Regularity and Turbulence in Galactic Star Formation

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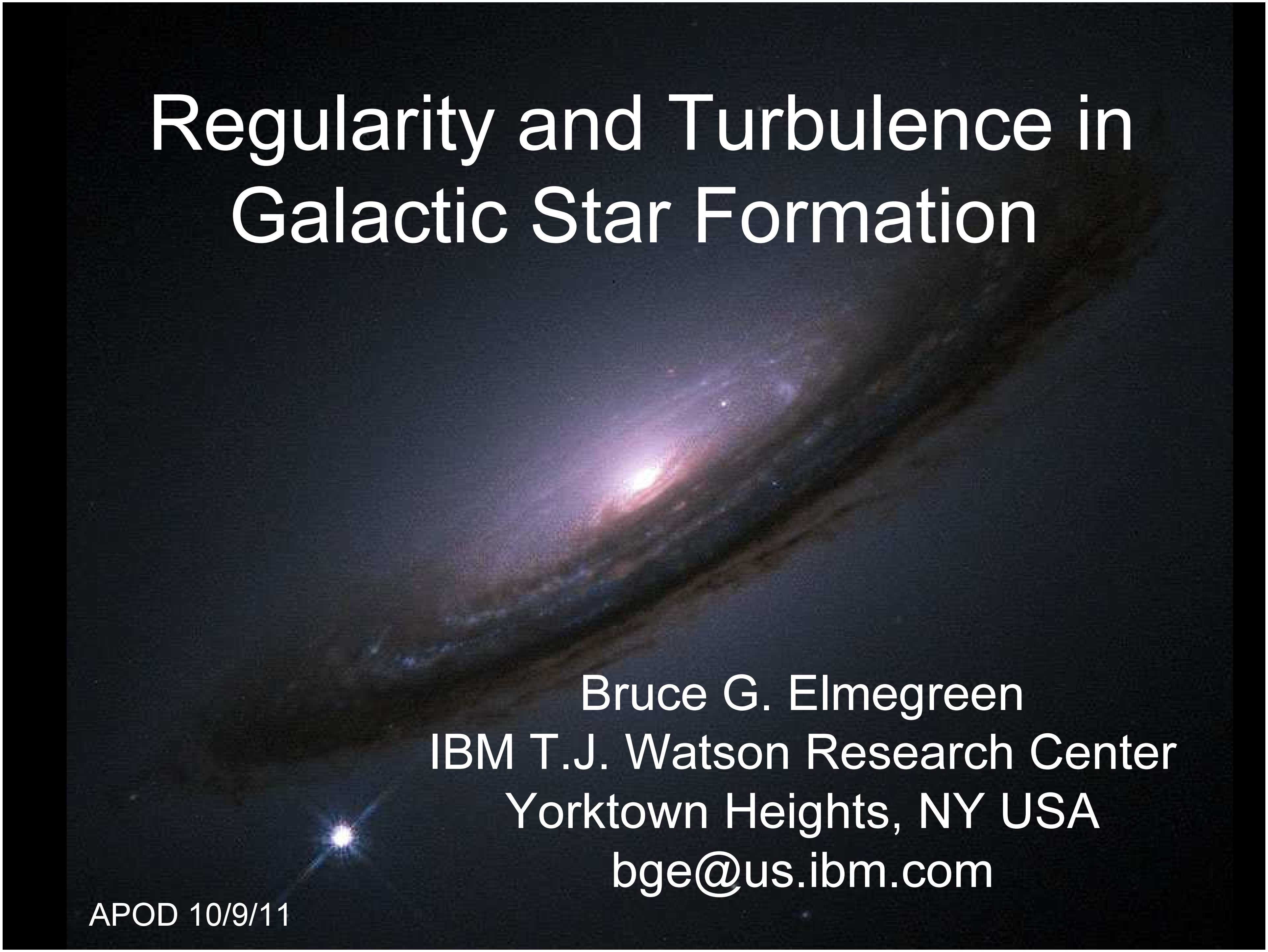
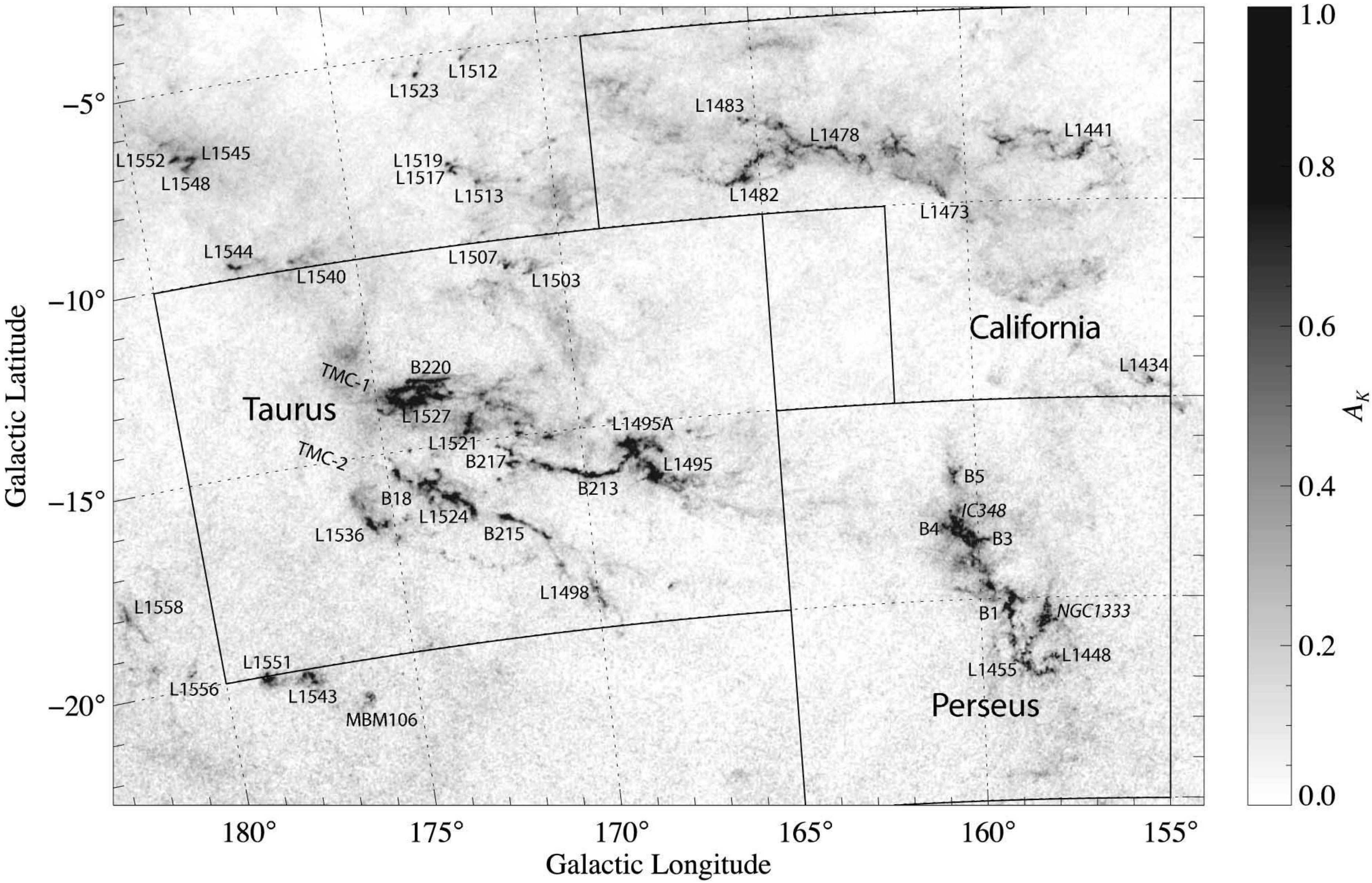


APOD 10/9/11

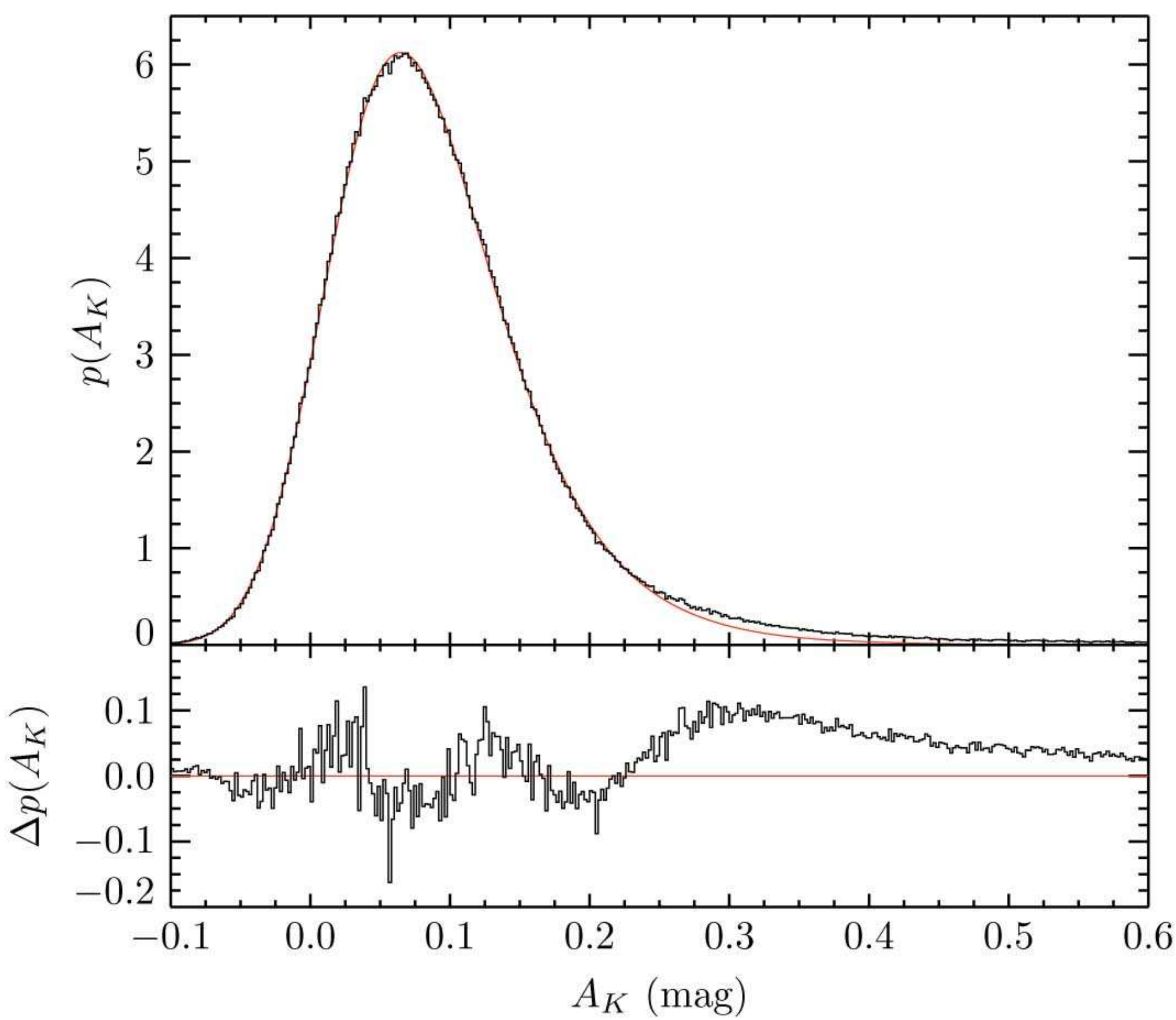
Overview

- HI to H_2 conversion
- Spiral wave star formation
- Azimuthal KS law
- Exponential Disks
- Star formation at low Σgas/Σcrit



L1512
L1523
L1483
L1478
L1441
L1552
L1545
L1548
L1519
L1517
L1513
L1482
L1473
L1544
L1540
L1507
L1503
California
L1434
TMC-1
B220
Taurus
L1527
L1495A
L1521
TMC-2
B217
L1495
B213
B5
IC348
B4
B3
B18
L1524
L1536
B215
L1498
B1
NGC1333
L1558
L1448
L1455
L1551
L1556
L1543
MBM106
Perseus
Galactic Latitude
Galactic Longitude
−5°
−10°
−15°
−20°
180°
175°
170°
165°
160°
155°
A_K
1.0
0.8
0.6
0.4
0.2
0.0

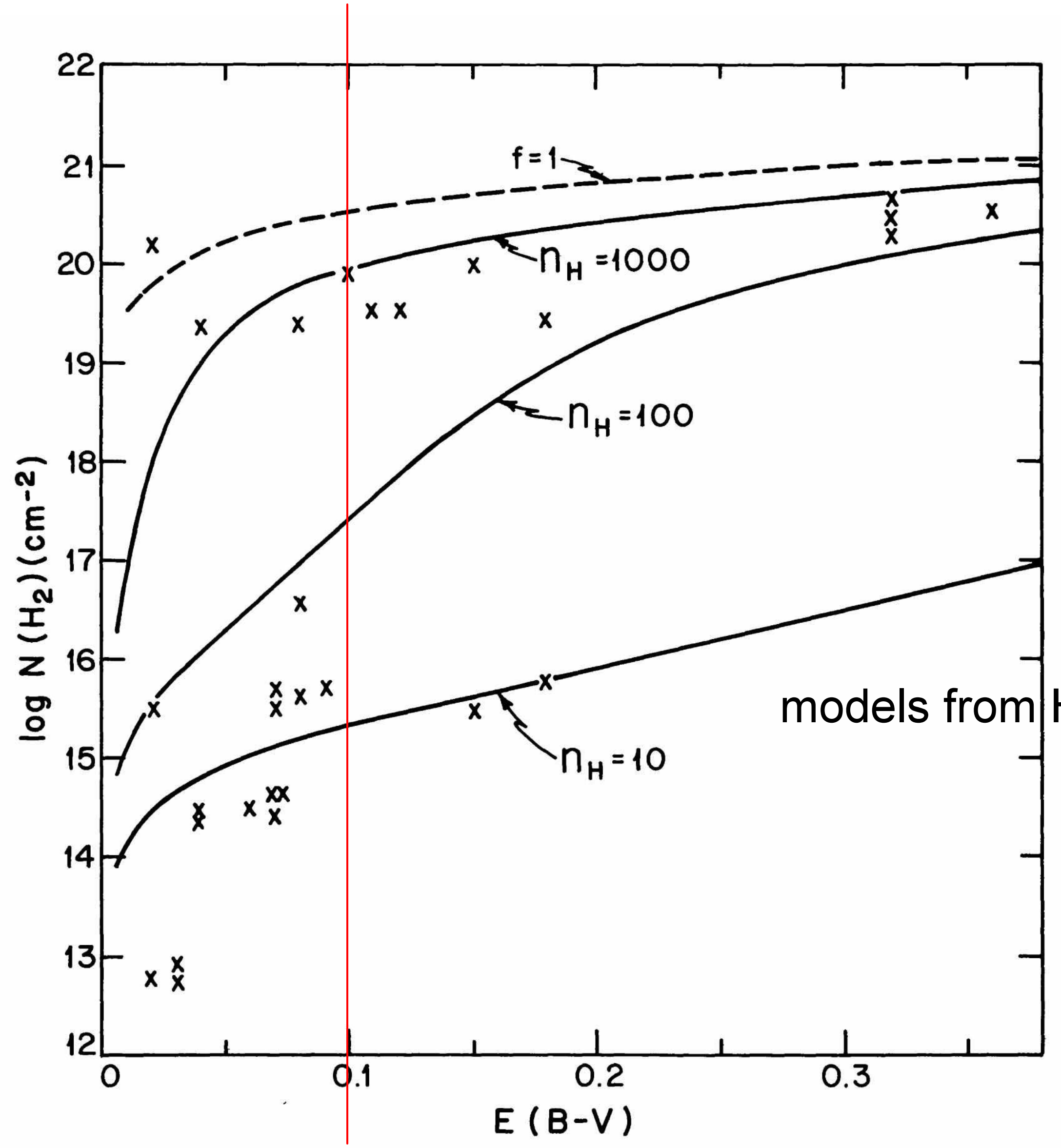
Lombardi +10



0.1 mag in K = 0.91 mag in V = 0.30 in E(B-V)

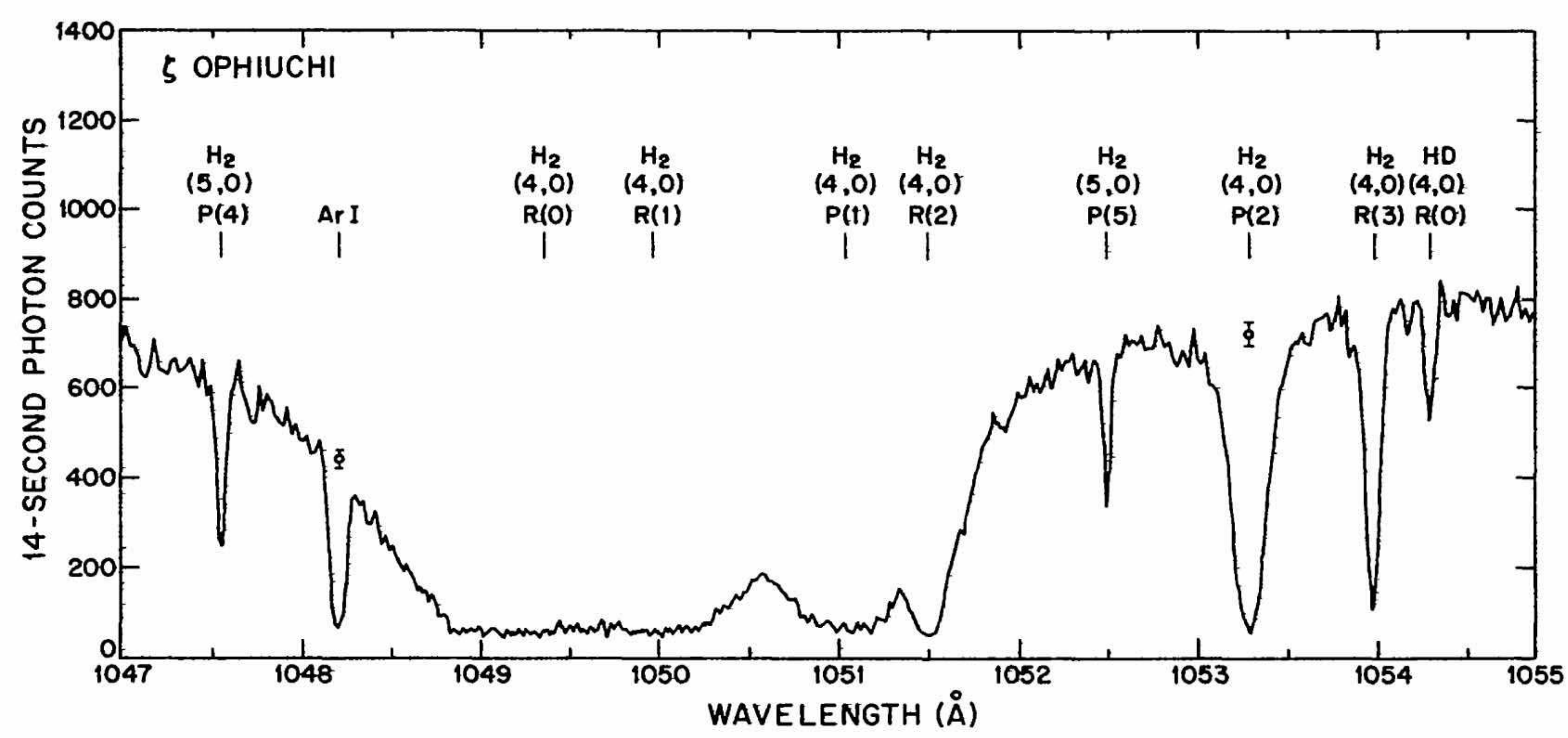
Lombardi +10

H_2 in diffuse clouds observed with *Copernicus*



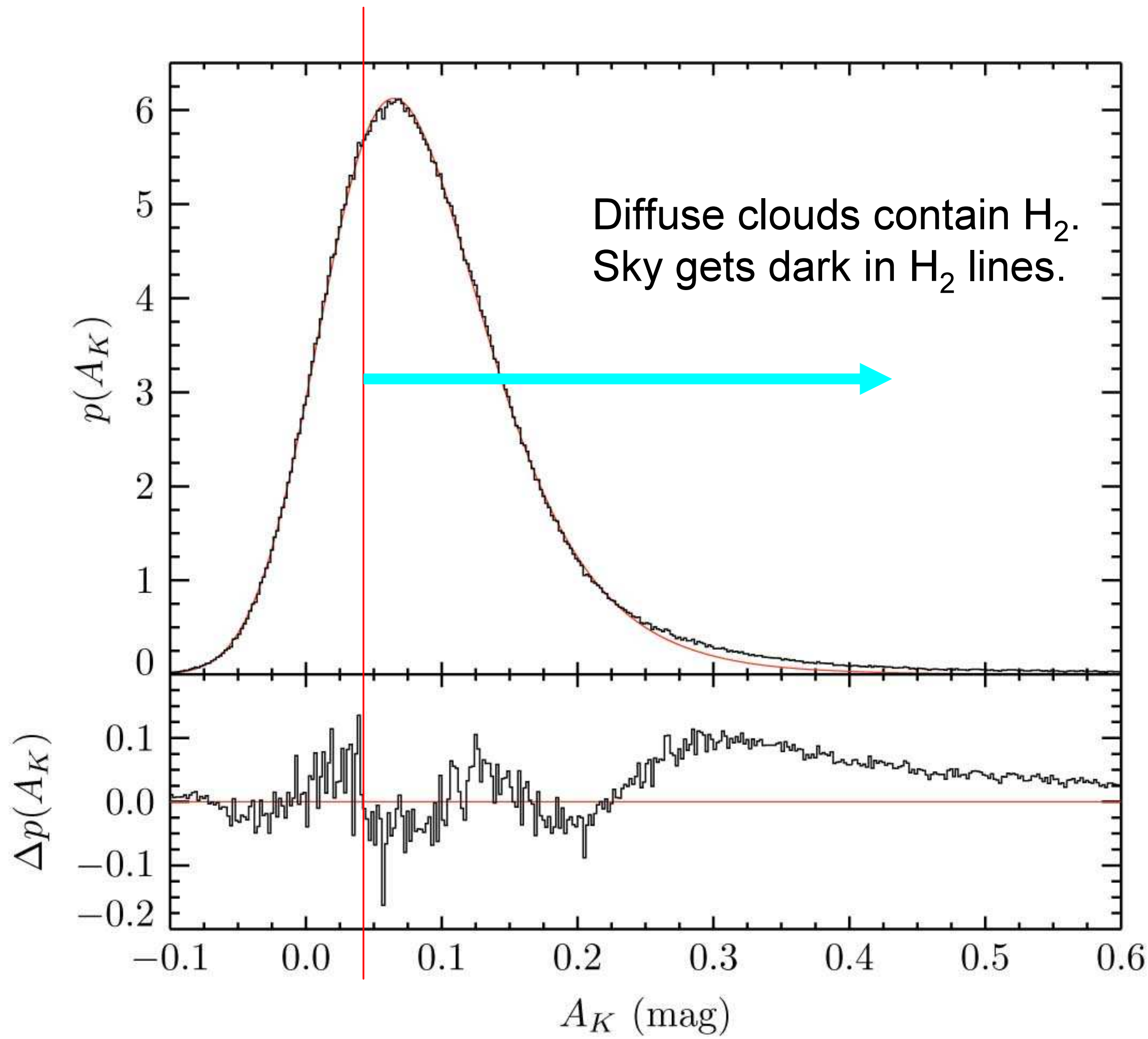
models from Hollenbach + 71

Spitzer & Jenkins 1975



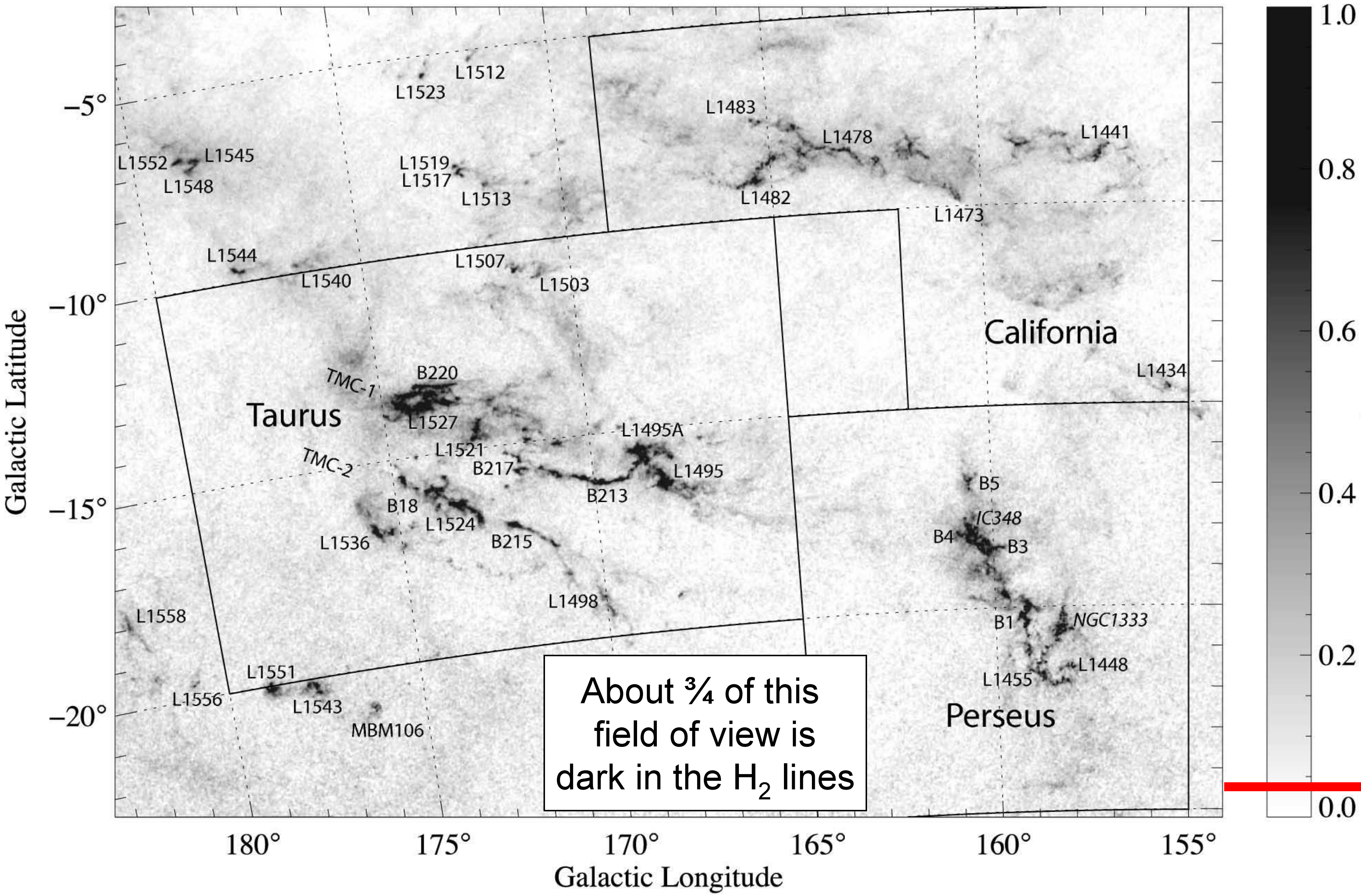
The line of sight to ζ Oph is dark in H_2 lines
E(B-V)=0.32

Spitzer & Jenkins 1975



0.1 E(B-V) = 0.3 mag in V = 0.033 mag in K

Lombardi +10



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Galactic Latitude
Galactic Longitude
−5°
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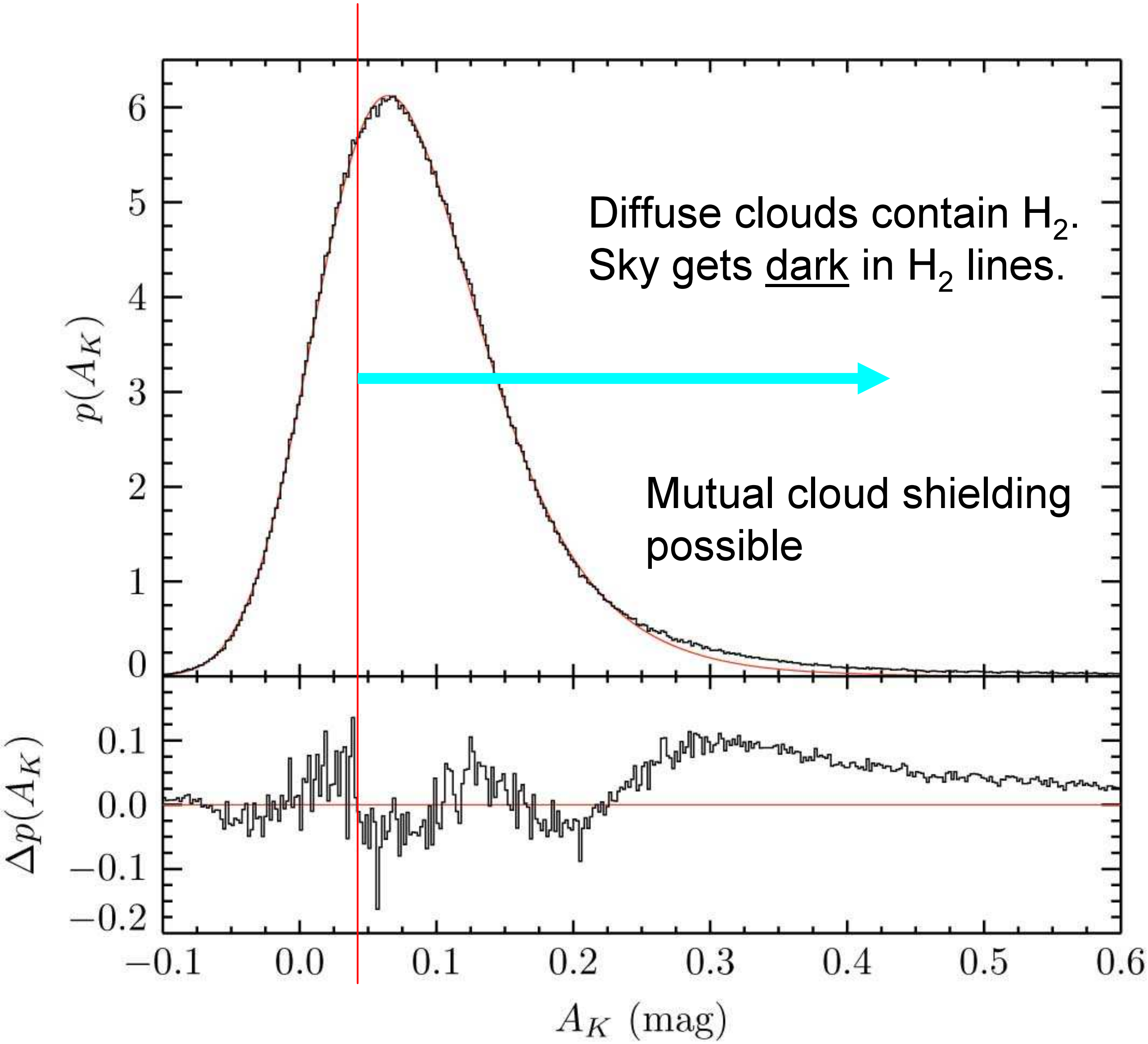
−15°
−20°
180°
175°
170°
165°
160°
155°
1.0
0.8
0.6
0.4
0.2
0.0
A_K
About ¾ of this field of view is dark in the H_2 lines



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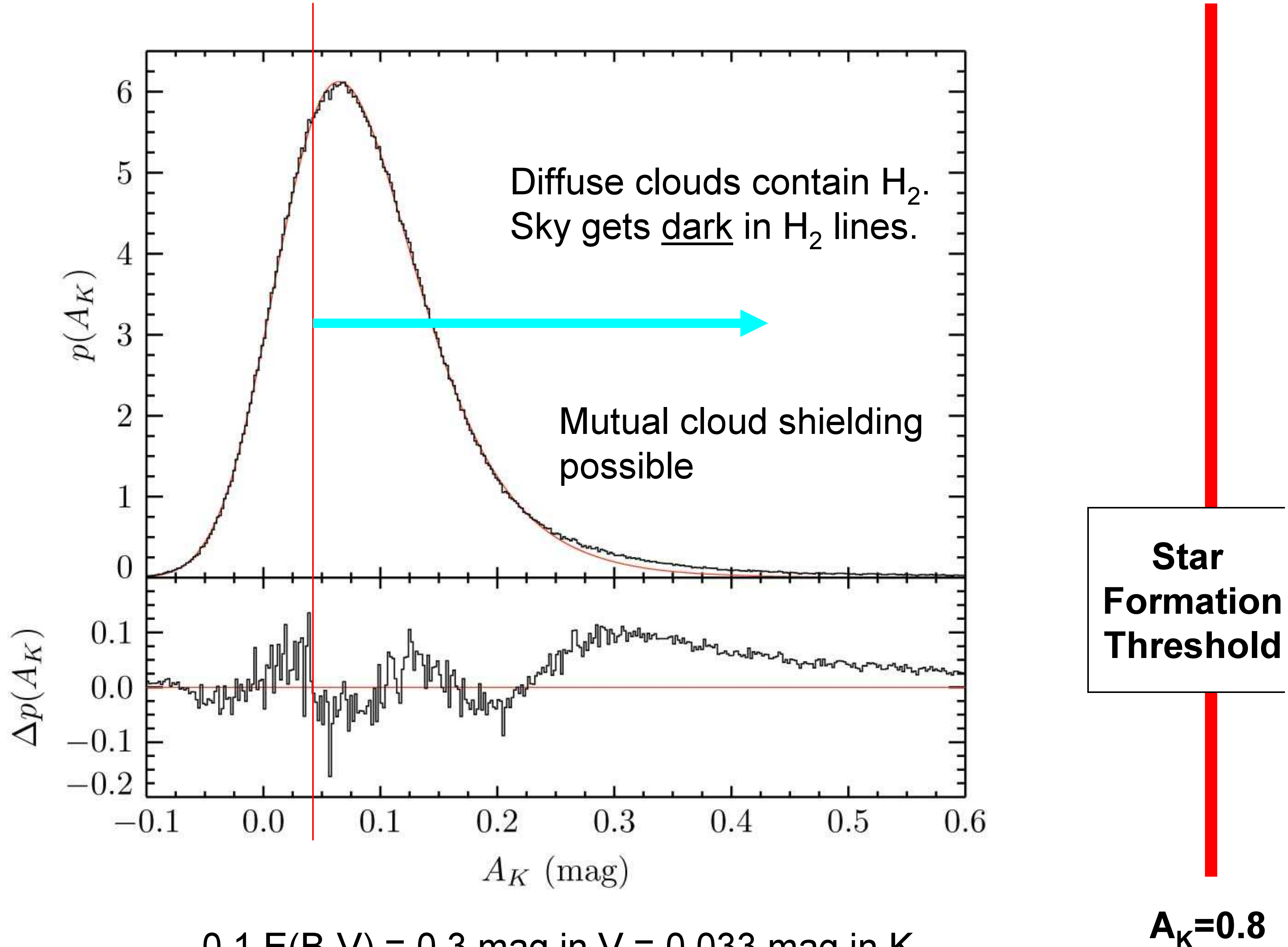
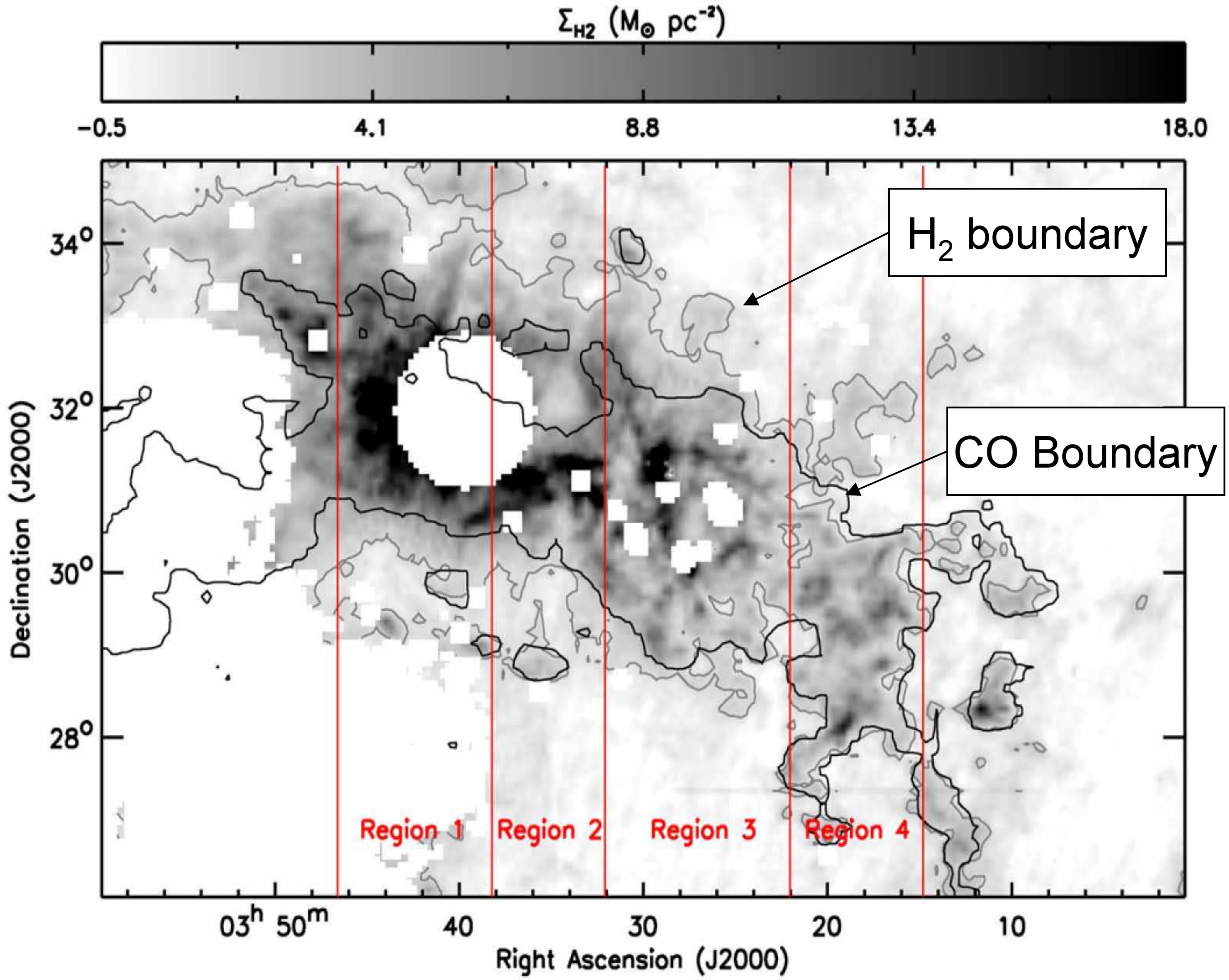


0.1 E(B-V) = 0.3 mag in V = 0.033 mag in K

Lombardi +10

Perseus: H_2 compared to CO

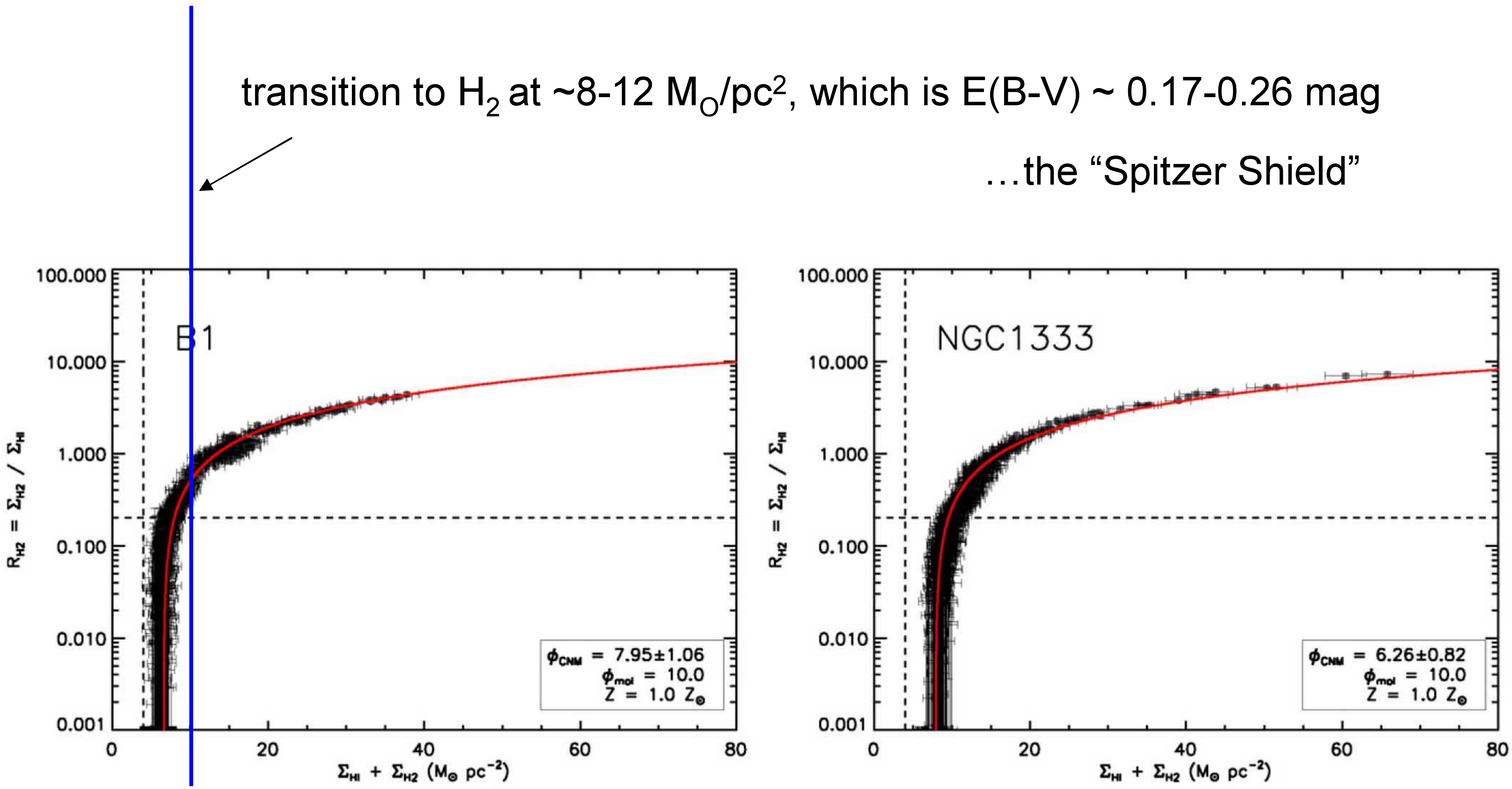


Lee +12

Matches well equilibrium models by Krumholz, McKee & Tumlinson 09
which is essentially the result of a constant shielding layer of HI for H_2 formation.

transition to H_2 at ~8-12 M_O/pc^2, which is E(B-V) ~ 0.17-0.26 mag

…the "Spitzer Shield"



Lee +12

Lee et al. 2012:

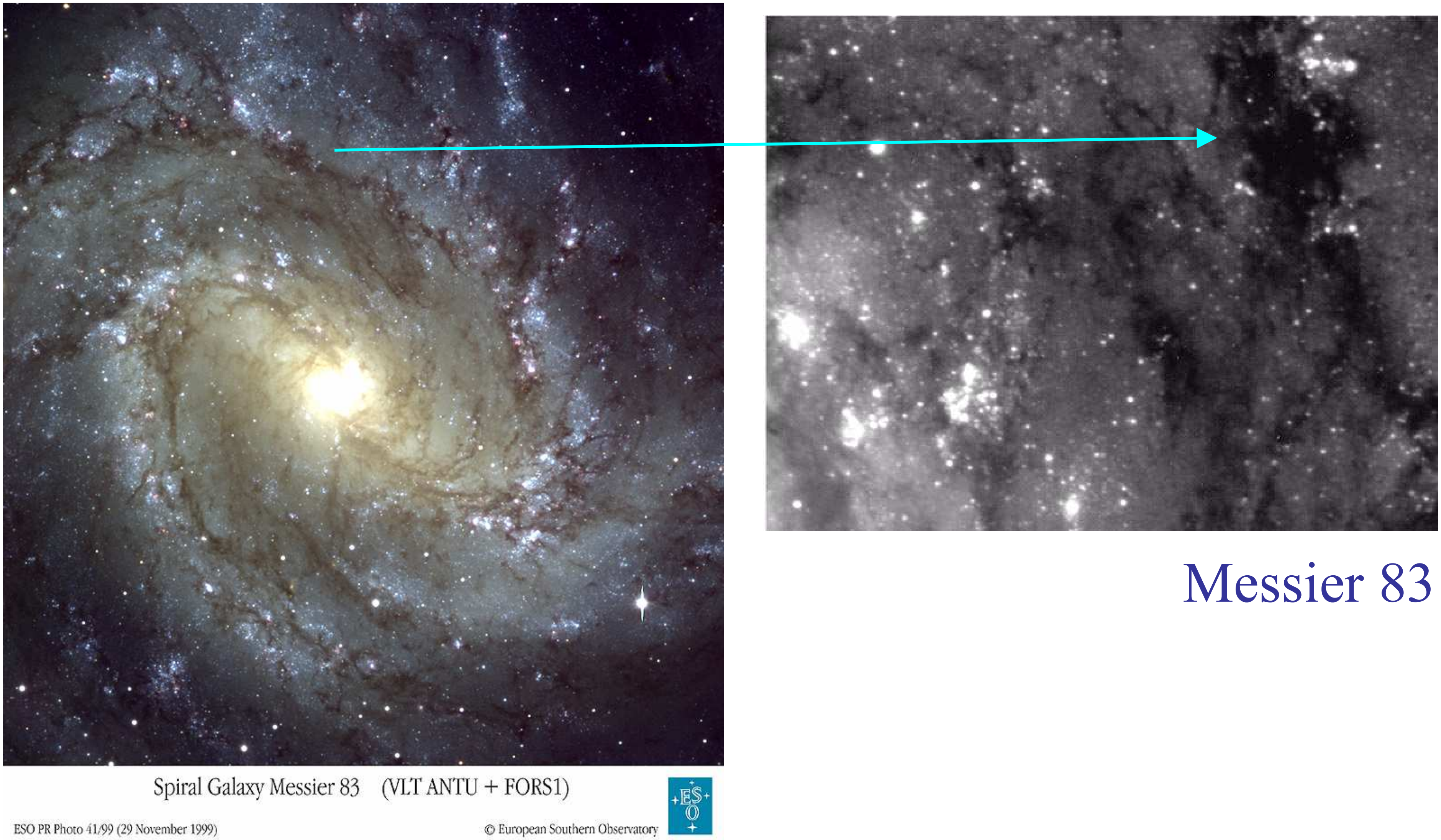
- Equilibrium models fit well: why?
  - equilibrium timescale ~20-30 Myr >> cloud lifetime
  - τ~20-30 Myr even with turbulence (which promotes H_2 formation only locally, e.g. Glover +10)
- H_2 is 40% more extended than CO
- HI/H_2 transition is broad:
  - thickness is 20%-40% of HI size

A Murky Environment for GMCs

Google

murk·y/ˈmərkē/
Adjective:
Dark and gloomy, esp. due to thick mist.
(of liquid) Dark and dirty; not clear.
Synonyms:dark - gloomy - obscure - somber - murk - sombre - dim

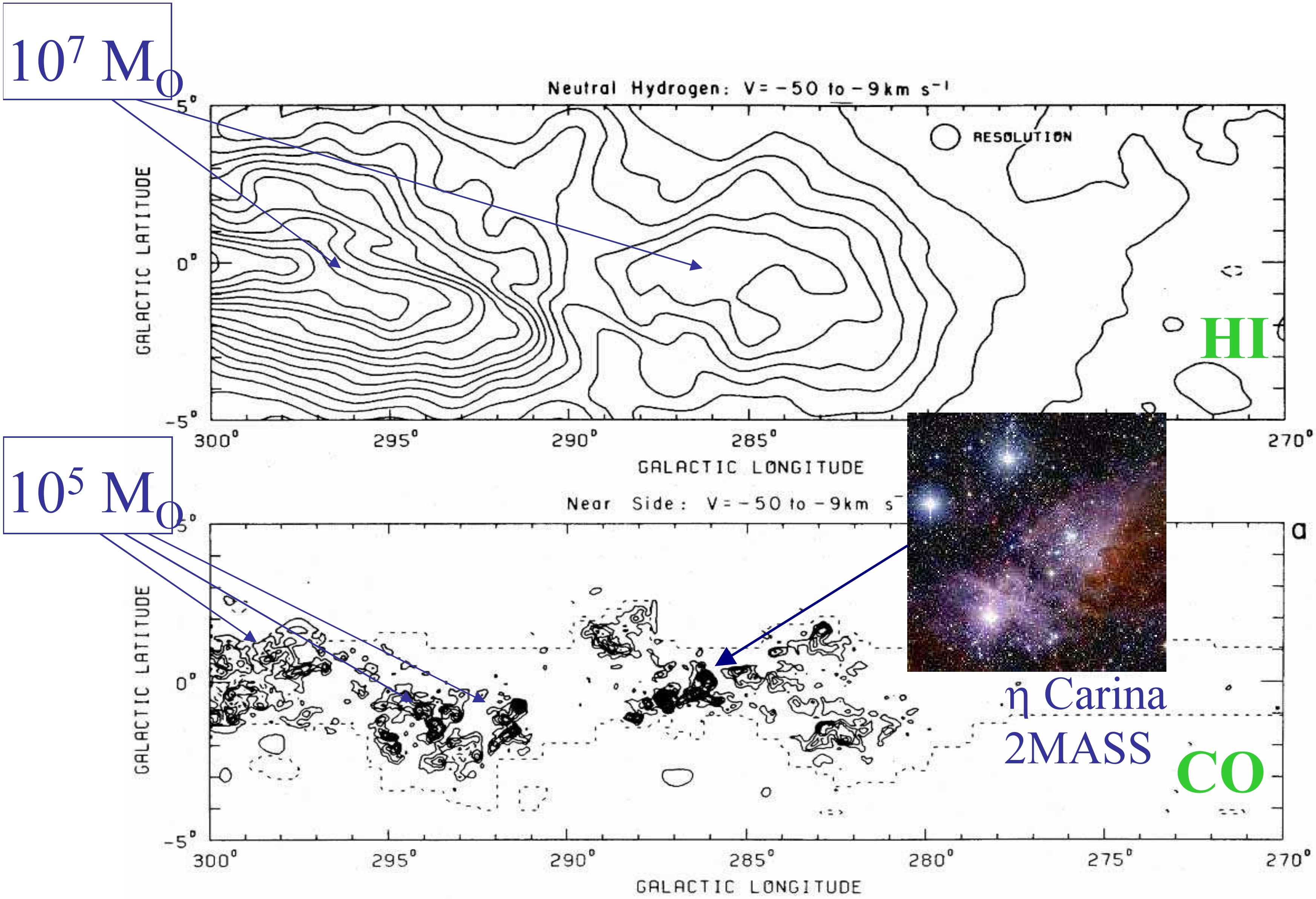
- → H_2 in diffuse gas darkens photodissociative radiation in a large neighborhood of a GMC…"murky Boundary Condition."
- → turbulence dissipation and self-gravity within this murky H_2 neighborhood make the star-forming cloud (CO-rich)
- → H_2 is pre-made in the extended diffuse medium: t_{cross} can be large (30 Myr is t_{cross} on 200 pc scale: ISM Jeans length connecting ambient gas gravity to ISM turbulence)



Messier 83

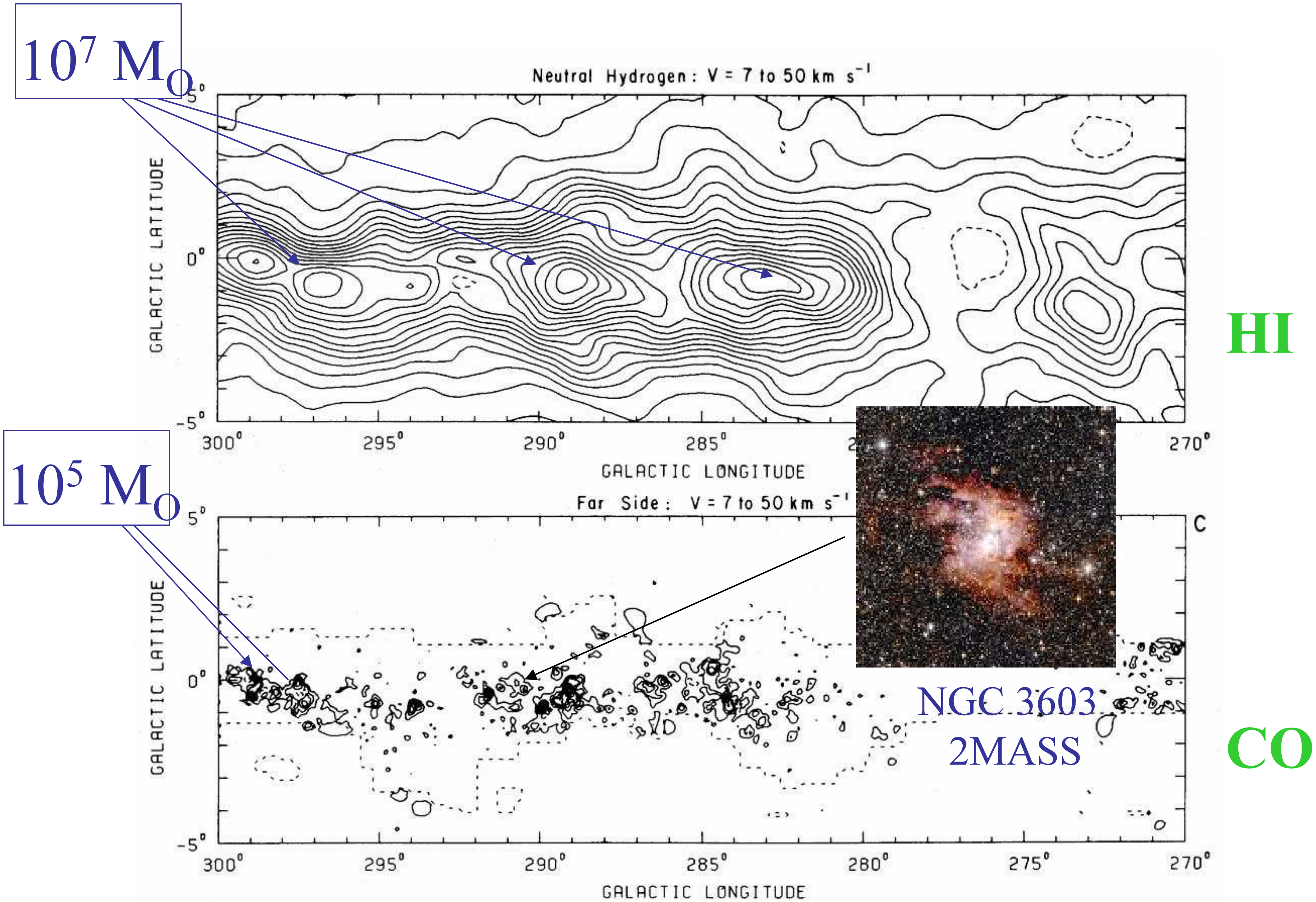
VLT at ESO

Star-forming regions are large and their neighborhoods are dark to ~1000Å radiation



Atomic (+H_2 ?) clouds with GMC cores line up on the Sagittarius-Carina arm of the Milky Way

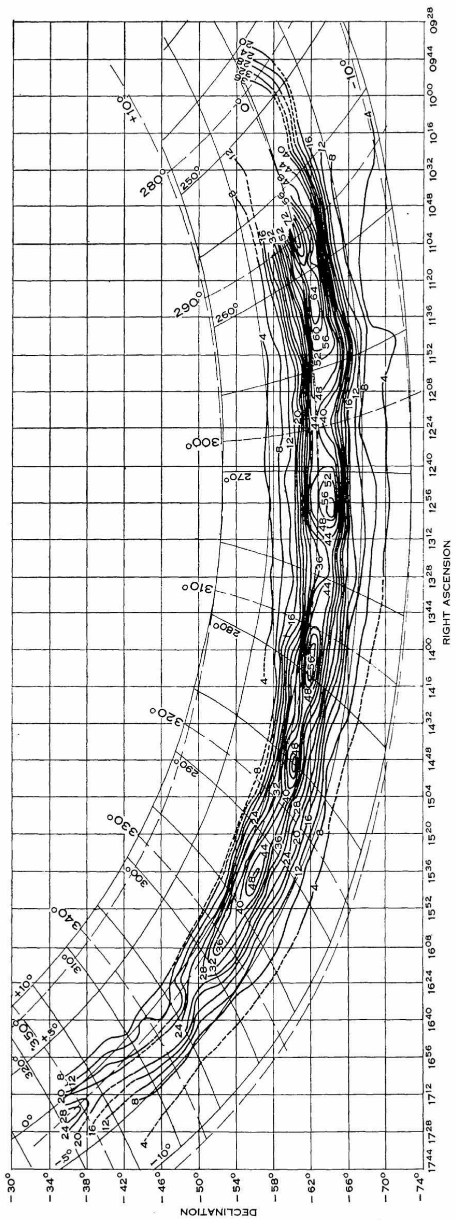
Grabelsky et al. 1987



Star formation in the Milky Way begins by forming 10^7 M_O HI+H_2 clouds (… Motte)

Grabelsky et al. 1987

McGee & Milton 1964



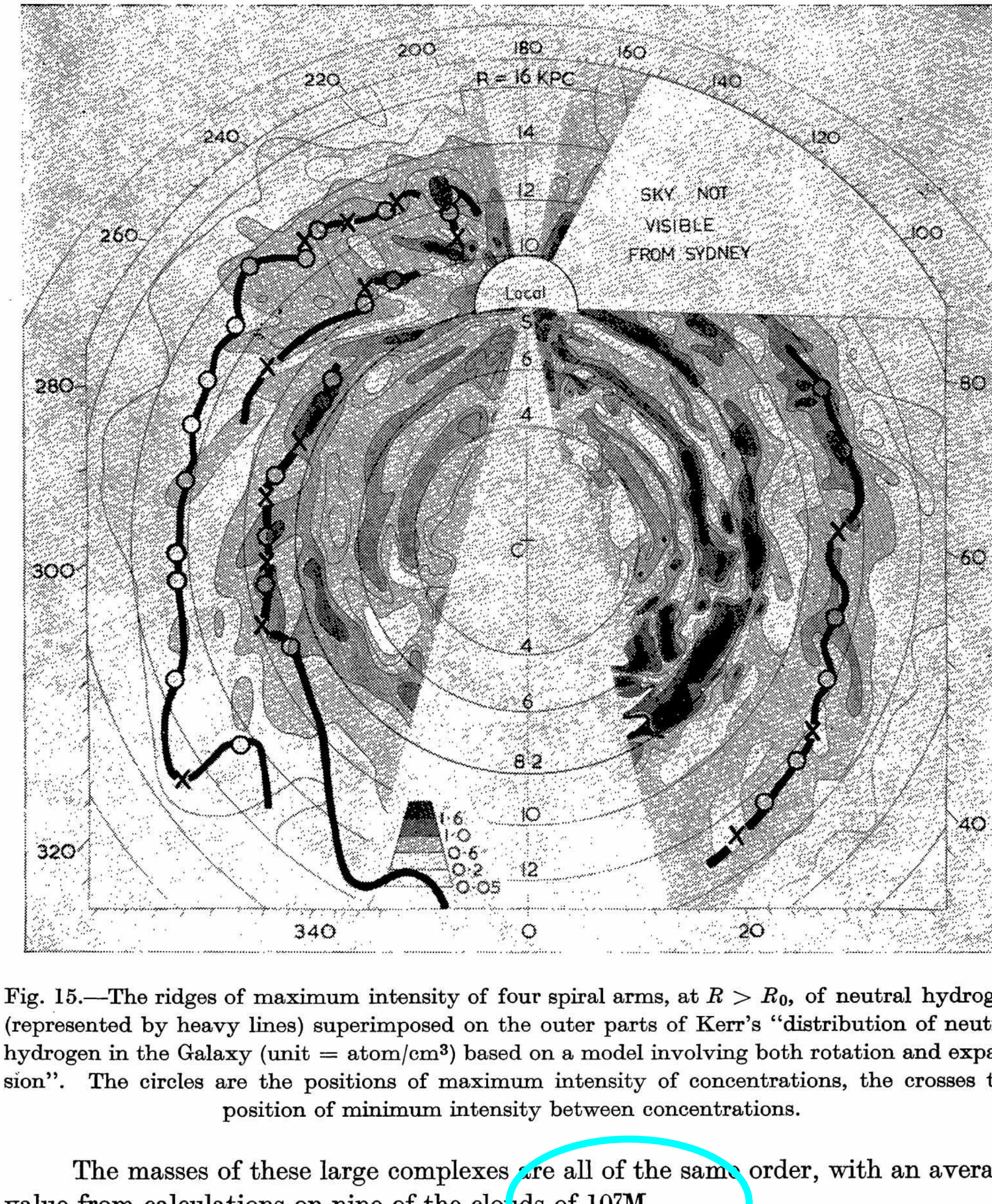
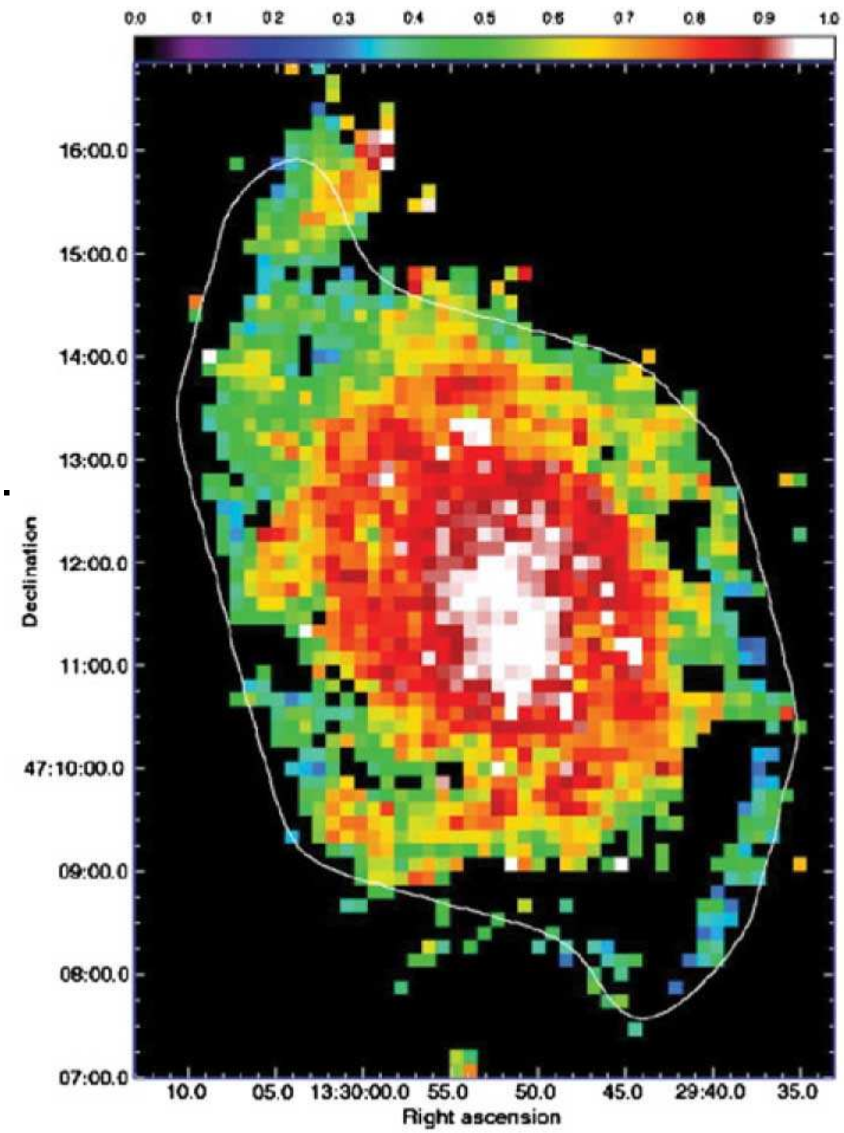


Fig. 15.—The ridges of maximum intensity of four spiral arms, at $R > R_0$, of neutral hydrogen (represented by heavy lines) superimposed on the outer parts of Kerr's "distribution of neutral hydrogen in the Galaxy (unit = atom/cm^3) based on a model involving both rotation and expansion". The circles are the positions of maximum intensity of concentrations, the crosses the position of minimum intensity between concentrations.

The masses of these large complexes are all of the same order, with an average value from calculations on nine of the clouds of $10^7 M_\odot$.

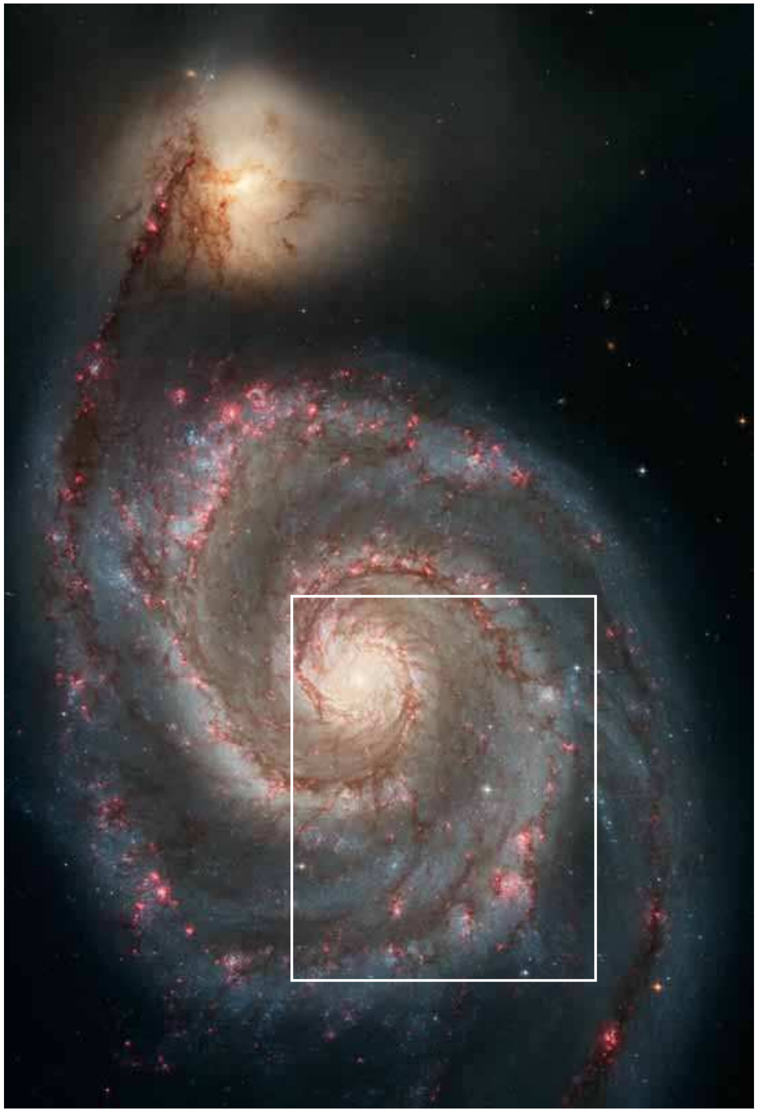
M51 has a high H_2 fraction so GMC formation is

GMC coagulation followed by GMC breakup without intermediate HI phase.



Koda +09

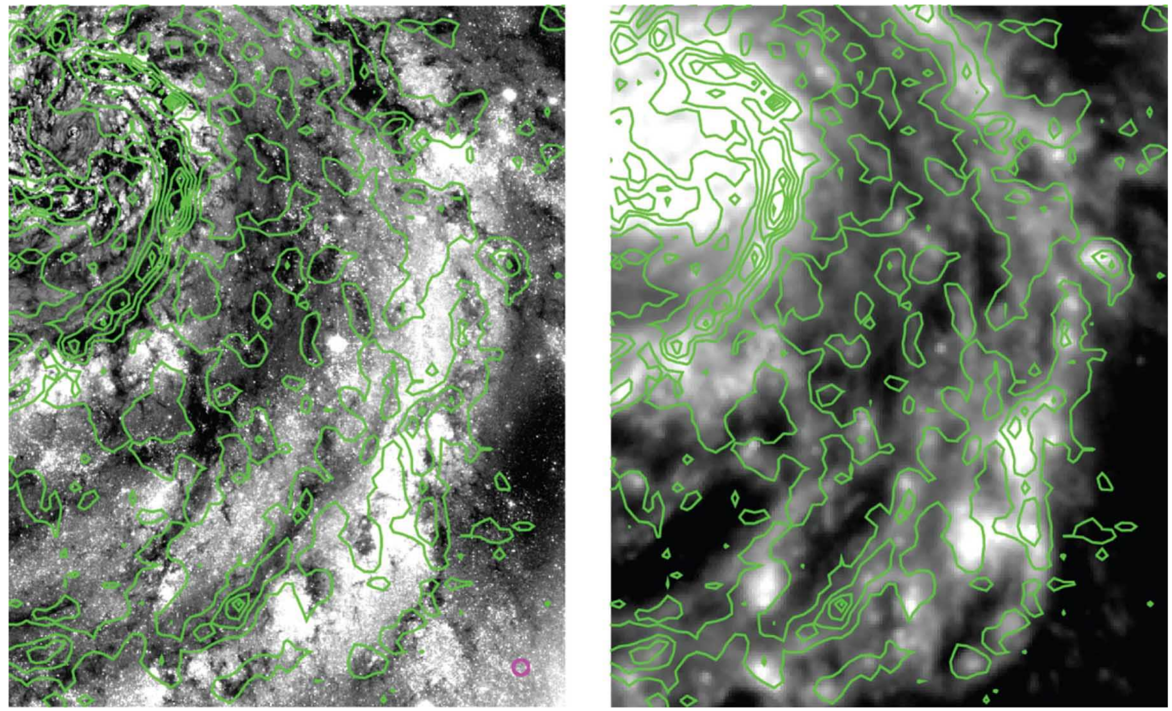
H_2 fraction of the gas



Koda +12

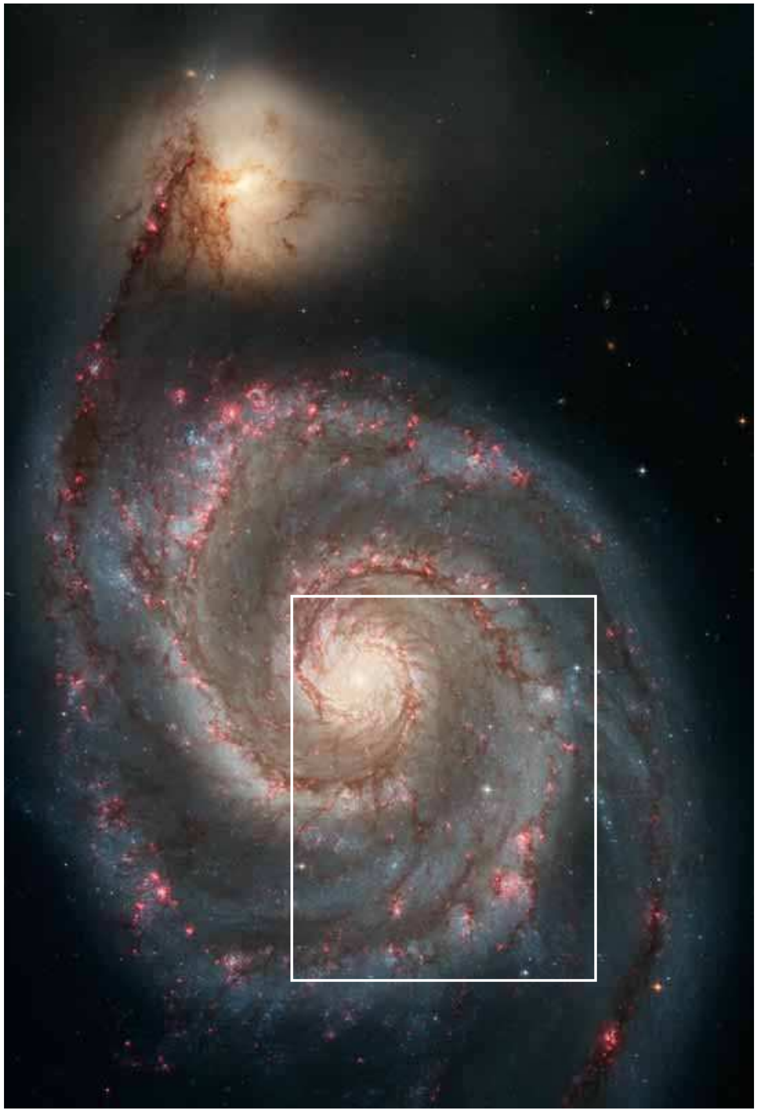
CO on HST B band

CO on Spitzer 8mu

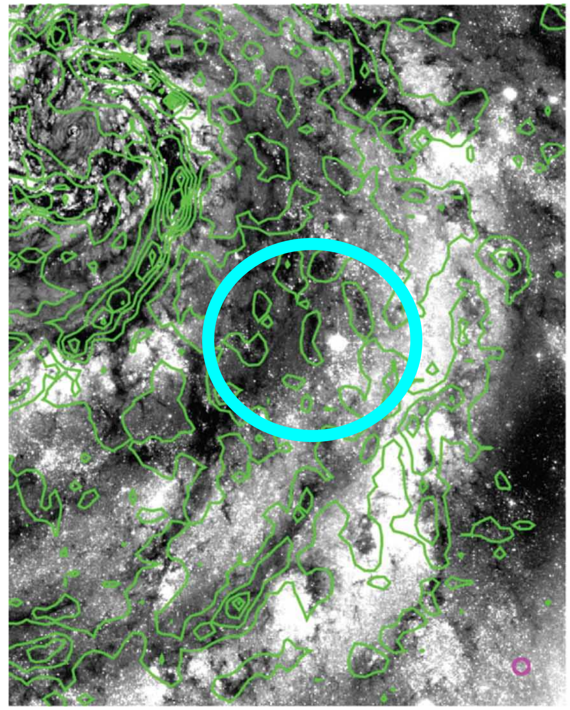


Dust clouds in M51 are molecular.

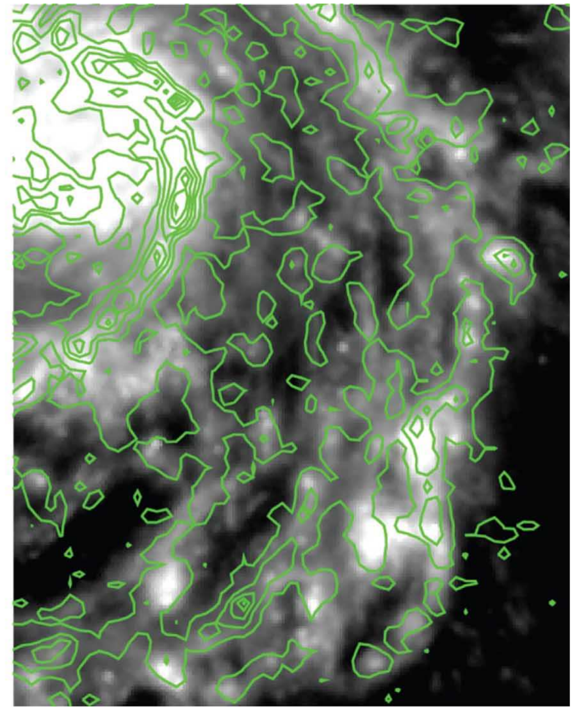
Interarm GMCs seem long-lived.



Koda +12
CO on HST B band

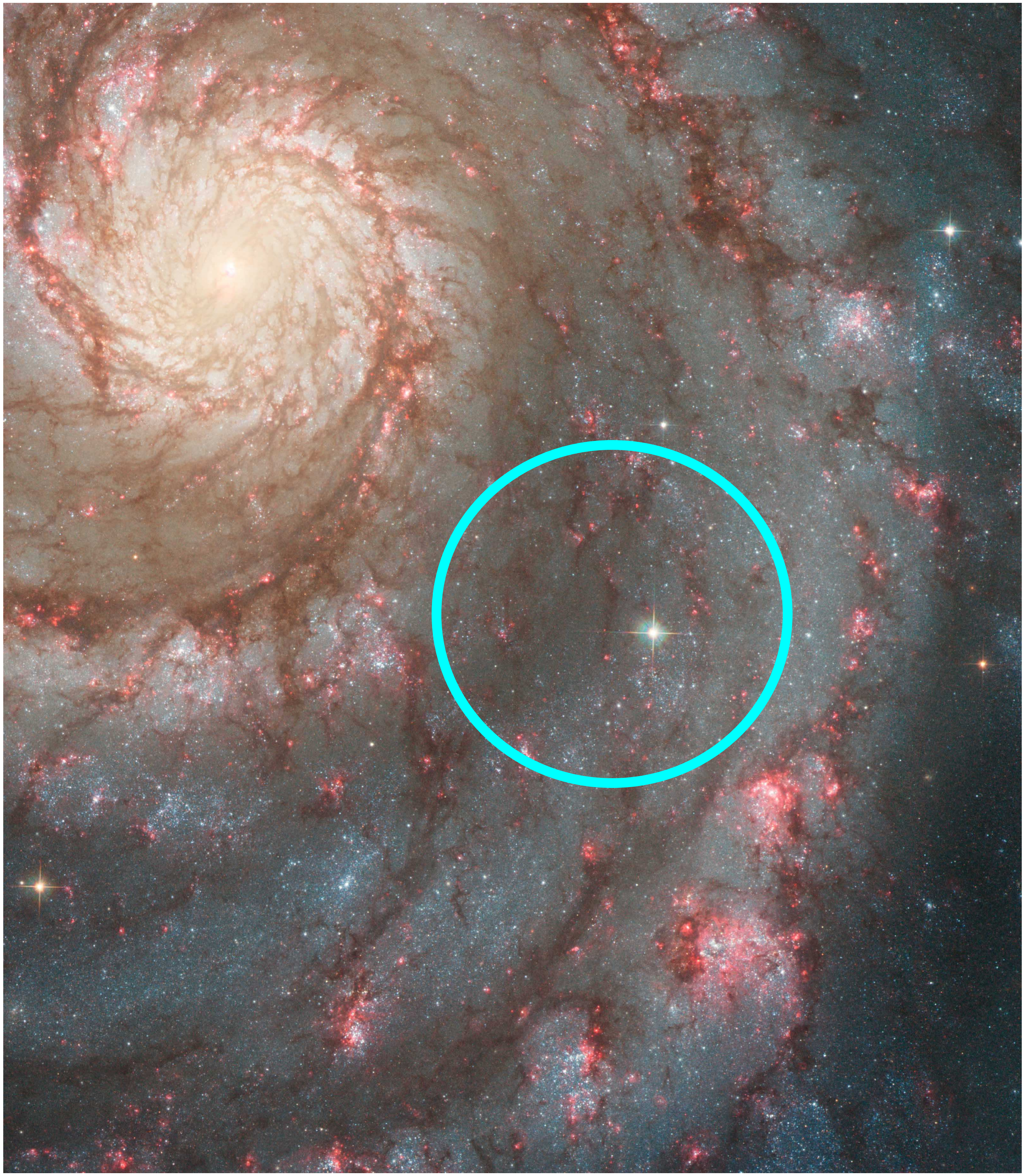


CO on Spitzer 8mu



Most dust clouds in M51 are molecular.

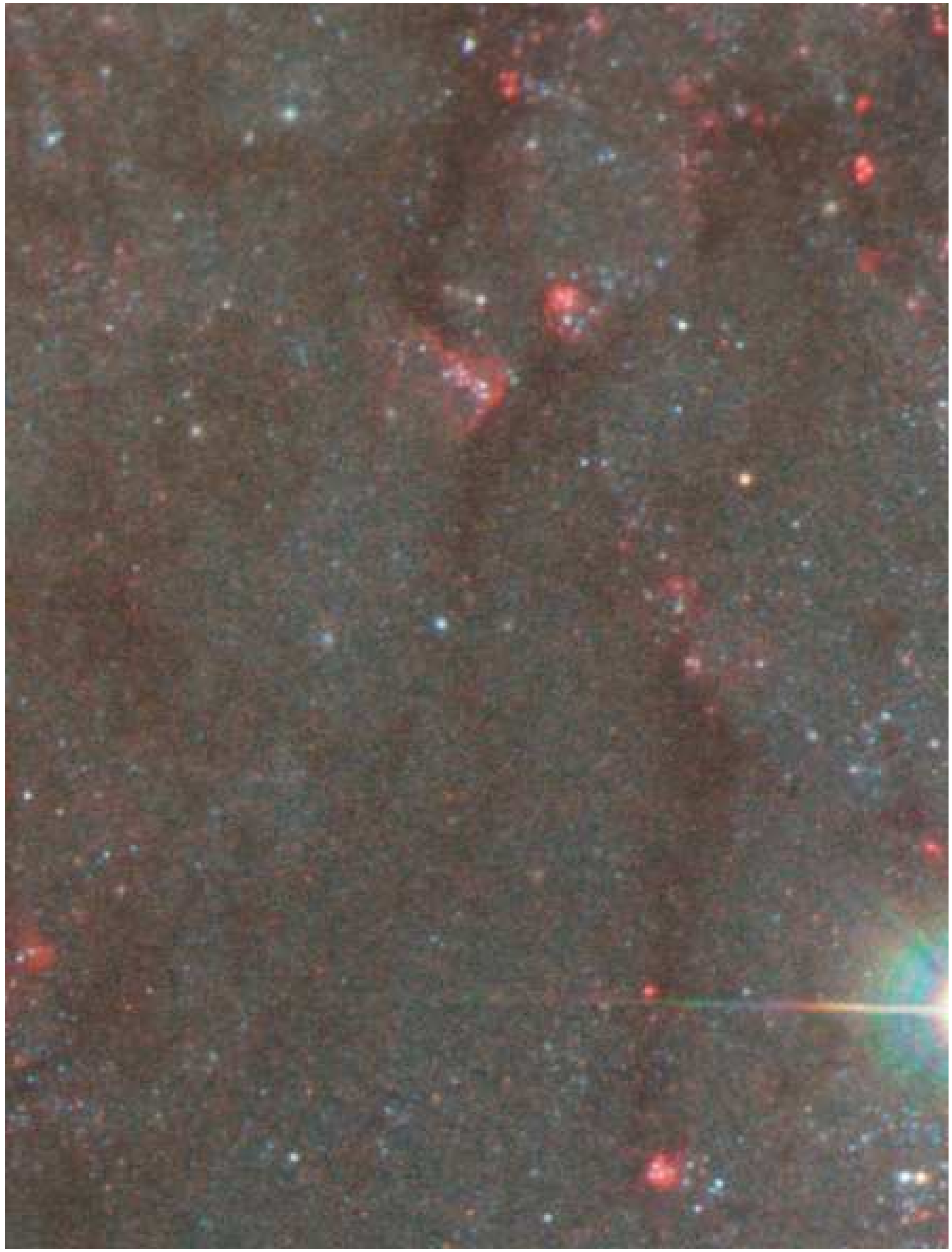
Interarm GMCs seem long-lived. Could turbulence be forming them there? if not they are <u>weakly self-gravitating,</u> maybe B-supported

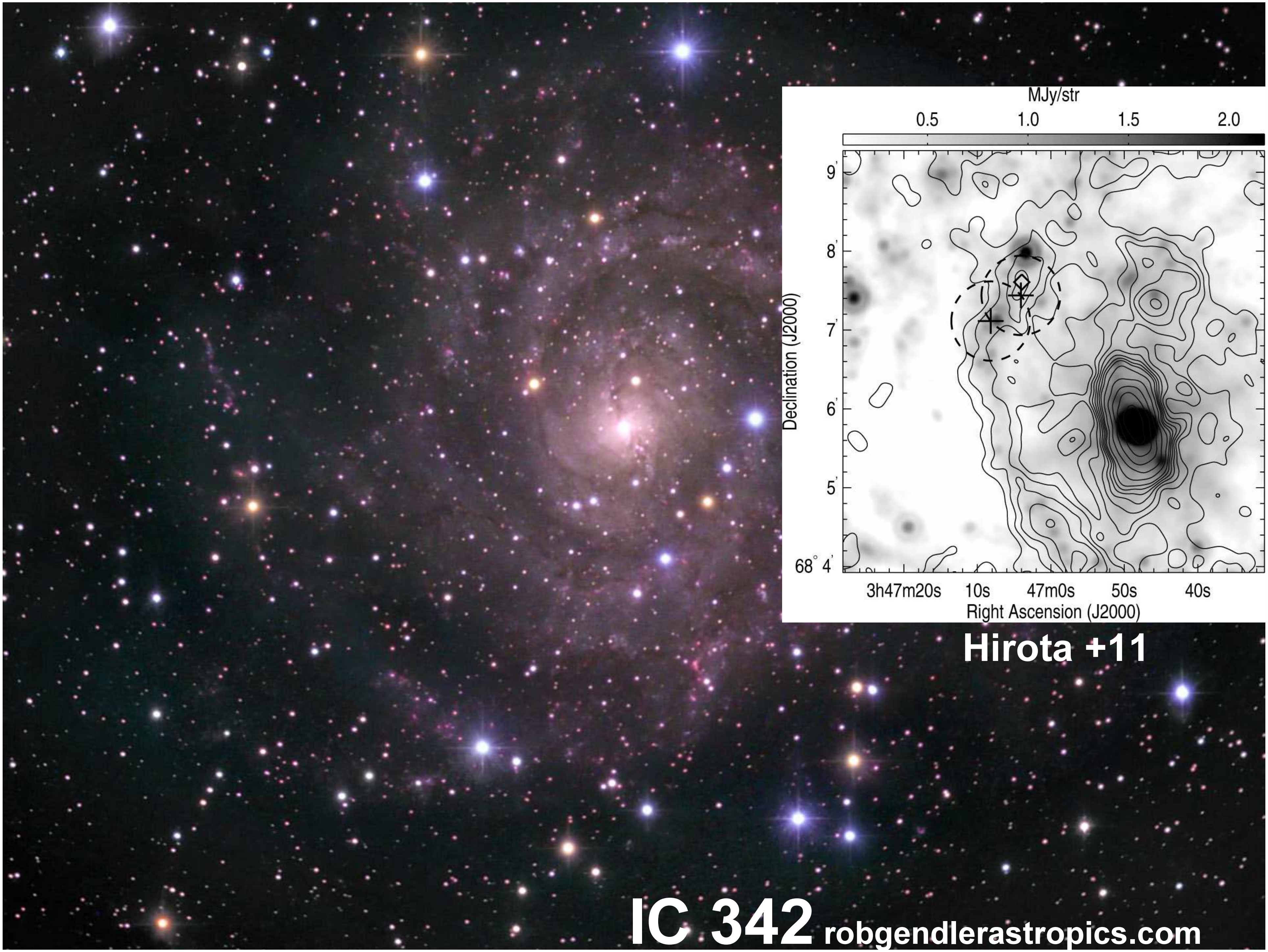


Long-lived clouds?

Diffuse CO?

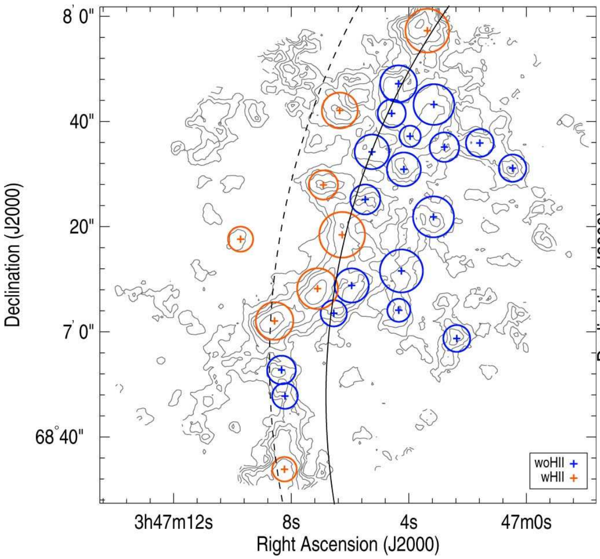
(high α)

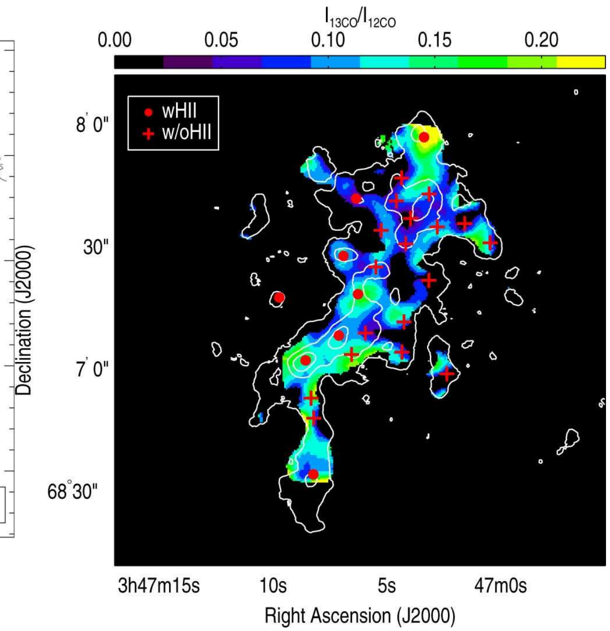



MJy/str
0.5
1.0
1.5
2.0
Declination (J2000)
9'
8'
7'
6'
5'
68° 4'
3h47m20s
10s
47m0s
50s
40s
Right Ascension (J2000)
Hirota +11
IC 342
robgendlerastropics.com

Hirota +11

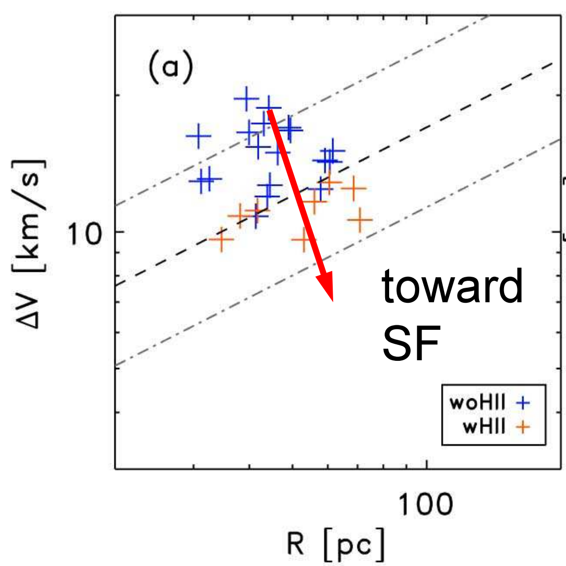
A GMC's linewidth decreases and its self-gravity strengthens as it passes through the arm.

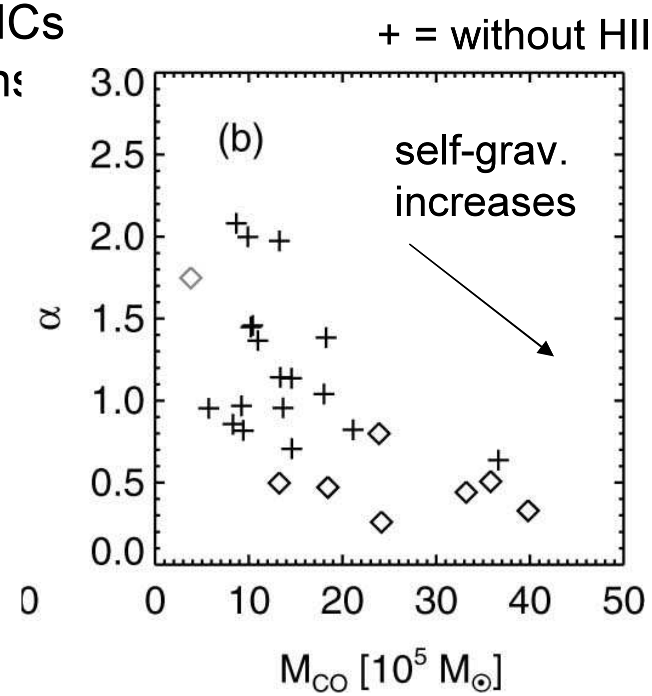




red = with HII,
blue = without HII

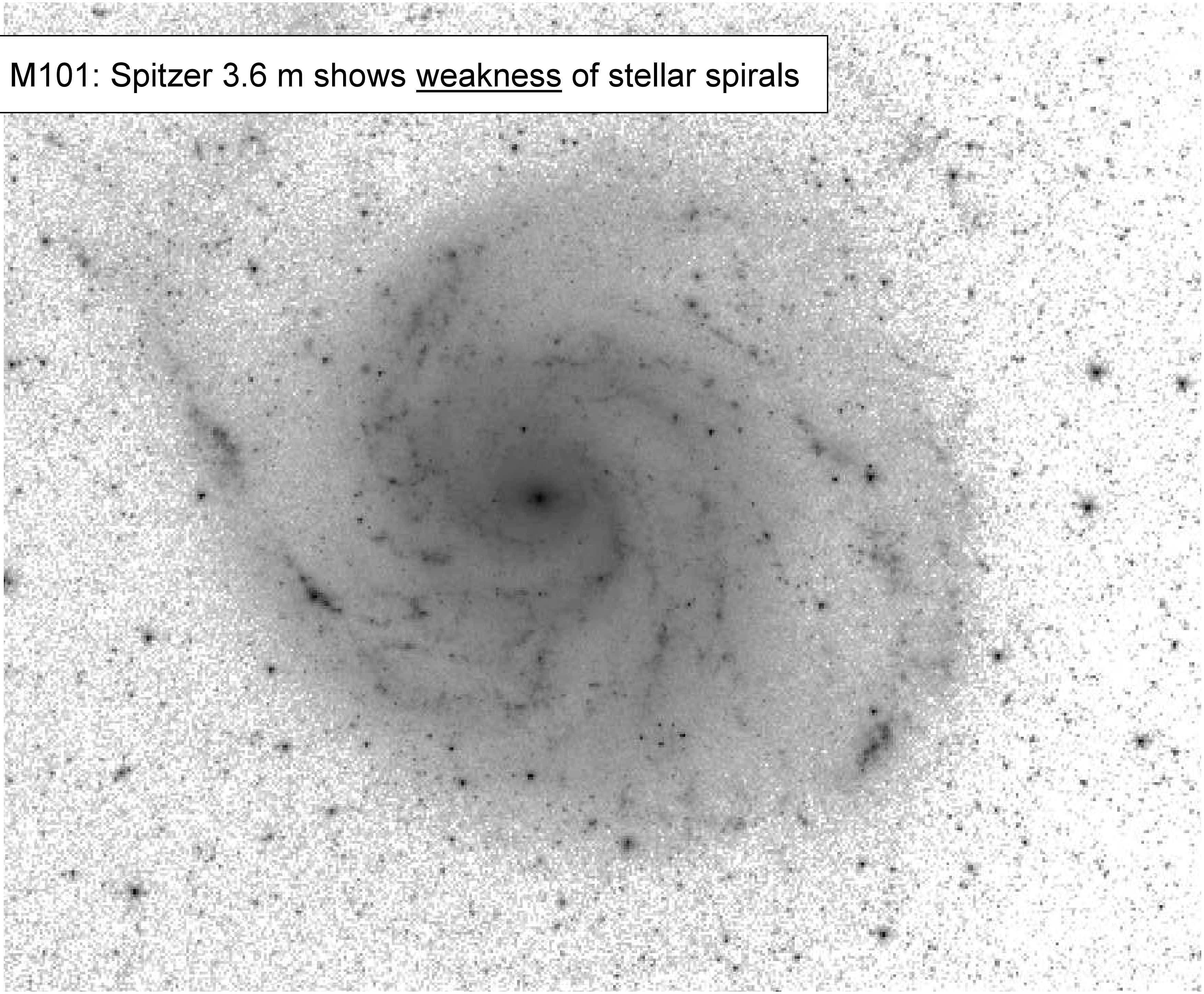
^{13}CO / ^{12}CO indicates diffuse CO in GMCs without HII regions



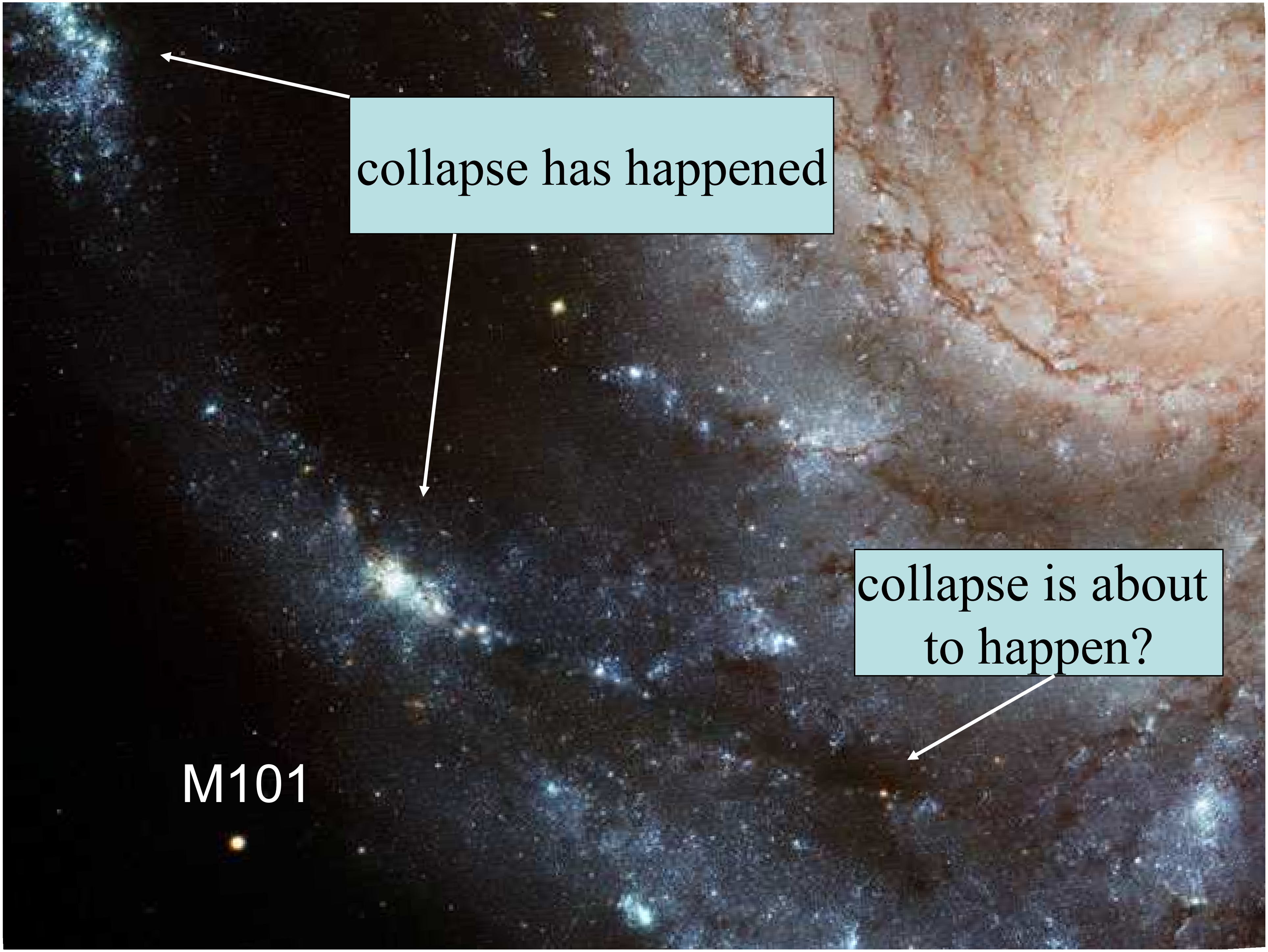


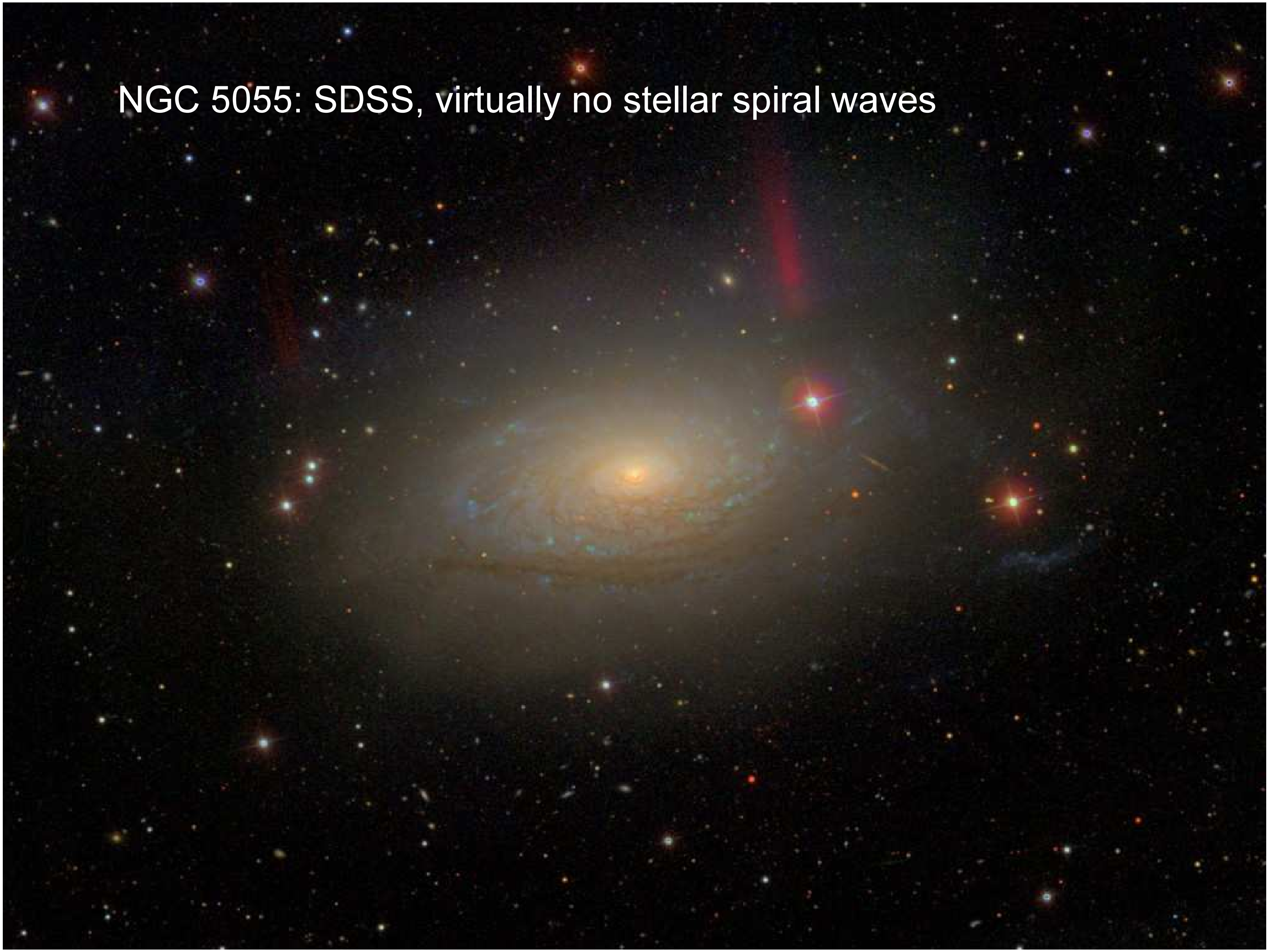
M101: a weaker global stellar spiral than in M51: more random star+gas collapse

M101: Spitzer 3.6 m shows weakness of stellar spirals

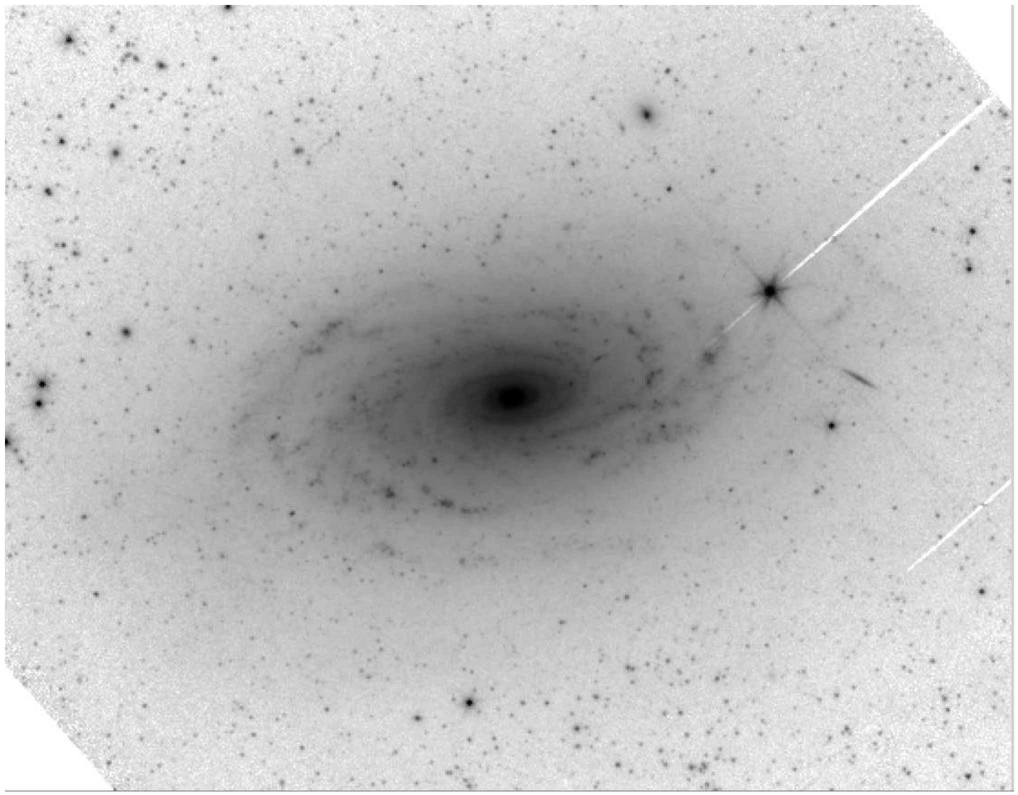


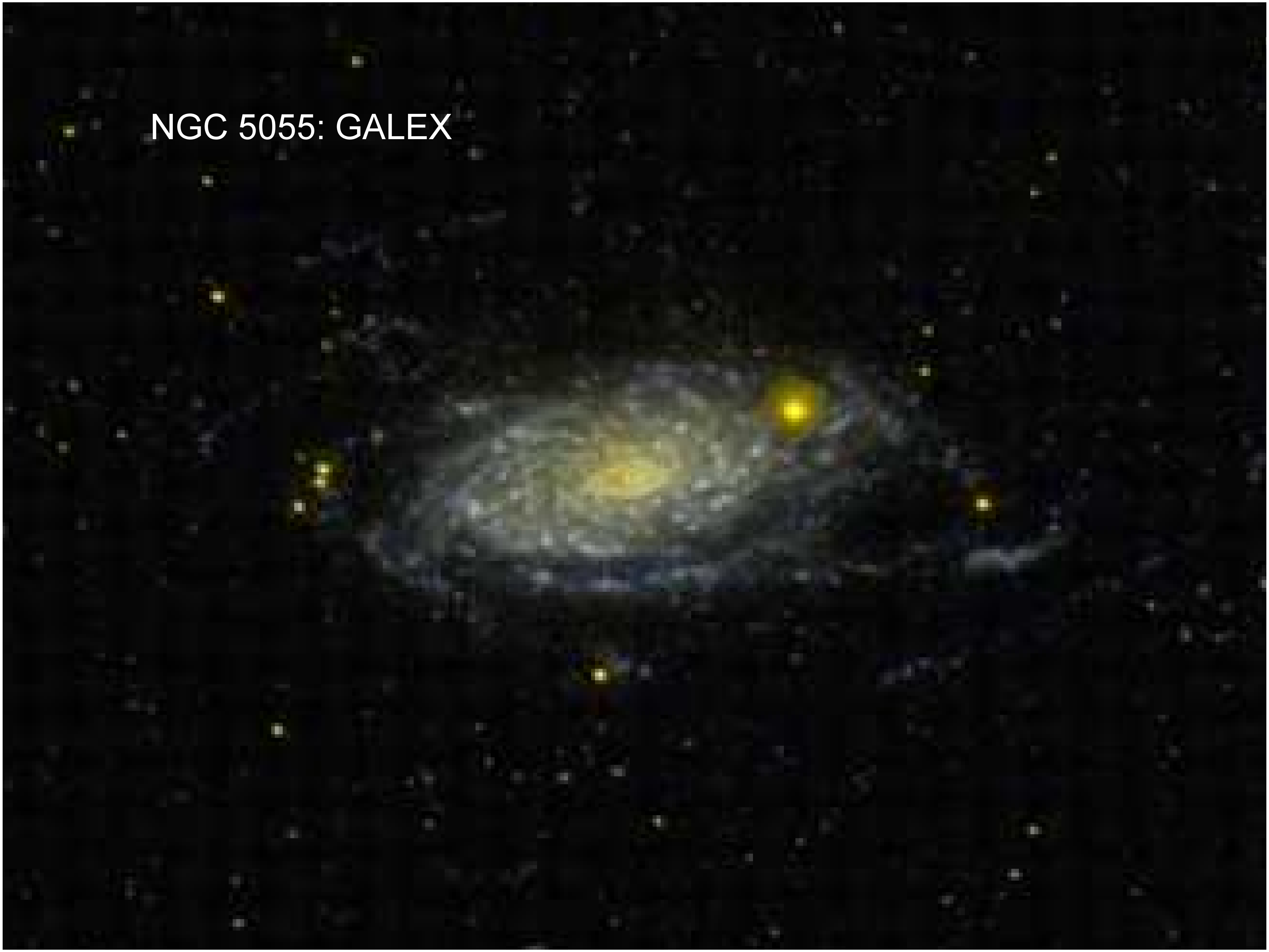

M101: GALEX
Beads on a string everywhere
Thicker arms have larger bead separations (and larger beads)

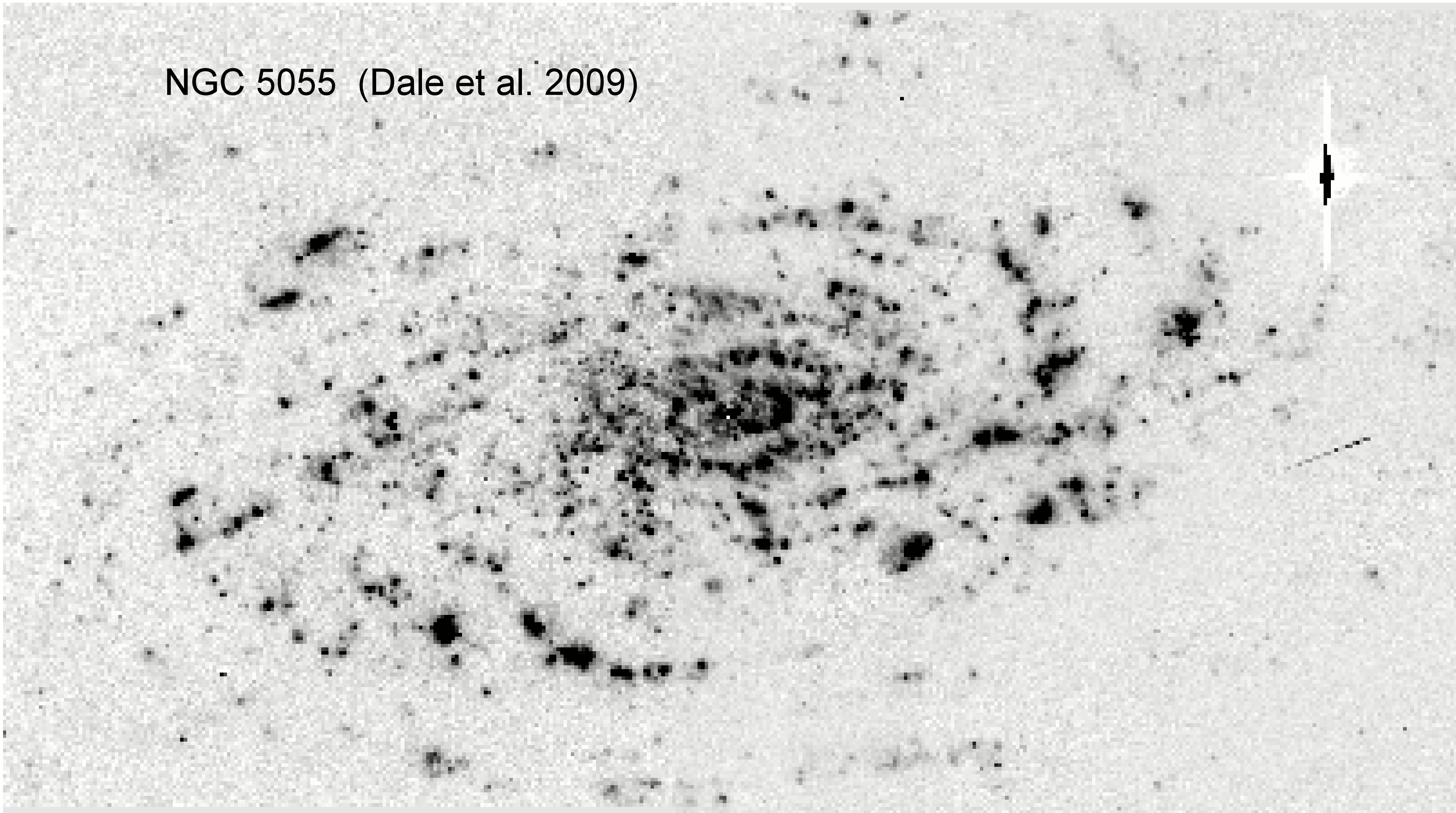

collapse has happened
collapse is about to happen?
M101


NGC 5055: SDSS, virtually no stellar spiral waves

NGC 5055: Spitzer 3.6μ




NGC 5055: GALEX

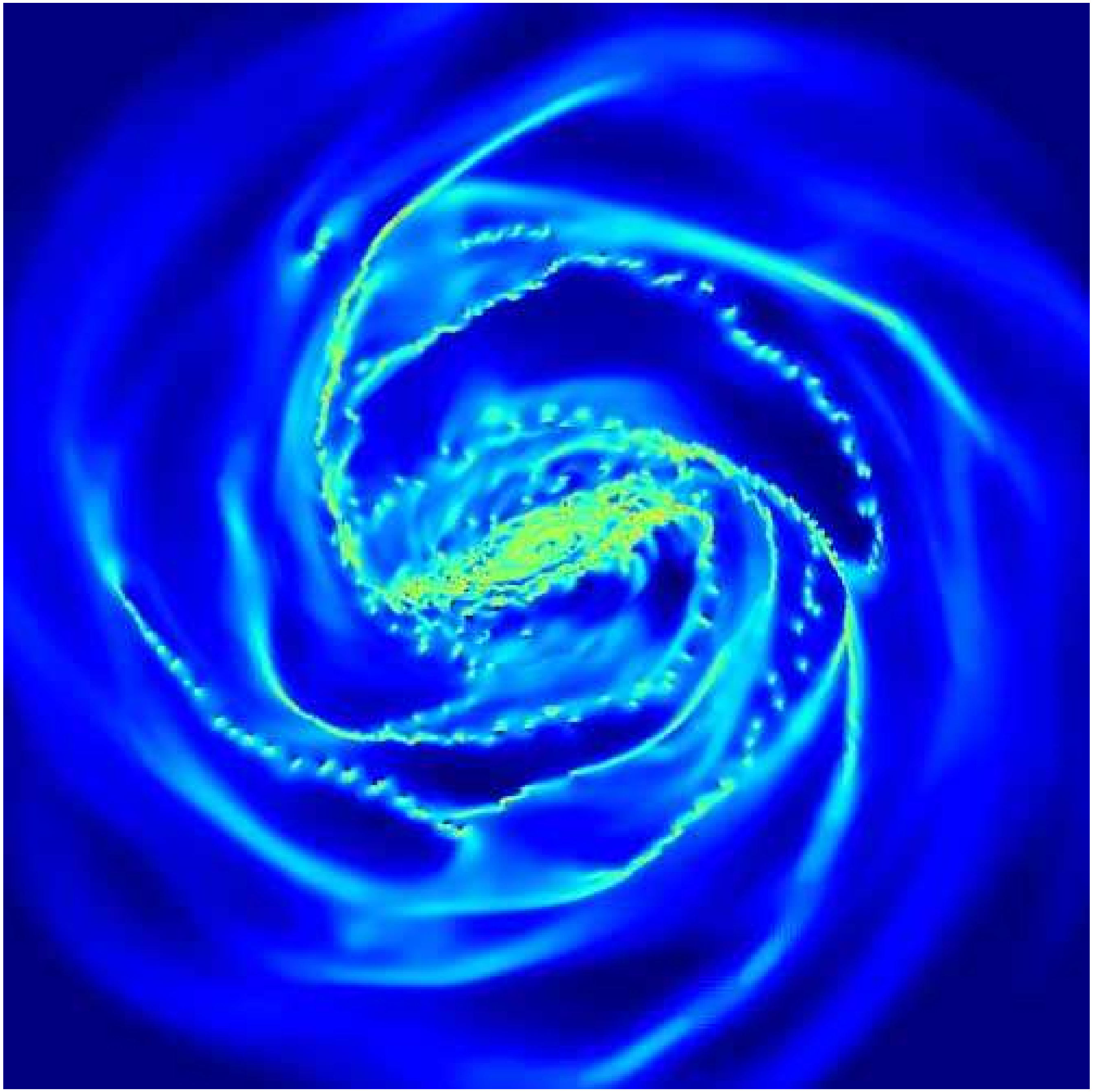


Still <u>beads-on-a-string of star formation</u>
Material arms form by gravitational instabilities in the gas and then shear away.
Two stage instability: (1) collapse of ambient gas to filament
(2) collapse of filament into stars

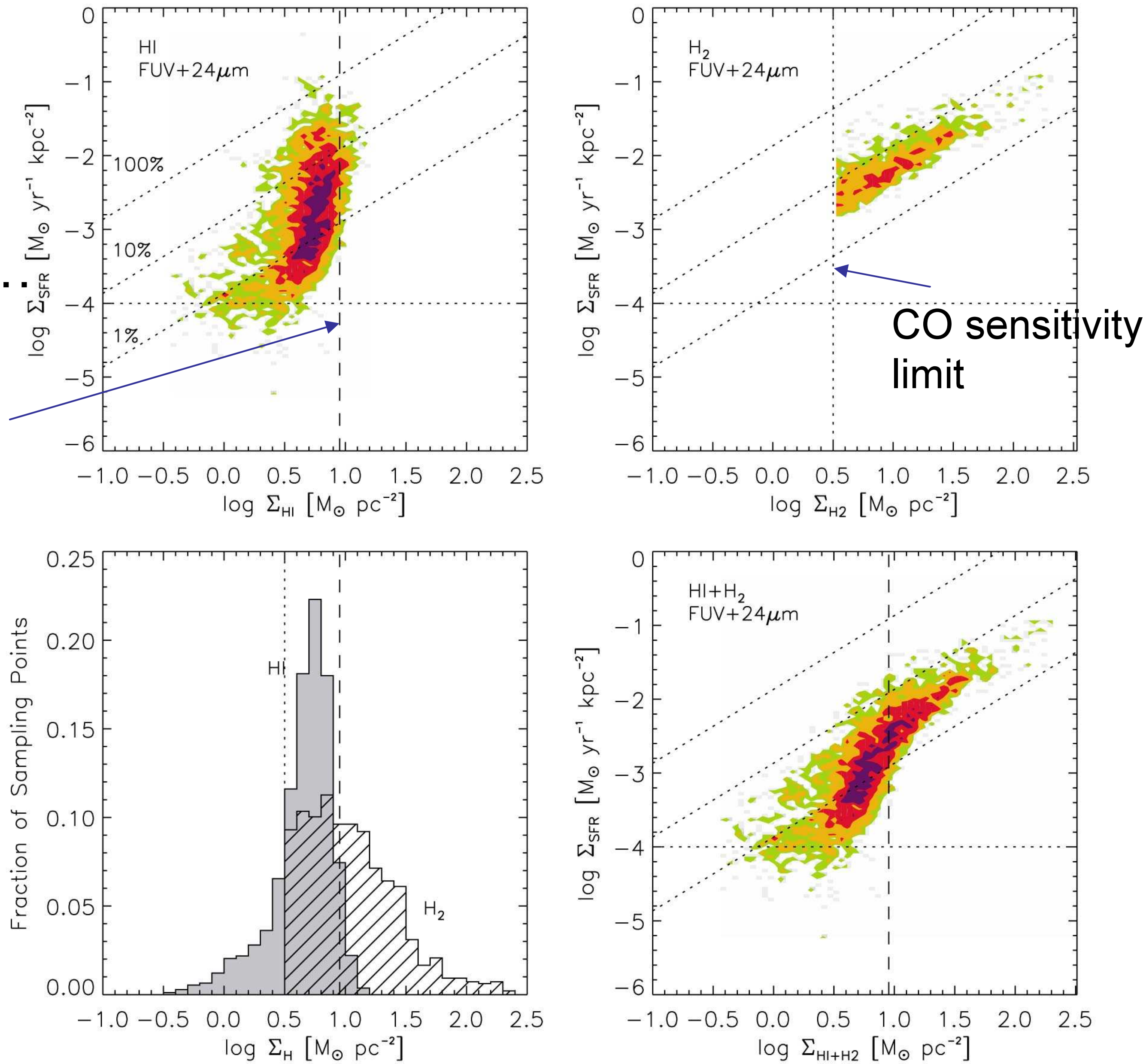
Milky Way Simulation with high resolution

Renaud, Bournaud, et al. 2012

Beads on a String



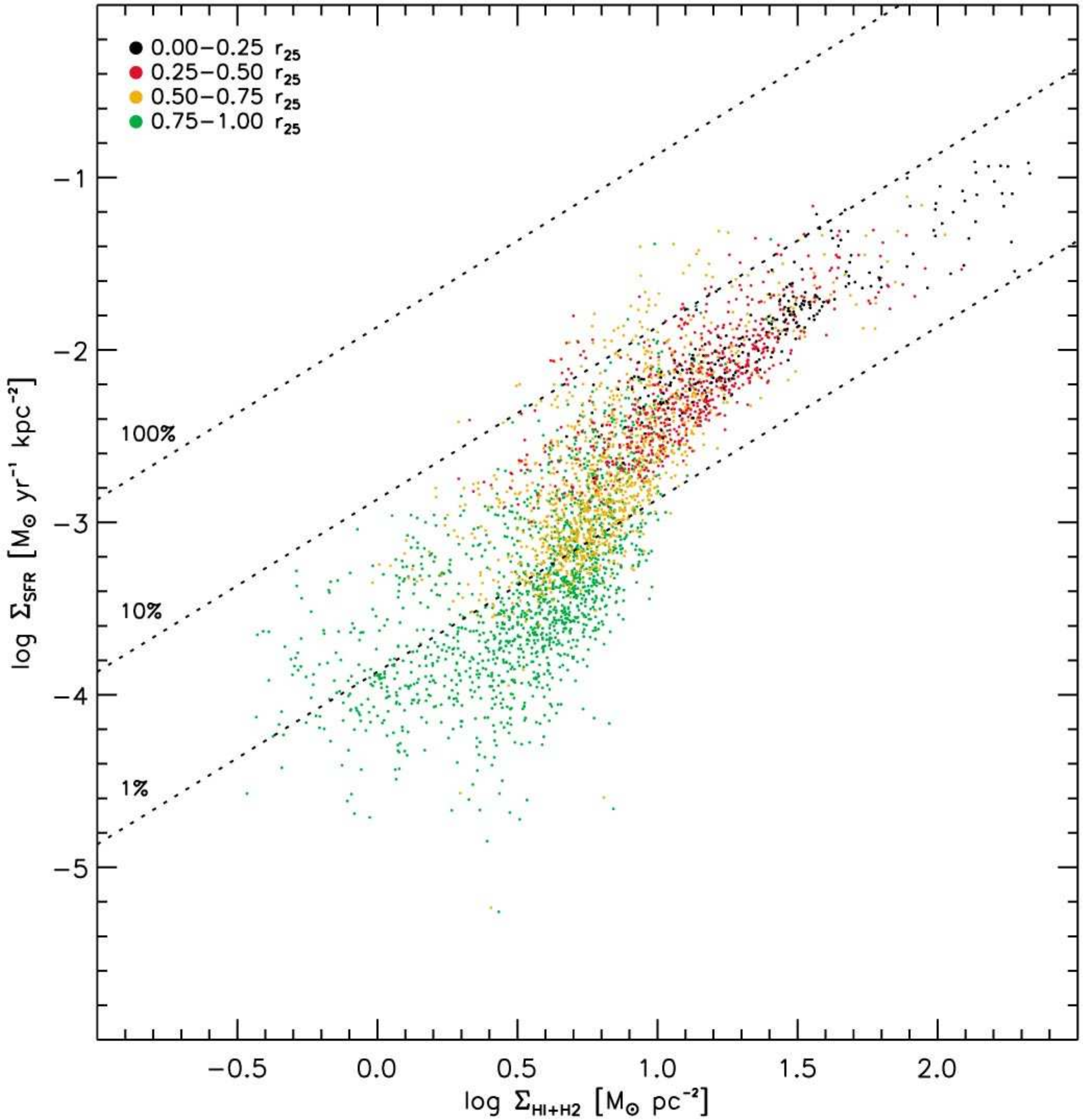
In global laws, the H_2 shielding layer appears on galactic scales…



The "Spitzer Shield" (HI saturation limit)

7 spirals superposed.

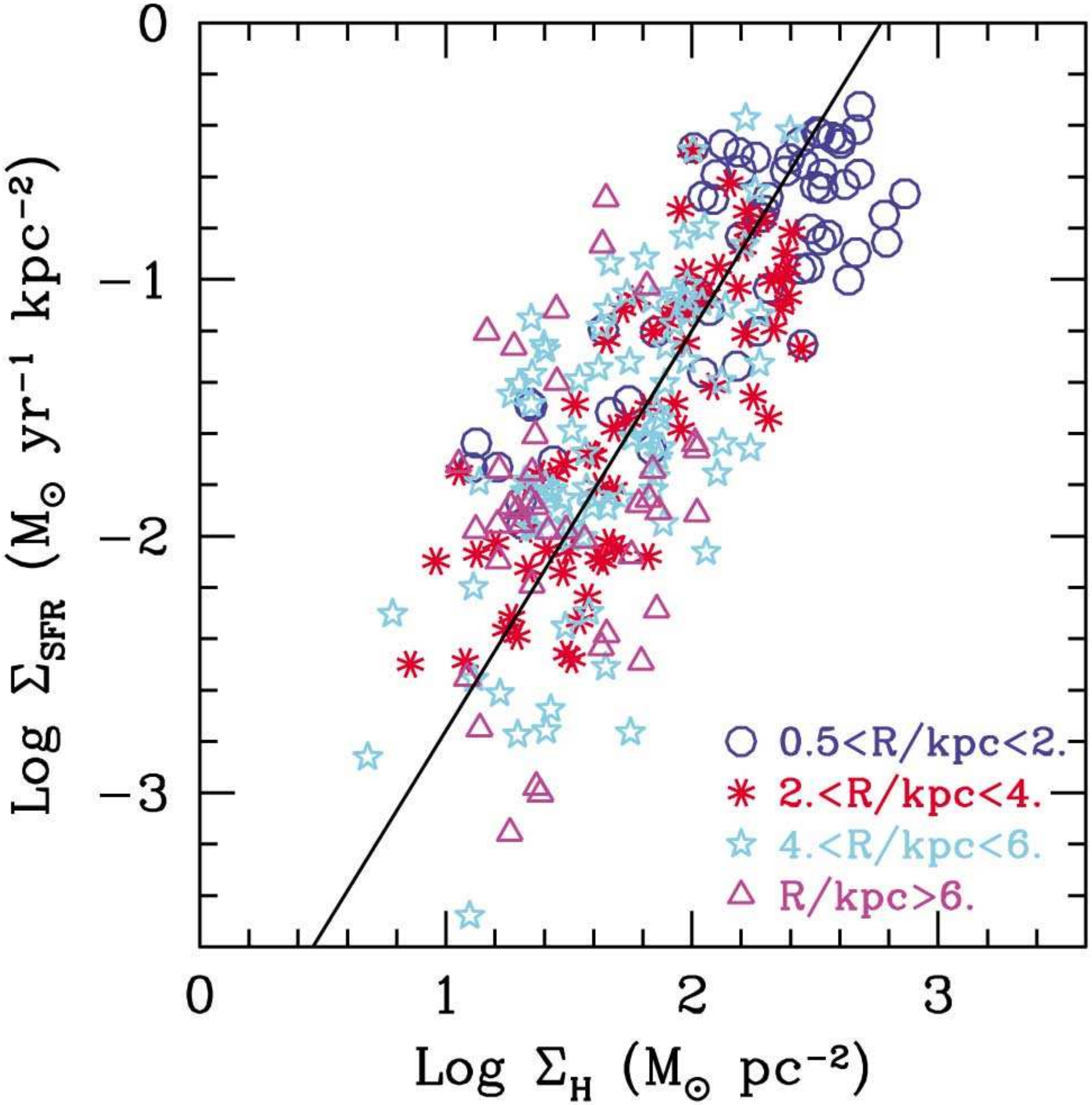
Bigiel +08



Bigiel +08

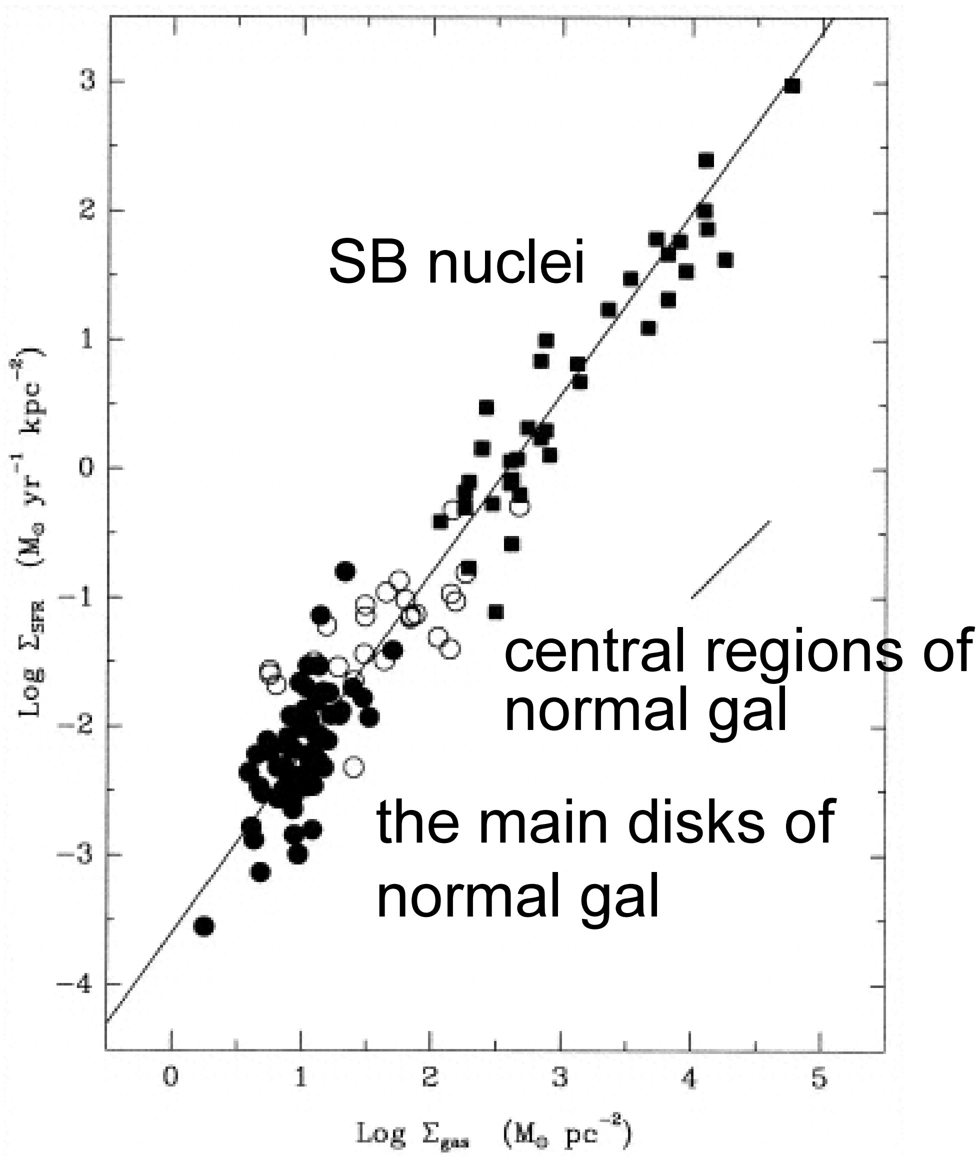
The other SFR correlation: variation with radius

Radial variation in M51



Kennicutt +07

The Kennicutt 1998 relation: one big radial variation



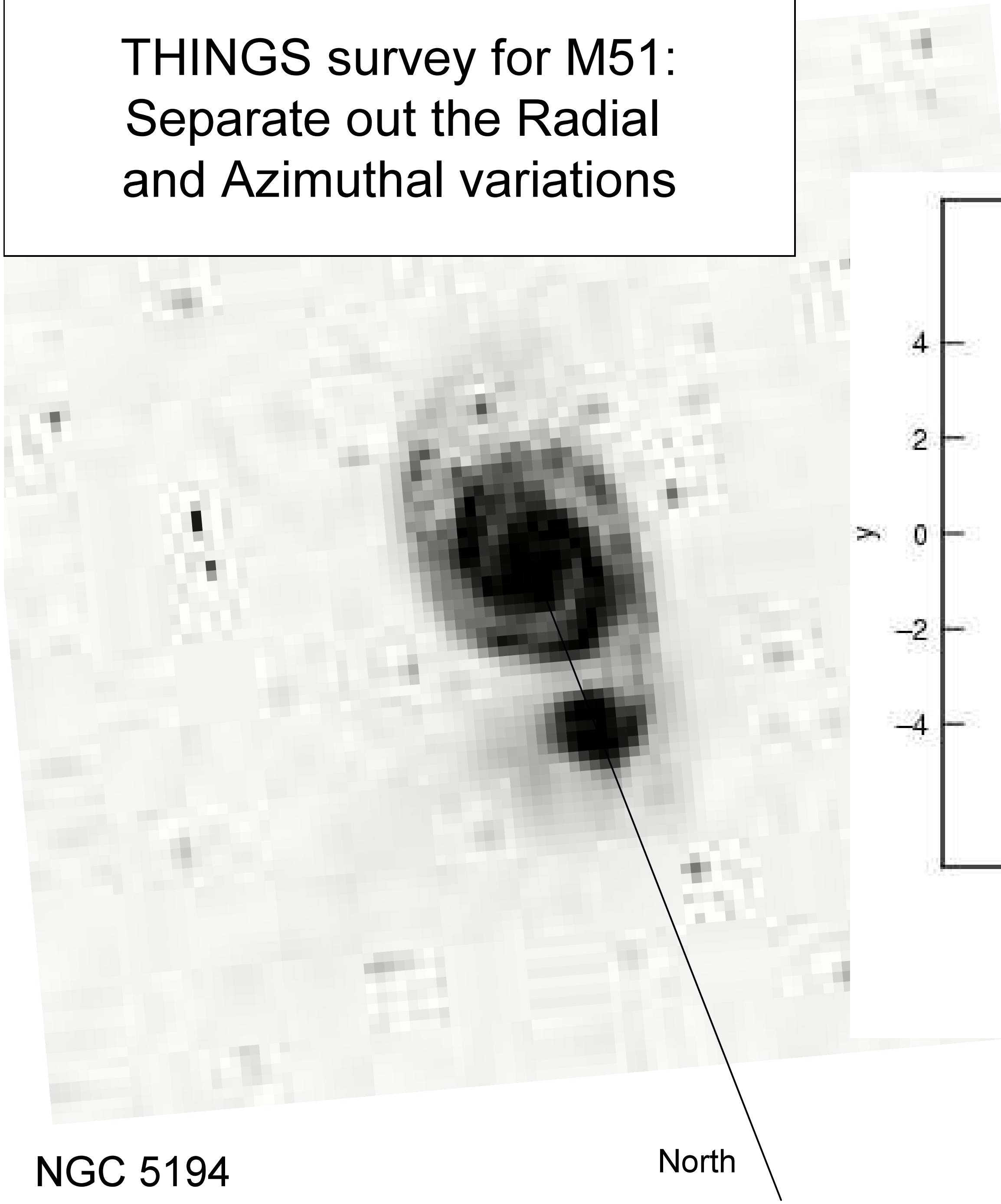
Two Laws?

1st: SF follows cold gas

2nd: cloud formation (& SF) both follow the exponential disk

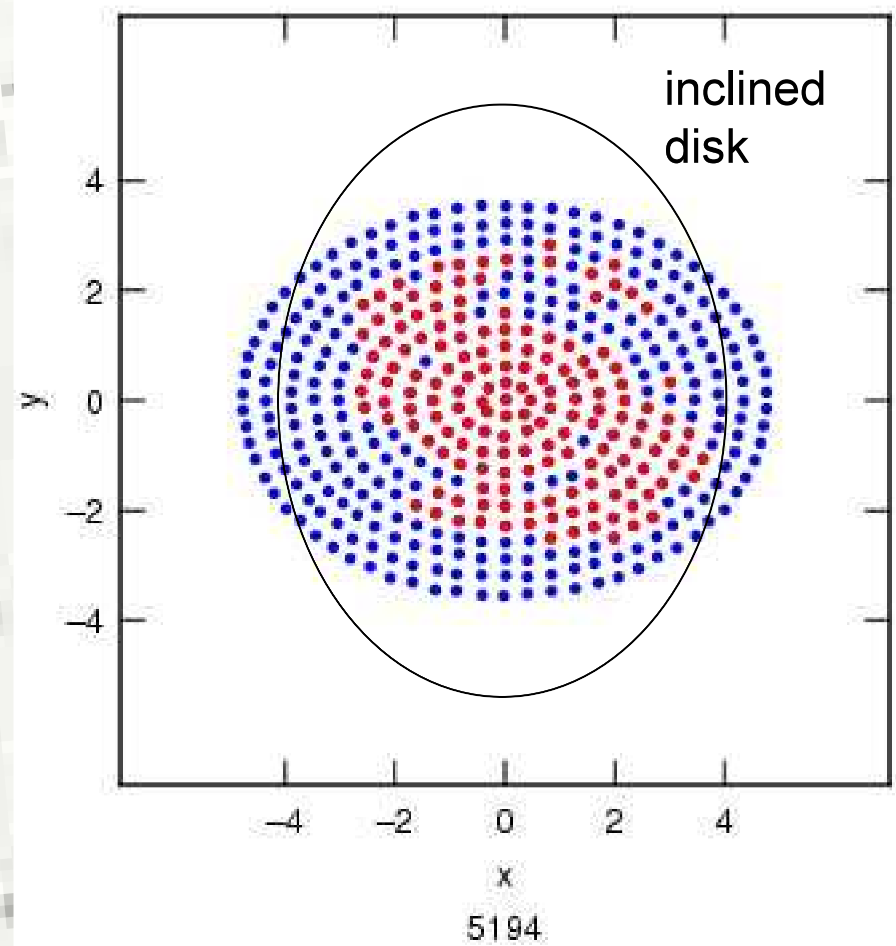
combined normal & SB: n=1.40pm0.05

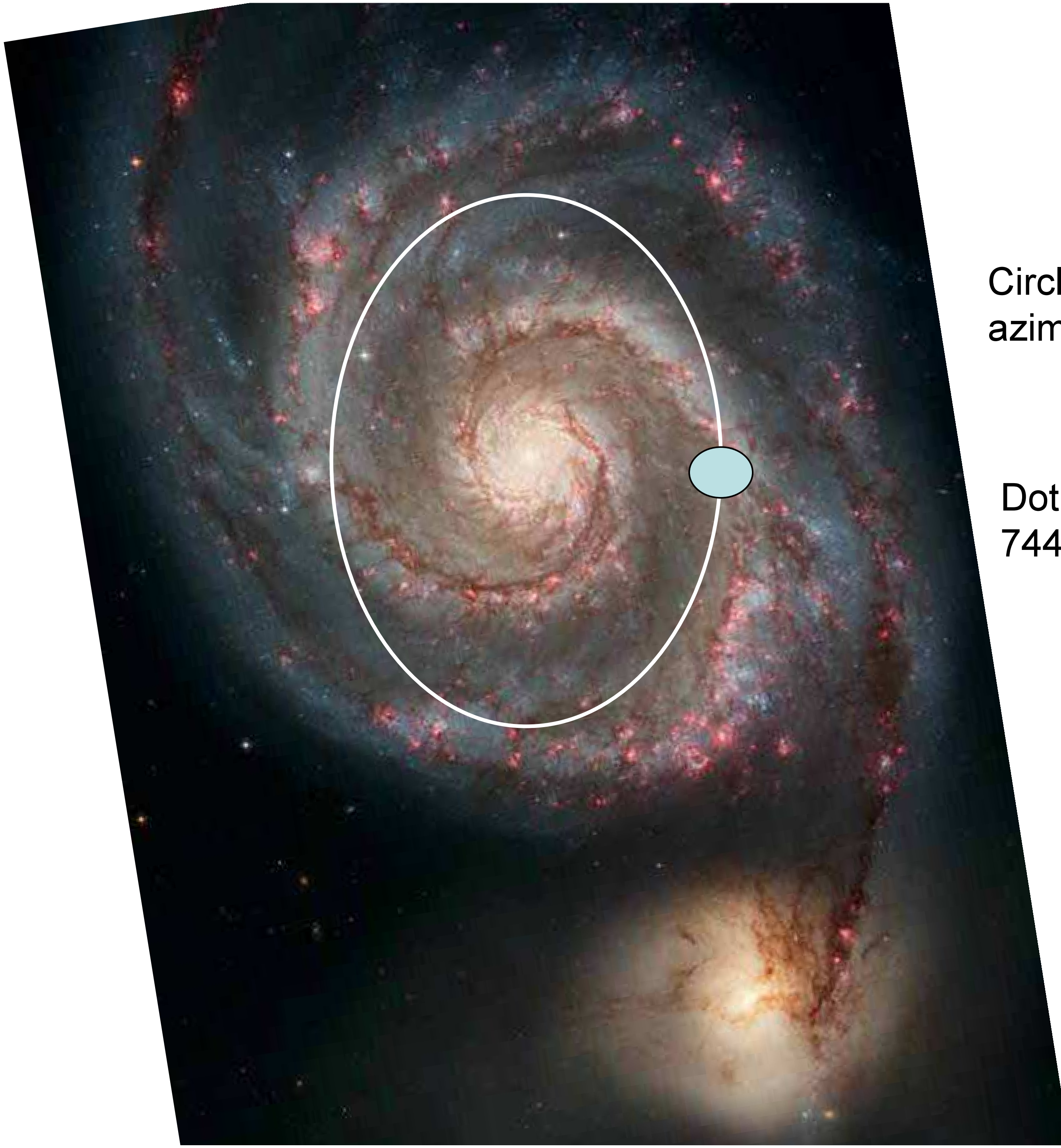
THINGS survey for M51:
Separate out the Radial
and Azimuthal variations



NGC 5194

red: log SFR(M_O/yr/kpc^2) > -2





Circle = 4th azimuthal profile

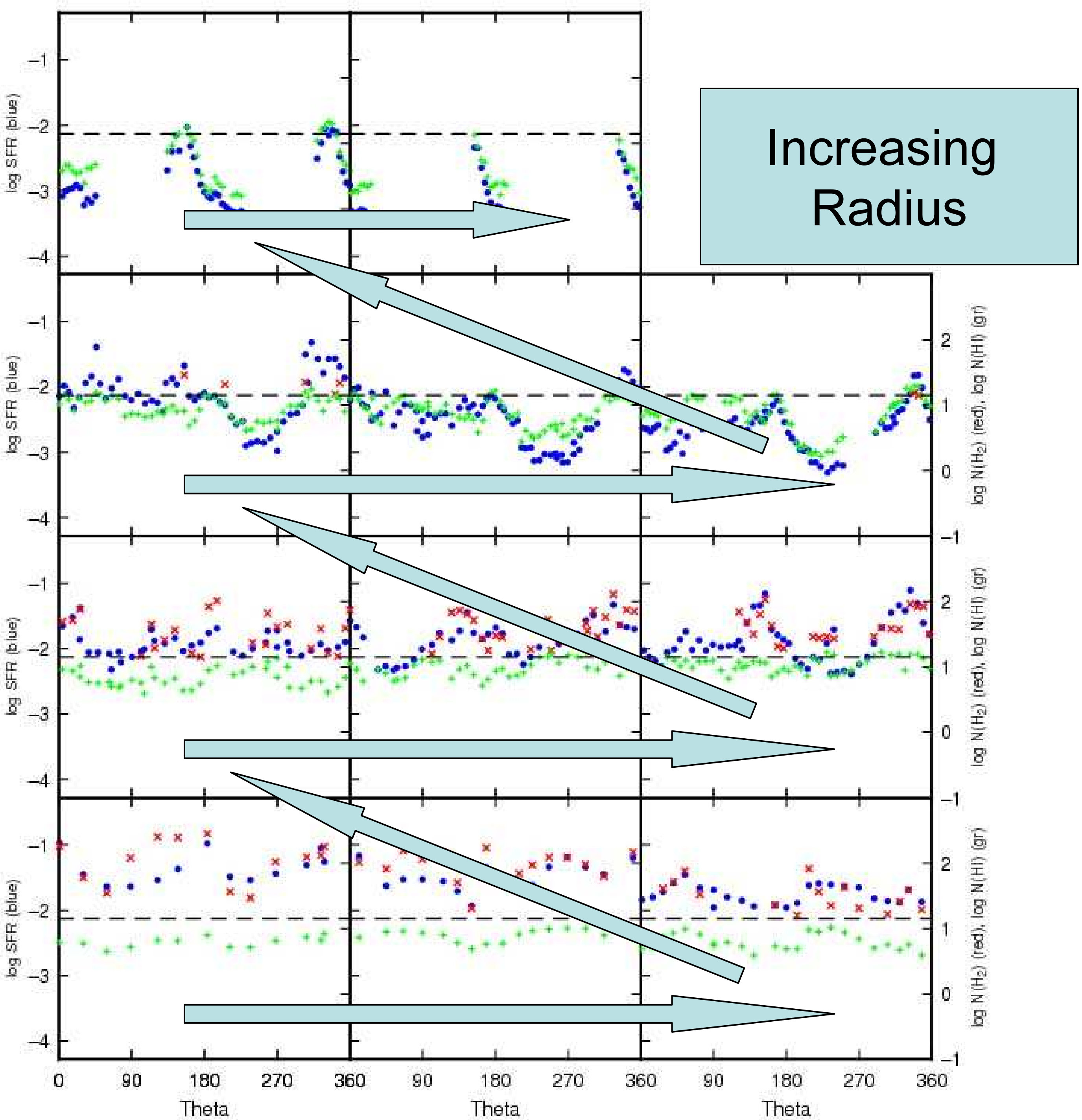
Dot ~ 744pc x 1023pc

NGC 5194

Azimuthal Variations in M51

Σ_{SFR} in M_O/My/kpc^2

Σ_{gas} in M_O/pc^2

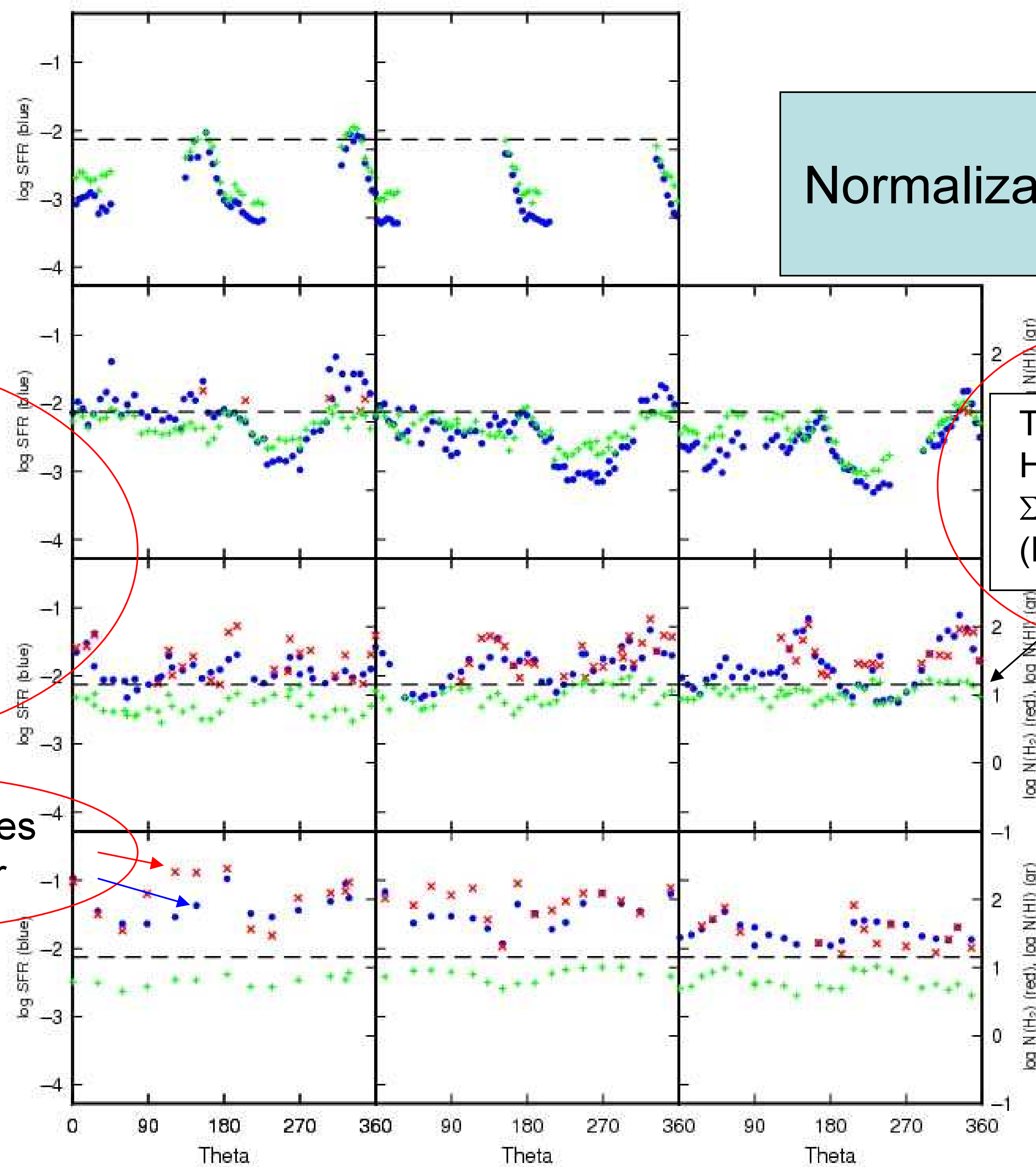


NGC 5194

Azimuthal Variations in M51

Red = CO
Green = HI
Blue = SFR

Gas and star axes offset by 1.9 Gyr



Normalizations

Threshold for HI→H_2
Σ_{gas}=14 M_O/pc^2
(Leroy +08)

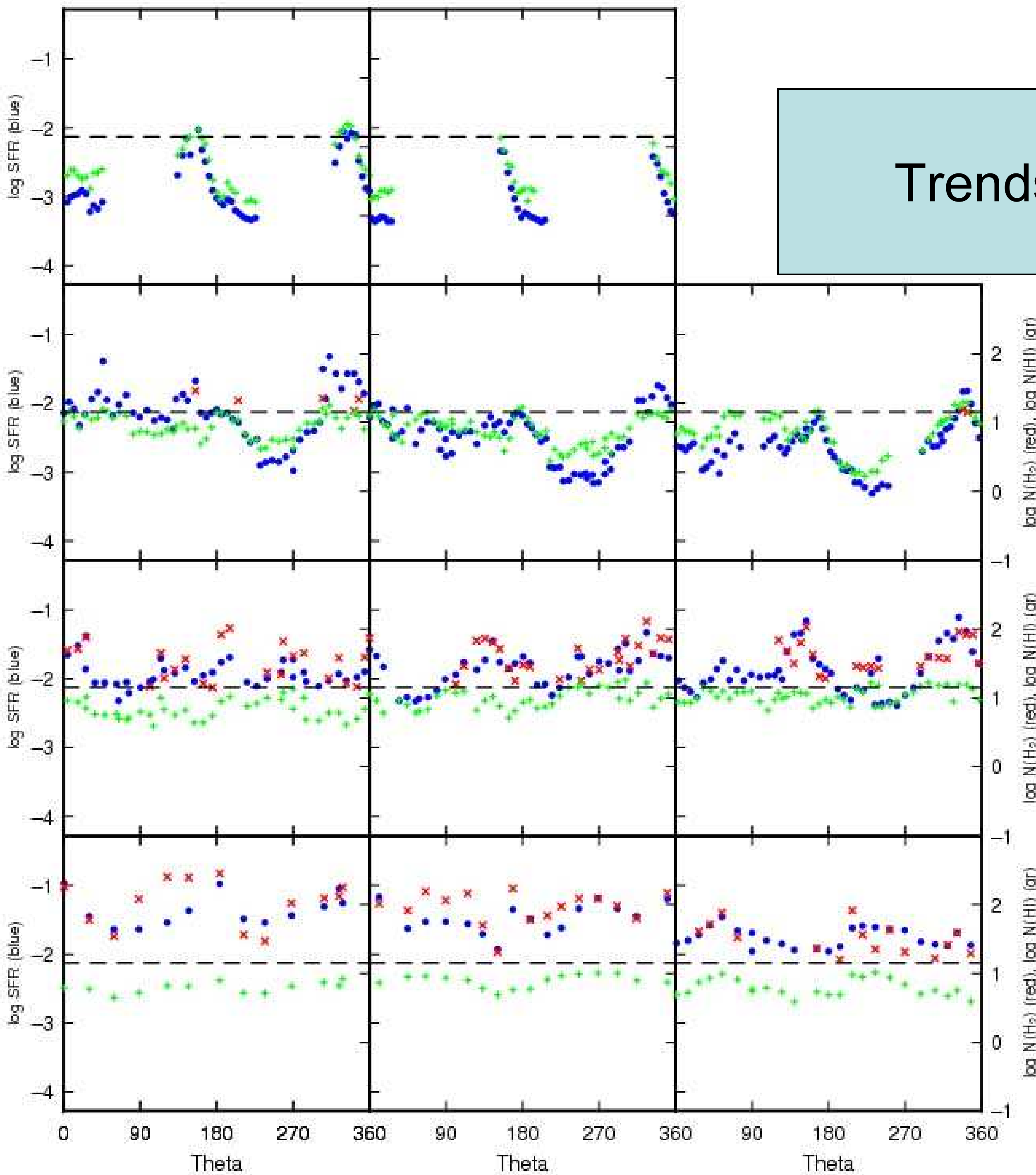
NGC 5194

Trends

HI-dominant outer disk. Spirals follow KS slope of 1 for HI.

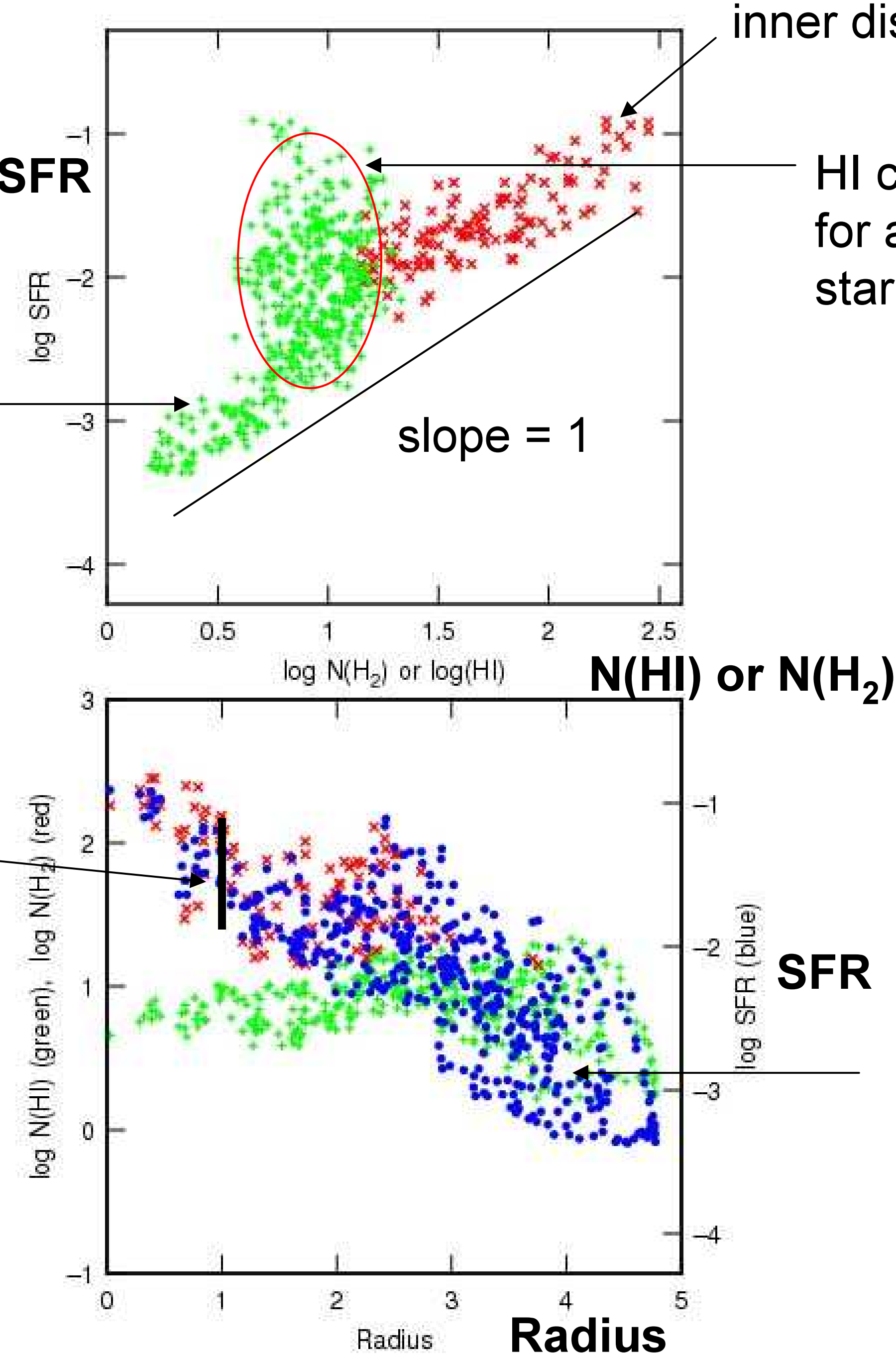
HI consumption time same as standard for H_2

H_2-dominant inner disk. Azimuth follows KS slope of 1



Red = CO
Green = HI
Blue = SFR

NGC 5194



inner disk

HI cloud envelopes for a wide range of star formation rates

outer disk HI follows Σ-Σ slope of 1 as in the inner disk

inner disk arm/interarm structure

N(HI) or N(H_2)

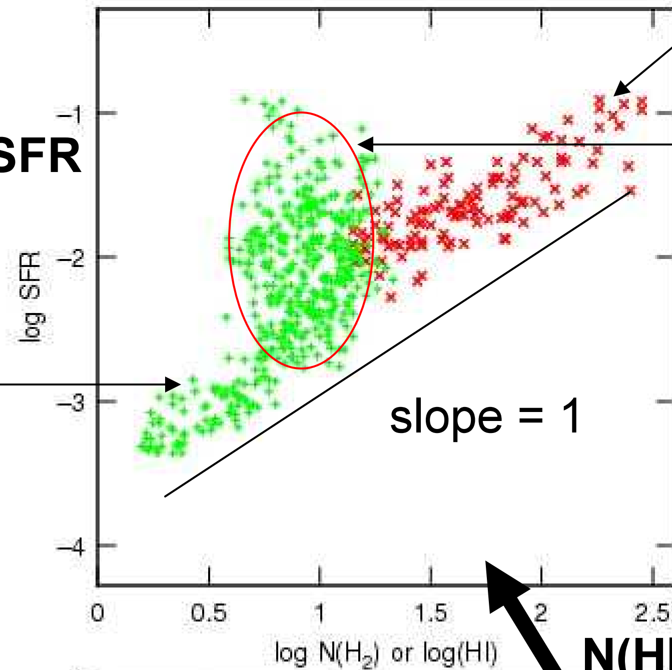
SFR

outer disk: arm-interarm structure in HI and SFR

Red = CO
Green = HI
Blue = SFR

NGC 5194

SFR



inner disk

HI cloud envelopes
for a wide range of
star formation rates

outer disk
HI follows
Σ-Σ slope of 1
as in the
inner disk

N(HI) or N(H_2)

inner disk
arm/interarm
structure

N(HI) or N(H_2)

Red = CO
Green = HI
Blue = SFR

…sk:
…erarm
…e in
…SFR

The SF "Law"

(Kennicutt-Schmidt)

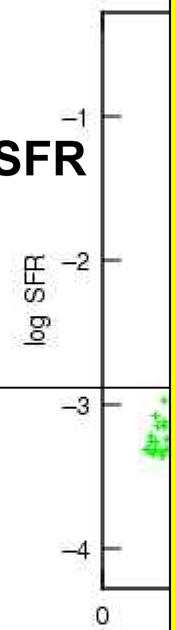
the 1st law of SF …

NGC 5194

The Exponential Disk

The 2nd Law of SF

SFR



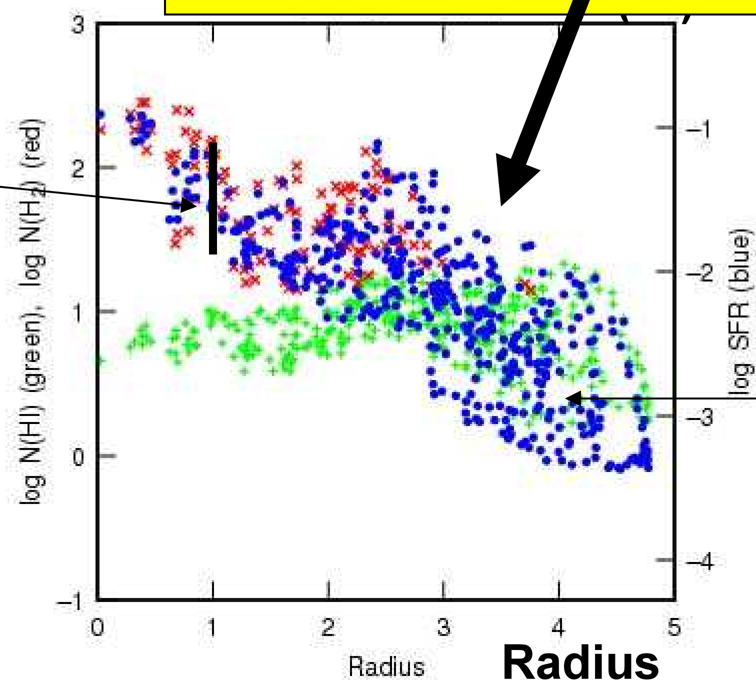
outer disk
HI follows
Σ-Σ slope of 1
as in the
inner disk

elopes
ge of
rates

inner disk
arm/interarm
structure

Red = CO
Green = HI
Blue = SFR

N(HI) or $N(H_2)$



SFR

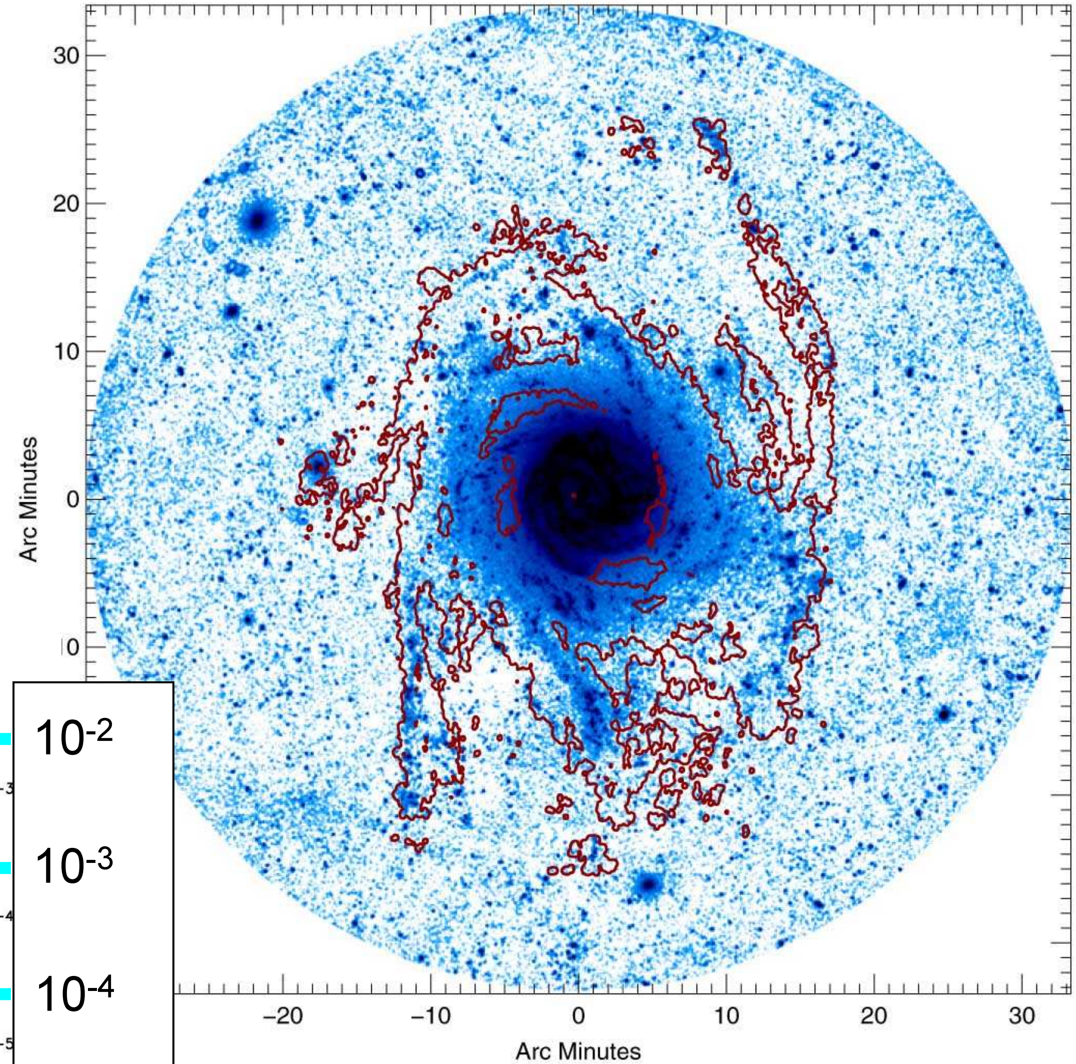
Radius

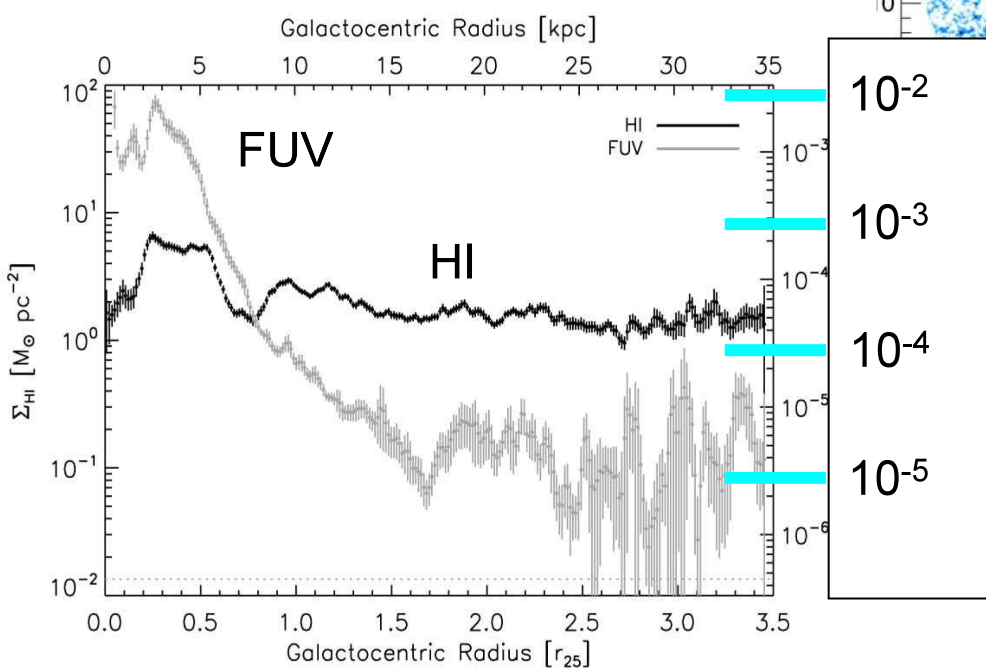
outer disk:
arm-interarm
structure in
HI and SFR

NGC 5194

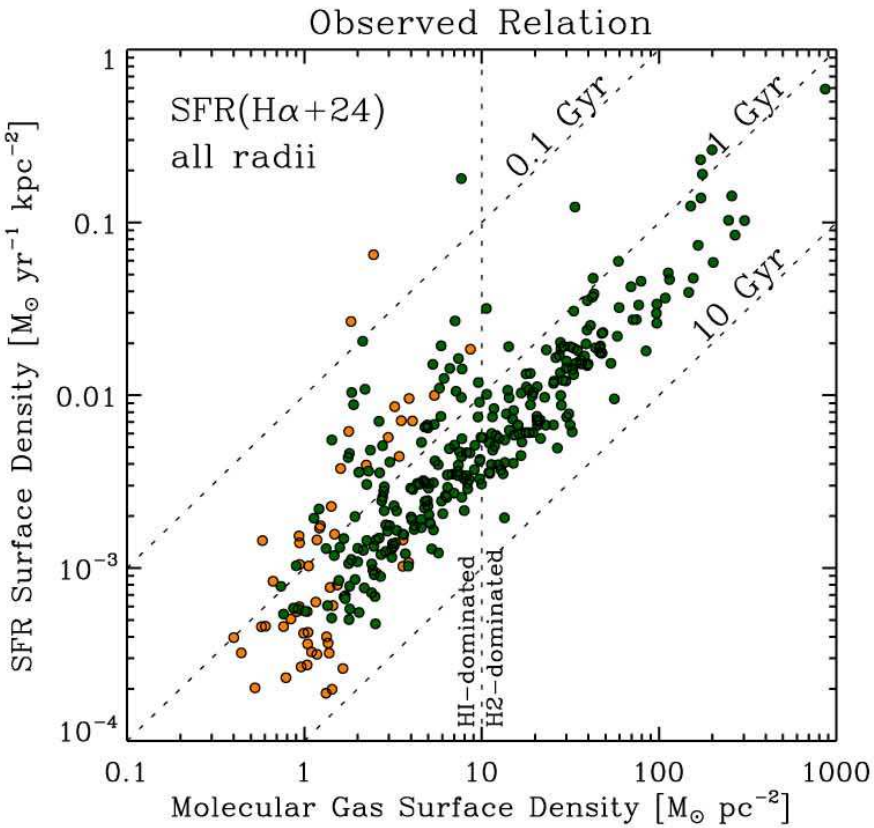
Bigiel et al. 2010:

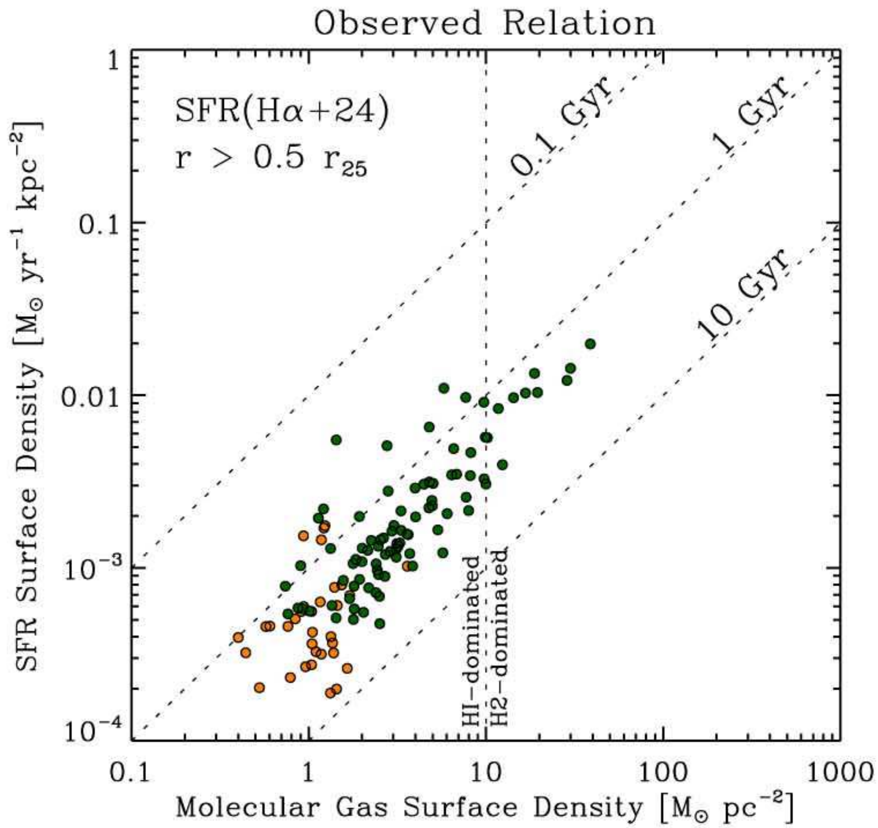
Outer disk SF seen
in deep GALEX images
follows HI gas down
to 0.2 M_O/pc^2 contours





SFR M_O /yr/kpc^2

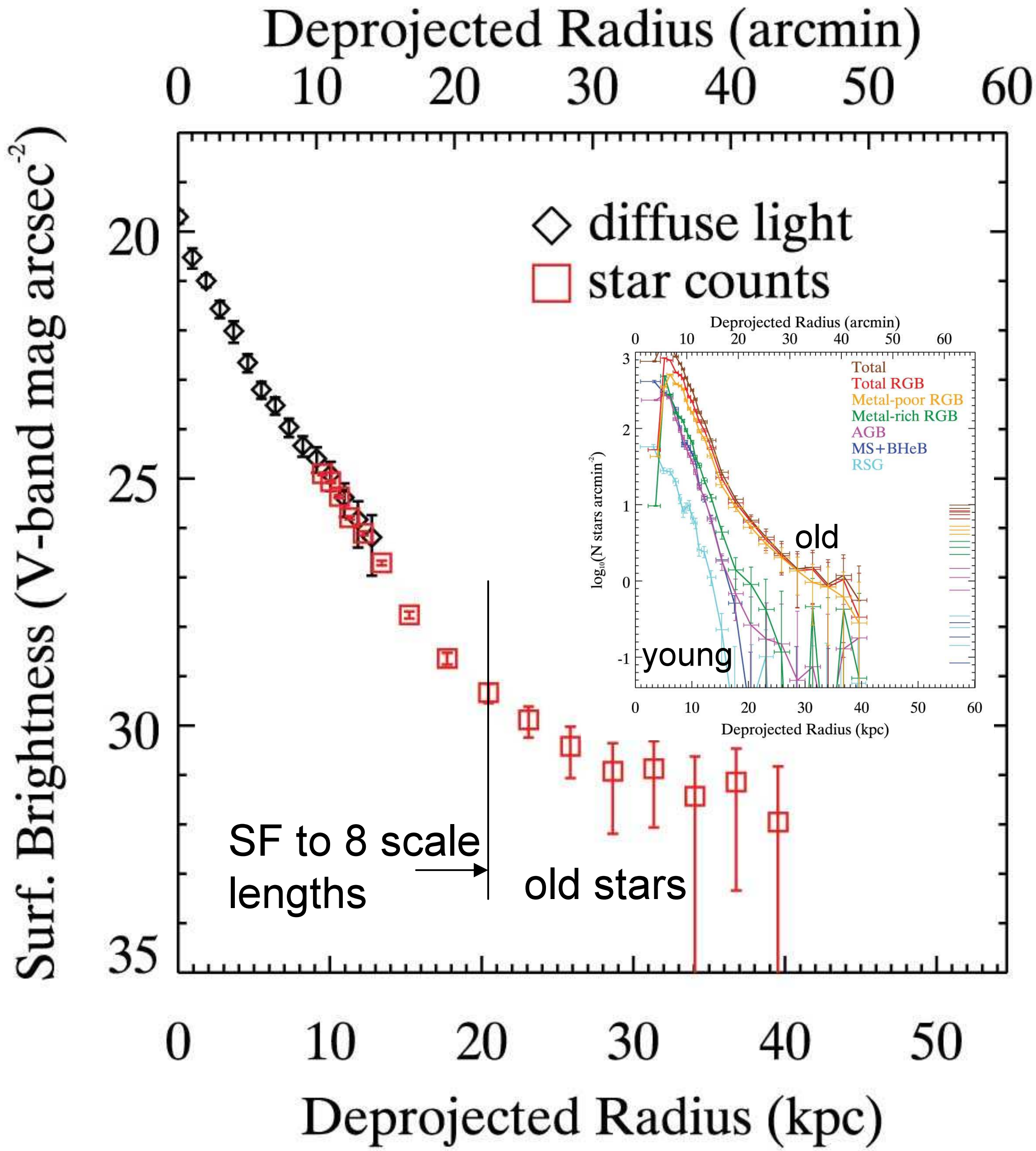




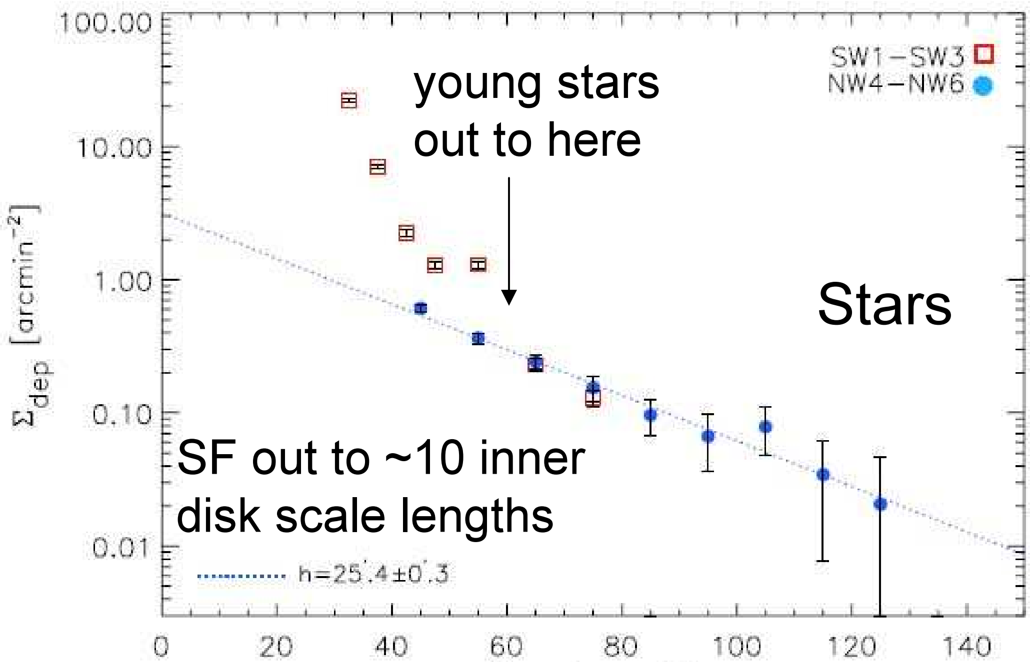
Schruba +11: stacking analysis in 33 galaxies shows faint CO connected with star formation in outer disks ... the 1st SF Law … but <u>why is the CO exponential</u> (the 2nd SF law)?

Barker + 2012:

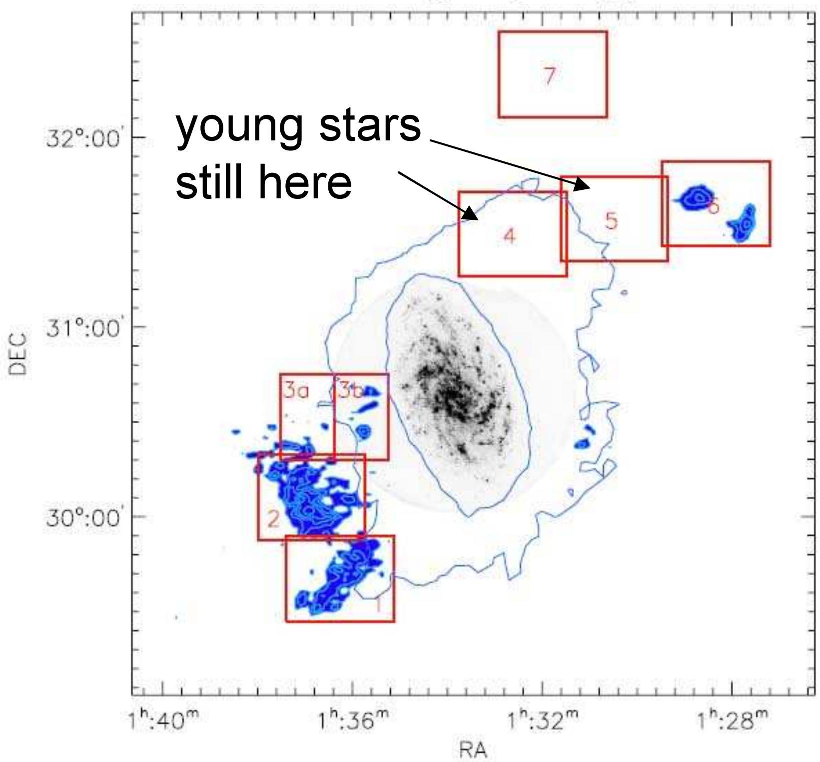
An extended outer disk in spiral galaxy NGC 2403

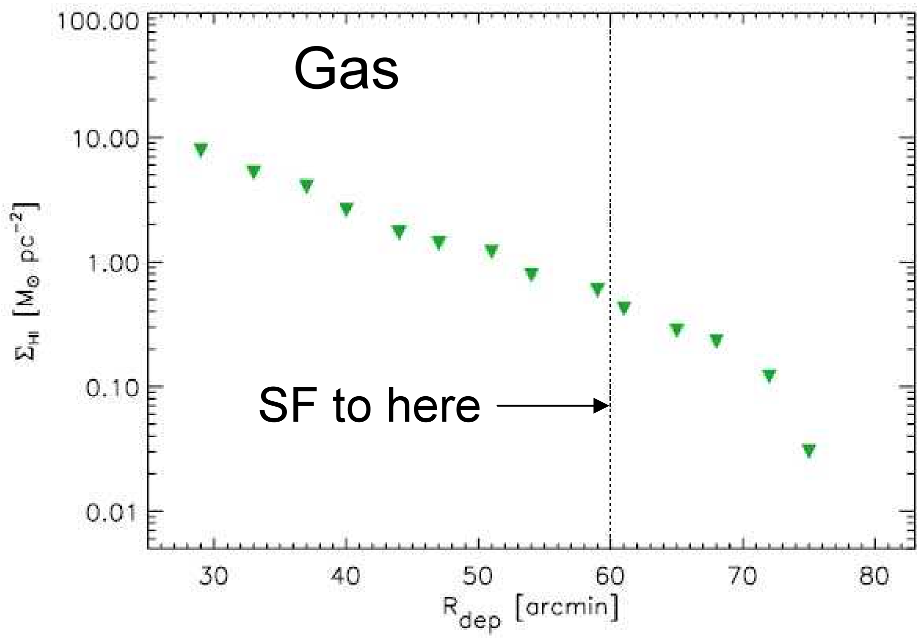


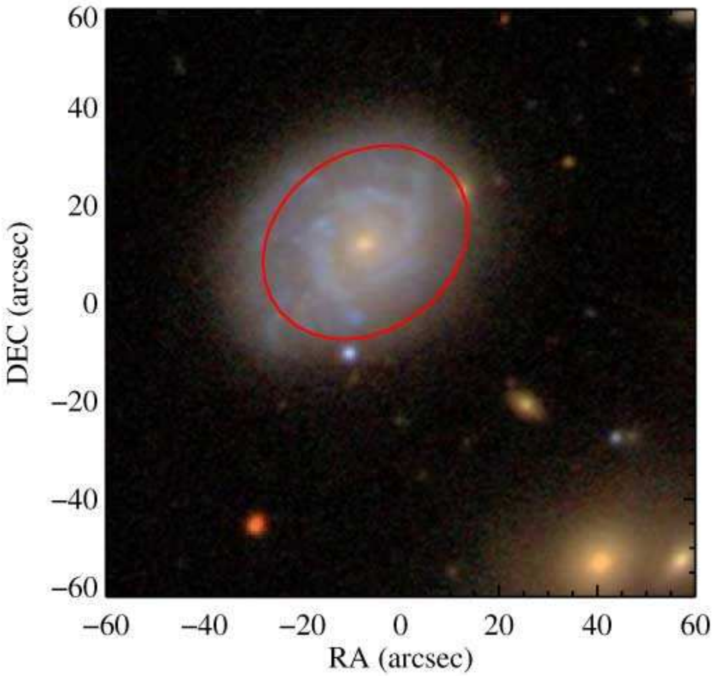
(image 24 kpc on a side)

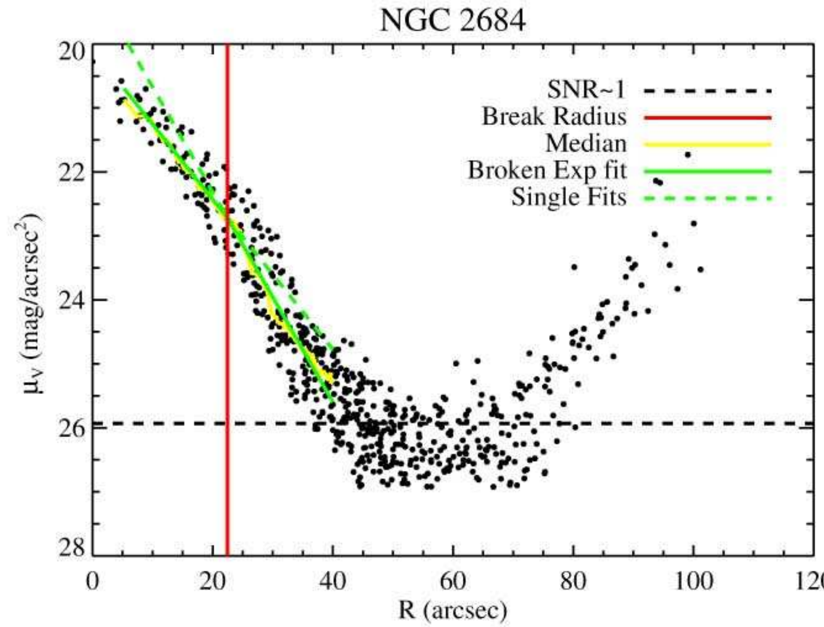


Grossi +11: M33 far outer disk, stars extend further than gas, but SF (200 Myr old) still at 60' where Σ_{gas} ~ 1 M_O/pc^2

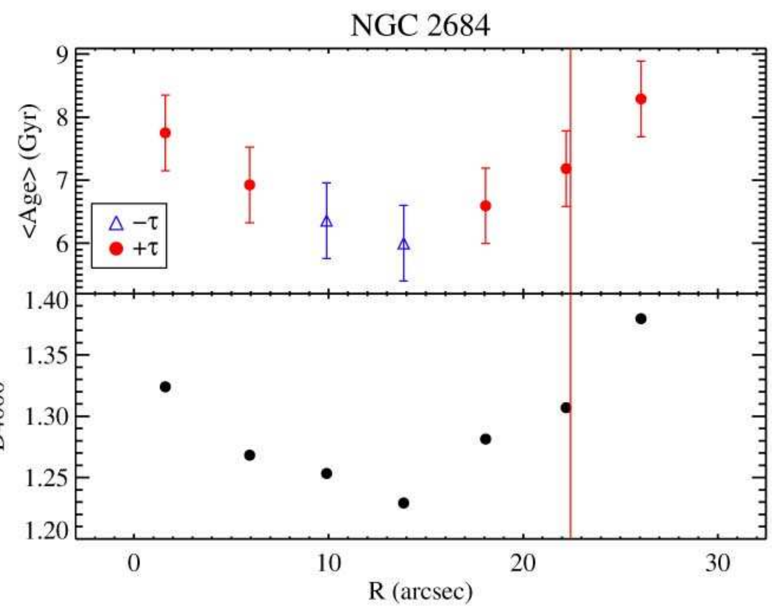








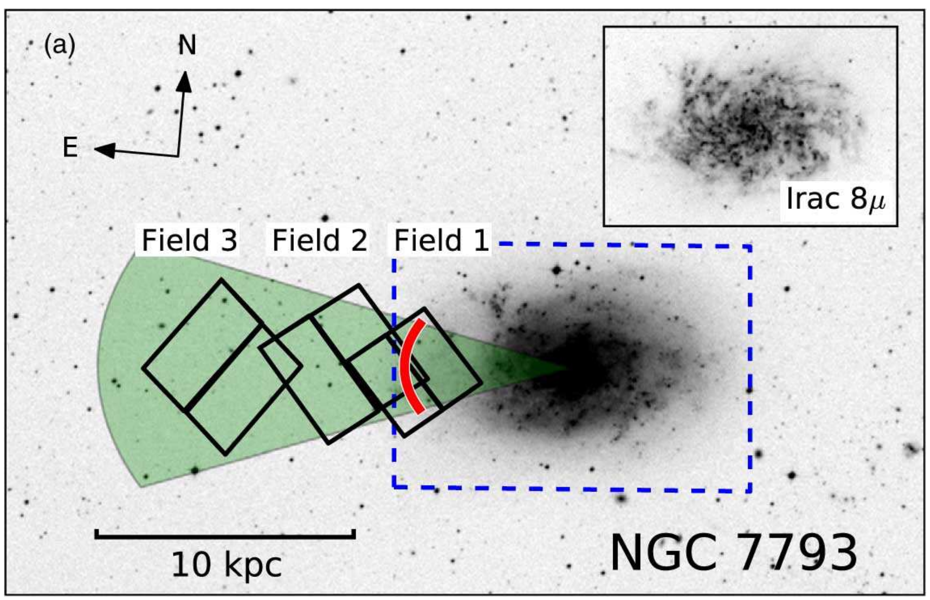
Yoachim +12: NGC 2684 and other galaxies have profile breaks and older ages outside

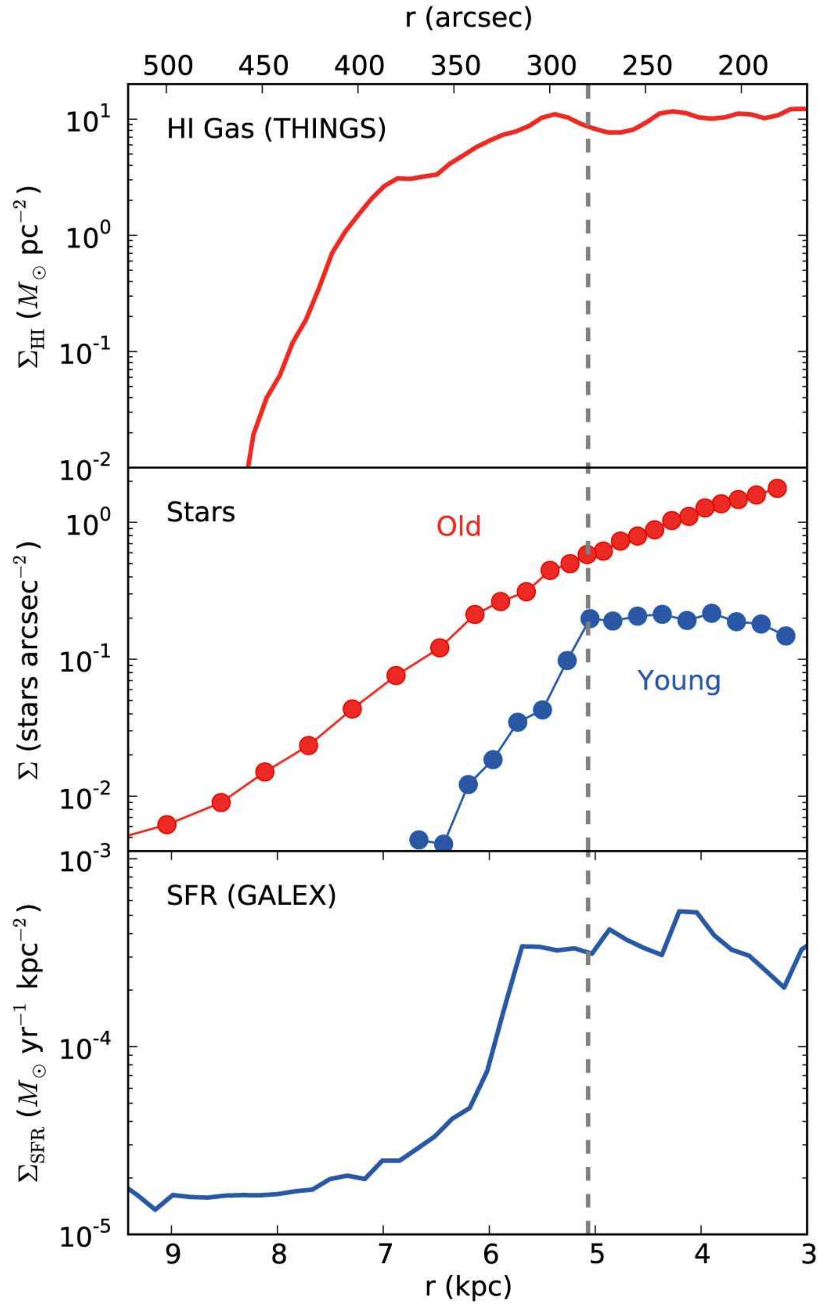


→stellar migration explains far outer parts, but SF (GMC formation) is exponential out to that.

Radburn-Smith+12: NGC 7793 radial migrations with spiral scattering can explain the disk profile.

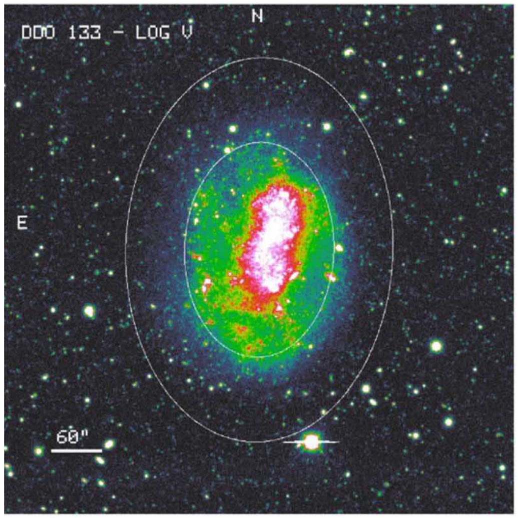
Star formation for a small distance into the outer disk, down to $\Sigma_{HI} \sim 1\ M_O/pc^2$

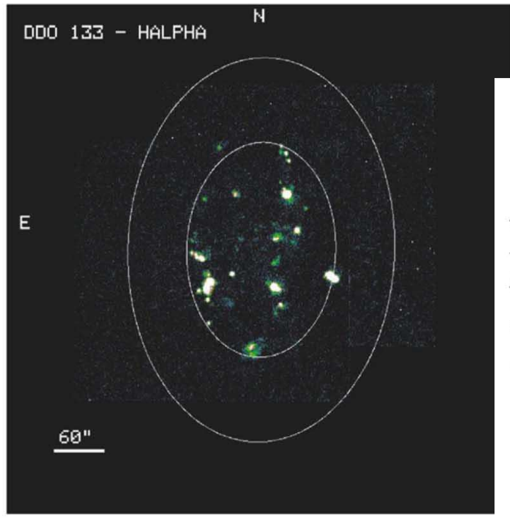


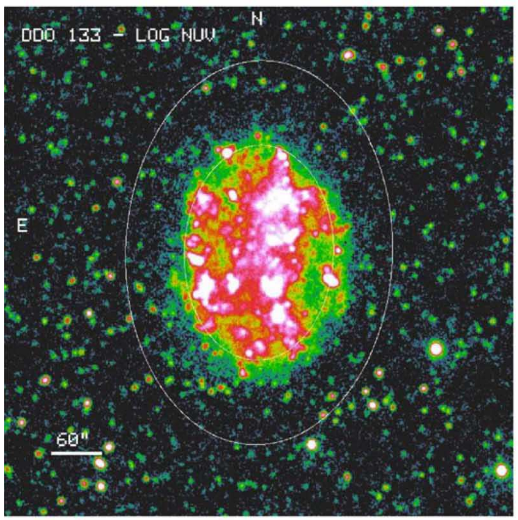


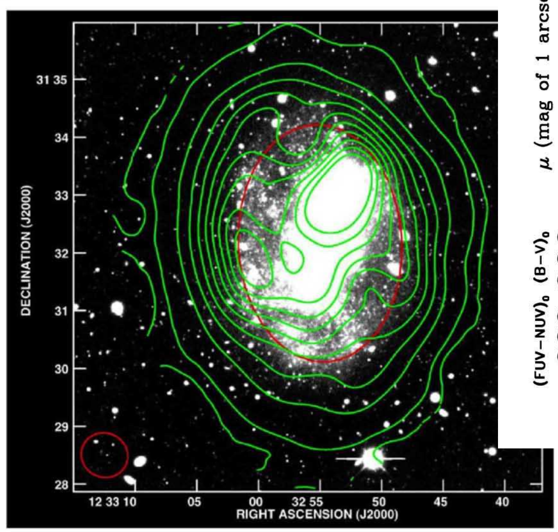
V, Hα, NUV images: DDO 133

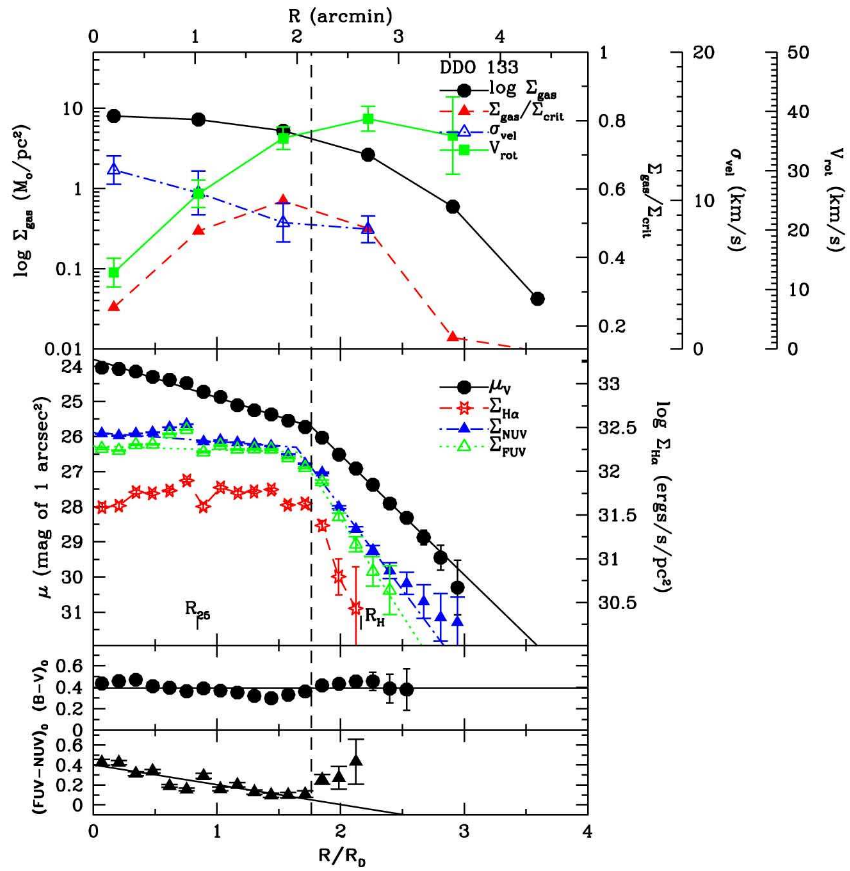
(ellipses = breaks & outer limit)











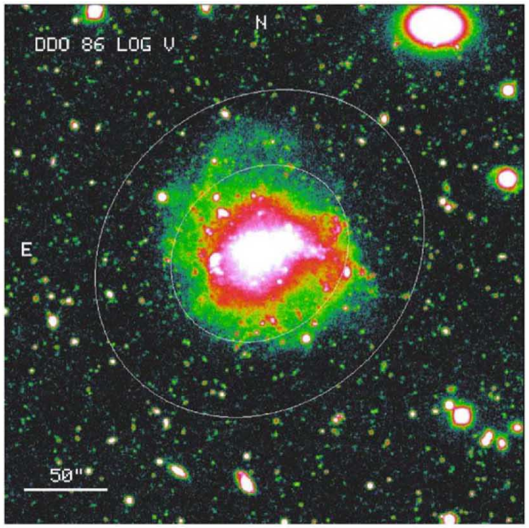
DDO 133

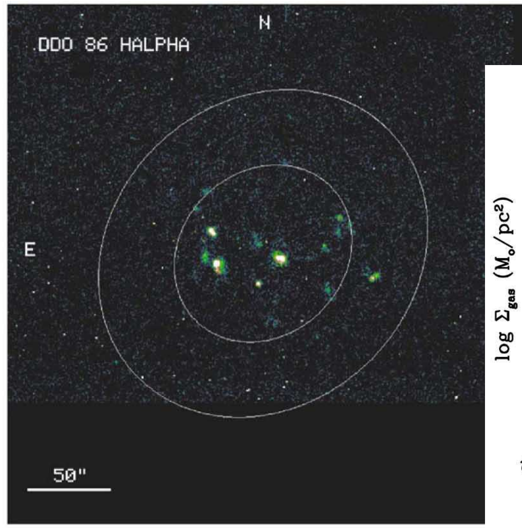
Hunter + 11: A deep study of the outer disks of 5 dwarf irregular galaxies

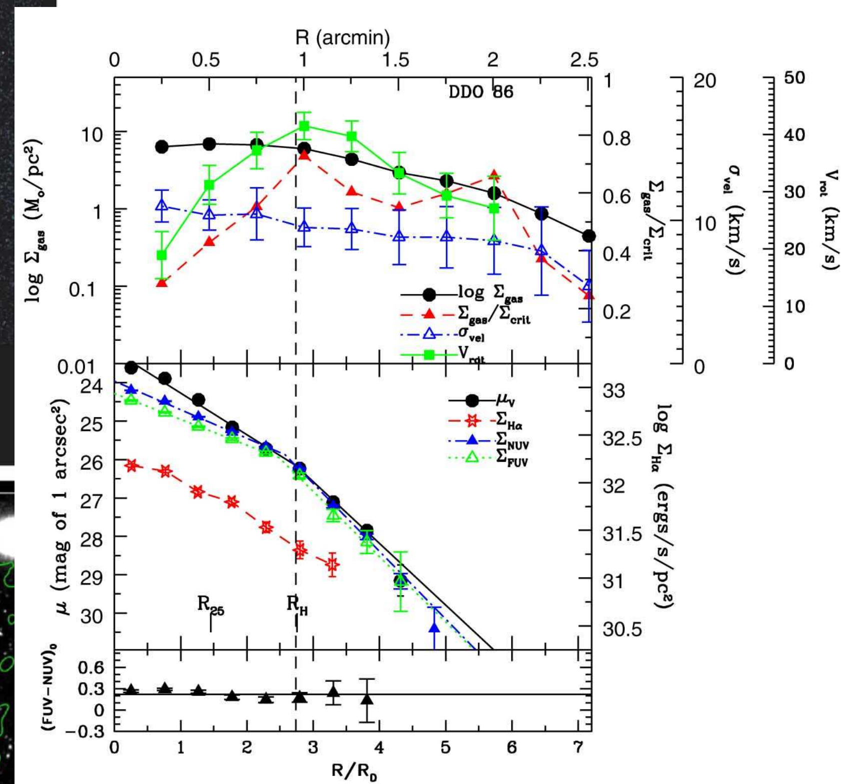
-- no spiral waves for star scattering, HI>>H_2, gas >> stars, extreme-low SFR

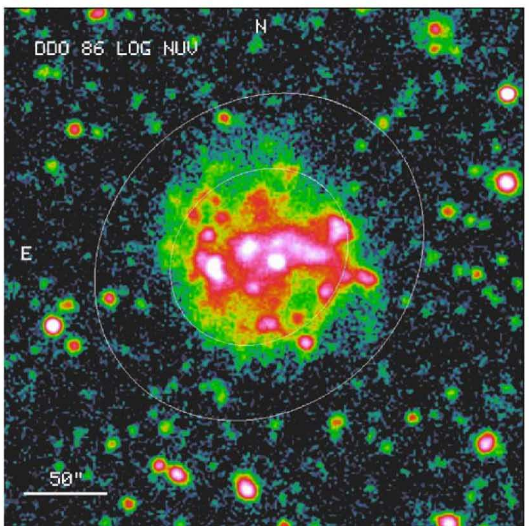
V, Hα, NUV images: DDO 86

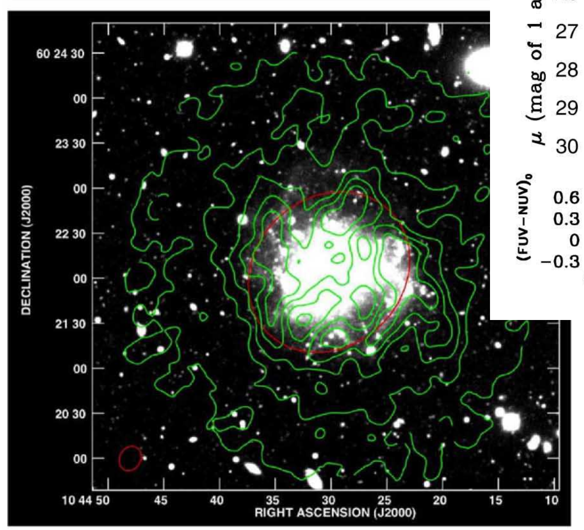
(ellipses = breaks & outer limit)







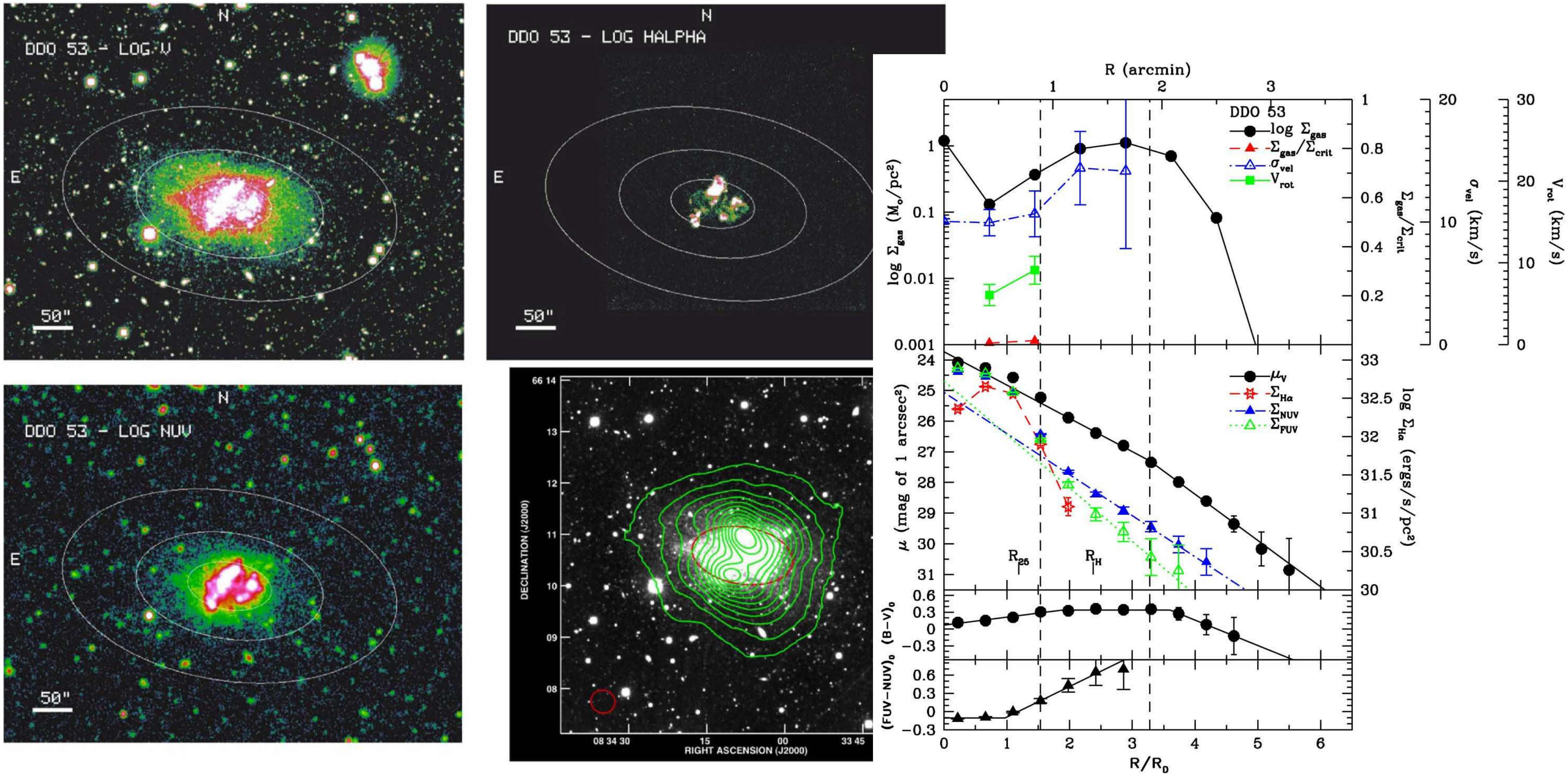




End of SF at $\Sigma_{HI} \sim 1\ M_O/pc^2$ or beyond

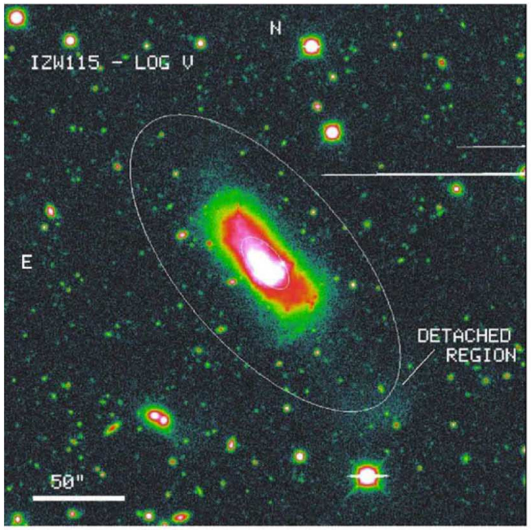
V, Hα, NUV images: DDO 53

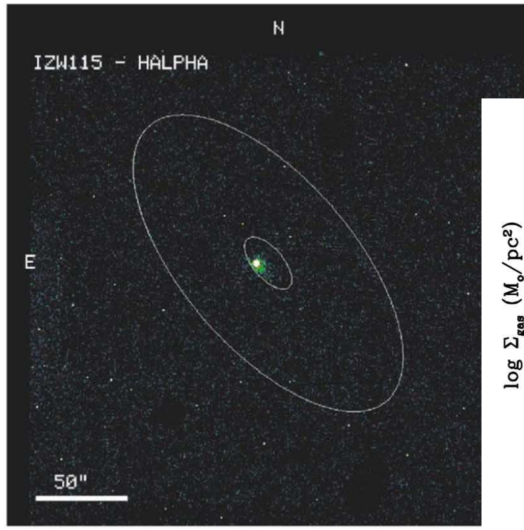
(ellipses = breaks & outer limit)



End of SF at Σ_{HI} ~ 1 M_O/pc^2 or beyond

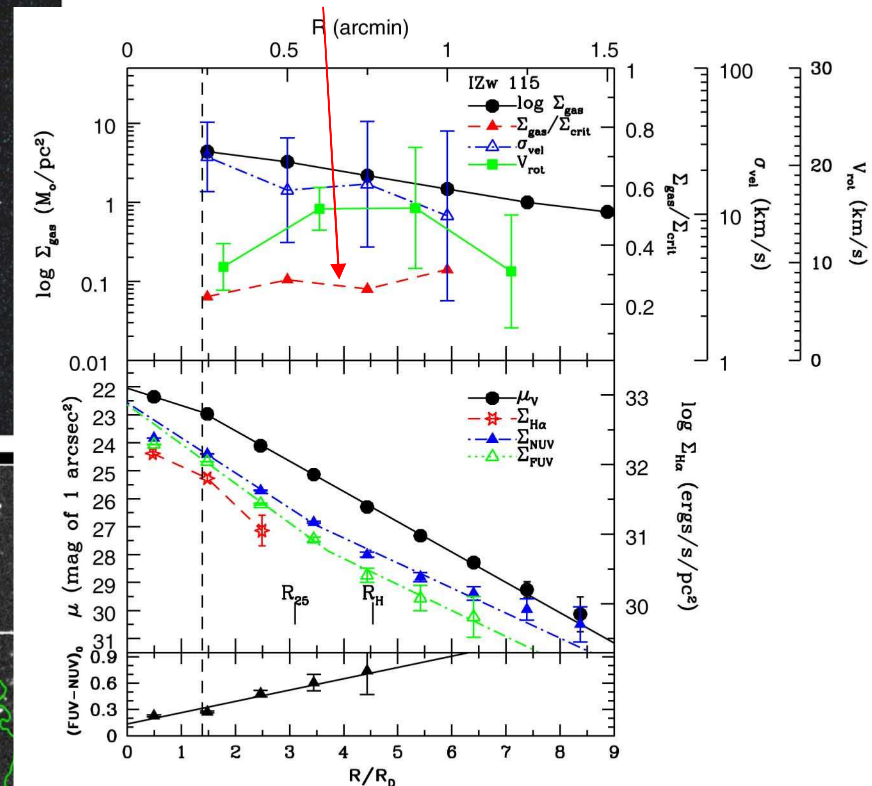
V, Hα, NUV images: I Zw 115

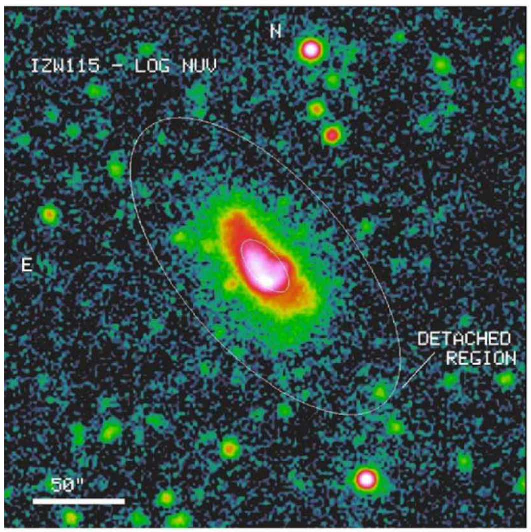


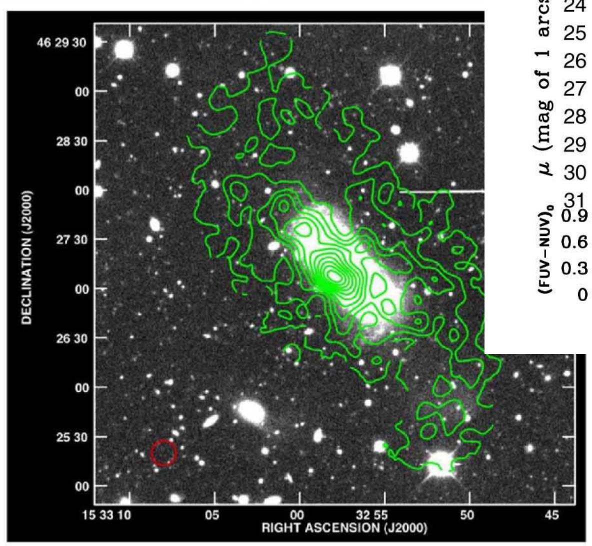


$\Sigma_{gas}/\Sigma_{crit}$ ~ 0.2-0.3

(Q ~ 3-5)



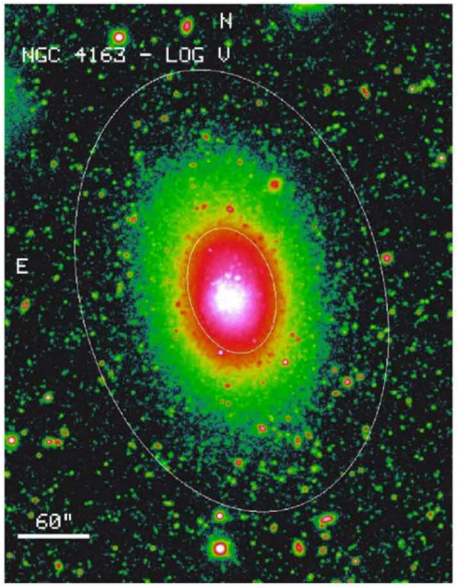


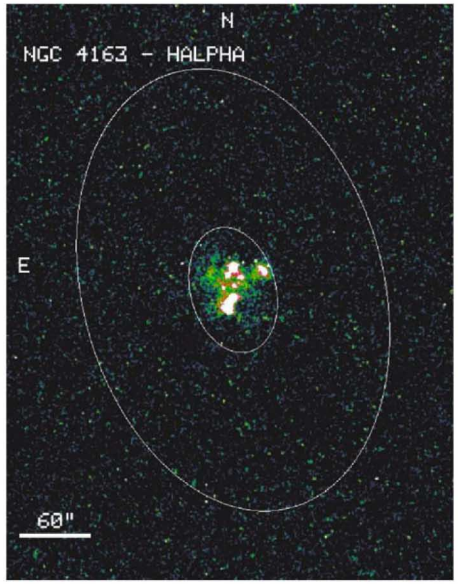


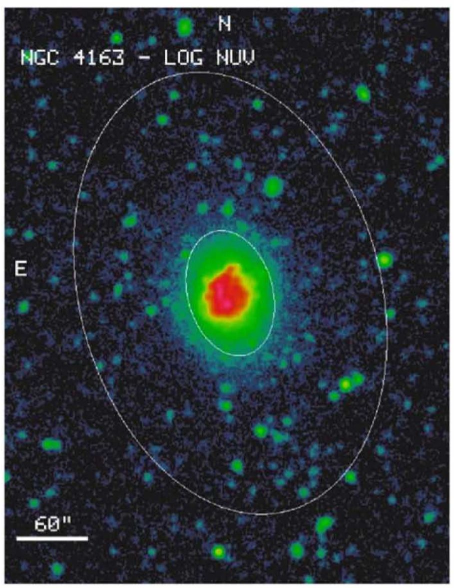
Σ_{gas} / Σ_{crit} is low in outer parts

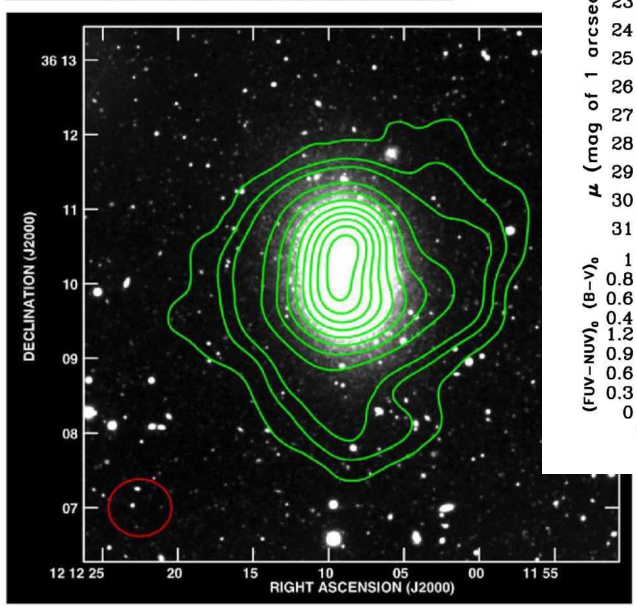
V, Hα, NUV images: NGC 4163

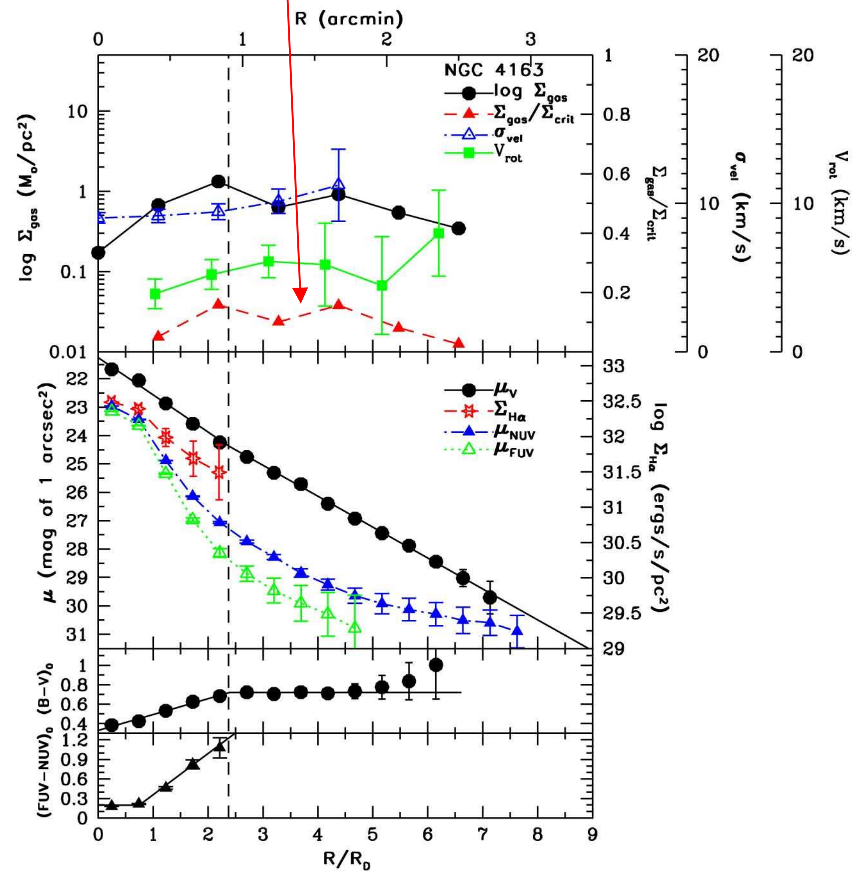
$\Sigma_{gas}/\Sigma_{crit} \sim 0.1$
(Q ~ 10)











Σ_{gas} / Σ_{crit} ultra low, and maybe SF has stopped in outer parts

For example, DDO 133:

At μ_V=29.5 mag/arcsec^2

In 1 kpc thick annulus (40 kpc^2):

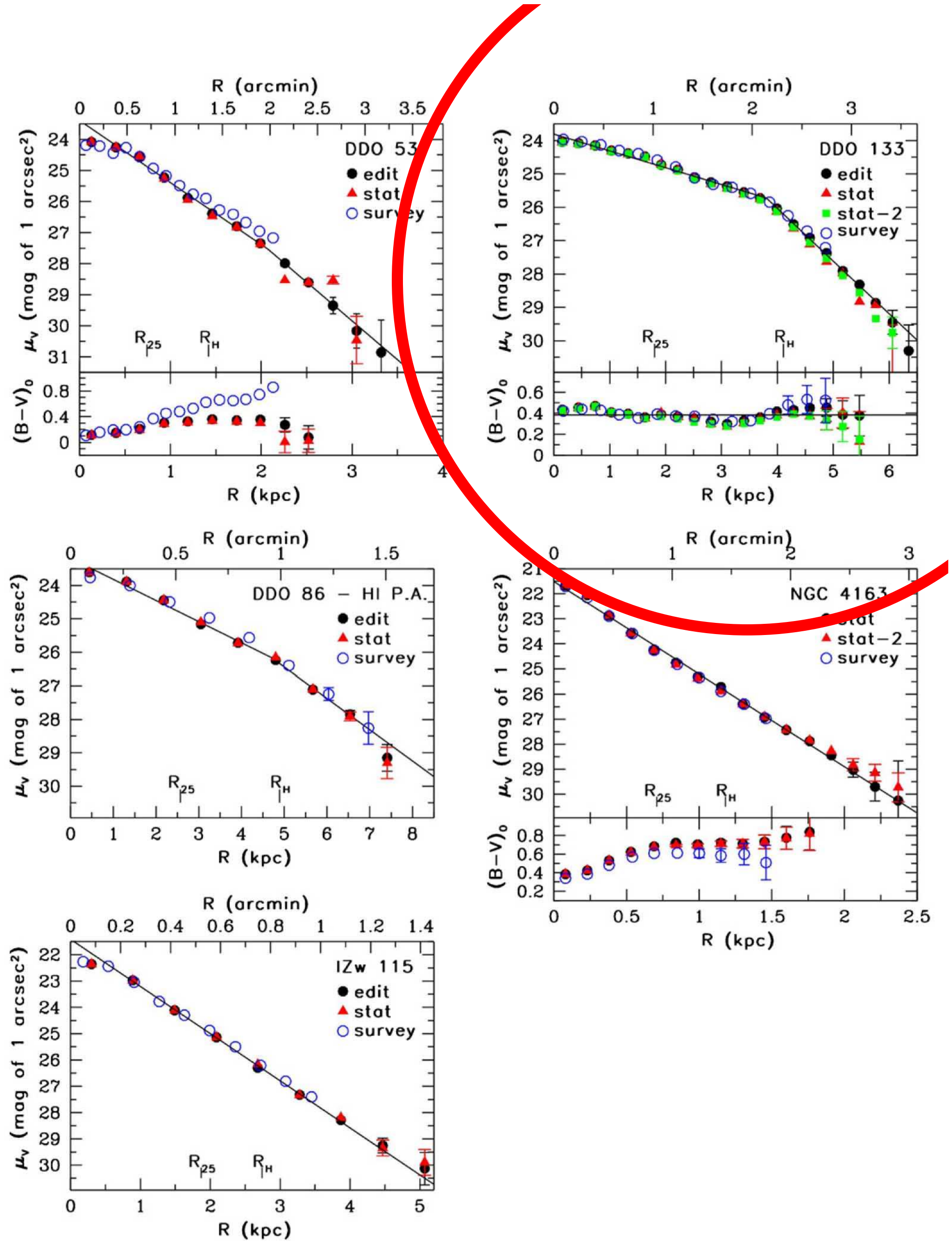
$M_{star}=2.5\mathrm{x}10^6\ M_O$

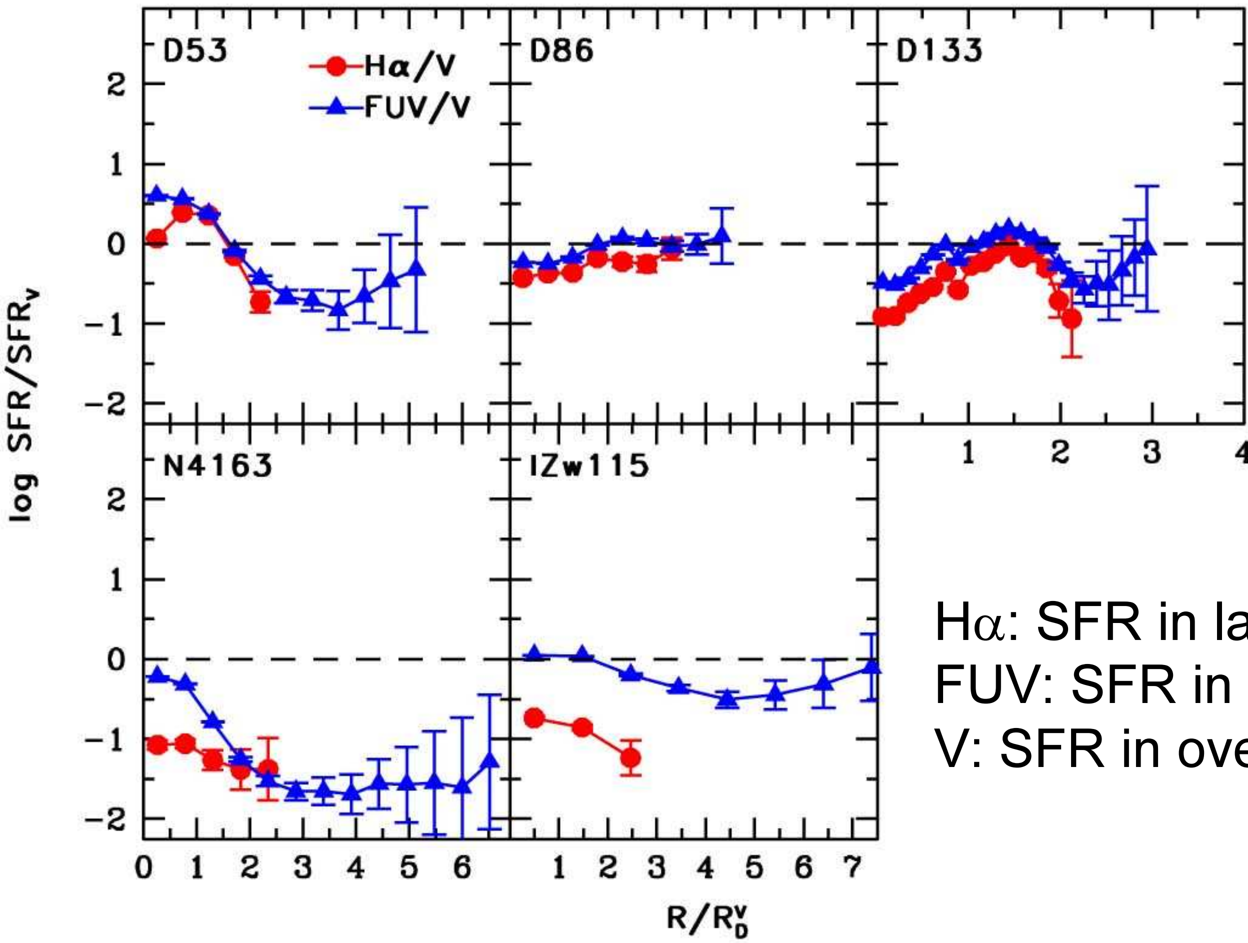
Σ_{stars} = 0.06 M_O/pc^2.

FUV-NUV color age of 300-600 Myr (dep. on metallicity)

SFR_{FUV}~SFR_V~10^{-5} M_O/yr/kpc^2, which is 0.0004 M_O/yr in annulus

That's 6 Orion nebulae/kpc





Hα: SFR in last 10 Myr
FUV: SFR in last several 100 Myr
V: SFR in over 1 Gyr

Aside from NGC 4163 (which has highly disturbed HI velocities), most have a nearly constant SFR over radius and time. (see also Leroy 2008)

<u>SF maintains the exponential disk for 3-6 inner scale lengths</u>

Two fluid GI in Turbulent Gas

- Q: How to form stars when Q~5-10 (outer disks of dwarf irregulars and maybe spirals)
- A: Q is not a firm threshold
  - Recall: $Q = \dfrac{\kappa\sigma}{\pi G \Sigma}$

determines the balance between self-gravity and centrifugal force in a Coriolis spun-up condensation at the Jeans length. <u>The equation of state is critical.</u>

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Two fluid GI in Turbulent Gas

- Sometimes we write
  - $Q = \dfrac{\gamma^{1/2}\kappa\sigma}{\pi G\Sigma}$
  - for γ = adiabatic index ($dP/d\rho = \gamma P/\rho$)
- In a "soft" gas, $\gamma \ll 1$ and the threshold for instability is lower

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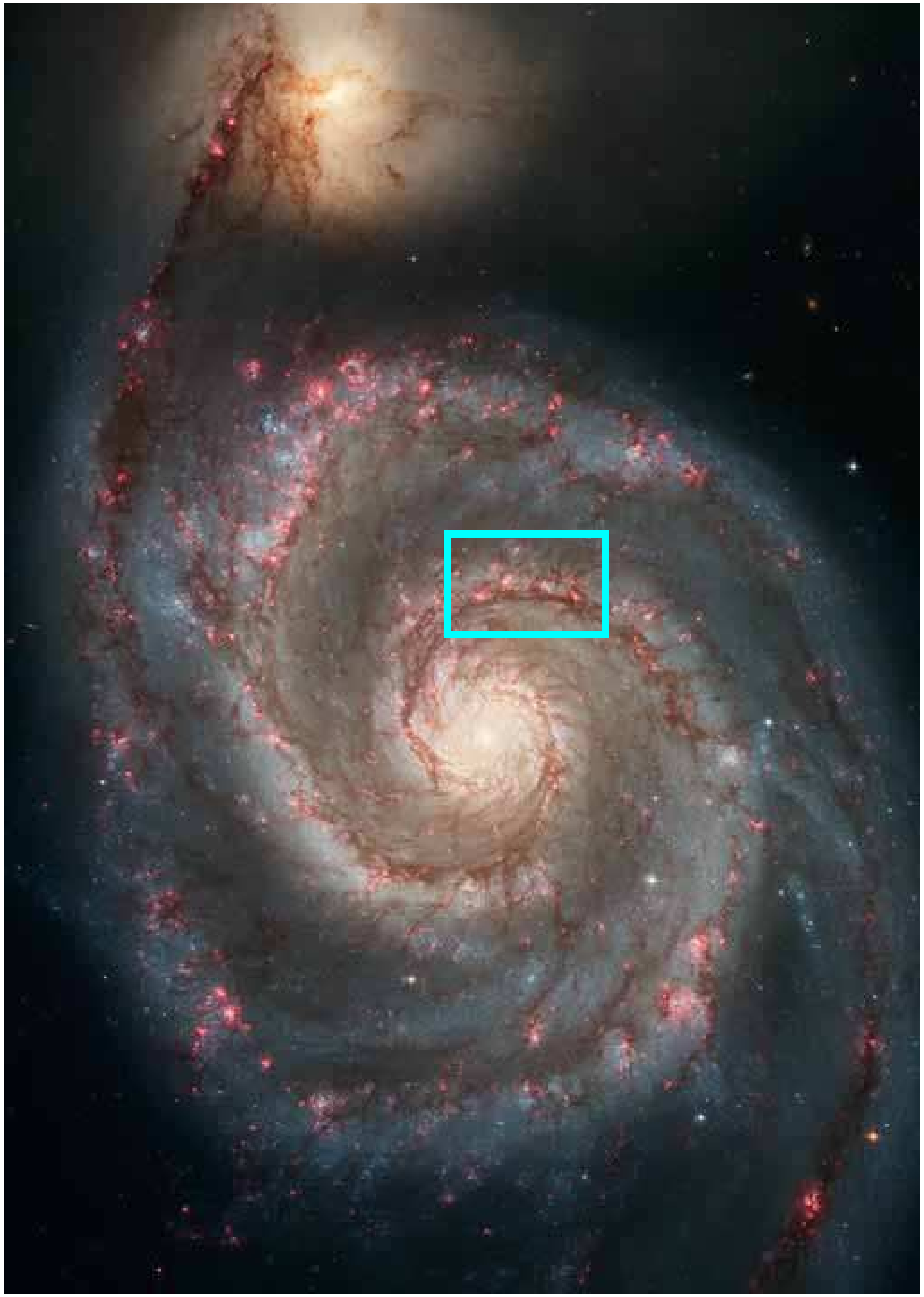
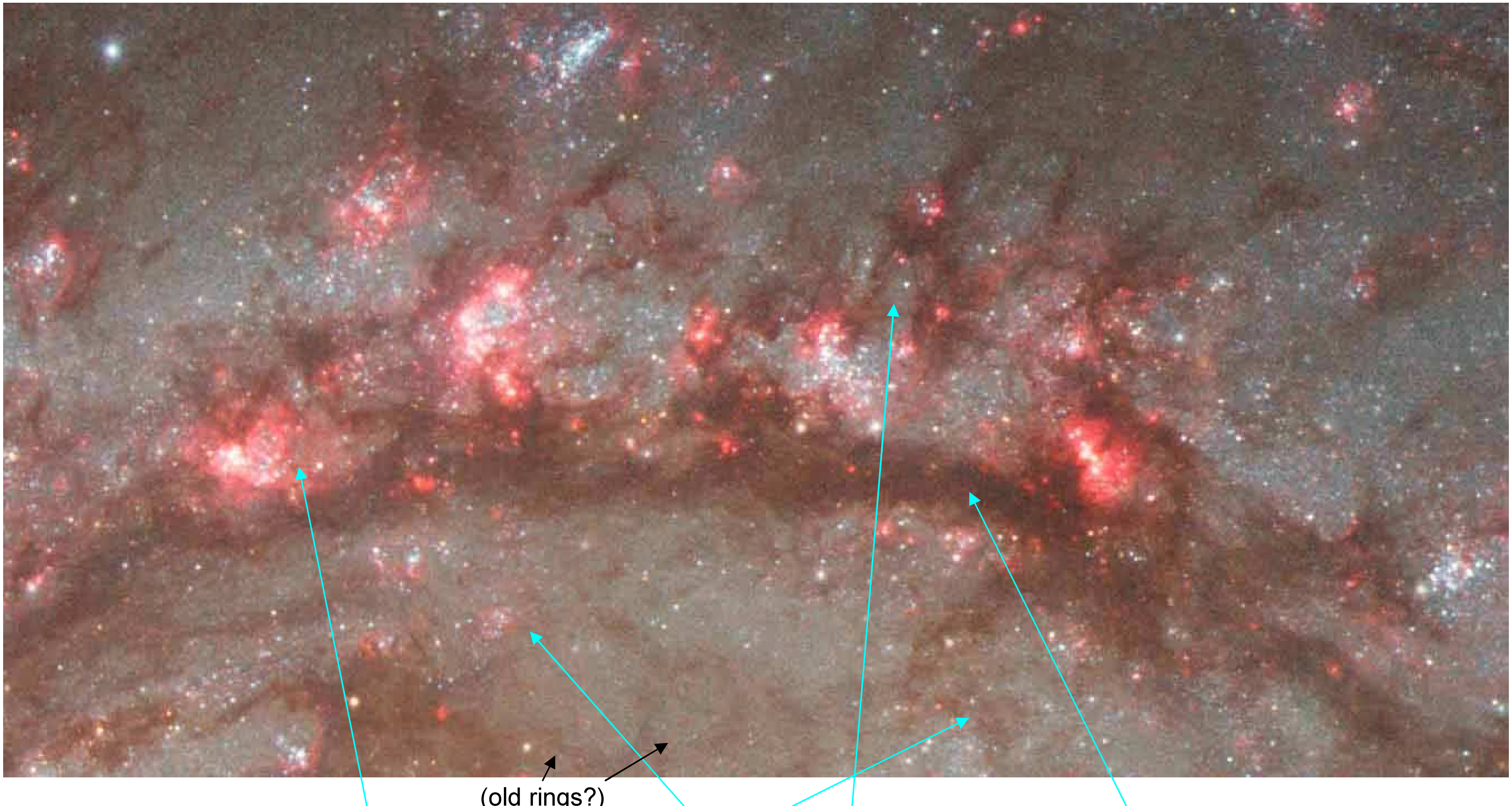
What is the equation of state for interstellar gas?

HST





The equation of state is time dependent:

(1) Ribbons & old rings of gas and dust impact the arm, (2) gas collapses,
(3) star formation breaks the gas off and accelerates it into the interarm region
(4) break-off structure is ring-like or comet-like, not spiral-like as in <grad P>

ISM is not an adiabatic or isothermal gas with automatic energy input on expansion.

Two fluid GI in Turbulent Gas

- In a turbulent gas, there is no fixed γ
  - the energy equation determines $dP/d\rho$:

$$\frac{\partial P}{\partial t} = \left(\frac{\gamma P_0}{\rho_{g,0}}\right)\left(\frac{\partial \rho}{\partial t}\right) + (\gamma - 1)(\Gamma - \Lambda) .$$

(γ=5/3)

  - Turbulent gas always dissipates. Before SF begins, there is little heating.
  - The dissipation rate is proportional to the crossing rate:

$(\gamma-1)\Lambda = \delta\sigma_g kP$ for proportionality constant δ

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Two fluid GI in Turbulent Gas

- The energy equation becomes:

$$\frac{\partial P}{\partial t} = \left(\frac{\gamma P_0}{\rho_{\rm g,0}}\right)\left(\frac{\partial \rho}{\partial t}\right) - \delta\sigma_{\rm g} k P.$$

- which has the perturbation solution:

$$P = \frac{\gamma P_0 \Sigma_{\rm g}}{\Sigma_{\rm g,0}}\left(\frac{\omega}{\omega + \delta\sigma_{\rm g} k}\right).$$

Pressure goes to 0 at the threshold of stability ω=0. This removes the minimum unstable length and the absolute stability threshold.

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Sample solutions:

Blue: Q_s = 0.5, 1, 1.5, 2 for Q_g = 1.

Red: Q_g = 0.5, 1, 1.5 for Q_s = 1.

(σ_g/σ_s = 0.5, δ = 0.5)

Blue: δ = 0, 0.1, 0.3, 0.5, 1; σ_g/σ_s = 0.5

Red: σ_g/σ_s = 0.1, 0.2, 0.3, 0.5, 1; δ = 0.5

($Q_s = Q_g = 1$)

Dimensionless parameters: $q=k\sigma_s/\kappa$, $s=\omega/\kappa$

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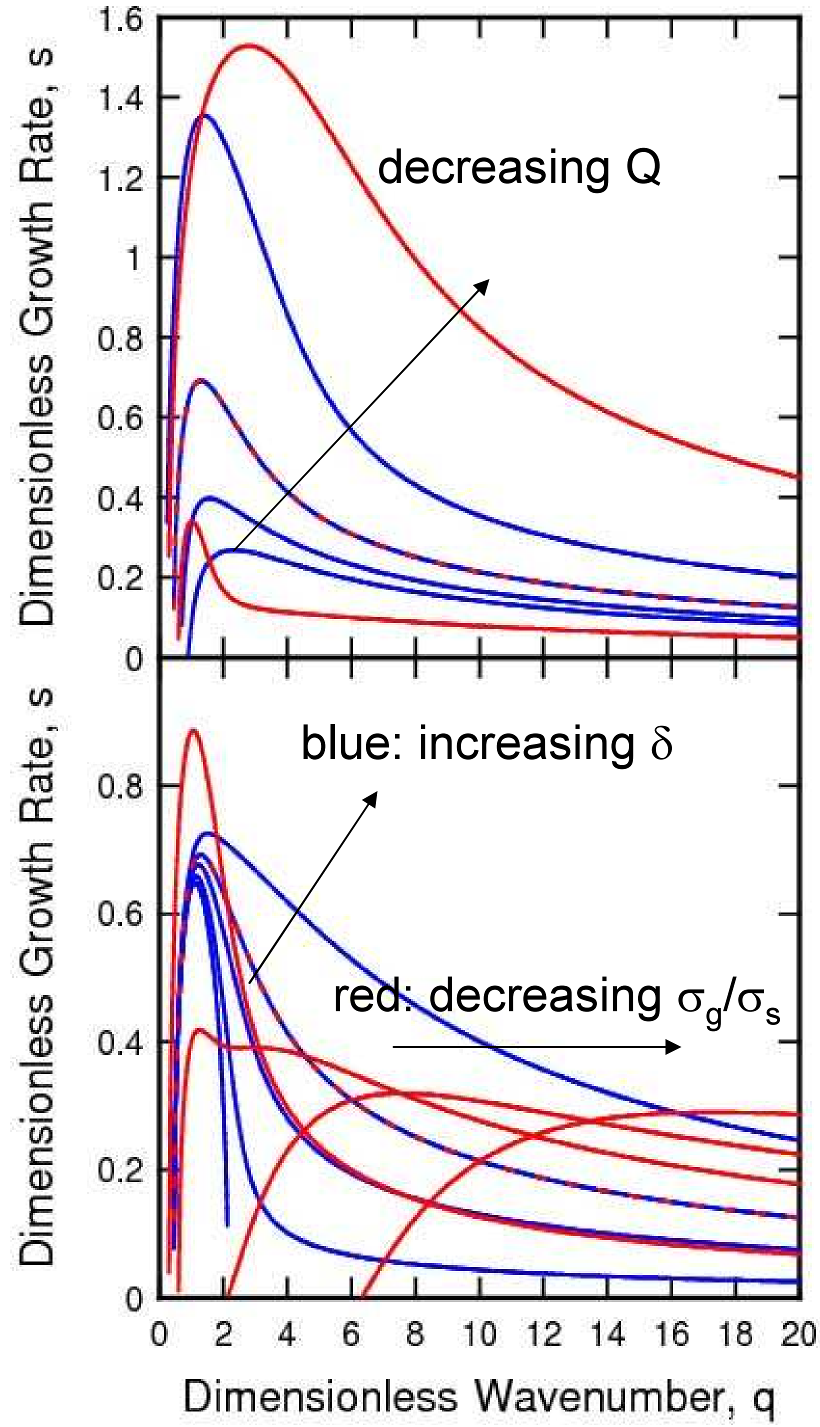
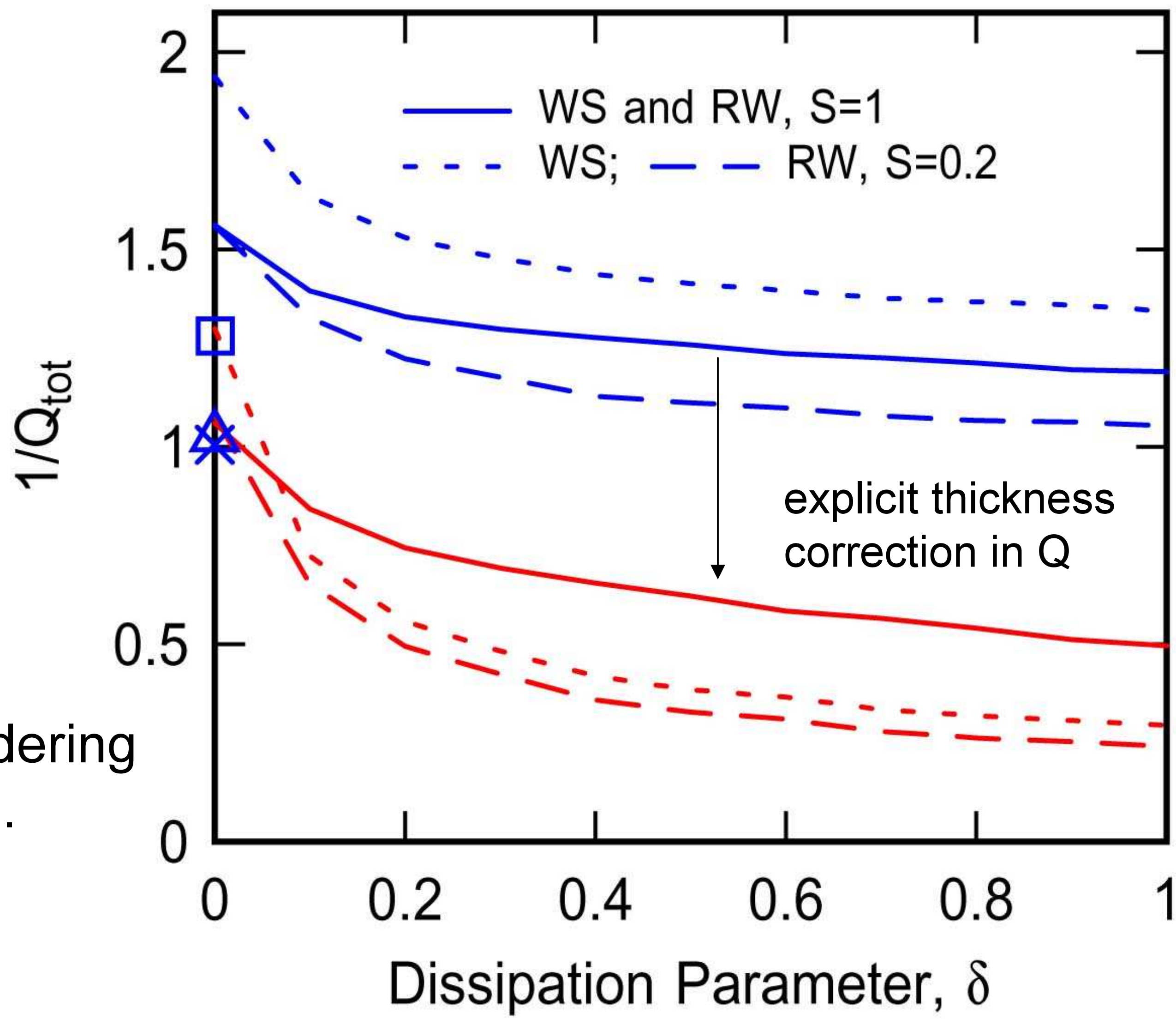


Corrections to the usual 2-fluid Q formula

WS = Wang & Silk '94
RW = Romeo & Wiegert '11



Q(2fluid) < 2 or 3 for instability when considering turbulence dissipation.

$\Sigma_{crit} > \Sigma_{crit,0} / 3$

Instabilities are 3x easier than we thought.

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SUMMARY

- H_2 is pervasive: CO clouds form by turbulence/SDW… compression & self-gravity in an H_2 –rich "murky" environment
- HI-rich (low-P) galaxies (MW, M33, …) form GMCs in cores of HI clouds
  - phase change accompanies cloud assembly
- H_2-rich (high-P) galaxies (M51) form GMCs by assembling other GMCs
  - H is in shielding layers (the "Spitzer Shield")
- SF beads-on-a-string suggest collapse following SDW compression ("converging flows")
  - transition from diffuse to self-gravitating in the SDW arm
- Azimuthal variations in SFR show KS law (sometimes in HI)
  - Law I: Σ_{SFR} vs Σ_{gas} , Law II: Σ_{SFR} & Σ_{gas} vs radius
- Outer disks have SF (in spiral arms) even to Σ_{HI} ~ 1 M_O/pc^2
  - Gravitational instabilities (cloud formation, SDW) active until Σ/Σ_{crit}~0.3