Gas and Stellar Spiral Arms and Their Offsets in the Grand-Design Spiral Galaxy M51

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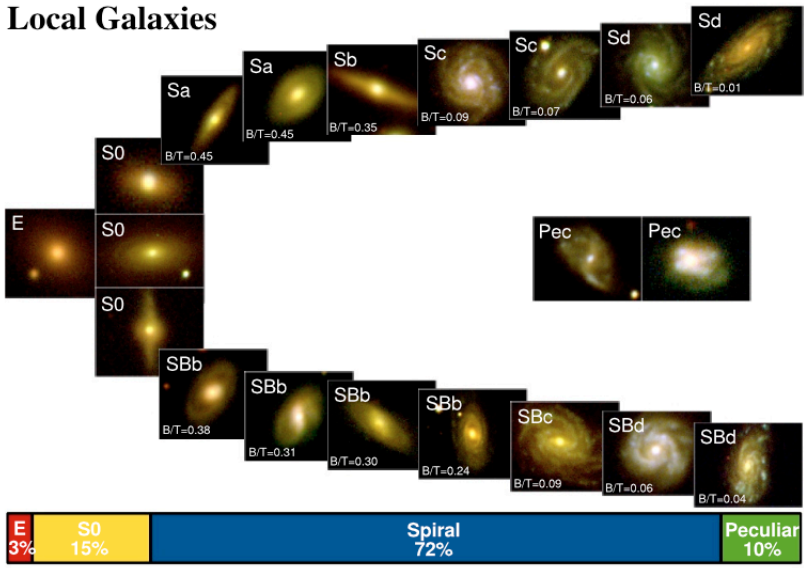
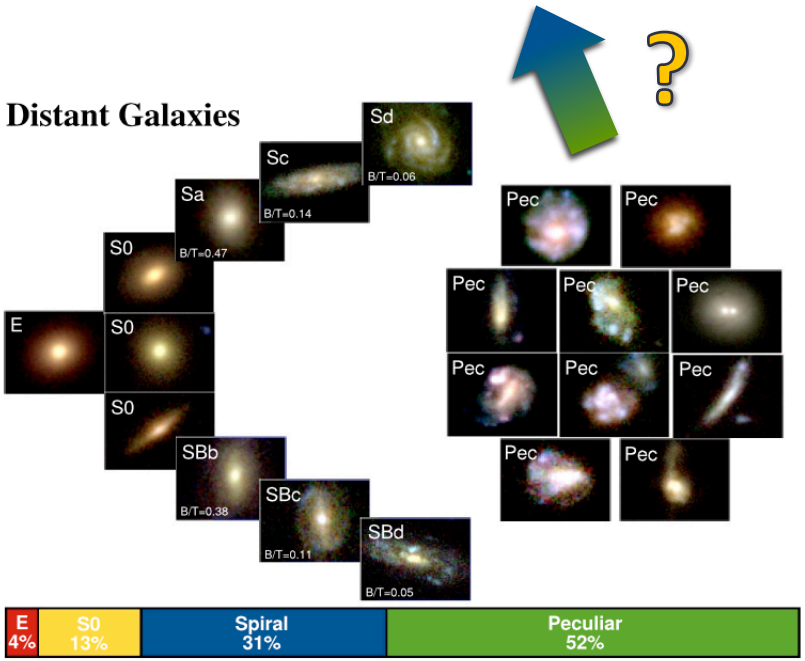
Egusa et al., 2017, MNRAS, 465, 460--471



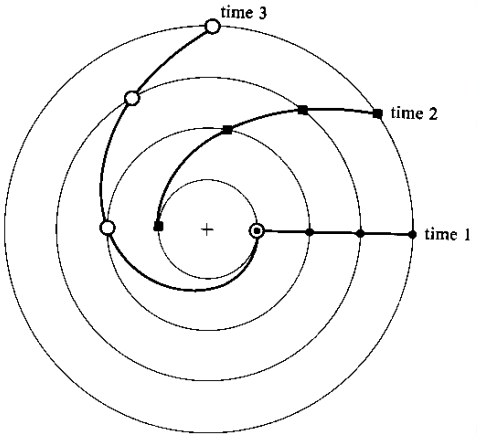


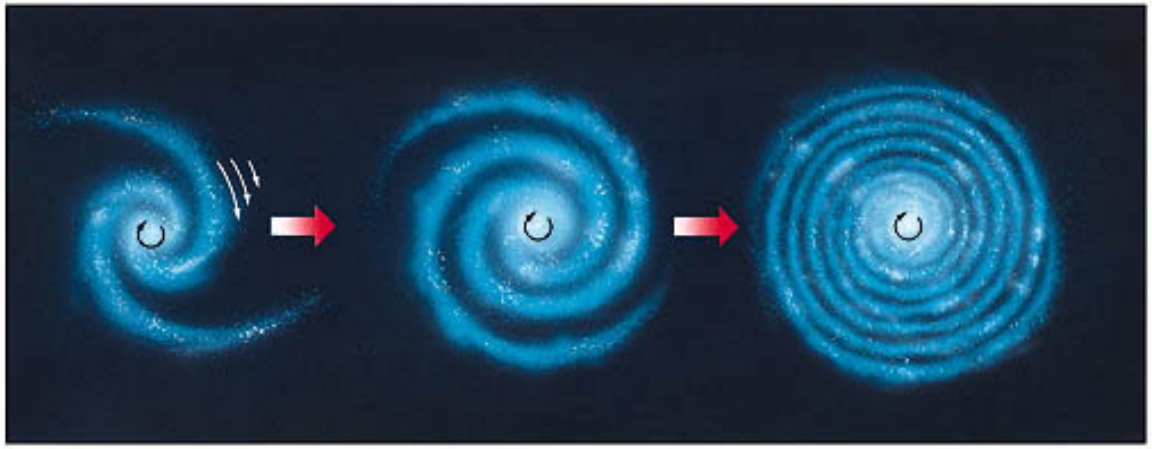
Key Question

- "What is a lifetime of spiral arms?"
  - "Are they long-lived or short-lived?"
  - this is related to an evolution of spiral galaxies
    - z=0: ~70% of galaxies are spiral
    - z=0.65 (6 Gyr ago): only ~30% of galaxies are spiral (Delgado-Serrano+2010)

Theories of Spiral Structure

- The winding problem
  - if spiral arms rotate differentially, they become too tightly wound within a few rotations, i.e. ~Gyr
  - this is against the current predominance of spiral galaxies

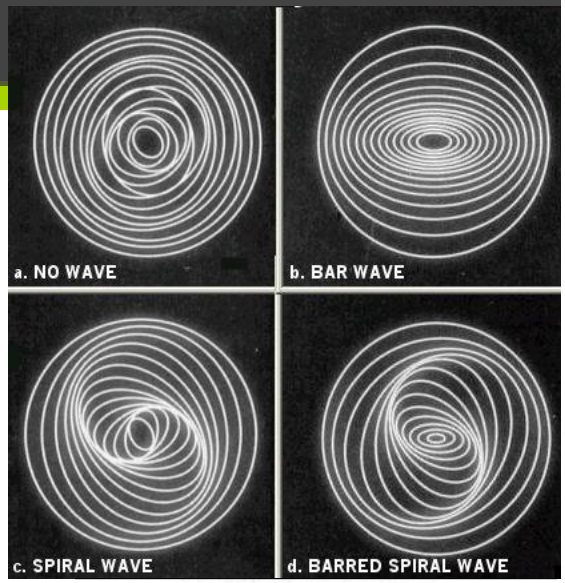


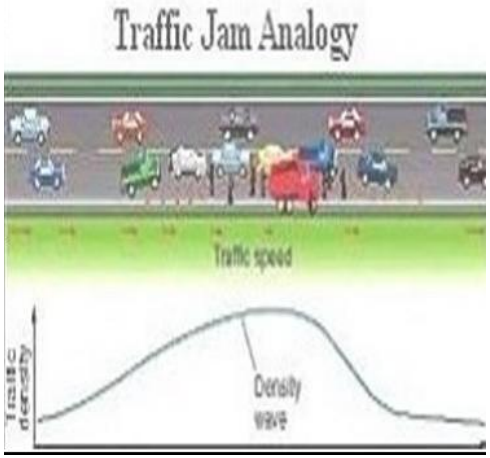


http://ircamera.as.arizona.edu/astr_250/Lectures/Lecture_23.htm

Density Wave Hypothesis

- Spiral arm is a quasi-stationary density wave (Lin & Shu 1964)
  - based on an idea that "spiral arms should be long-lived"
  - linear and local analysis assuming tightly-winding spiral arms
  - spiral pattern is a rigid body for > a few Gyr

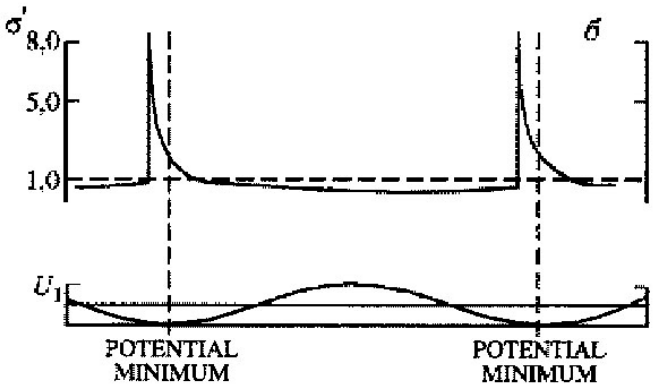




http://asterisk.apod.com/viewtopic.php?f=31&t=22397

Galactic Shock

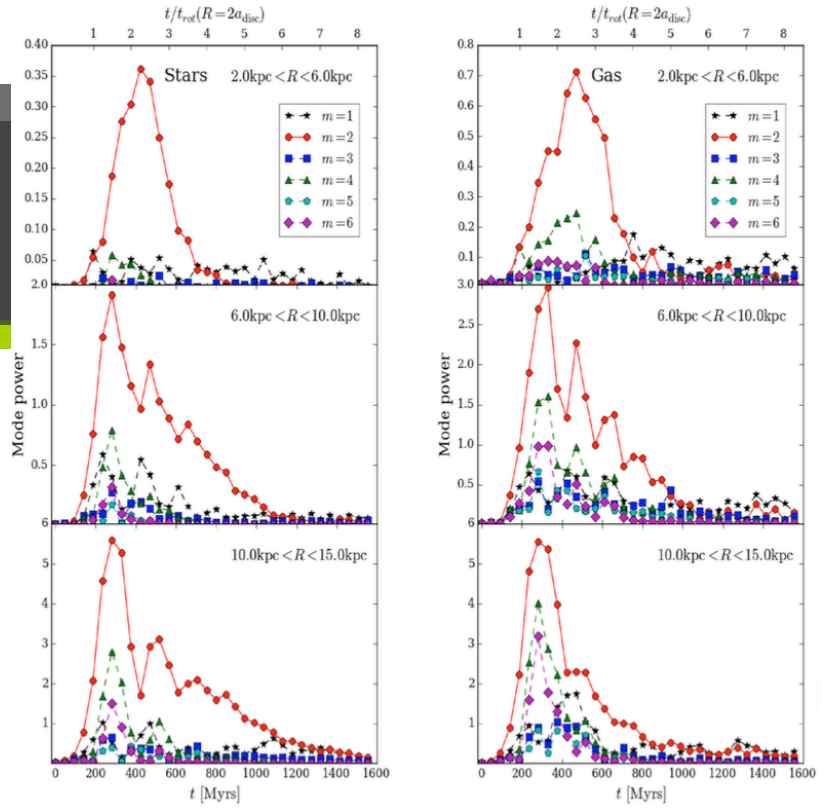
- Gas response to fixed stellar spiral arms
  - Fujimoto (1968), Roberts (1969)
  - super-sonic gas flow experience a shock around potential minima
  - increased gas density has been regarded as a trigger of star formation



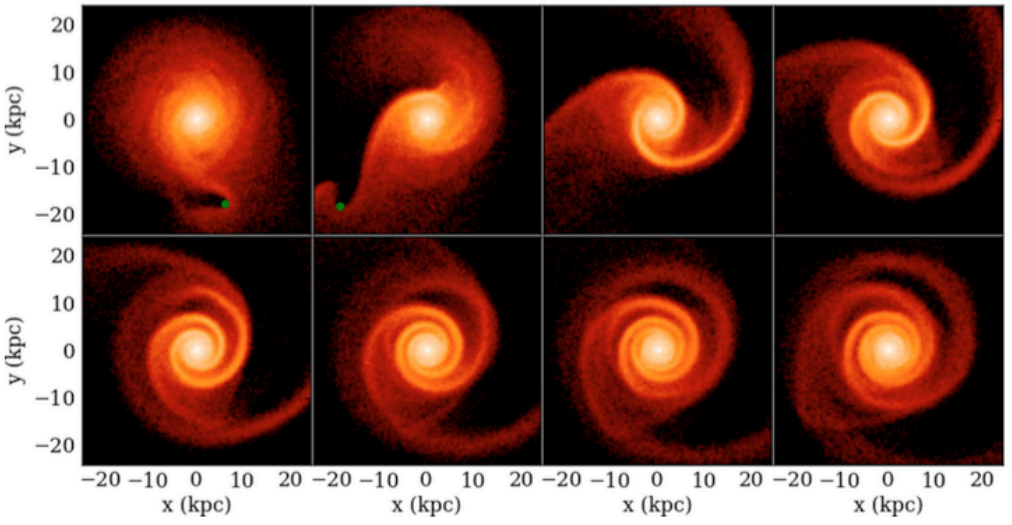
reproduced from Roberts (1969), http://ned.ipac.caltech.edu/level5/Sept04/Pasha2/Pasha2_3.html

Tidal Arms

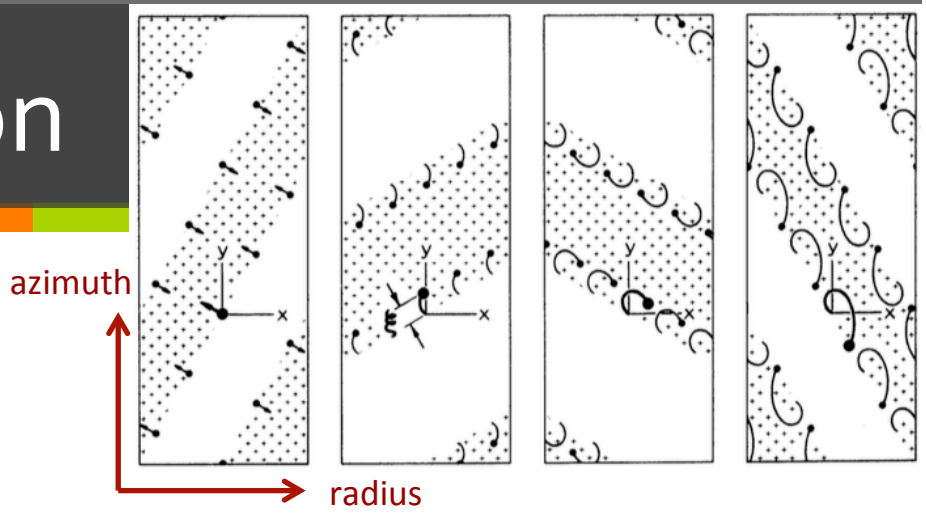
- Indication from simulations
  - isolated two-armed spiral structure w/o bar is difficult to form
- Interaction with a companion galaxy can drive m=2 spiral
  - Toomre&Toomre1972, Dobbs+2010, Pettitt+2016
  - tidal arms are still transient but live ~1 Gyr



top: amplitude of mode for stellar and gas disk
bottom: stellar disk for 800 Myr (Pettitt+2016)

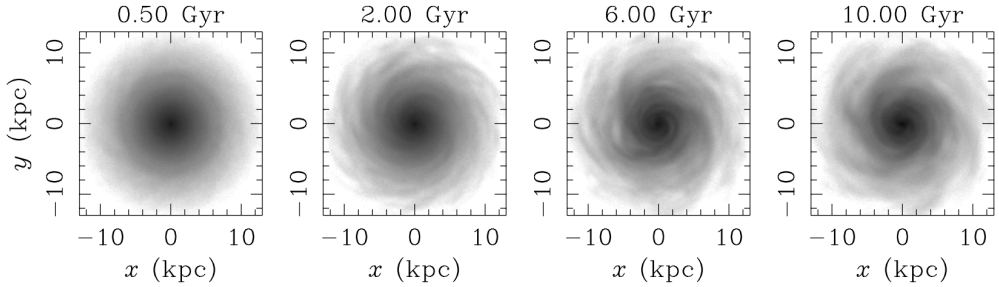


Swing Amplification



From leading to trailing (left to right), arm density becomes higher due to epicyclic motion (Toomre 1981)

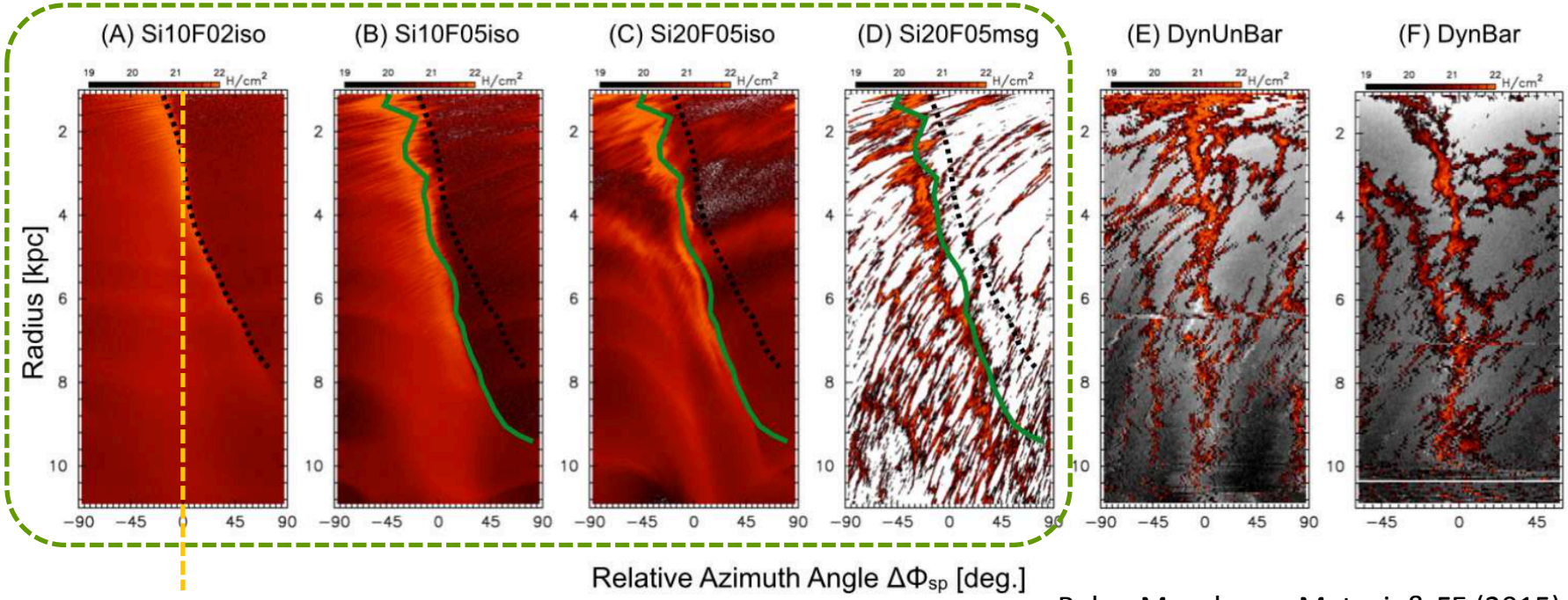
- Spiral arm becomes stronger when it changes from leading to trailing
  - Goldreich & Lynden-Bell (1965), Julian & Toomre (1966), Toomre (1981)
  - has been regarded as a model for multi-arm and/or flocculent galaxies
- High-res. N-body simulations
  - stellar disk can maintain spiral structure w/o cooling (Fujii+2011)



Transient but recurrent multi-arm structure (Fujii+2011)

steady (fixed) spiral models

dynamic spiral models



location of stellar spiral

Baba, Morokuma-Matsui, & FE (2015)

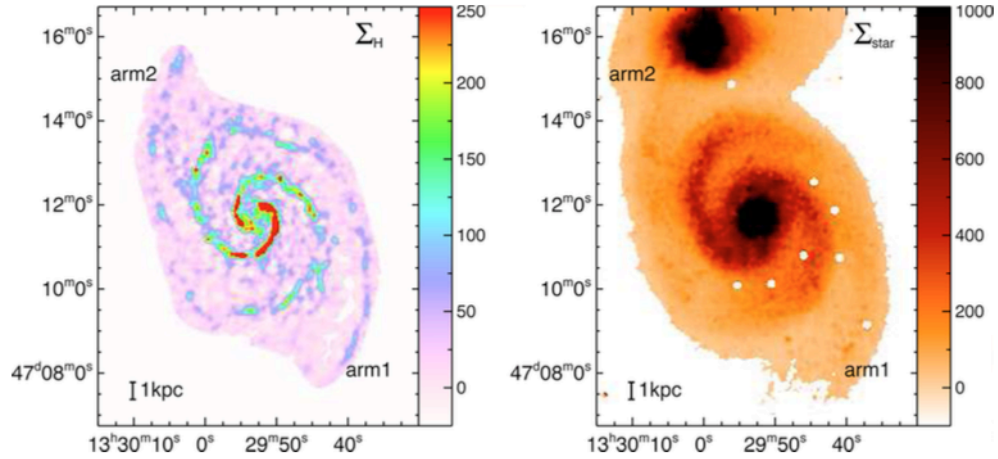
color: gas density

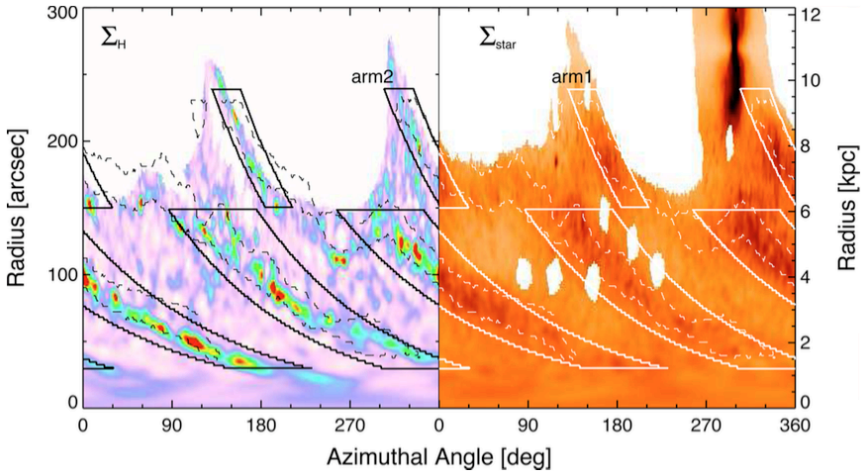
steady spiral model:

- shock location moves from downstream to upstream with increasing radius (i.e. different pitch angles for stellar and gas arms)
- same trend for all models with different parameters

dynamic spiral model: shock almost coincides with potential minima

Gas-Star Offsets in M51

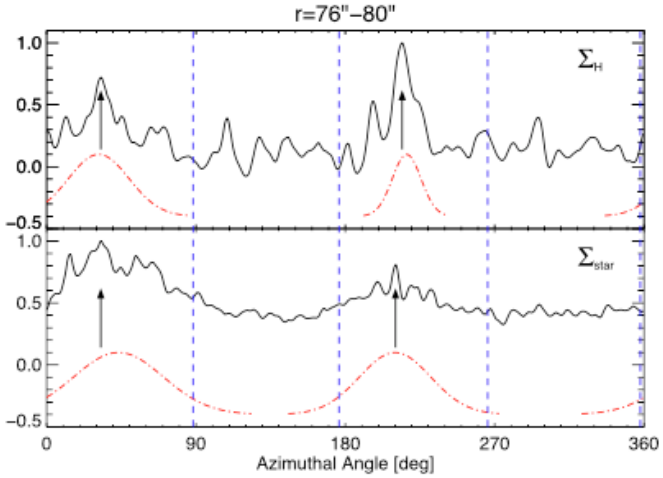




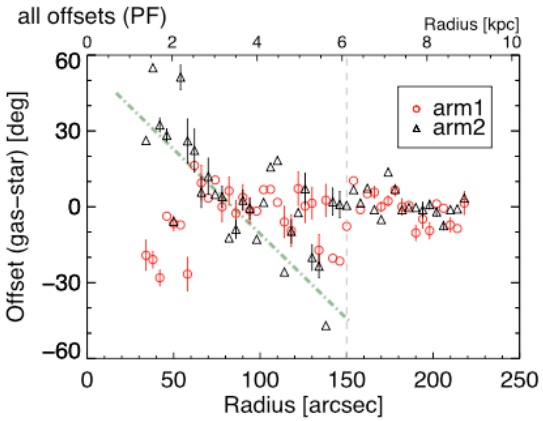
- M51 (NGC 5194)
  - nearby grand-design spiral galaxy
  - one of the best studied galaxies
- Data
  - Σ_H: from HI + CO
  - Σ_{star}: from SED fitting

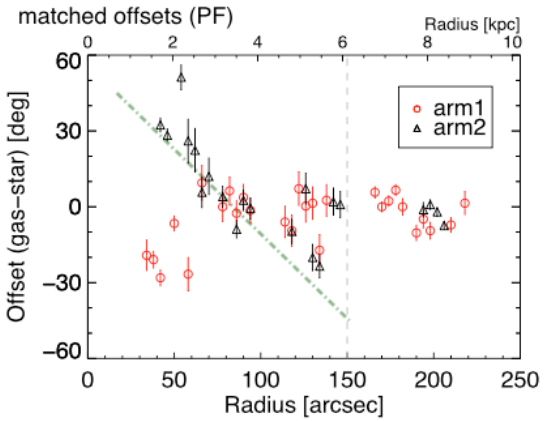
Gas and stellar surface density in the sky (RA, DEC) and in the polar coordinates (r, θ). Solid contours are the arm definition.

Gas-Star Offsets in M51



- Gas and stellar peak positions from azimuthal profiles
  - peak (by arrow)
  - gauss-fit (red dashed curve)

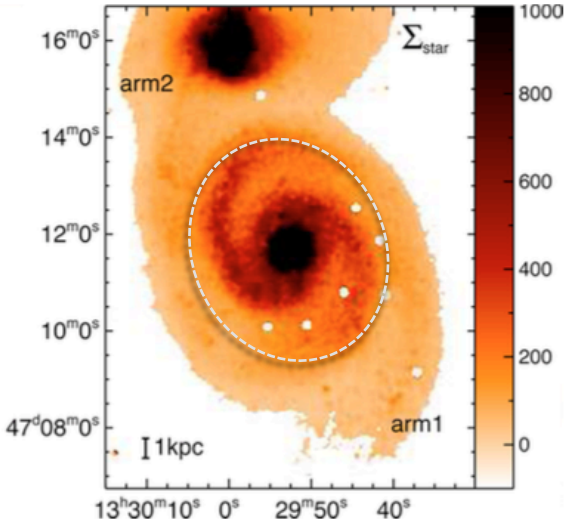




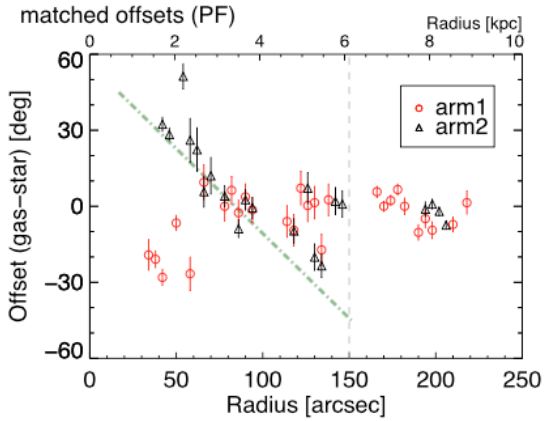
Gas-star offsets vs radius from the peak-finding method. Two arms separated by colors. “matched” means peaks from both methods consistent. Green-dashed line represent a prediction of fixed spiral (i.e. galactic shock) model by Baba+2015.

In the inner region (r<150”), two arms behave differently.

Gas-Star Offsets in M51

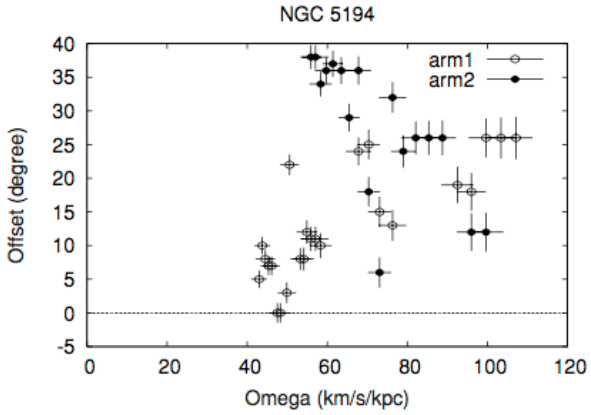


- Inner region (r<150")
  - arm1: inconsistent with galactic shock
    - short-lived (< 0.5 Gyr), dynamic spiral
  - arm2: consistent with galactic shock
    - long-lived (> 0.5 Gyr), steady spiral



CO-Hα offsets (Egusa+2009):
arm1: consistent with density waves
- 10 Myr < lifetime < 0.5 Gyr

arm2: inconsistent with density waves
- why??



Lifetime by Two Offset Methods

CO-Hα offset method: "successful?"		arm-gas offset method: "galactic shock?" NO	arm-gas offset method: "galactic shock?" YES
	YES	**"slowly-winding"** M51 arm1	**"long-lived"**
	NO	**"co-rotating"**	noncircular motion? t_{SF} not constant? M51 arm2

long

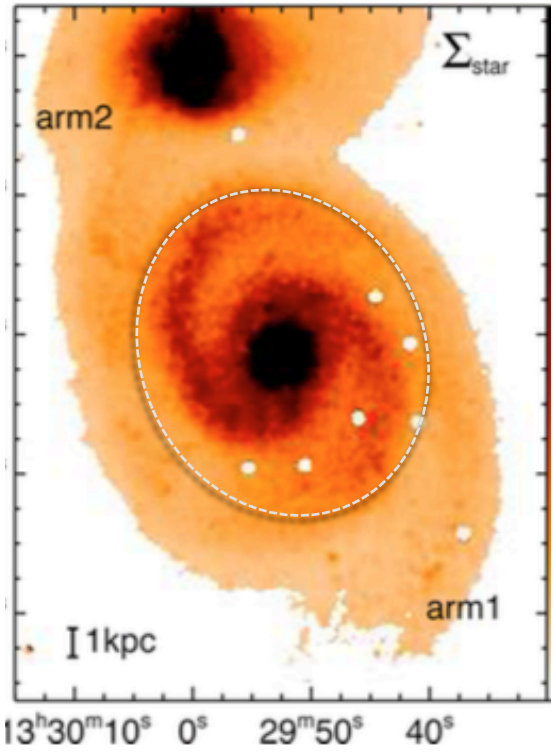
lifetime

short

$t \lesssim 500$ Myr $t \gtrsim 500$ Myr

$t \gtrsim 10$ Myr

$t \lesssim 10$ Myr



Summary

- "What is a lifetime of spiral arms?"
- Numerical simulations suggest that gas-star offset can tell if spiral arms are long-lived or short-lived.
- Gas-star offsets in M51
  - different behaviors for two arms
  - arm1: short-lived, consistent with slowly winding tidal arm?
  - arm2: long-lived, but not consistent with CO-Hα offset result?