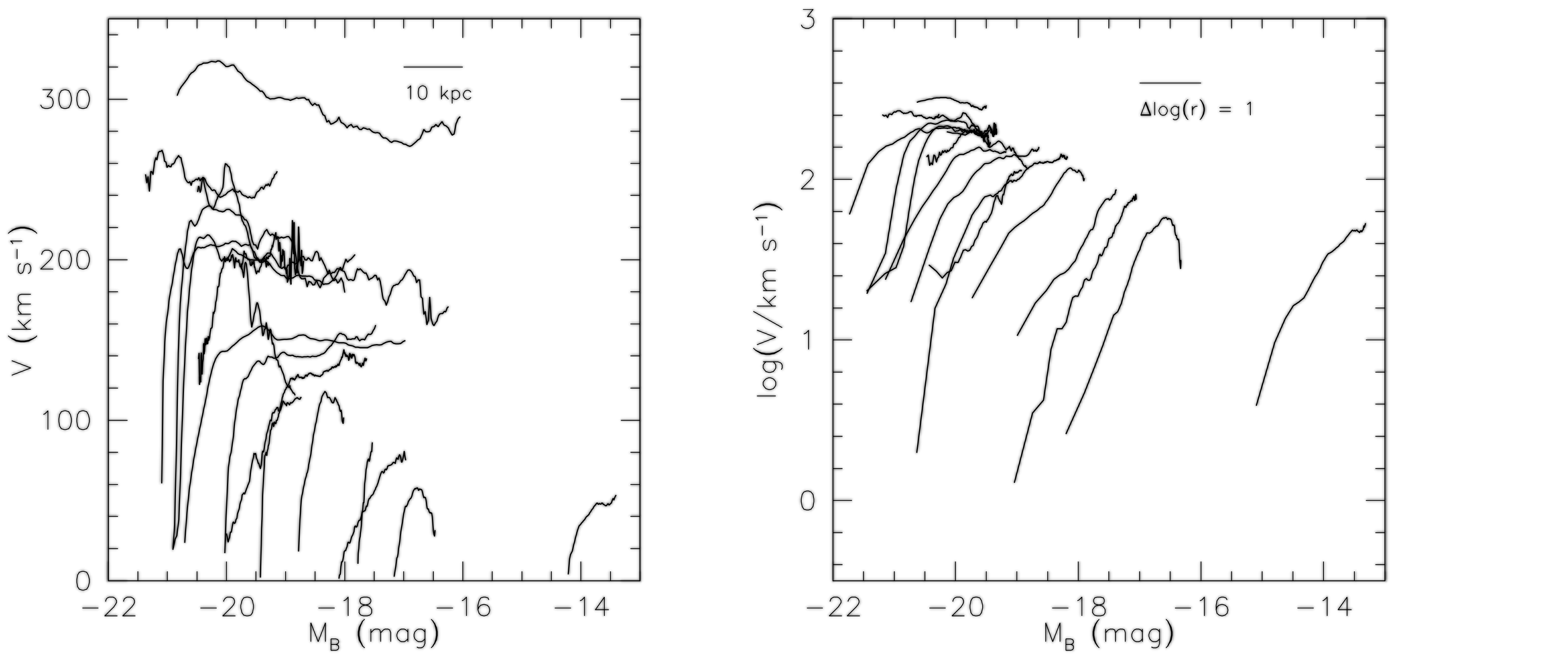


Fig. 57.— All THINGS rotation curves plotted in linear units in the left panel and in logarithmic units in the right panel. The origin of the rotation curves has been shifted according to their absolute luminosity as indicated on the horizontal axis. The bar in the respective panels indicates the radial scale.

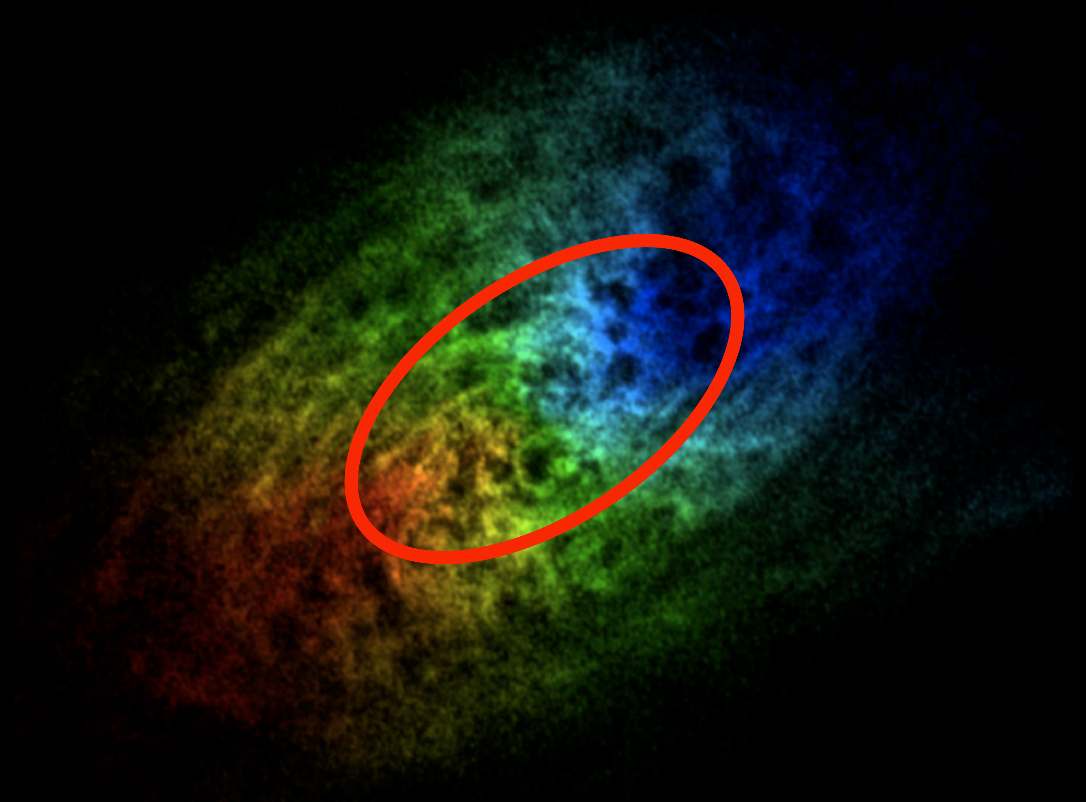
- Hermite fits were used to derive high-resolution HI rotation curves of 19 THINGS galaxies

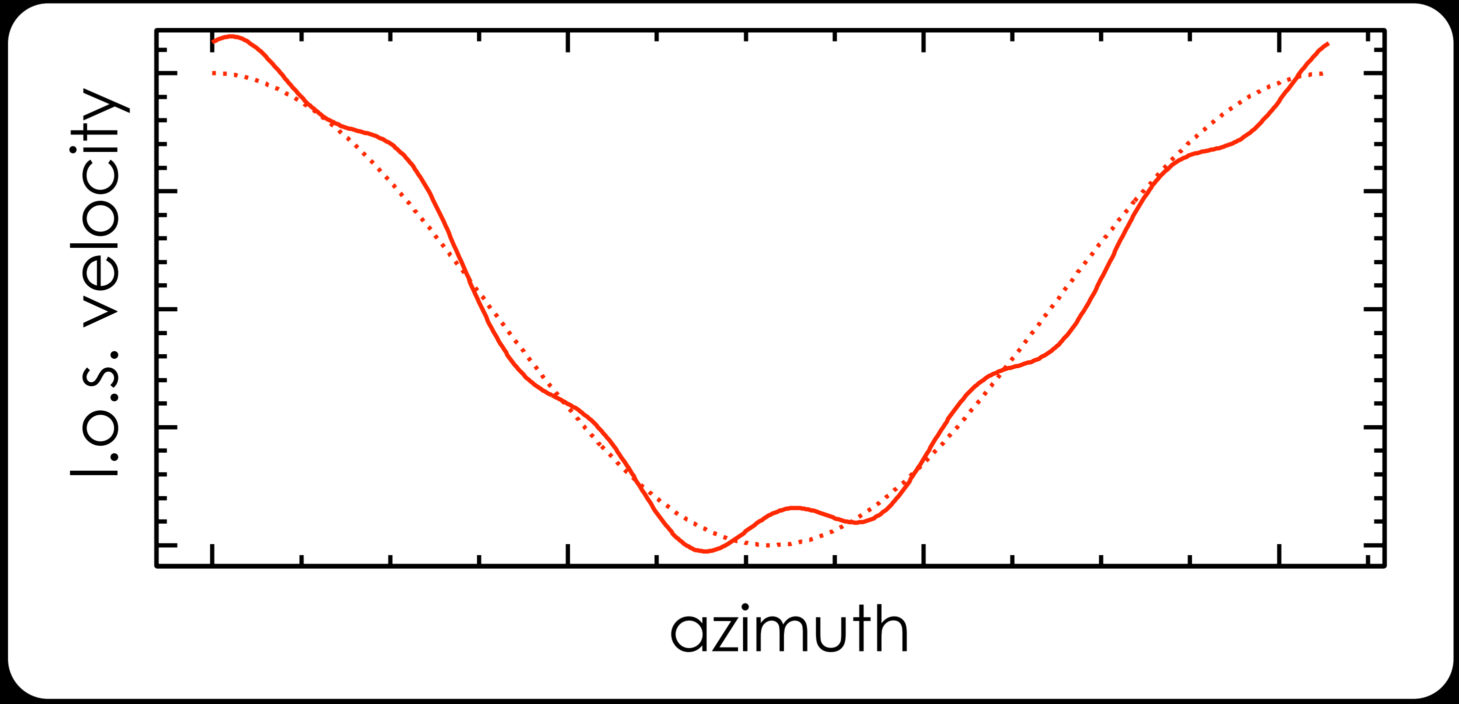
Harmonic Decomposition

A good way to test for non-circular motions is deriving **harmonic decompositions** of velocity fields

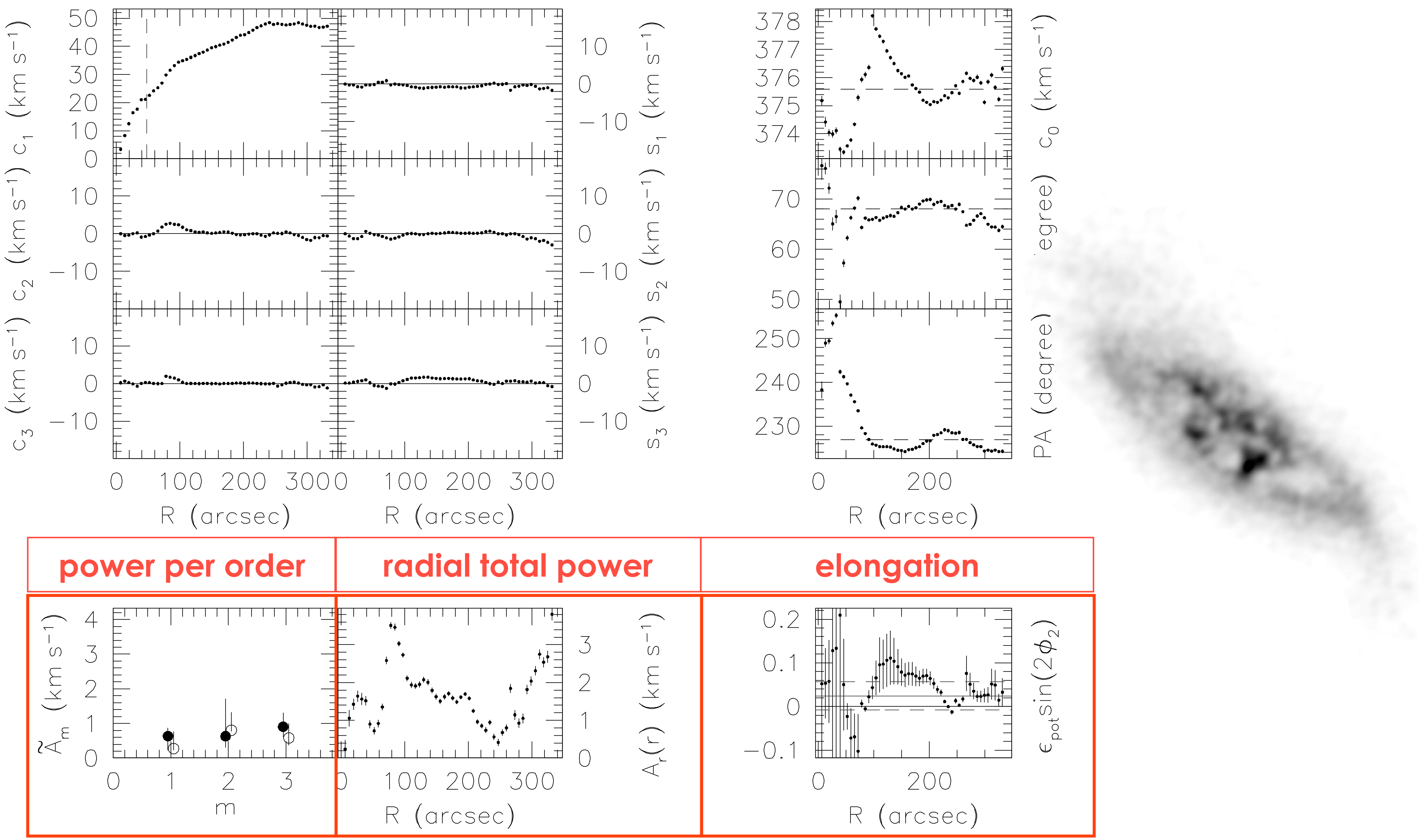
$$v_{\mathrm{los}}(r) = v_{\mathrm{sys}}(r) + \sum_{m=1}^{N} c_m(r)\cos m\psi + s_m(r)\sin m\psi$$

c_1 = circular velocity
rest = non-circular

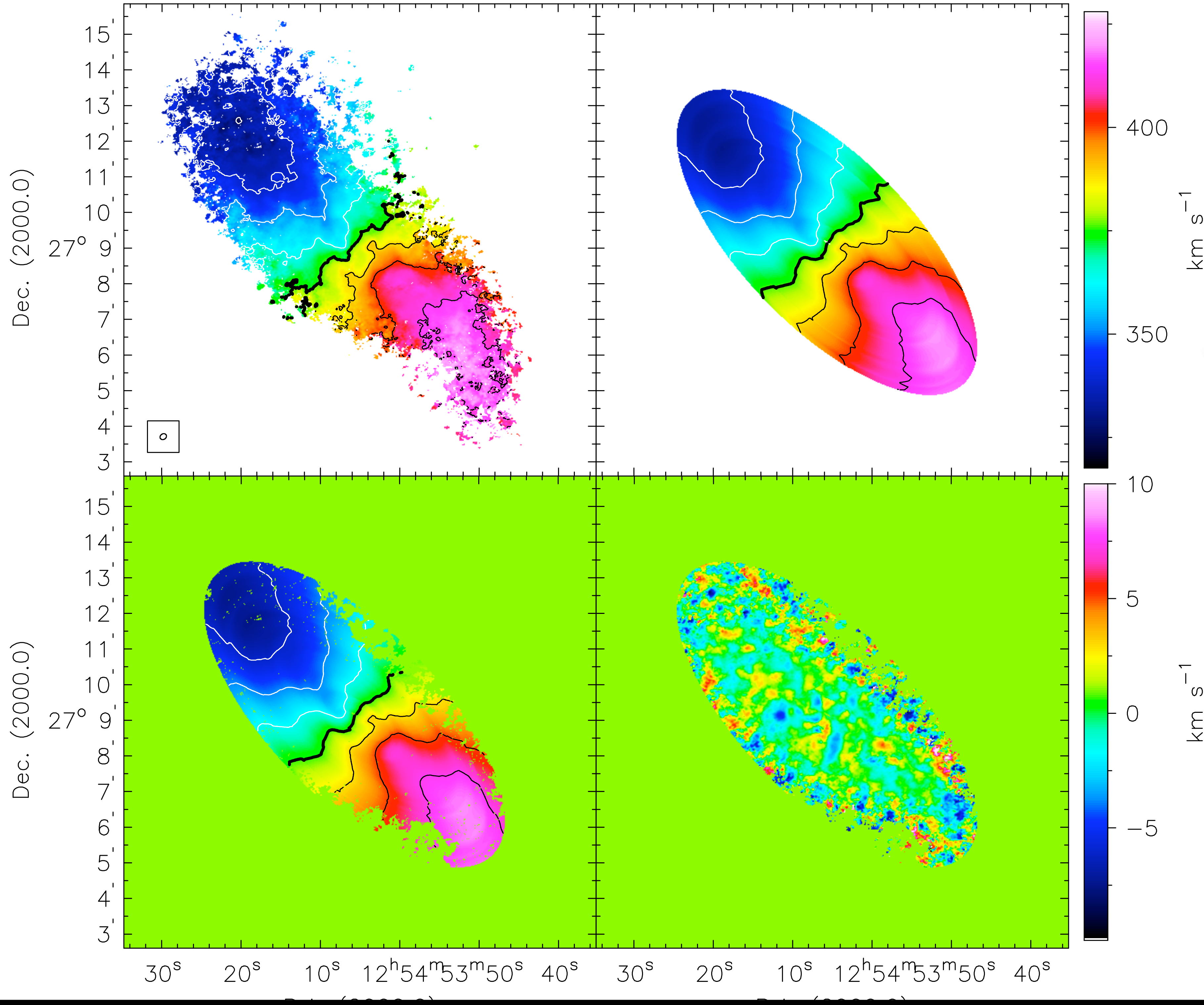


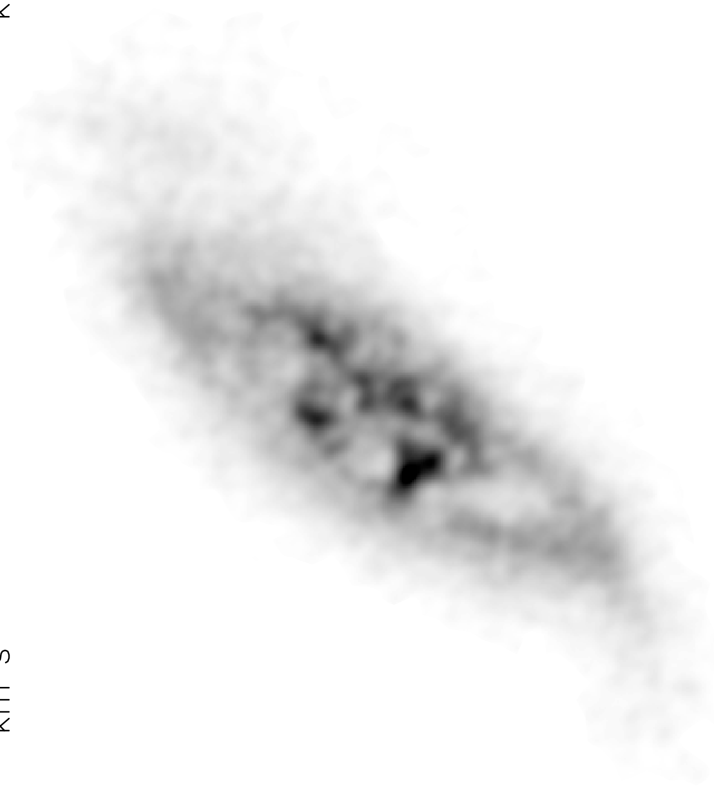


DDO 154 Harmonic Example

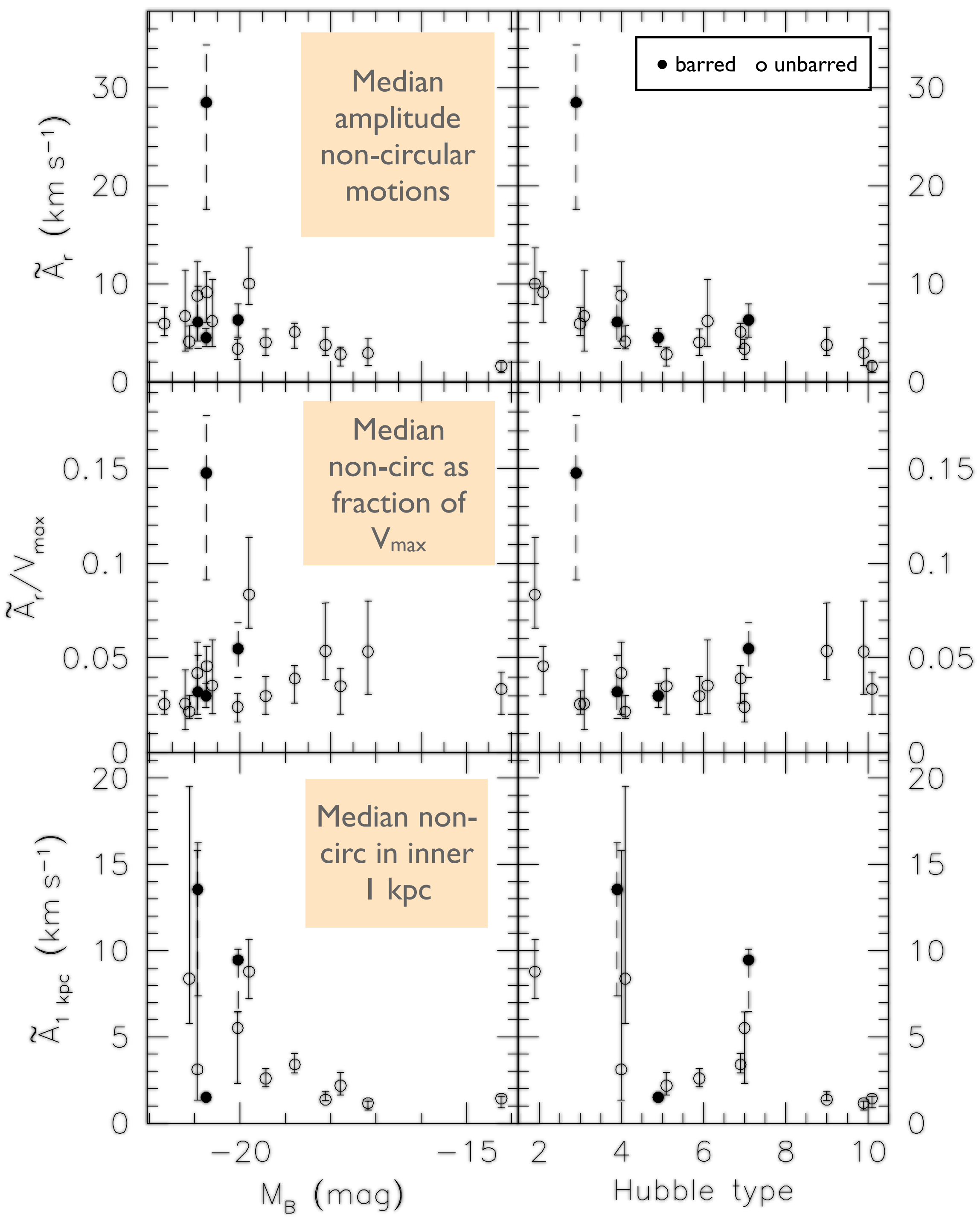


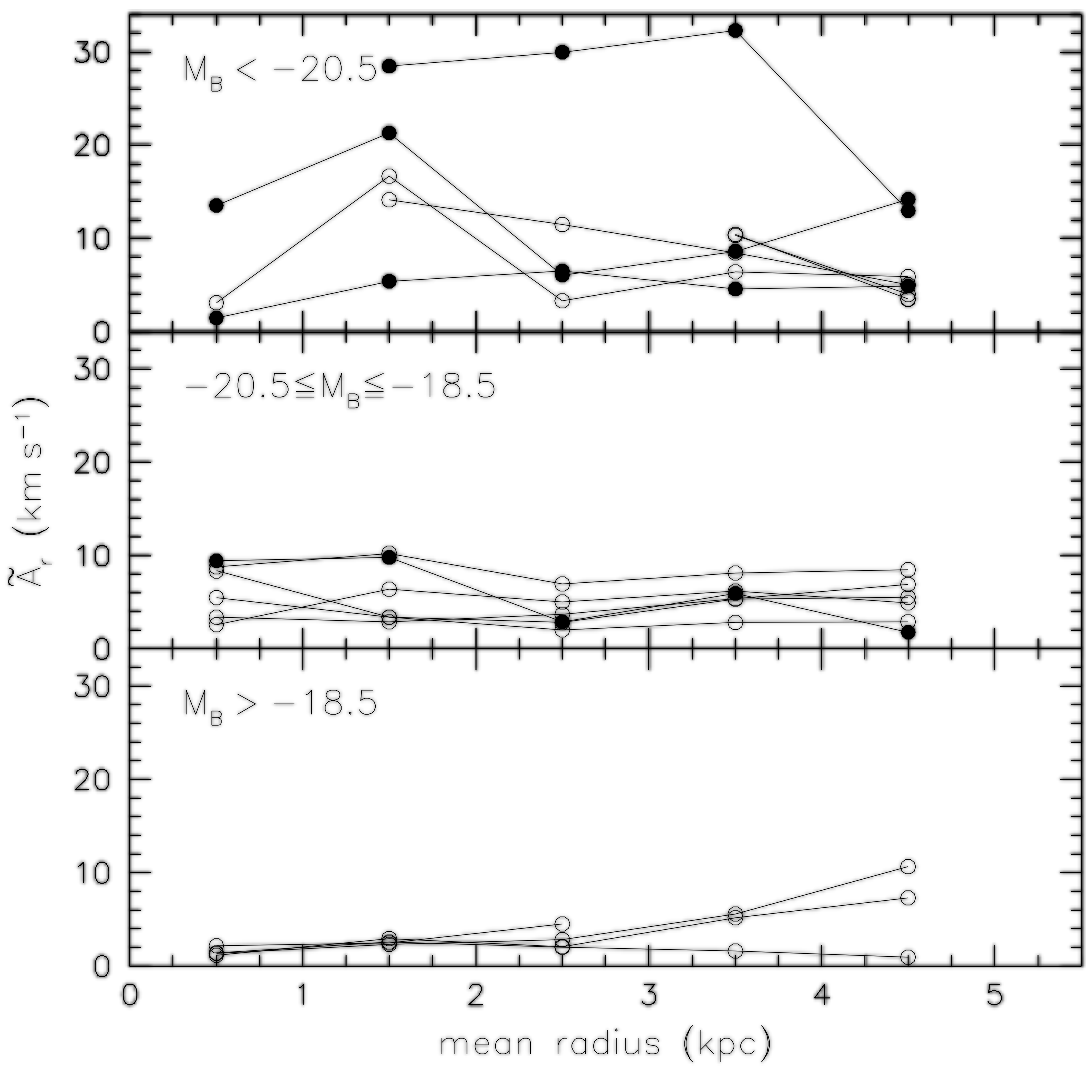
DDO 154 Harmonic Example





Non-circular motions



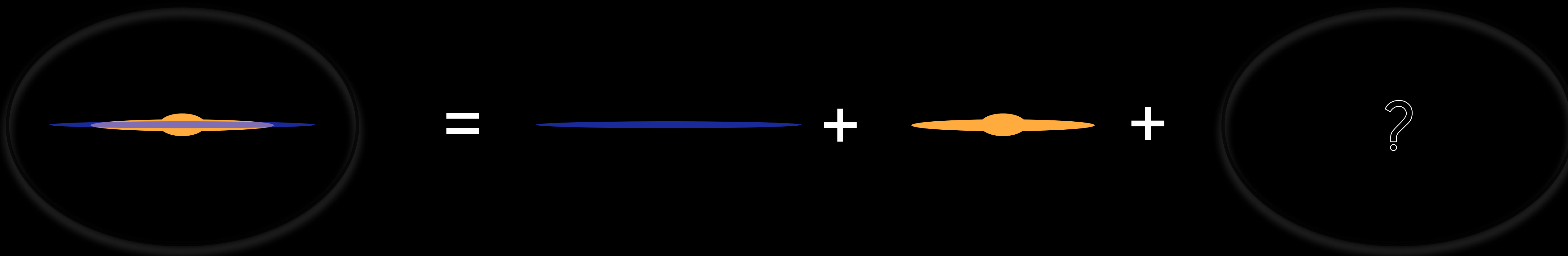


- Non-circular motions in THINGS sample decrease globally and locally with decreasing luminosity
- Are low luminosity galaxies also DM dominated throughout?

Multi-wavelength mass models

- Rotation curves apply to entire mass distribution: dark+visible matter
- Need to disentangle dark from visible matter
- Derive rotation curves of visible matter based on observed mass distributions
- Subtract visible from total matter

Mass models: stars and gas

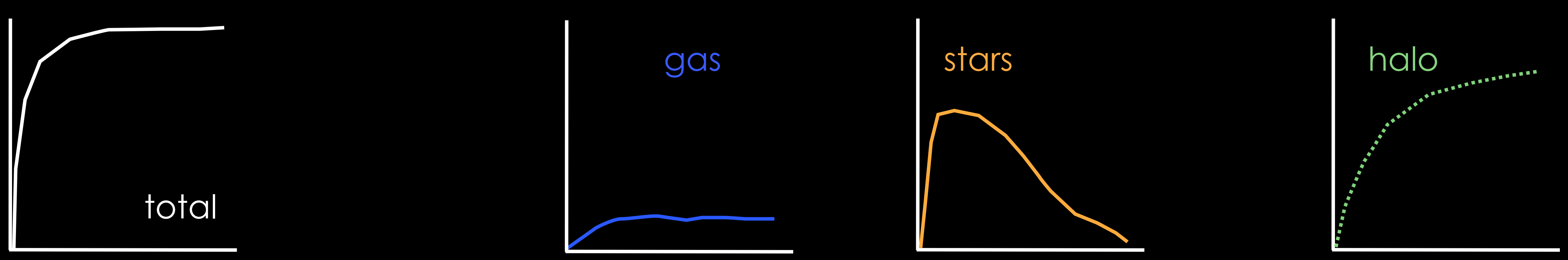


$$M_{tot} = M_{gas} + M_{disk} + M_{halo}$$

$M_{gas} \leftrightarrow V^2_{gas}$: $1.4 M_{HI}$

$M_{disk} \leftrightarrow V^2_{disk}$: Υ_*

$$V^2_{tot} = V^2_{gas} + V^2_{disk} + V^2_{halo}$$



Constraining stellar M/L in THINGS

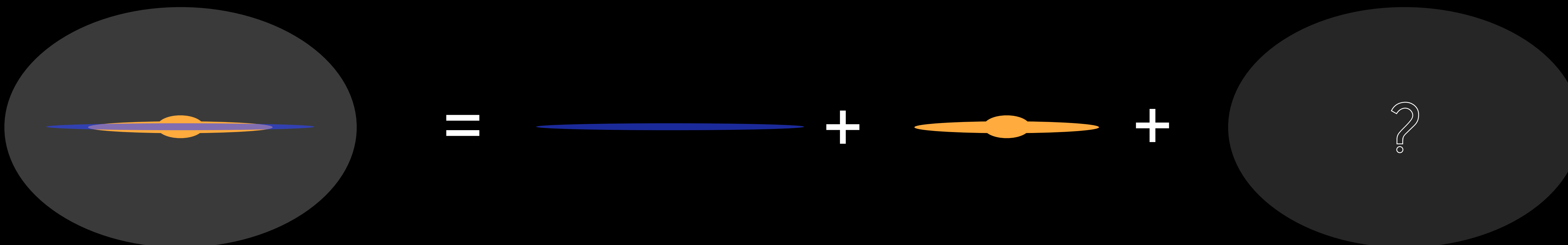
Fixed M/L*

- Recent star formation affects optical M/L strongly
- In IR only small variation (factor 2); fairly independent of SFH/metallicity
- Spitzer 3.6 μm close to K, traces (mostly) old stars (SINGS)
- Not many pop-synth models available yet:
- Use J-K colour from 2MASS LGA with Bell & de Jong (2001) models and empirical K-3.6 μm relation
- These values still depend on the assumed IMF. Consider diet-Salpeter (maximum) and Kroupa (Milky Way)

Free M/L*

- Or let the fitting programme do the work
- THINGS data has high enough spatial and velocity resolution to determine "stellar dynamical M/L"

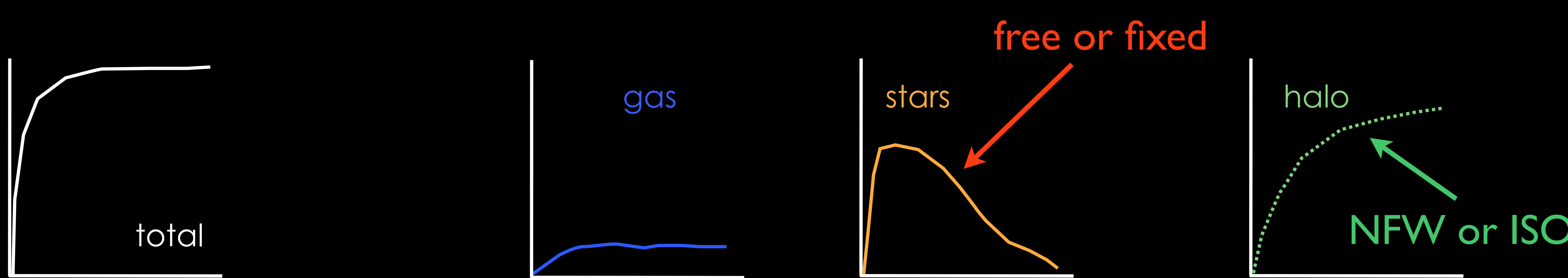
Mass models: stars and gas



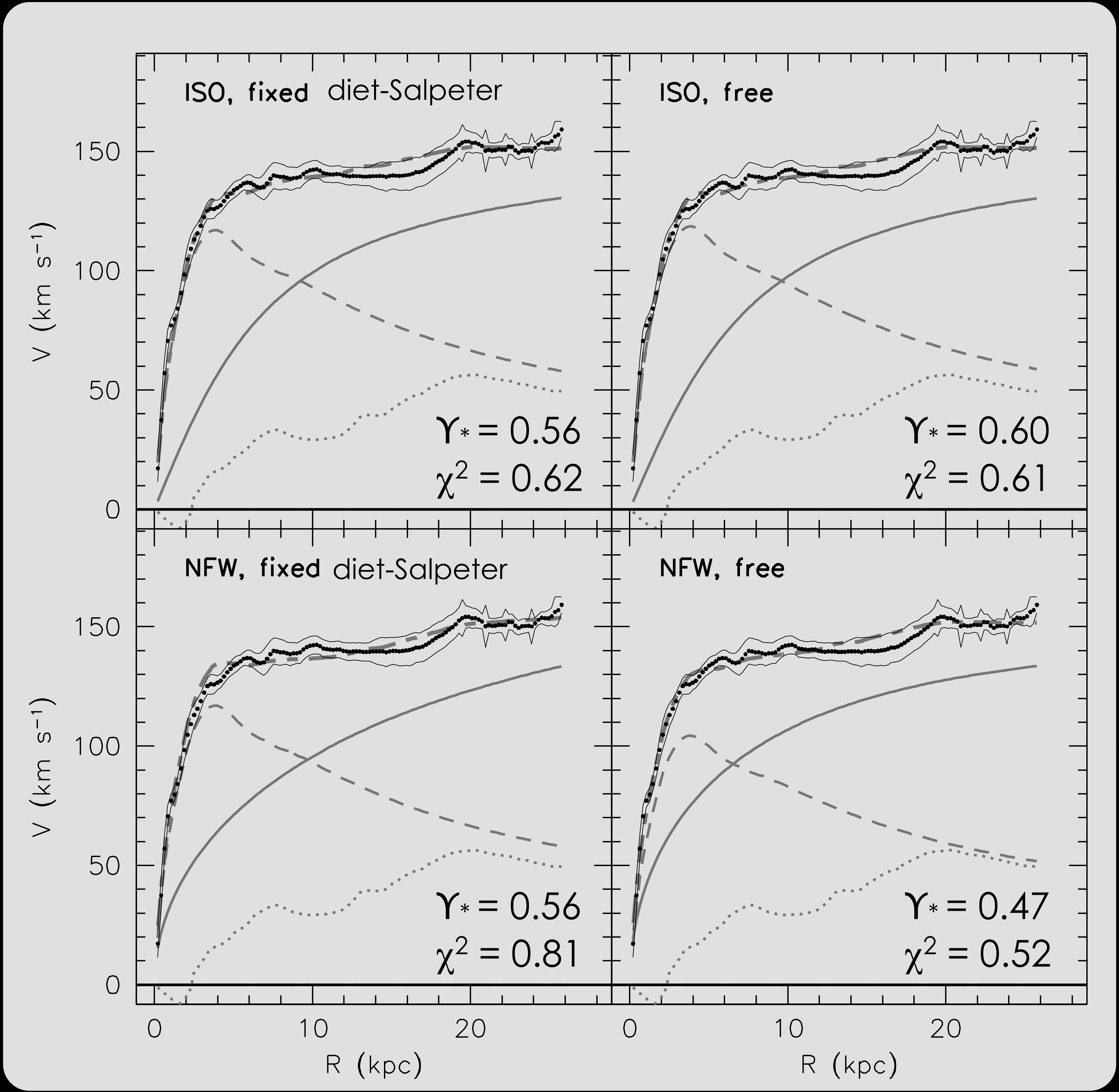
$$M_{tot} = M_{gas} + M_{disk} + M_{halo}$$

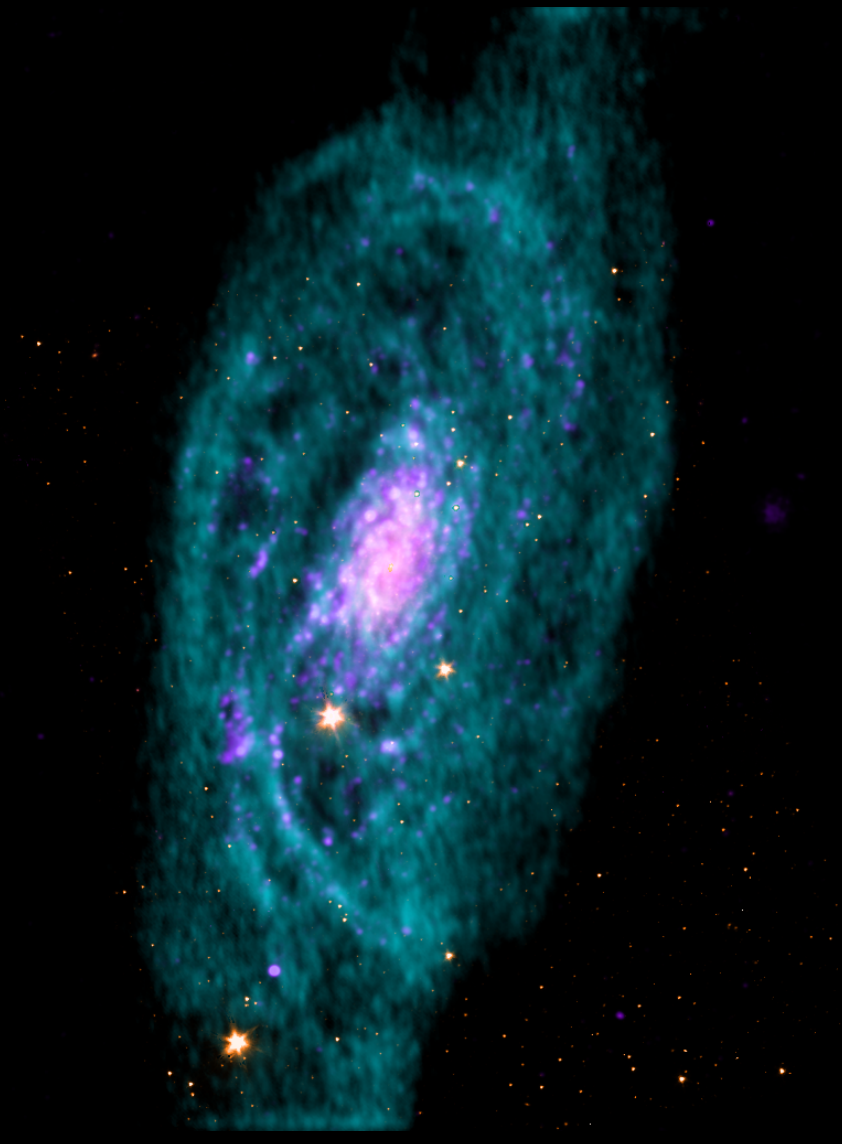
$1.4M_{HI}$ Υ_*

$$V^2_{tot} = V^2_{gas} + V^2_{disk} + V^2_{halo}$$



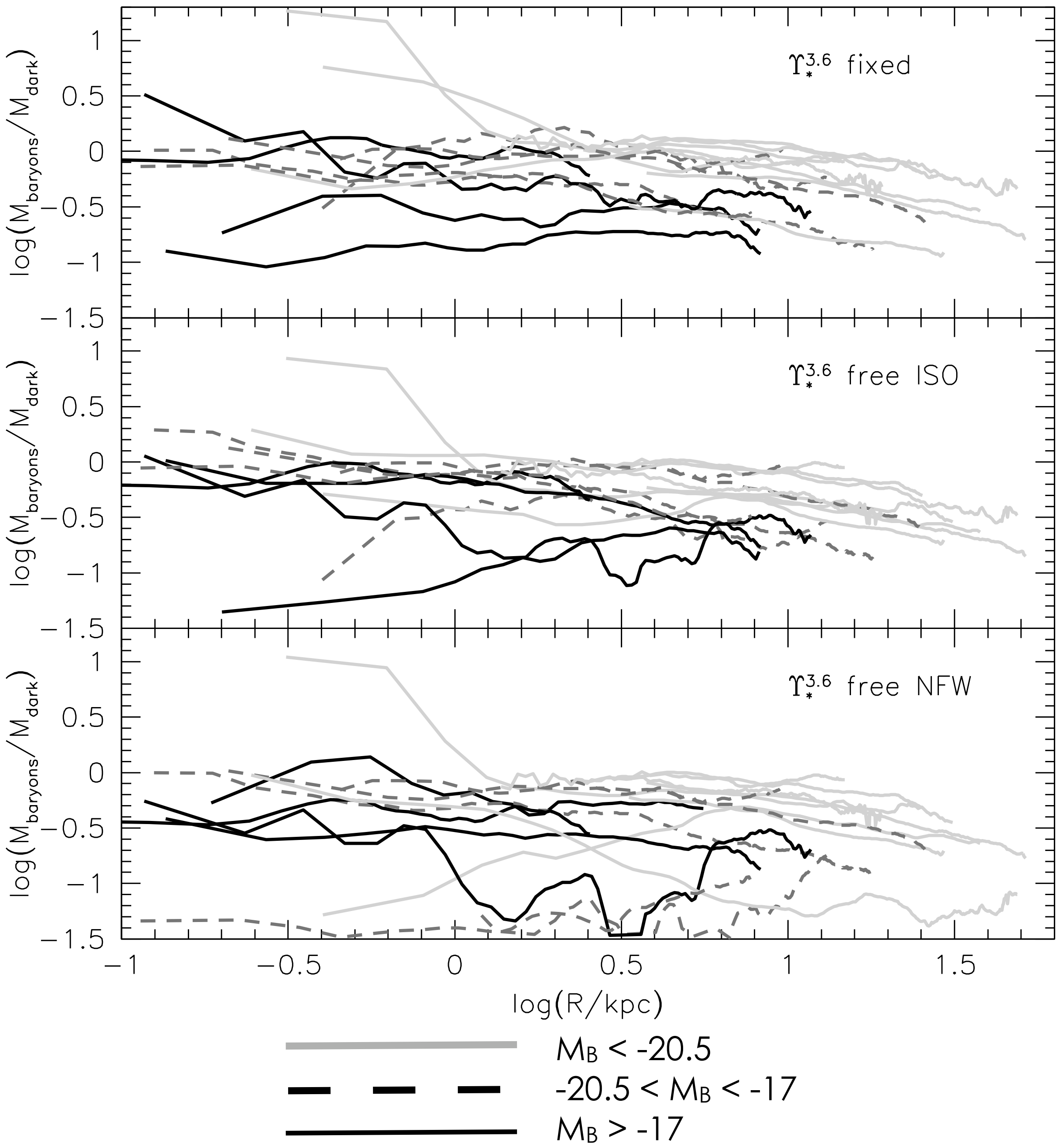
THINGS mass model: NGC 3621





For every galaxy produce models with Υ_* fixed for several IMFs as well as with Υ_* free

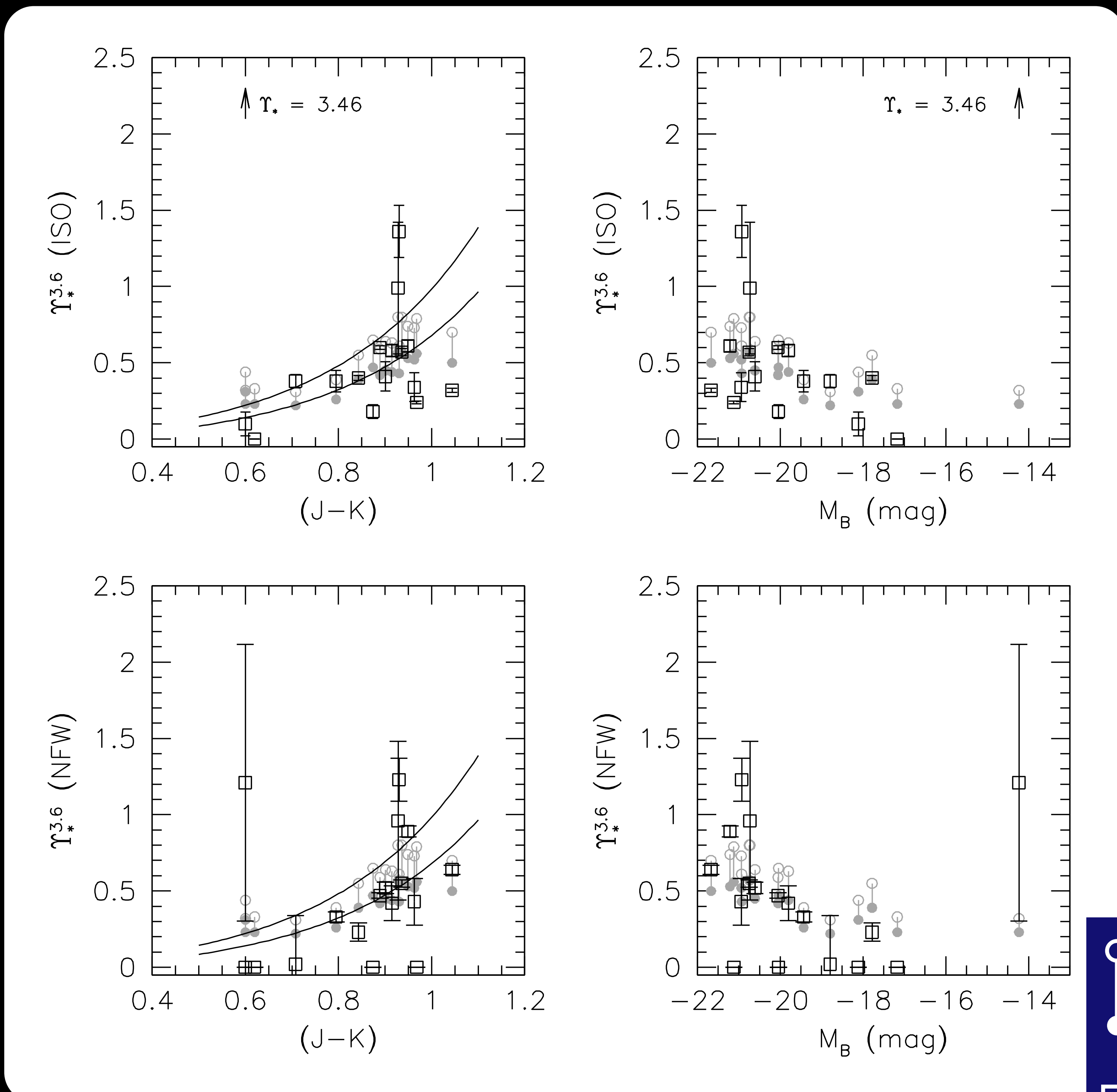
Baryons and dark matter in THINGS



$$\left(\frac{M_{\rm baryons}}{M_{\rm dark}}\right)^2 = \frac{V_{\rm gas}^2 + \Upsilon_\star V_\star^2}{V_{\rm obs}^2 - V_{\rm gas}^2 - \Upsilon_\star V_\star^2},$$

- Low luminosity galaxies are more dark matter dominated
- This is valid globally and locally
- This trend persists when fitted ϒ* values are used
- Less well-defined for NFW

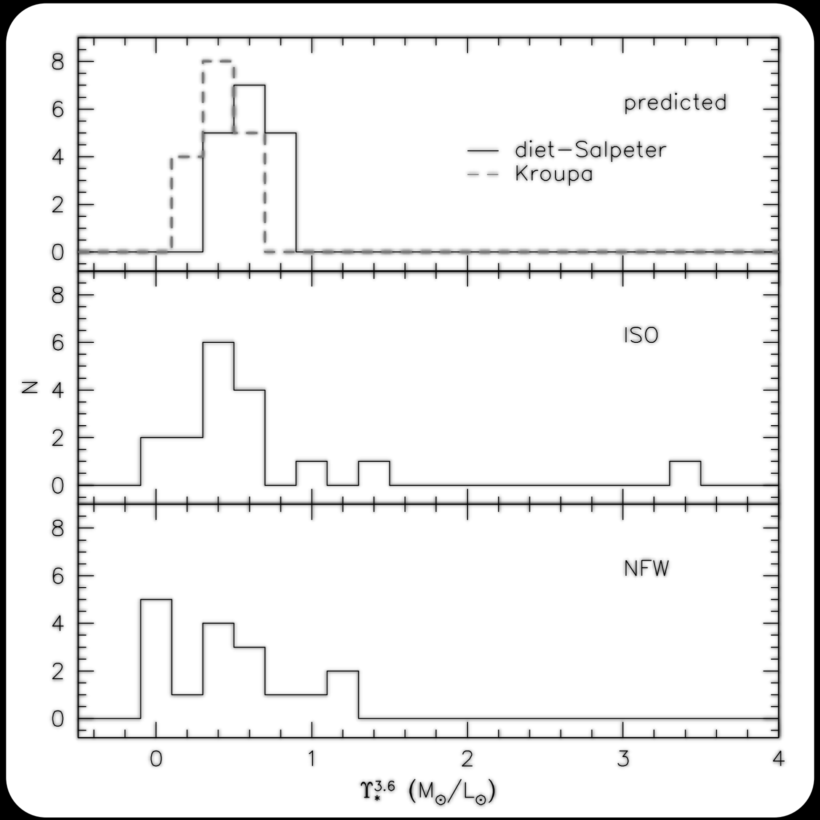
Free and Fixed M/L*

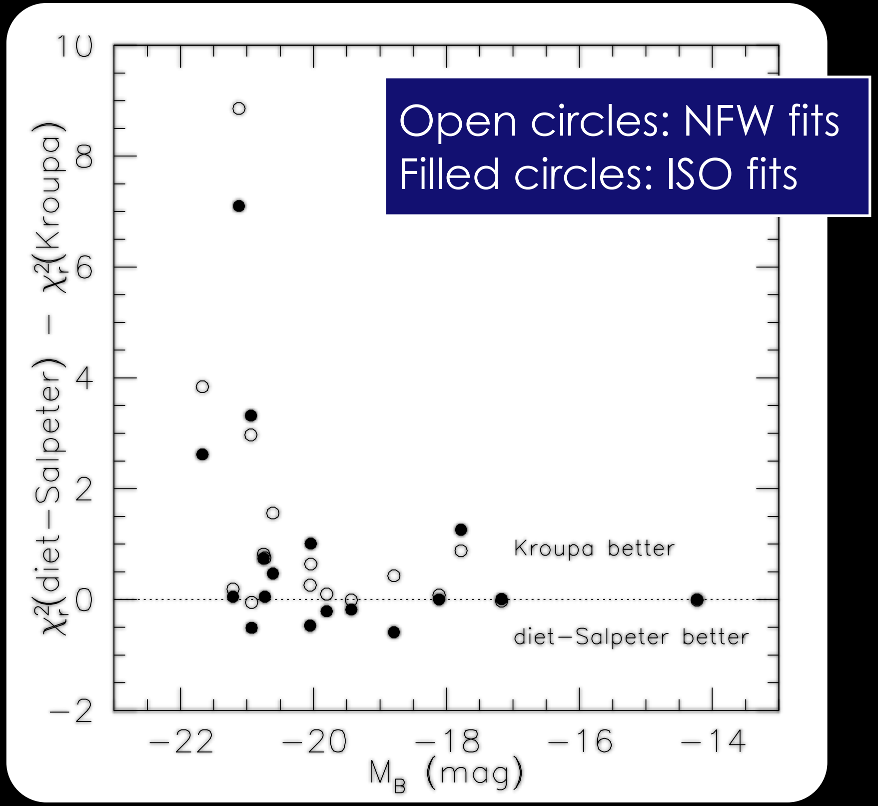


- Free and fixed M/L* decrease with luminosity
- Free M/L* tends to be lower than diet-Salpeter-IMF fixed M/L*
- Better agreement with Kroupa IMF

M/L* and IMF

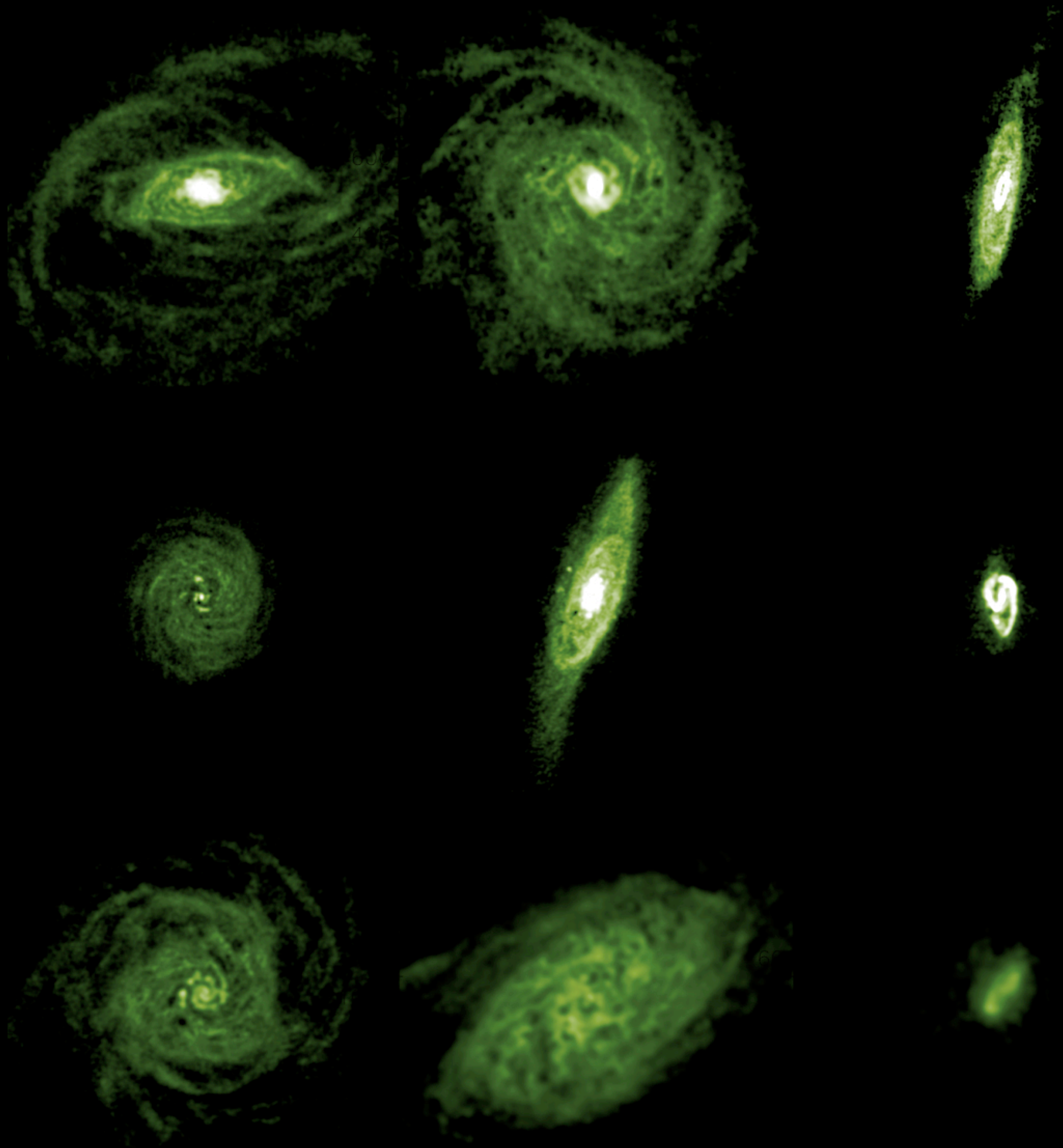
- Free M/L* slightly lower than diet-Salpeter M/L*
- Agree nicely with Kroupa M/L*
- IMF not relevant for low-luminosity galaxies
- For M~ -19 NFW prefers Kroupa, ISO prefers diet-Salpeter
- For high-luminosity galaxies bulge dynamics becomes important





Multi-λ data cubes

- HI show us the cold neutral gas in galaxies
- Coldest (molecular) gas not visible
- Use CO (tracing H_2) to detect this component
- Leroy et al: observe 19 THINGS galaxies in CO(2-1)
- Use HERA array at IRAM 30m
- Beam 11" and velocity resolution 2.6 km/s (=THINGS)



Combined HI and CO for 9 THINGS galaxies (courtesy A. Leroy)

Multi-λ data cubes

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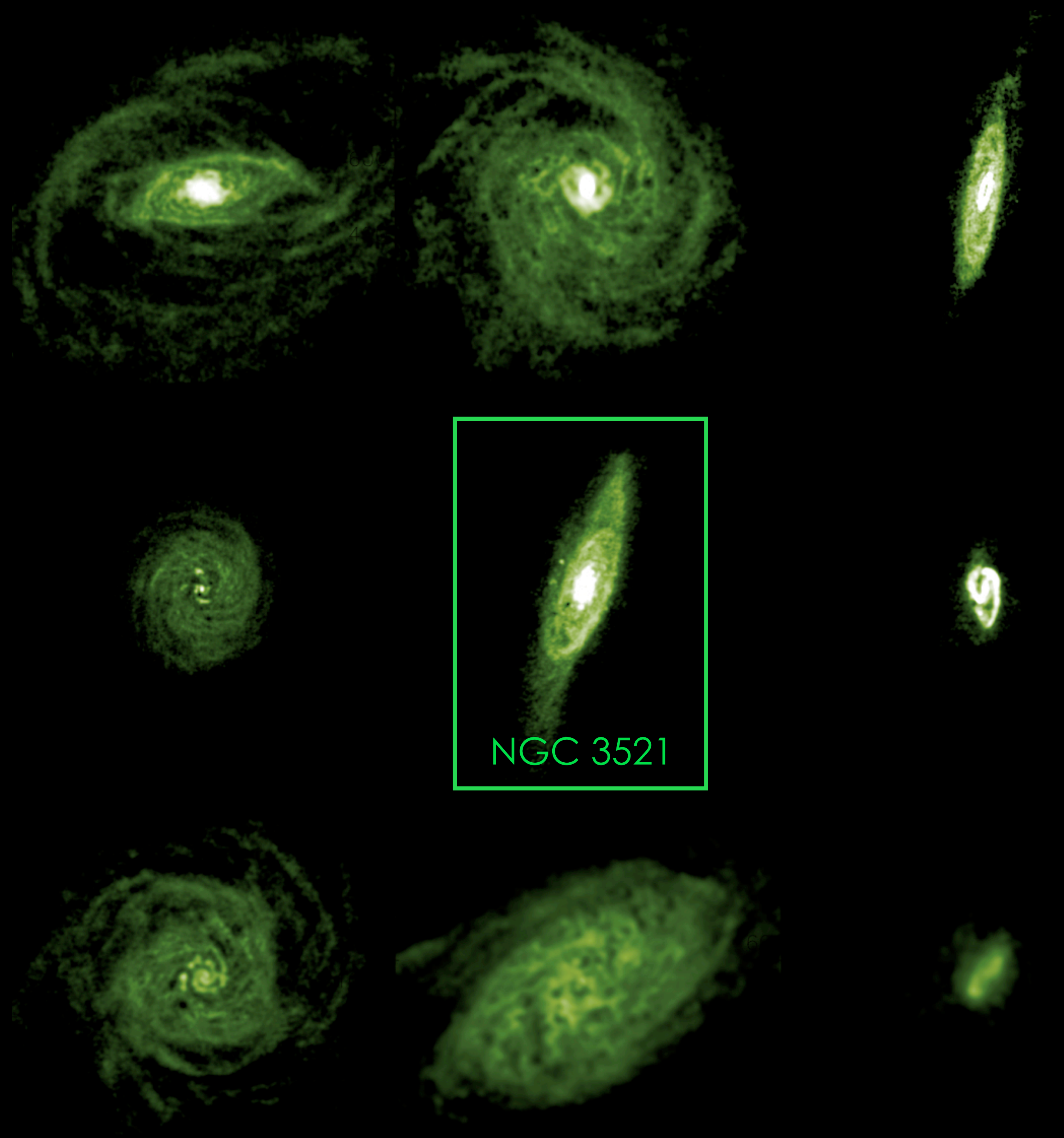


Combined HI and CO for 9 THINGS galaxies (courtesy A. Leroy)

An (atypical) THINGS example

- Compare HI and CO for NGC 3521
- Early-type Sab with prominent LINER
- Morphology suggests possible past interaction?
- Strong CO component

Hogg et SDSS 2007

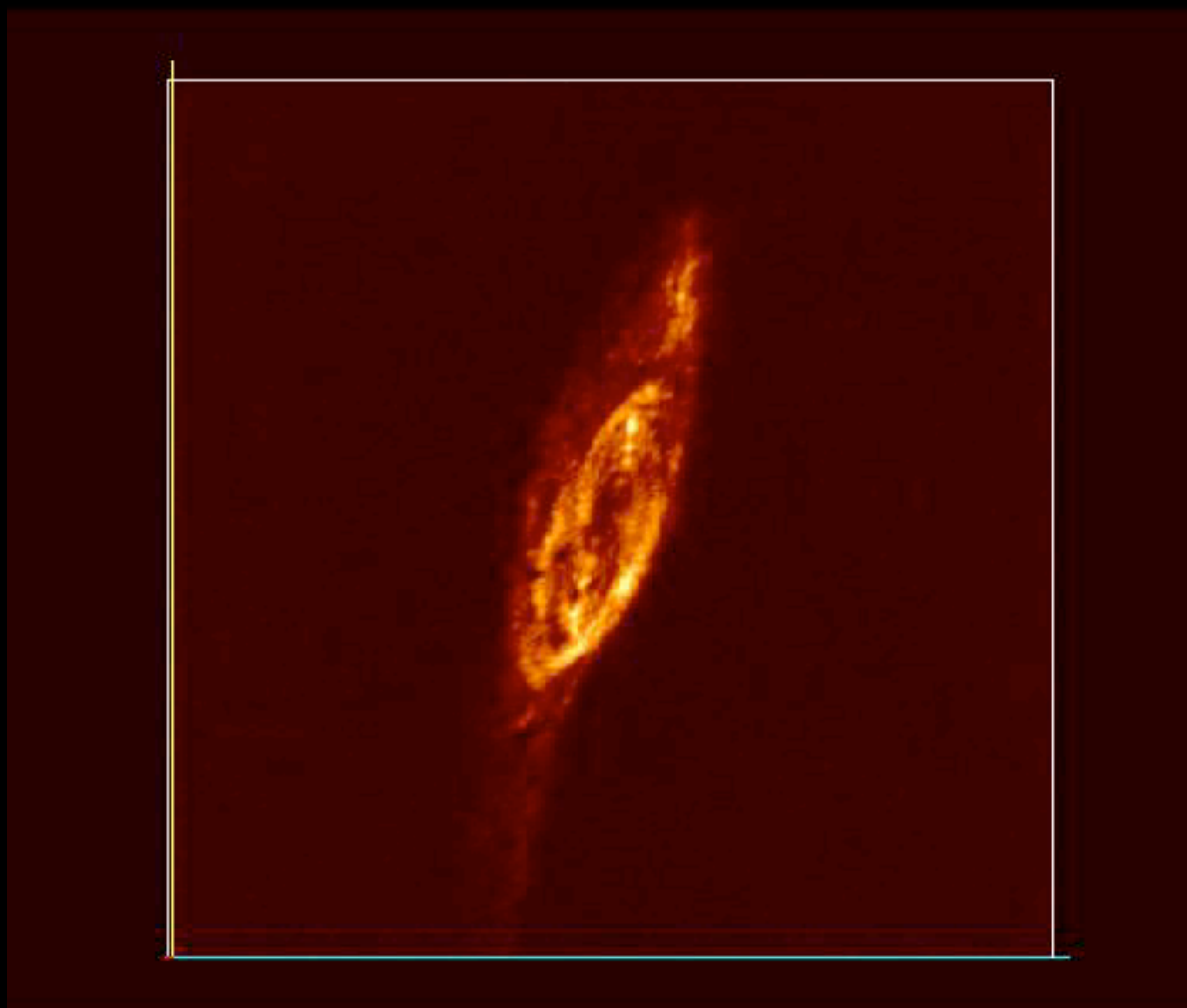
An (atypical) THINGS example

- Compare HI and CO for NGC 3521
- Early-type Sab with prominent LINER
- Morphology suggests possible past interaction?
- Strong CO component

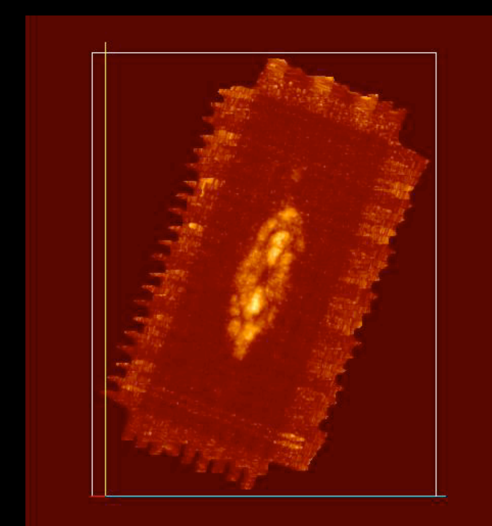
Hogg et SDSS 2007

NGC 3521 side-by-side

cubes at identical spatial scale

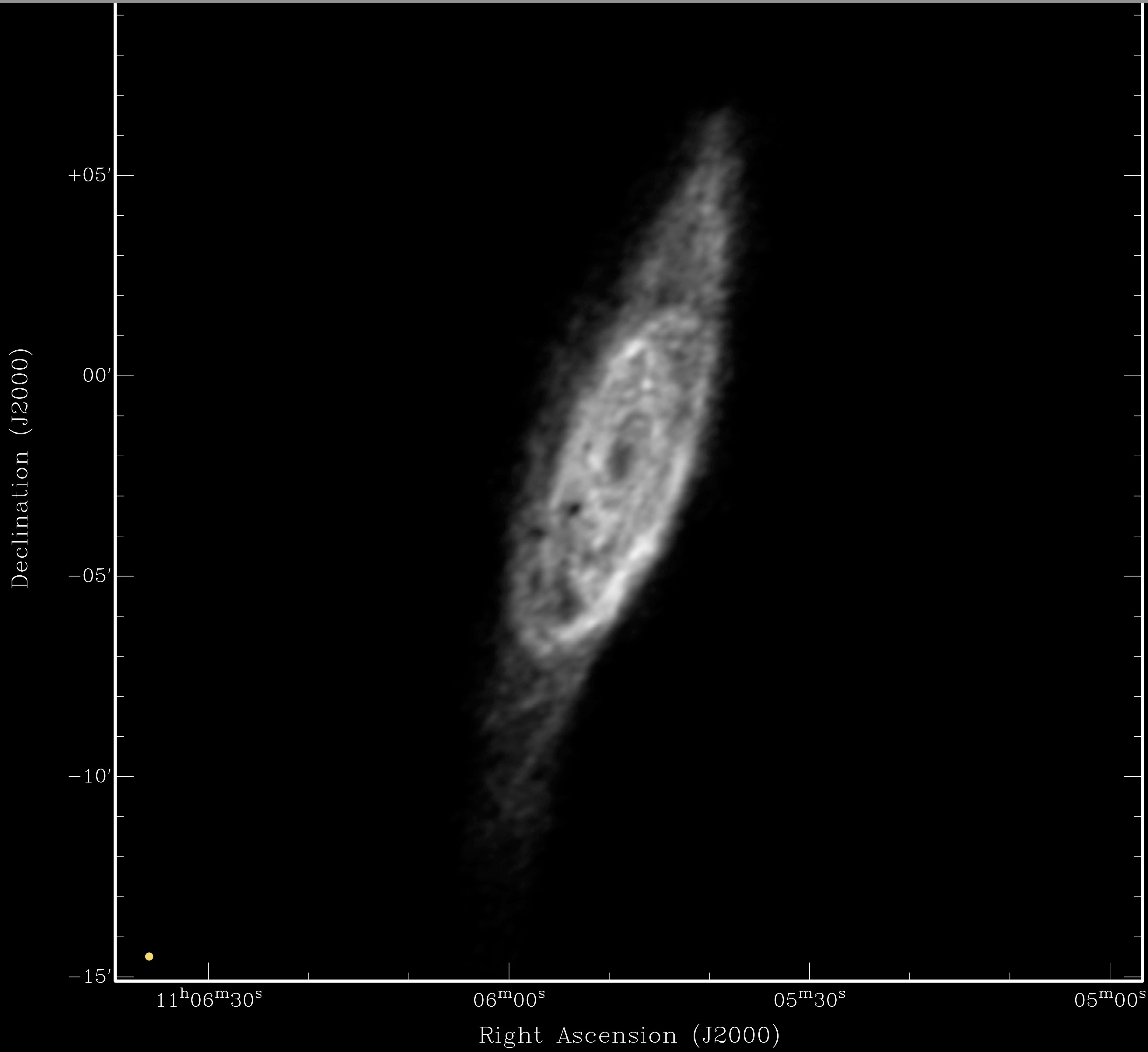


THINGS HI Natural-weighted

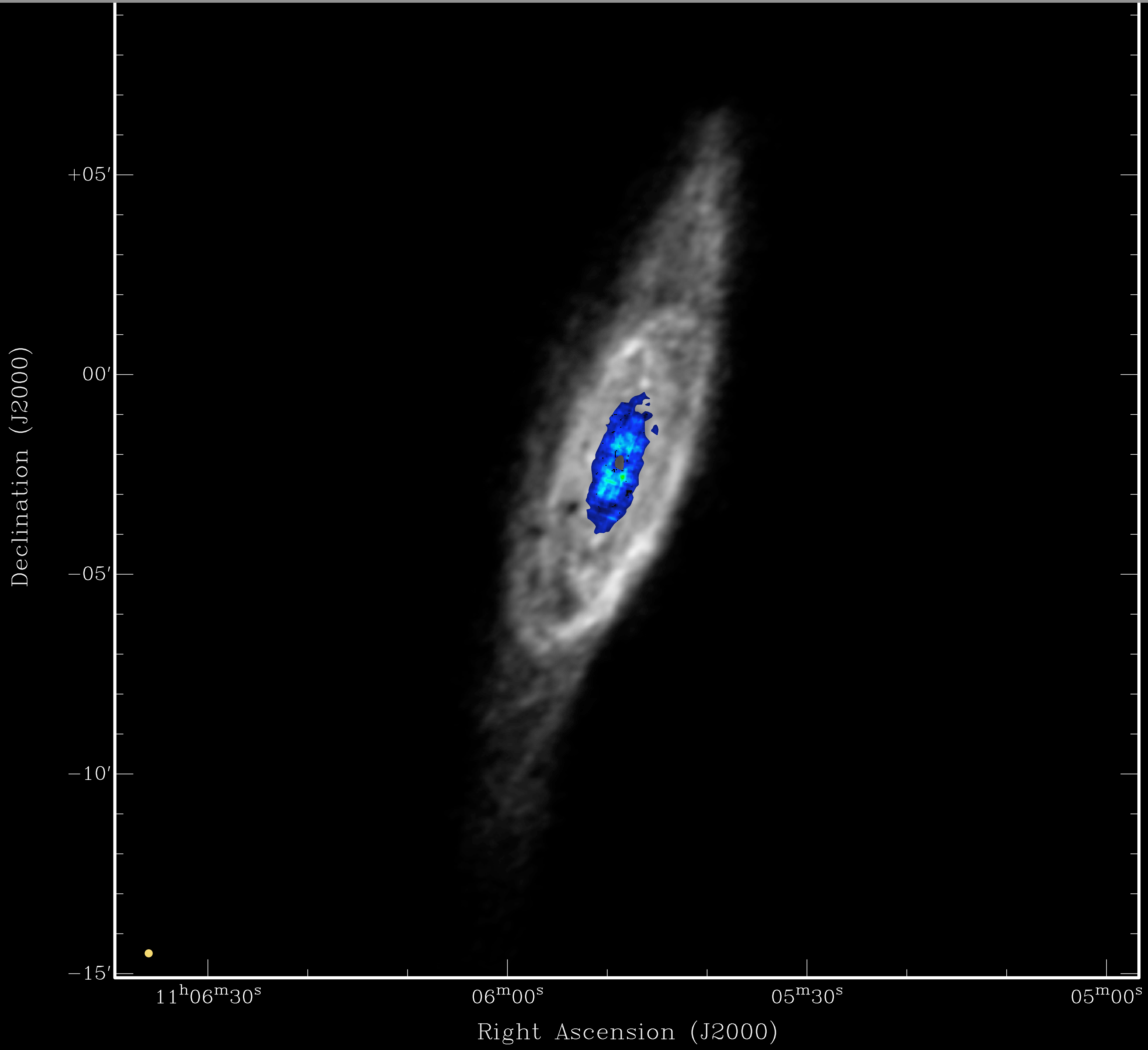


HERA CO(2-1)

Integrated emission

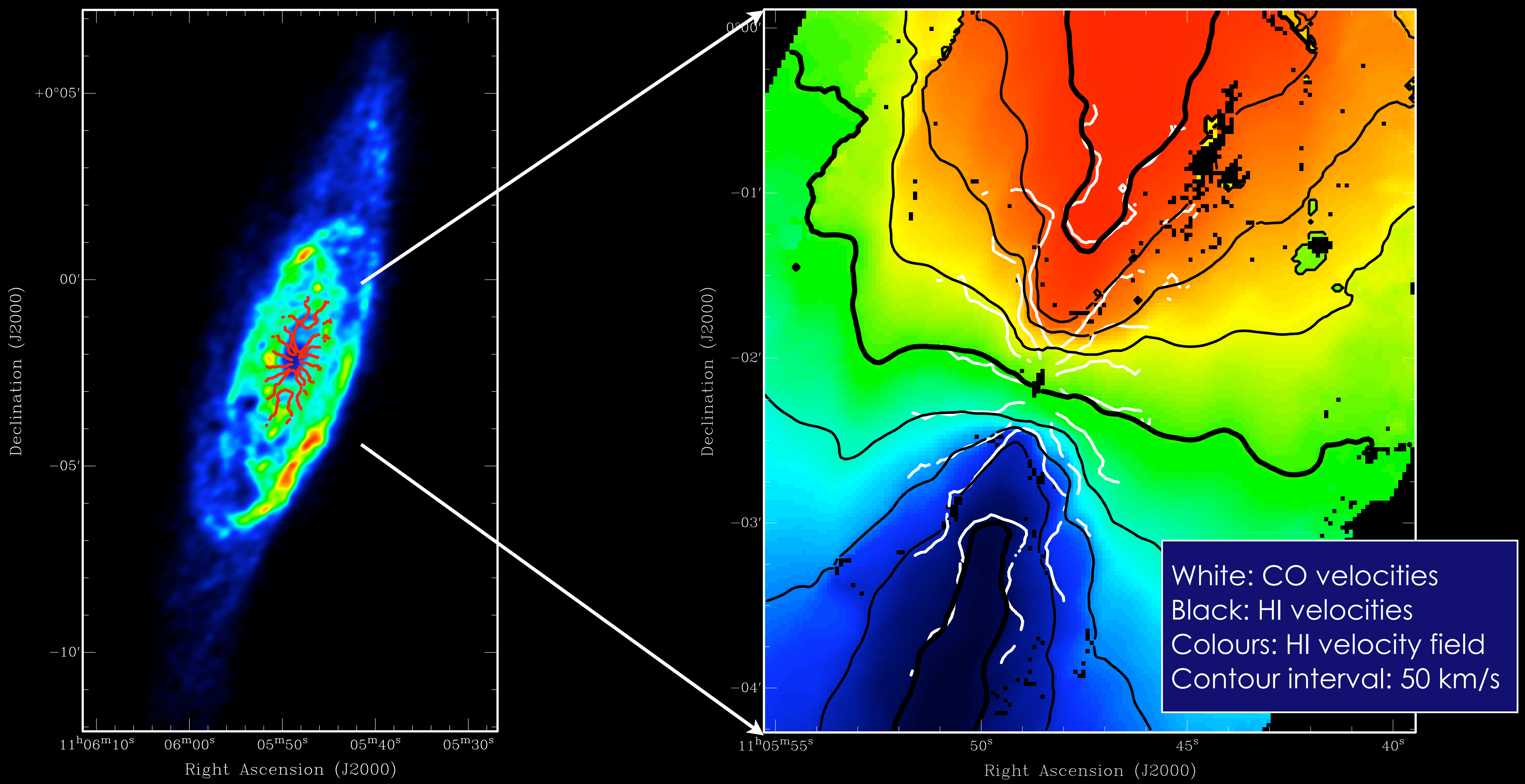


Integrated emission

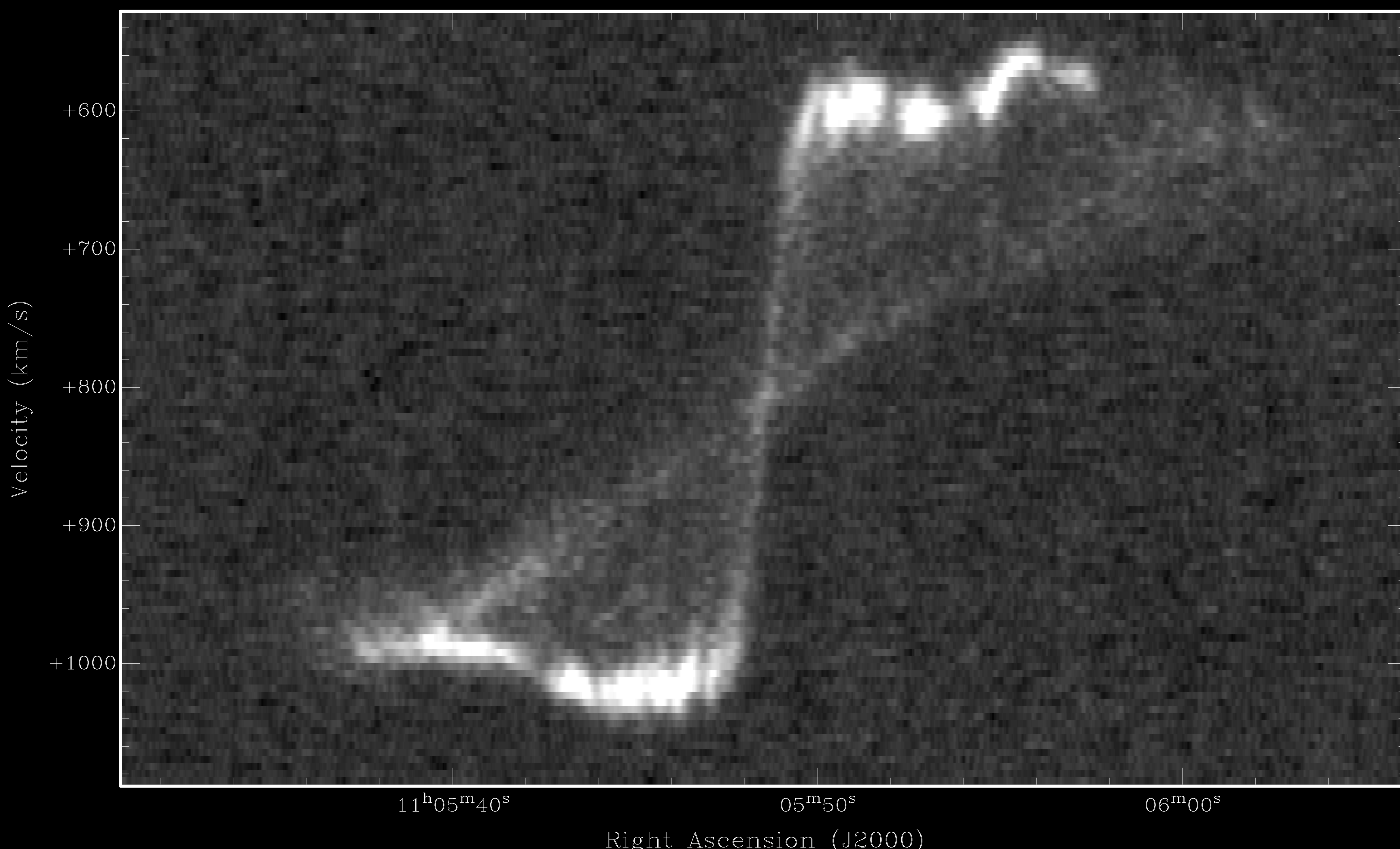


CO velocity field

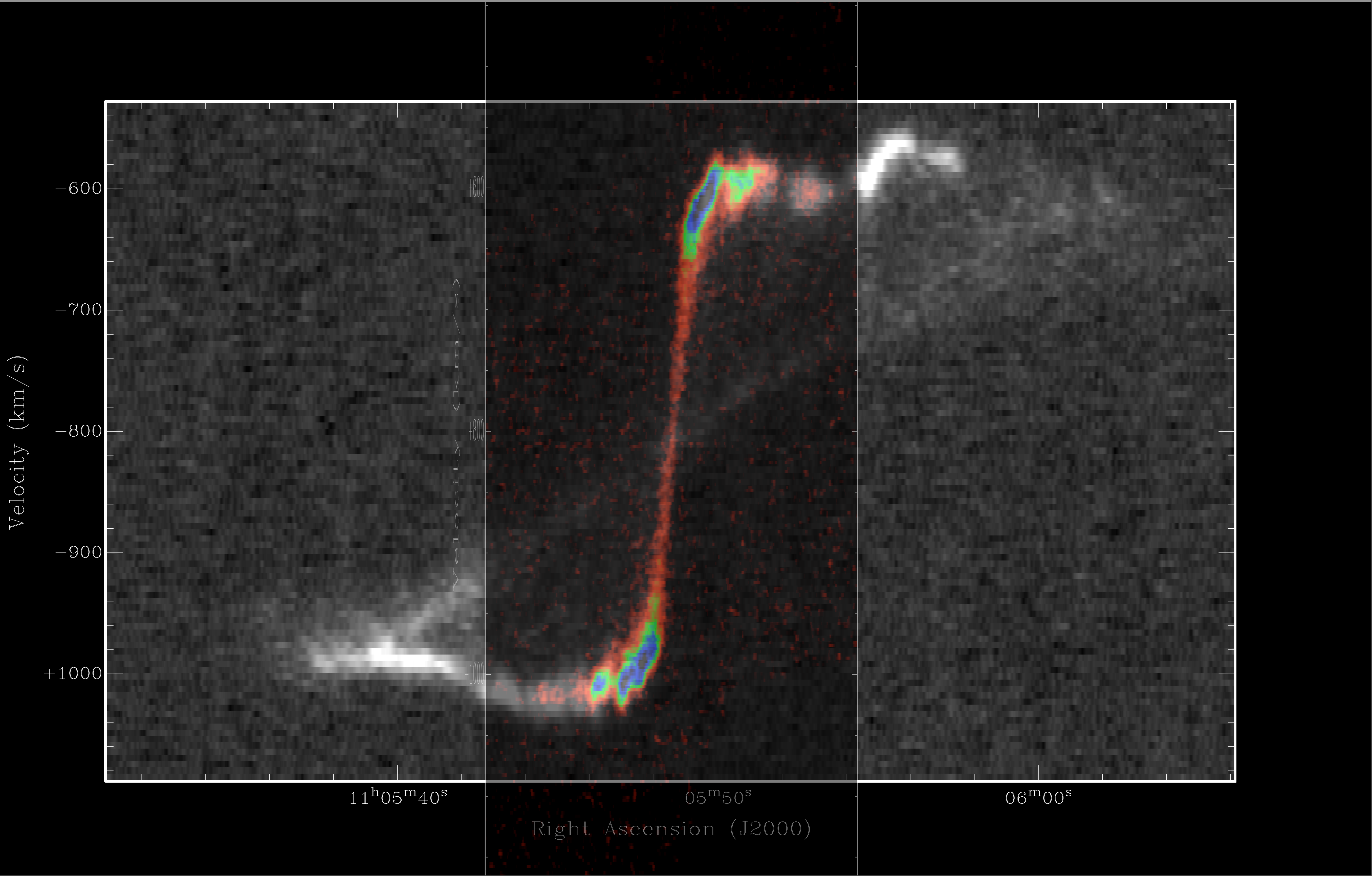
- Derive velocity field of CO data using Hermite profile fits
- Note pointy CO contours - but identical resolutions



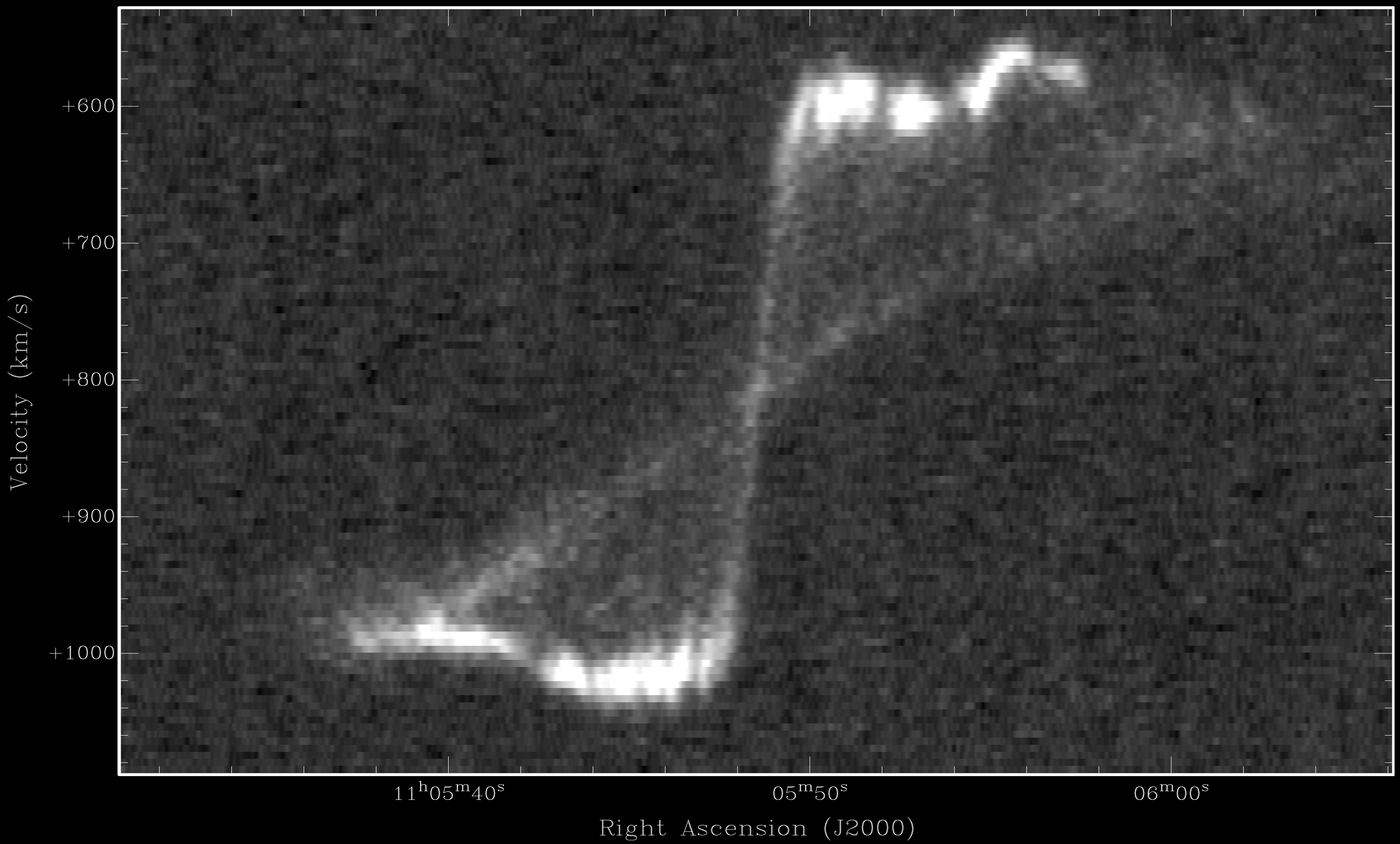
Major axis position velocity diagrams



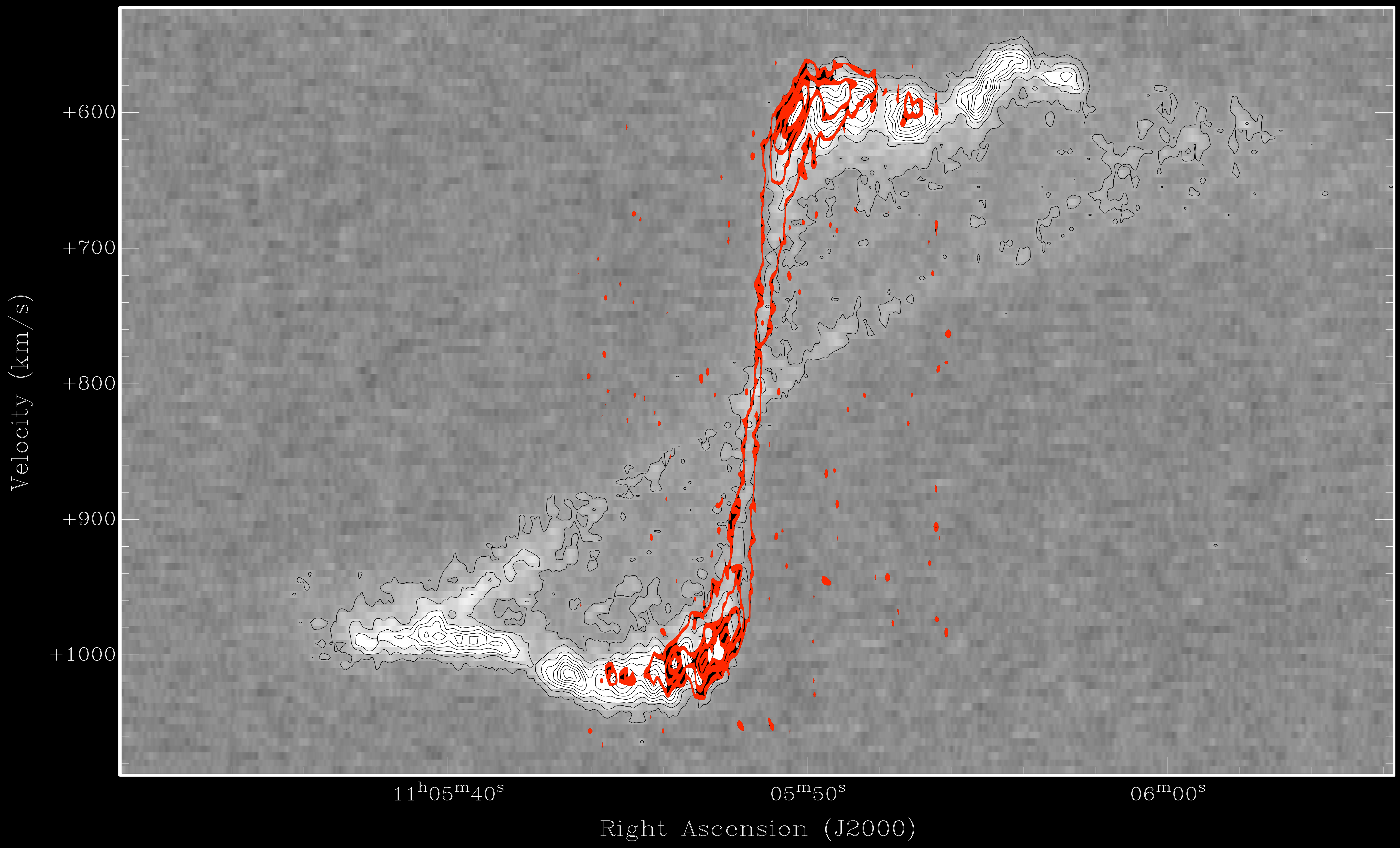
Major axis position velocity diagrams



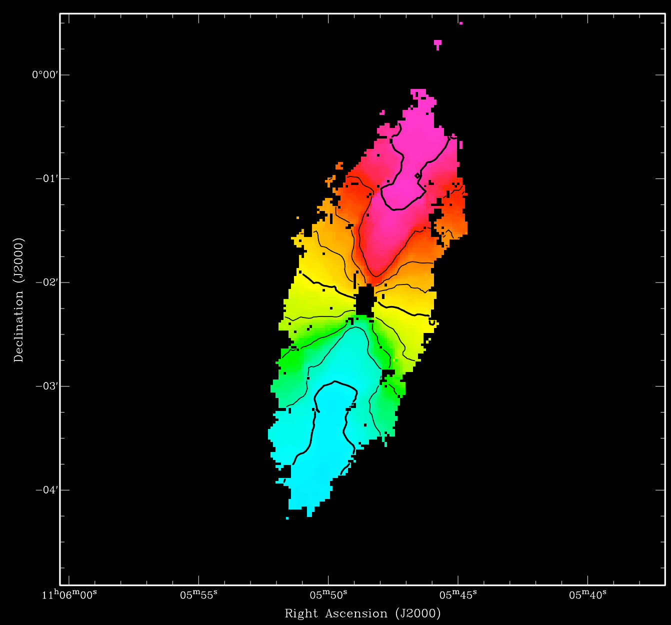
Major axis position velocity diagrams



Major axis position velocity diagrams

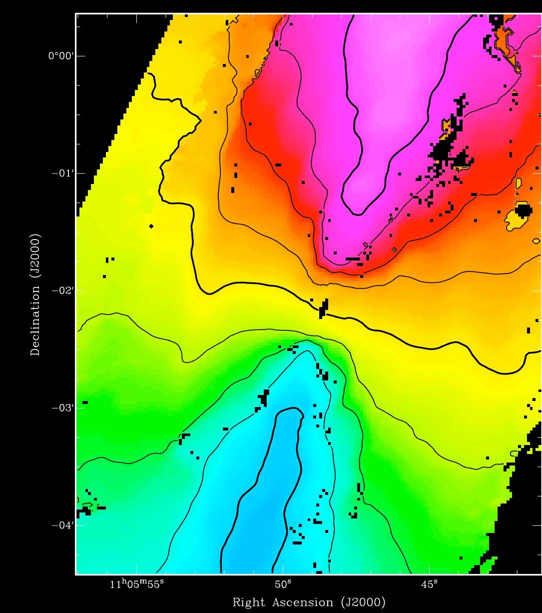


Difference velocity field



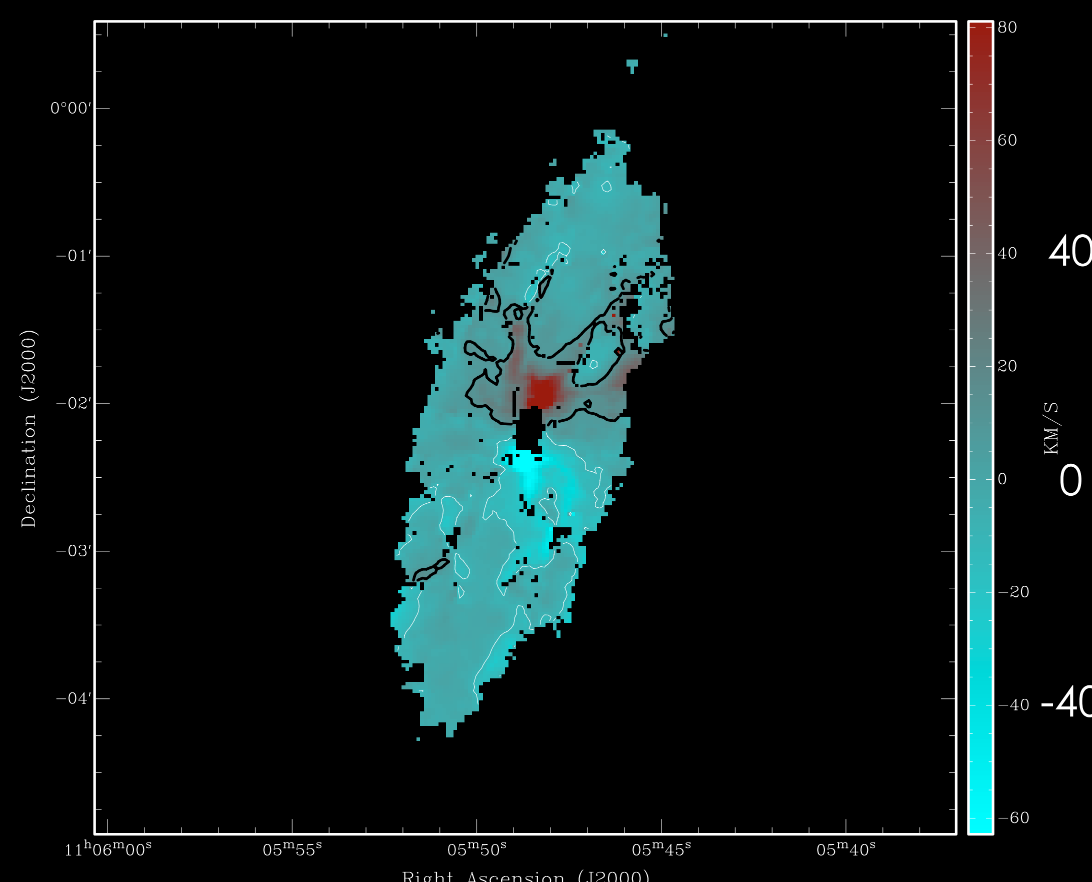
CO

−



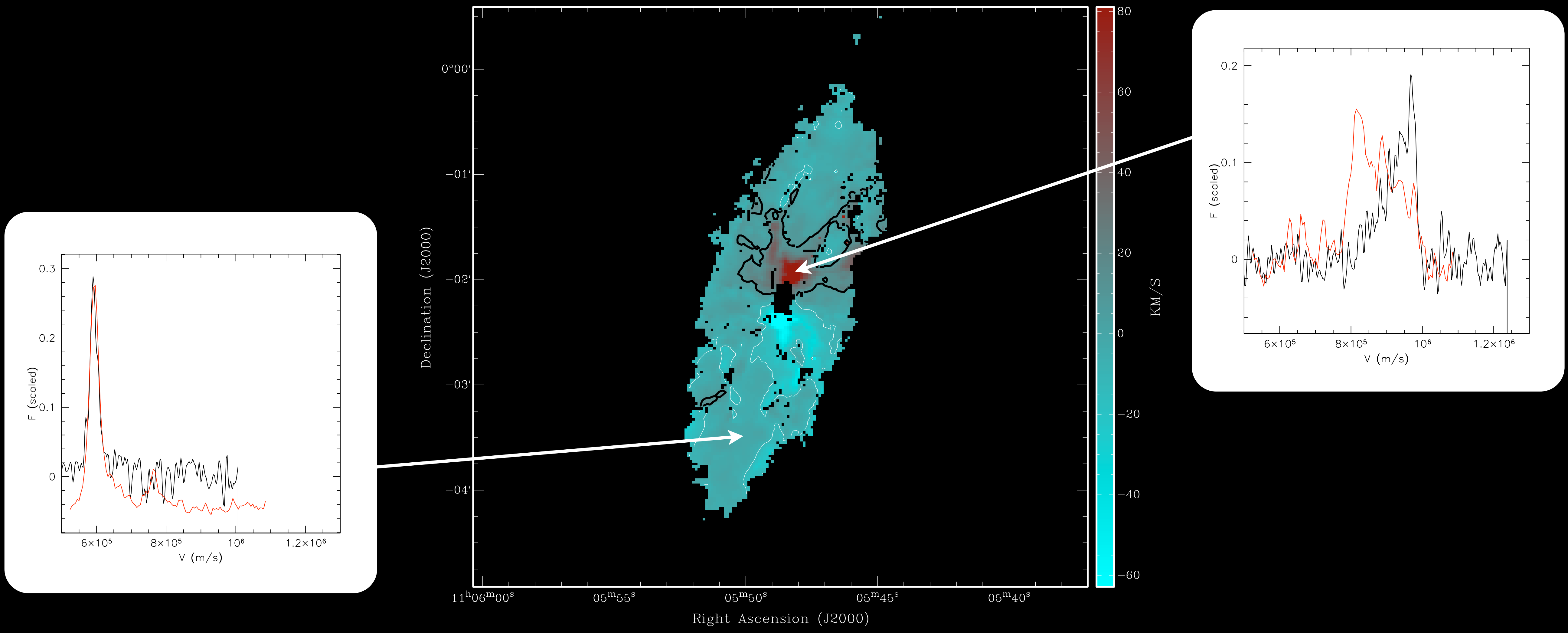
HI

=



Red: positive difference
Blue: negative difference
Contours: -10 and +10 km/s
Maximum difference: ~60 km/s

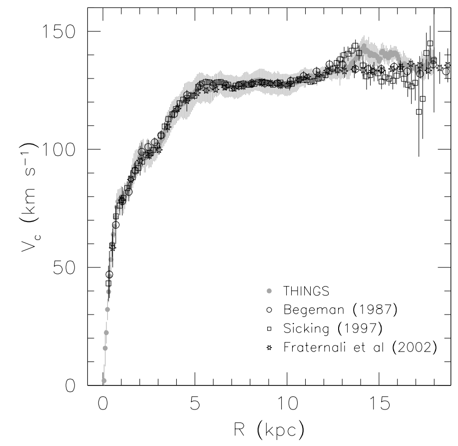
Difference velocity field



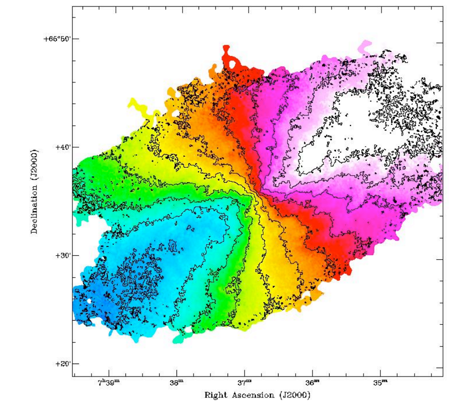
- CO and HI profiles in complete agreement in outer CO disk
- Large differences in “hot spots”
- Gas flows feeding the star formation feeding the LINER?

Summary

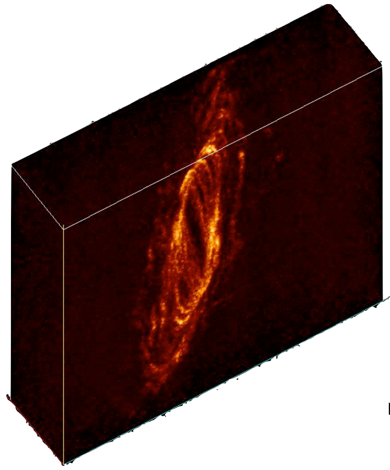
- Creation of velocity fields involves choice
- First-moment insufficient
- Profile fitting (Hermite h_3) better
- Ideally full data cube fitting
- Comparing multi-wavelength cubes through standard methods still cumbersome
- Prospects for 3D comparisons.....?



1D



2D



3D