Star Formation Processes and Energy Sources in Interstellar Gas

Bruce G. Elmegreen
IBM T.J. Watson Research Center
Yorktown Heights, NY
bge@us.ibm.com

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Yuri Efremov, Elba 1992

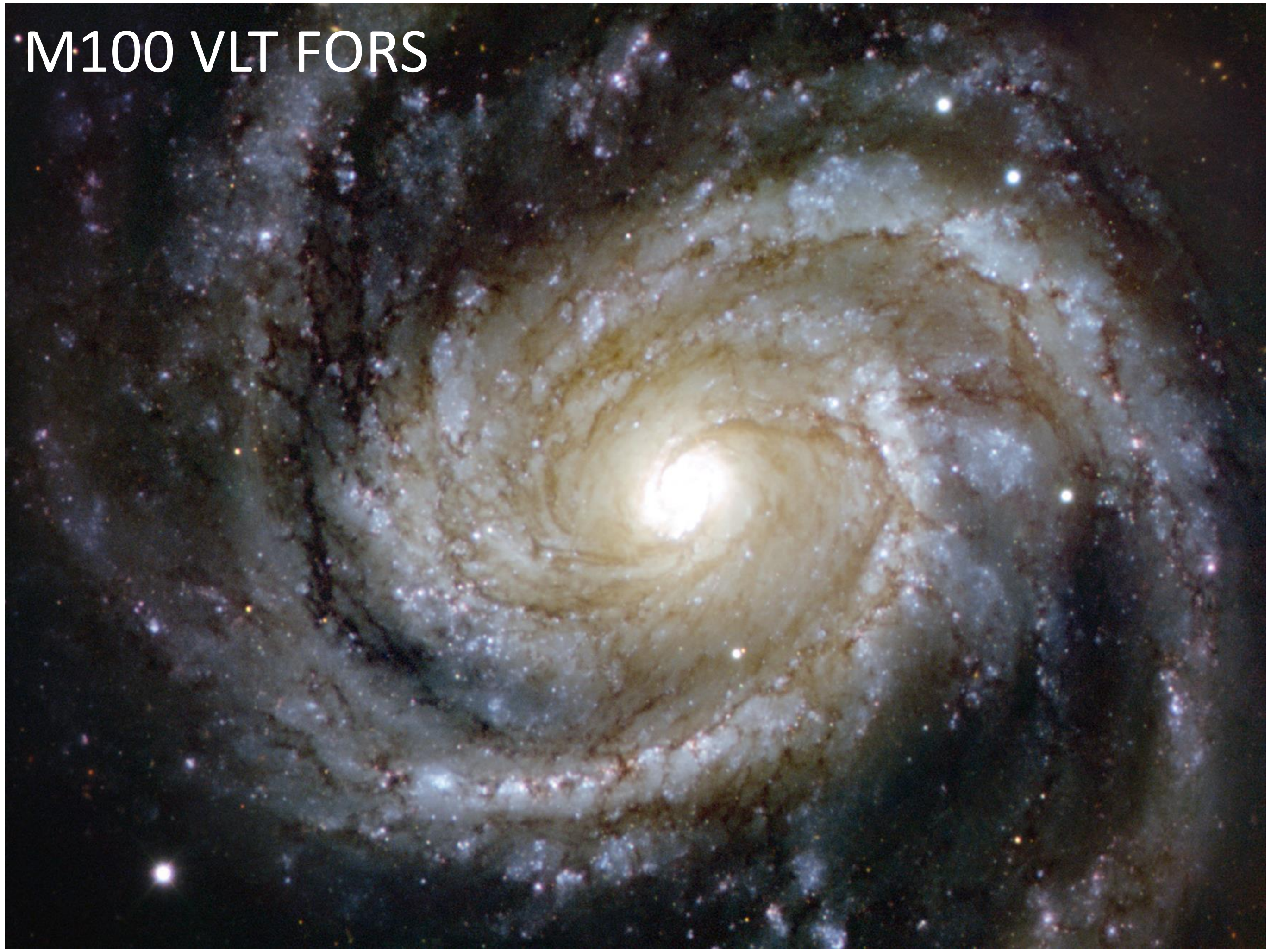
Questions to address:

What starts the star formation process in spiral galaxies?

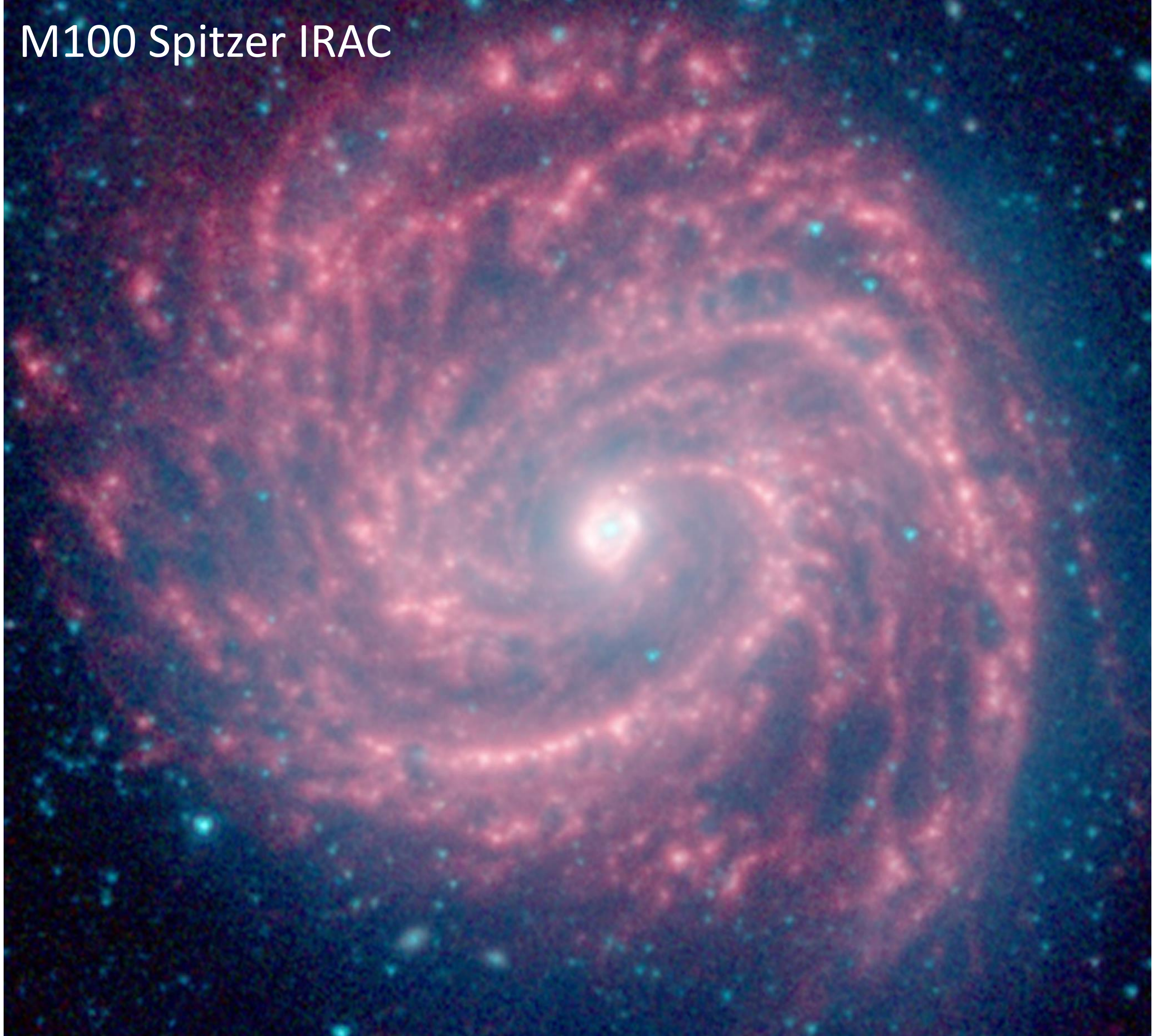
What drives the turbulence?

How does turbulence affect star formation?

What is happening to the ISM in a spiral density wave?



ESO

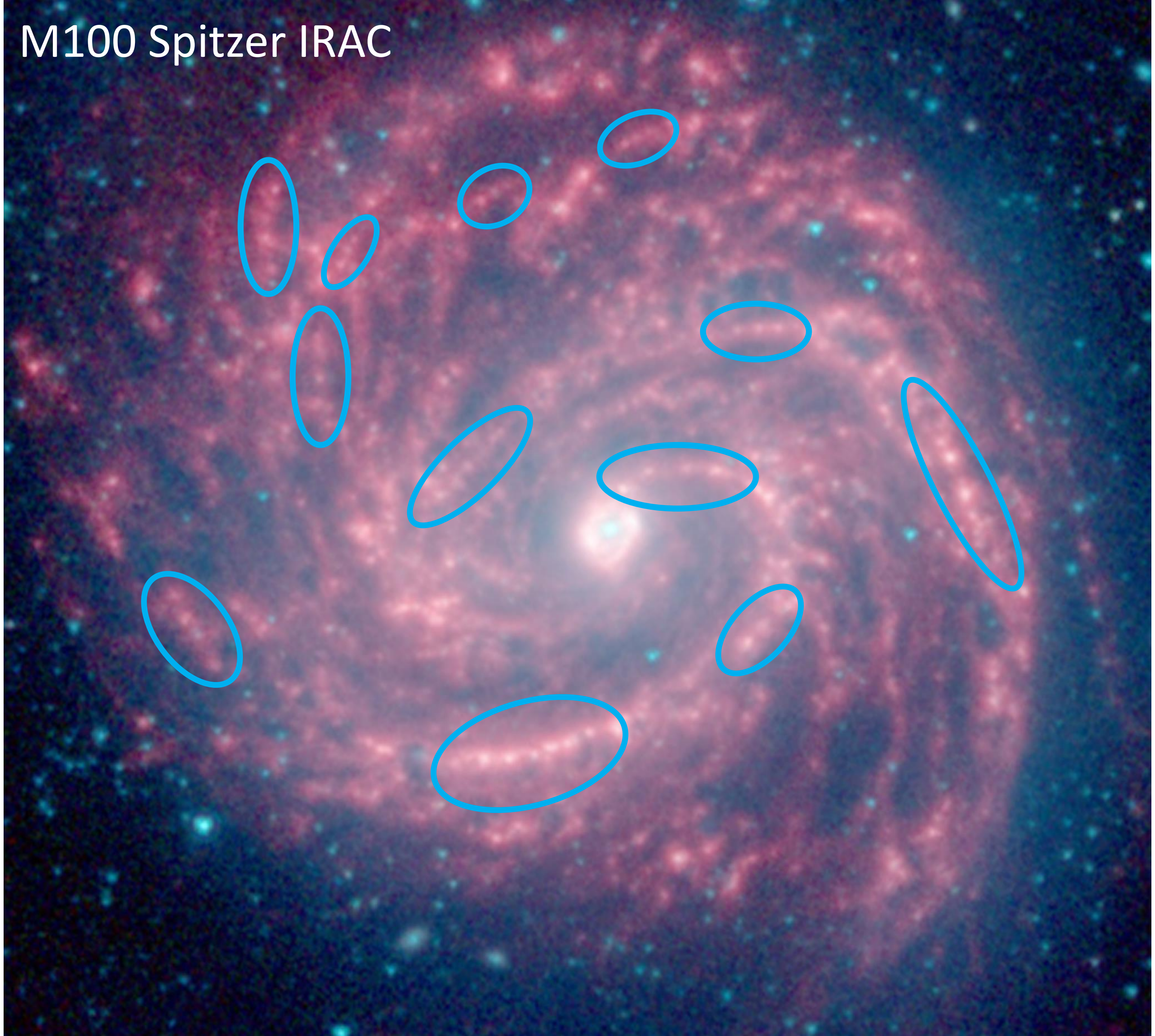


The arms have IR clumps.

3.6, 4.5,
5.8 and 8 μm

NASA/JPL-Caltech

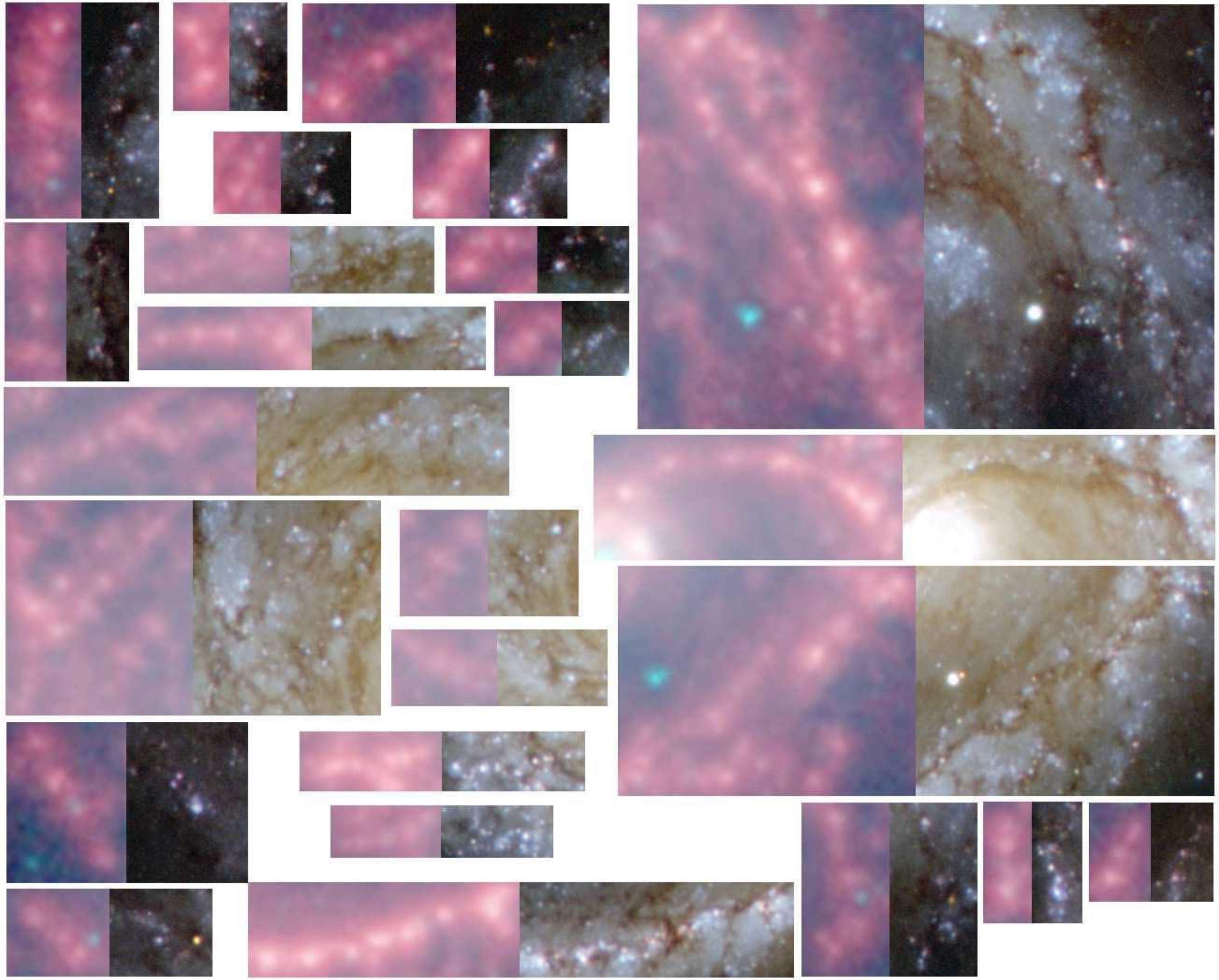
The arms have IR clumps.



3.6, 4.5,
5.8 and 8 μm

NASA/JPL-Caltech

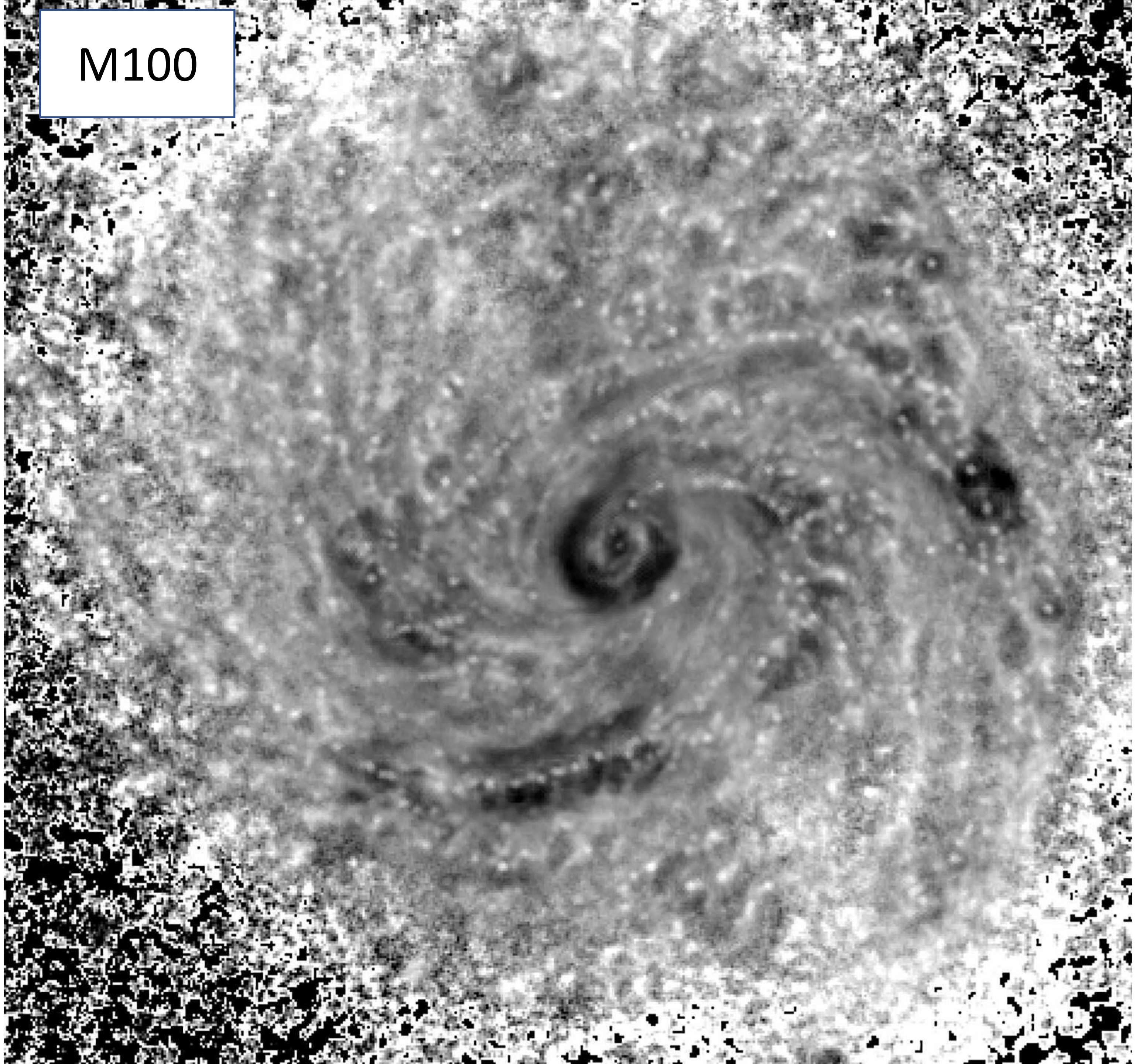
The IR clumps are nearly invisible in the optical.



Elmegreen,
Elmegreen,
Efremov ‘18

IRAC 8μm divided by MIPS 24 μm

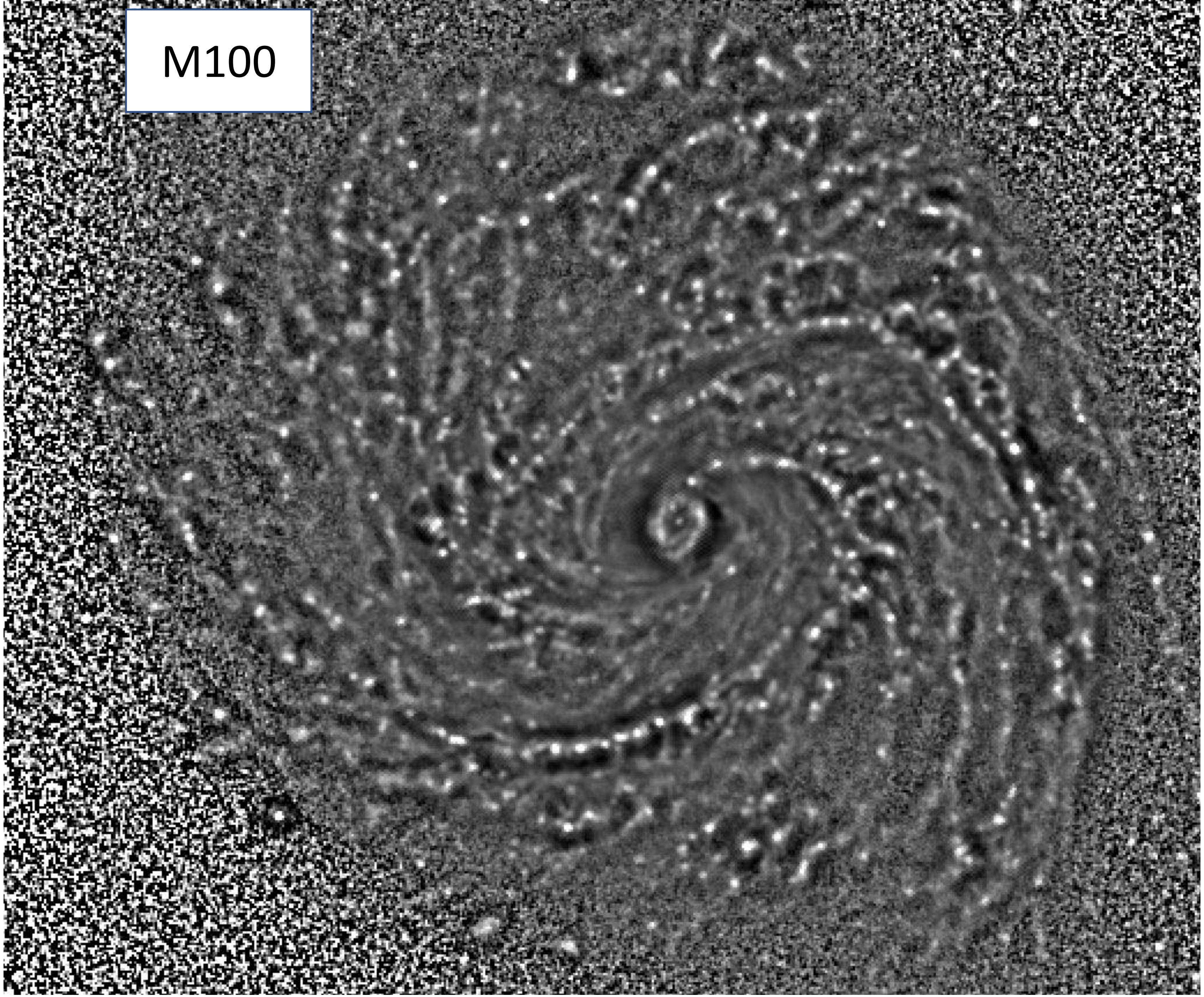
(like an unsharp Mask: 2.4” vs 7.1” resolution)



The IR clumps are revealed by an unsharp mask

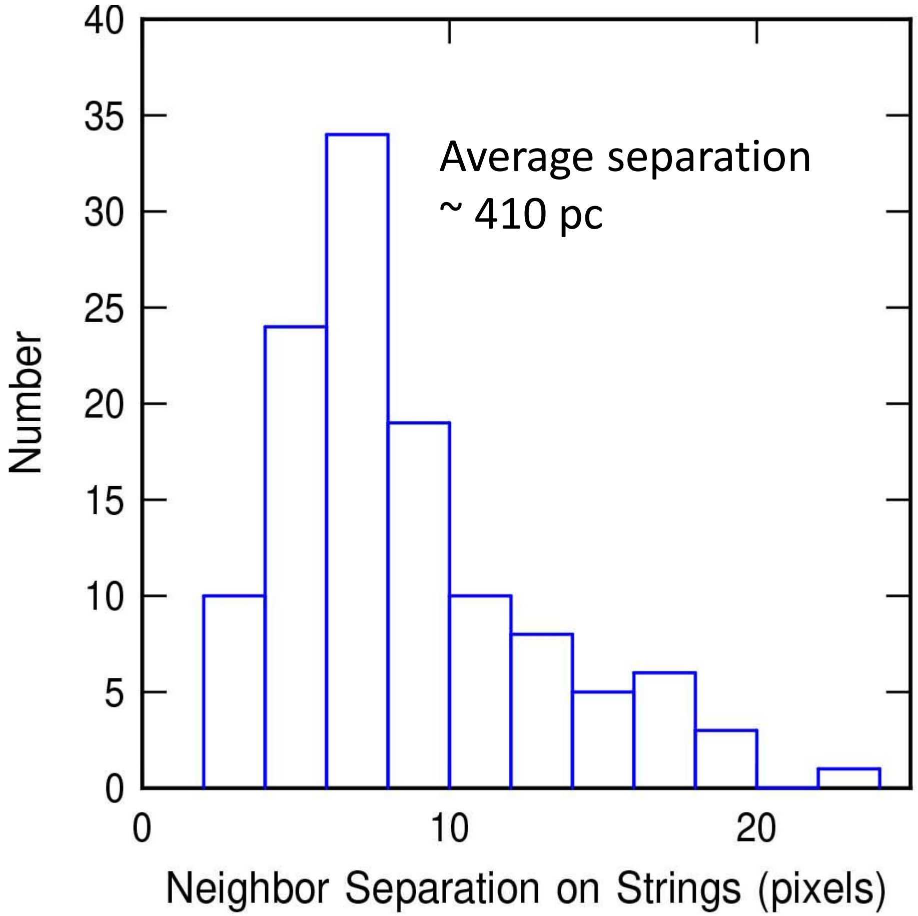
Elmegreen, Elmegreen, Efremov ‘18

IRAC 8μm divided by 3 pixel blur of itself



The IR clumps are revealed by an unsharp mask

M100: The clumps are approximately equally spaced along the filaments,



Average separation
~ 410 pc

… suggesting gravitational instabilities (sausage-like)

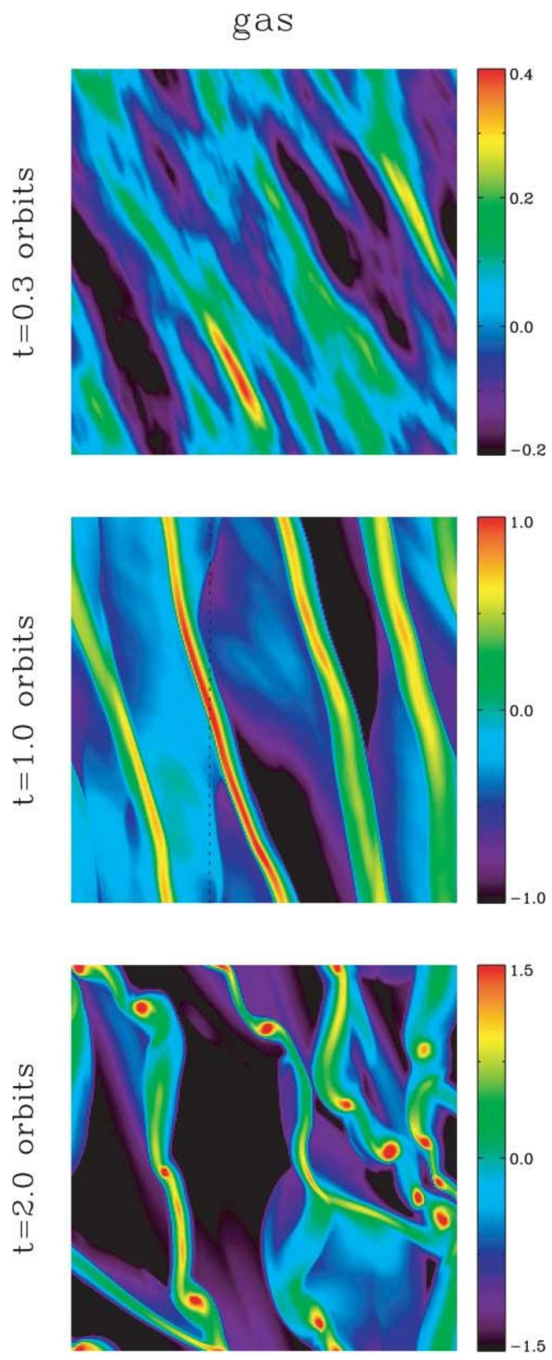
Elmegreen,
Elmegreen,
Efremov ‘18

Kim & Ostriker ‘07:

2D Shearing sheet hydrodynamic simulations of spiral waves found arm clumping at $Q_{gas} < 1.4$

(see also Kim & Ostriker ’01, Kim +02, +03, +09)

Time

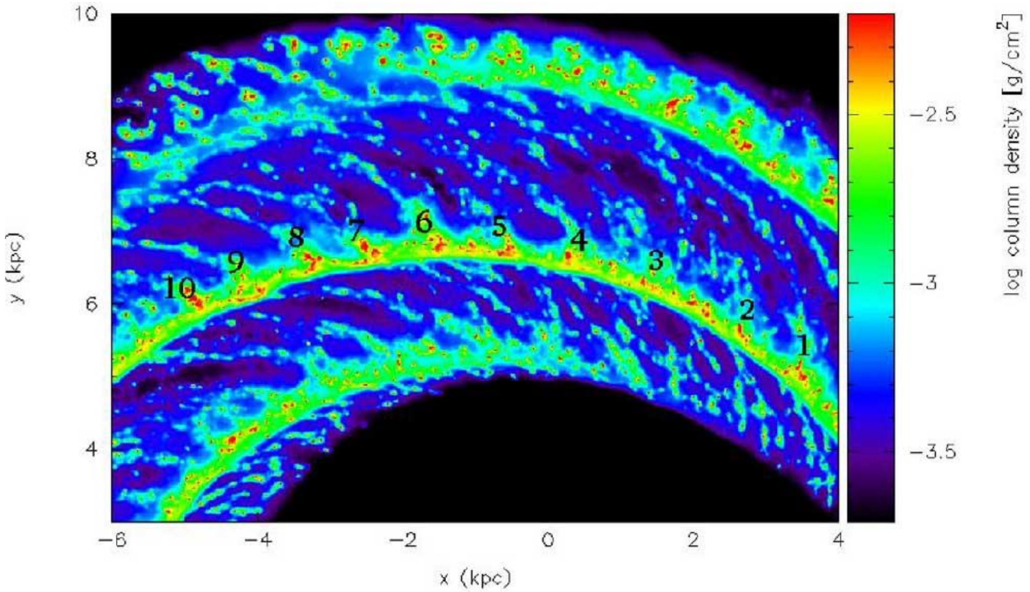


Dobbs ’08:

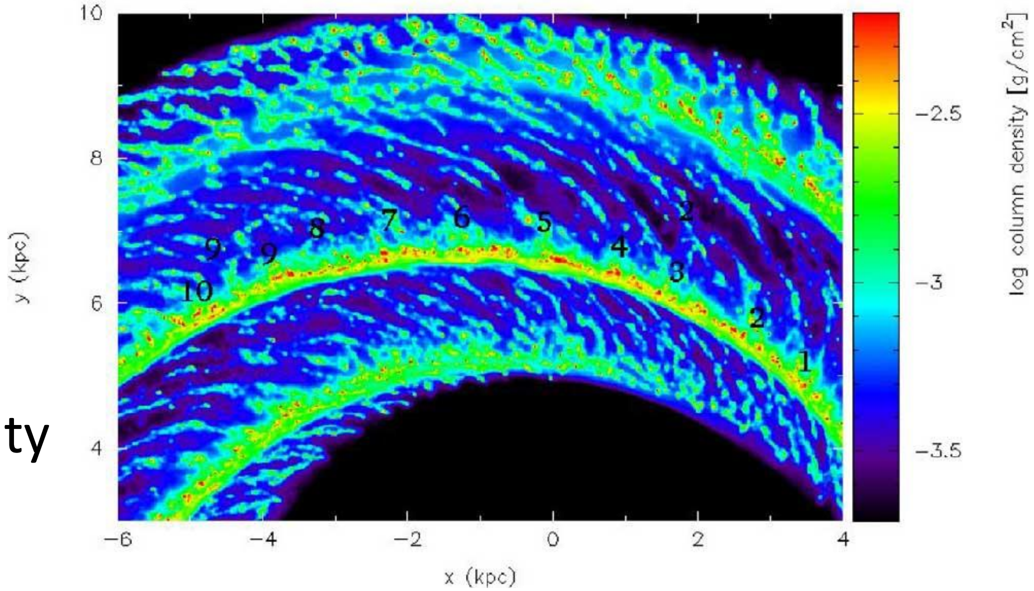
Cloud structure in spiral arms is from a combination of small-cloud agglomeration, self-gravity, and flow instabilities.

Self-gravity makes the structures more regular

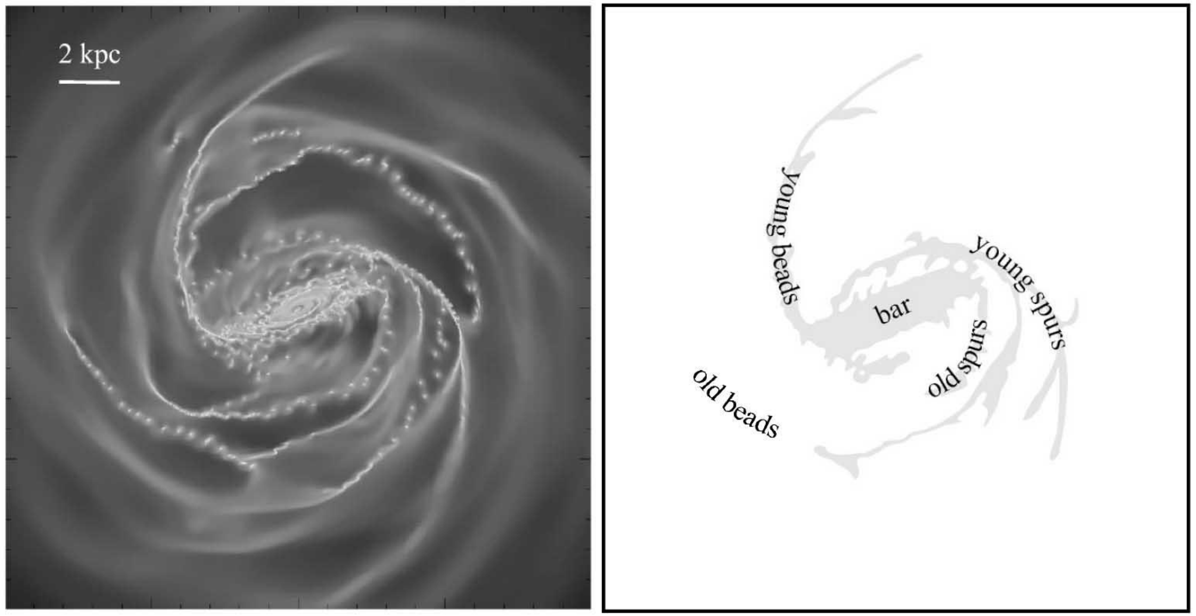
With self-gravity

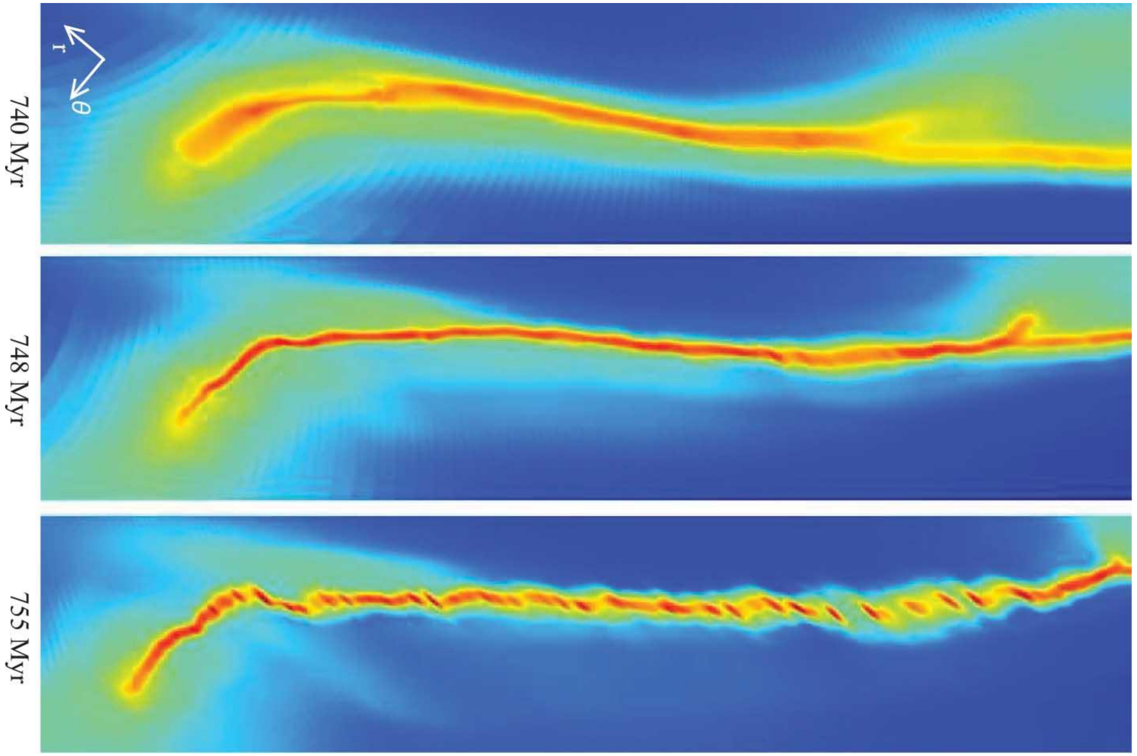


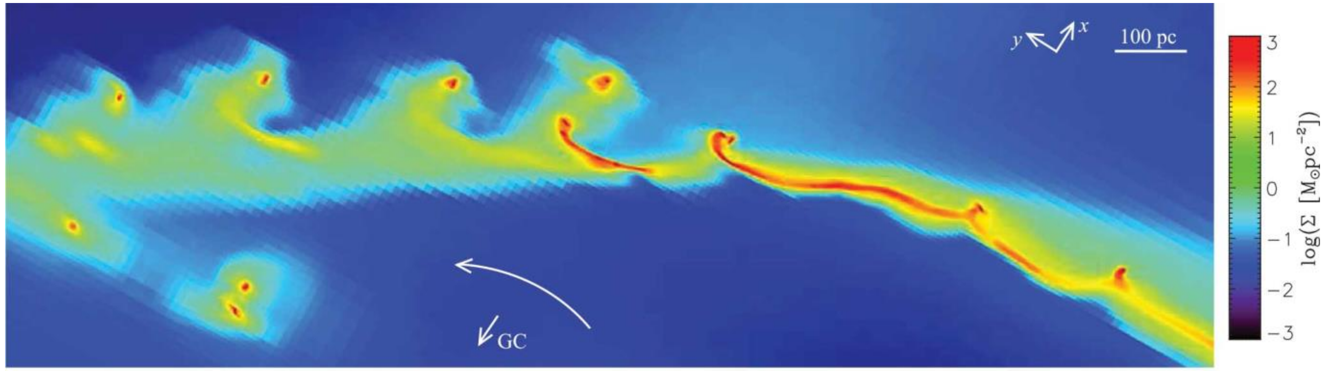
Without self-gravity



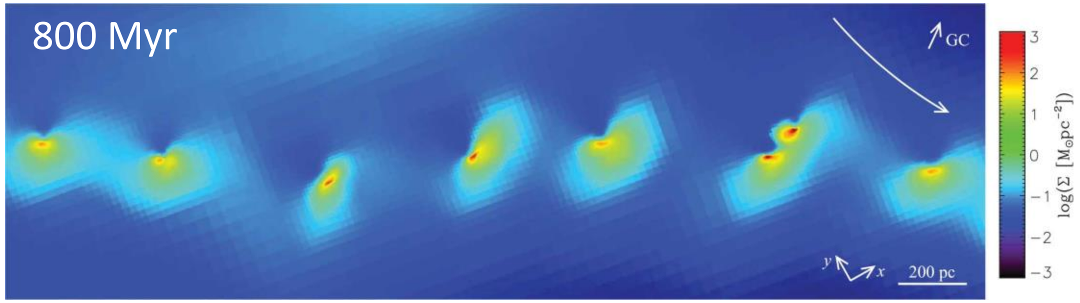
Renaud +13,14: beads and spurs







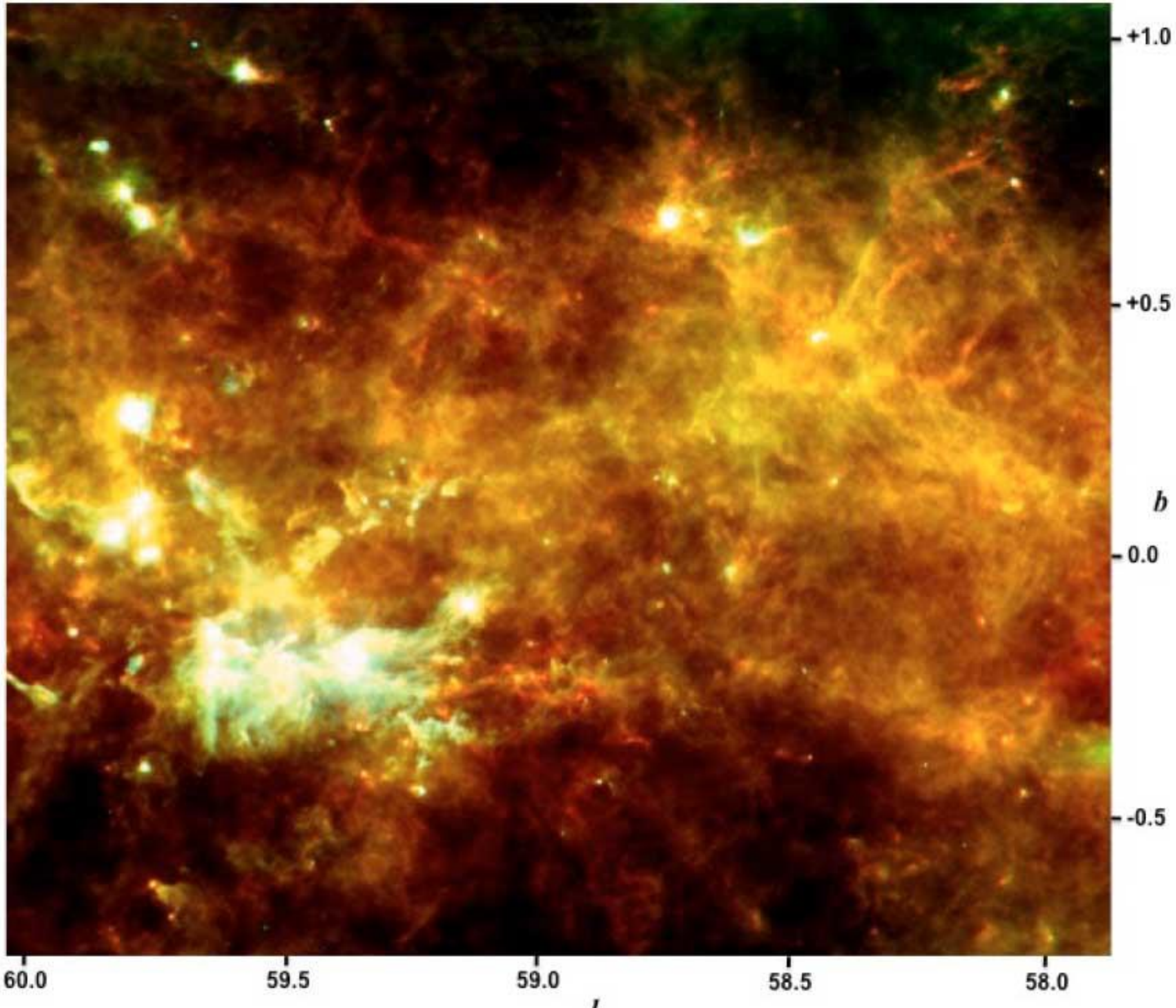
Spurs from Kelvin-Helmholtz-type instabilities



Beads from gravitational instabilities form in ~10 Myr at n ~ 30 cm^{-3}

Molinari +10

Herschel:
Milky Way
longitude = 59°
(70μm, 160μm, 350μm)



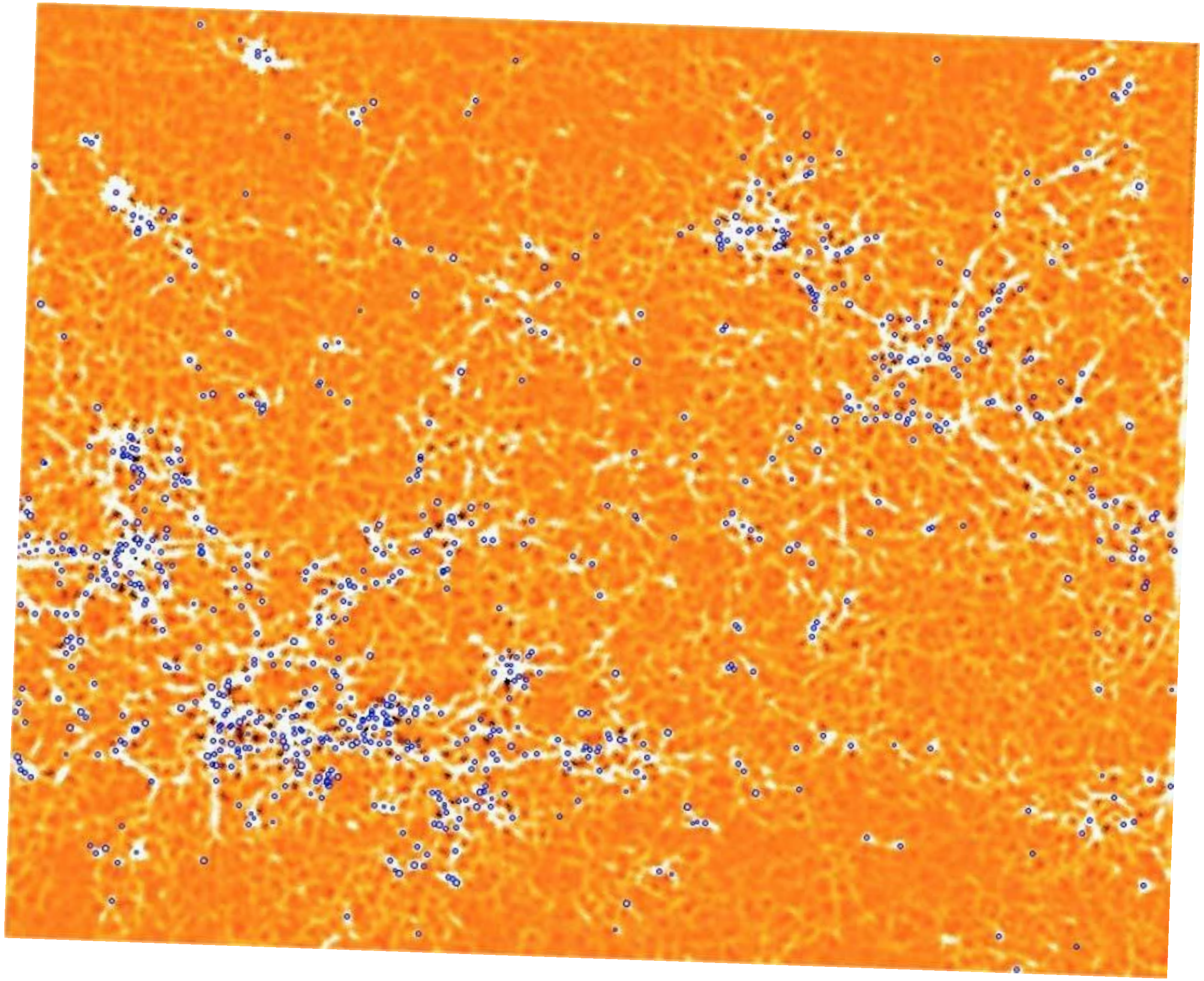
Molinari +10

Herschel:
Milky Way
longitude = 59^o

Second derivative shows clumps and filaments

→ Most SF is in filaments.

Galactic spirals are the largest scale



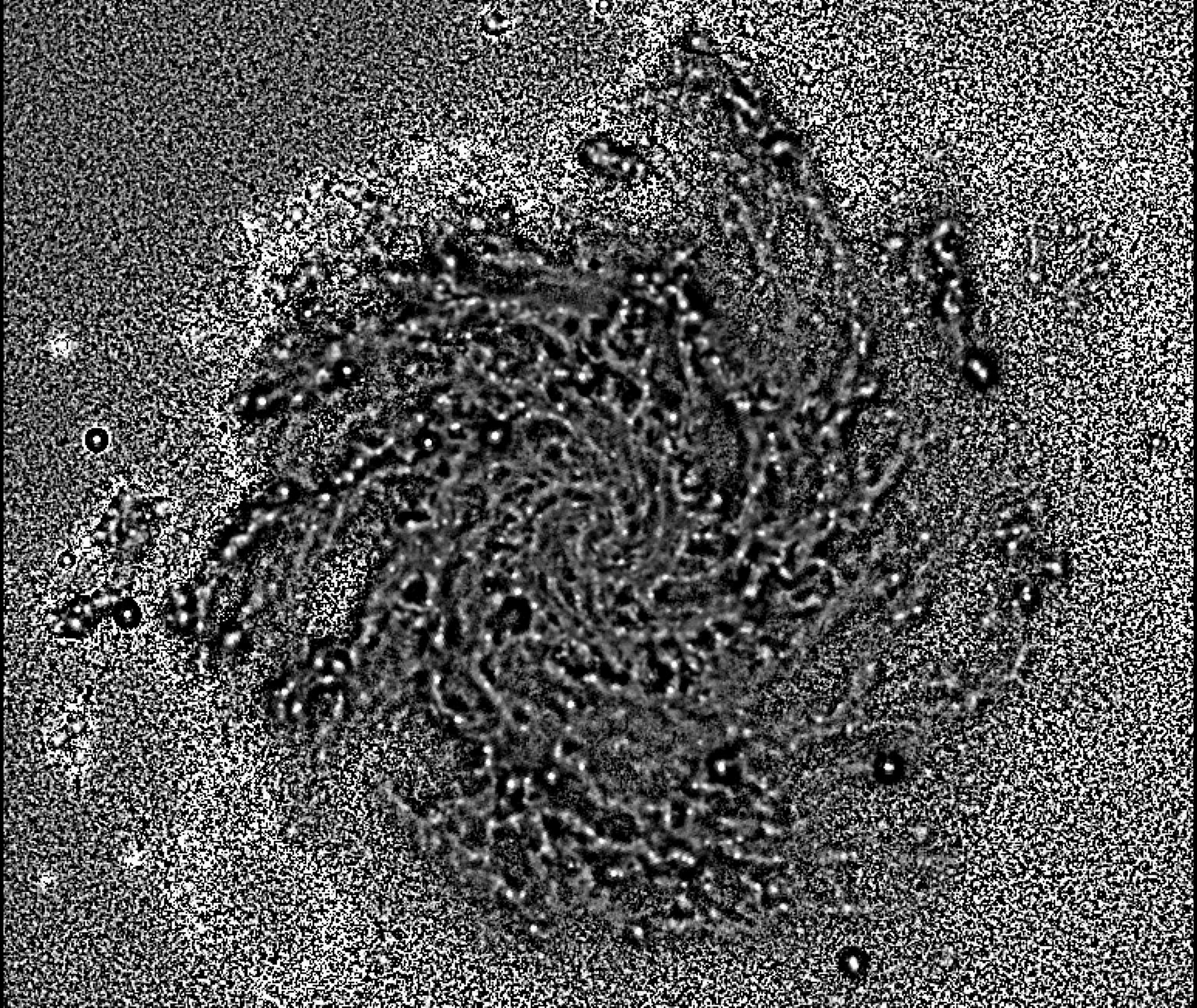
Mean clump separation along filaments, 1.8 pc

NGC 628

Spitzer IRAC

Elmegreen &
Elmegreen '19

NGC 628



Spitzer 8μ
unsharp mask

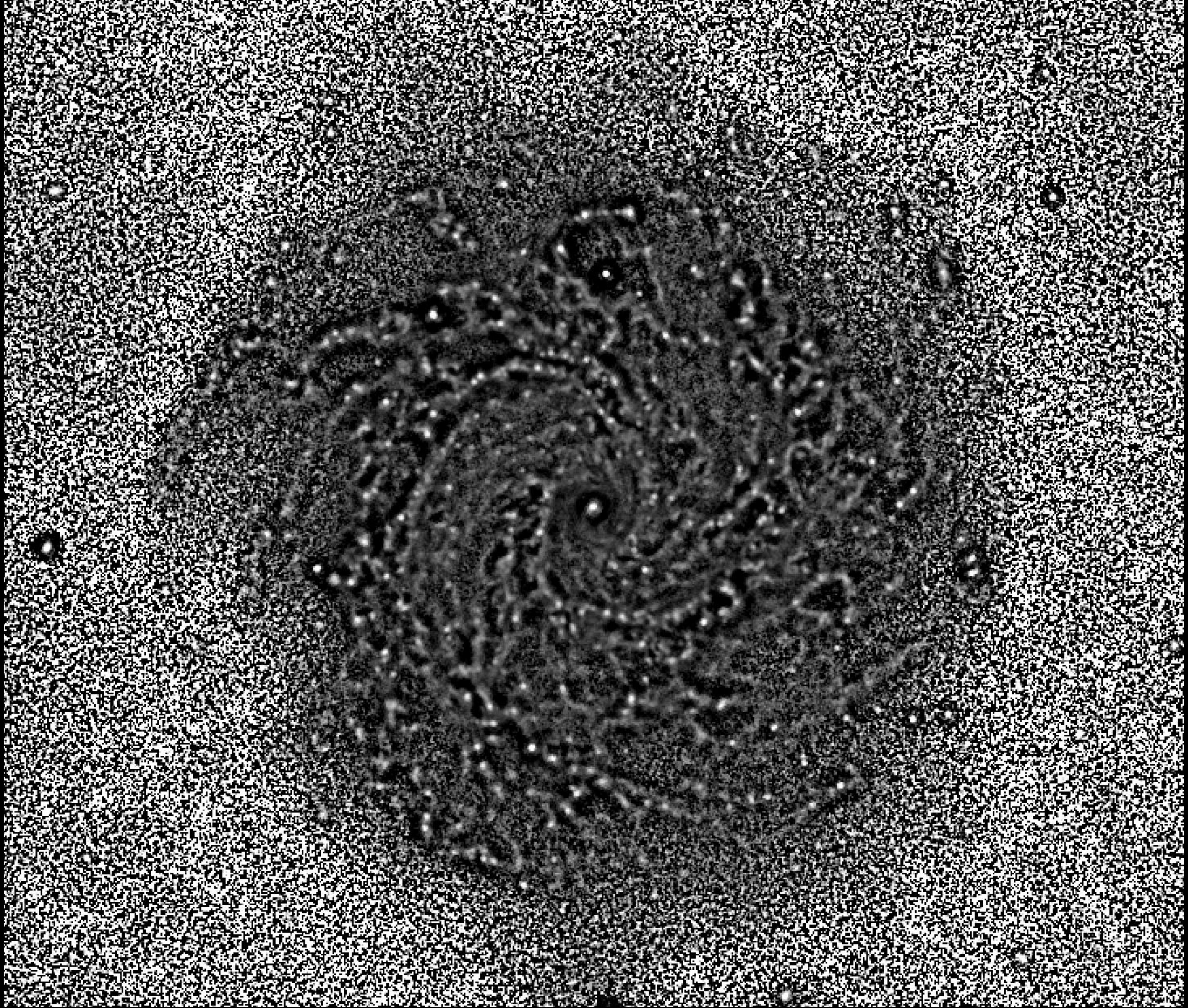
Elmegreen &
Elmegreen ‘19

NGC 3184

Spitzer IRAC

Elmegreen &
Elmegreen ‘19

NGC 3184



Spitzer 8μ
unsharp mask

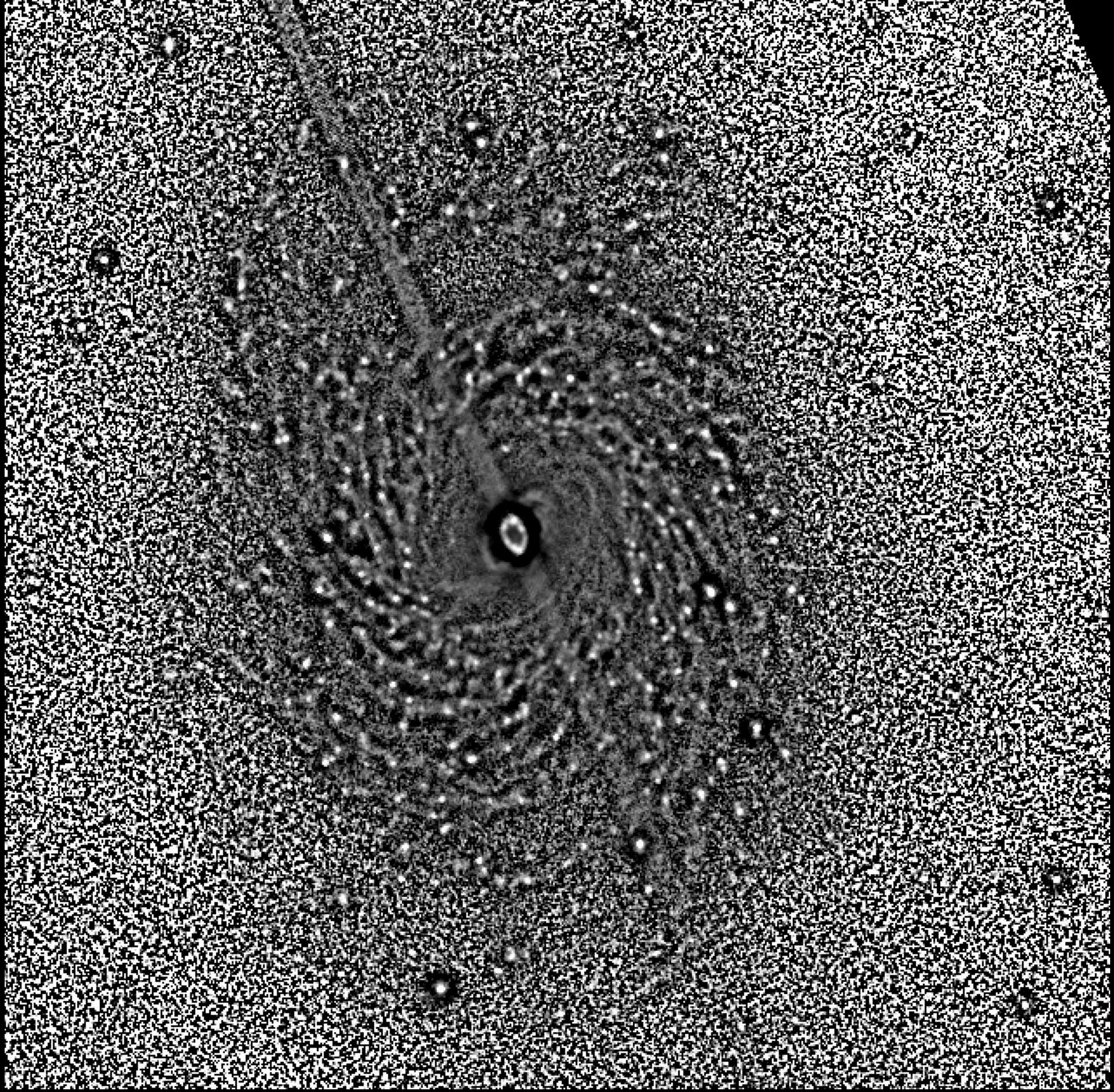
Elmegreen &
Elmegreen ‘19

NGC 3351

Spitzer IRAC

Elmegreen &
Elmegreen ‘19

NGC 3351



Spitzer 8μ
unsharp mask

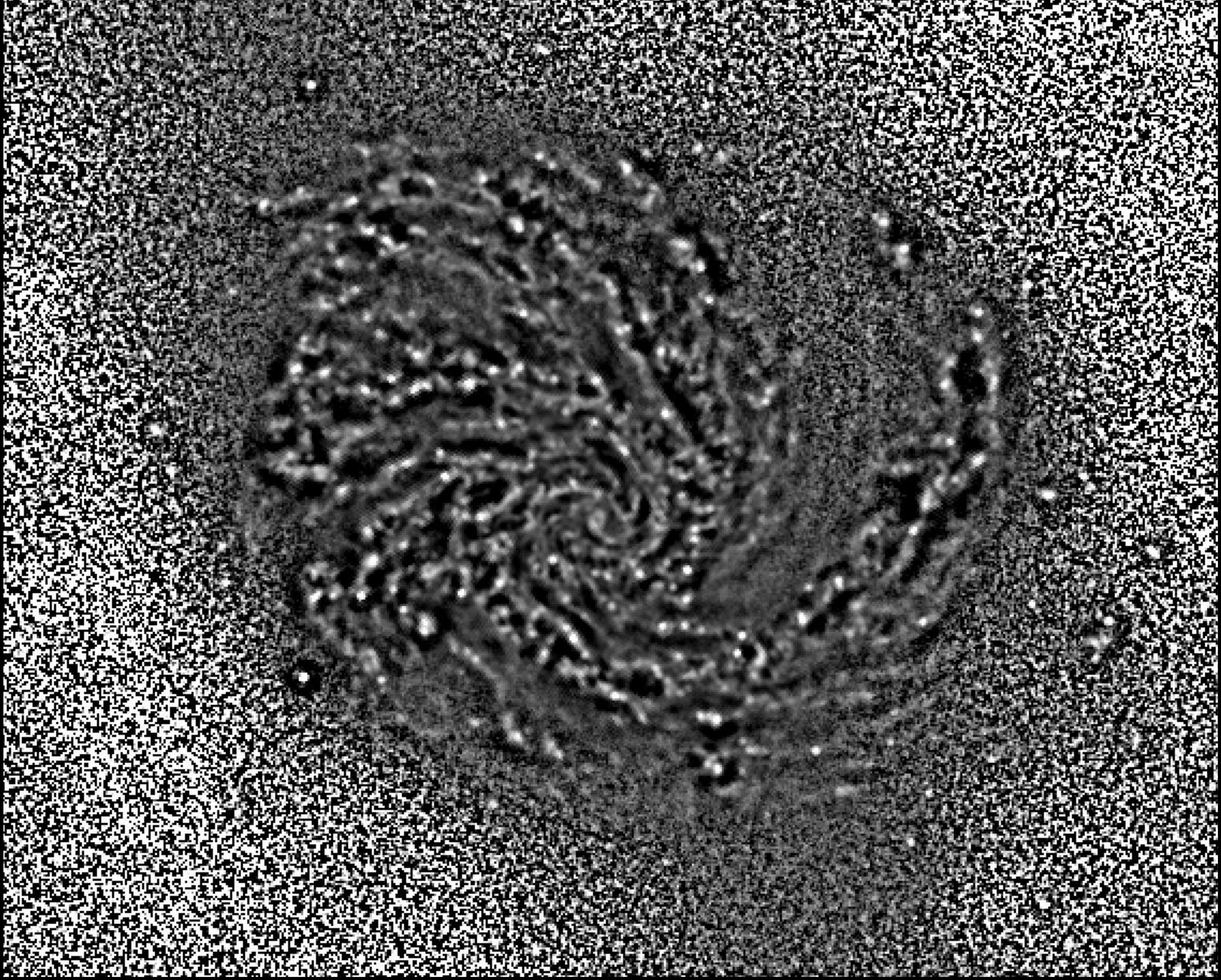
Elmegreen &
Elmegreen ‘19

NGC 4254

Spitzer IRAC

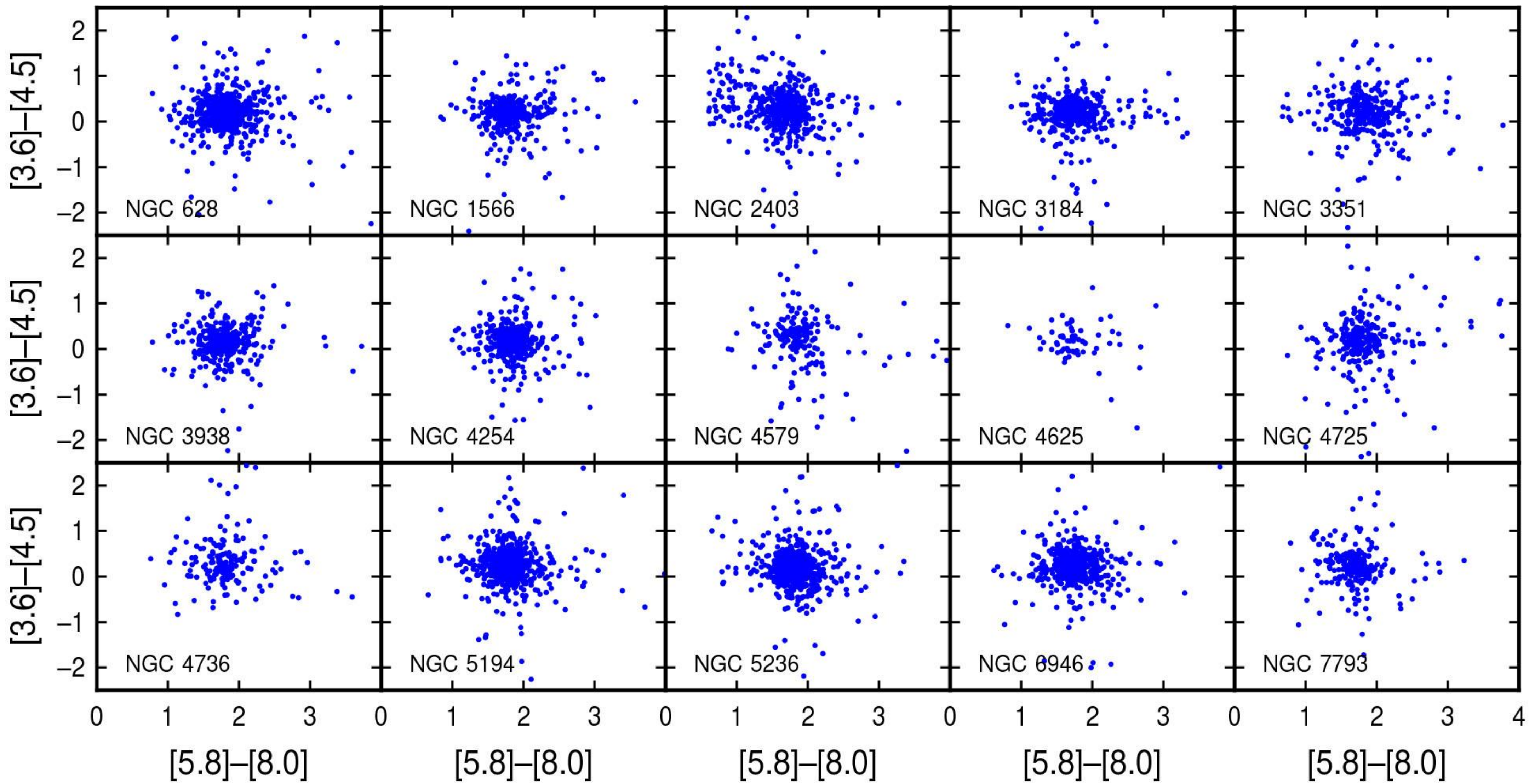
Elmegreen & Elmegreen ‘19

NGC 4254



Spitzer 8μ
unsharp mask

Elmegreen &
Elmegreen '19



[3.6]-[4.5] from photospheres with ~15 mag of visual extinction (Σ_{gas}~300 M_O/pc^2)
[5.8]-[8.0] from PAH emission.

→ <u>These are highly extincted young SF regions</u>

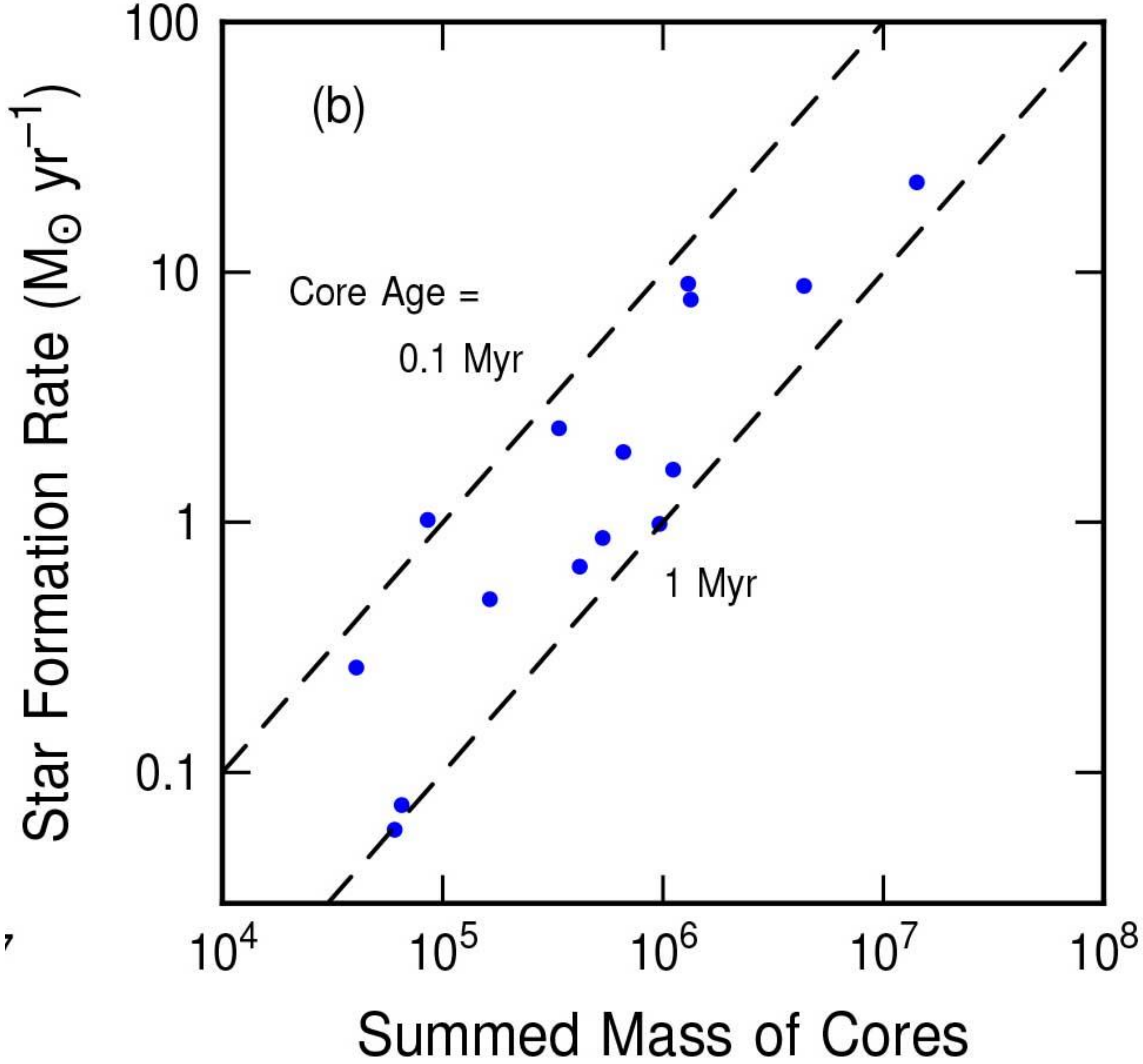
Elmegreen &
Elmegreen '19

Extrapolate the IRAC luminosity to bolometric luminosity (Xu '01) and then to mass for a population age < 1 Myr (Bruzual & Charlot '03).

The SFR correlates with the summed mass of cores.

The ratio gives a timescale.

If these cores last for 0.1 – 1 Myr, then they can account for essentially all of the SF in these galaxies.

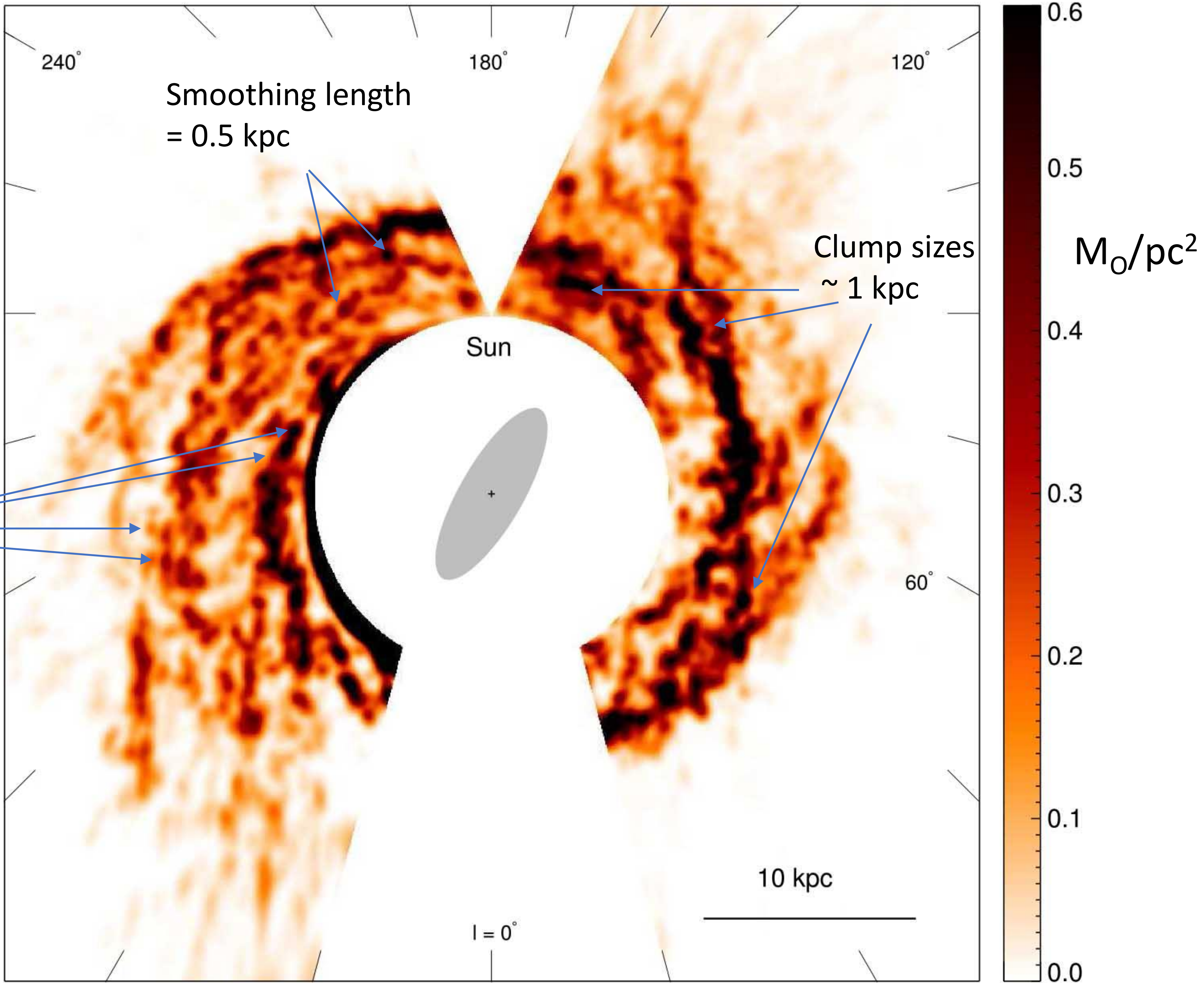


Elmegreen & Elmegreen '19

Milky Way

Koo +17

HI in the outer Milky Way spiral arms is clumpy



Smoothing length = 0.5 kpc

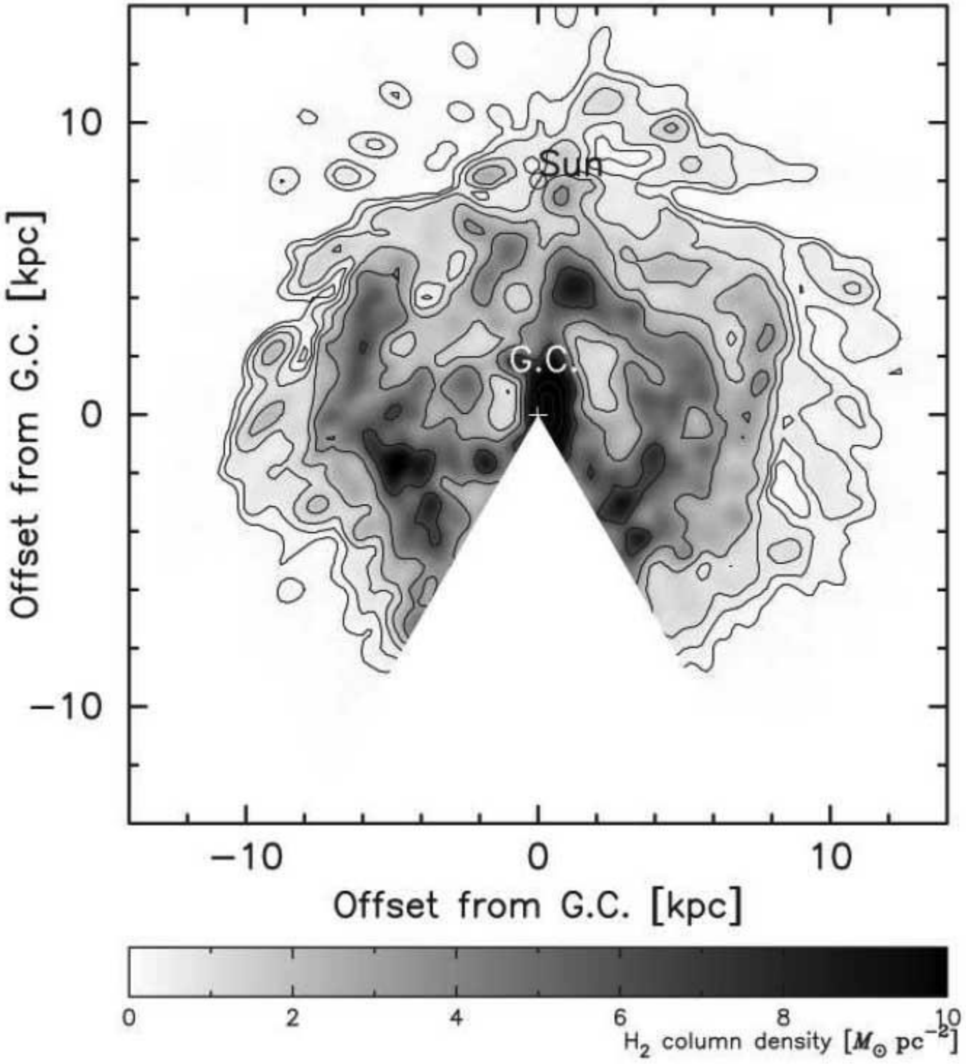
Clump sizes ~ 1 kpc

separation 1 to 2 kpc

Clumps look like gravitational instabilities

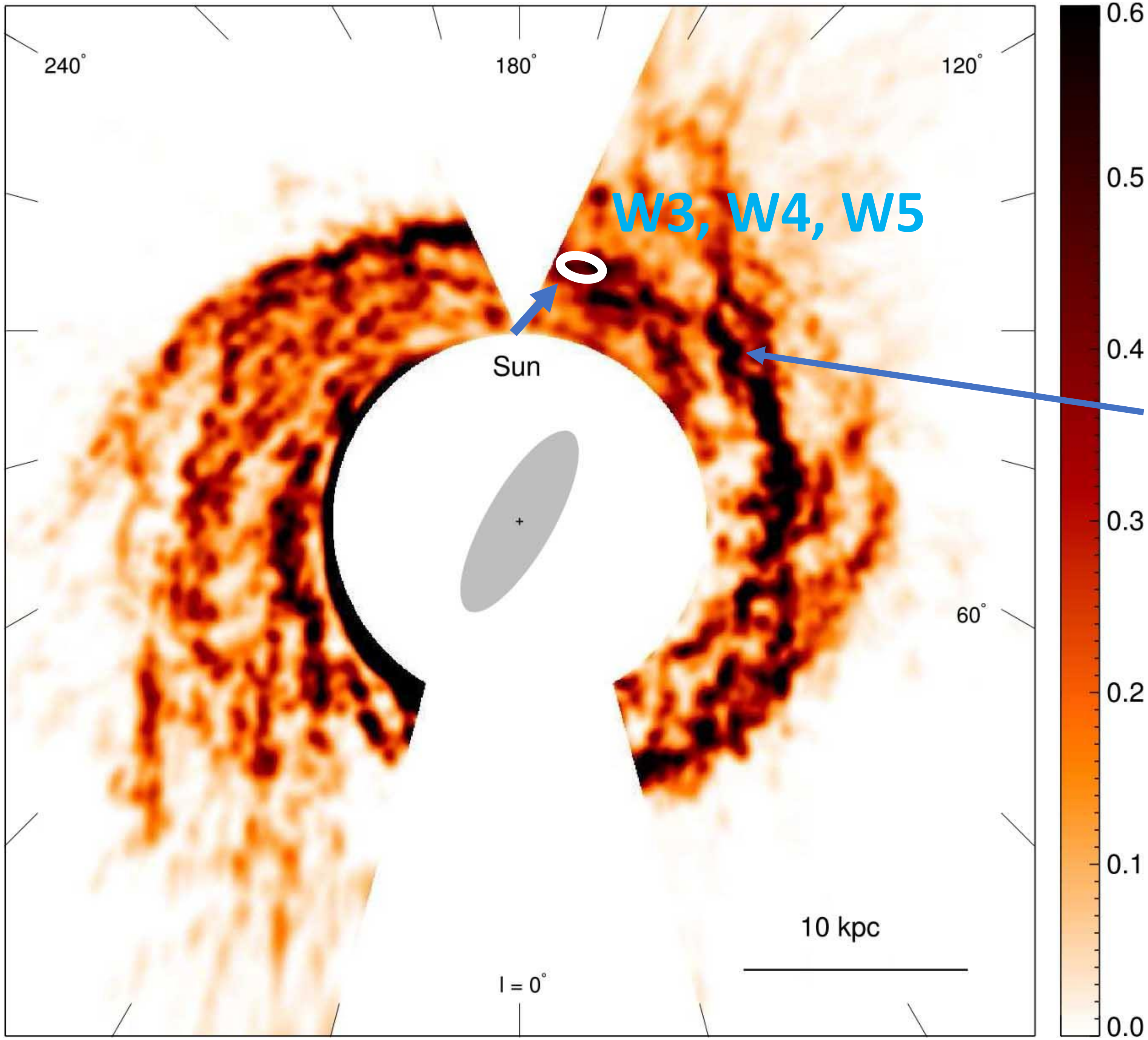
Xu 2018: CO

From Dame +01; processed by Nakanishi & Sofue '06



Koo +17

HI in the Outer Milky Way



W3, W4, W5

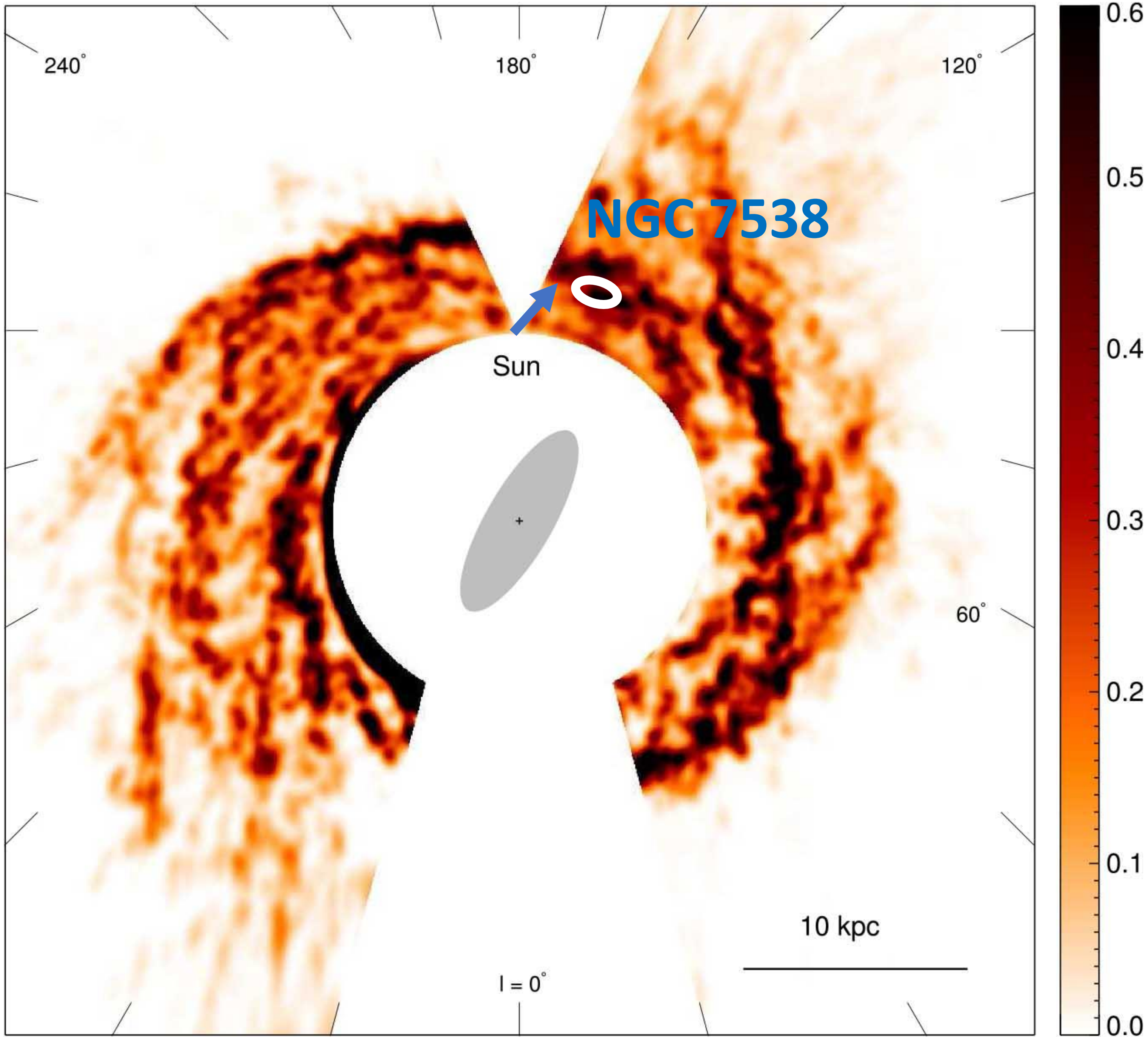
Perseus arm

Herschel

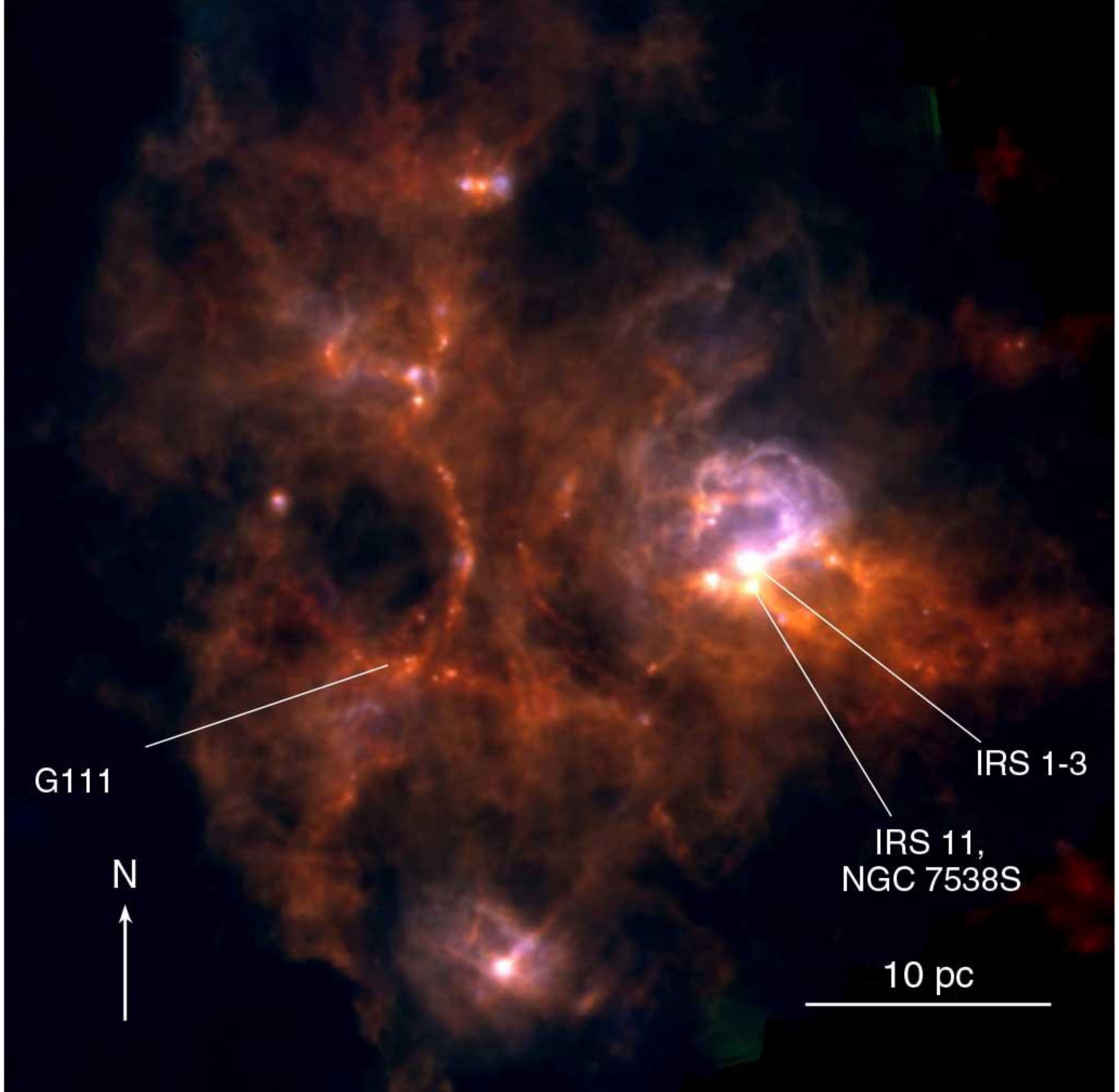
http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2017/09/celebrating_herschel_s_legacy/17154062-1-eng-GB/Celebrating_Herschel_s_legacy.jpg

Koo +17

HI in the
Outer Milky Way



NGC 7538

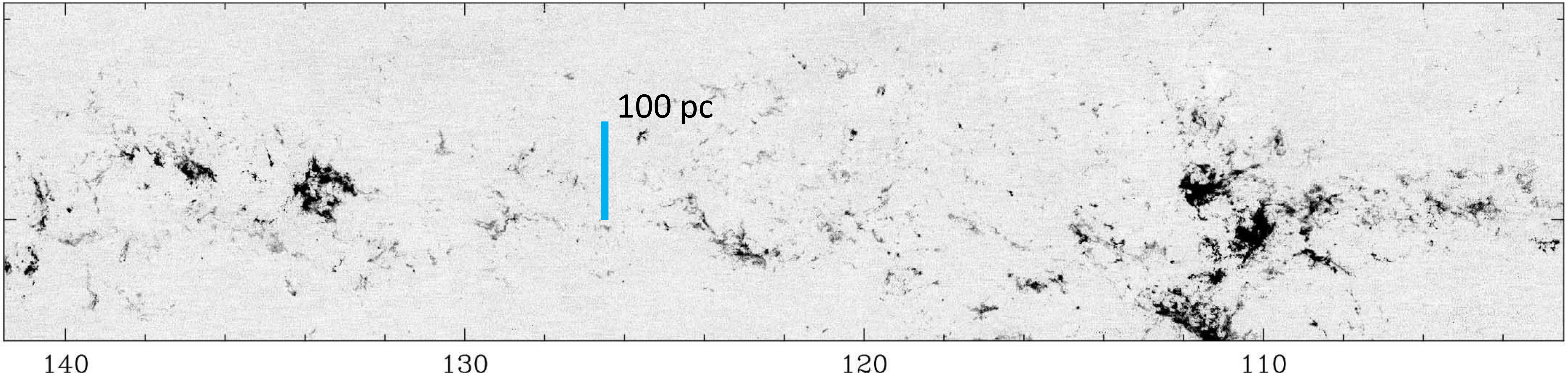


Fallscheer +13, Herschel

Heyer + 98: Outer Galaxy FCRAO CO survey: Local and Perseus arm emission

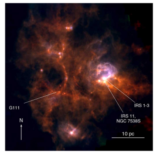
W3,4,5

NGC 7538



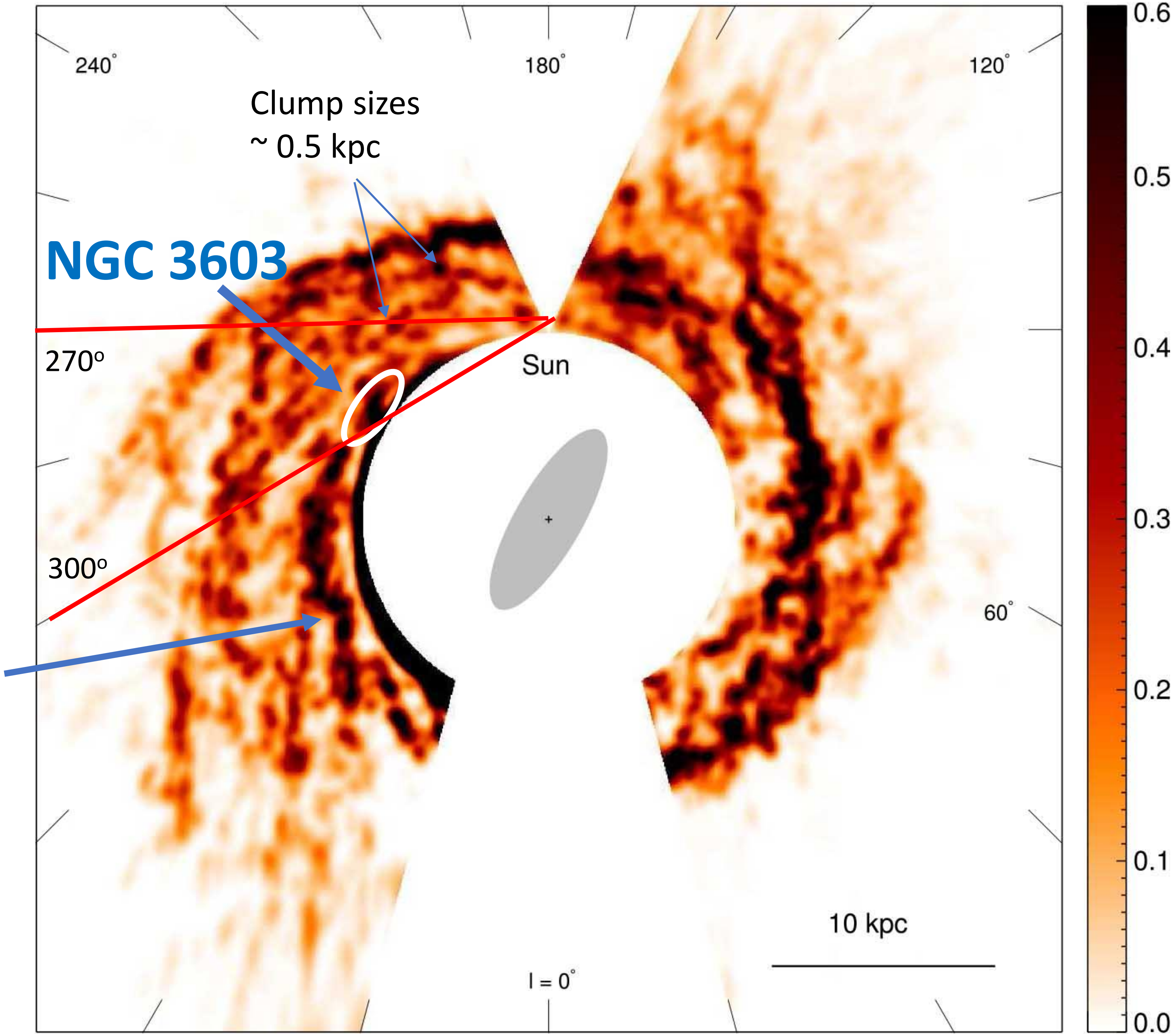
CO at Perseus arm velocities

Heyer +98


G111
IRS 1-3
IRS 11,
NGC 7538S
N
10 pc

Koo +17

HI in the Outer Milky Way



Clump sizes
~ 0.5 kpc

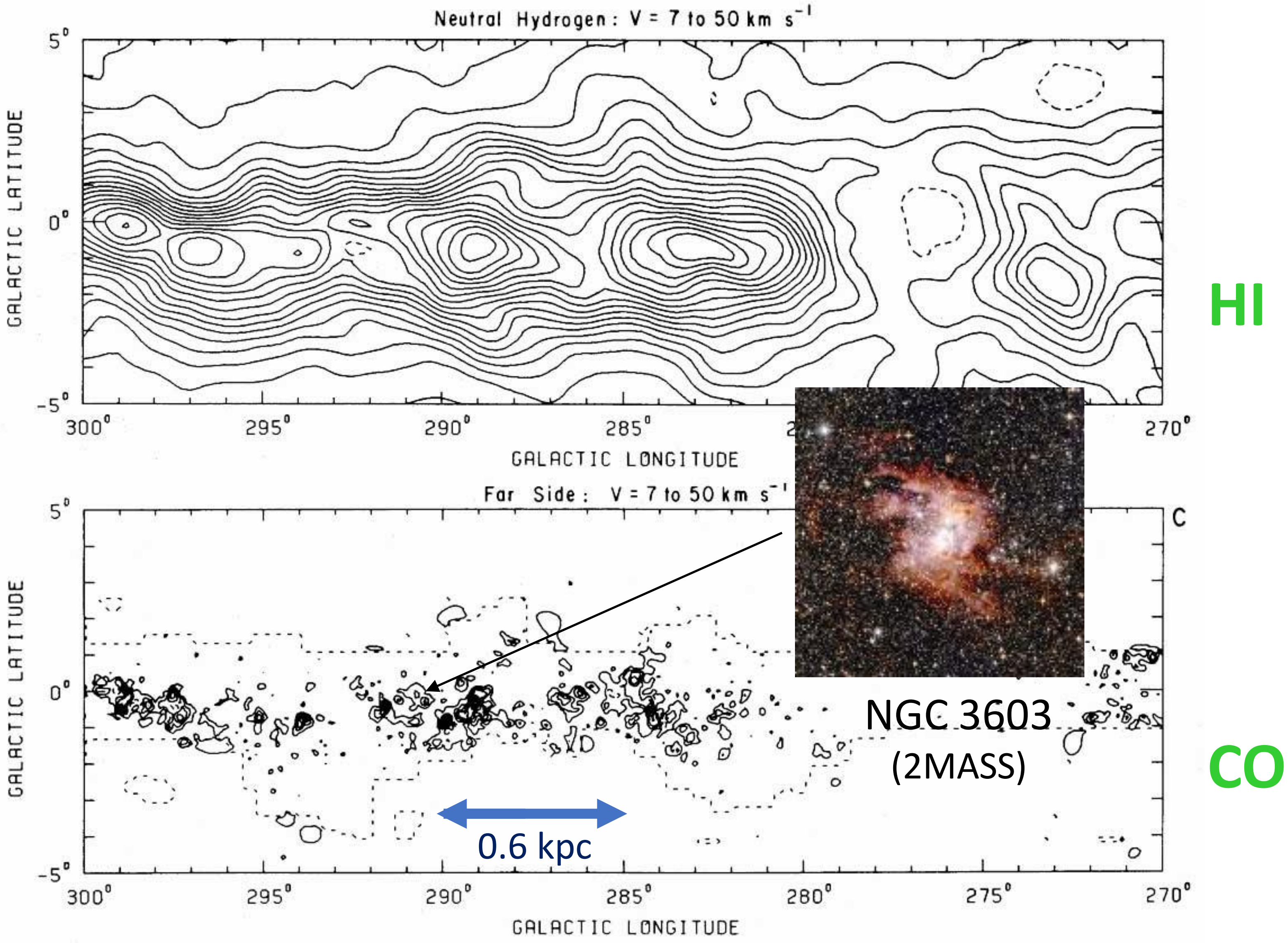
NGC 3603

Carina arm

Grabelsky et al. 1987

kpc size HI clouds
in the Carina arm
Mass ~ 10^7 M_O

CO is in the
denser parts.



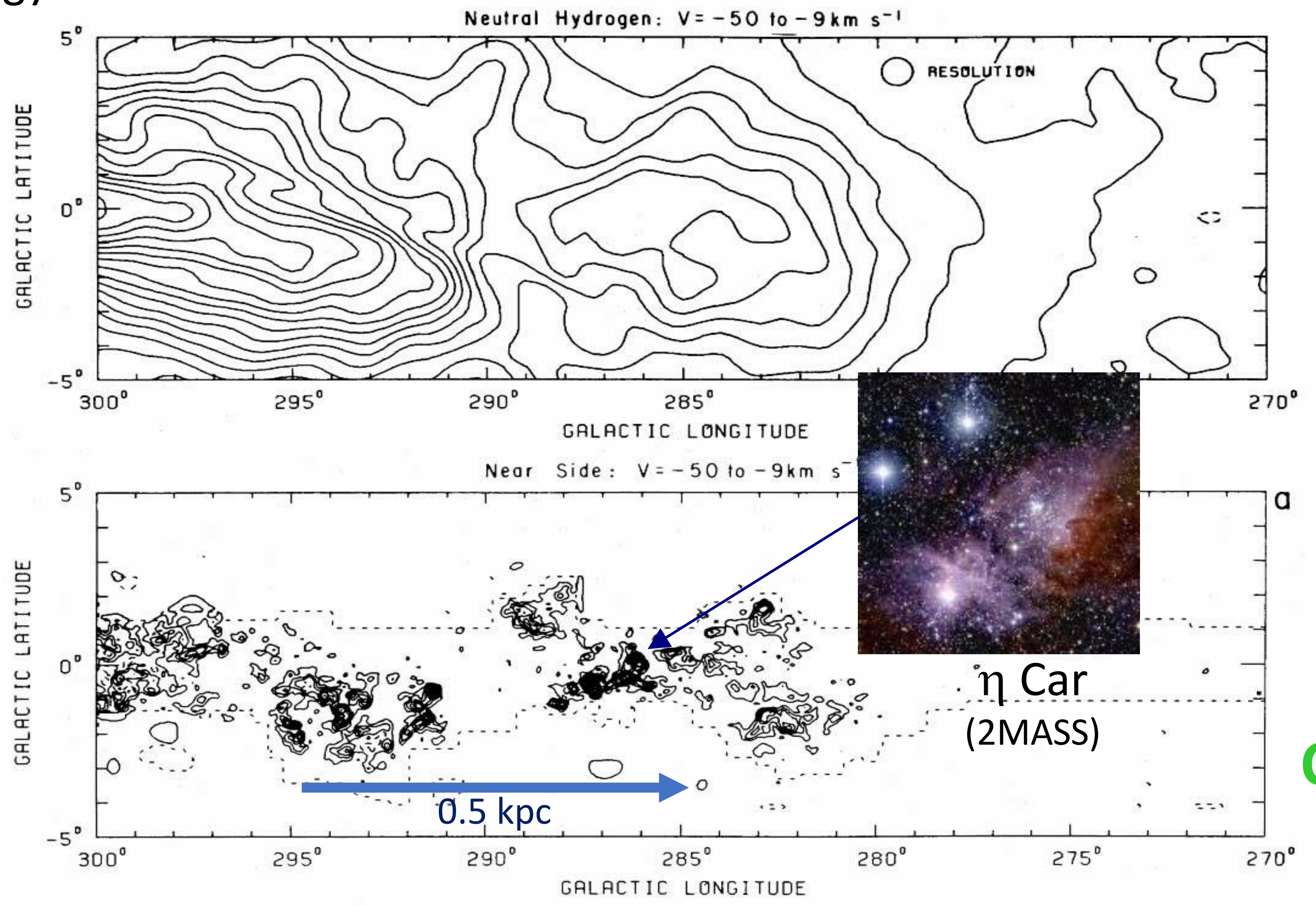
Major SF regions are tiny on these scales

Grabelsky et al. 1987

kpc size HI clouds in the Carina arm

Mass ~ 10^7 M_O

CO is in the denser parts.



η Car

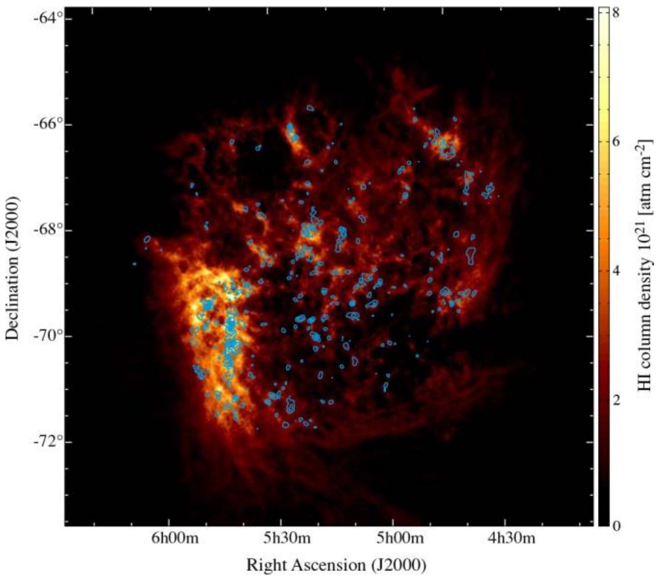
(2MASS)

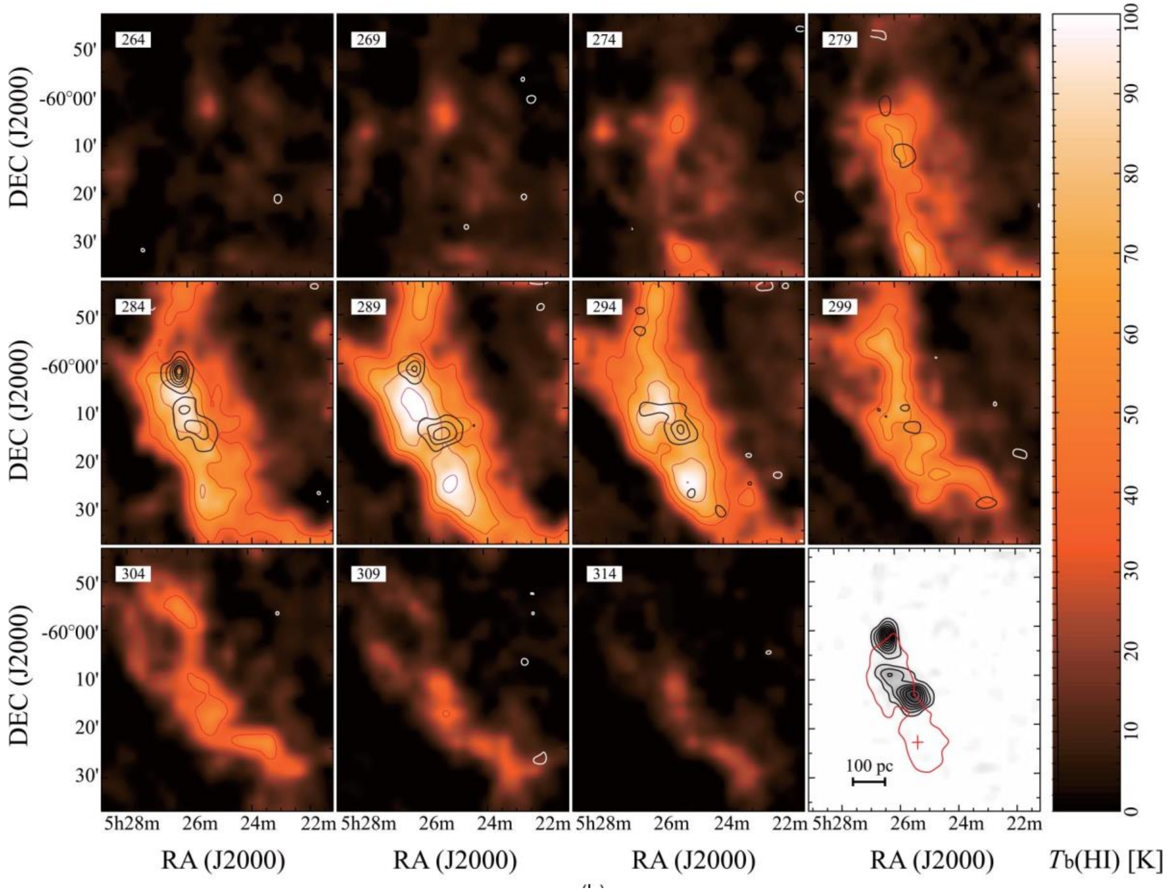
HI

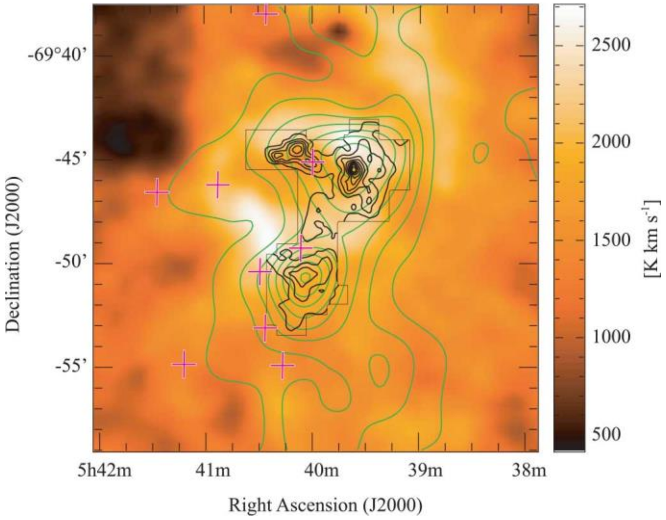
CO

Major SF regions are tiny on these scales

Fukui +09: LMC HI and CO

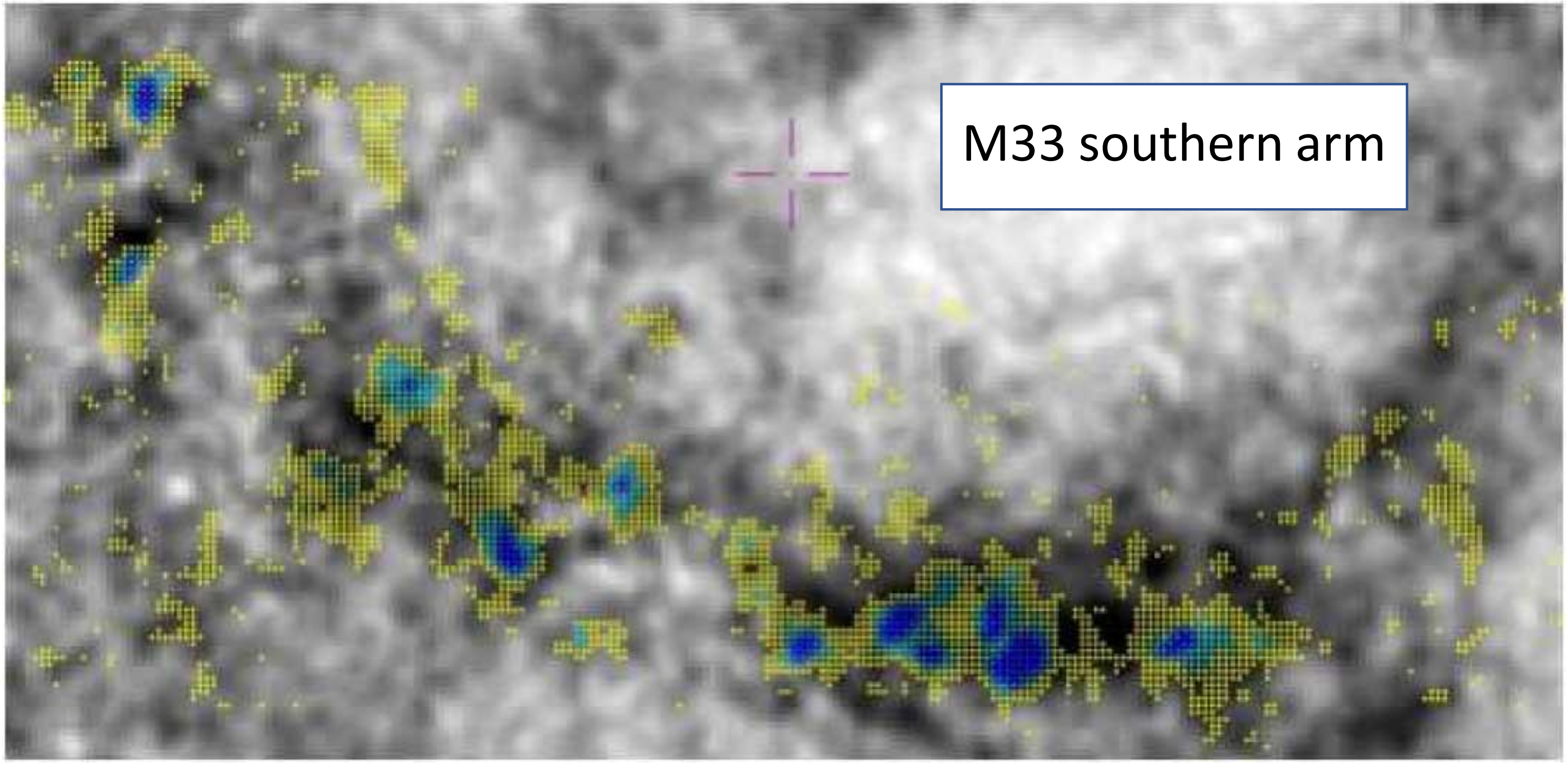


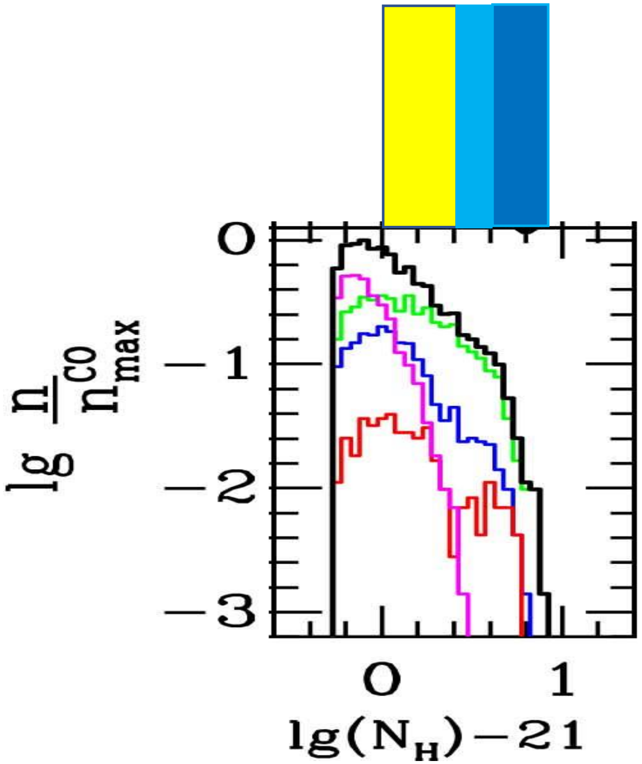




HI envelopes (<n> ~ 10 cm^{-3}) are gravitationally bound to the GMCs.

Corbelli, Elmegreen, Braine, Thilker +18: HI and CO N-PDFs in M33





For CO, the power law in the PDF corresponds to the power-law radial profiles of clouds (i.e., self-gravity):

yellow: N(Htot) = 10^{21} to 2.5×10^{21} cm^{-2}
cyan: N(Htot) = 2.5×10^{21} to 4×10^{21} cm^{-2}
blue: N(Htot) > 4×10^{21} cm^{-2}

Probability Density Function for CO

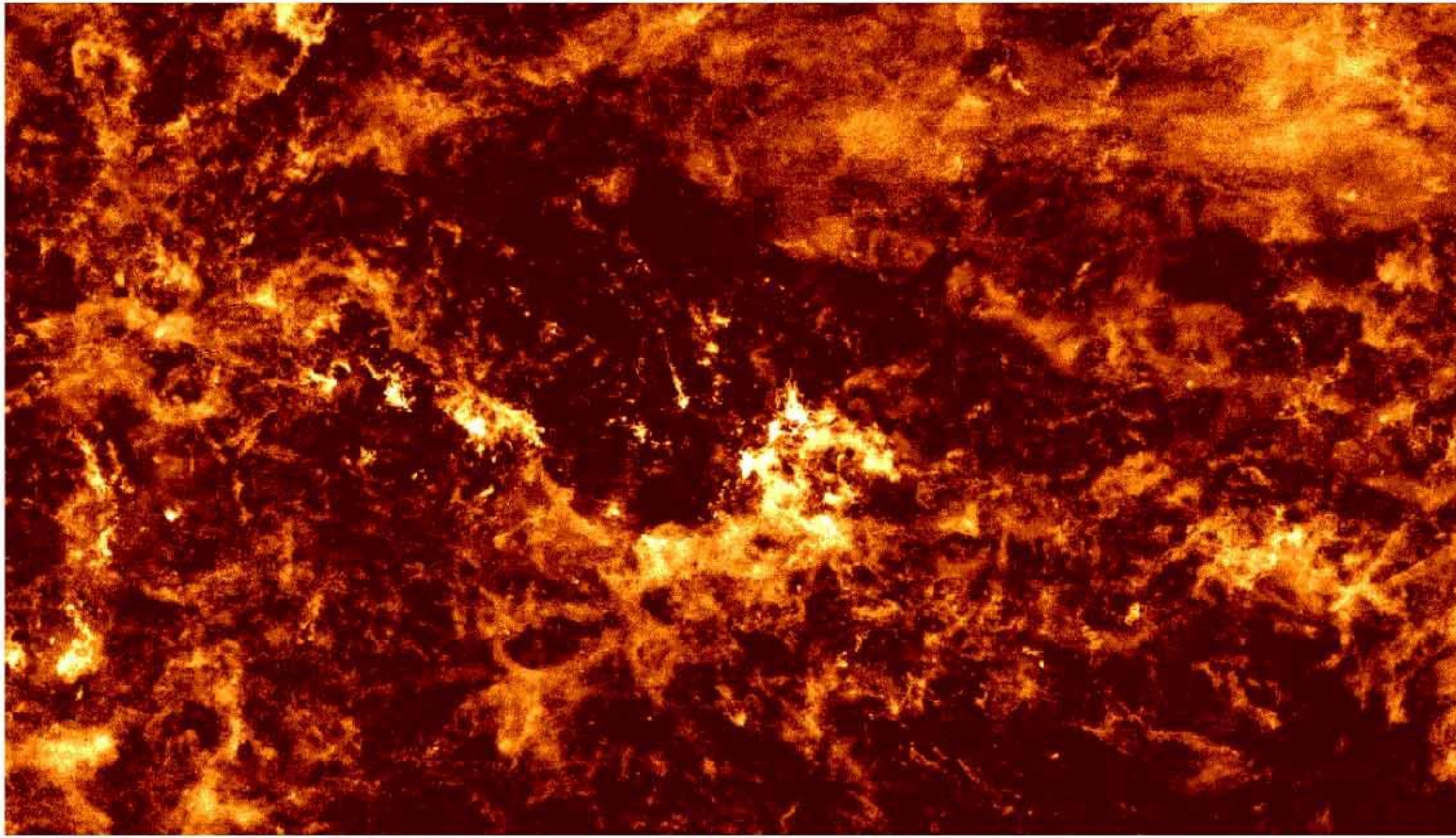
What starts the star formation process in spiral galaxies?

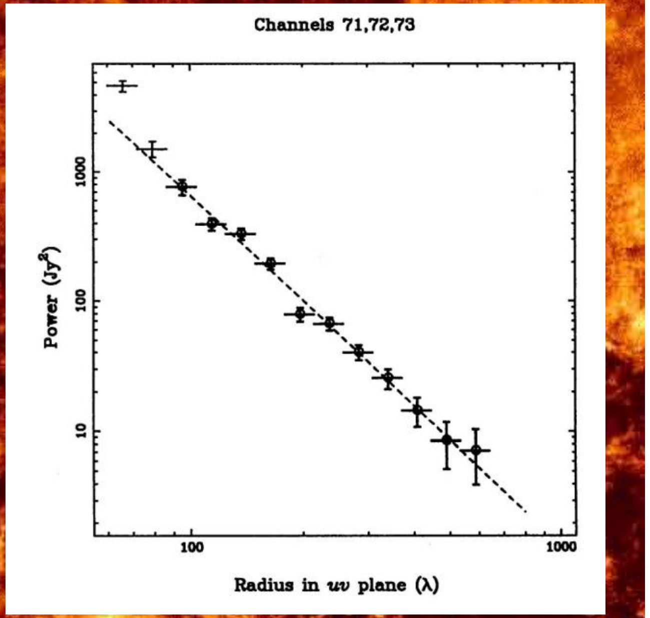
Spiral arms and essentially all large-scale gas filaments have chains of compact 8μ clumps that appear to be the first stages of star formation, accounting for most of the current star formation rate.

High resolution observations of these clumps (Milky Way, LMC, M33) show giant clouds with HI envelopes and CO cores.

This morphology suggests that shocked ISM gas (i.e. filaments) collapses into self-gravitating cores which produce new star clusters and OB associations that become visible after ~ 1 Myr.

What drives the turbulence?





Green ‘93: HI power spectrum in Perseus arm. See also Crovisier & Dickey ‘83

Heyer + 98: Outer Galaxy FCRAO CO survey

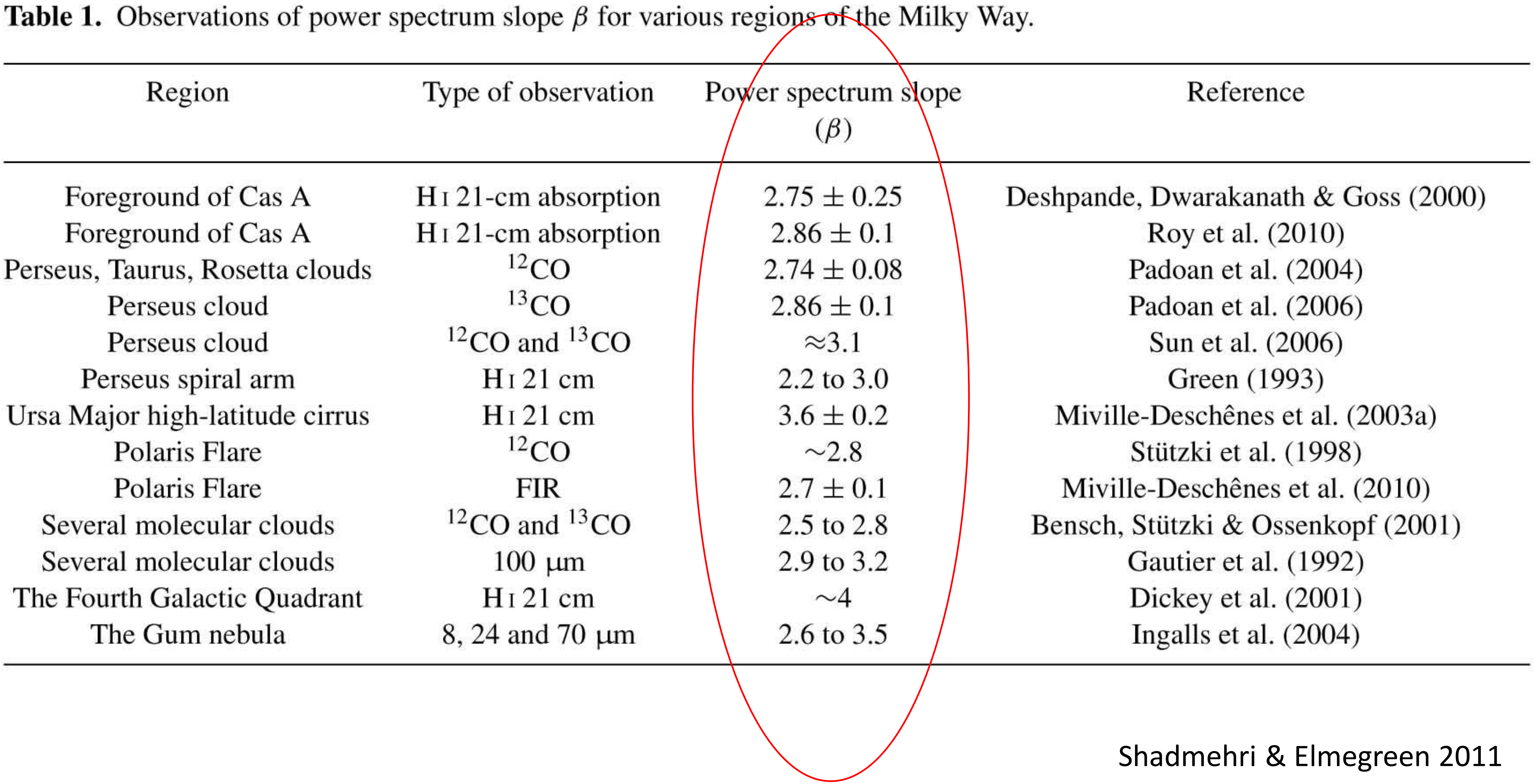


Table 1. Observations of power spectrum slope β for various regions of the Milky Way.

Region	Type of observation	Power spectrum slope (β)	Reference
Foreground of Cas A	H I 21-cm absorption	2.75 ± 0.25	Deshpande, Dwarakanath & Goss (2000)
Foreground of Cas A	H I 21-cm absorption	2.86 ± 0.1	Roy et al. (2010)
Perseus, Taurus, Rosetta clouds	^{12}CO	2.74 ± 0.08	Padoan et al. (2004)
Perseus cloud	^{13}CO	2.86 ± 0.1	Padoan et al. (2006)
Perseus cloud	^{12}CO and ^{13}CO	≈ 3.1	Sun et al. (2006)
Perseus spiral arm	H I 21 cm	2.2 to 3.0	Green (1993)
Ursa Major high-latitude cirrus	H I 21 cm	3.6 ± 0.2	Miville-Deschênes et al. (2003a)
Polaris Flare	^{12}CO	~ 2.8	Stützki et al. (1998)
Polaris Flare	FIR	2.7 ± 0.1	Miville-Deschênes et al. (2010)
Several molecular clouds	^{12}CO and ^{13}CO	2.5 to 2.8	Bensch, Stützki & Ossenkopf (2001)
Several molecular clouds	100 μm	2.9 to 3.2	Gautier et al. (1992)
The Fourth Galactic Quadrant	H I 21 cm	~ 4	Dickey et al. (2001)
The Gum nebula	8, 24 and 70 μm	2.6 to 3.5	Ingalls et al. (2004)

Shadmehri & Elmegreen 2011

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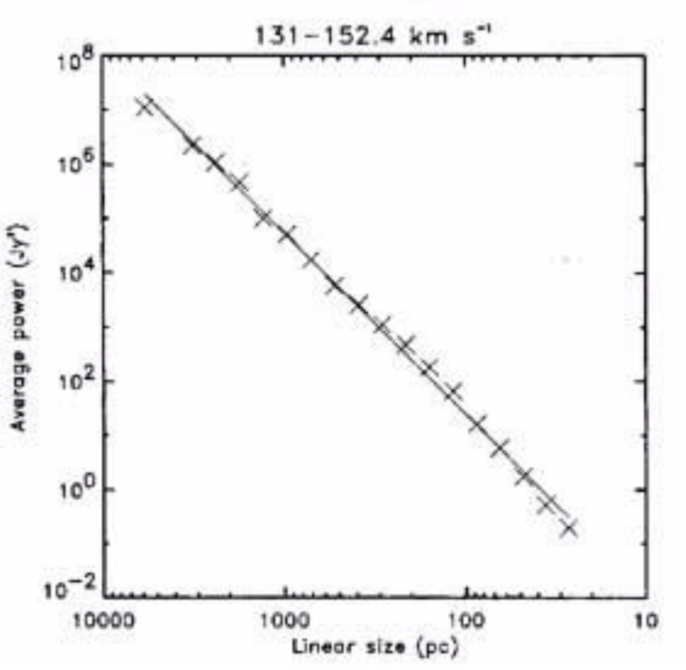
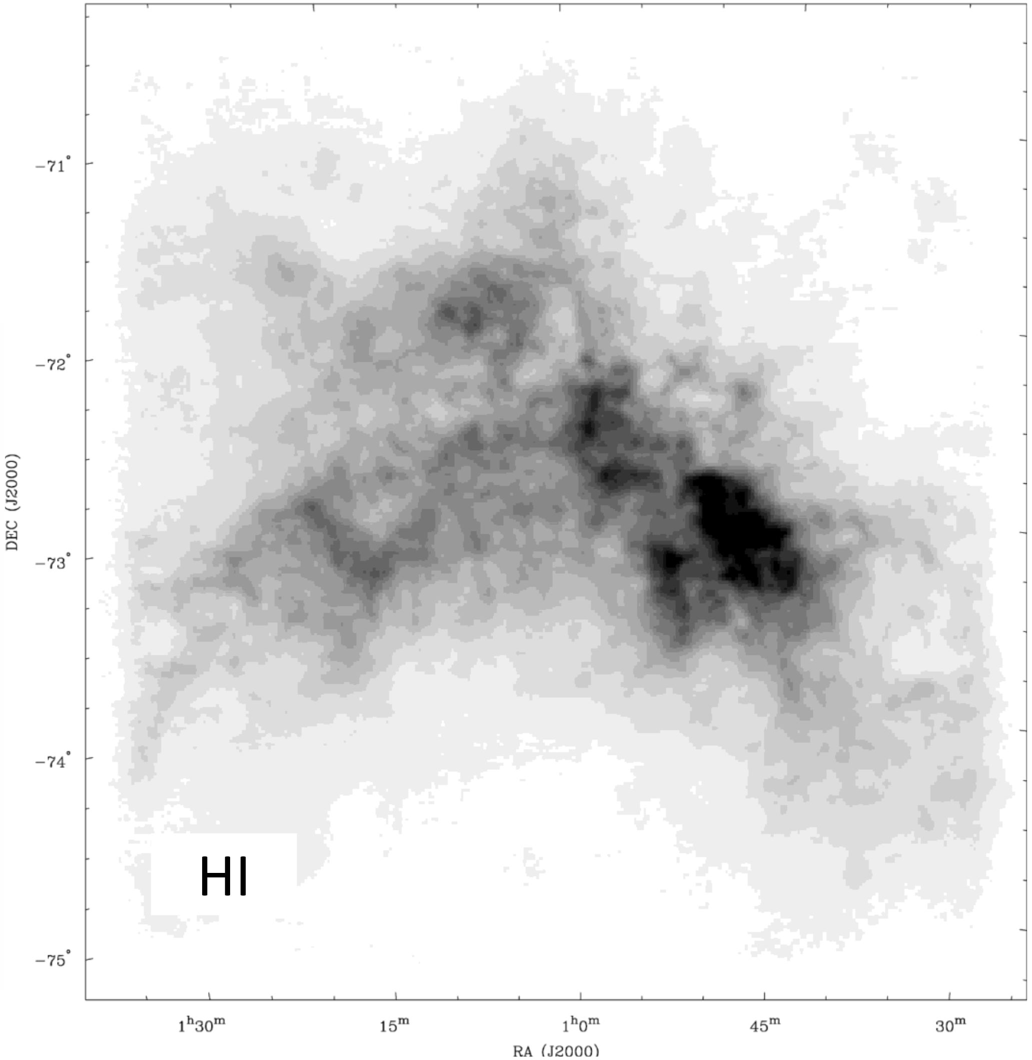
The whole ISM in the SMC has a power law distribution of column density for HI.

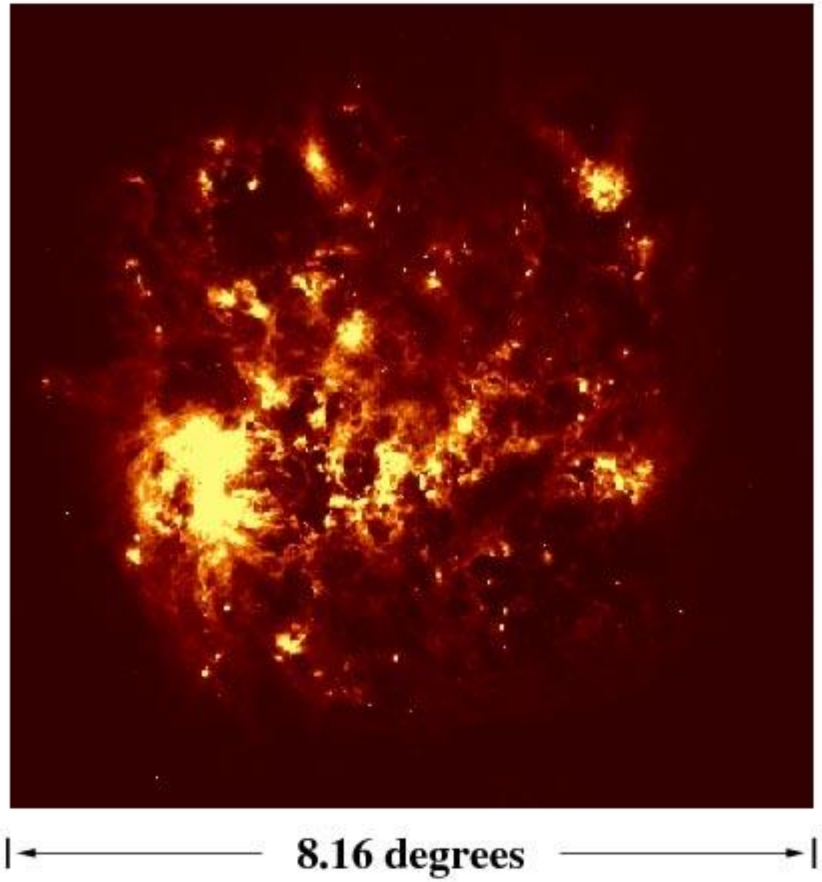




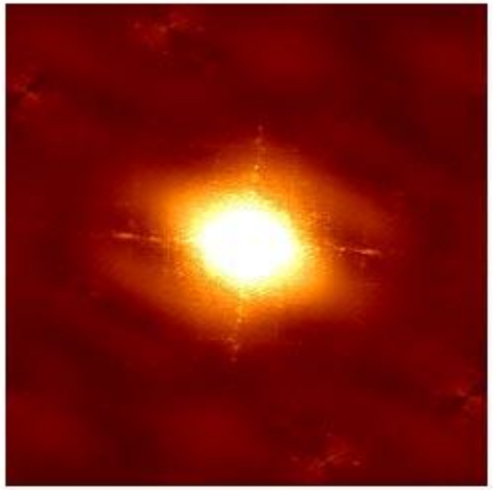
Stanimirovic et al. 1999

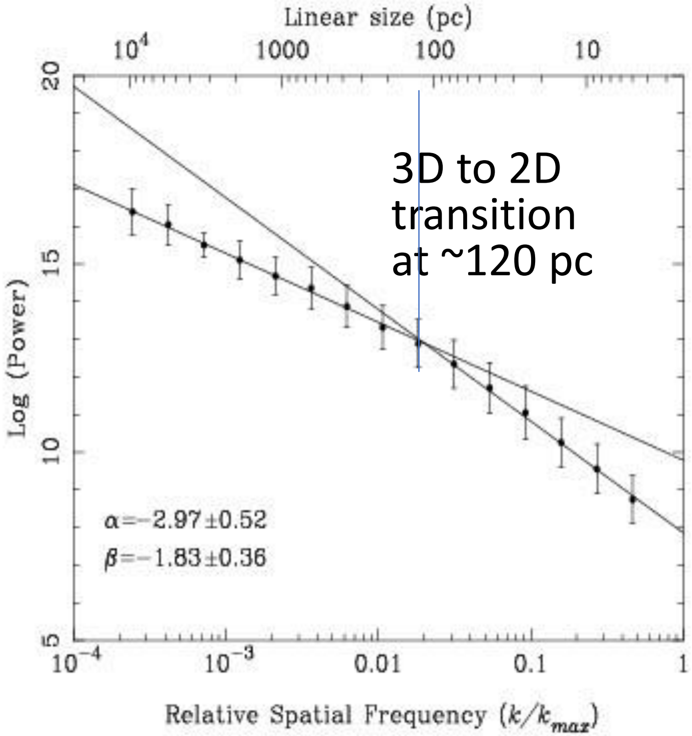
The power spectrum of the LMC is bent

LMC – 70 microns



Fourier Transform





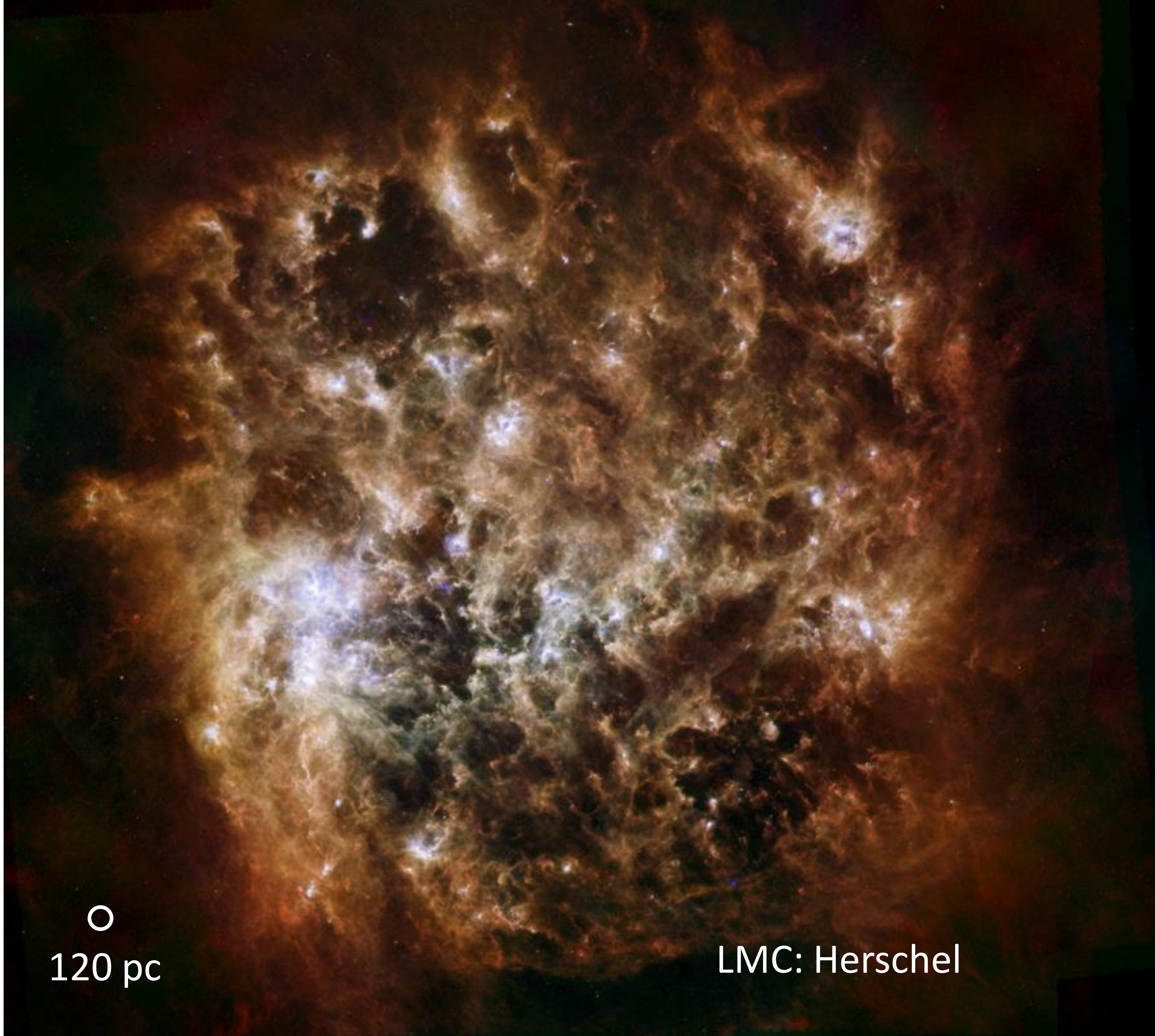
3D to 2D transition at ~120 pc

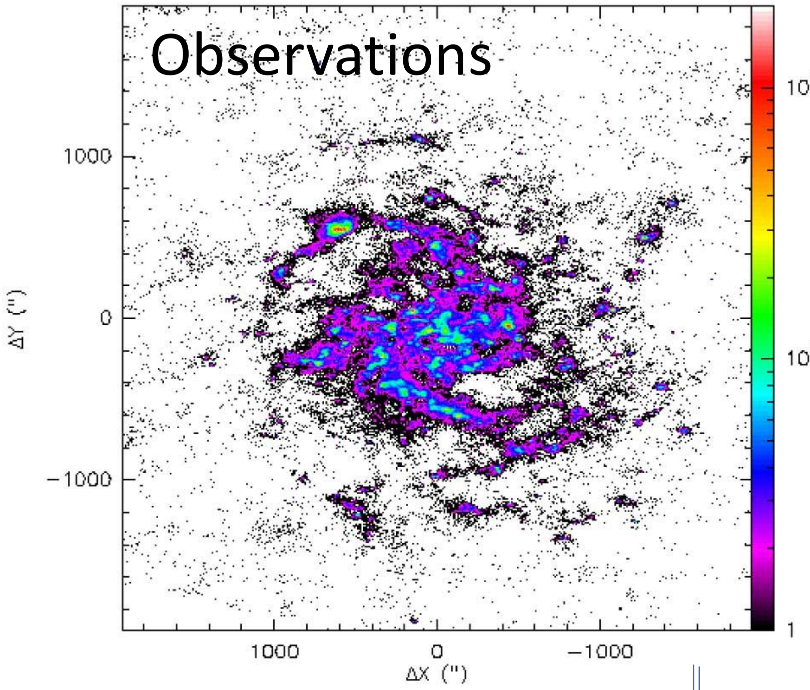
Block, Elmegreen +10: Spitzer IRAC data

The break in the power spectrum has the size of the circle.

This is approximately the disk thickness, where turbulence changes from 2D to 3D.

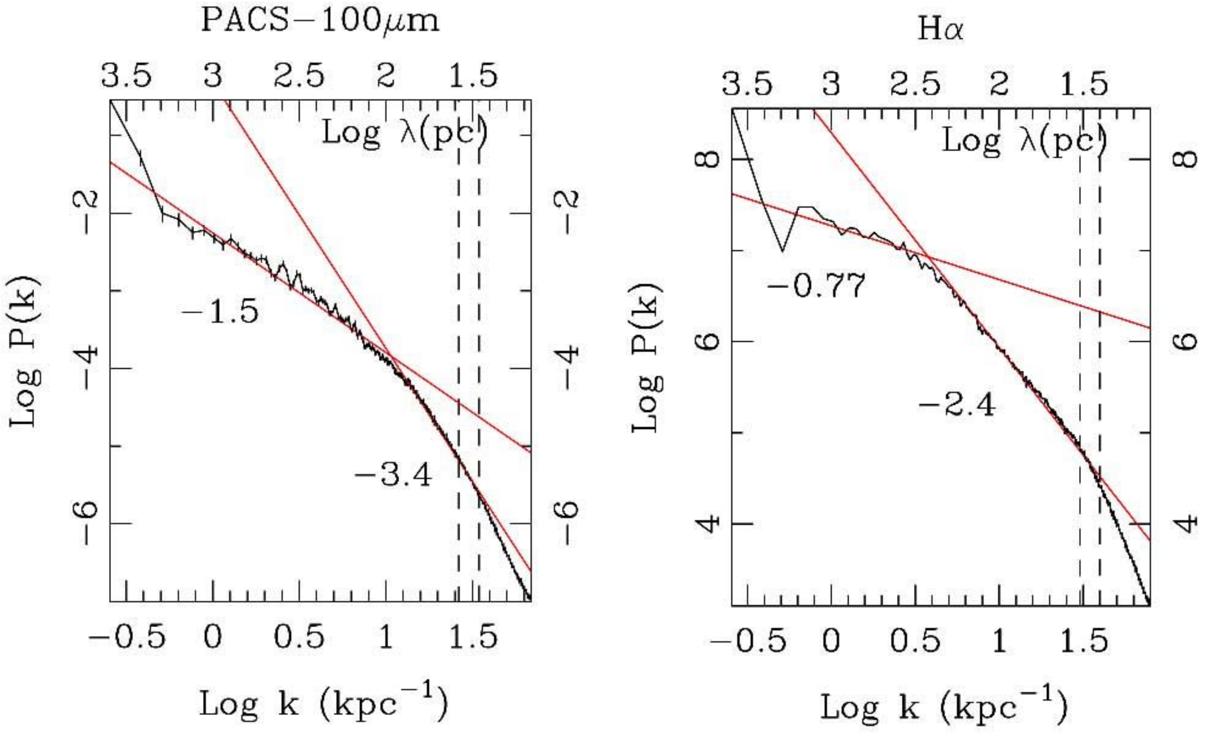
Star formation feedback can power 3D turbulence, but larger holes suggest there is a loss of feedback energy into the halo.





Combes +11: M33

100 μm, Hα, …



(100 pc = 23”)

(Hα has thicker disk than 100μm)

Similar power spectrum break for M33.

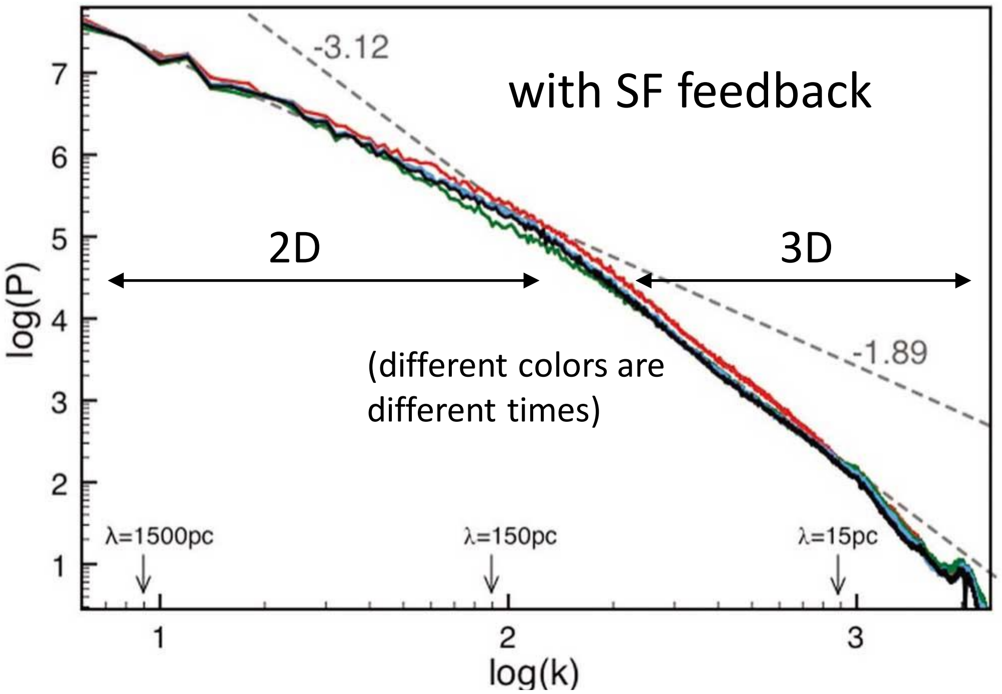
As for the LMC, the biggest holes are bigger than the thickness.

Bournaud, Elmegreen +10 LMC model:

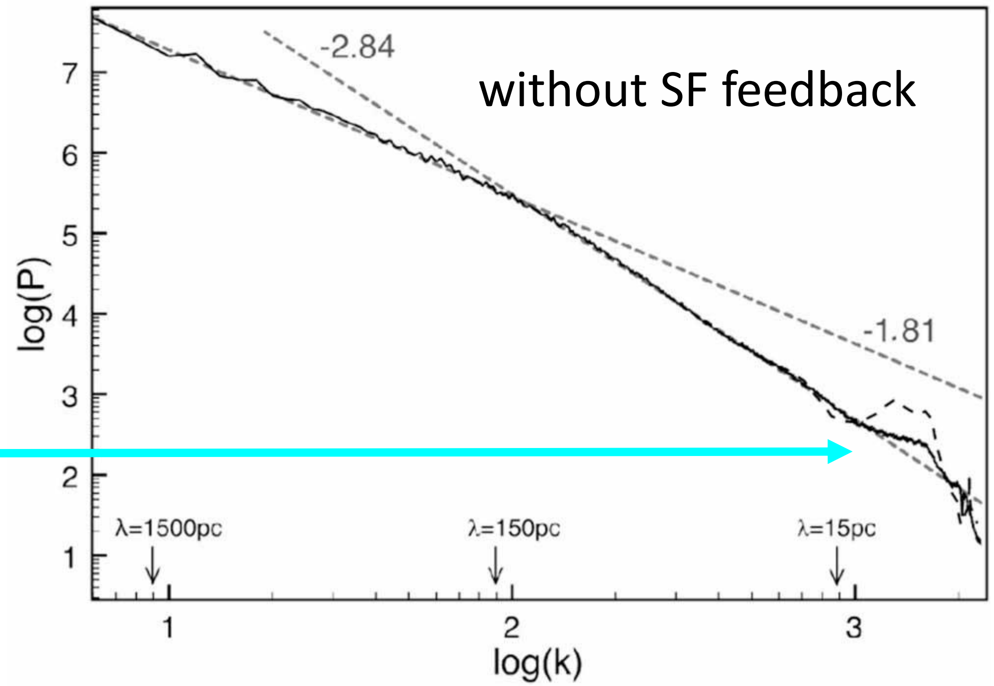
Spirals (gravity) cause 2D turbulent power spectrum at large scales

Gravity + cascade-down causes 3D power spectrum on small scales with and without feedback.

Feedback breaks apart dense clouds at the bottom of the cascade but need not pump all the 3D turbulence.

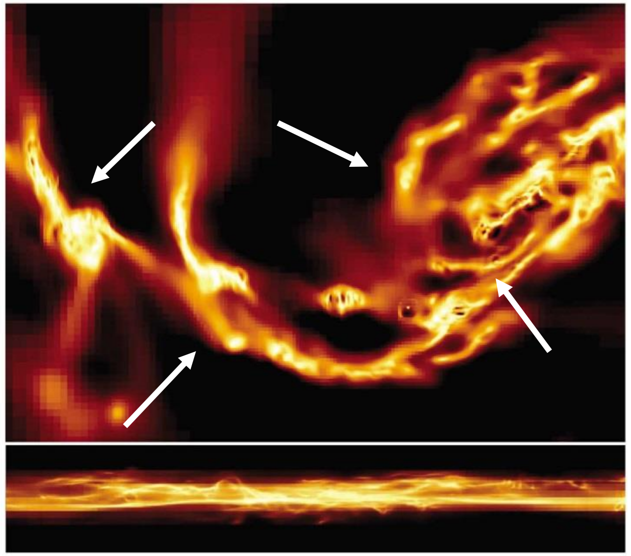

with SF feedback

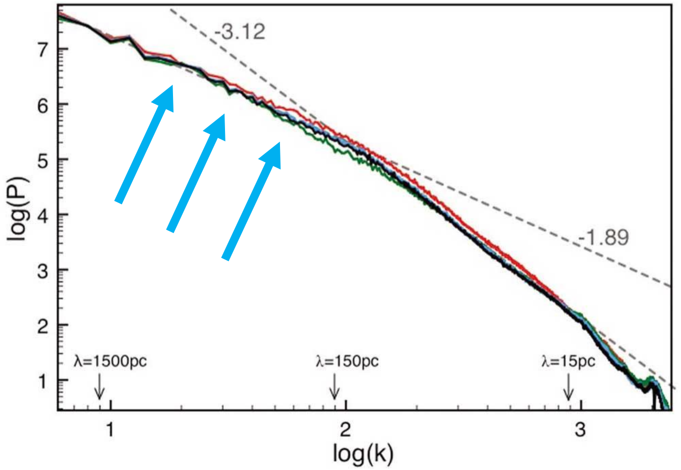
(different colors are different times)


without SF feedback

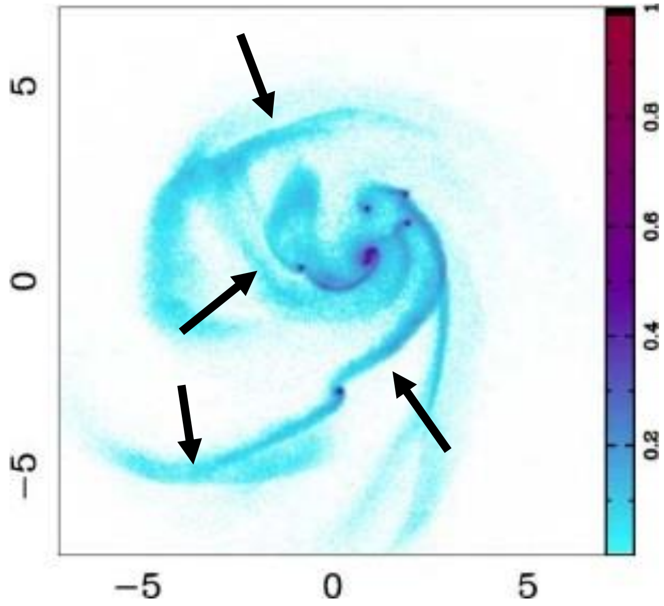
Feedback breaks the clouds apart

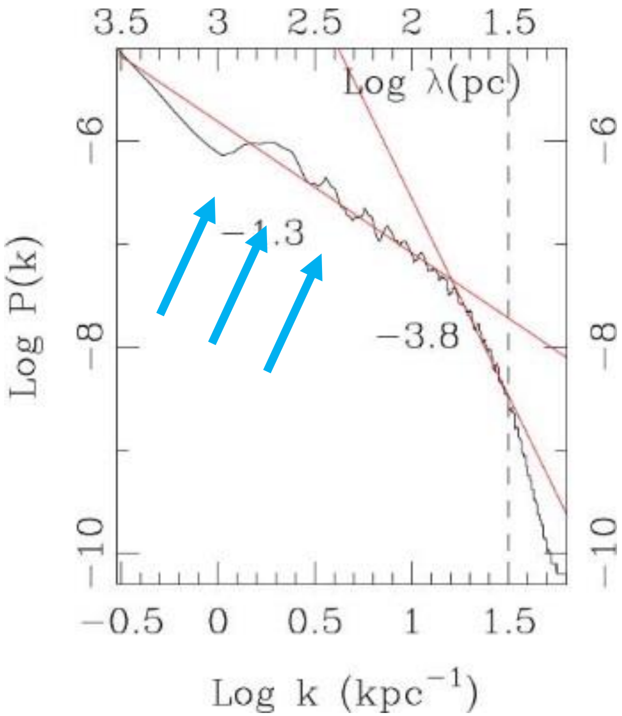
Bournaud +10
LMC model
(half the galaxy
shown)





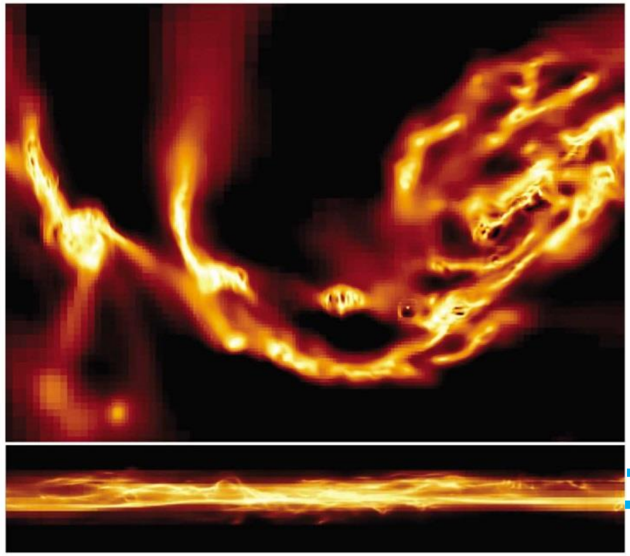
Combes +12
M33 model



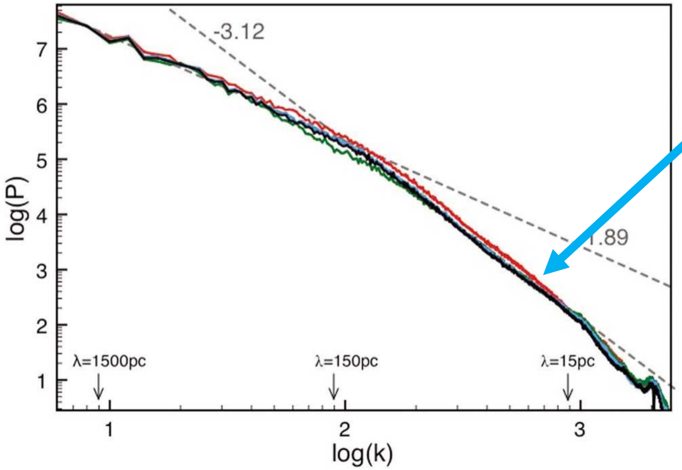


Large-scale structure (<u>everything larger than the thickness</u>) gives the low-k power spectrum

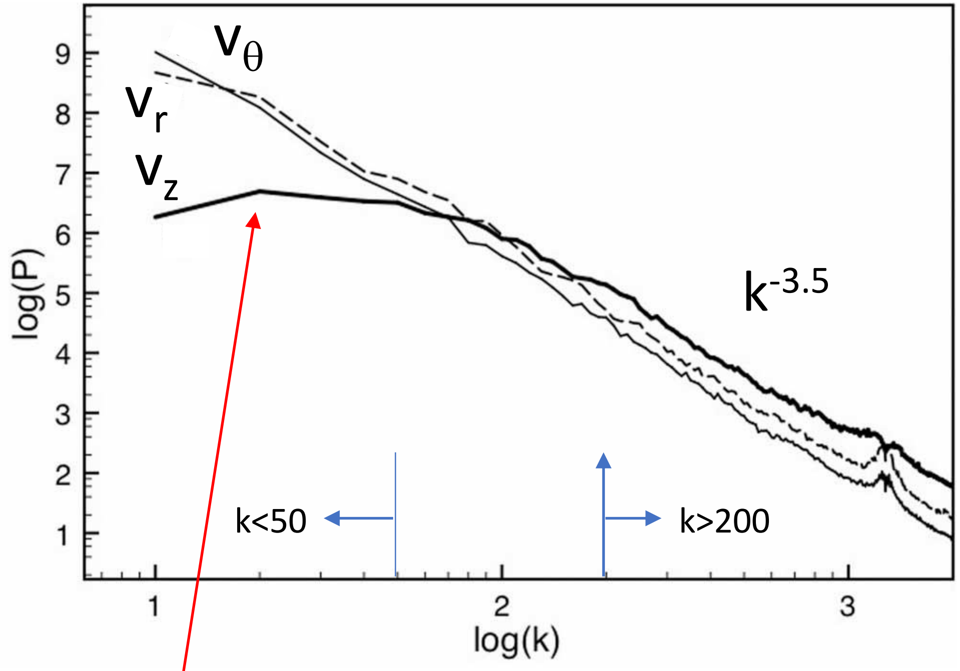
Bournaud +10
LMC model
(half the galaxy
shown)



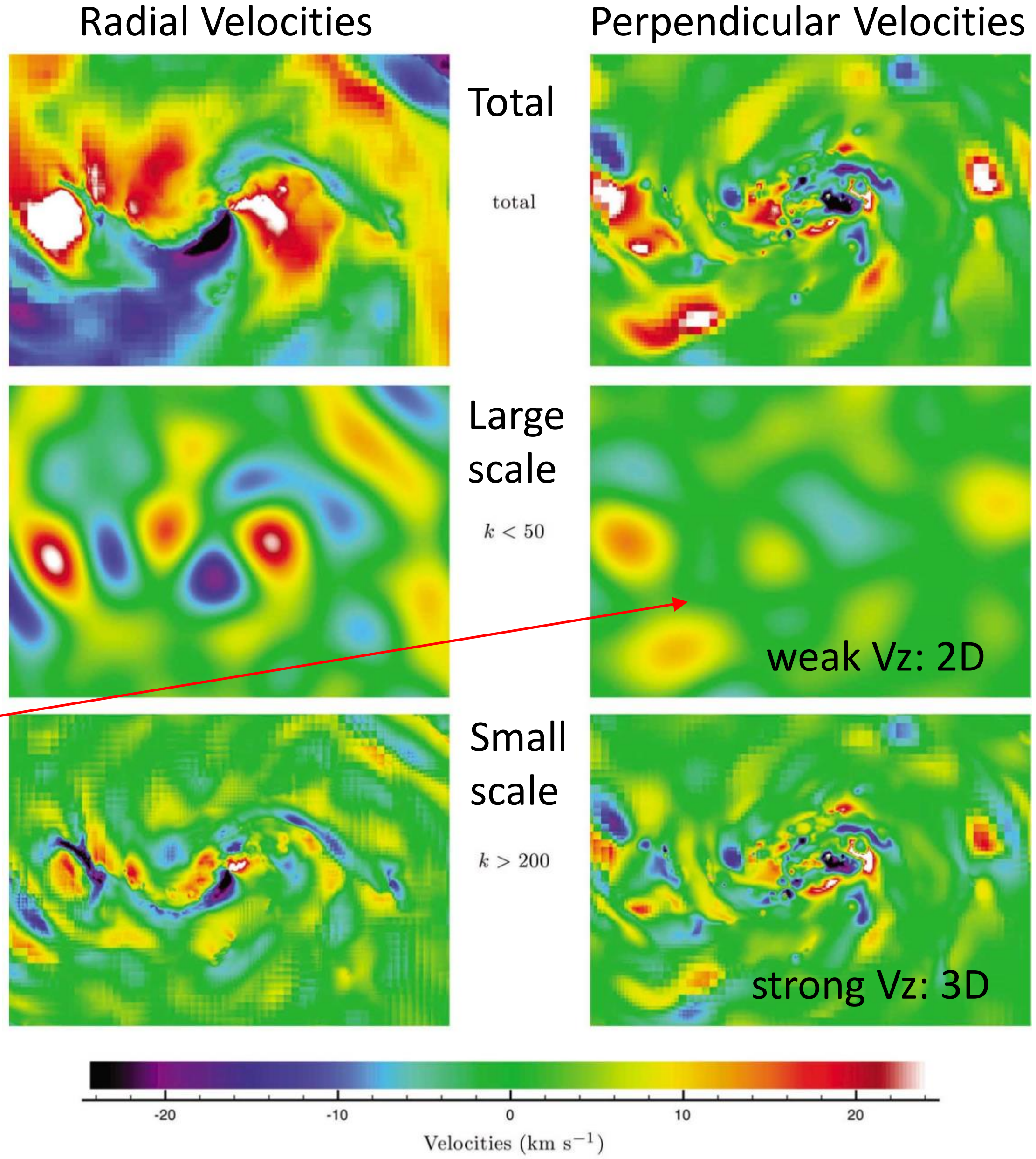
thickness



Small-scale structure (everything smaller than the thickness) gives the high-k power spectrum



v_z (from SF) lacks energy on large scales

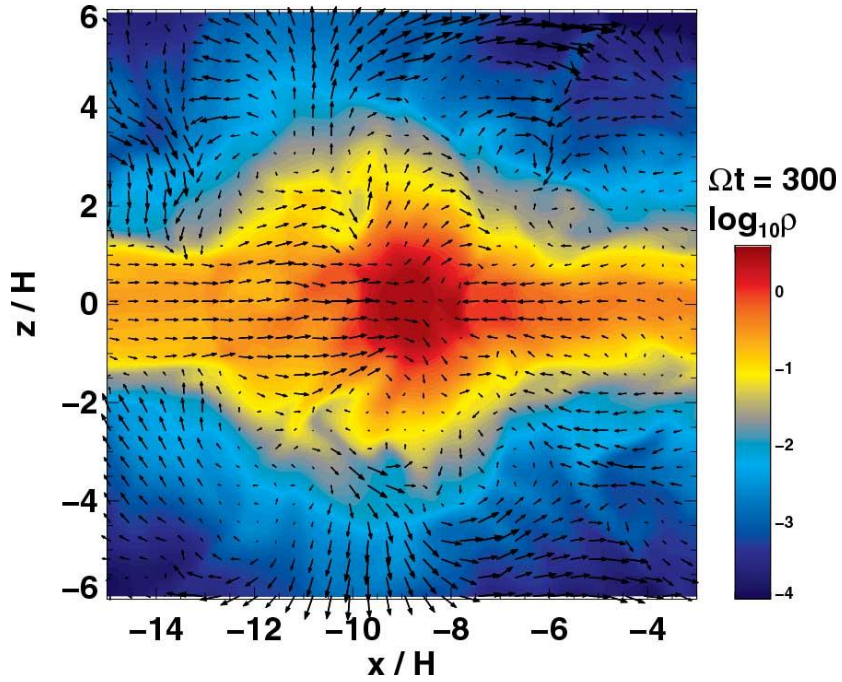


Mass-weighted velocities along the line of sight

Bournaud, Elmegreen, Teyssier, Block, Puerari ‘10

Shi & Chiang 14: Simulation of a shearing sheet for a self-gravitating protoplanetary disk (no SF feedback) shows gravity-driven converging flows in the radial direction generating turbulence and making a splash to high z.

This is the turbulent cascade from 2D gravity-driven turbulence to 3D dissipating turbulence.



Is there a way to tell how much small-scale ISM turbulence is a cascade from large scales, where it is driven by gravity and galaxy interactions,

versus originating on a small scale and driven by star formation feedback?

-- Feedback-dominated SF: energy put in on small scales (Franco & Cox ‘83, …, Agertz +09, Dobbs +11…)

two versions:

(1) Ostriker et al.: Feedback controls P → H → $<\rho>$ → $\Sigma_{SFR} \sim \epsilon_{ff}\Sigma_{gas}(32G\rho/3\pi)^{0.5}$

$\sigma \sim 0.4\epsilon_{ff}$ (p*/m*); $H \sim \sigma^2/(\pi G\Sigma_{gas})$; $\Sigma_{SFR} \sim 2\pi G\Sigma_{gas}^2$ (m*/p*) -- Ostriker & Shetty ’11; starbursts

(2) Hopkins +11 … “FIRE”: Feedback destroys GMCs and limits their collapse

(as in Bournaud +10; see also Whitworth 79…Kruijssen +19)

-- Gravity-dominated SF: energy put in on large scales (Goldreich & Lynden Bell ‘65, Larson ‘69, …)

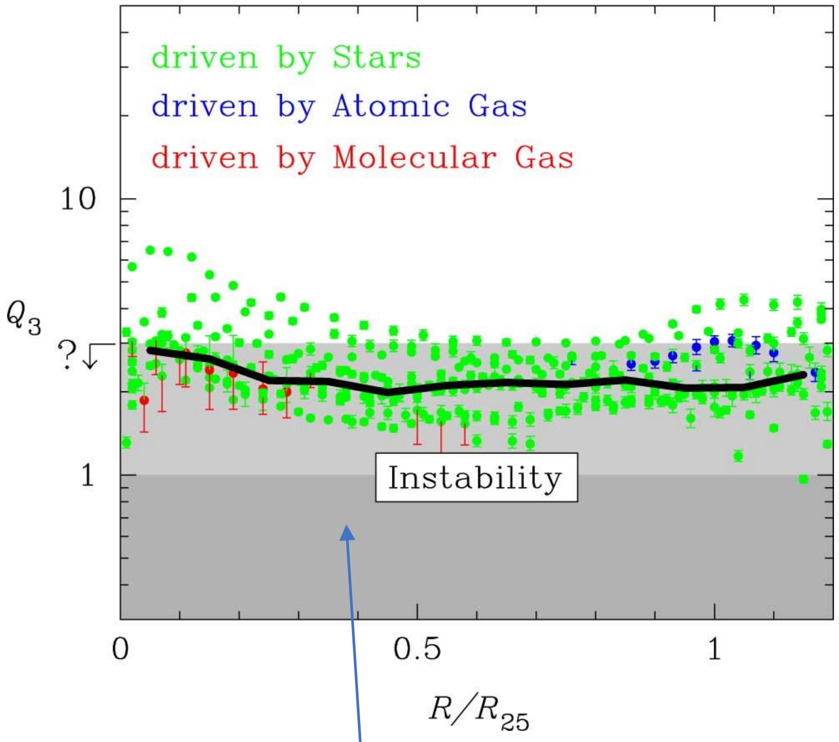
(Kim & Ostriker 07, Agertz 09, Elmegreen 02,03, Bournaud, MacLow, Krumholz, Vazquez-Semadeni)

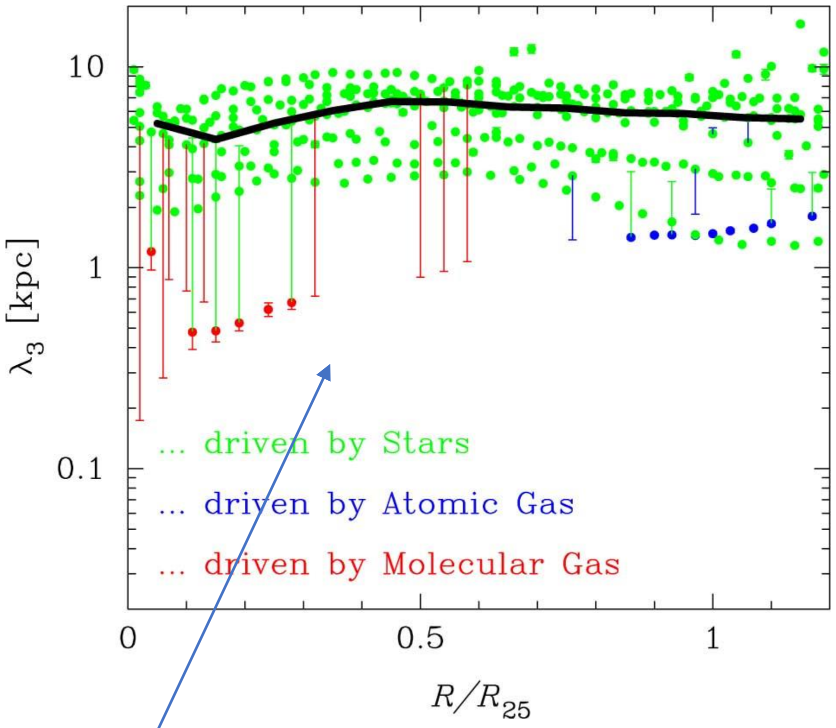
Q ~ constant

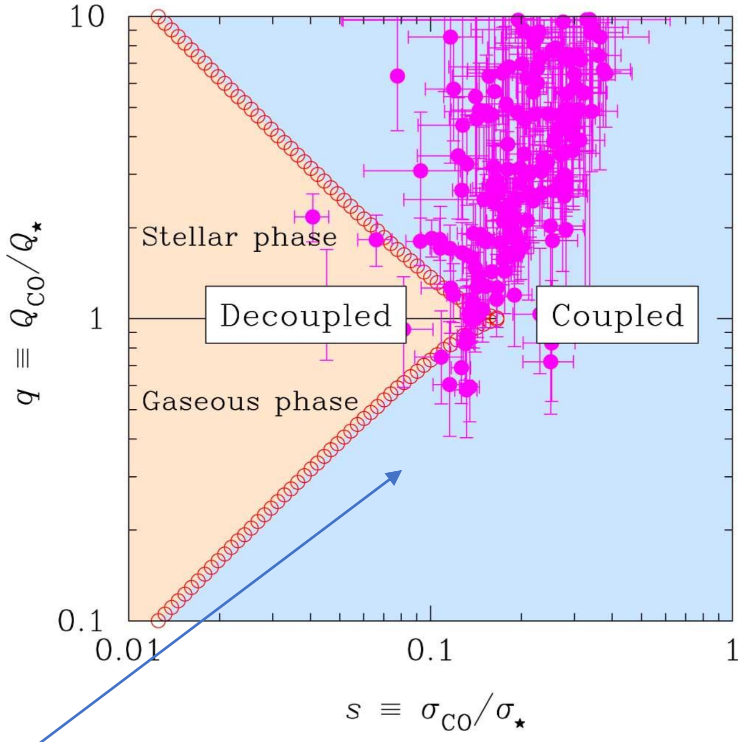
$\sigma = \pi G\Sigma_{2F}Q/\kappa$; $H = \sigma Q/\kappa = \pi G\Sigma_{2F}Q^2/\kappa^2$ (propto r^2e^{-r} ~ constant) → $\Sigma_{SFR} = \epsilon_{ff}\ (16G / 3\pi H)^{1/2}\ \Sigma_{gas}^{3/2}$

-- e.g. Elmegreen ‘15,’18

Romeo & Mogotsi (2017): Q is constant (the Multi-fluid GI using $\sigma_{CO}(R)$ for THINGS galaxies)

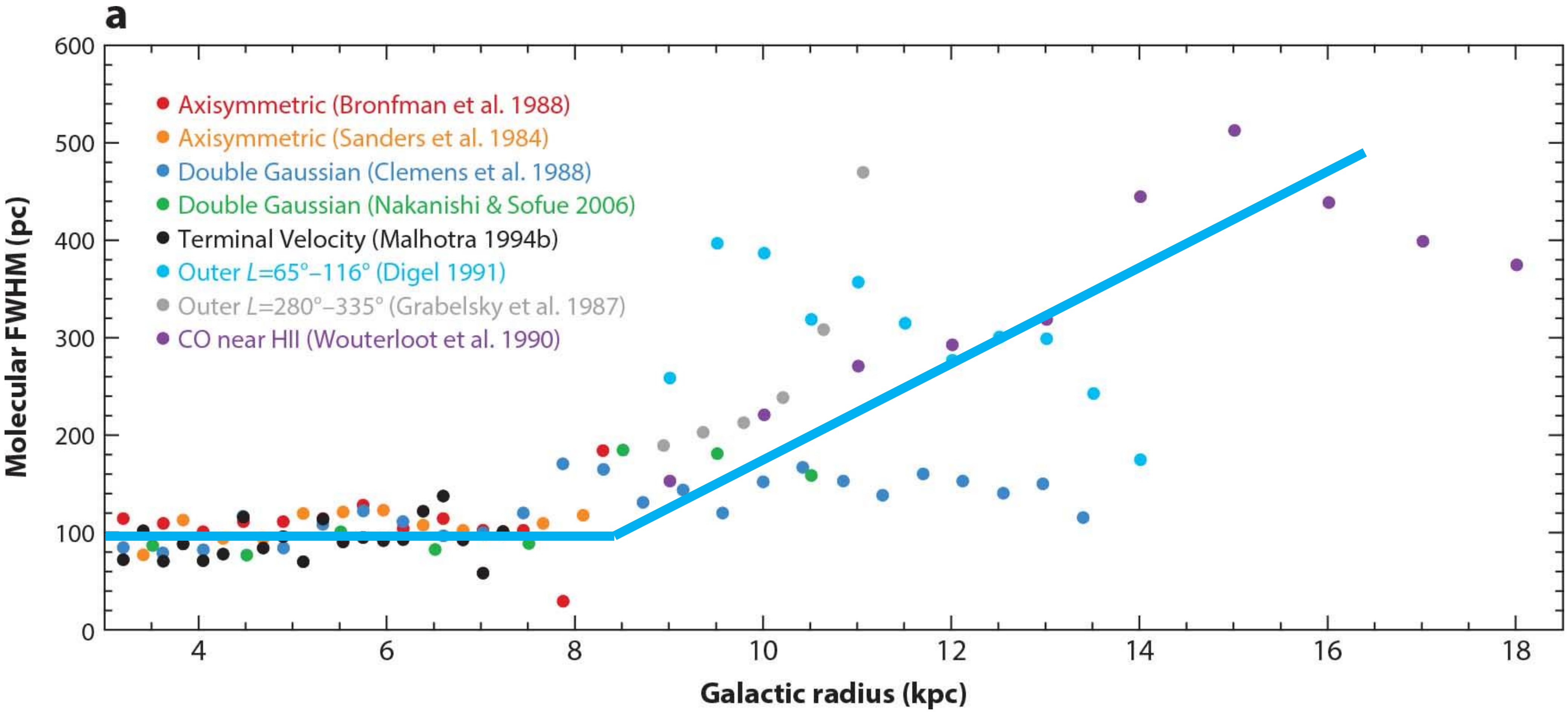






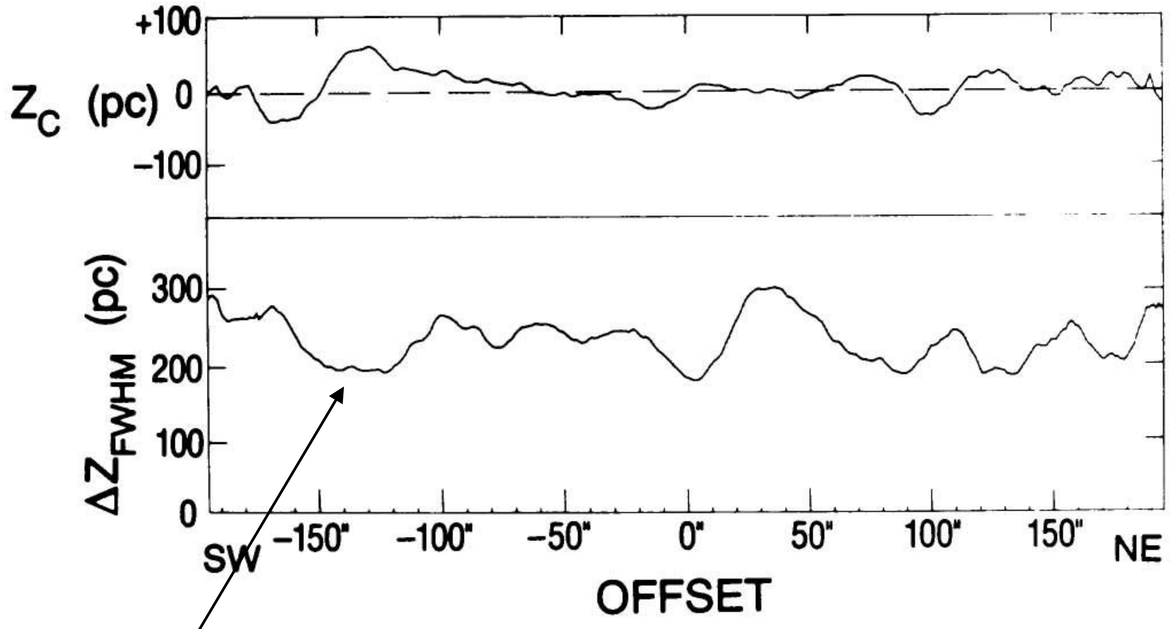
Stellar dominance, a large dominant scale, a high coupling between gas and stars, and a constant level of stability (Q~3) suggest self-regulation of large-scale σ by spiral instabilities

Heyer & Dame 2015 ARA&A



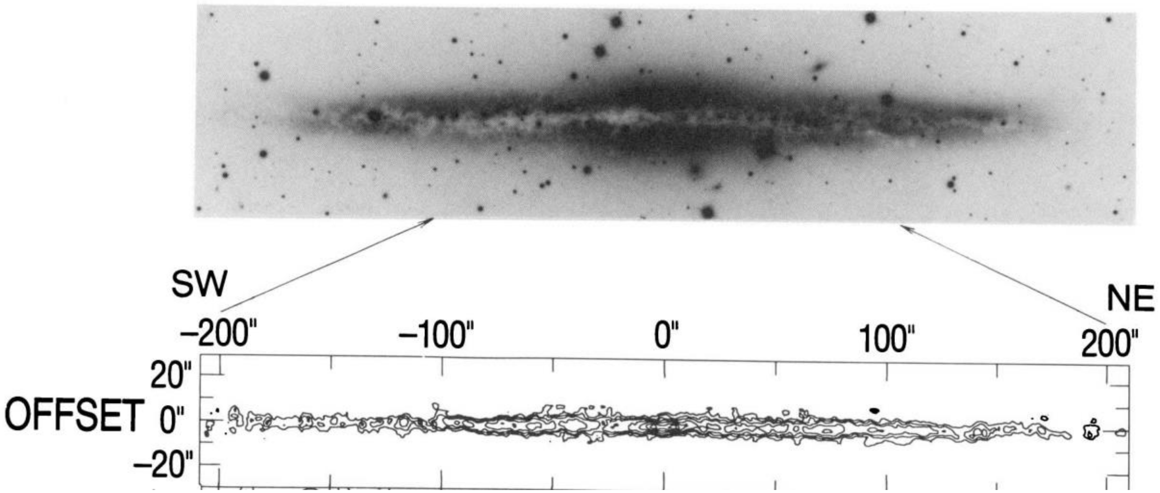
H ~ constant in main disk

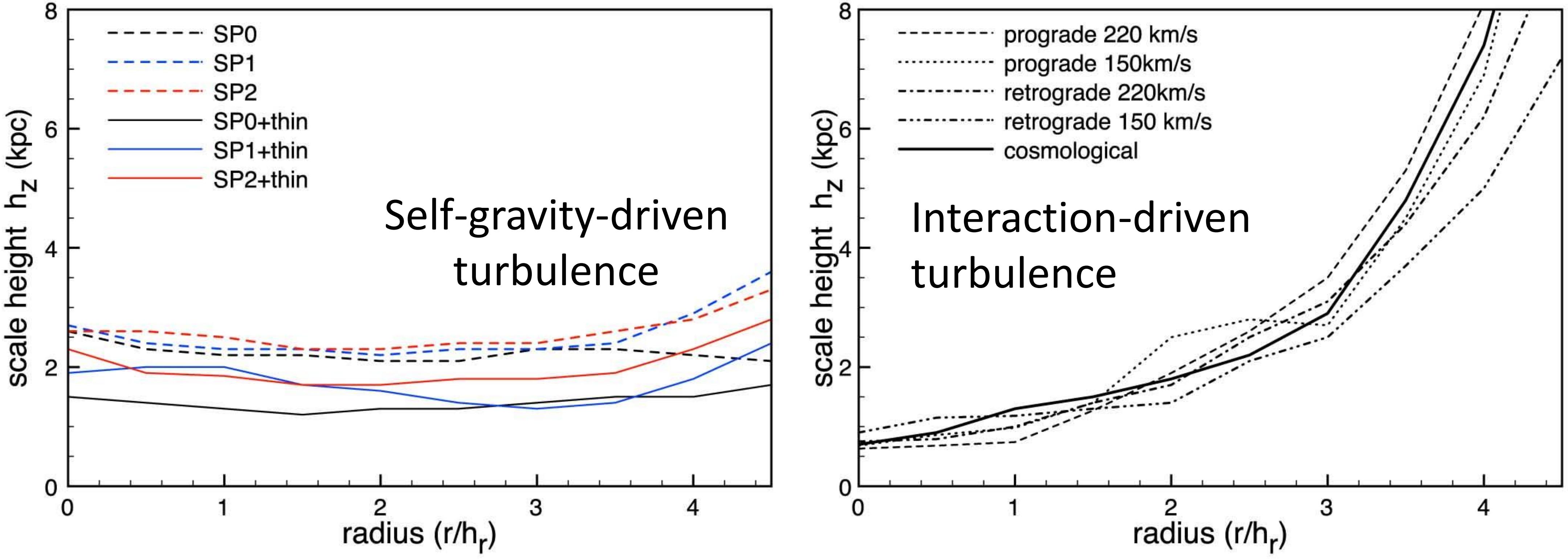
Flare in outer disk



Scoville +93, CO vertical profile of NGC 891

→ constant H



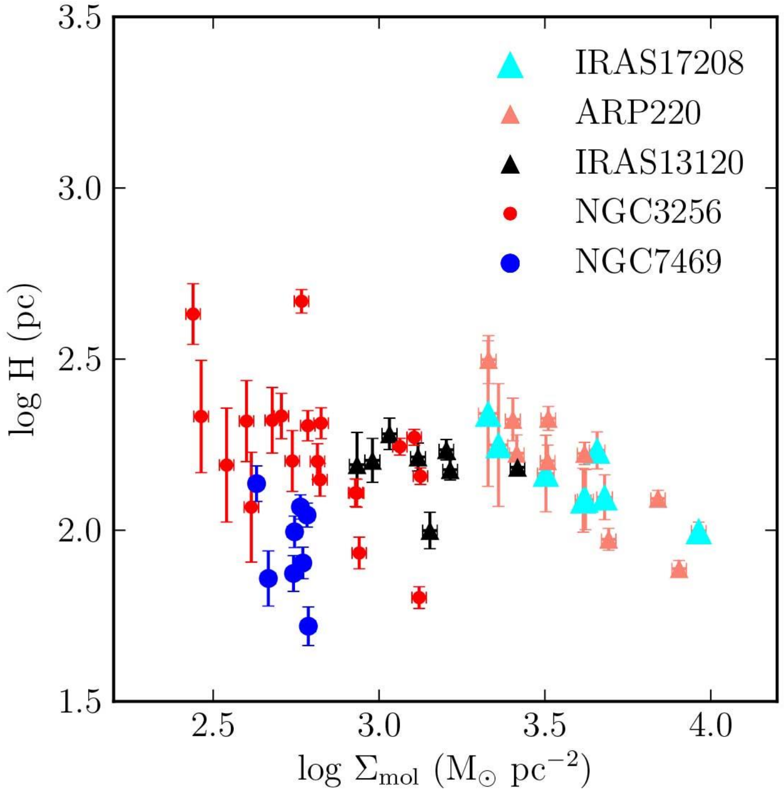

Self-gravity-driven turbulence

Interaction-driven turbulence

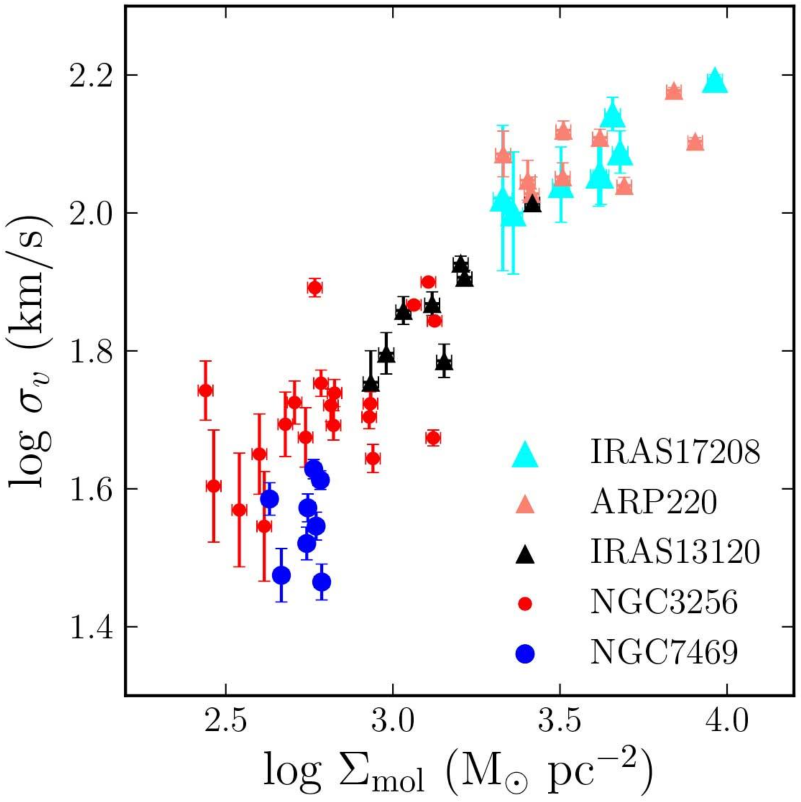
Bournaud, Elmegreen +09: Gravity-driven turbulence in young thick disks:
constant scale height with radius

Wilson, Elmegreen, +19: determined $H=0.5\sigma^2/\pi G\Sigma_{mol}$ for 5 U/LIRGS

- CO uses a constant starburst X_{CO}
- H equation assumes B contributes 30% support (Kim & Ostriker '15)
- ~ 30% extra attraction from background galactic gravity ("cancels" B)
- ~ x2 extra attraction from disk stars and DM inside the gas layer
- 1.1" beam is small, so velocity-gradient corrections to σ from mom2 are < 10%



H ~ constant (150-170 pc) over x30 in Σ_{mol}



$\sigma \sim \Sigma_{mol}^{0.5}$ (from 25 km/s to 160 km/s)

Conclusion: $Q \sim$ constant, $H \sim$ constant (inner disks), σ increasing with Σ suggest that gravity is driving the gas velocity dispersion, not supernova feedback (where $\sigma \sim$ const., $H \sim 1/\Sigma$).

The 1.4-slope Kennicutt-Schmidt relation (for total gas) is trivially reproduced by assuming

Q ~ constant

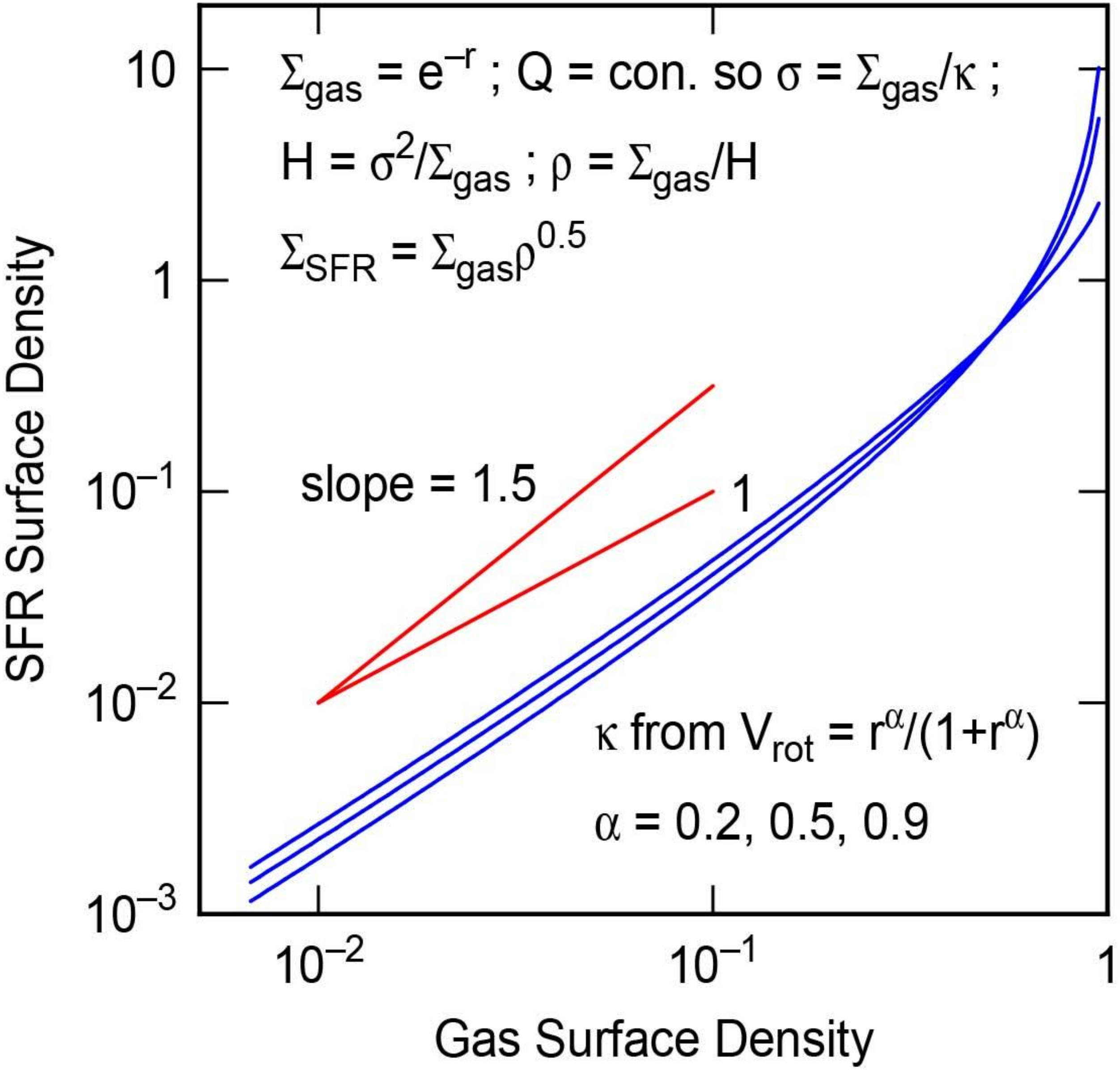
in an exponential disk

(because H is much more constant than Σ_{gas}, so ρ scales with Σ_{gas})

…

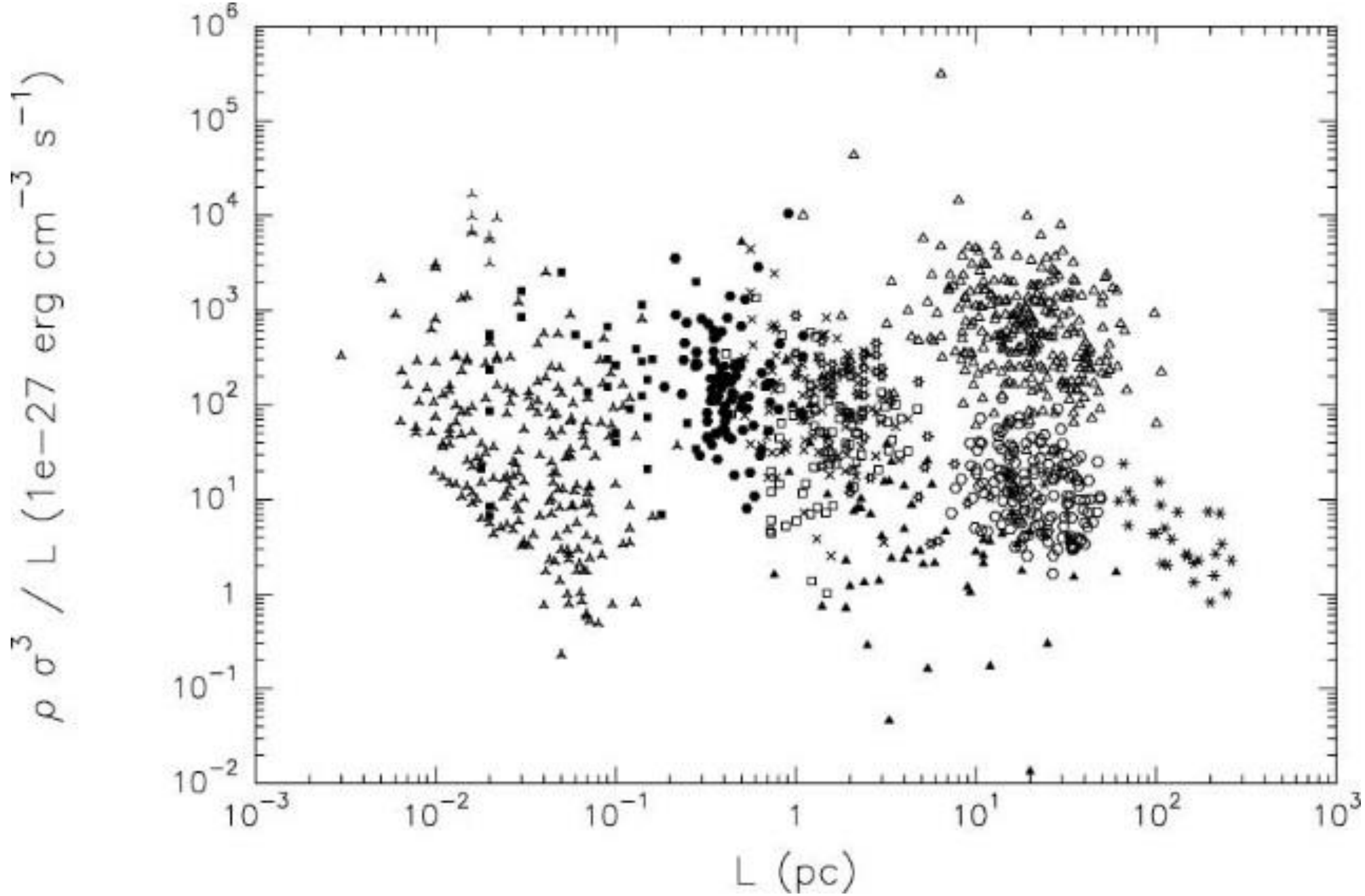
This result is the same as

$\Sigma_{SFR} \sim \Sigma_{gas}\,\kappa$

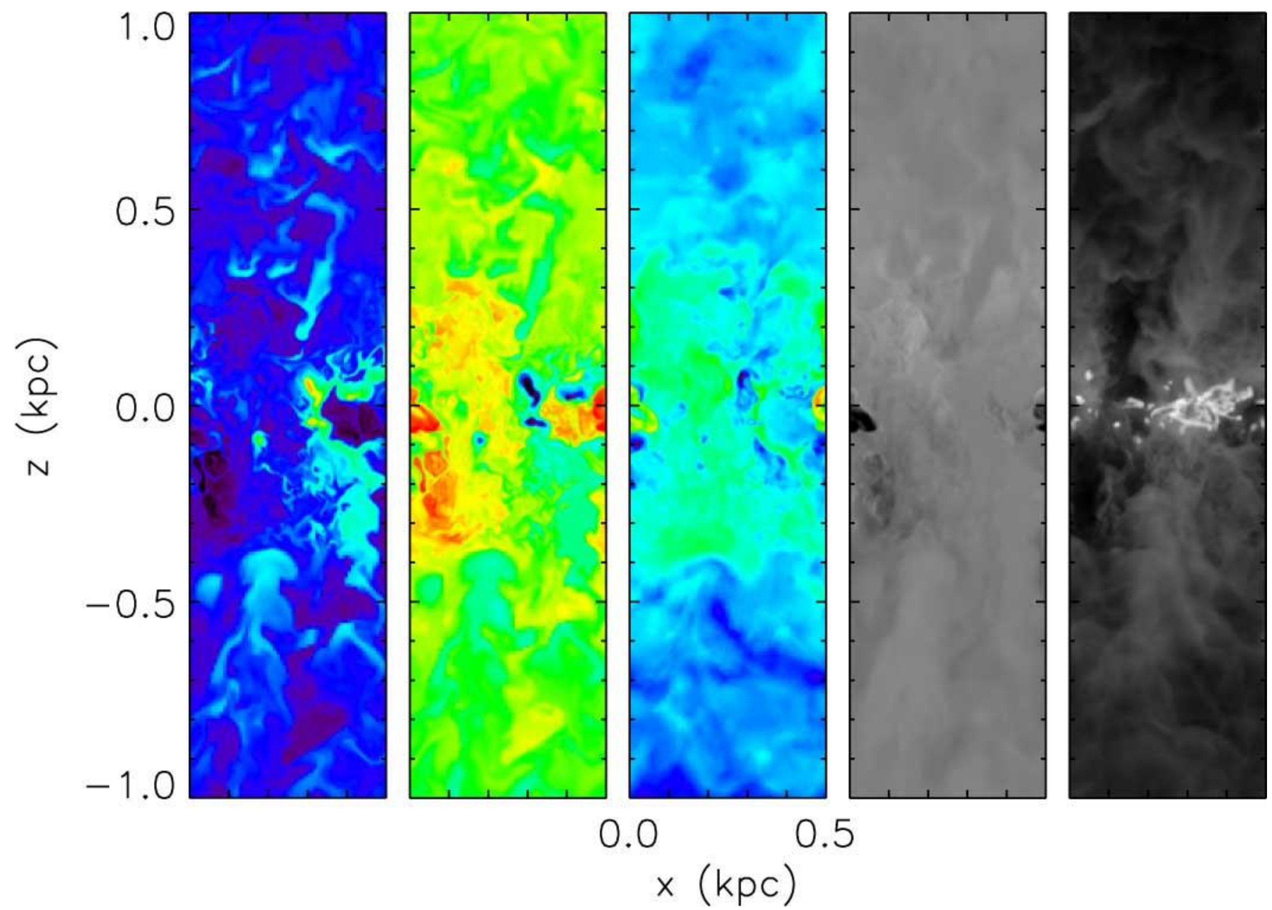


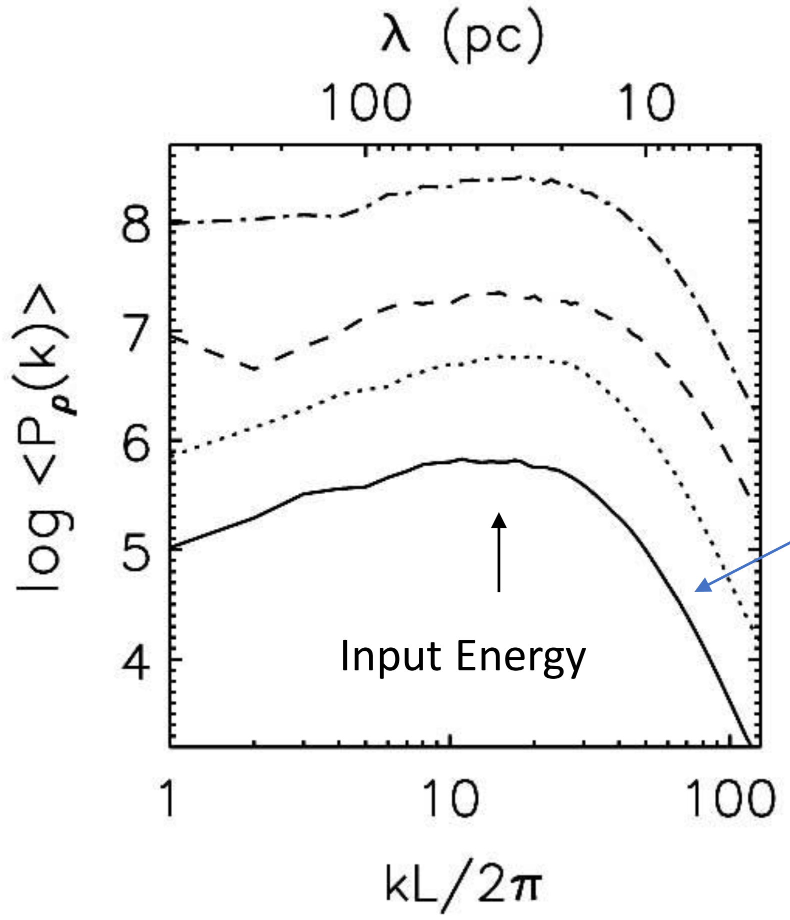
Elmegreen '19

What about *inside* GMCs: does turbulence come from a continuation of a large-scale cascade (i.e., GMC formation) or from feedback (GMC disruption)?



Hennebelle & Falgarone '12: Energy dissipation rate ($\rho\sigma^3/R$) in ^{12}CO clouds of the MW is independent of size and comparable to the dissipation rate in atomic gas. → Energy input to GMCs is <u>from outside</u> (recall the giant HI clouds that have GMCs in their cores…)





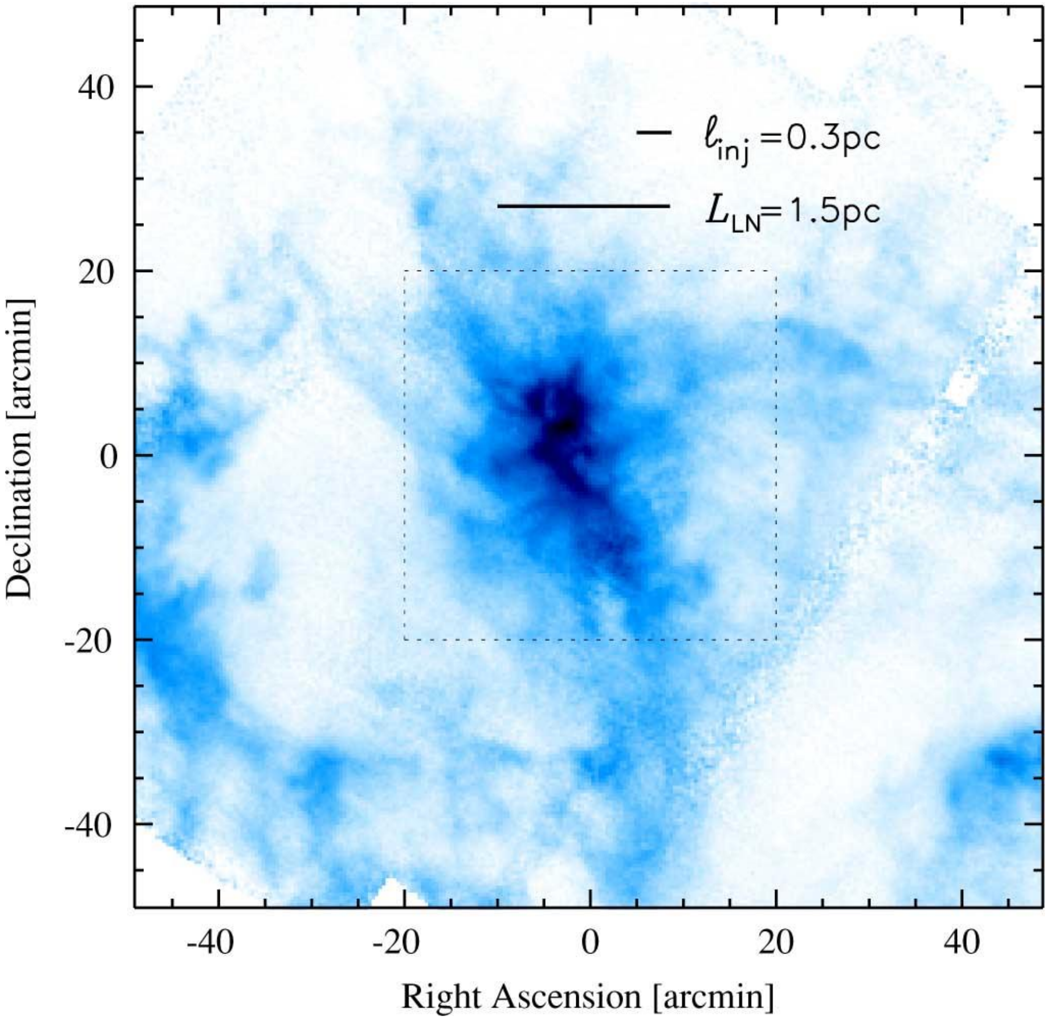
Input Energy

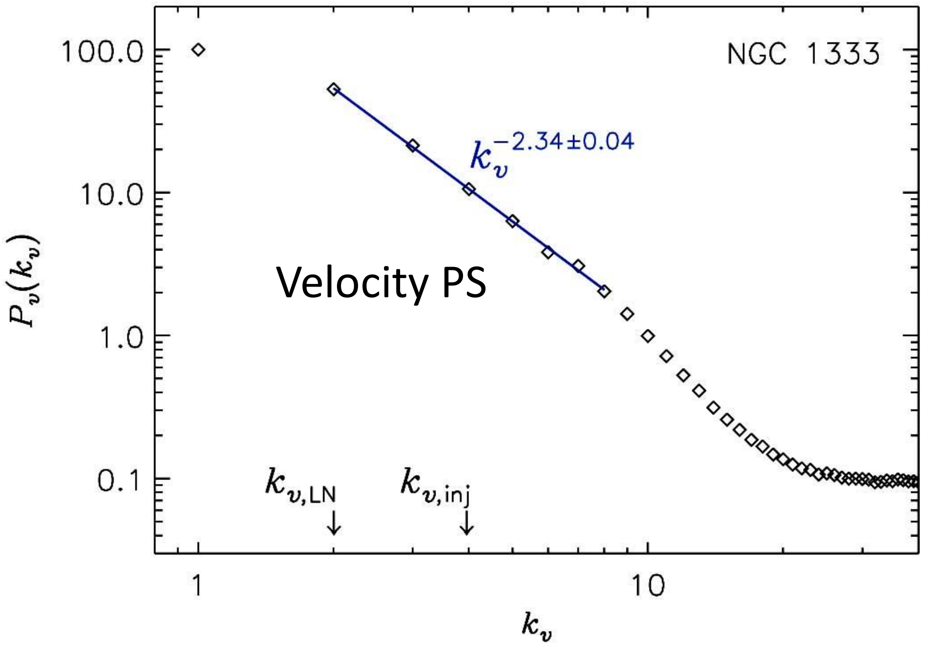
Power law on smaller scales

Joung, MacLow & Bryan 09: SN driven ISM: Feedback only.

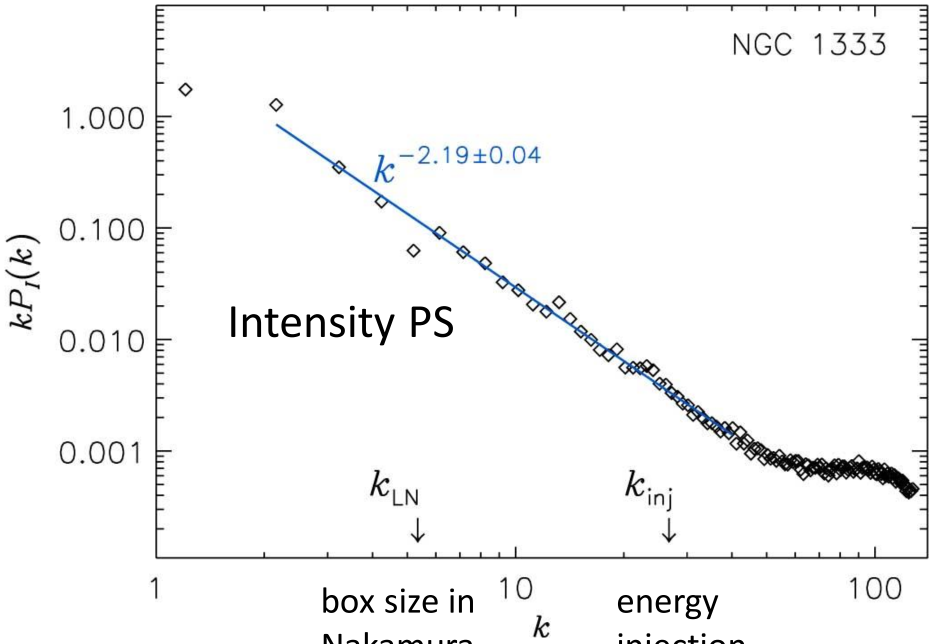
Density power spectrum is a power law only on scales smaller than the energy injection scale.

Padoan +09: NGC 1333: A star-forming, self-gravitating cloud has no peak in the power spectrum at an energy injection scale → most of the turbulent energy comes from outside the cloud (e.g. from cloud formation).





Velocity PS

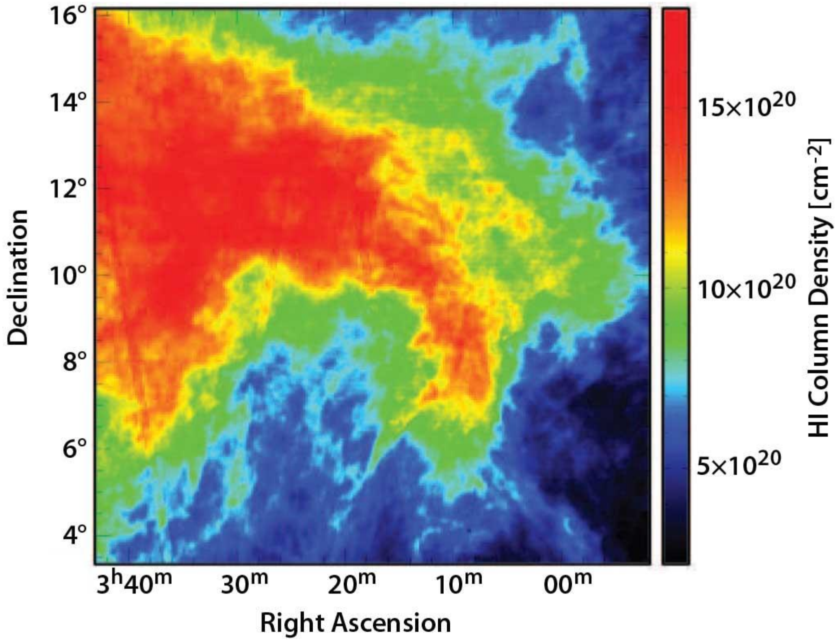


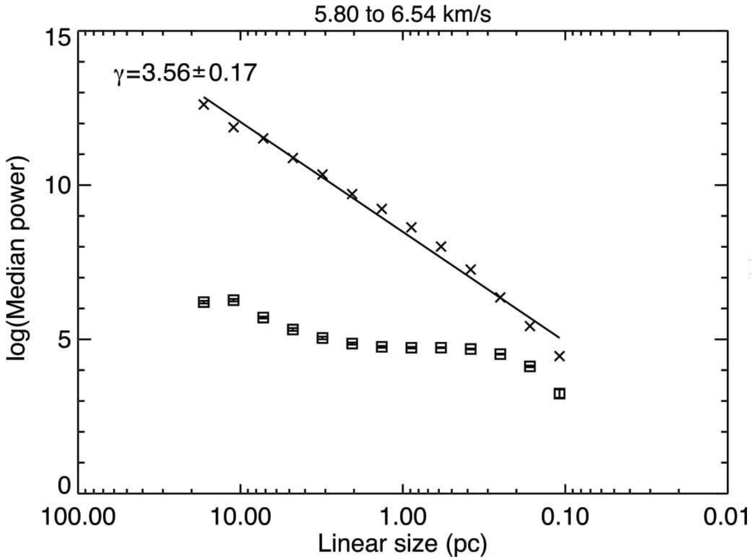
Intensity PS

box size in Nakamura & Li 07

energy injection scale

Pingel +13 MBM 16: A non star-forming, non self-gravitating cloud. The power spectrum is steeper than in the general ISM which is consistent with no feedback input. There is also no turnover at large scales, which means that turbulent energy coming from outside.



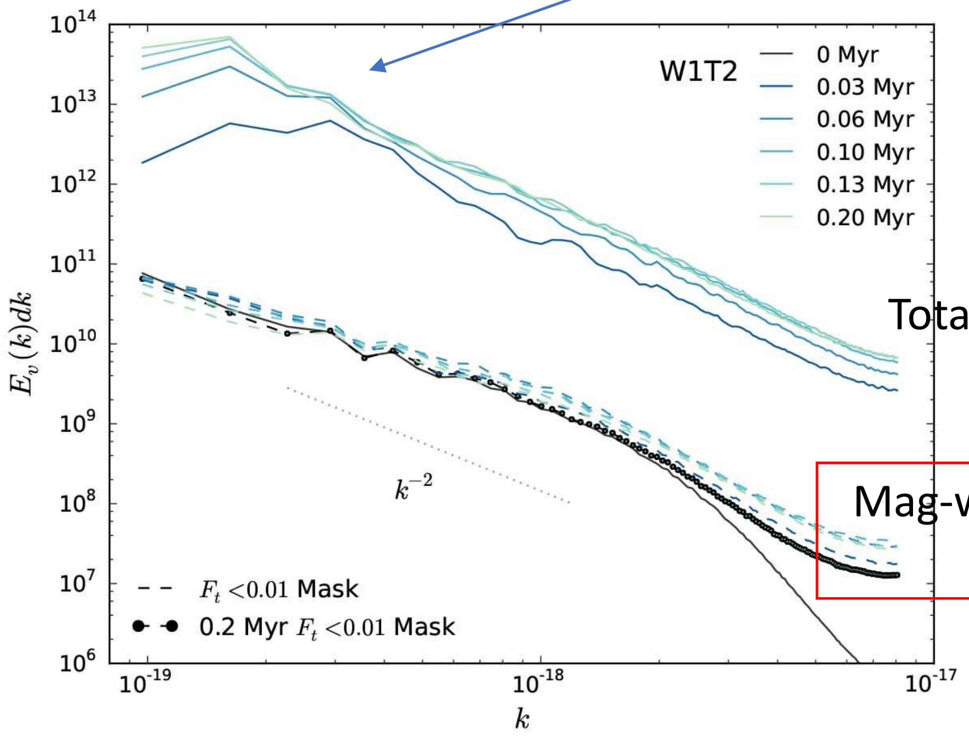


Power spectrum has no turnover on large scales

Also, Seifried +18 show from MHD simulations that external SNe have a negligible effect on GMC turbulence (too dissipative)

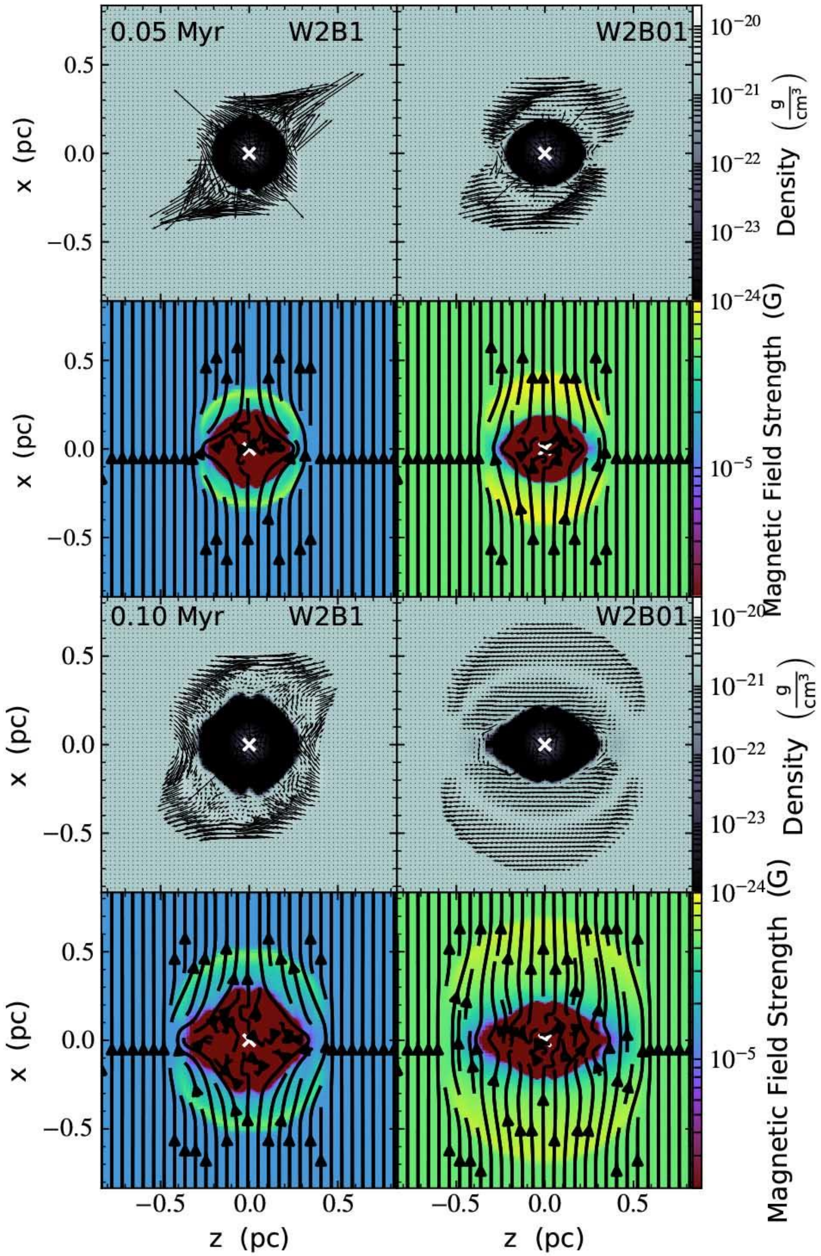
Offner & Liu ’18: MHD models of clouds with stellar winds suggest that magnetic waves can distribution feedback energy, possibly accounting for GMC turbulence (see also Gammie & Ostriker ‘96).

wind energy input on 1-3 pc scale makes total gas PS peak

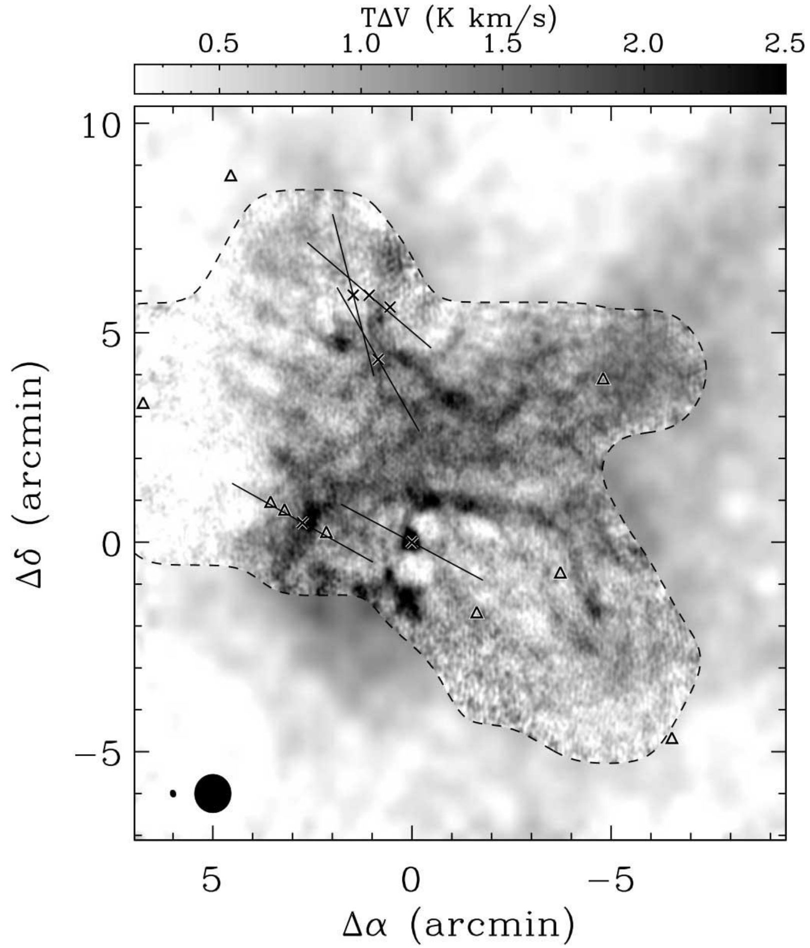


Total gas

Mag-wave region continues PS to larger scales.

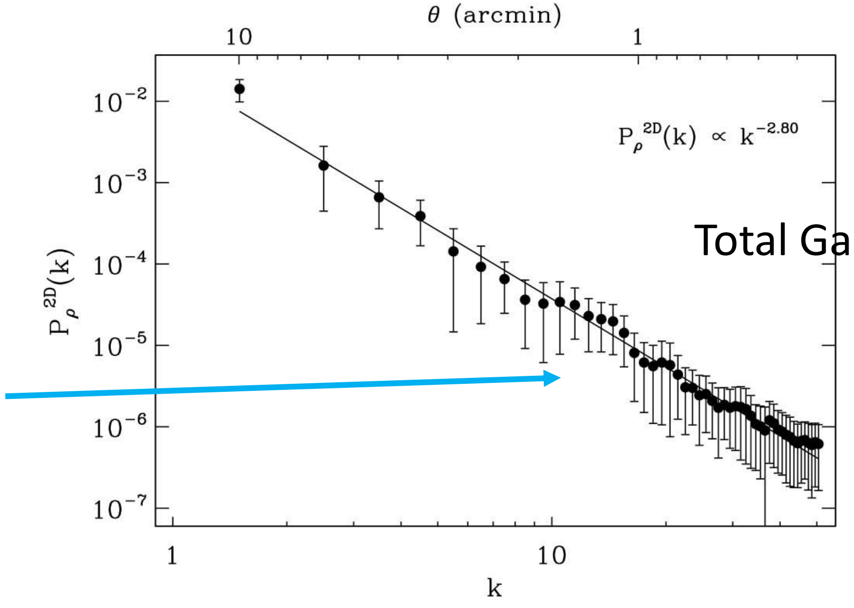


Swift & Walsh ’08: Evidence for wind energy input in the Power Spectrum of line wing emission in L1551



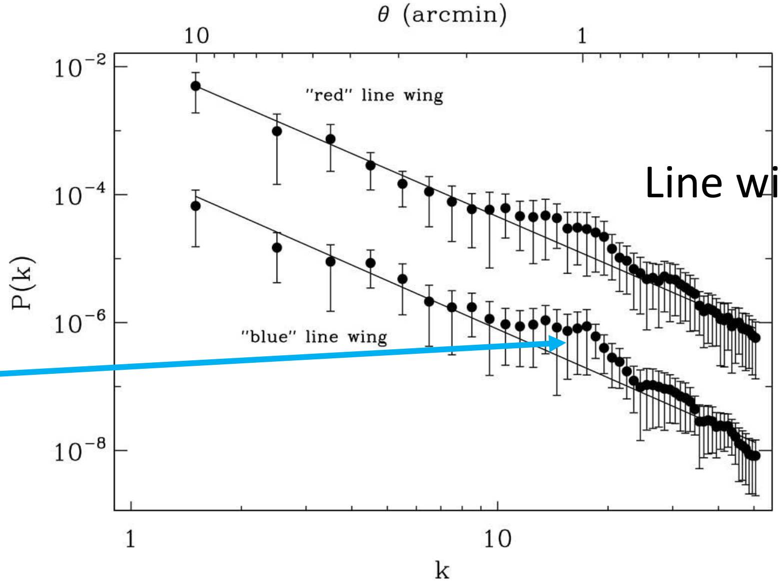
Velocity integrated C^{18}O

Total C^{18}O line emission shows no significant features



Total Gas

Line wing emission for ^{13}CO shows a feature at 1’ (0.05 px) presumed to be the scale of pre-main sequence winds.



Line wings

What drives the turbulence?

Gravity on galactic scales drives spiral arms which appear to drive the large-scale gas velocity dispersion, giving Q ~ constant and H slowly varying with radius in the main disk.

Cloud-scale turbulence mostly driven from larger scales, i.e., cloud formation, with weak signatures from star formation feedback, i.e., cloud destruction.

How does turbulence affect star formation?

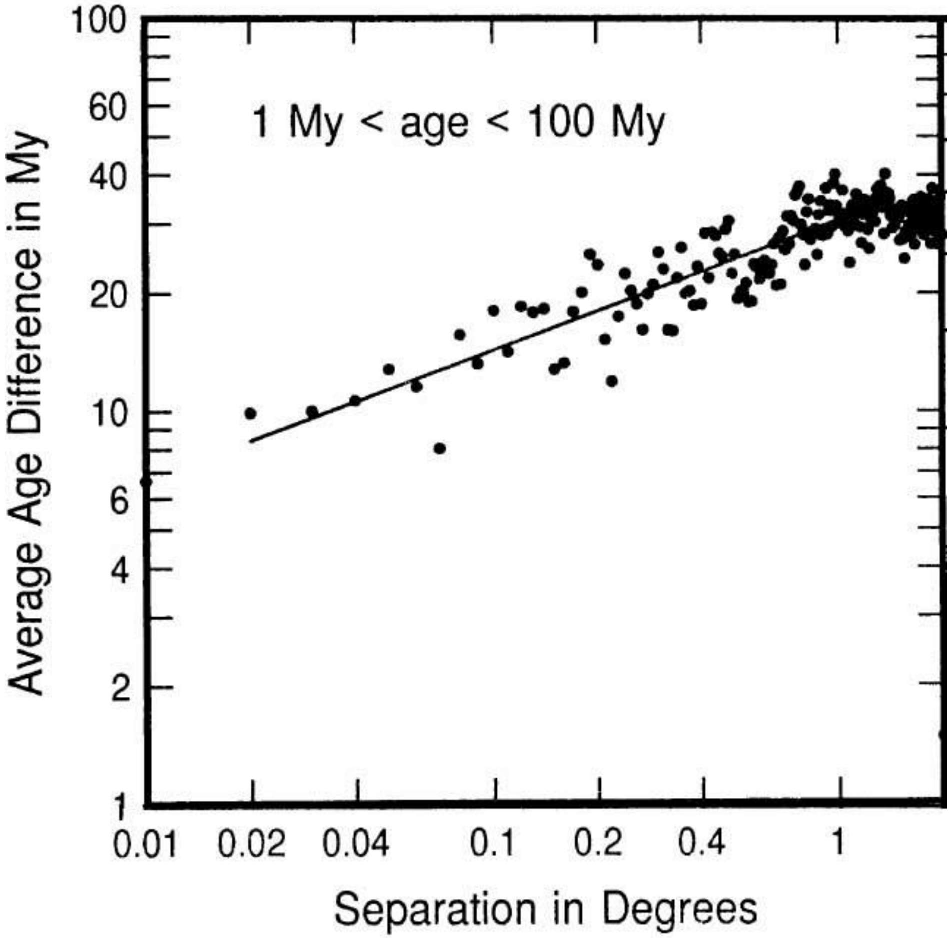
Elmegreen & Efremov ’96,
Efremov & Elmegreen ’98:

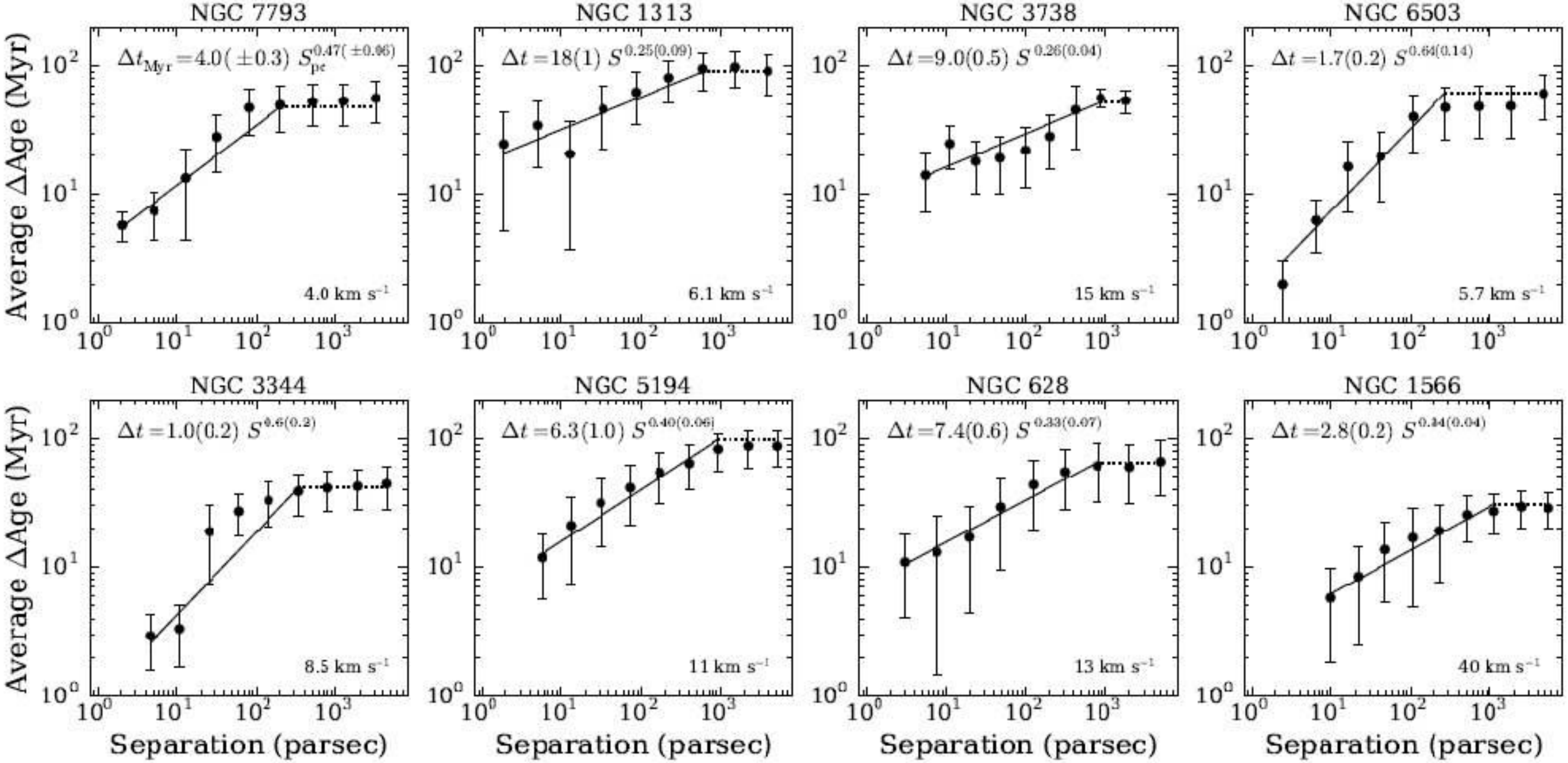
LMC star clusters are correlated in space and time.

Closer clusters in space are also closer in age.

The slope of the relation is the same as the size versus crossing-time slope for GMC turbulence.

Turbulence structures the gas and the resulting stars that form.





Grasha, Elmegreen +17: (LEGUS): finds the same for 8 other galaxies:

The age difference between cluster pairs increases with separation up to a few 100 pc and 20-100 Myr ($\Delta t \sim \Delta R/\sigma(R) \sim R^{0.5}$)

→ Star formation operates on a local dynamical time, which varies with size

Summary: “Star Formation Processes and Energy Sources in Interstellar Gas”

1. Spiral arm and other large-scale shocks make self-gravitating filaments on kpc scales that collapse into giant cloud complexes (HI/CO) and form stars
    - Collapse time ~ 1 - 10 Myr (from density and scale), core time ~ 0.1 – 1 Myr
    - Resemble clumpy filaments in the local ISM (which are 1% the size)

2. ISM turbulence viewed by the power spectrum is consistent with large-scale collapse energy pumping most HI and GMC motions
    - Constant ISM thickness argues against constant p*/m* feedback and in favor of Q-regulation on large scales and cloud-destruction feedback on small scales

3. “Turbulent fragmentation” (Kolesnik & Ogul’Chanskii 1990) determines the positions and formation times of young stellar clusters and OB associations