

# The Outer Disk of M101

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*with Harding, Spengler, Rudick, and Feldmeier  
and Keating, Holley-Bockelmann, Pisano, and Kassim*



## Question: *Why study disk outskirts?*

- “Inside out” models for disk evolution argue that disk outskirts are *relatively* unevolved.
- “First contact” for material accreting onto the disk from the environment.
- Loosely bound material more sensitive to subtle encounters.
- Long dynamical times – information is preserved.
- Extreme environments for star formation.

## Question: *Why study individual, nearby galaxies?*

- Better physical resolution (@D=7 Mpc, 1" = 30 pc).
- Discrete stellar populations are accessible.

***But information is at low surface brightness ( $\mu_V > 27$  mag/arcsec<sup>2</sup>) and low column density ( $N_{HI} < 10^{19}$  cm<sup>-2</sup>), spread over large area.***

# M101

D = 7 Mpc

1' = 2 kpc



M101

NGC 5477

NGC 5474

2.5 degrees, 300 kpc



# Disk evolution in M101

M101: experiencing a *common* phase of galaxy evolution: interactions within the group environment.

*Key questions:*

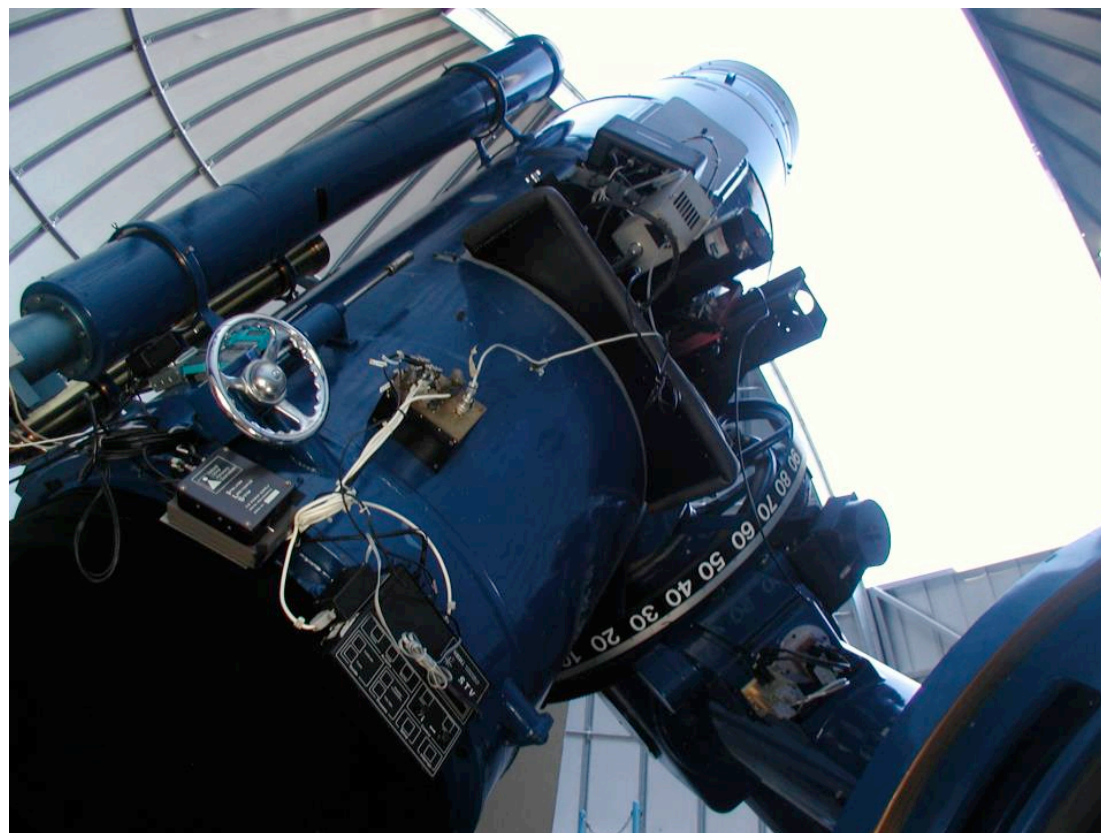
- What does M101's *outer* stellar disk look like?
- What drives the disk asymmetry?
- Interaction signatures in M101 and companion galaxies?
- Stellar populations in disk outskirts?
- Nature of M101's XUV disk?

# Deep optical imaging

CWRU Burrell Schmidt  
(24/36") @ KPNO

Optimized for deep wide  
field surface photometry

- Wide FOV (2.7 deg<sup>2</sup>)
- Closed tube
- Baffling/Flocking
- Aggressive A/R coatings



	Exposure (hours)	Limiting surfb (mag/arcsec <sup>2</sup> )
B	20	29.5
V	15	29.0

M101

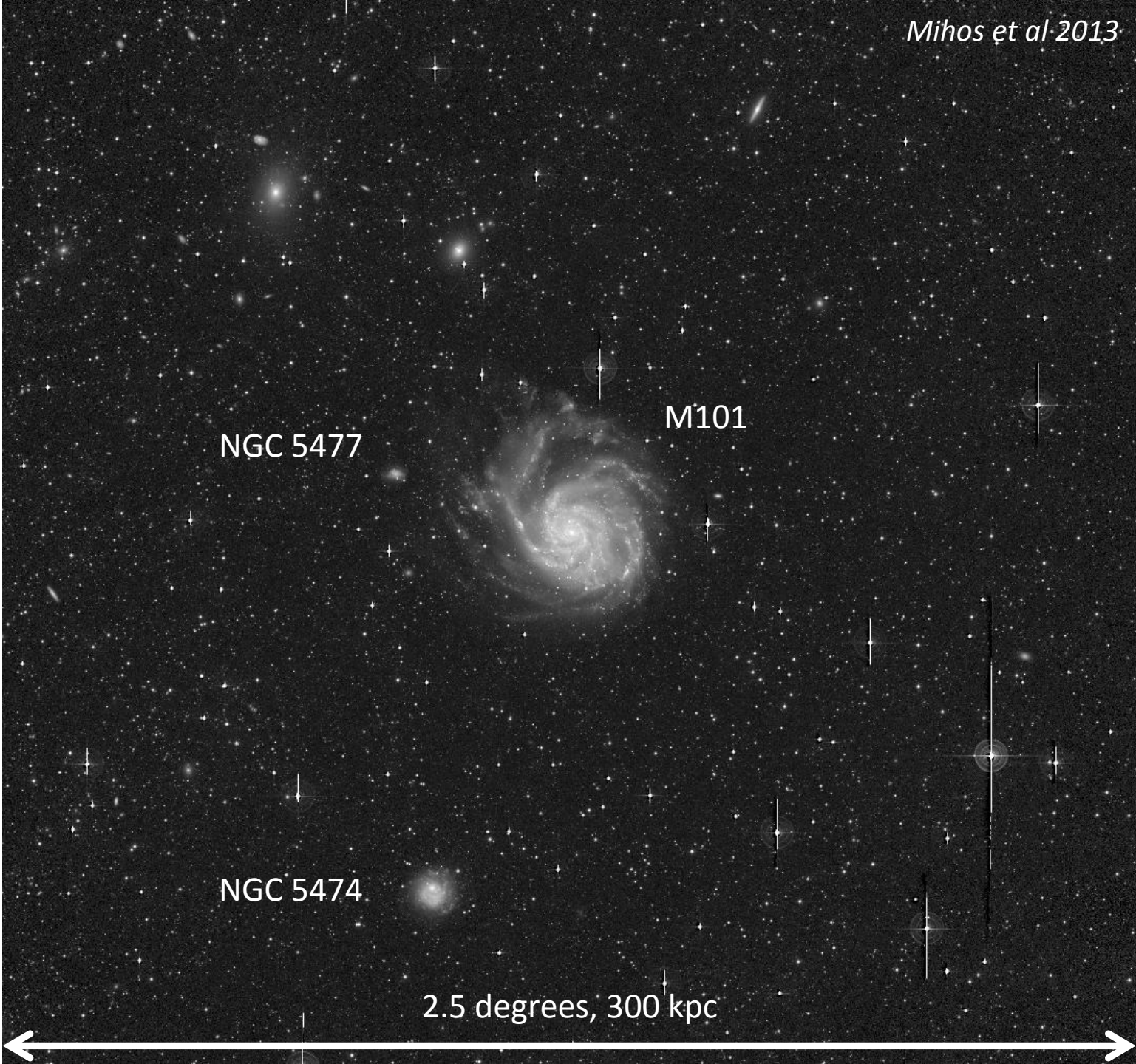
$\mu_{\text{lim}} \sim 26$

NGC 5477

M101

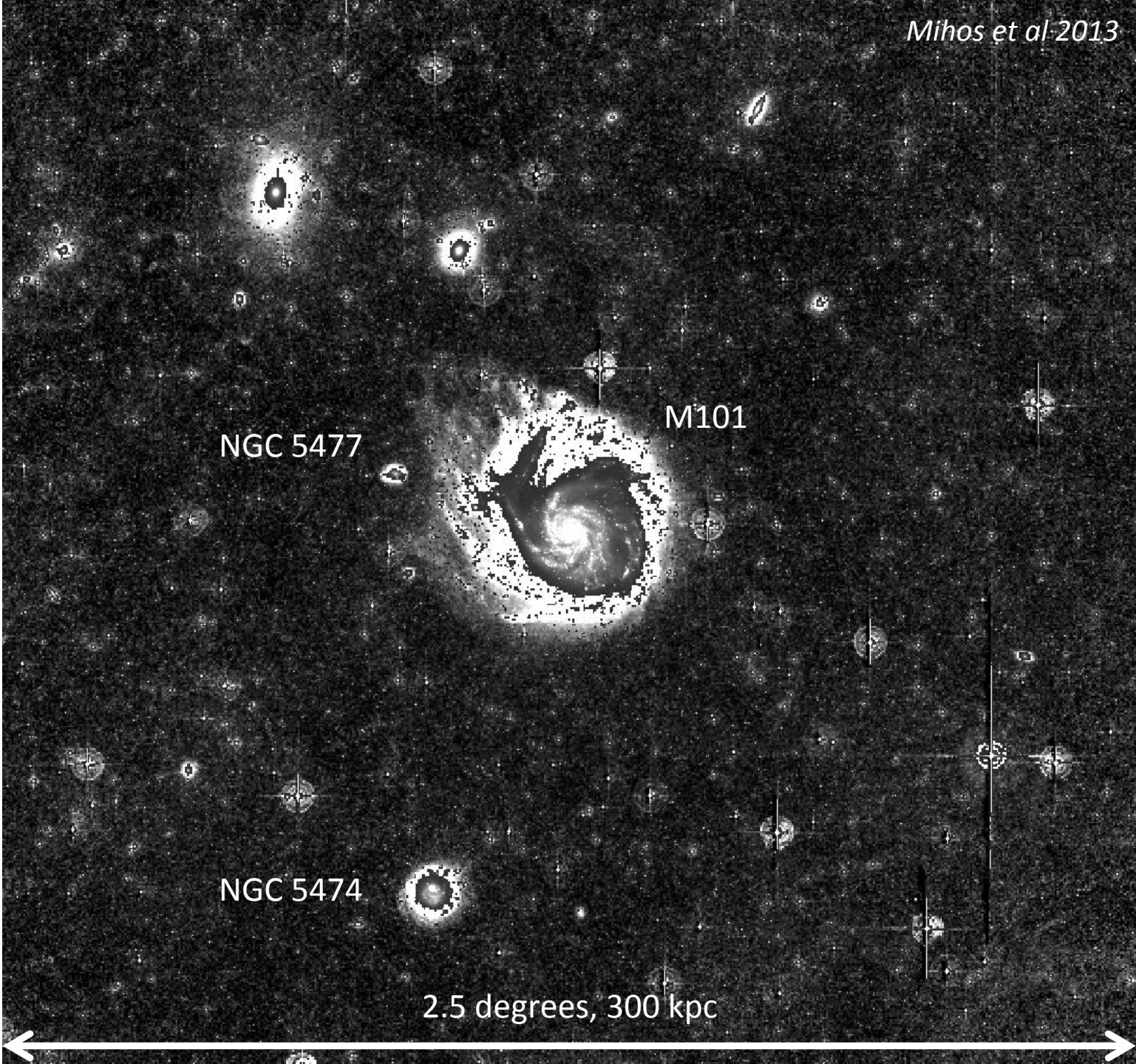
NGC 5474

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M101

$\mu_{\text{lim}} \sim 29.5$



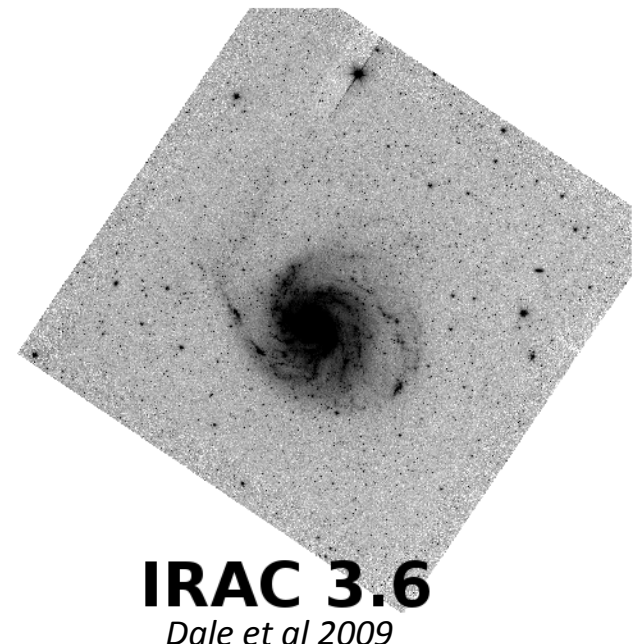
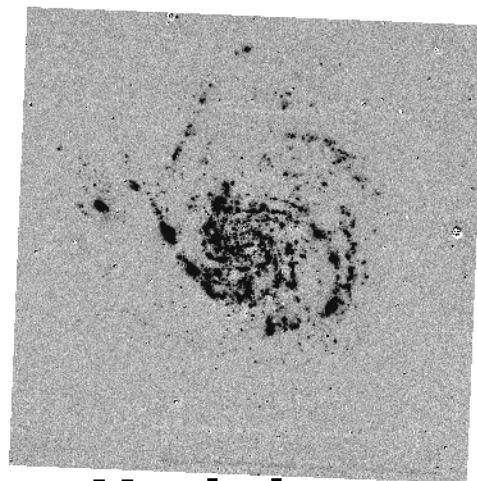
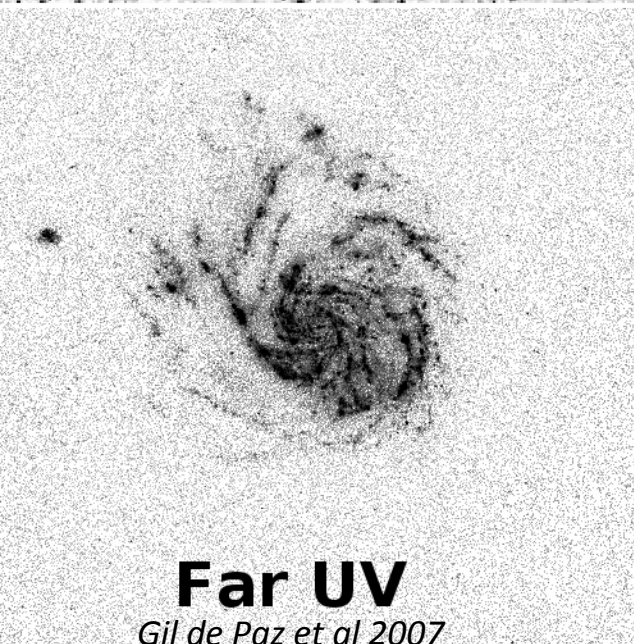
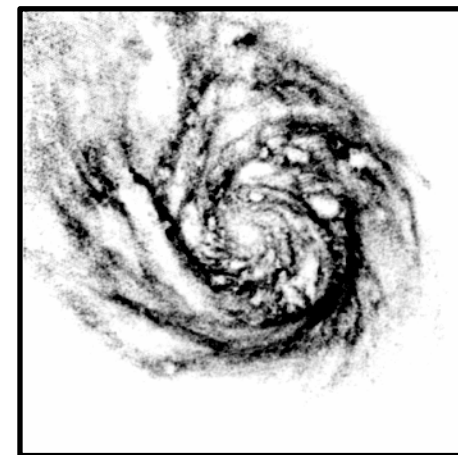
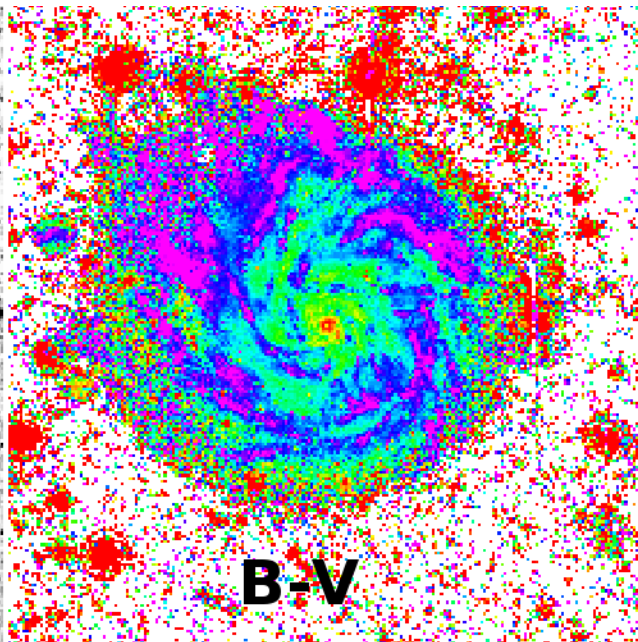
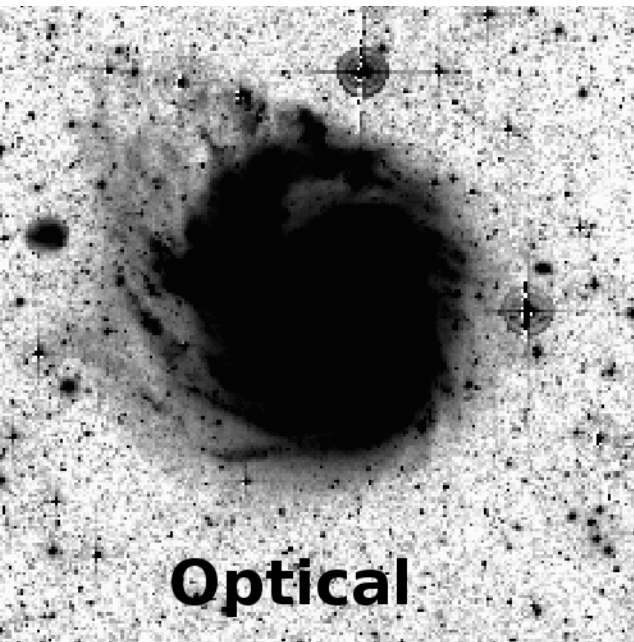
NGC 5477

M101

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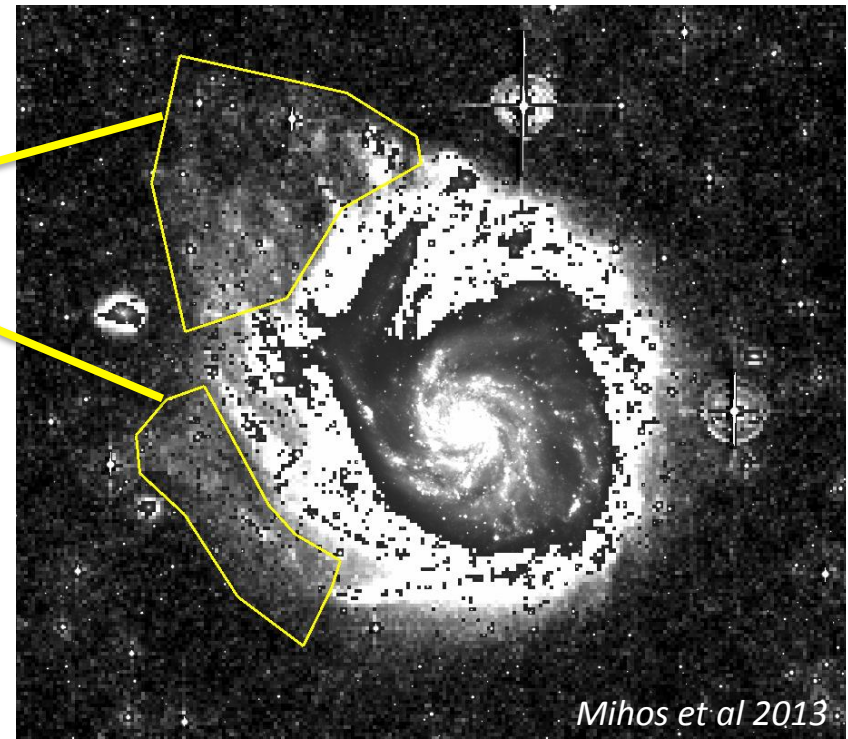
# Multi-wavelength Montage





# Star Formation History

	NE Plume	E Spur
$L_V [10^8 L_\odot]$	0.66	0.65
B-V	$0.20_{\pm 0.05}$	$0.45_{\pm 0.02}$
$\Sigma_{\text{HI}} [M_\odot/\text{pc}^2]$	1.9	1.1
SFR [ $M_\odot/\text{yr}$ ]	0.015	0.006



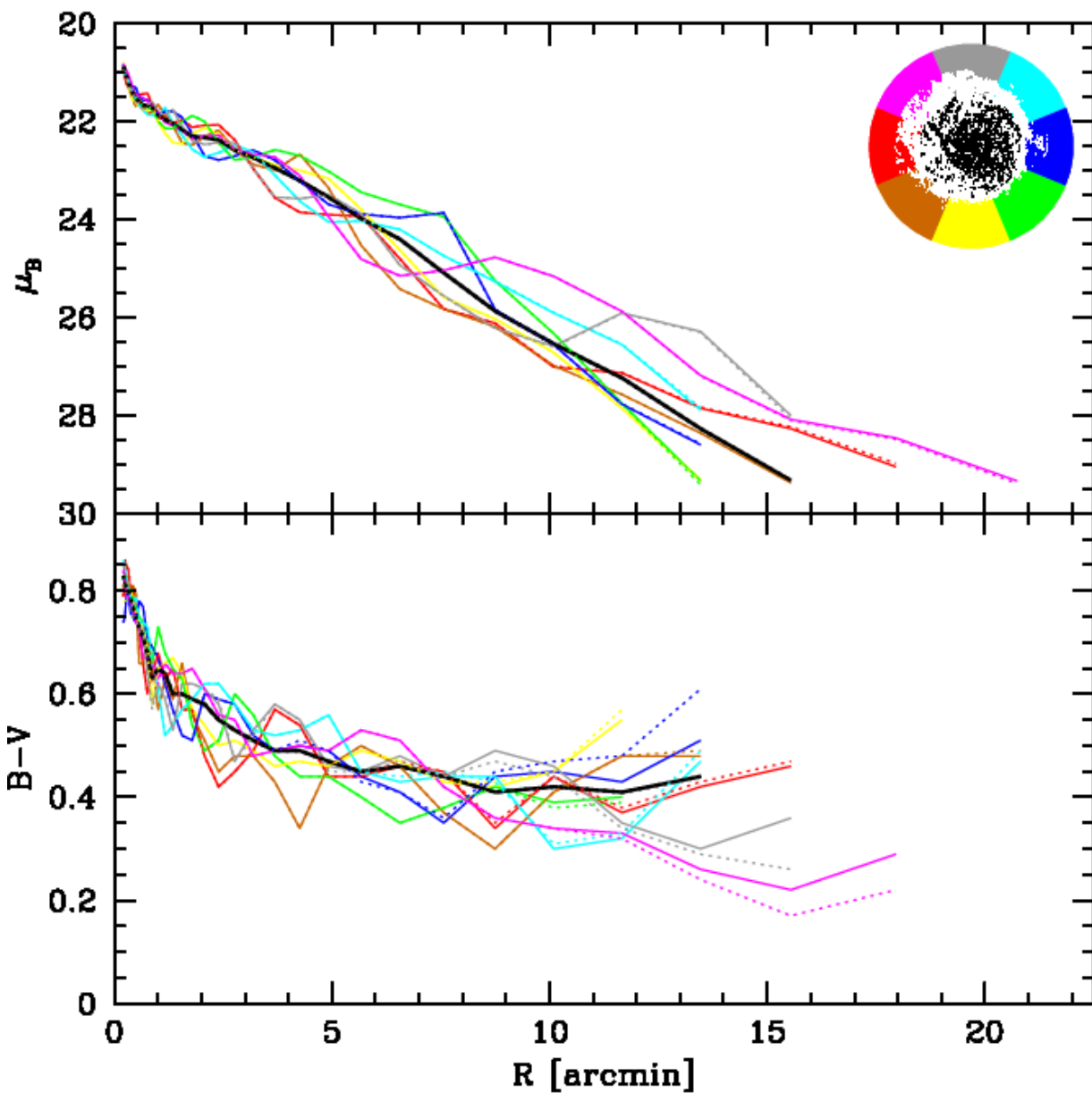
## NE Plume:

- Constant SFR model: color matches at 1.0-1.5 Gyr, but SFR too low to reproduce total luminosity.
- Gaussian burst: matches color and luminosity with a short ( $\sigma \sim 75\text{-}100$  Myr), modest (peak SFR  $\sim 0.2 M_\odot/\text{yr}$ ) burst observed  $\sim 250\text{-}350$  Myr past peak.

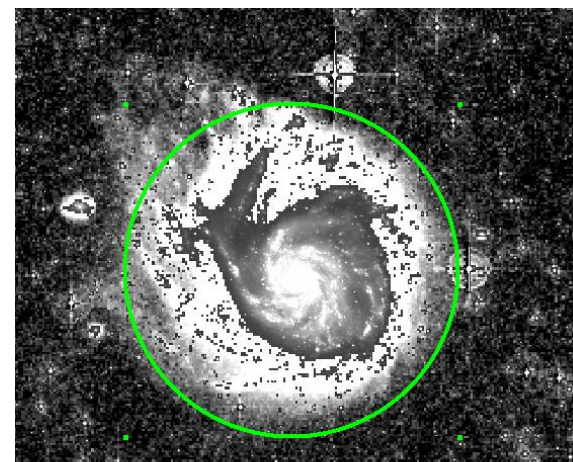
## E Spur:

- Redder colors consistent w/ a variety of star formation models. Little constraining power....

# M101 Radial Profiles



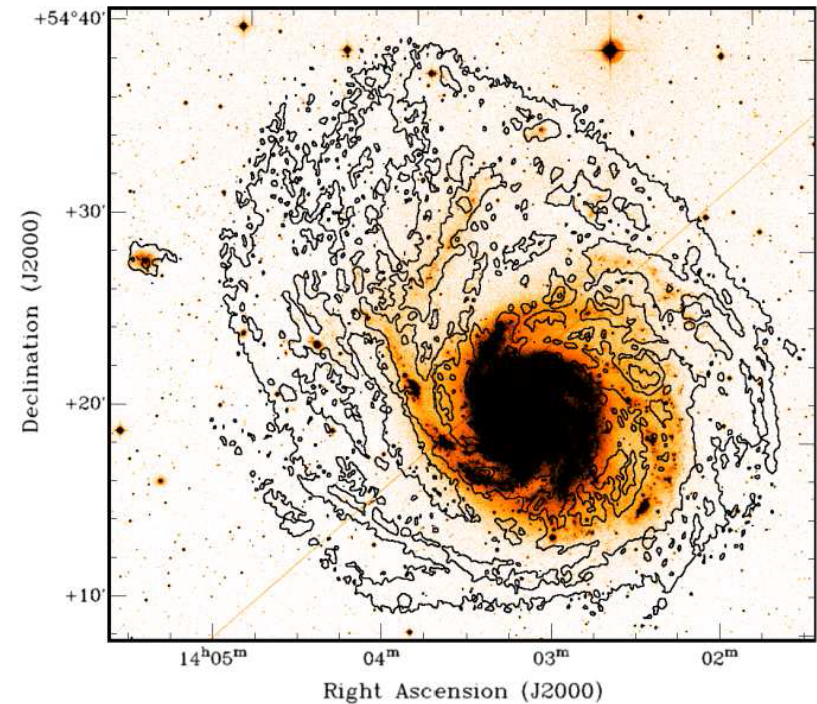
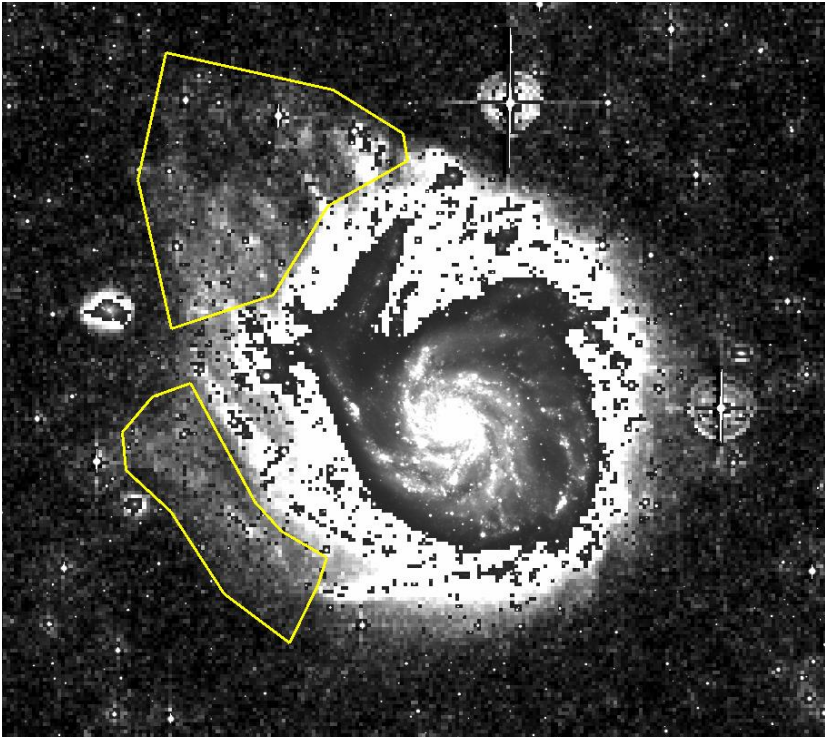
	Inner scale length ( $R < 7'$ )	Outer scale length ( $R > 9'$ )
NE	1.9'	2.8'
SW	3.4'	1.2'



# HI properties

Deep single dish (Huchtmeier & Witzel 1979) and interferometry (van der Hulst & Sancisi 1988; Walter et al 2008):

- Extended, distorted HI disk ( $M_{\text{HI}} \sim 2.4 \times 10^{10} M_{\odot}$ )
- High velocity gas ( $M_{\text{HI}} \sim 10^7\text{--}10^8 M_{\odot}$ )

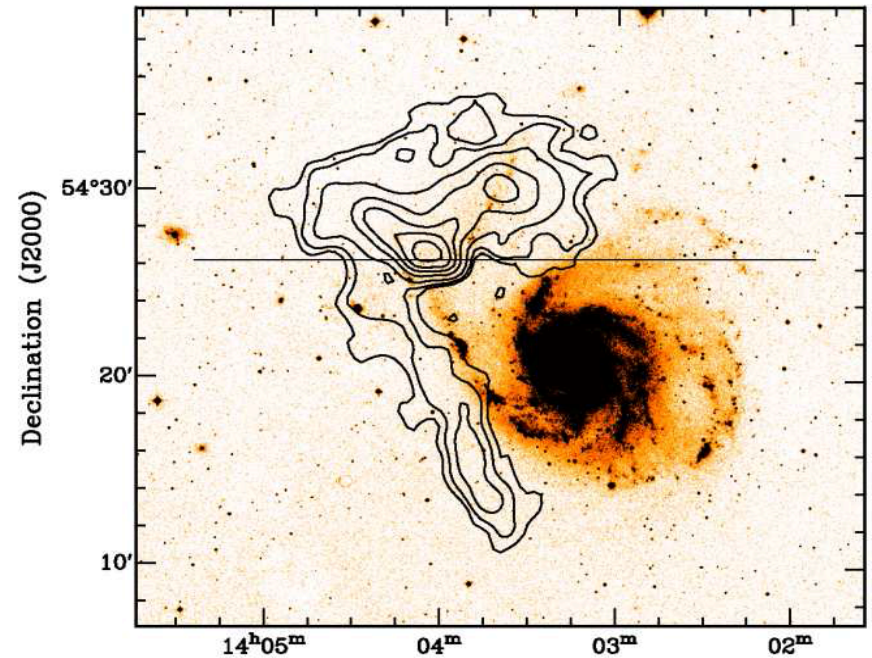
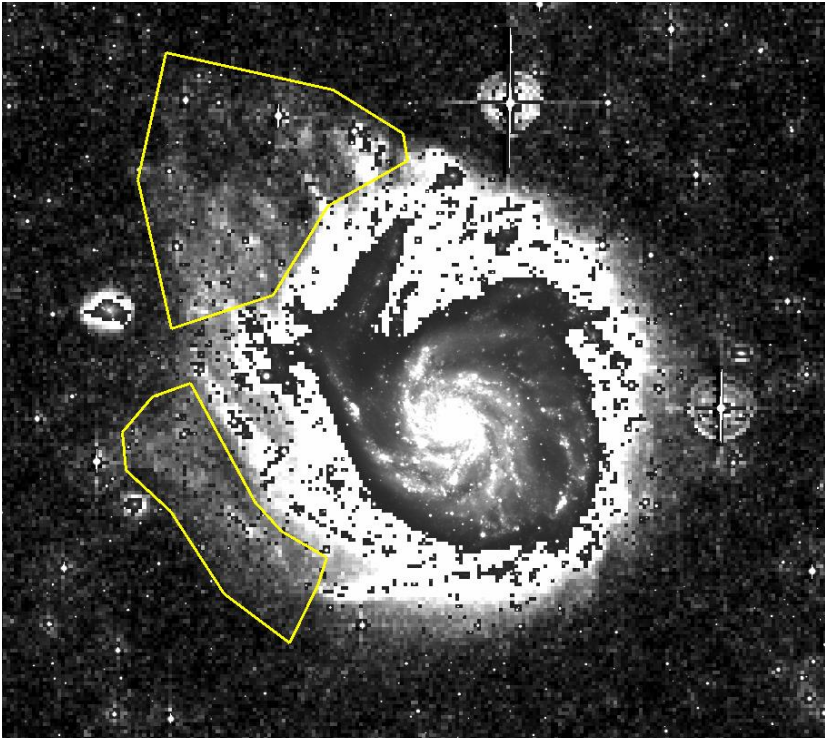


*from Kamphuis (2008), in Sancisi et al (2008)*

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# Deep HI mapping

GBT observations (Spring 2011)

Survey area:  $\sim 1$  Mpc around M101,  
inner  $\sim 300$  kpc mapped at higher  
sensitivity.

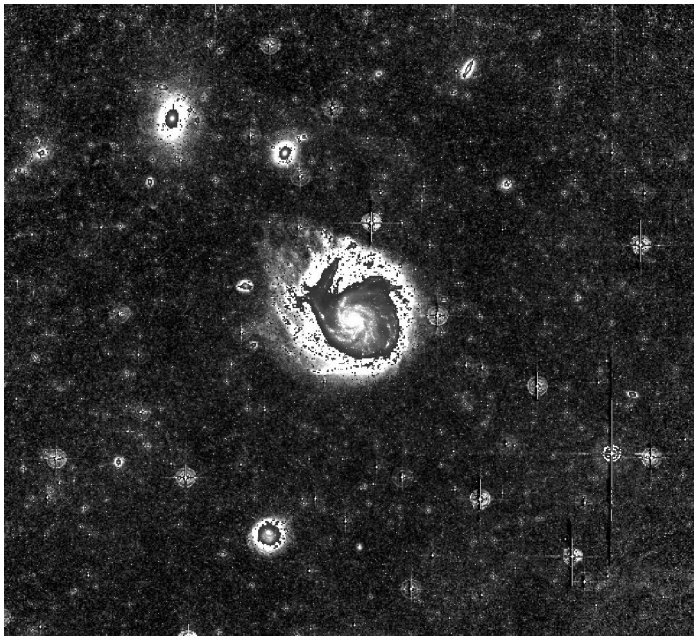
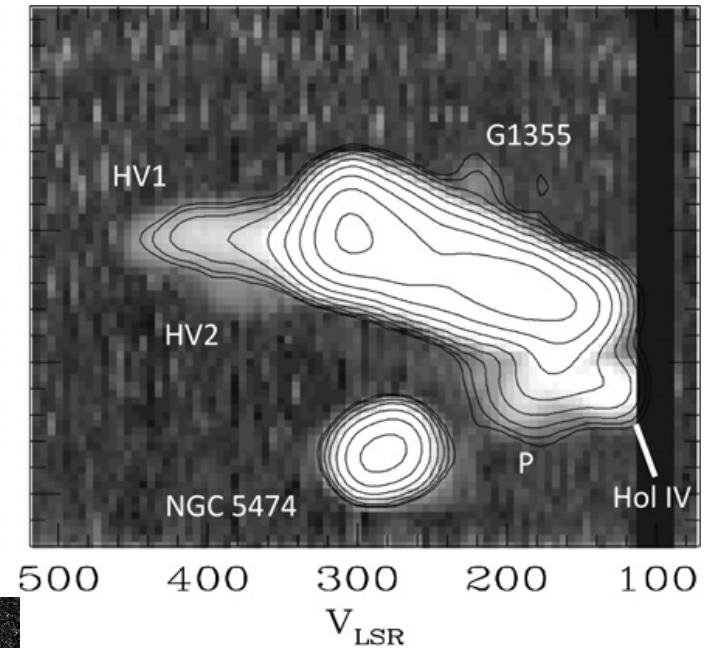
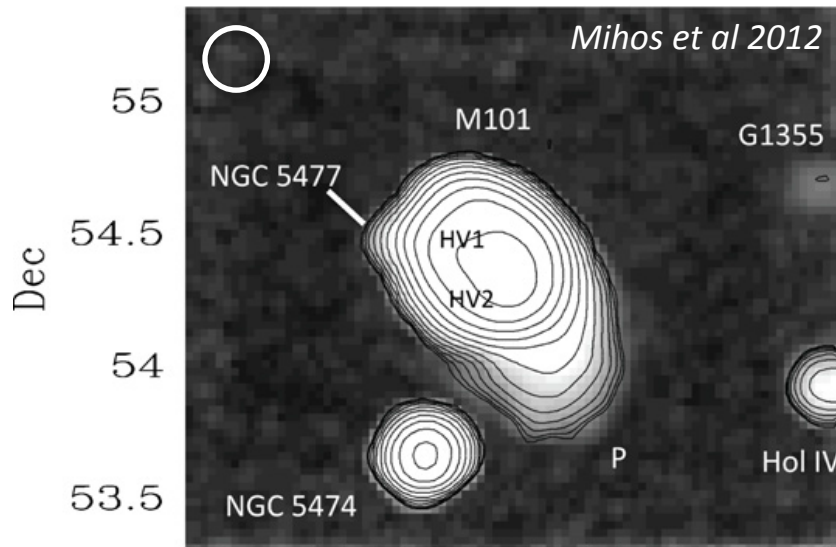
Velocity range:  $-787$  to  $+1855$  km/s

Velocity channels:  $5.2$  km/s

Beam size:  $9.1'$  /  $18$  kpc

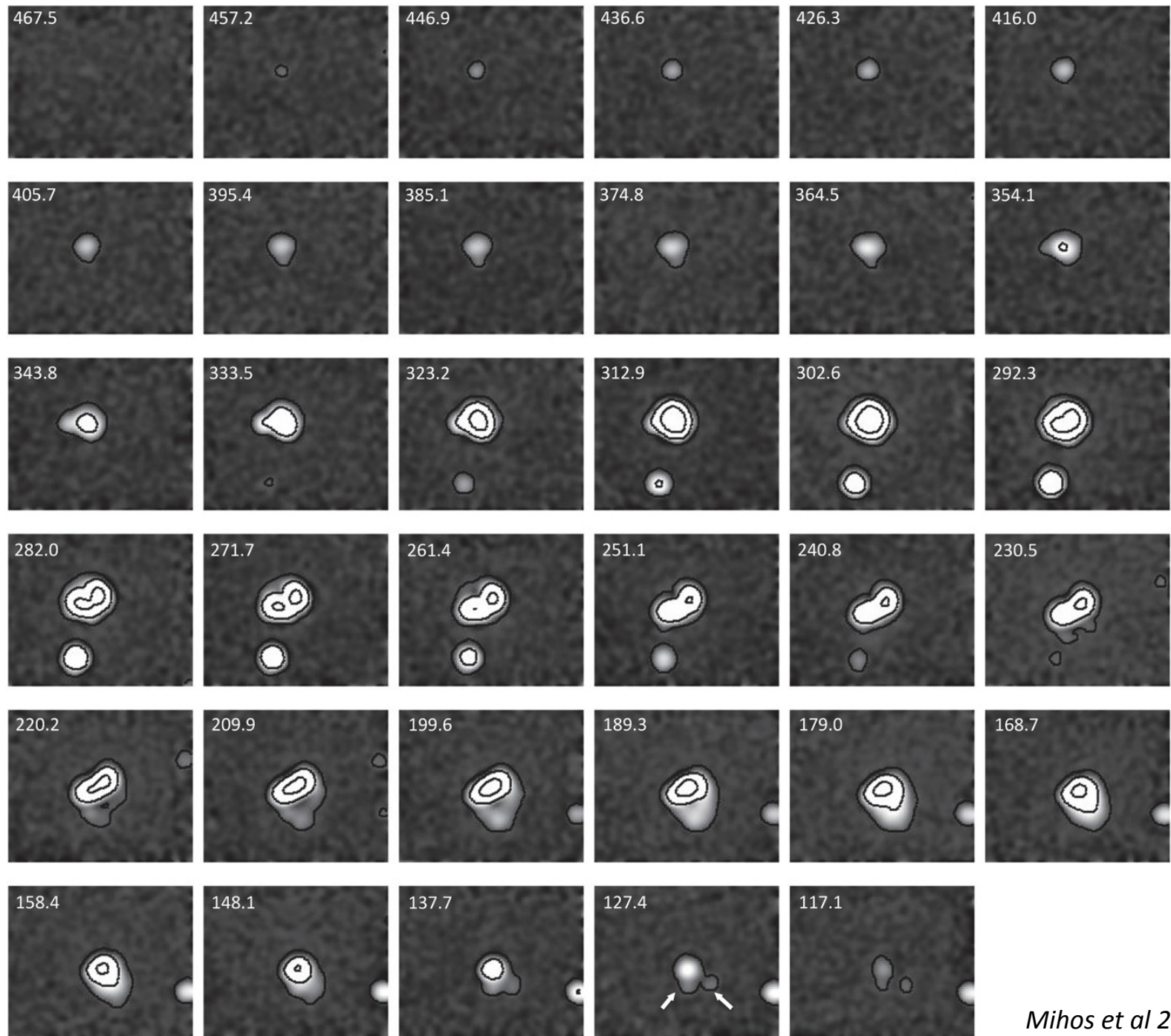


	Inner	Outer
Noise (mJy/beam)	3.0	15.0
Sensitivity ( $\log N_{\text{HI}}$ )	16.8	17.5
$5\sigma$ Cloud Mass ( $10^6 M_{\odot}$ )	2	10



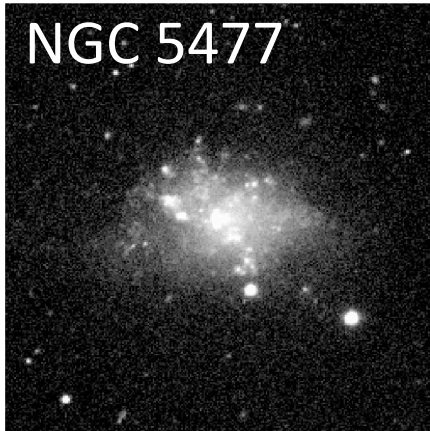
### Southwest HI Plume:

- $\sim 100$  kpc in length
- Peak  $\log(N_{\text{HI}}) \sim 17.3 \text{ cm}^{-2}$
- $M_{\text{HI}} \sim 10^8 M_{\odot}$
- No stellar counterpart

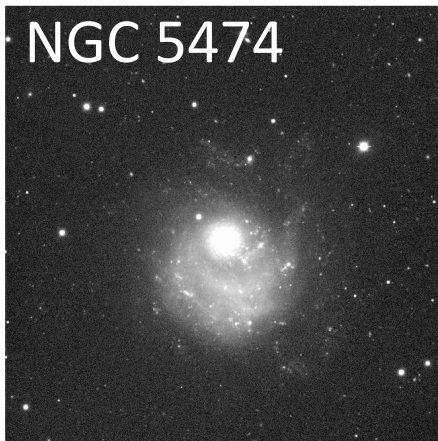


# Interaction History: who's to blame?

- Morphology and stellar pops in M101's outer disk suggest a fly-by interaction approximately 250-350 Myr ago.
- Long SW HI plume, clouds, and HVCs also indicative of return of tidal gas.



Currently in the gap between the NE Plume and E Spur, similar to generic interaction models. But likely too low in mass to drive M101's global asymmetry.

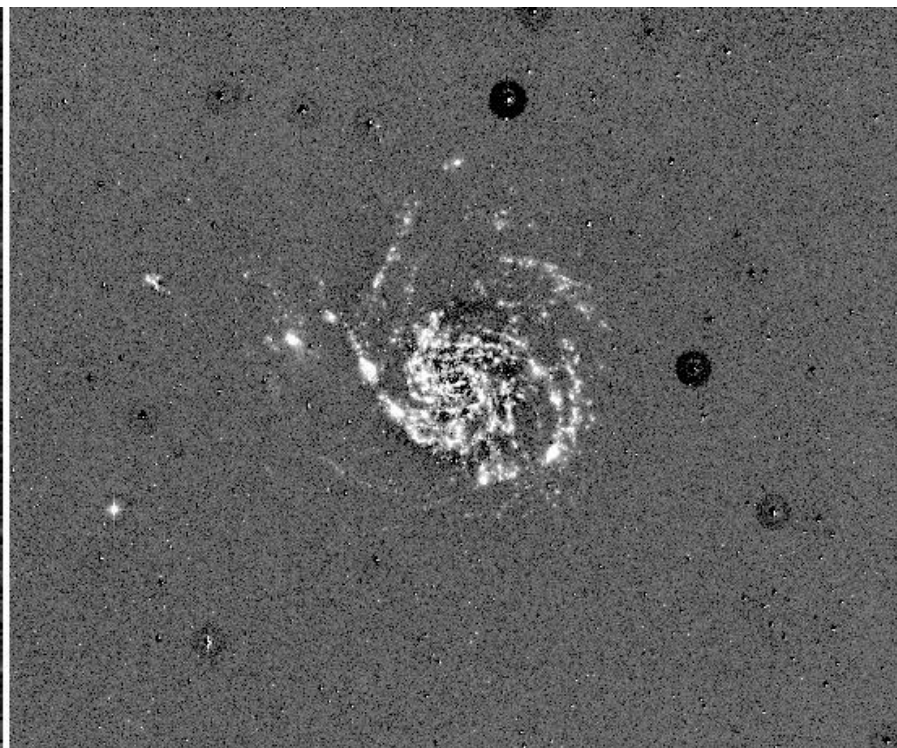
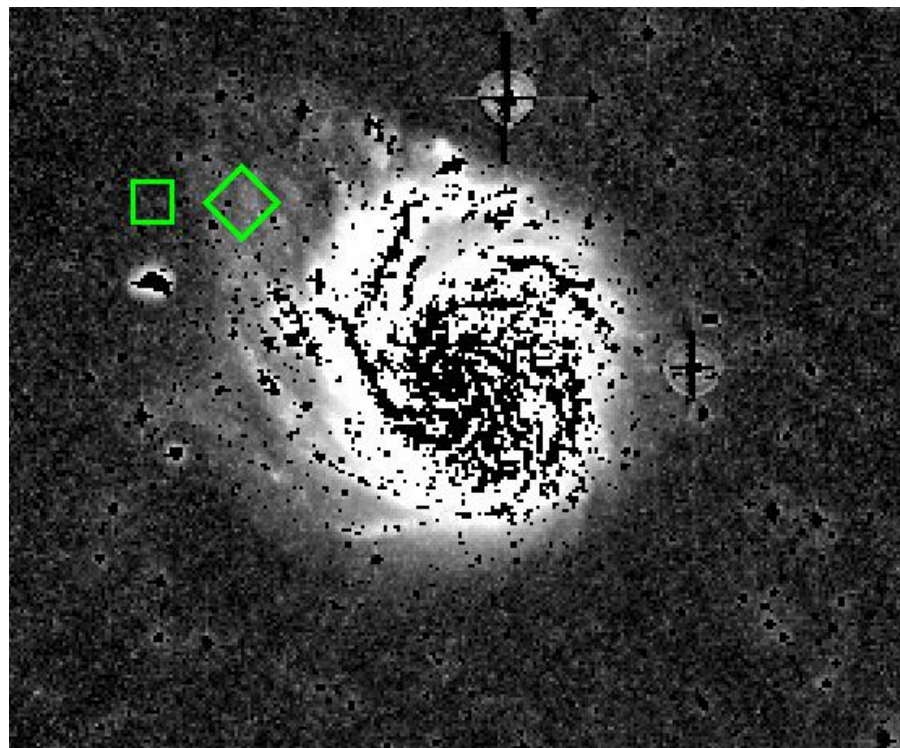


More massive, more able to drive global asymmetry. Preliminary model (Linden+ in prep):

- close (5 kpc),
- recent ( $\sim 250$  Myr),
- retrograde encounter



# More data on the way...



## HST Cycle 22: Resolved Pops

- 26 Orbits in V and I
- ACS pointing on NE Plume
- Offset (Halo?) WFC3 pointing
- Probe CMD to  $V=29.9$  ( $M_V=+0.7$ )

## Deep Wide-field Schmidt $H\alpha$

- Watkins et al in prep
- $\sim 17$  hours in on-band
- Study faint, extended SF

# Summary

- Deep imaging shows extended ( $\sim 50$  kpc) optical disk.
- Extended disk extremely asymmetric, opposite inner disk.
- Radial profiles varied (Type 1, 2, and 3!)
- Stellar populations in NE Plume suggest age of  $\sim 250$ -350 Myr
- Extended ( $\sim 100$  kpc), starless HI plume to SW
- Close retrograde encounter with NGC 5474 appx 250 Myr ago.

