Power spectra of galaxies: thickness, turbulence, and gravity

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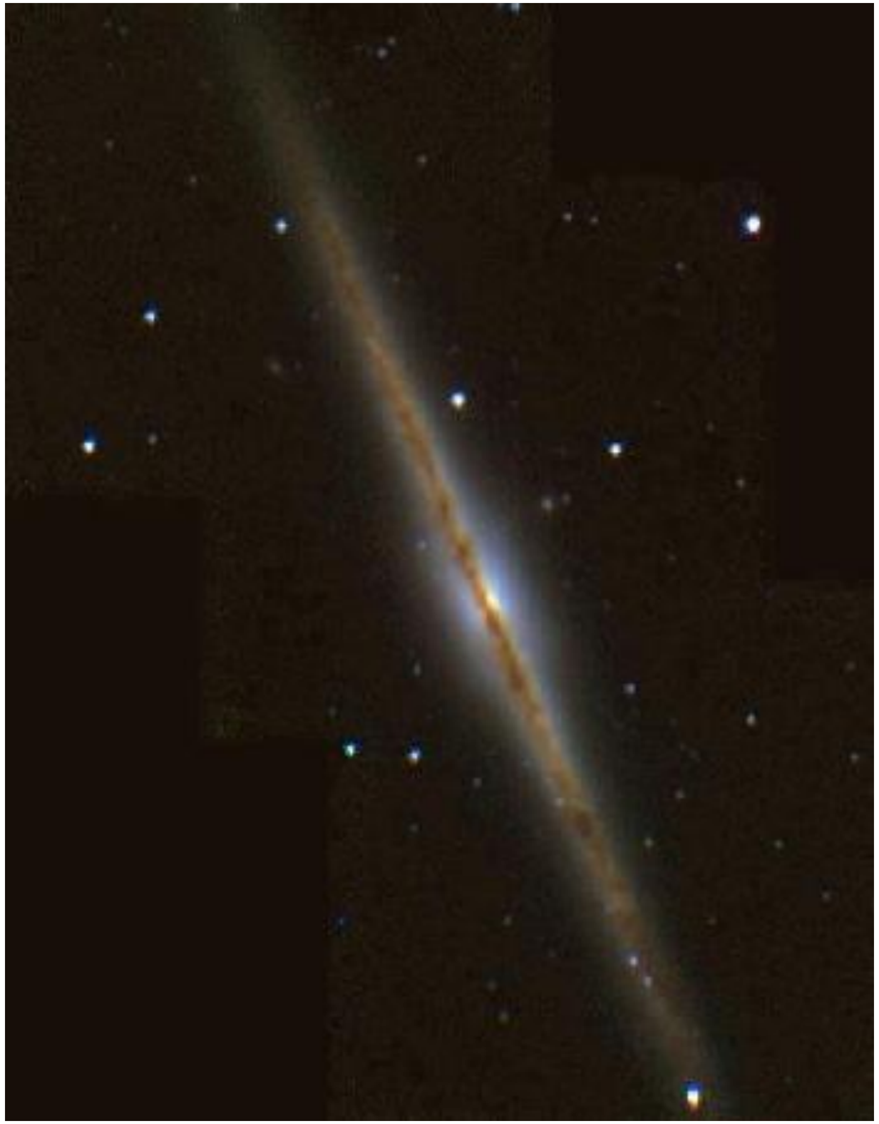
Katonah, NY, retired

Marstrand, Sweden
June 10-13, 2025

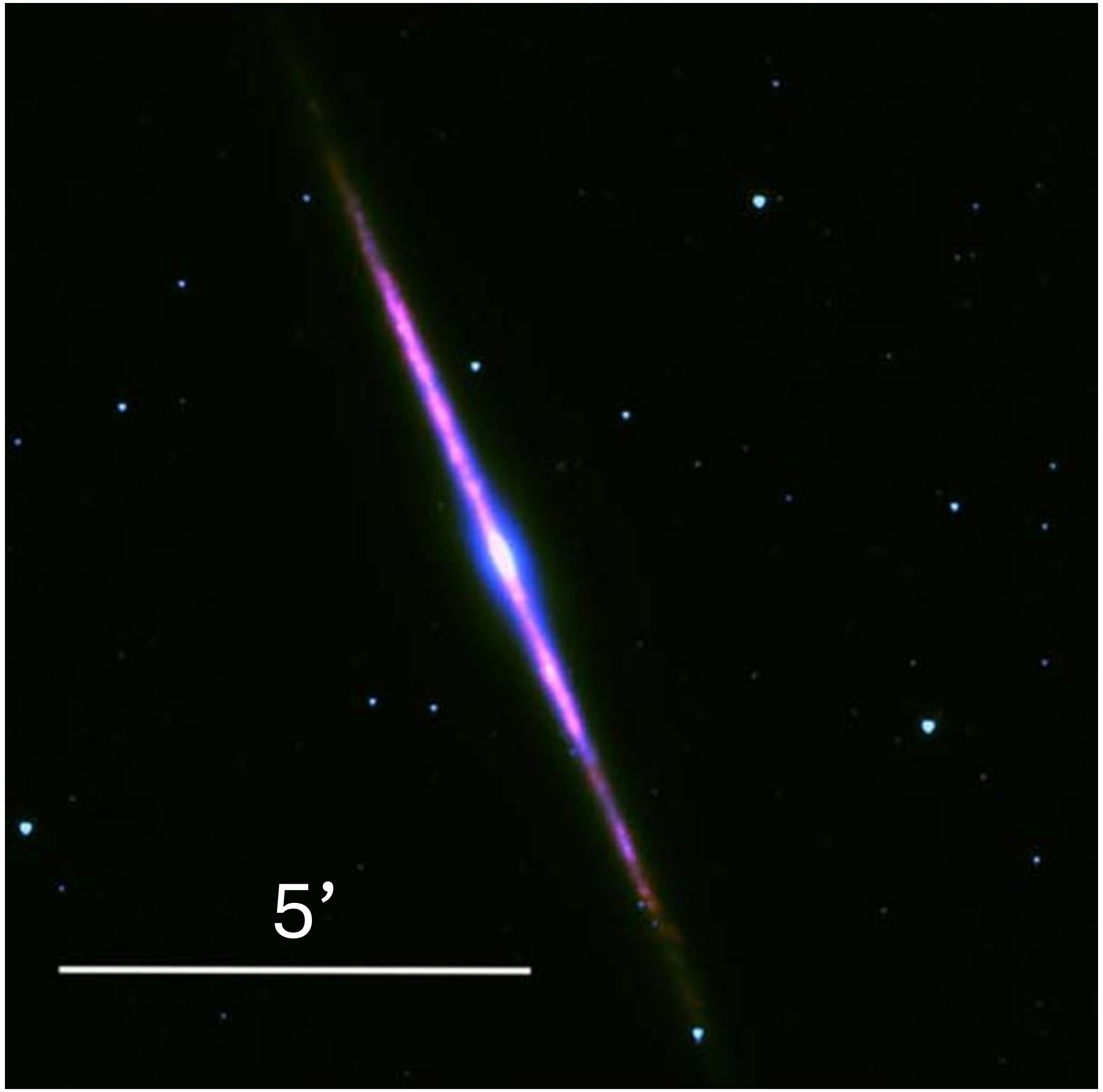
NGC 891:
Spitzer: 3.6 μ (B), 4.5 μ (G), 8 μ (red)

NGC 891: APOD Feb 28, 1997



J. C. Barentine & G. A. Esquerdo (PSI), 1.3-m Tel., Kitt-Peak, NOAO

Spitzer: 3.6 μ (B), 4.5 μ (G), 8 μ (red)



B.G. Elmegreen & D.M. Elmegreen 2020 ApJ , 895, 17

NGC 891

Spitzer 8μ unsharp mask
resolution ~ 106 pc

Gas disks are **extremely thin**:

$H = \sigma^2/\pi G \Sigma$

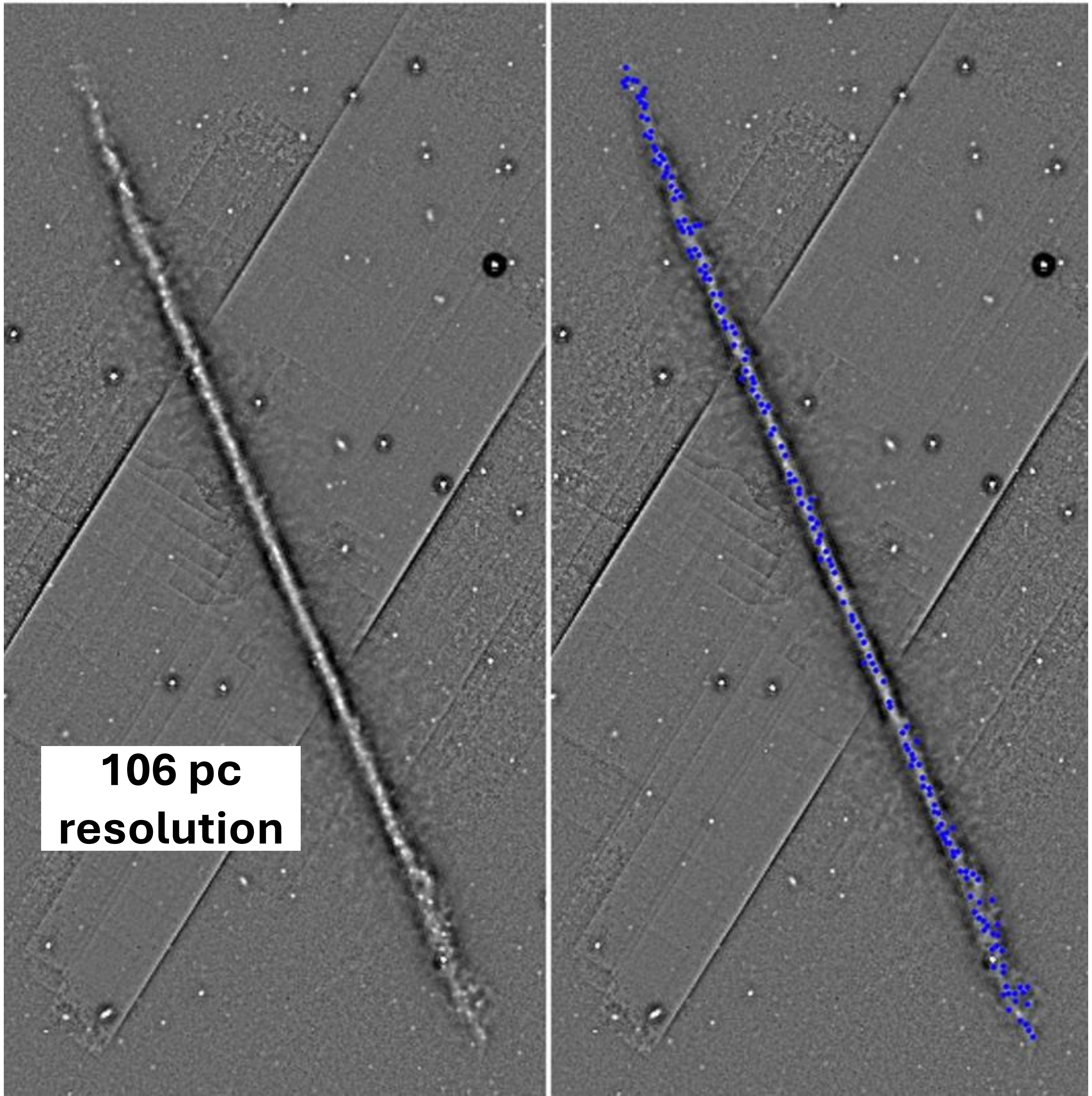
$V_{rot}^2 = GM/R = G\pi R \Sigma_{gal}$

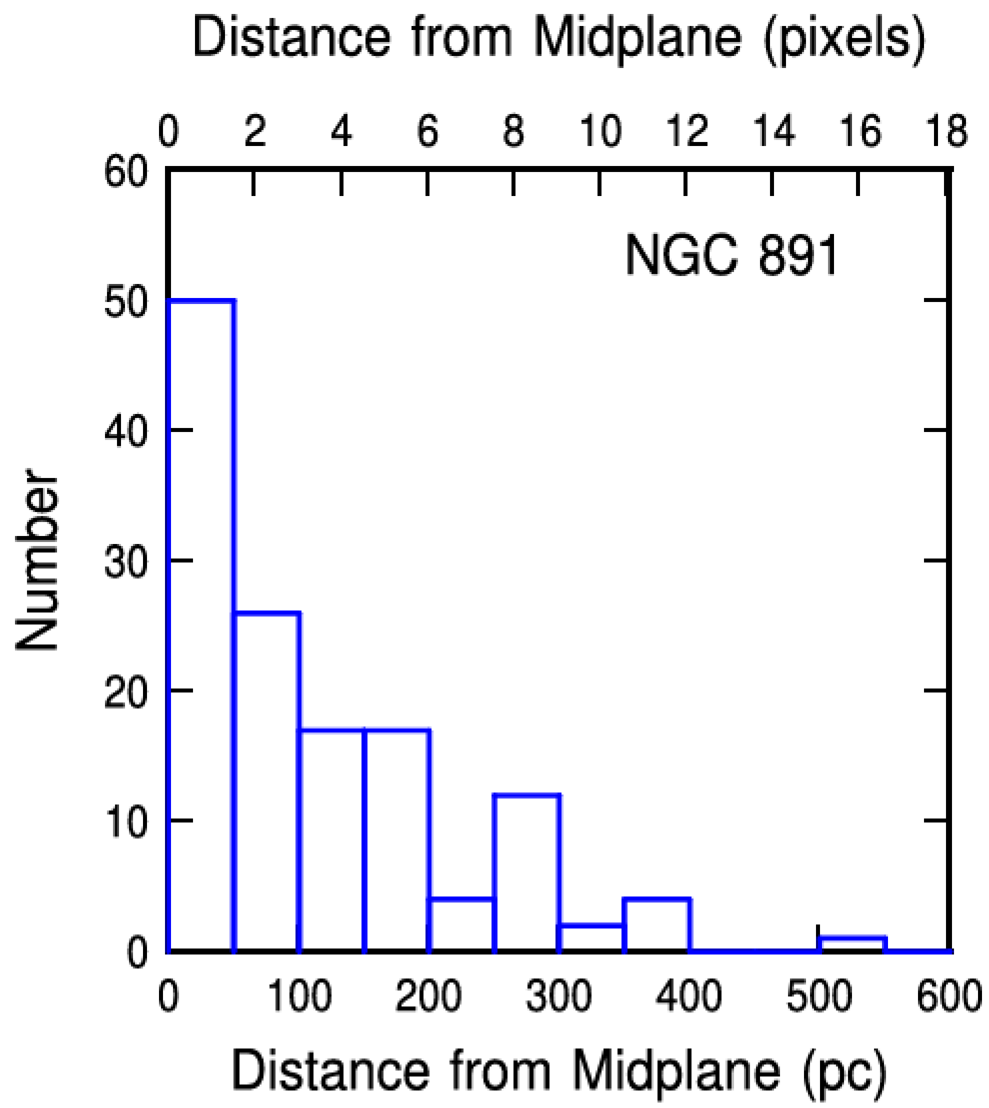
$\rightarrow H/R \sim \sigma^2/V_{rot}^2 * (\Sigma_{gal}/\Sigma)$

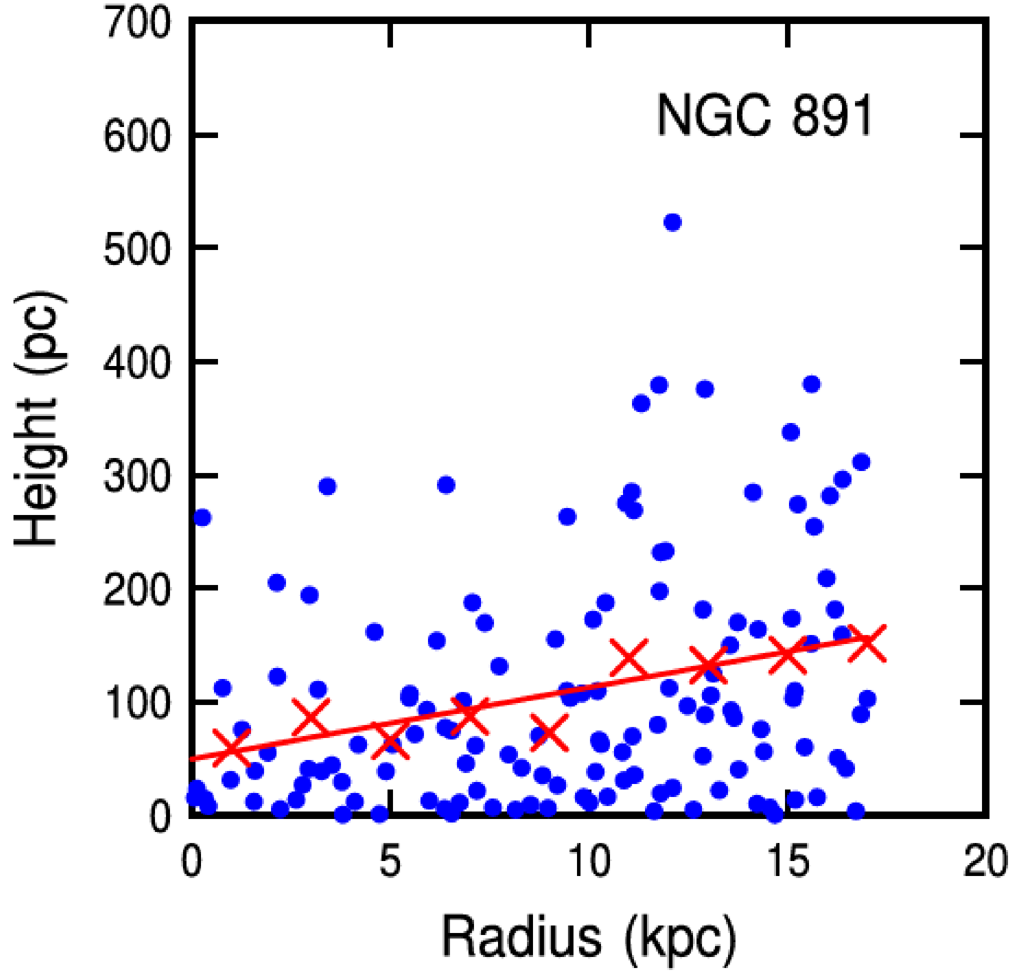
$\sim 10^2/200^2 * \text{few} = 0.0025 * \text{few}$

173 point sources identified

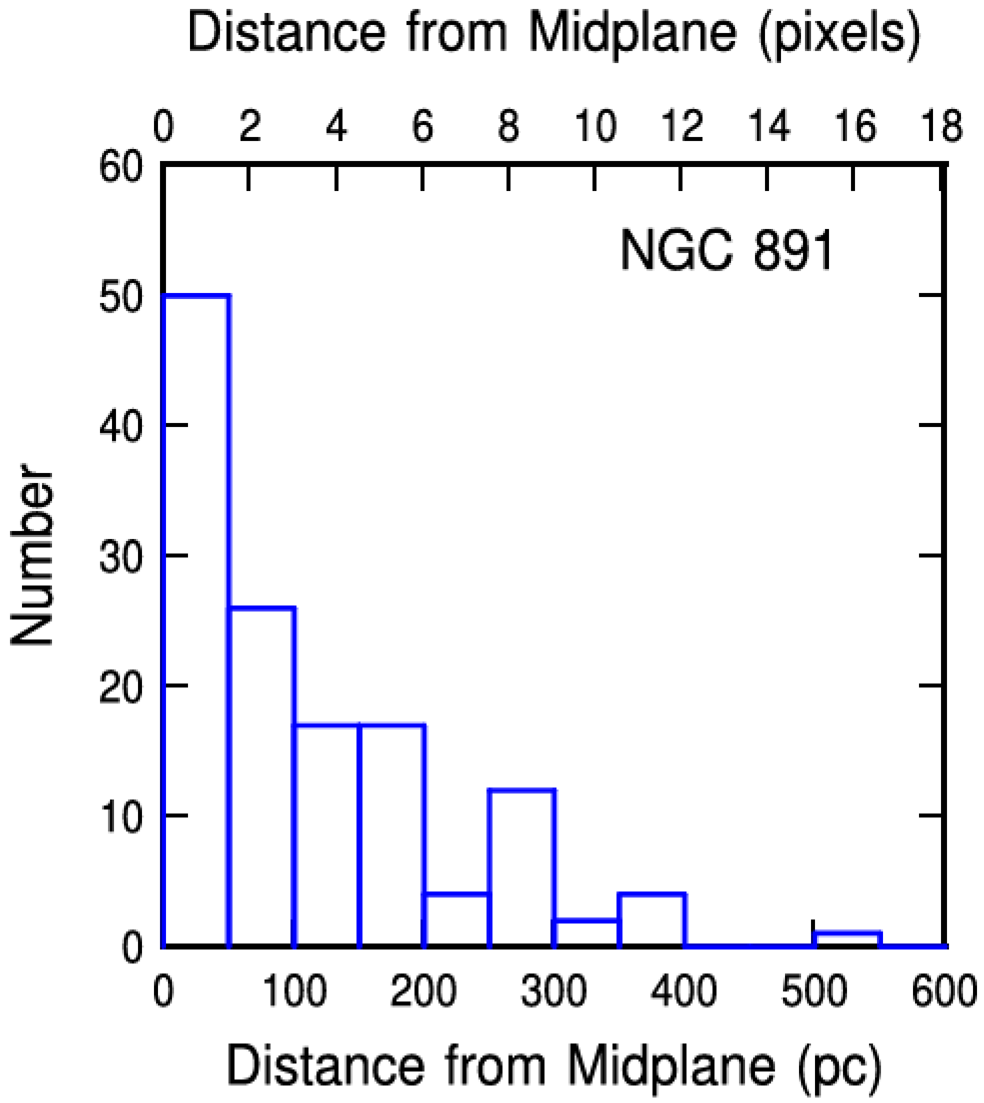
B.G. Elmegreen & D.M. Elmegreen 2020 ApJ , 895, 17

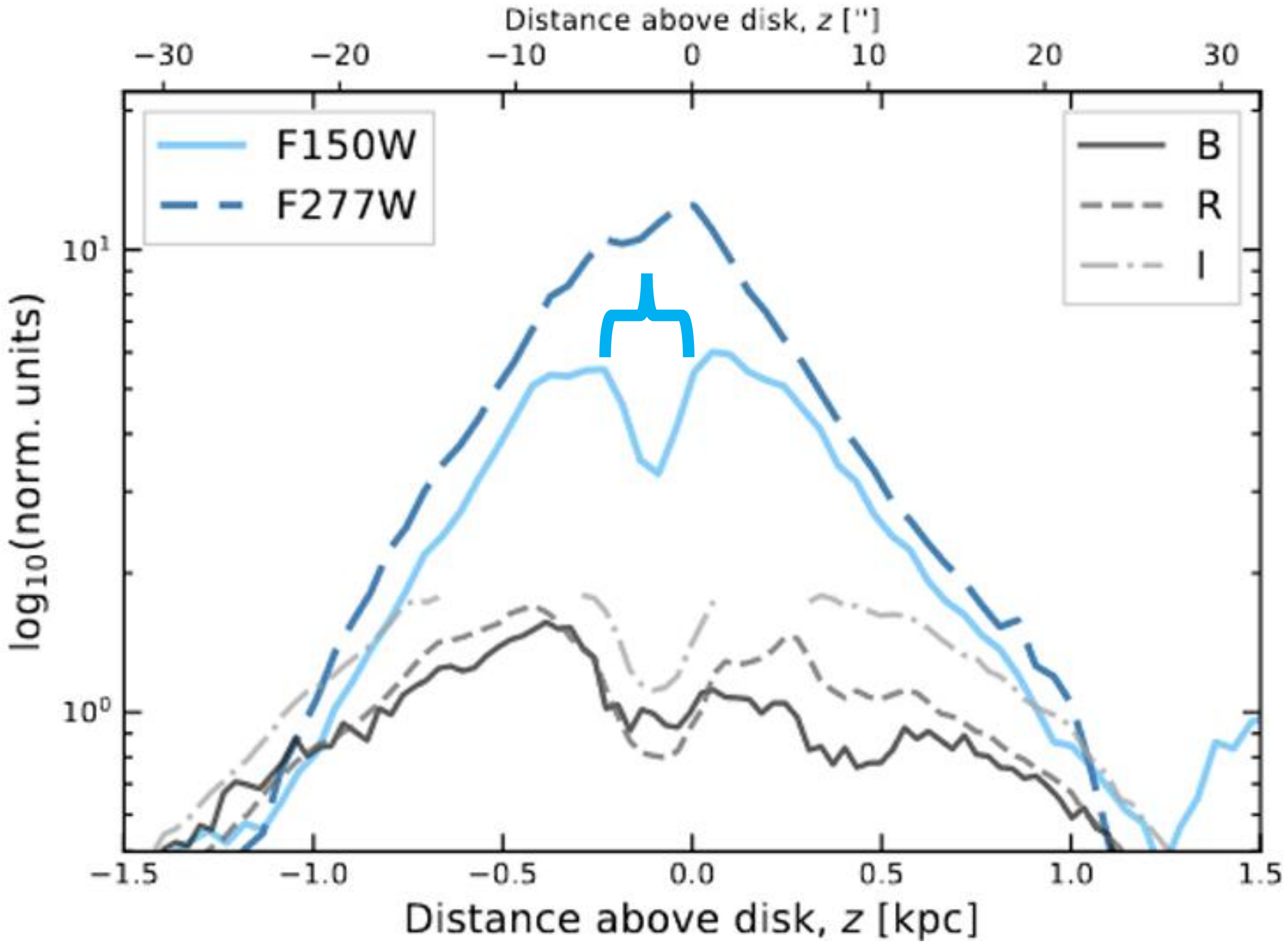






B.G. Elmegreen & D.M. Elmegreen 2020 ApJ , 895, 17





B.G. Elmegreen & D.M. Elmegreen 2020 ApJ , 895, 17

NGC 891 JWST: Chastenet +24

Direct measurements of gas HWHM in **edge-on galaxies**:

Milky Way: dense **CO ~50 pc** inside the solar circle (Heyer & Dame '15).
diffuse CO (detected only in ^{12}CO) ~50% thicker (Roman-Duval+16).

NGC 891: **CO ~110 pc** (Scoville +93) to 160 pc (Yim +11)
8μ cores ~105 pc (Elmegreen & Elmegreen '20).
DIG and **vertical Hα filaments: ~1 kpc** (Dettmar '90; Rand +90; Howk & Savage '00; Rossa +04).
CO thick disk (Garcia-Burillo +92; maybe not: Yim +11),
HI ~435 pc or 325 pc + 1 kpc fits (Yim +11)

NGC 7331 (spiral): **CO ~50-80 pc** at mid-radius (Patra '18)

KK250 (dIrr): **H I 350 pc** (Patra '14)

IC 2233 (spiral): **H I 500 pc** (Matthews & Uson '08)

NGC 4157, NGC 4565, and NGC 5907: **CO 120 pc, 45 pc, and 50 pc**;
HI 450 pc, 180 pc, and 400 pc at 4 kpc radius (Yim +14)

Indirect measurements assuming vertical equilibrium:

HI:

Milky Way in Kalberla +07; Banerjee & Jog +11
M31 in Banerjee & Jog ‘08
20 galaxies in Bagetakos +11
4 dIrrs in Banerjee +11
superthin galaxies in Banerjee +10 and Banerjee & Jog ‘13
20 dIrrs Elmegreen & Hunter ‘15
7 spirals and 23 dwarfs in Patra ’20ab
10 dIrrs in Bacchini +20
28 H I-rich galaxies and 26 comparison galaxies in Randriamampandry +21
An ultradiffuse galaxy plus 14 dIrrs in Li +22

HI and CO:

12 spirals in Bacchini +19
32 dIrrs and spirals in Mancera Piña +22

CO:

8 spirals in Patra +19
5 ULIRGS in Wilson +19
2 starbursts at z~0.15 in Molina +20
NGC 6946: a thin component with 30% of emission at 50 pc and thick component coincident with HI, in Patra ‘21

Mancera Pina et al. 2022 MNRAS 514, 3329

32 dwarf and spiral galaxies with gas and star surface densities, bulge-disk decomposition, rotation curves: hydrostatic equilibrium: H ~ $\sigma^2 / \pi G \Sigma_{total}$

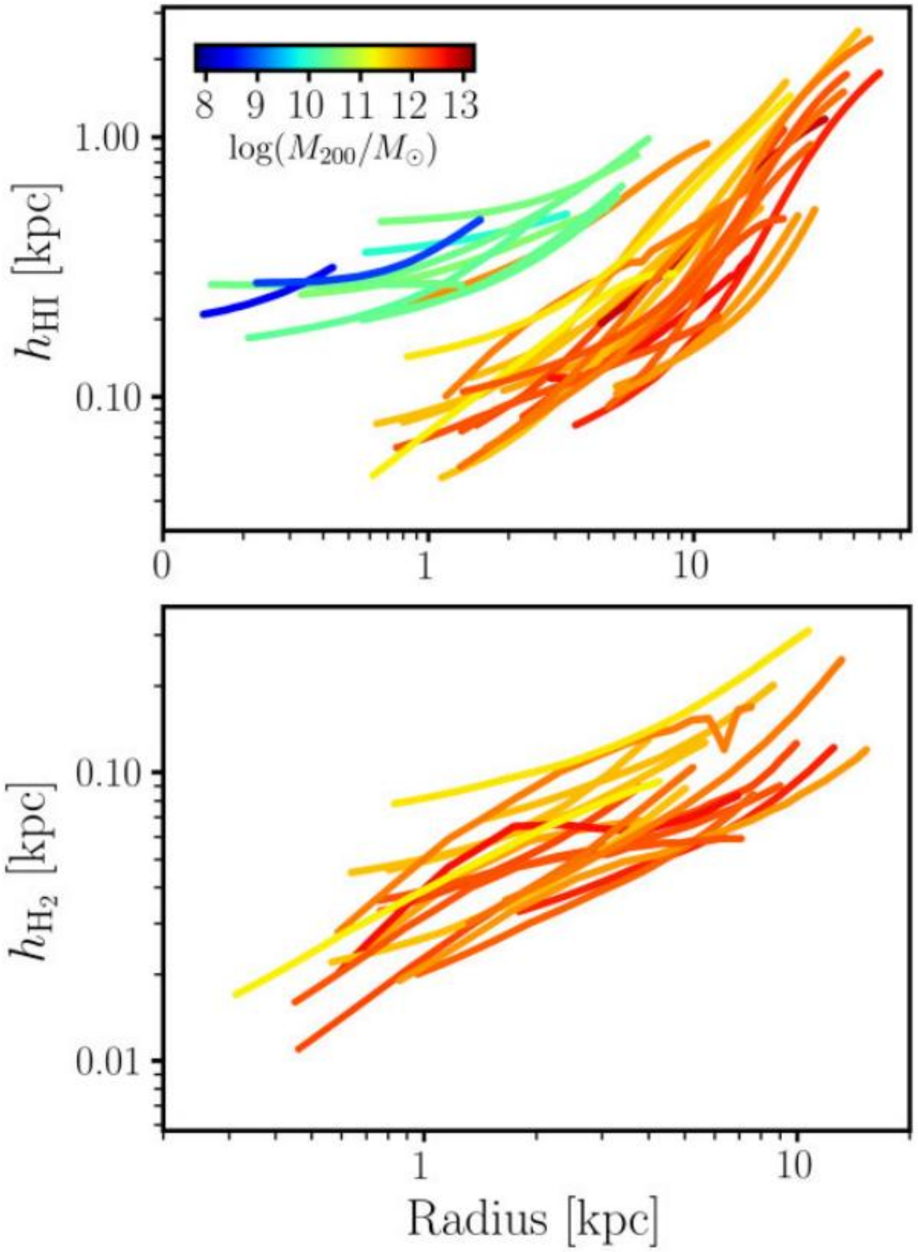
Scale Heights:

Molecular layers in spirals:
~ 30 pc at 1 kpc to ~100 pc at 10 kpc

Atomic layers in spirals:
~ 100 pc at 1 kpc to 250 pc at 10 kpc to 1 kpc at 20 kpc

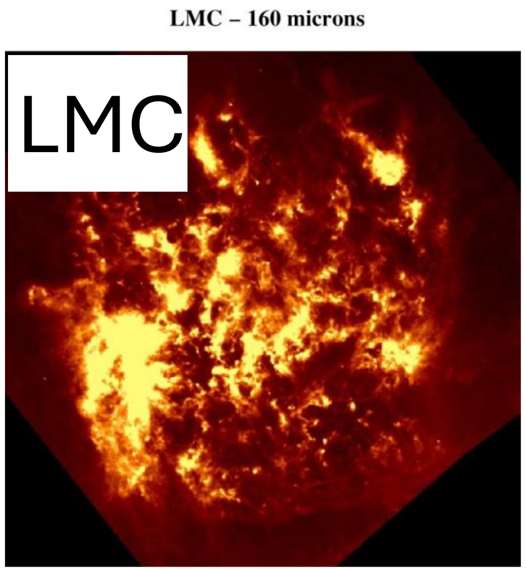
Atomic layers in dwarfs:
~ 300 pc at 1 kpc to ~500 pc at 3 kpc

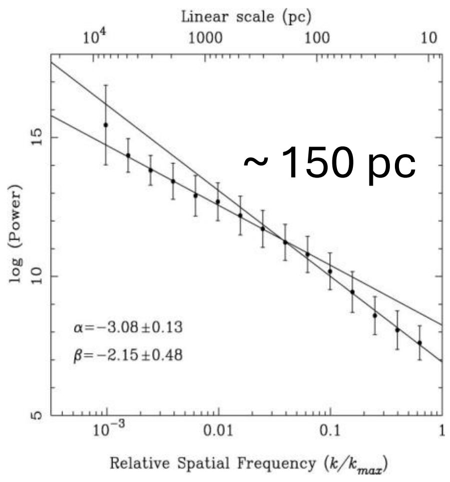
Uncertainties: magnetic &cosmic ray pressures, variability



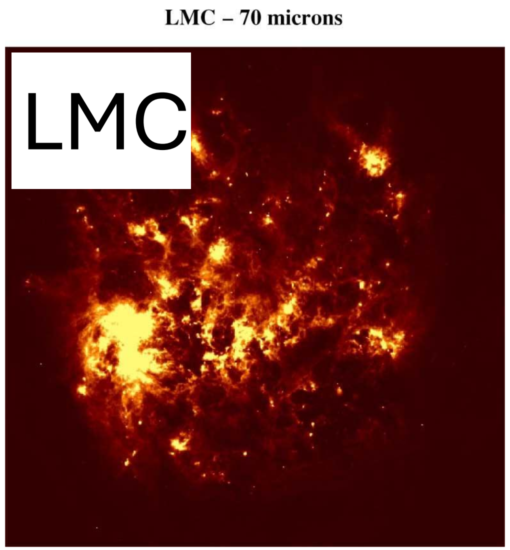
Direct measurement of thickness for a **face-on galaxy** from a **break in the power spectrum**

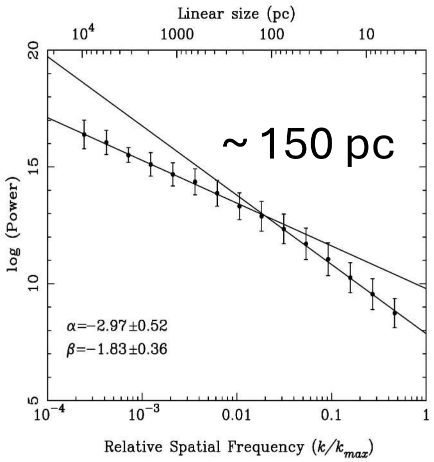
(Elmegreen et al. 2001)



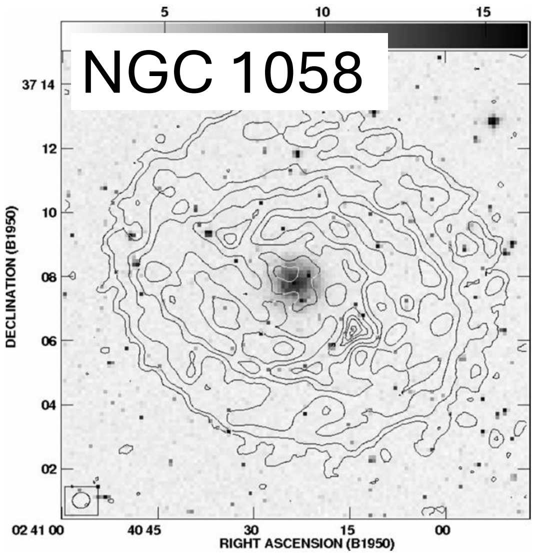


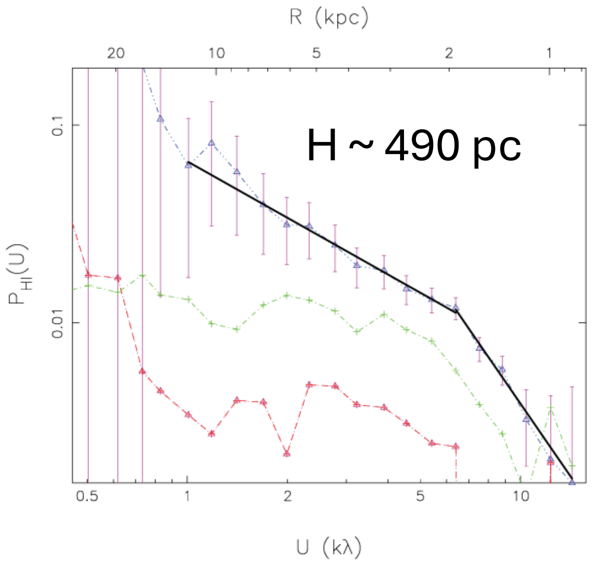
Block et al. 2010



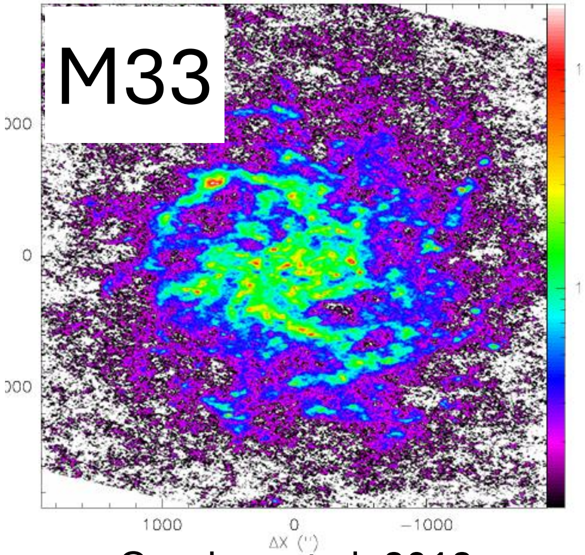


Block et al. 2010

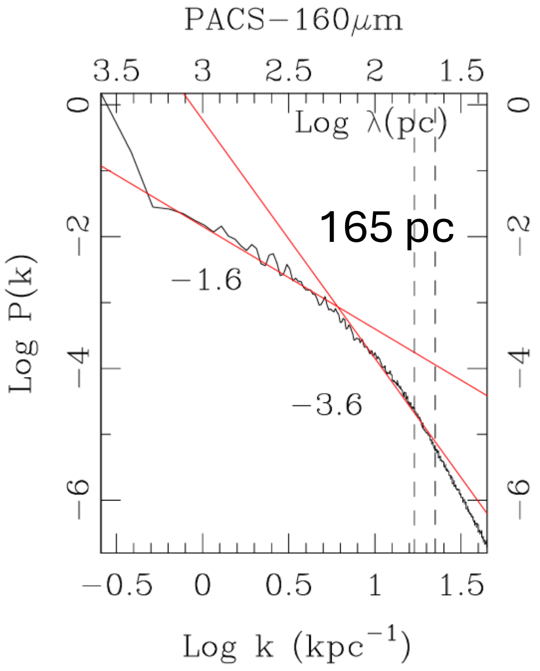




Dutta et al. 2009



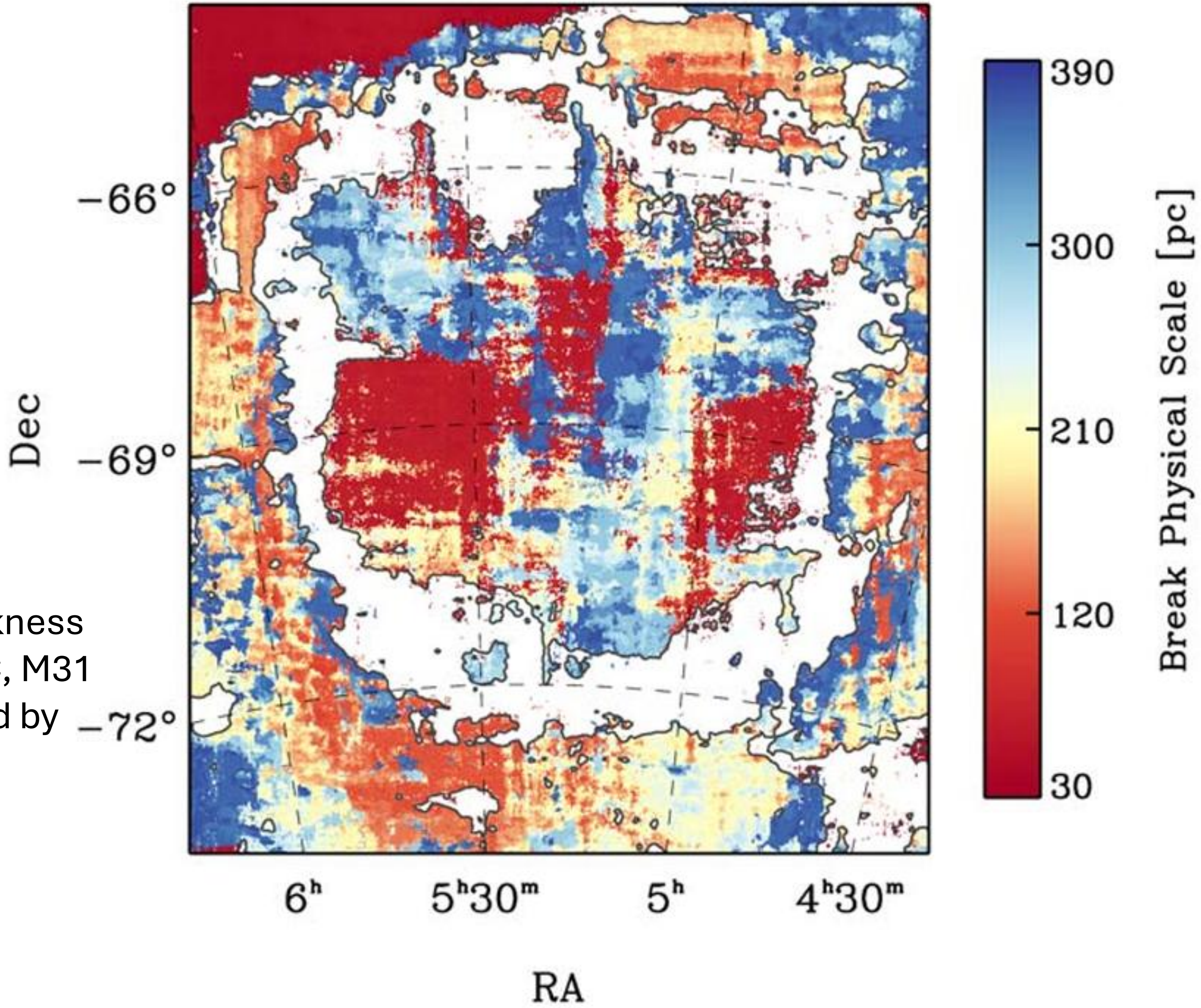
Combes et al. 2012



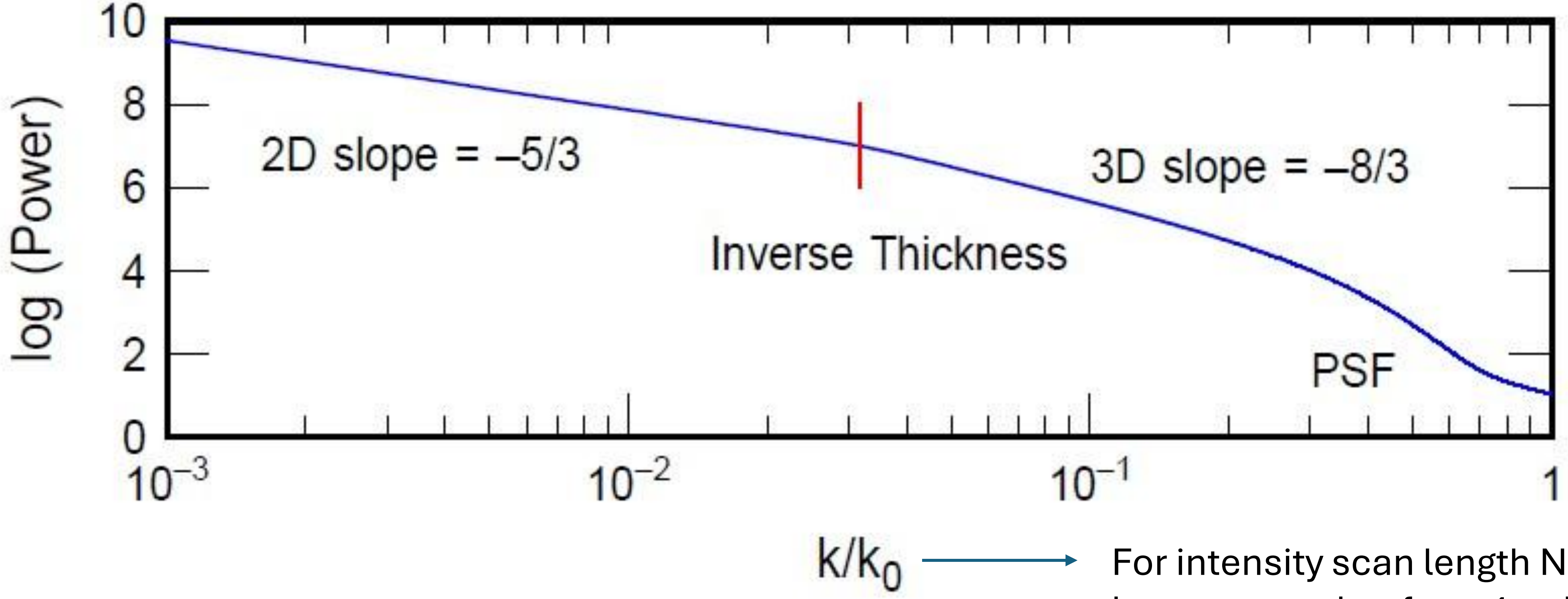
Thickness map for LMC

Szotkowski et al. 2019

*Koch et al. (2020) did not see thickness breaks from FIR maps of LMC, SMC, M31 and M33: suggest PS are dominated by PSF and exponential disks
-- discussed below



Disk thickness from a **break** in the Power Spectrum

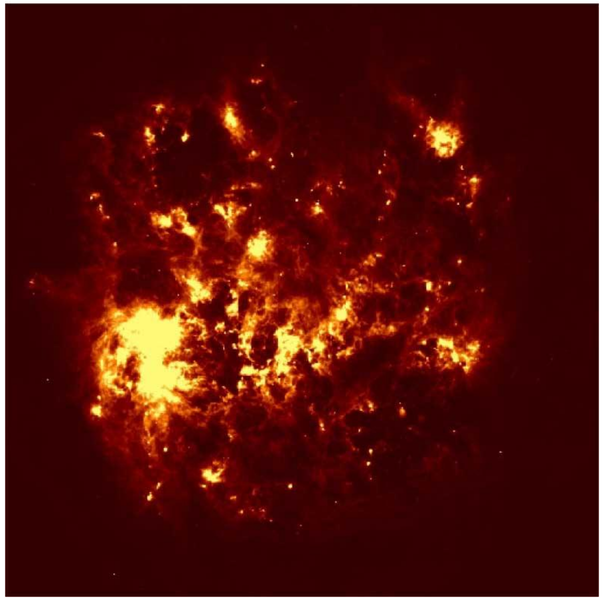


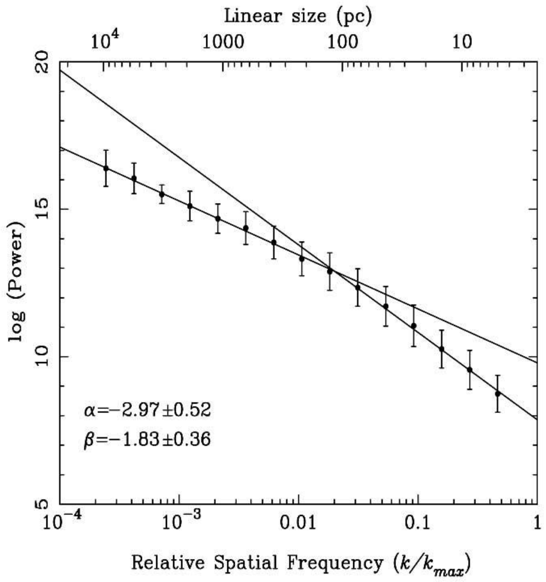
For intensity scan length N,
k = wavenumber from 1 to N/2
and k_0 = N/2

$$P(k) = S^2(k) + C^2(k) \quad \begin{cases} S(k) = \dfrac{1}{N}\displaystyle\sum_{m=1}^{N} I(m)\sin(2\pi km/N), \\ C(k) = \dfrac{1}{N}\displaystyle\sum_{m=1}^{N} I(m)\cos(2\pi km/N) \end{cases}$$

Observe: two-part power spectrum of Spitzer 70 mu in the LMC - Block et al. 2010

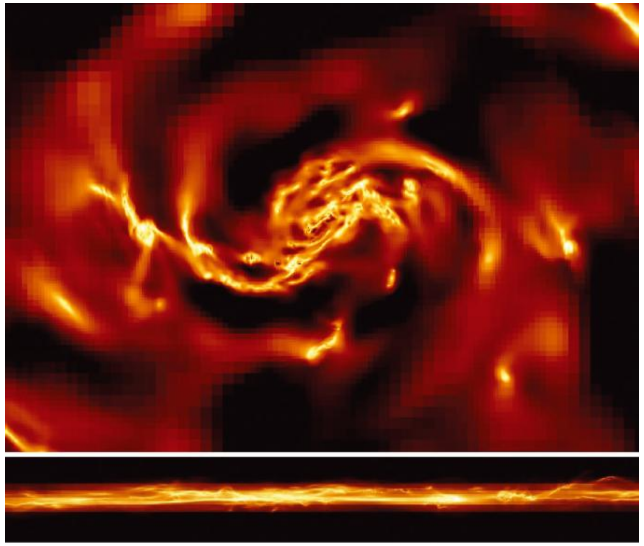
LMC – 70 microns

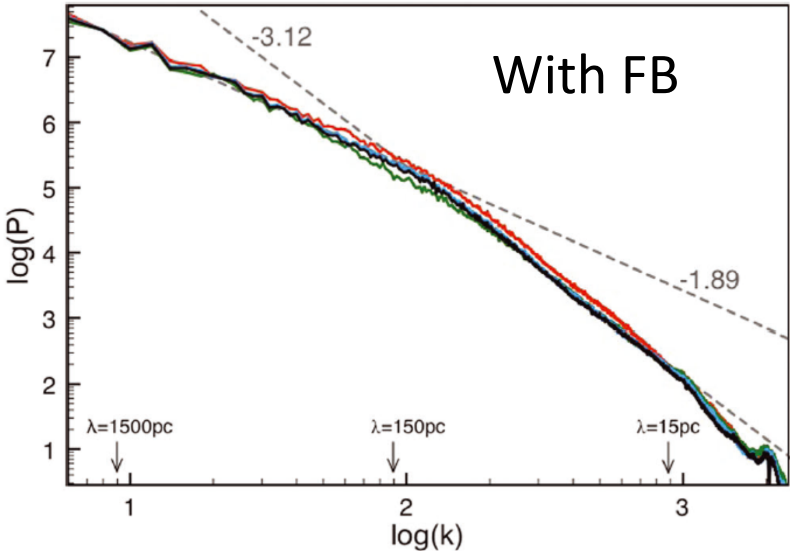


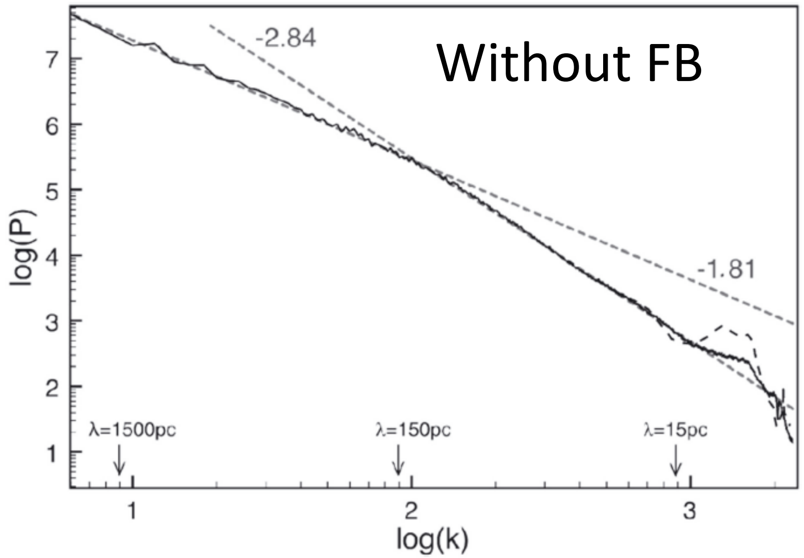


HD model of LMC with 0.8 pc resolution without and with feedback

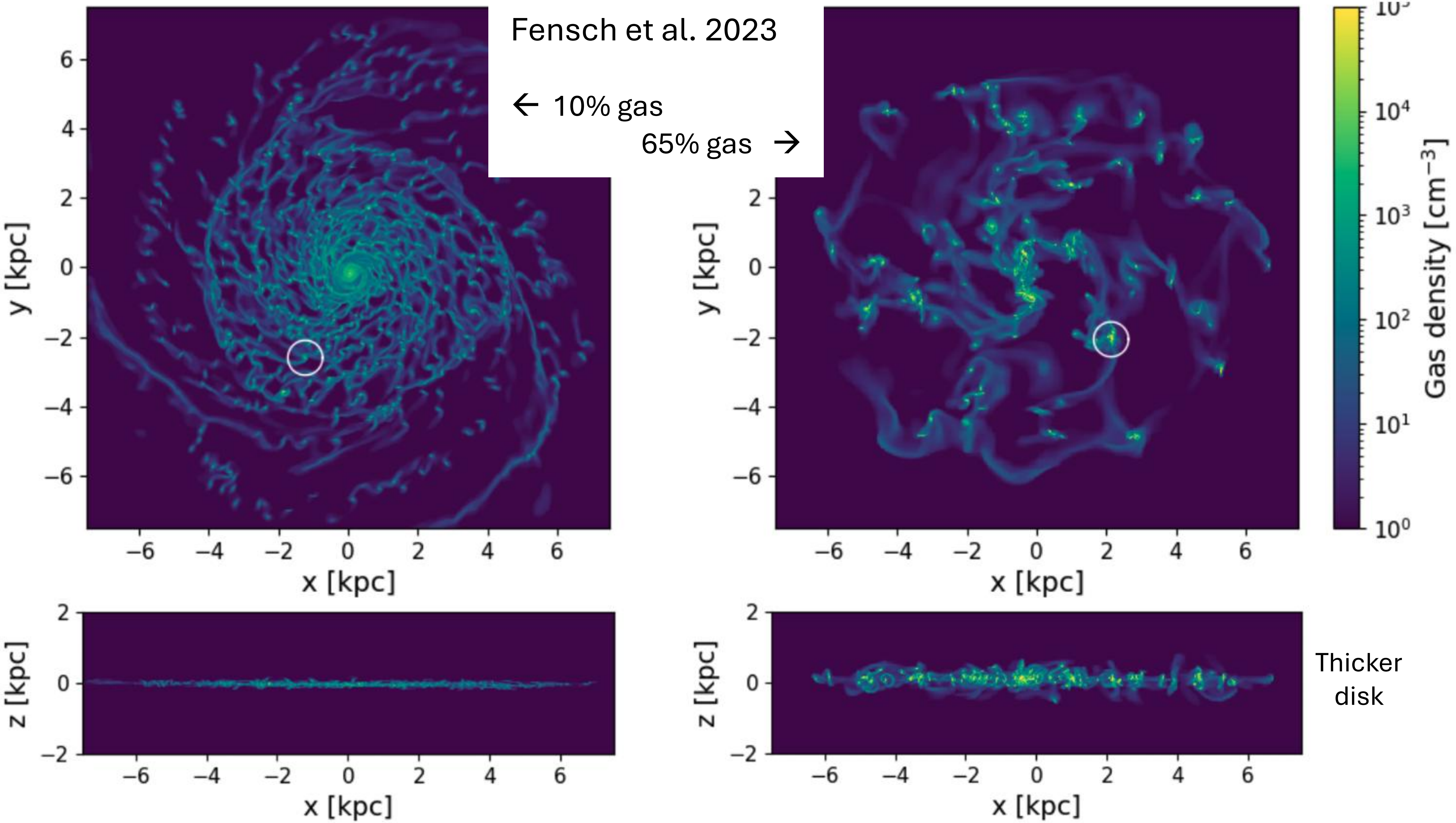
- Bournaud et al. 2010





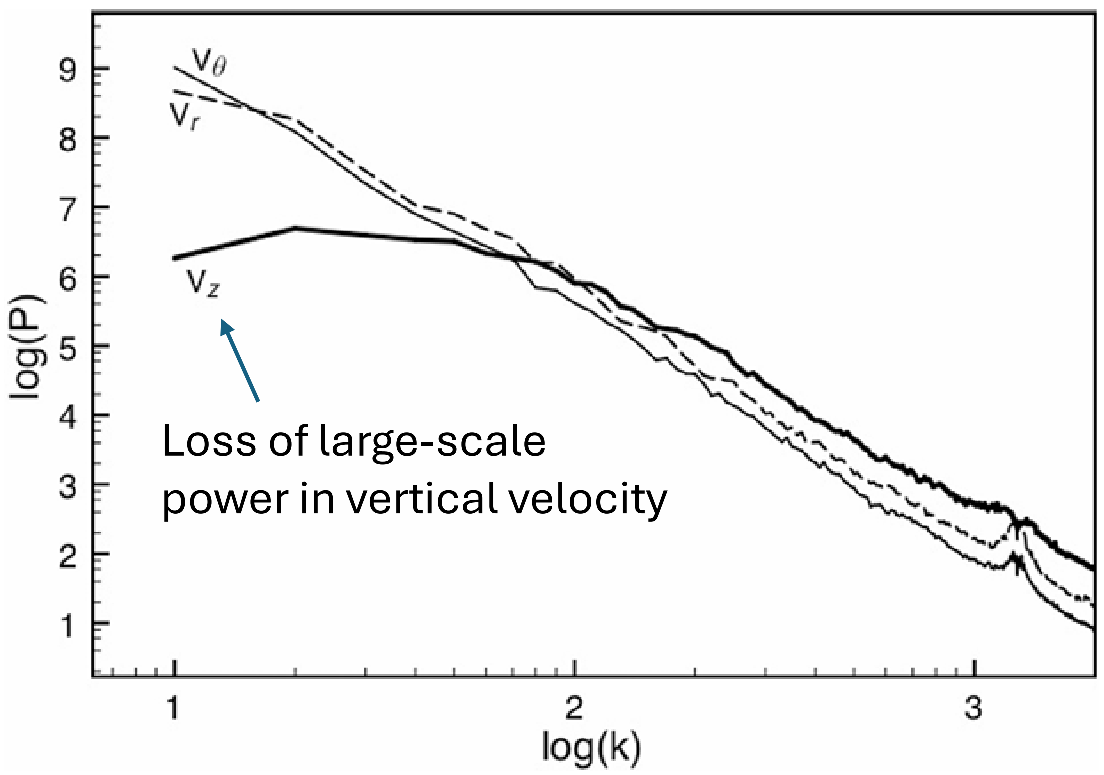


→ **Independent of FB**, so the structure is from **gravity**

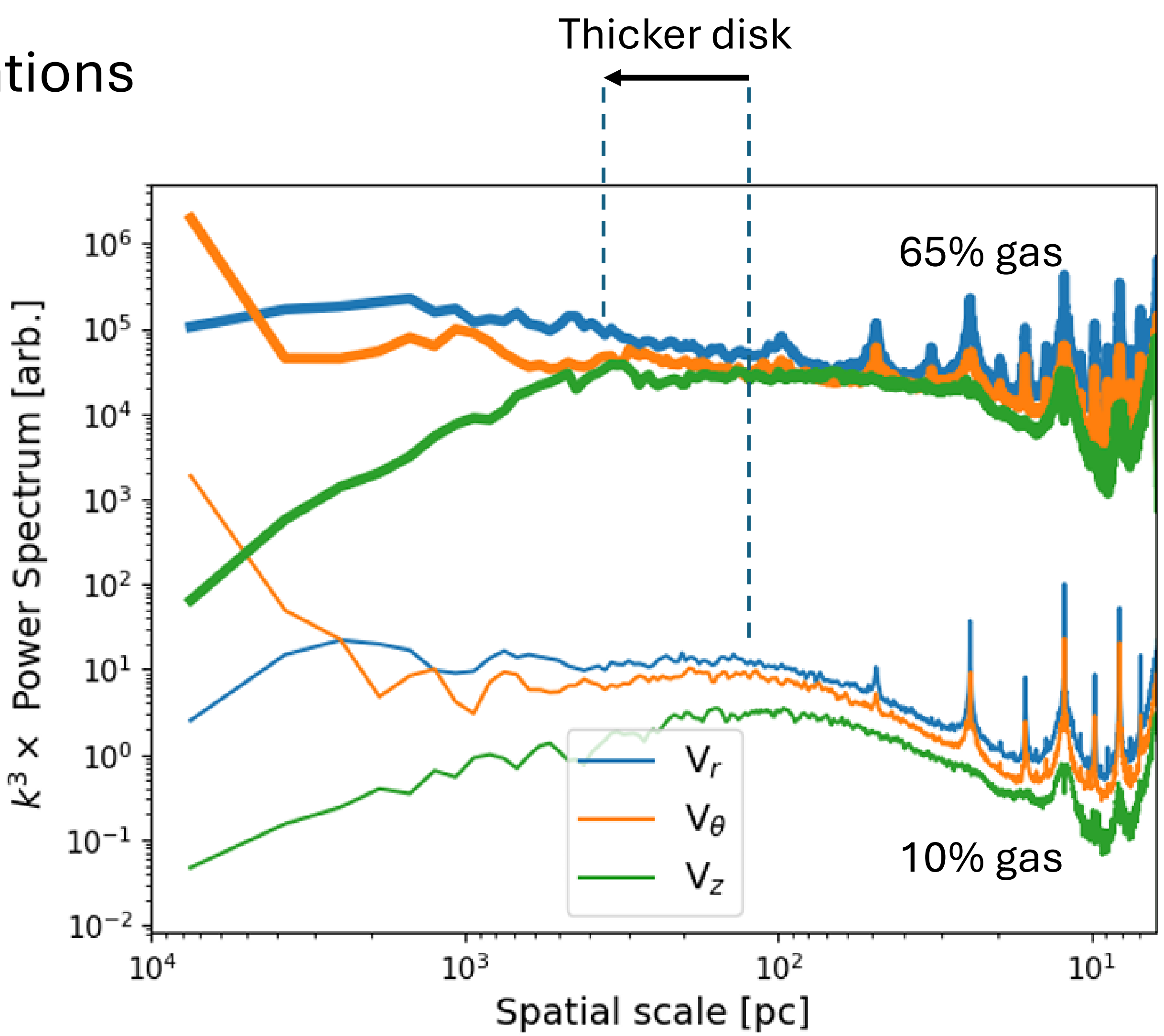


Fensch et al. 2023
← 10% gas
65% gas →
y [kpc]
x [kpc]
z [kpc]
Gas density [cm⁻³]
Thicker disk

Velocity power spectra from simulations



Bournaud et al. 2010



Fensch et al. 2023

Constraints on the Power Spectrum Method for Disk Thickness

- Must spatially resolve the galaxy thickness by a factor of ~10 so the power spectrum to the right of the break can be recognized
  - For a thickness of 100 pc, need galaxy distance < 2.1 Mpc/(resolution in arcsec)
- The galaxy has to be larger than the thickness by a factor of ~10 so the power spectrum to the left of the break can be recognized
  - Rules out most dwarf galaxies, which are intrinsically thick

These two constraints are almost mutually exclusive for arcsec resolution
aside from M33 and M31, most thin galaxies (spirals) are > 2 Mpc

- The emission has to come from a multiscale structure, such as turbulent gas

There are also **many studies** of galaxy power spectra (HI, CO, and/or IR) **without** thickness measurements (only the large-scale PS slope is seen)

- SMC HI (Stanimirovic et al. 1999; Pingel et al. 2022)
- Nuclear dust in NGC 4450 and NGC 4736 (Elmegreen, Elmegreen, Eberwein 2002)
- Optical structure (B-band) in 6 spiral galaxies (Elmegreen et al. 2003a,b)
- Magellanic Bridge HI (Muller et al. 2004)
- 9 dwarfs (V band, Ha and HI) (Willett et al. 2005)
- DDO 210 HI (Begum et al. 2006)
- NGC 628 HI (Dutta et al. 2008)
- And IV, NGC 628, UGC 4459, GR 8,DDO 210, NGC 3741 (Dutta et al. 2009) → **Larger SFR has steeper slope**s
- NGC 4254 HI (Dutta et al. (2010) → **harassed galaxy with steeper slope in outer part**
- 24 dwarf irregulars HI (Zhang et al. 2012) → **slopes depend on SFR but not on SFR/Area: non-stellar sources drive turbulence** (same conclusion by Nestingen-Palm et al. 2017 for SMC)
- 18 spirals HI (Dutta et al. 2013)
- 6 spirals HI (Grisdale et al. 2017)
- NGC 5236 HI (Nandakumar & Dutta (2020)
- NGC 6946 HI (Nandakumar & Dutta 2023) → **driving scale > 6 kpc**

POWER SPECTRA OF JWST IMAGES OF LOCAL GALAXIES: SEARCHING FOR DISK THICKNESS

BRUCE G. ELMEGREEN [1], ANGELA ADAMO [2], VARUN BAJAJ [3], ANA DUARTE-CABRAL [4], DANIELA CALZETTI [5], MICHELE CIGNONI [6,7,8], MATTEO CORRENTI [9,10], JOHN S. GALLAGHER, III [11], KATHRYN GRASHA* [12,13], BENJAMIN GREGG [5], KELSEY E. JOHNSON [14], SEAN T. LINDEN [15], MATTEO MESSA [6], GÖRAN ÖSTLIN [2], ALEX PEDRINI [2], AND JENNA RYON [3]

2025 Open Journal of Astrophysics, 8, 21

https://i.pinimg.com/originals/9e/56/d5/9e56d5ce1360ec5ea8553ec878fdc1c4.jpg
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https://www.free-photos.biz/images/nature/galaxies/thumb/starburst_in_ngc_4449__captured_by_the_hubble_space_telescope_.jpg
https://telescope.live/sites/default/files/2023-04/NGC5068%202023-04-01_int_LRGB.jpg


NGC 628


NGC 5236


NGC 4449

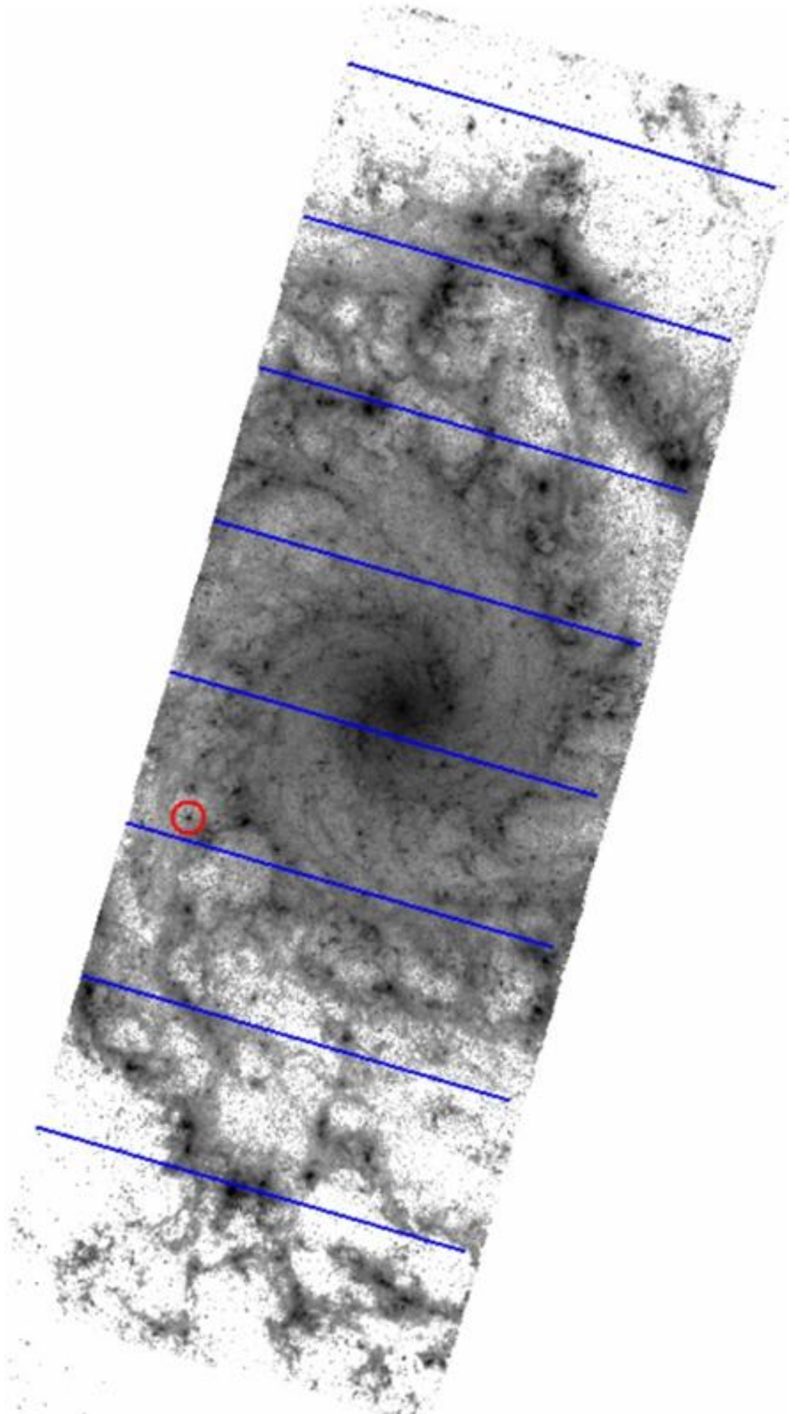

NGC 5068

FEAST SURVEY (Adamo et al.)	Distance	Source	Passbands	Pixel	FWHM (pc)
NGC 628	9.84	FEAST – JWST (Adamo +25)	F560W, F770W, F1000W, F2100W	0.08”	9.9, 12.8, 15.6, 32.1
NGC 5236	4.66	FEAST – JWST (Adamo +25)	F560W, F770W	0.08”	4.7, 6.1
NGC 4449	4.27	FEAST – JWST (Adamo +25)	F560W, F770W	0.08”	4.3, 5.6
NGC 5068	5.2	PHANGS – JWST (Lee +23)	F1000W, F2100W	0.11”	8.3, 17.0

NGC 628, F560W (5.6 microns)

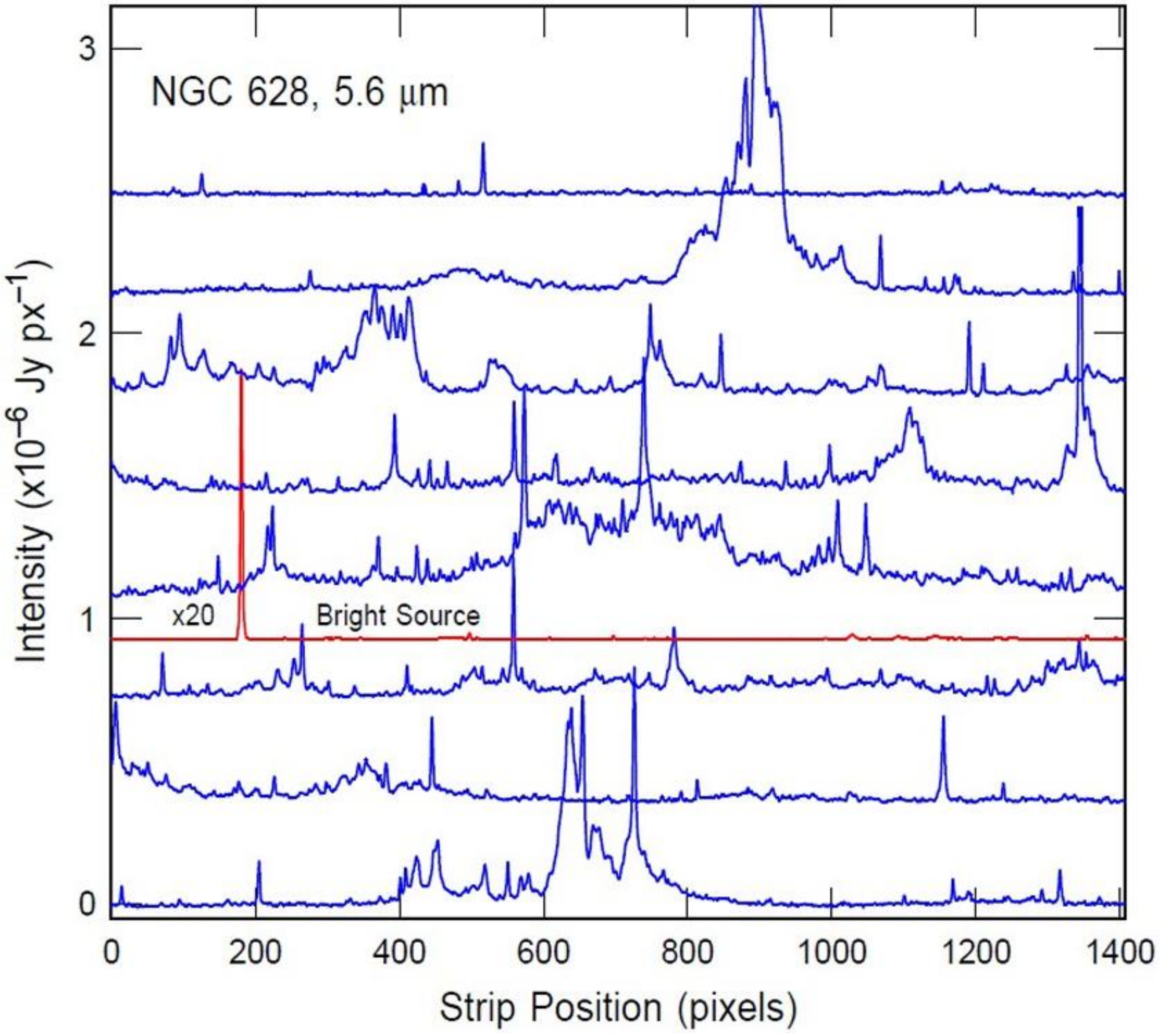
Sample scan directions for intensity

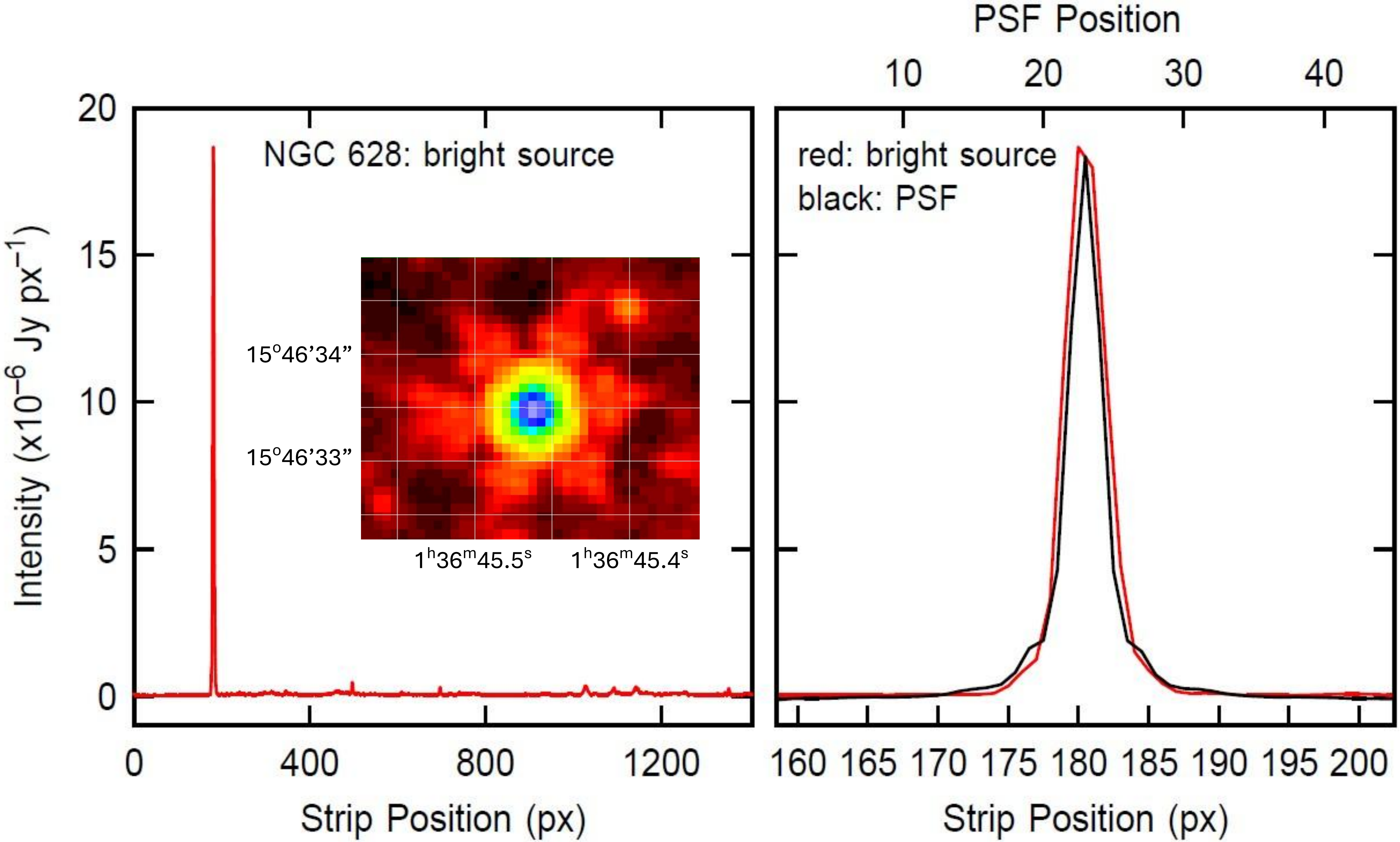
Total scans: 4055
Scan length: 1408 pixels



Corresponding intensity scans

plus a scan through the bright source at the red circle



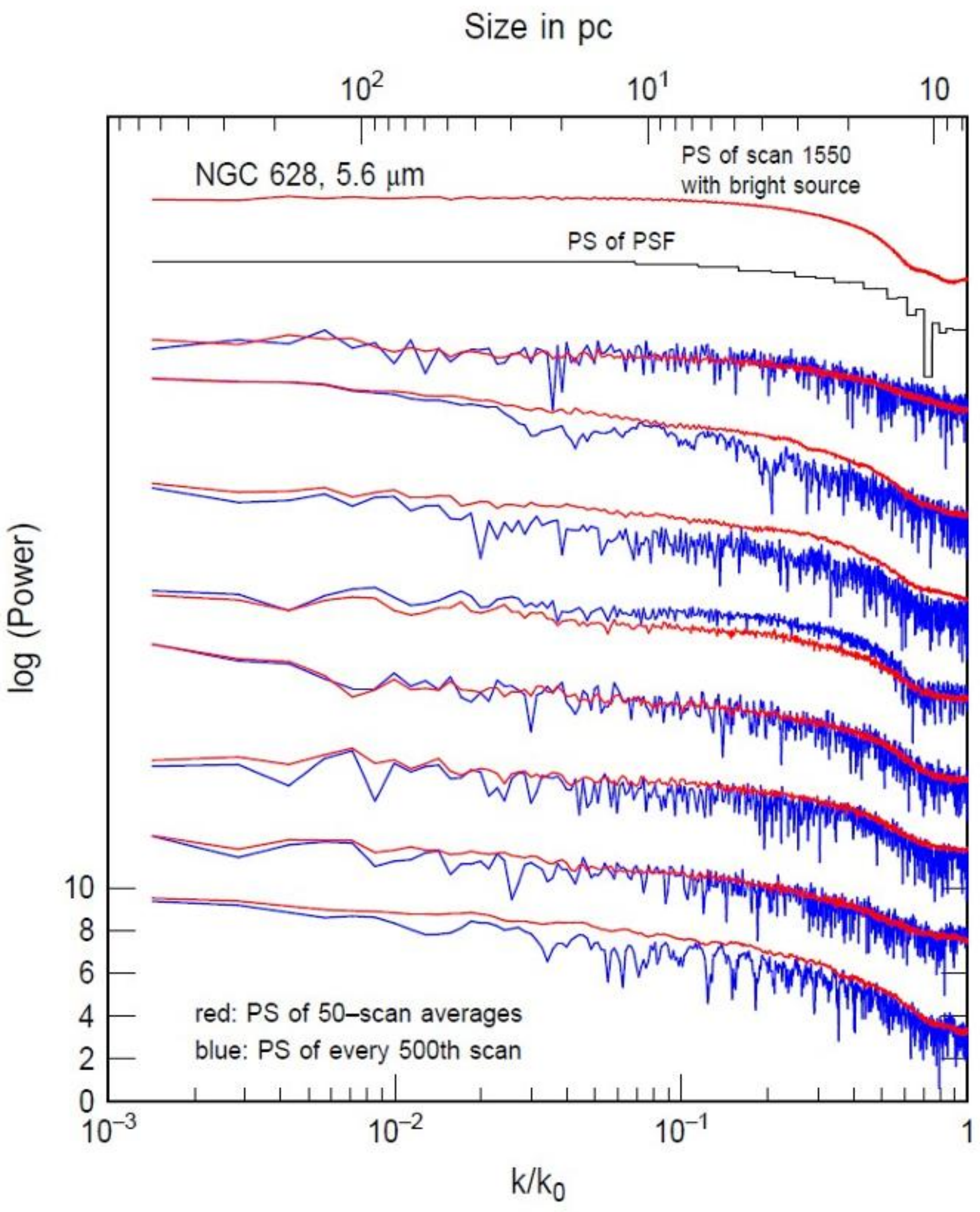


NGC 628: bright source
15°46'34"
15°46'33"
1h36m45.5s
1h36m45.4s
Intensity (x10−6 Jy px−1)
Strip Position (px)
PSF Position
red: bright source
black: PSF

Corresponding power spectra:
Blue = PS of individual scan,
Red = average of 50 PS around that one

(top) PS of the PSF (black)
(top) PS of the scan through the bright source (red)

- → All have a power law PS at low k/k0 with a steepening at high k/k0 from the PSF
- → Bright point-like sources have flat PS
- → No obvious breaks in any PS

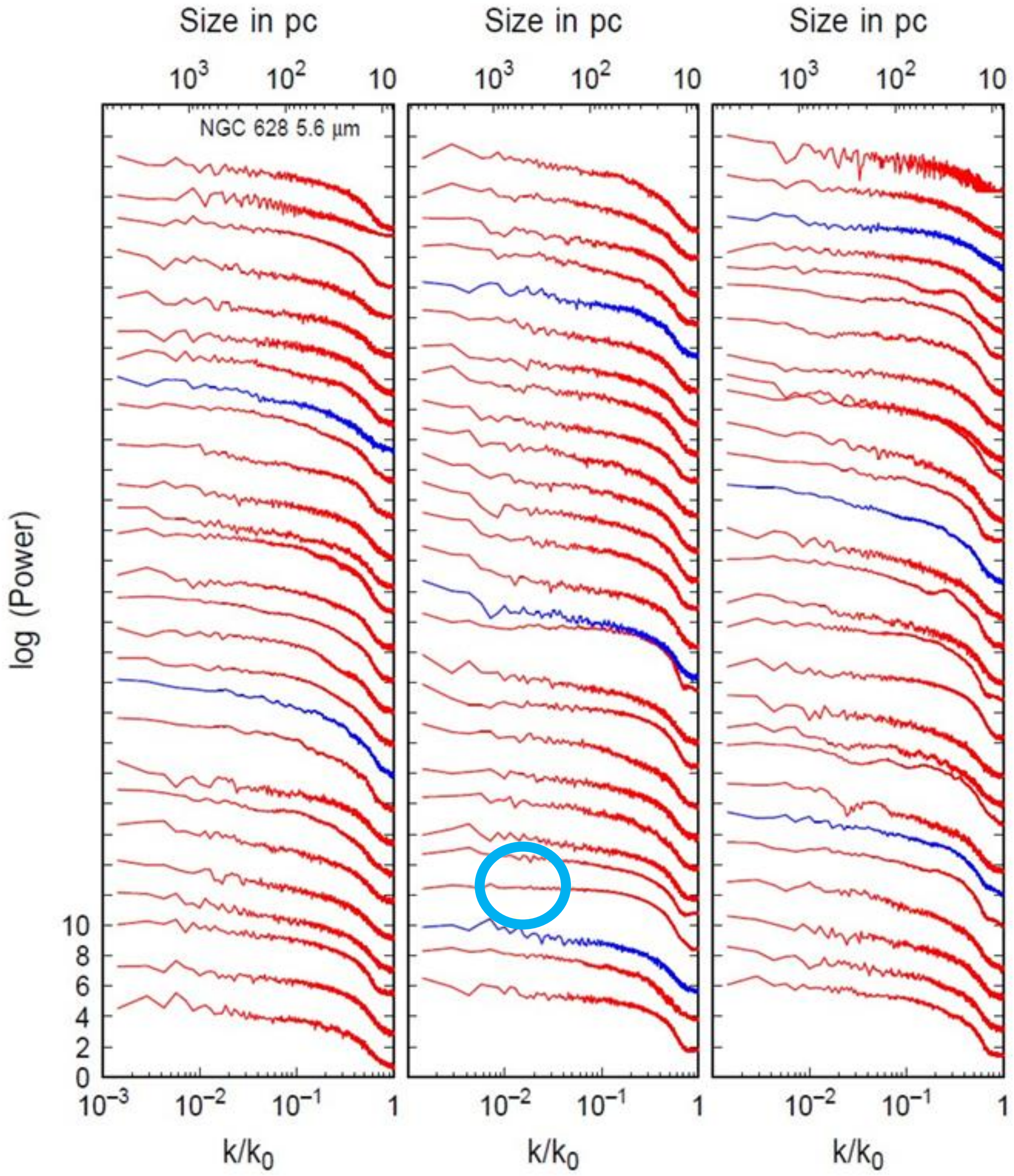


All the averages of 50 power spectra, covering whole image.

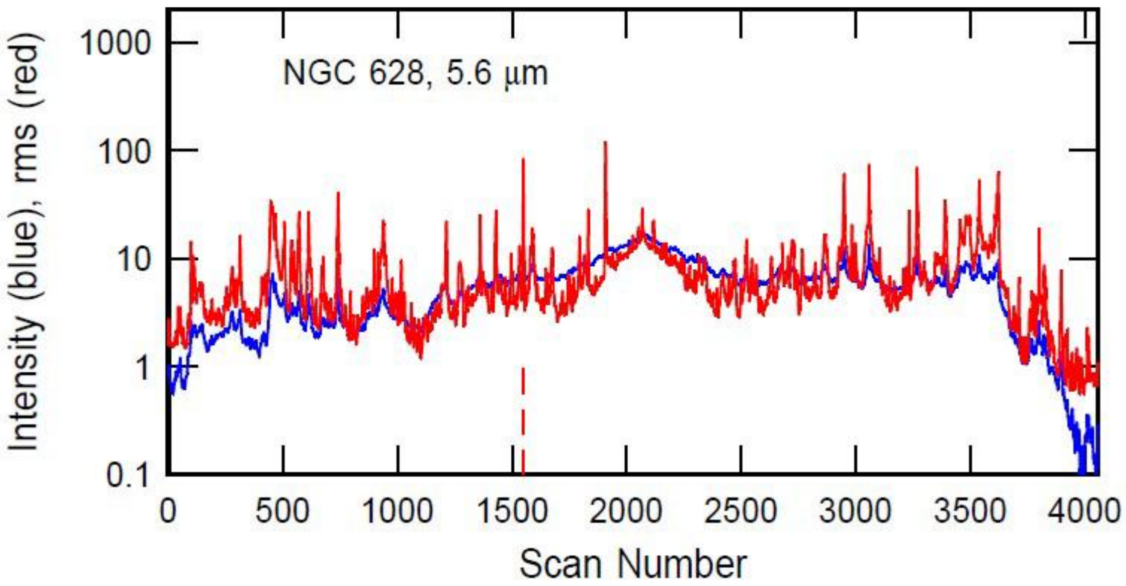
PS are flatter for averages that contain a PS from a scan with a bright point-like source

→ Scan with bright source

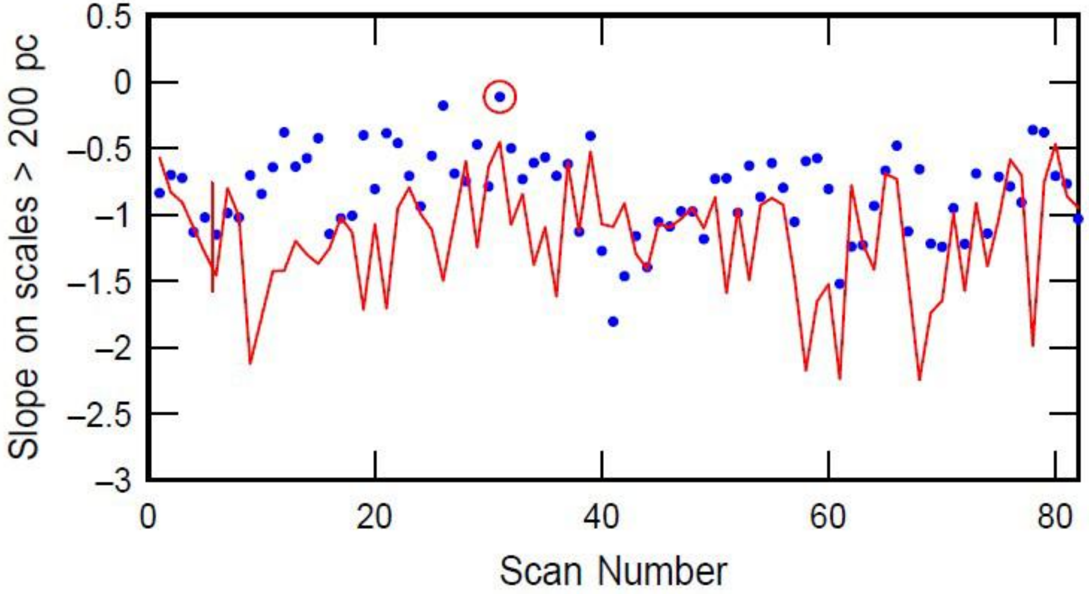
→ Variations from place to place are so large that an average PS is useless as a thickness indicator



Average intensities and rms for all scans.



PS slopes on large scales (λ>200 pc, blue) and small scales (λ<200 pc, red) for 50-PS averages



Red circle and dashed line are at the scan through the bright source (slope~0 at small k/k0)

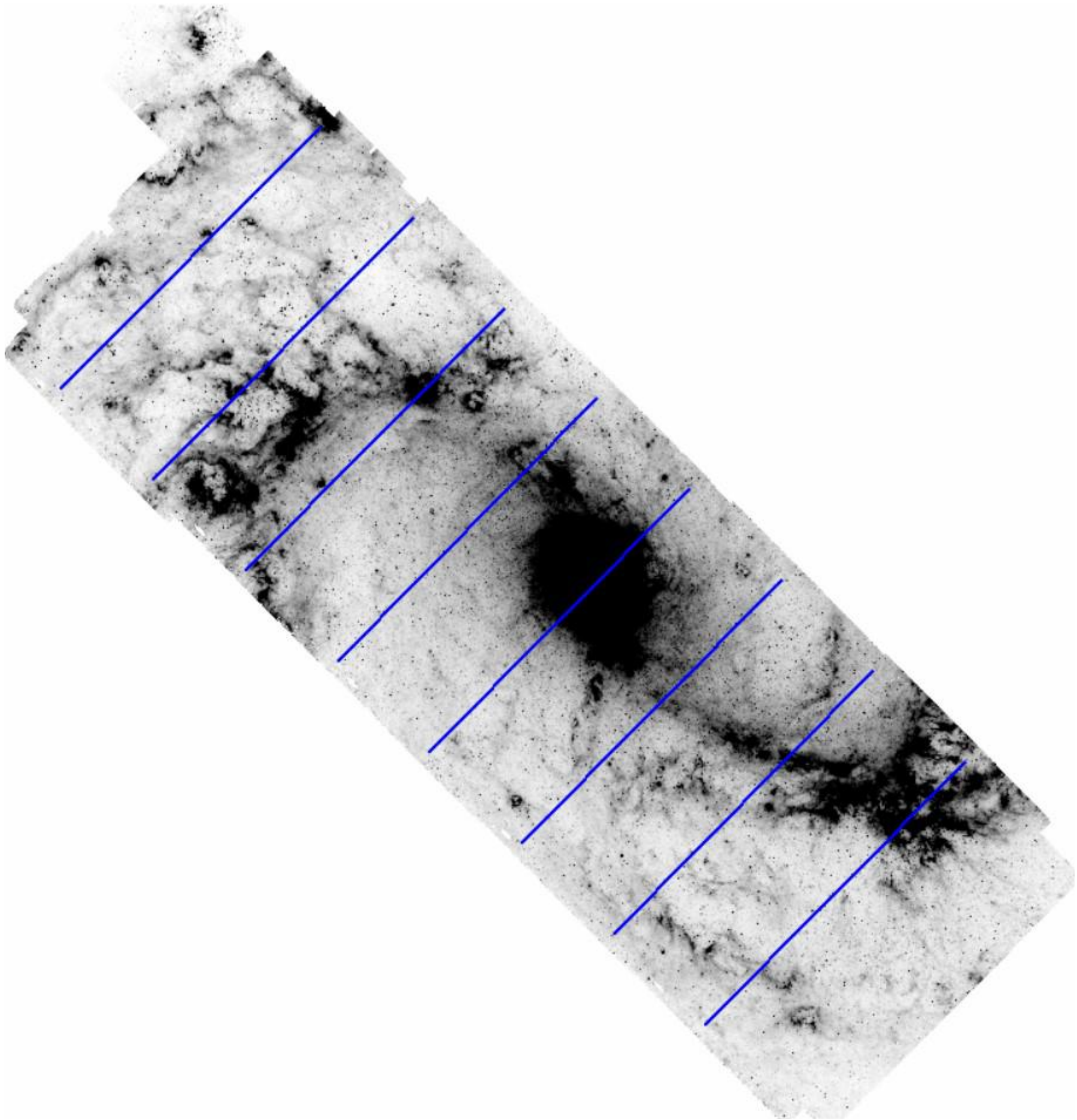
→ Large scale slope (L > 200 pc) increases near the galaxy center because the **exponential disk** profile adds to power at low k

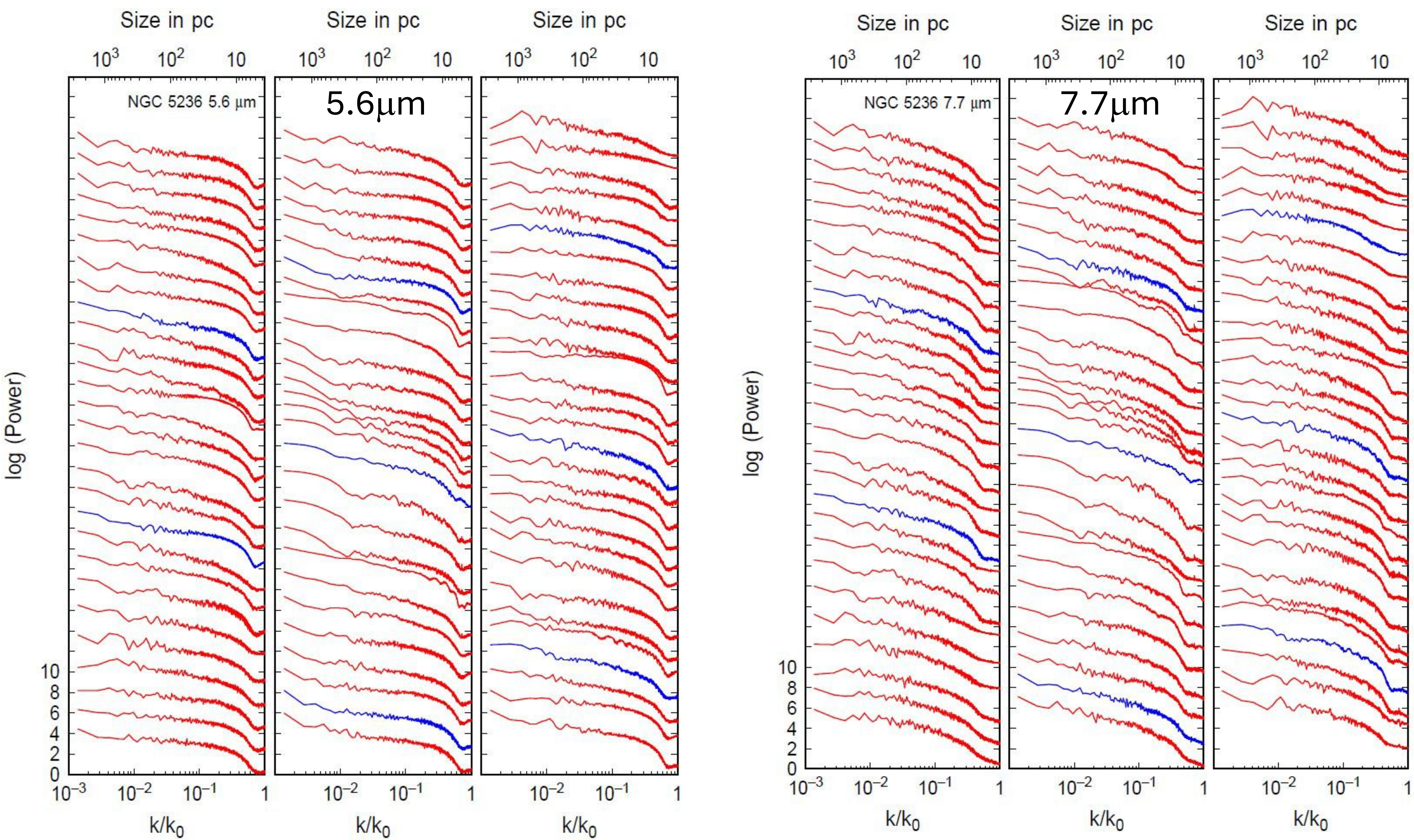
→ Slope steepens at L < 200 pc

NGC 5236, F560W (5.6 microns)

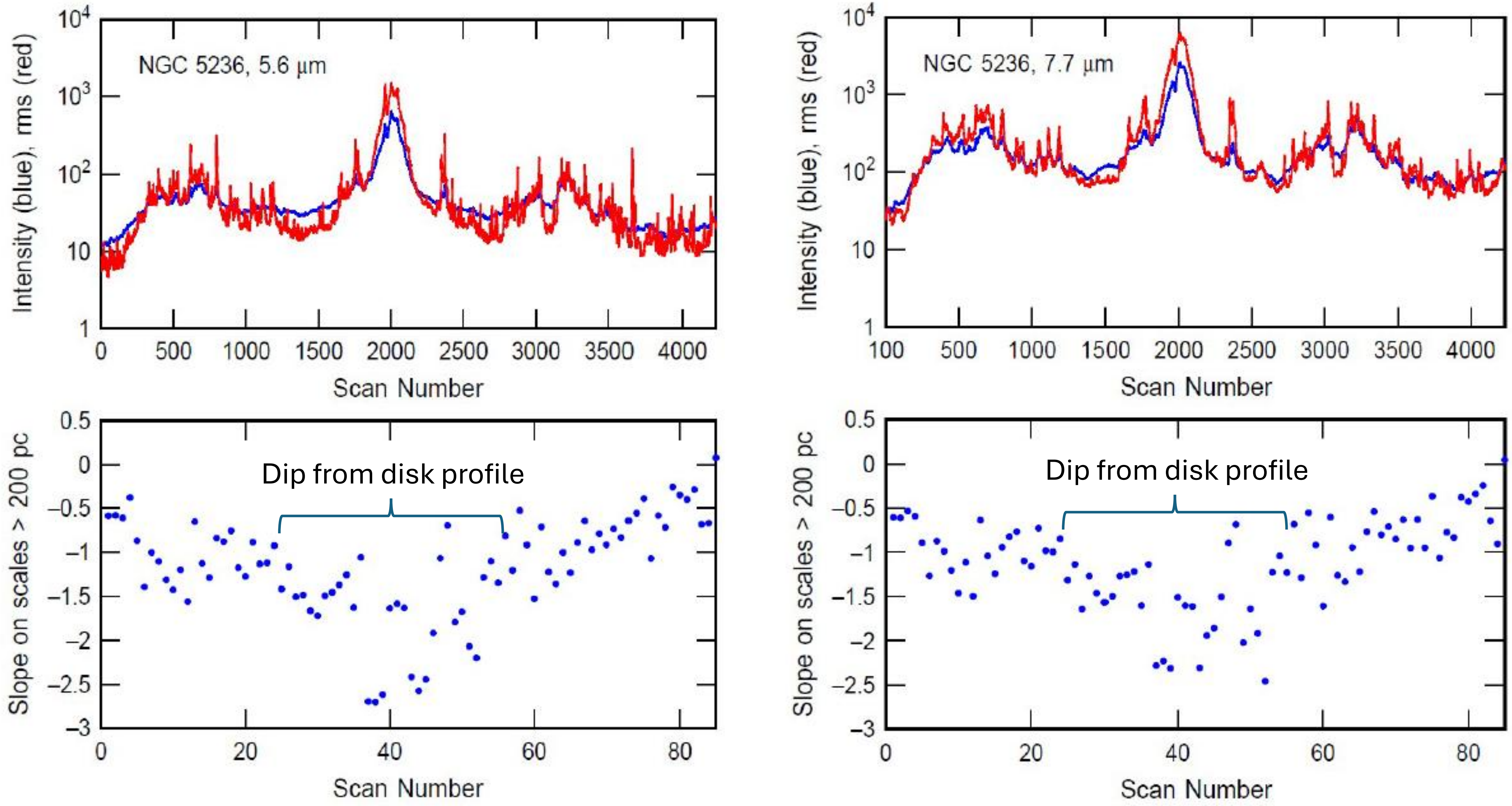
Sample scan directions for intensity

Total scans: 4232
Scan length: 1472 pixels





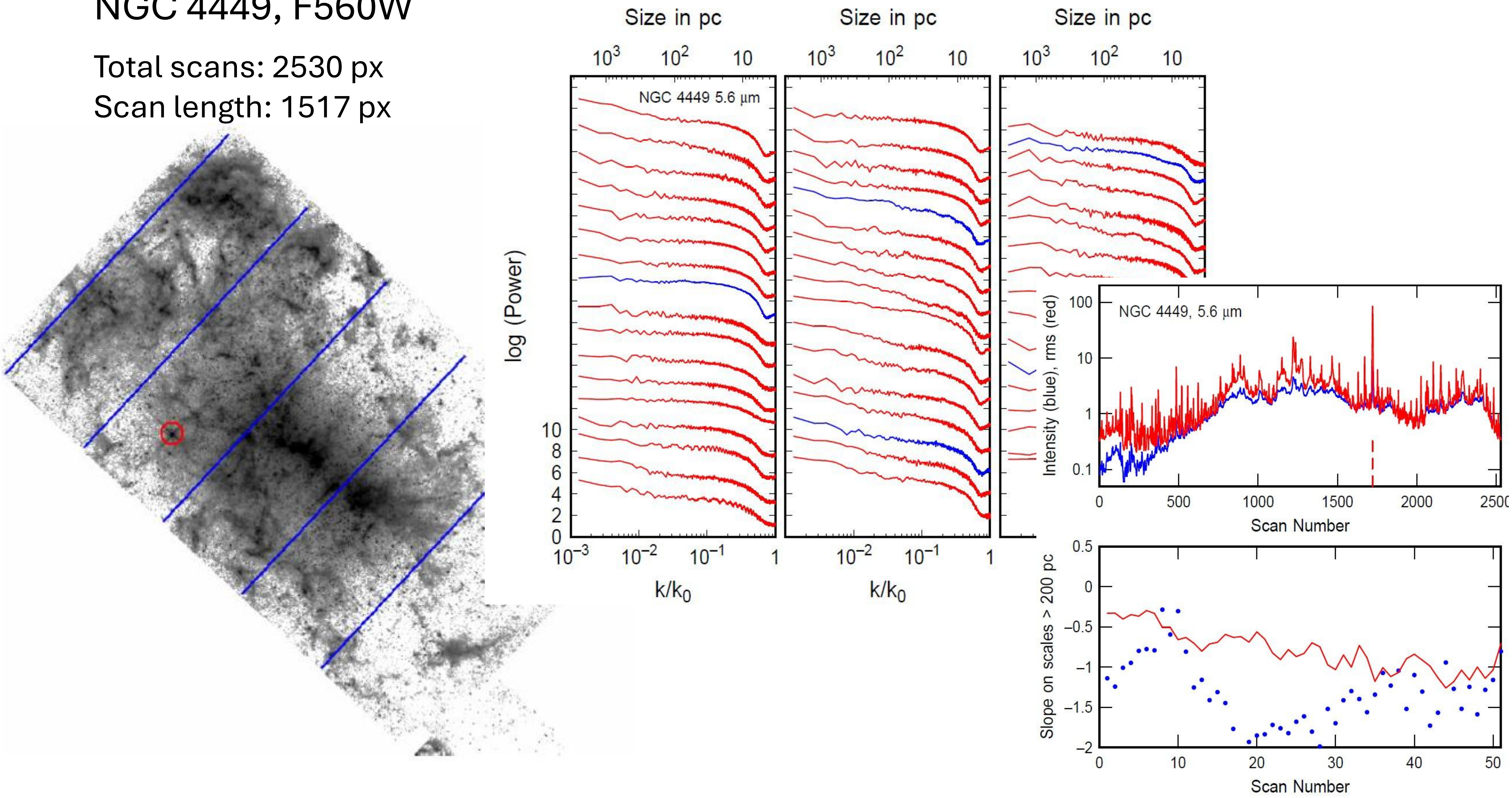
Size in pc
10^3 10^2 10
NGC 5236 5.6 μm
5.6μm
NGC 5236 7.7 μm
7.7μm
log (Power)
10
8
6
4
2
0
10^{-3} 10^{-2} 10^{-1} 1
k/k_0



NGC 5236, 5.6 μm
Intensity (blue), rms (red)
Scan Number
NGC 5236, 7.7 μm
Intensity (blue), rms (red)
Scan Number
Slope on scales > 200 pc
Dip from disk profile
Scan Number
Slope on scales > 200 pc
Dip from disk profile
Scan Number

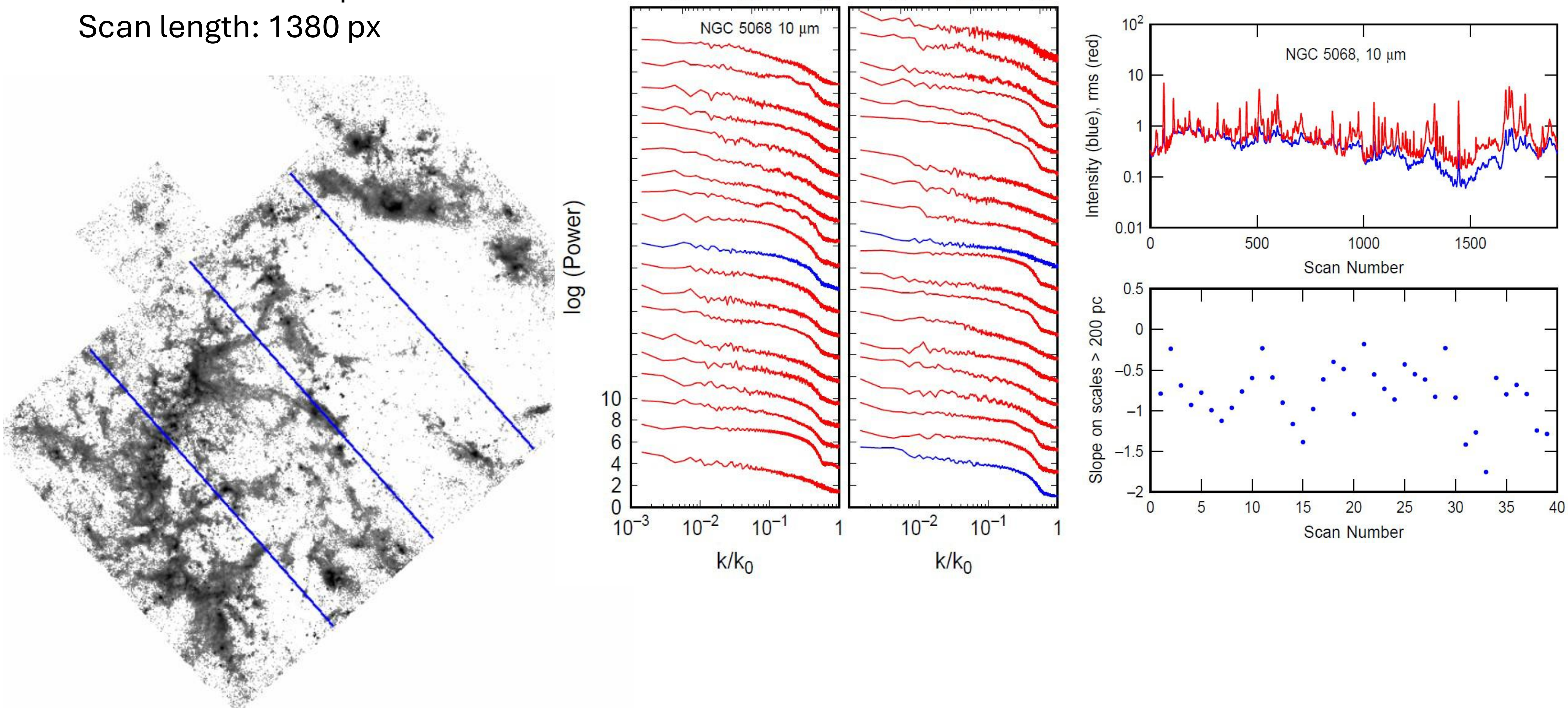
NGC 4449, F560W

Total scans: 2530 px
Scan length: 1517 px



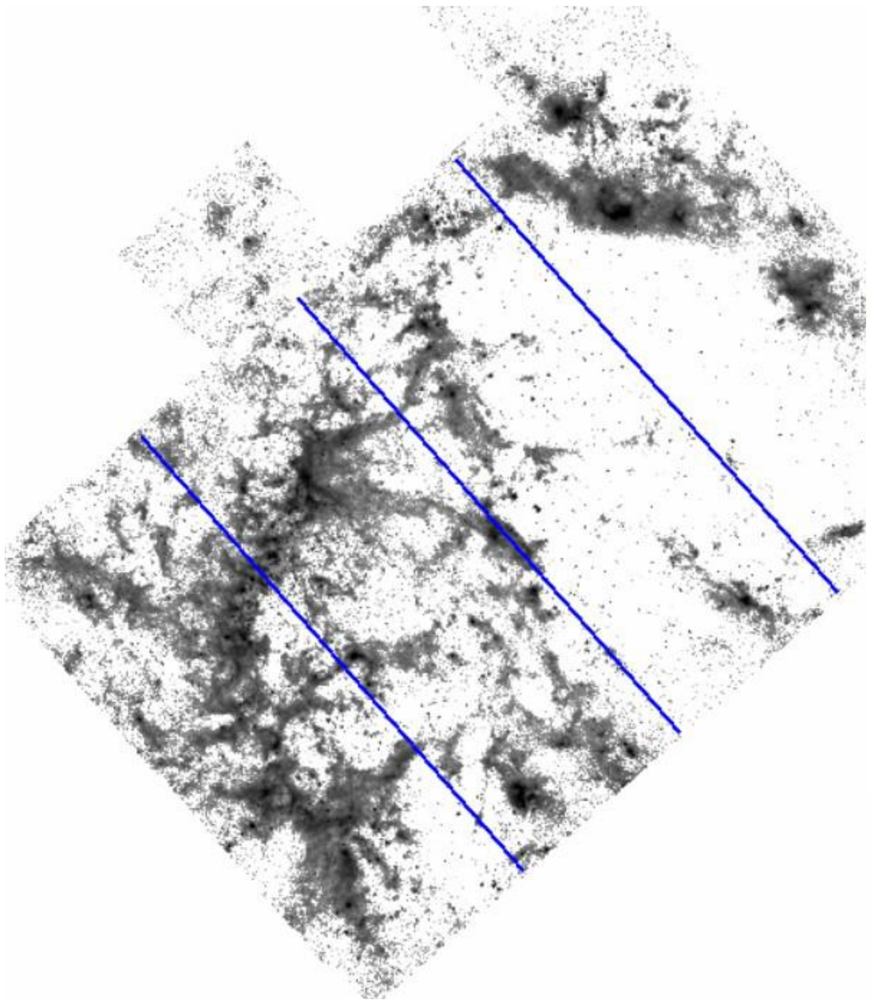
NGC 5068, F1000W

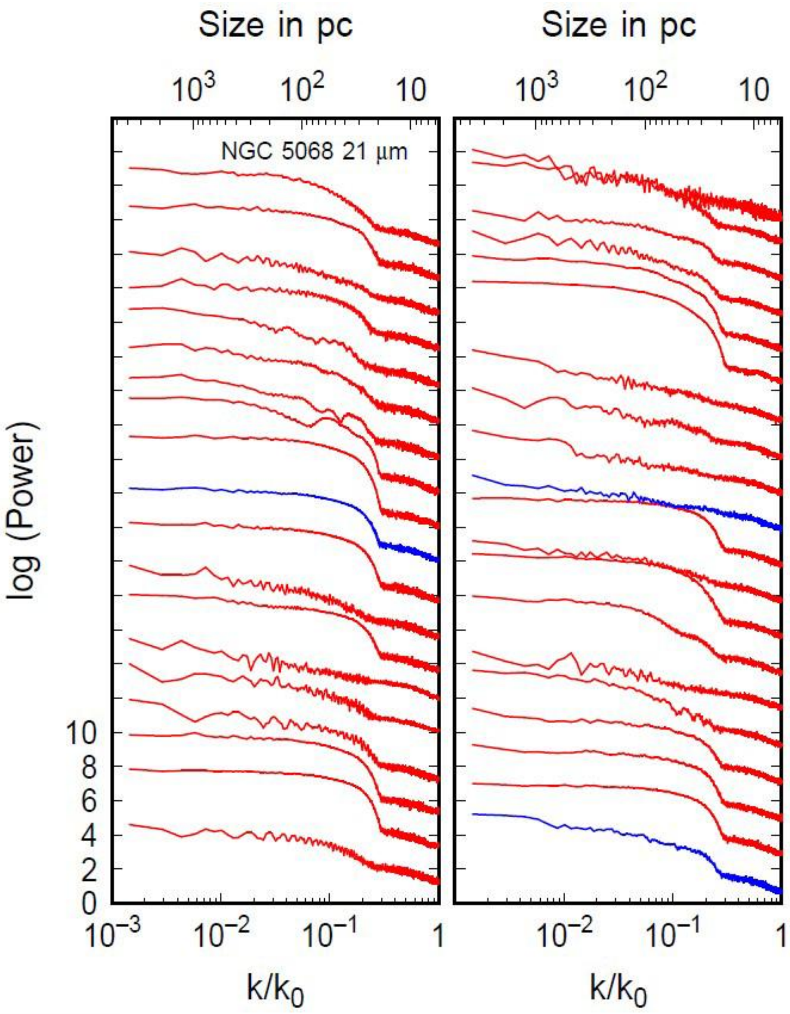
Total scans: 1908 px
Scan length: 1380 px

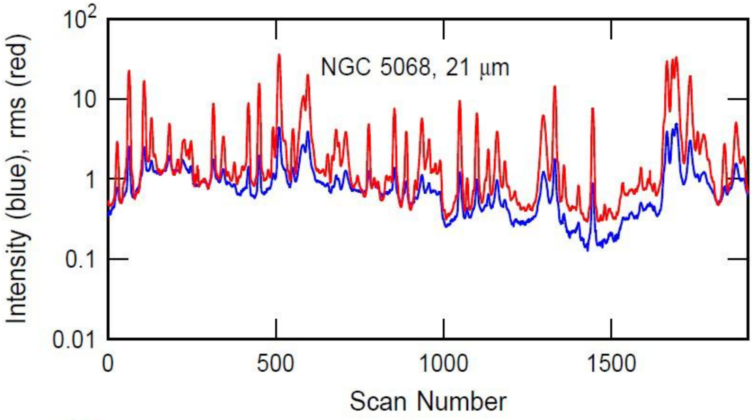


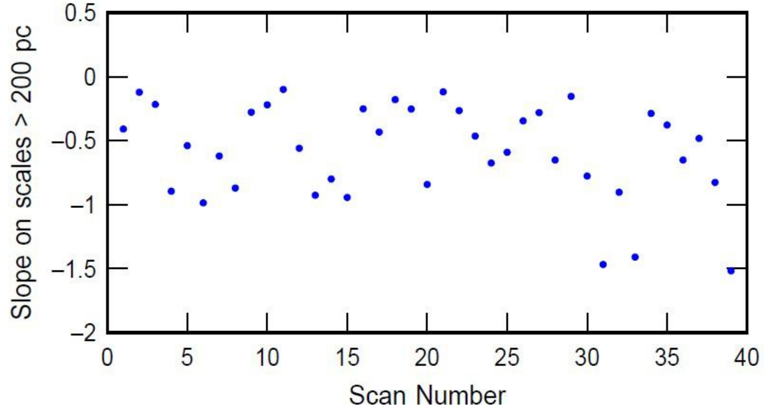
NGC 5068, F2100W

Total scans: 1908 px
Scan length: 1380 px









Sum: Four galaxies at 5.5μm to 21μm: warm dust and PAH

No break in any PS on scales larger than ~ 50 pc

- Point sources and exponential disk prevent good profiles (Koch +22)
- Dust layer is too thin. Recall H_{mol} ~ 30 pc - 100 pc (at 1-10 kpc) in Mancera Pina +22
- Wings of the JWST PSF are too broad

  Upper limit to k/k_0 ~ 5xFWHM: 50 pc at 5.6μm, 64 pc at 7.7μm, 78 pc at 10μm, 160 pc at 21μm

The Astrophysical Journal, 986:13 (14pp), 2025 June 10
https://doi.org/10.3847/1538-4357/adcee6
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An Investigation of Disk Thickness in M51 from Hα, Paα, and Mid-infrared Power Spectra

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New: **HST Hα**, Paα images at 2.55 pc resolution → a different ISM phase
use **azimuthal intensity profiles** instead of strips to avoid the exponential disk
use only intensity profiles **without bright sources** and average their PS

Result: Observe thickness in Hα, Paα is too faint, and JWST images still do not show it

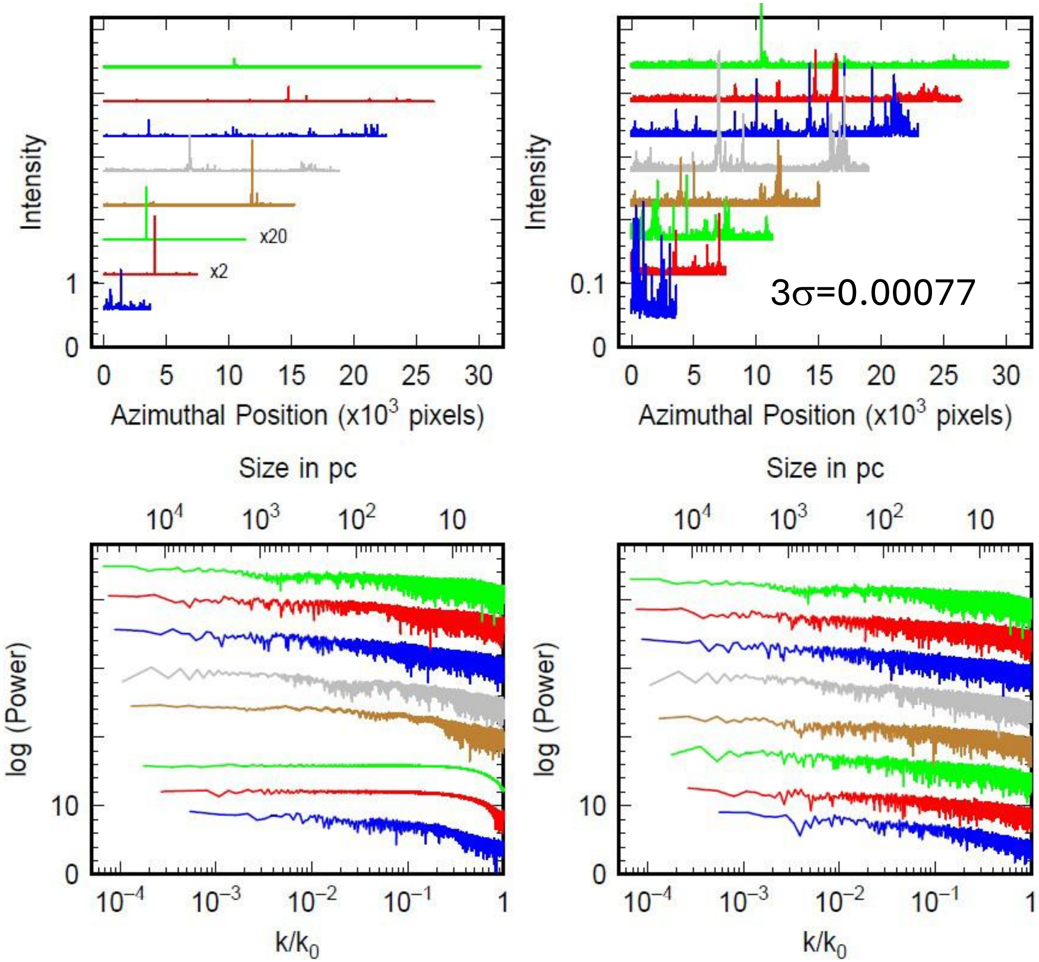
M51 HST Hα, circles every 600 pixels (872 pc), intensity scan every 3rd pixel

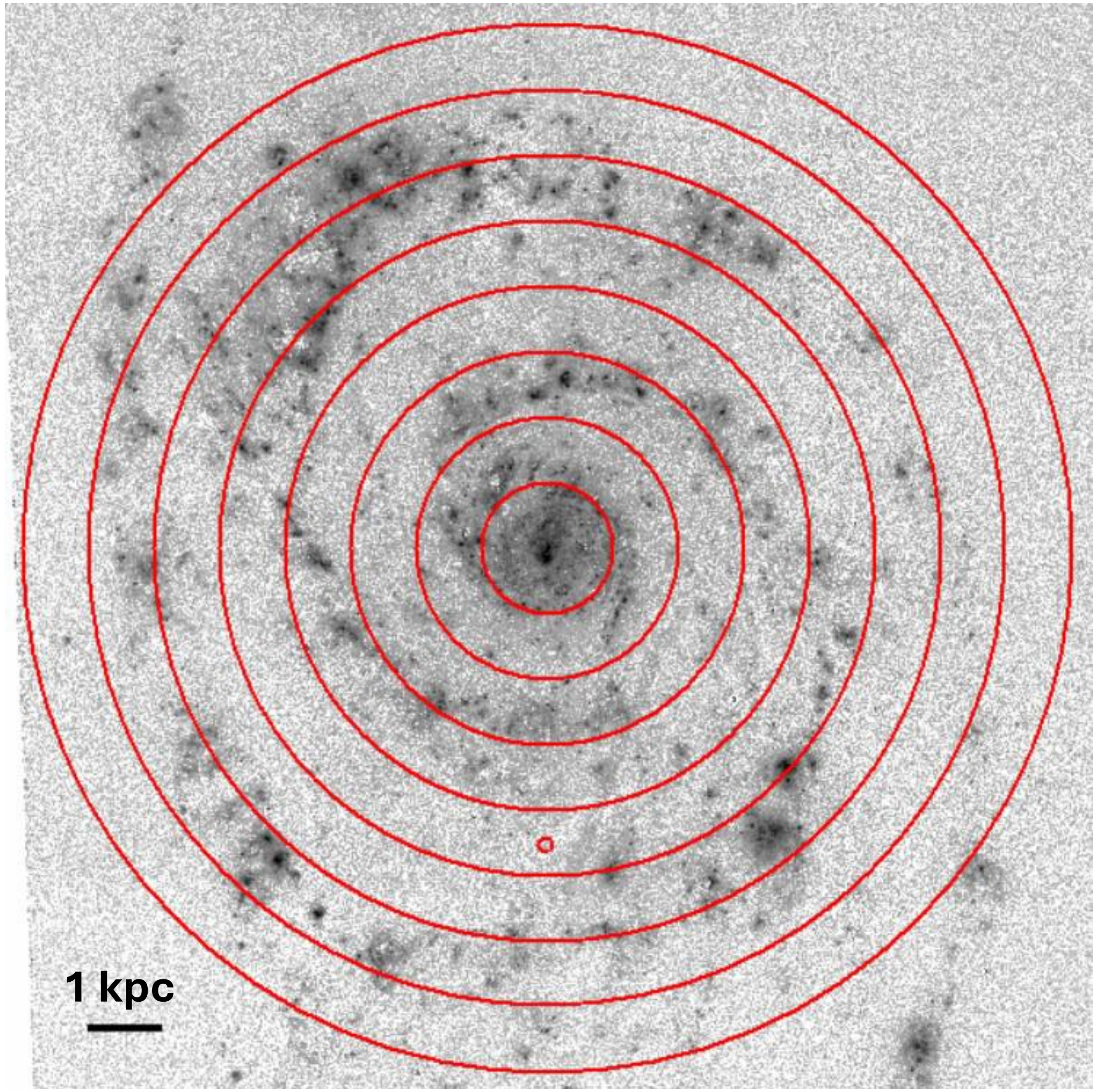
Small circle has a diameter of 200 pc.

Elmegreen +25

Left: Intensity scans (in 10^{-13} erg s^{-1} cm^{-2} arcsec^{-2}) and PS at circles.

Right: Nearby scans with no strong sources (10x scale) and more uniform PS





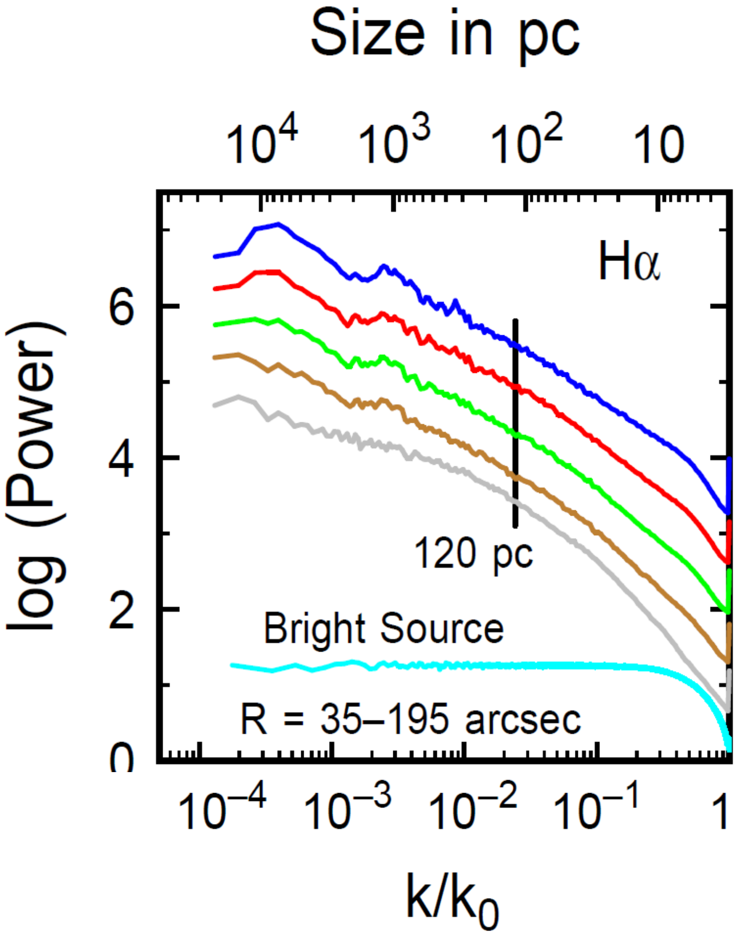
0.07” resolution = 2.55 pc; 0.04” pixels.

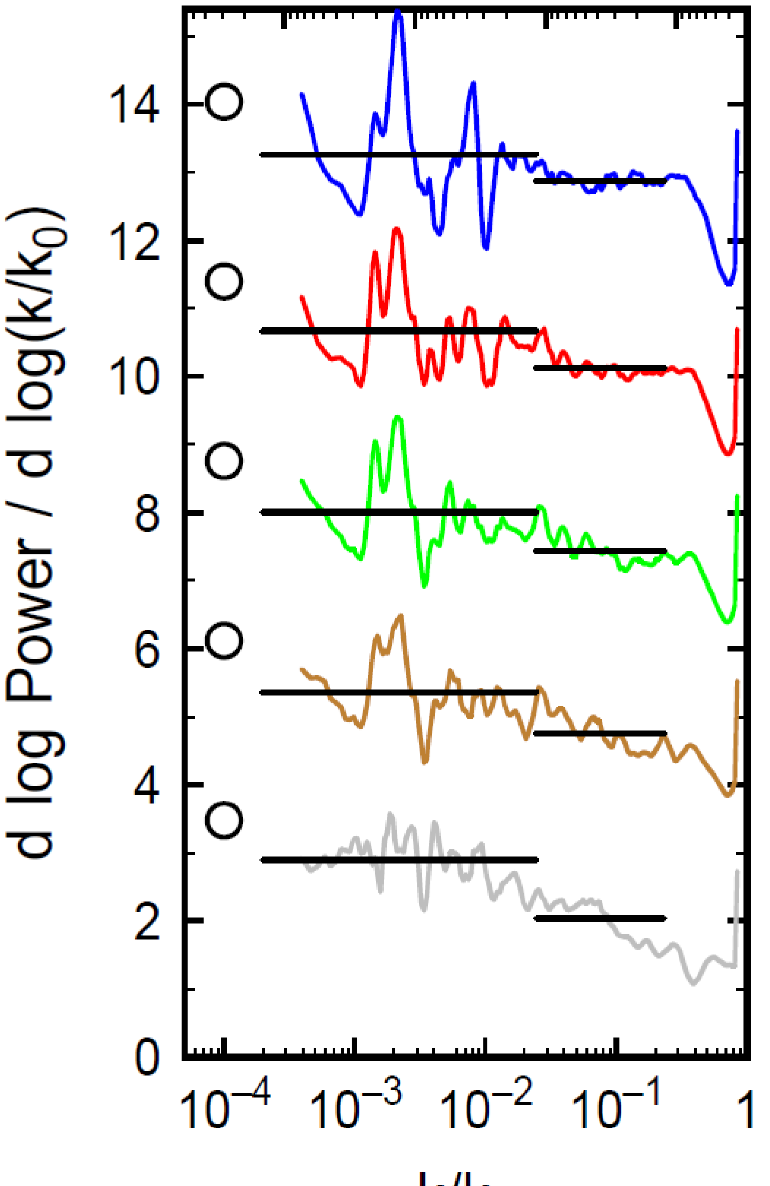
Distance assumed to be 7.5 Mpc

Hα PS and running slopes

PS from top to bottom have higher cutoffs, including more scans with higher peaks

A break at 1/k ~ 120 pc is in the top three Hα PS





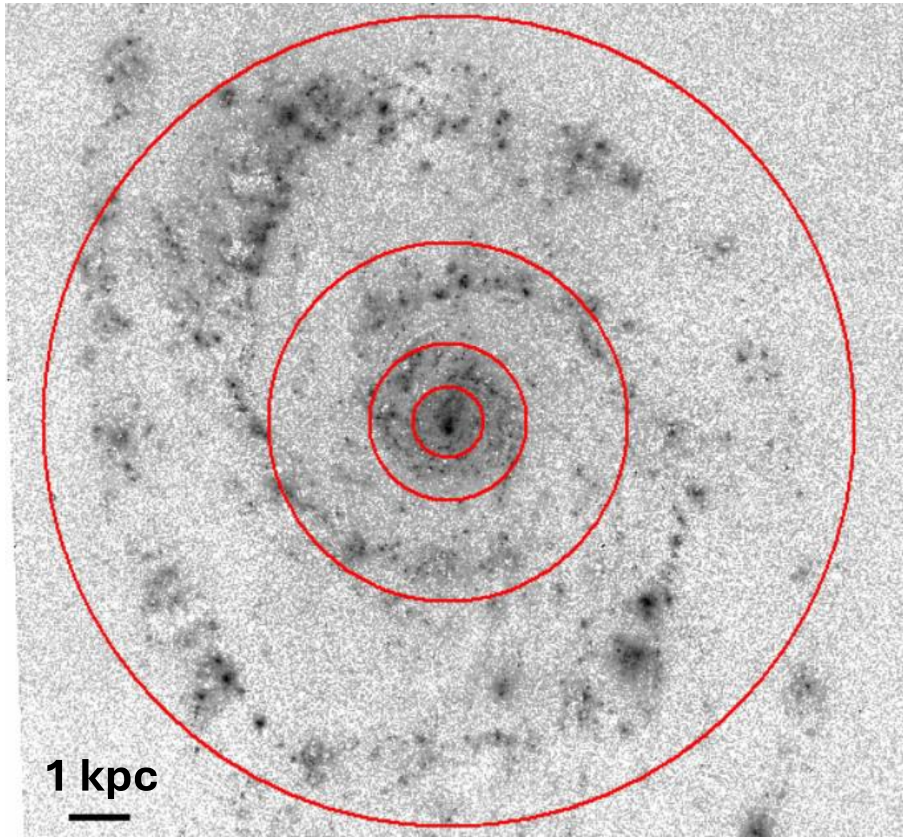
zero-levels indicated by circles

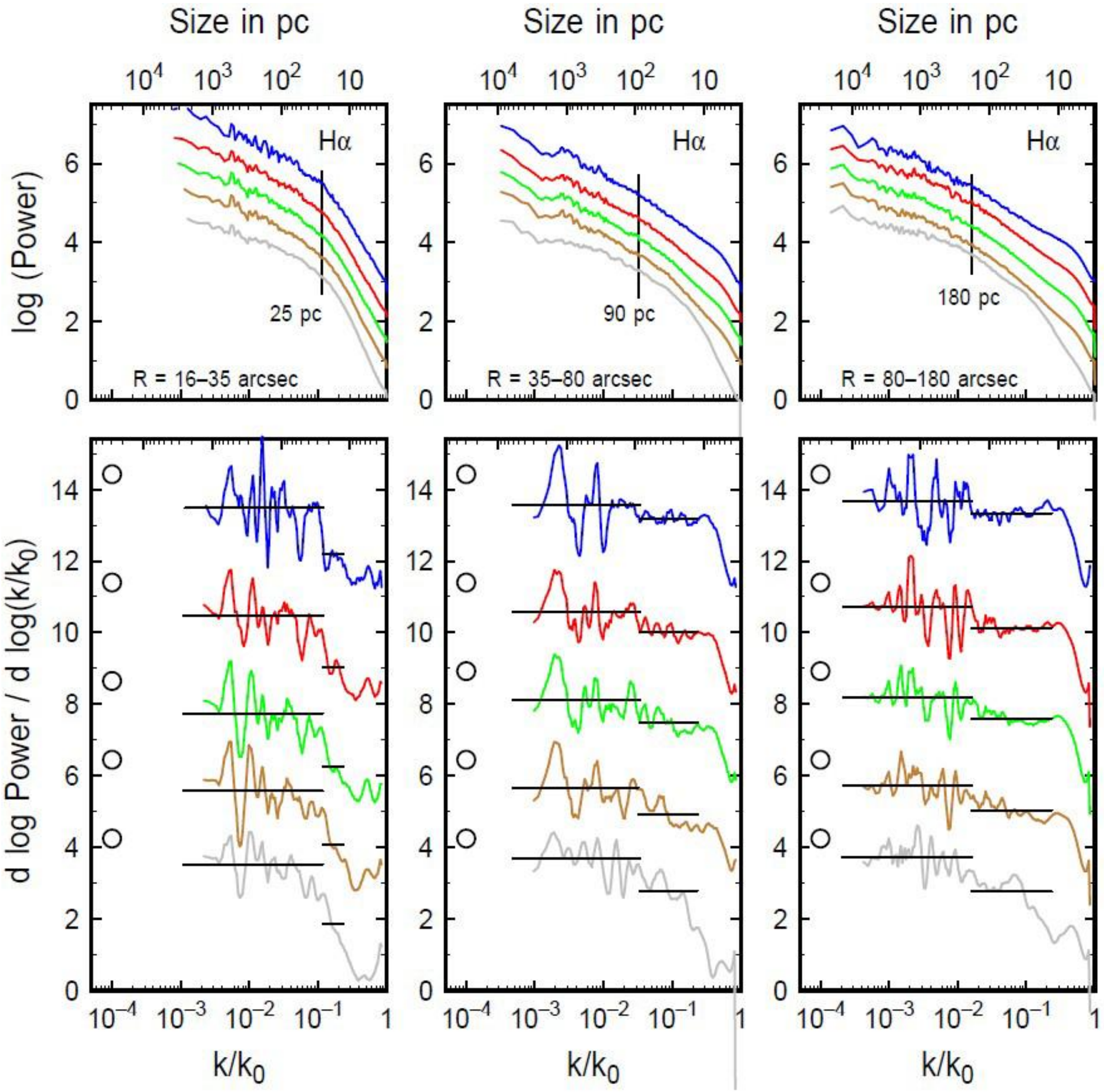
Elmegreen +25

3 intervals of galactocentric radius

peak intensities and the number of PS in the averages increase from the top to bottom

PS break scale increases with radius.





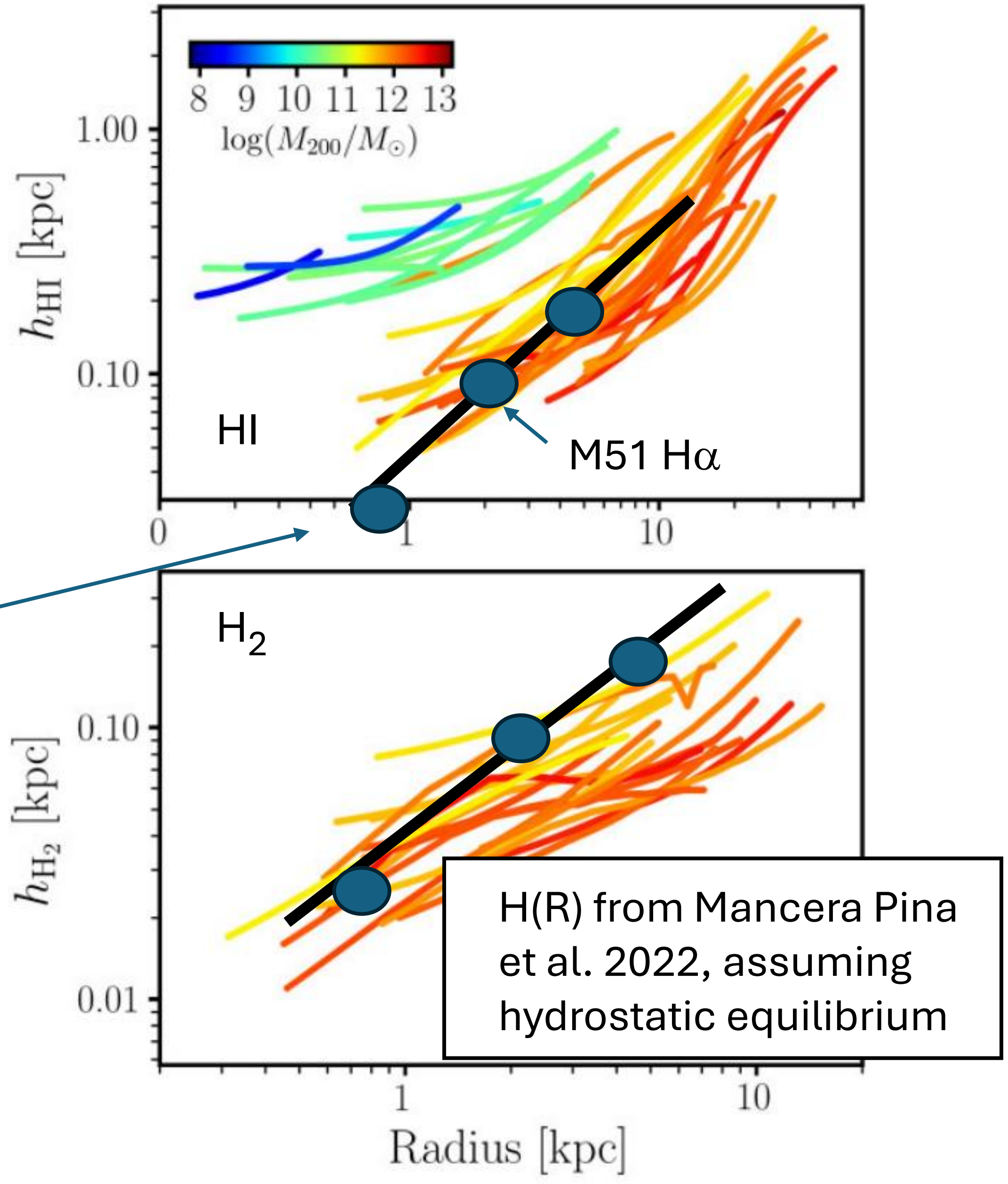
The scale for Hα increases with radius,

from

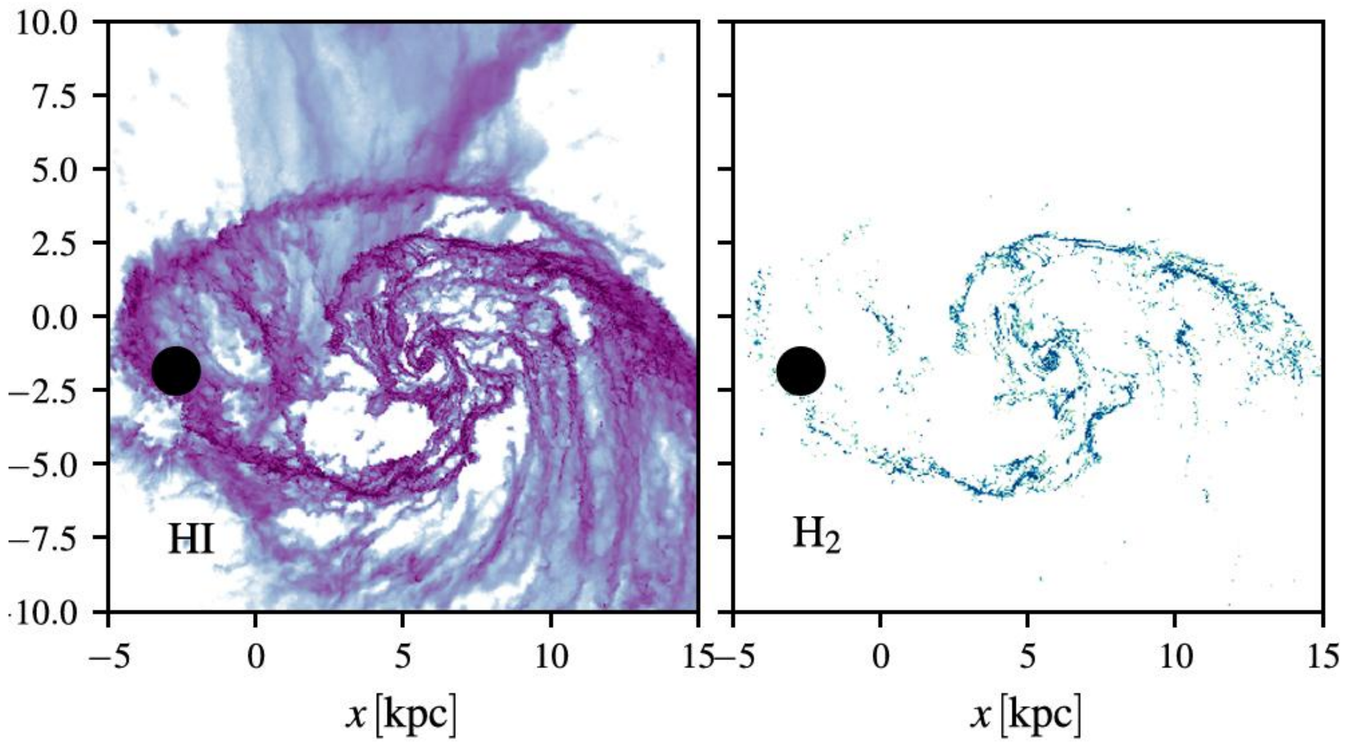
~ 25 pc at 0.5-1 kpc radius to
~ 90 pc at 1.27-2.91 kpc to
~ 180 pc at 2.91-6.54 kpc

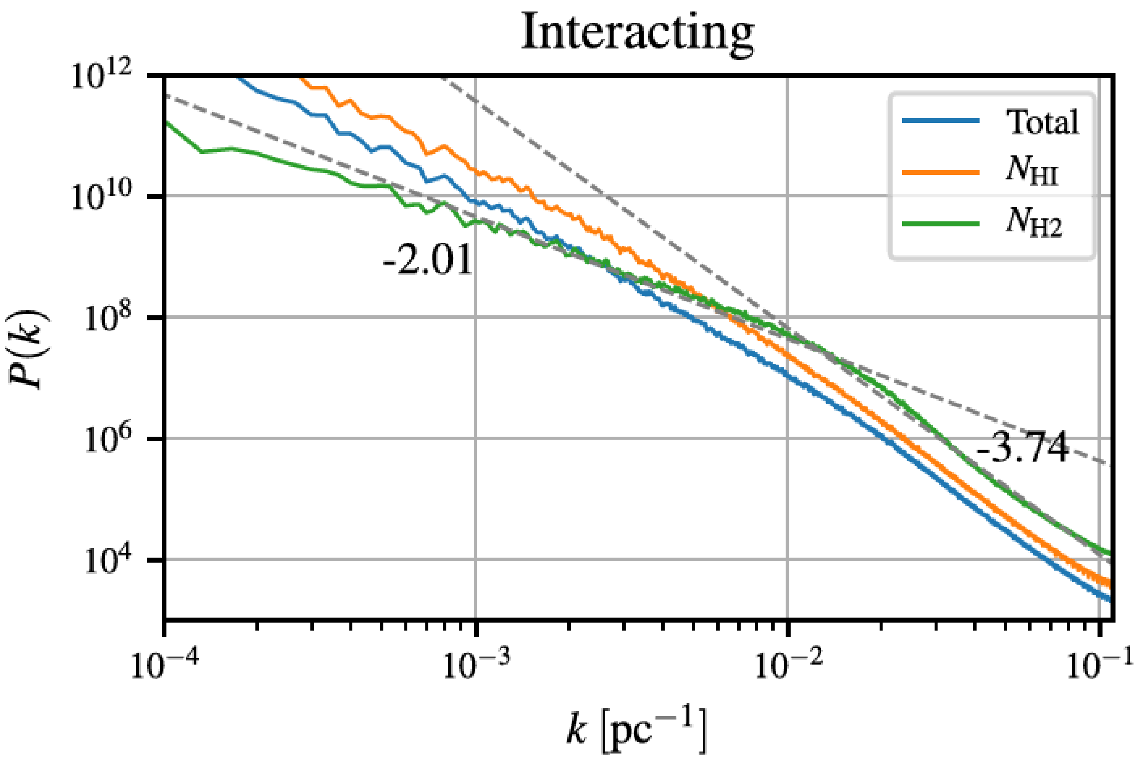
→ Scale increase ~ 40 pc/kpc

Looks **typical** for spiral galaxies.



Tress et al. (2020): simulation of M51 with power spectrum





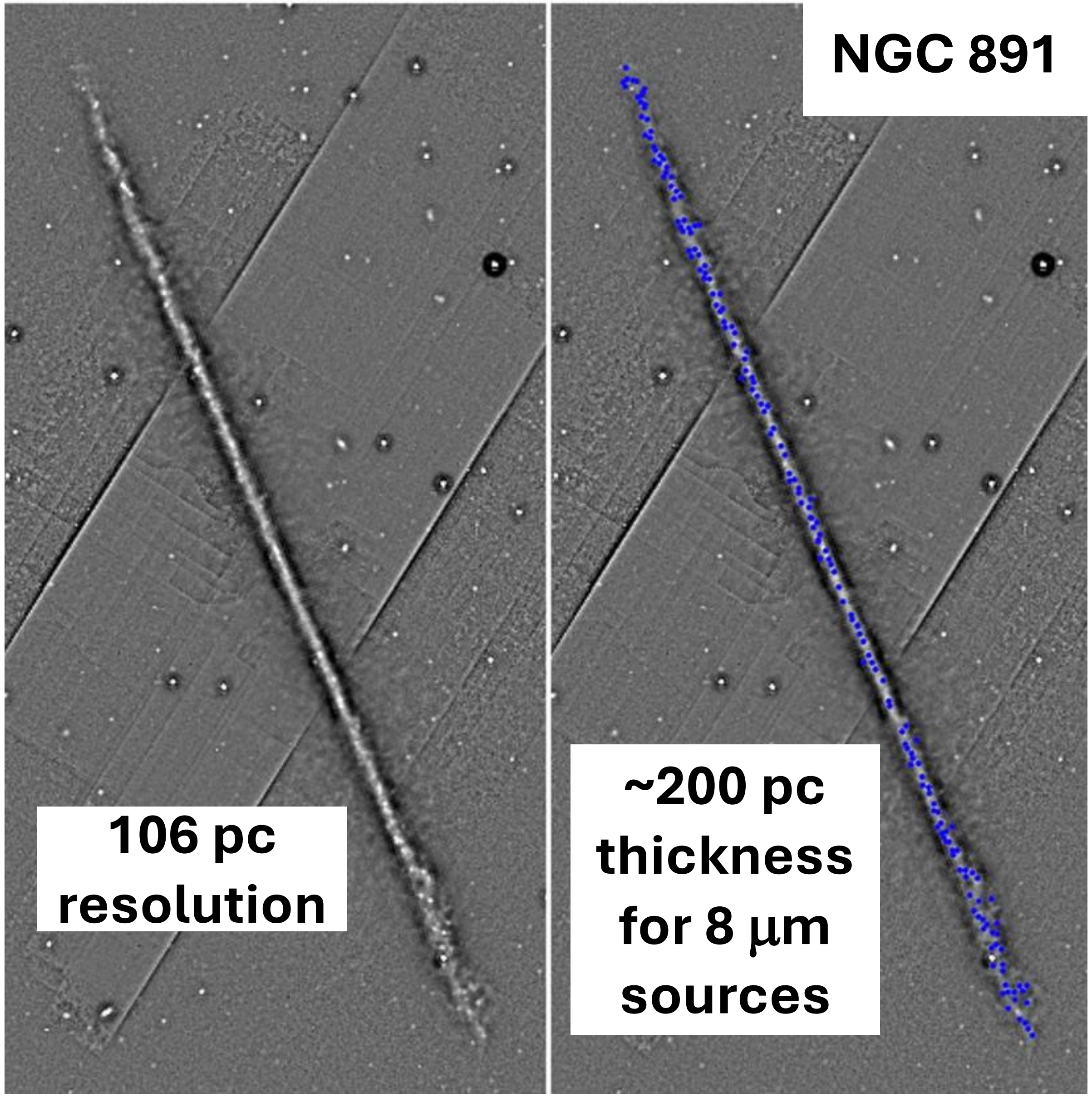
1/k is 1% of this distance

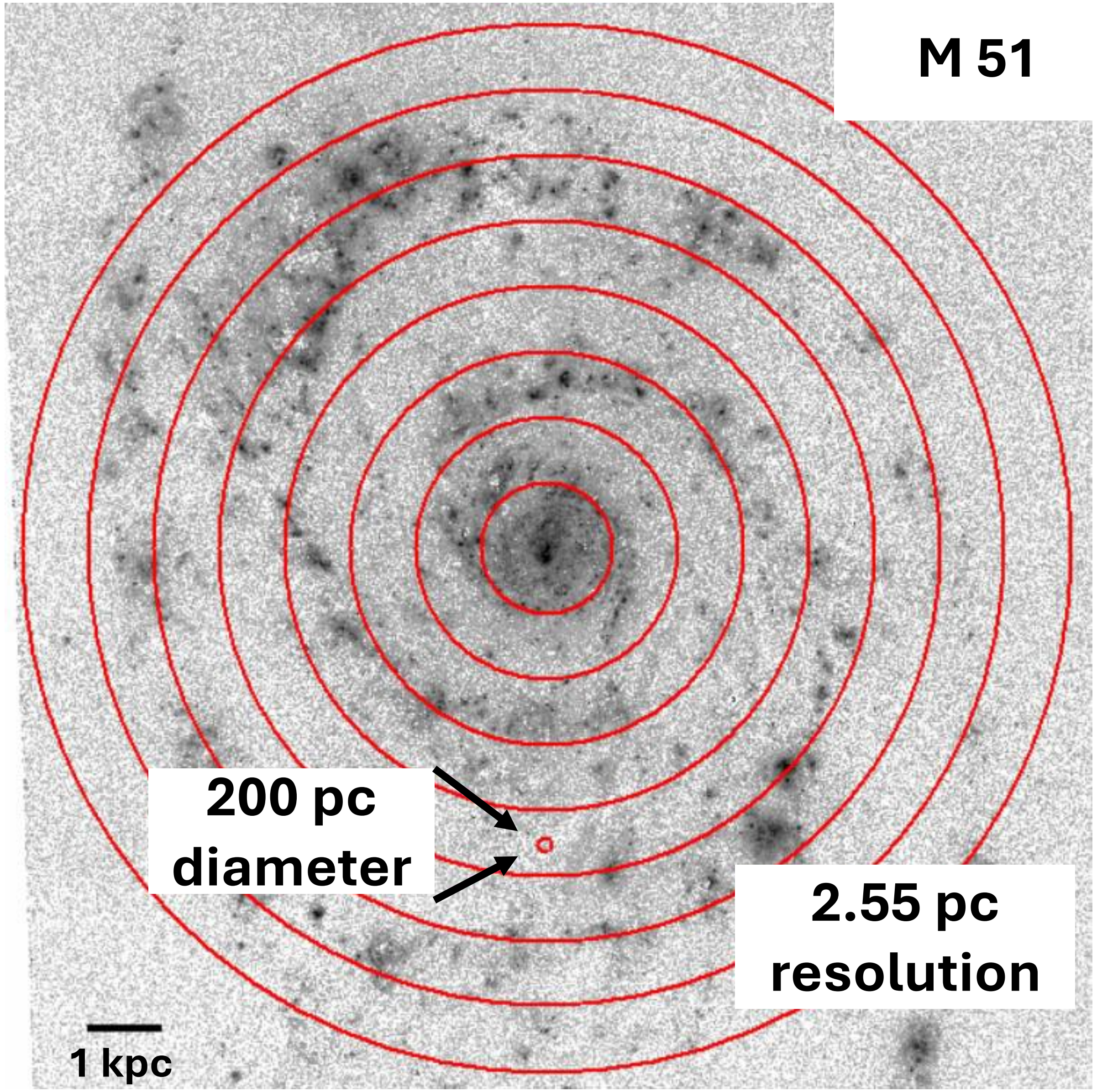
total (blue), HI (orange), H_2 (green) column densities

~ 50 pc change of scale for H_2

What is the origin of the structure on scales > 200 pc and < 200 pc?

Is it all “turbulence” or are different processes contributing?



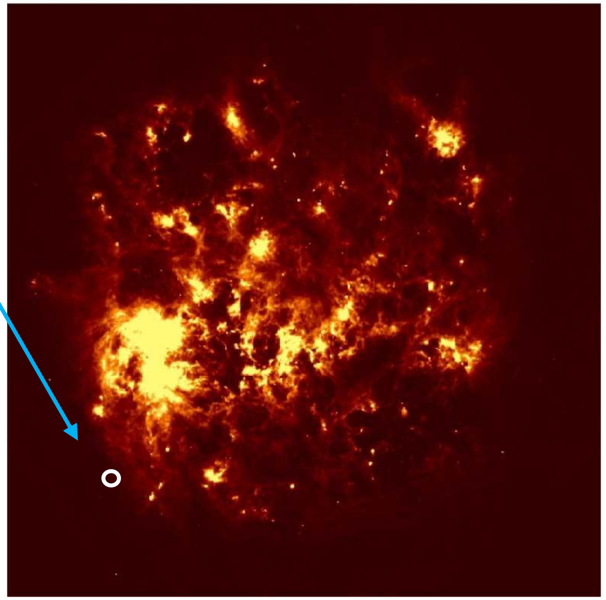


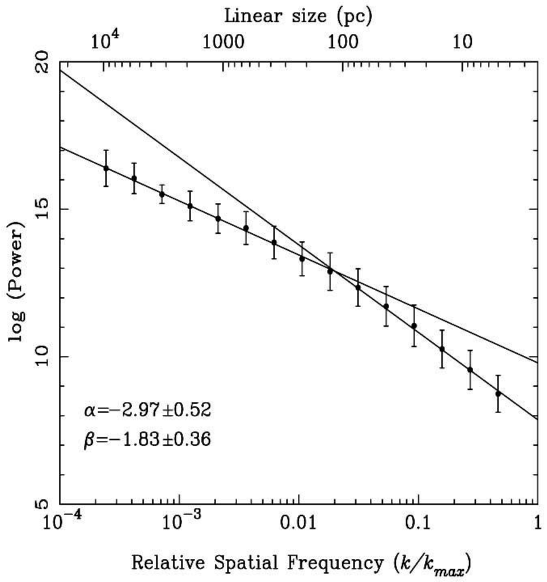
M51 is 35x bigger than circle and resolution is 78x smaller

Recall: FIR PS for the LMC (Block +10)

150 pc circle

LMC – 70 microns



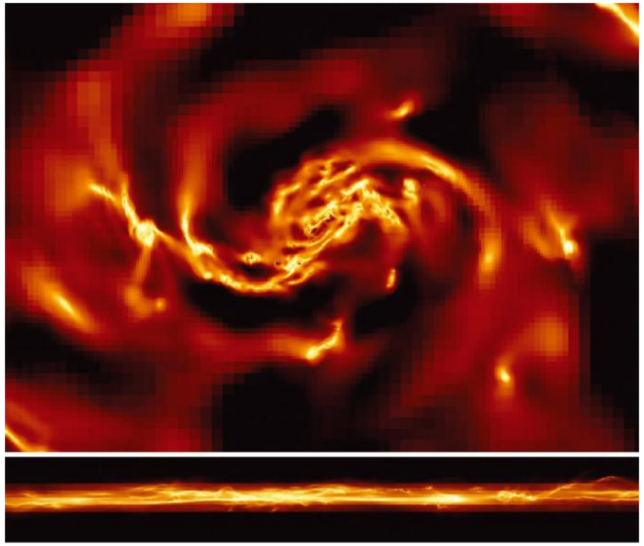


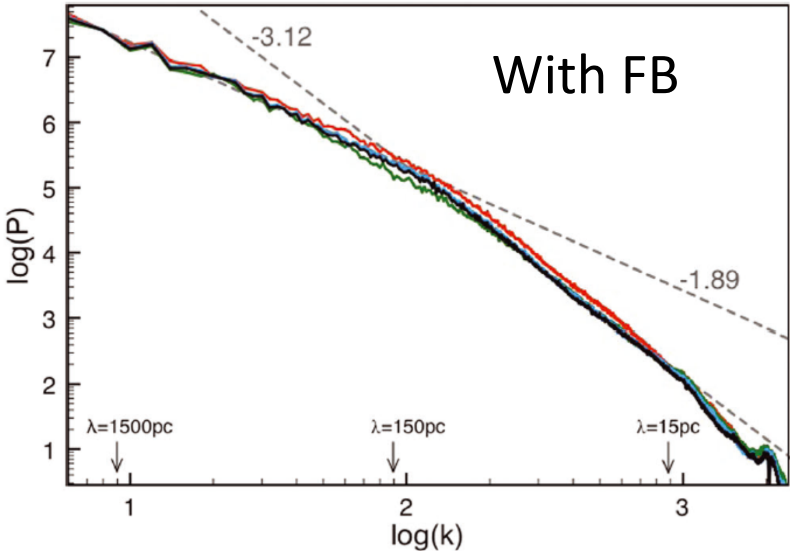
HD model of LMC (Bournaud +10)

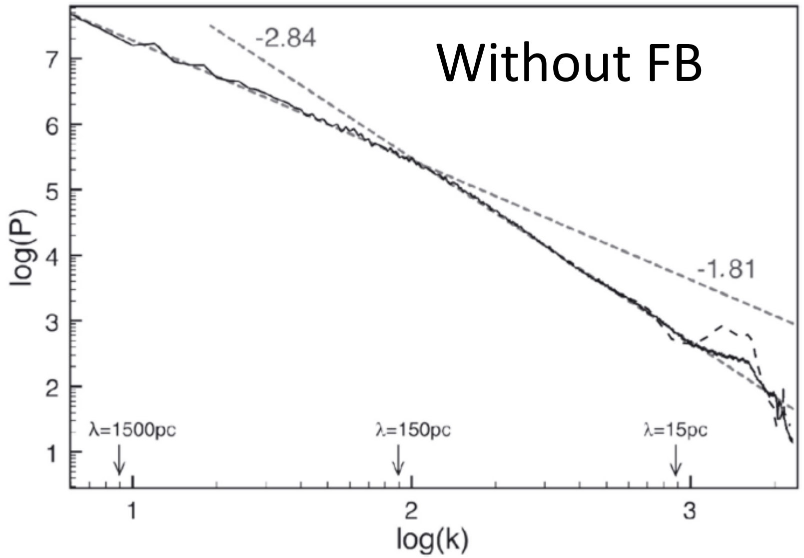
Does not look the same:

large scales from **gravity**

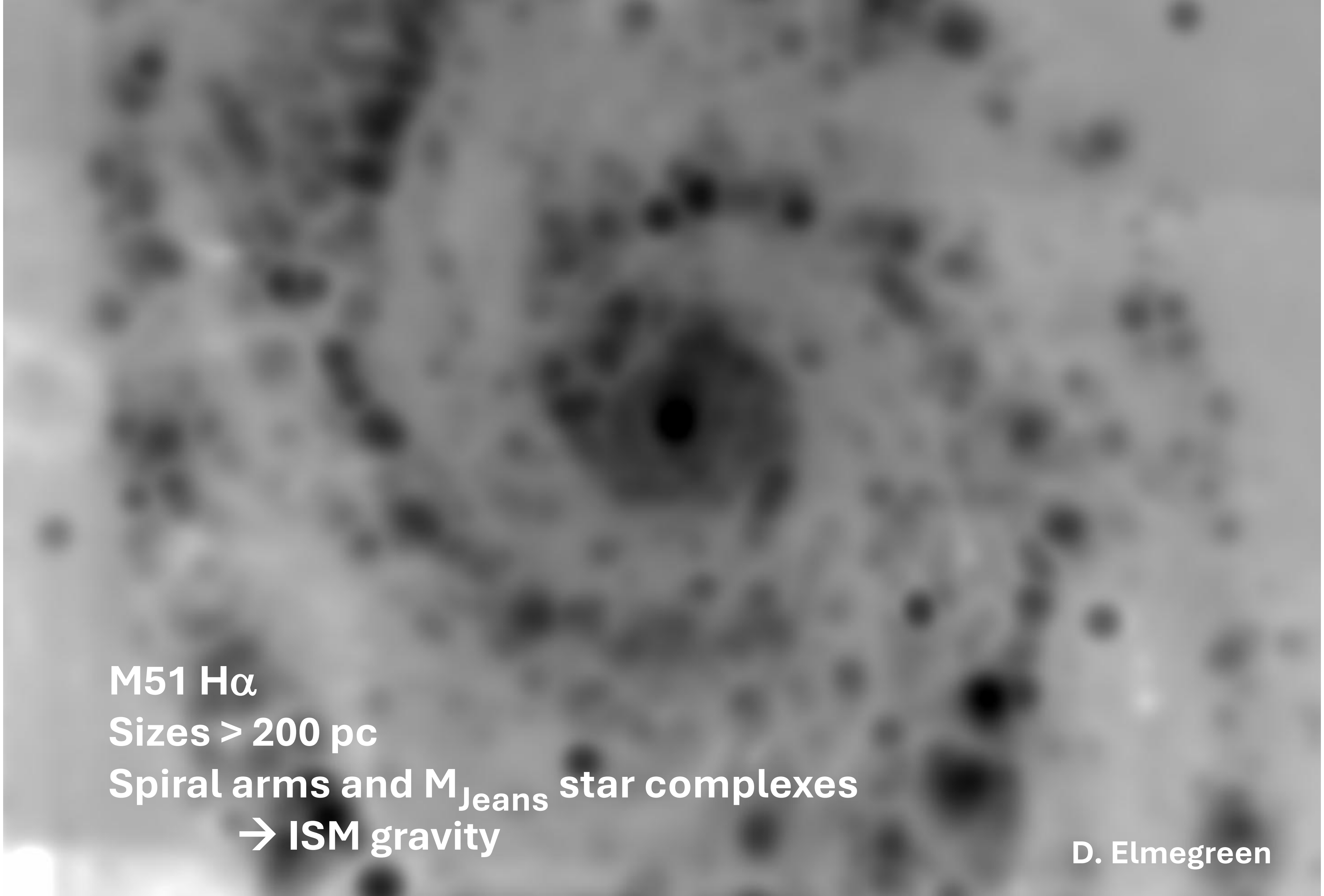
small scales from top-down **cascade**

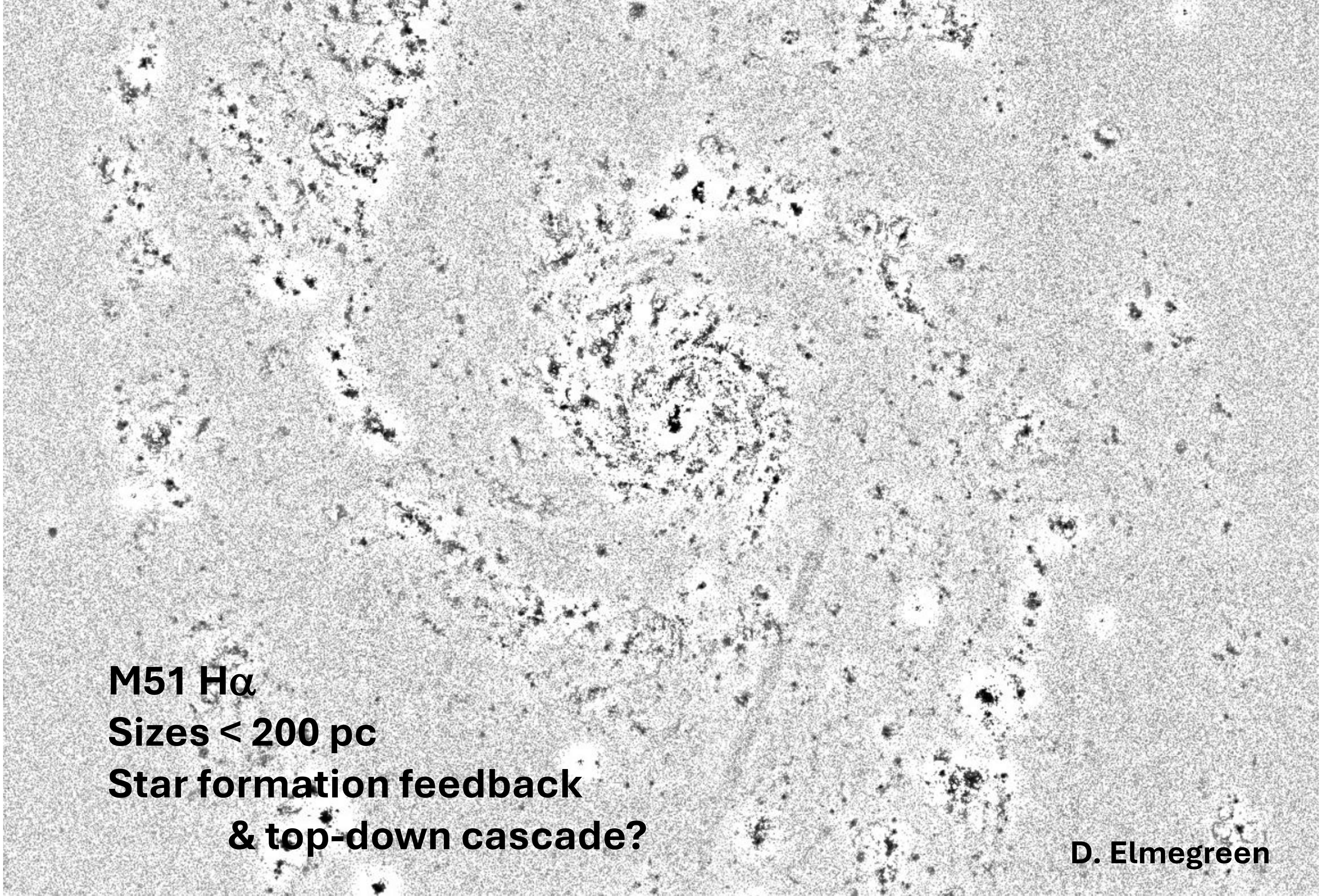




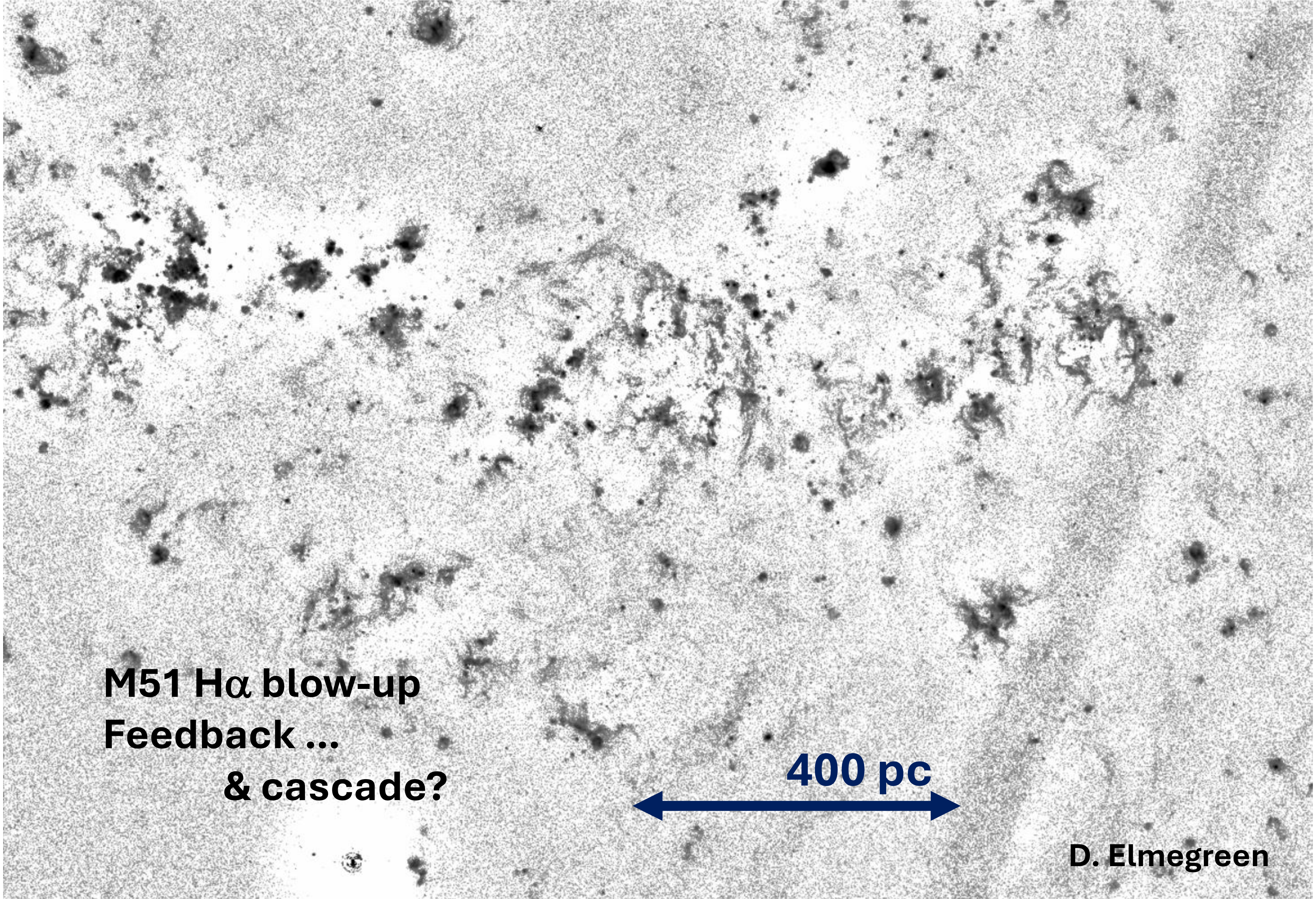


→ **Independent of FB**, so the structure is from gravity


M51 Hα
Sizes > 200 pc
Spiral arms and M_{Jeans} star complexes
→ ISM gravity
D. Elmegreen

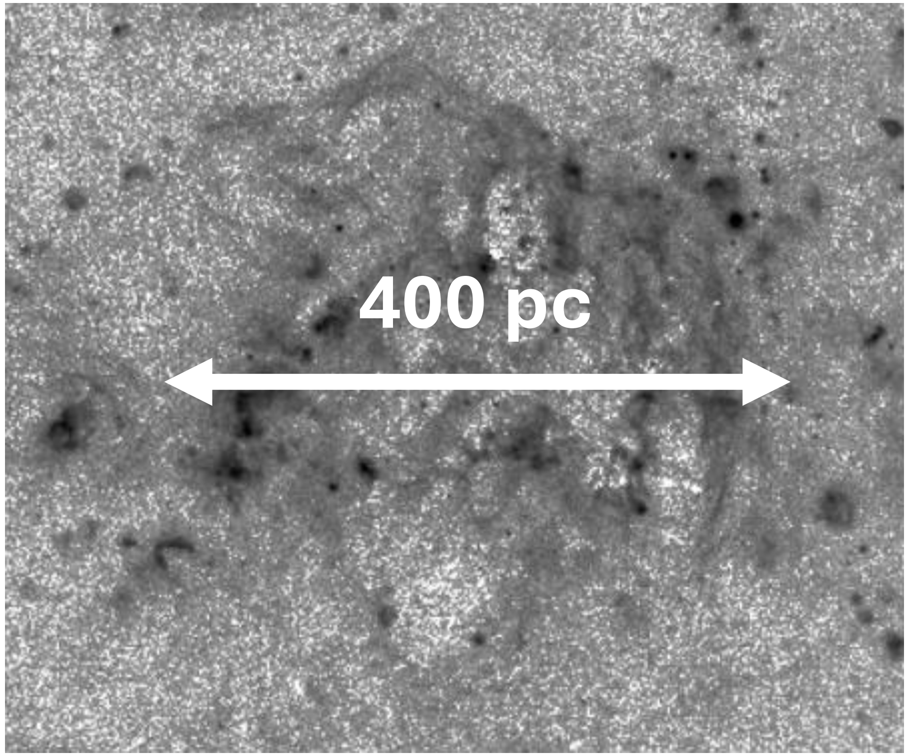

M51 Hα
Sizes < 200 pc
Star formation feedback
& top-down cascade?
D. Elmegreen


M51 Hα blow-up
Star complexes
D. Elmegreen

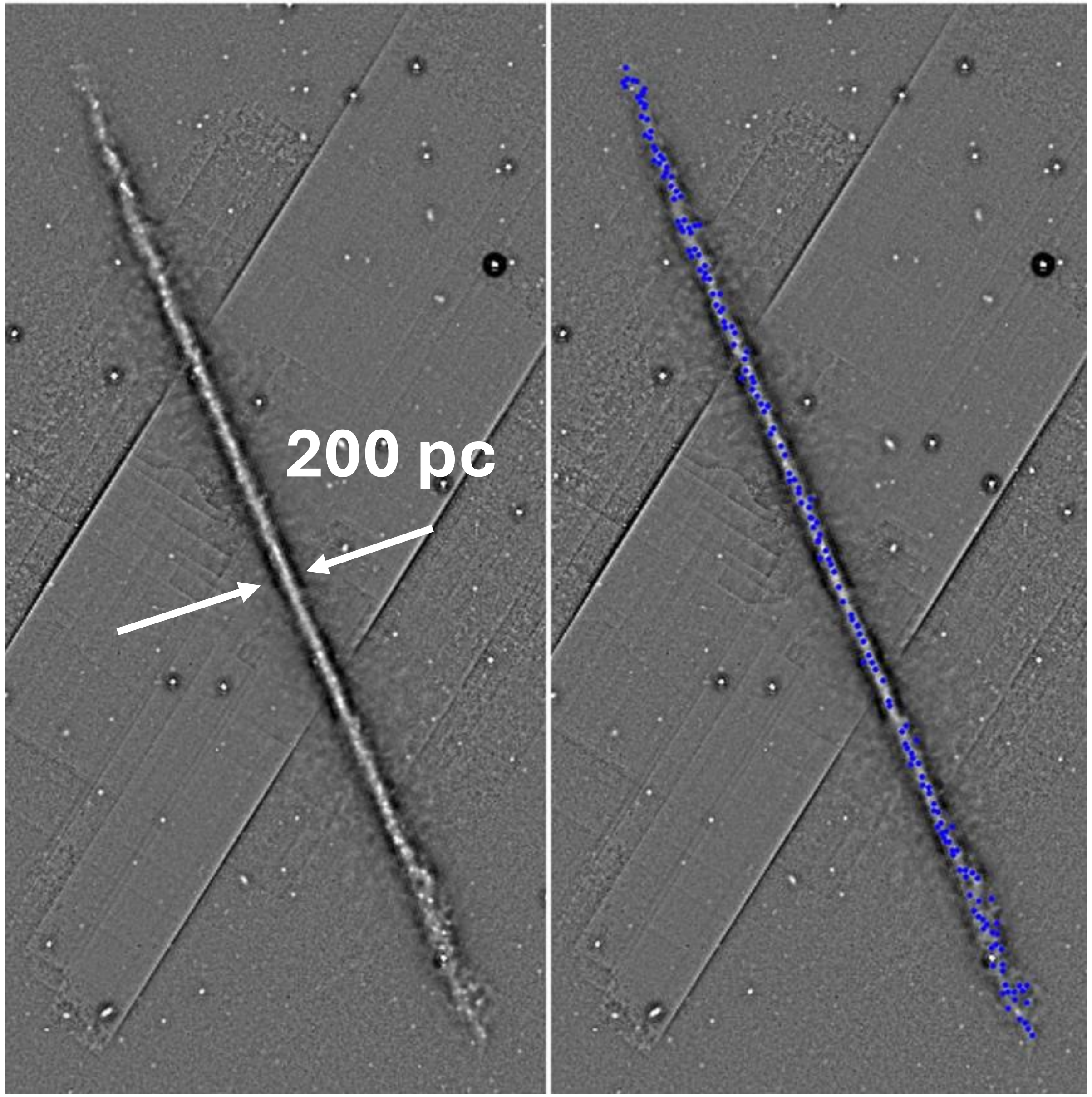

M51 Hα blow-up
Feedback ...
& cascade?
400 pc
D. Elmegreen

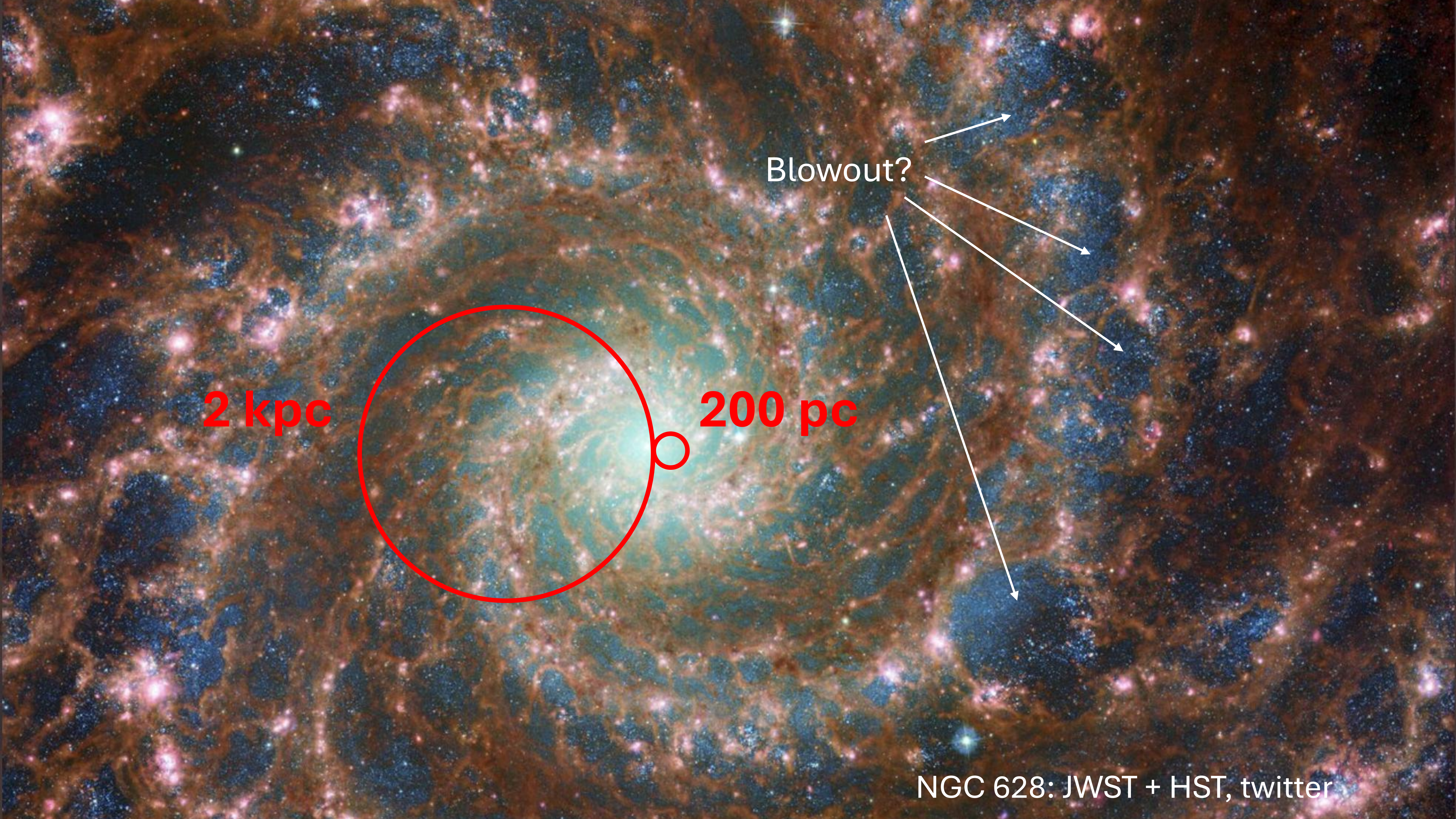
Where does star formation feedback go?
Blowout?

M51 - Hα

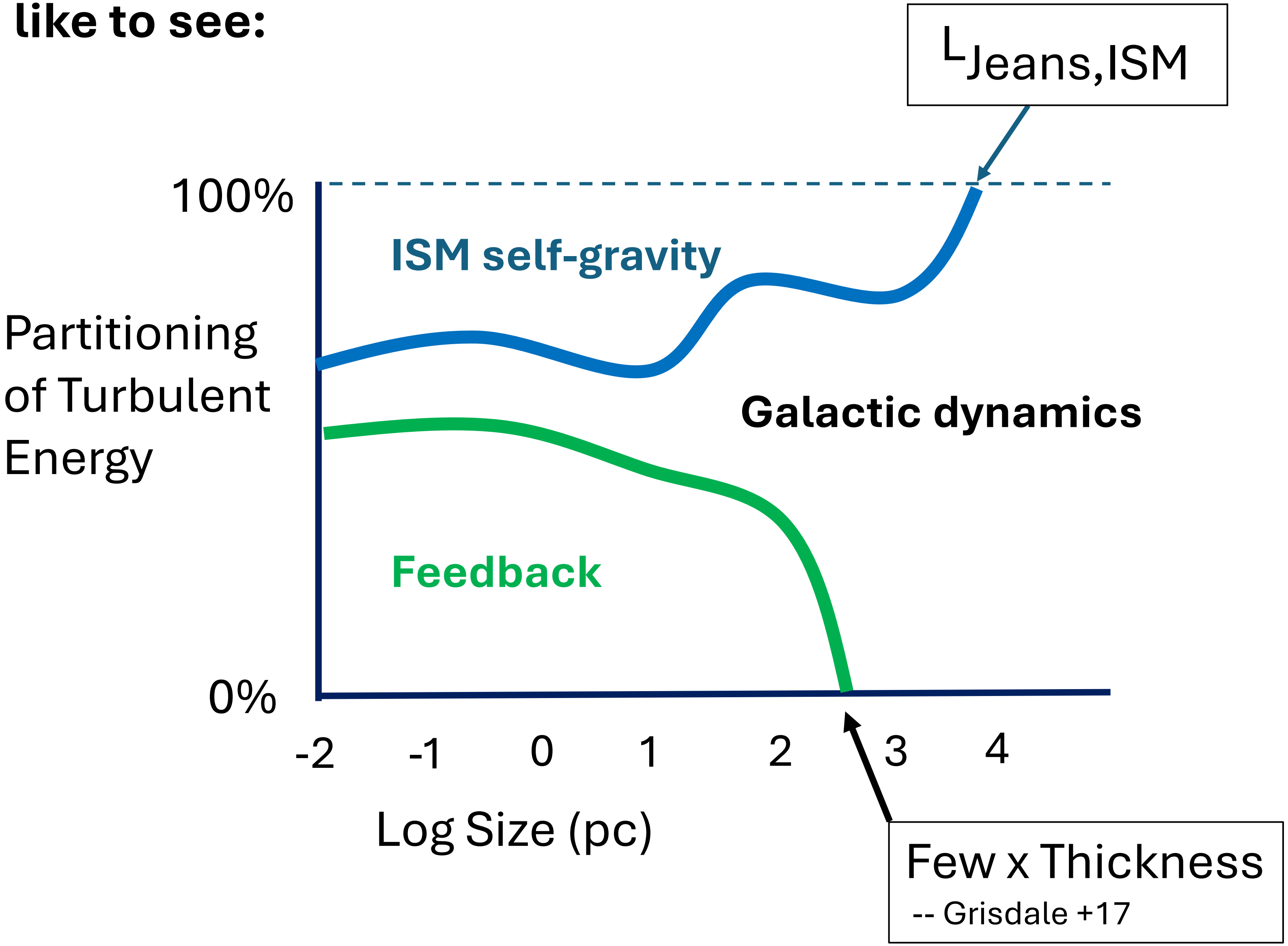


NGC 891



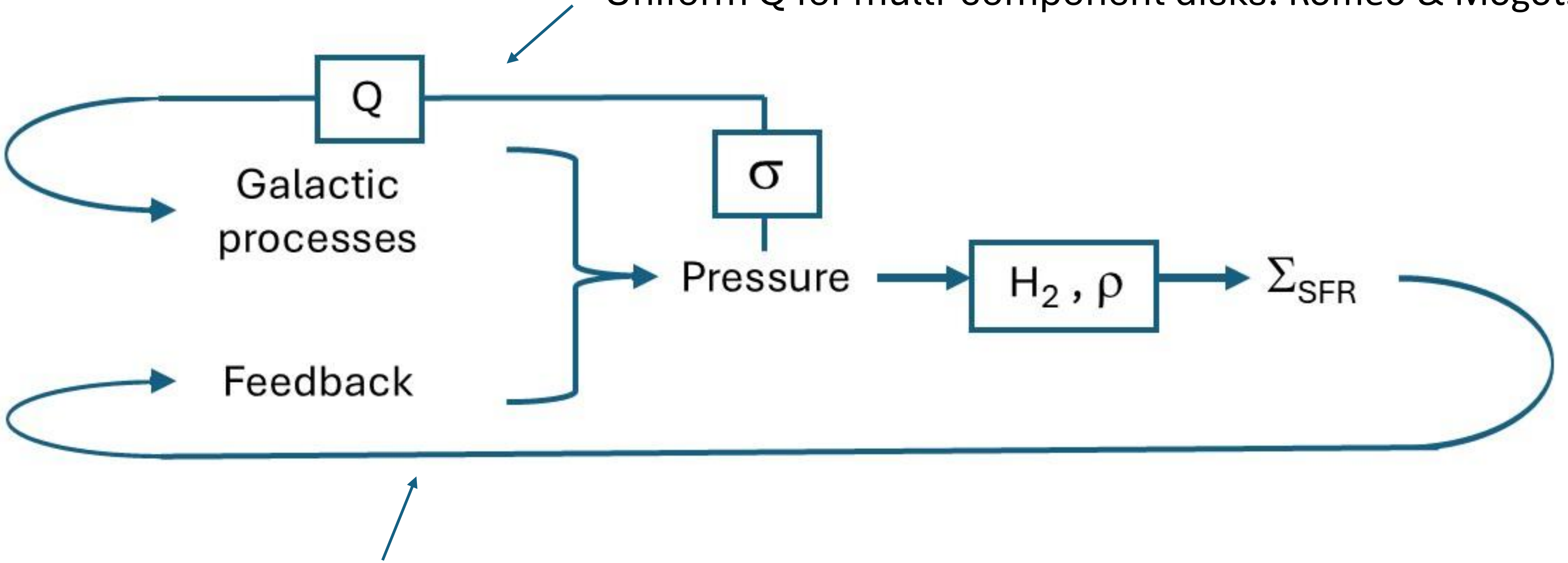

Blowout?
2 kpc
200 pc
NGC 628: JWST + HST, twitter

A plot I would like to see:



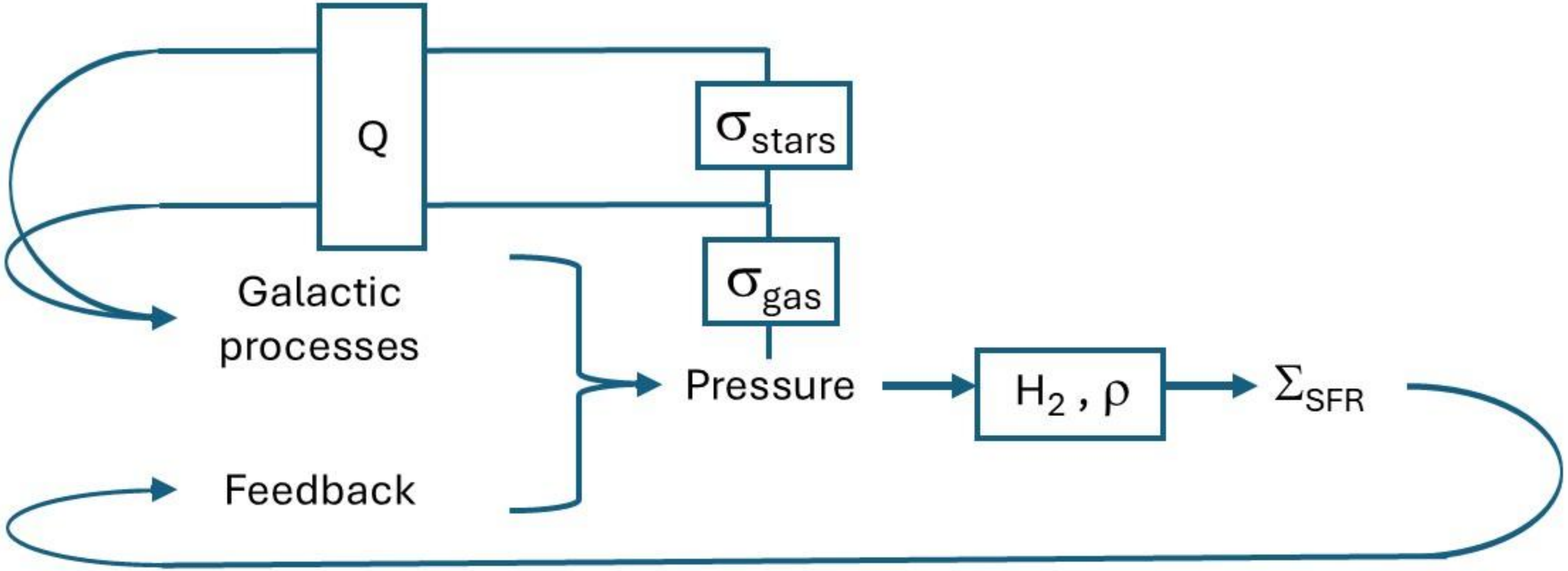
Two “control cycles”

Fleck ’81, Bertin ’97, Huber & Pfenniger ’02, Wada +02, ...
Uniform Q for multi-component disks: Romeo & Mogotsi ‘17



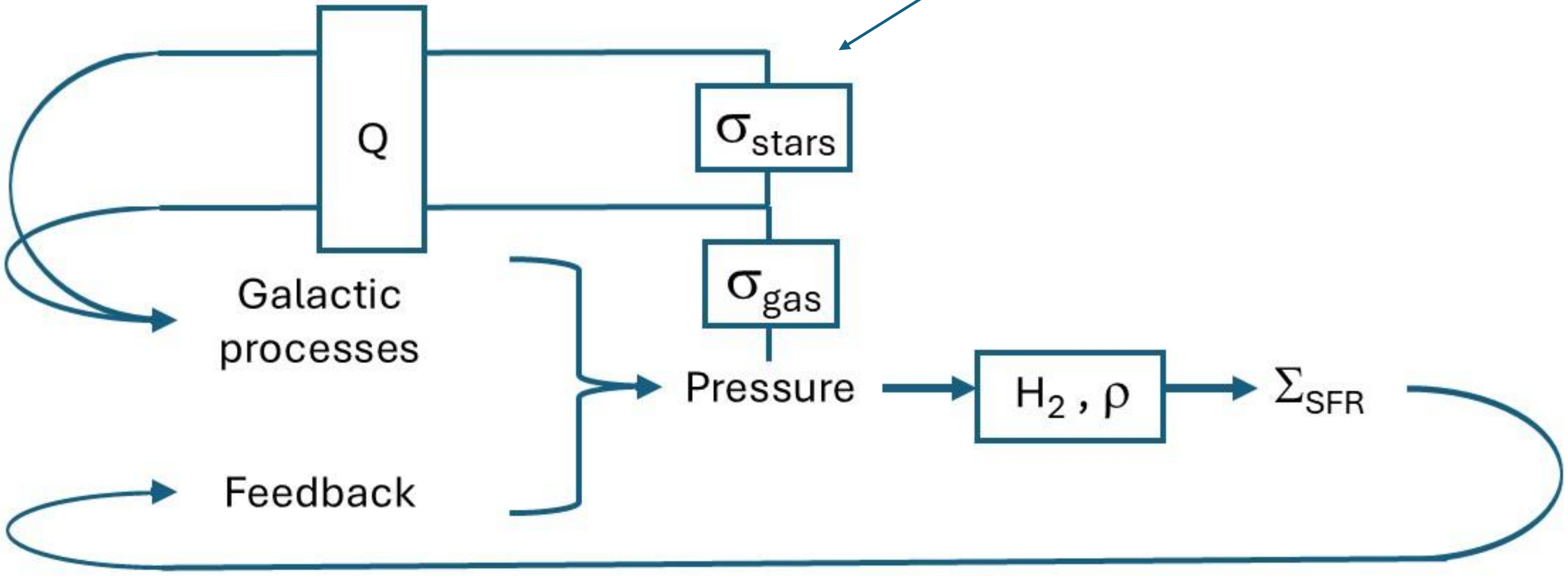
Goldreich & Lynden-Bell ’65, … Joung +09, Faucher-Giguère +13, …
Ostriker +10 (“pressure-regulated feedback model”)
Simulations in Dobbs +14, Hung +19, Ostriker & Kim ’22, …

Two “control cycles”



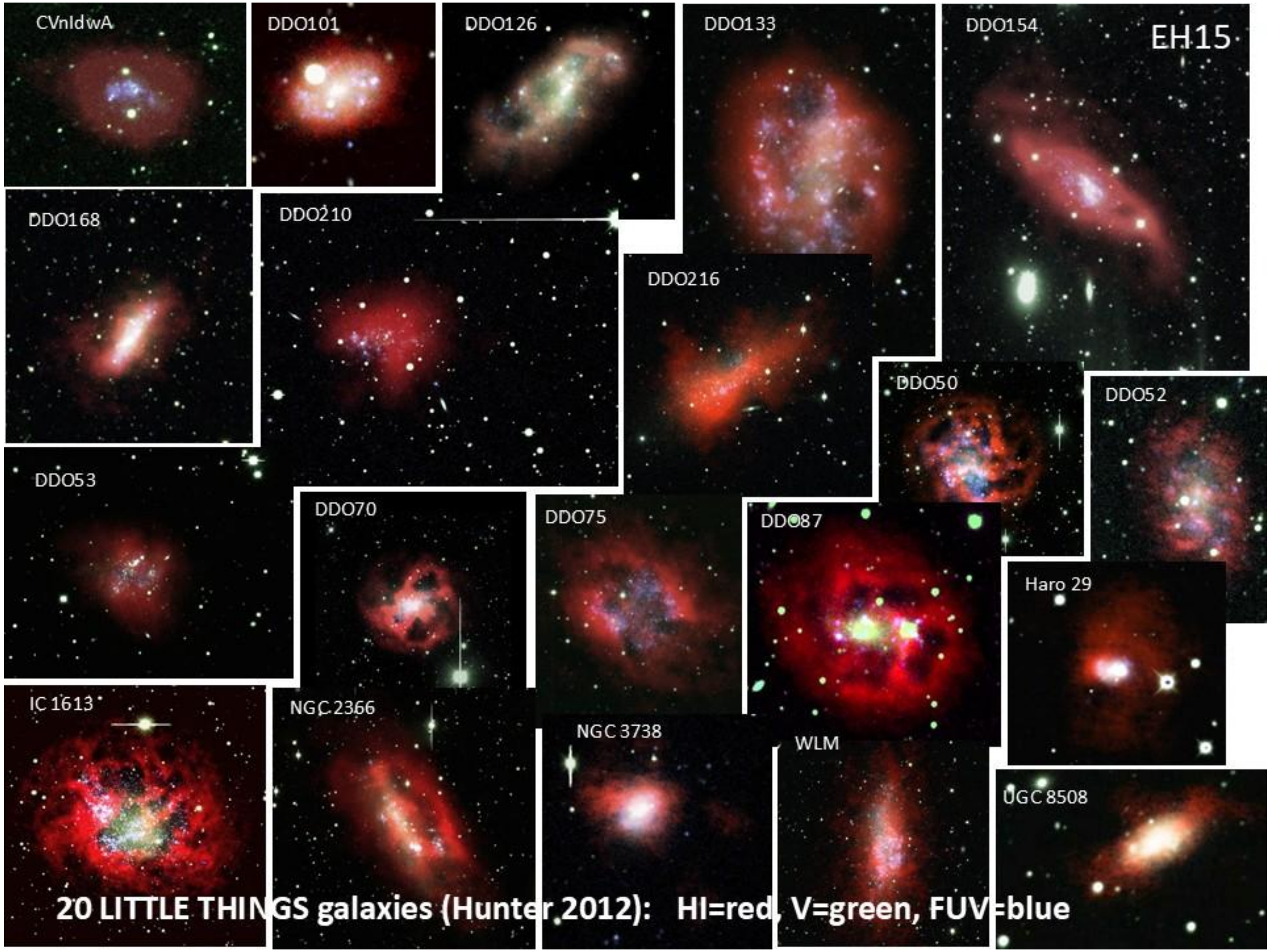
Two “control cycles”

The “Alessandro Romeo Cycle”

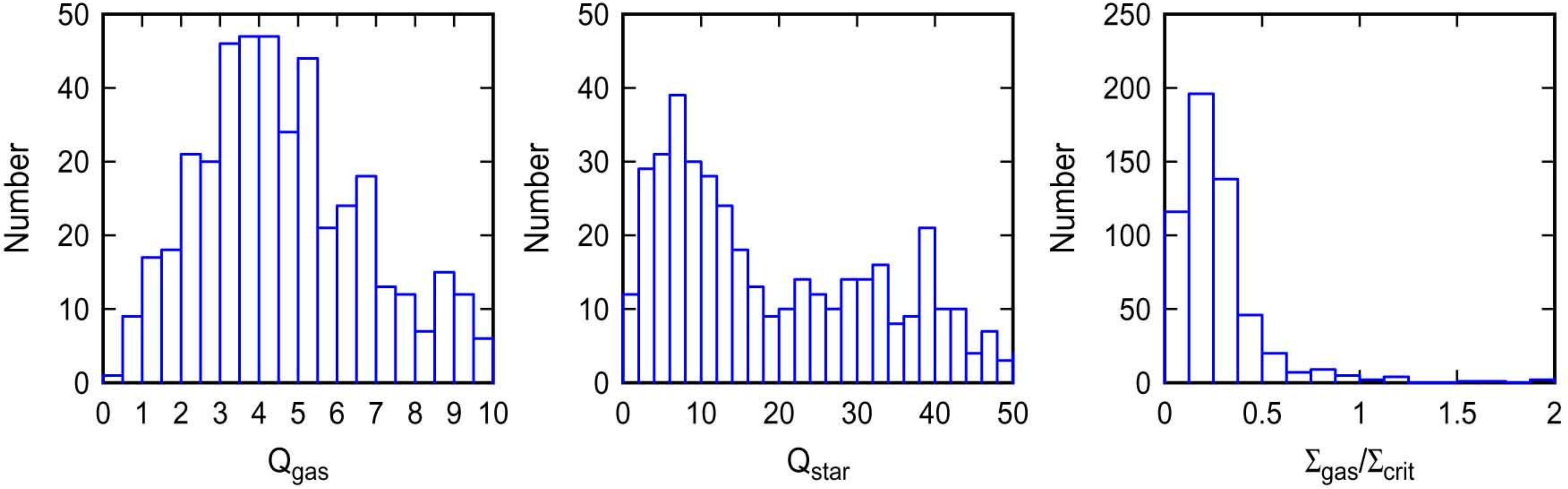


What happens when the *Alessandro Romeo Cycle* turns off?

This may happen in dwarf irregular galaxies, especially their **outer parts**.



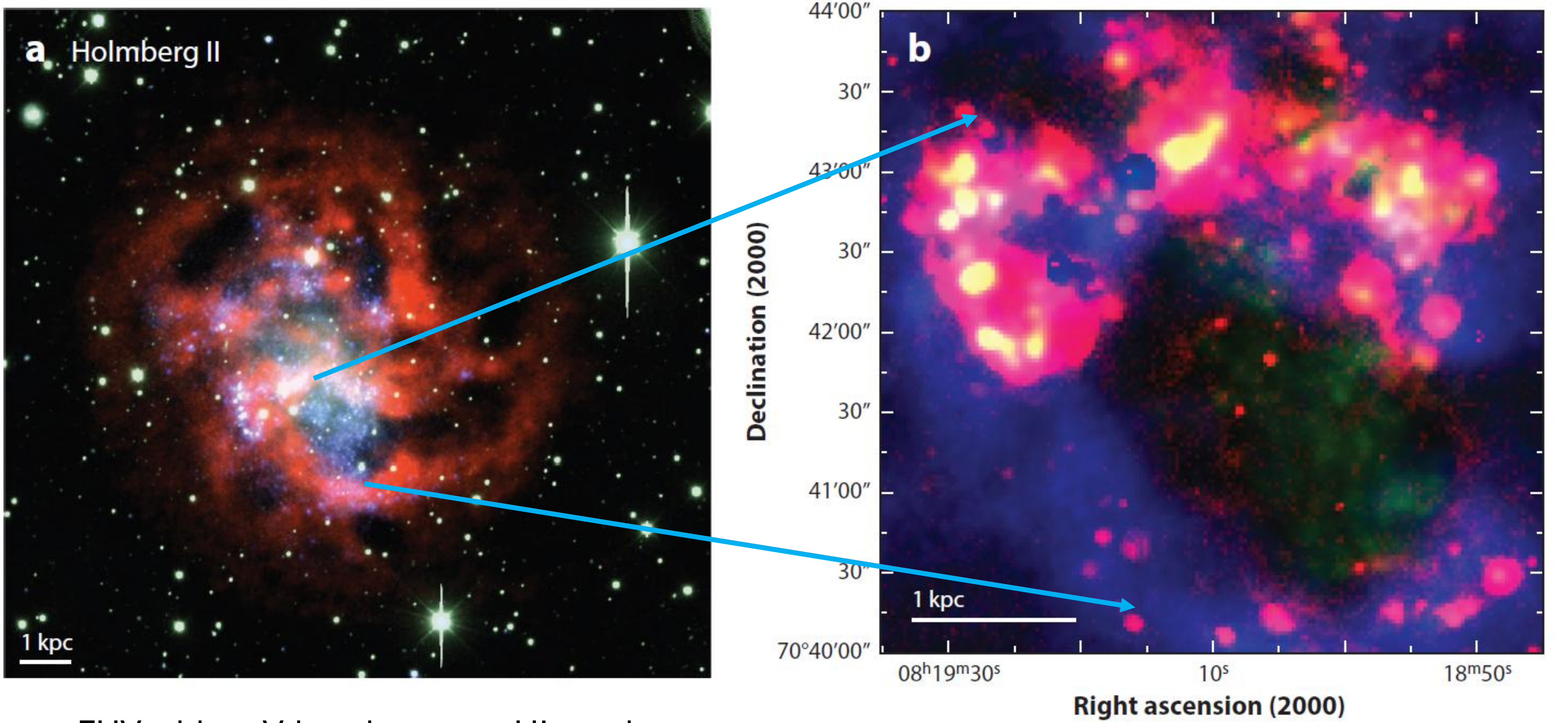
Elmegreen & Hunter ‘15



Using V_{rot}, Σ_{gas}, σ_{gas}, Σ_{star}, σ_{star} for radial annuli in 20 galaxies
(Narayan & Jog ’02, Elmegreen +11)

Q_{gas} and $Q_{star} >> 1$; $\Sigma_{gas} / \Sigma_{crit} << 1$

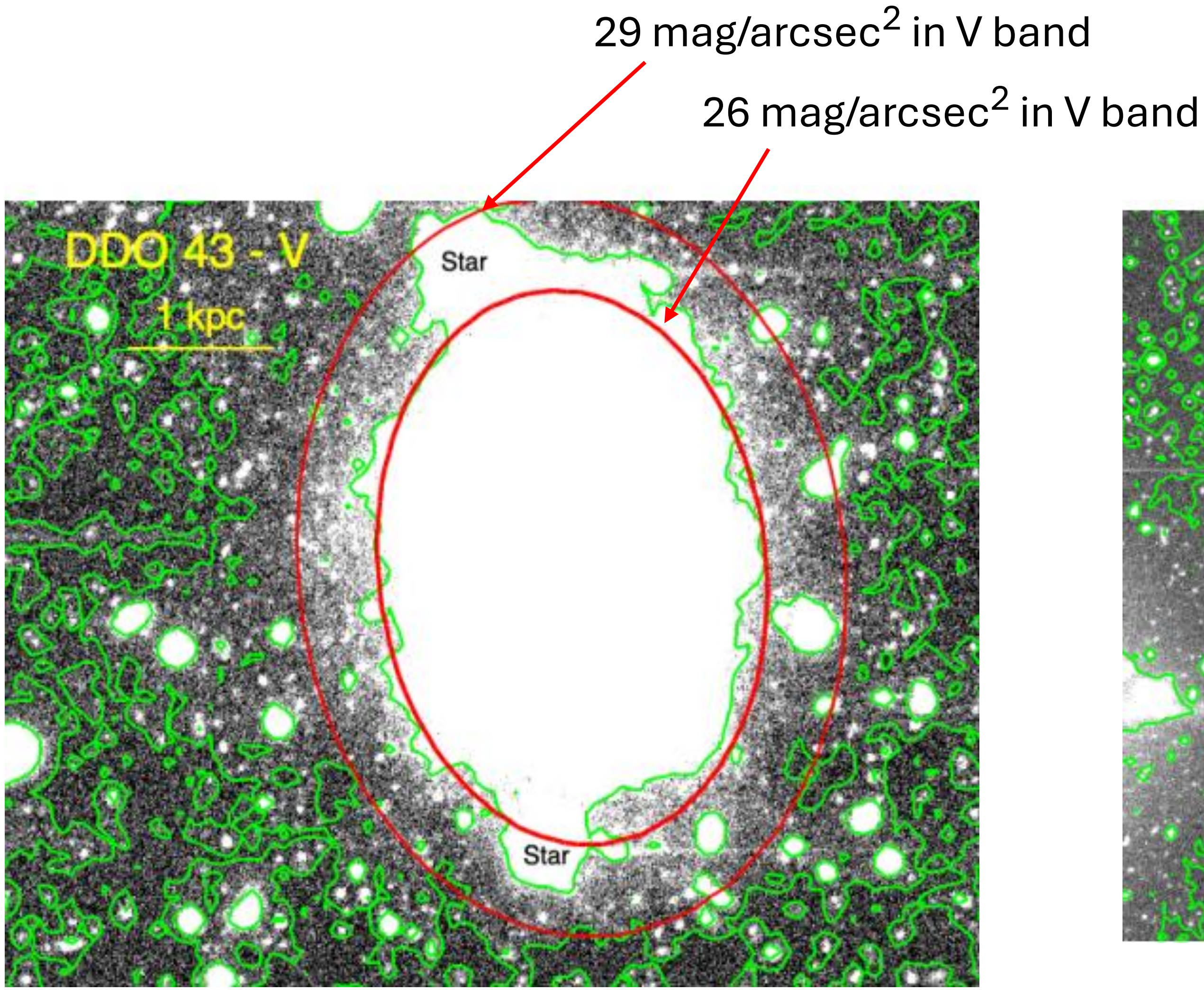
Yet star formation is pervasive and normal

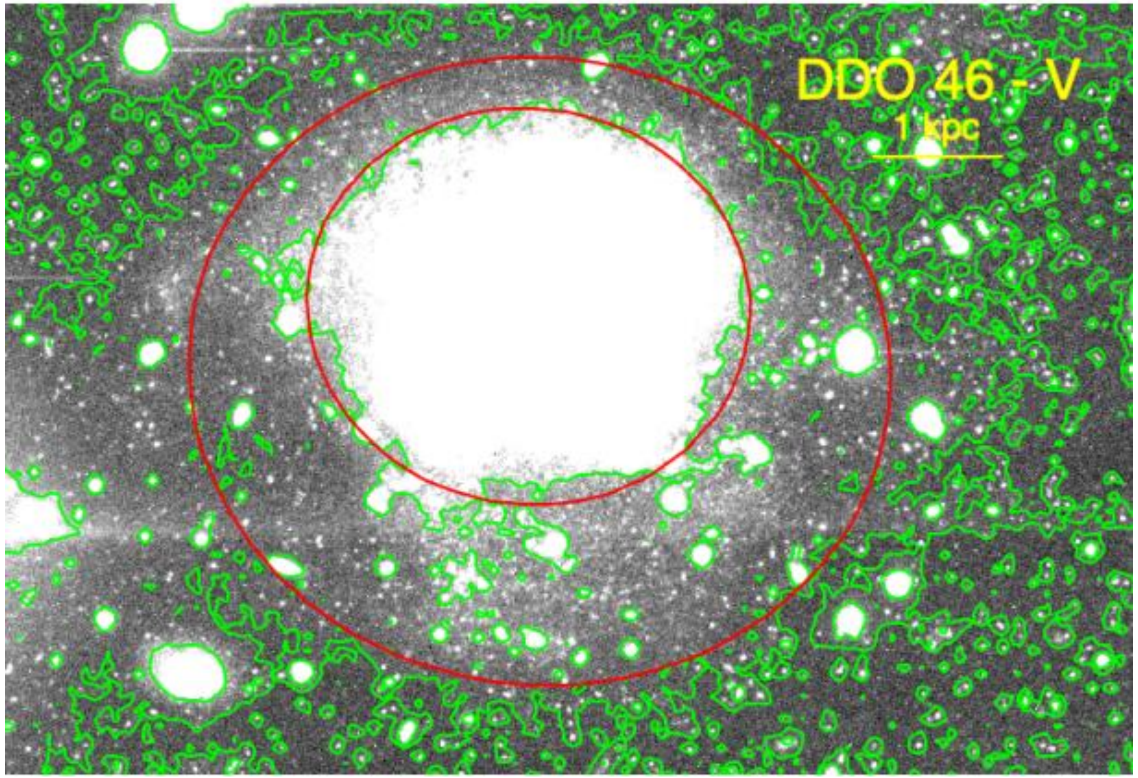


FUV = blue; V-band = green; HI = red
(Lauren Hill and Deidre Hunter, 2024, Egorov +17)

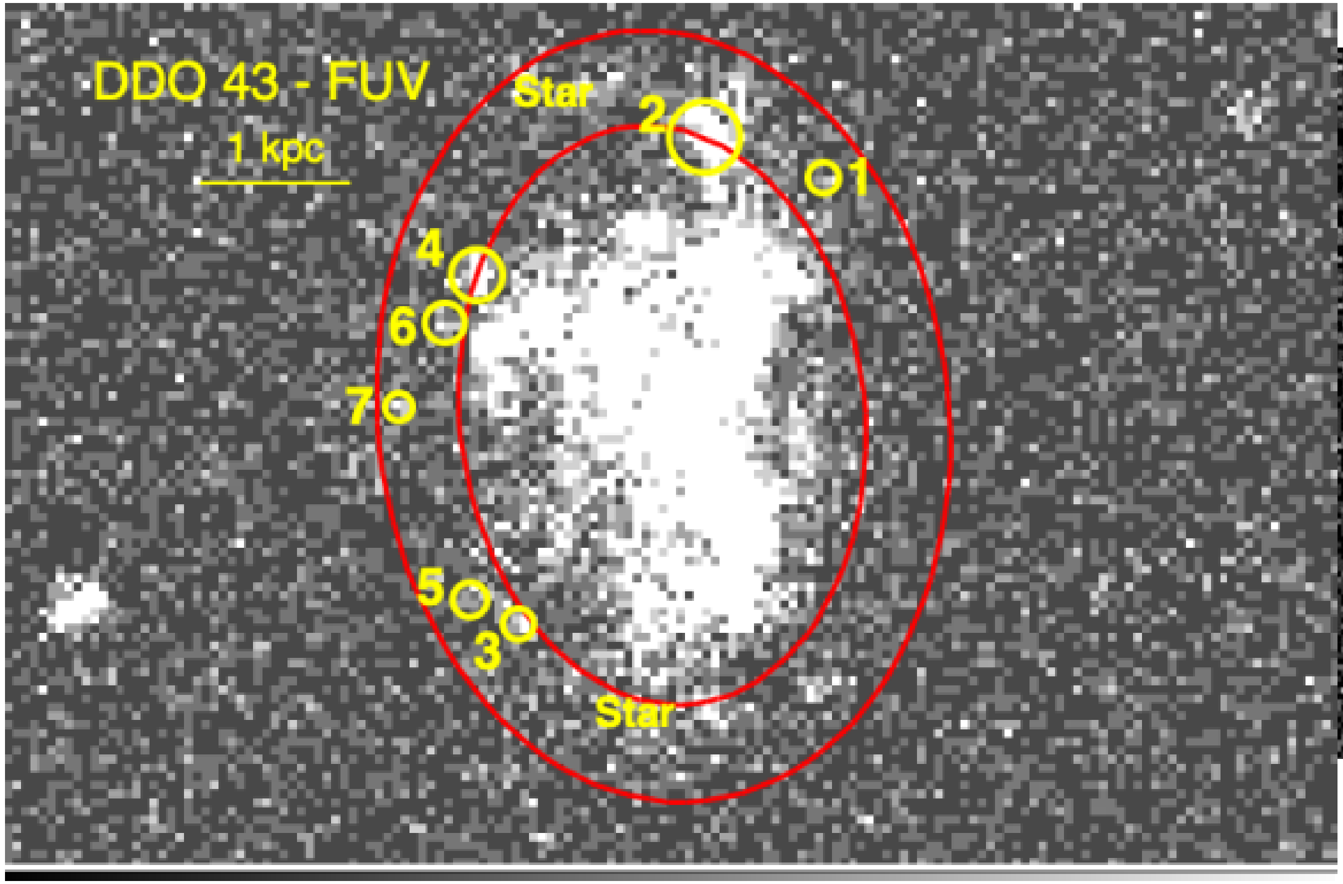
Ha = red; FUV = green; HI = blue (Egorov +17)

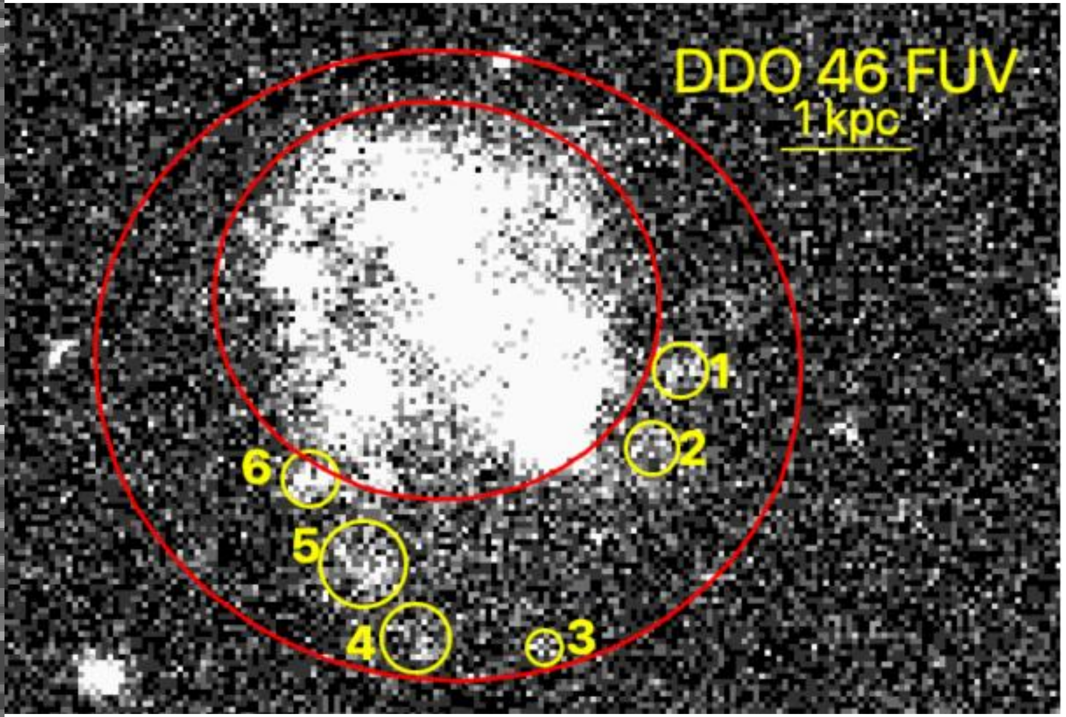
Hunter +25
DOI: 10.3847/1538-3881/ade154





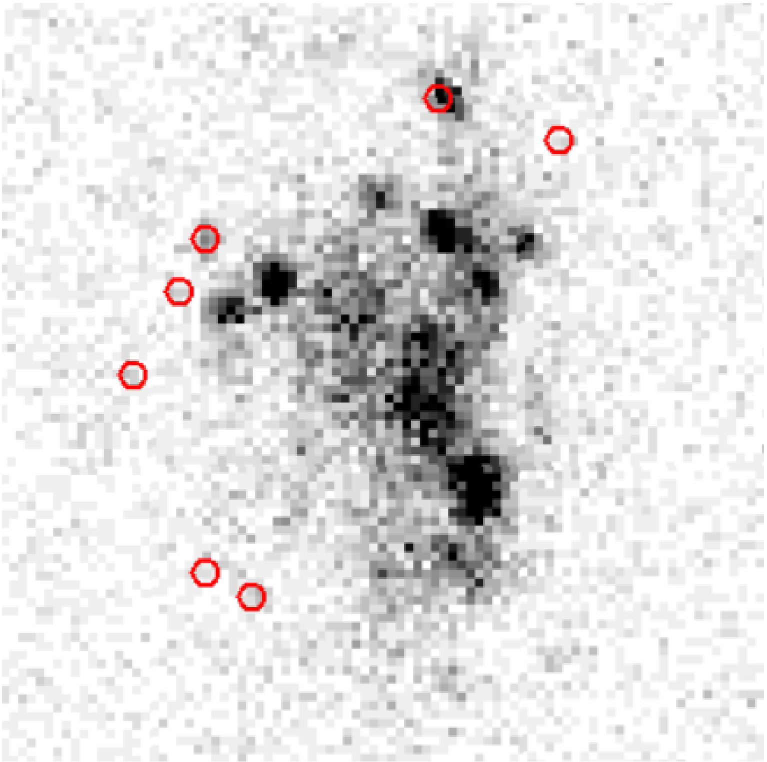
Hunter +25





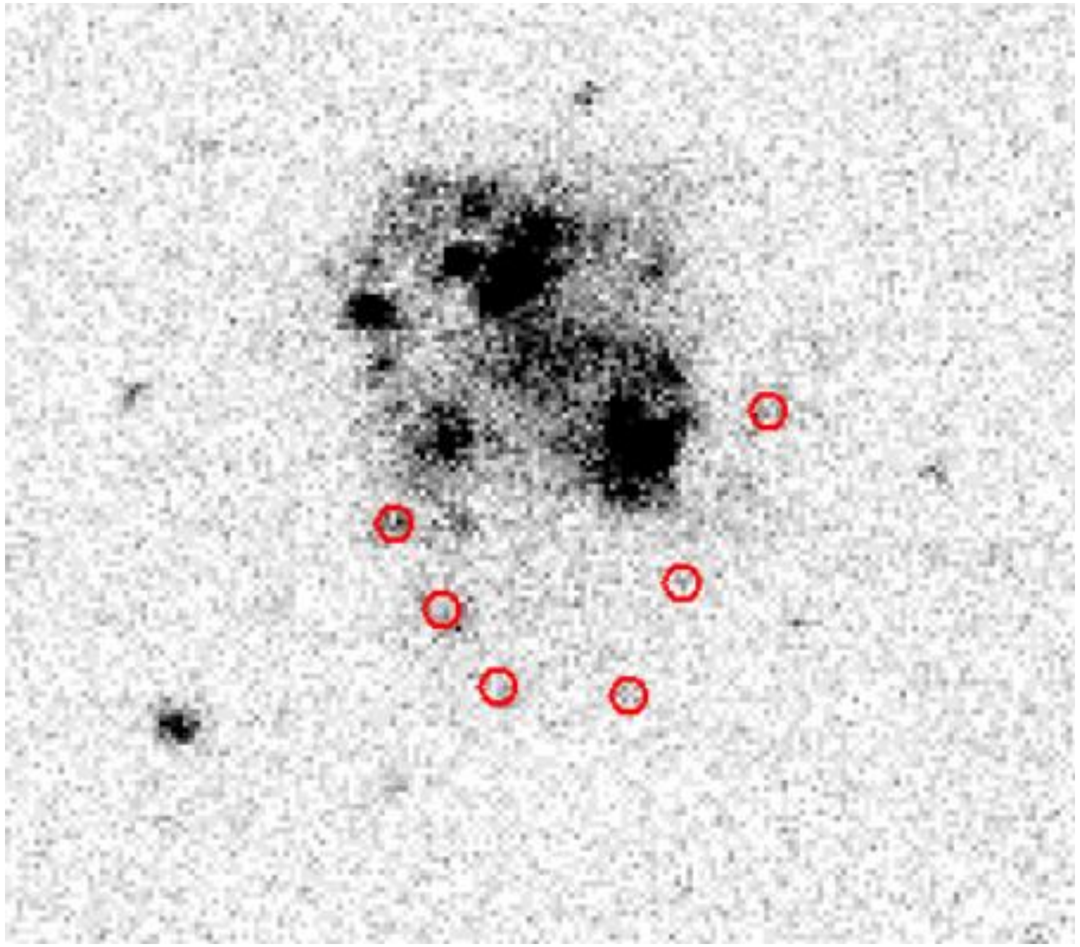
Hunter +25

DDO 43 - FUV

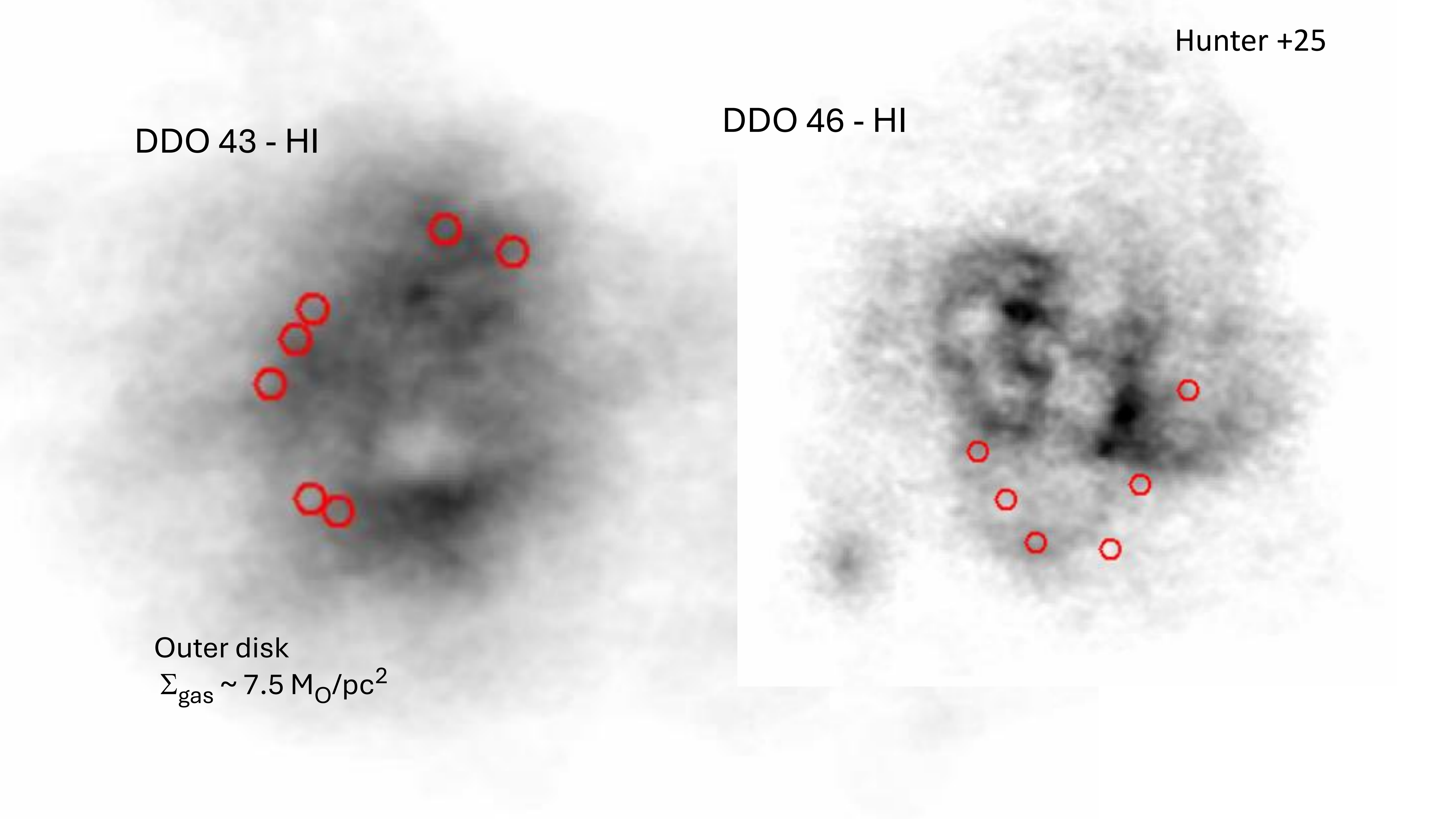


Outer disk
$\Sigma_{SFR} \sim 6.3x10^{-4}\ M_O/Myr/pc^2$

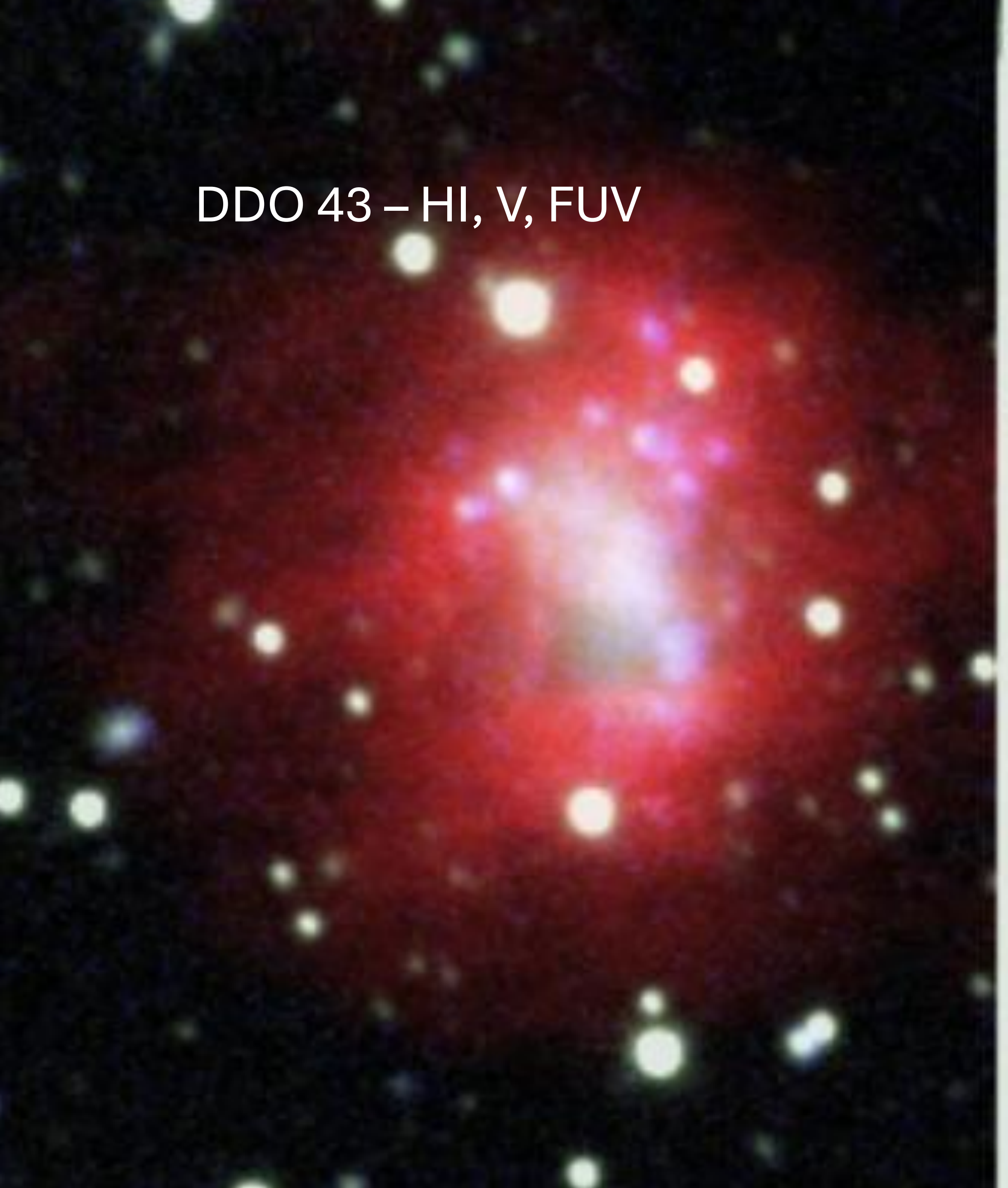
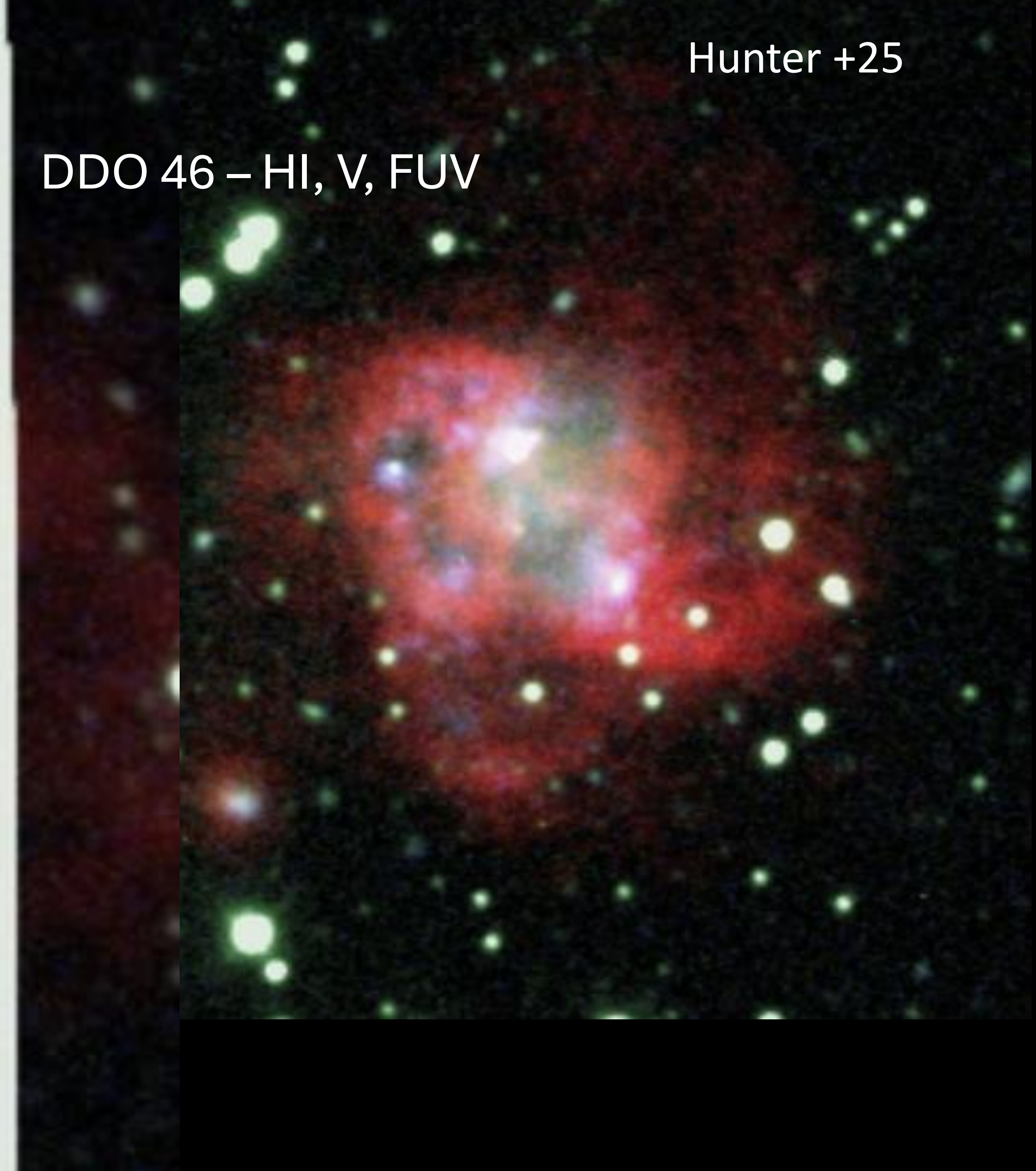
DDO 46 - FUV

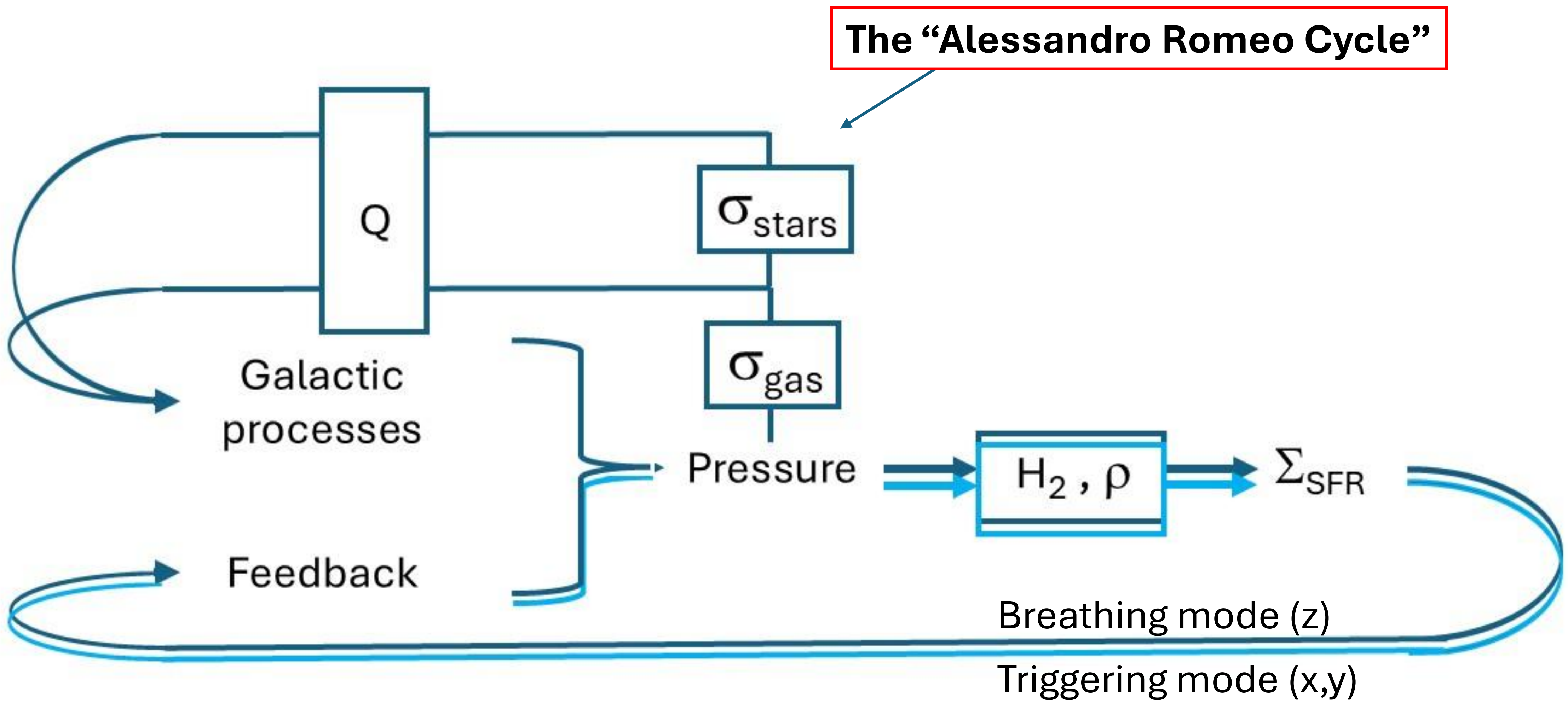


Outer disk
$\Sigma_{SFR} \sim 1.6x10^{-5}\ M_O/Myr/pc^2$

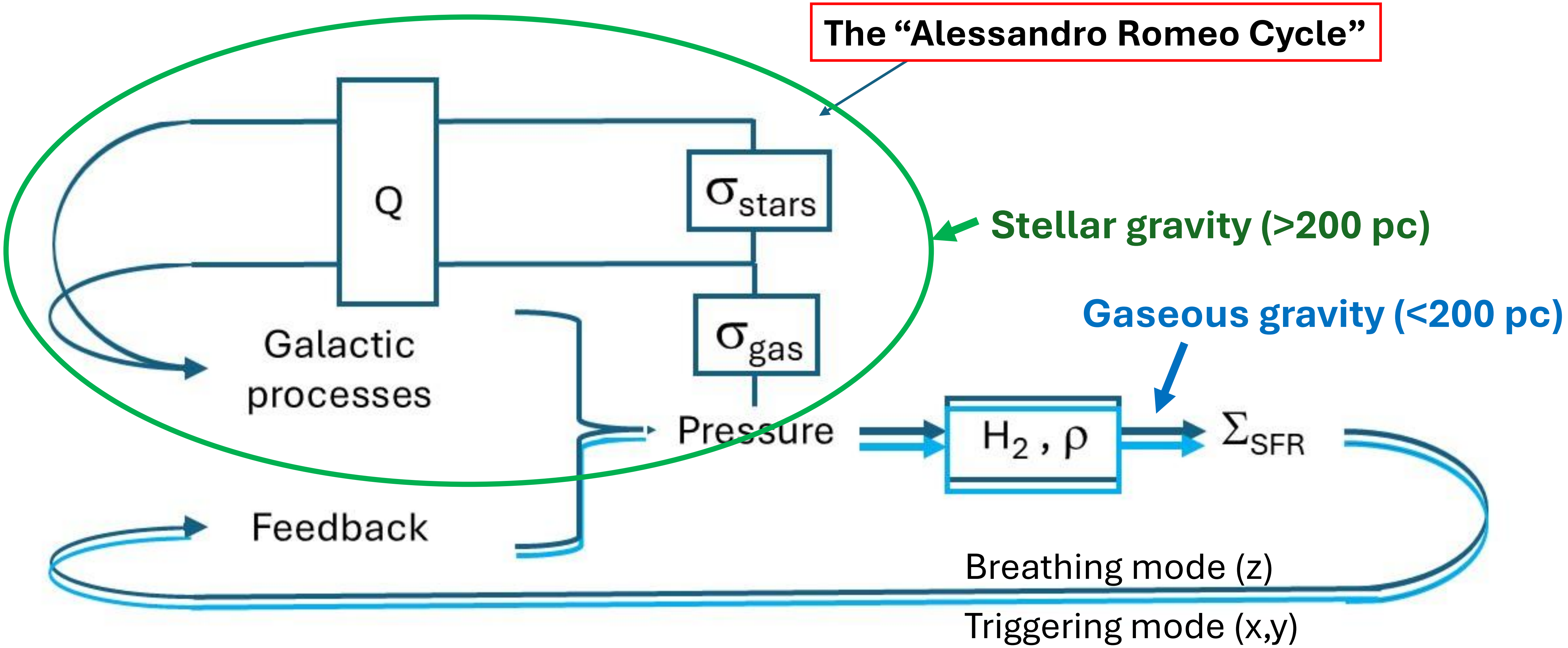


Hunter +25
DDO 43 - HI
DDO 46 - HI
Outer disk
$\Sigma_{gas} \sim 7.5\ M_O/pc^2$


DDO 43 – HI, V, FUV

Hunter +25
DDO 46 – HI, V, FUV



The "Alessandro Romeo Cycle"
Q
σstars
σgas
Galactic processes
Feedback
Pressure
H2 , ρ
ΣSFR
Breathing mode (z)
Triggering mode (x,y)


The "Alessandro Romeo Cycle"
Q
σ_{stars}
σ_{gas}
Stellar gravity (>200 pc)
Gaseous gravity (<200 pc)
Galactic processes
Pressure
H_2 , ρ
Σ_{SFR}
Feedback
Breathing mode (z)
Triggering mode (x,y)

Summary

1. For a limited sample of galaxies, the line-of-sight thickness can be measured with Fourier Transform Power Spectra of the ISM
    - But mostly for (relatively thin) spirals closer than ~10 Mpc at >0.1” resolution

2. The thickness is the inverse wavenumber at a break (if there is one) between two power-law portions of the power spectrum
    - These portions separate the 2D (large-scale) from the 3D (small scale) emission
    - Need to be careful to avoid the high-k steepening from the point spread function

3. JWST Mid-IR bands do not show PS breaks in NGC 628, NGC 5236, NGC 4449 and NGC 5068
    - possibly because the emitting layers are too thin to resolve (< 50 pc)
    - and the PSF has broad wings

4. HST Hα images of M51 at 2.55 pc resolution show breaks in the power spectrum, suggesting Hα disk thickness increasing with galactocentric radius as ~ 40 pc/kpc

5. Large scale structure (>thickness) appears to be from disk gravity (spirals, MJeans complexes) and may be regulated by the ***Alessandro Romeo Cycle***

6. Small scale structure is from star formation feedback, ISM gravity, and possibly a galactic cascade