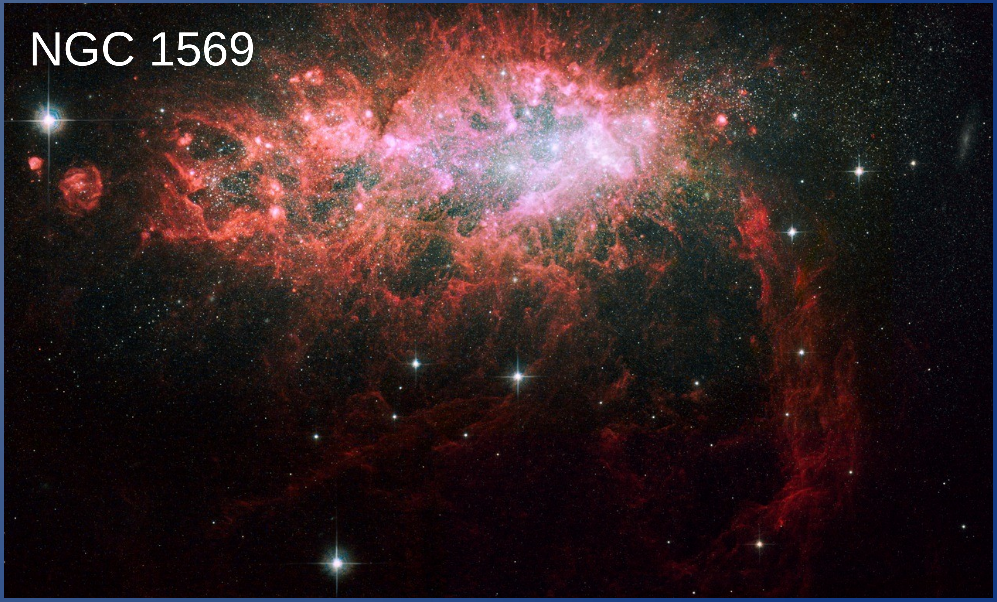
Gas Dynamics and Star Formation in Low-Mass Galaxies



Federico Lelli (ESO Fellow - Garching)

Strasbourg Observatorie, 12 May 2017

Outline

- Overview on Dwarf Galaxies

  Structure, dynamics, and evolution

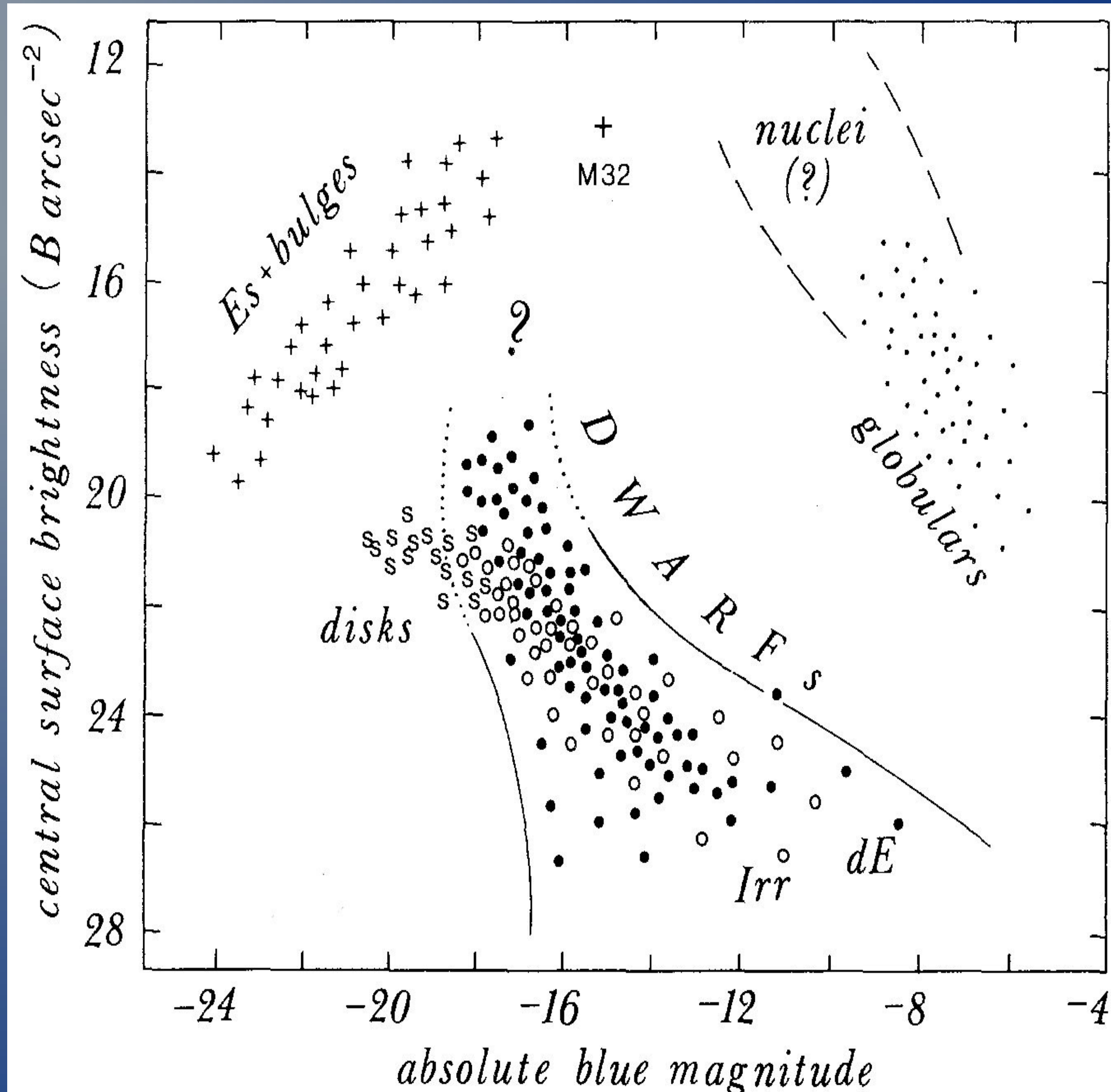
- Starburst Dwarf Galaxies

  Understanding stellar feedback and galaxy evolution

- Tidal Dwarf Galaxies

  A new channel to form low-mass galaxies at z=0?

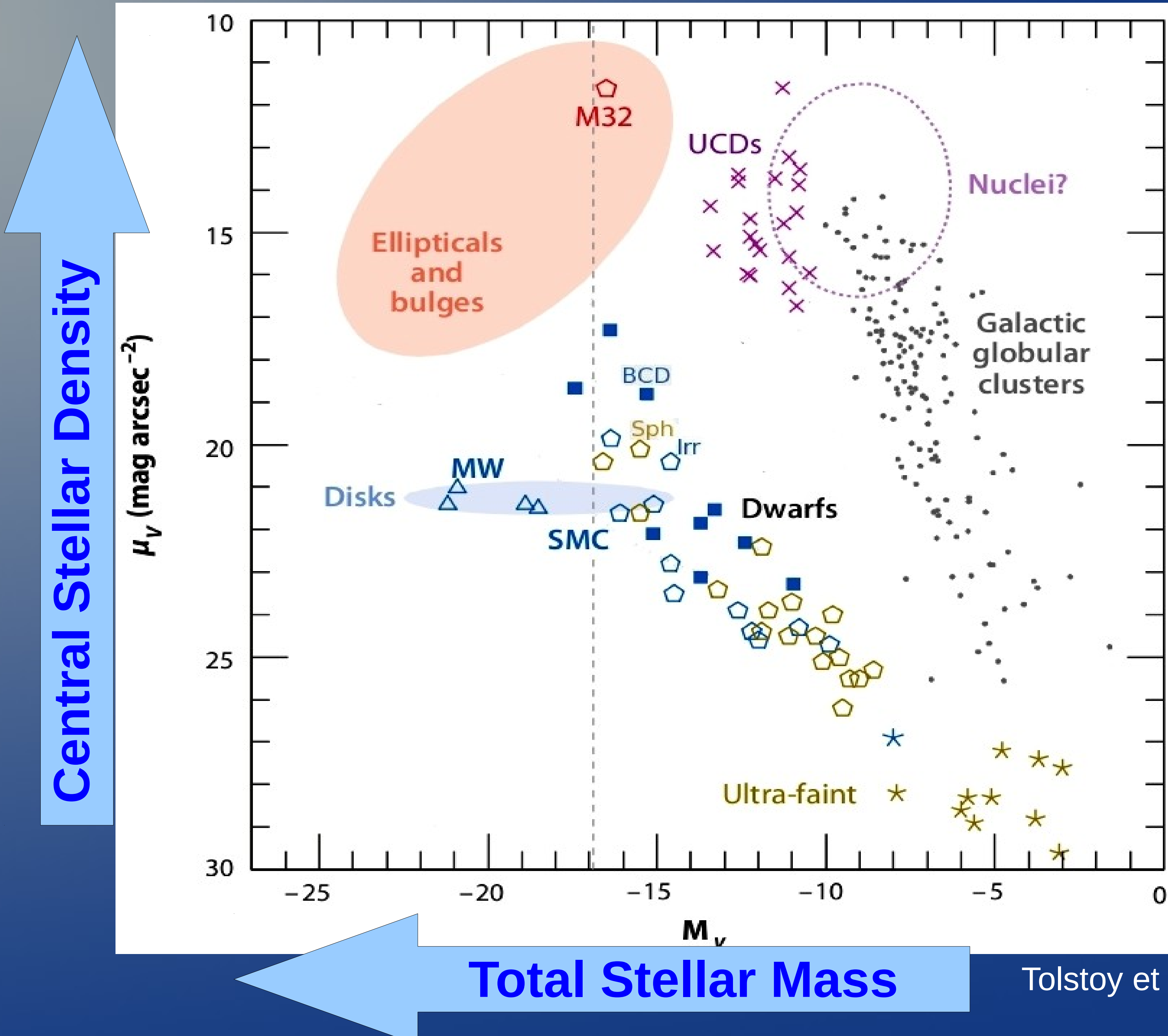
Overview on Dwarf Galaxies



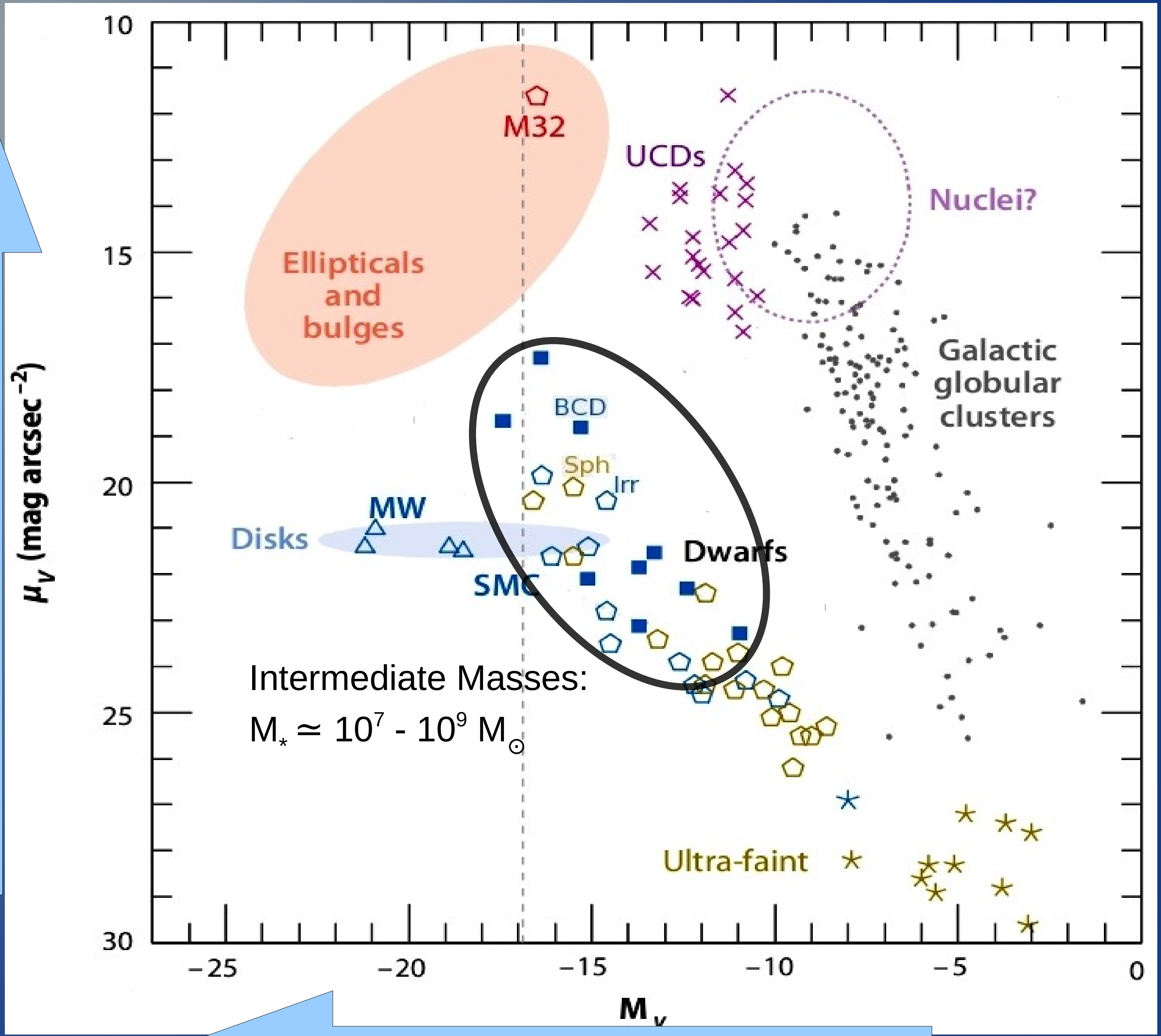
Central Stellar Density

Total Stellar Mass

Binggeli (1994)



Tolstoy et al. (2009)



Intermediate Masses:

$M_* \simeq 10^7$ - $10^9\ M_\odot$

Central Stellar Density

Total Stellar Mass

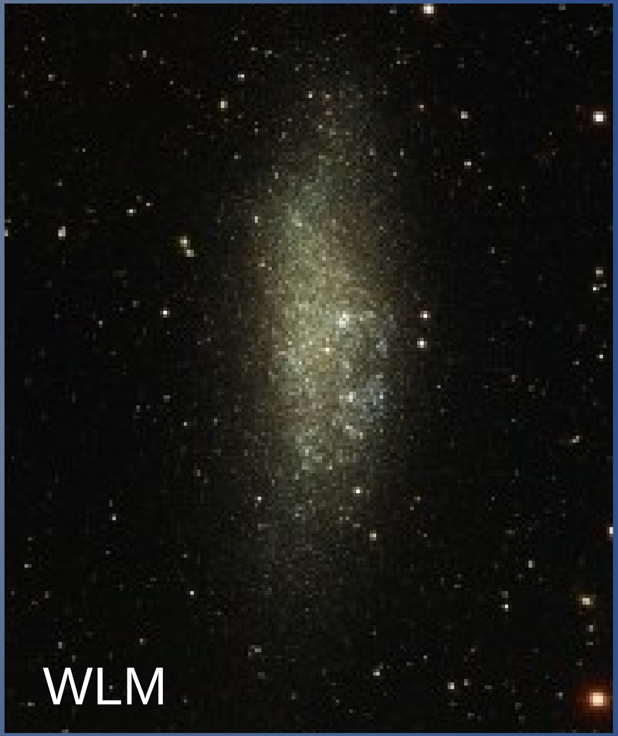
Tolstoy et al. (2009)

Spheroidals | Irregulars | Starburst dwarfs

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

Other names:

dE, Early-Type Dwarfs



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

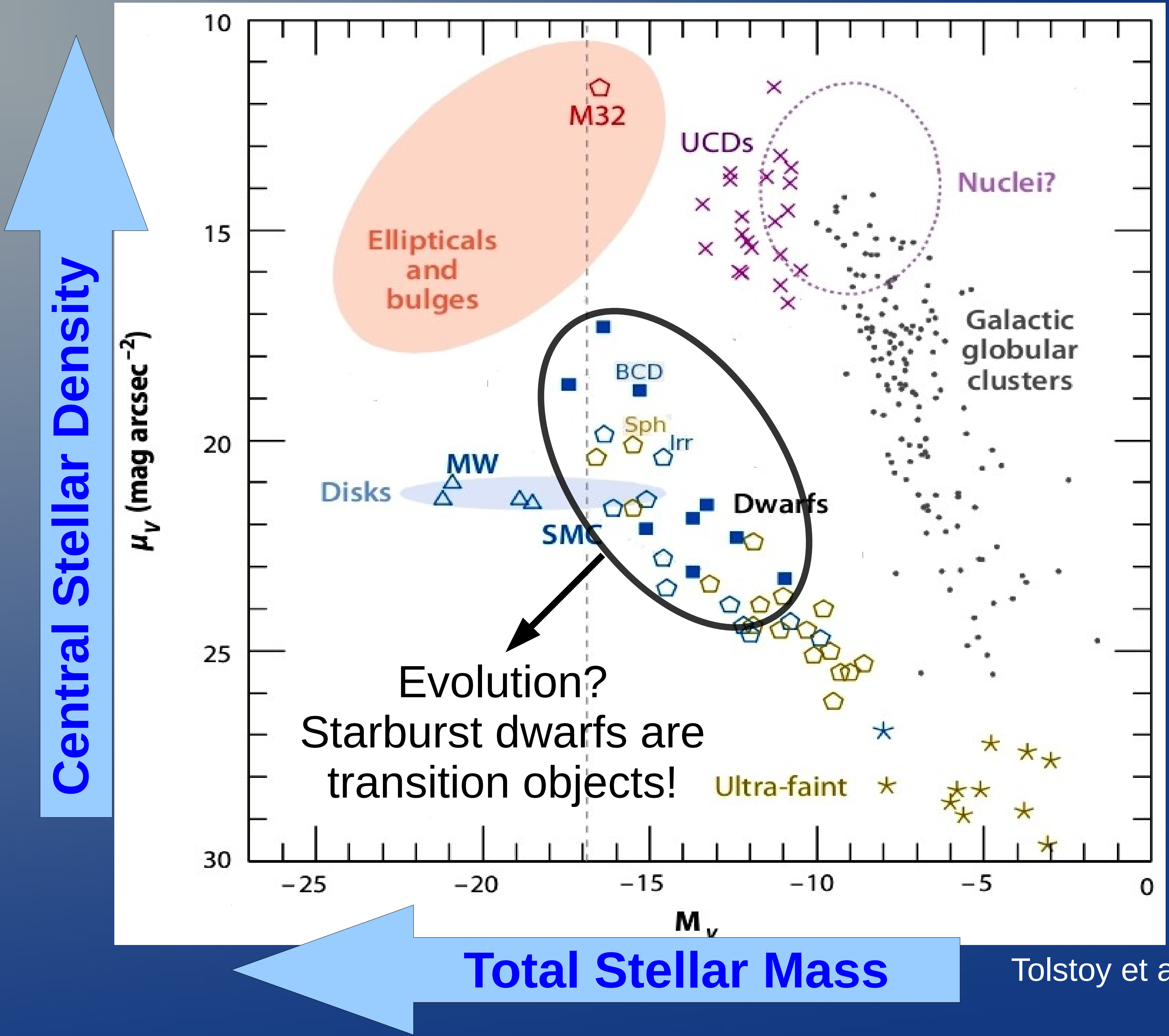
Other names:

Im, Sm, Late-Type 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 dwarf

Gas-poor dwarf

Internal Processes

- Feedback & Outflows?
- SF and Starvation?

External Processes

- Ram-Pressure Stripping?
- Tidal Stripping / Harassment?

Evolution of Dwarf Galaxies

Gas-rich dwarf

Gas-poor dwarf

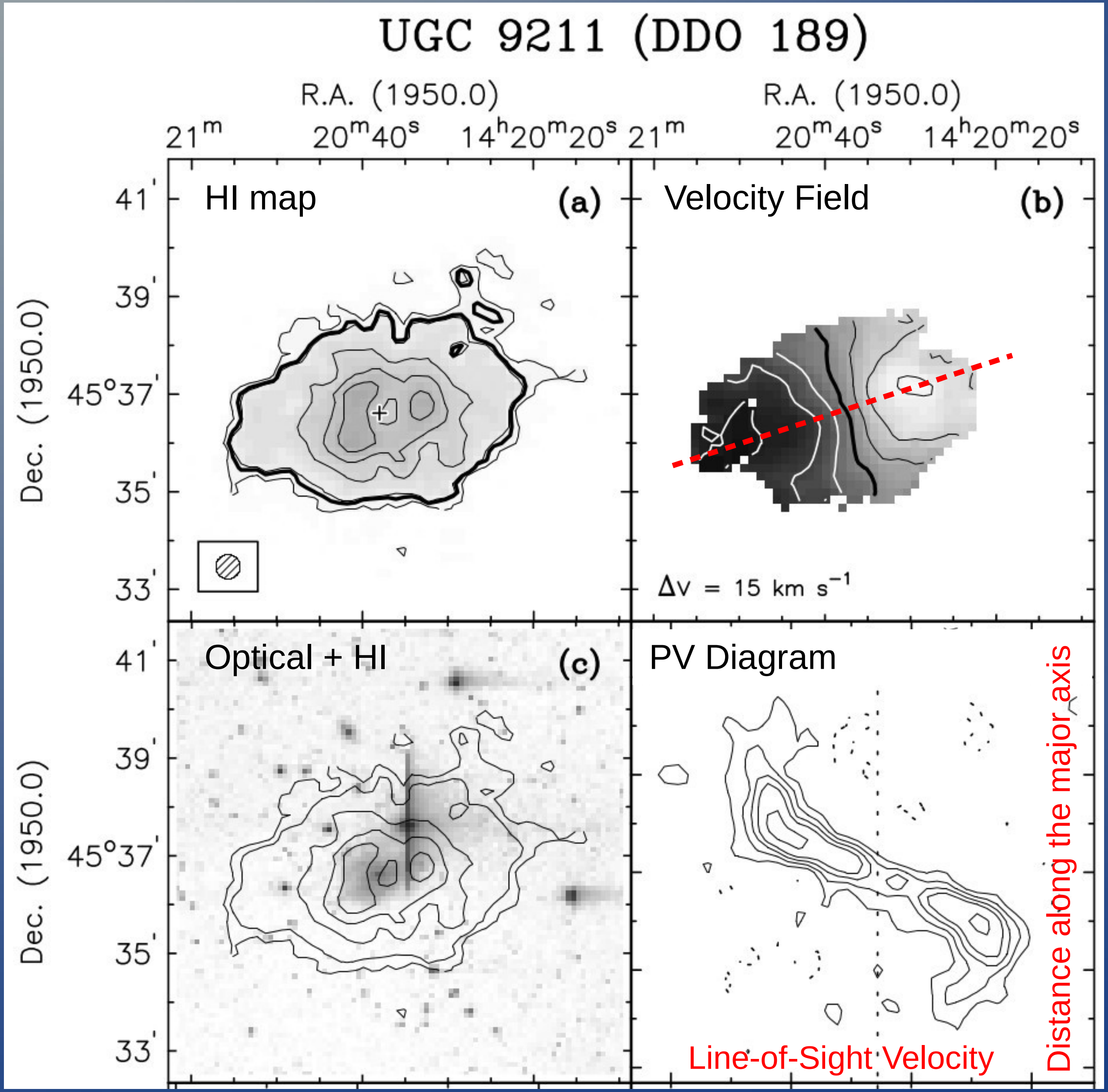
Internal Processes

NOT AN OPTION!!!

External Processes

- Gas Accretion from the IGM?
- Merger with gas-rich dwarf?

Dwarf Irregulars are very regular in HI!



Swaters+(1999, 2002)

73 late-type dwarfs from WHISP survey:

- 90% have regularly rotating HI disks
- 10% are mergers or poorly resolved disks

Starburst Dwarfs

In collaboration with:

Marc Verheijen, Filippo Fraternali, Renzo Sancisi,

Kristen McQuinn, Evan Skillman, Anna McLoed, Giacomo Beccari

Why do we care about starbursts?

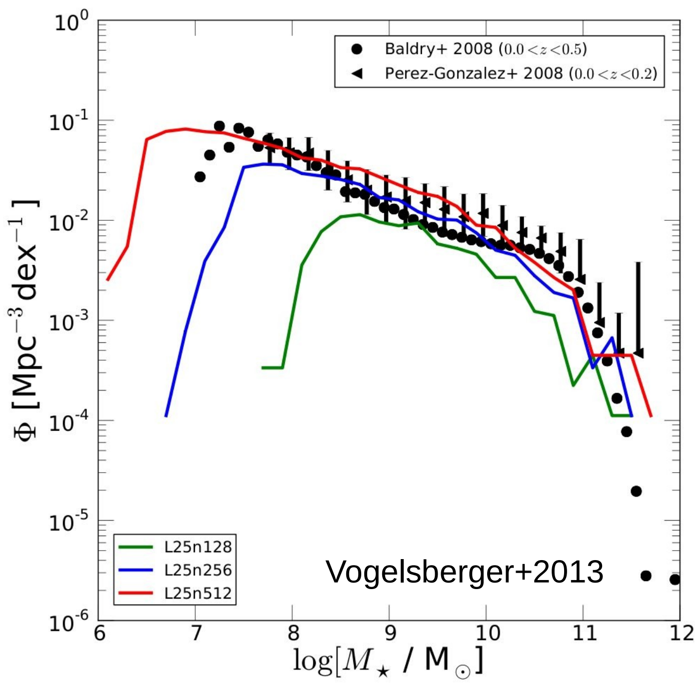
Stellar feedback is needed to solve several problems in LCDM:

- galaxy stellar mass function (e.g. Kauffmann+1993, Vogelsberger+2013)

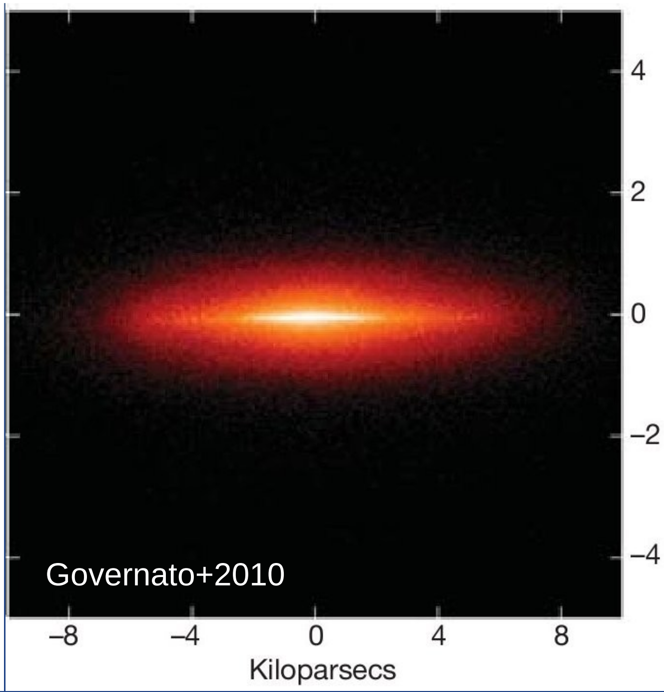
- bulgeless & superthin galaxies (e.g. Governato+2010, Brook+2011)

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

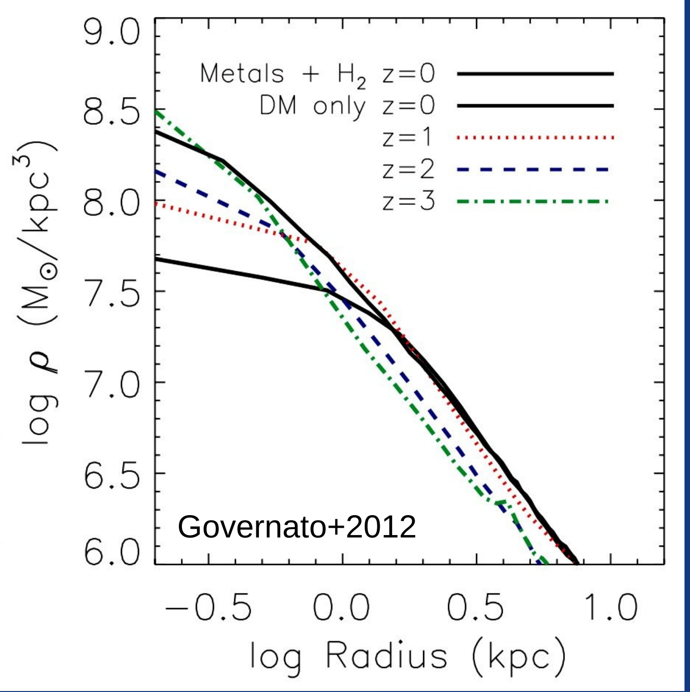
Galaxy Stellar-Mass Function



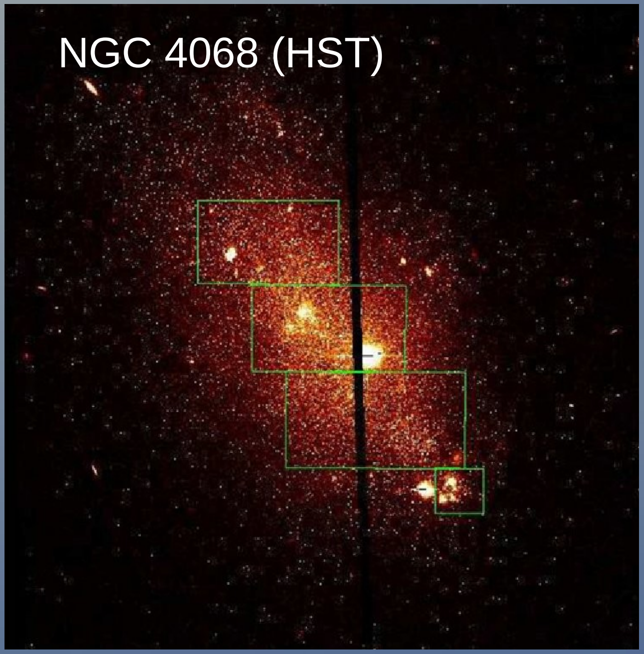
Simulated Dwarf Galaxy

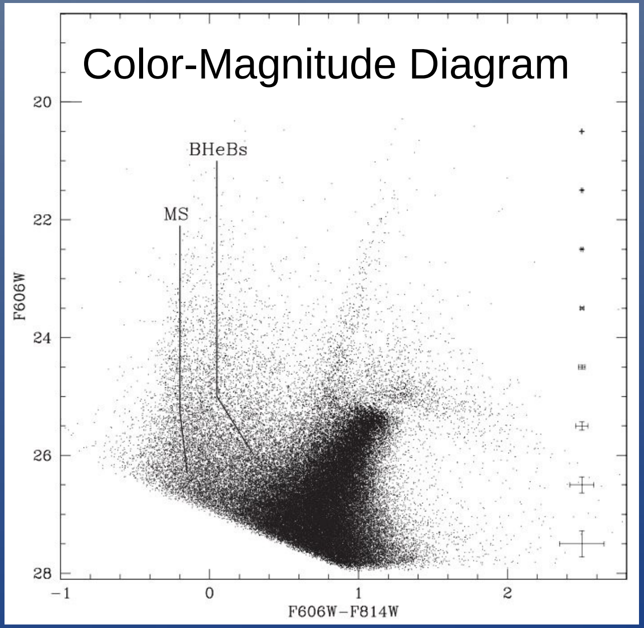


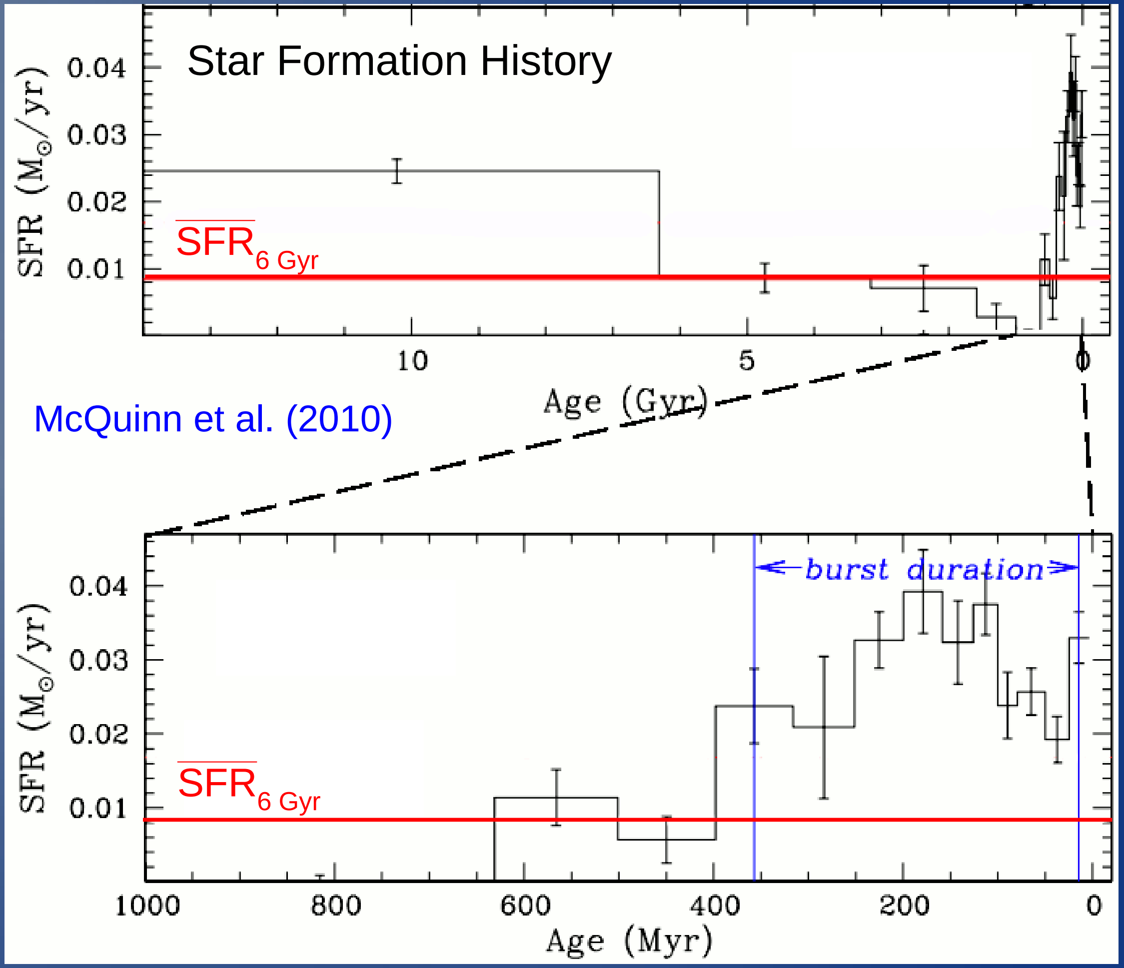
DM density profile



Stellar populations in Starburst Dwarfs

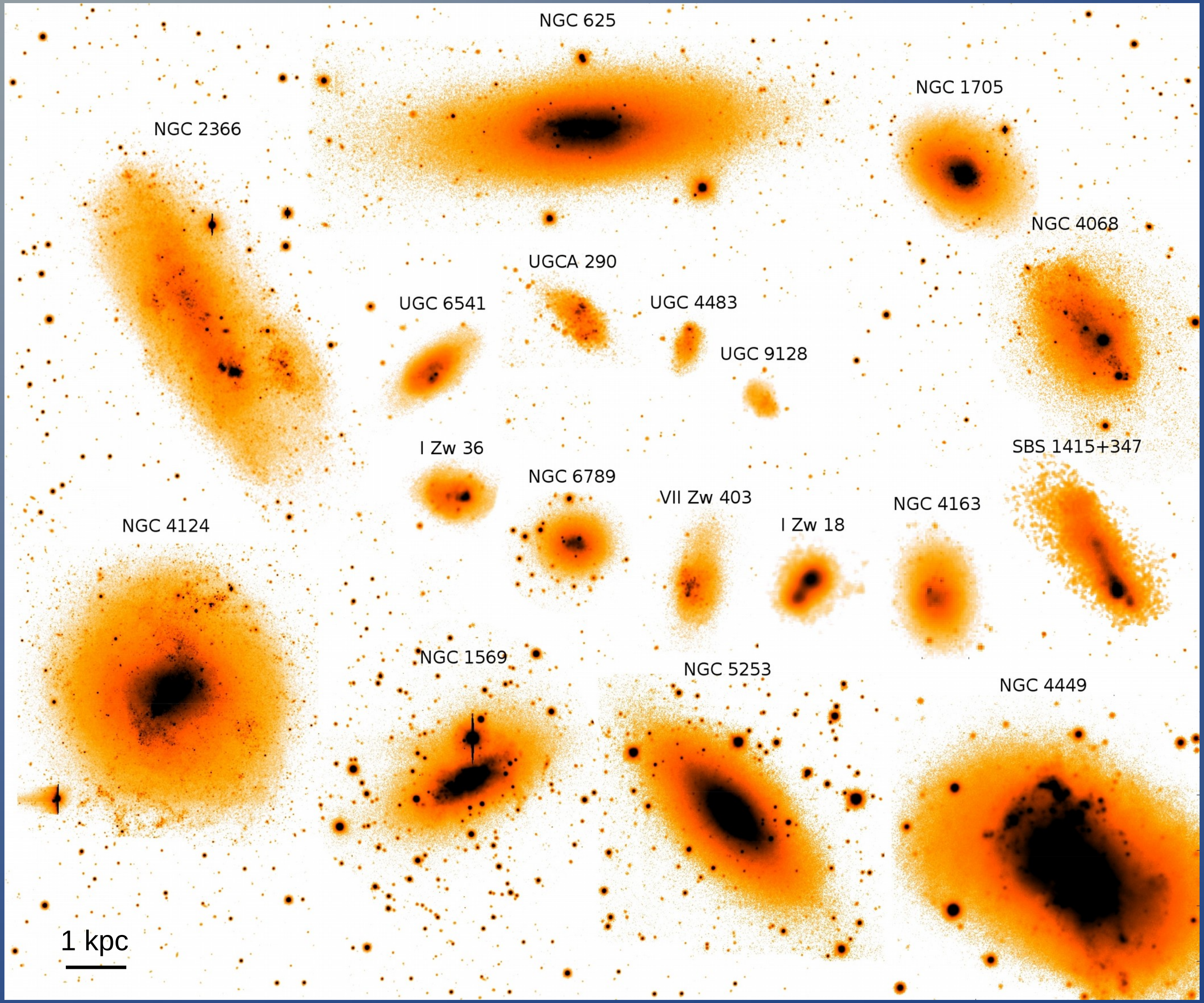






- Birthrate = $SFR(t_{peak}) / \overline{SFR} \geq 3$
- Starburst durations (few 100 Myr)
- Energies from SN & stellar winds

Sample of 18 Starburst Dwarfs



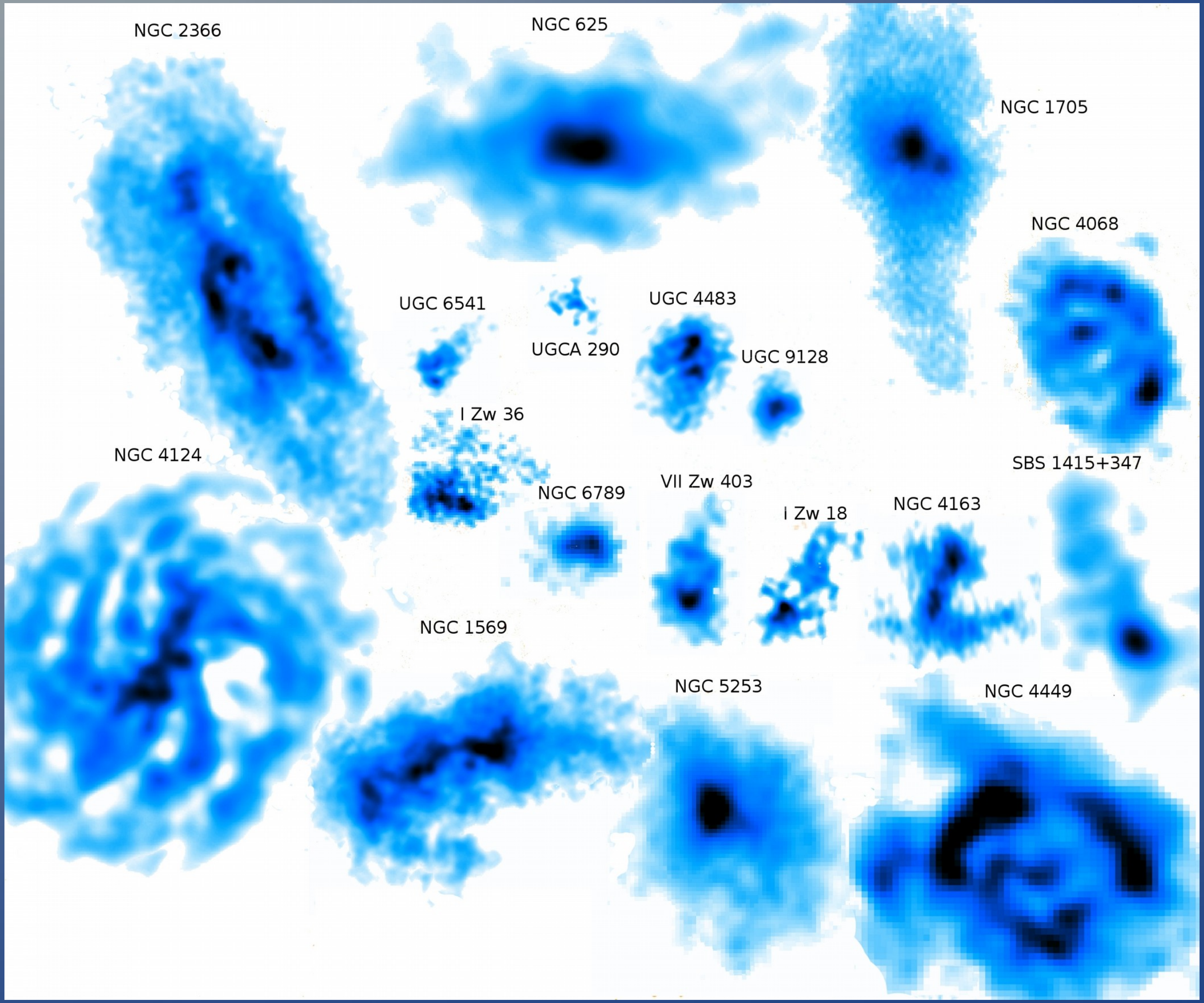
$M_* \sim 10^7 - 10^9\ M_\odot$ $R_{opt} \sim 0.5 - 5$ kpc

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)

Sample of 18 Starburst Dwarfs



Resolved into single stars by HST obs:

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

21-cm line obs (VLA, WSRT, ATCA):

- HI distribution
- HI kinematics

Lelli, Verheijen & Fraternali (2014)

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

Questions:

- What triggers the starburst?

  (External *vs* Internal mechanisms)

- What is the effect of stellar feedback?

  (Gas outflows? Shocks?)

- What are the progenitors/descendants?

  (Evolutionary links with Irrs and Sphs?)

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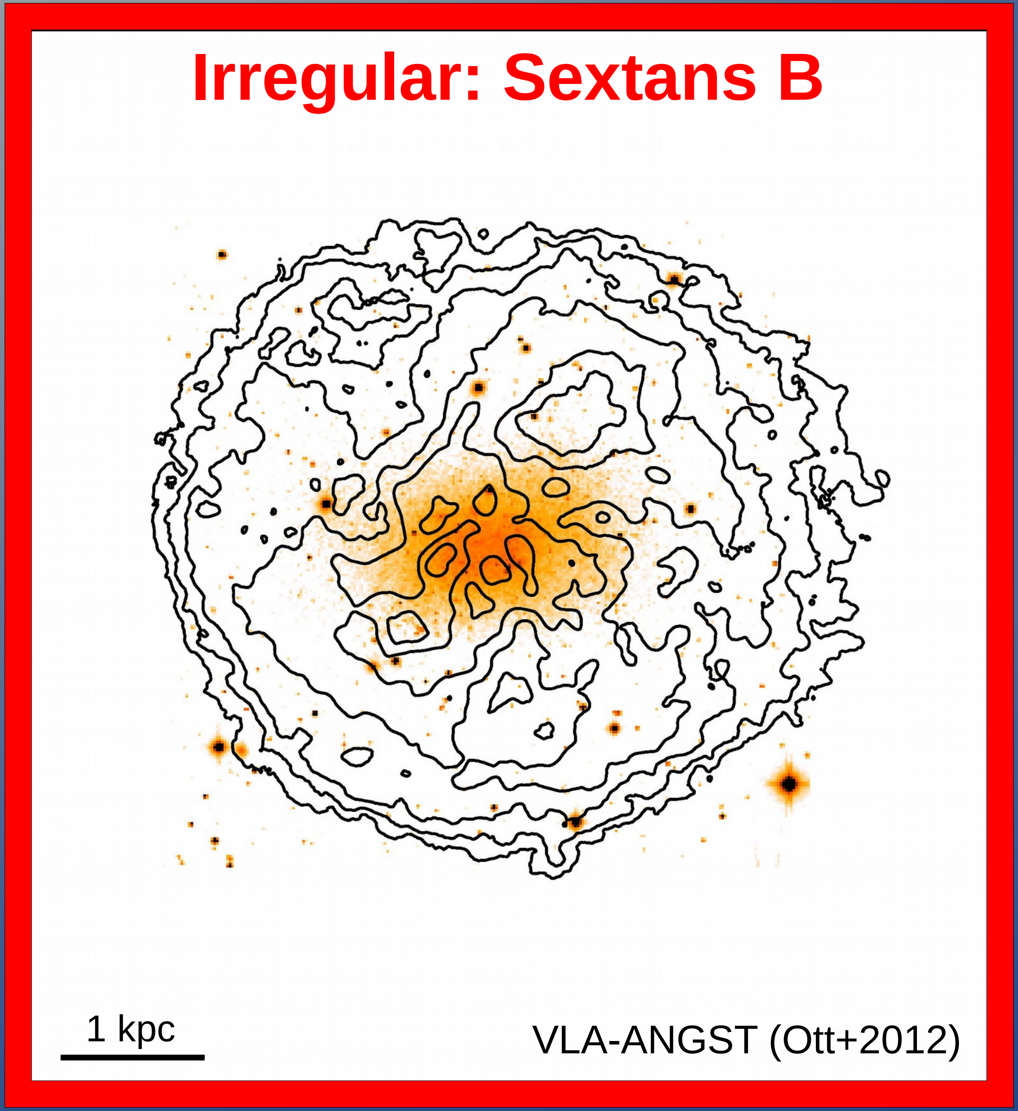
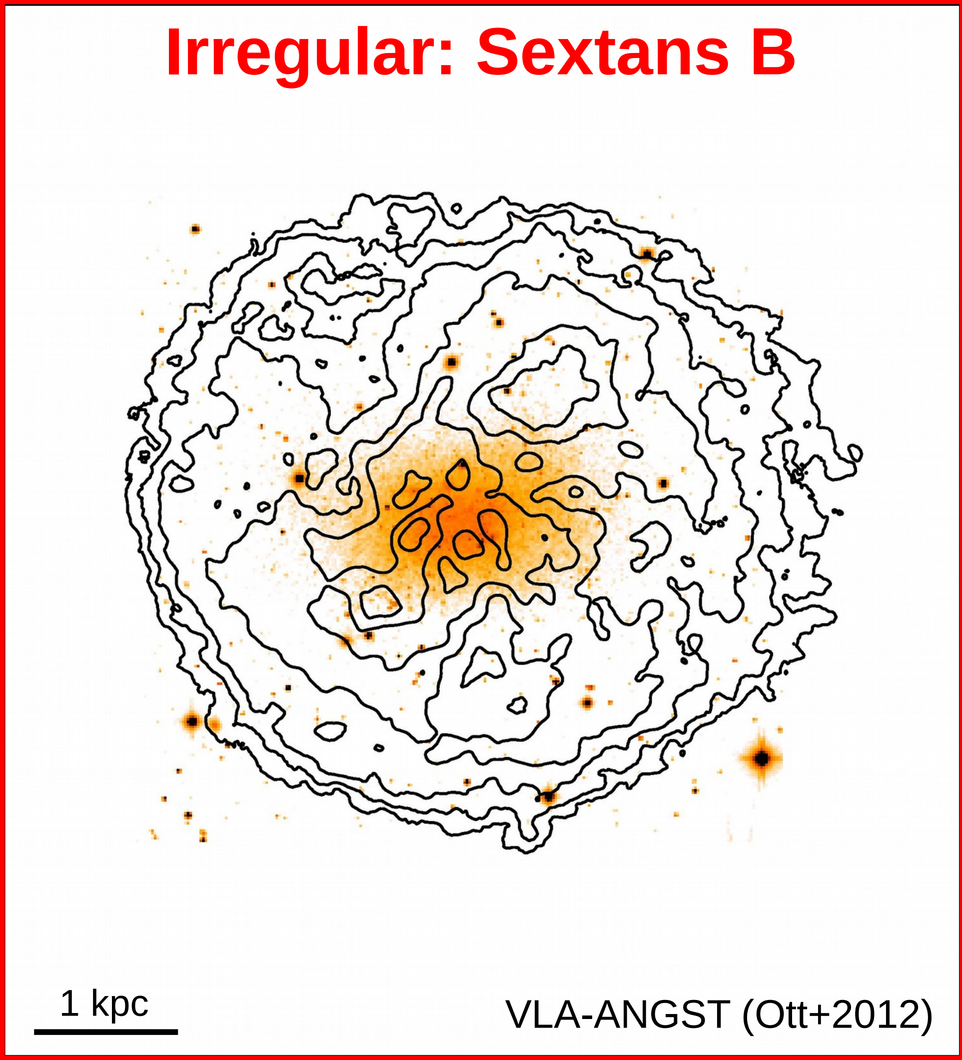
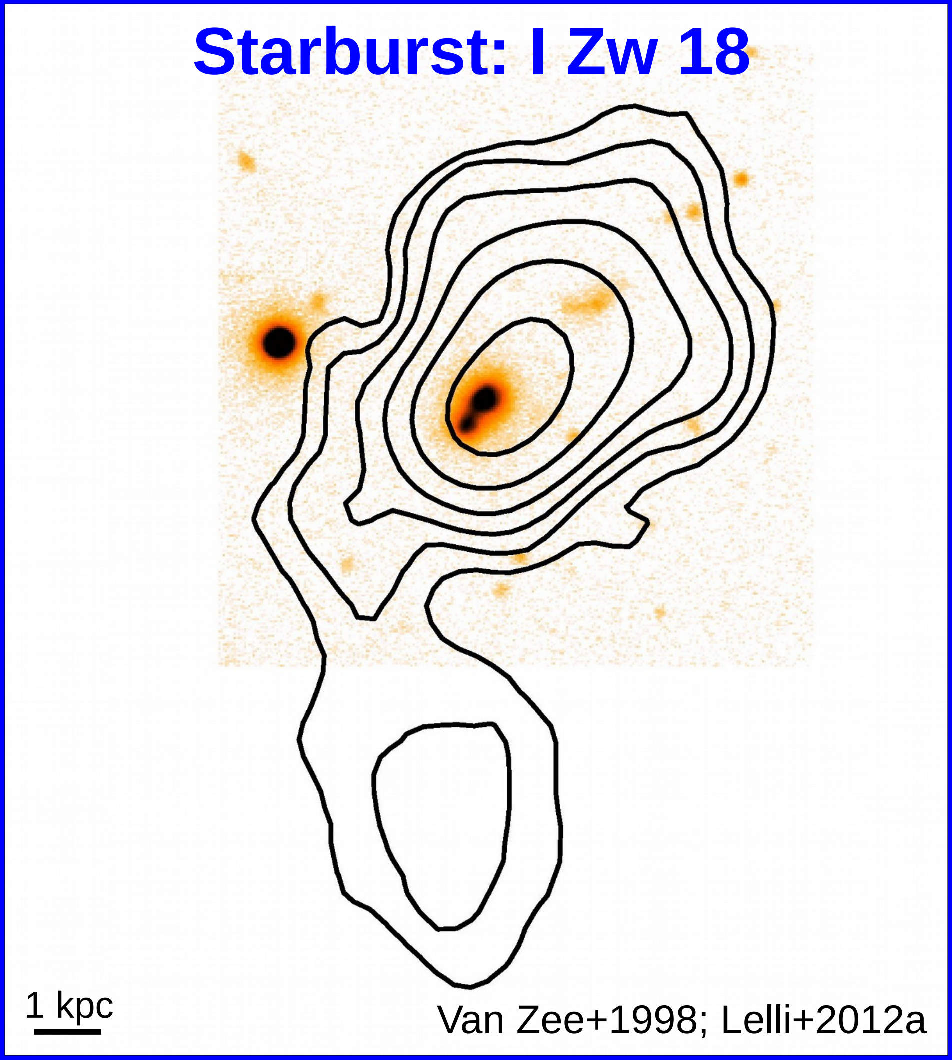
Large-scale HI distribution



Lowest HI contour = 5×10^{19} cm^{-2}

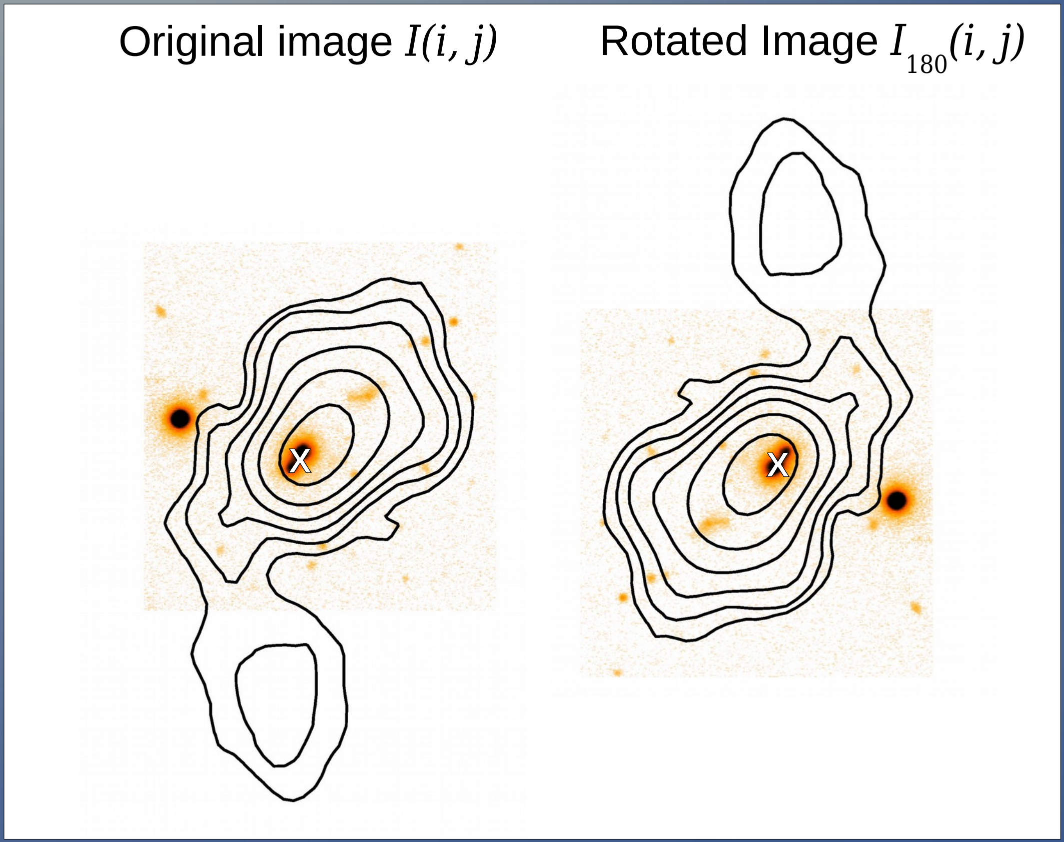
Large-scale HI distribution





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)

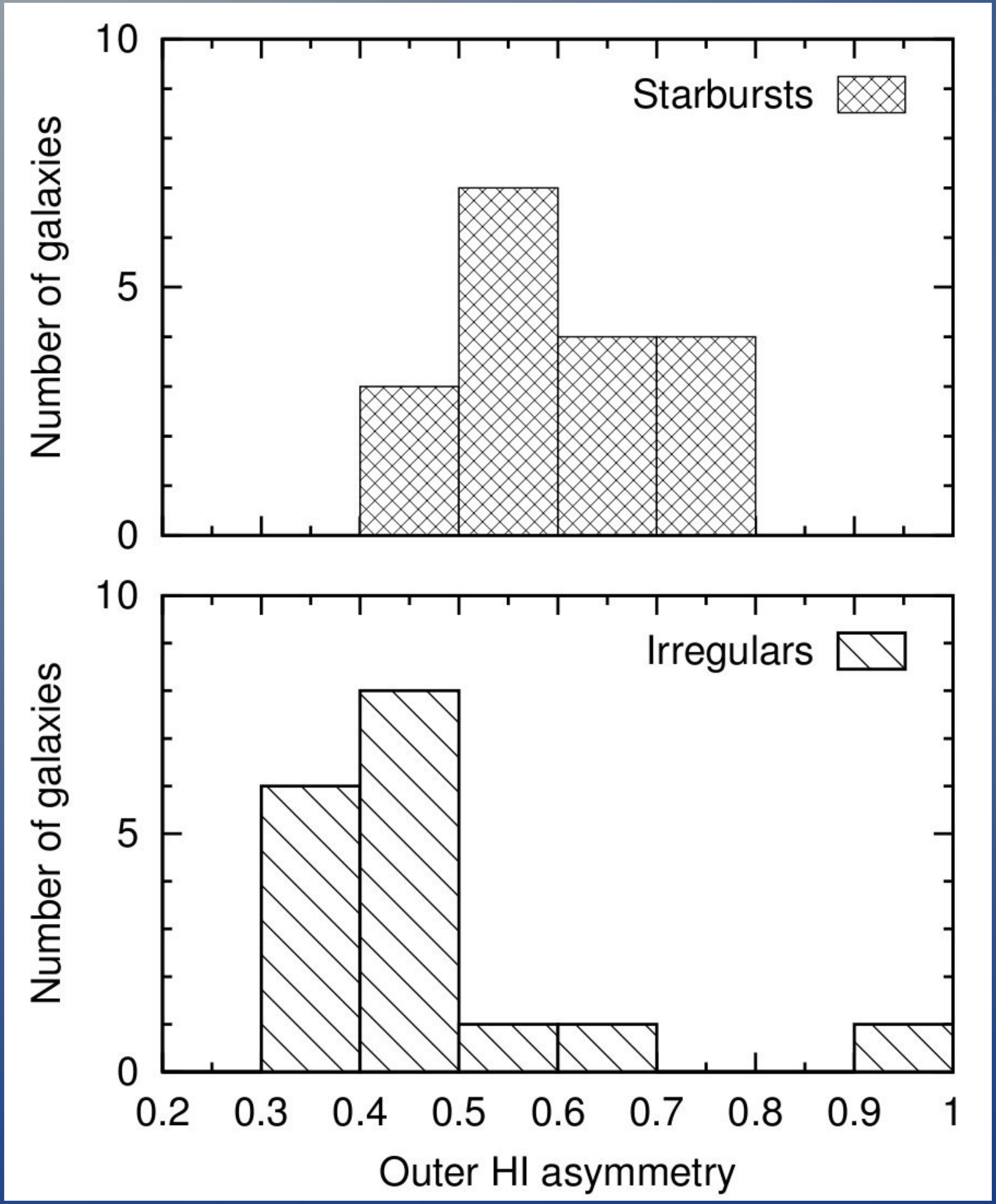
$$A = \frac{1}{N} \sum_{i,j}^{N} \frac{|I(i,j) - I_{180^\circ}(i,j)|}{|I(i,j) + I_{180^\circ}(i,j)|}$$

→ Good for outer regions!

For all galaxies:

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

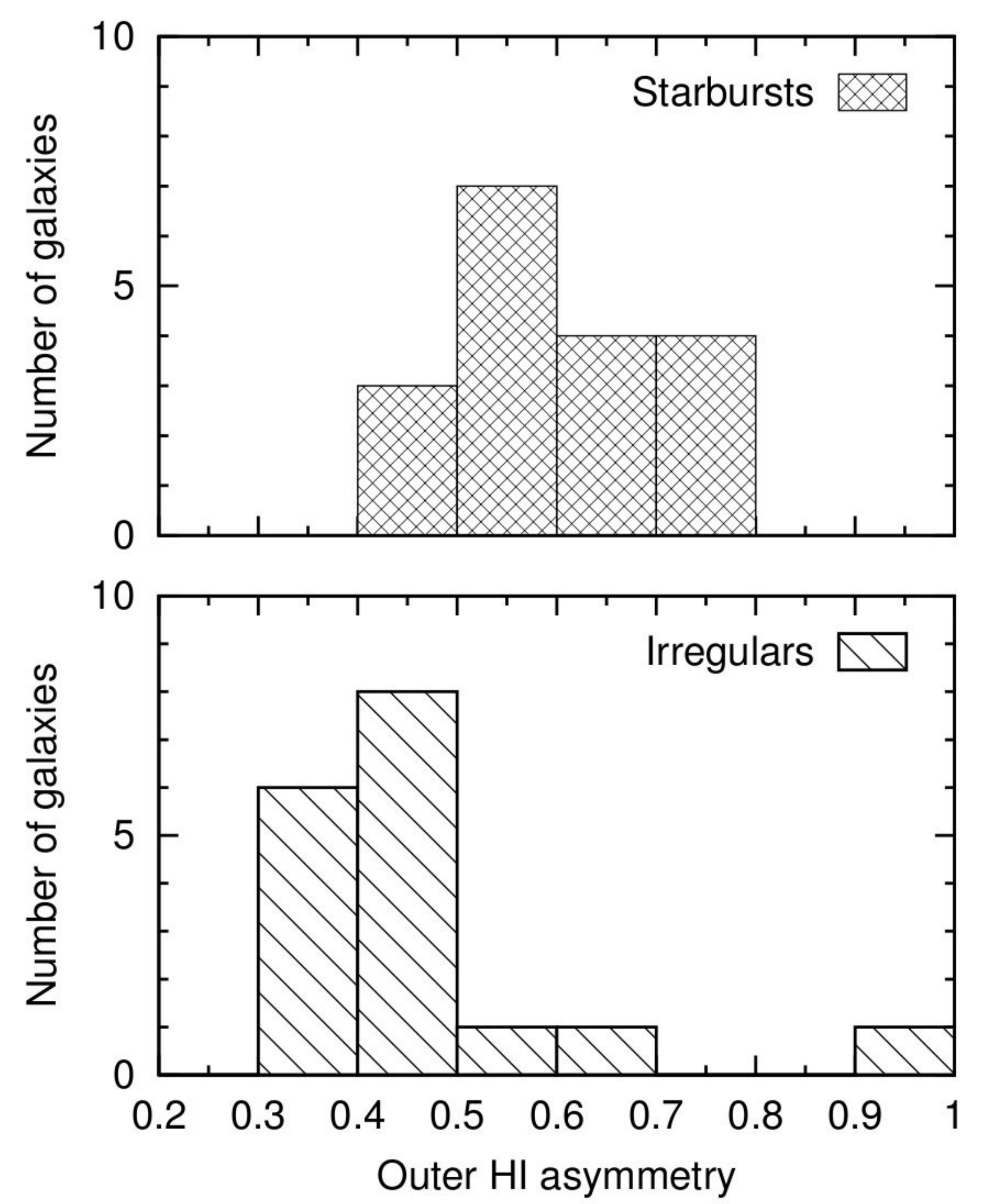
HI Asymmetry: Starbursts *vs* Irrs



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

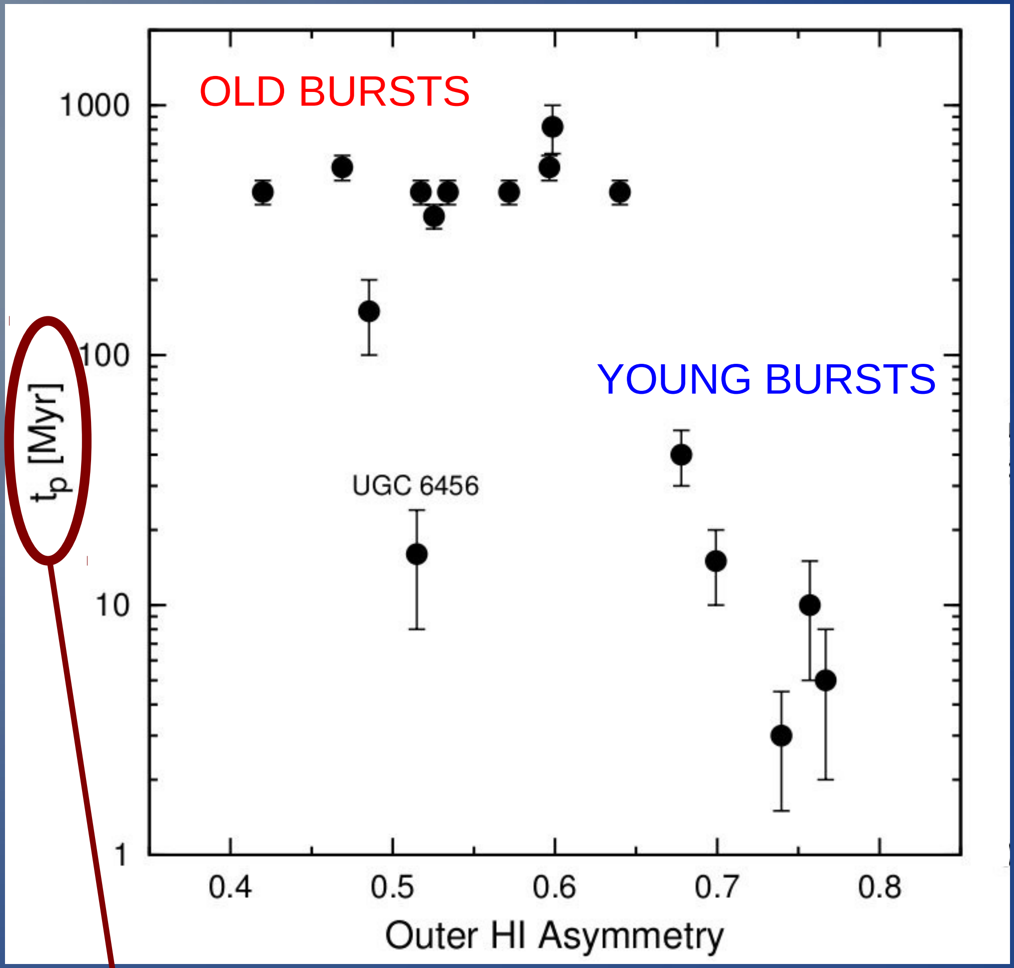
External mechanisms triggered the starburst:

- Interactions/mergers?
- Cold gas accretion?

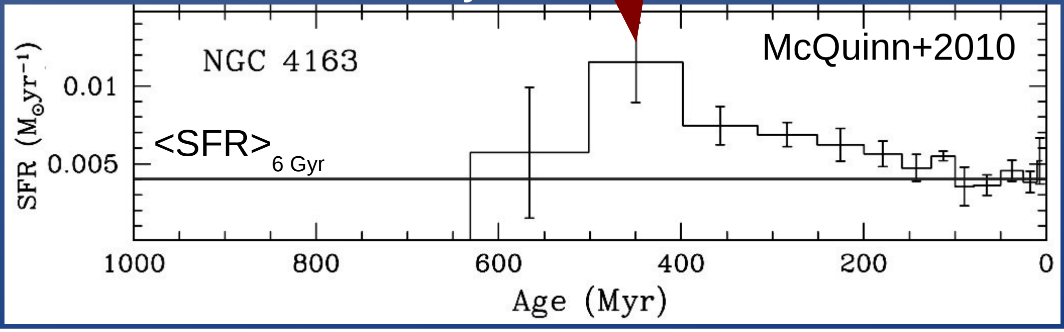
See also: Ekta & Chengalur (2010); Lopez-Sanchez et al. (2010).

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 rotation!

Questions:

- What triggers the starburst?

  (External *vs* Internal mechanisms)

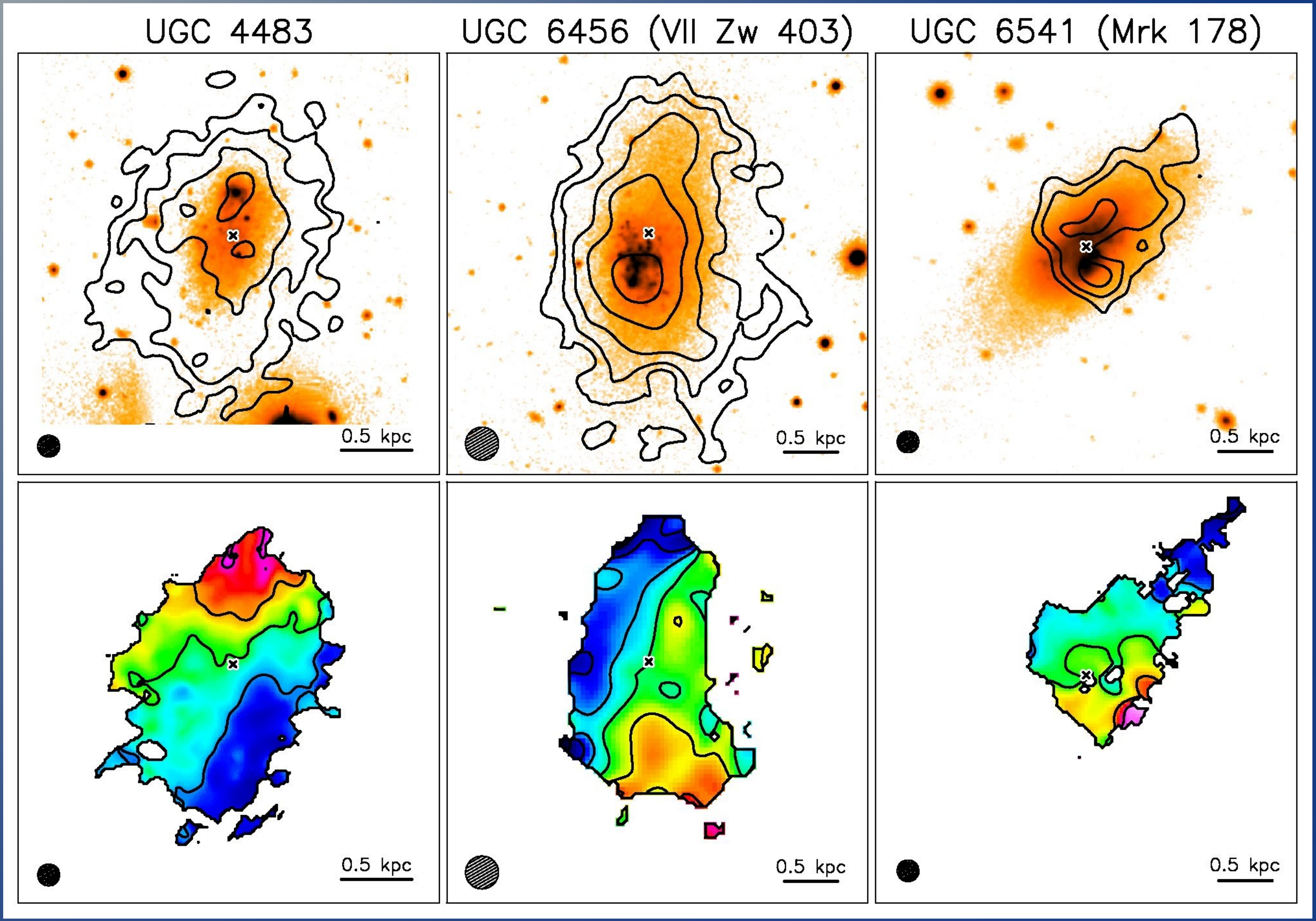
- What is the effect of stellar feedback?

  (Gas outflows? Shocks?)

- What are the progenitors/descendants?

  (Evolutionary links with Irrs and Sphs?)

Internal HI Kinematics of Starbursts

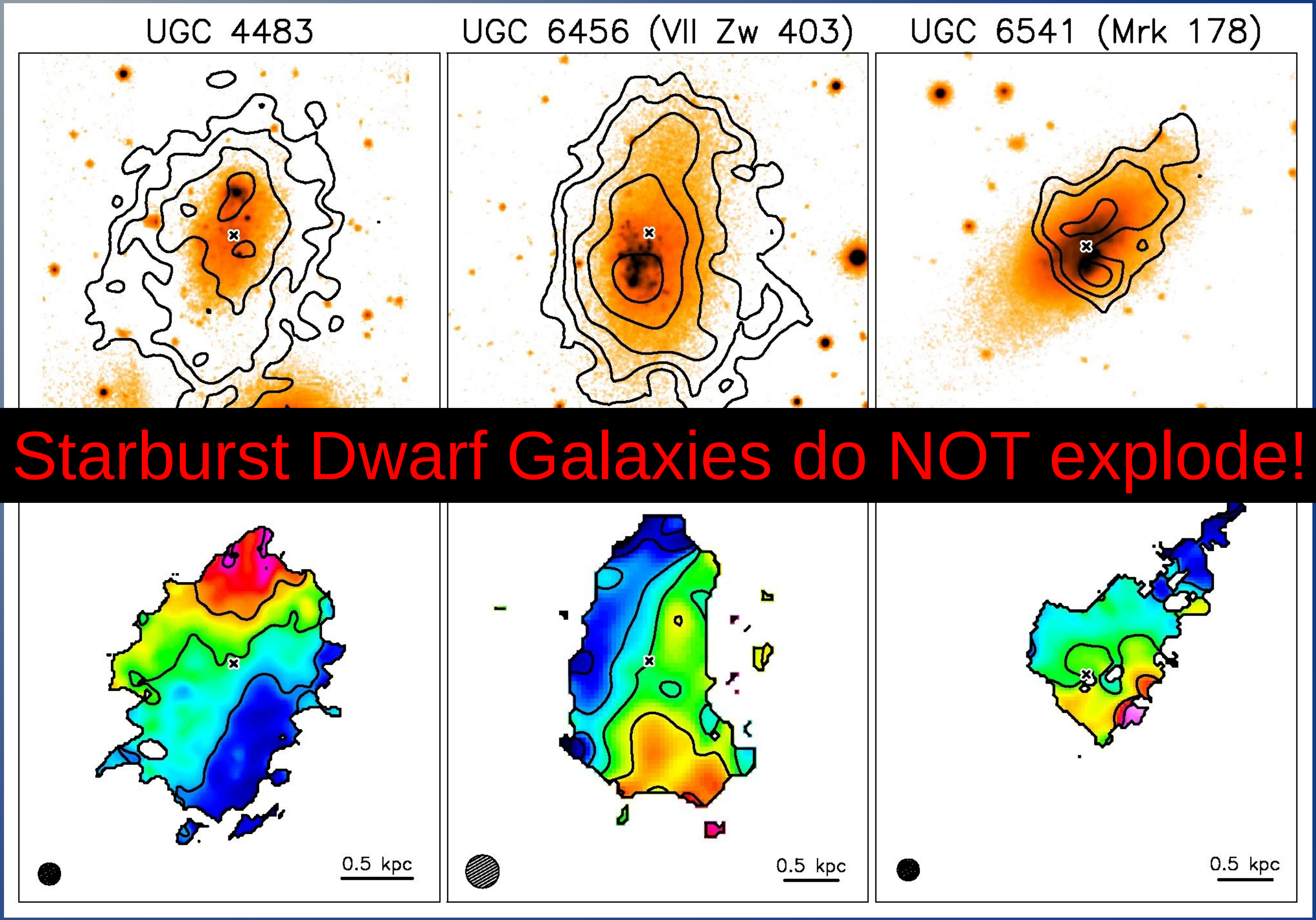


~50%
rotating HI disk

~40%
kin. disturbed HI disk

~10%
unsettled HI distr.

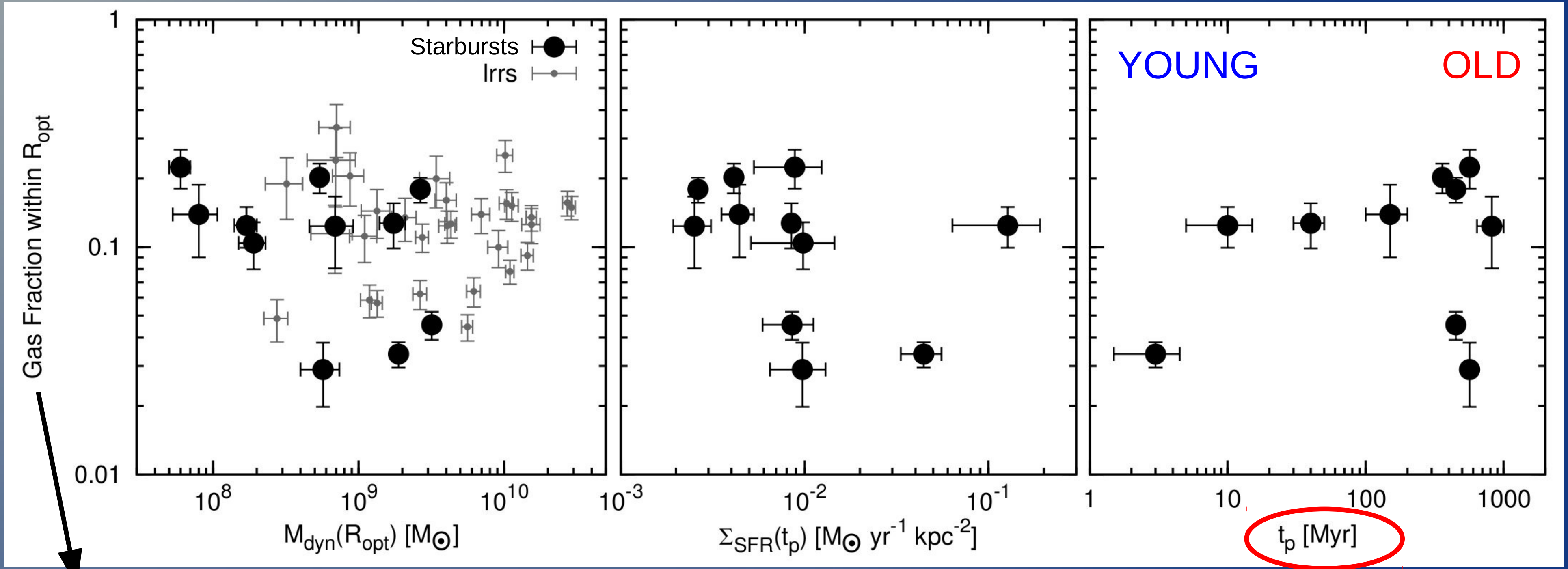
Internal HI Kinematics of Starbursts



Starburst Dwarf Galaxies do NOT explode!

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

Gas Fractions: Starbursts vs Irrs

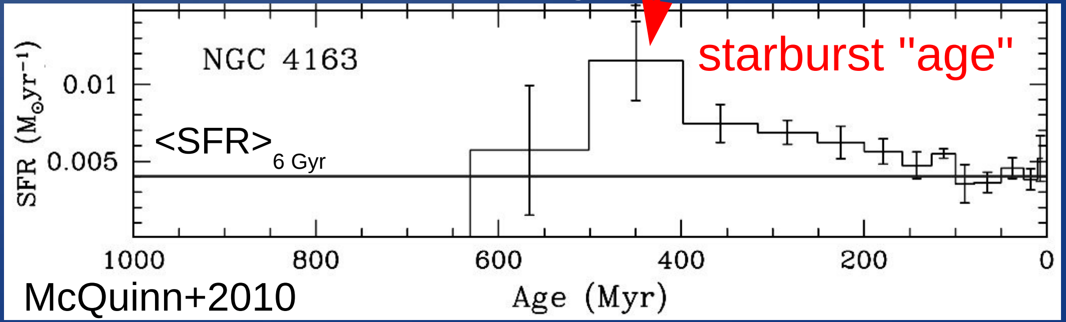


$F_{gas} = M_{HI}/M_{dyn}$ within R_{opt} (Irrs from Swaters+2009)

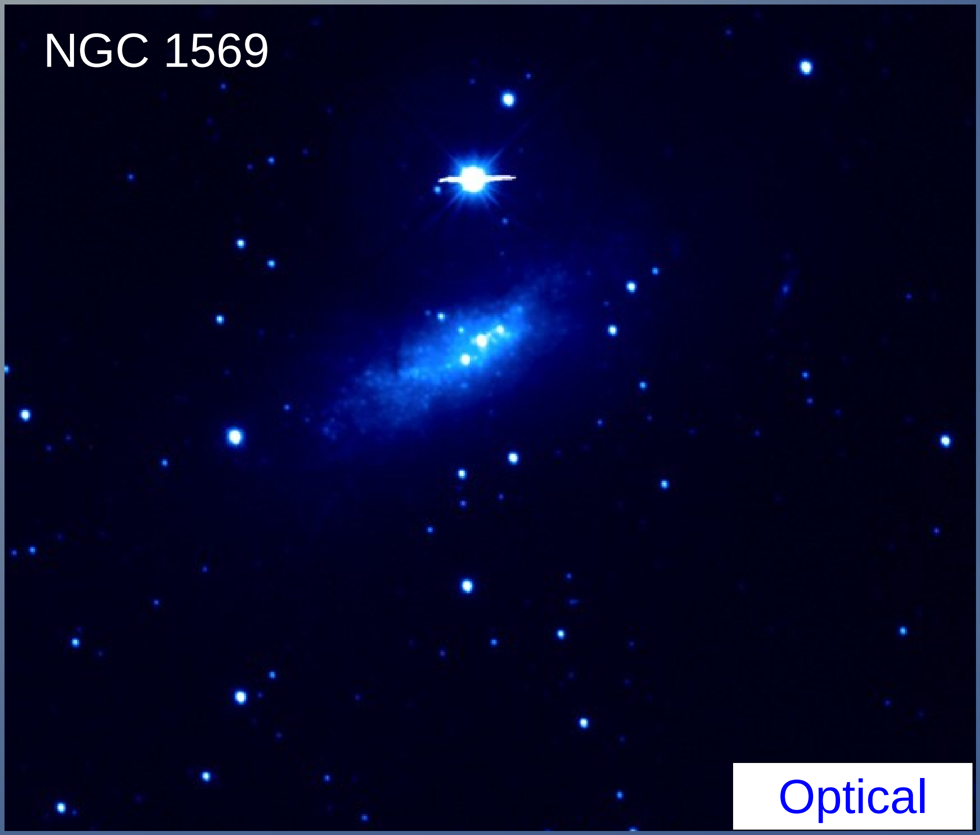
Similar f_{gas} as typical Irrs:

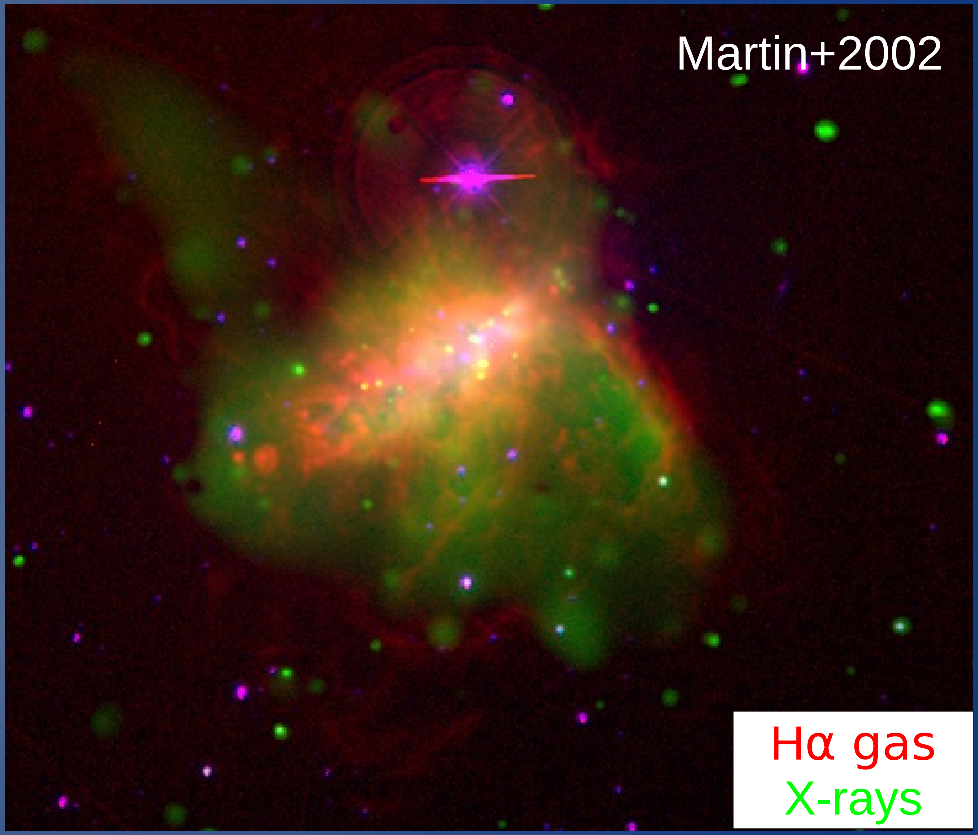
- No evidence for massive outflow
- $t_{dep} = M_{HI}/SFR$ = 2-10 Gyrs (up to 20 Gyr for Irrs)

Star-Formation History



Gas Outflows in Hα and X rays



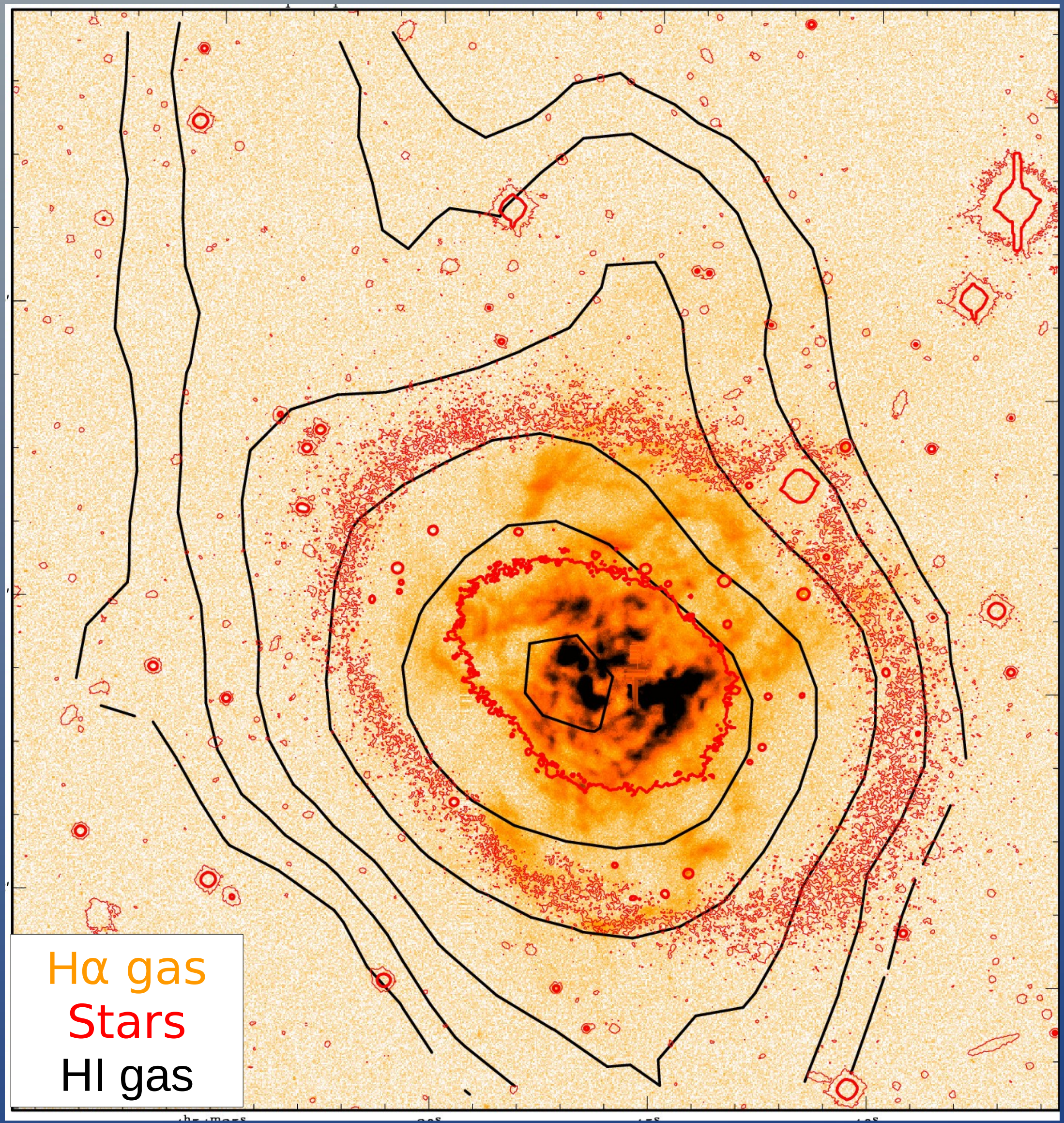


- Velocity of the ionized gas does *not* exceed V_{esc}

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

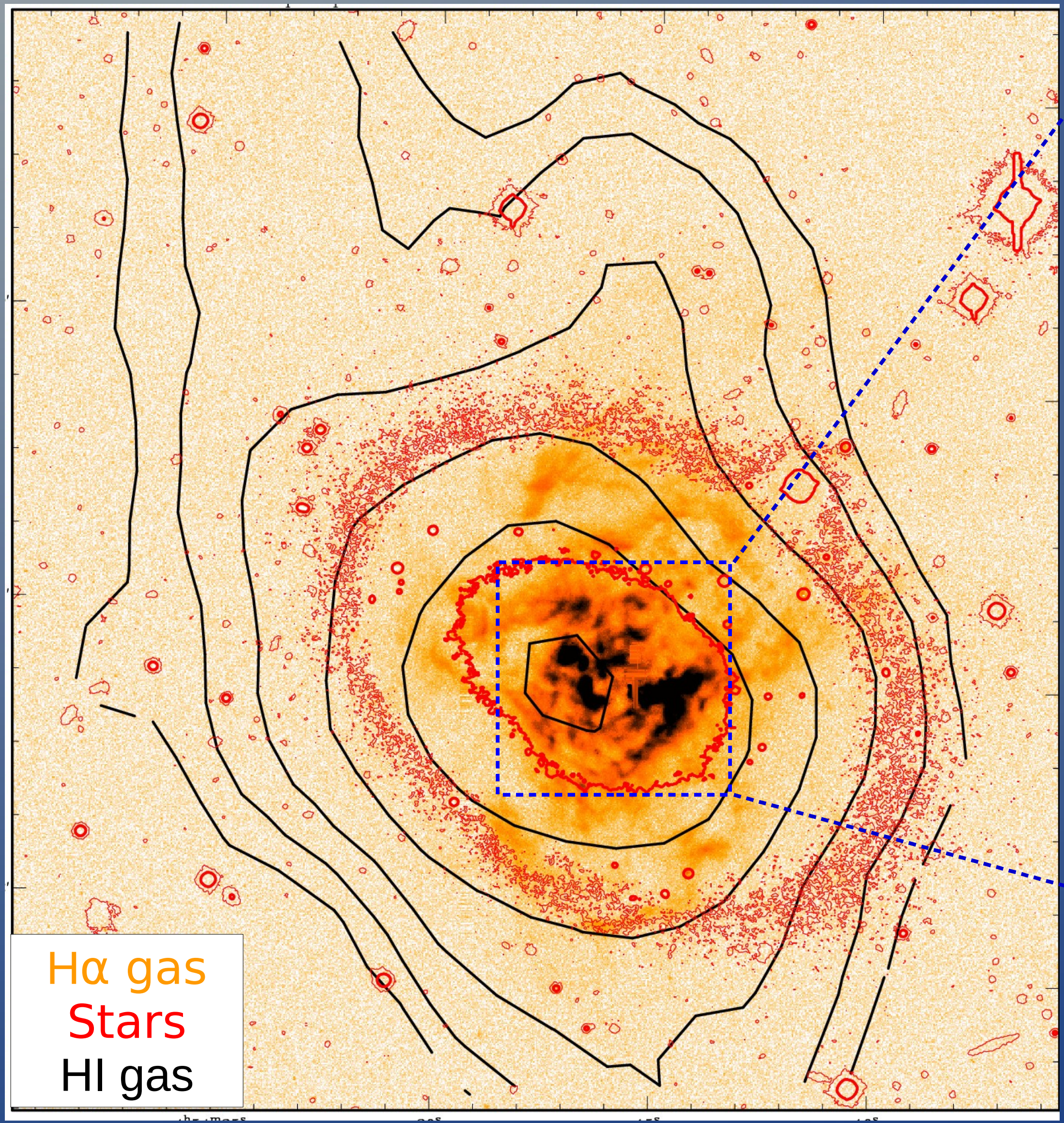
- Mass of the hot gas ~1% M_{HI} (e.g. Ott+2005)

NGC 1705: a case-study with MUSE



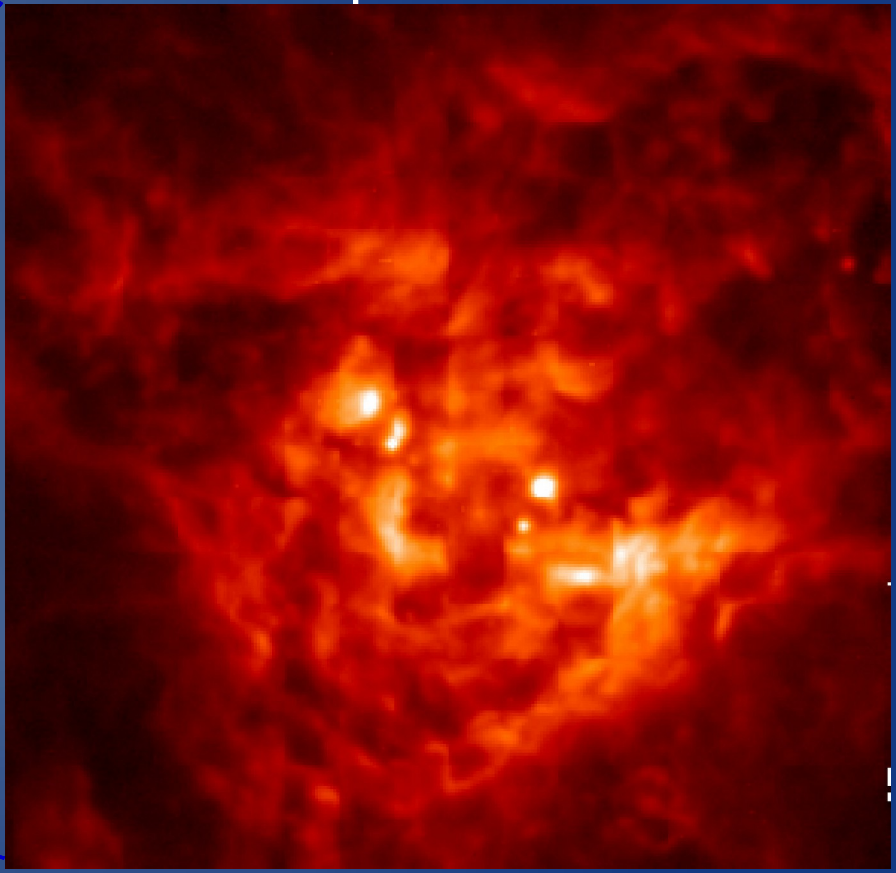
McLeod, Lelli & Beccari (in prep.)

NGC 1705: a case-study with MUSE



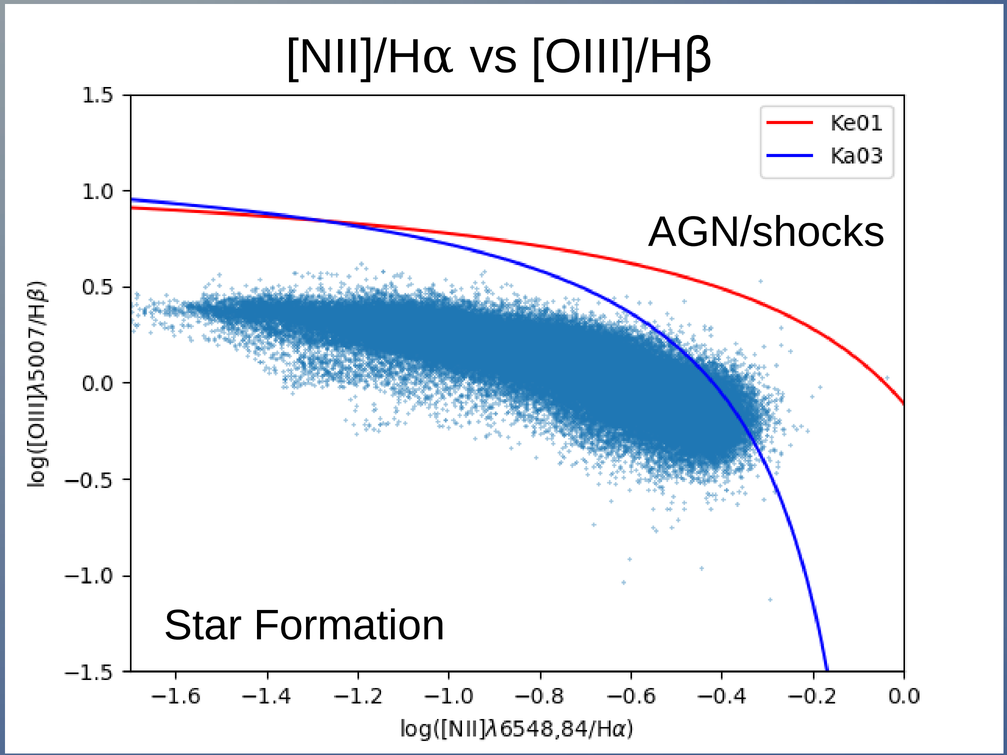
McLeod, Lelli & Beccari (in prep.)

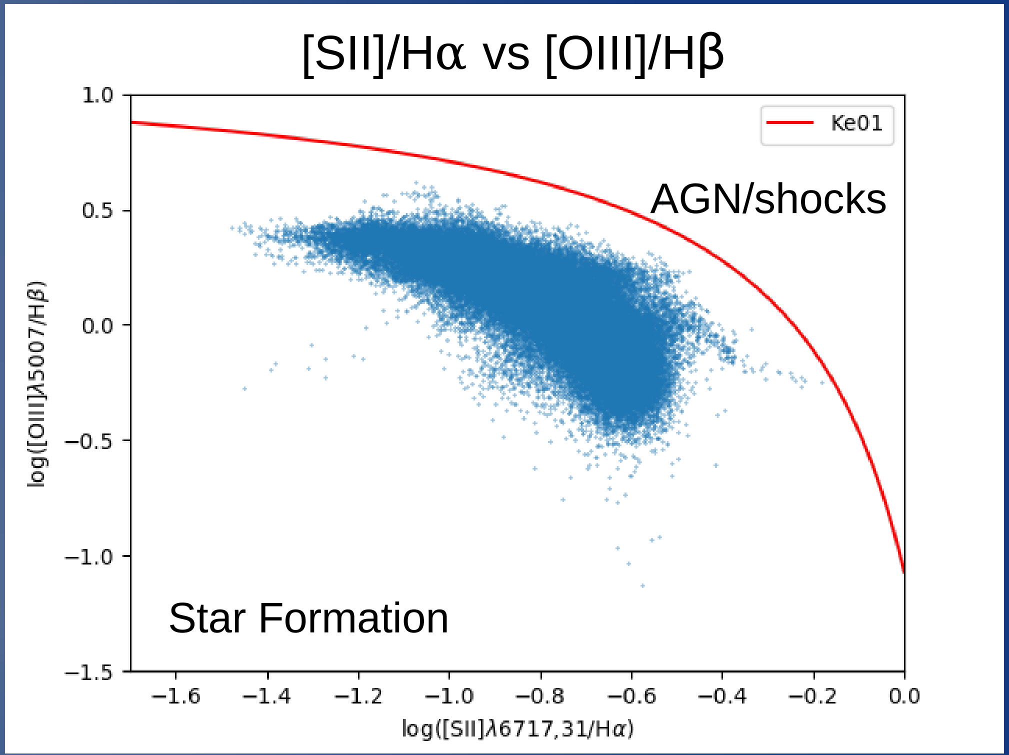
Hα map from MUSE

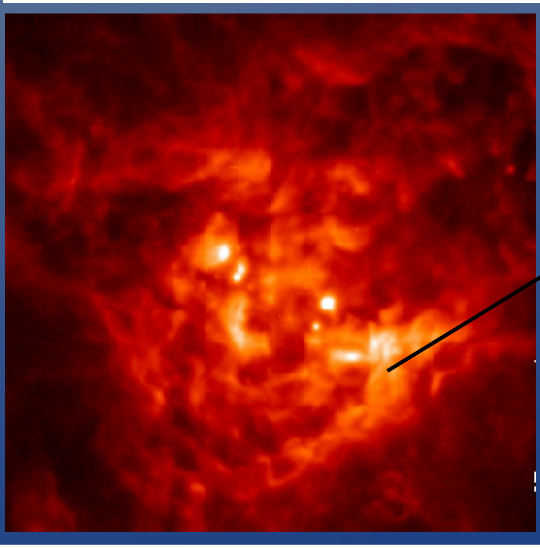


Similar maps for Hβ, HeI, [NII], [OI], [OII], [OIII], [SII], [SIII], [ArIII]

NGC 1705: BPT diagrams from MUSE







No evidence for shocks. Young stars do the job!

Are these radiation fronts?

Hα kinematics show no outflowing gas.

McLeod, Lelli & Beccari (in prep.)

Questions:

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  (External *vs* Internal mechanisms)

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  (Gas outflows? Shocks?)

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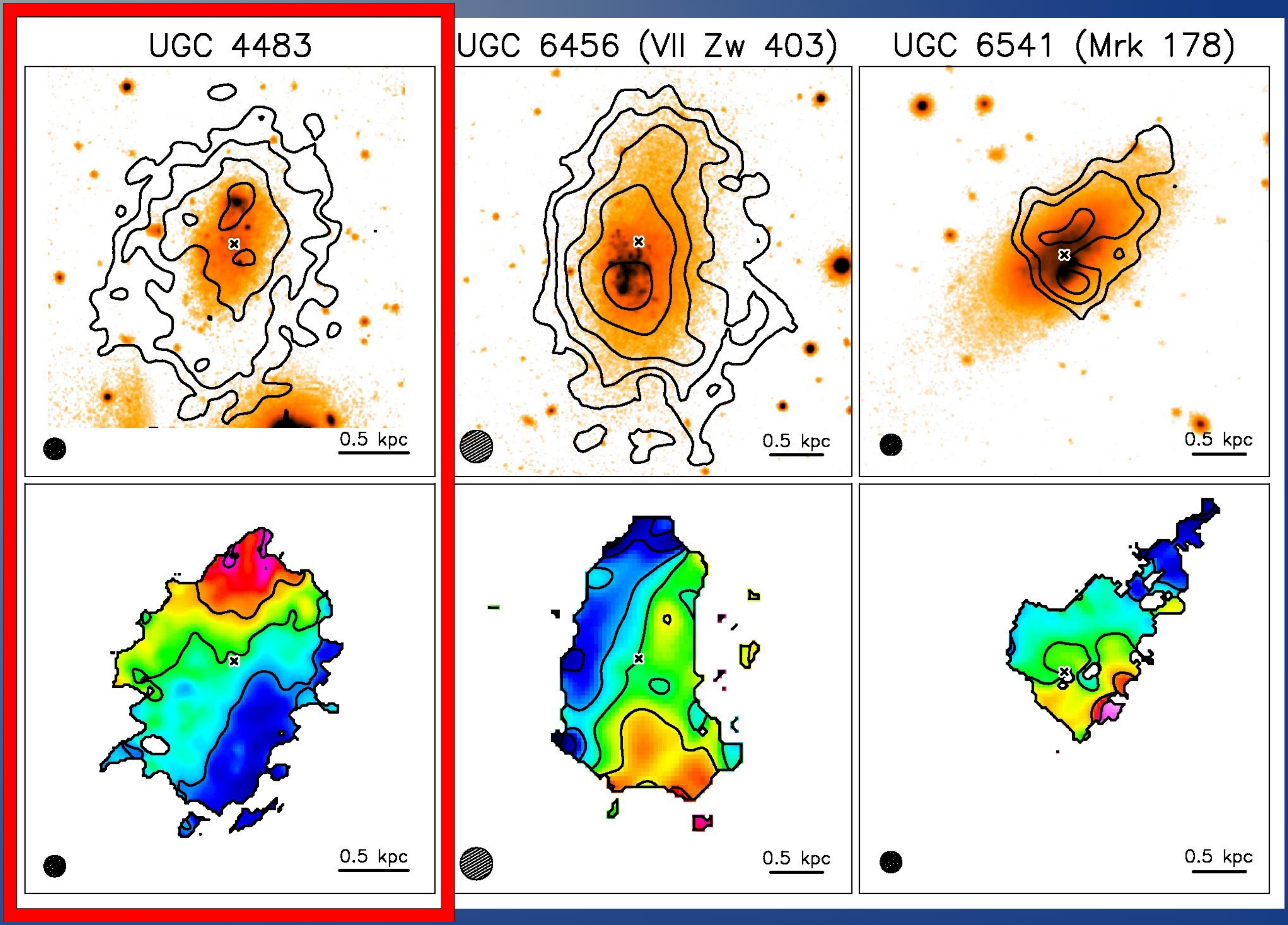
  (Evolutionary links with Irrs and Sphs?)

HI Kinematics of Starburst Dwarfs



~50%
rotating HI disk

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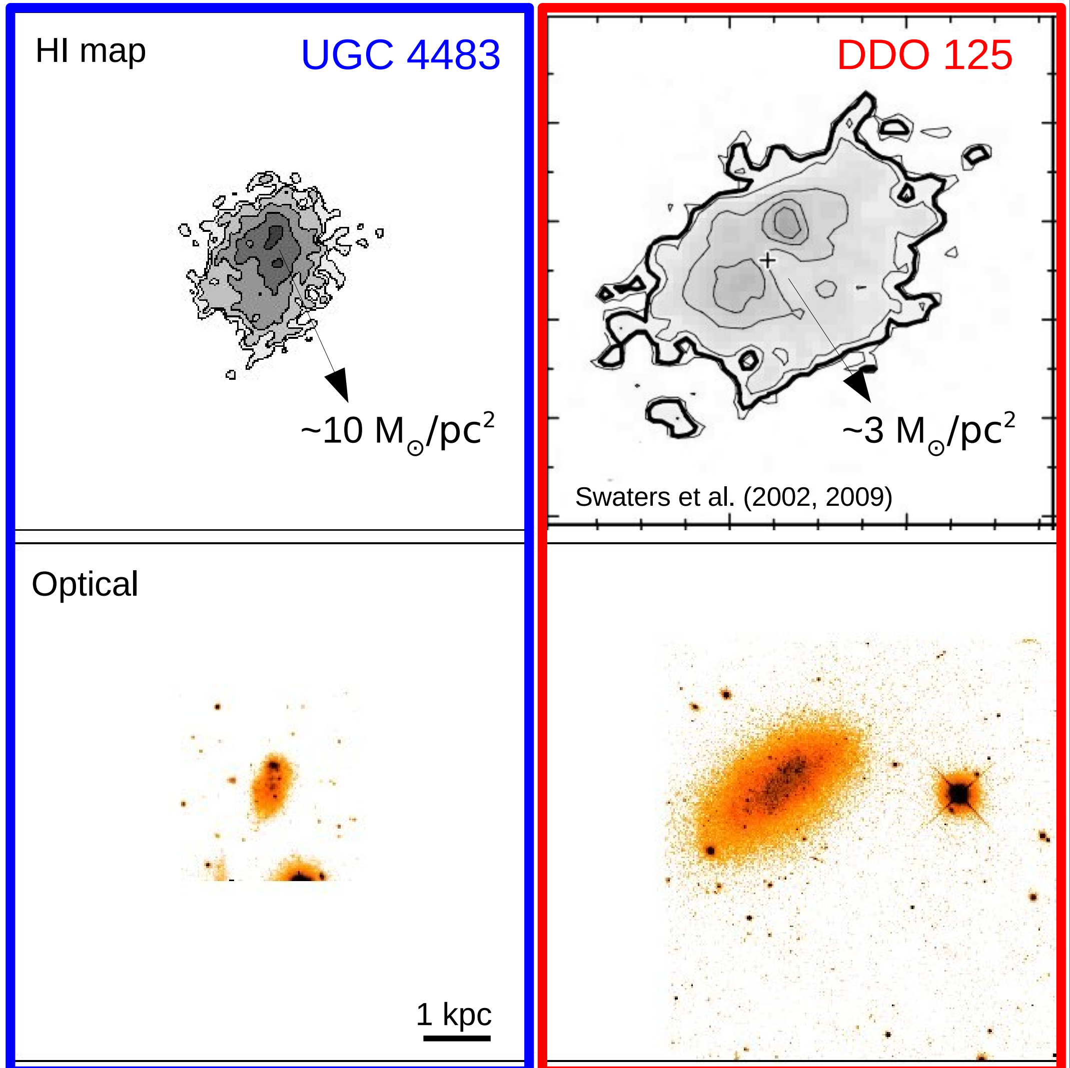
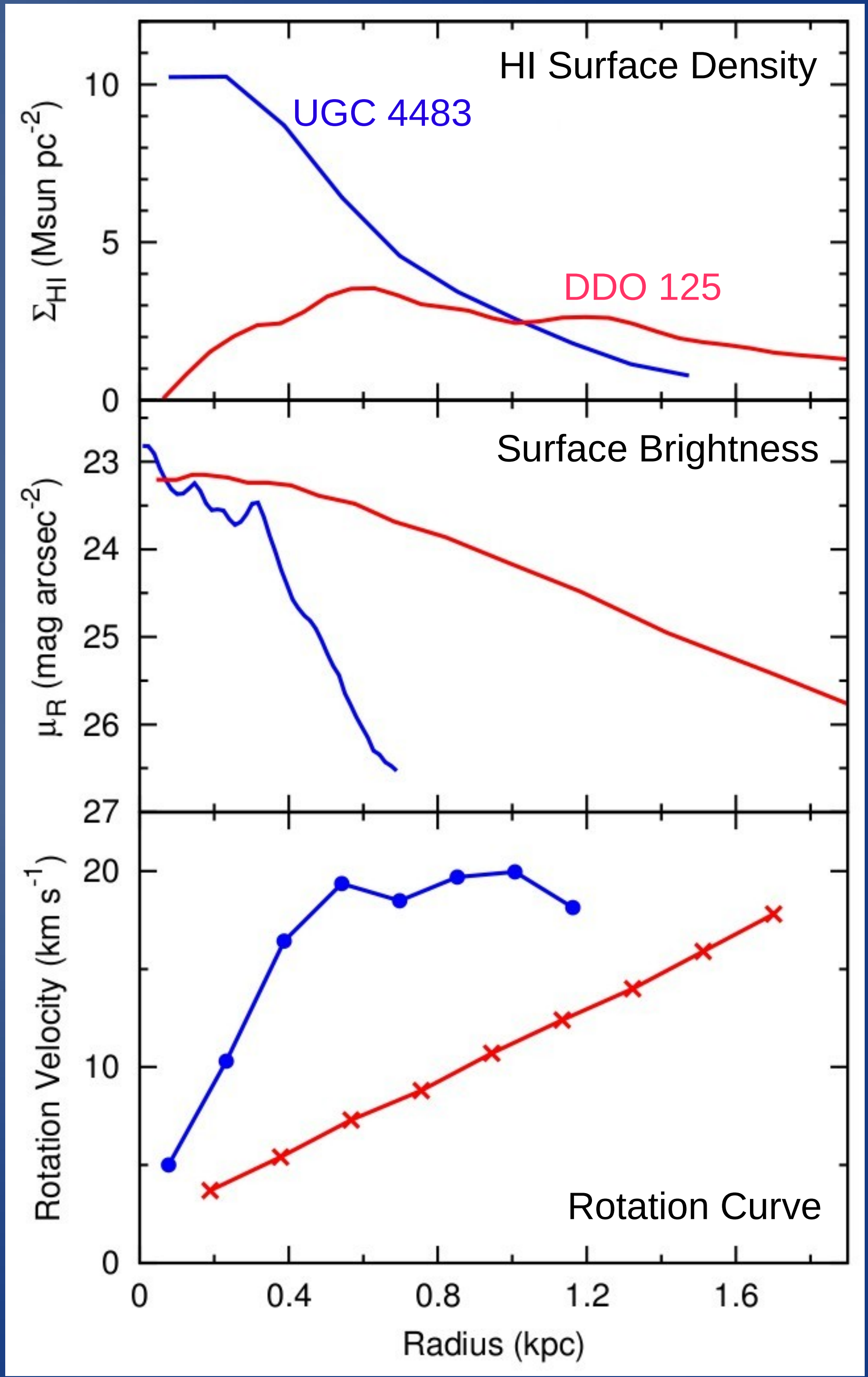
Starburst *vs* Irregular

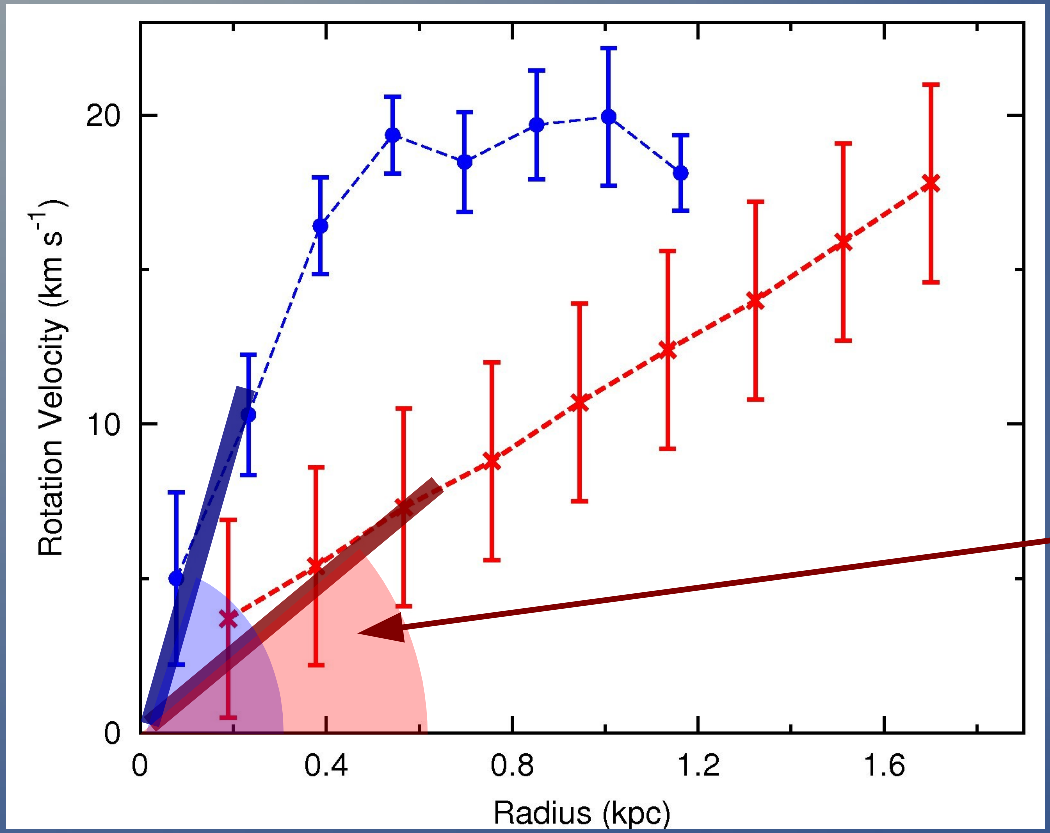




$M_{dyn} \sim$ 1-2 x 10^8 $M_{\odot}$

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:

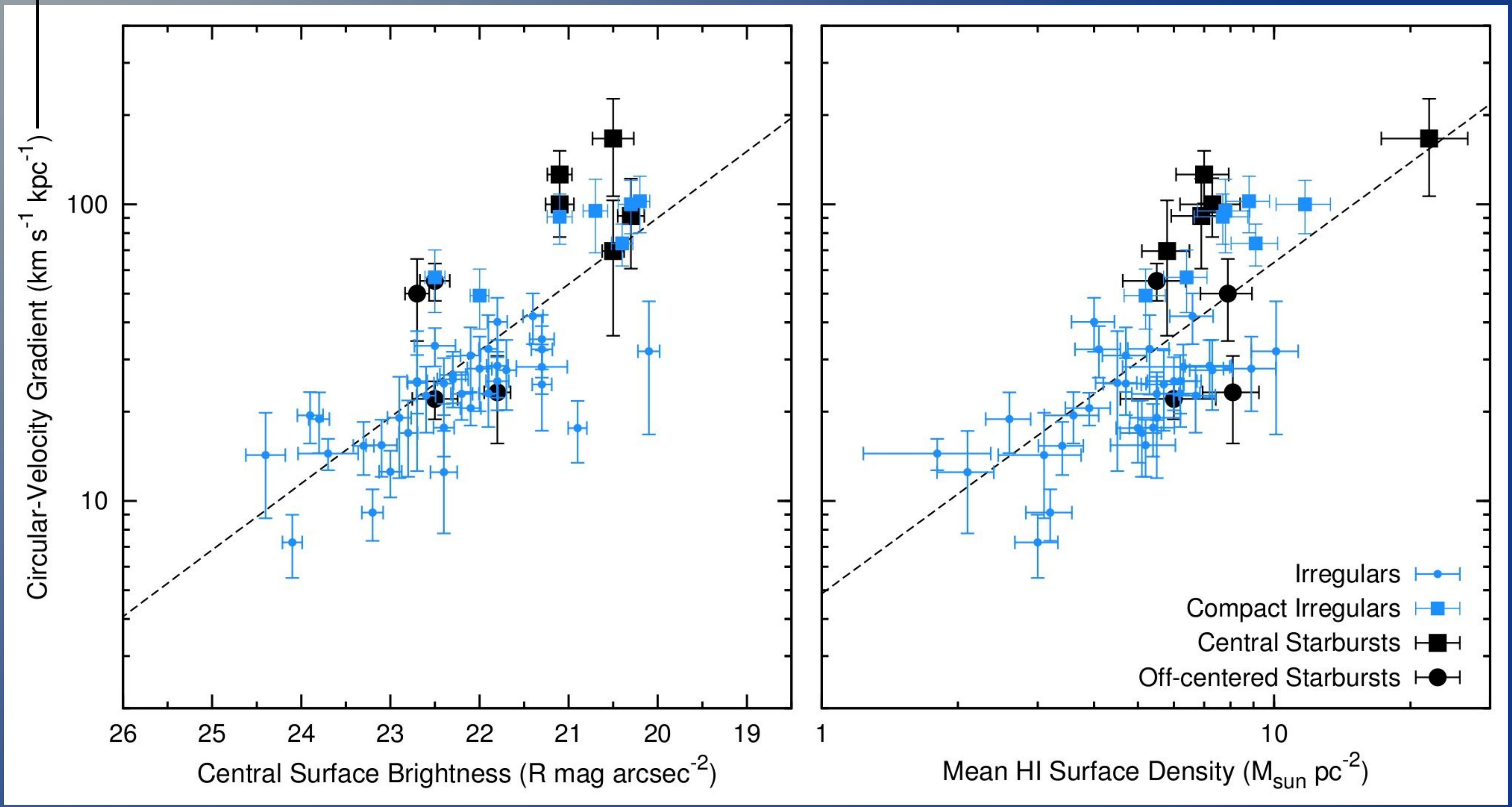
$dV/dR \sim V(R_d)/R_d$

R_d = disk scale length

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

Starbursts *vs* Irrs

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

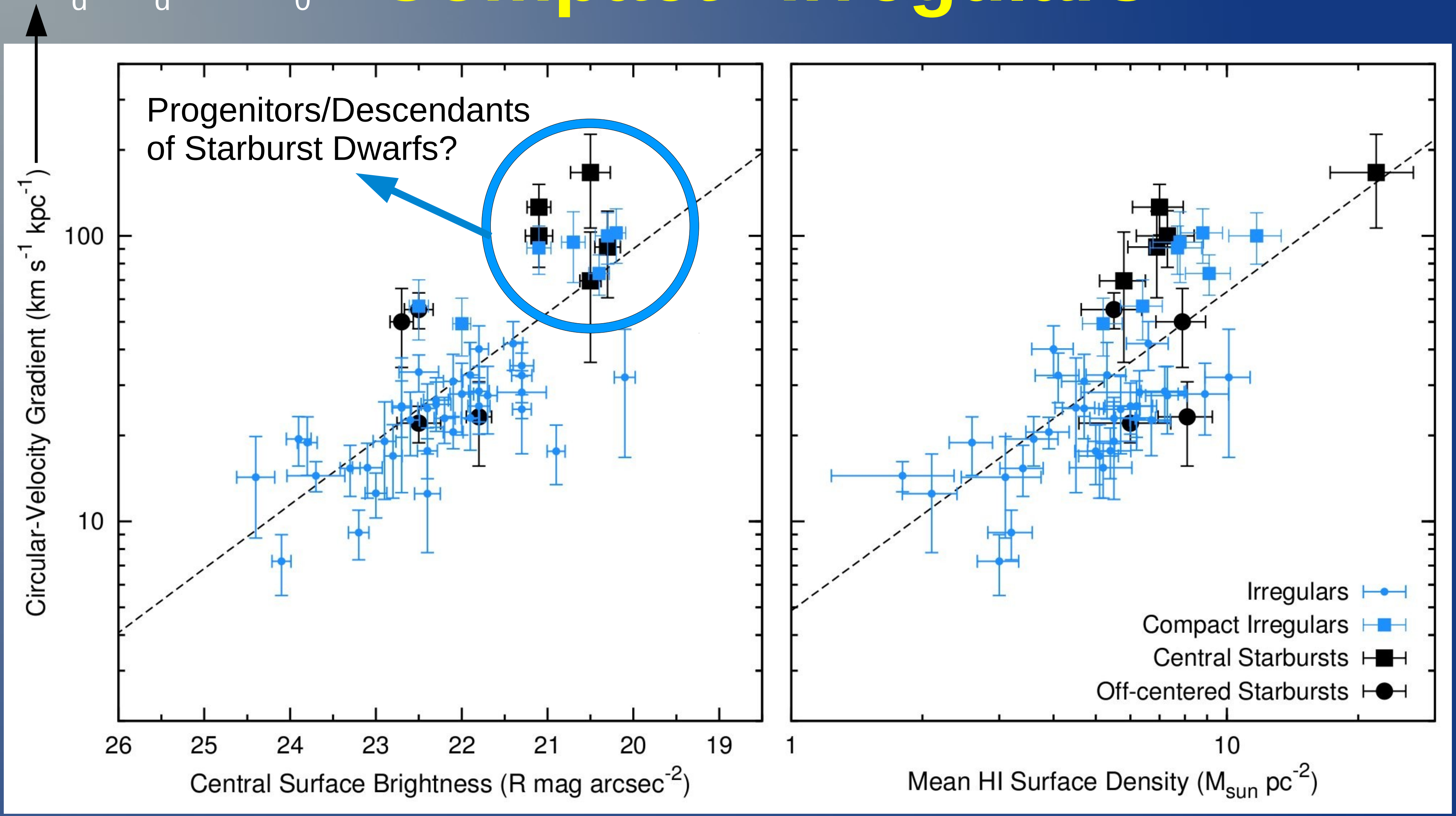


Link: Star Formation – inner potential well

Lelli, Fraternali & Verheijen 2014

(Irrs from Swaters et al. 2009)

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



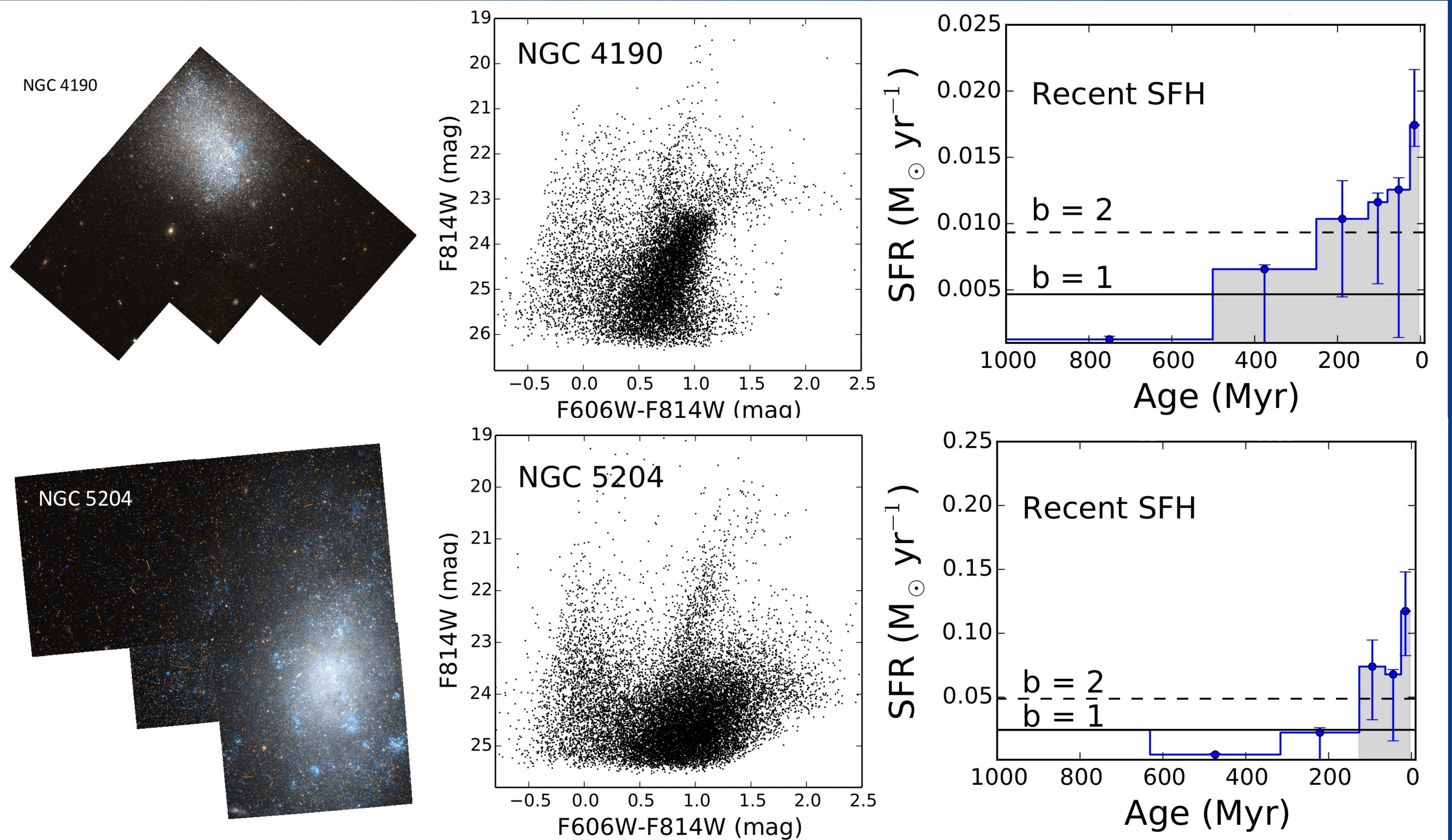
Link: Star Formation – inner potential well

Compact Irrs = similar ρ_0 as starbursts

Lelli, Fraternali & Verheijen 2014

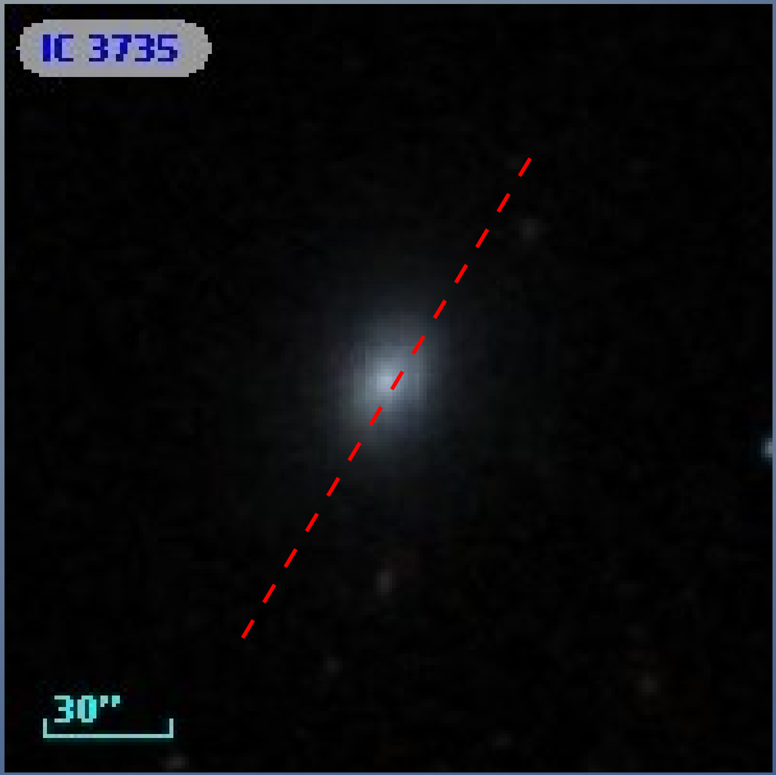
(Irrs from Swaters et al. 2009)

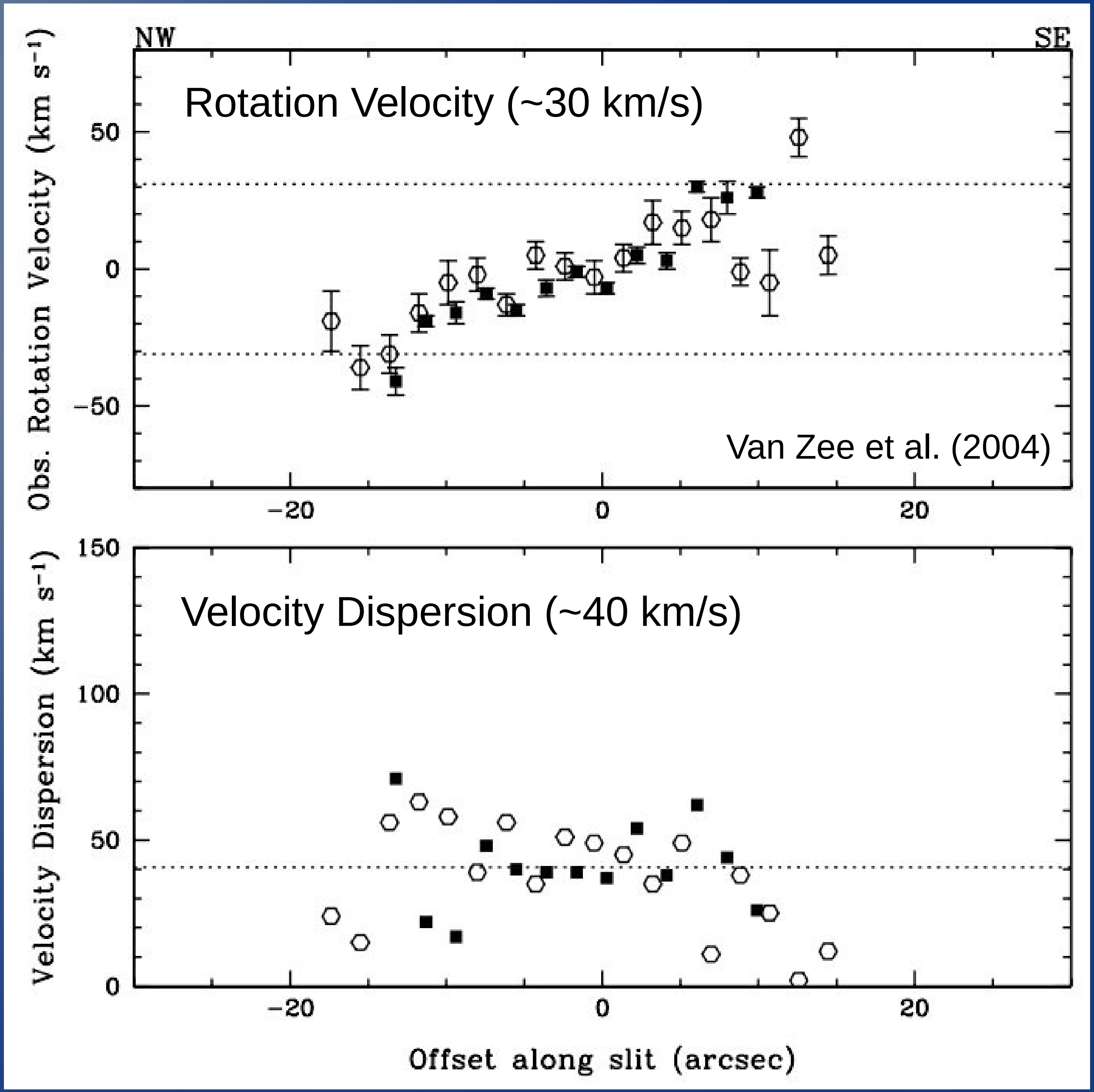
SF histories of "compact" Irrs



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)

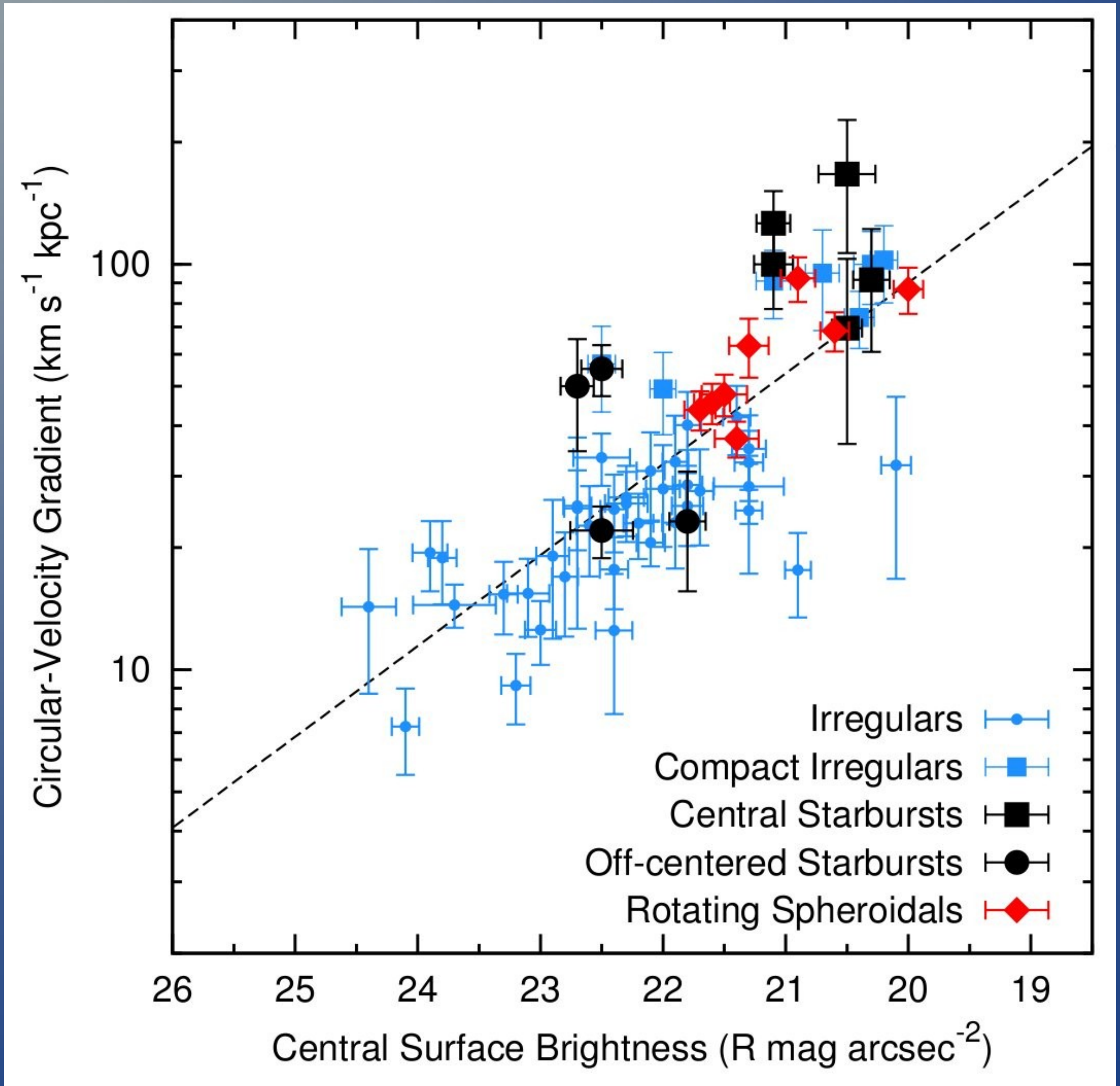
van Zee et al. (2004)

Chilingarian et al. (2007, 2009)

Toloba et al. (2011, 2012, 2014)

Rys et al. (2013, 2014)

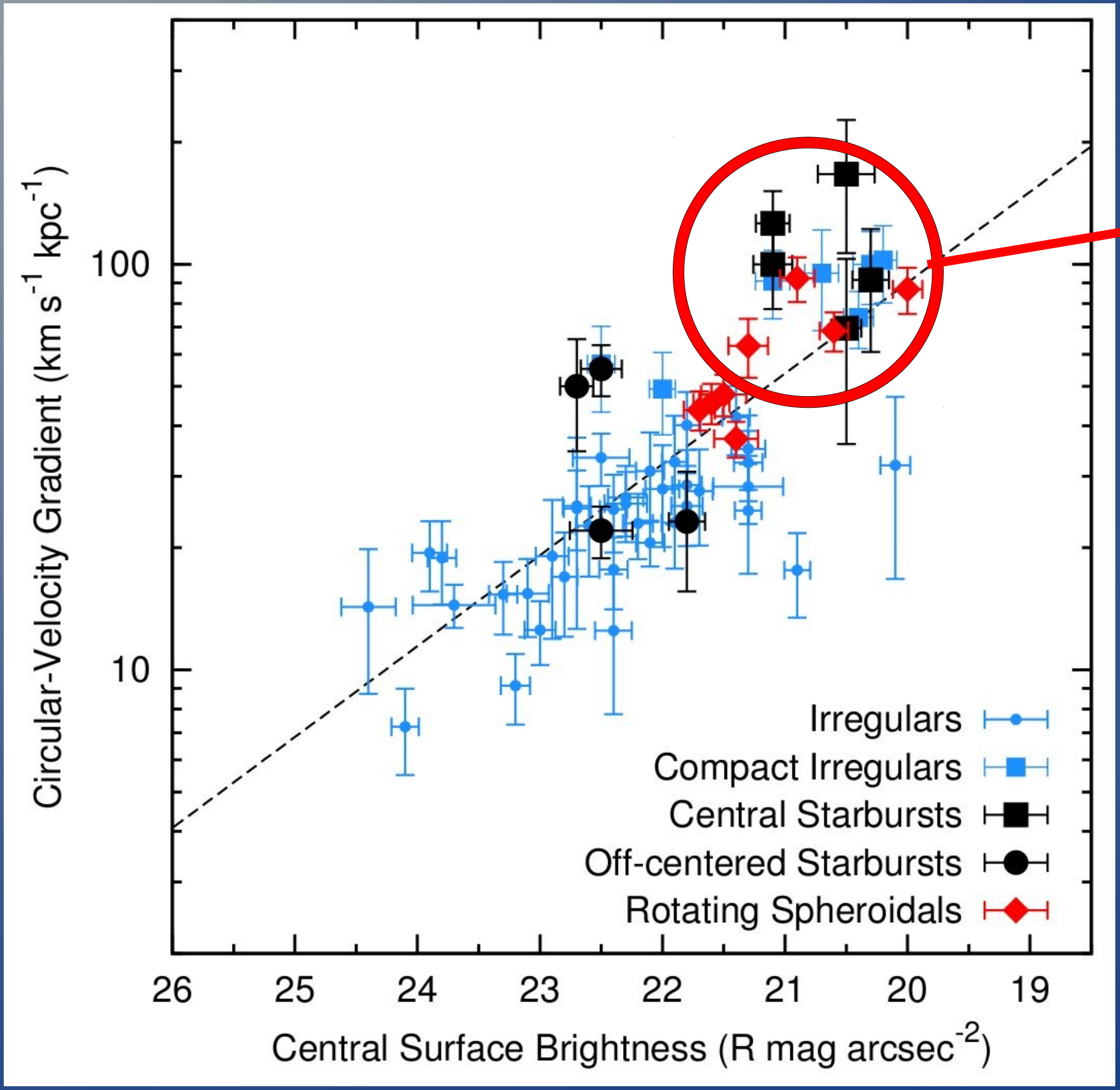
Rotating dE/Sph in the Virgo Cluster



Lelli, Fraternali & Verheijen 2014

(Sphs from van Zee et al. 2004)

Rotating dE/Sph in the Virgo Cluster



Descendants of

Starburst Dwarfs?

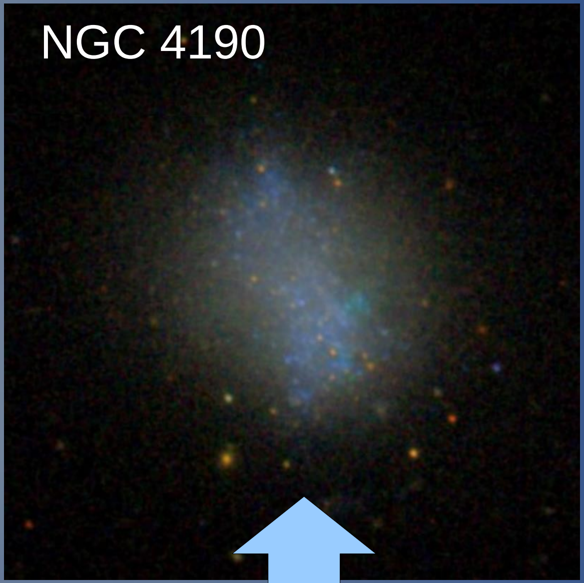
Not of typical Irrs?

Lelli, Fraternali & Verheijen 2014

(Sphs from van Zee et al. 2004)

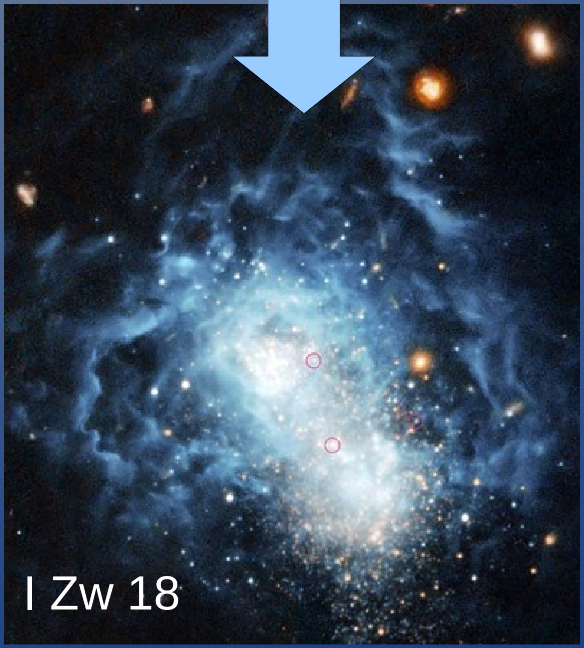
Typical LSB Irrs

Compact HSB Irrs



Rotating dEs

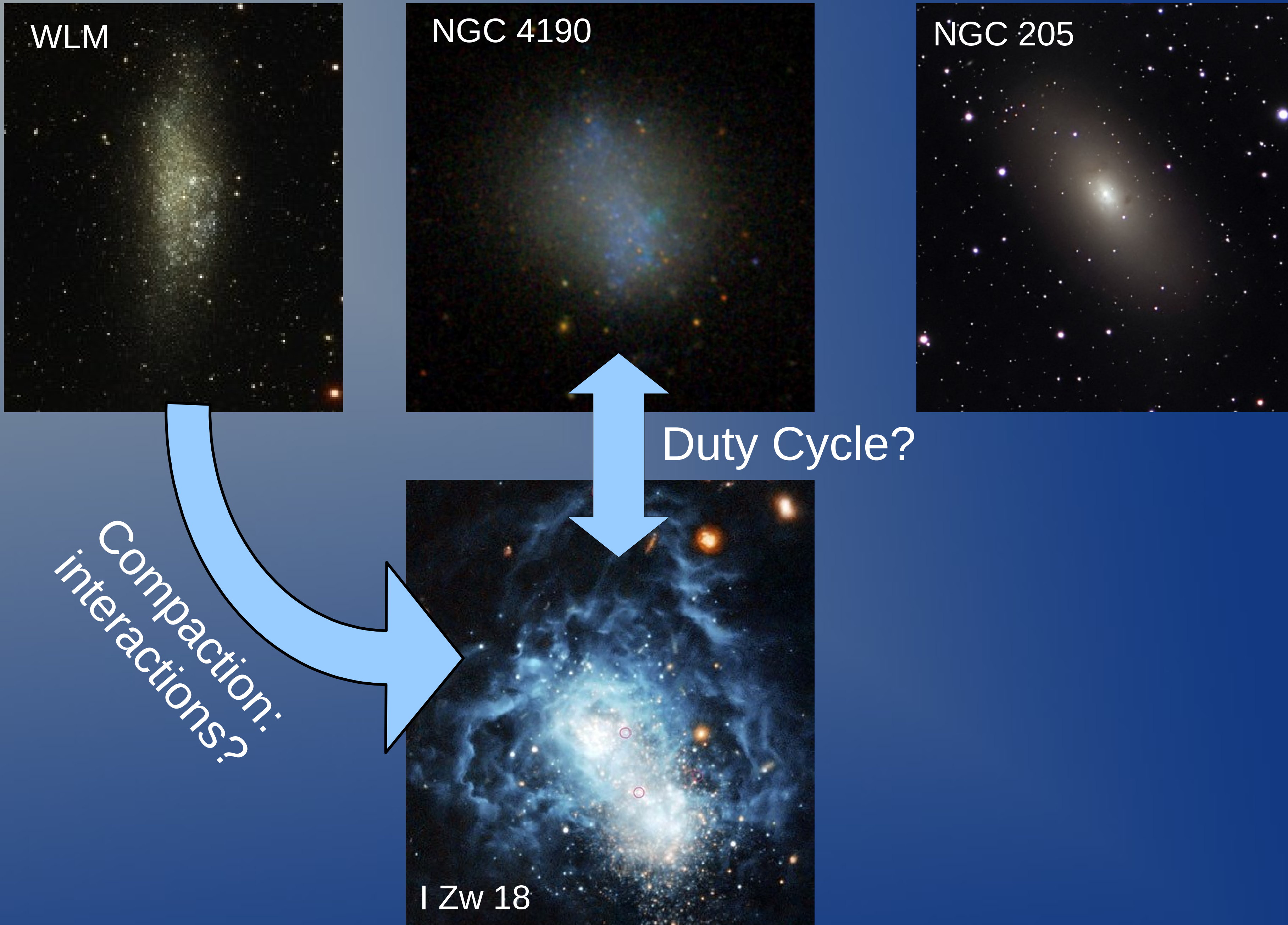
Duty Cycle?



Starbursts (~5%?)

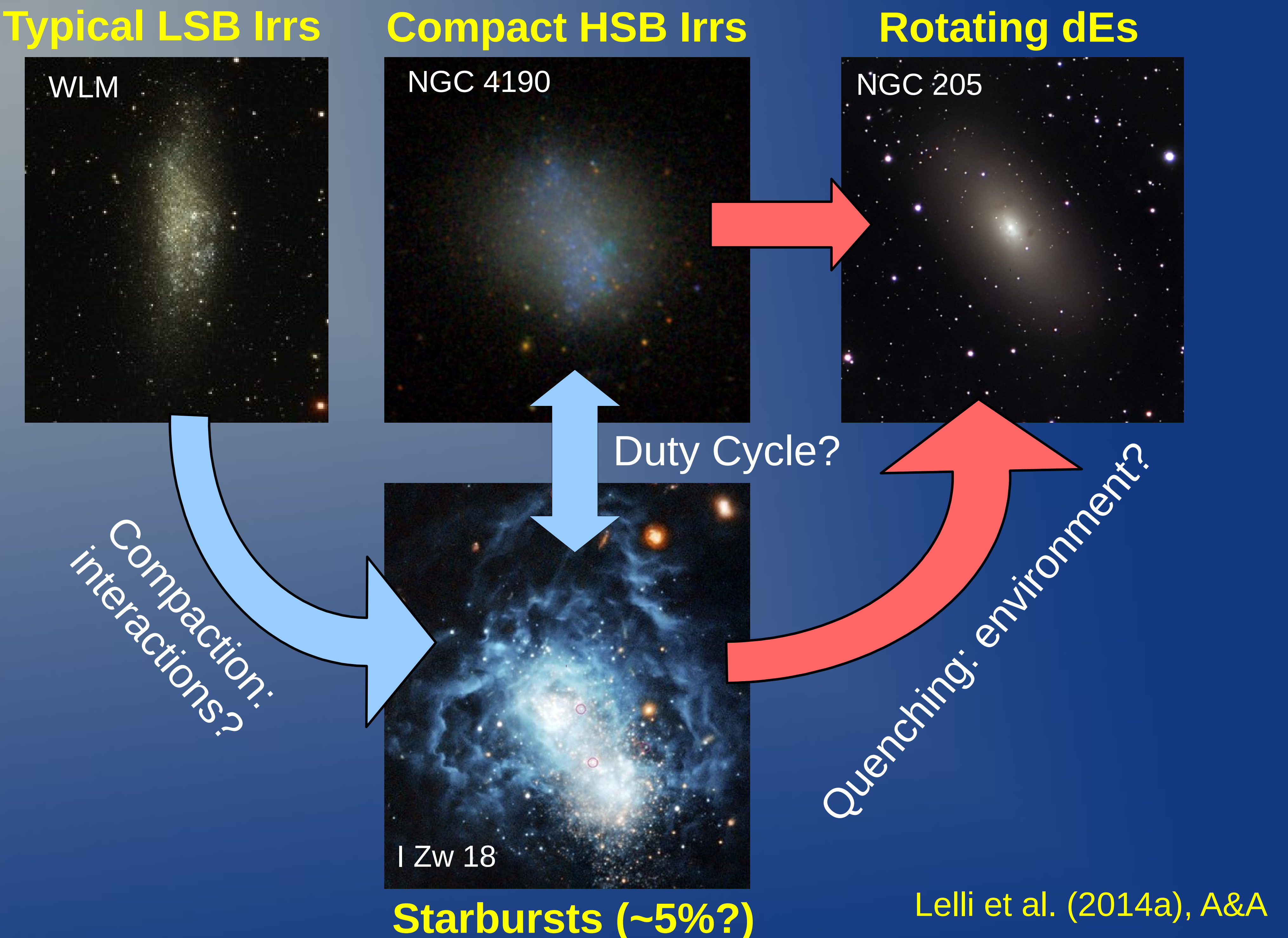
Lelli et al. (2014a), A&A

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



Starbursts (~5%?)

Lelli et al. (2014a), A&A


Typical LSB Irrs
Compact HSB Irrs
Rotating dEs
WLM
NGC 4190
NGC 205
Duty Cycle?
Compaction: interactions?
Quenching: environment?
I Zw 18
Starbursts (~5%?)
Lelli et al. (2014a), A&A

Summary on Starburst Dwarfs

- Starbursts are triggered by external mechanisms

  Interactions/mergers or cold gas accretion

- No evidence for massive gas outflows

  Stellar feedback may play a role but on local scales

- Starbursts have high central mass concentrations

  Star Formation <--> Inner Gravitational Potential

  Starburst Dwarfs <--> Compact Irr or Rotating dE/Sph

Tidal Dwarf Galaxies

In collaboration with:

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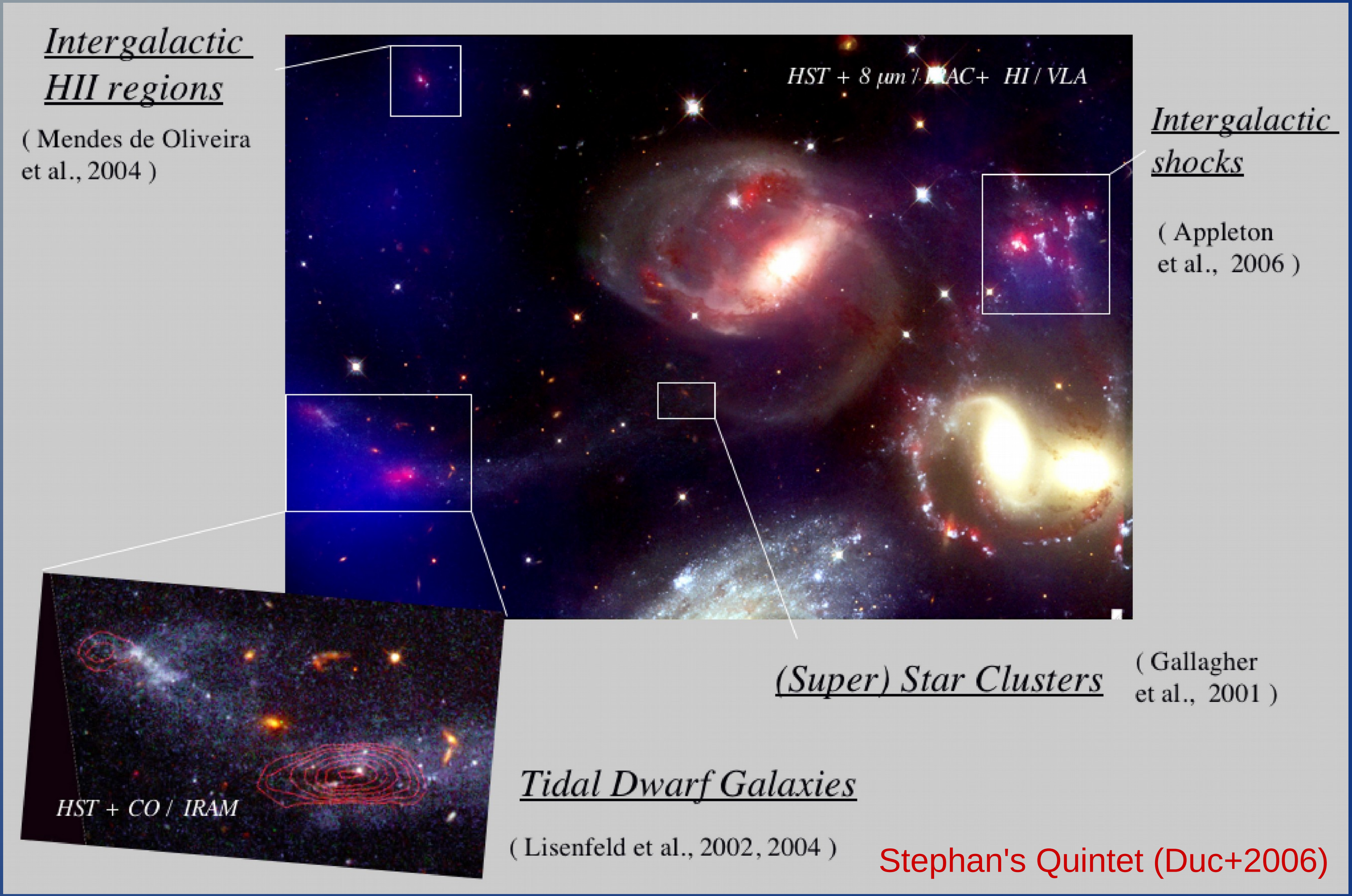
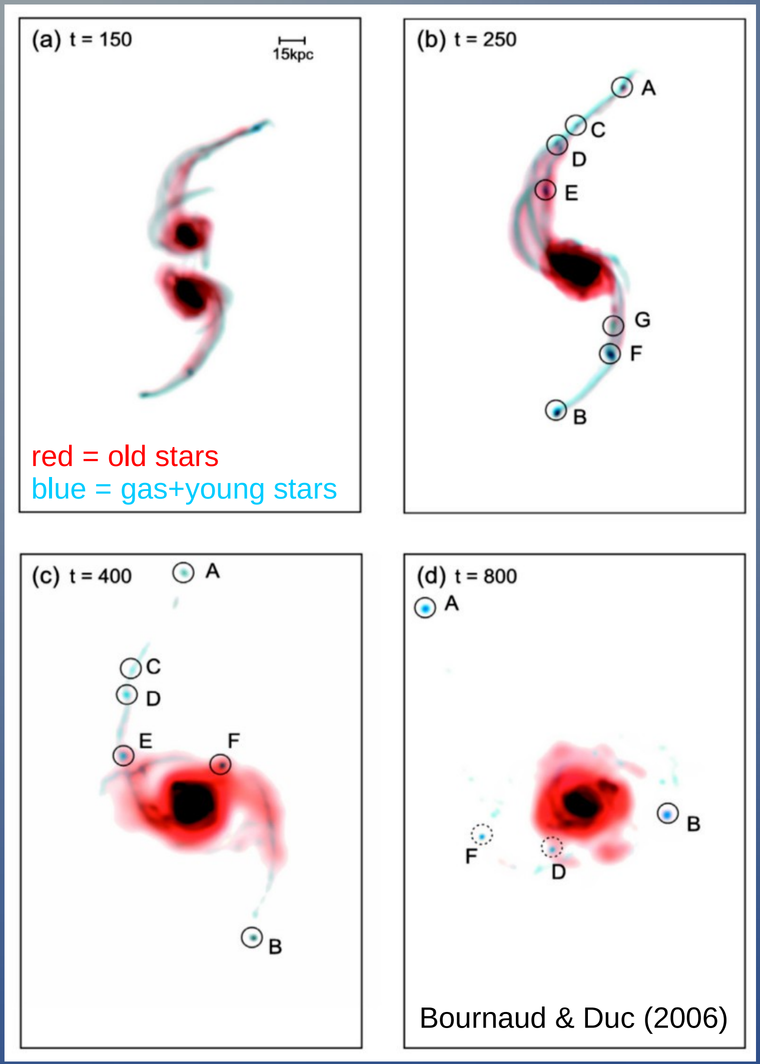
What is a Tidal Dwarf Galaxy (TDG)?

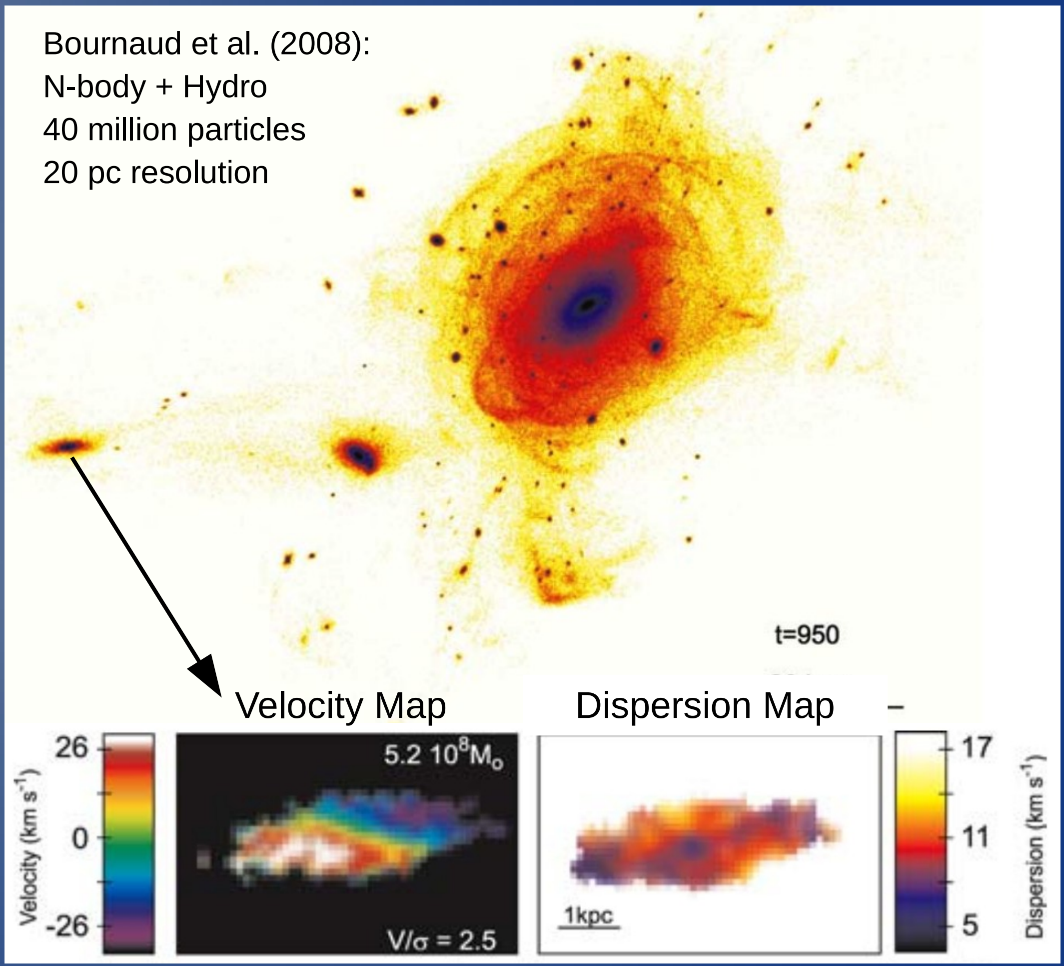
Different types of objects are formed during interactions/mergers:



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

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  - Disc --> tails, bridges, and eventually TDGs
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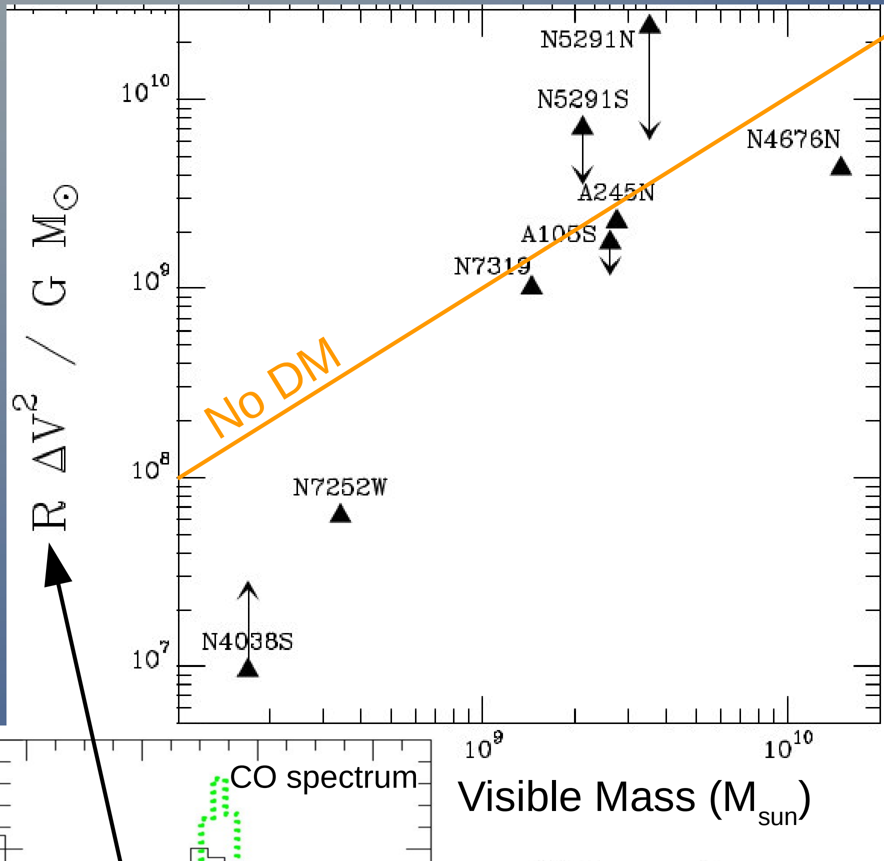
- Baryons & DM are "segregated" in phase-space

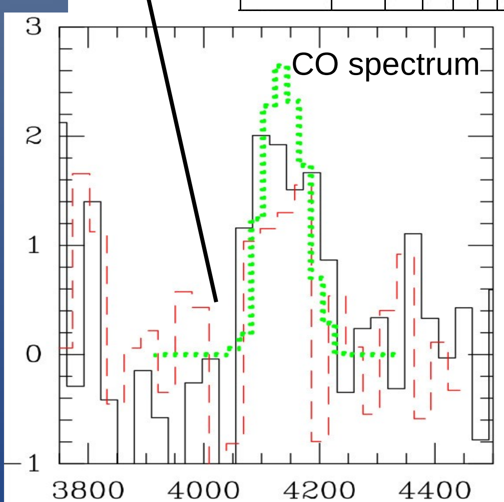
- TDGs have shallow potential wells with V_{rot} < 50 km/s:

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

Previous kinematic studies on TDGs

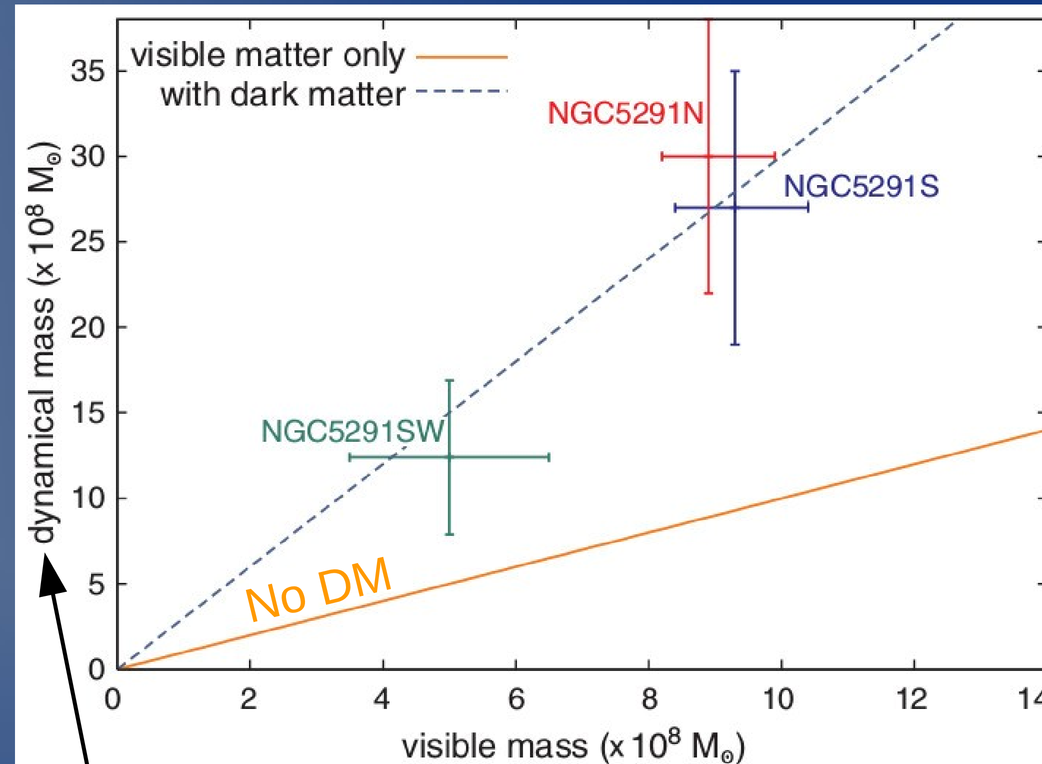
Braine+2001: No evidence of DM!

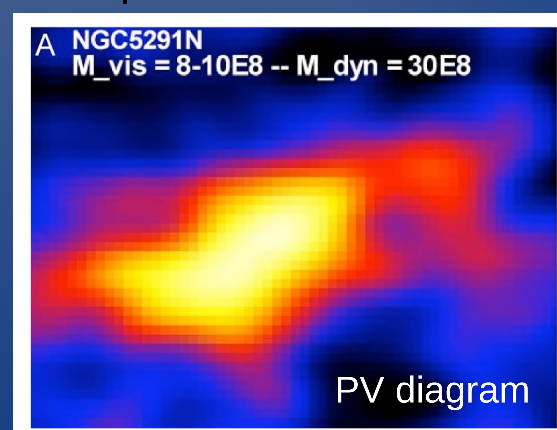




Rotation velocities from CO line-widths (TDGs unresolved)

Bournaud+2007: Evidence of DM!

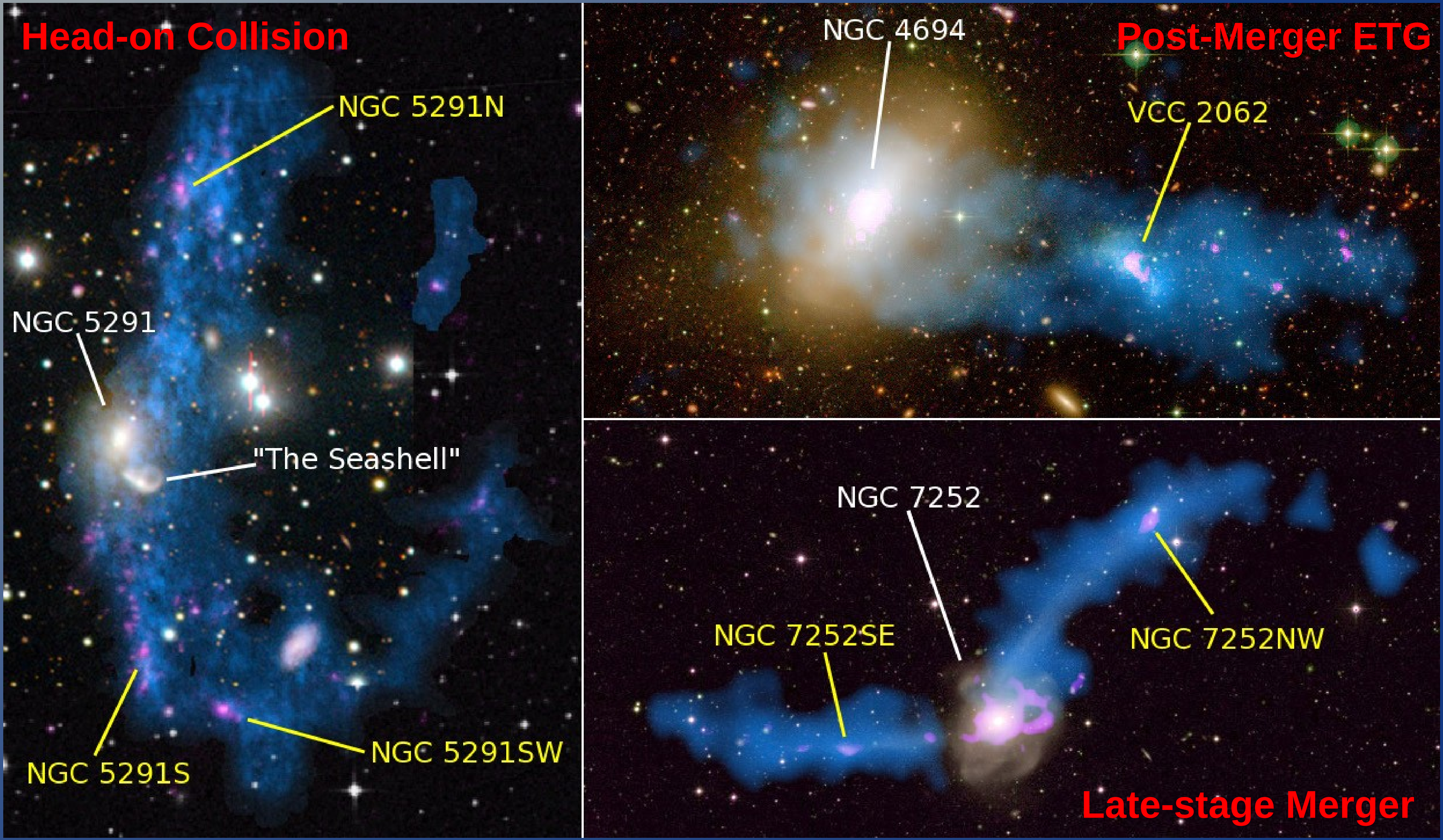




Rotation velocities from HI interferometry (TDGs barely resolved)

Missing mass in TDGs? CO-dark molecules?

Sample of 6 bona-fide TDGs



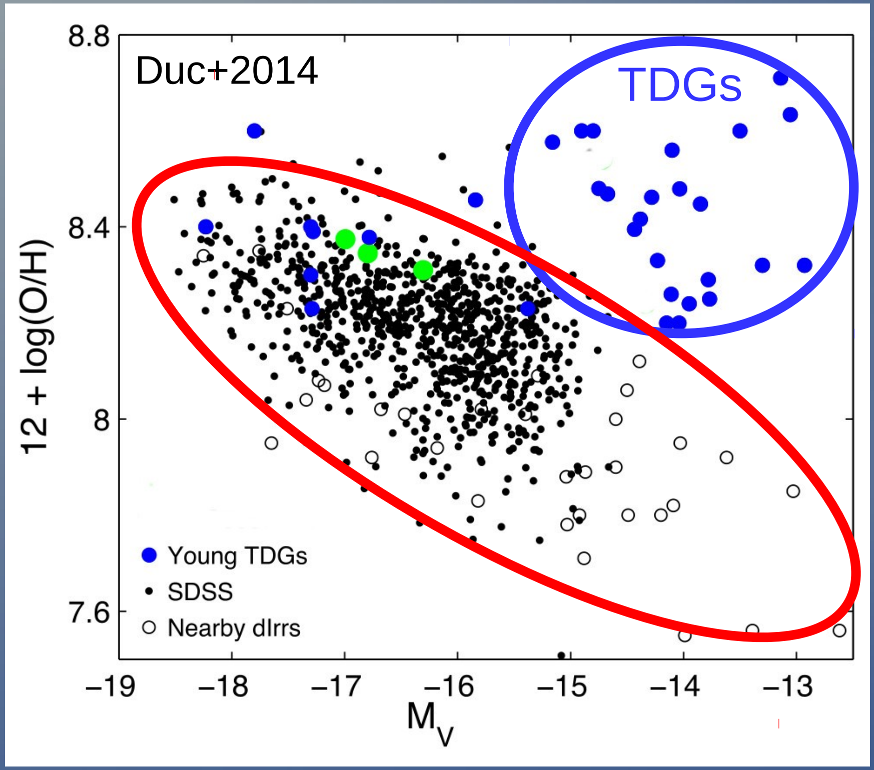
Blue = HI (VLA)
Pink = FUV (GALEX)

Yellow = Tidal Dwarf Galaxies

Lelli, Duc, Brinks et al. 2015, A&A

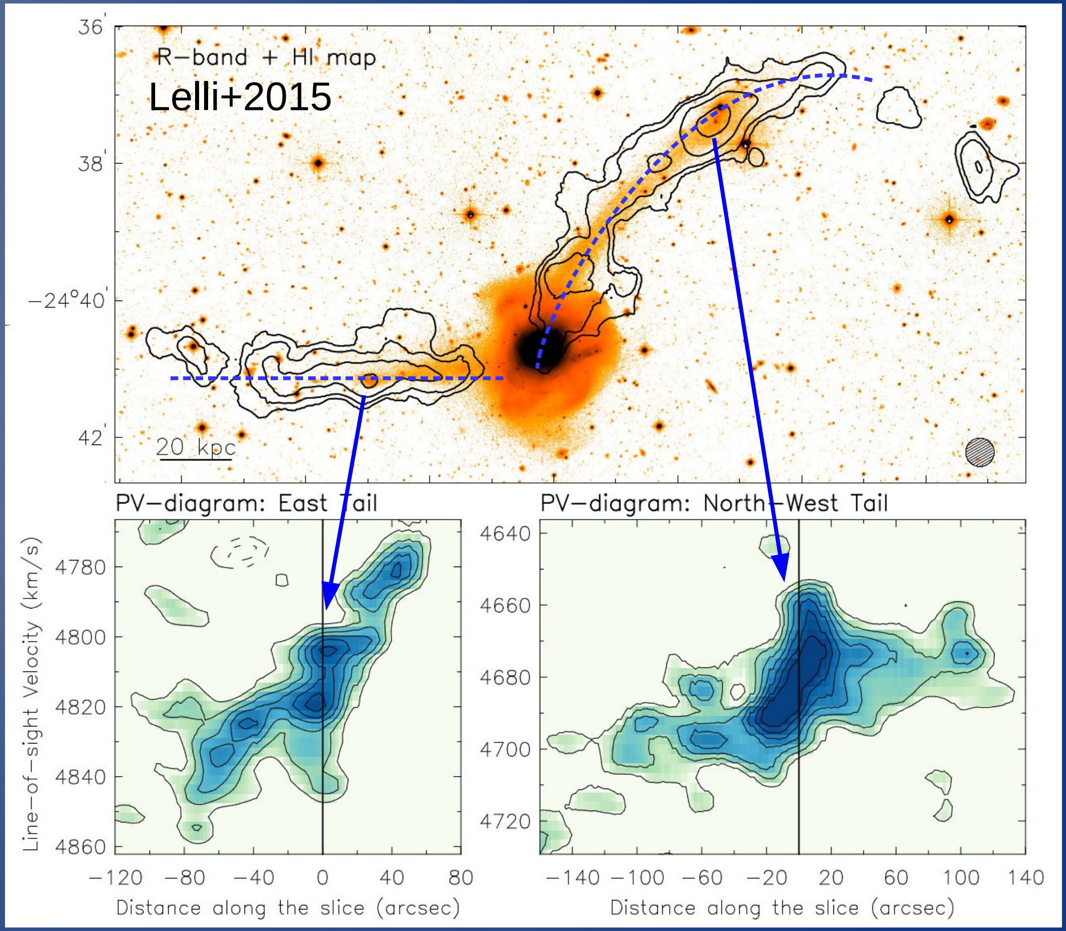
Requirements to be a bona-fide TDG

1) High metallicities



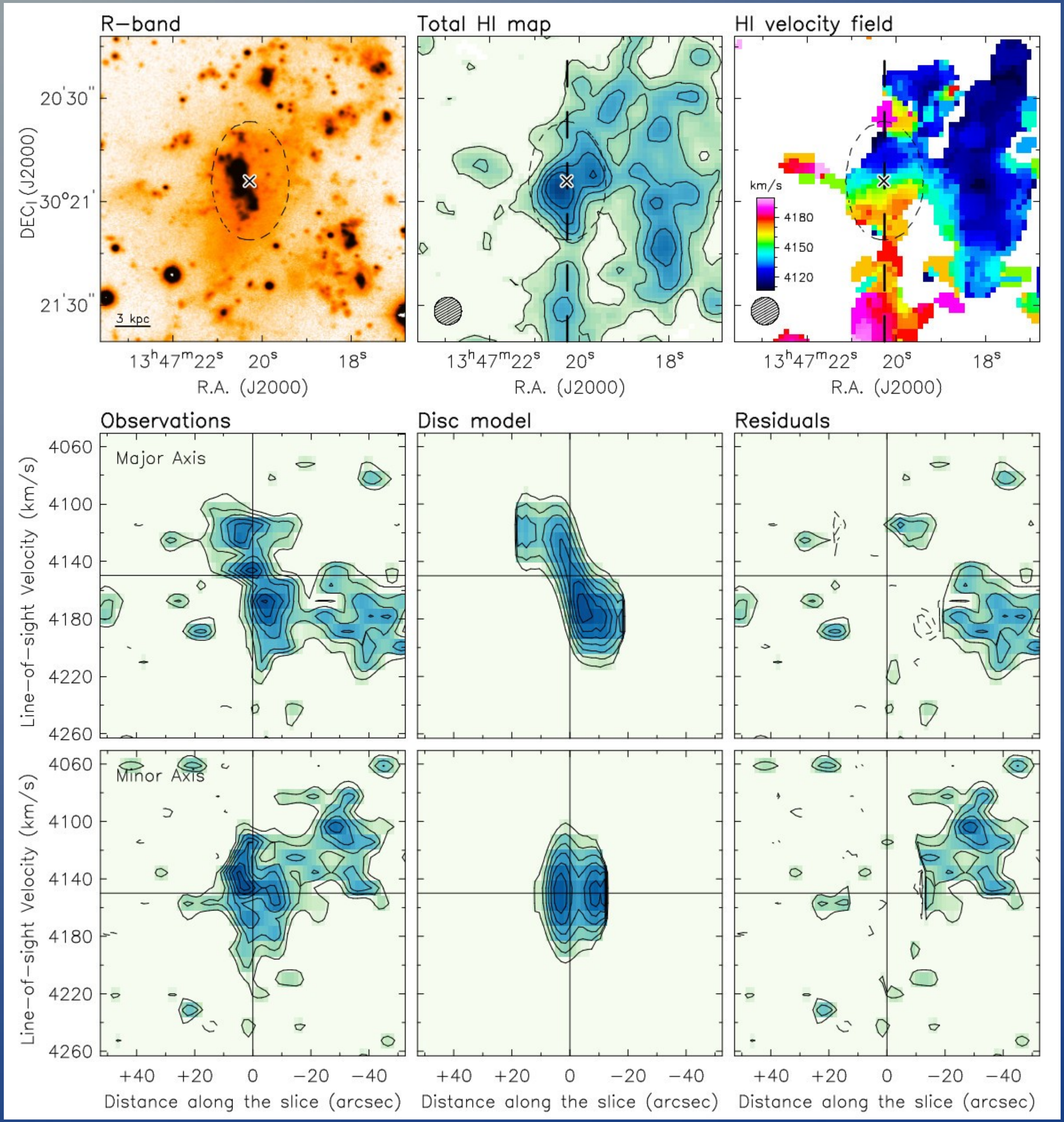
Young TDGs are forming out of pre-enriched material ejected from massive progenitors!

2) Kinematically distinct components



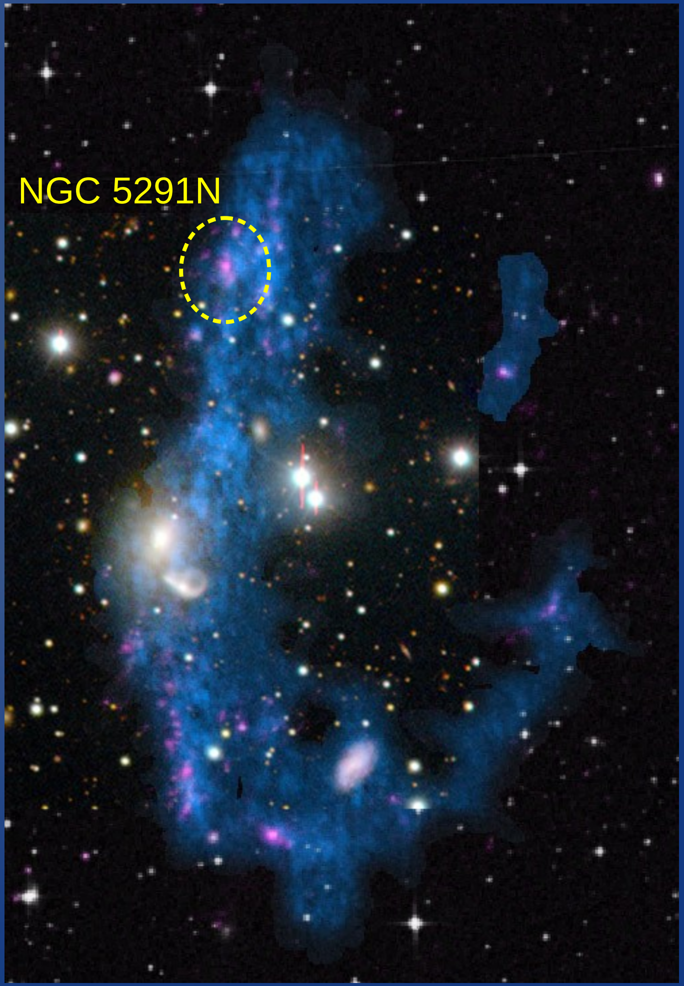
TDGs are associated with steep HI velocity gradients: rotation in a local potential well? Gravitationally bound?

Rotating disk models for TDGs

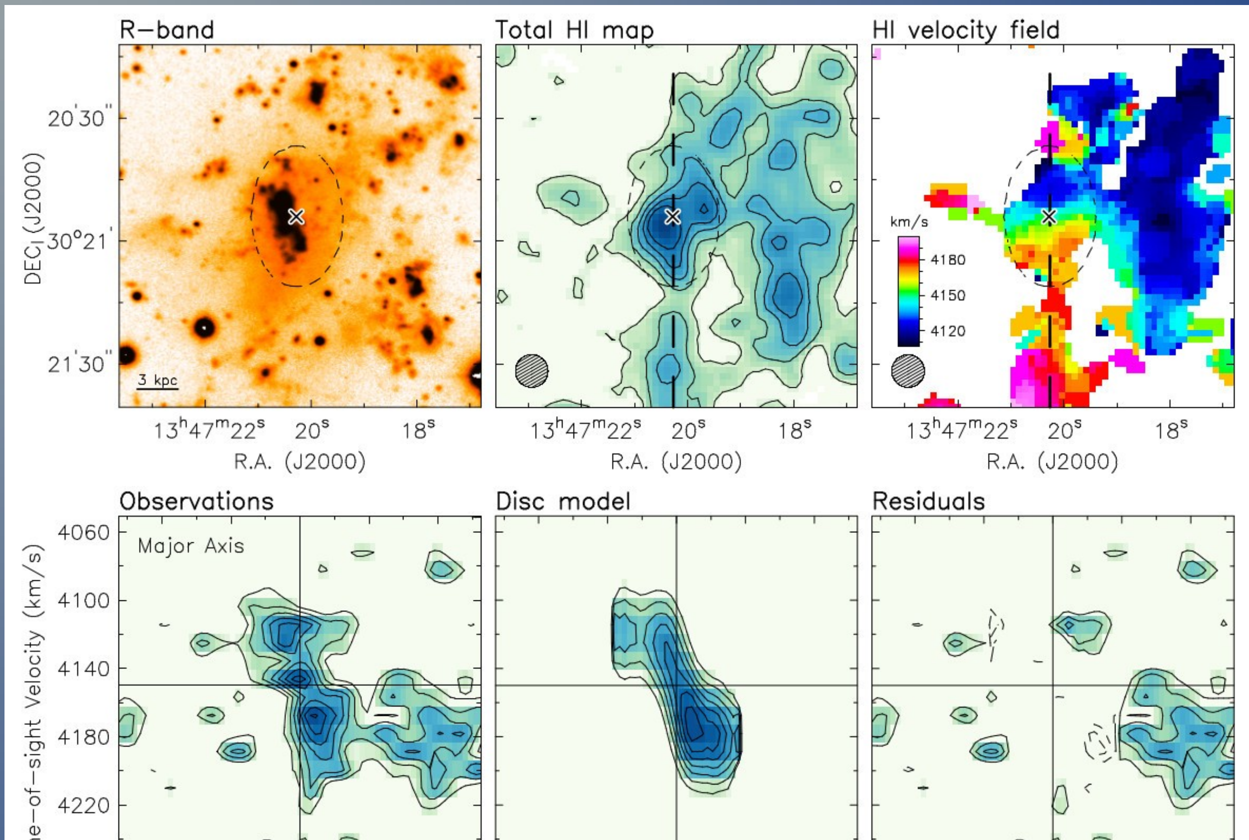


Lelli et al. (2015), A&A:

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



Rotating disk models for TDGs



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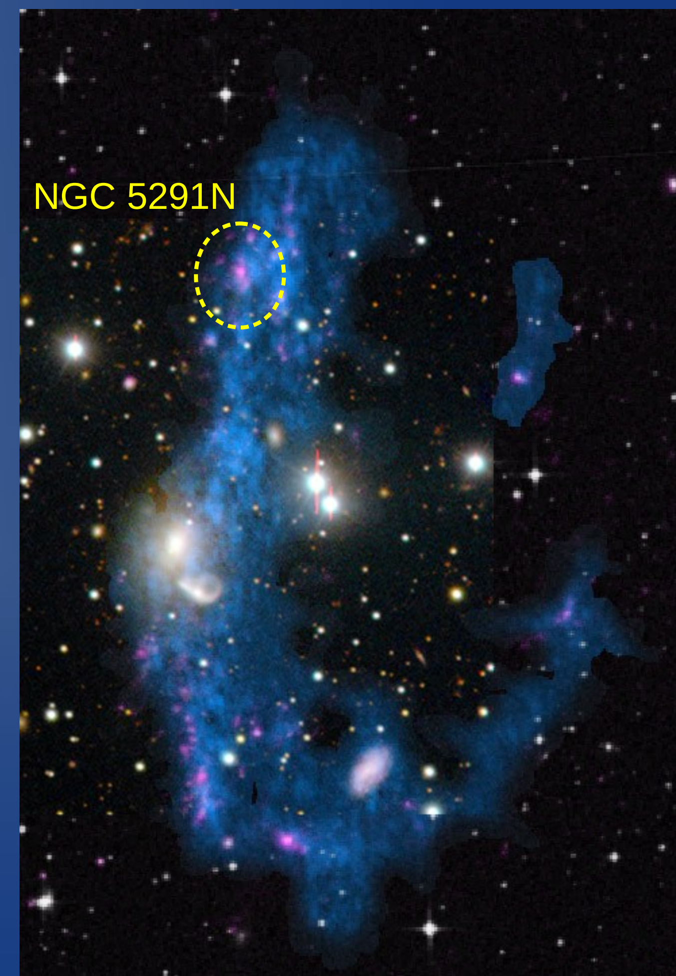


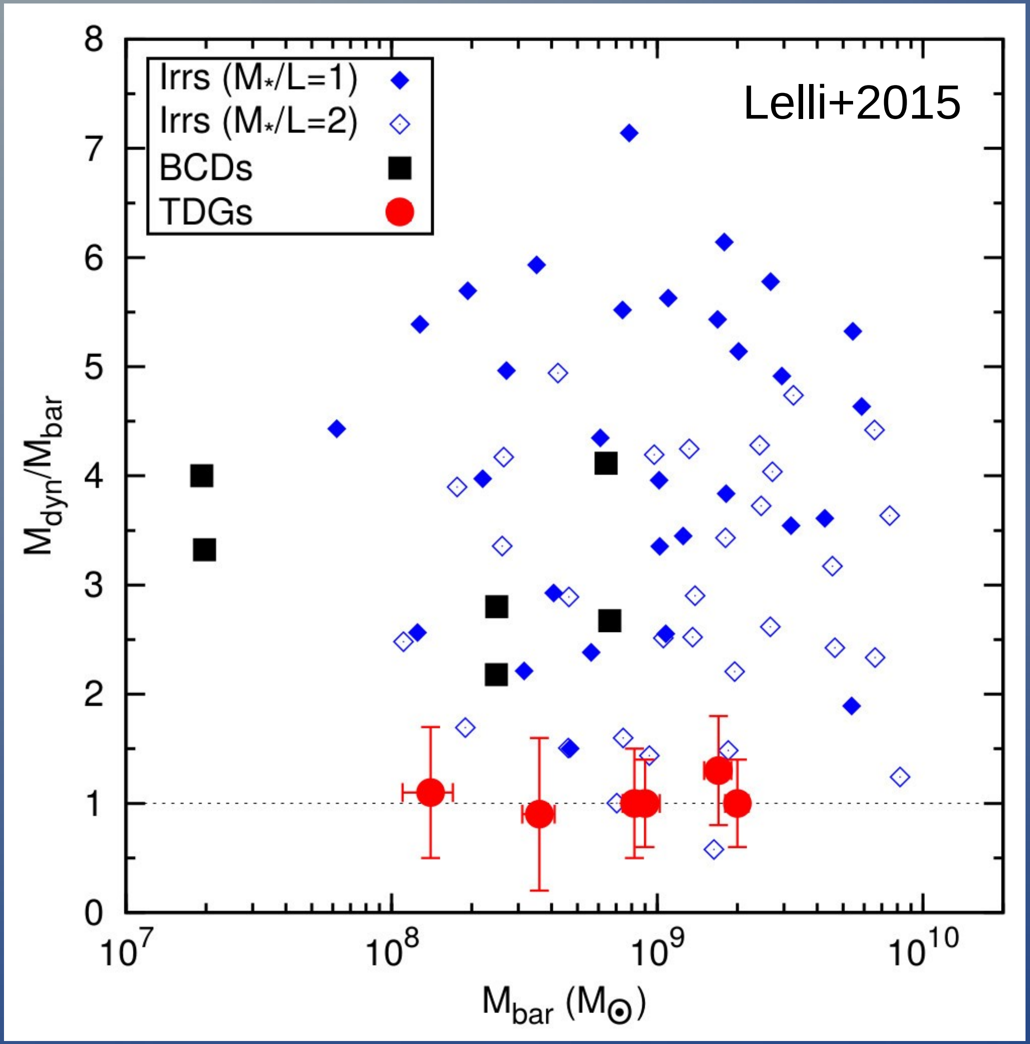
Puzzling Issue: $t_{orb} > t_{merg}$ (or TDG "age")

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

Are TDGs in dynamical equilibrium?

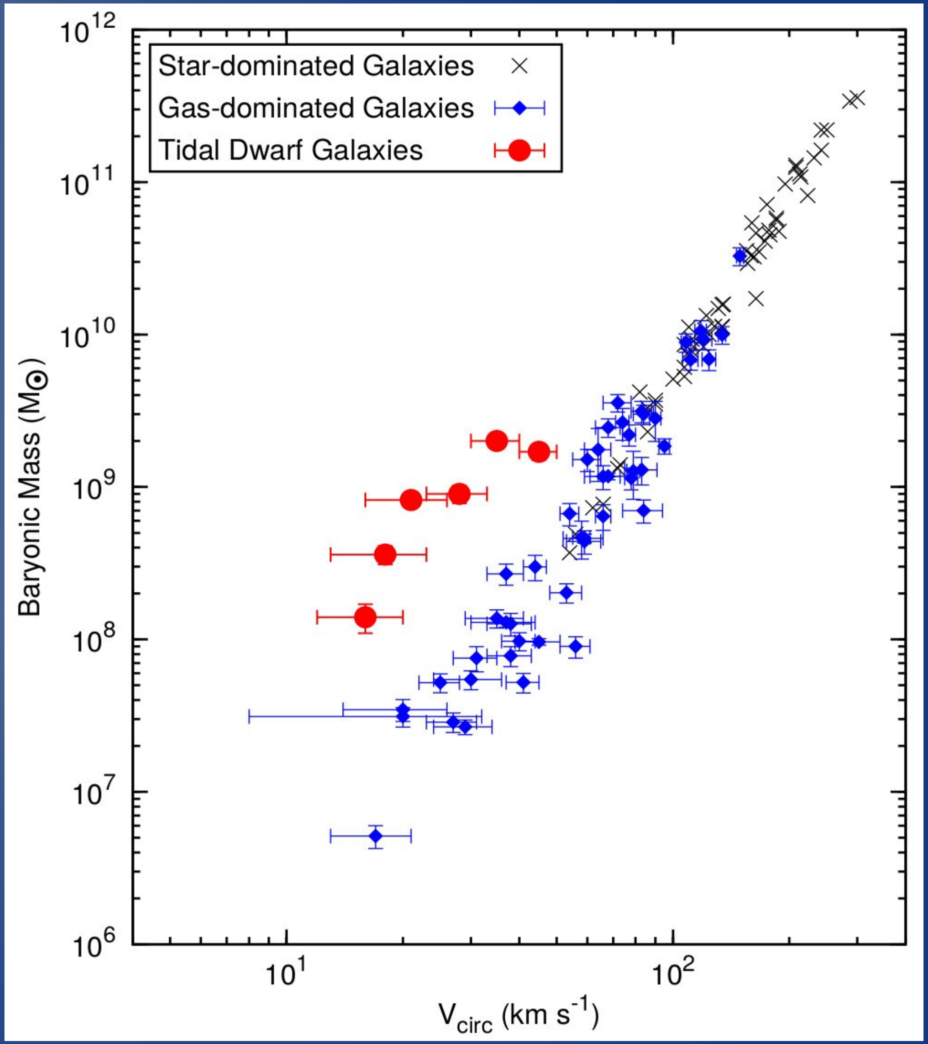
IF TDGs are in dynamical equilibrium...

No Dark Matter! (as expected from simulations)



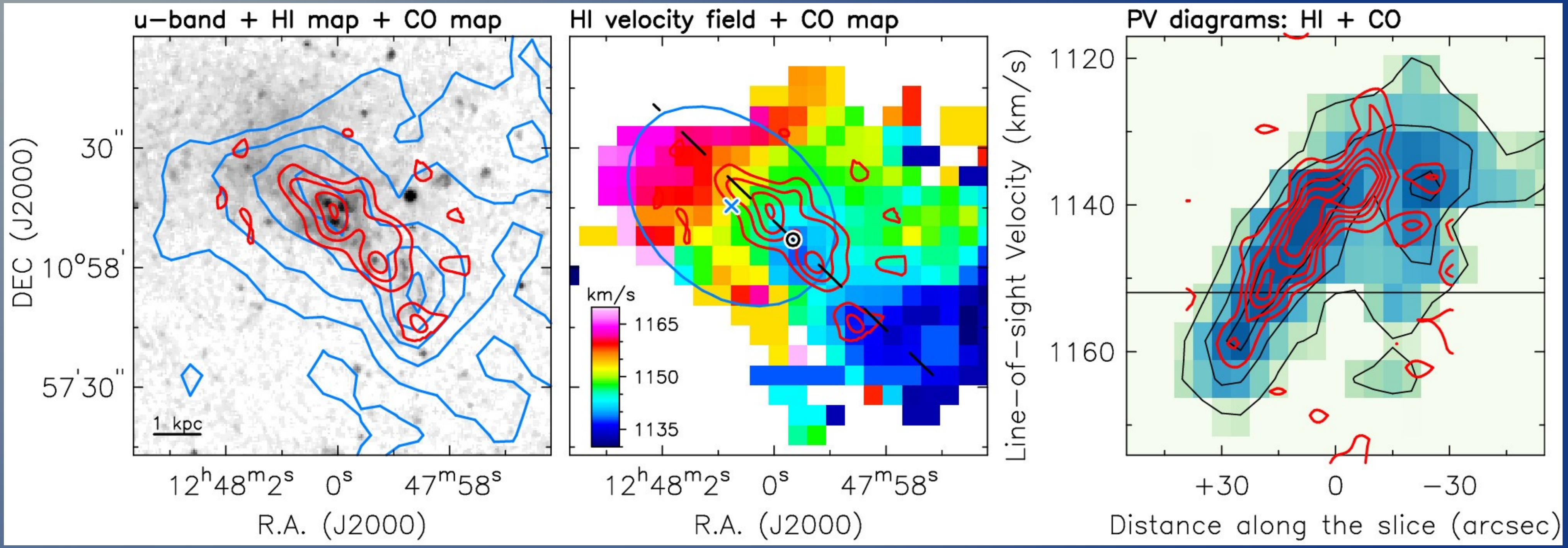
M_{dyn}/M_{bar} ~ 1! The high values reported by Bournaud et al. (2007) are *not* confirmed.

Deviation from the baryonic TF relation!



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

CO(1-0) in VCC 2062 from IRAM PdBI

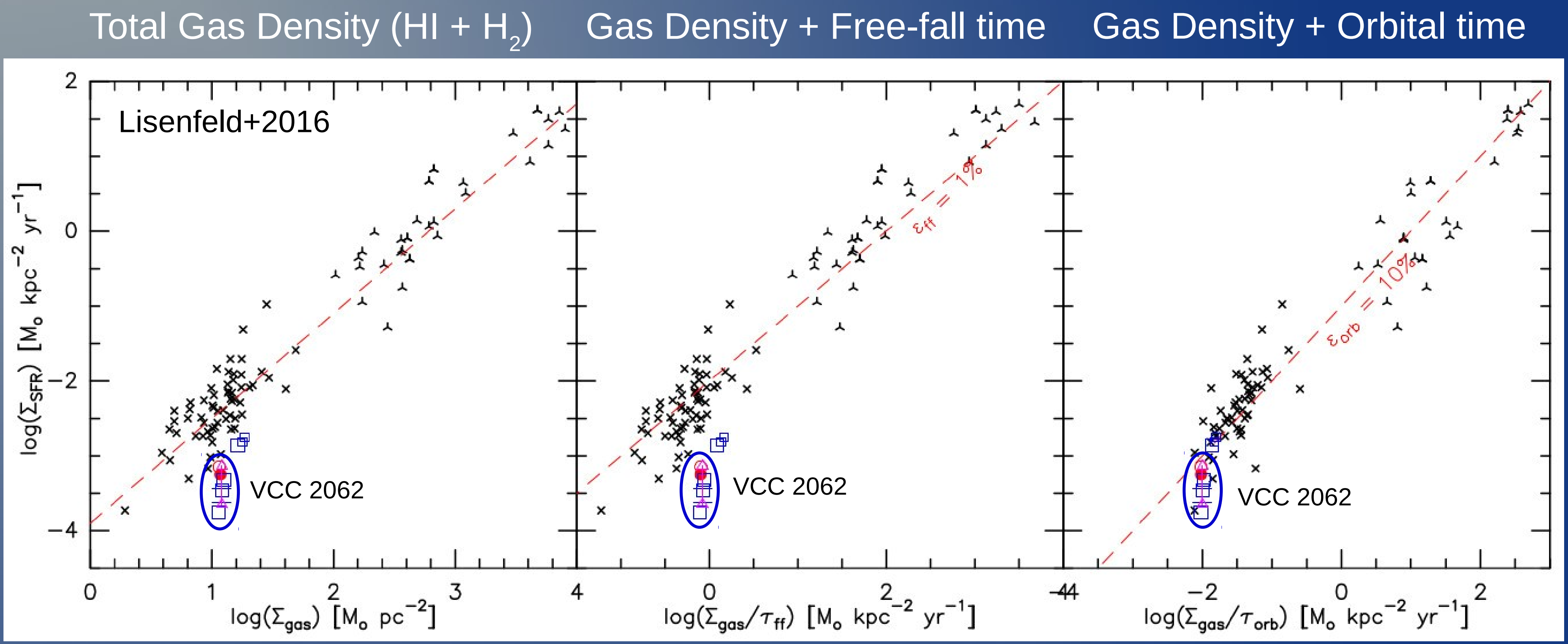


HI (blue) + CO (red)

Lisenfeld et al. 2016, A&A

- CO covers only a fraction of the HI disk
- CO and HI kinematics are consistent
- CO forms locally within the tidal HI debris

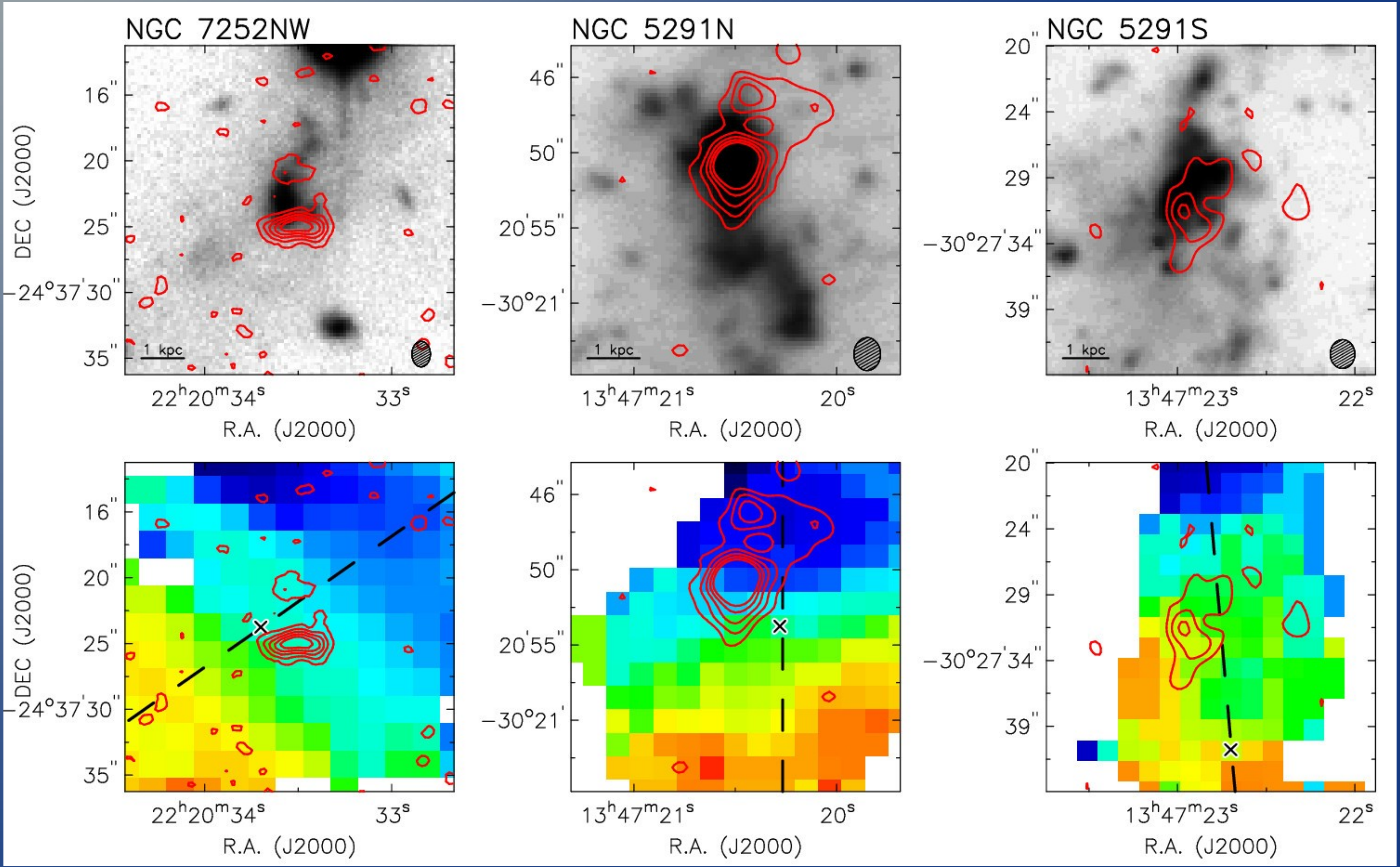
Star-Formation Laws in VCC 2062



Star-Formation Efficiency in VCC 2062 lower than in normal galaxies:

- Low stellar surface density (low vertical force)?
- Intermittent star-formation (short temporal variations)?
- Long orbital times (low DM fraction)?

CO(1-0) in TDGs from ALMA



Lelli et al. in preparation

Summary on Tidal Dwarf Galaxies

- TDGs are clumps of HI, molecules, and young stars:

  Masses, sizes, and SFRs similar to dwarf galaxies

- TDGs are associated with rotating HI disks:

  No evidence for DM but dynamical equilibrium is an issue!

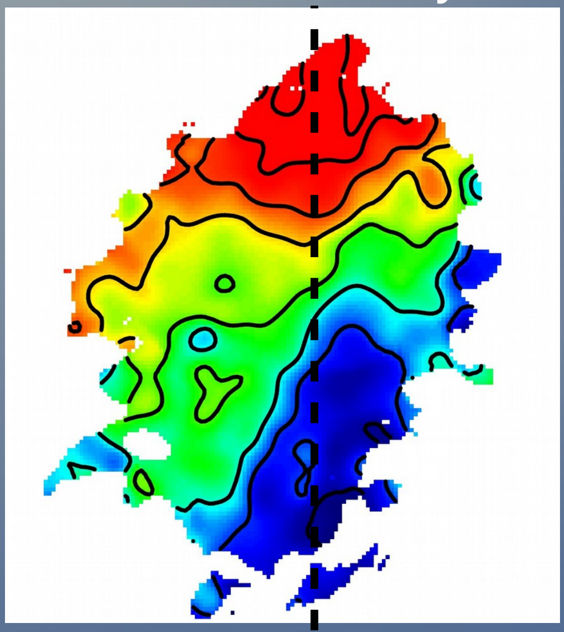
- Molecular gas seems less efficient in forming stars:

  Reasons unclear. New ALMA data under analysis!

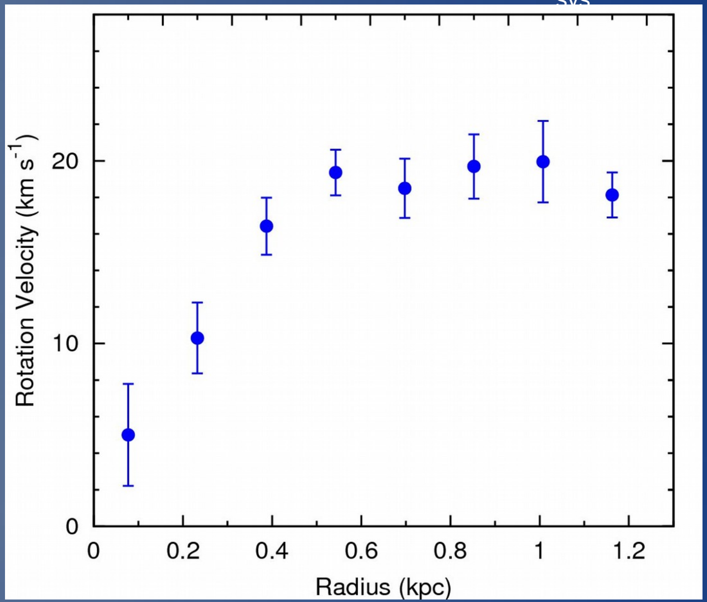
More Slides

Derivation of the Rotation Curve

2D fit to the Velocity Field



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



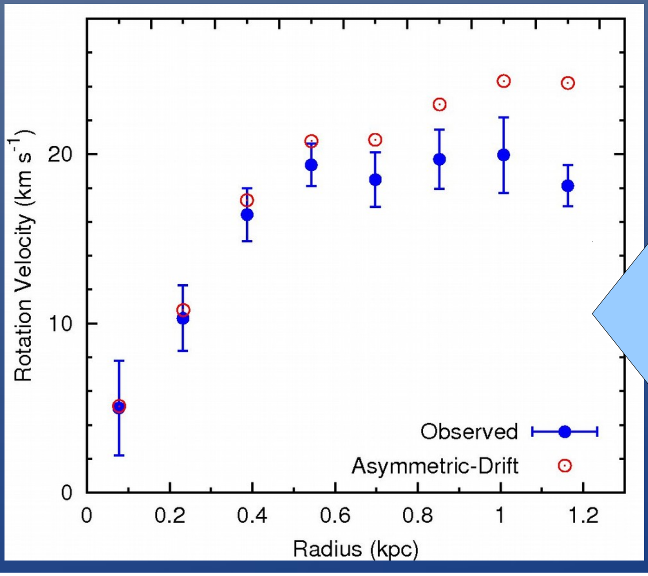
V_{rot} ~ 20 km/s

V_{rad} ~ 5 km/s

σ_{HI} ~ 8 km/s

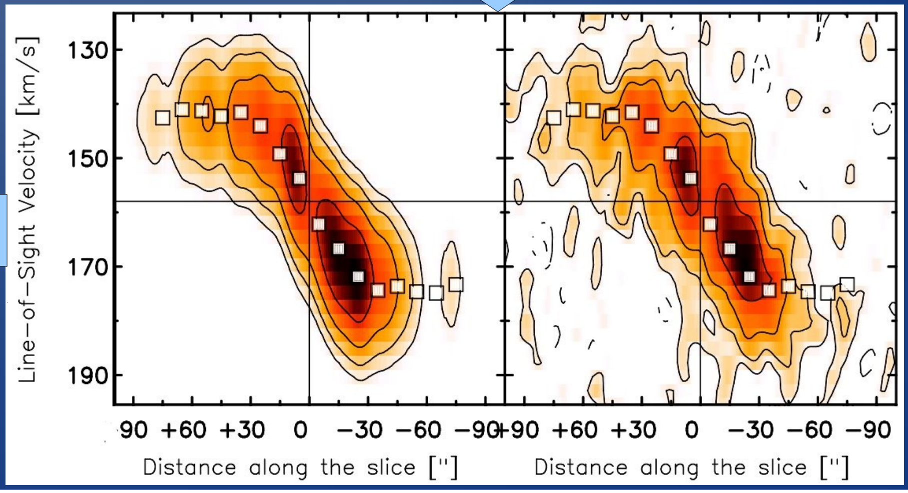
V_{rot}/σ_{HI} ~ 2-3

Correction for pressure-support



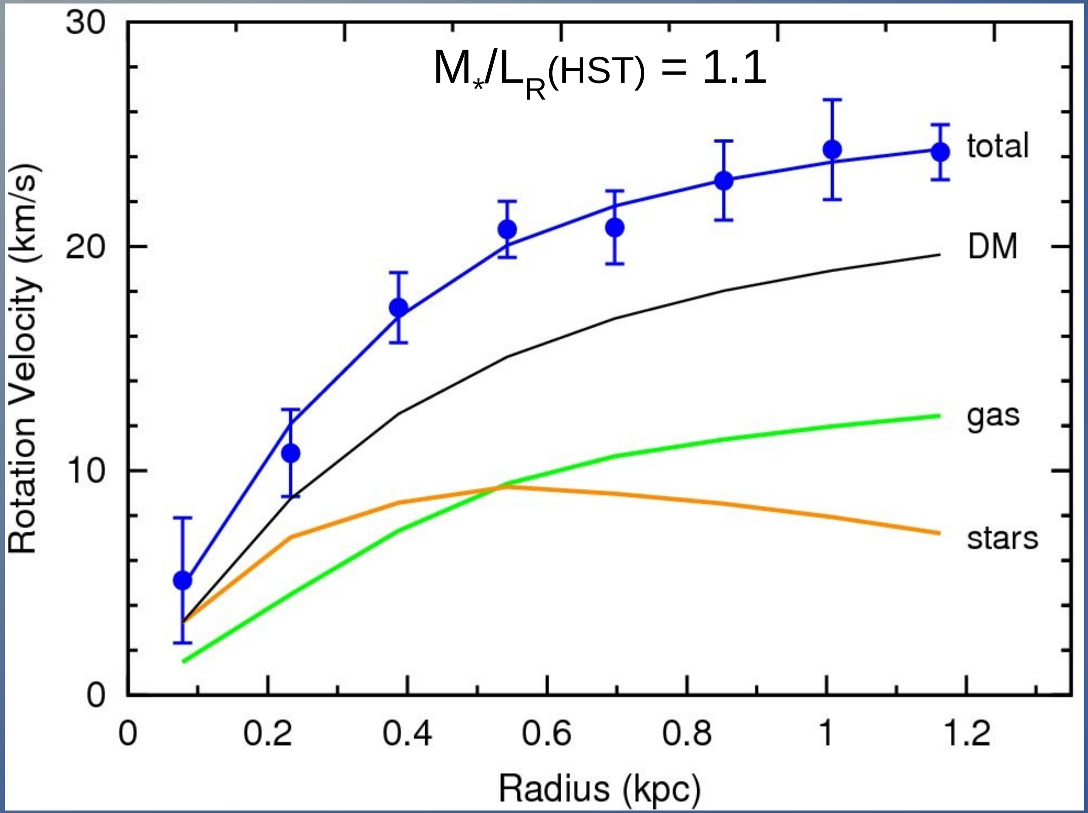
3D disk model

Observations



Mass Model Example: UGC 4483

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



M_{dyn} = (16 ± 3) x 10^7 $M_\odot$

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

Assuming Salpeter IMF (McQuinn+2010)

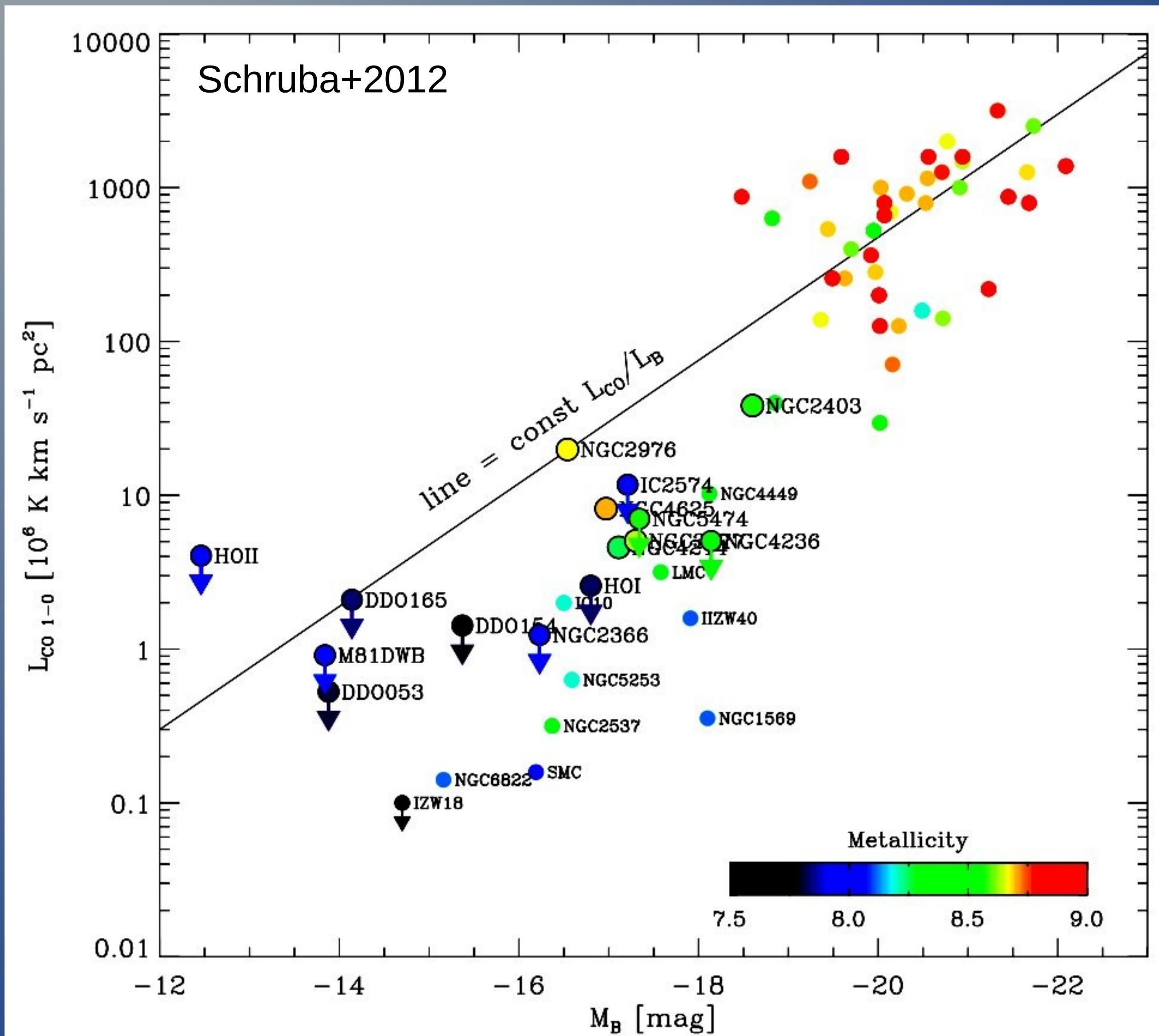
M_{gas} = (3.3 ± 0.4) x 10^7 $M_\odot$

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

M(molecules) ~ ?

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

Molecular mass is unknown...



Dwarfs are metal-poor

CO lines undetected

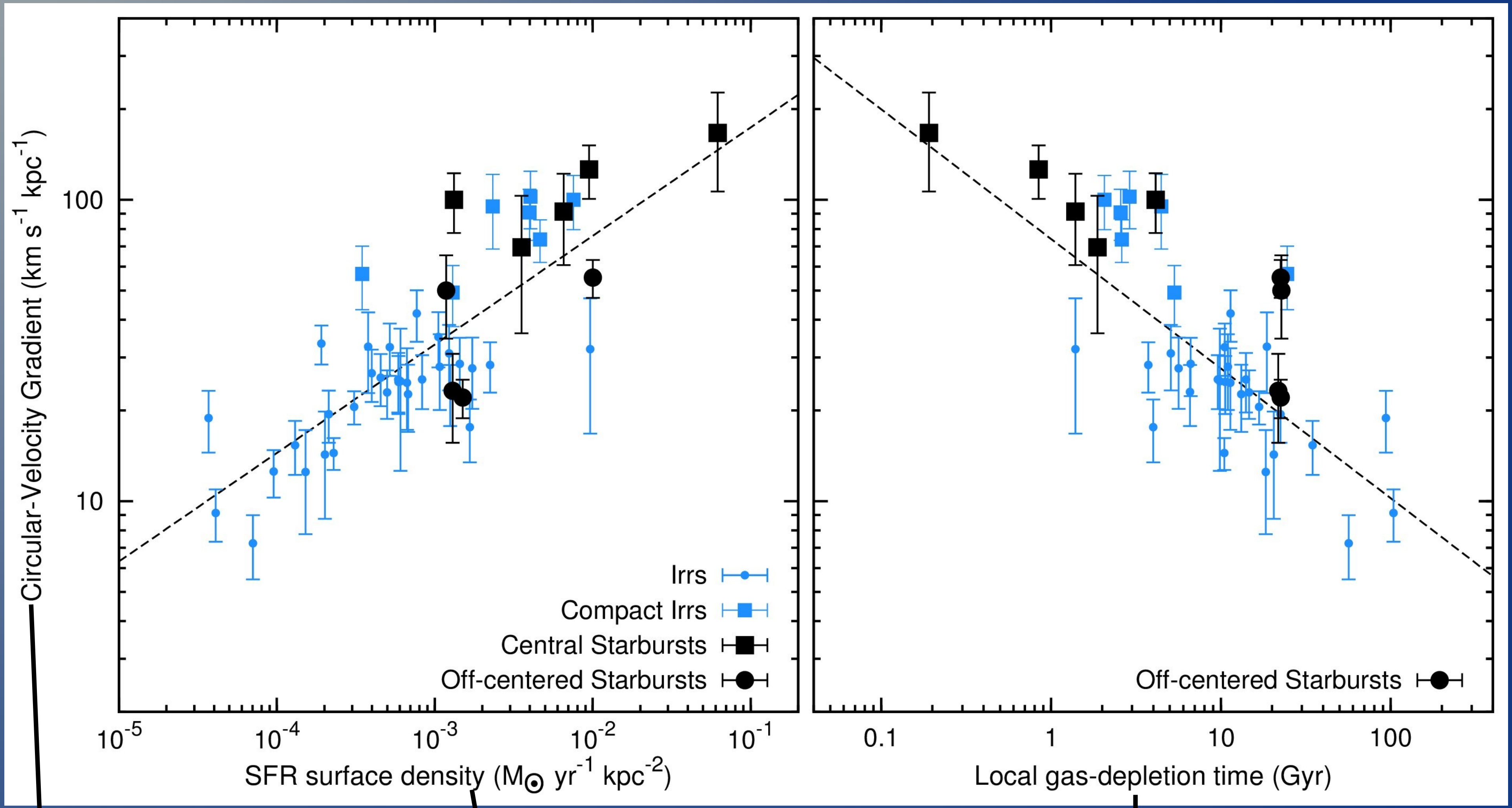
CO-to-H_2 conversion may depend on Z!

Indirect estimate:

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

(e.g. Leroy+2008)

Link: Dynamics - Star Formation



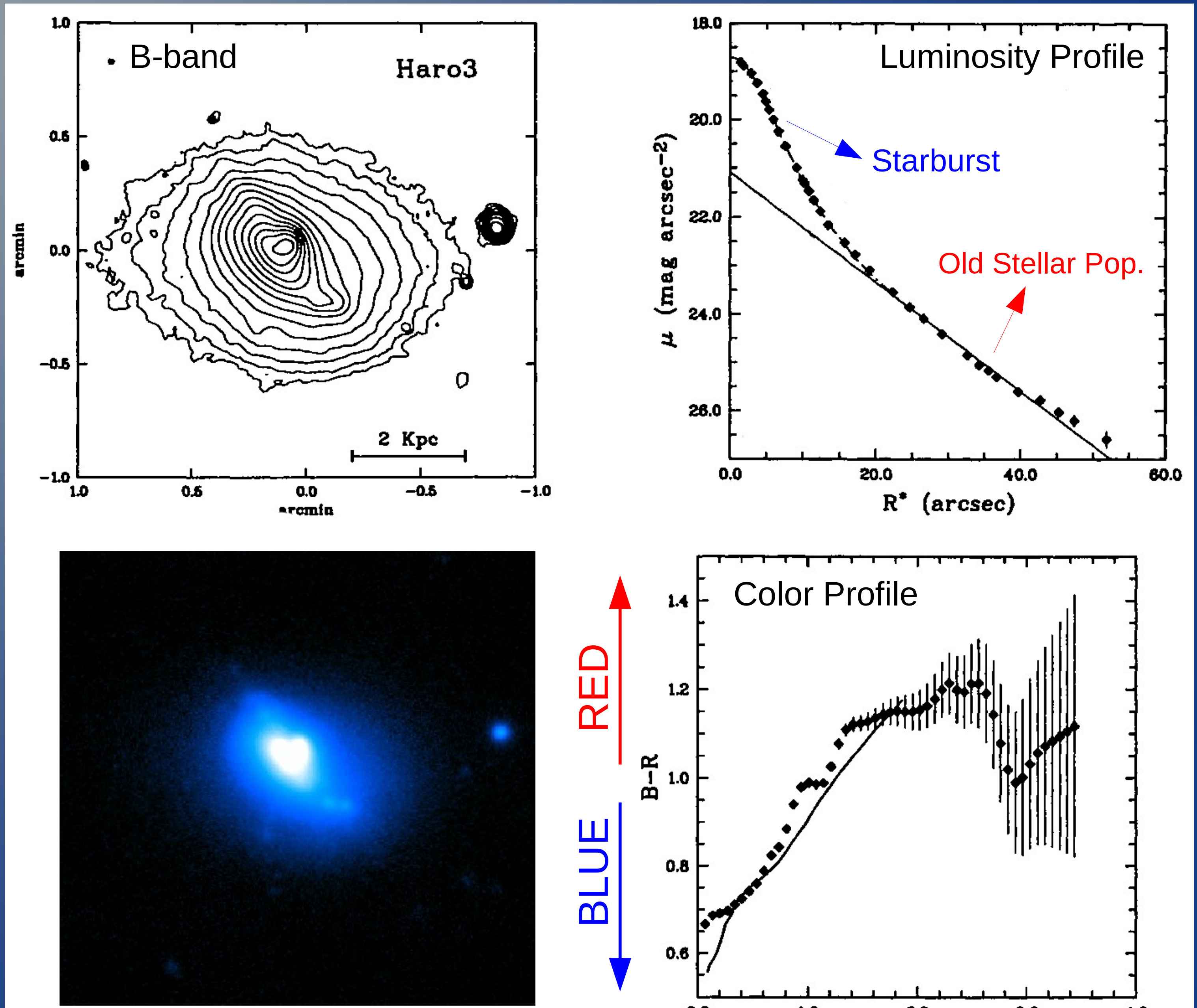
$V(R_d)/R_d \propto \Sigma_{Toomre}$

$\Sigma_{SFR} = SFR_{H\alpha}/(\pi\, R_{opt}{}^{2})$

Hα fluxes from Kennicutt+2008

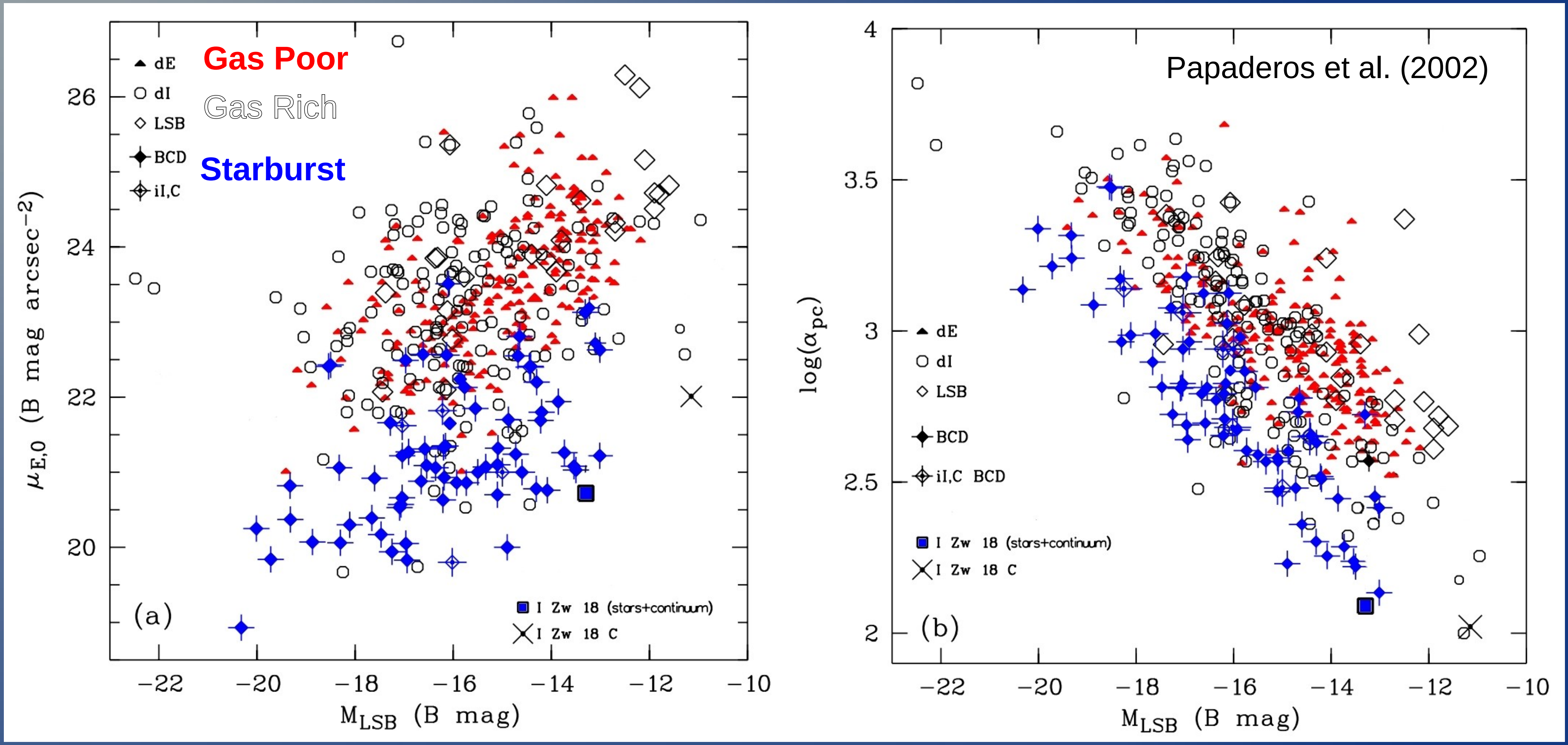
$T_{dep} = \Sigma_{SFR} / \Sigma_{gas}$

Optical Structure of BCDs



Papaderos et al. (1996)

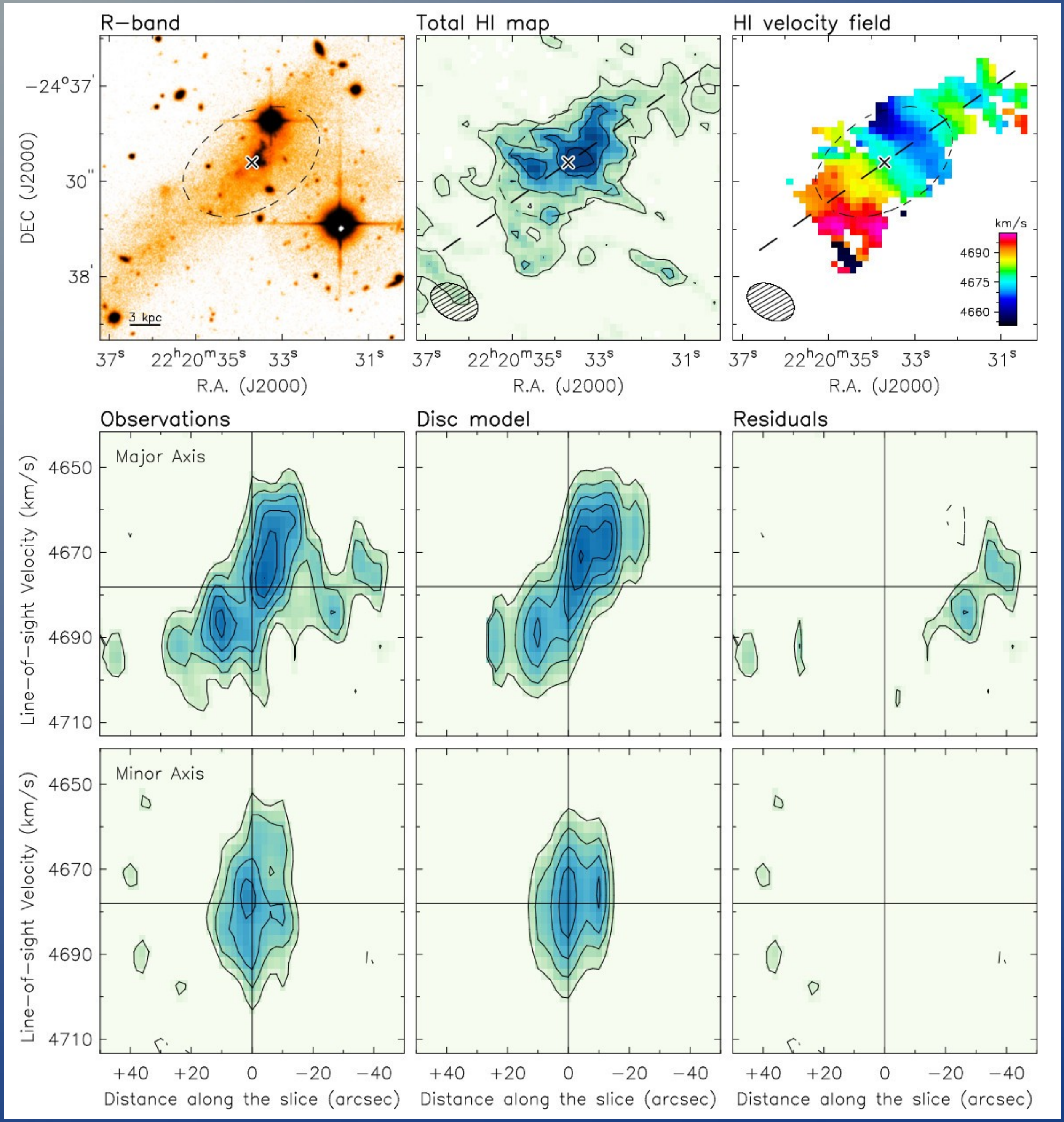
Optical Structure of BCDs



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).

Rotating disk models for TDGs



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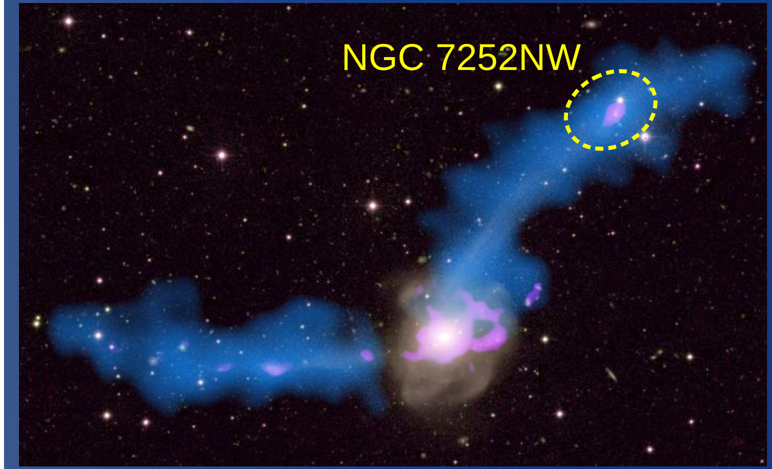
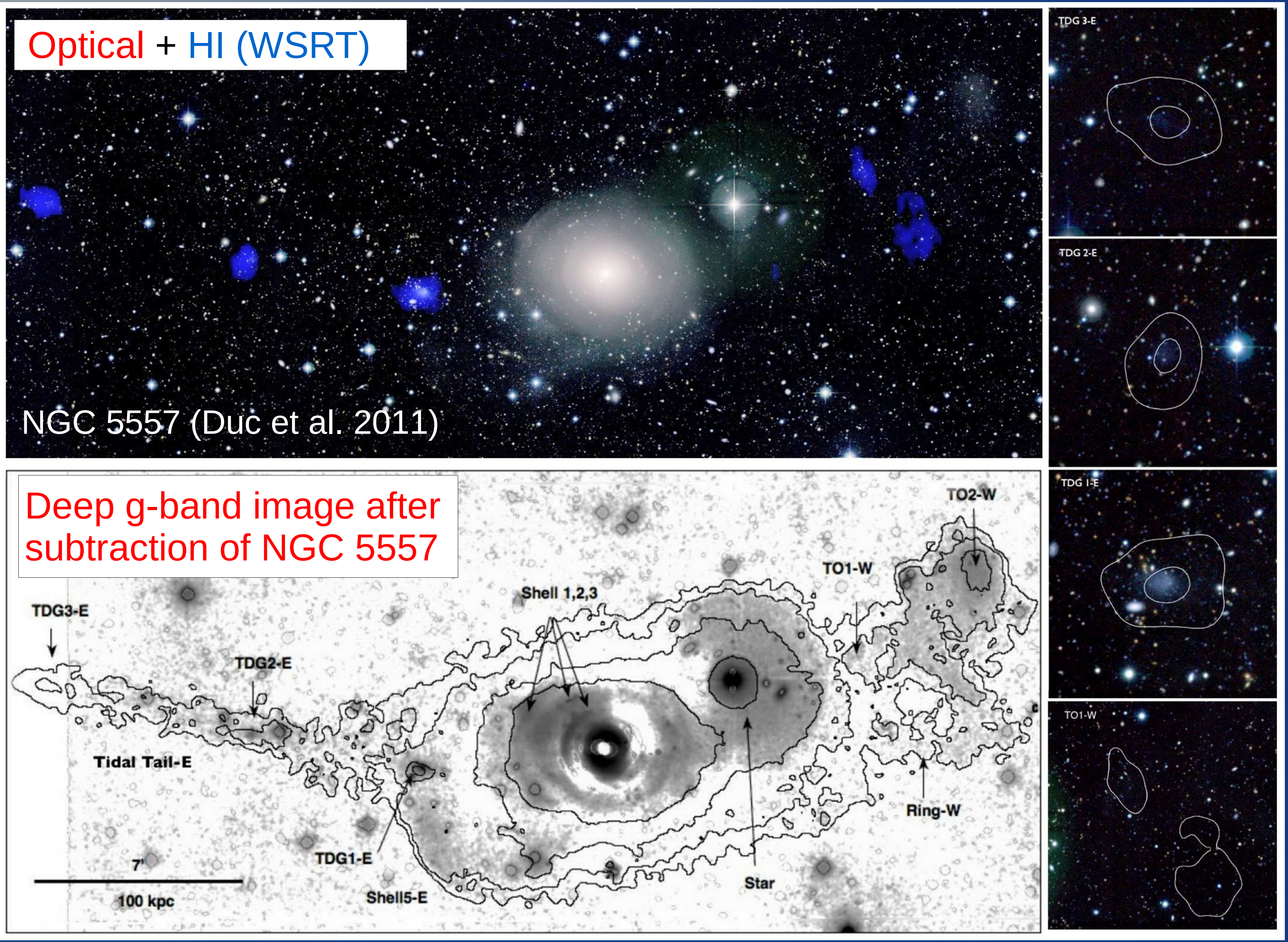


V_{rot} ~ 20 km/s

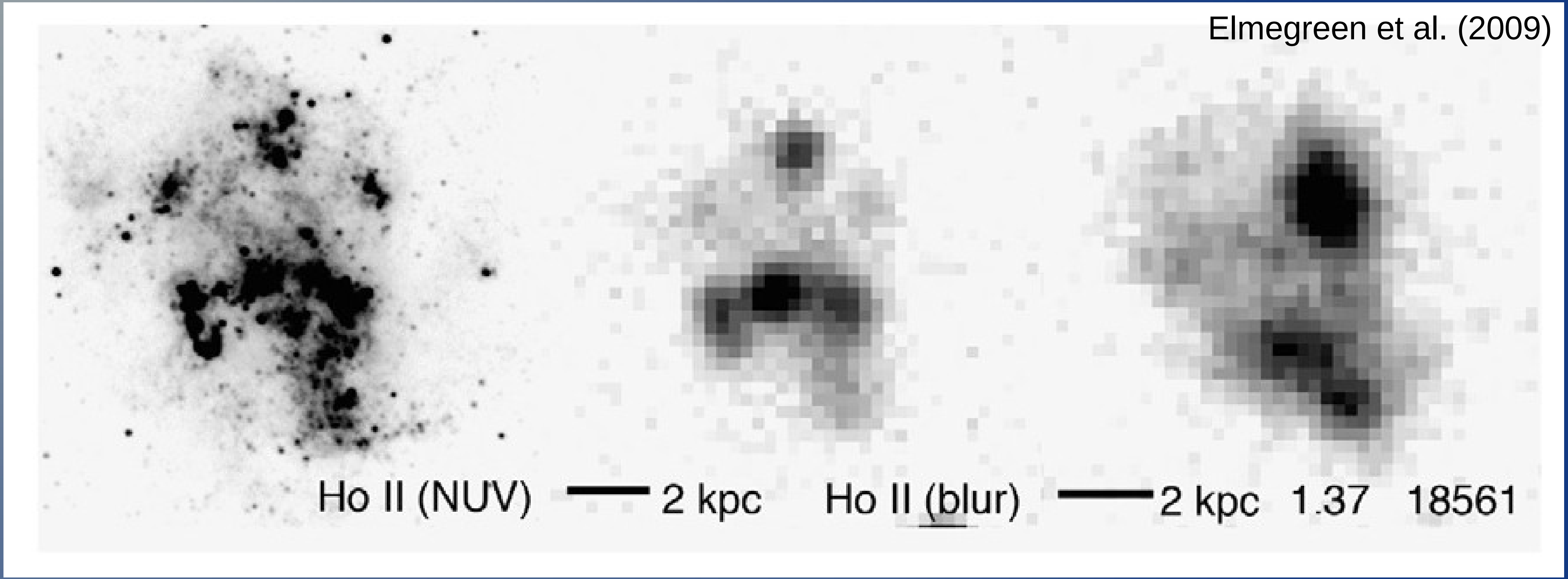
R_{HI} ~ 8 kpc

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

Old TDGs around Ellipticals

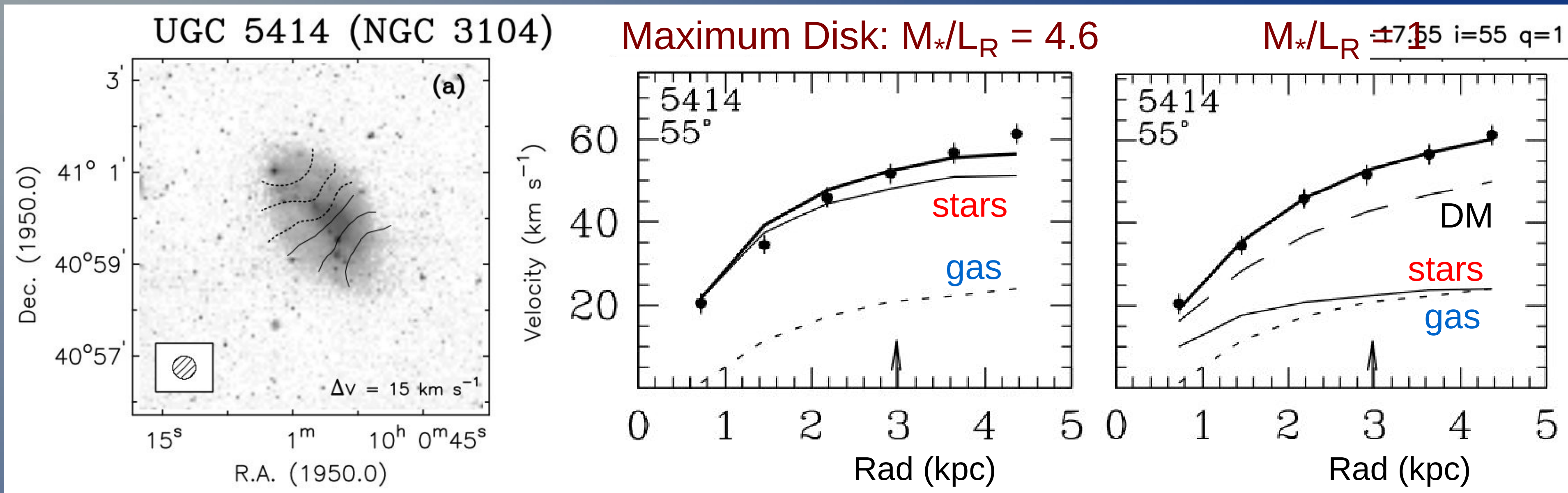


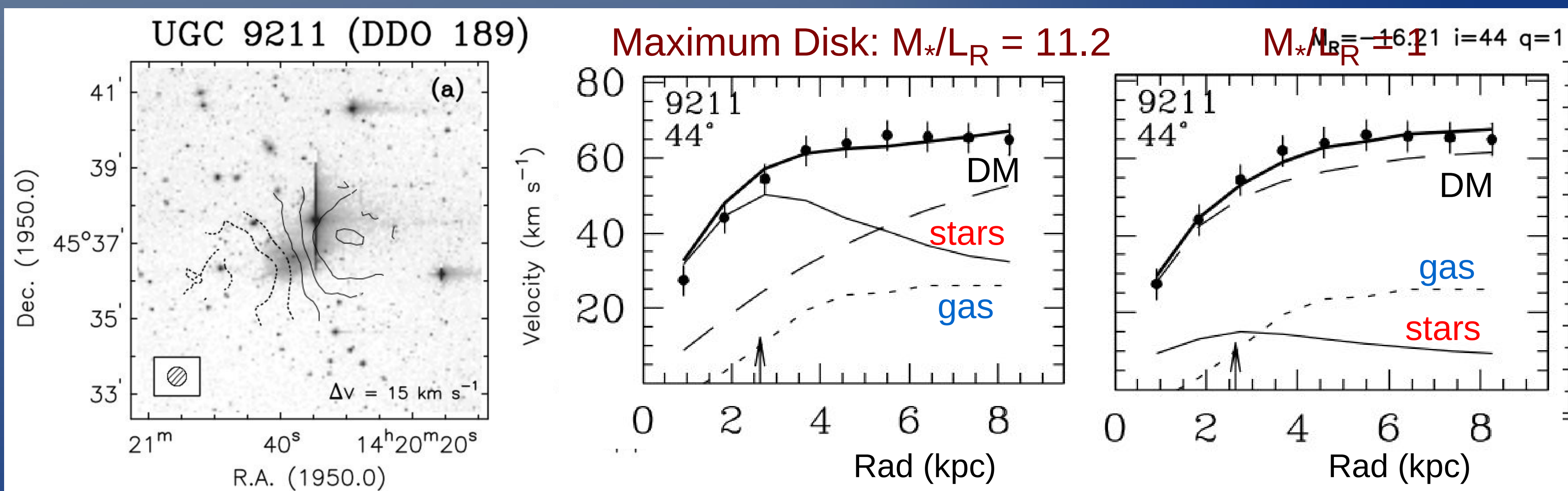
Starburst Dwarfs ~ High-z Galaxies?



- 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)

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





Swaters et al. (2011, 2012)