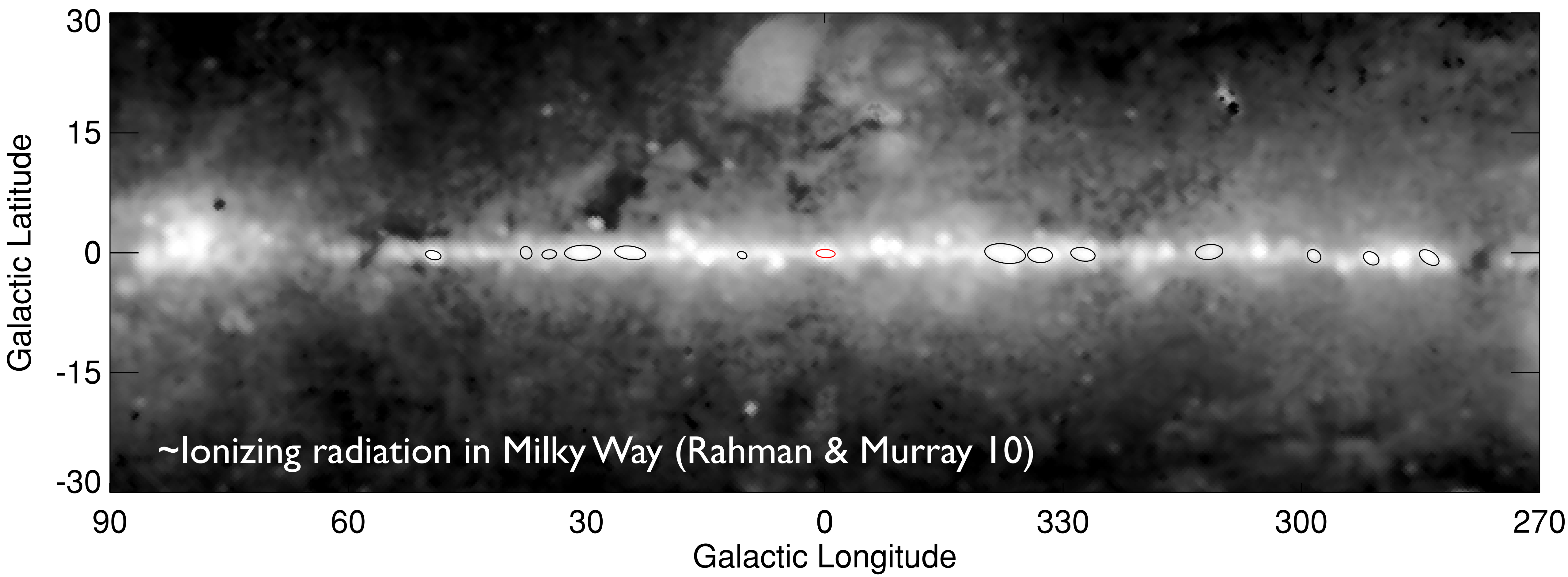
# Toomre instability and the formation of gravitationally-bound gas clouds

# Stars form in giant molecular clouds

- In Milky Way, 1/3 of current star formation occurs in 33 GMCs

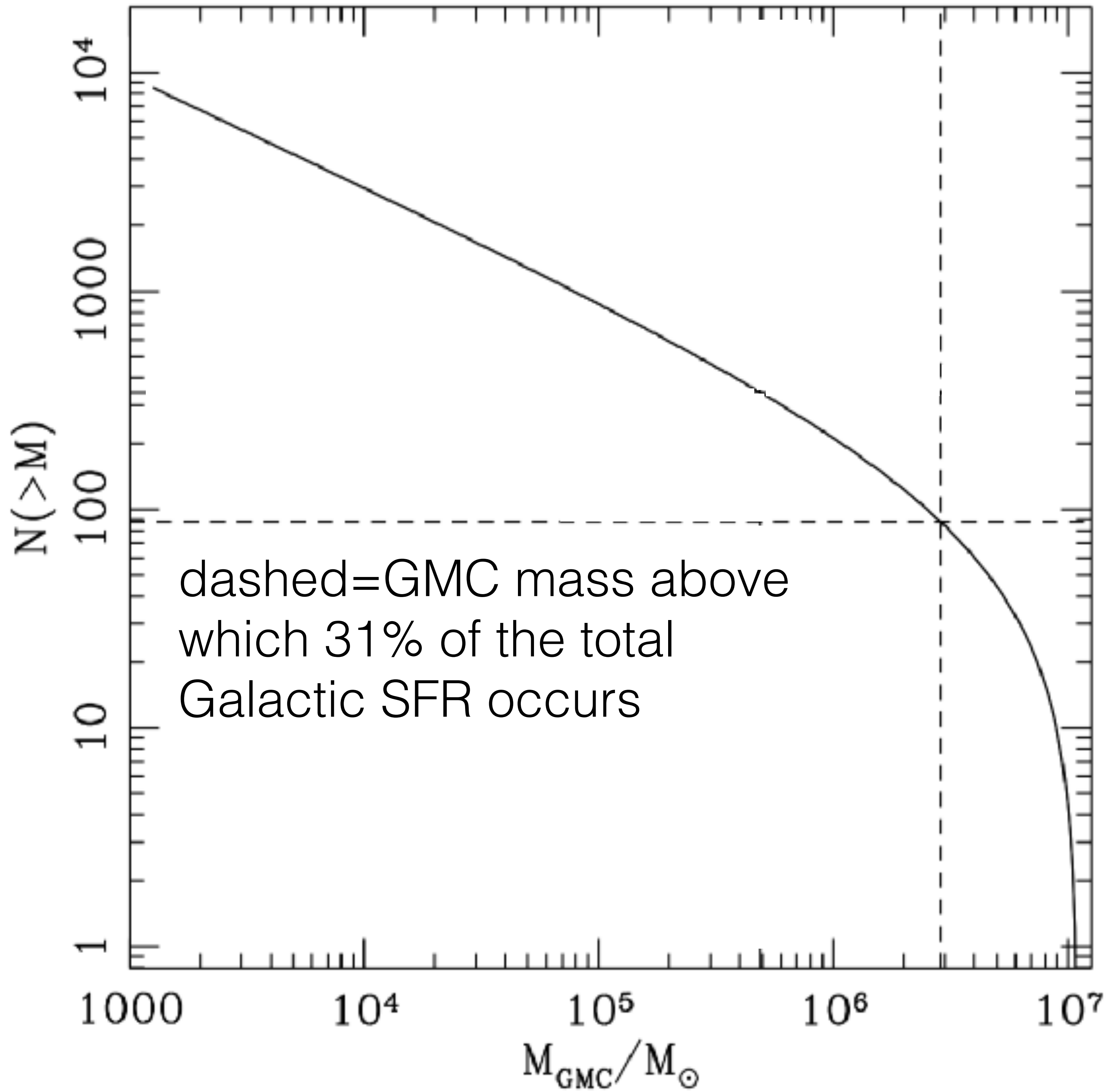



- Gravitational instability forms GMCs and sets their mass
  $M_T \sim \lambda_T^2\ \Sigma_g \sim h^2\ \Sigma_g$

# The mass spectrum of GMCs

- Most massive GMCs have mass $M_T \sim 10^7$ $M_{sun}$
- Many more, lower-mass clouds form from density fluctuations in the turbulent ISM

Milky Way GMC mass function
(fiducial model based on Williams & McKee 97 data)

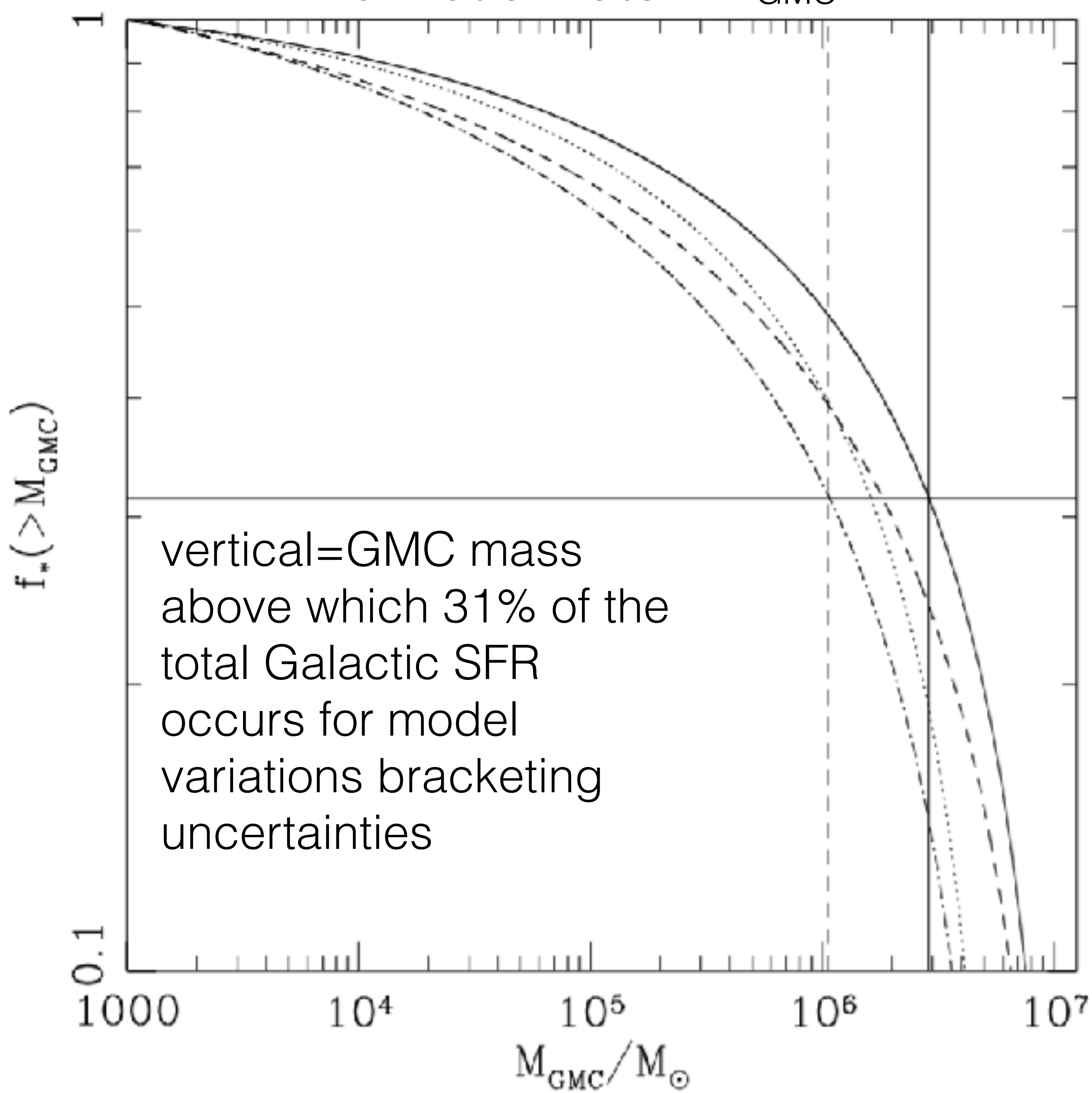



Murray 11

# Most star formation occurs in the most massive GMCs

- Not in the numerous lower mass clouds
- Good for simulations: to model galactic SFRs, most important is to resolve the most massive GMCs

Cumulative fraction of Galactic star formation rate >$M_{GMC}$

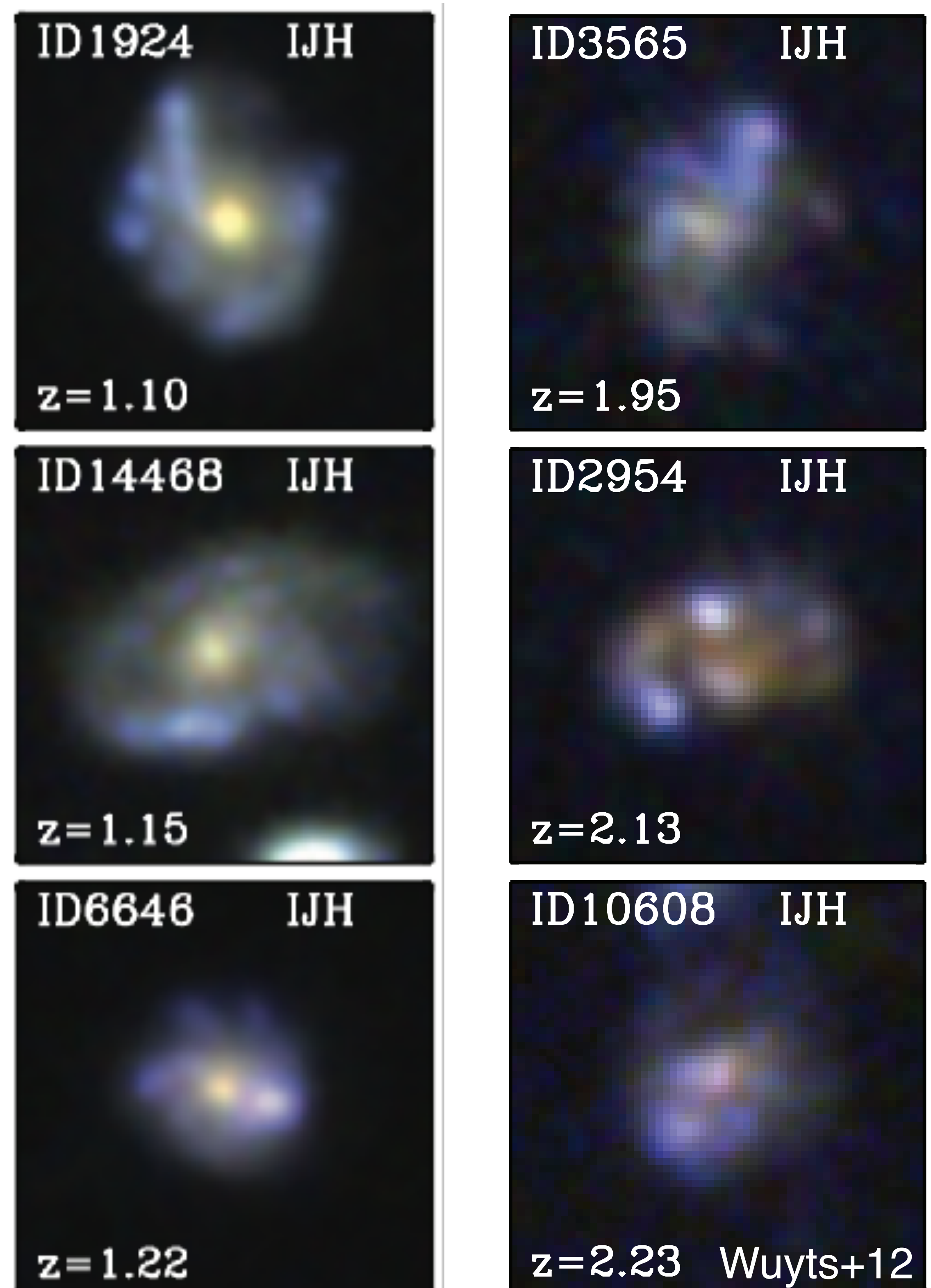



Murray 11

# Increasingly massive star-forming clumps with increasing redshift

$z$=0

$z$~1 $z$~2



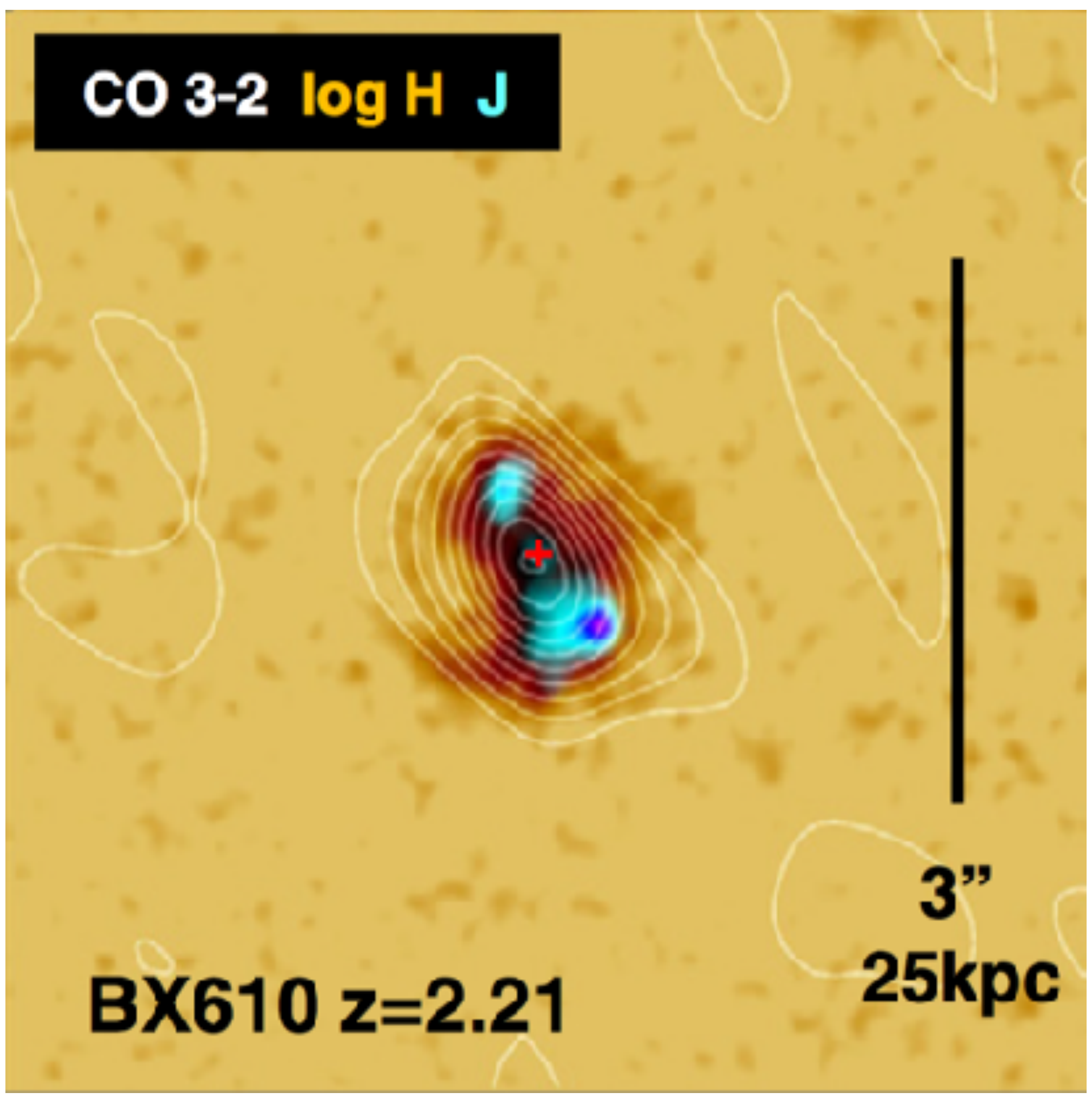

For *Q*~*1*, $h/r \propto c_{\rm T}/v_{\rm c} \propto f_{\rm g}$

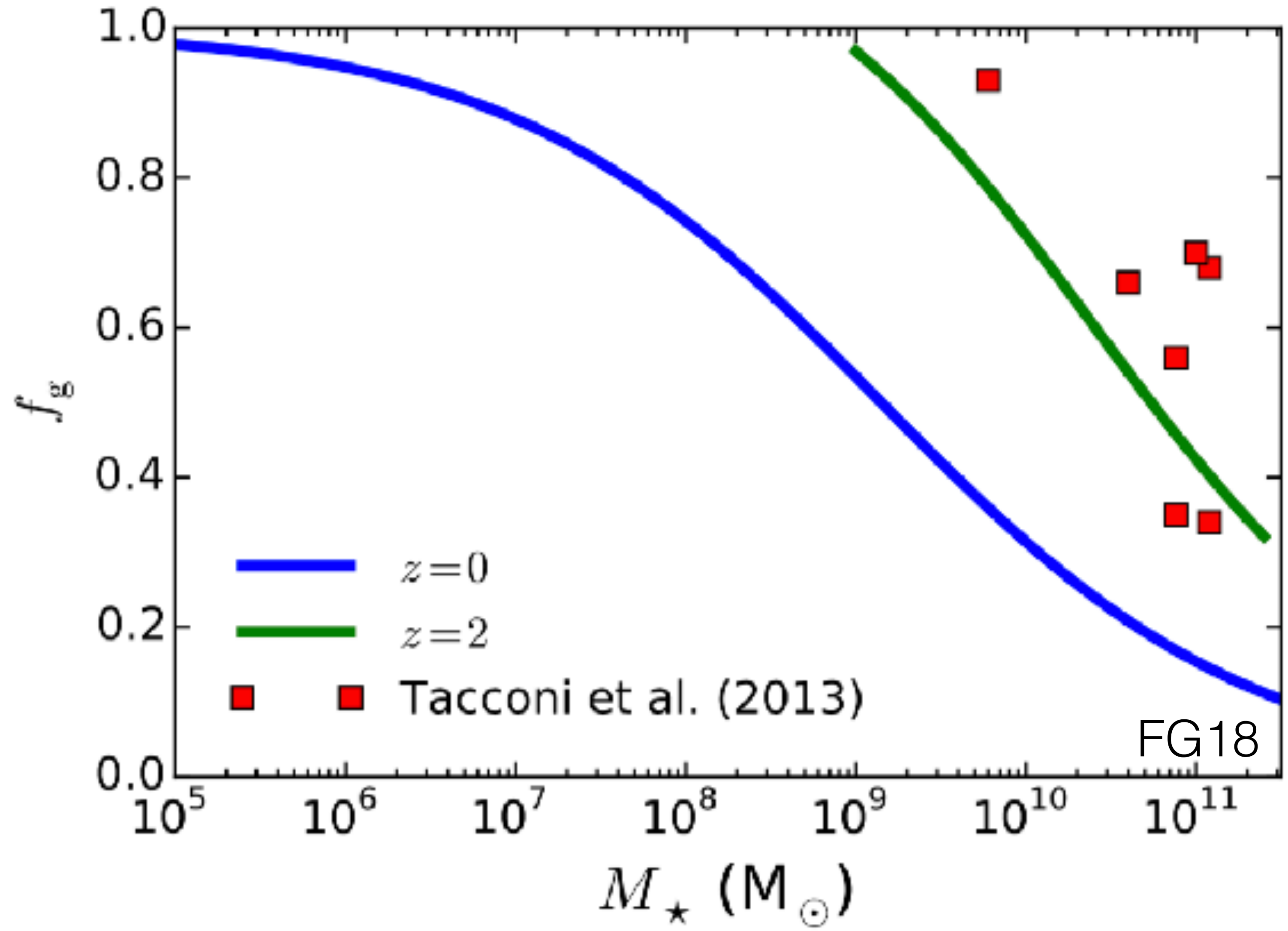
$$\Rightarrow M_{\rm T} \propto h^2 \Sigma_{\rm g} \propto f_{\rm g}^3 M_{\rm gal}$$

e.g., FG+13

# Gas fractions are elevated at high redshift


PdB interferometer

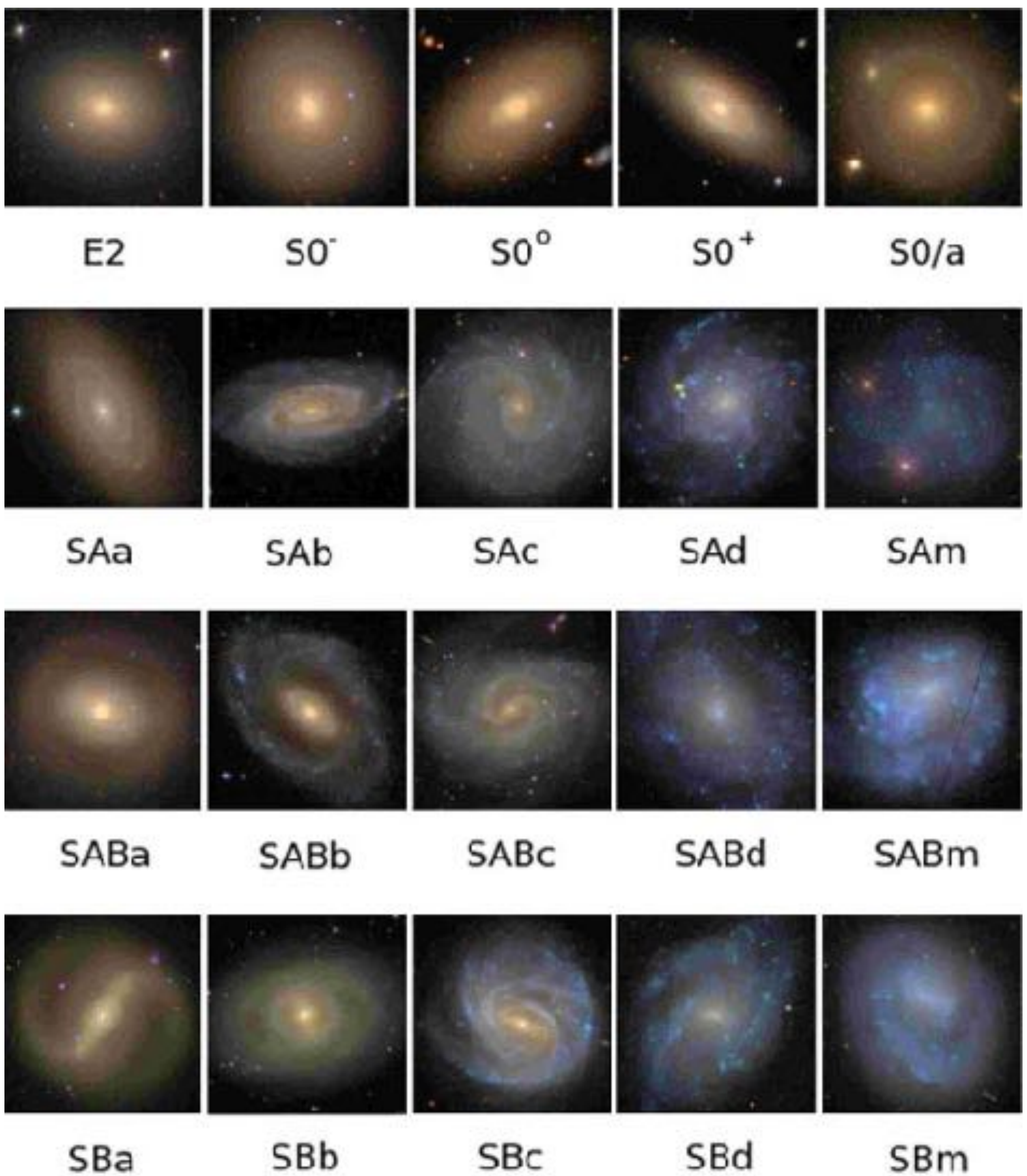



CO molecular gas observations superposed on top of HST J-band image (Tacconi+13)

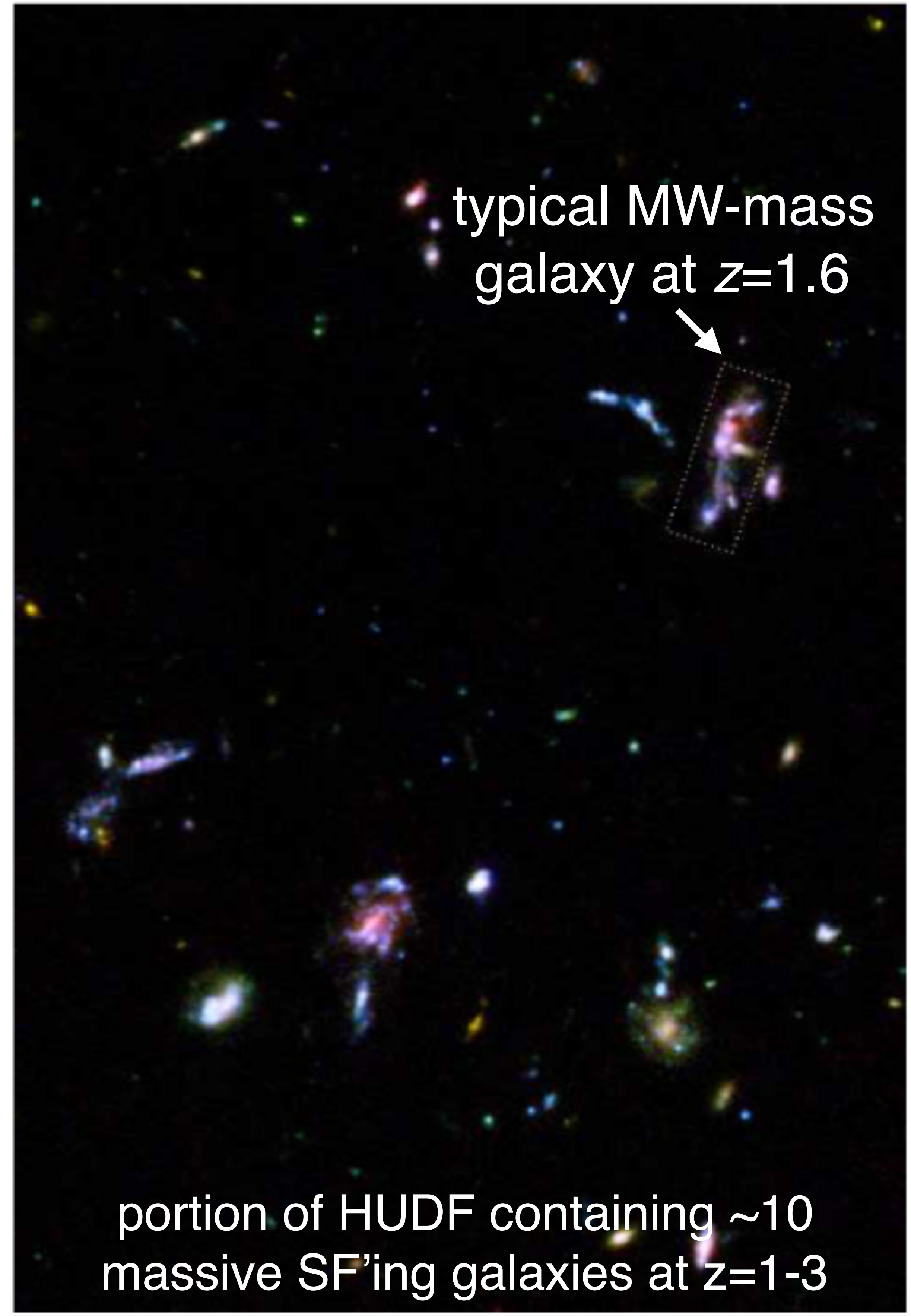
# Other illustrations of redshift evolution

## Nearby galaxies



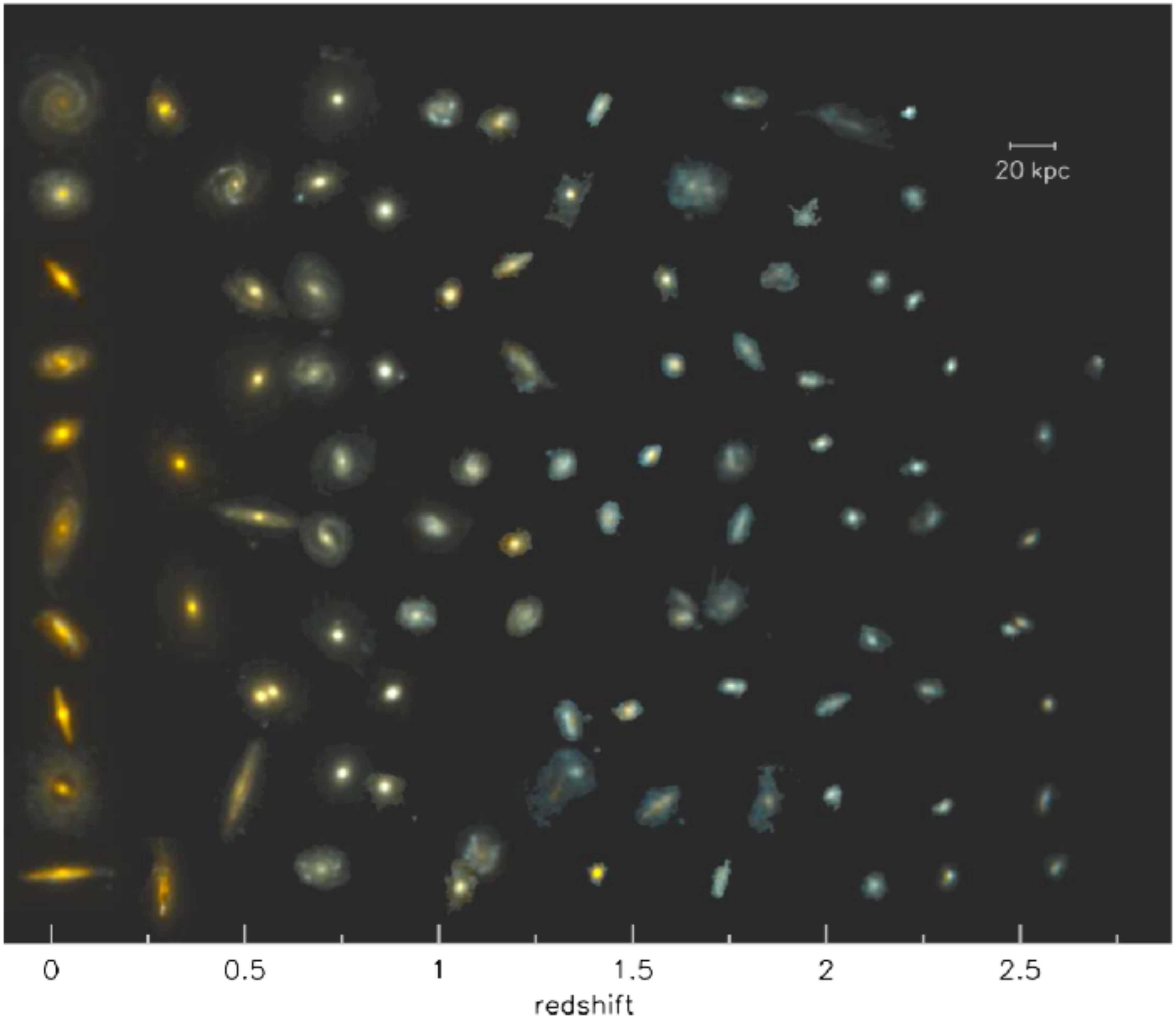

Buta 2011

## High redshift




Bournaud 2015

# Tracing progenitors of MW-mass galaxies using comoving number density




van Dokkum+13

At high $z$, galaxies are:

- smaller (even at same mass)
- clumpier (esp. in UV — young stars)
- bluer (younger stellar populations, higher SFRs)

# Swing amplification

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Leading local perturbations unwind and are amplified

Amplification can be factor ~10-100 (disks respond strongly!)

Amplification strongest when disk is barely *Q*-stable, *Q*~1-2

Swing-amplified perturbations likely explain most observed spiral structure

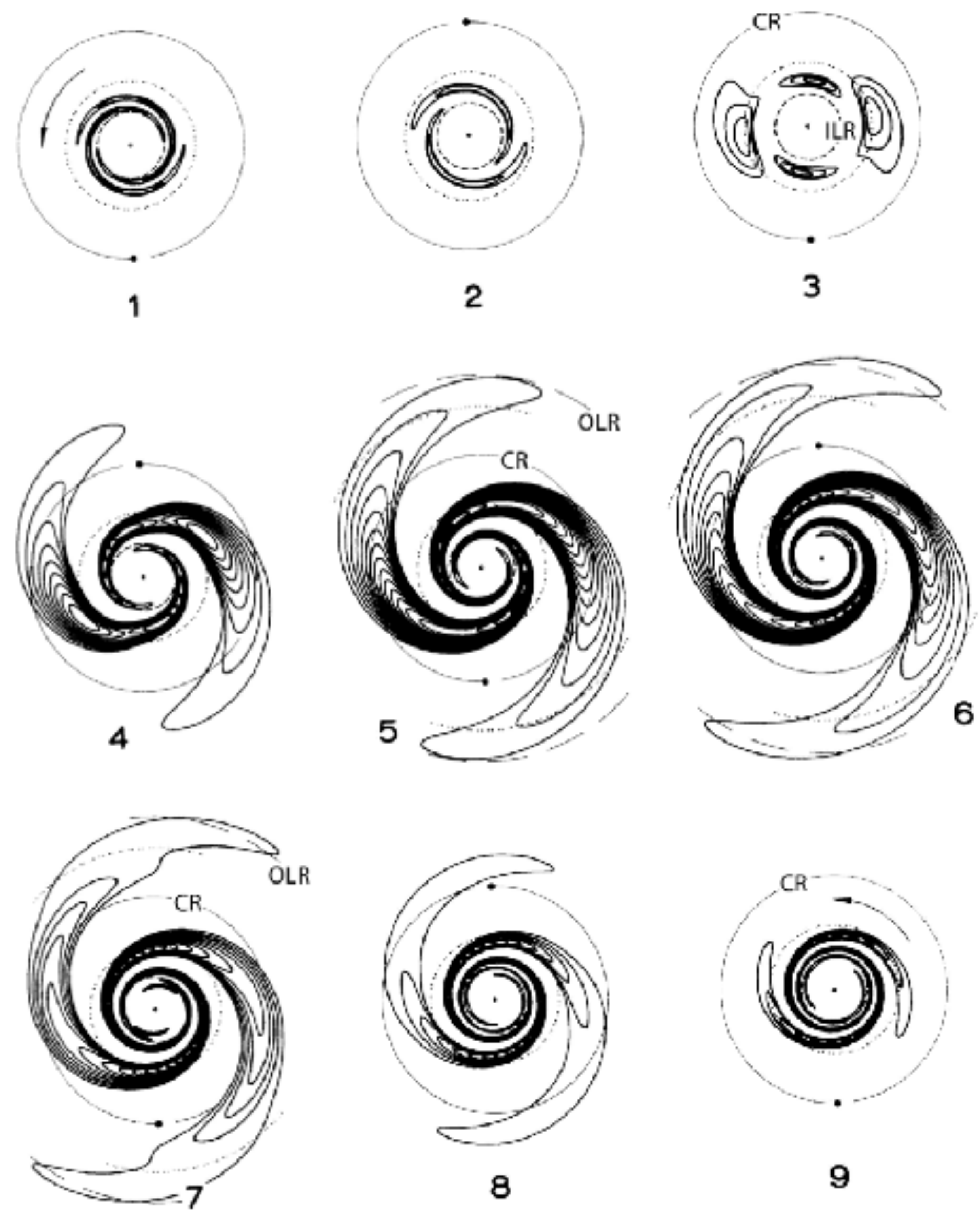



**Figure 6.19** Evolution of a packet of leading waves in a Mestel disk with $Q = 1.5$ and $f_d = 1/2$ (equal contributions from the disk and the rigid halo to the flat circular-speed curve). Contours represent fixed fractional excess surface densities; since the calculations are based on linear perturbation theory, the amplitude normalization is arbitrary. Contours in regions of depleted surface density are not shown. The time interval between diagrams is one-half of a rotation period at corotation. ILR, CR, and OLR denote the radii of the inner Lindblad resonance, the corotation resonance, and the outer Lindblad resonance. From Toomre (1981), © Cambridge University Press 1981. Reprinted by permission of Cambridge University Press.

# Result of swing amplification depends on whether perturbations are local (flocculent) or global (grand design)

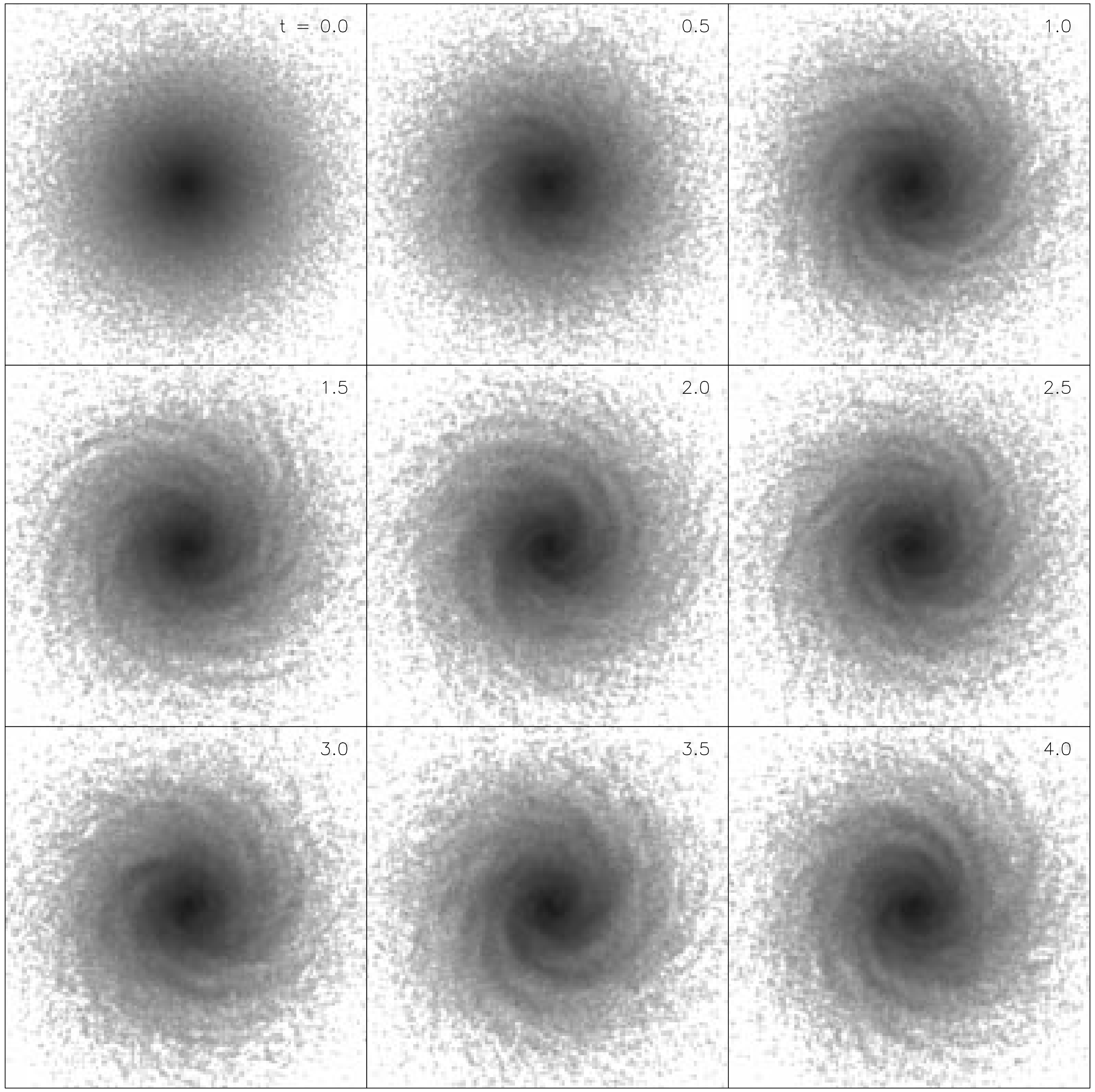



Figure 15.2: Stable disk.simulation. Initially, this disk has $Q \simeq 1.26$, suffcient to curb local instabilities. The galaxy model includes a bulge and a halo (not shown); the disk is 15% of the total mass. Each frame is 15 disk scale lengths on a side; times are given in units of the rotation period at $\sim 3$ disk scale lengths.

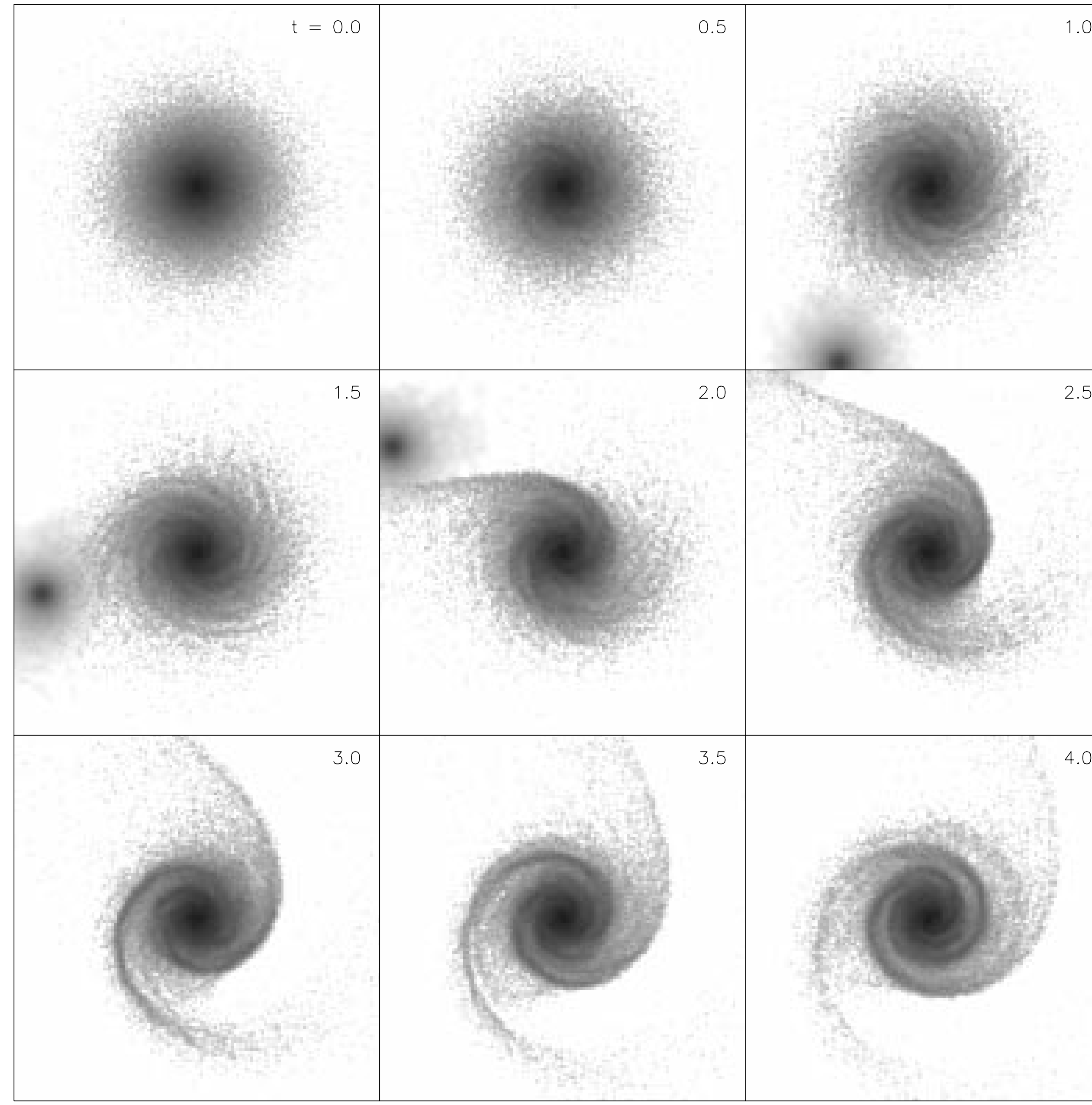
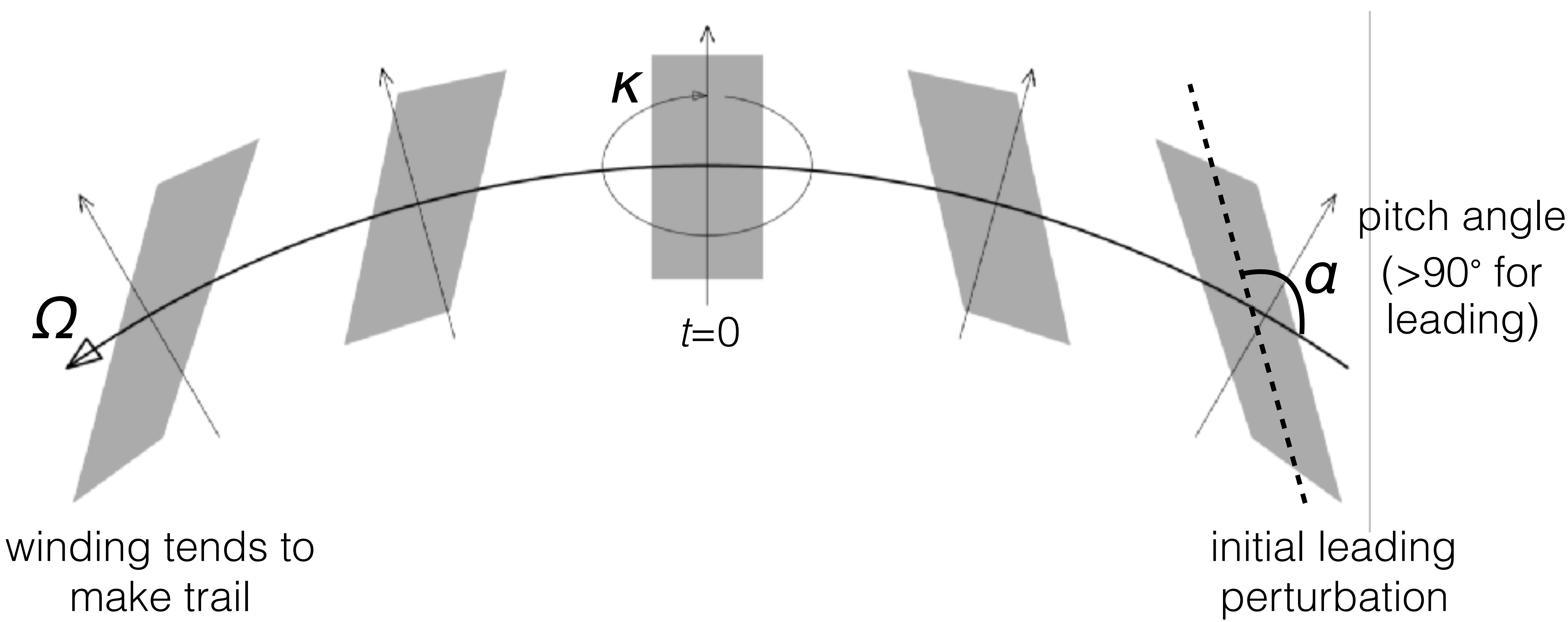



Figure 15.3: Tidal encounter between the disk in Fig. 15.2 and a companion of 10 the total mass. This compaion approached on a parabolic initial orbit and reached an apocenter of $\sim 9$ disk scale lengths at $t = 1.5$. Each frame is 24 scale lengths on a side; times are given in units of the rotation period at $\sim 3$ scale lengths.

Barnes

spiral structure trailing in both cases, in agreement with observations

# Swing resonance




Homework: Perturbation unwinds at rate $\frac{d\alpha}{dt} = -\frac{2A}{1+4A^2t^2}$

where $A \equiv -\frac{1}{2}R\frac{d\Omega}{dR}$ = Oort constant, quantifies shear (how much $\Omega$ changes with $R$)

# Swing resonance (continued)

$$\frac{d\alpha}{dt} = -\frac{2A}{1+4A^2t^2}$$

maximum as perturbation “swings" from leading to trailing ($t=0$)

Then, swing rate is $2A \sim \Omega \sim \kappa$. (show for representative examples, e.g. flat rotation curve)

Temporary near match between $2A$ and $\kappa$ (both in same sense of rotation) enhances effect of gravitational force from the perturbation on stellar orbits — and the contribution of the stars’ own gravity to the perturbation.
[Note: absent resonance, rotation would tend to move stars out of perturbation.]

$\Longrightarrow$ swing amplification

Swing amplification + winding by differential rotation $\Longrightarrow$ formation of trailing spirals

# Swing resonance (continued)

<u>Other intuitive way to think about swing amplification:</u>

In rotating disk, epicycles with frequency $\kappa$ stabilize generic long-wavelength modes (Toomre analysis).

Absent rotation, long-wavelength modes are gravitationally unstable and grow (Jeans analysis).

The swing resonance picks up particular perturbations for which the stabilizing effects of rotation are reduced, allowing them to grow in a manner analogous to the Jeans case.

The perturbations then get wound into trailing spirals by differential rotation.