Gas Dynamics and Star Formation in Dwarf Galaxies

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Filippo Fraternali (University of Bologna)
Renzo Sancisi (University of Groningen)

With financial support from the John Templeton Fundation.

Outline

- Overview on Dwarf Galaxies:

  Structure, dynamics, and evolution

- Starburst Dwarf Galaxies:

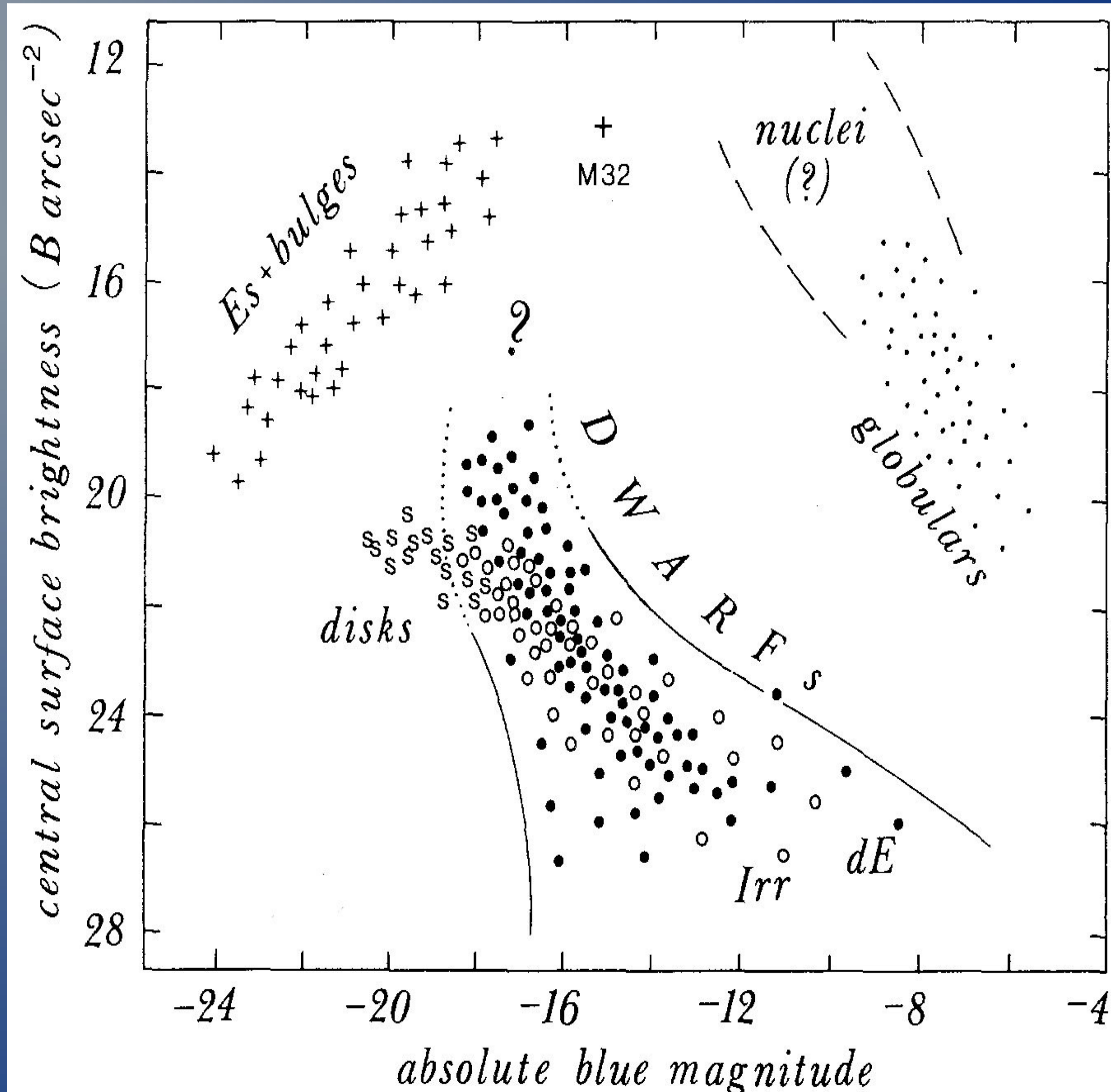
  Key objects for galaxy evolution and stellar feedback

- Tidal Dwarf Galaxies:

  A new channel to form low-mass galaxies?

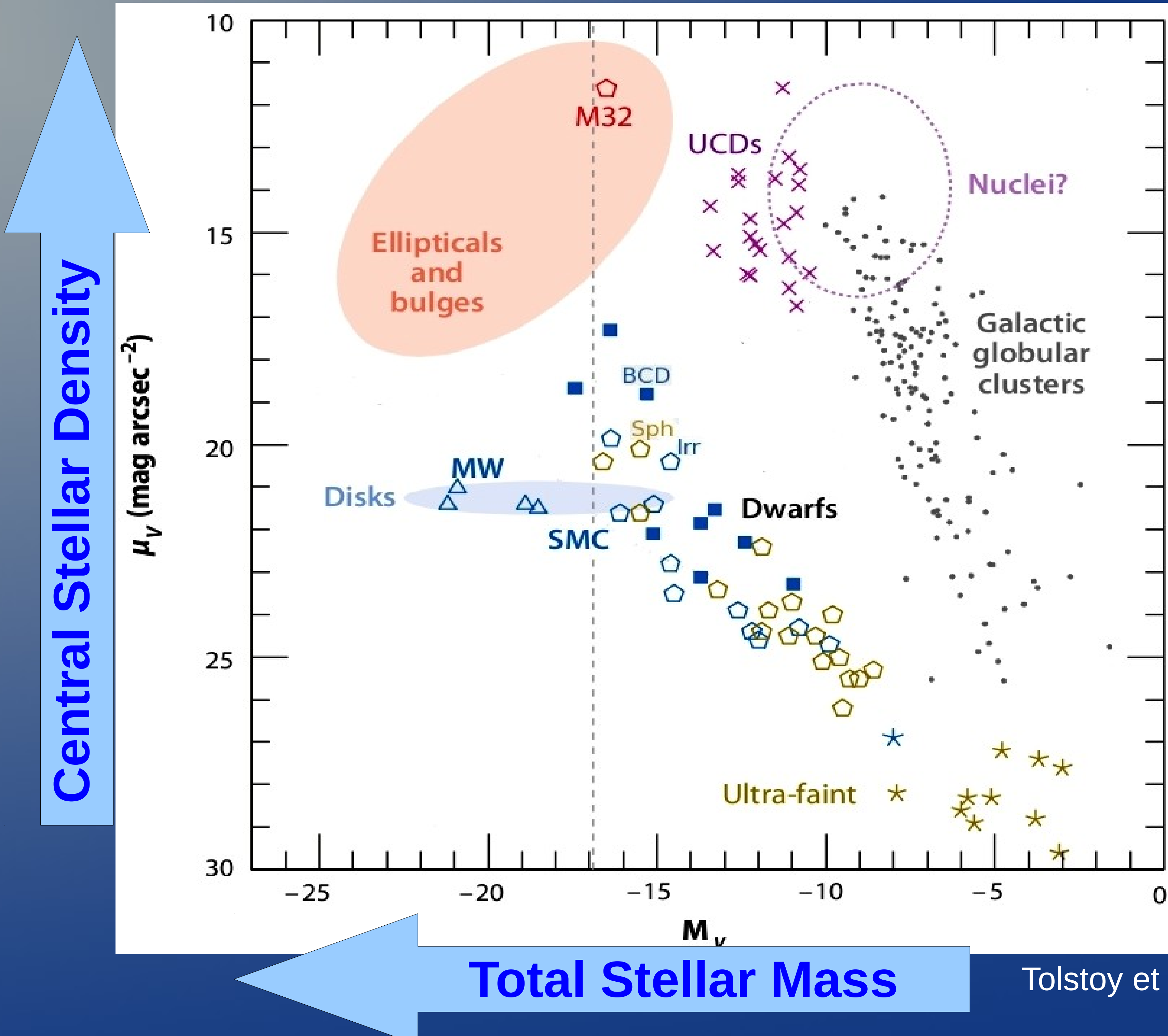
Overview on
Dwarf Galaxies

Central Stellar Density

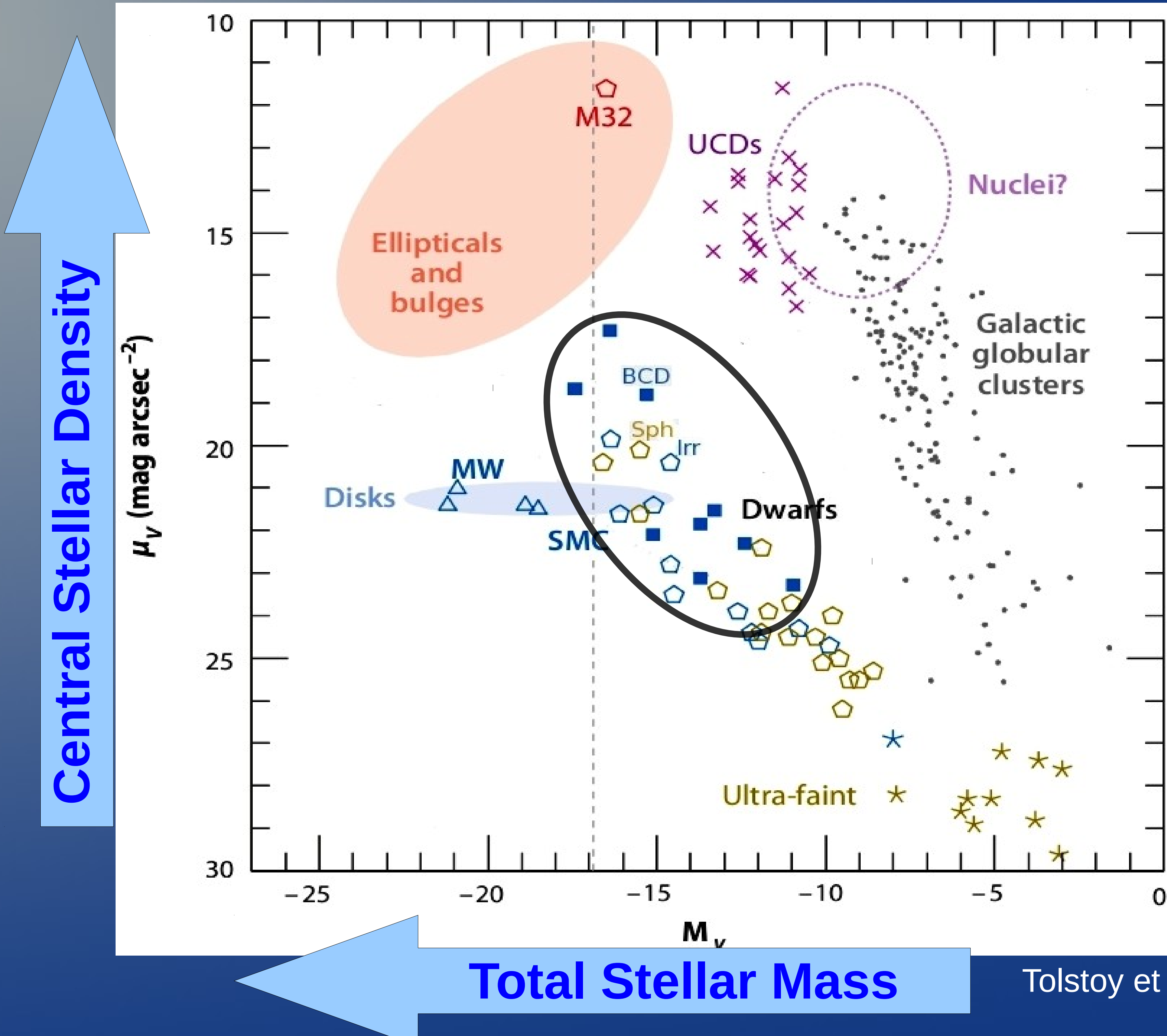


Binggeli (1994)

Total Stellar Mass



Tolstoy et al. (2009)



Tolstoy et al. (2009)

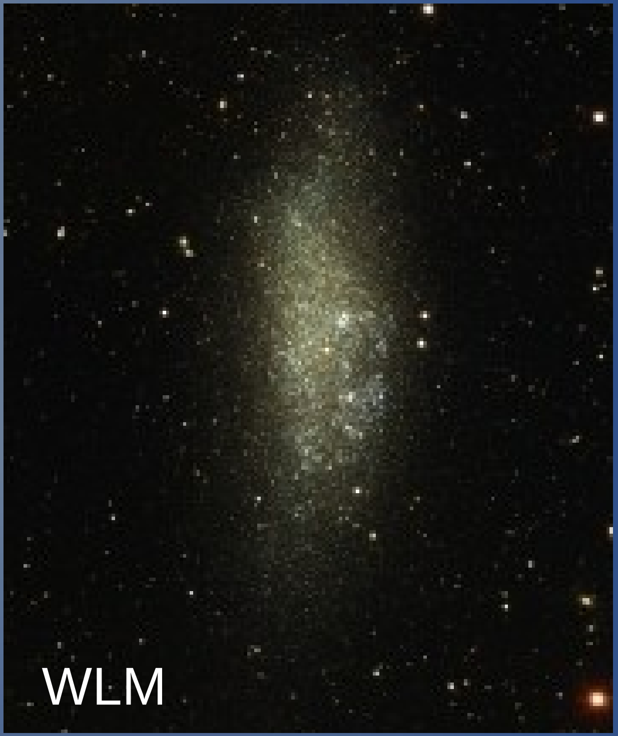
Spheroidals

- Gas poor. No SF.
- Close to spirals or in galaxy cluster

Other names:

dE, Early-Type Dwarfs

Irregulars



- Gas rich. Low SF.
- Isolated, groups, or outskirts of clusters

Other names:

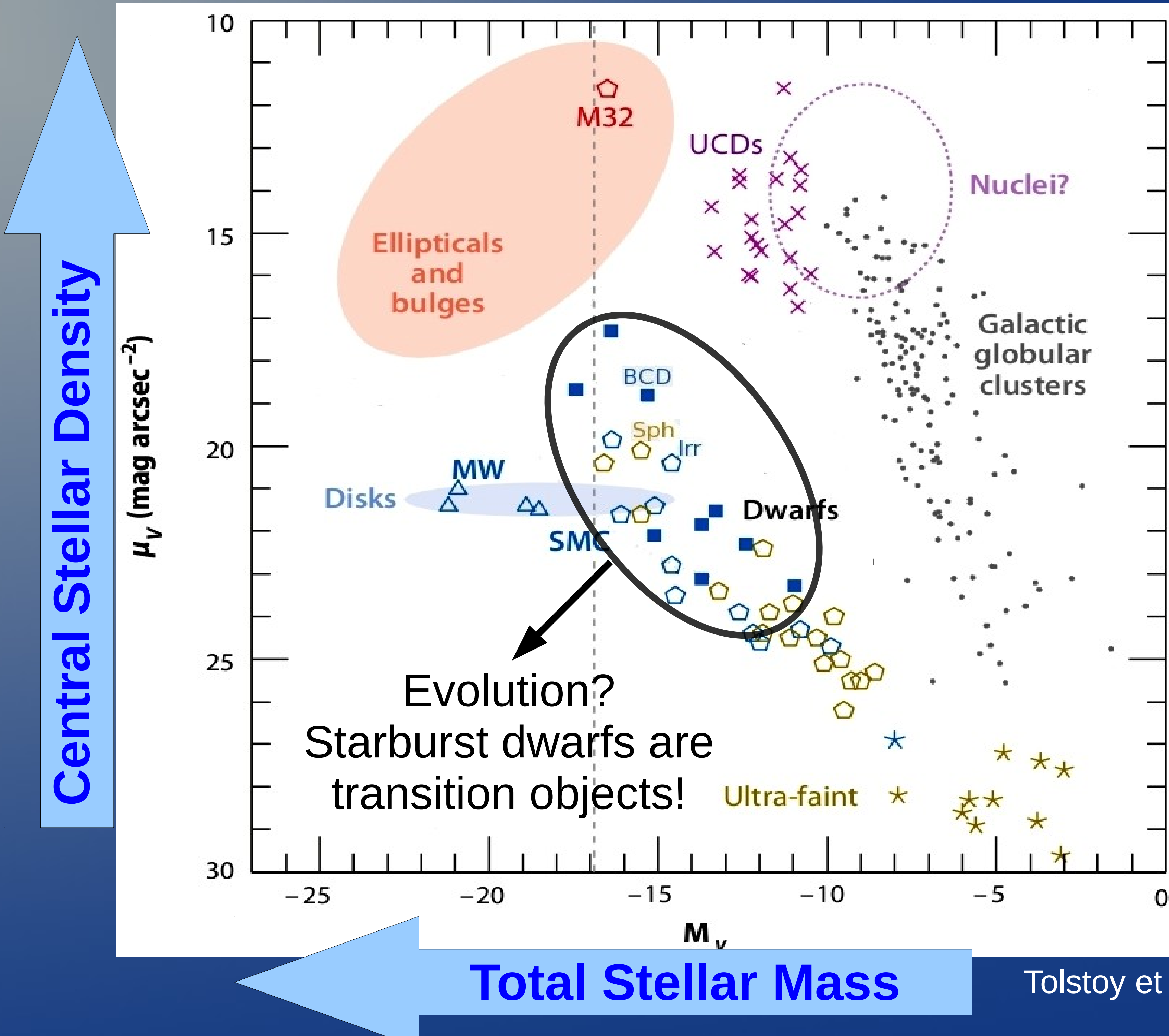
Im, Sm, Late-Type Dwarfs

Starburst dwarfs

- Gas rich. Burst of SF.
- Isolated, groups, or outskirts of clusters

Other names:

BCDs, H_{II} gals, Amorphous



Tolstoy et al. (2009)

Evolution of Dwarf Galaxies

Gas-Rich Irr/BCD >> Gas-Poor dE/Sph

- Internal Mechanisms

  - Starvation: gas is consumed by SF and is not replenished

  - Outflow: gas is ejected by SN feedback (Dekel & Silk 1986)

- External Mechanisms

  - Ram Pressure Stripping: ICM or Hot Coronae (Gunn & Gott 1972)

  - Tidal Stripping/Harassment: Massive Gal. or Cluster (Moore+1998)

Evolution of Dwarf Galaxies

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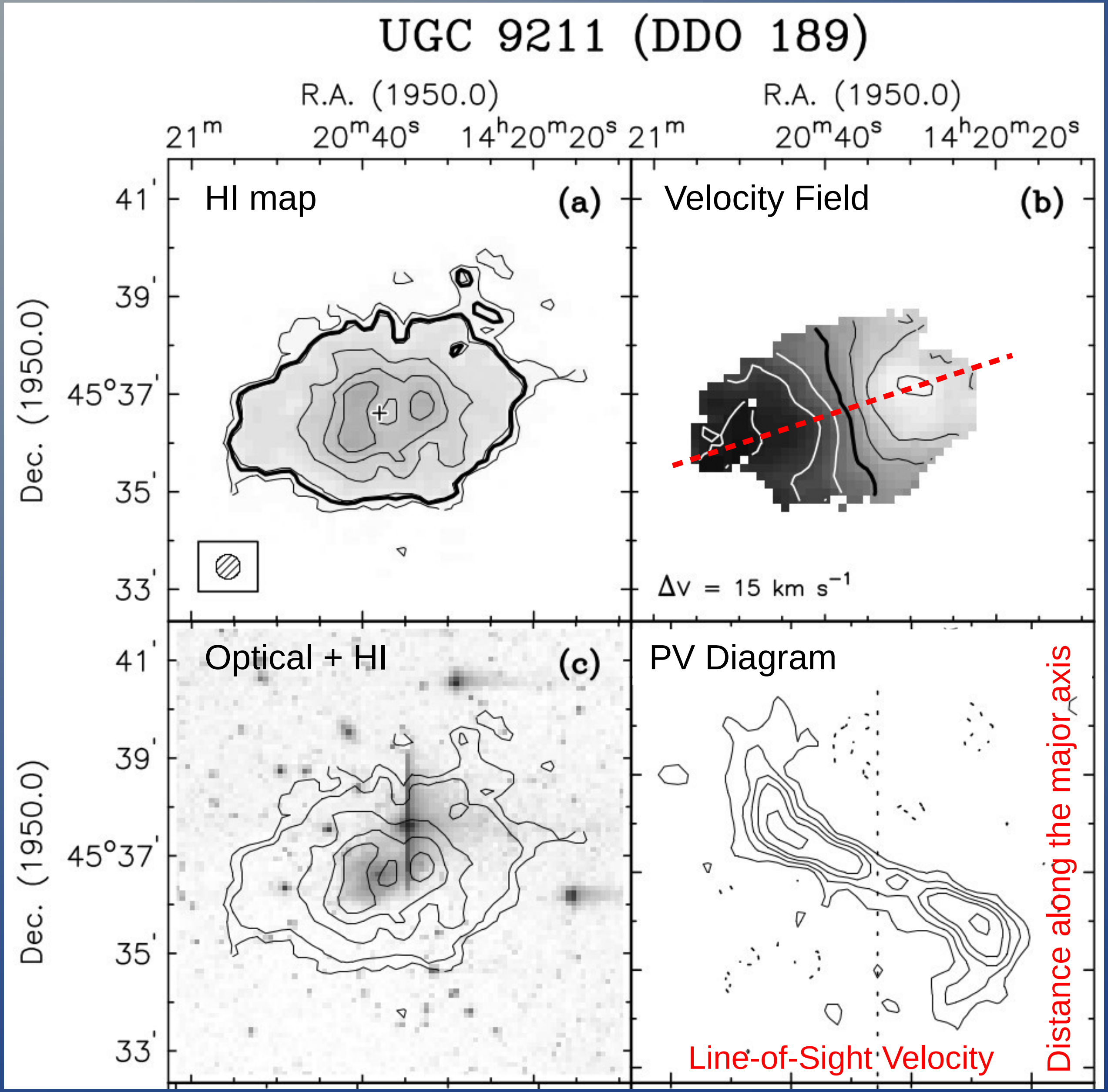
Gas-Poor dE/Sph >> Gas-Rich Irr/BCD

- External Mechanisms
  - Gas Accretion from the IGM
  - Merger between Sph & Irr/BCD

Dwarf Irregulars are very regular in HI!

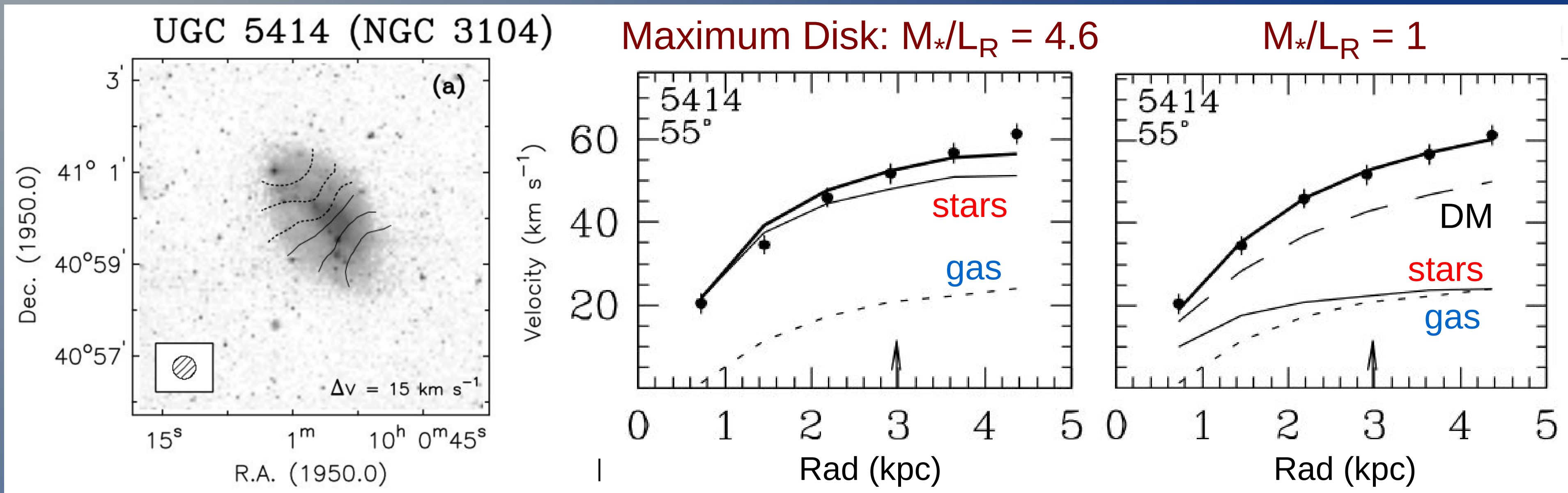


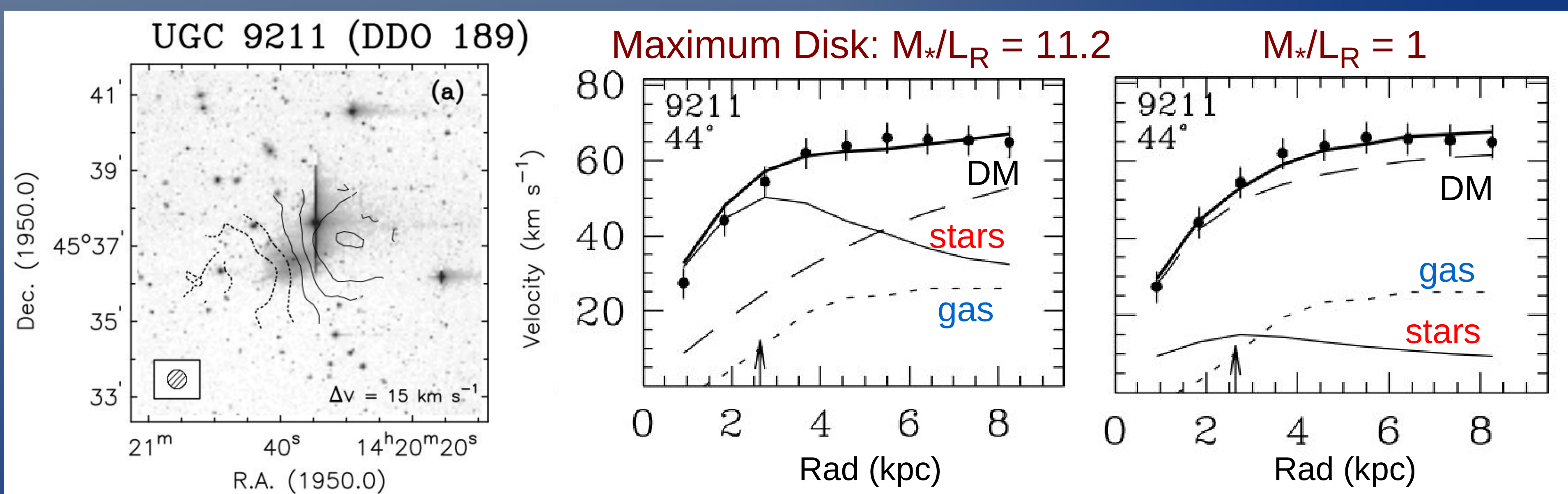
Swaters+(1999, 2002)

- 73 late-type dwarfs from WHISP survey
- 90% have regularly rotating HI disks
- $R_{HI} \sim 2\ R_{opt}$ (as in spirals)

HI observations are essential to probe the kinematics at large radii (deep in the DM halo)

Irrs are DM dominated (using typical M_*/L)





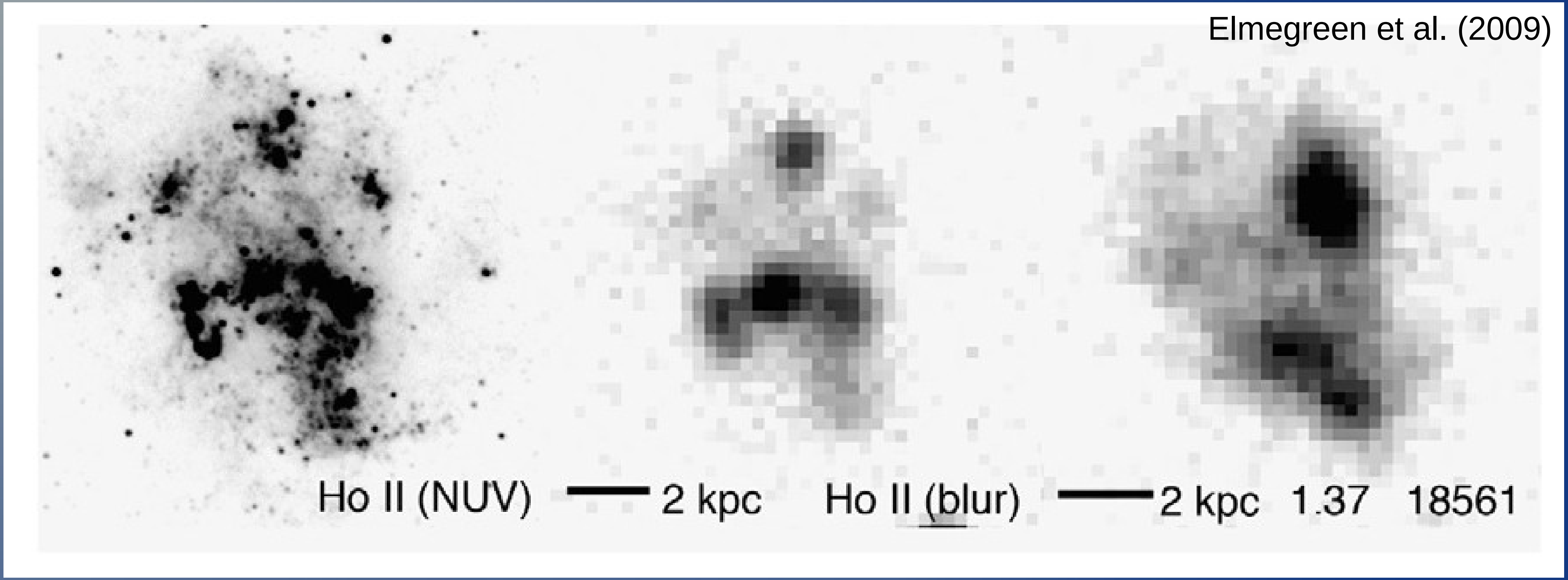
Swaters et al. (2011, 2012)

Starburst Dwarfs

In collaboration with Marc Verheijen,

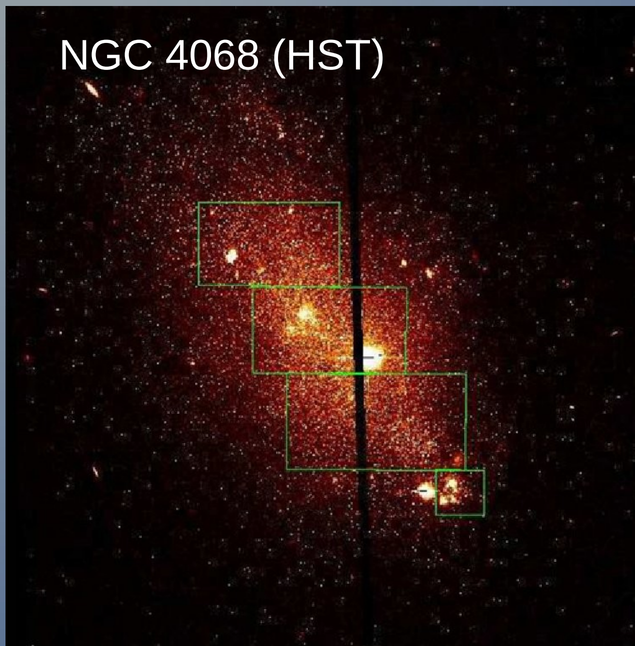
Filippo Fraternali & Renzo Sancisi

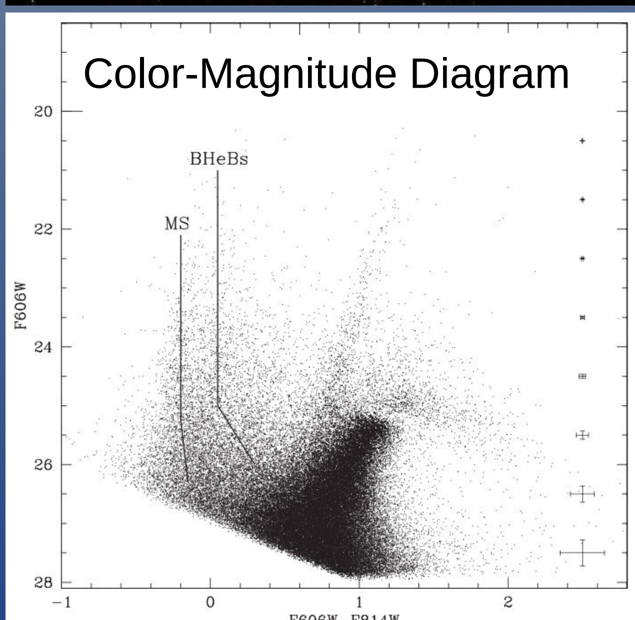
Starburst Dwarfs ~ High-z Galaxies?

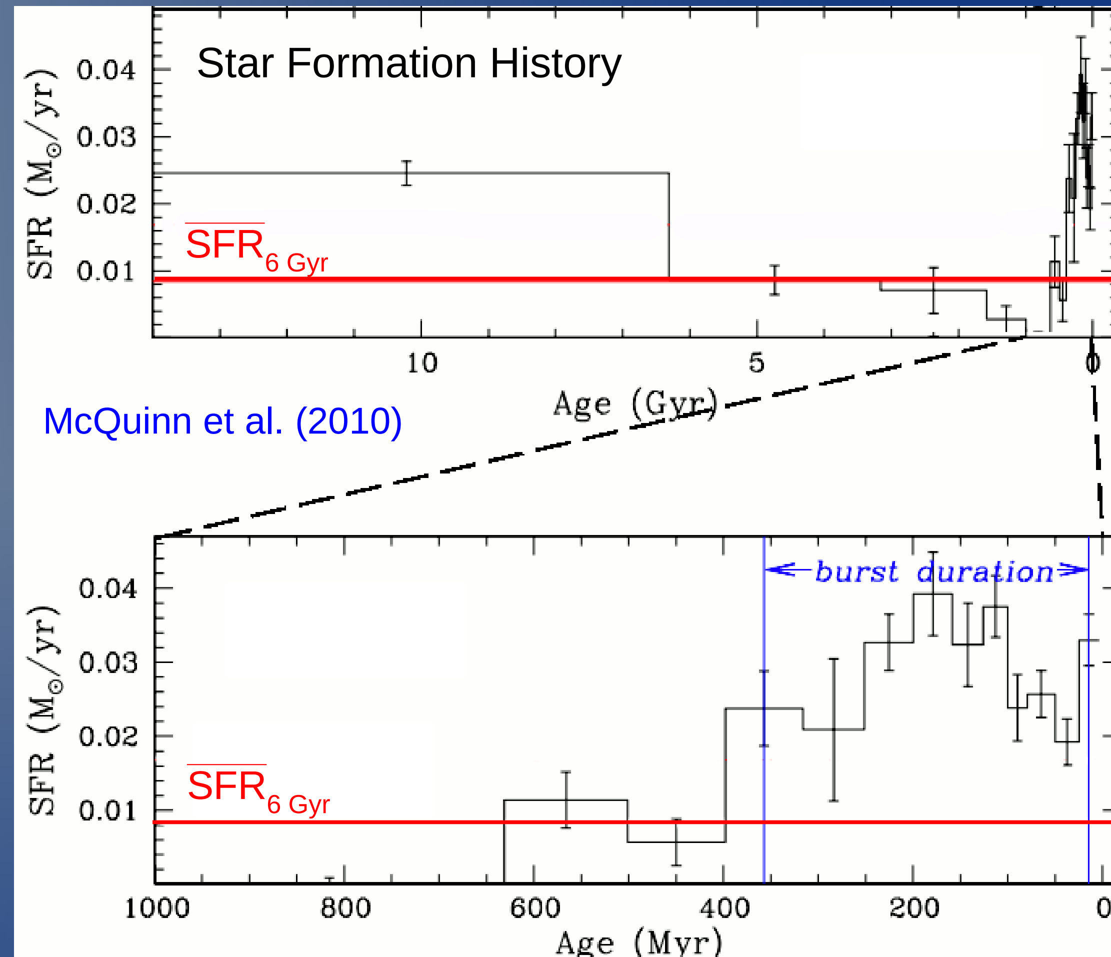


- Clumpy morphologies (e.g. Elmegreen+2009)
- High gas fractions: $M_{gas}/M_{*} > 1$ (e.g. Salzer+2002)
- Low metallicities: $Z < 0.3\ Z_{\odot}$ (e.g. Izotov & Thuan 1999)

Stellar populations in Starburst Dwarfs

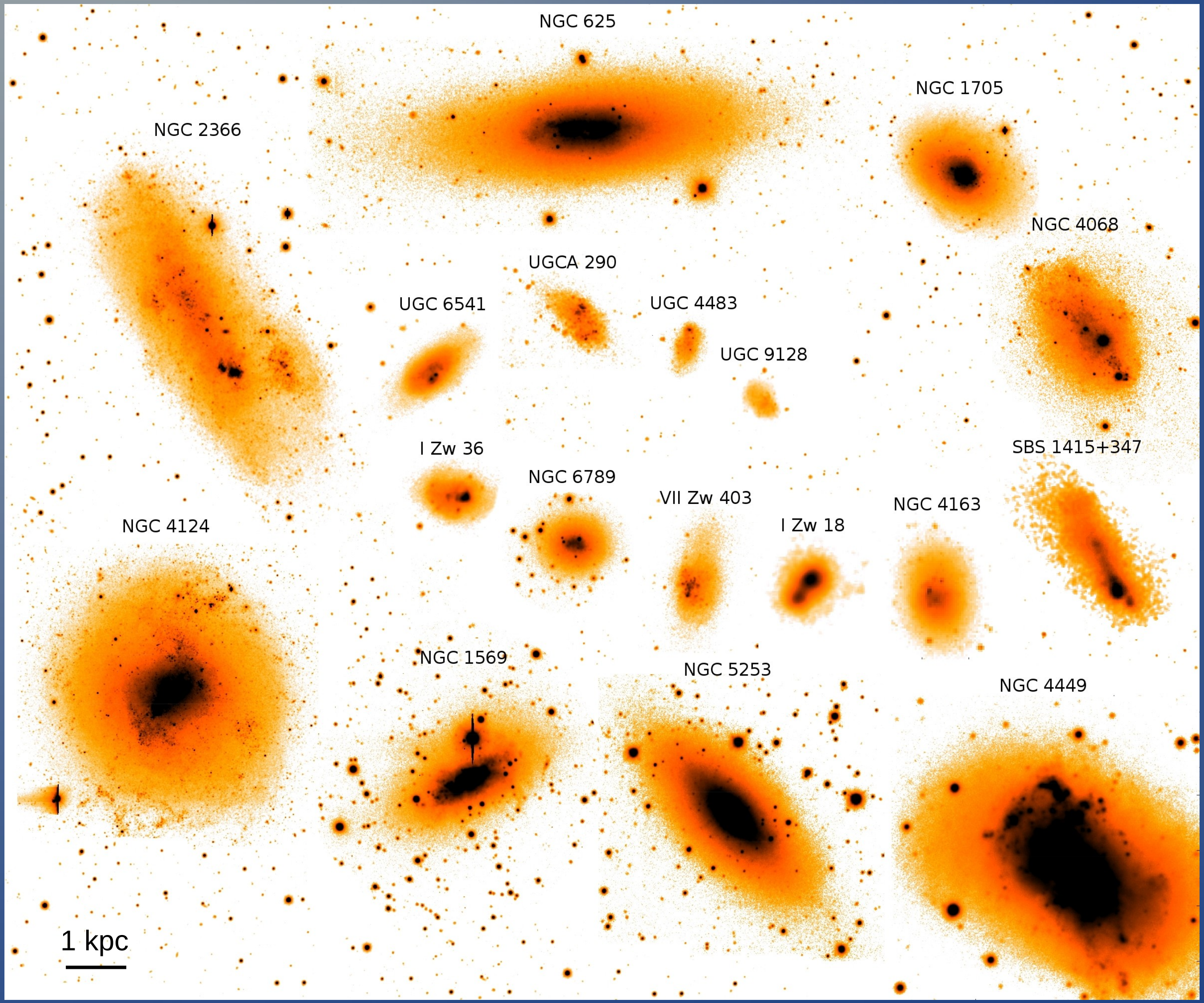






- Birthrate = SFR(t_{peak}) / $\overline{SFR}$ ≥ 3
- Starburst durations (few 100 Myr)
- Energies from SN & stellar winds

Sample of 18 Starburst Dwarfs



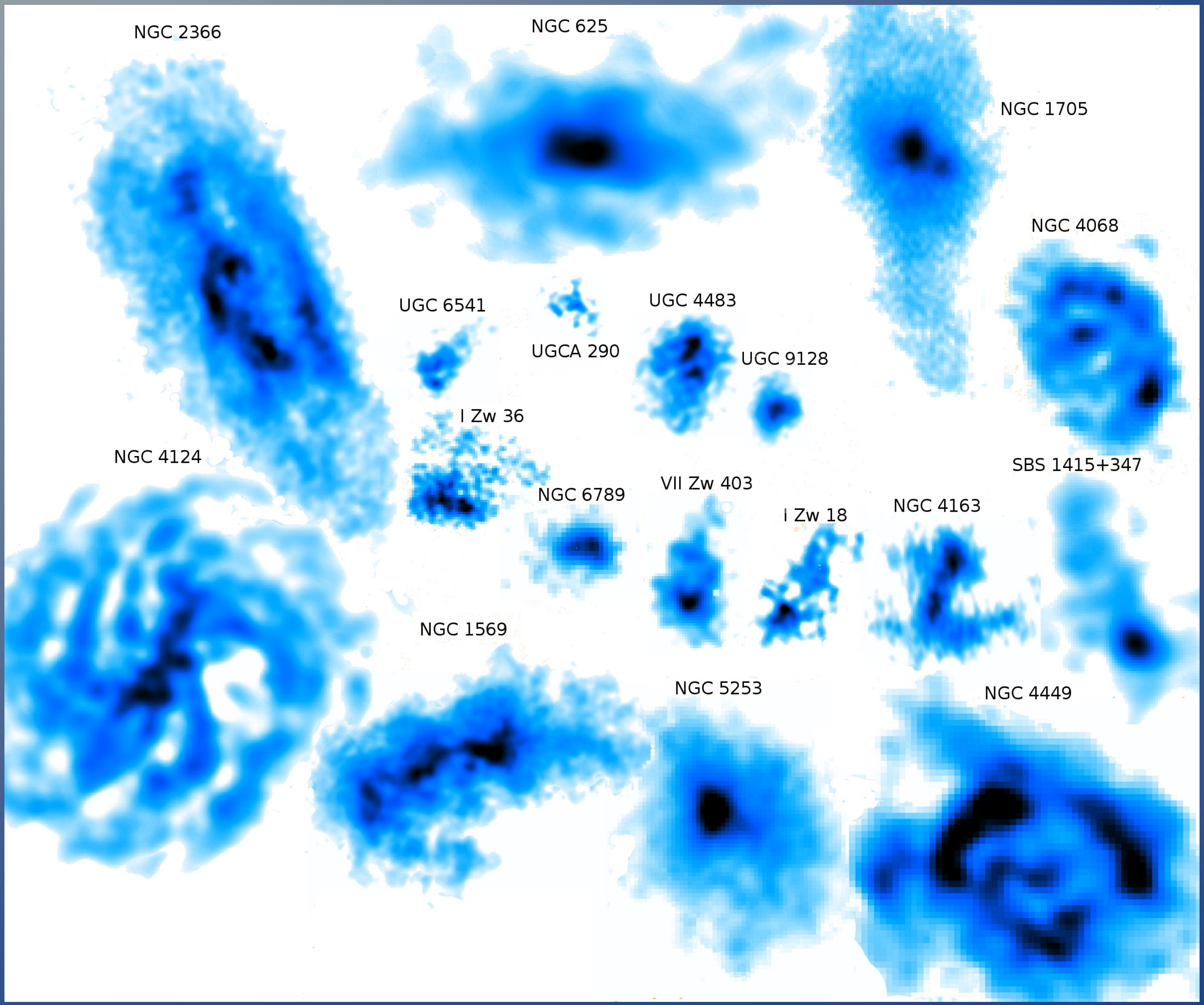
Resolved into single stars by HST obs:

- Distance (< 5 Mpc)
- Star Formation History
- $b = SFR(t_{peak})/\overline{SFR} \geq 3$

Lelli, Verheijen & Fraternali (2014)

$M_* \sim 10^7 - 10^9\ M_\odot$ $R_{opt} \sim 0.5 - 5$ kpc

Sample of 18 Starburst Dwarfs



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- Distance (< 5 Mpc)
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21-cm line obs (VLA, WSRT, ATCA):

- HI distribution
- HI kinematics

Lelli, Verheijen & Fraternali (2014)

Series of Papers on Starburst Dwarfs

- I. Internal Dynamics & DM content

  Lelli, Verheijen, Fraternali & Sancisi 2012a, A&A

  Lelli, Verheijen, Fraternali & Sancisi 2012b, A&A

  Lelli, Verheijen & Fraternali, 2014a, A&A

- II. Dynamics & Galaxy Evolution

  Lelli, Fraternali & Verheijen 2014b, A&A

  McQuinn, Lelli, Skillman et al. 2015, MNRAS

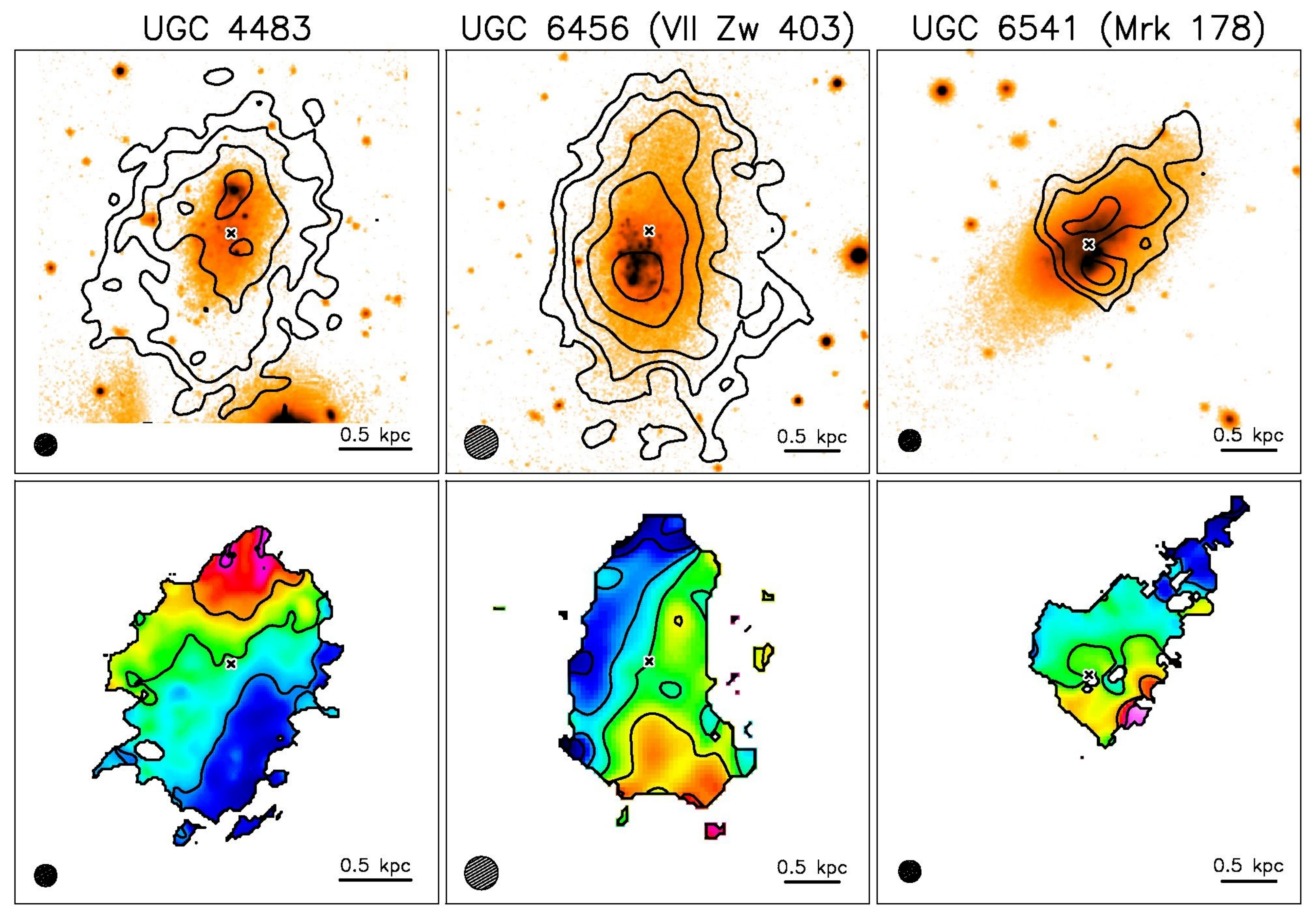
- III. Starburst Triggering Mechanism

  Lelli, Verheijen & Fraternali 2014c, MNRAS

Starburst Dwarfs

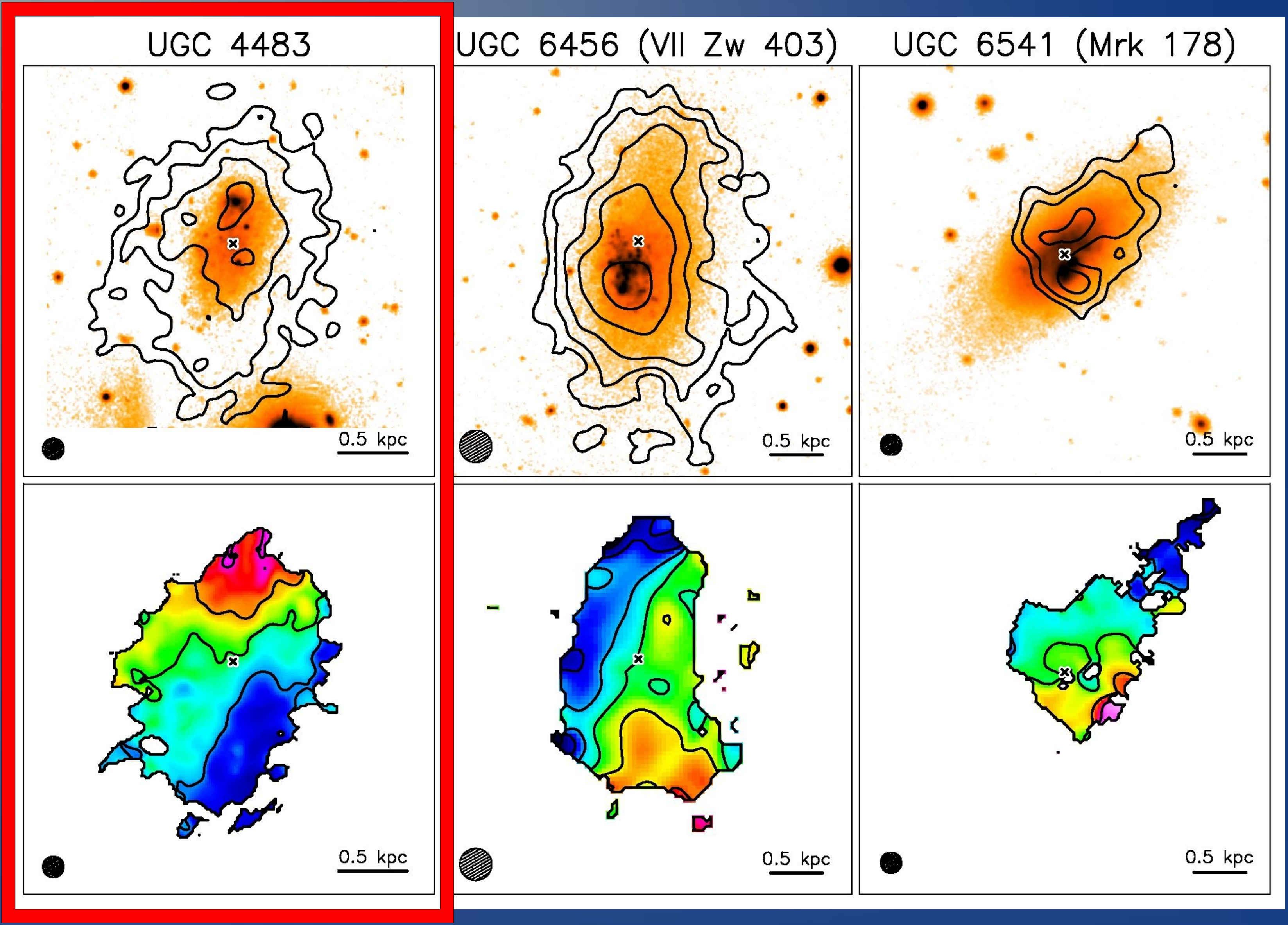
I. Internal Dynamics

HI Kinematics of Starburst Dwarfs



~50%	~40%	~10%
rotating HI disk	kin. disturbed HI disk	unsettled HI distr.

HI Kinematics of Starburst Dwarfs



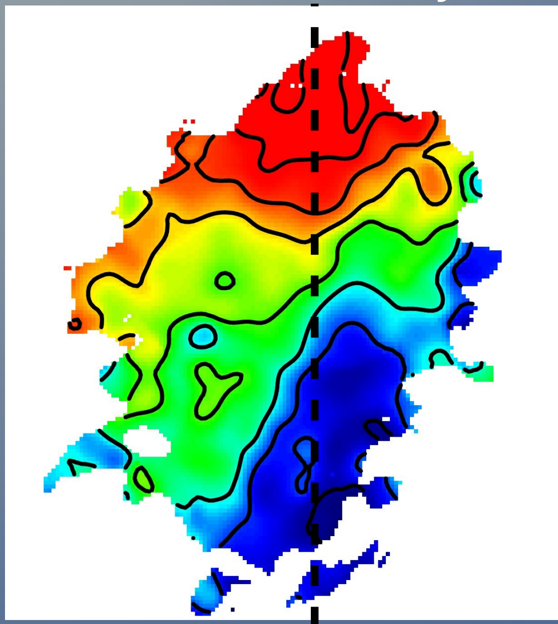
~50%
rotating HI disk

~40%
kin. disturbed HI disk

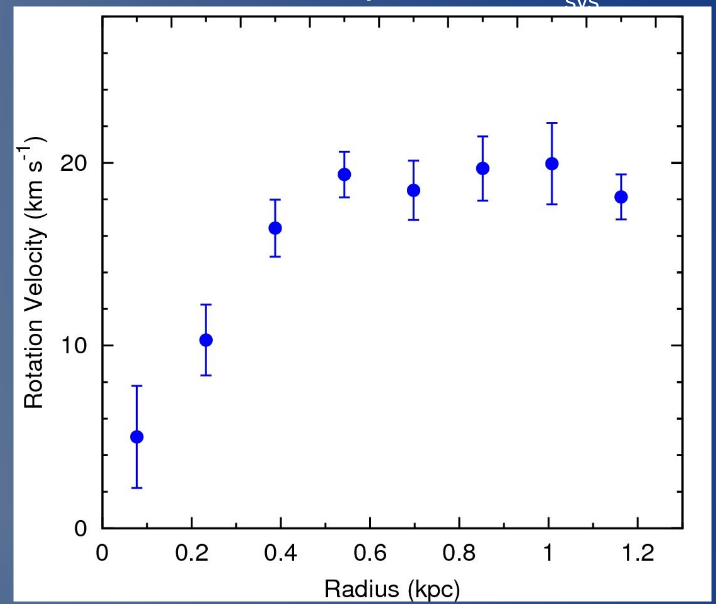
~10%
unsettled HI distr.

Derivation of the Rotation Curve

2D fit to the Velocity Field



Rotation curve (+ center, V_{sys}, PA, incl.)



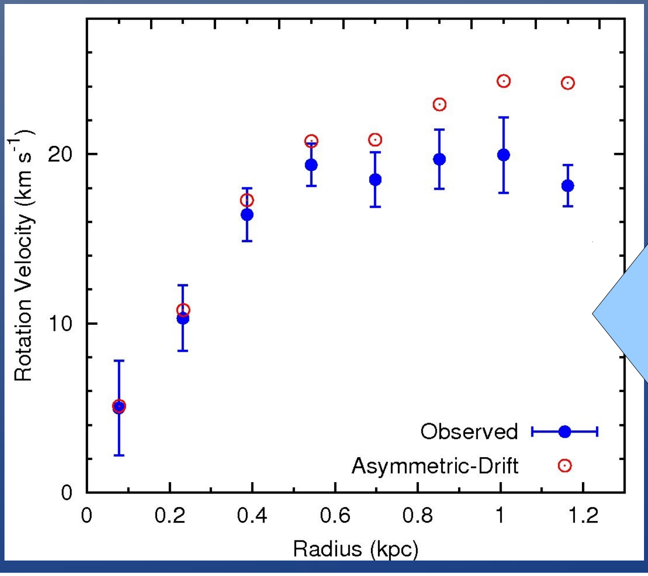
V_{rot} ~ 20 km/s

V_{rad} ~ 5 km/s

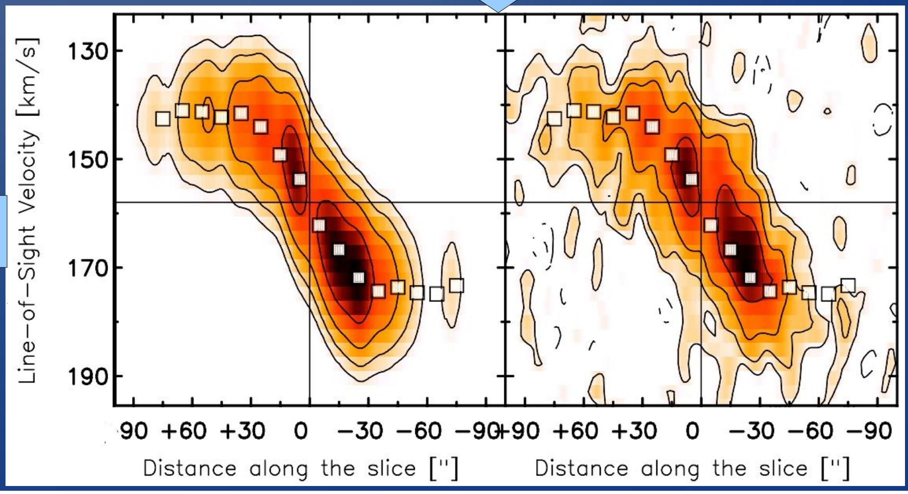
σ_{HI} ~ 8 km/s

V_{rot}/σ_{HI} ~ 2-3

Correction for pressure-support

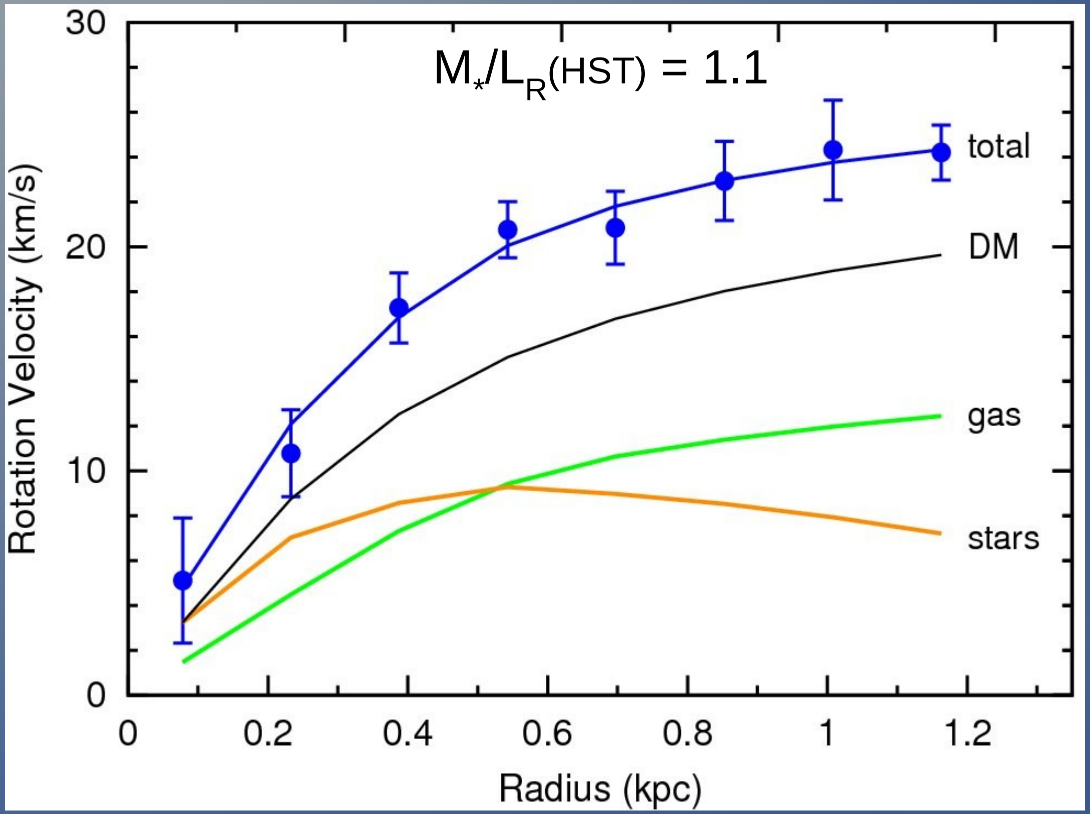


3D disk model Observations



Mass Model Example: UGC 4483

Lelli et al. 2012, A&A, 544, 145L



$M_{dyn} = (16 \pm 3) \times 10^7\ M_\odot$

$M_{*(HST)} = (1.0 \pm 0.3) \times 10^7\ M_\odot$

Assuming Salpeter IMF (McQuinn+2010)

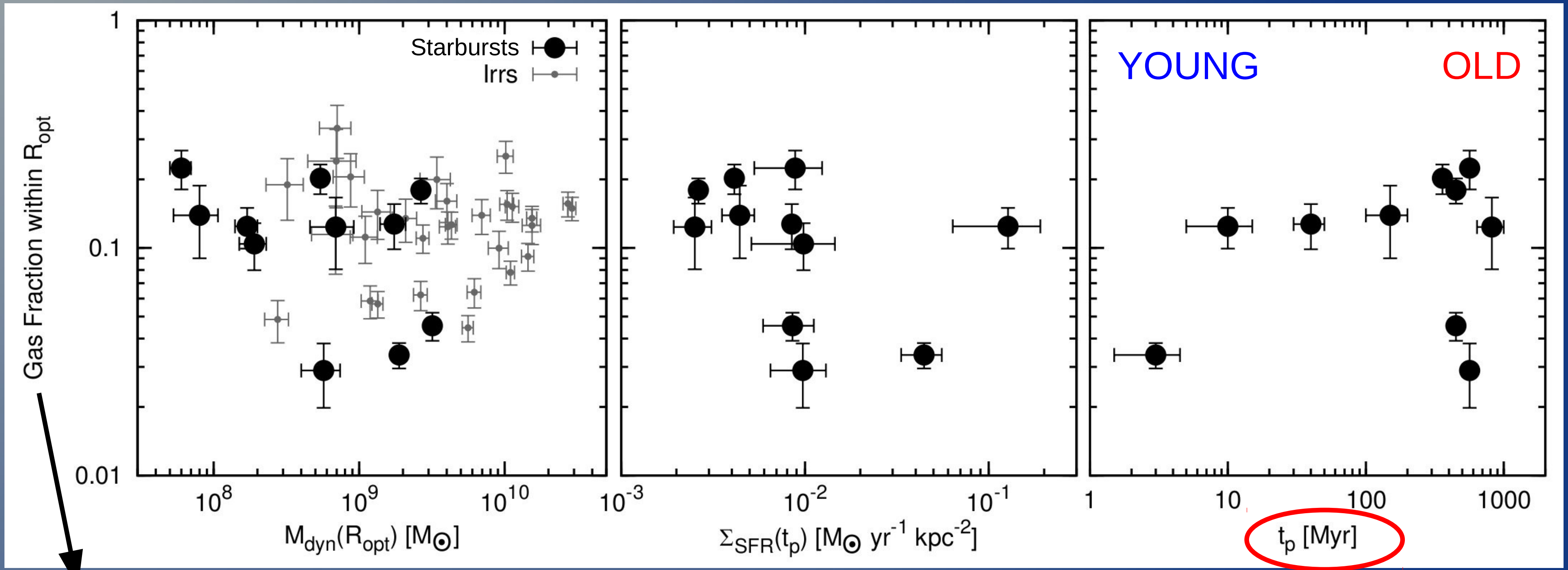
$M_{gas} = (3.3 \pm 0.4) \times 10^7\ M_\odot$

M_*(young) ~ $0.2 \times 10^7\ M_\odot$

M(molecules) ~ ?

At least ~30% of the mass within R_{opt} is baryonic (gas + old stars)

Gas Fractions: Starbursts vs Irrs

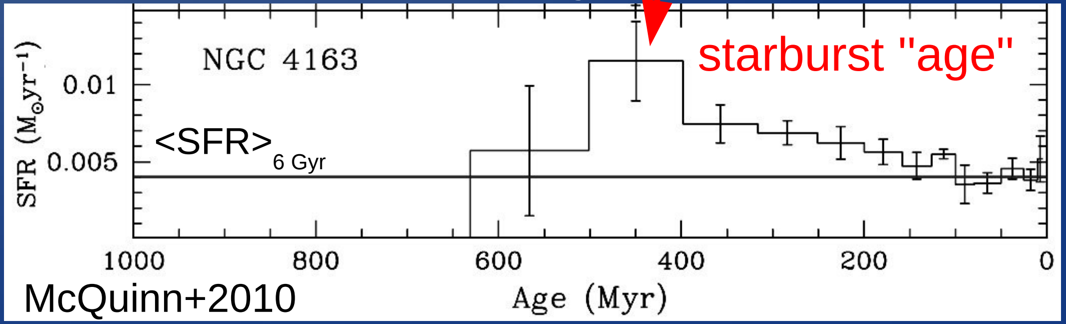


$F_{gas} = M_{HI}/M_{dyn}$ within R_{opt} (Irrs from Swaters+2009)

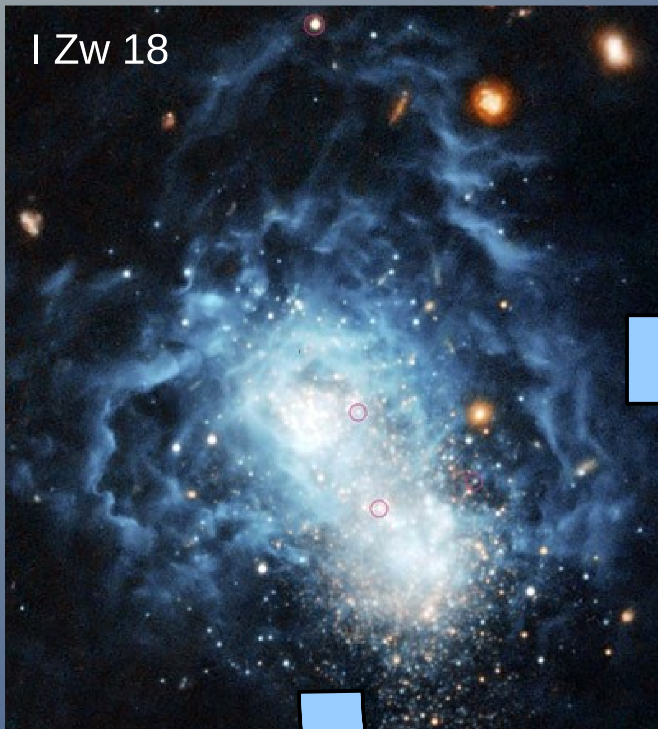
Similar f_{gas} as typical Irrs:

- No evidence for <u>massive</u> outflow
- $t_{dep} = M_{HI}/SFR$ = 2-10 Gyrs (up to 20 Gyr for Irrs)

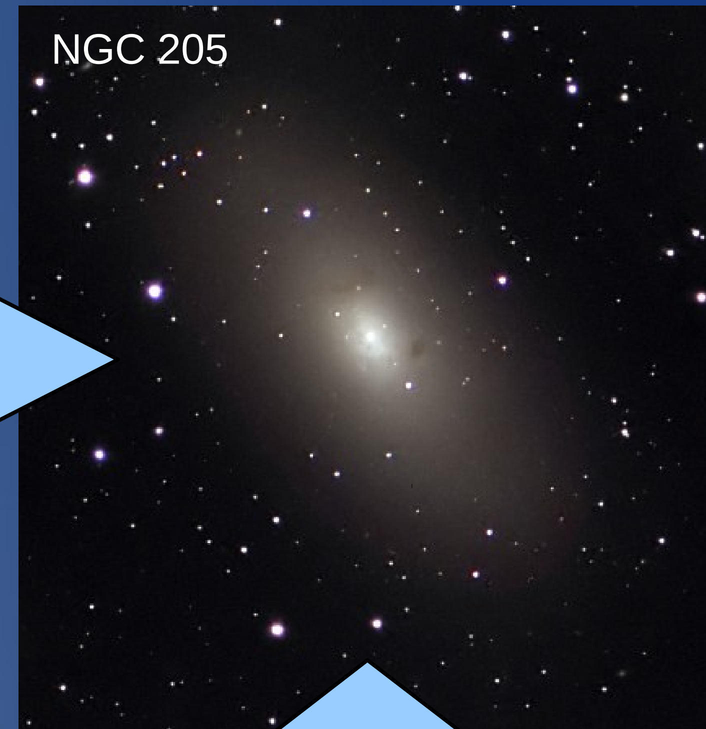
Star-Formation History



Starburst dwarfs



Gas-poor Sphs



Gas Outflow or Starvation

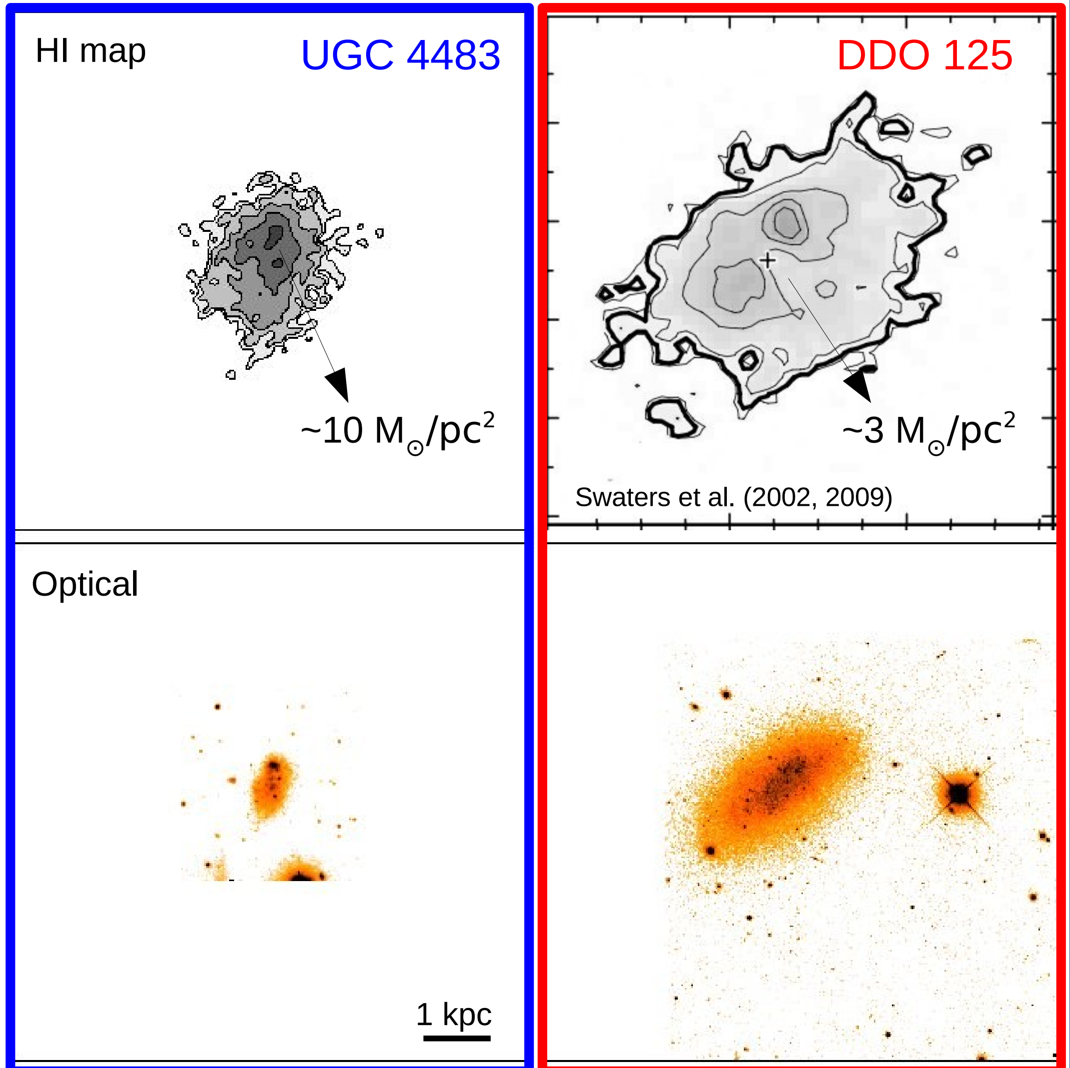
External mechanisms:

- ram-pressure stripping
  (e.g. Gunn&Gott 1972)
- galaxy harassment
  (e.g. Moore+1998)
- tidal stirring
  (e.g. Mayer+2006)

Starburst Dwarfs

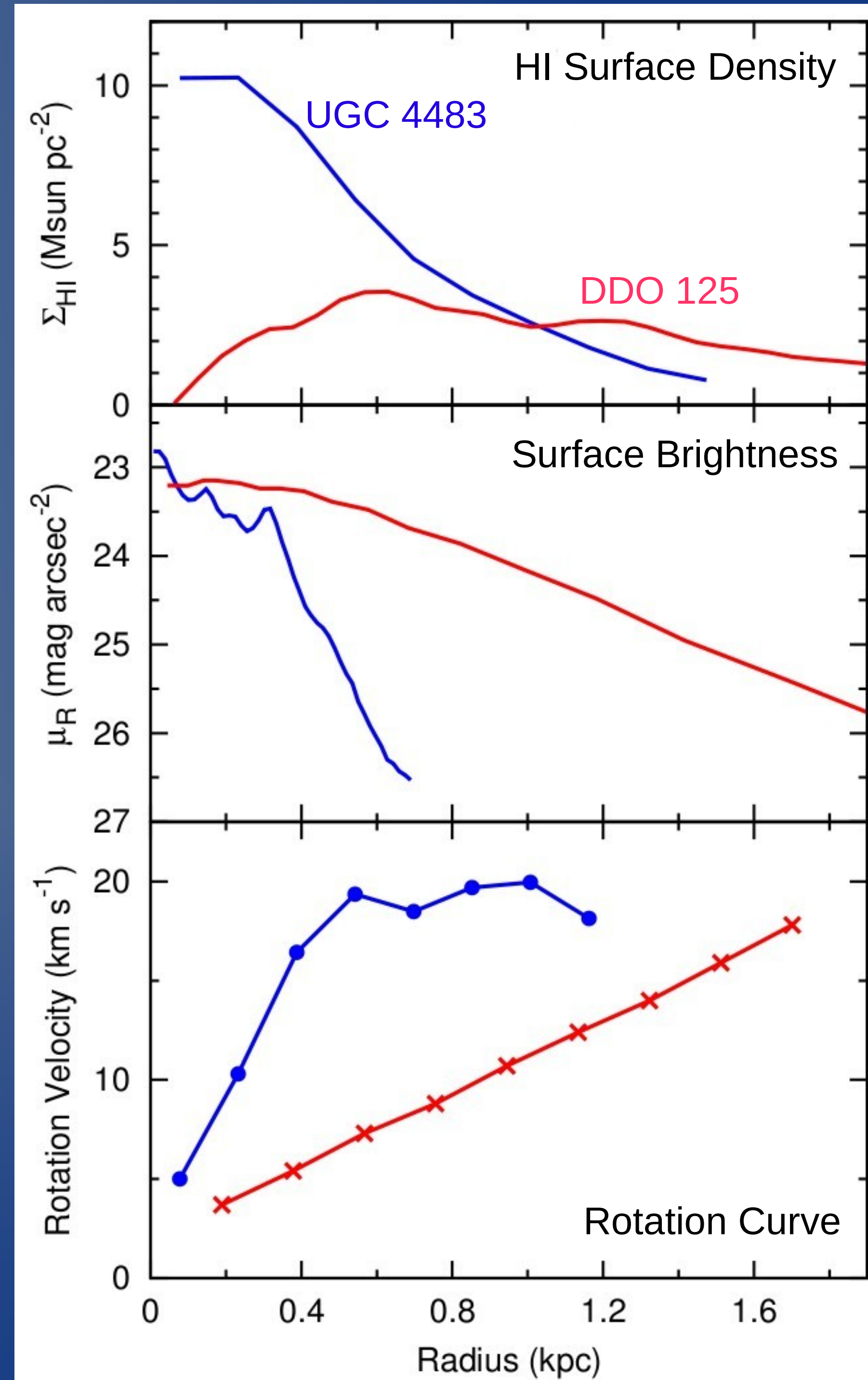
II. Dynamics & Evolution

Starburst *vs* Irregular

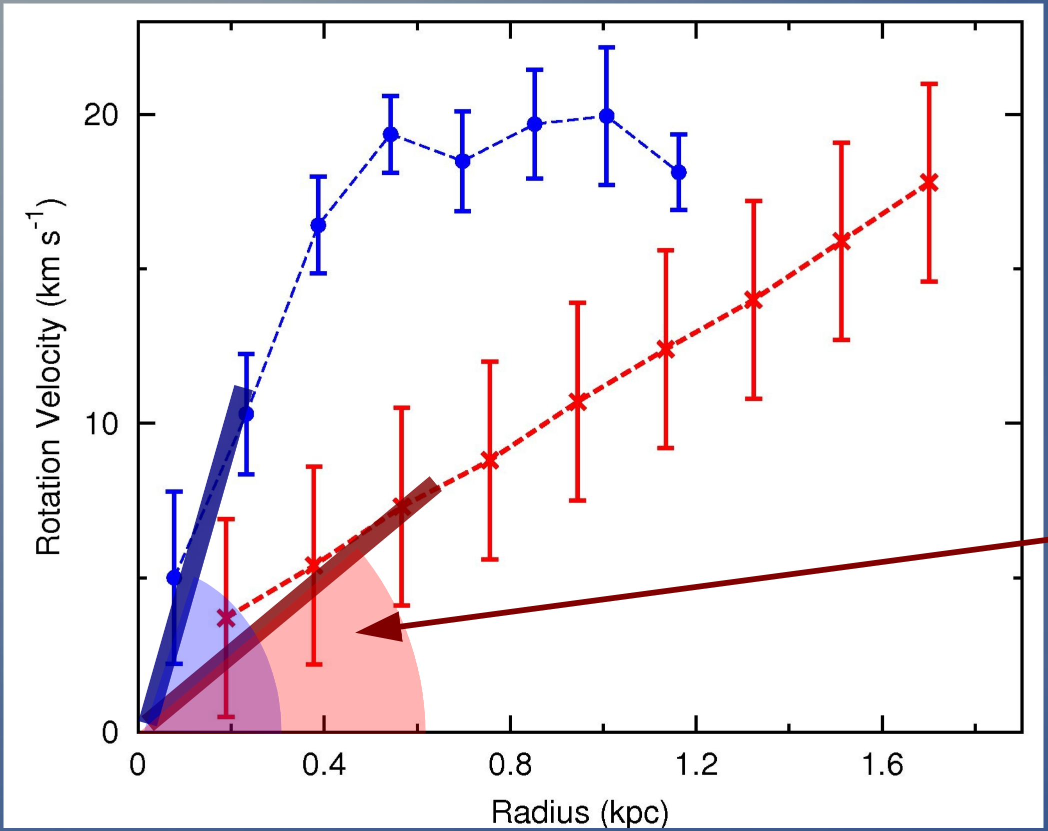


$M_{dyn} \sim 1\text{-}2 \times 10^8\ M_\odot$

Lelli et al. (2012a, 2012b)



Inner Circular-Velocity Gradient



$$\lim_{R \to 0} \frac{dV_{\rm circ}(R)}{dR} \propto \sqrt{\rho_0}$$

ρ_0 = central dynamical mass density

For a bulgeless disk galaxy:

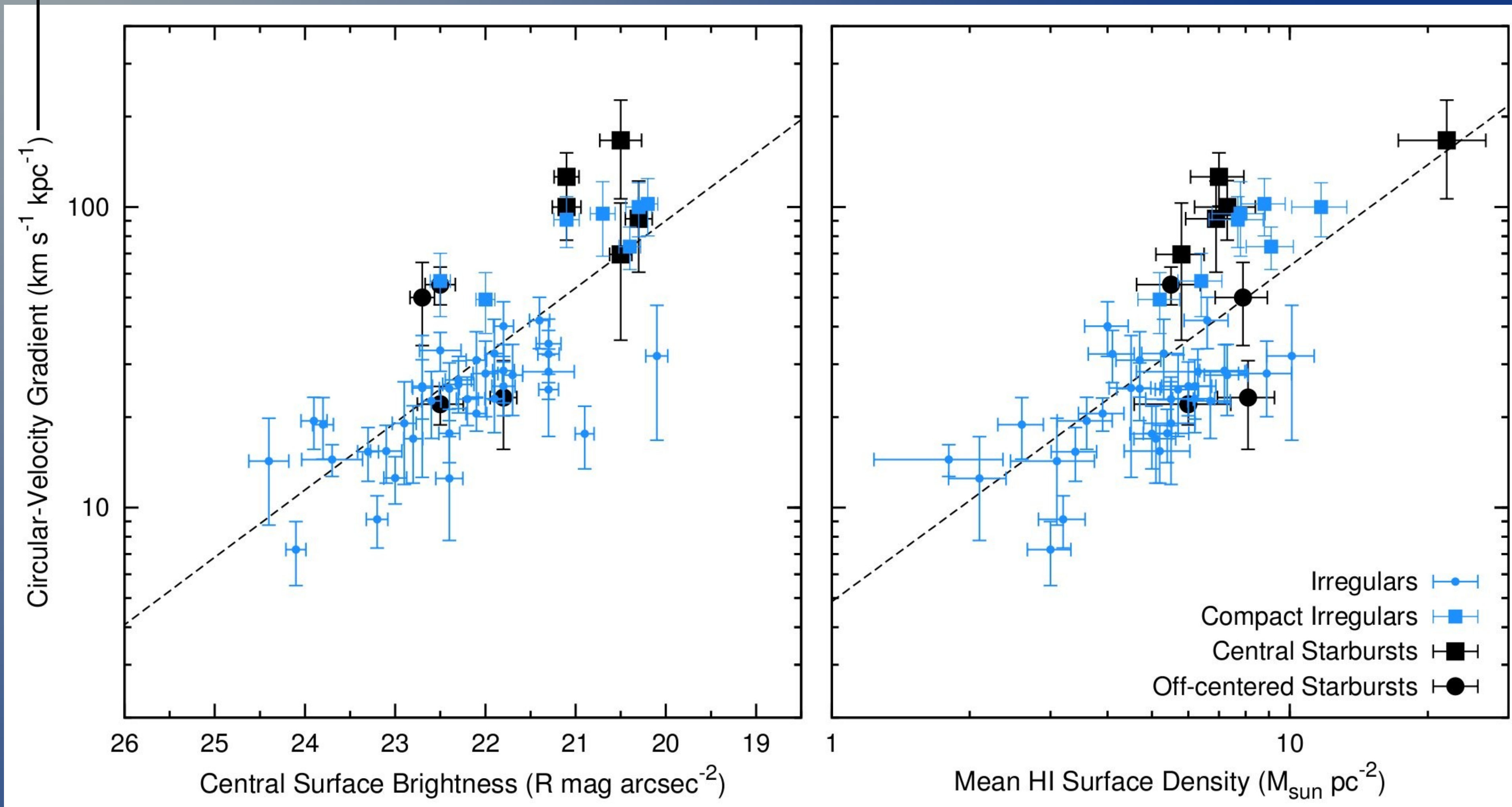
$dV/dR \sim V(R_d)/R_d$

R_d = disk scale length

- Measure the inner shape of the potential well
- Equal to the angular speed along the solid-body part

$V(R_d)/R_d \propto \sqrt{\rho_0}$

Starbursts *vs* Irrs

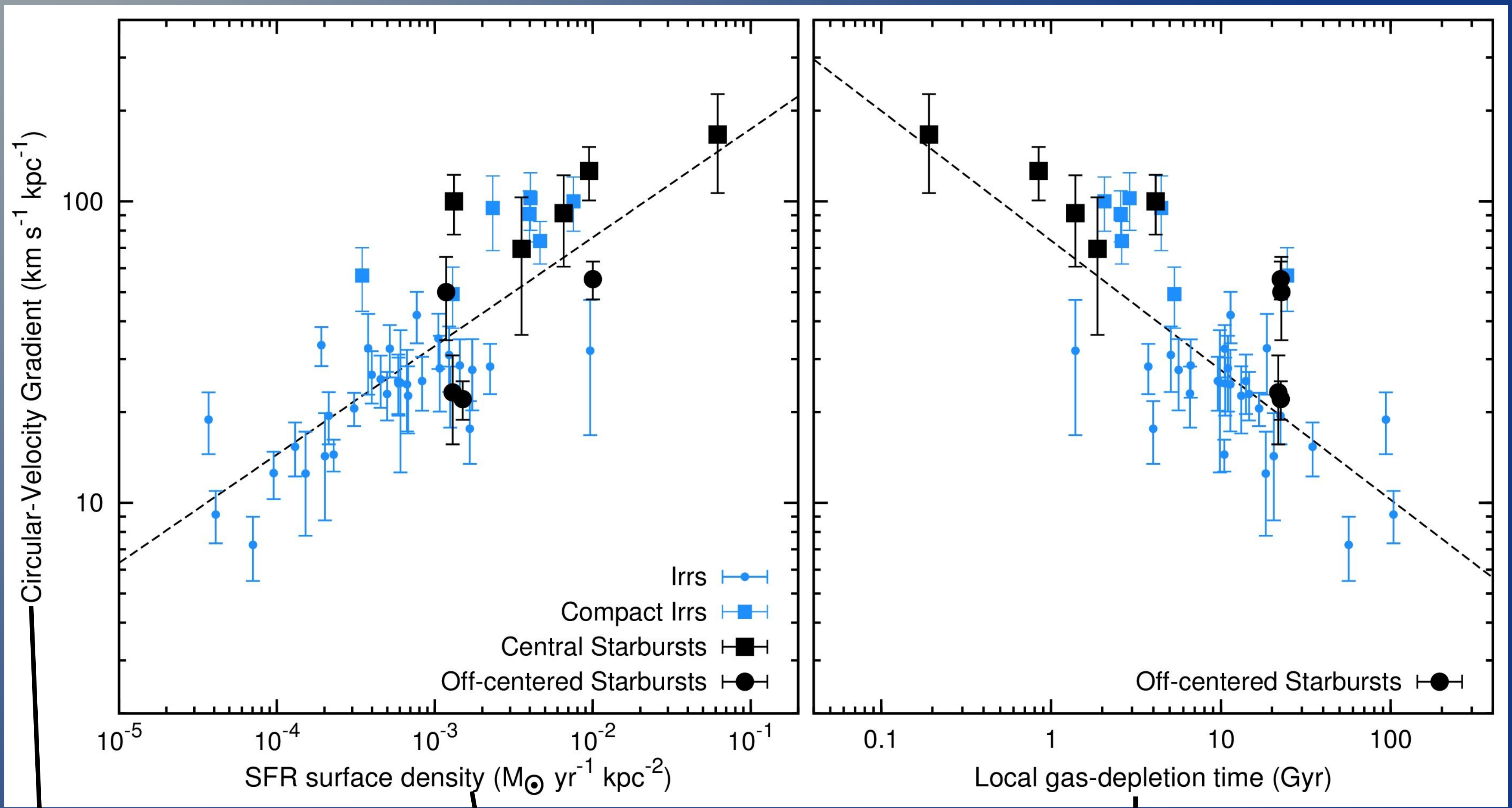


Link: Star Formation – inner potential well

Lelli, Fraternali & Verheijen 2014

(Irrs from Swaters et al. 2009)

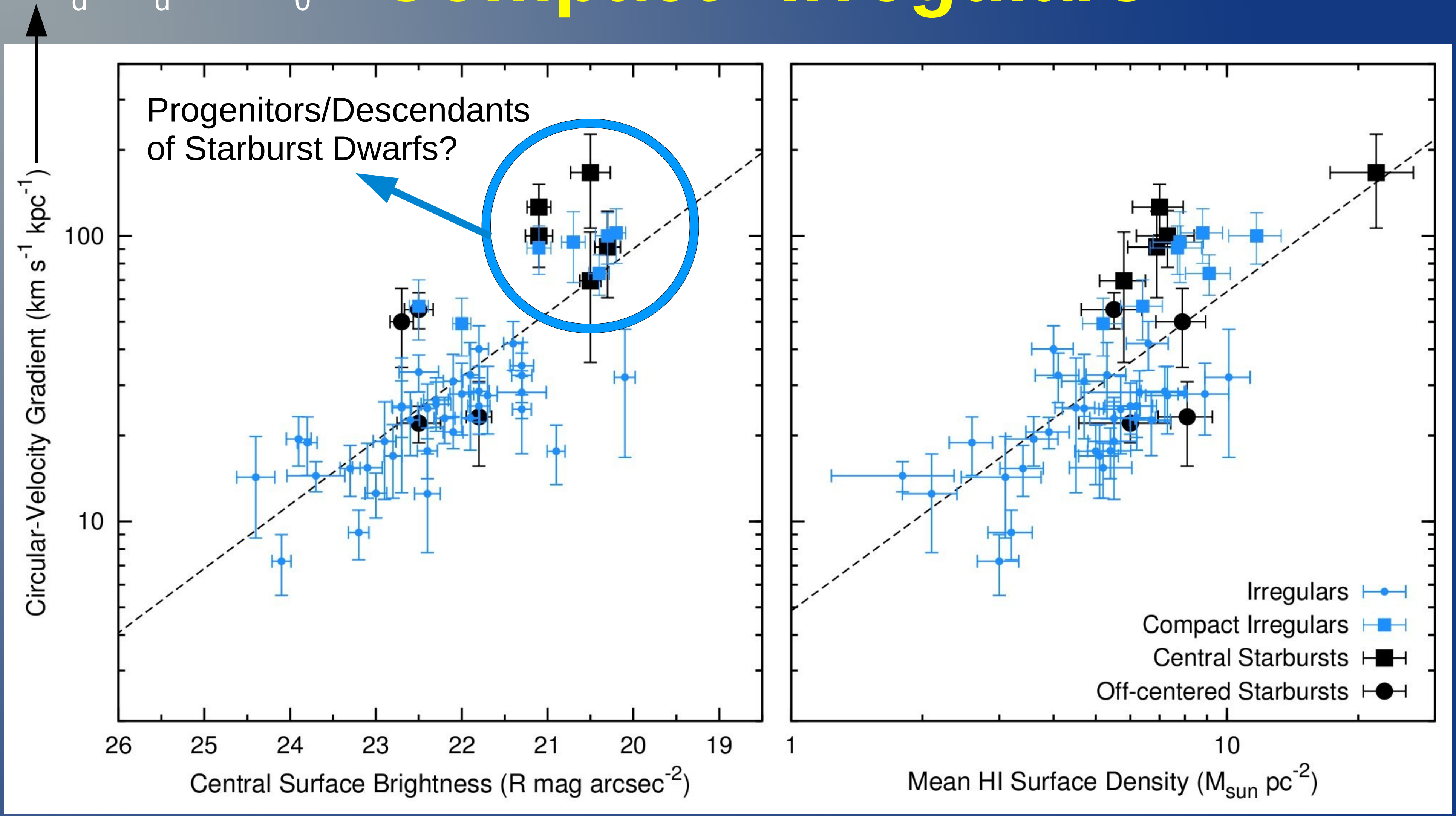
Link: Dynamics - Star Formation



$V(R_d)/R_d \propto \Sigma_{Toomre}$ $\Sigma_{SFR} = SFR_{H\alpha}/(\pi\, R_{opt}^{\ 2})$ $T_{dep} = \Sigma_{SFR}/\, \Sigma_{gas}$

Hα fluxes from Kennicutt+2008

$V(R_d)/R_d \propto \sqrt{\rho_0}$ "Compact" Irregulars



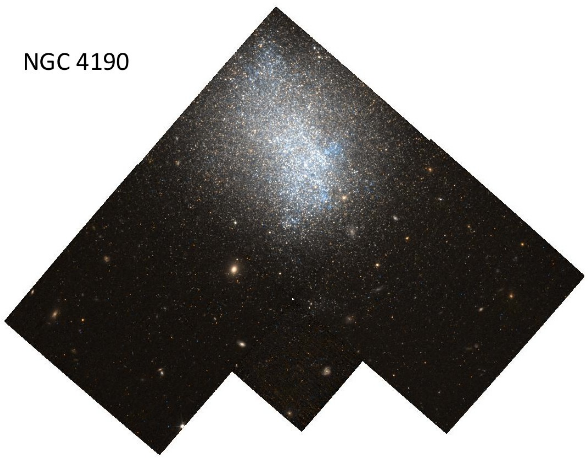
Link: Star Formation – inner potential well

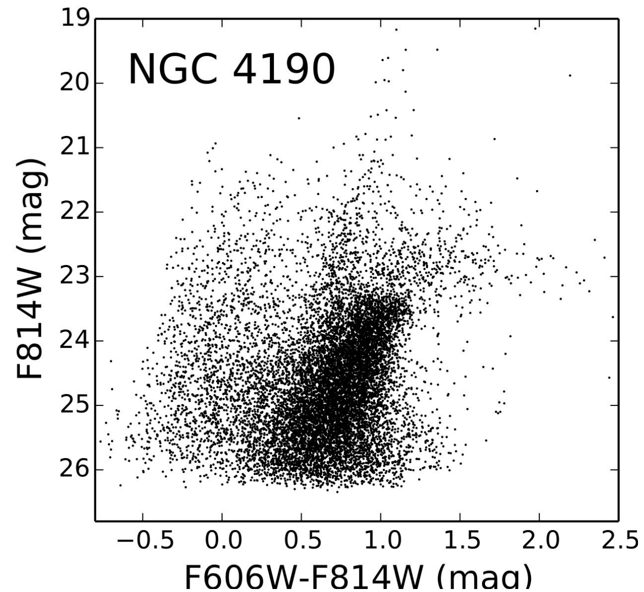
Compact Irrs = similar ρ_0 as starbursts

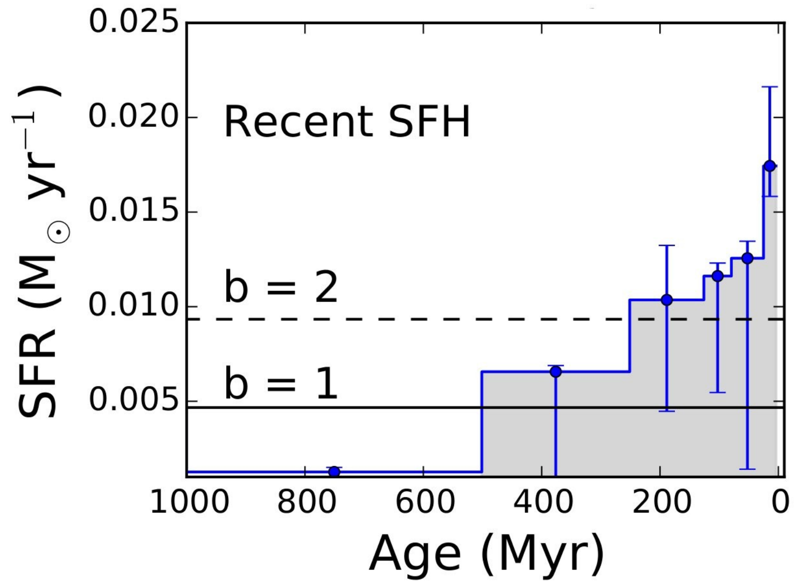
Lelli, Fraternali & Verheijen 2014

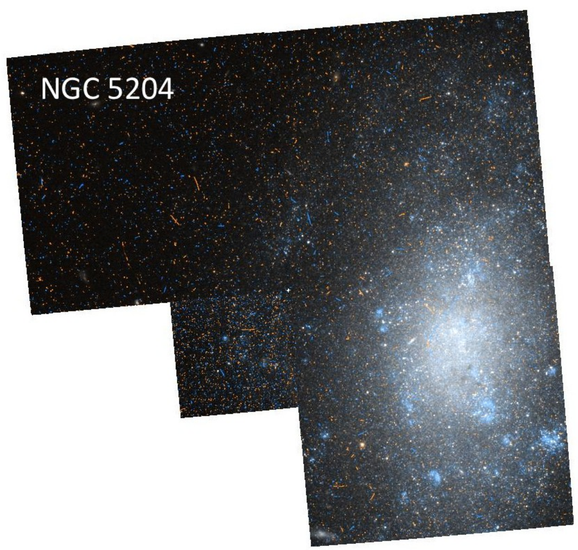
(Irrs from Swaters et al. 2009)

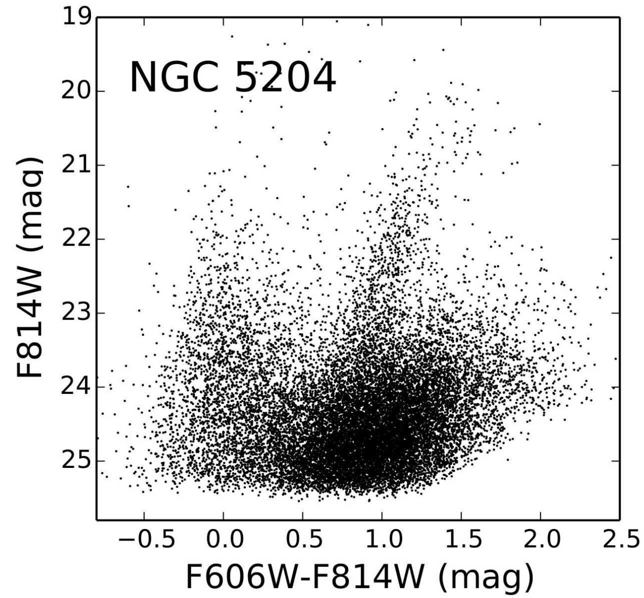
SF histories of "compact" Irrs

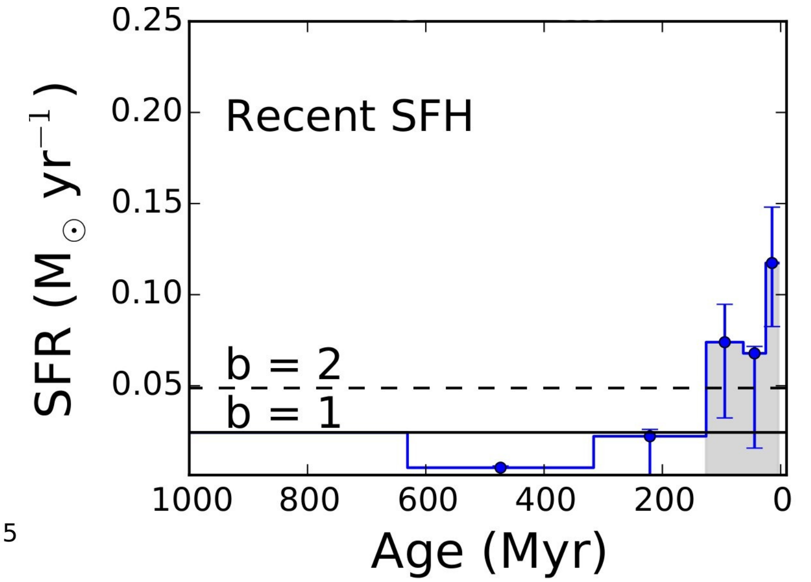






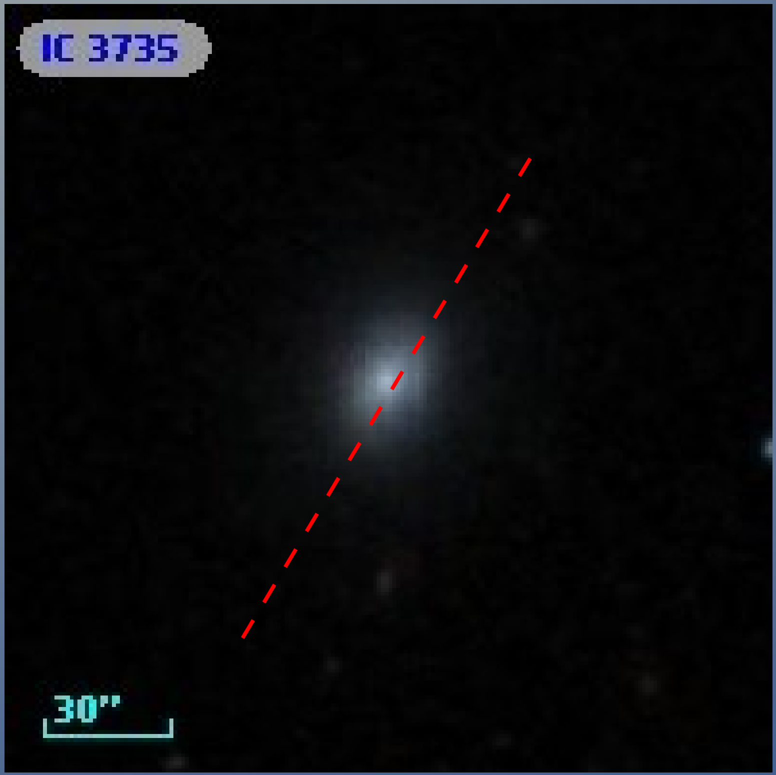


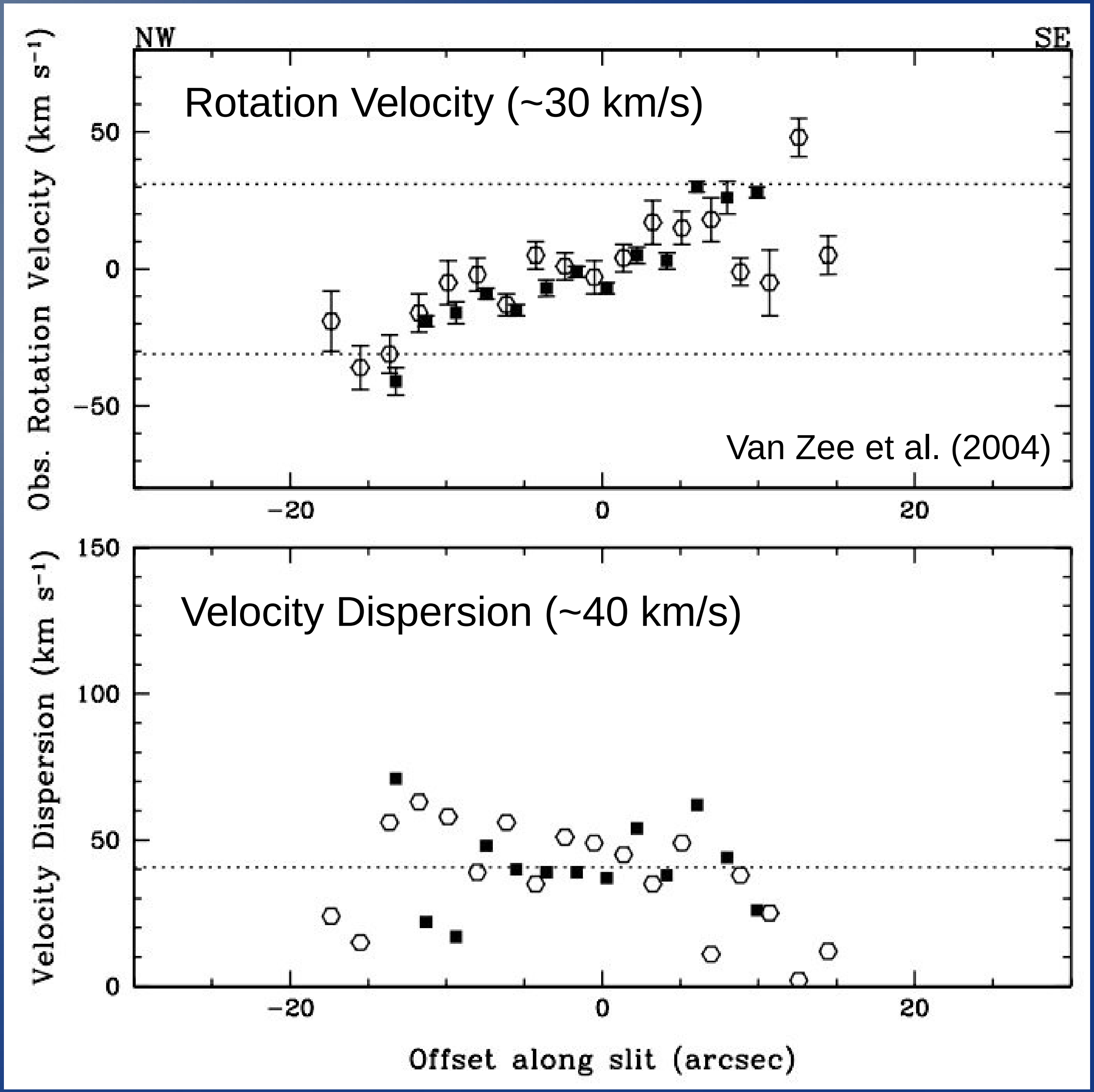




Some compact Irrs may be misidentifies starbursts! McQuinn, Lelli, Skillman et al. 2015

Rotating dE/Sph in the Virgo Cluster





Optical Spectroscopy:

Geha et al. (2002, 2003)

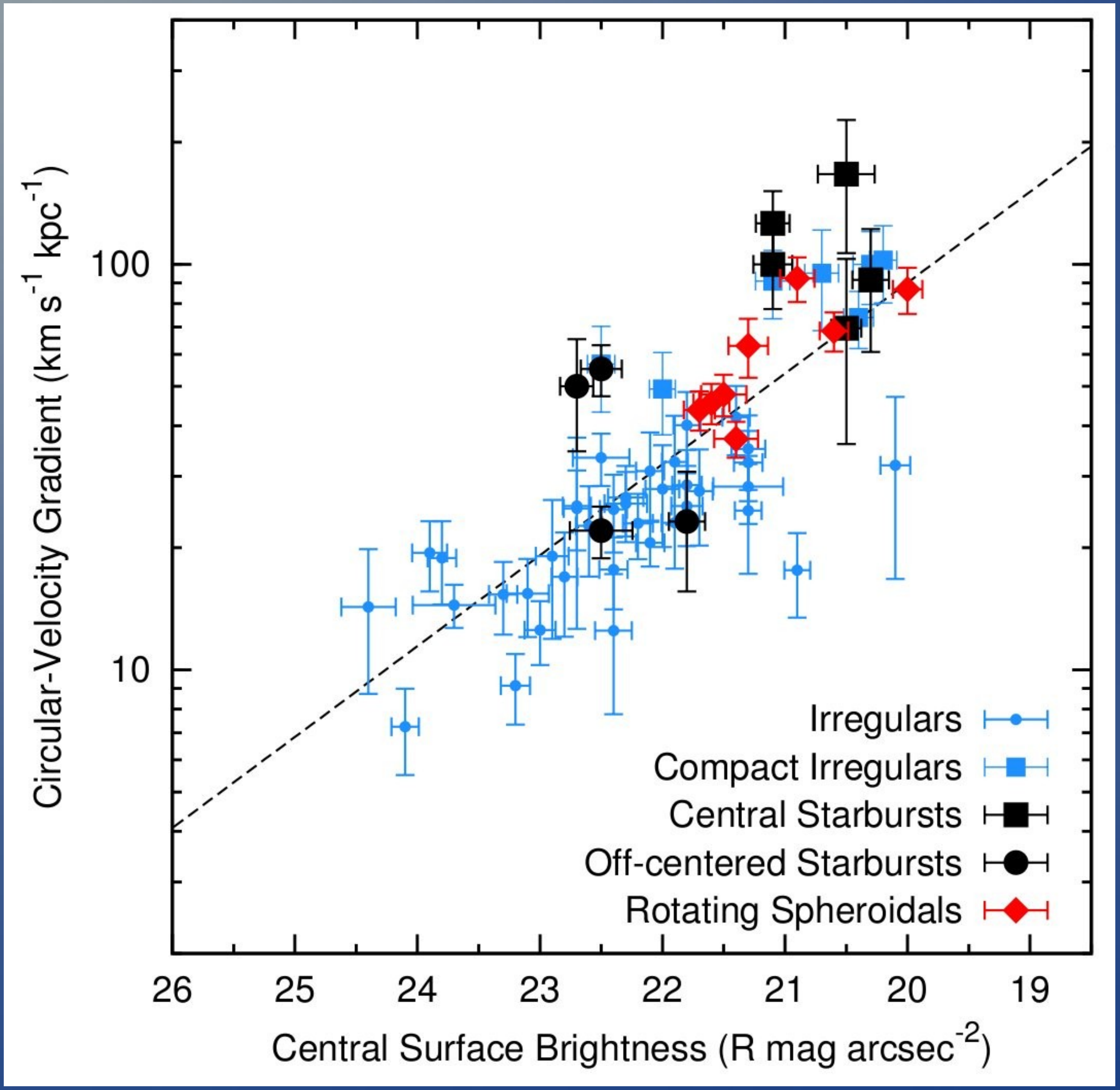
van Zee et al. (2004)

Chilingarian et al. (2007, 2009)

Toloba et al. (2011, 2012, 2014)

Rys et al. (2013, 2014)

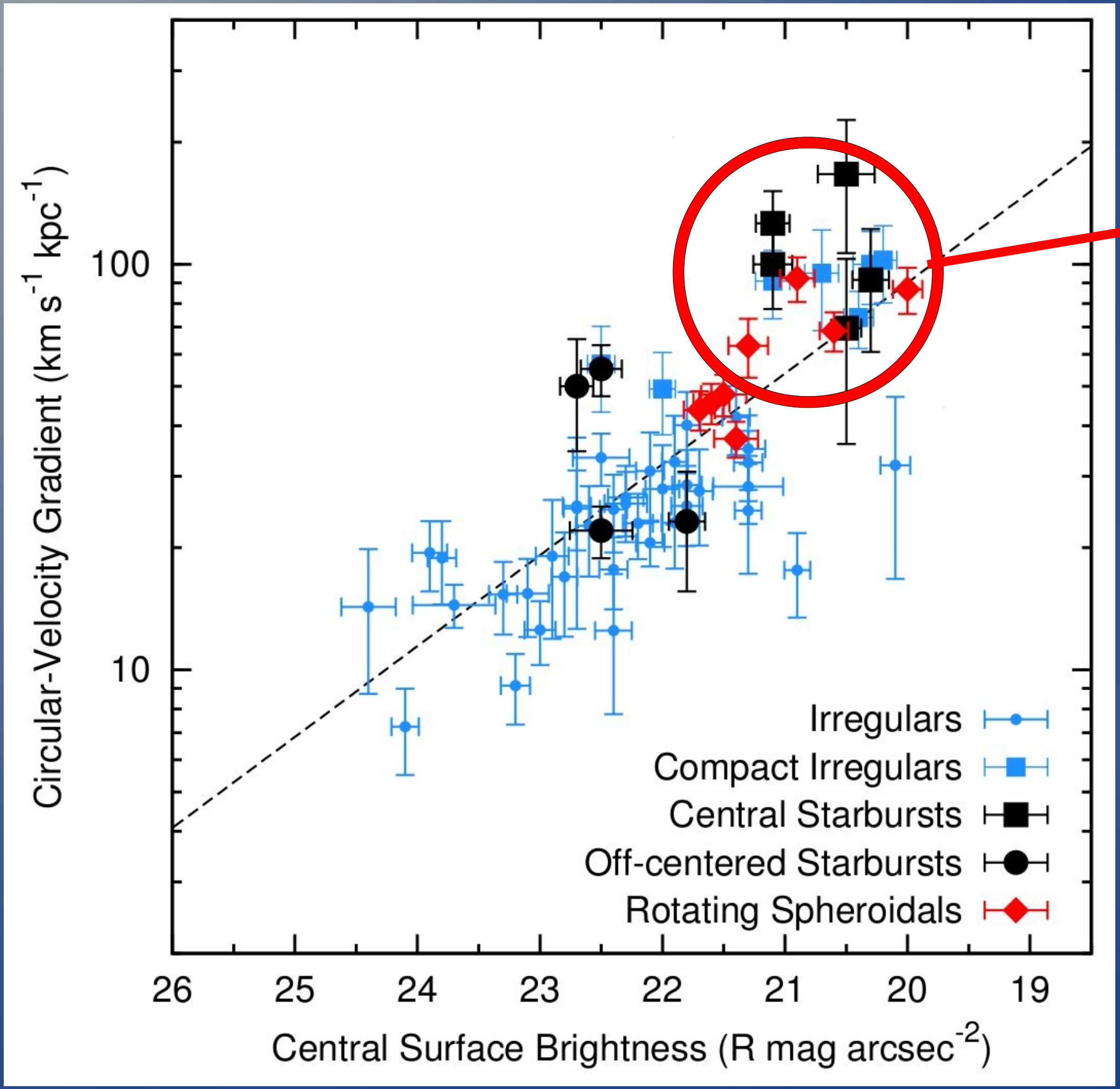
Rotating dE/Sph in the Virgo Cluster



Lelli, Fraternali & Verheijen 2014

(Sphs from van Zee et al. 2004)

Rotating dE/Sph in the Virgo Cluster



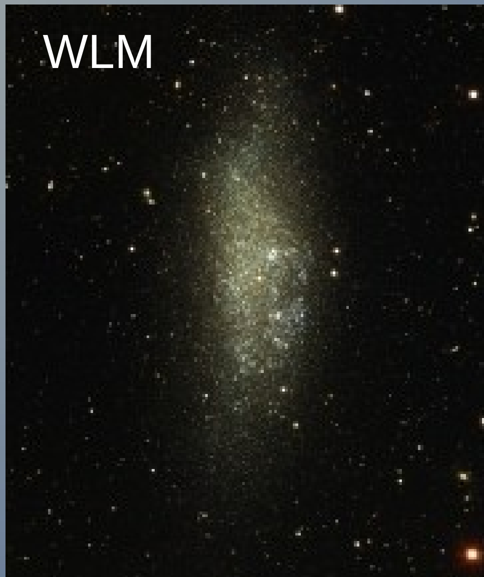
Descendants of Starburst Dwarfs?

Not of typical Irrs?

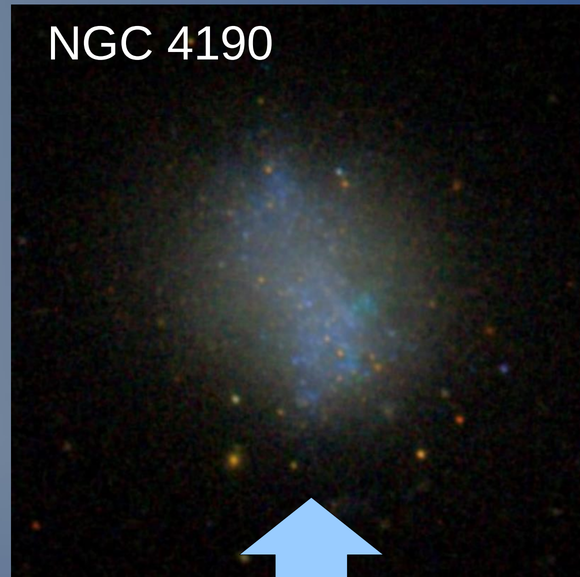
Providing that some external mechanism removes the gas.

Lelli, Fraternali & Verheijen 2014 (Sphs from van Zee et al. 2004)

Typical LSB Irrs



Compact HSB Irrs



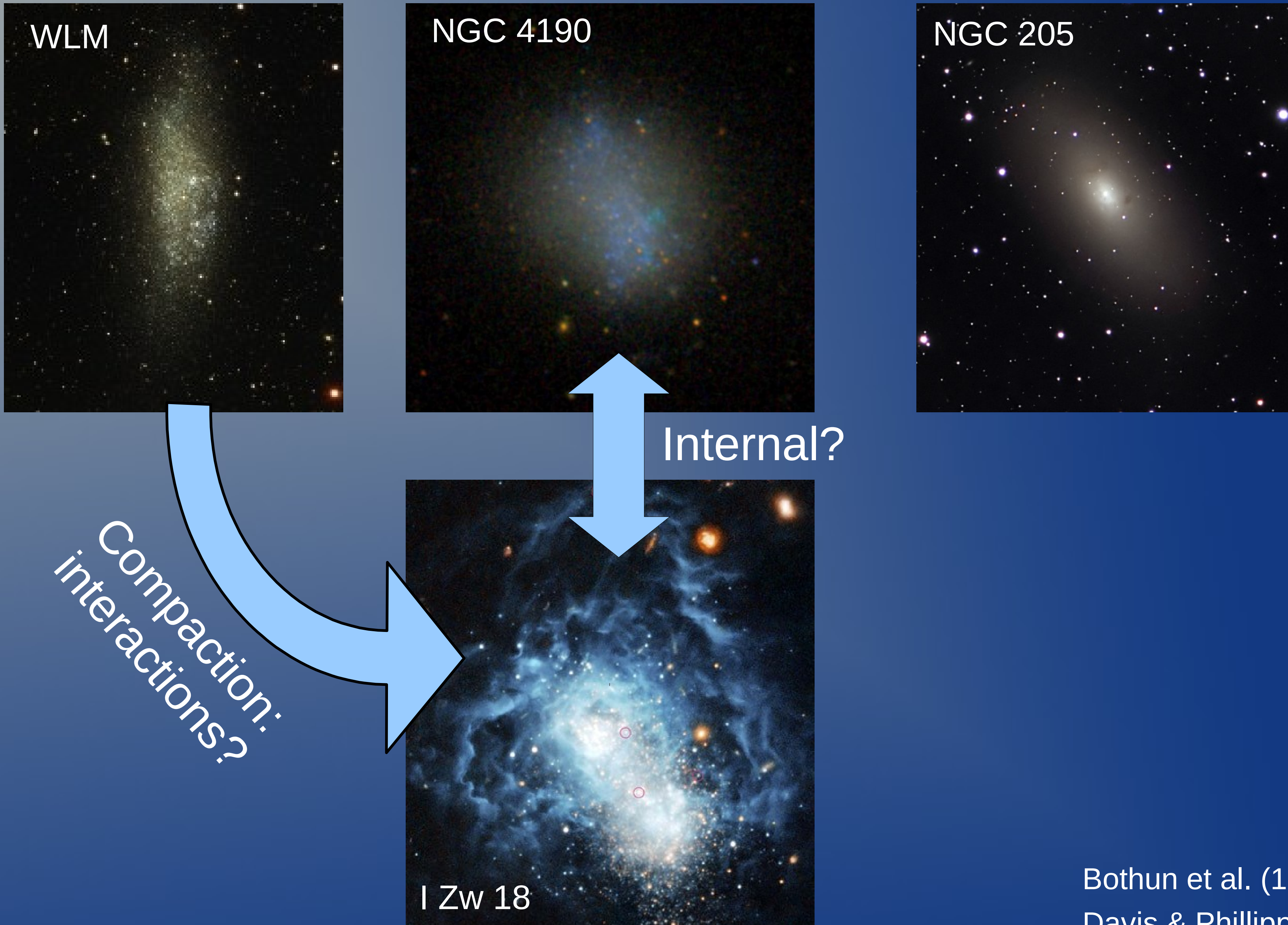
Rotating dEs

Internal?

Starbursts (~5%?)

Bothun et al. (1986)
Davis & Phillipps (1988)
Papaderos et al. (1996)

Typical LSB Irrs | **Compact HSB Irrs** | **Rotating dEs**



Starbursts (~5%?)

Bothun et al. (1986)
Davis & Phillipps (1988)
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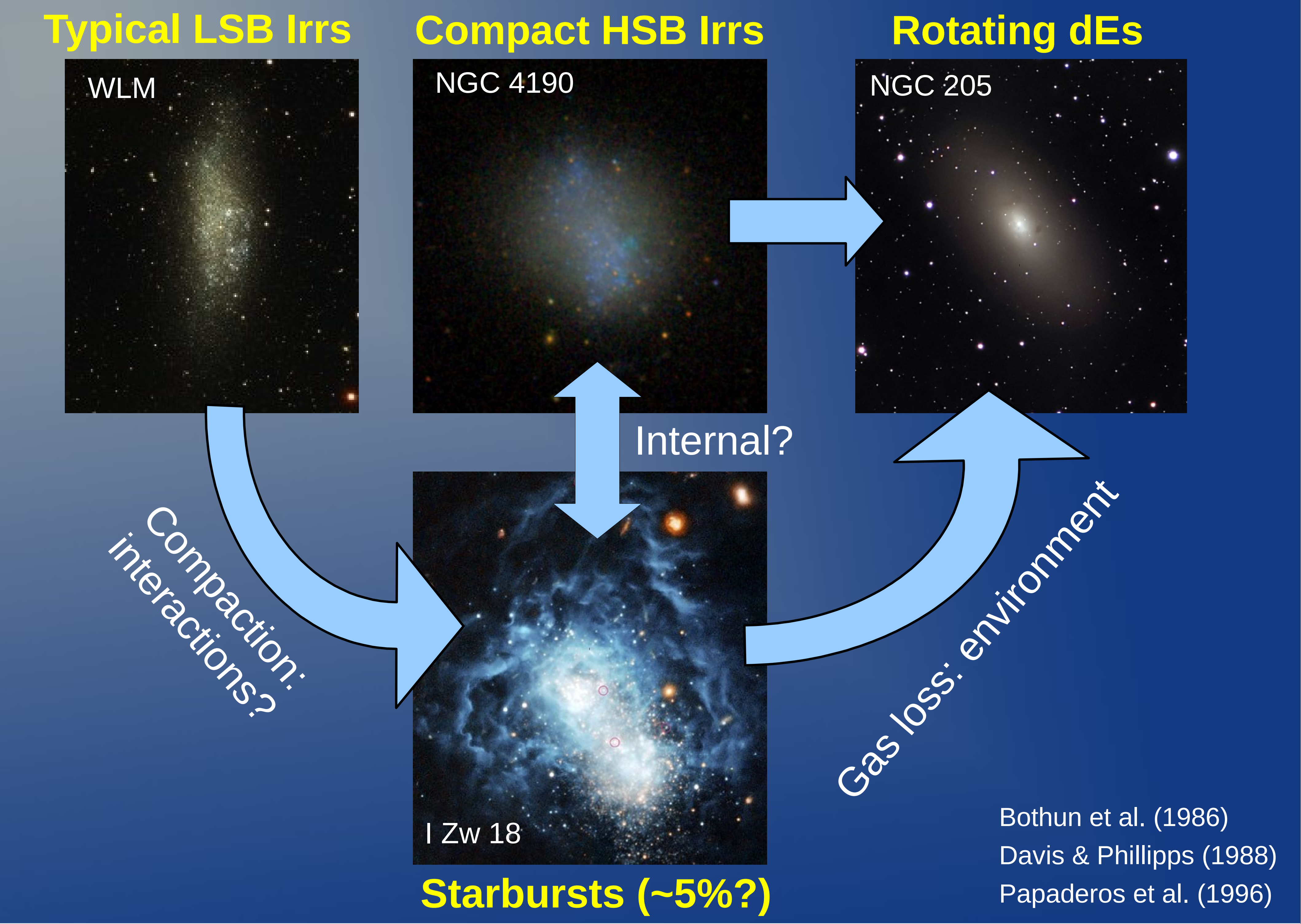
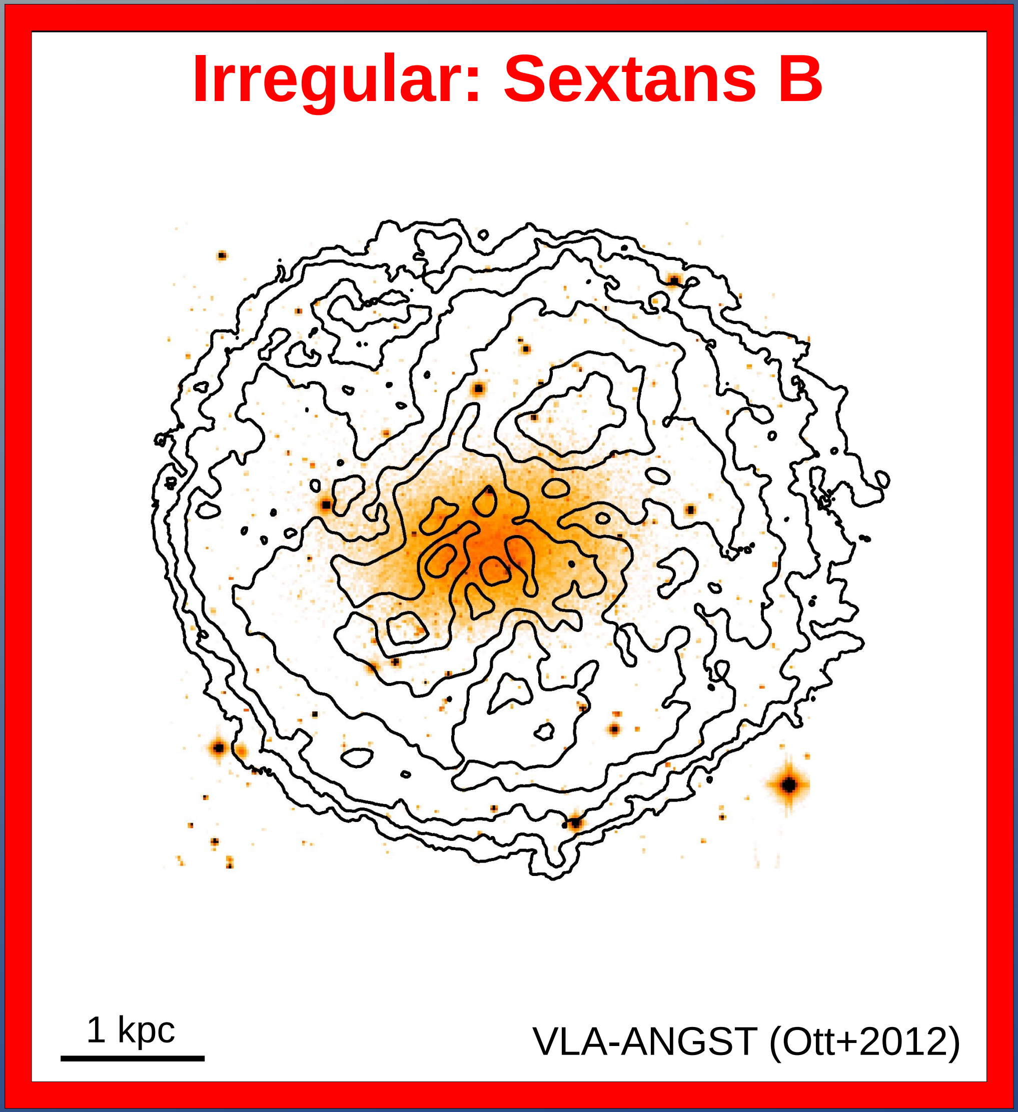

Typical LSB Irrs
Compact HSB Irrs
Rotating dEs
WLM
NGC 4190
NGC 205
Internal?
Compaction: interactions?
Gas loss: environment
I Zw 18
Starbursts (~5%?)
Bothun et al. (1986)
Davis & Phillipps (1988)
Papaderos et al. (1996)

Starburst Dwarfs

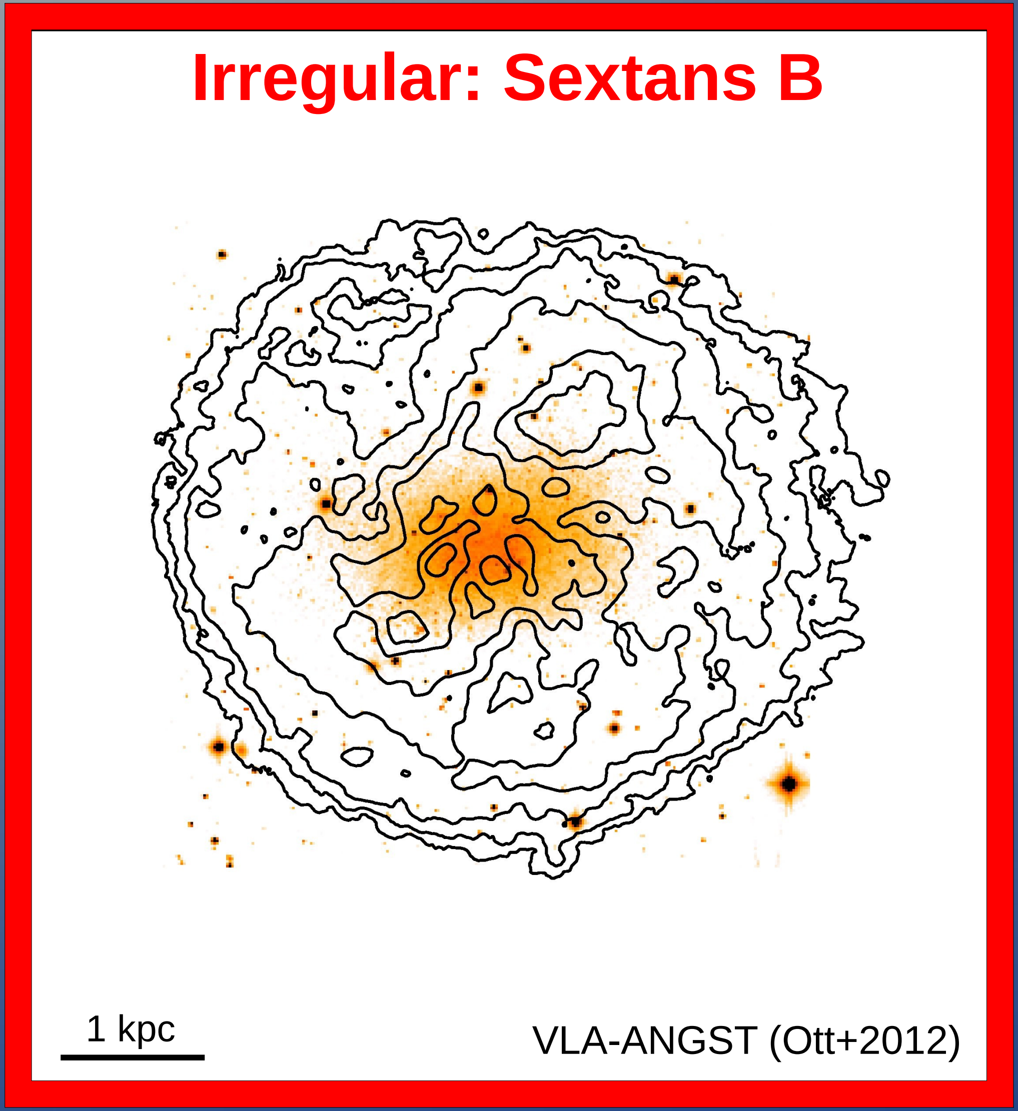
III. Triggering Mechanism

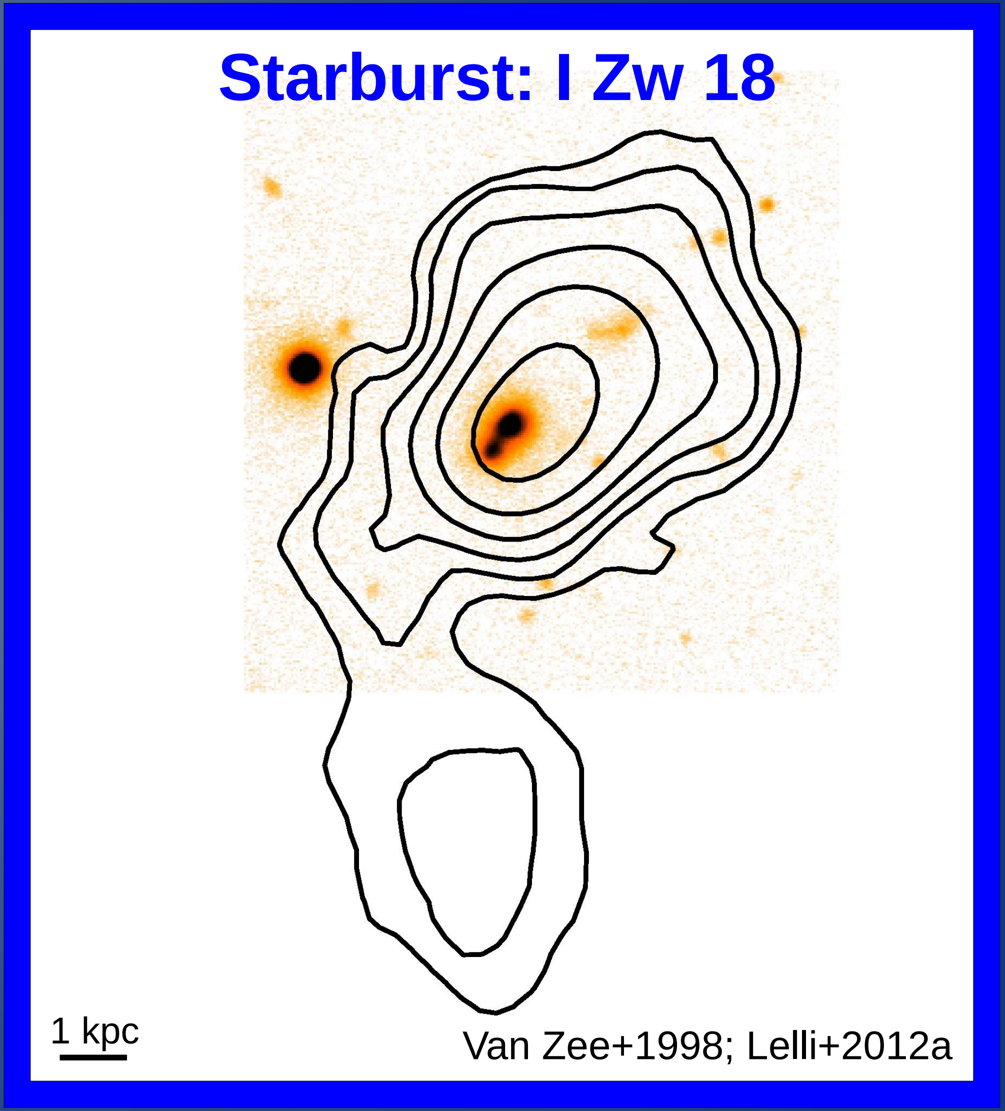
Large-scale HI distribution



Lowest HI contour = 5 x 10^{19} cm^{-2}

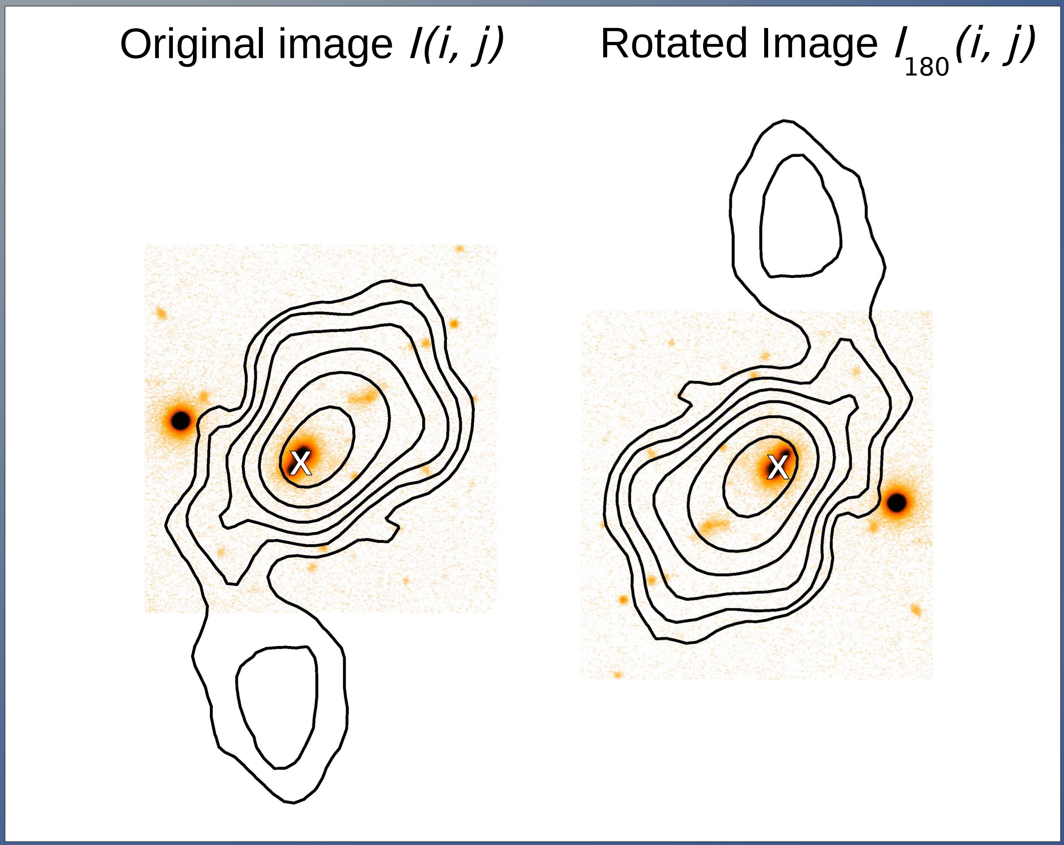
Large-scale HI distribution





Lowest HI contour = 5 x 10^{19} cm^{-2}

Quantifying the outer HI Asymmetry



Standard *A* parameter

(e.g. Bershady 2000, Holwerda+2011)

$$A = \frac{\sum_{i,j} |I(i,j) - I_{180^\circ}(i,j)|}{\sum_{i,j} |I(i,j)|}$$

Our *A* parameter (Lelli+2014, MNRAS)

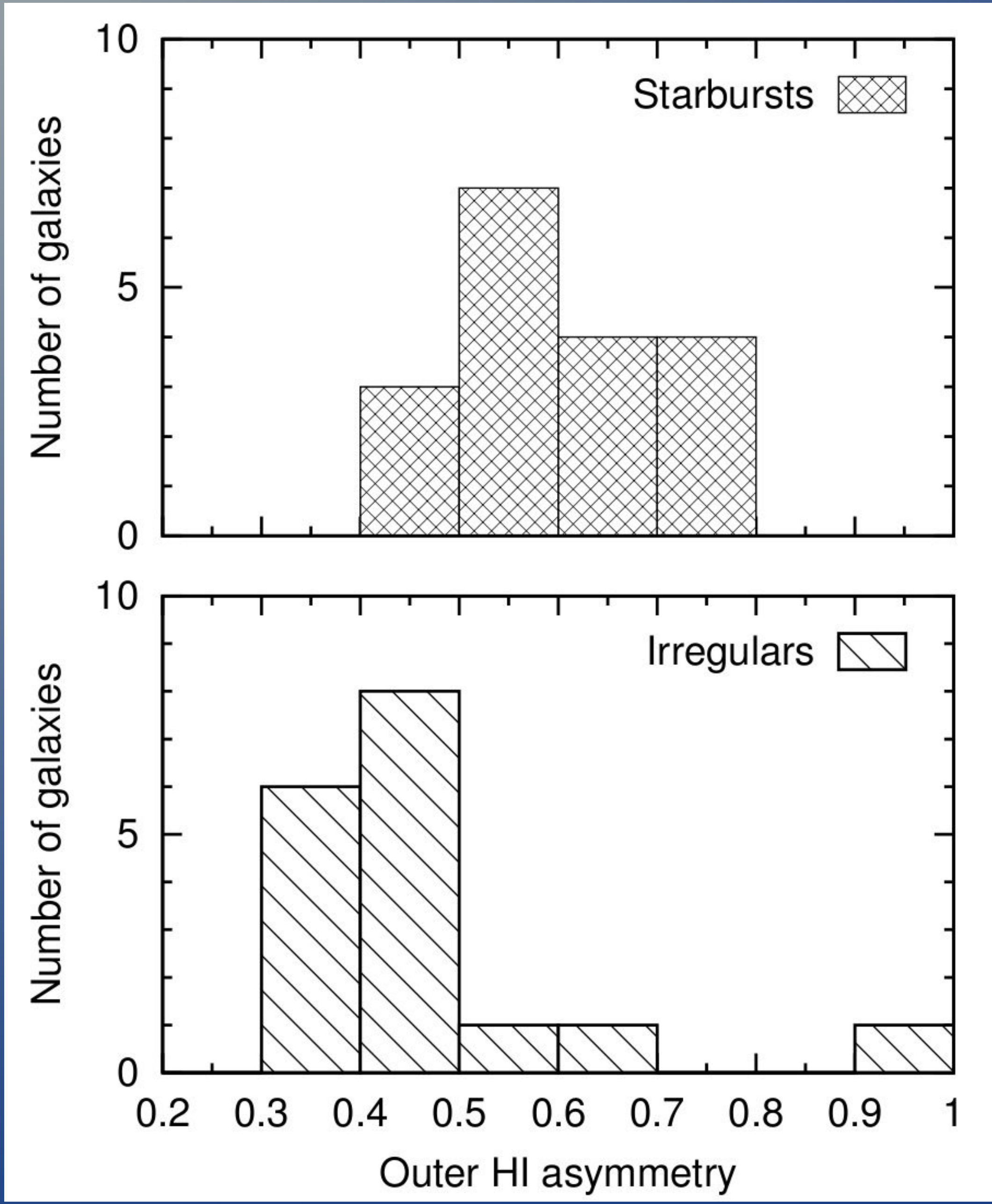
$$A = \frac{1}{N} \sum_{i,j}^{N} \frac{|I(i,j) - I_{180^\circ}(i,j)|}{|I(i,j) + I_{180^\circ}(i,j)|}$$

→ Good for outer regions!

For all galaxies:

- Uniform column density sensitivity
- Similar linear resolution (in kpc)

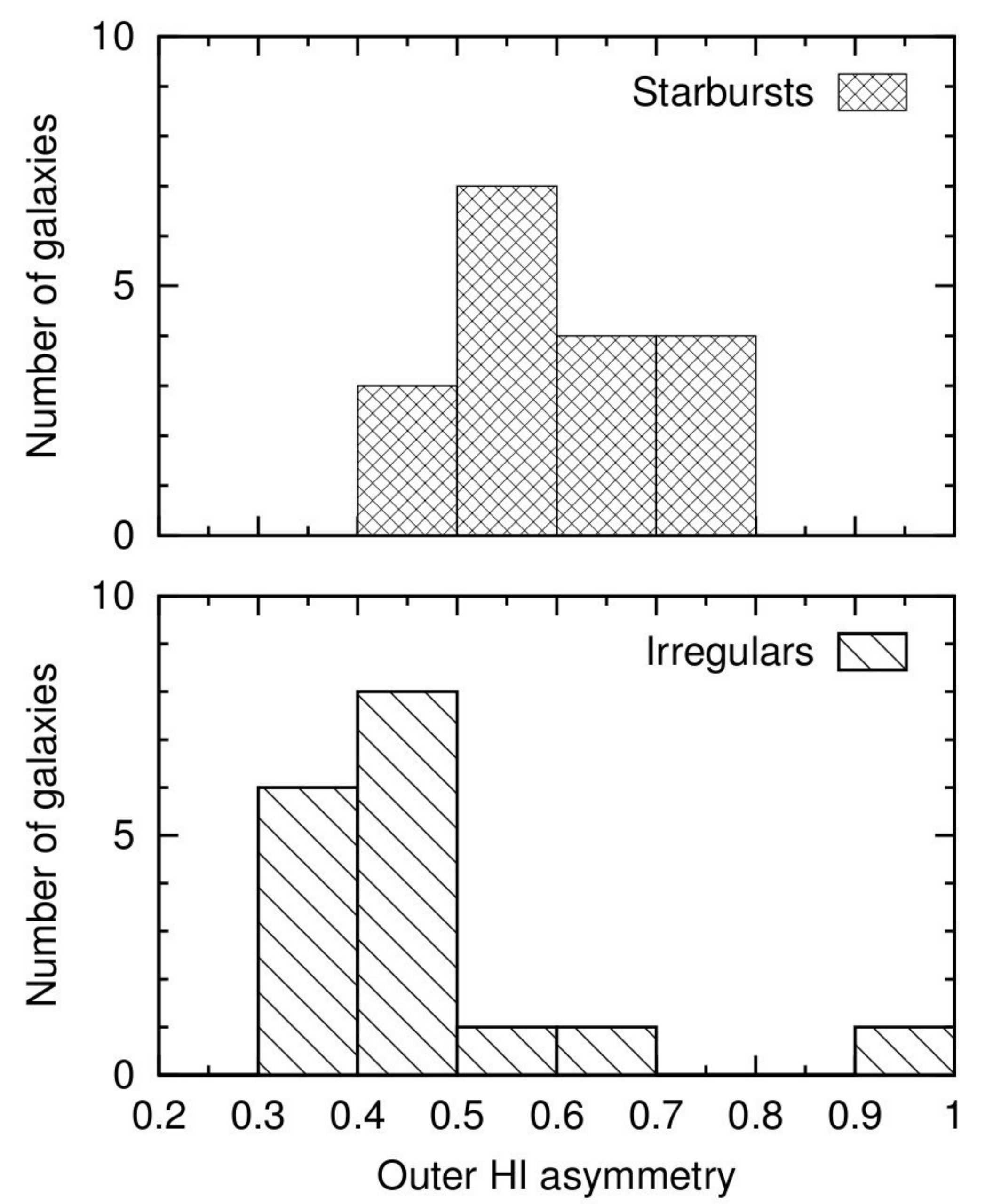
HI Asymmetry: Starbursts *vs* Irrs



Starbursts have more asymmetric outer HI distributions than Irrs

Irrs from VLA-ANGST (Ott et al. 2012)

HI Asymmetry: Starbursts *vs* Irrs



Starbursts have more asymmetric outer HI distributions than Irrs

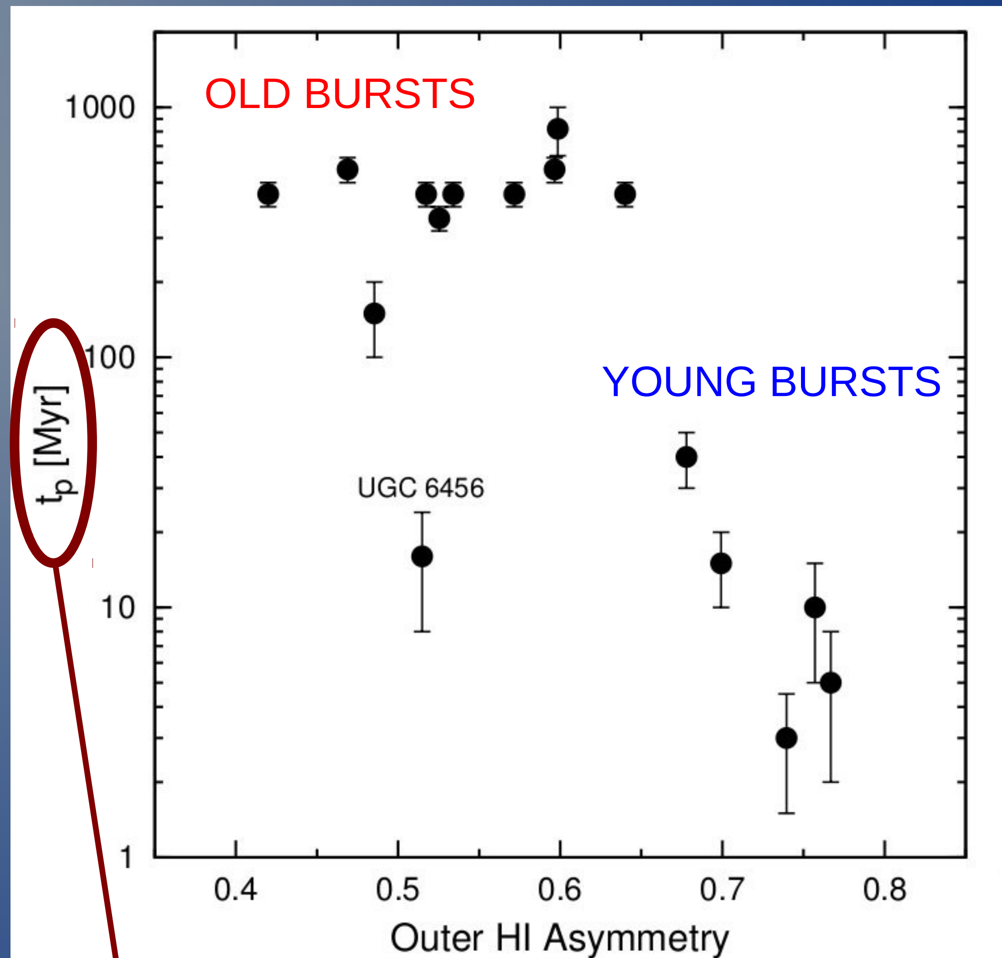
External mechanisms triggered the starburst:

- Interactions/mergers?
- Cold gas accretion?

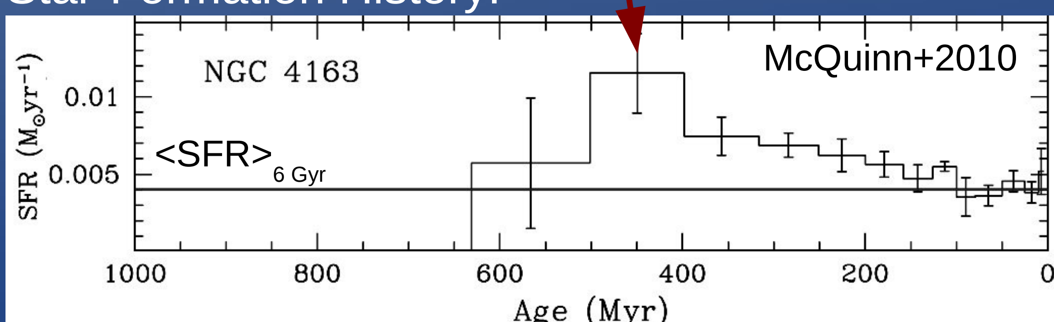
See also: Ekta & Chengalur (2010); Lopez-Sanchez et al. (2010).

Irrs from VLA-ANGST (Ott et al. 2012)

HI Asymmetry *vs* Starburst "age"



Star-Formation History:



FOR OLD BURSTS:

$t_p \sim t_{orb}$ in outer parts. HI distribution can be regularized by diff. rotation!

Summary on Starburst Dwarfs

- Starbursts & Irrs have similar gas fractions

  - No evidence for massive outflows or starvation

  - Irr/Starburst --> dE/Sph: only with external mechanisms

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- Starbursts have asymmetric outer HI distributions

  - Burst triggered by external mechanisms

  - Interactions/mergers or cold gas accretion from the IGM

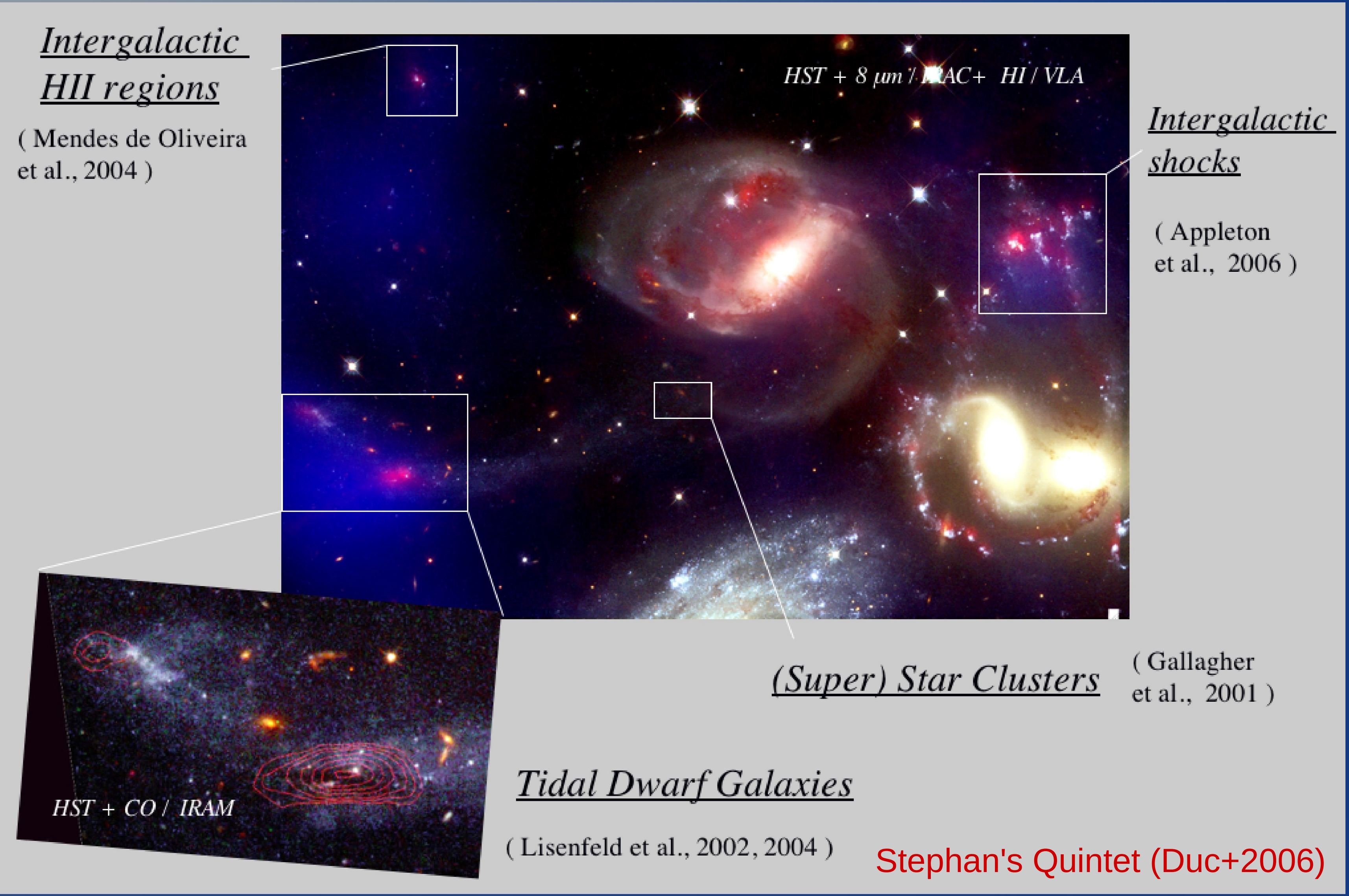
Tidal Dwarf Galaxies

In collaboration with Stacy McGaugh,

Pierre-Alain Duc, Elias Brinks et al.

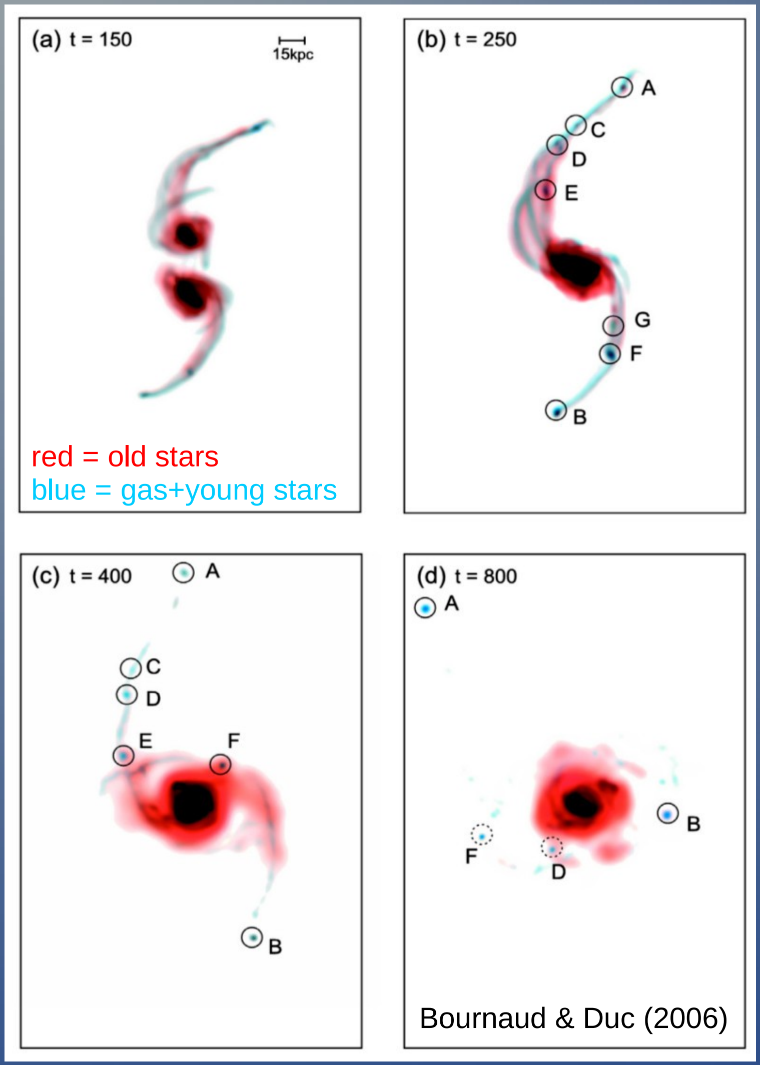
What is a Tidal Dwarf Galaxy (TDG)?

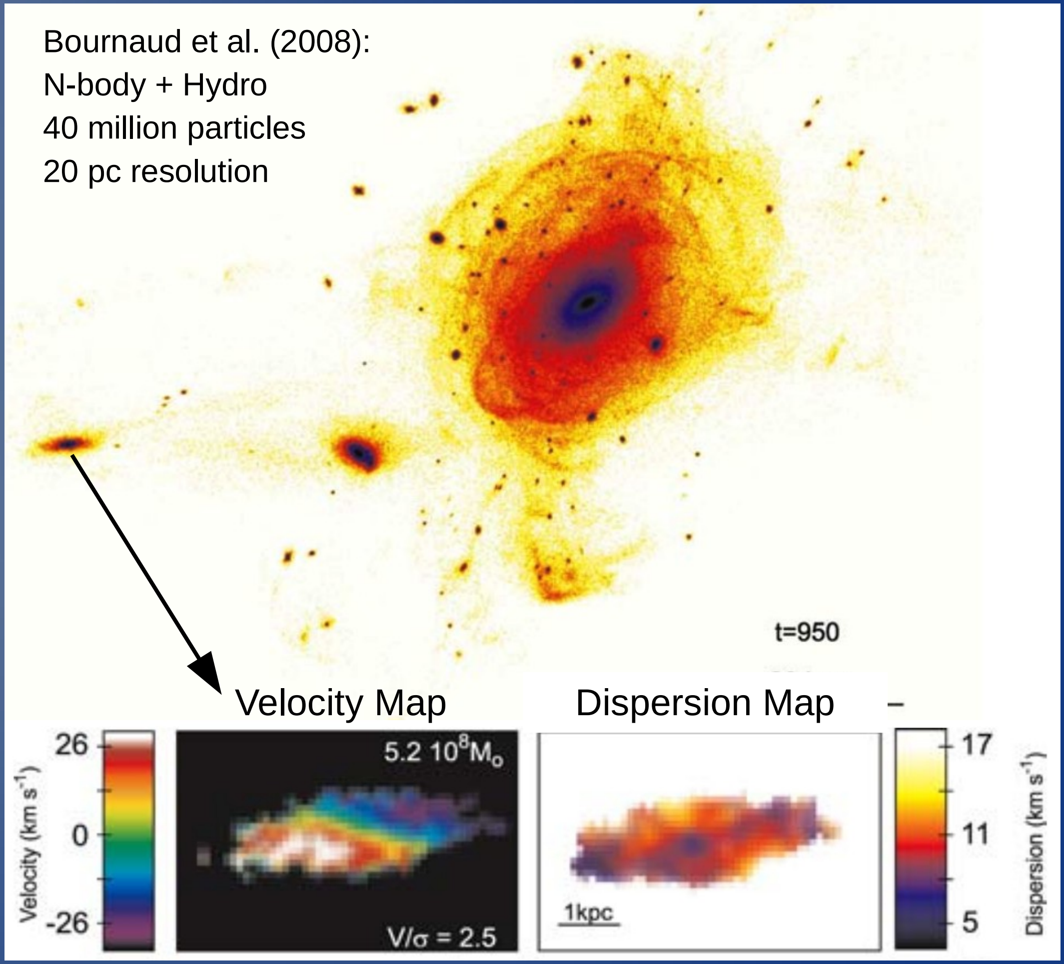
Different types of objects are formed during interactions/mergers:



TDG candidates = Massive condensations of gas & young stars (~10^8-10^9 M_{sun})

TDGs from numerical simulations





Most massive TDGs can survive:

How many dwarfs have tidal origin?

(Bournaud & Duc 2006; Ploeckinger+2014, 2015)

Simulated TDGs are rotation supported and devoid of non-baryonic dark matter!

(Barnes & Hernquist 1992; Elmegreen+1993; Duc+2004; Bournaud & Duc 2006; Wetzestein+2007; Bournaud+2008)

Prediction: TDGs should be free of DM!

- Tides have different effects on the dynamically-cold disc w.r.t. the dynamically-hot DM halo (e.g. Barnes & Hernquist 1992):

  - Disc --> tails, bridges, and eventually TDGs

  - Halo --> too dynamically-hot to form tails

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- Baryons & DM are "segregated" in phase-space

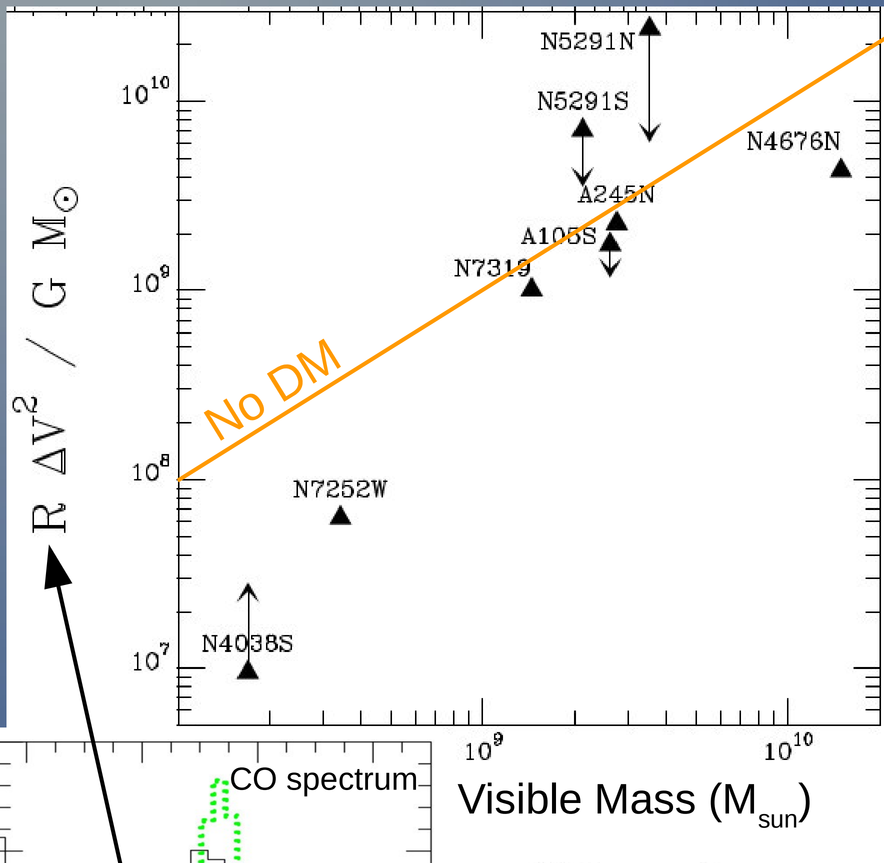
- TDGs have shallow potential wells with V_{rot} < 50 km/s:

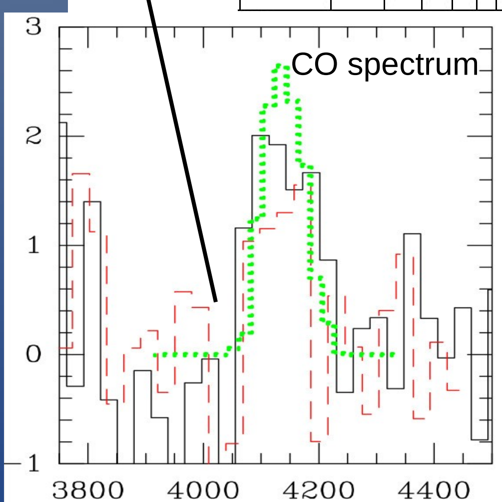
  They cannot accrete DM particles with σ_V ~ 200 km/s!

Previous kinematic studies on TDGs

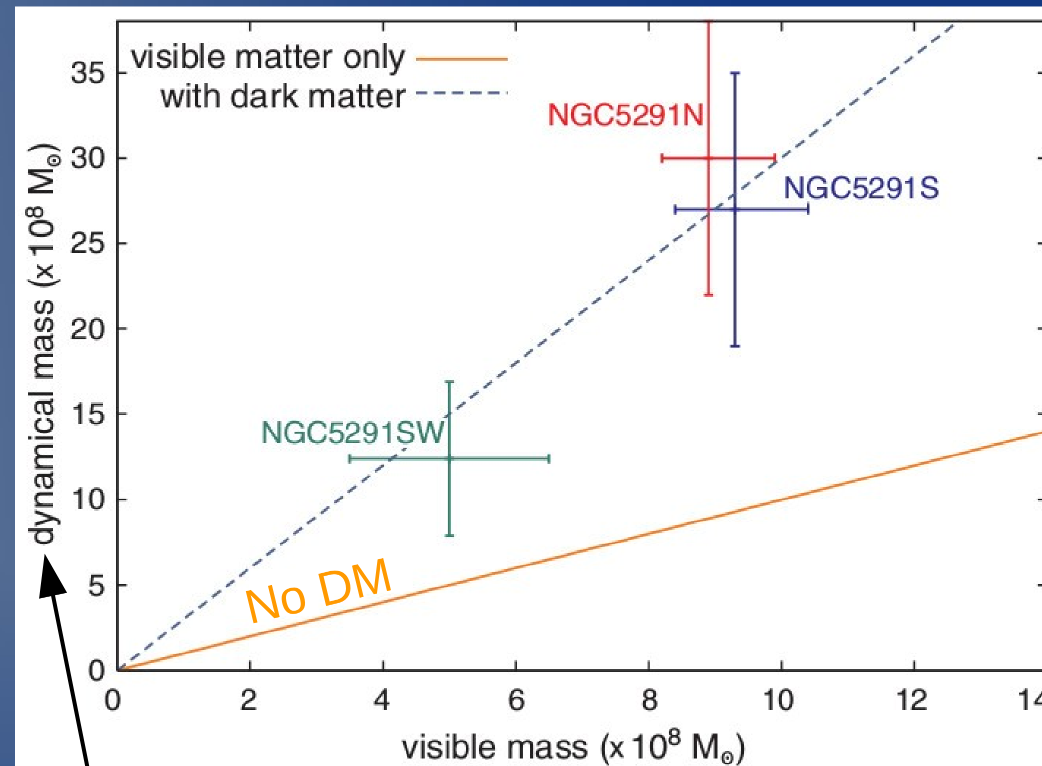
Braine+2001: No evidence of DM!

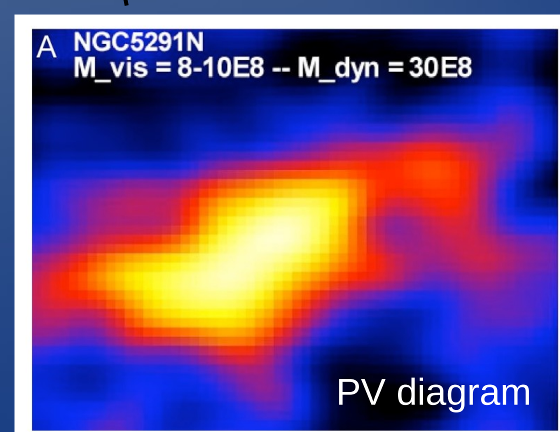
Bournaud+2007: Evidence of DM!





Rotation velocities from CO line-widths (TDGs unresolved)

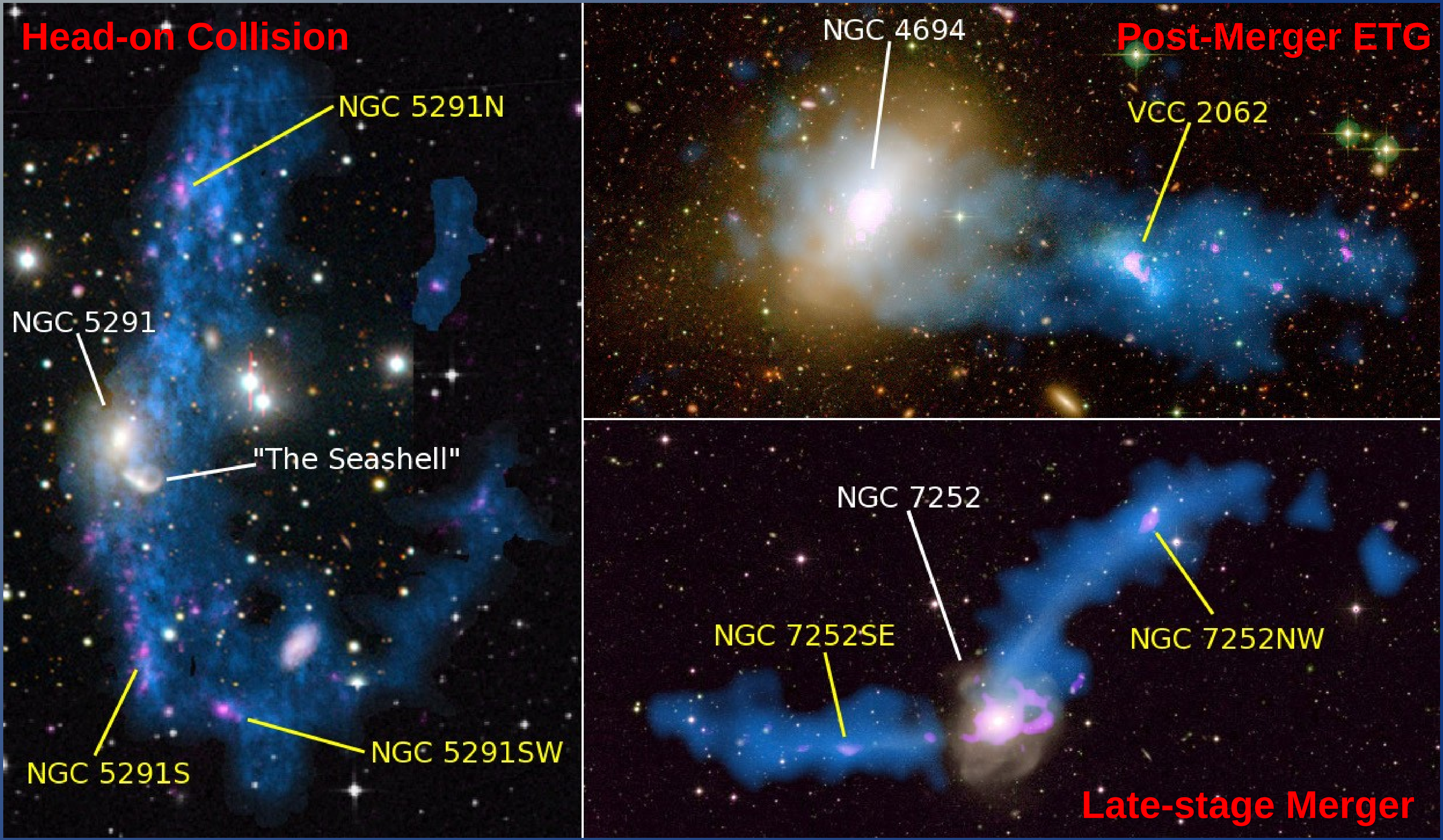




Rotation velocities from HI interferometry (TDGs barely resolved)

Missing mass in TDGs?
CO-dark molecules?

Sample of 6 bona-fide TDGs

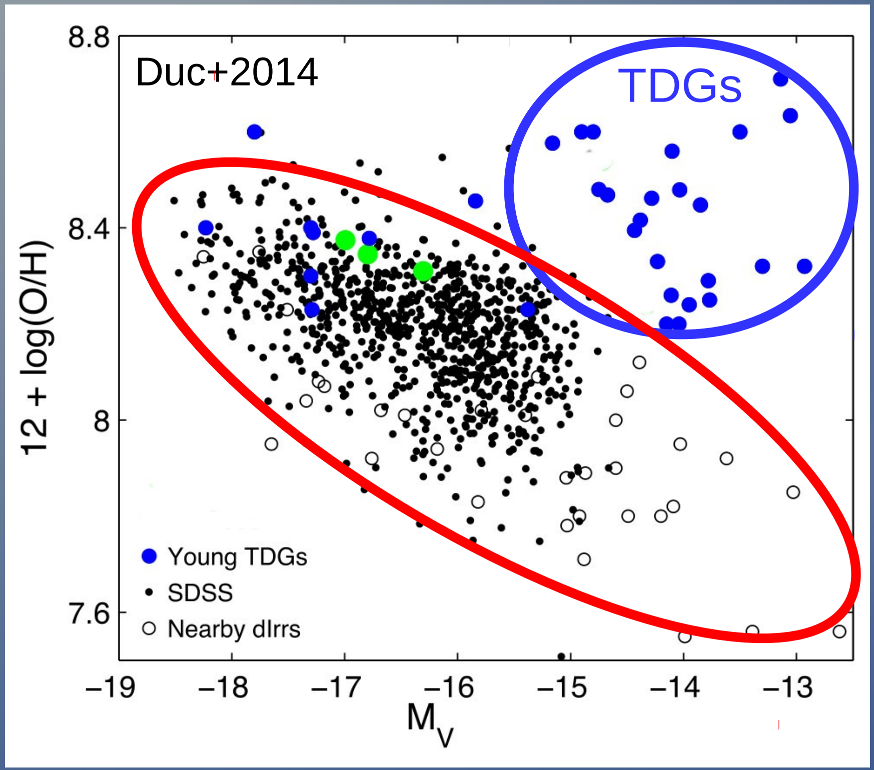


Blue = HI (VLA)
Pink = FUV (GALEX)

Yellow = Tidal Dwarf Galaxies
Lelli, Duc, Brinks et al. 2015, A&A

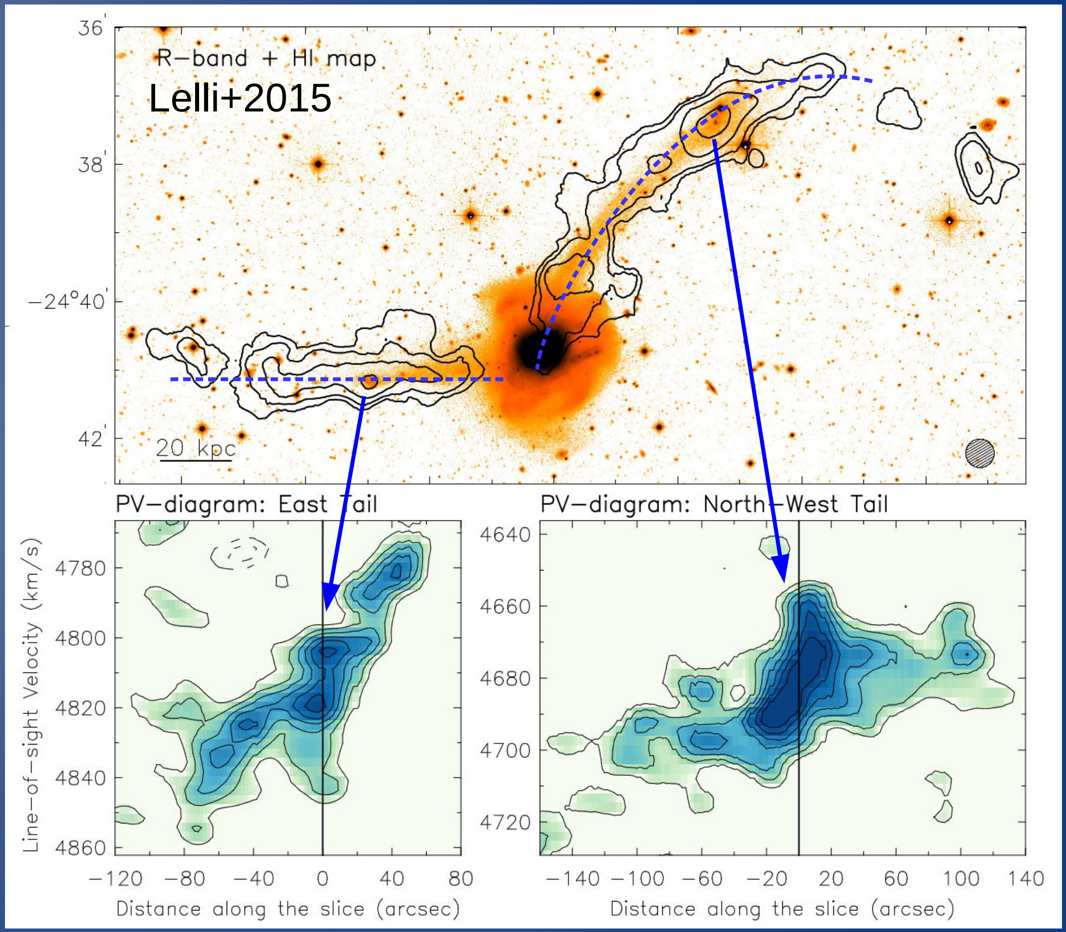
Requirements to be a bona-fide TDG

1) High metallicities



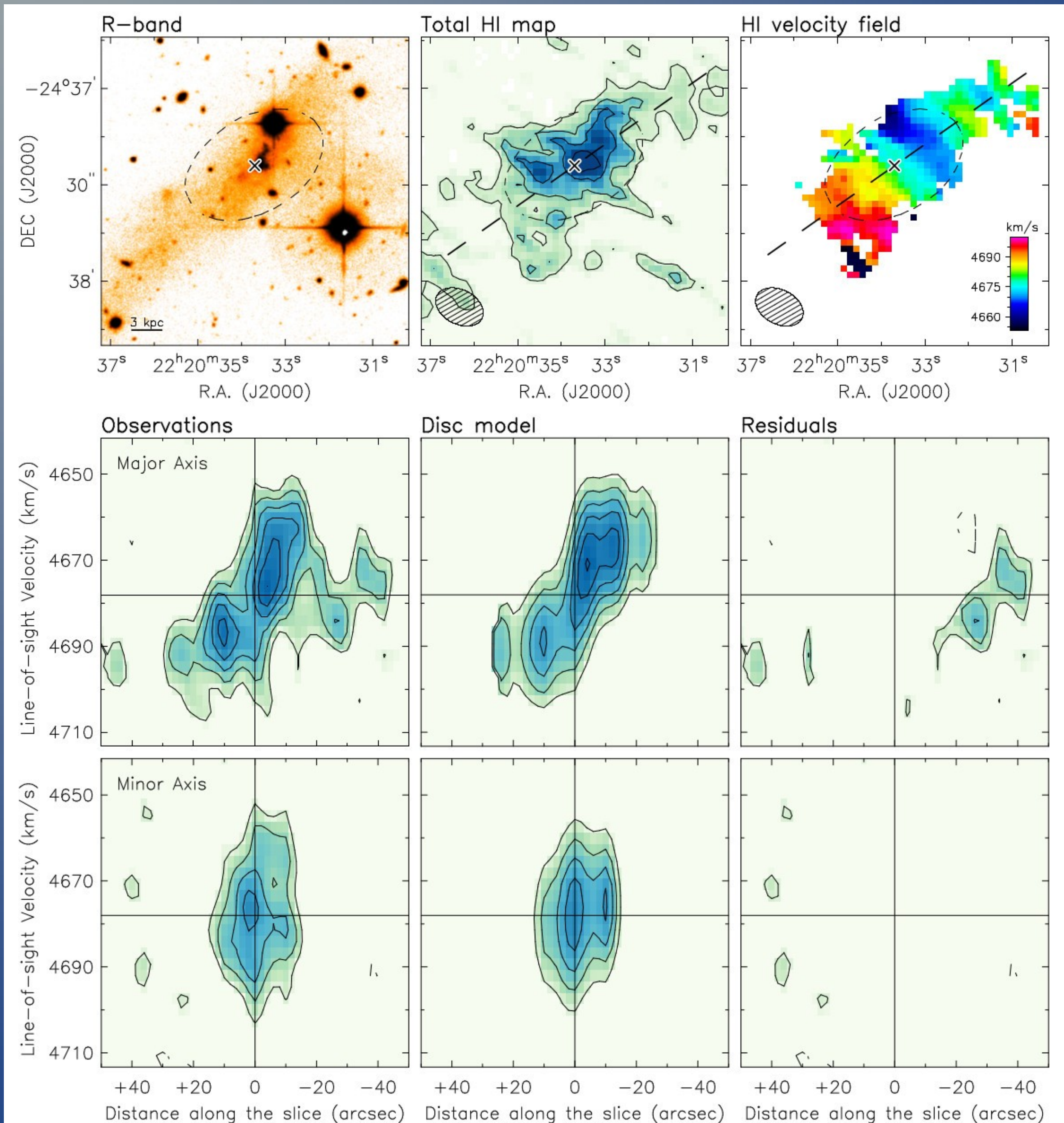
Young TDGs are forming out of pre-enriched material ejected from massive progenitors!

2) Kinematically distinct components



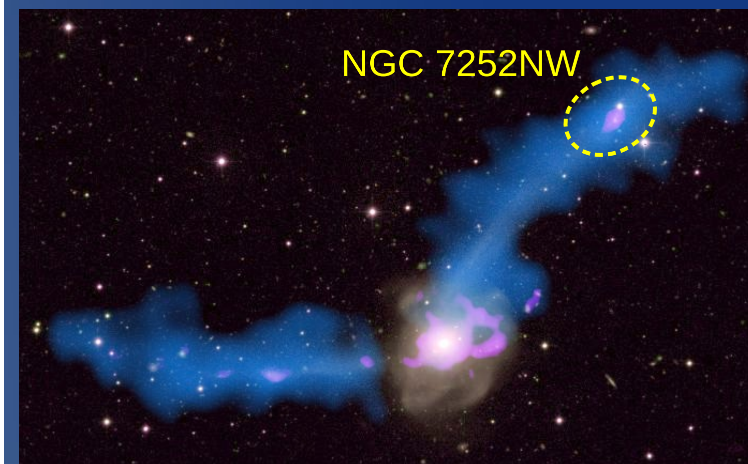
TDGs are associated with steep HI velocity gradients: rotation in a local potential well? Gravitationally bound?

Rotating disk models for TDGs



Lelli et al. (2015), A&A:

- High-Res. VLA data
- 3D kinematical model

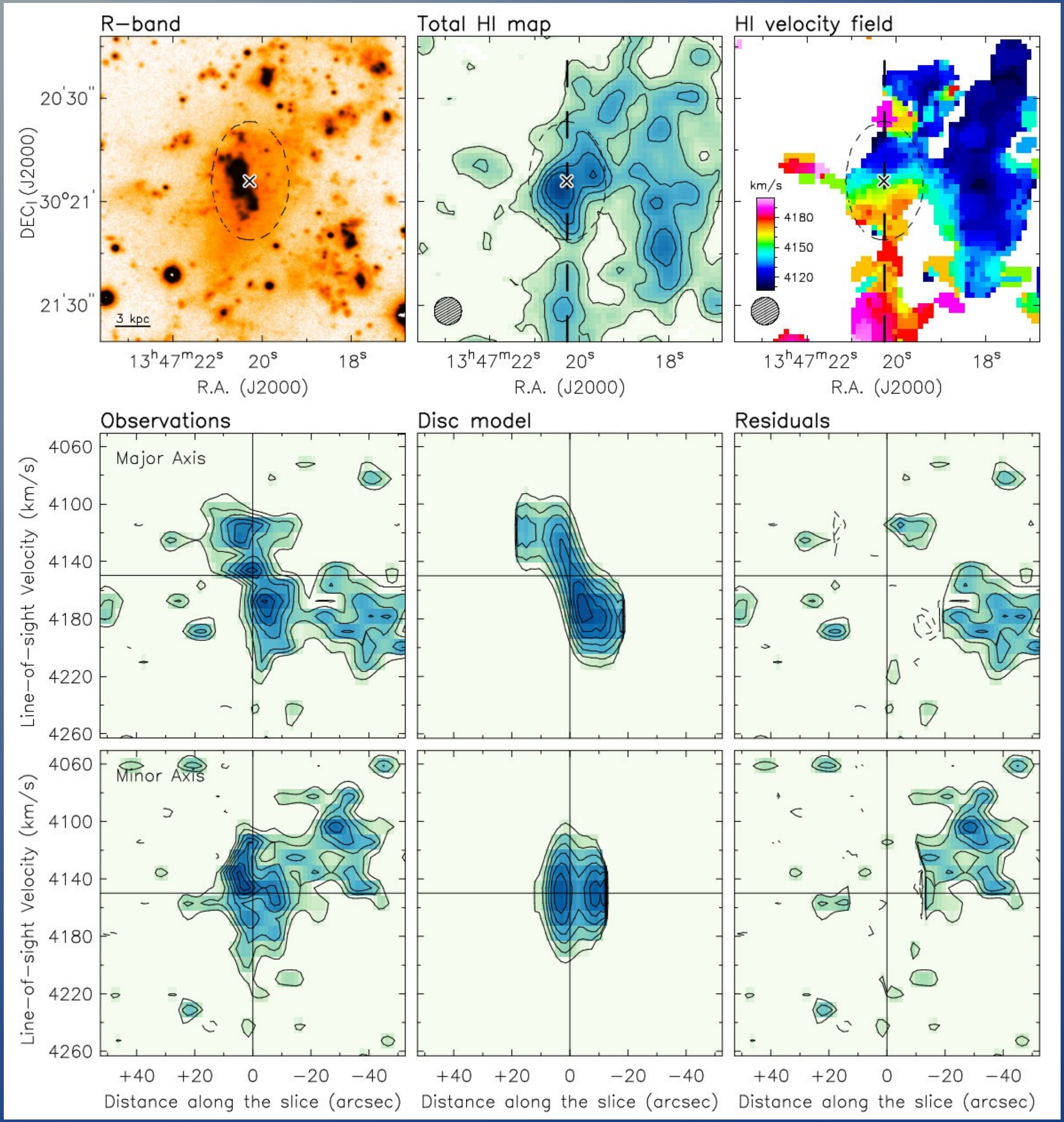


V_{rot} ~ 20 km/s

R_{HI} ~ 8 kpc

M_{gas}/M_{*} ~ 8!!

Rotating disk models for TDGs



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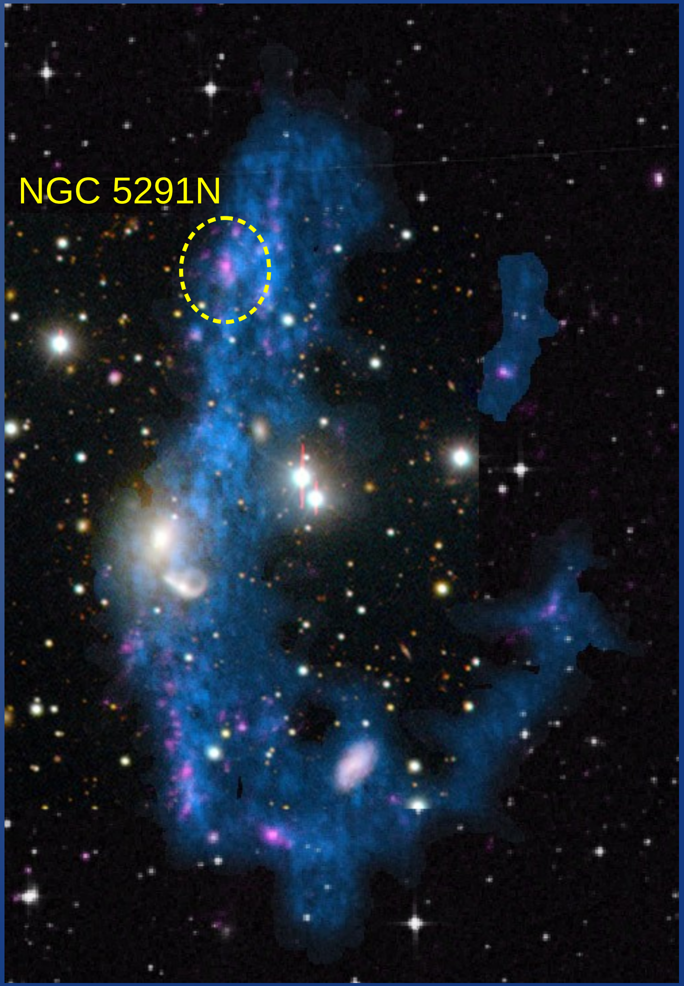

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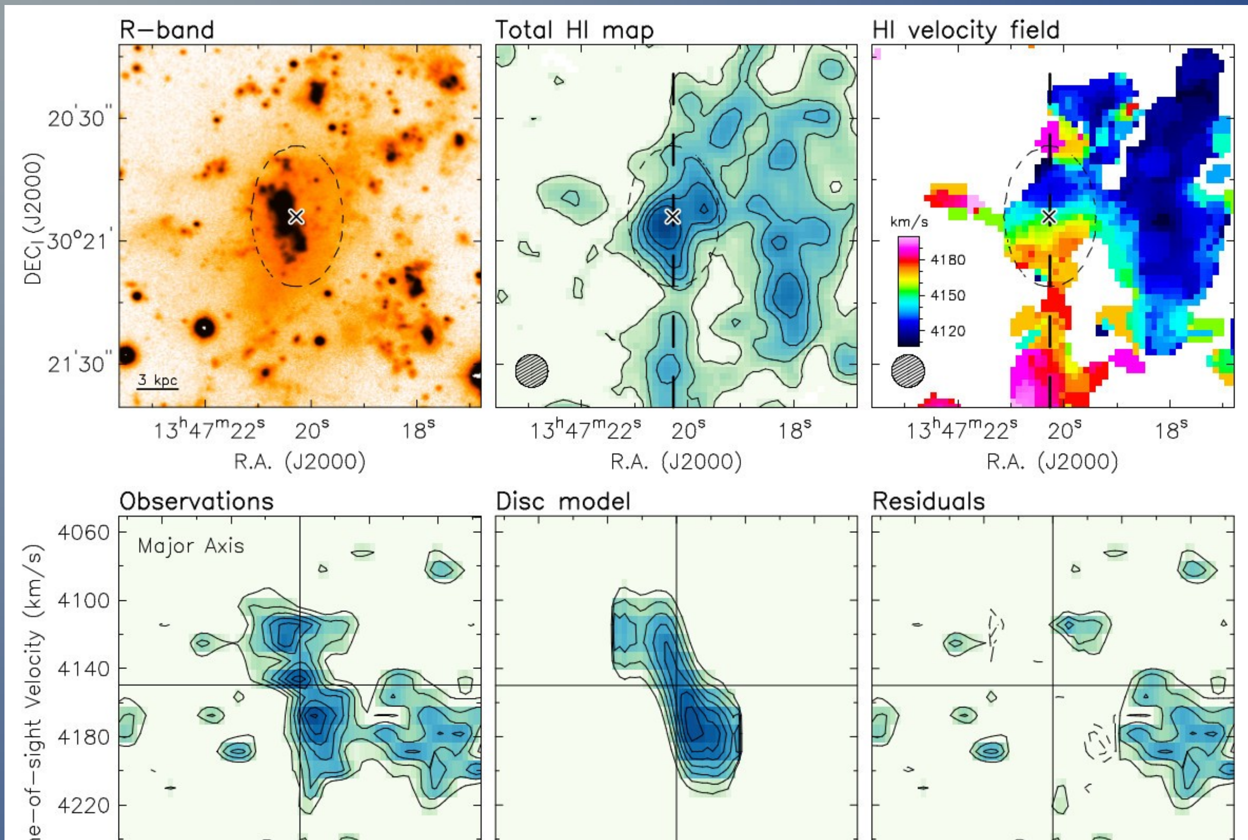


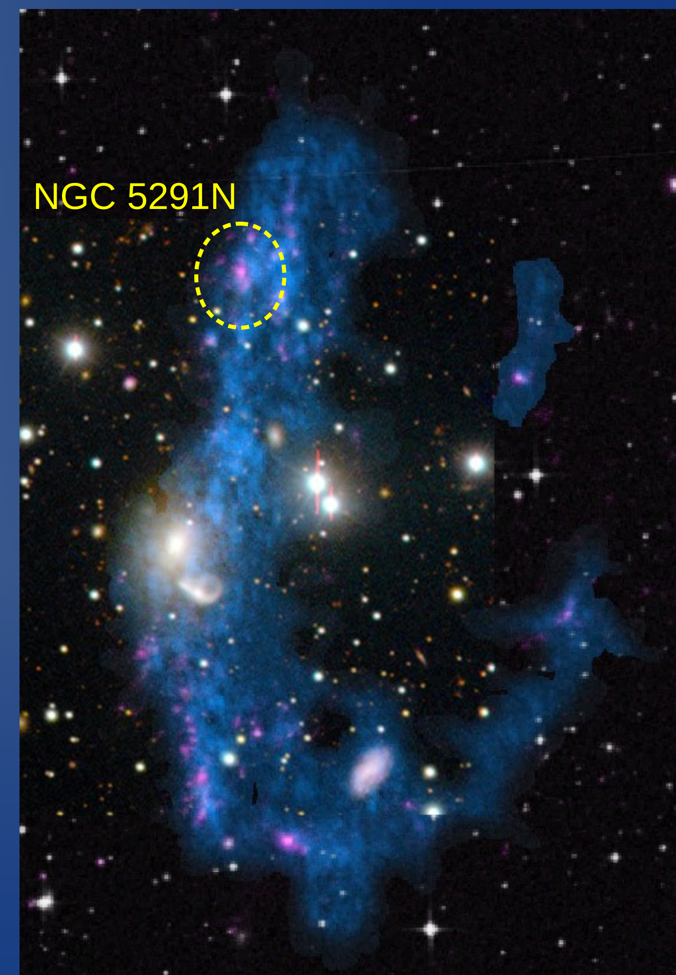
Puzzling Issue: $t_{orb} > t_{merg}$ (or TDG "age")

The disk didn't have time to make one orbit!

Are TDGs in dynamical equilibrium?

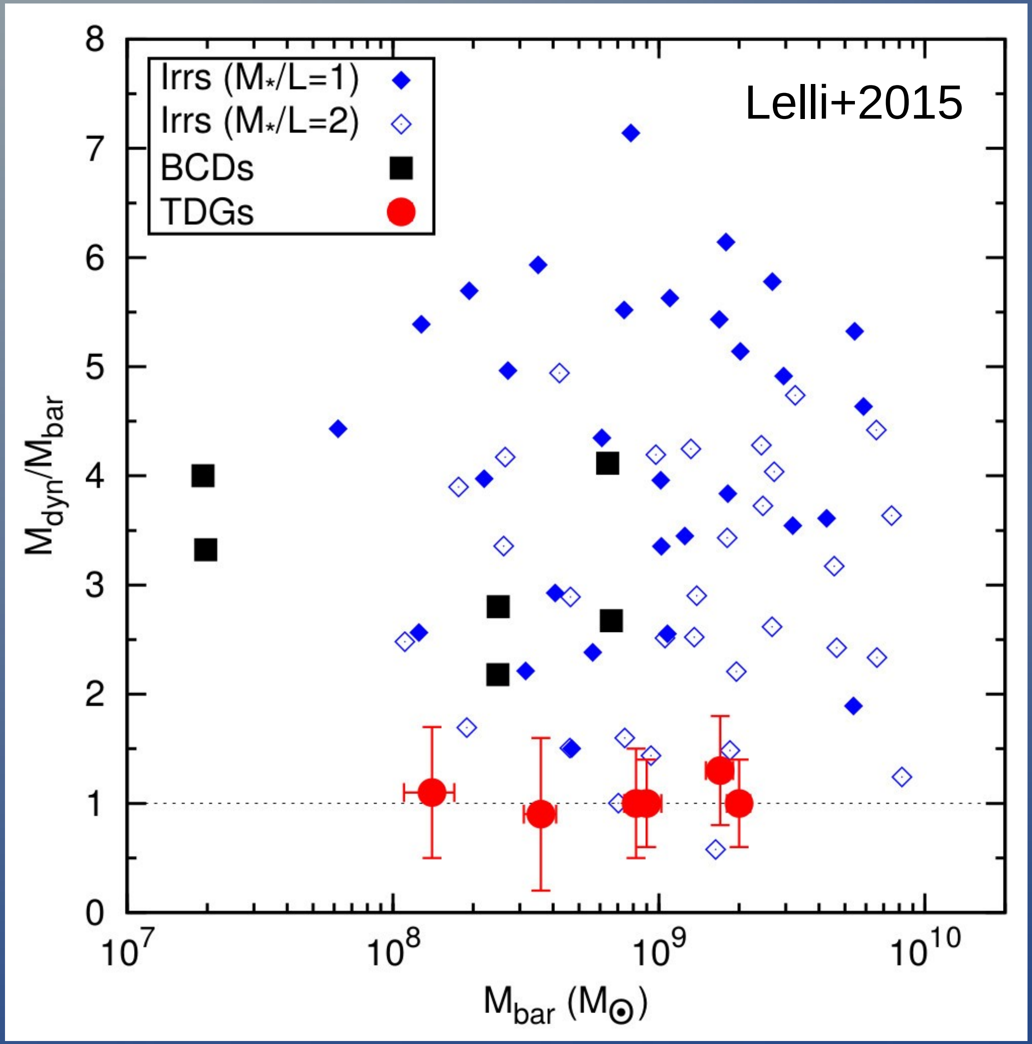
Lelli et al. (2015), A&A:

- High-Res. VLA data
- 3D kinematical model



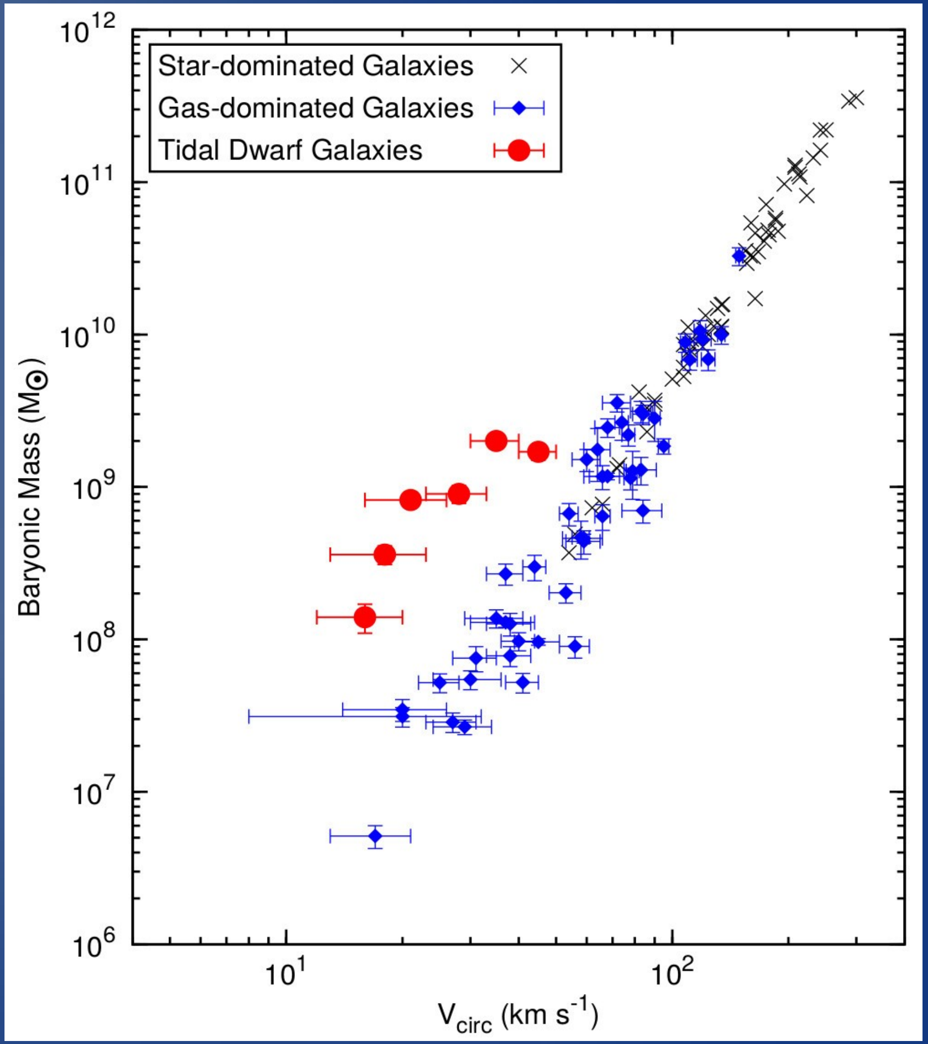
IF TDGs are in dynamical equilibrium...

No Dark Matter! (as expected from simulations)



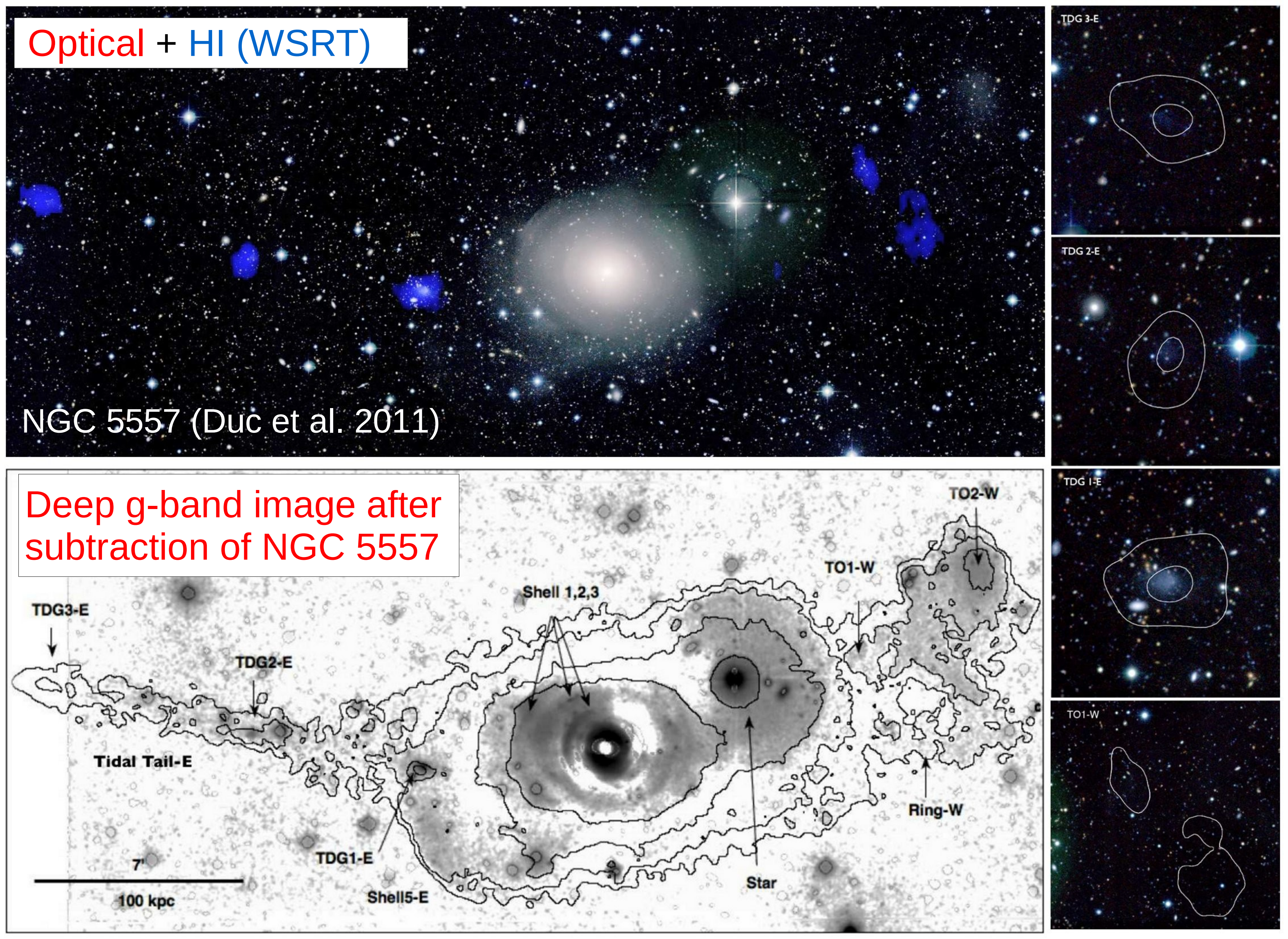
M_{dyn}/M_{bar} ~ 1! The high values reported by Bournaud et al. (2007) are *not* confirmed.

Deviation from the baryonic TF relation!

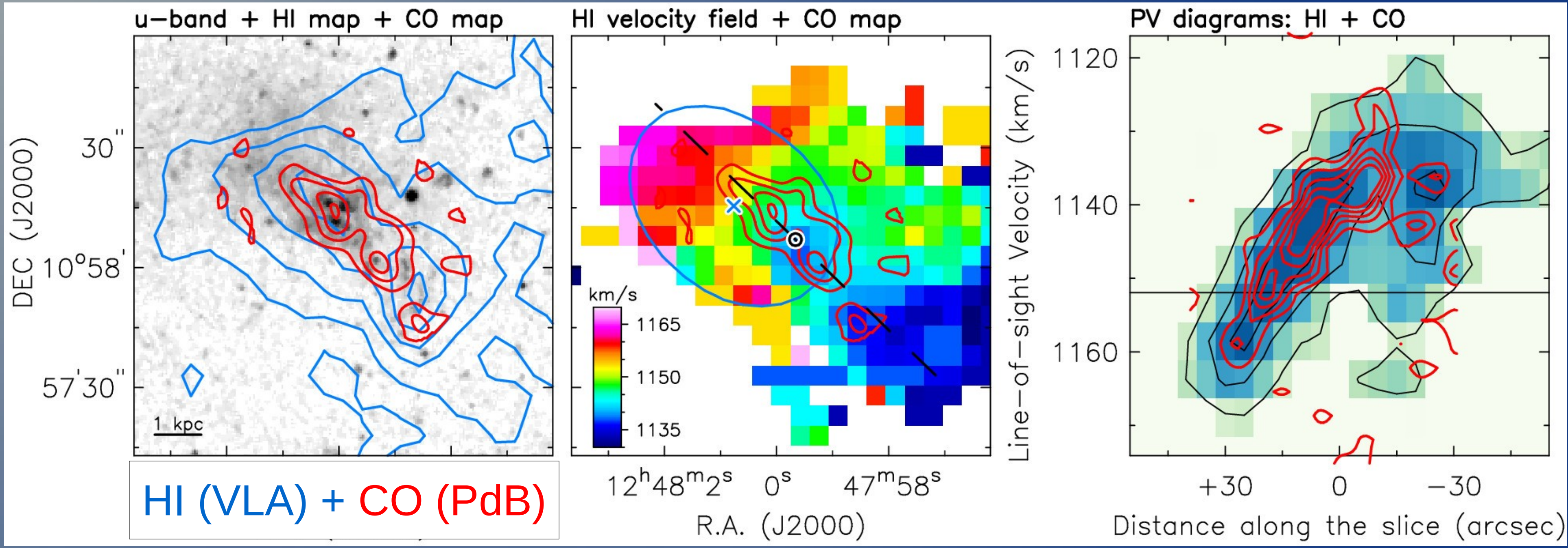


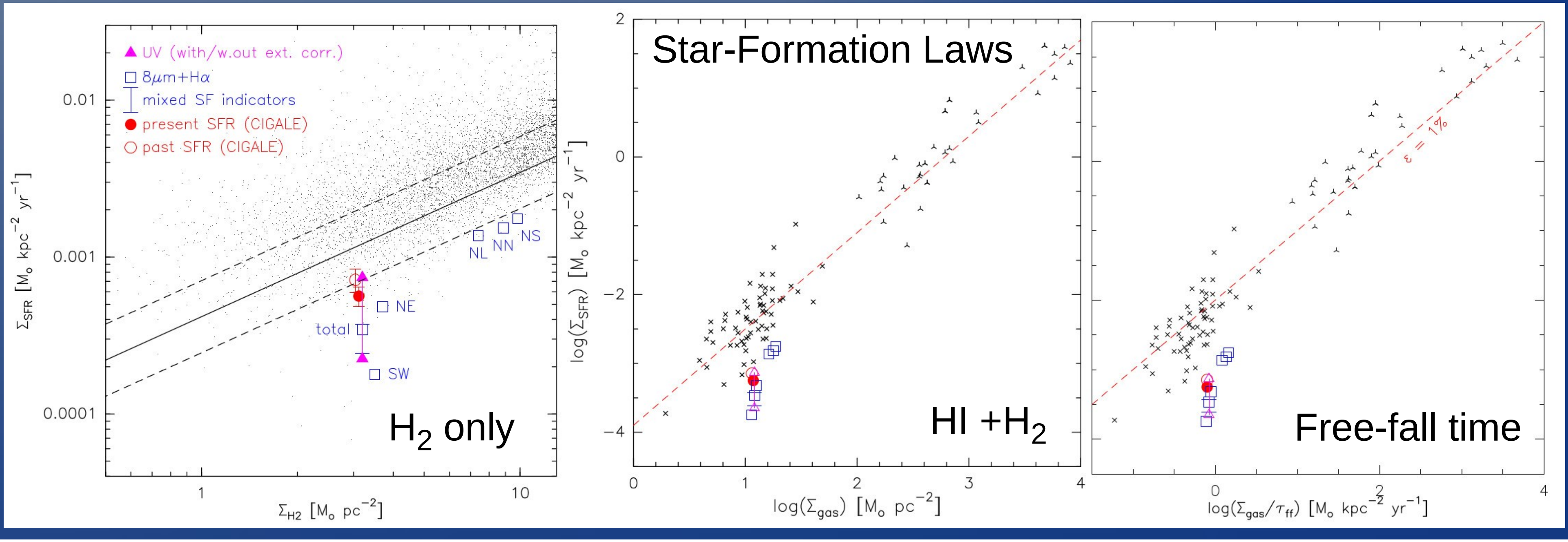
Caution: the shape of the rotation curve is uncertain. We may not be tracing V_{flat}

Old TDGs around Ellipticals



CO in VCC 2062 (Lisenfeld et al. submitted)





Summary on Tidal Dwarf Galaxies

- Condensations of HI, molecules, and young stars:

  Masses, sizes, and SFRs similar to dwarf galaxies

- TDGs are associated with rotating HI disks:

  But they have undergone less than one revolution!

- IF TDGs are in dynamical equilibrium...

  No DM (as expected) and deviation from the BTF relation

- Future prospects to investigate the DM content:

  New HI data for ~10 TDG candidates (JVLA, GMRT)

  New CO(1-0) data from ALMA at high resolutions (~1")

More Slides

Starbursts in a cosmological context

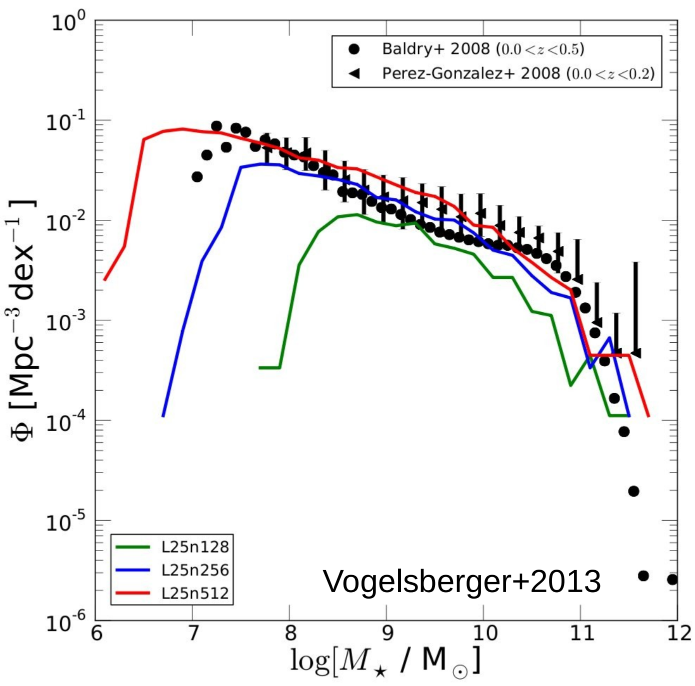
Stellar feedback is invoked to solve several problems in LCDM:

- number density of low-mass galaxies (e.g. Kauffmann+1993, Vogelsberger+2013)

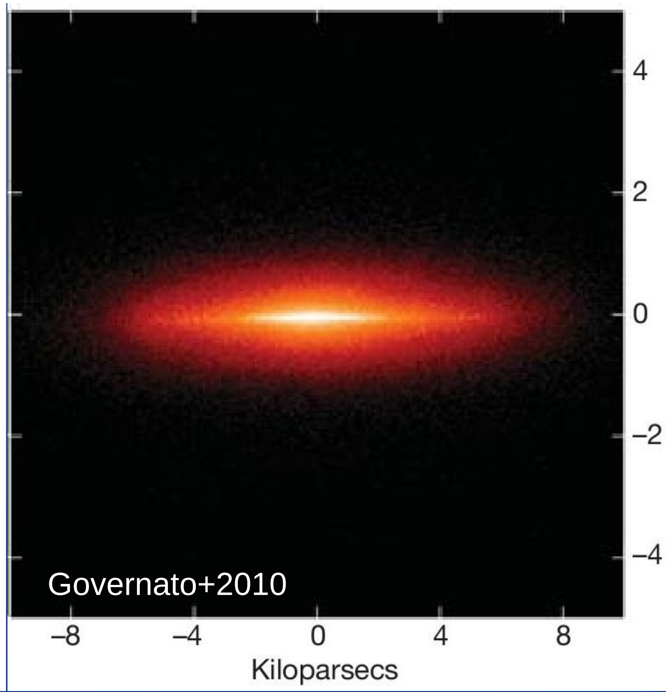
- existence of bulgeless galaxies (e.g. Governato+2010, Brook+2011)

- cusp-core problem (e.g. Navarro+1996, Oh+2011, Governato+2012)

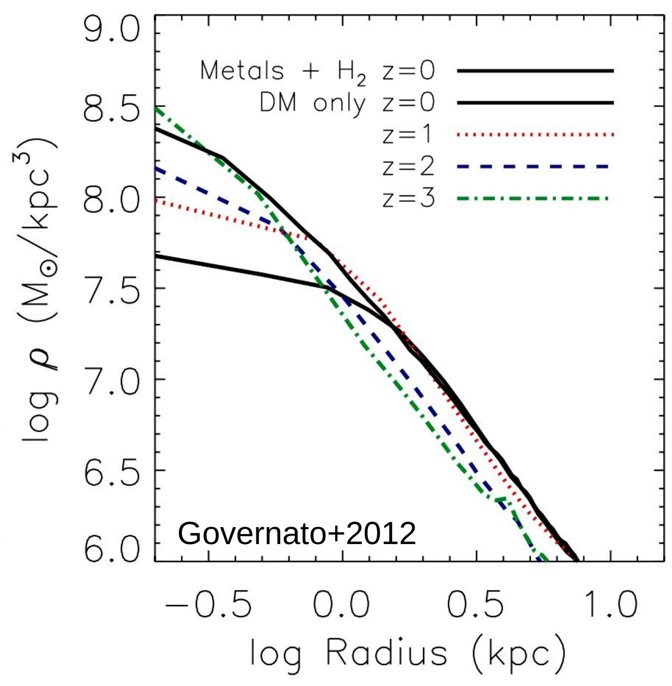
Galaxy Stellar-Mass Function



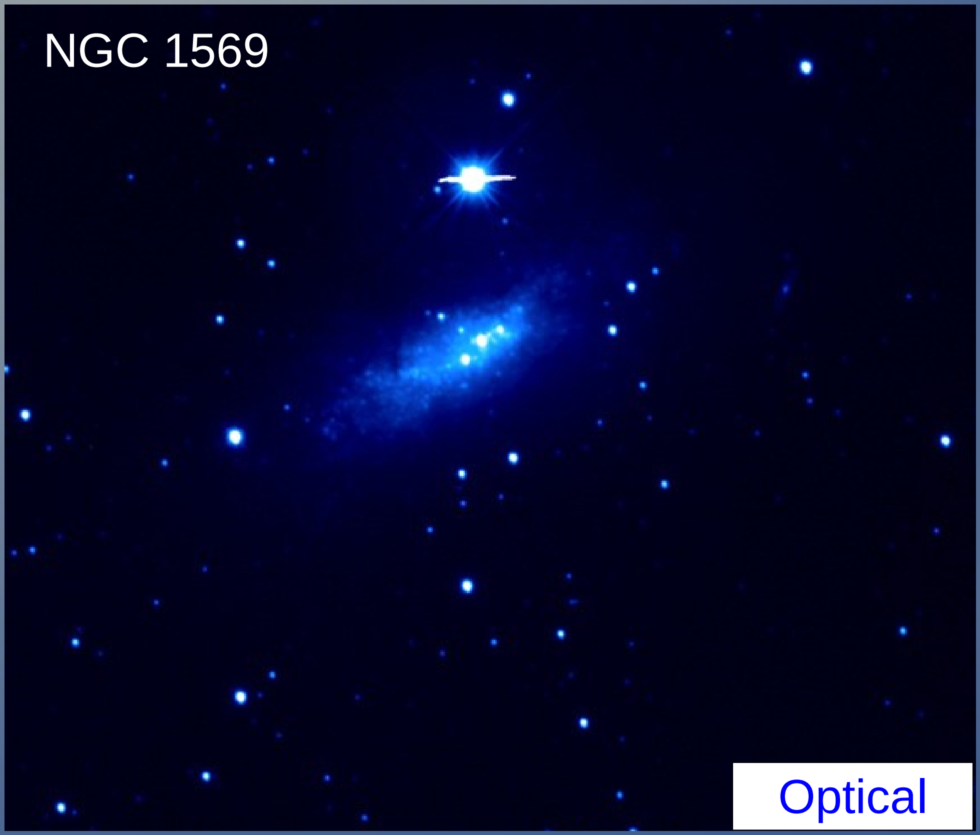
Simulated Dwarf Galaxy

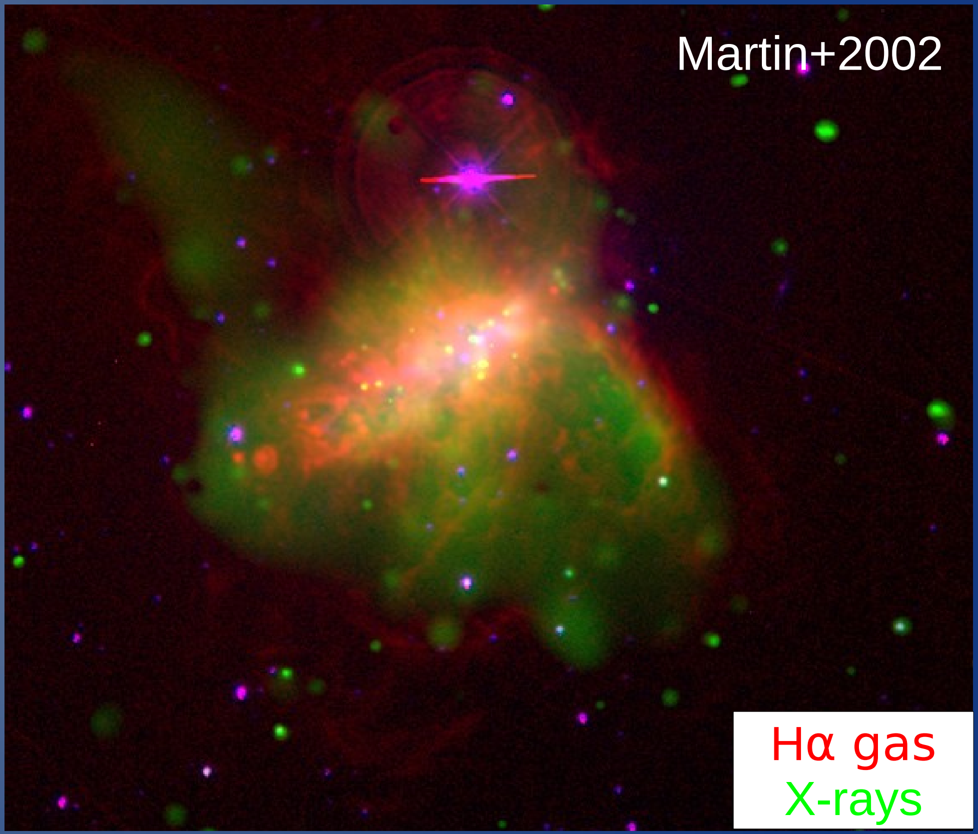


DM density profile



Stellar Feedback in Starburst Dwarfs





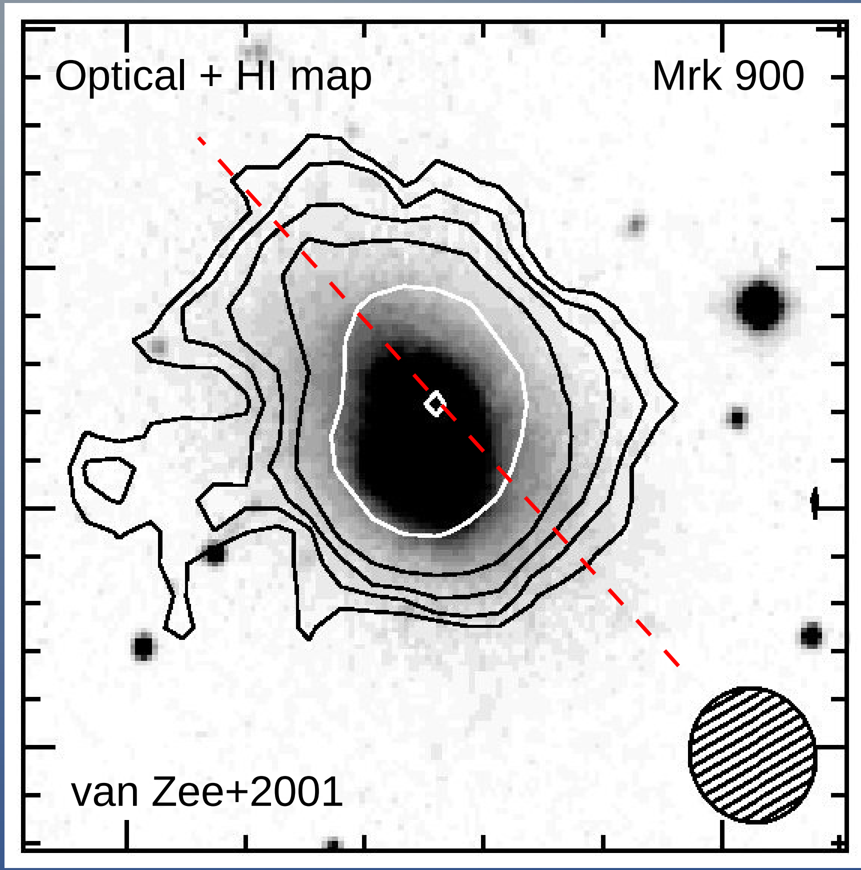
- Velocity of the ionized gas does *not* exceed V_{esc}

(e.g. Martin 1996, 1998; Schwartz & Martin 2004; van Eymeren+2009, 2010)

- Mass of the hot gas ~1% M_{HI} (e.g. Ott+2005)

HI properties of Starburst Dwarfs

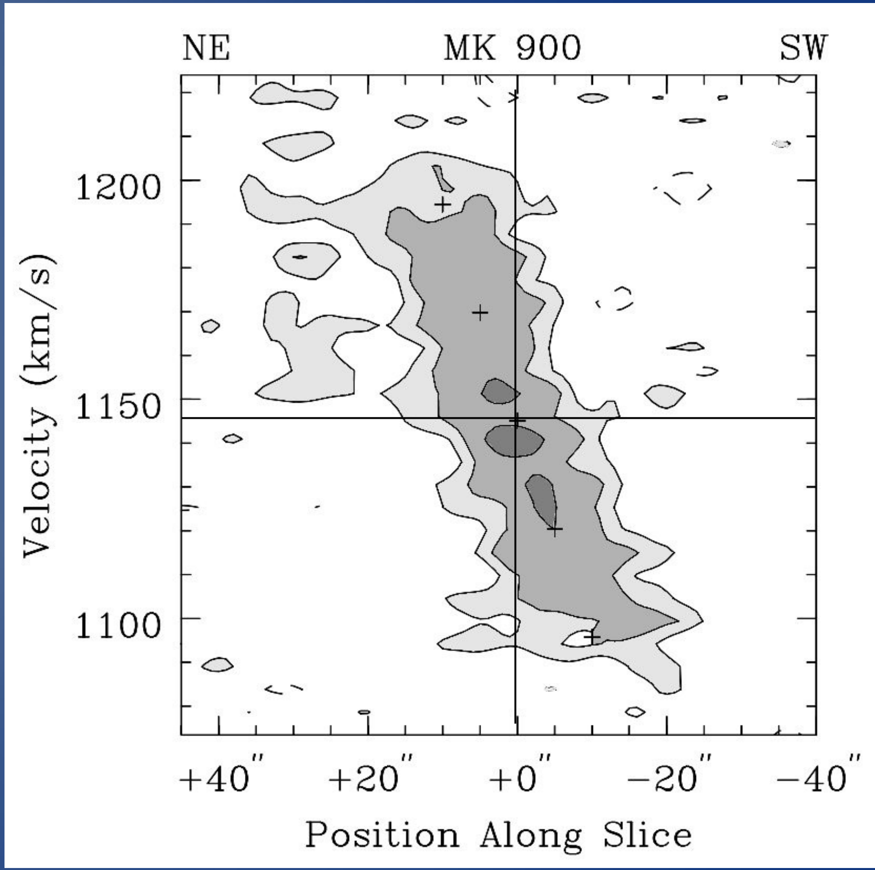
Strong HI Concentration



Central HI densities 2-3 higher than Irrs

(e.g. Taylor+1994; van Zee+1998; vanZee+2001; Simpson & Gottesman 2000; Most+2013)

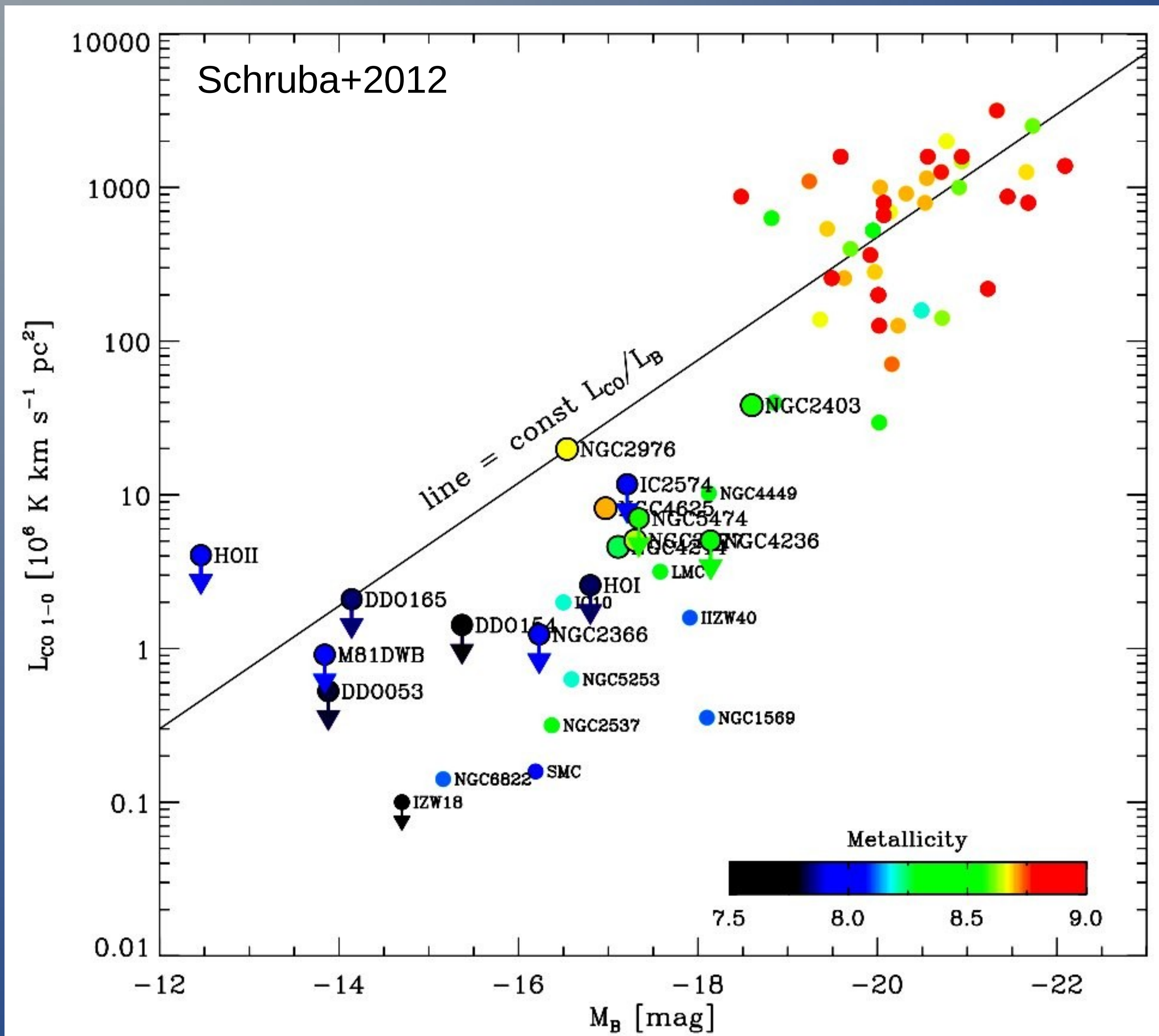
Steep Velocity Gradients



Fast rotation? Inflows/outflows?

(e.g. Meurer+1996; Meurer+1998; van Zee+1998; van Zee+2001; Thuan+2004)

Molecular mass is unknown...



Dwarfs are metal-poor

CO lines undetected

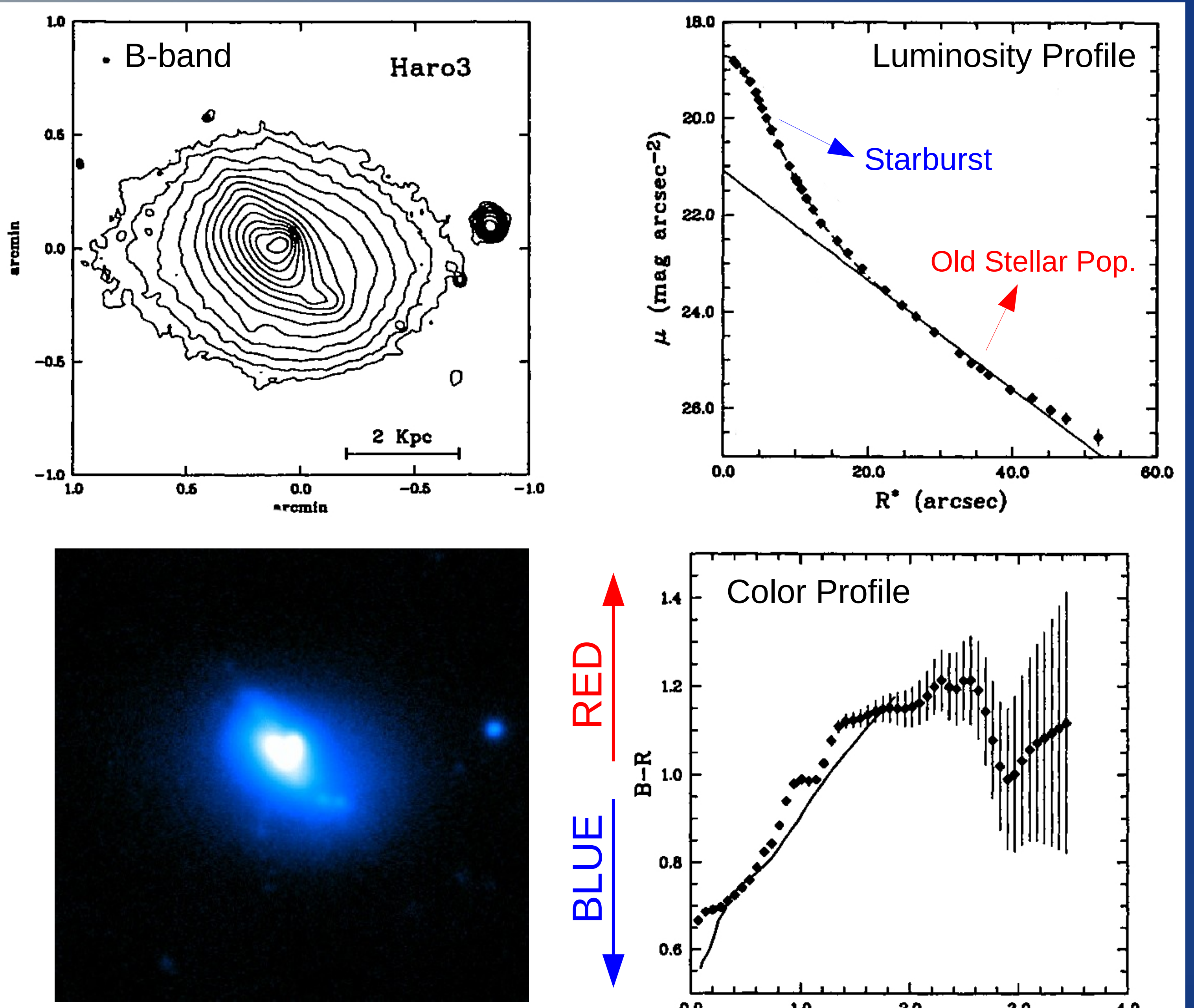
CO-to-H_2 conversion may depend on Z!

Indirect estimate:

$M_{mol}(M_\odot) \sim 2 \times 10^9$ SFR $(M_\odot/yr)$

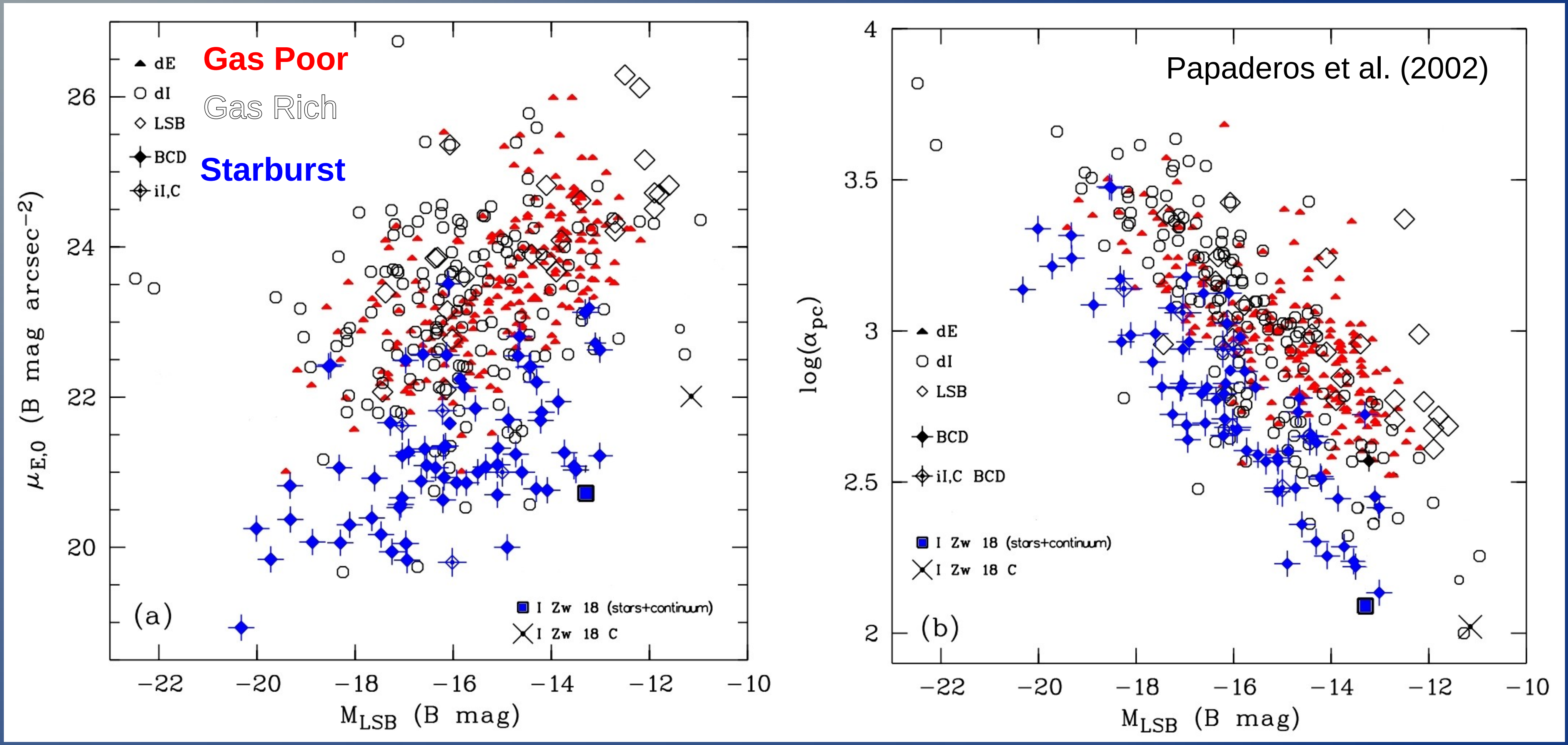
(e.g. Leroy+2008)

Optical Structure of BCDs



Papaderos et al. (1996)

Optical Structure of BCDs



Old component of BCDs: $\mu_0 \sim 21.5$ mag asec^{-2} (Freeman value)

Papaderos et al. (1996, 2002); Salzer & Norton (1999); Cairos et al. (2001);

Gil de Paz & Madore (2005); Amorin et al. (2009).