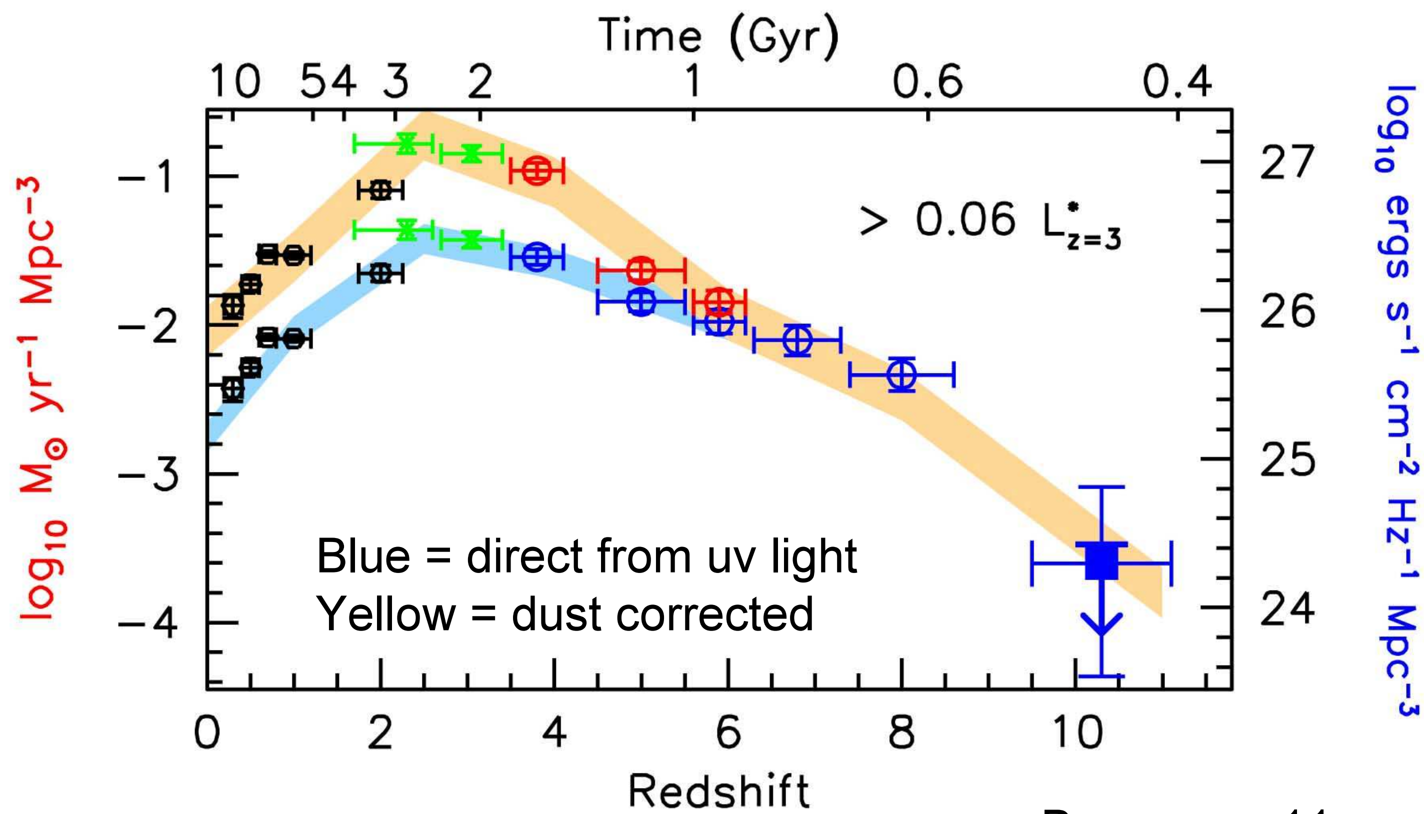
Cosmic Evolution of Star Formation Processes in Spiral Arms

Bruce Elmegreen
IBM T.J. Watson Research Center
Lin-Shu Symposium, Beijing, 6-25-13

Star Formation History of the Universe



Bouwens +11

Reionization requires a SFR ~ 0.018([1+z]/8)^3 (Shull +12)
which is consistent with reionization by z~7

On cosmological scales: accretion determines the star formation rate

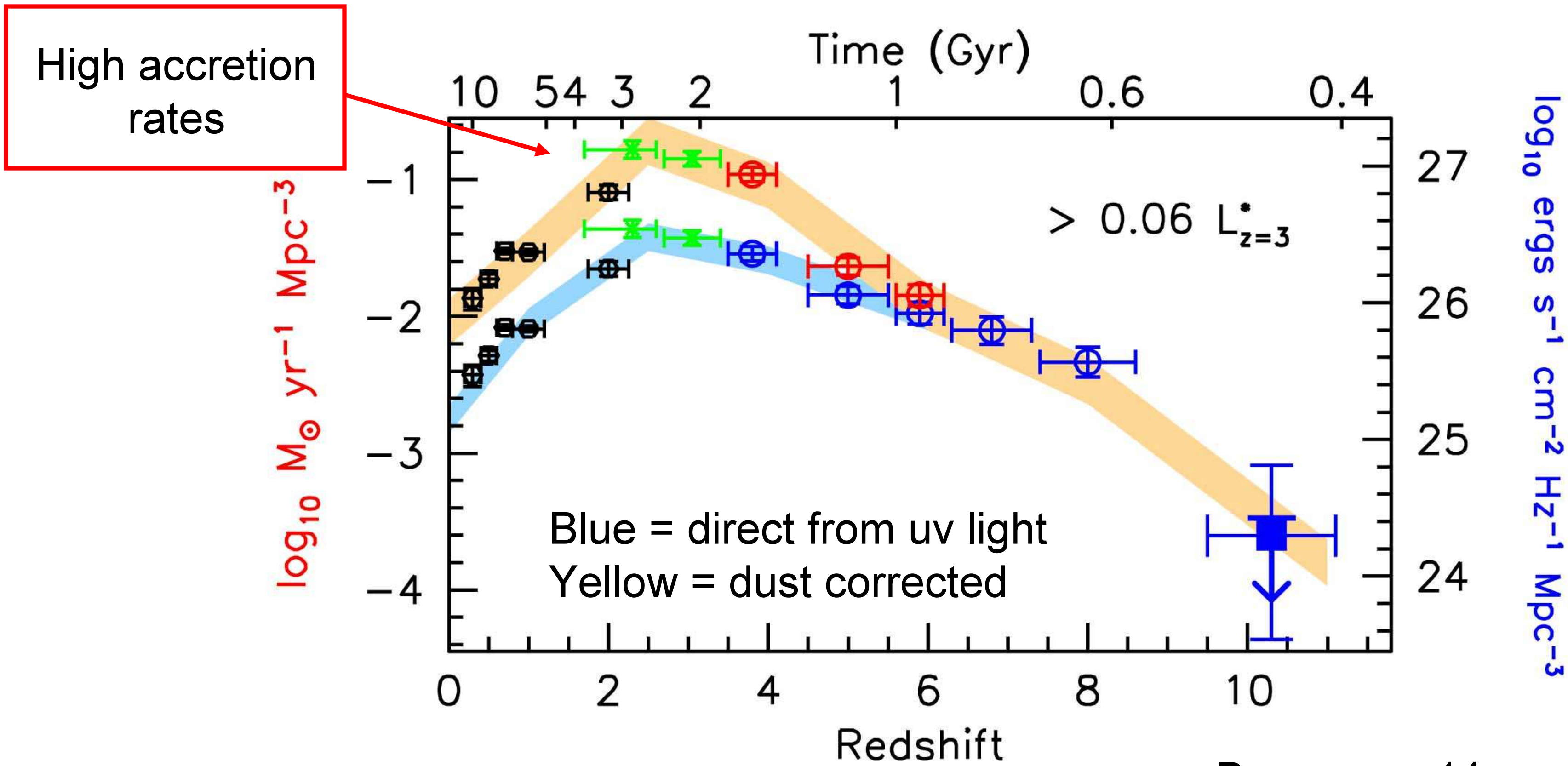
For a galaxy:

$$\frac{d\,M_{gas}}{dt} = \left.\frac{d\,M_{gas}}{dt}\right|_{accretion} - SFR$$

where $SFR = A\,M_{gas}^{n}$

solution for time >> $\frac{M_{gas}}{SFR}$ is $SFR \sim \left.\frac{d\,M_{gas}}{dt}\right|_{accretion}$

Star Formation History of the Universe



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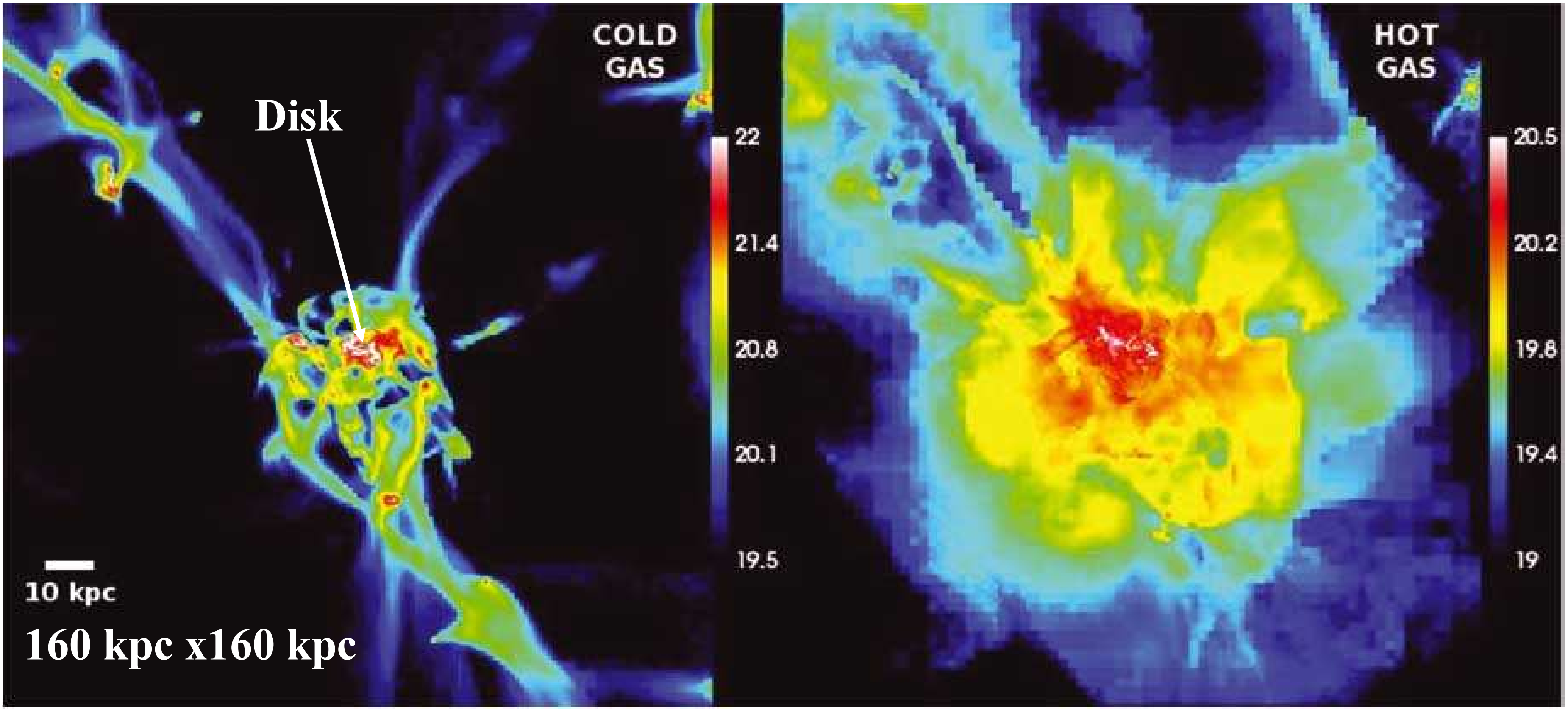


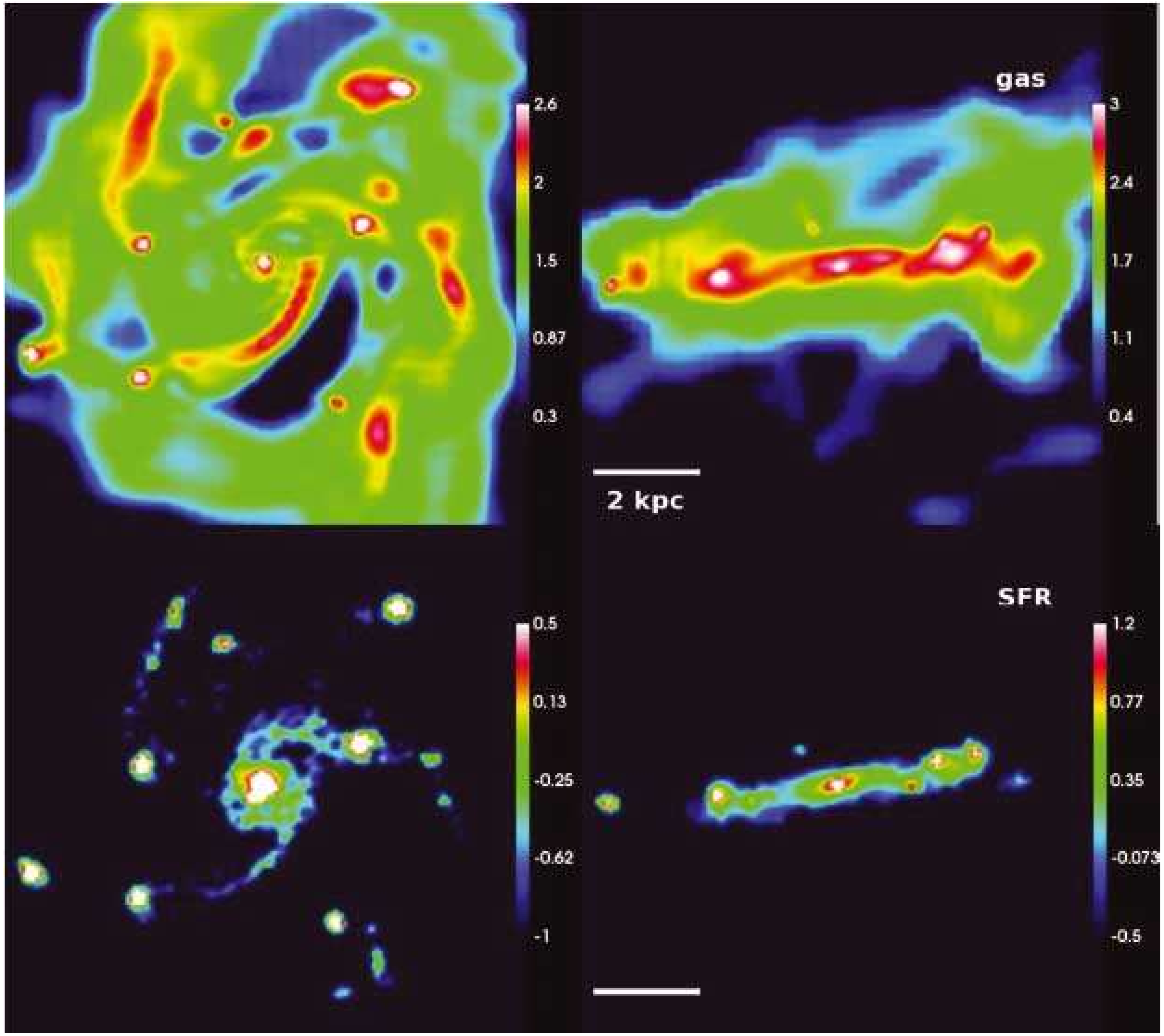
Disks are clumpy during high accretion

simulation of cold and hot flows with disk galaxy formation.
σ/V_{rot} high because of inflow energy & high Σ_{gas} (Q_{Toomre}~1)

Ceverino, Dekel & Bournaud 2010

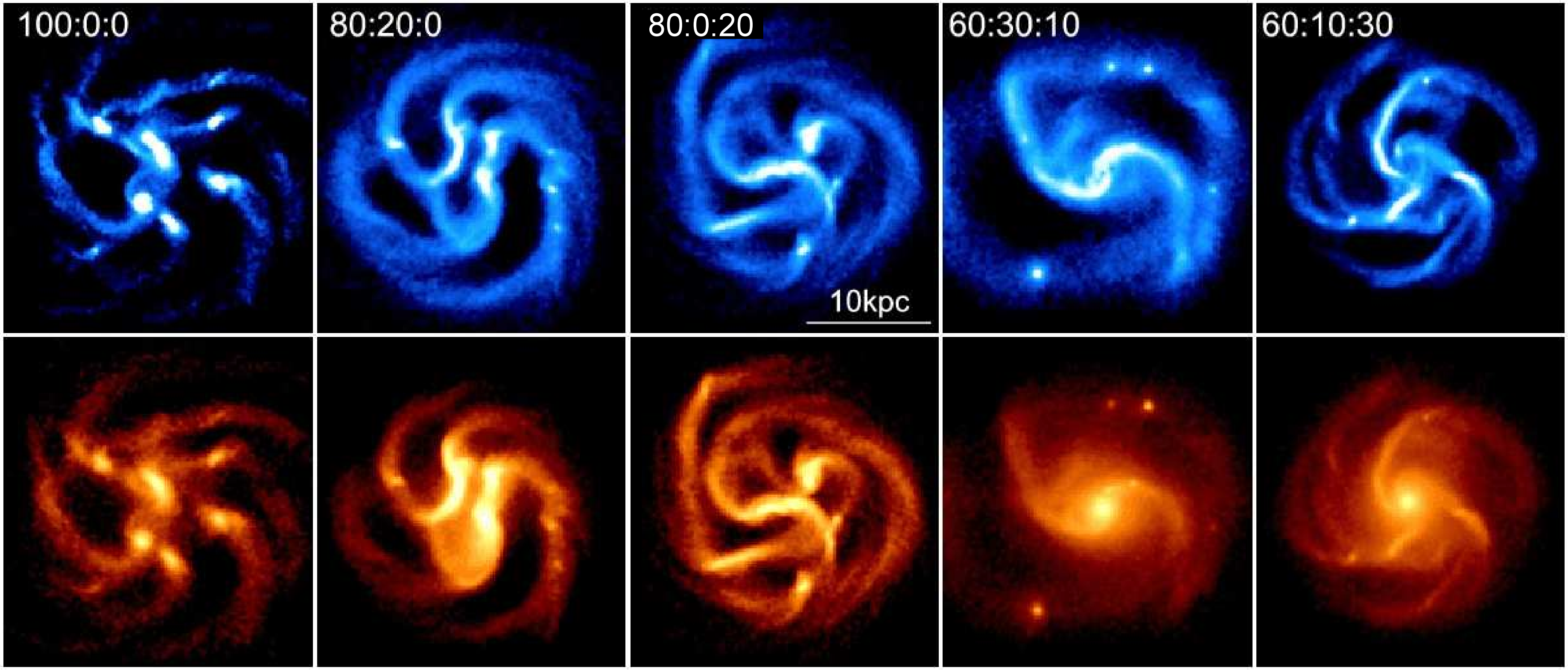
Gas

SFR



Clumps form by gravitational instabilities and migrate to the center because of torques

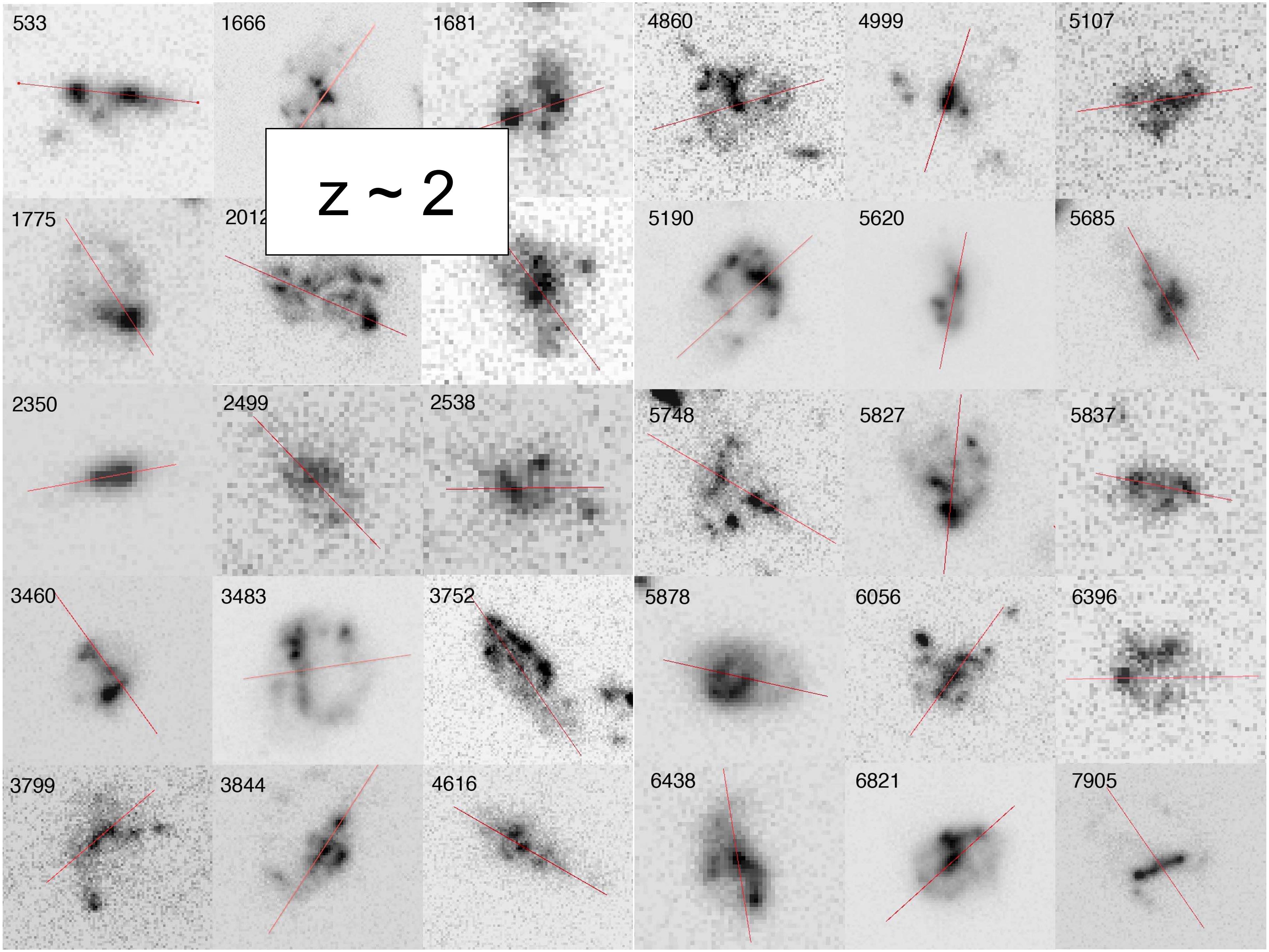
Ceverino +10



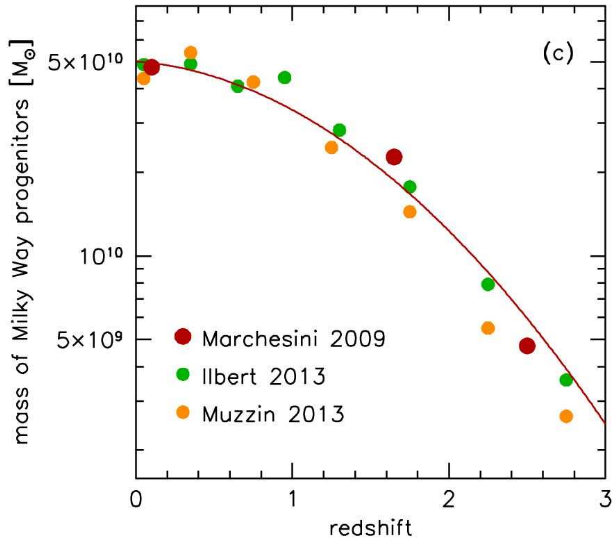
Various stellar mass fractions in disk:bulge:halo

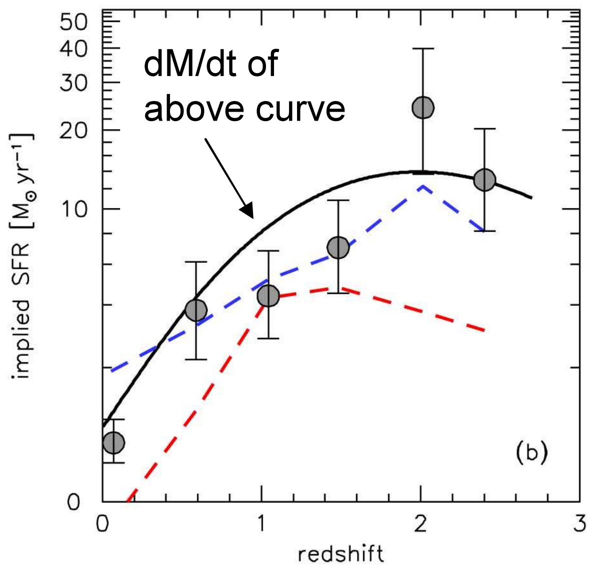
σ_{gas}=50 km s^{-1}, 3x10^6 particles each for gas, stars, DM;
30 pc resolution, $M_{gas}=M_{stars}$ =6x10^{10} M_O, M_{halo}=0.5(M_{stars}+M_{gas})
Bournaud & Elmegreen 09

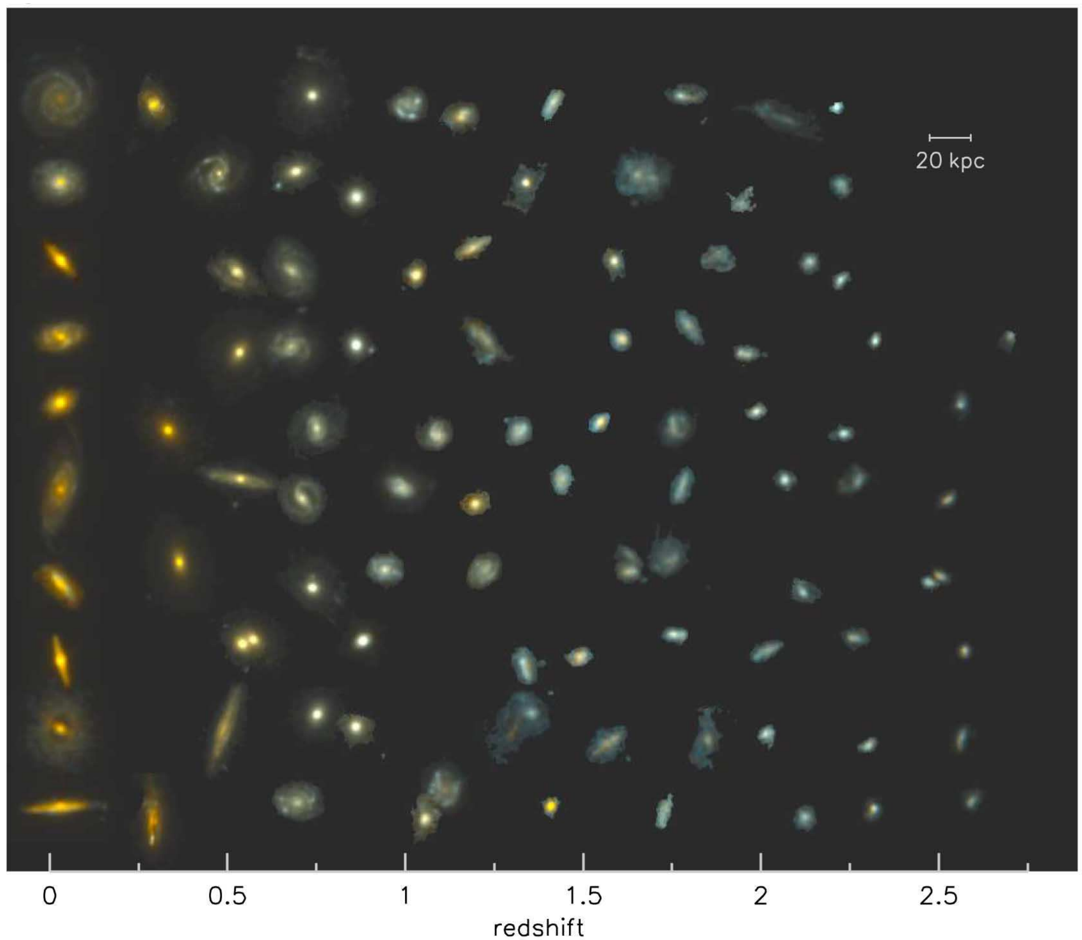
Giant clump formation requires >80% of the stars (and all of the gas)in a disk. Makes even minor mergers (10:1) unlikely during galaxy build-up. *Requires smooth gas accretion*.


533
1666
1681
4860
4999
5107
z ~ 2
1775
2012
5190
5620
5685
2350
2499
2538
5748
5827
5837
3460
3483
3752
5878
6056
6396
3799
3844
4616
6438
6821
7905

Galaxies at different redshifts with space density like the MW







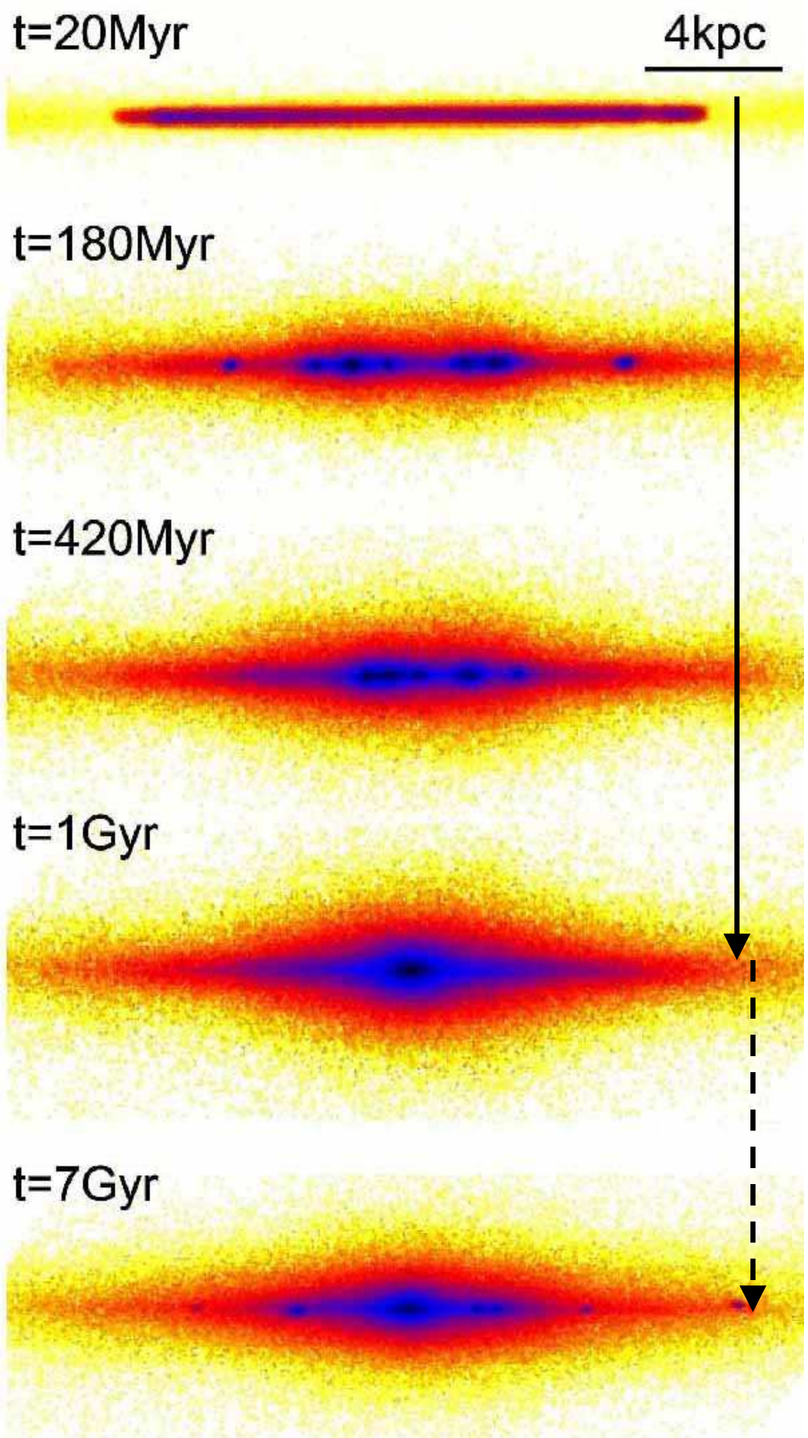
MW type galaxies built by gas accretion and star formation -- not mergers.

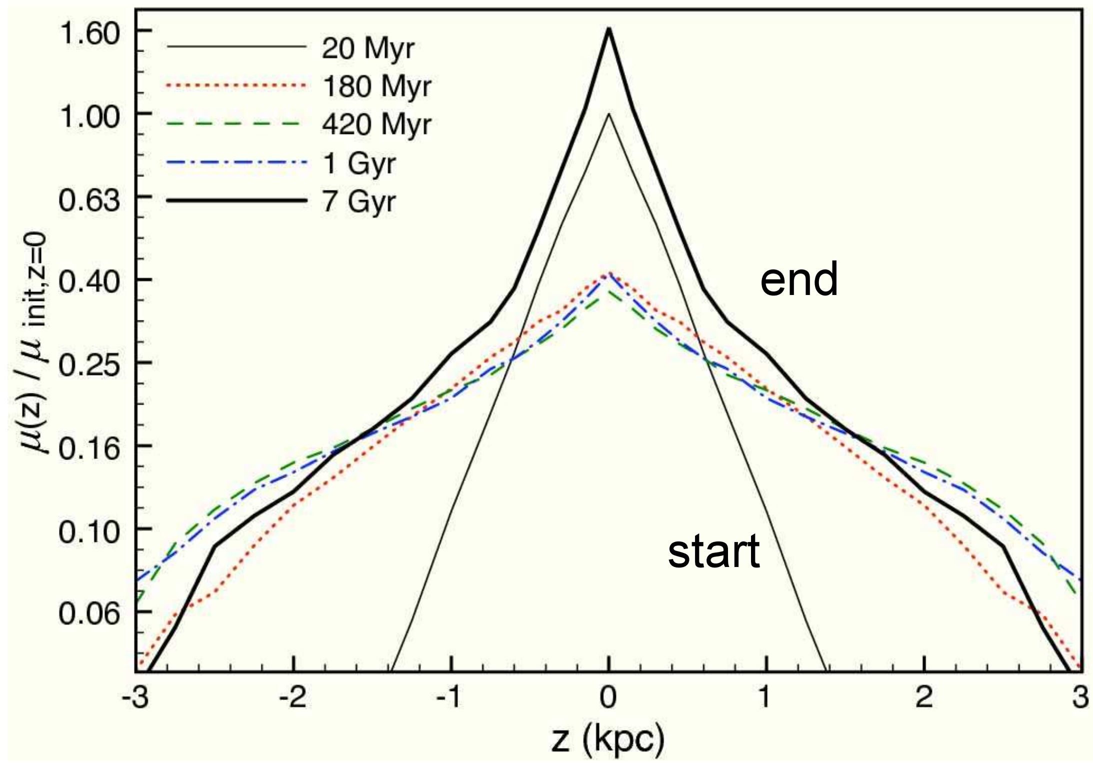
van Dokkum +13

Clumpy disks should also be *thick disks*

- In Milky Way, the similarity in α/Fe (Melendez +08), K-giant abundances (Bensby +10) and ages for bulge and thick disk

  → bulge and thick disk formed at the same time.
- High σ_{gas} at z~2 makes clumps big
- High σ_{gas} at z~2 makes disk thick
  - big clumps stir disk and drive accretion (Elmegreen +06, Genzel +08, Bournaud +09)
- z~2 disks don't look like mergers
- If thick disks made by clump stirring, then the scale height should be nearly constant with radius (i.e., internal forcing proportional to mass)
  - mergers and harassment make thick disks flare (Bournaud +09)





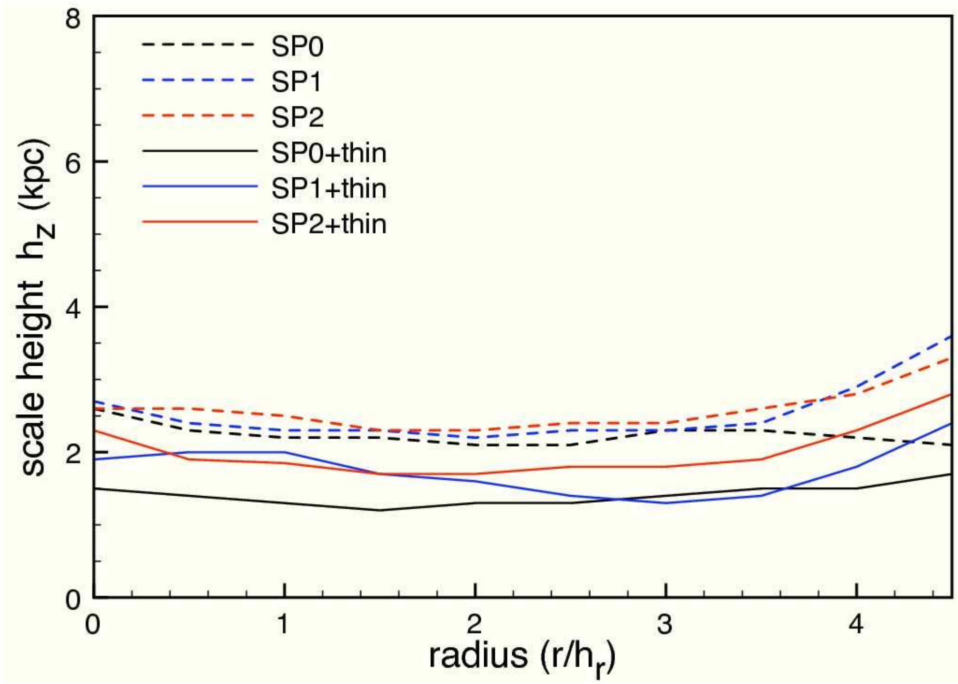
First Gyr, clumps build thick disk

Next 6 Gyr, gas added slowly to the outer disk with the average angular momentum of the inner disk builds the thin disk without destroying the older thick disk

Bournaud, Elmegreen + 09

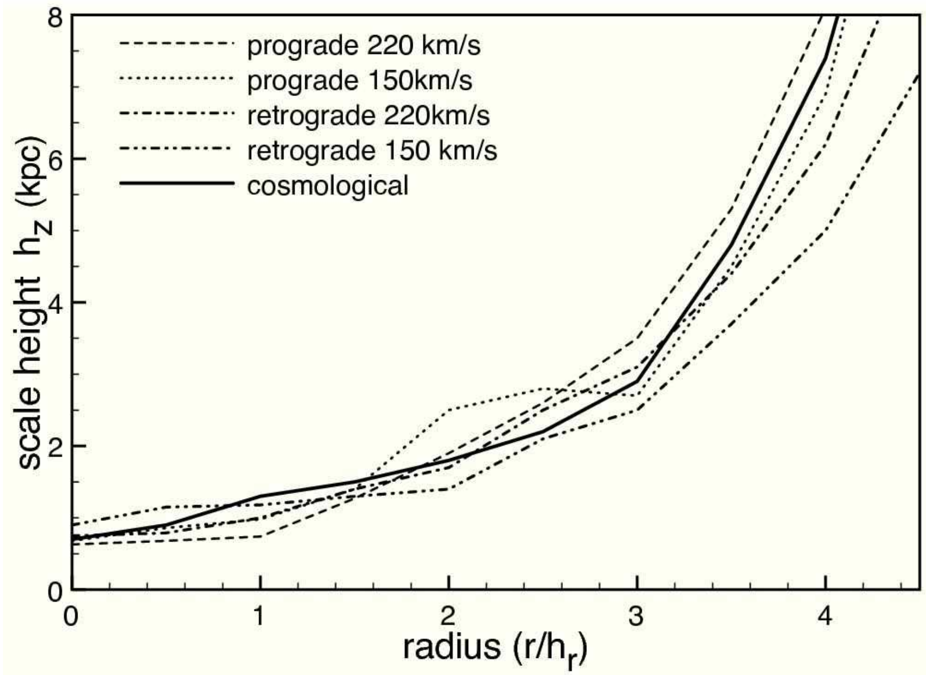
Simulations:

Thick disk scale height is independent of radius



Minor mergers (10:1)
and a cosmological merger
make thick disks with increasing scale heights

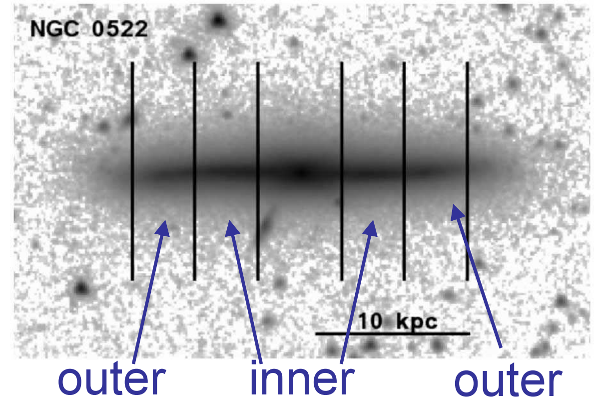
(35 deg orbital plane;
30 kpc impact parameter;
1M particles in G,S,DM;
20% bulge, 500 pc initial scale height)

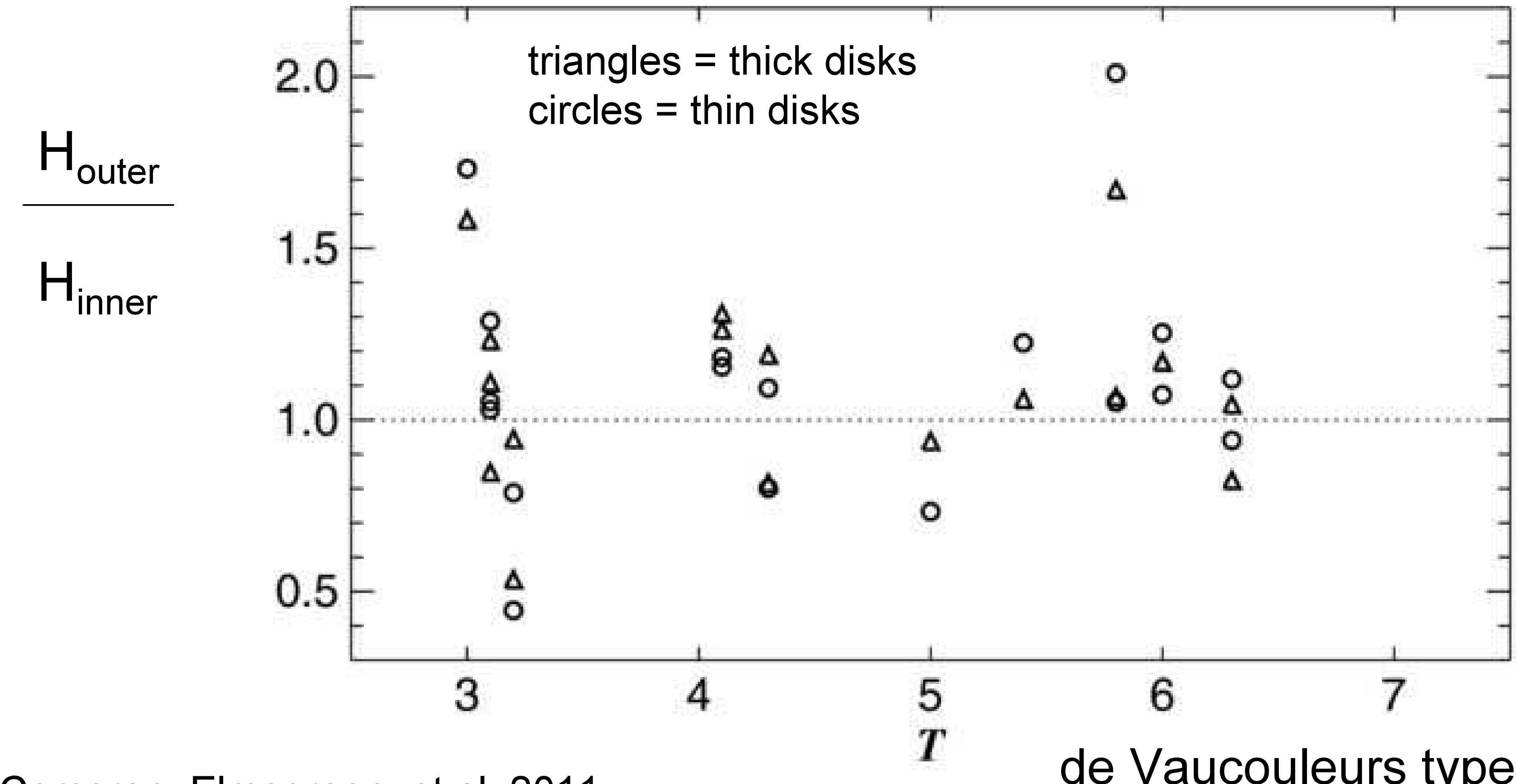


Bournaud, Elmegreen + 09

Observations:

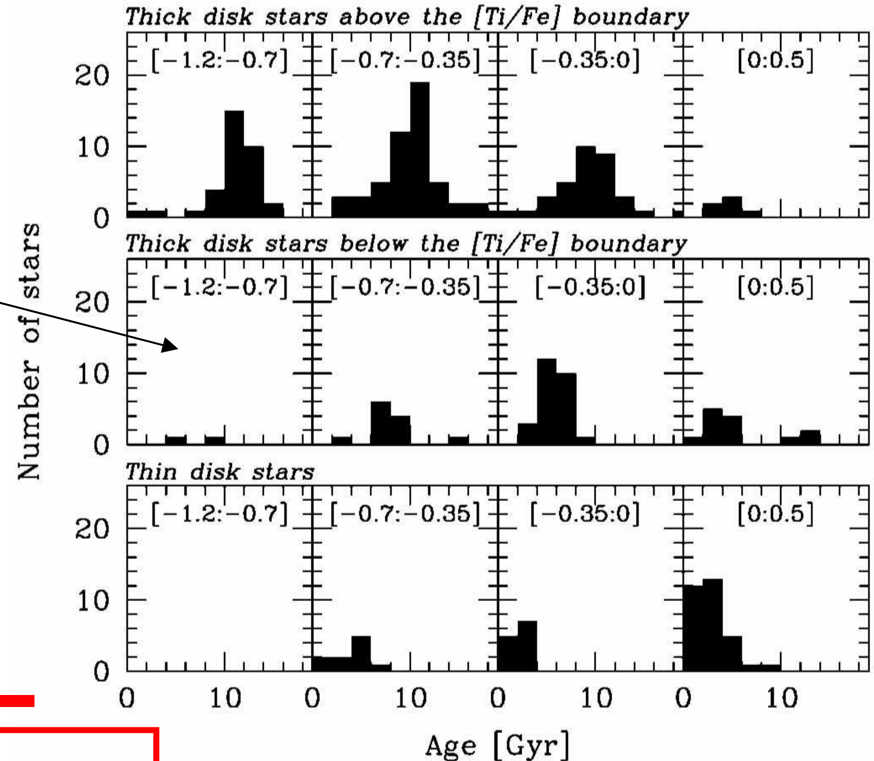
Thick disk scale height independent of radius
(46 edge-on galaxies observed with Spitzer at 3.4 μm)

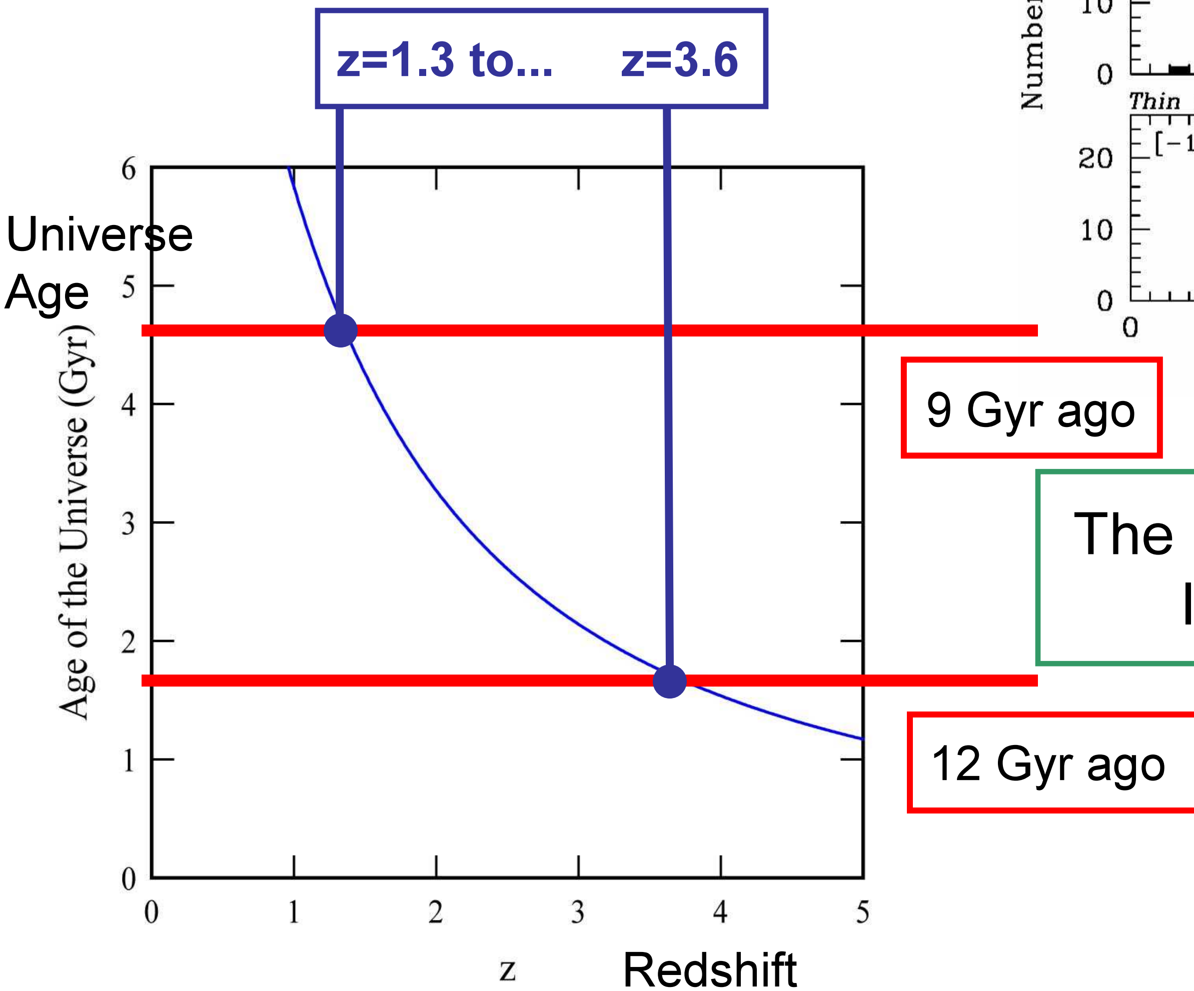




Comeron, Elmegreen, et al. 2011

Milky Way thick disk (defined kinematically) has metallicities up to solar.
The most metal rich are ~8-9 Gyr old.
The thick disk formed from ~12 to ~9 Gyr

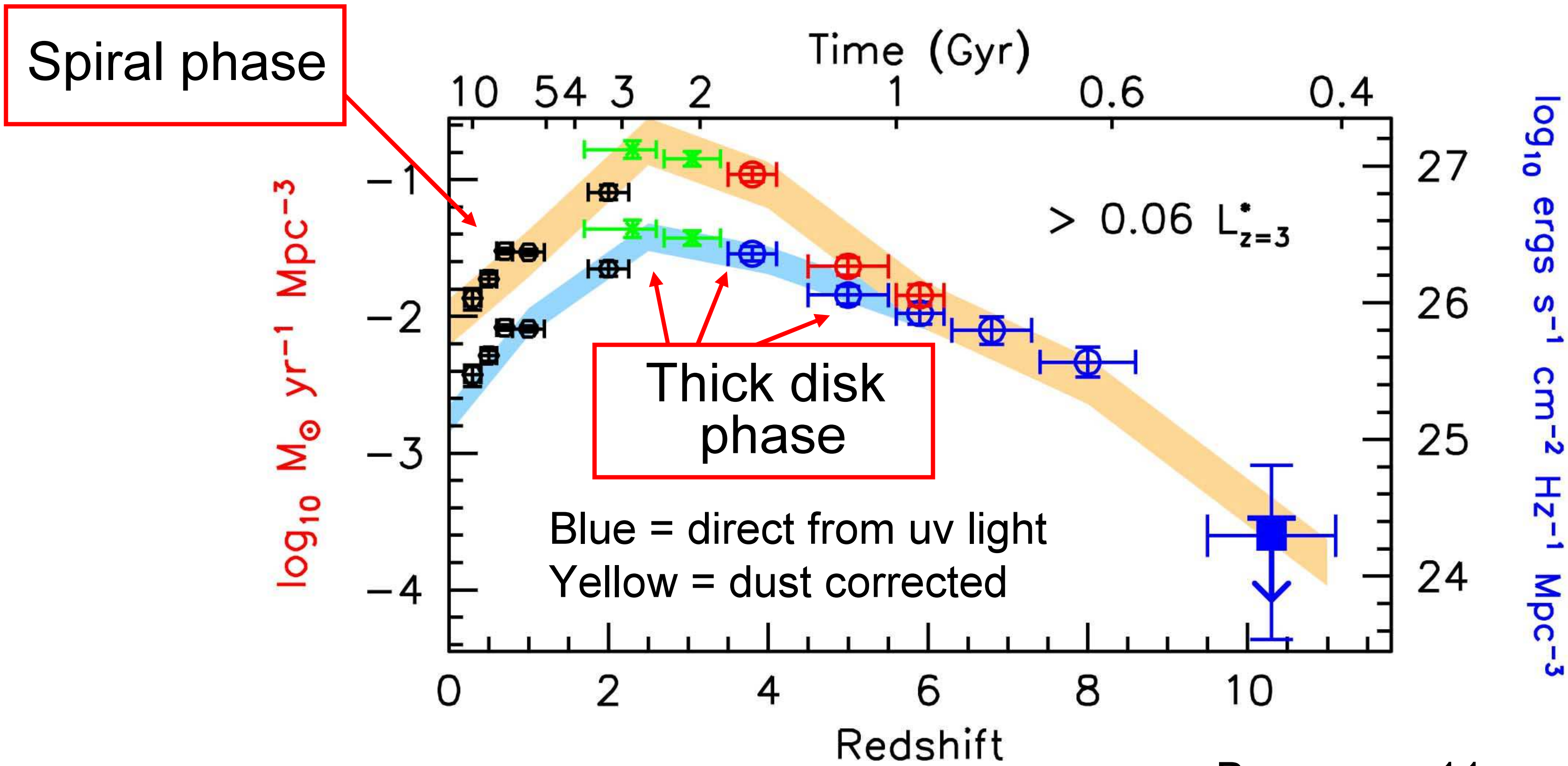




The Milky Way's clumpy phase lasted until ~9 Gyr ago

Bensby +07

Star Formation History of the Universe



Bouwens +11

Reionization requires a SFR ~ $0.018([1+z]/8)^3$ (Shull +12)
which is consistent with reionization by z~7

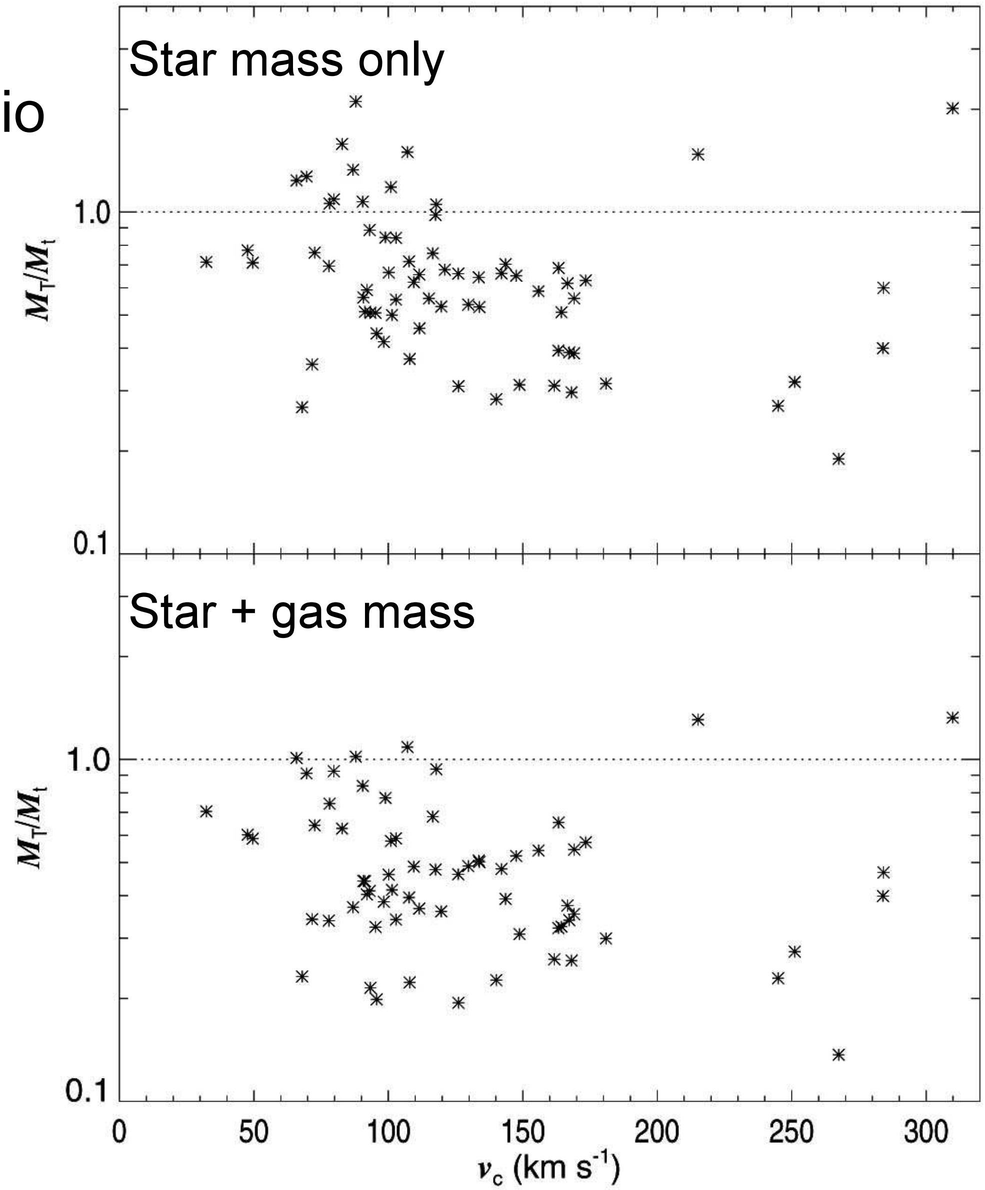
Thick disk / Thin disk mass ratio versus circular velocity

Assumes conservative ratio of

$[M/L]_{Thick} / [M/L]_{thin} \sim 1.2$

(gives the least thick disk mass)

Thick disks contain about 1/3 of the total disk mass



Comeron, Elmegreen, et al. 2012
(based on Spitzer 3.6 mm survey of vertical disk light profiles)

The thick disk stellar mass is $1\text{-}4 \times 10^{10}\ M_O$ for V_c = 200 km/s.

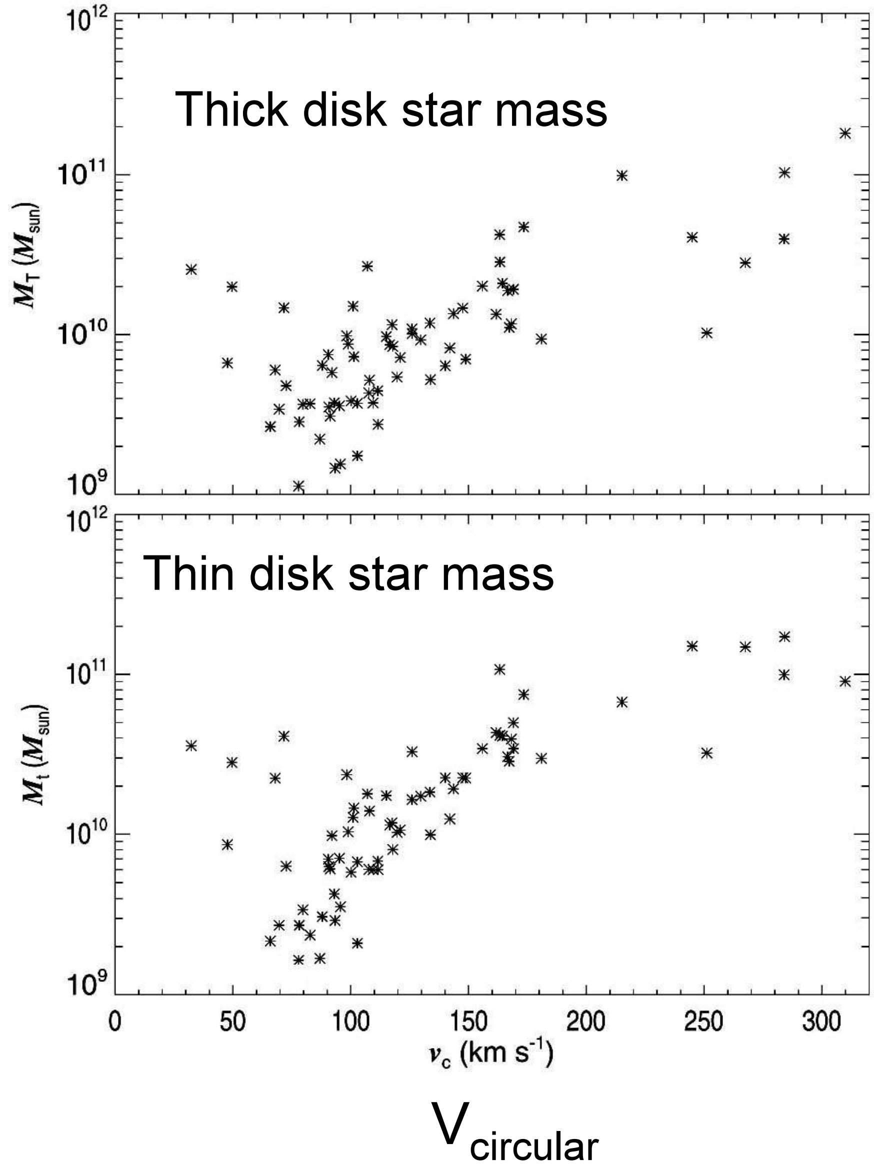
That is from a *high* SF rate of 10-20 M_O/yr for ~ 1-2 Gyr

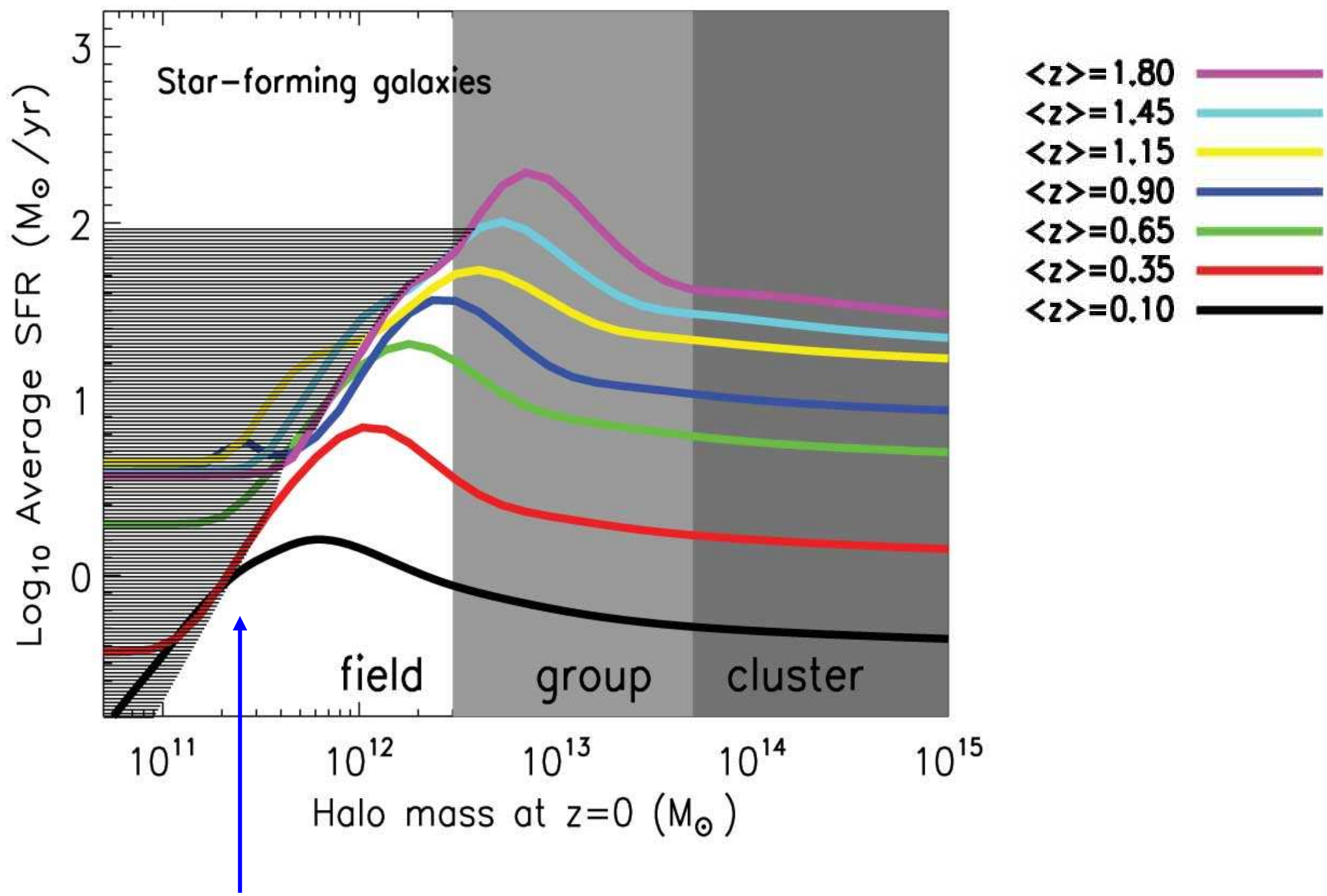
(the duration of the clumpy phase)

The thin disk stellar mass is $4\text{-}8 \times 10^{10}\ M_O$ for V_c = 200 km/s.

That is from a low SF rate of 4-8 M_O/yr for ~ 10 Gyr

(the duration of the spiral phase)



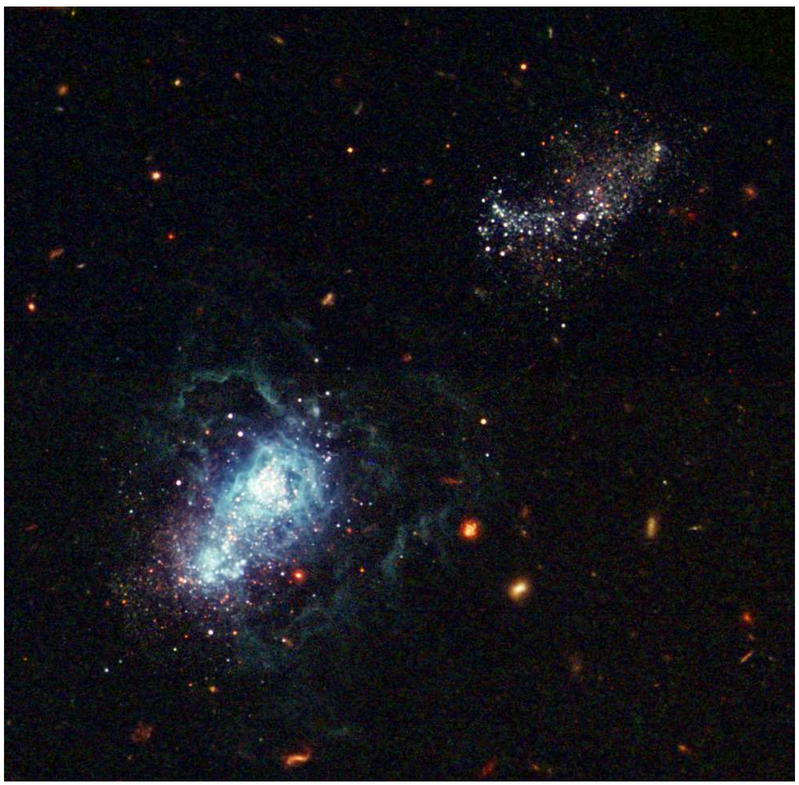


Downsizing: today's "young galaxies" are starbursting dwarfs

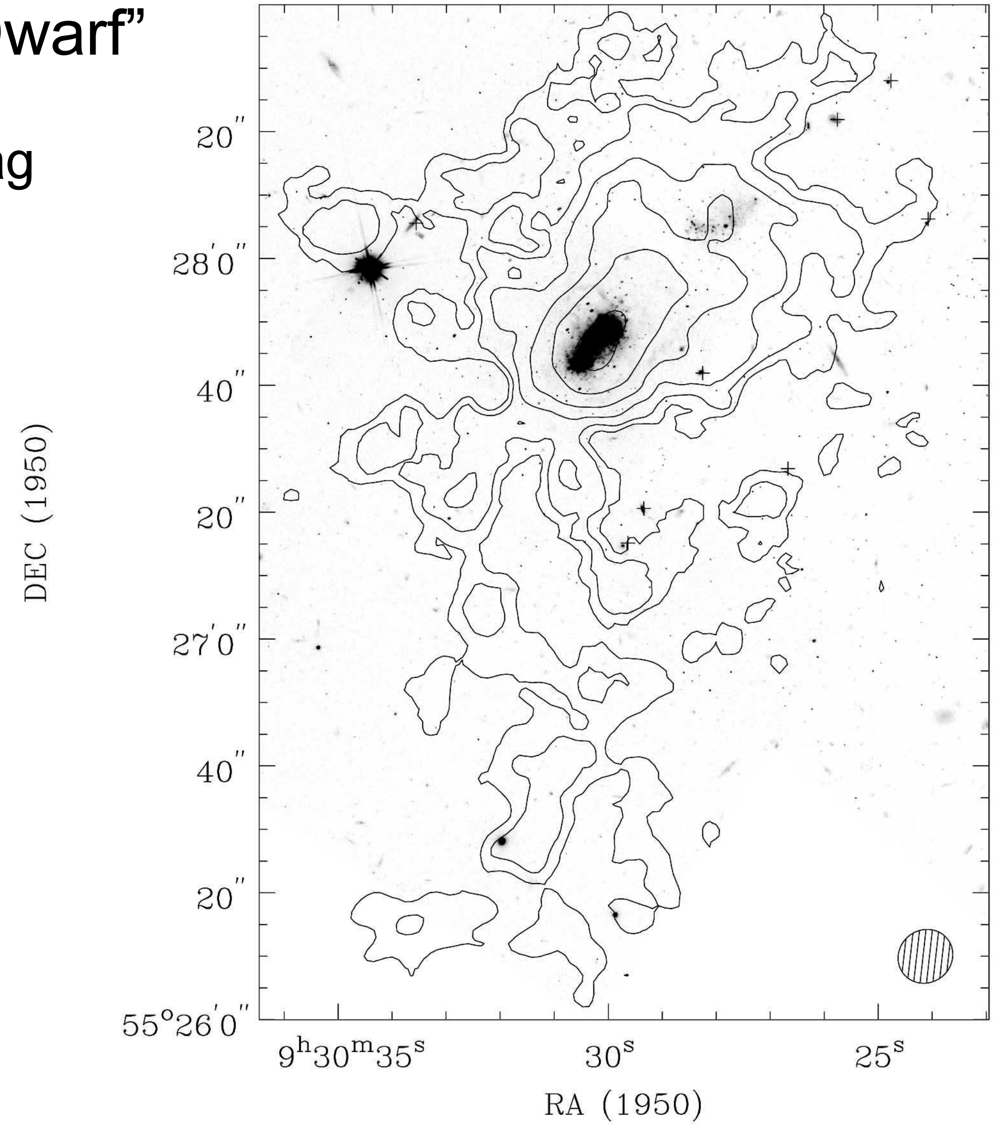
Wang +13

I Zw 18, a “Blue Compact Dwarf”

M_{dyn} = 2.6x10^8 M_O, M_B = -15.4 mag
metallicity ~ 0.02 Z_O



HST

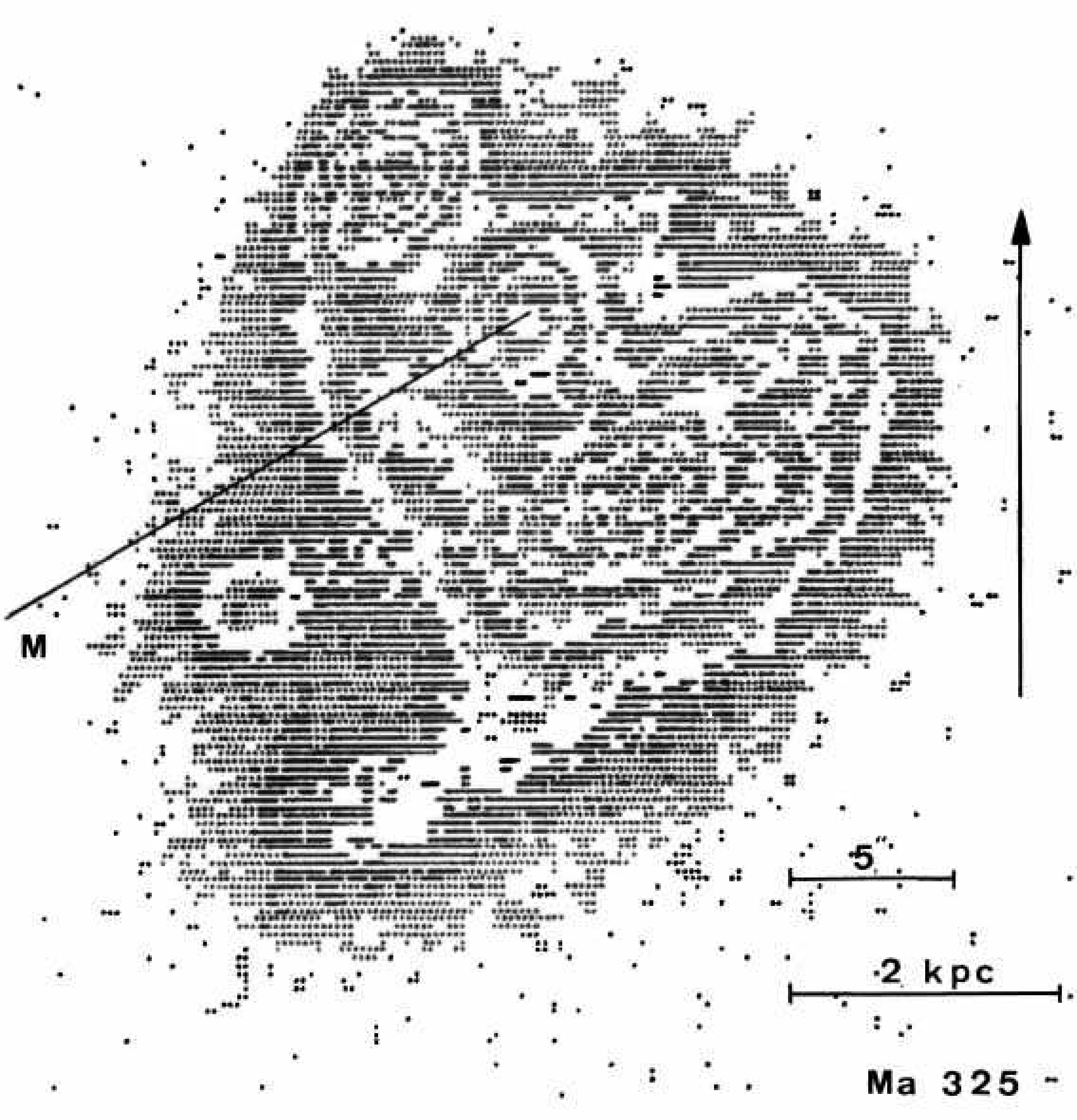


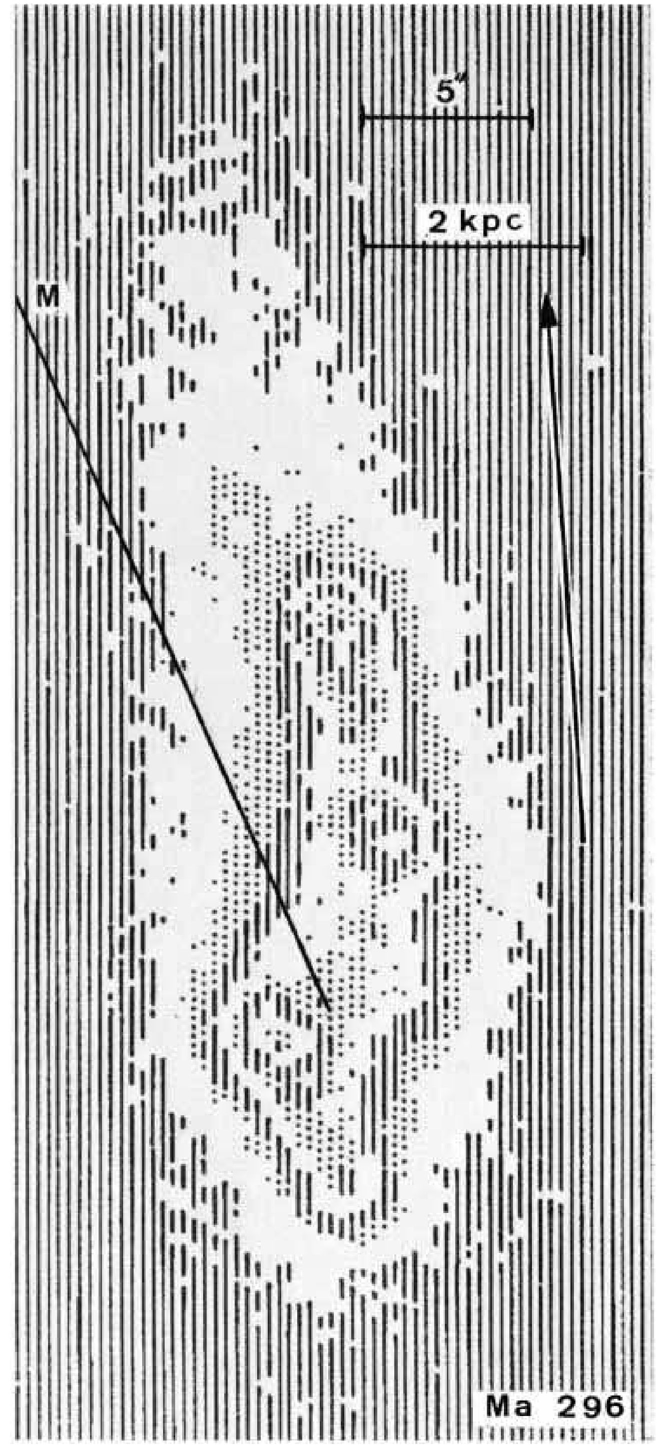
van Zee +98

Summary 1

- Star formation on cosmic scales is driven by gas accretion
- Fast-accreting galaxies are clumpy (gas dominated)
  - Clumpy disks are thick disks
- The main SF phase in a disk galaxy occurs when it is clumpy
  - accounts for 1/3 of a disk's mass
- Star Formation in spirals occurs later, and is less active
- The Milky Way grew by gas accretion (not mergers)
- The Milky Way ended its clumpy (thick) phase at z~1, which was ~9 Gyrs ago
  - then the MW could support a spiral wave (models: Cacciato +12)
  - the sun formed in a "spiral" galaxy, not a clumpy galaxy
- Lower mass galaxies end their accretion/clumpy phase later

- Next: rare clumpy massive galaxies in the local universe





"Clumpy Irregular Galaxies"
Casini & Heidmann 1976

Casini & Heidmann 76ab and Maehara +88 discovered local clumpy irregular galaxies of normal size:

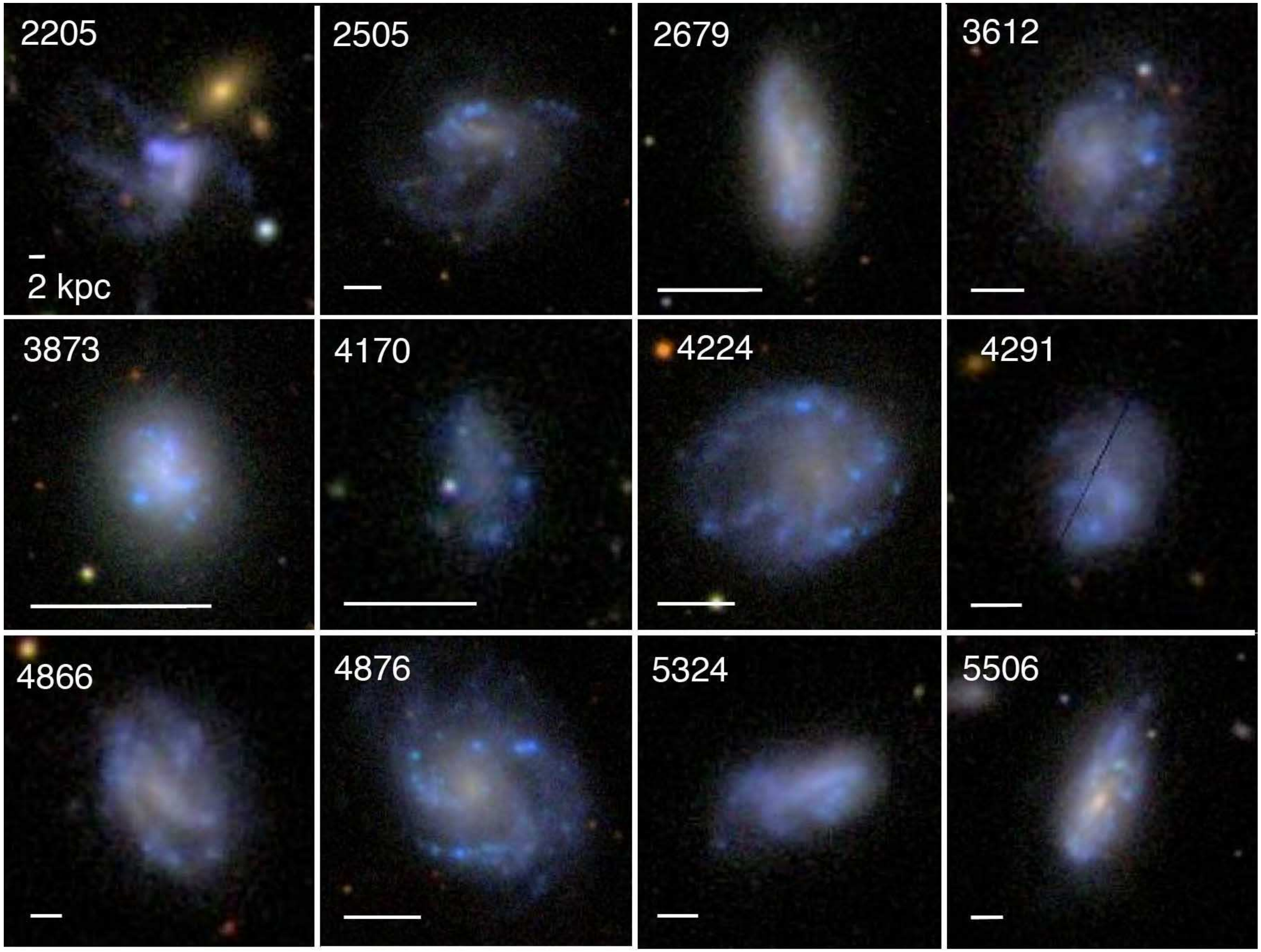
Markarian 296, 325, 7, 8 (ultraviolet galaxies)
Kiso UV excess galaxies 1618+378, 1624+404, 1626+413, and Mrk 297

Casini & Heidmann 1976:

Following a scheme proposed as a working hypothesis by Casini *et al*. (1974) for the recent production of galaxies, these Ic's could still be in a turbulent or fragmented state, with large cells where the rate of star formation is high. At a later stage, these galaxies might settle down to a more classical morphological type if their internal total energy is negative, or disrupt if it is positive.

A recent study of clump properties in Kiso clumpy galaxies, using SDSS

These galaxies are also asymmetric with irregular spiral arms



Elmegreen + 2013

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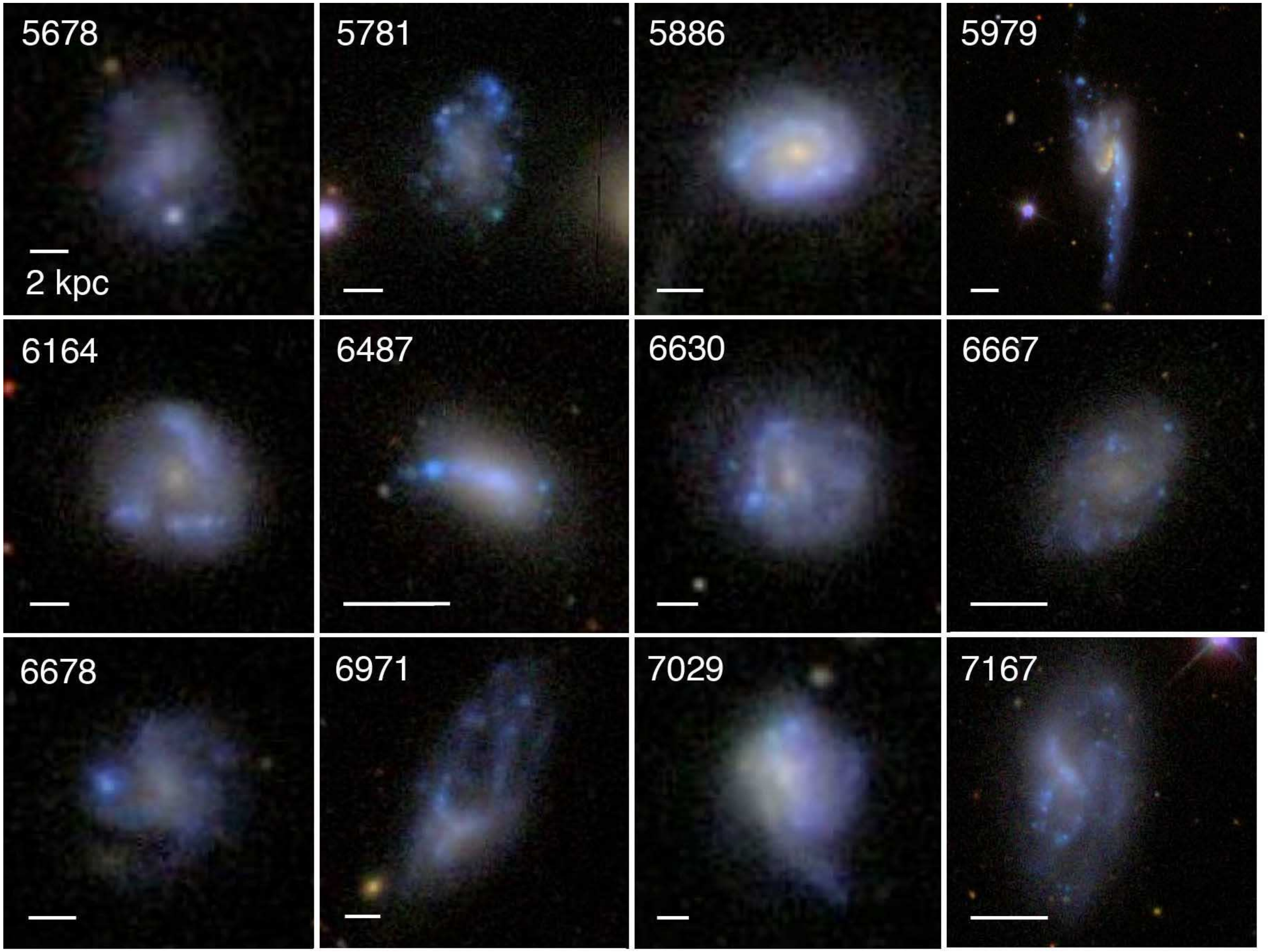

Elmegreen + 2013

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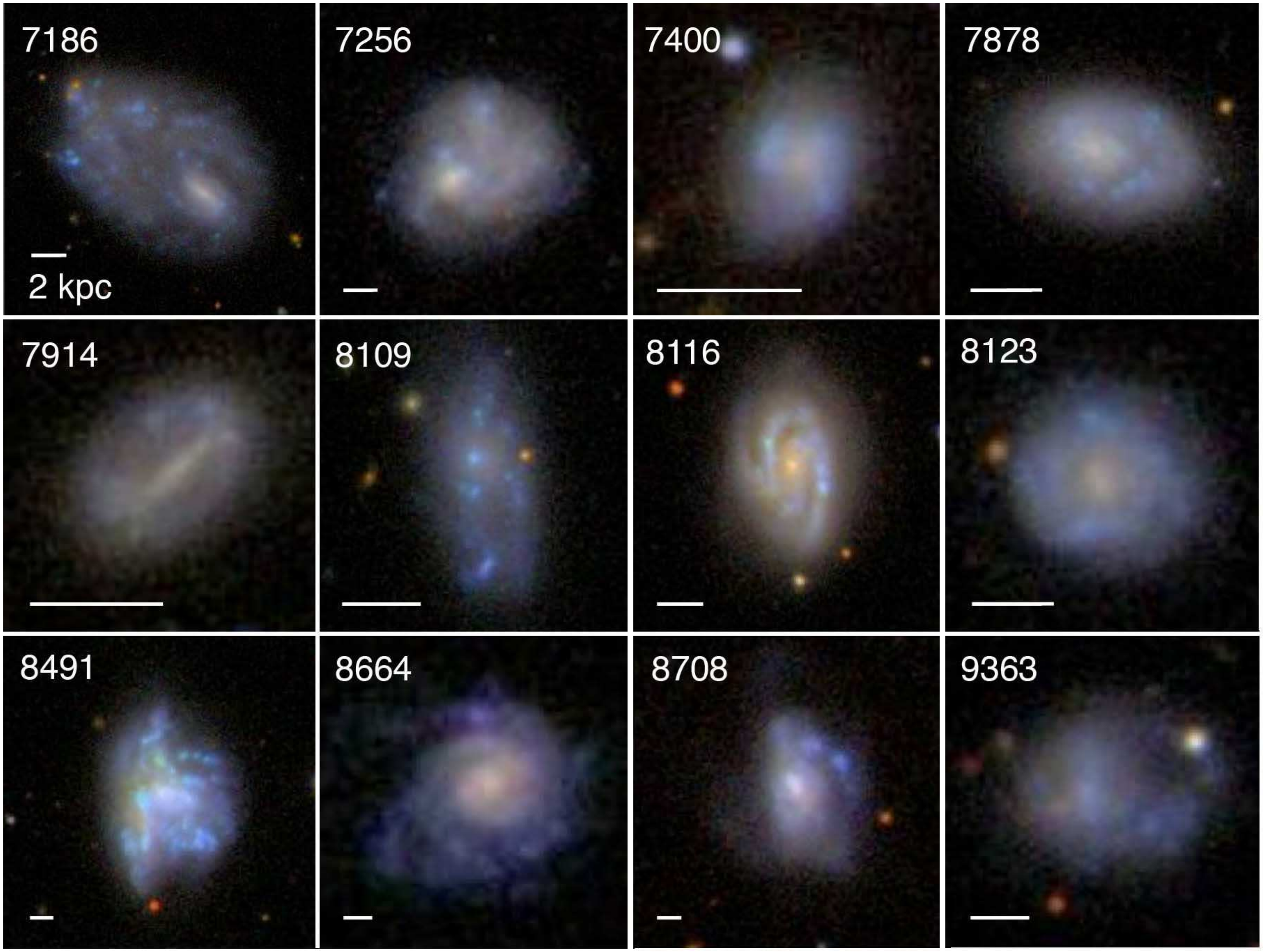
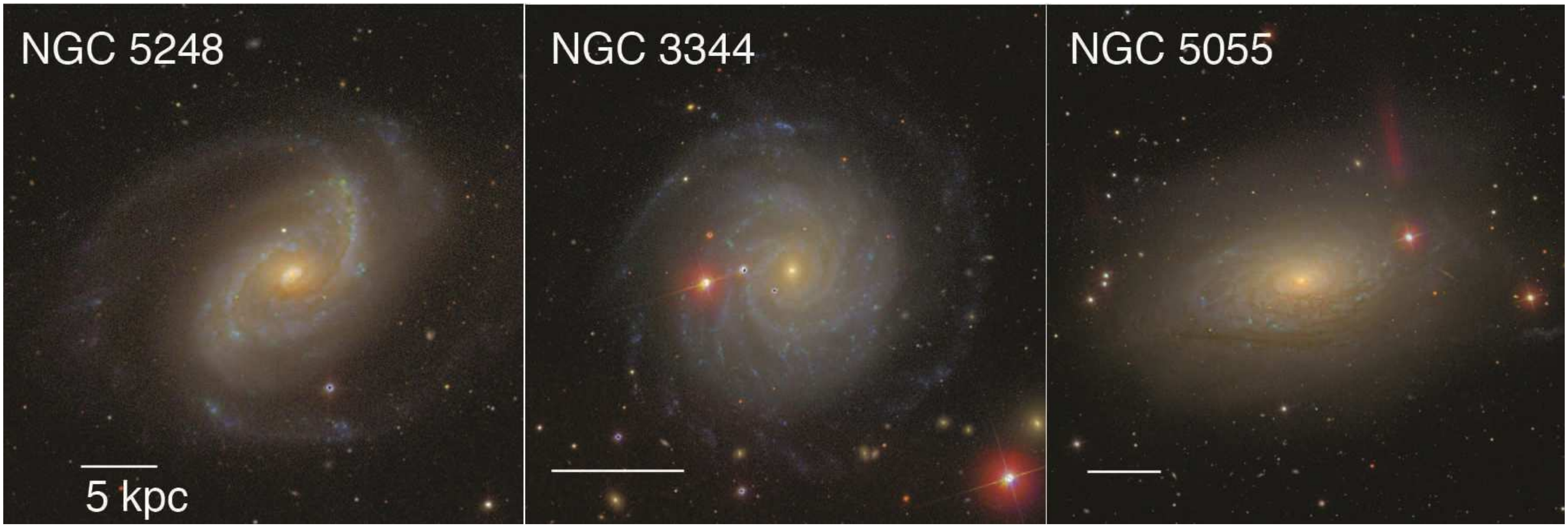


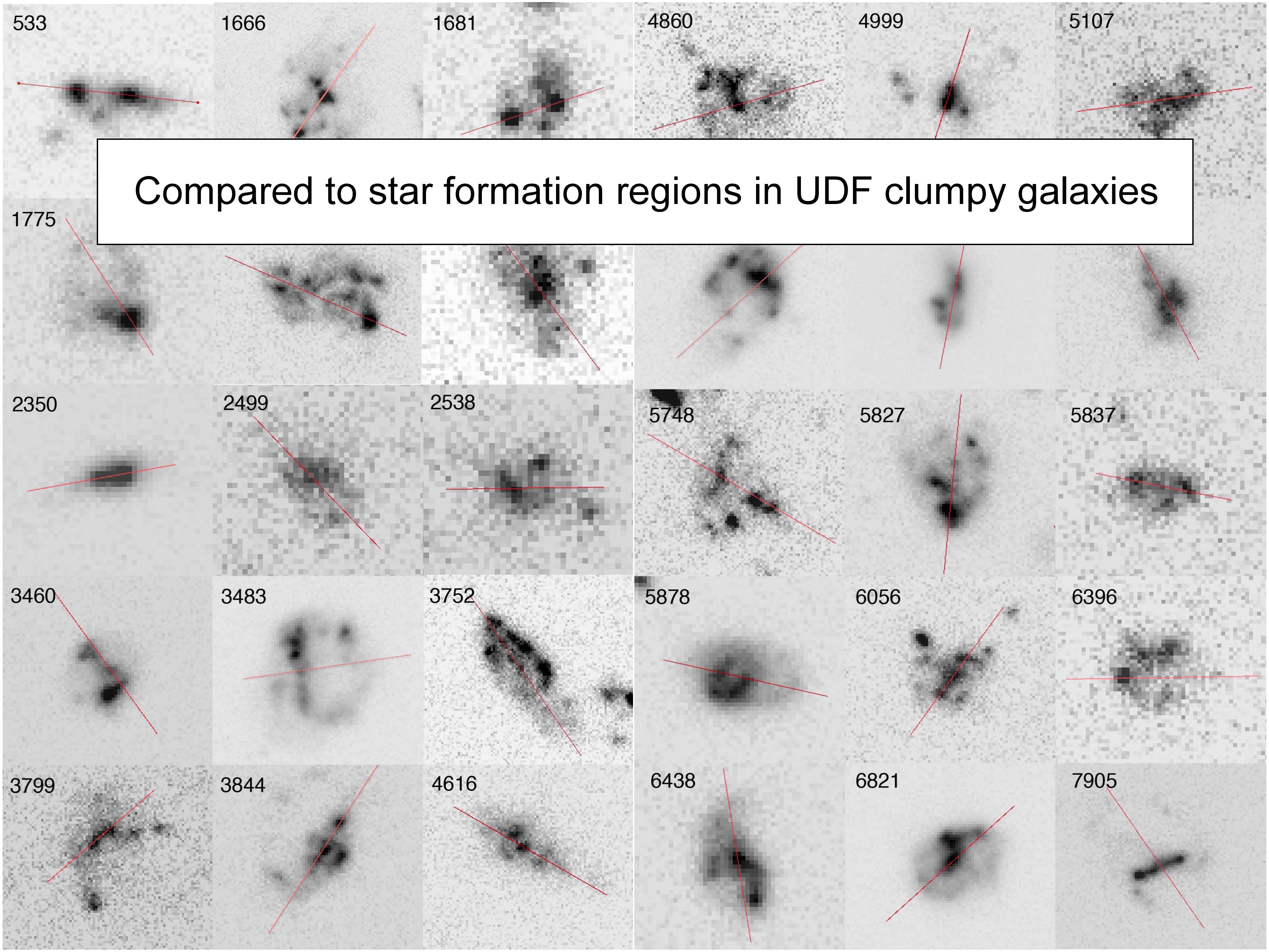
Elmegreen + 2013

Compared to star formation regions in normal spiral galaxies



Elmegreen + 2013

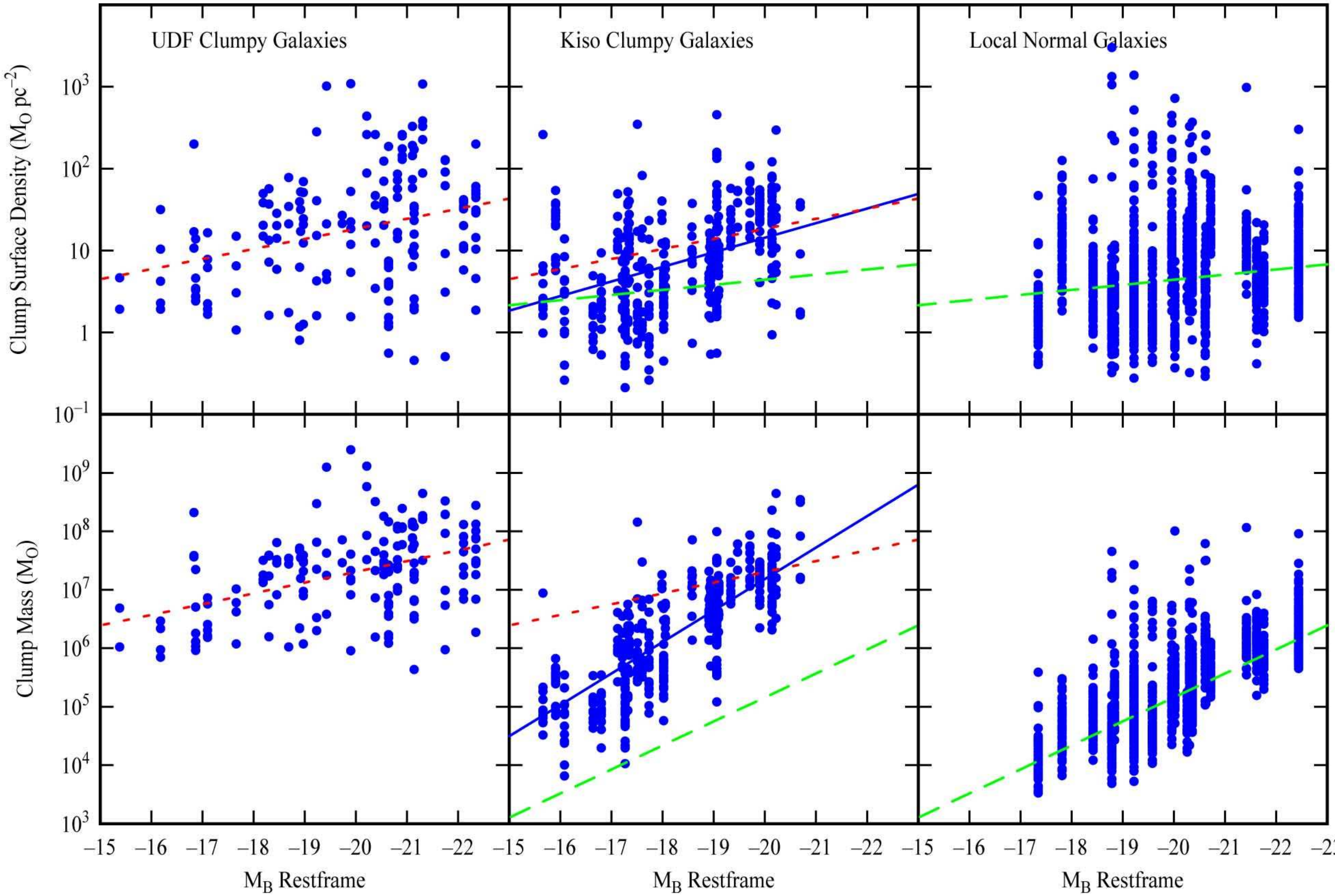
Compared to star formation regions in UDF clumpy galaxies



30 UDF clumpies | 36 Kiso clumpies | 20 Normal Spirals

Clump Surface Density

Clump Mass



Restframe Absolute Magnitude

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If clump mass = turbulent Jeans mass ~ $\sigma^4/\pi G\Sigma$

Sequence = normal spirals: Kiso clumpies: UDF clumpies

Low M_B: Mass: 1 : 36 : 1008; Σ= 1 : 1.4 : 3.1; σ= 1 : 2.7 : 7.6

High MB: Mass: 1 : 120 : 120; Σ= 1 : 4 : 5.2; σ=1 : 4.7 : 5.2

A sequence of increasing column density and turbulent speed:

Kiso SF clumps are midway between spiral and UDF clumps

Elmegreen + 2013

Summary

- In addition to “downsizing,” galaxies of all types occupy the present universe
  – clumpy, spiral, intermediate
- Trend from high-z clumpy to modern spirals is a trend in mass of star forming regions
  – likely from a trend in decreasing velocity dispersion and decreasing gas column density
- Disk gravitational instabilities change from pure-clump to thick and irregular clumpy spirals to thin and regular small-clump spirals (“beads on a string” patterns)

- Next: Today’s star formation processes in spiral arms

Milky Way size galaxies today have mild gravitational instabilities that appear as spiral arms.

Spiral arms concentrate the gas in 3 ways:

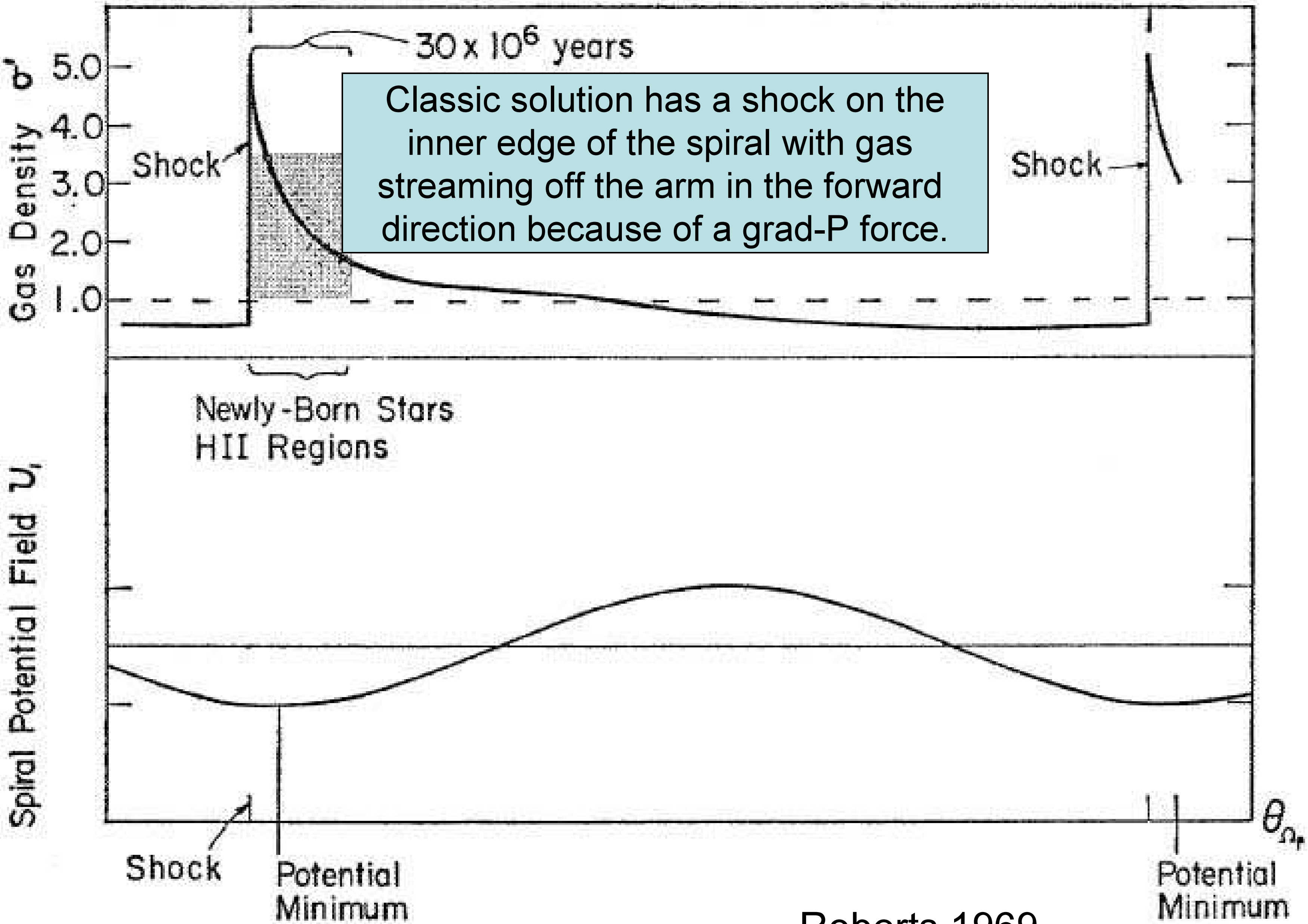
1. the instability itself (in a material arm)
2. by coordination of epicycles (in a Lin-Shu density wave)
3. by shocks when the material and wave have different speeds

Star formation is concentrated in the arms because the gas is. But is star formation triggered in otherwise quiescent clouds?

THE ASTROPHYSICAL JOURNAL, Vol. 158, October 1969

LARGE-SCALE SHOCK FORMATION IN SPIRAL GALAXIES AND ITS IMPLICATIONS ON STAR FORMATION

W. W. ROBERTS*
Massachusetts Institute of Technology
Received 1969 February 3



Classic solution has a shock on the inner edge of the spiral with gas streaming off the arm in the forward direction because of a grad-P force.

Roberts 1969

THE ASTROPHYSICAL JOURNAL, **173**:557–592, 1972 May 1

GALACTIC SHOCKS IN AN INTERSTELLAR MEDIUM WITH TWO STABLE PHASES

FRANK H. SHU, VINCENZO MILIONE, AND WILLIAM GEBEL
State University of New York at Stony Brook

C. YUAN
City College of New York

D. W. GOLDSMITH*
University of California at Berkeley

AND

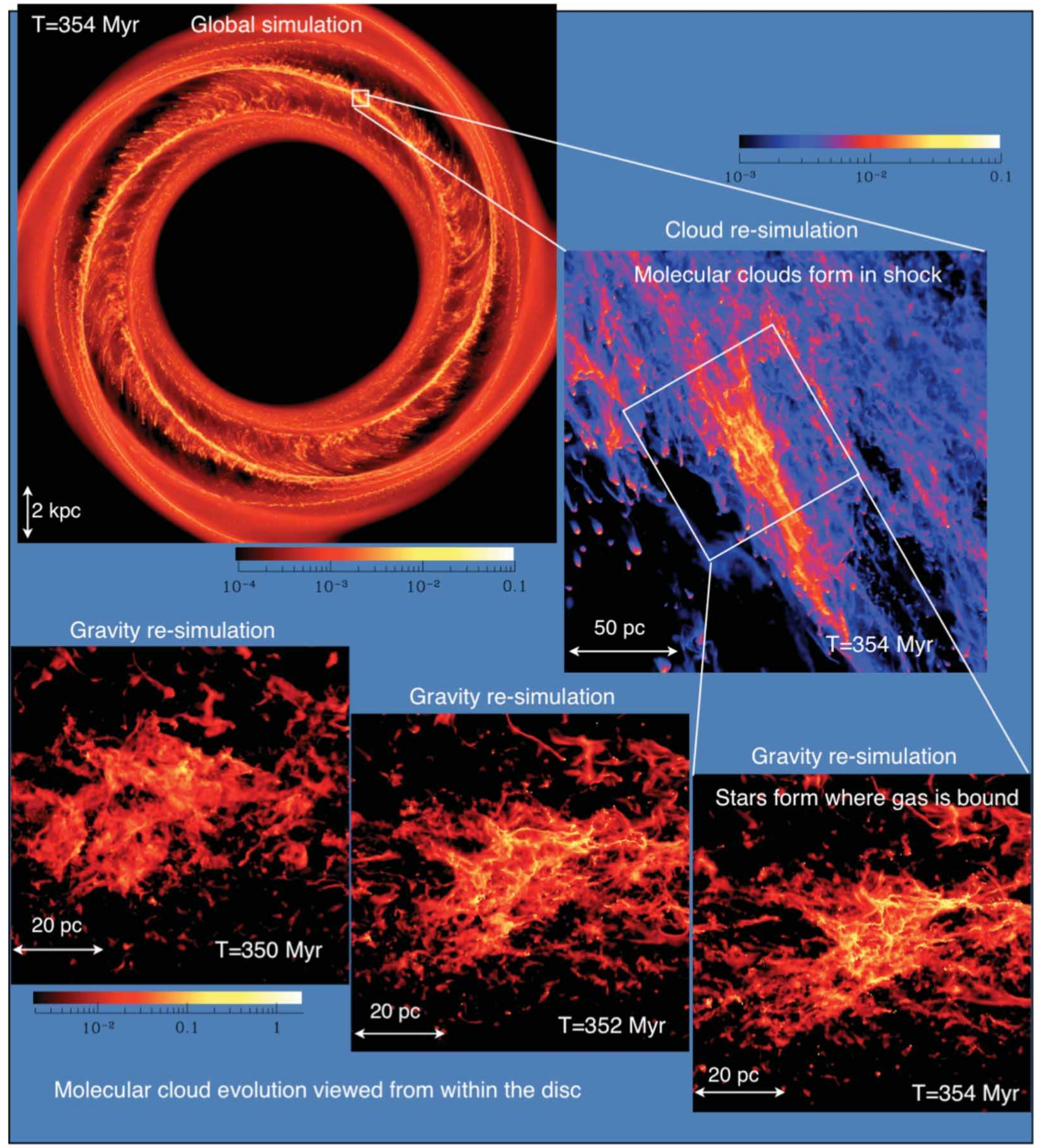
W. W. ROBERTS
University of Virginia
Received 1971 October 19; revised 1971 November 16

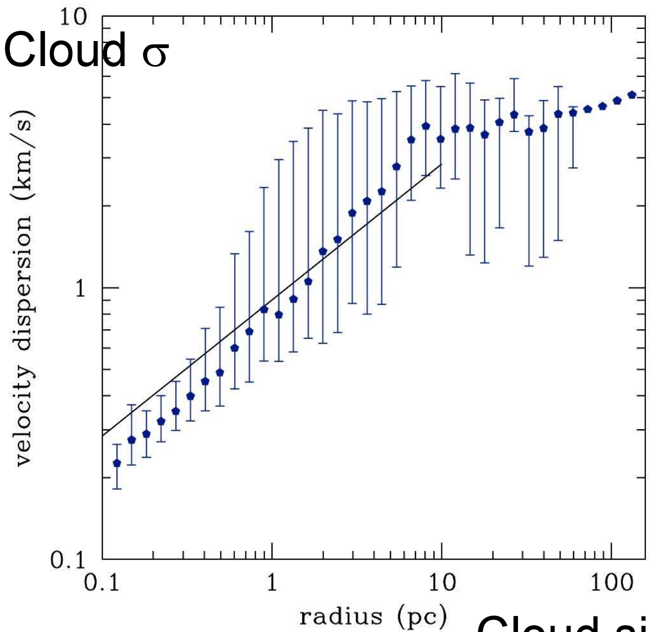
Bonnell +13

Recent simulation:

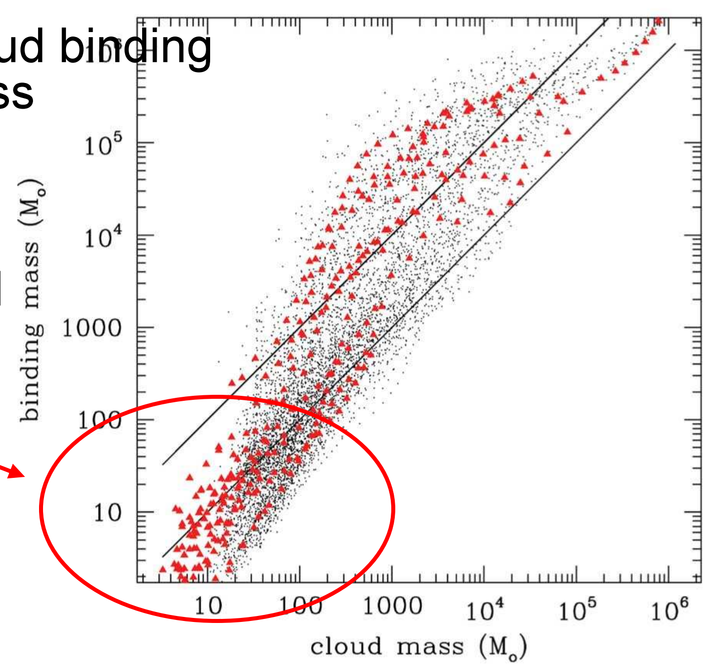
Two-phase ISM in spiral wave

A $1.7 \times 10^{6}\ M_{O}$ cloud resimulated at high resolution





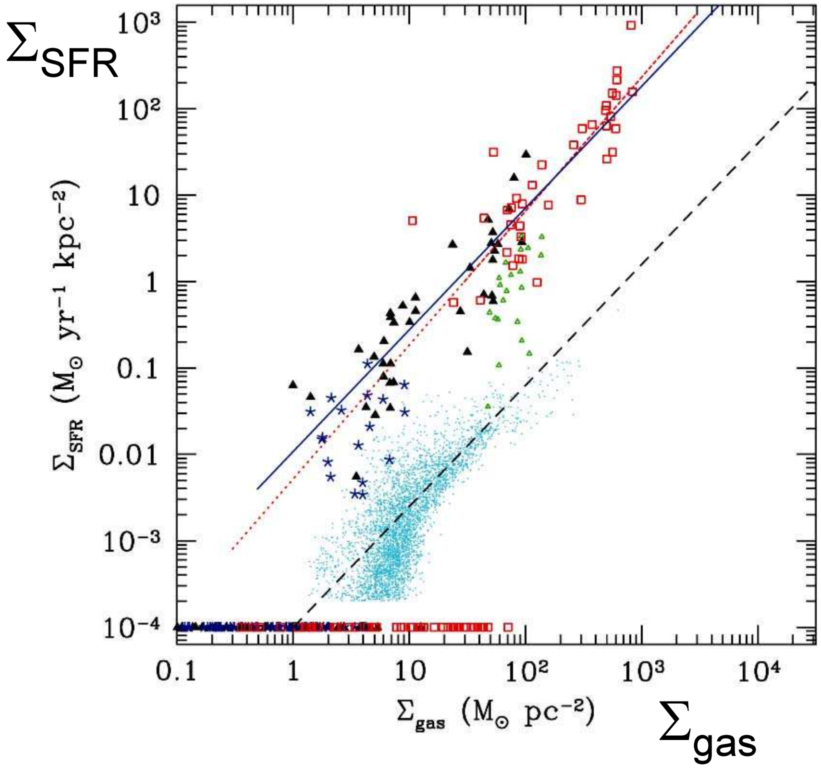
Cloud velocity dispersion versus size
indicates turbulence pumped by the spiral shock



Only the small clouds pieces are gravitationally bound

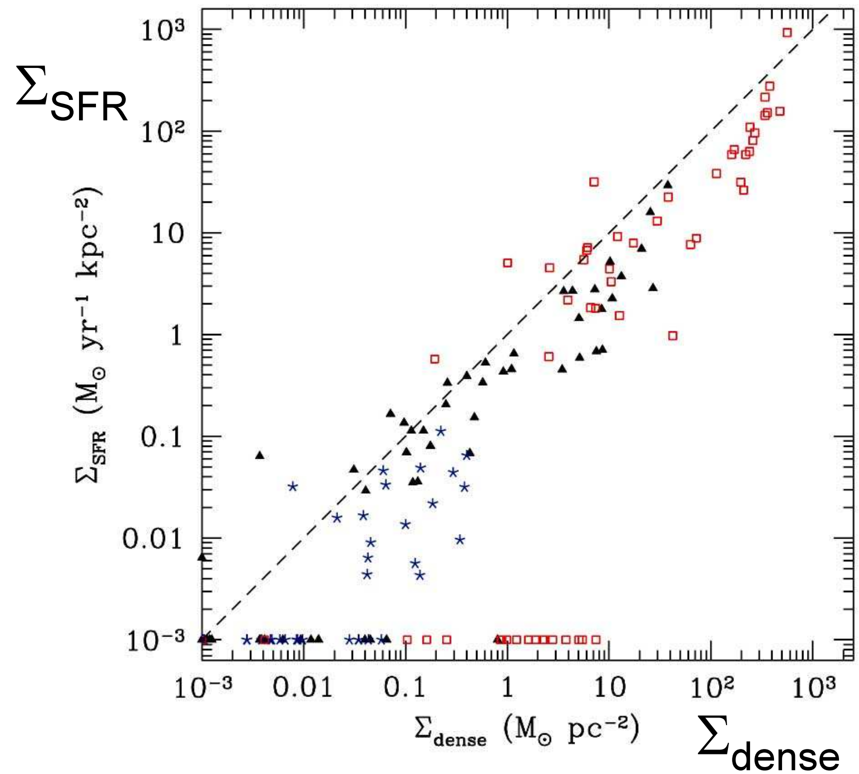
Stars form in tiny bound cores.

Bonnell +13

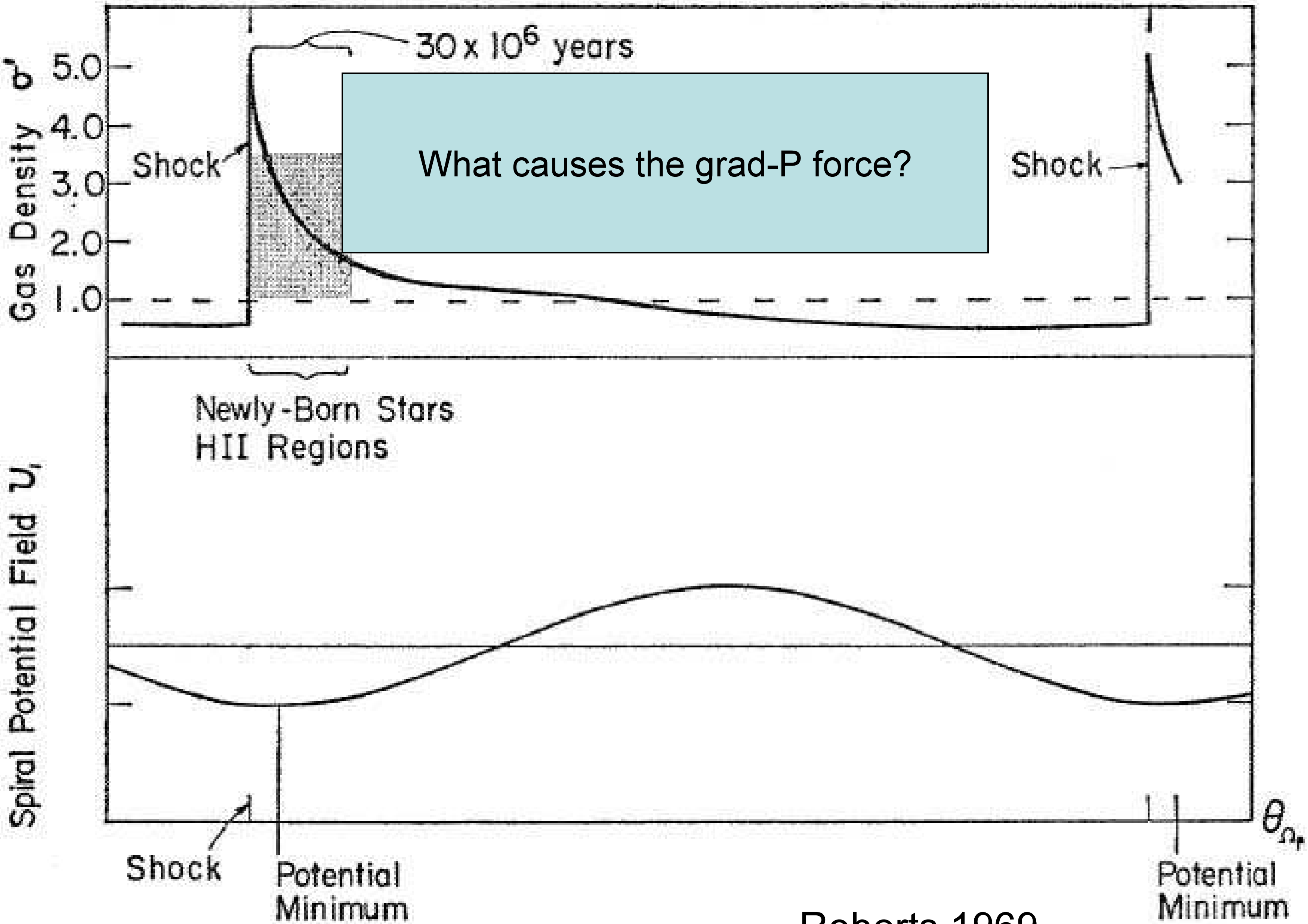


The star formation rate scales with the 1.4 power of the total gas surface density…

and linearly with the dense gas surface density

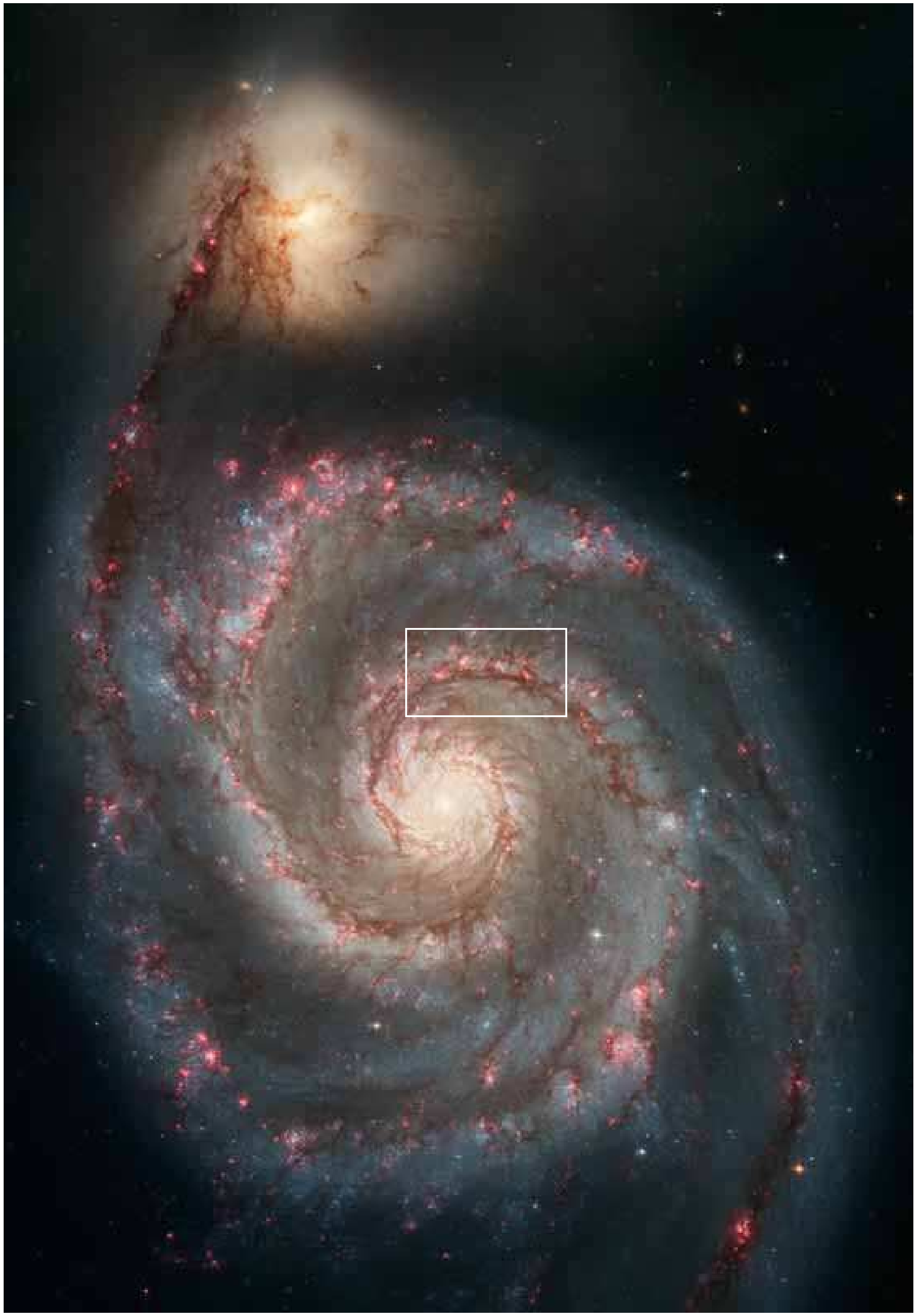


Bonnell +13



What causes the grad-P force?

Roberts 1969



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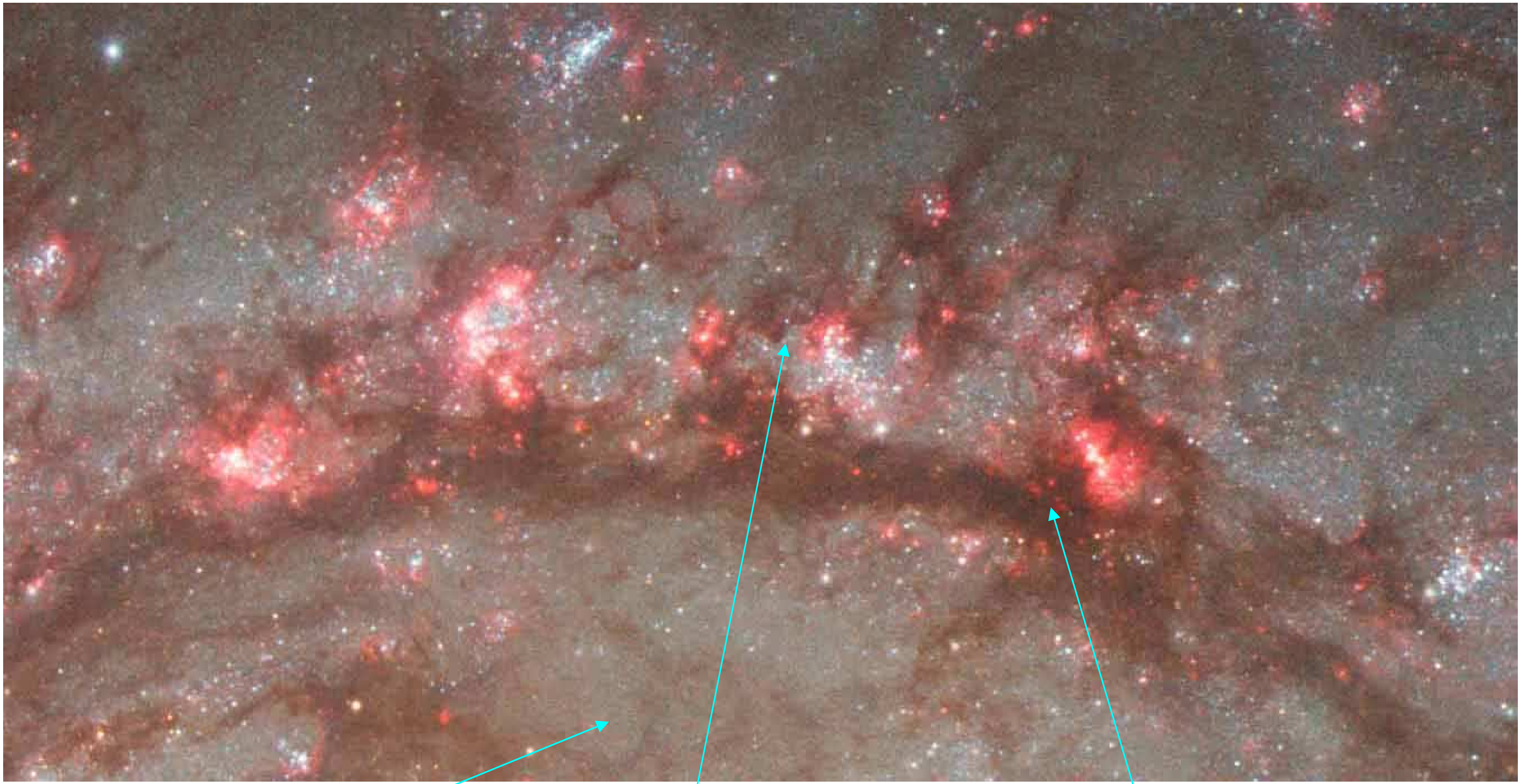
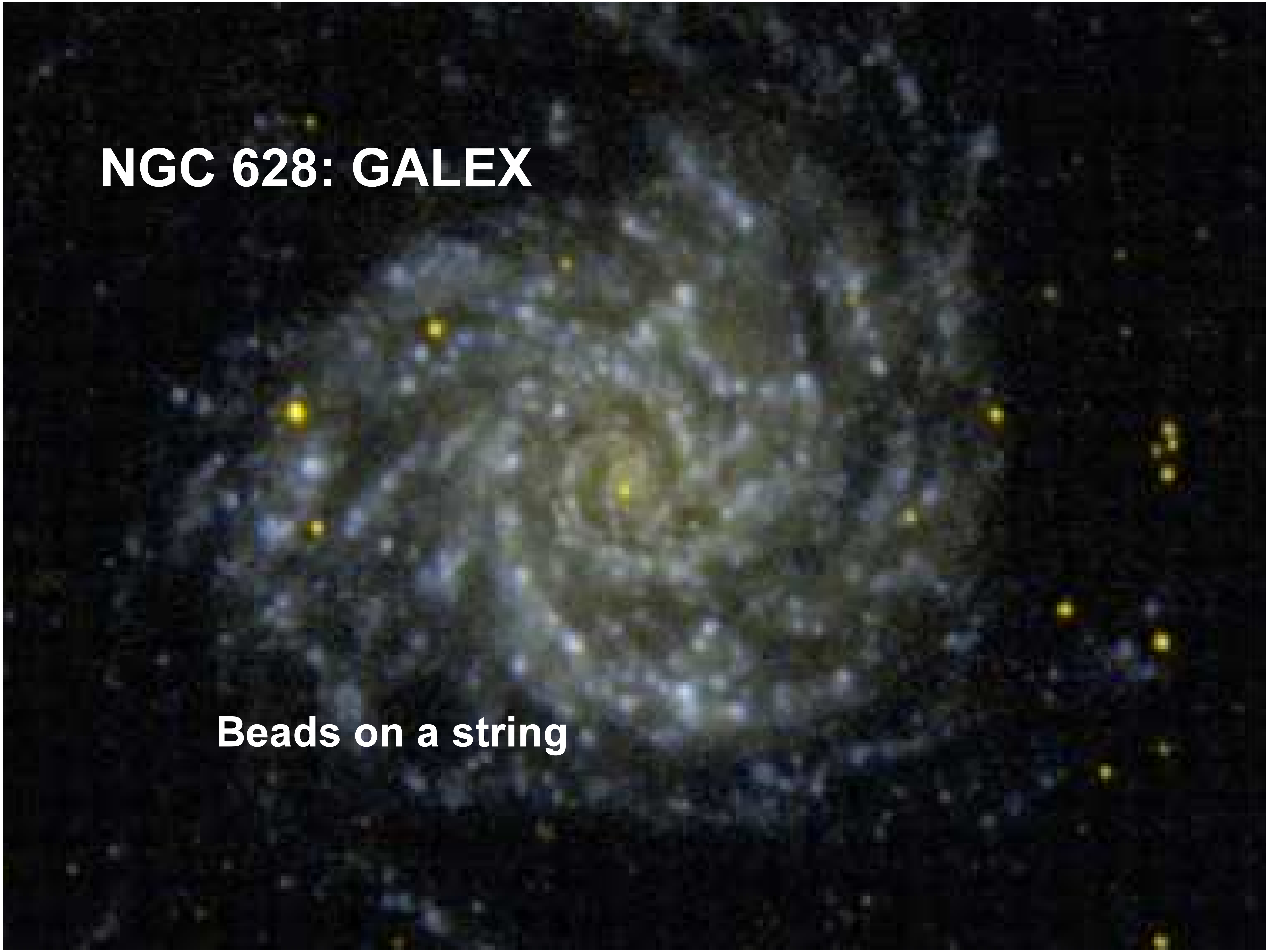
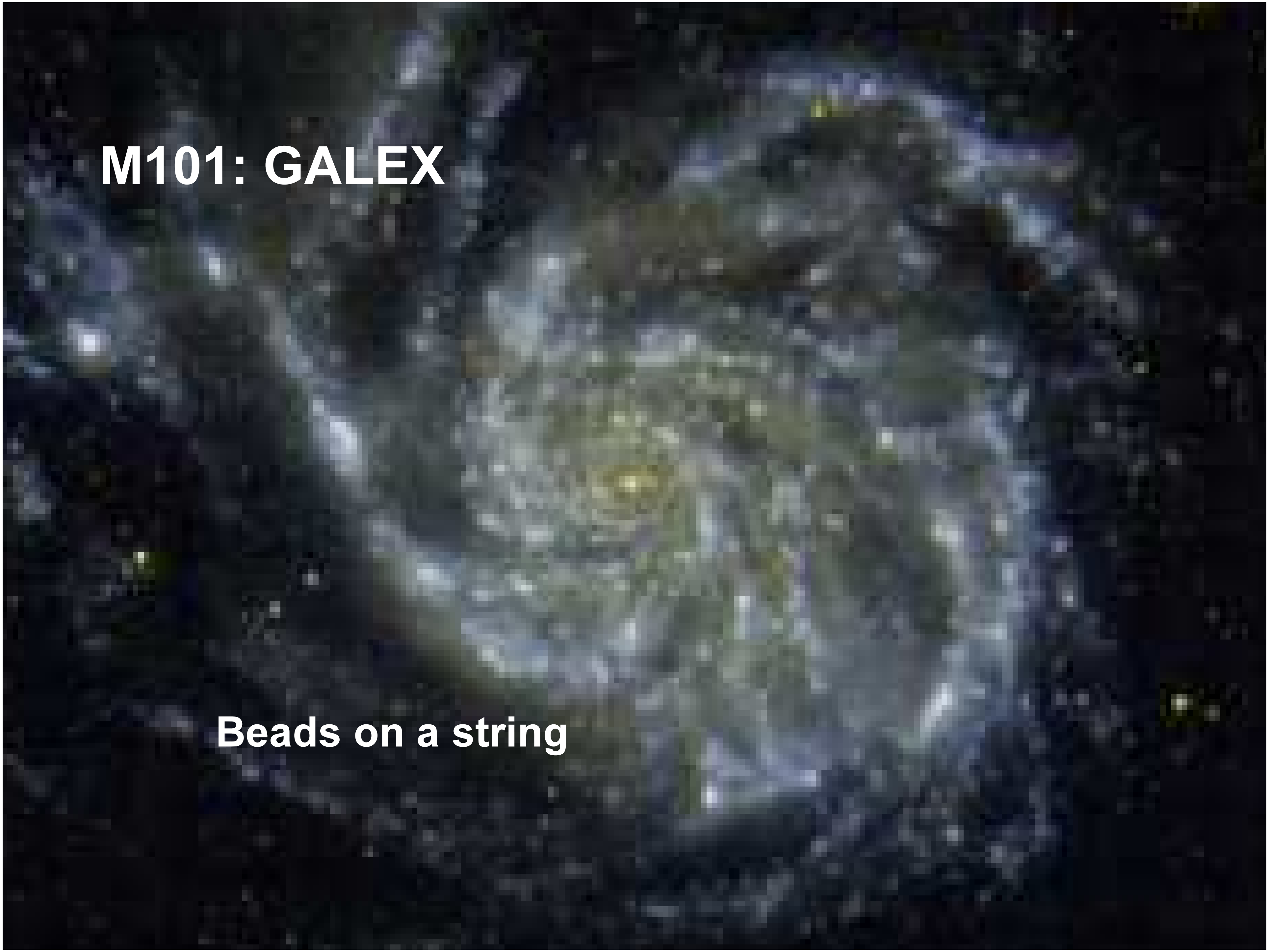
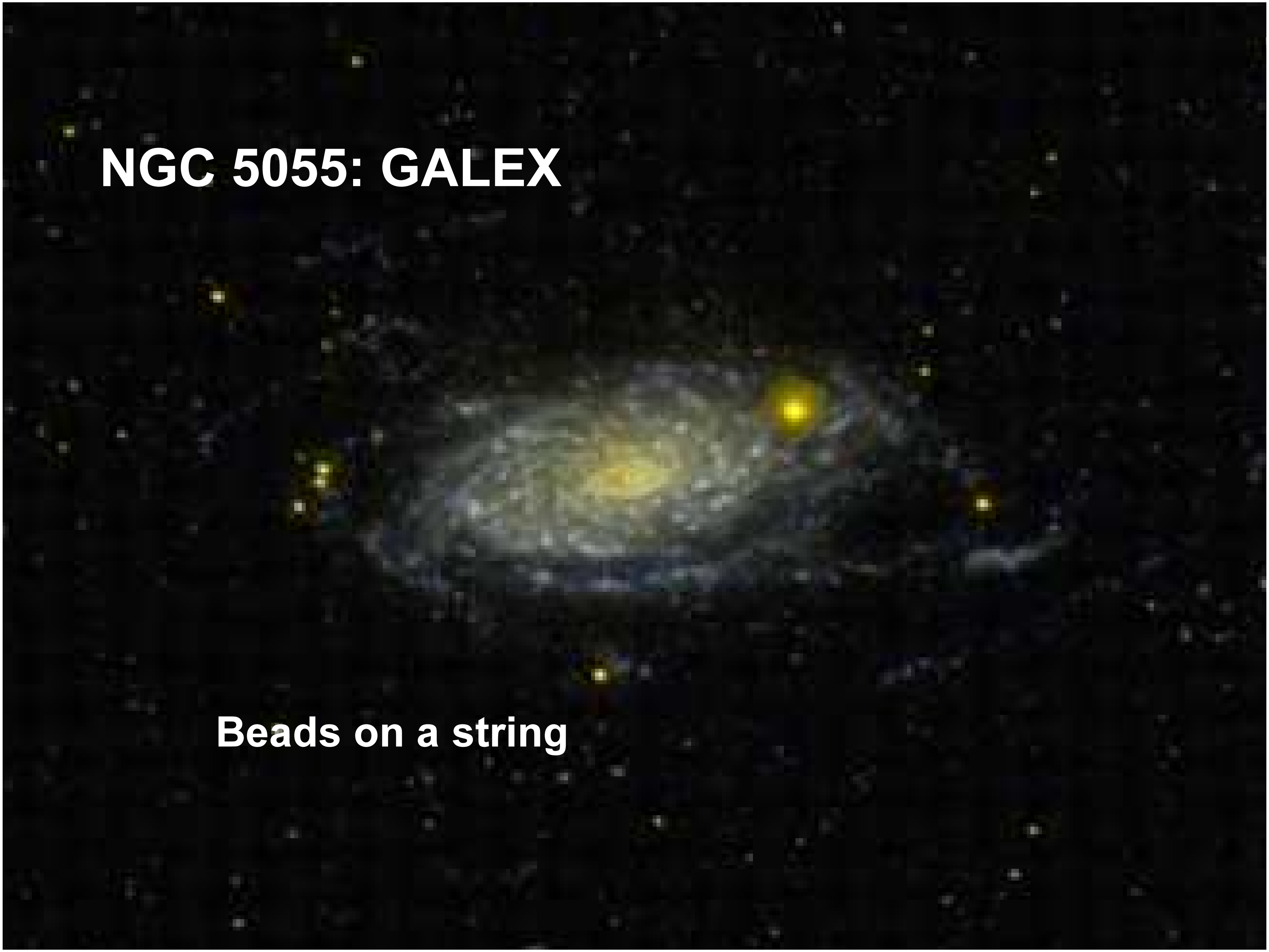


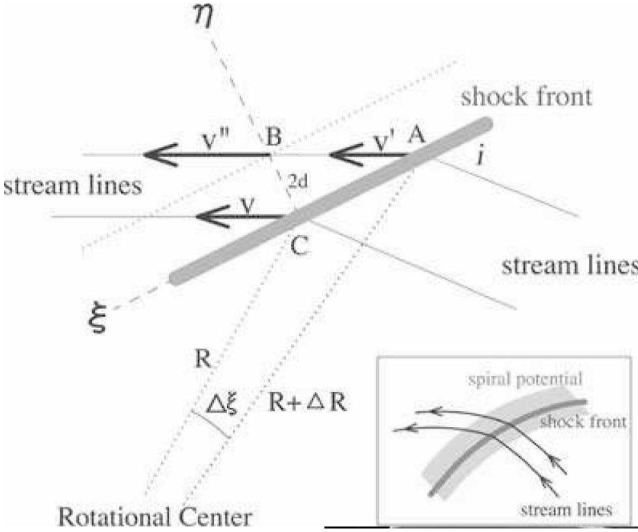
(1) Ribbons & old rings of gas and dust impact the arm, (2) gas collapses,
(3) star formation breaks the gas off and accelerates it into the interarm region
(4) break-off structure is ring-like or comet-like

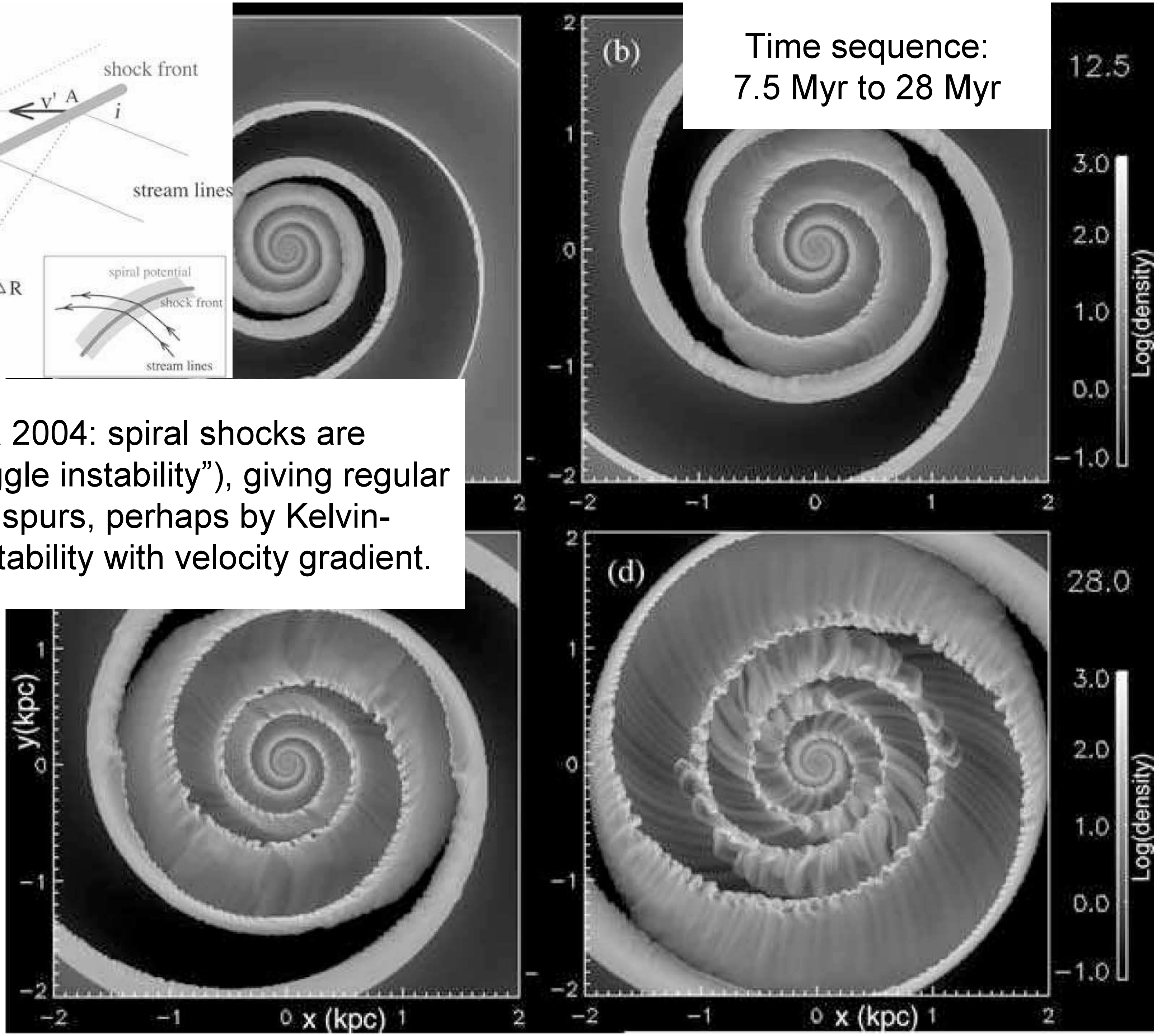
ISM is not “isothermal” but star formation feedback maintains a steady state.


NGC 628: GALEX
Beads on a string


M101: GALEX
Beads on a string

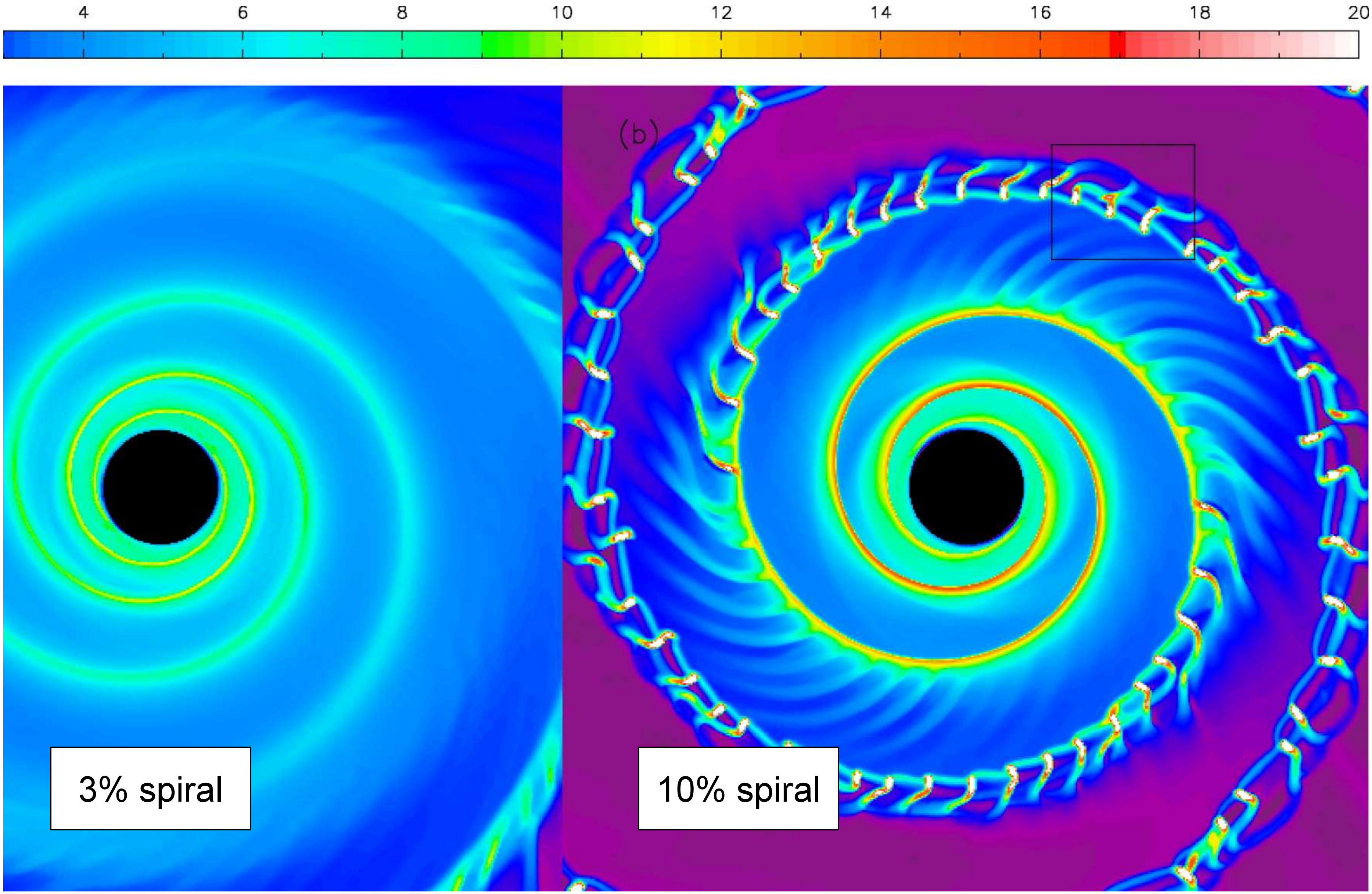

NGC 5055: GALEX
Beads on a string





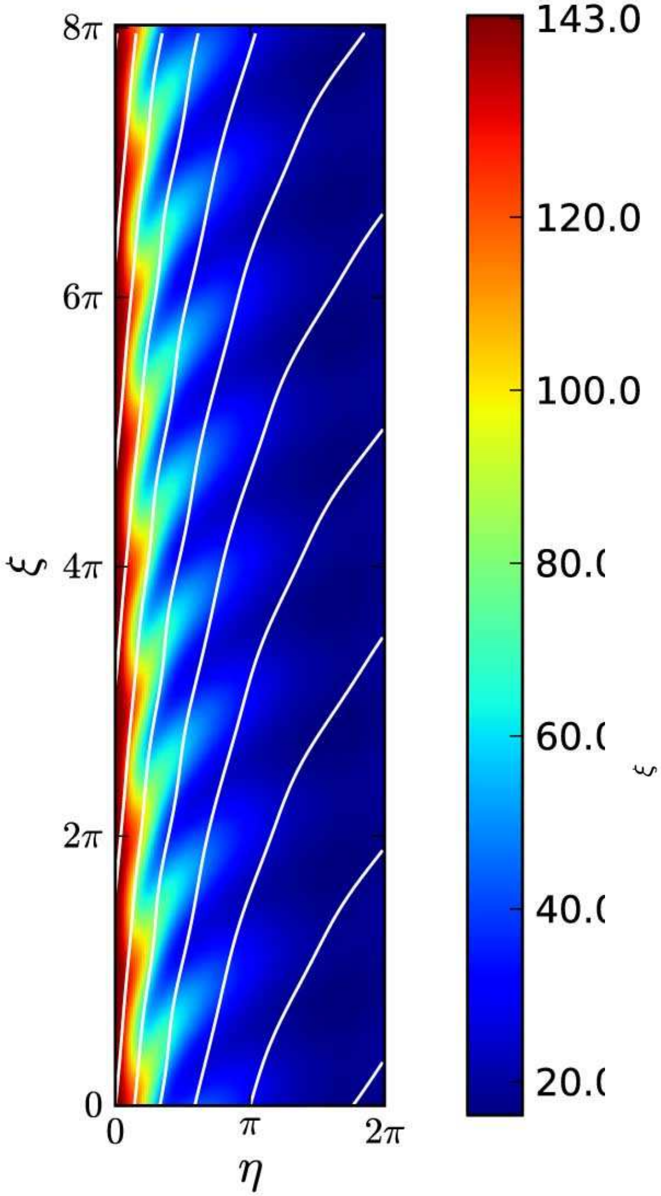
Time sequence:
7.5 Myr to 28 Myr

Wada & Koda 2004: spiral shocks are unstable ("wiggle instability"), giving regular spacings and spurs, perhaps by Kelvin-Helmholtz instability with velocity gradient.

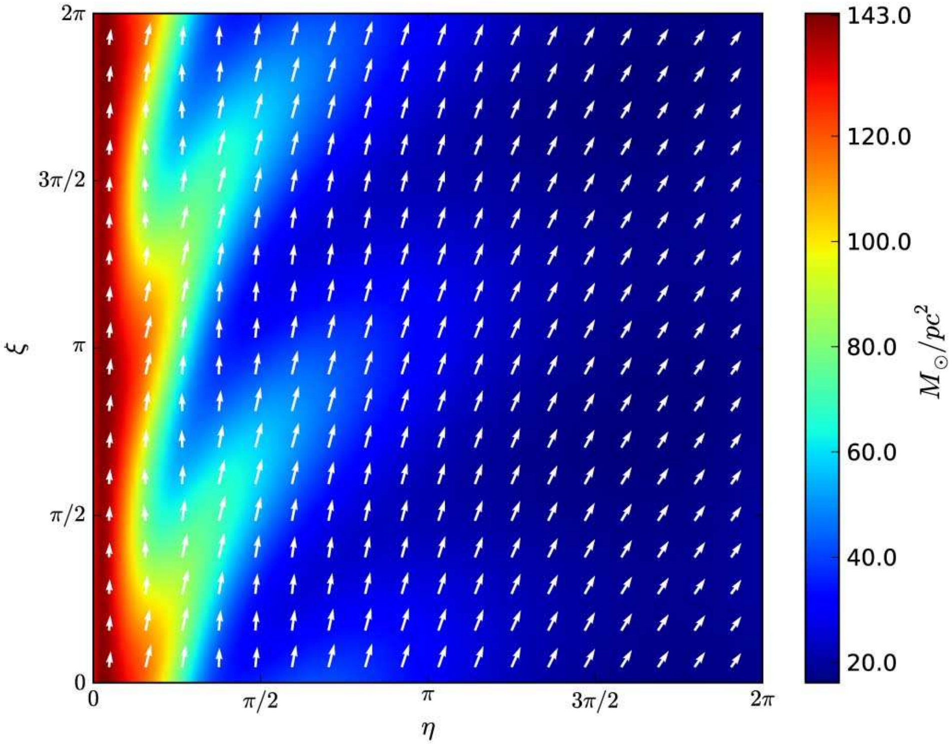


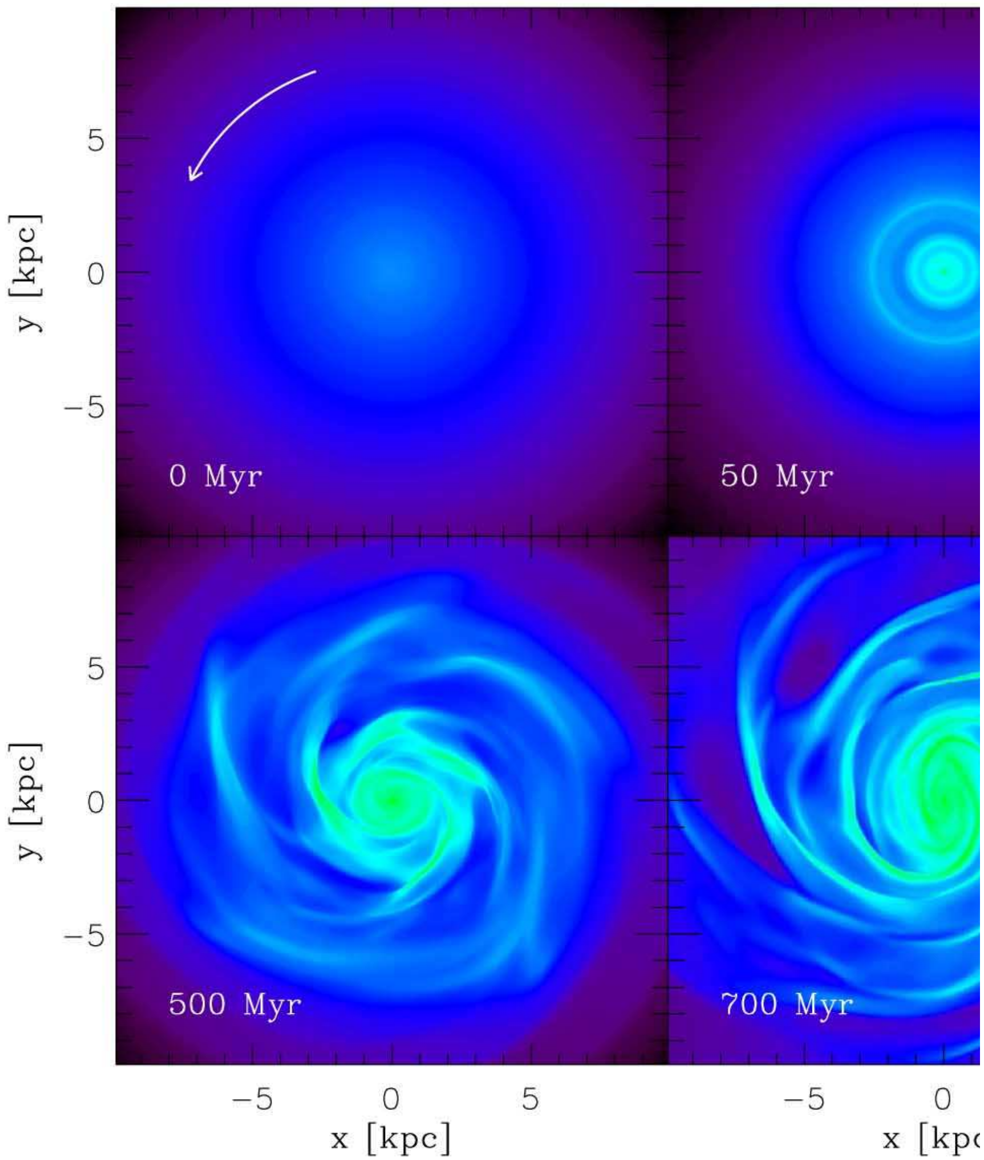
Shetty & Ostriker 2006: feathering instability in spiral flow: gravity + shocks

Lee and Shu 2012: Feathering instability, analytical result with spiral shock, self-gravity and magnetic fields.



see talk by Wing-Kit Lee on Thursday, 13:30-14:10





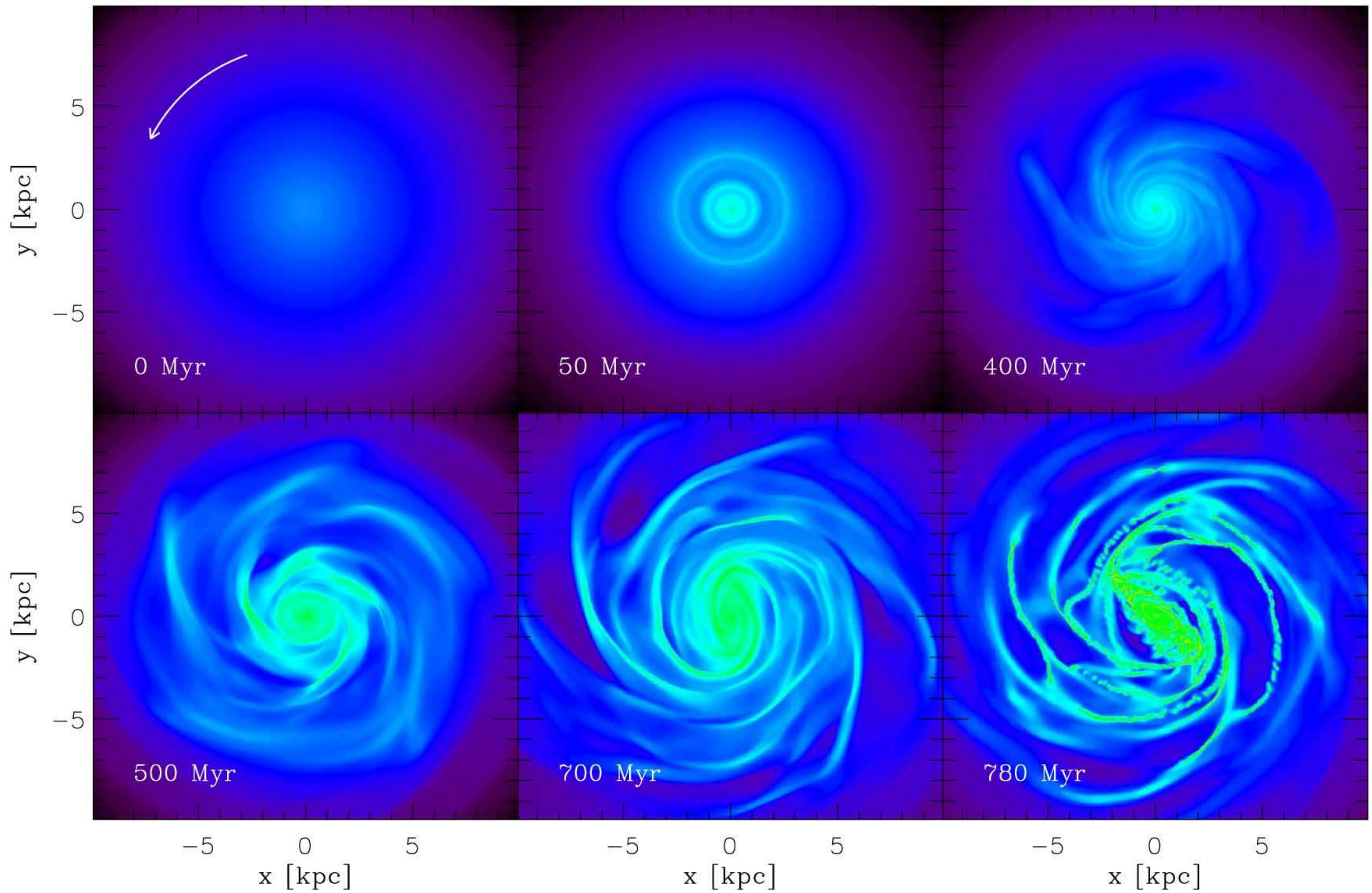
Recent 3D Simulation of the Milky Way gas, stars and dark matter

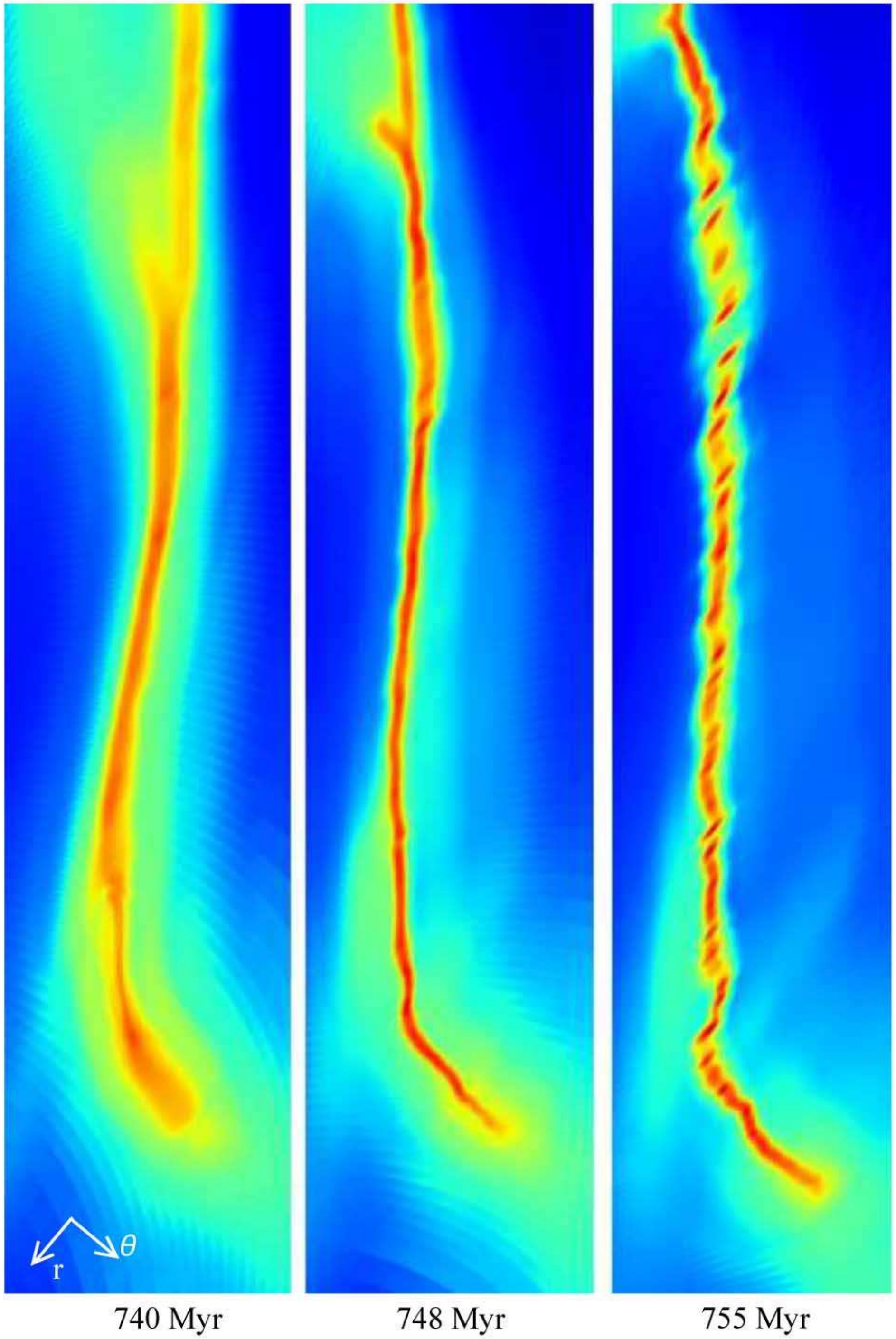
Adaptive Mesh for gas from
100 kpc to 0.05 pc

Star formation, feedback,
multi-phase gas, …

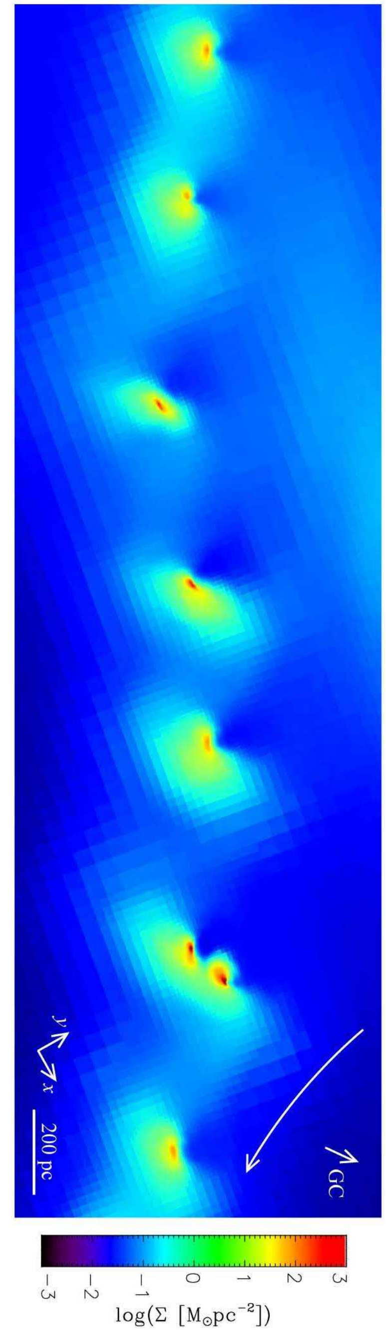
Beads on a string in spiral arms

Renaud, Bournaud, Elmegreen + 13


0 Myr
50 Myr
400 Myr
500 Myr
700 Myr
780 Myr
y [kpc]
x [kpc]
5
0
−5

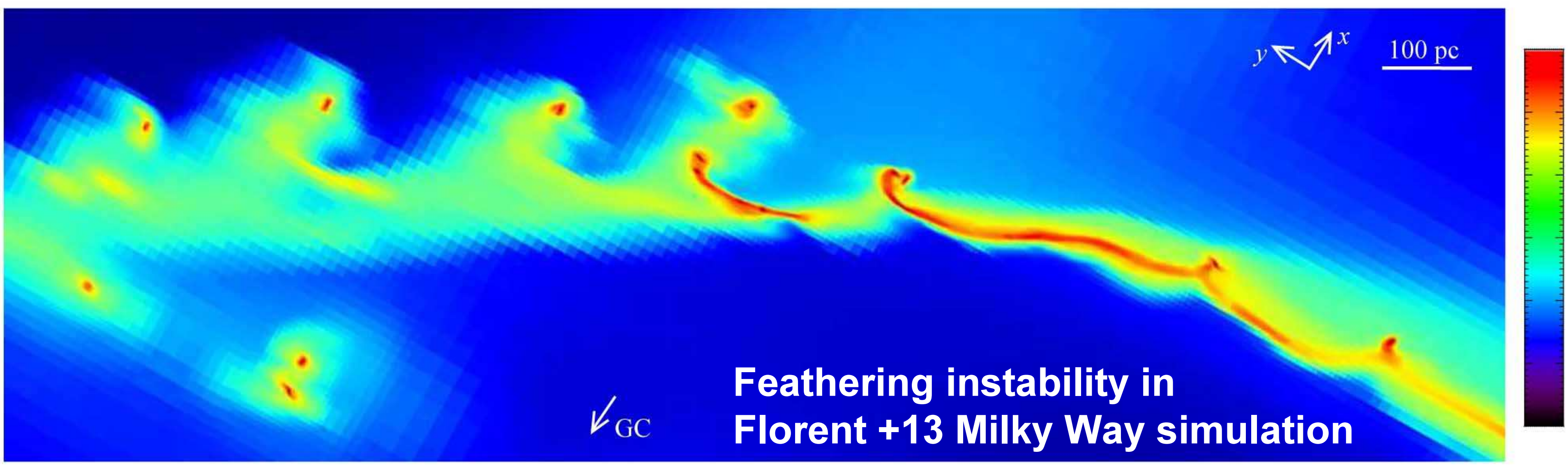


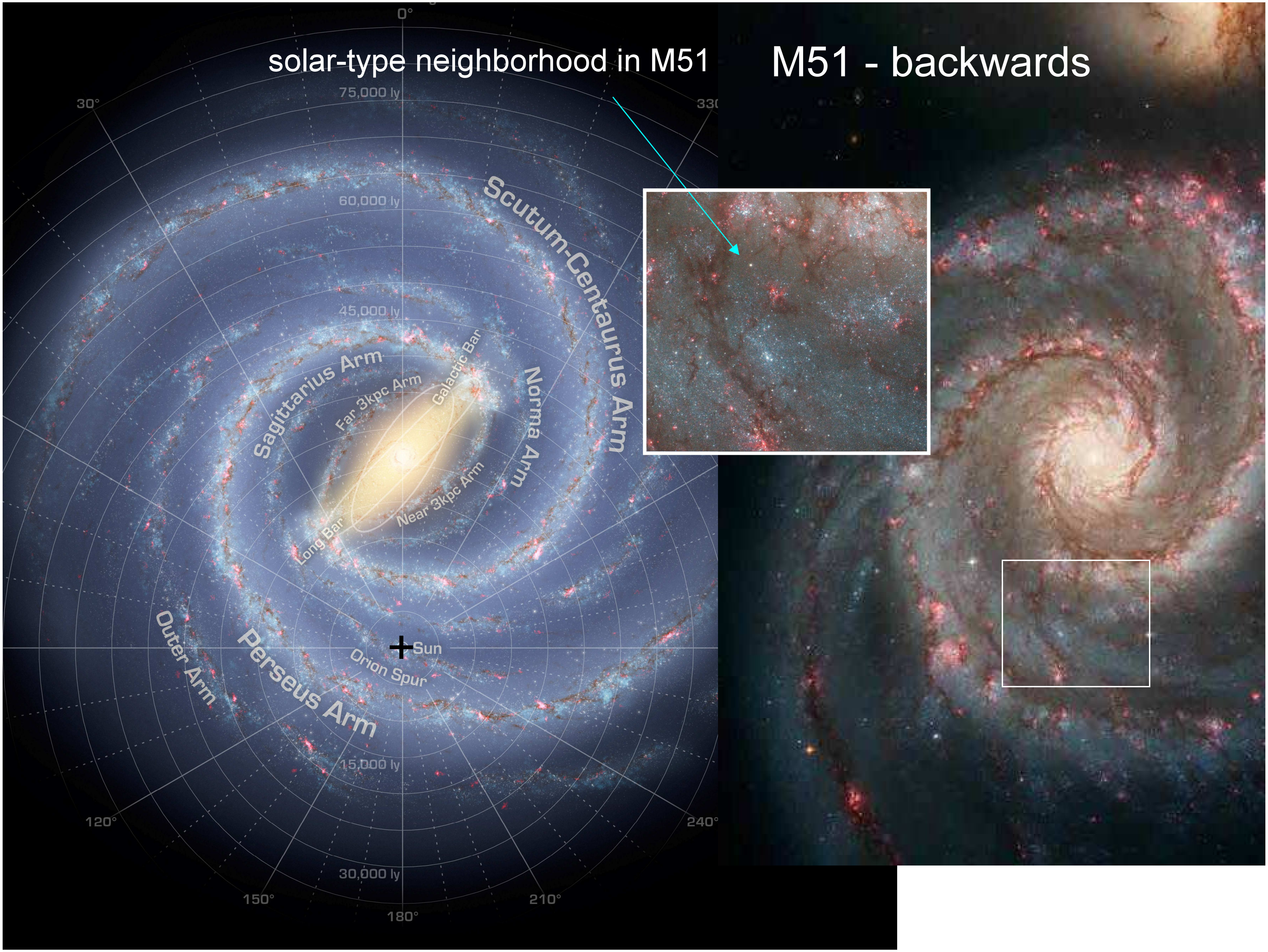
r
θ
740 Myr
748 Myr
755 Myr



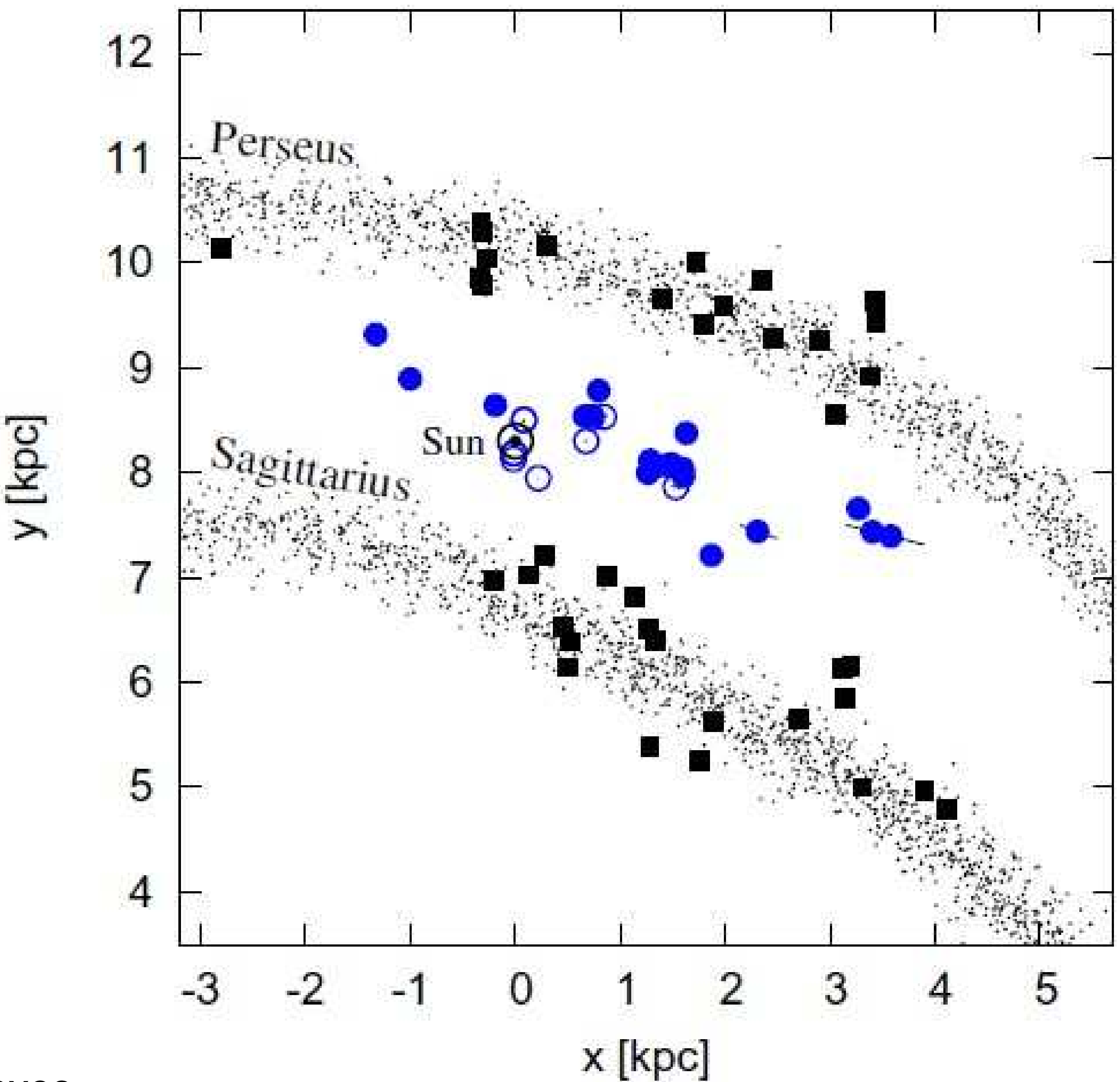
y
x
200 pc
GC
−3 −2 −1 0 1 2 3
log(Σ [M⊙pc⁻²])


HST: M51

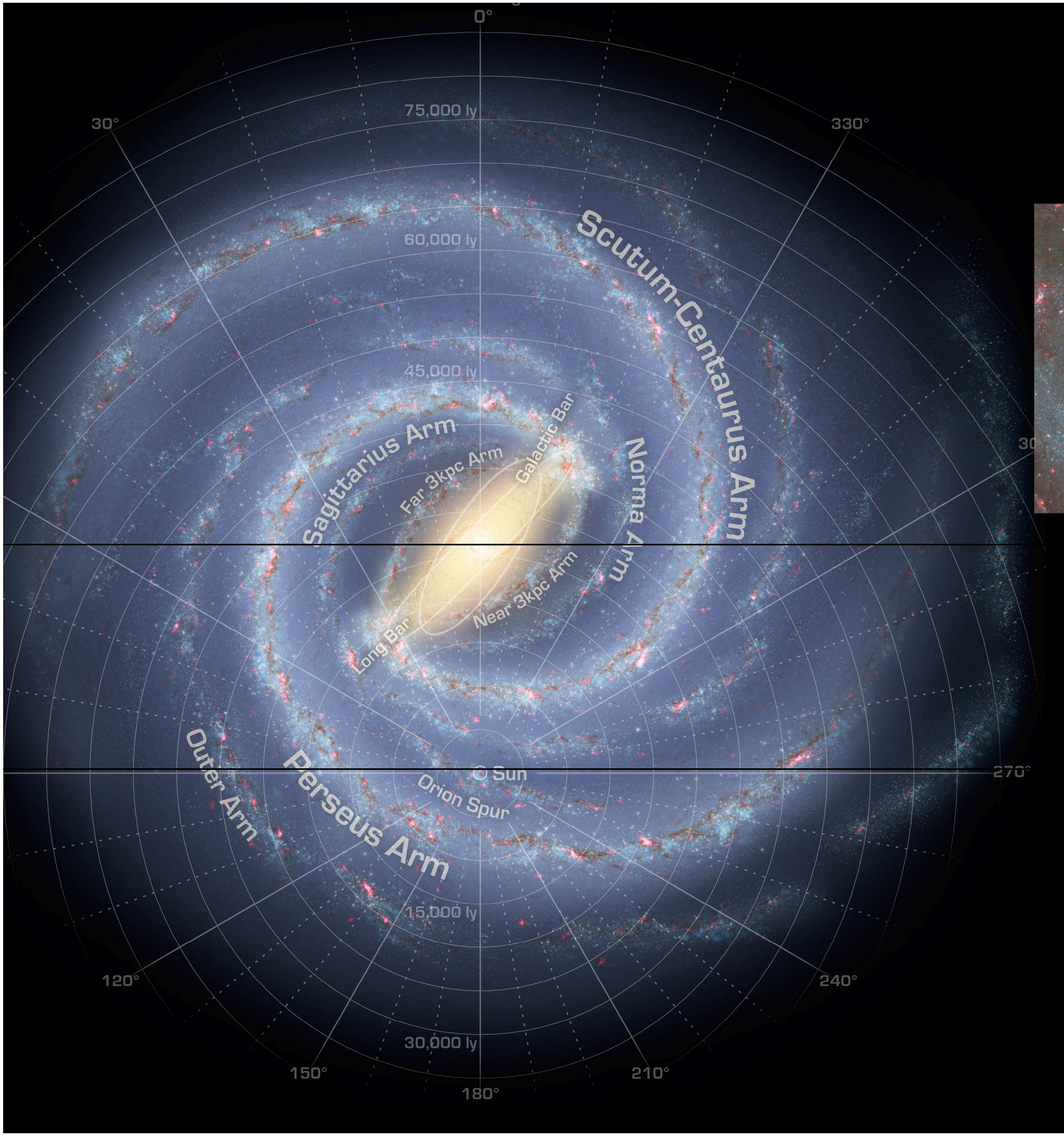

y
x
100 pc
GC
Feathering instability in
Florent +13 Milky Way simulation

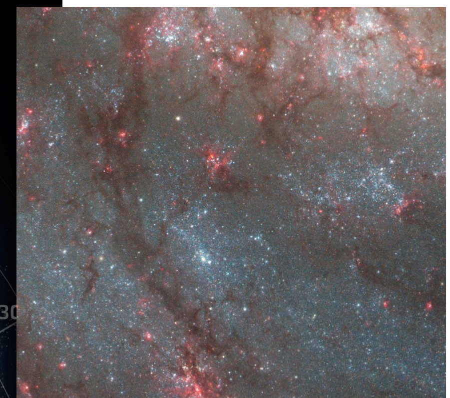


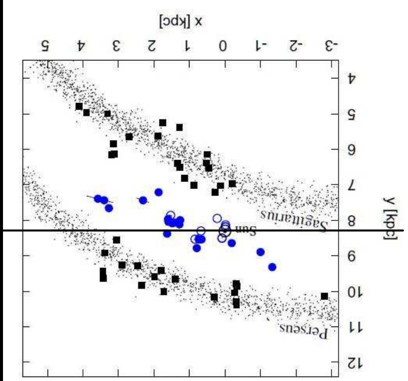
solar-type neighborhood in M51
M51 - backwards
0°
30°
330
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
120°
150°
180°
210°
240°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

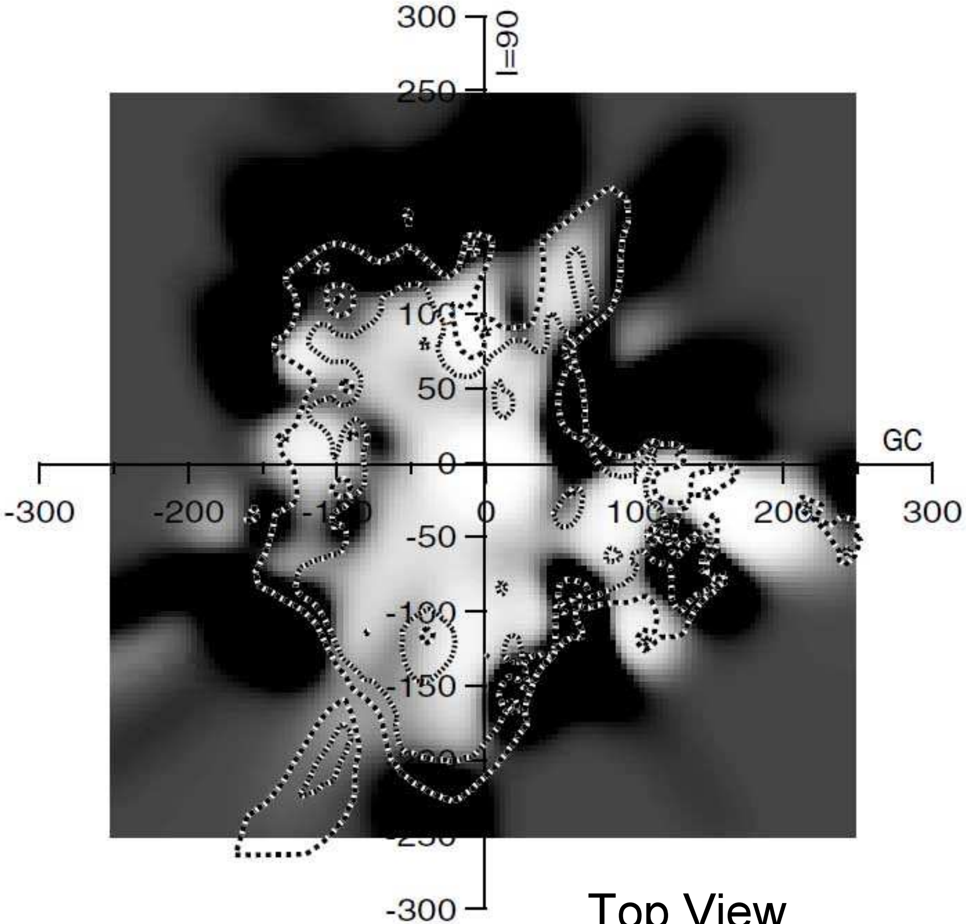


Xu +13:
VLBI parallaxes

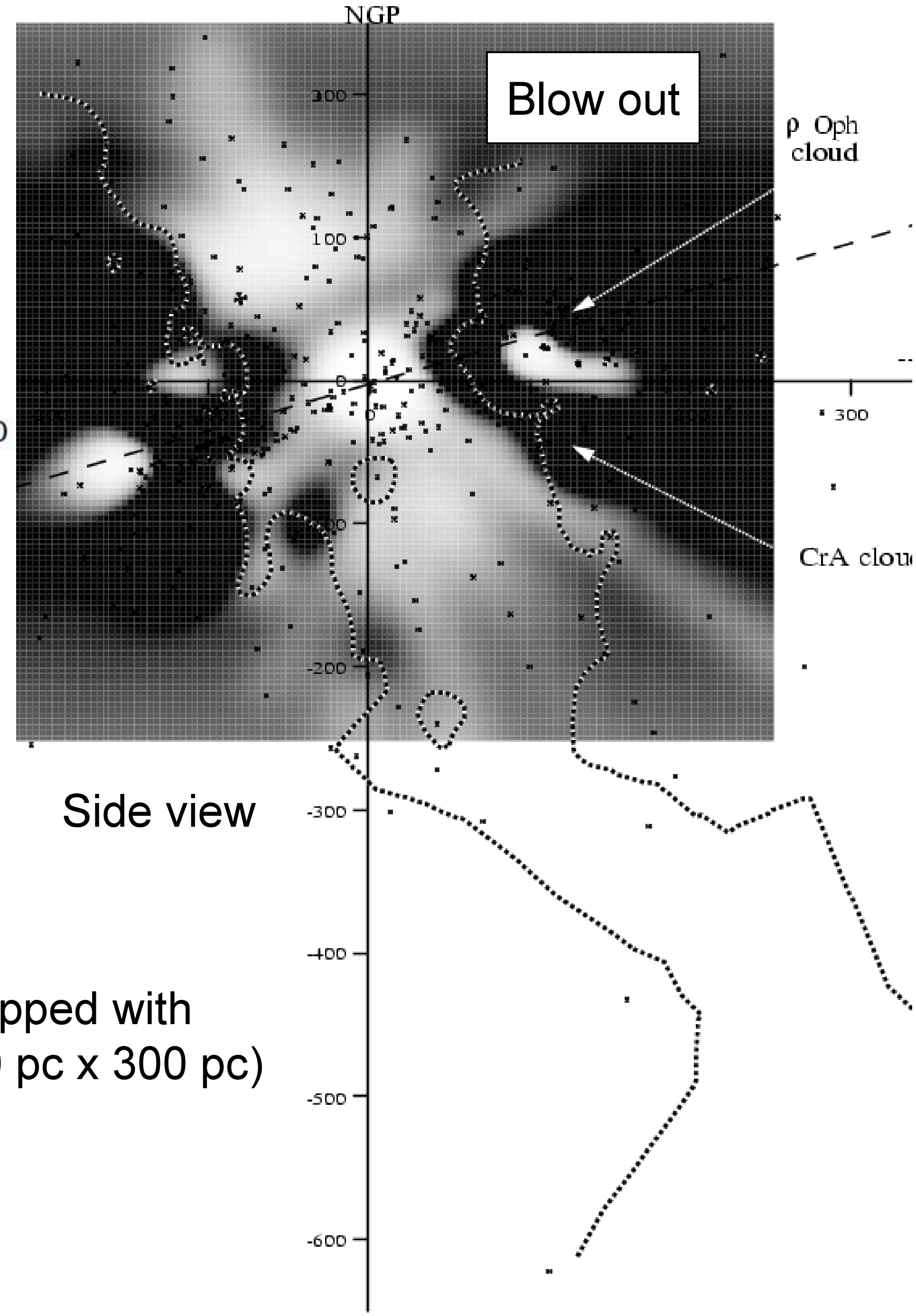

0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
Sun
270°
120°
240°
150°
210°
180°




x [kpc]
y [kpc]
Sagittarius
Perseus
Sun



Top View



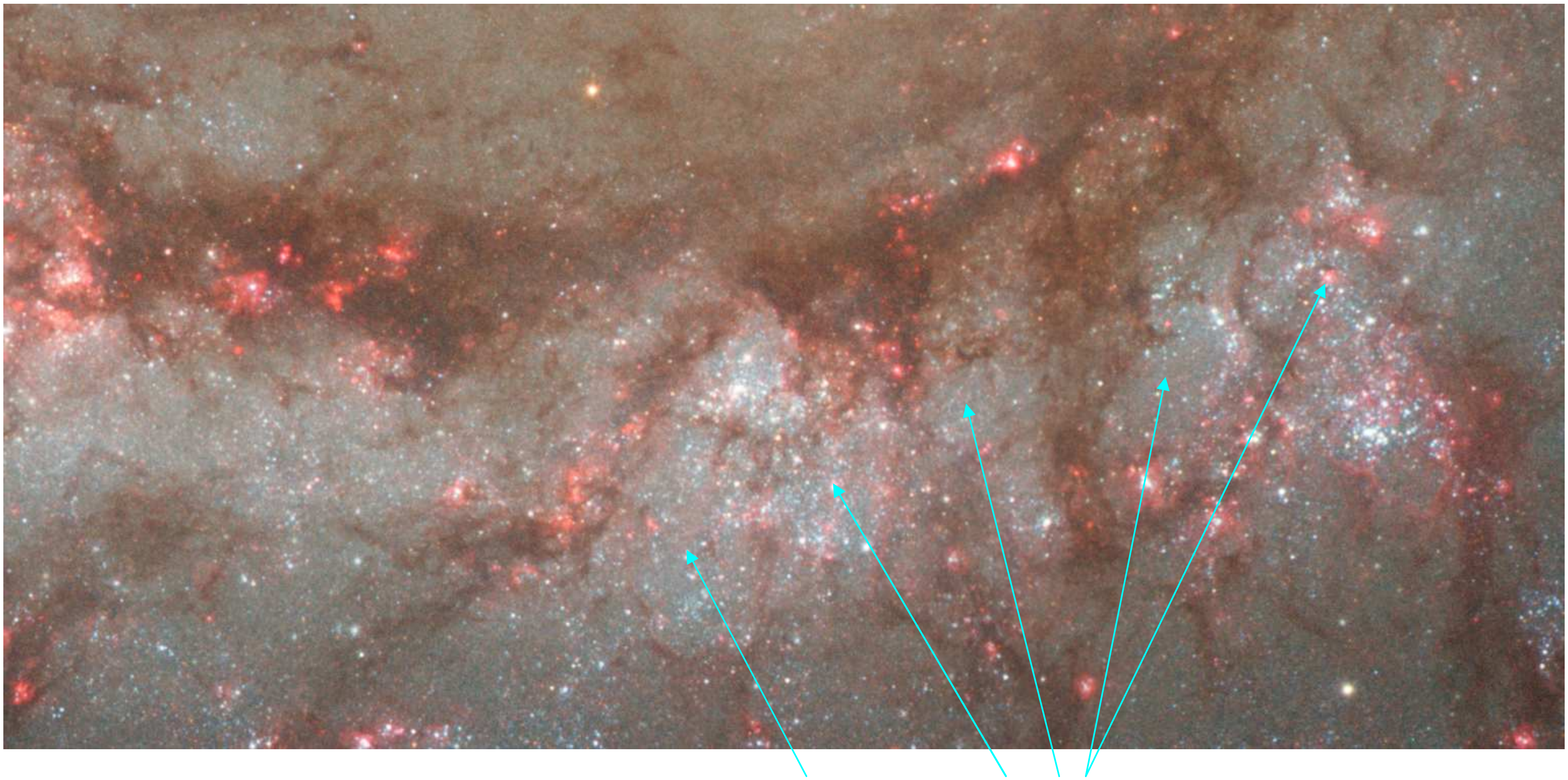
Side view

Lallement et al. (2003): Local Cavity mapped with Na absorption lines to nearby stars (100 pc x 300 pc)

Corresponds to “Lindblad’s Ring” of HI and “Gould’s Belt” of young stars

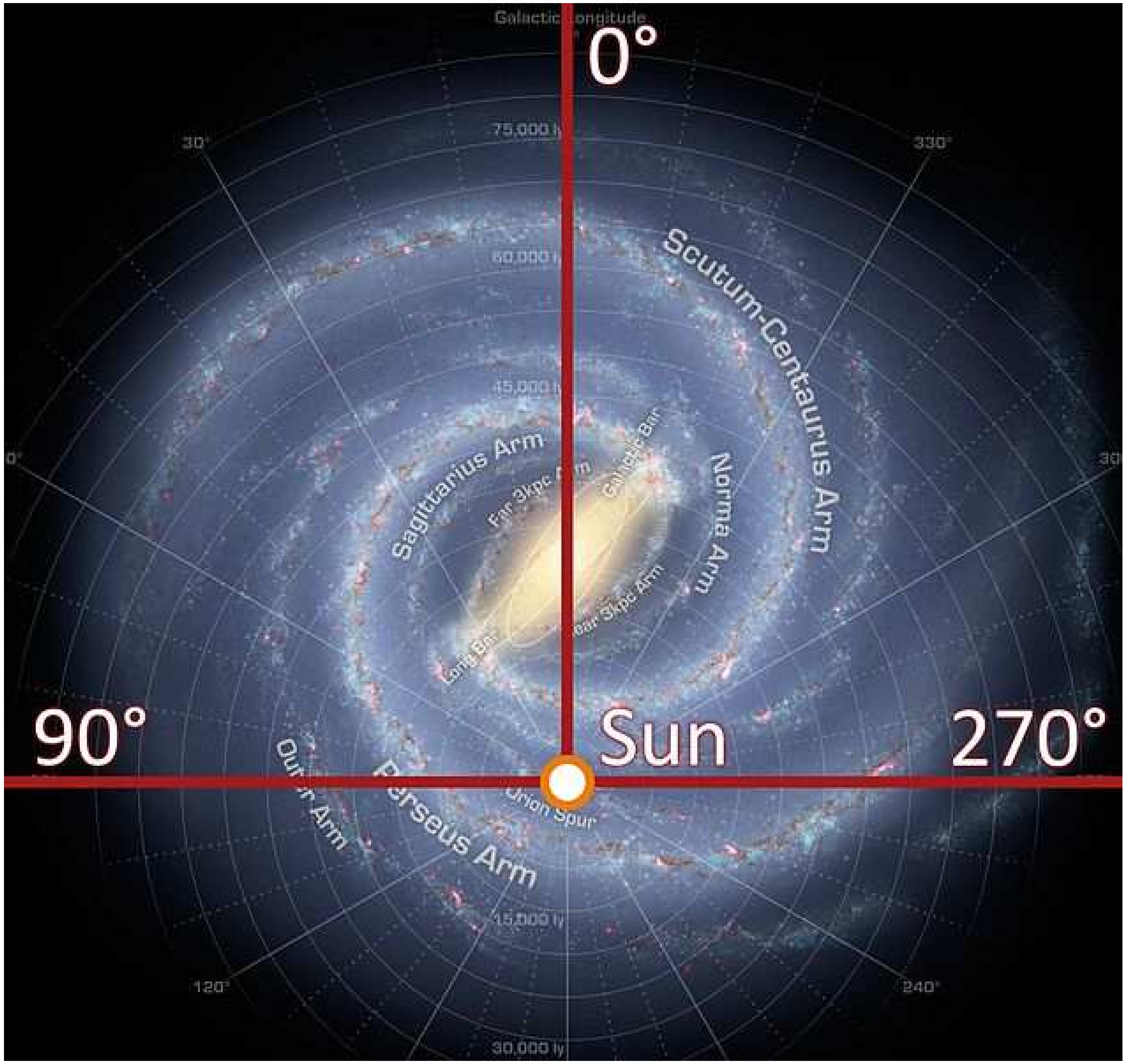
Secondary star formation

M51 Southern Inner Arm



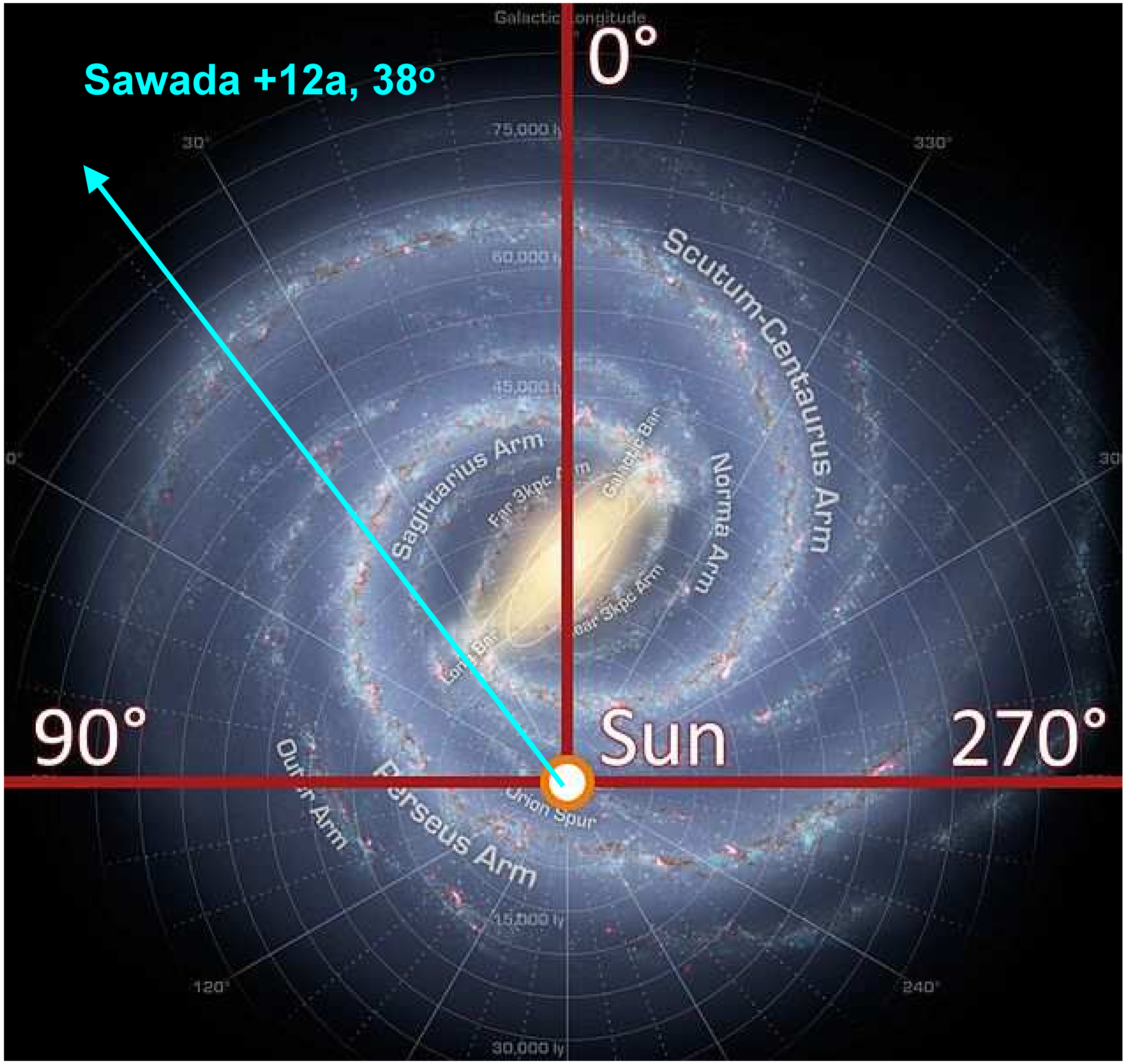
Downstream: ~200 pc rings with OB associations inside and star formation along the edge that is triggered or lingering

How much triggering is in the arms?



NASA

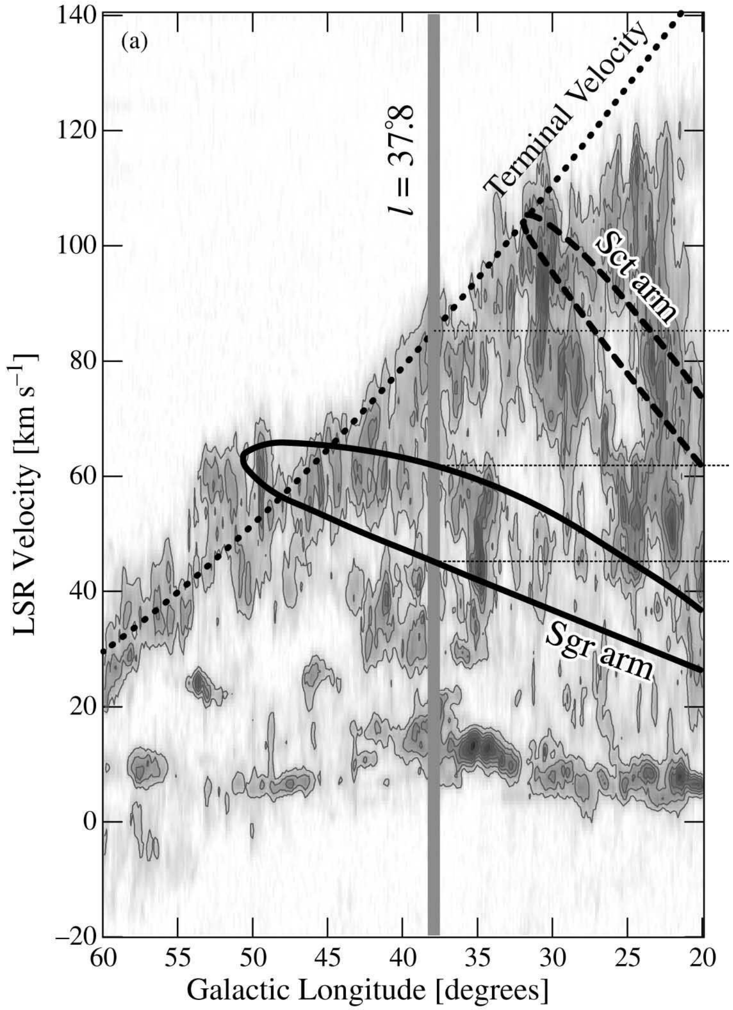
How much triggering is in the arms?

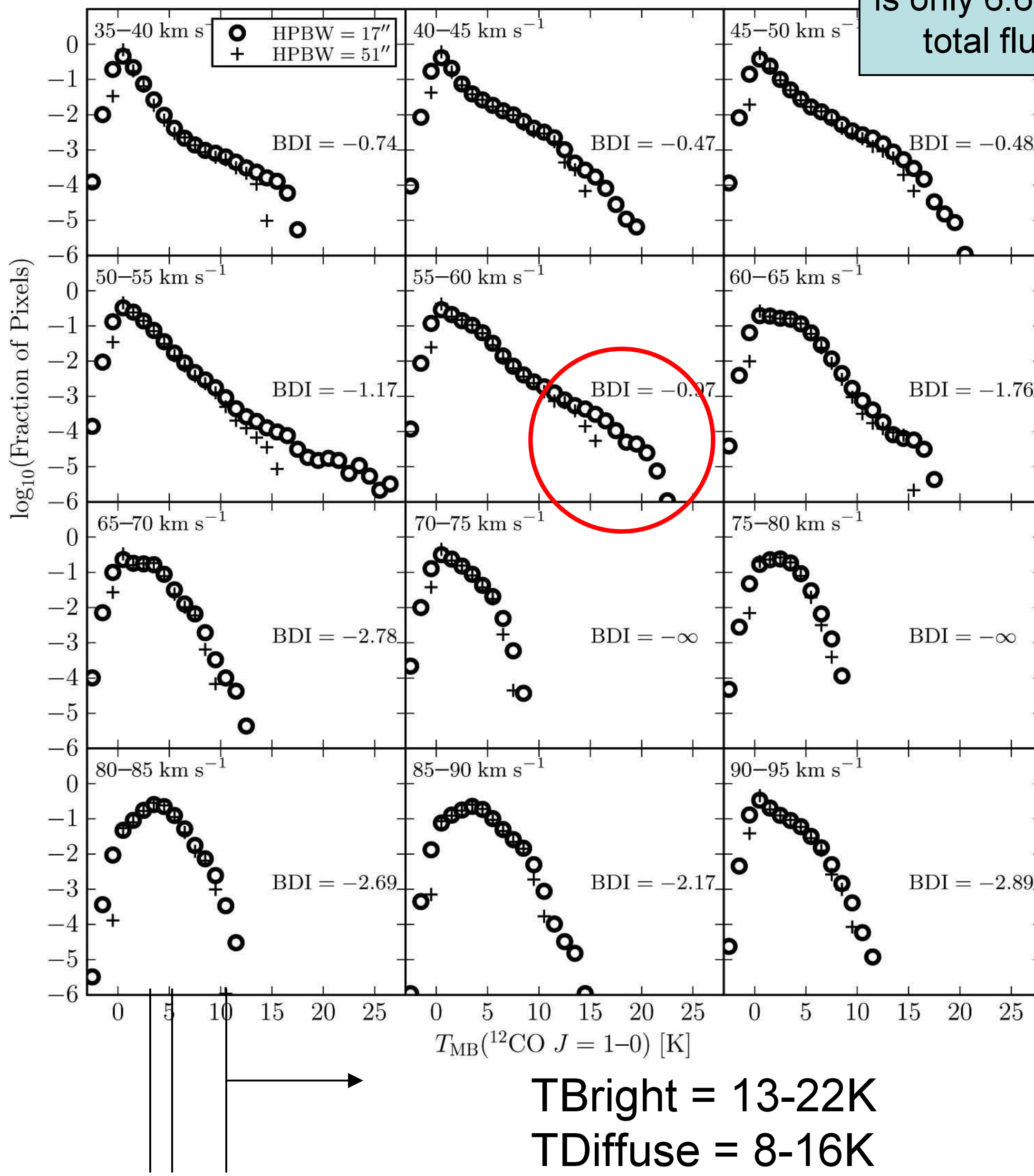


NASA

Brightness Distribution Index = log[F(TB>10k)/F(TB=3-5K)]

At max, the bright emission is only 6.6% of total flux

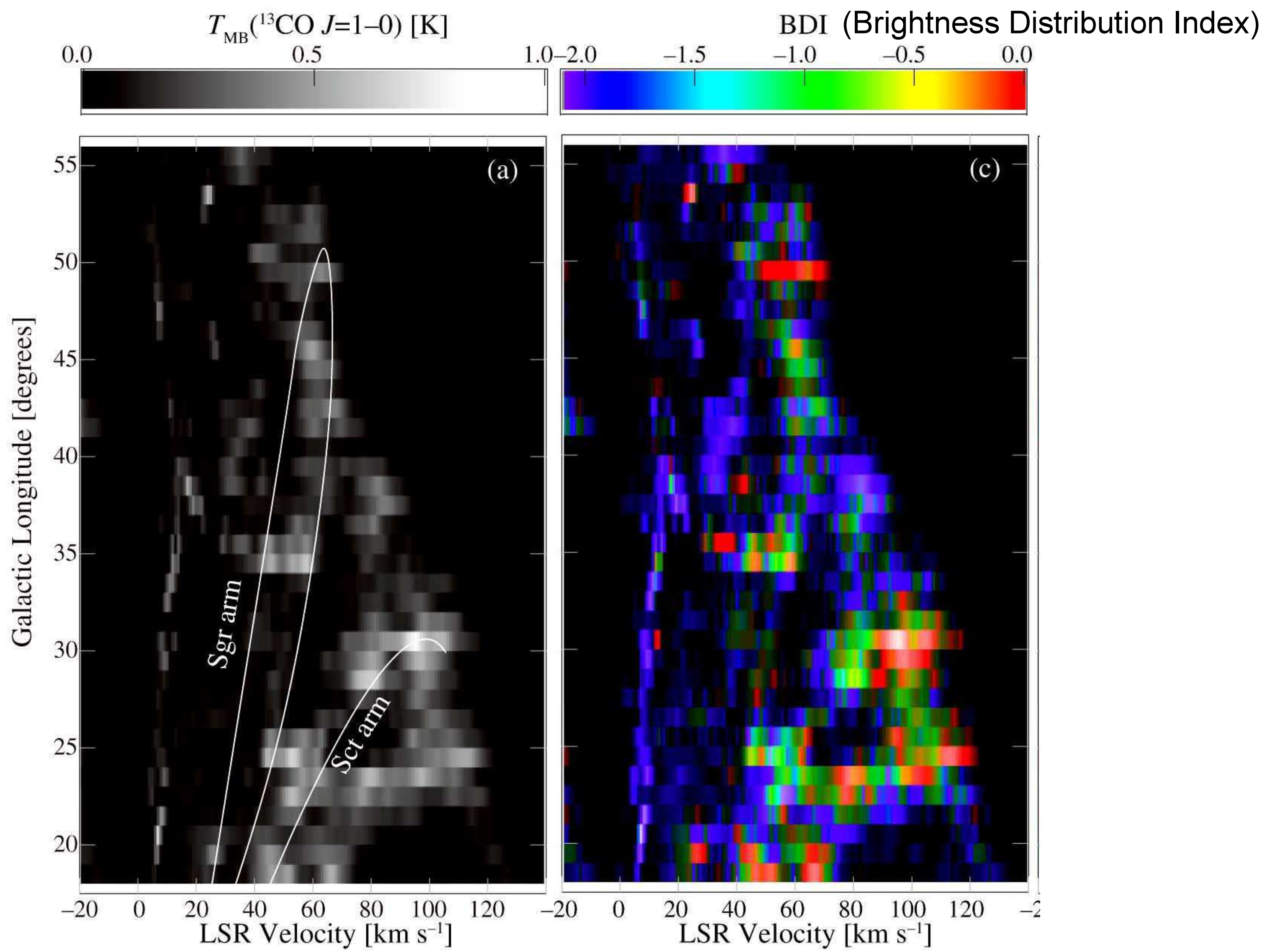




Sawada +12a

TBright = 13-22K

TDiffuse = 8-16K

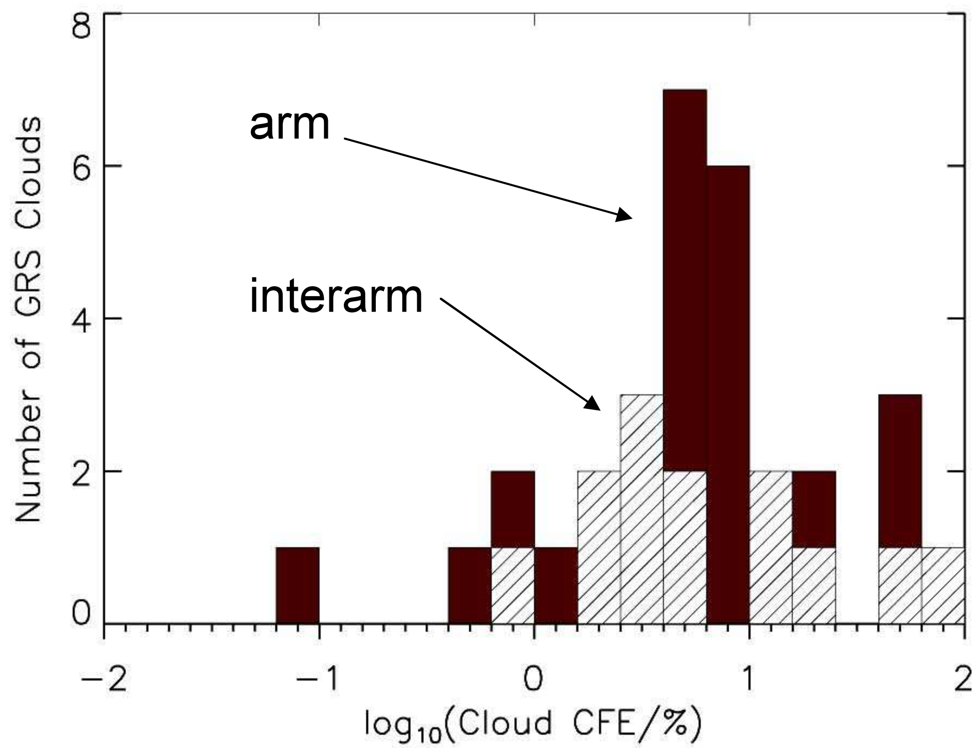


Sawada +12b: molecular clouds in spiral arms have bright cores

However, also at 38º MW longitude, the core mass fraction

M(1mm cores) / M(cloud)

is the same for arm & interarm regions

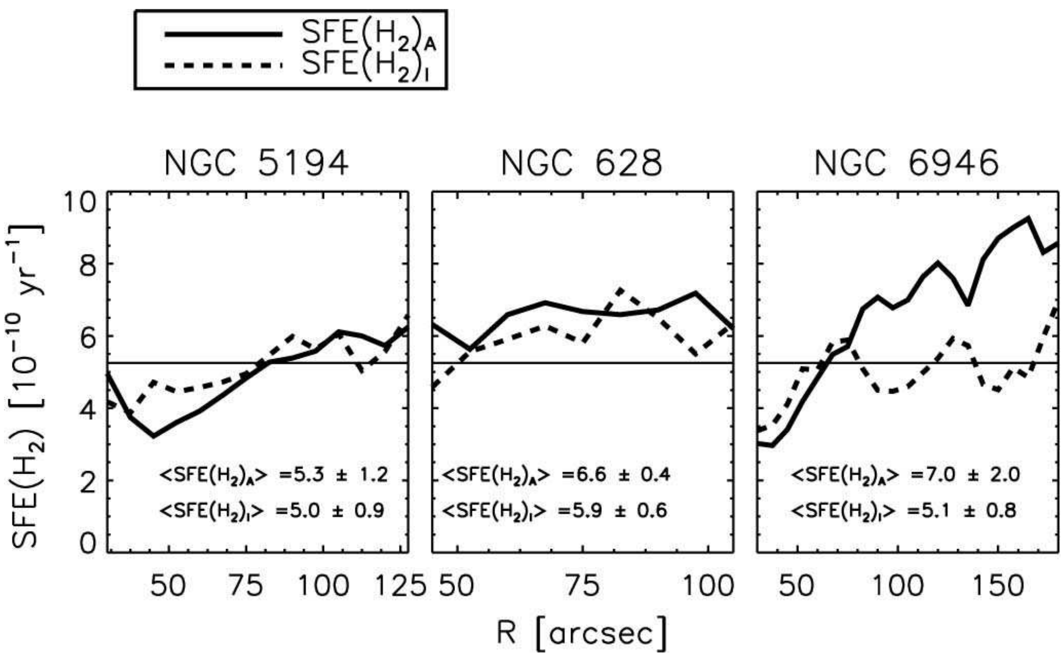


Eden et al. 2013

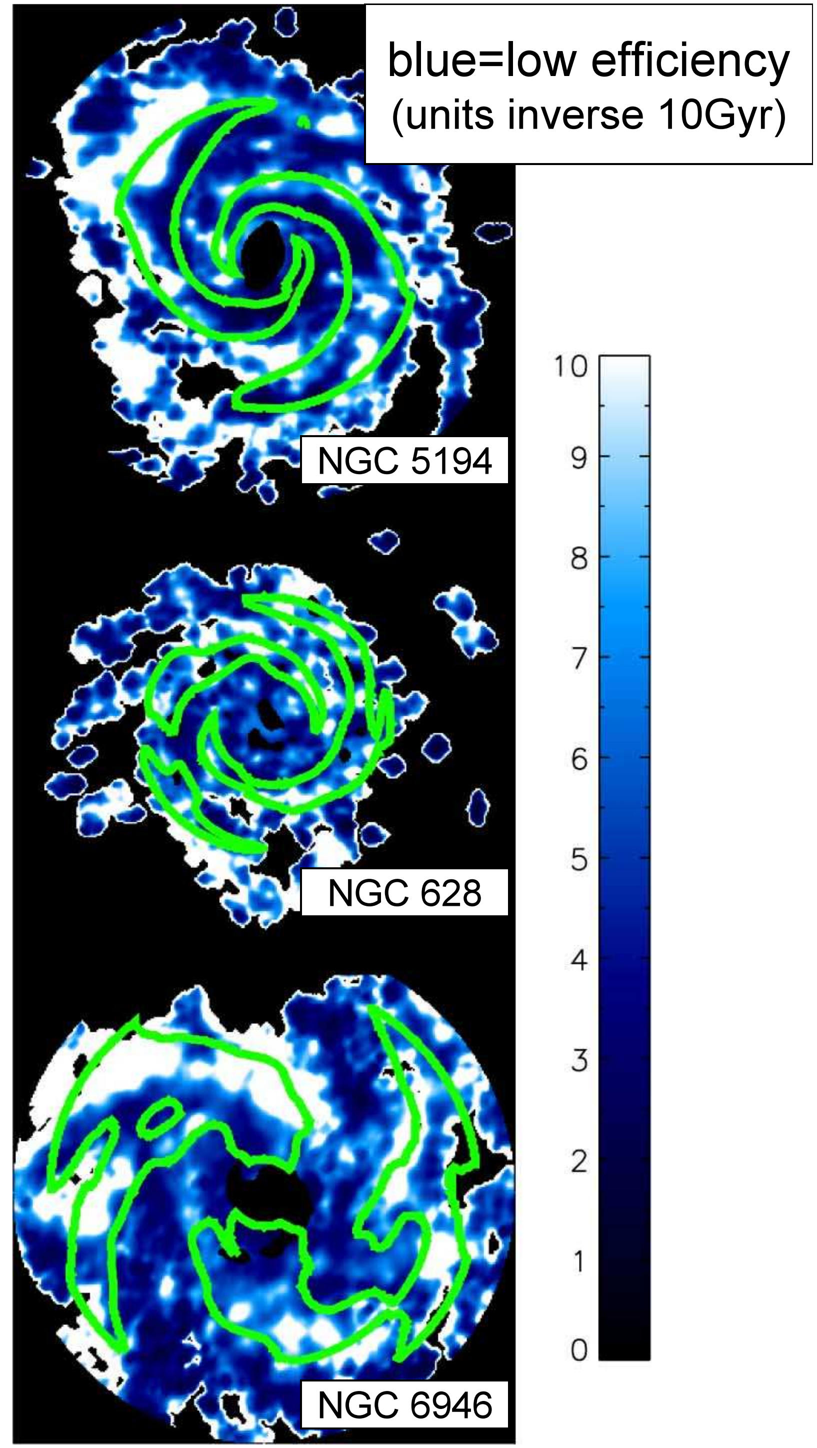
Star Formation Efficiency:

SFR (uv and 24μm)/CO(2-1)

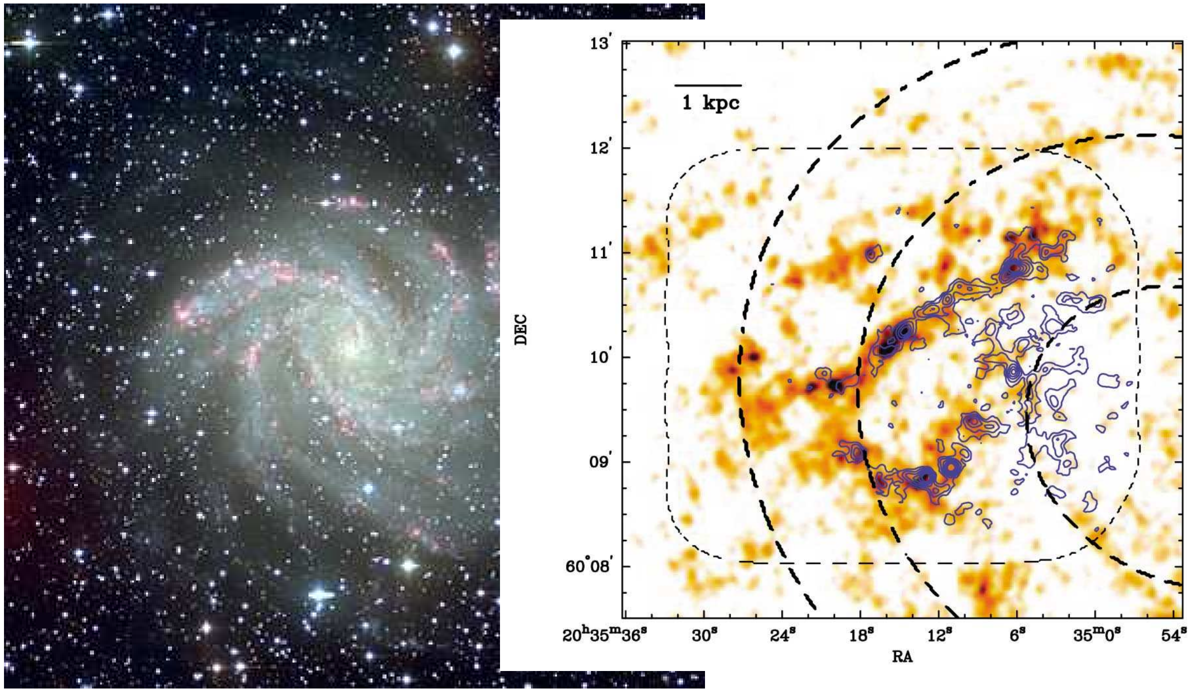
often the same in the arms & interarms



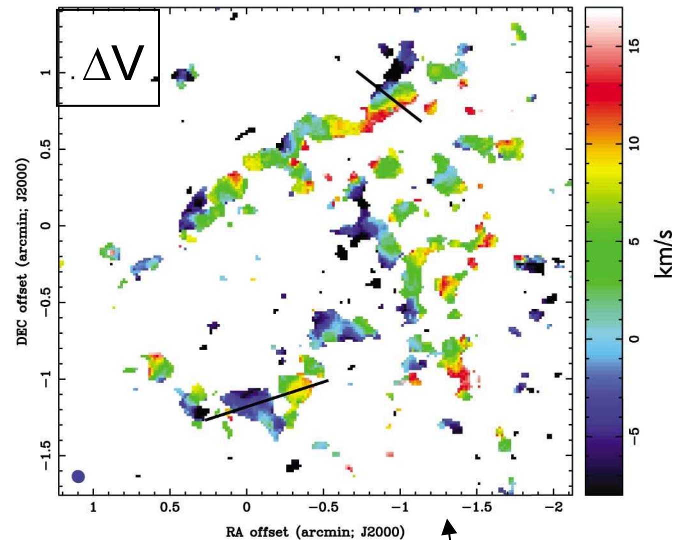
Foyle et al. 2010



Rebolledo +12: Eastern part of NGC 6946

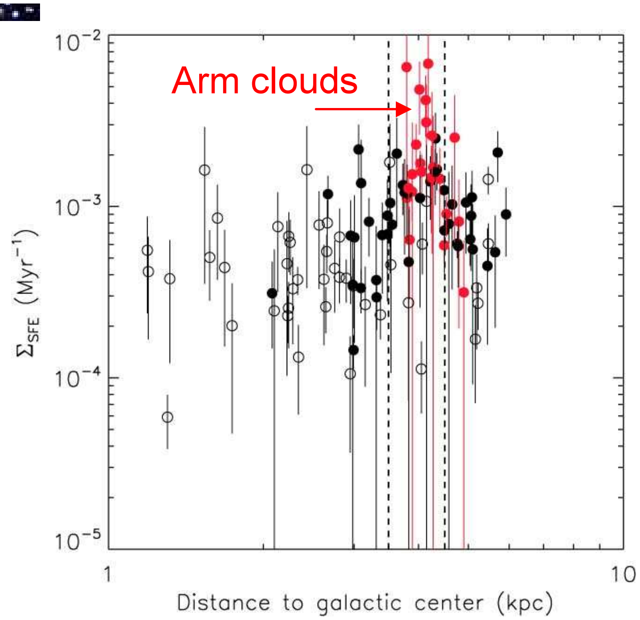


CO(1-0) contours
HI grayscale

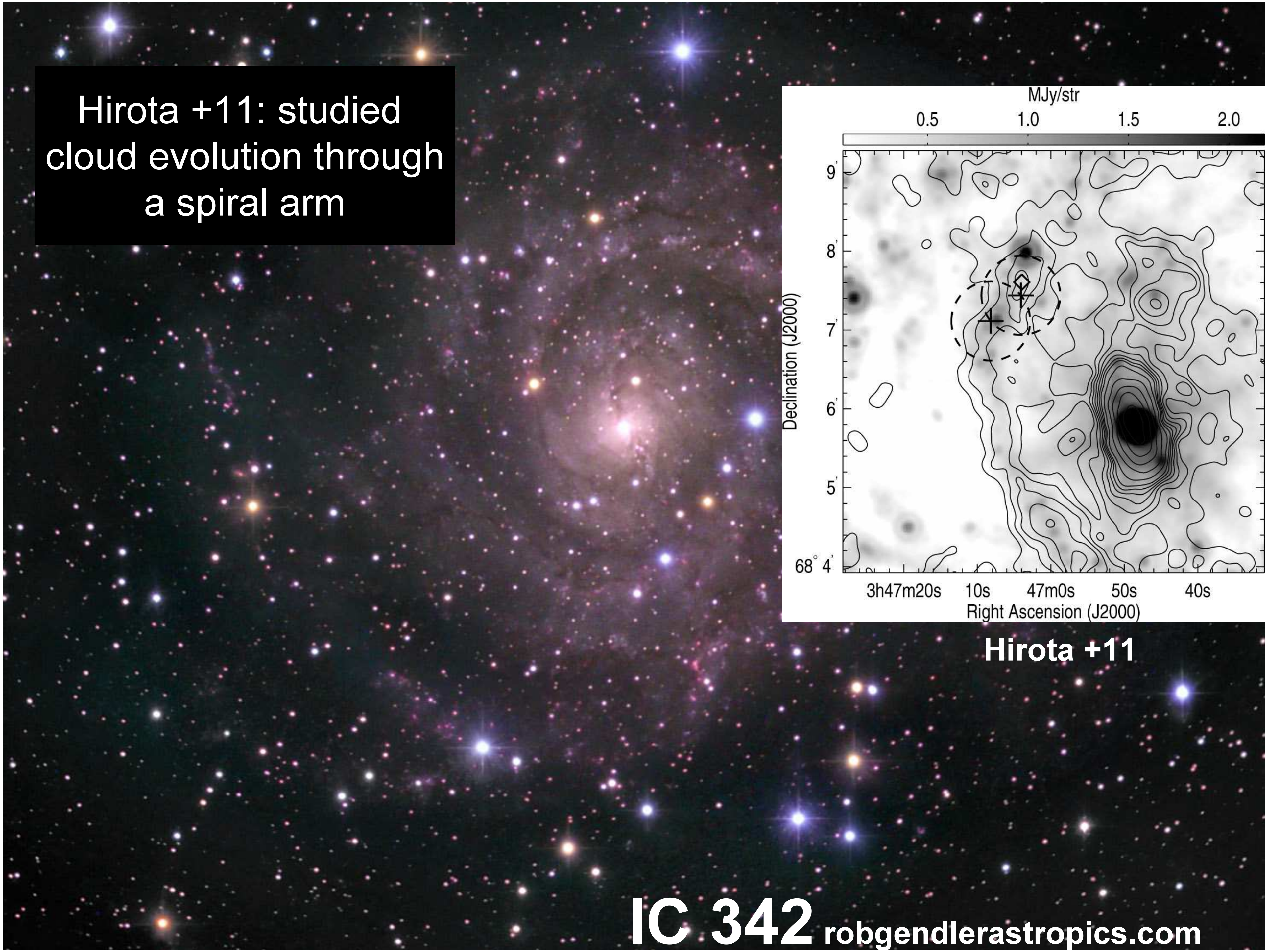


spiral arm shocks

Spiral arm molecular clouds have higher SF efficiencies

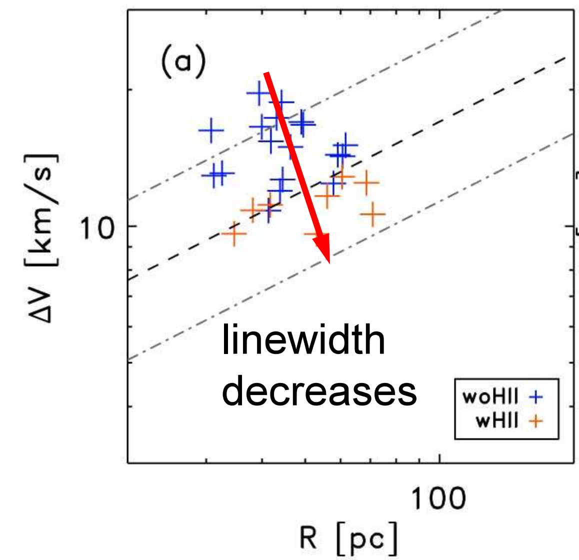


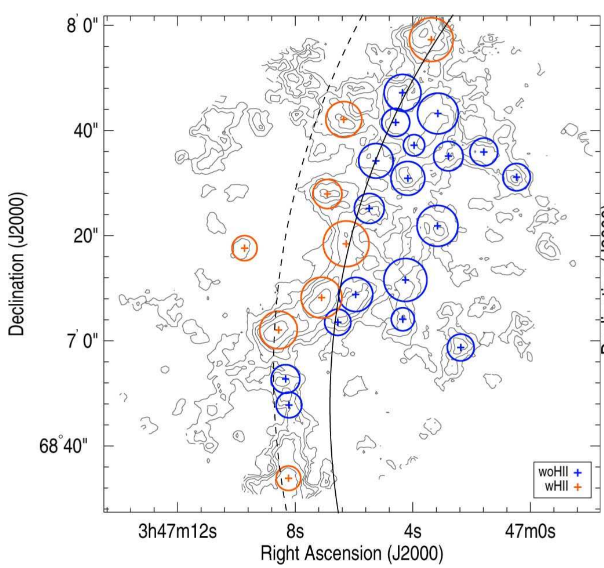
Hirota +11: studied cloud evolution through a spiral arm

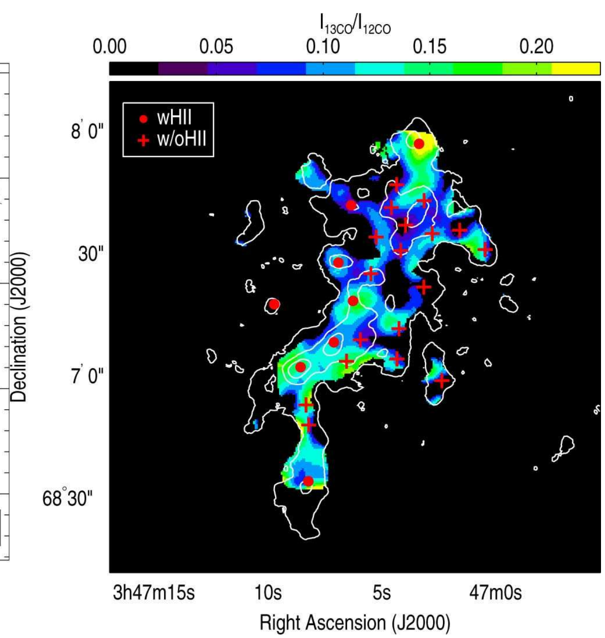


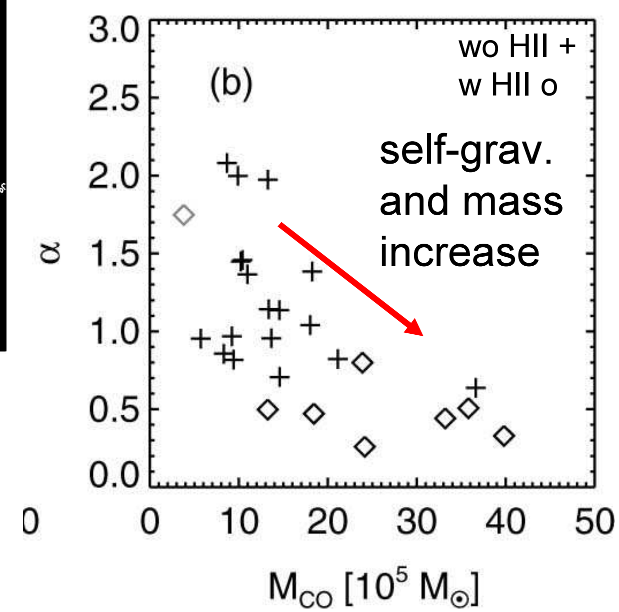
Linewidths decrease, self-gravity and mass increase as molecular clouds pass through arm.

diffuse CO → gravitating CO → stars









red = with HII,
blue = without HII

^{13}CO /^{12}CO indicates *diffuse* CO without the HII regions

Hirota +11

Summary: Cosmic Evolution of Star Formation in Spiral Arms

- Spiral arms appear when the strong accretion phase ends
  - rapid accretion makes gas-rich thick disks that collapse into big clumps
  - spirals form later in a cooler stellar disk

- The morphology of gravitational instabilities changes from clumps to clumpy irregular spirals, to thin regular spirals as the turbulent speed drops
  - pure-clump disks need high gas fractions
  - whereas spirals need cool gas+stars for the wave itself, plus hot (stabilizing) stars (and dark matter) to prevent clumping

- Gas in spiral arms is complicated: 2-phase instability, beading gravitational instability, feathering instability, cloud collisions, star formation feedback, … not all of this is related to star formation

- Star formation is *sometimes* triggered in spiral arms, but often it just *concentrated* there without increasing the efficiency inside clouds