Molecular Gas, Star, and Disk Formation in Local Early-Type Galaxies

Martin Bureau, Oxford University

CO
(L.M. Young, L. Blitz, F. Combes)
(Alison Crocker, Timothy Davis, Katey Alatalo)

GALEX
(Hyunjin Jeong, S. Yi)

Optical
(SAURON + Atlas3D teams)

Plans:

Optical/SAURON, UV/GALEX: Stellar populations in E/S0s
CO/30m: H_2 census (L, dynamics, environment)
CO/BIMA+PdBI+CARMA: H_2 origin, star formation
UV/GALEX, HI: Star formation, H_2 – HI relation
Summary

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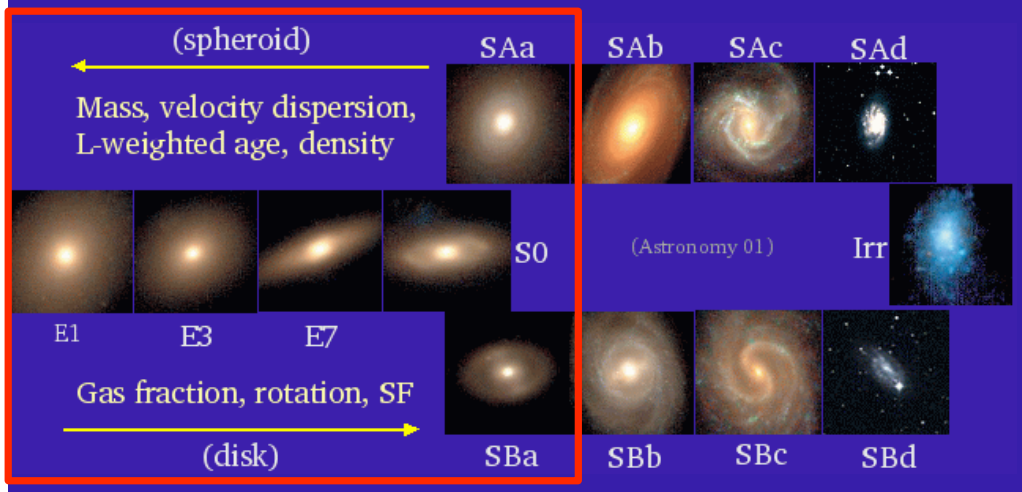
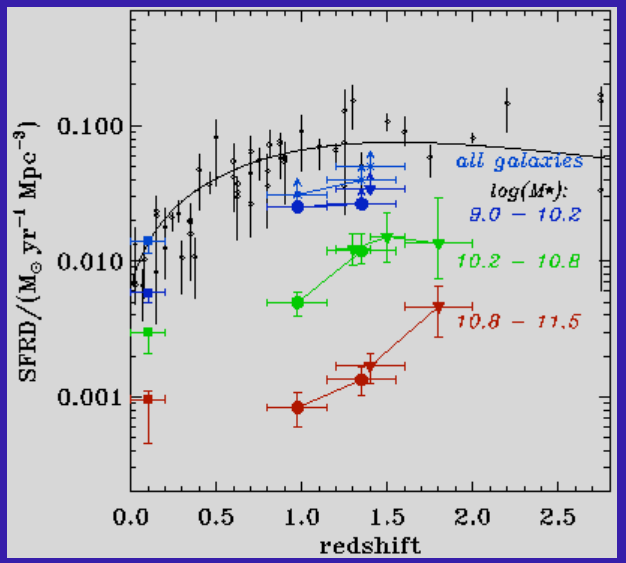
SAURON+Atlas3D: Broad Aims



(Juneau et al 05)



Goals:

- Mass assembly history
  (gas, stars, kinematics)
- Chemical enrichment history
  (age, metallicity, SFH)

Context:

- Hierarchical structure formation
  (merging, harassment, ...)
- Internal dynamical evolution
  (BH/triaxiality-driven, ...)

⇒ Exploit "fossil record"
(near-field cosmology)

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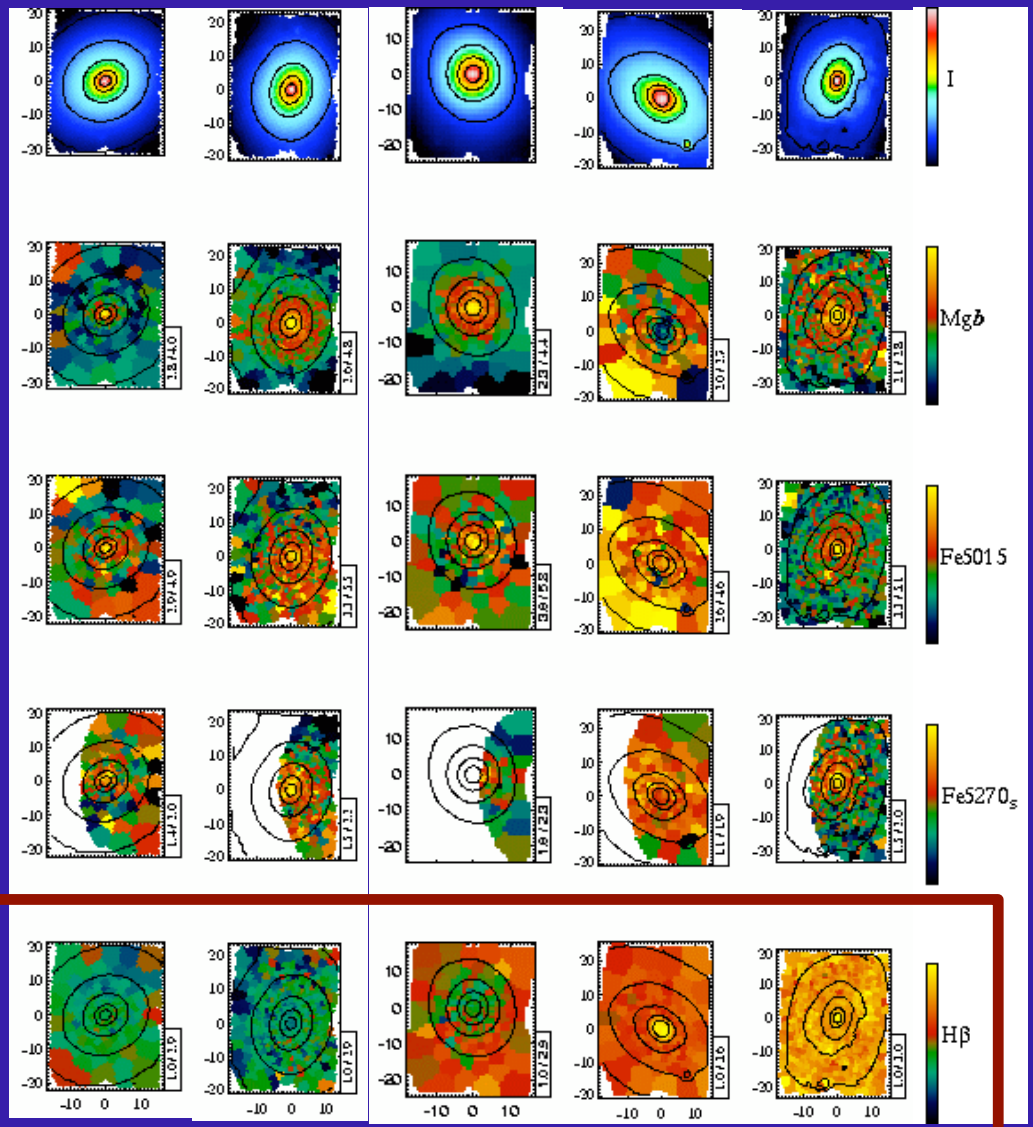
SAURON: Stellar Linestrengths

(Kuntschner et al. 06, 09)

Main results:

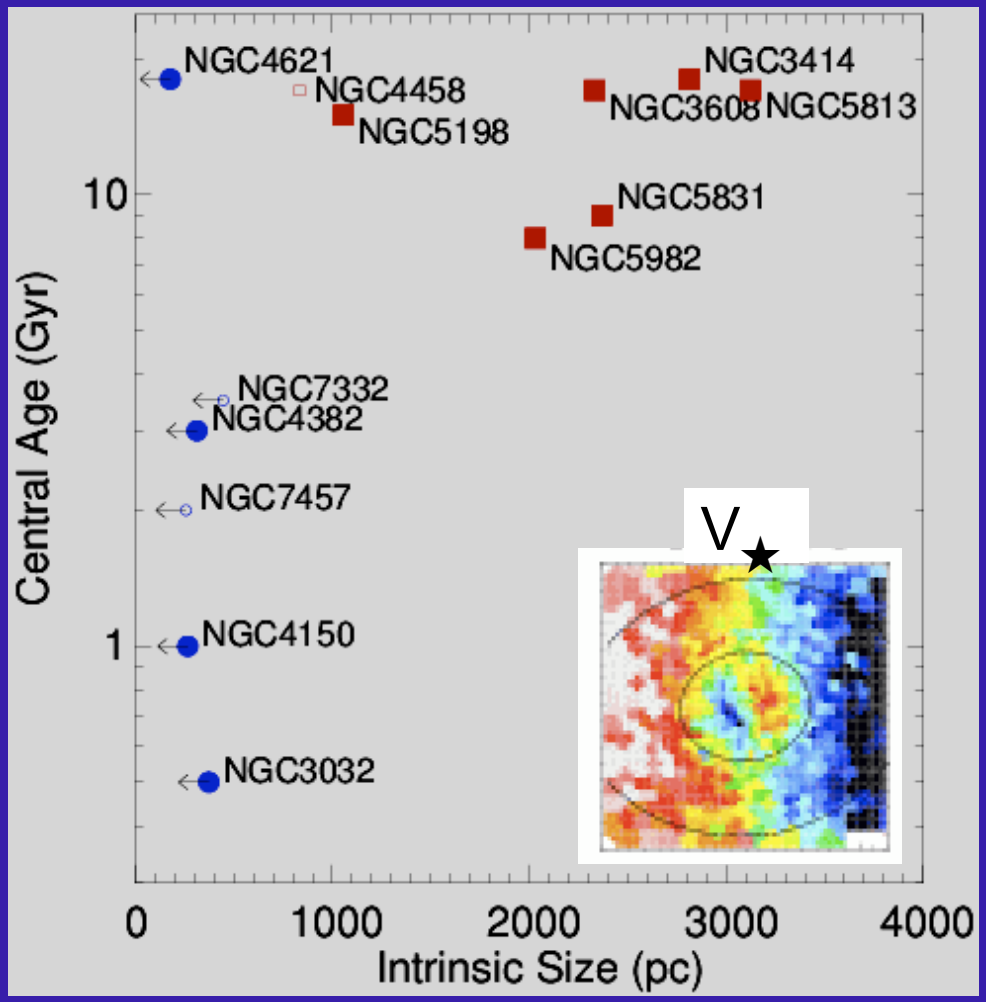
- Standard:
  Homogeneously old, decreasing metallicity (larger spread among S0s)
- Occasional:
  Young core/body, increasing metallicity
- Isoindices:
  Mg_b isoindex countours often flatter than light (40%; fast rotators)



KDCs: Age-Size Dichotomy

(McDermid et al. 06)

SAURON-OASIS Data:



Compact KDCs:

- Small: 100 pc's ($\leq 0.1\ R_e$)
- Young: distinct, increasingly young toward center
- Fast-rotators
- Recent dissipative minor merging/accretion?

Classic KDCs:

- Large: kpc's ($0.3\text{-}0.4\ R_e$)
- Coeval: homogeneously old
- Slow-rotators
- Early (dissipative) or recent dissipationless major merging (dry mergers)?

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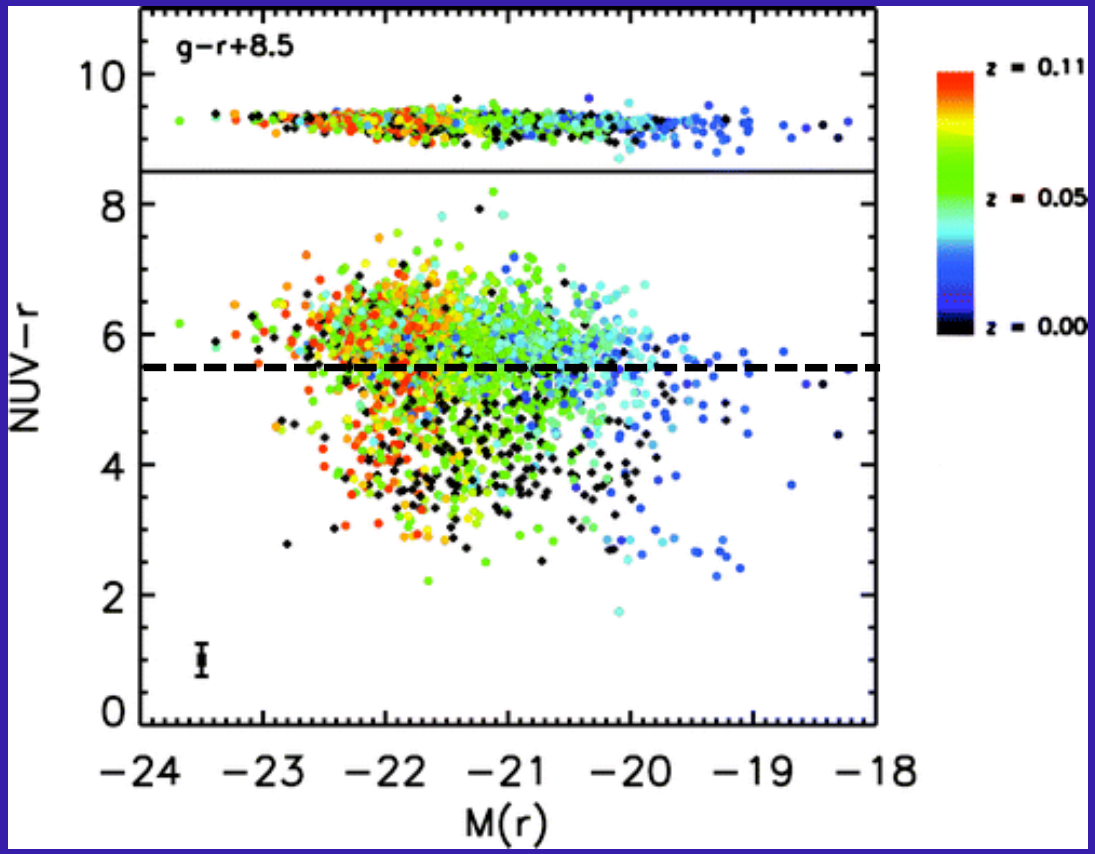
UV C-M Relations: Residual SF

(Yi et al. 05; Schawinski et al. 06; Kaviraj et al. 07)

GALEX-SDSS Data:



(Kaviraj et al. 07)

UV CMDs:

- Correlations nearly absent
- Red sequence indistinct, blue cloud significant even for E/S0s

⇒ Low-level (residual) SF pervasive
(>≈ 30% of objects;
few % by mass)

⇒ Significant support for hierarchical formation

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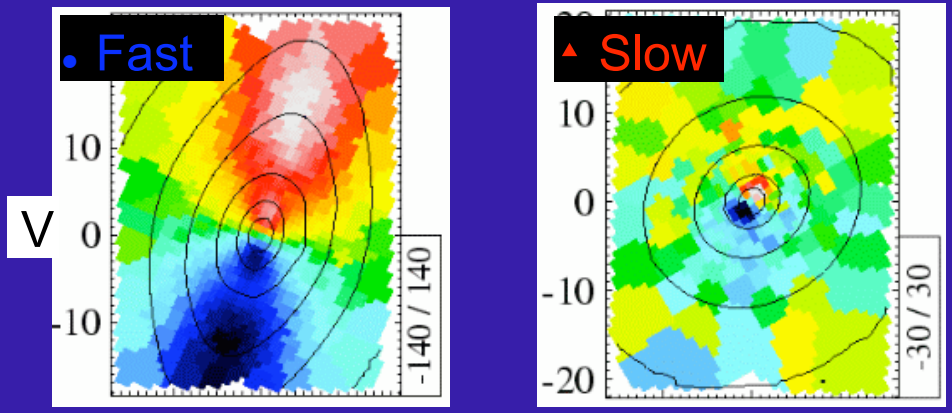
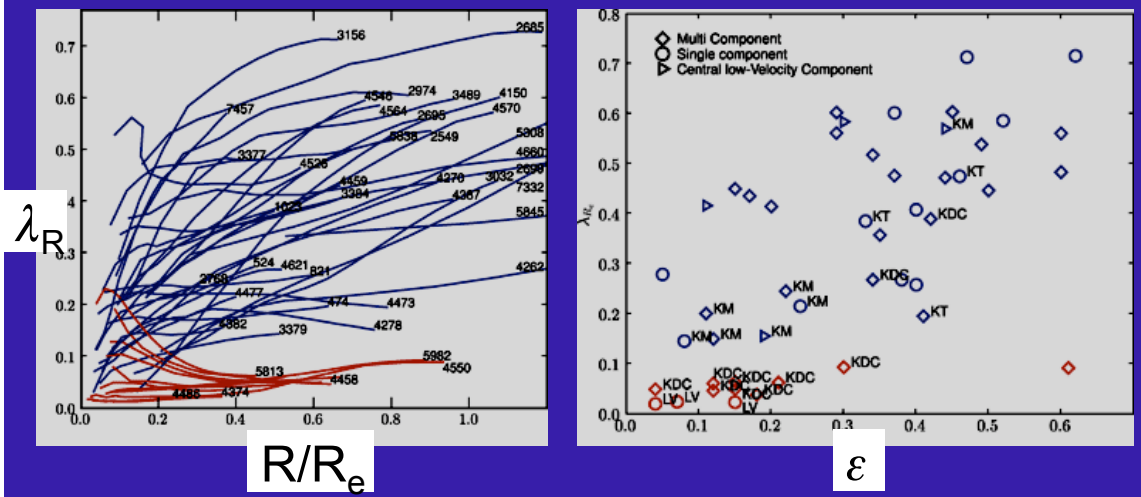
Dynamics: E Dichotomy?

(Emsellem et al. 07; Cappellari et al. 07)

Specific angular momentum λ_R:





Fast rotators: common

- Flattened disk-like rotation (some with bars)
- Aligned kinematics
- True S0s/Ss ?
- Anisotropic !

Slow rotators: rare

- Mildly triaxial
- Decoupled cores, misalignments, twists, …
- True Es ?
- Isotropic !

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Complete Survey of Early-Type Galaxies

Volume-limited sample:

- 263 E/S0s without spiral structure; $M_K < -21.5$, $D < 41$ Mpc
- Fast/slow rotators; wet/dry mergers; low-z census; SF + feedback

Datasets:

- Optical integral-field spectroscopy: WHT/SAURON (38 nights; done)
- Optical photometry: Multi-bands (SDSS, INT, 2MASS; done)
- Single-dish CO: IRAM 30m (^{12}CO(1-0) + (2-1); done)
- HI interferometry: WSRT (~150 North galaxies excl. Virgo; ongoing)
- CO interferometry: CARMA (^{12}CO detections only; ongoing)
- Archival data: Chandra, XMM, GALEX, HST, Spitzer, …

Simulations:

- Cosmological, individual galaxies/binary mergers, SAMs

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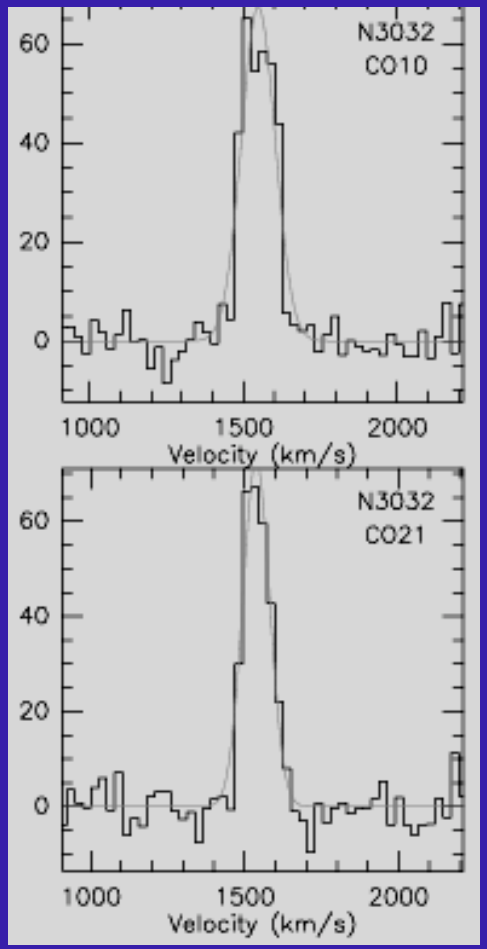
Summary

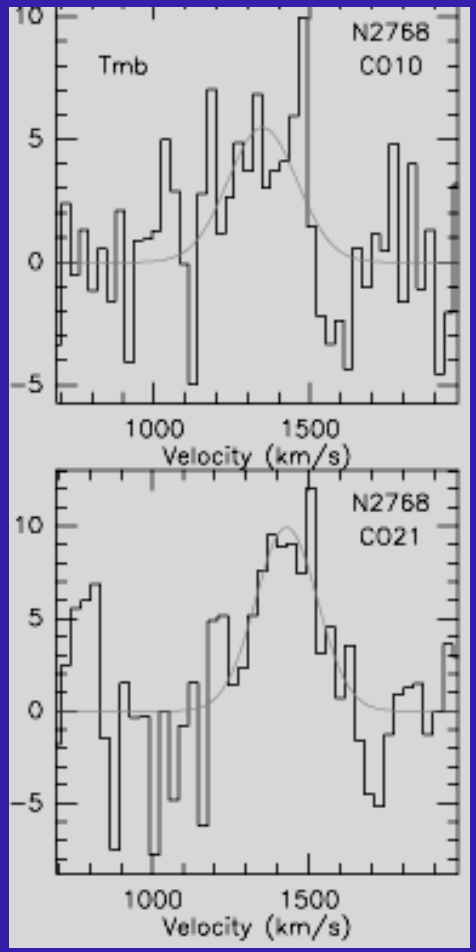
CO: Single-Dish Survey

(Young et al. 09)

High S/N:



Low S/N:



IRAM 30m Survey:

- CO(1-0), 23" FWHM
  (2-1), 12" FWHM
- 263+ Atlas3D E/SOs
- Sensitivity: 3 mK (30 km s^{-1})
  20 mJy
  3 x 10^7 $M_\odot$

Results:

- 23% detection rate
- CO(2-1)/CO(1-0) ≈ 1 - 2

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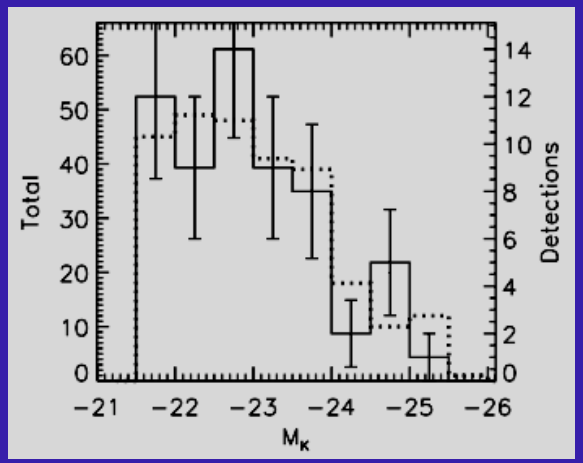
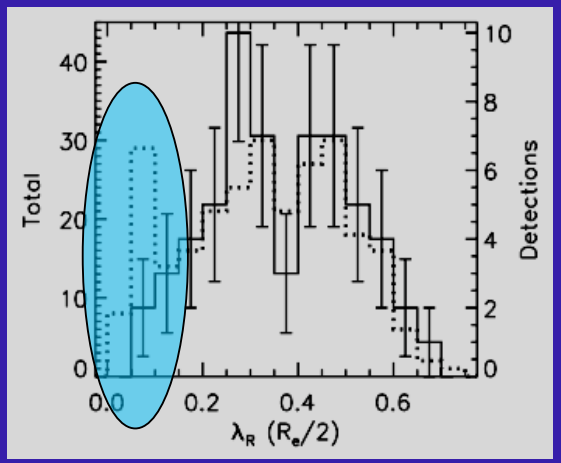
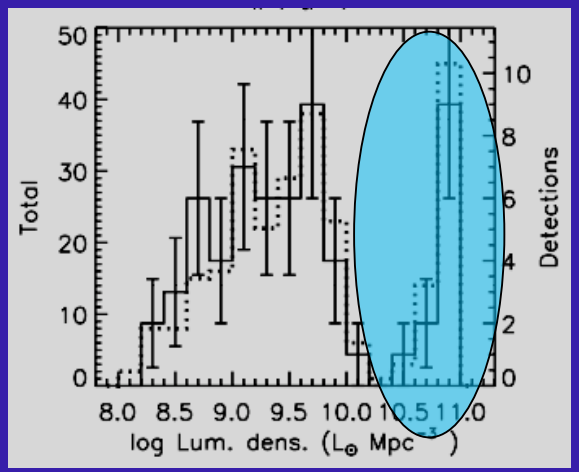
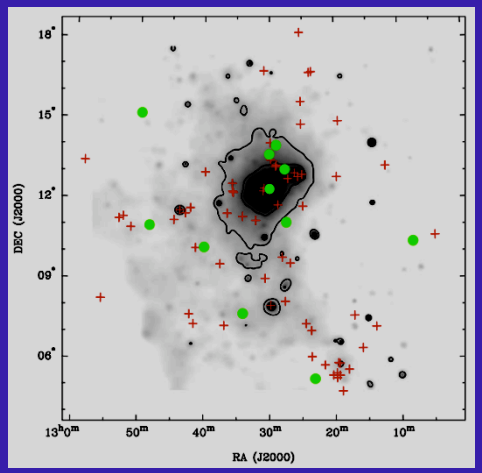
CO: Main Results

(Young et al. 09)









IRAM 30m Results:

- Detection rate largely independent of:
  - Luminosity
  - Dynamics (λ_R)
  - Environment (Virgo)
  - …
- ❖ Slow-rotator H_2 poor
- Expected correlations with linestrengths (CO associated with young stars)

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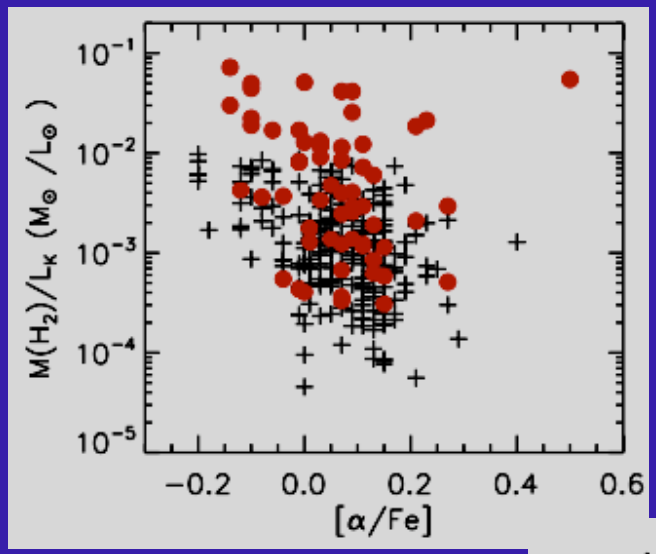
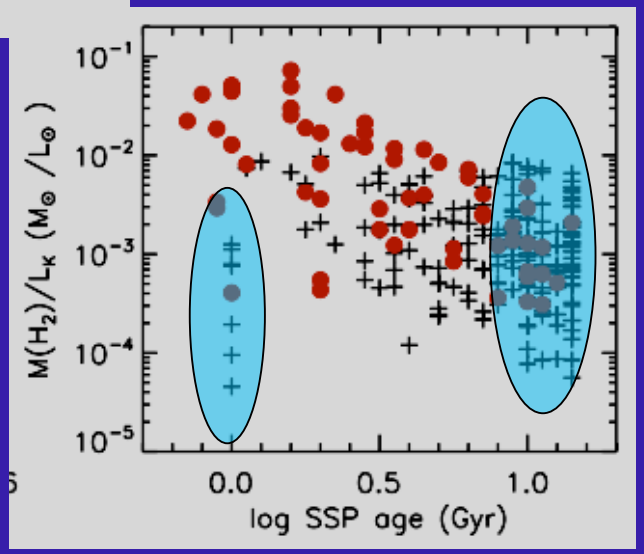
CO: Main Results

(Young et al. 09)





IRAM 30m Results:

- Detection rate largely independent of:
  - Luminosity
  - Dynamics (λ_R)
  - Environment (Virgo)
  - …
- ❖ Slow-rotator H_2 poor
- Expected correlations with linestrengths (but no straight CO-SF relation; SF sequence?)

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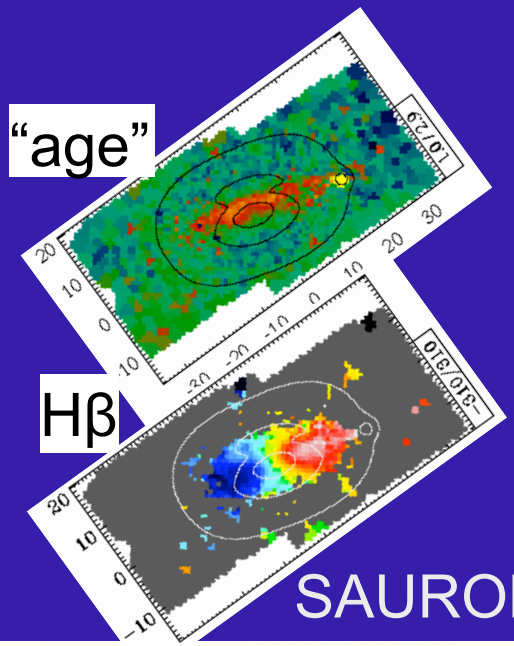
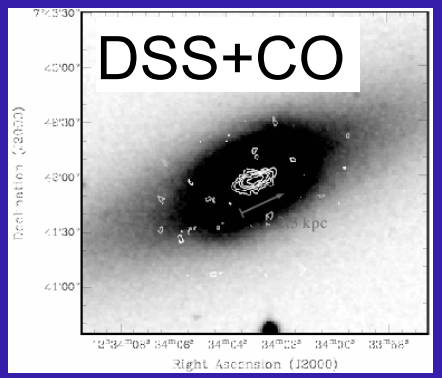
CO: Central Disks

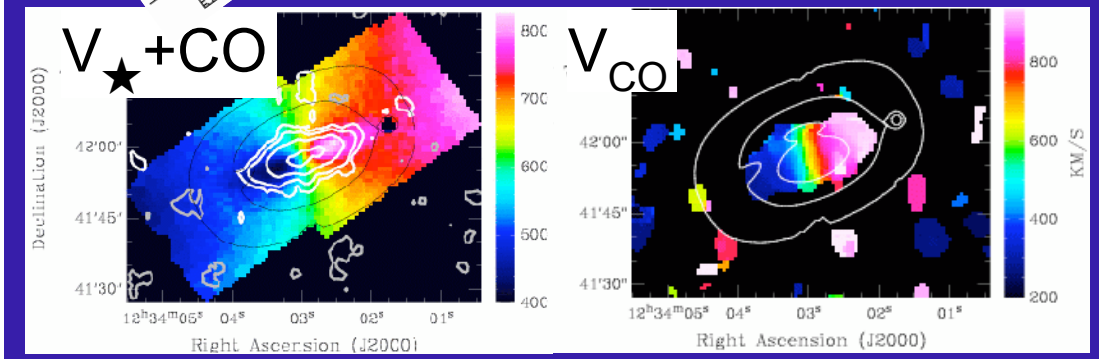
(Young, Bureau & Cappellari 08; Crocker et al. 09)

BIMA-SAURON Data: NGC4526





SAURON CO



Central Disks:

- CO cospatial with young stars and central stellar/gas disk
- CO and stars/gas co-rotating

CRs:

- CO roughly cospatial with young stars and CR/gas (generally less extended)
- CO and stars/gas kinematics unrelated ? (triggered SF?)

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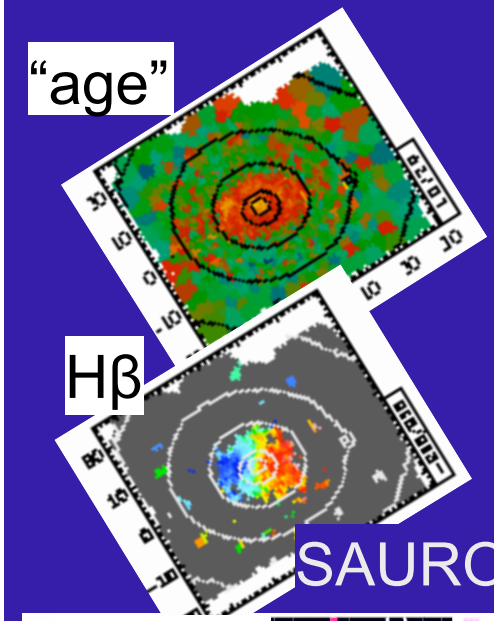
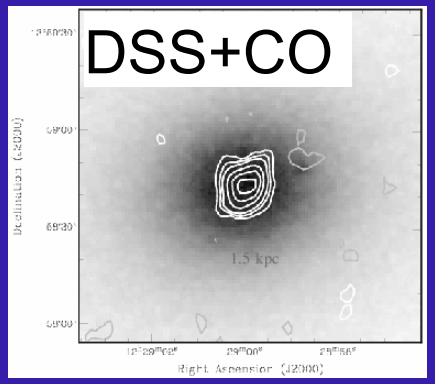
CO: Central Disks

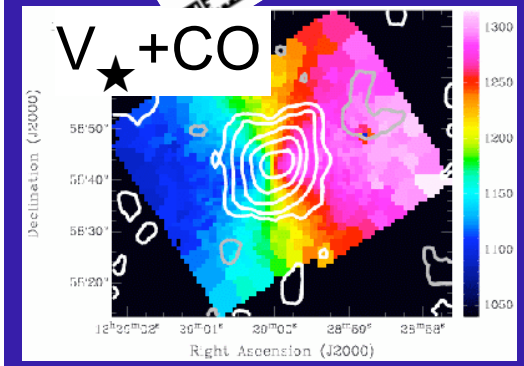
(Young, Bureau & Cappellari 08; Crocker et al. 09)

BIMA-SAURON Data: NGC4459

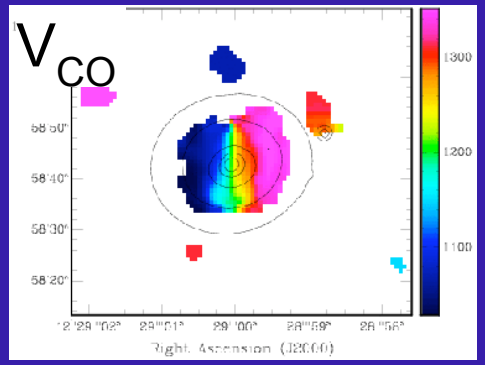




SAURON



CO



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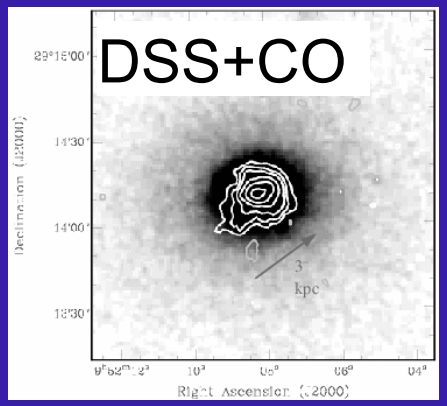
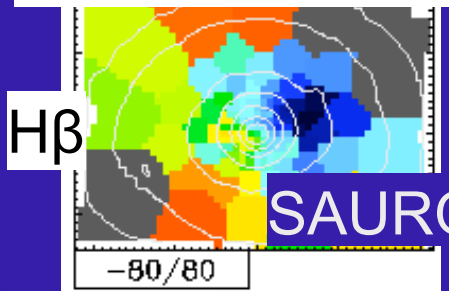
CO: Central Disks

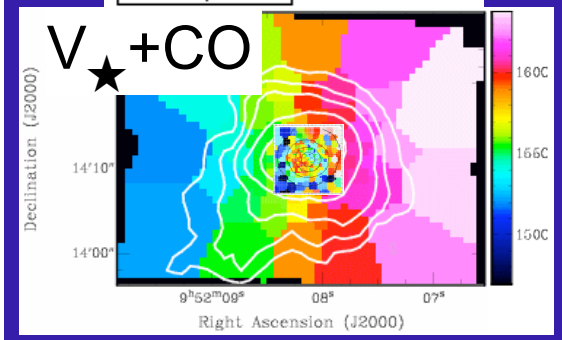
(Young, Bureau & Cappellari 08; Crocker et al. 09)

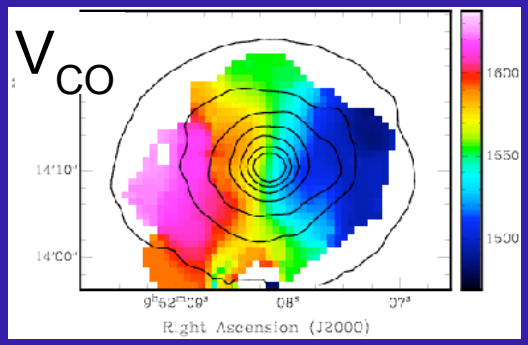
BIMA-SAURON Data: NGC3032





CO





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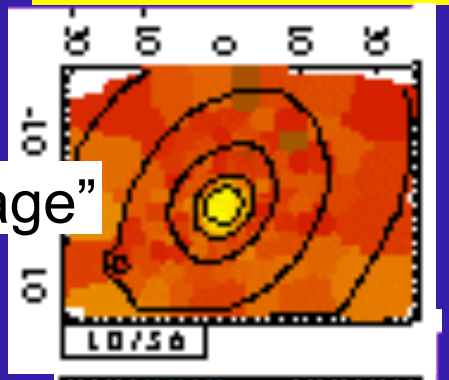
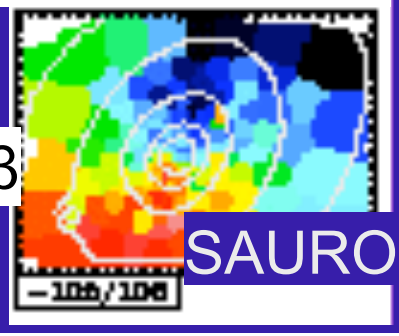
CO: Central Disks

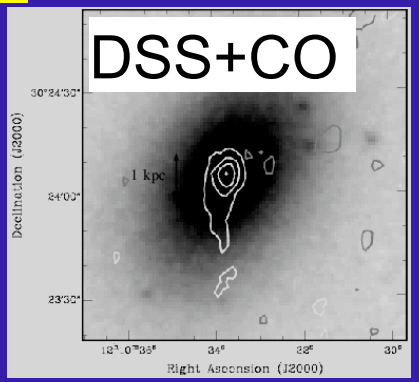
(Young, Bureau & Cappellari 08; Crocker et al. 09)

BIMA-SAURON Data: NGC4150

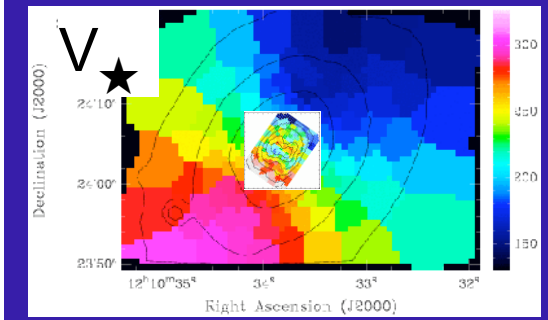


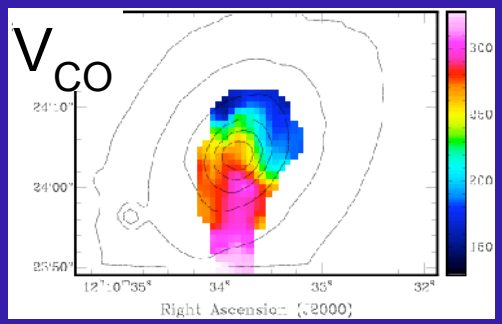


SAURON



CO





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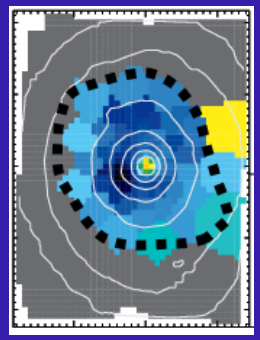
Type 1: Currently Star Forming

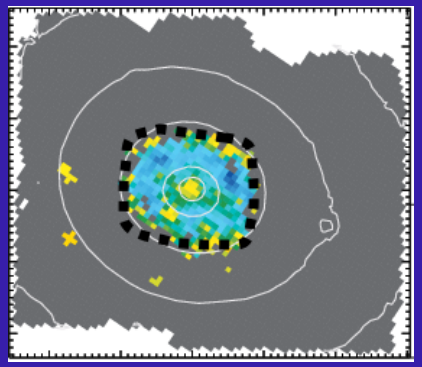
(Crocker et al. 09)

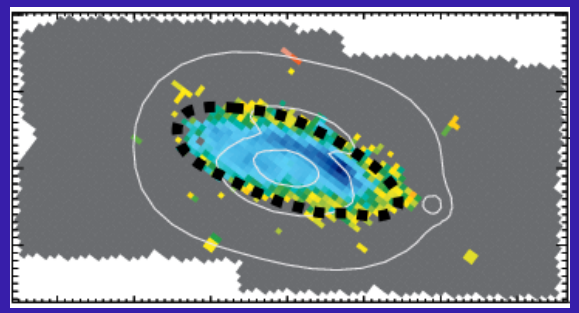
NGC3032

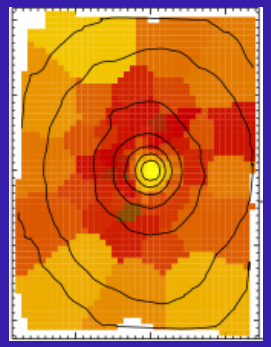
NGC4459

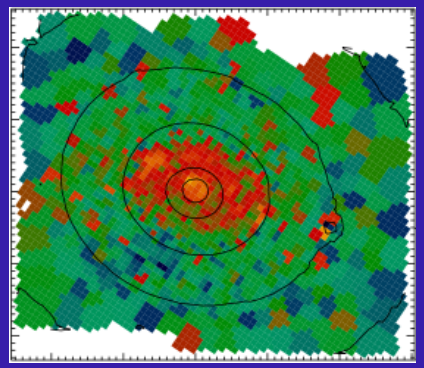
NGC4526

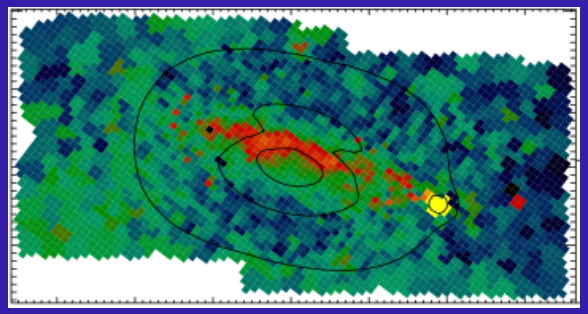












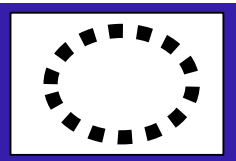
Ionised gas:

log(OIII/Hb)

Stellar population:

Hβ linestrength (A)

CO extent



- Onging star formation and young stars

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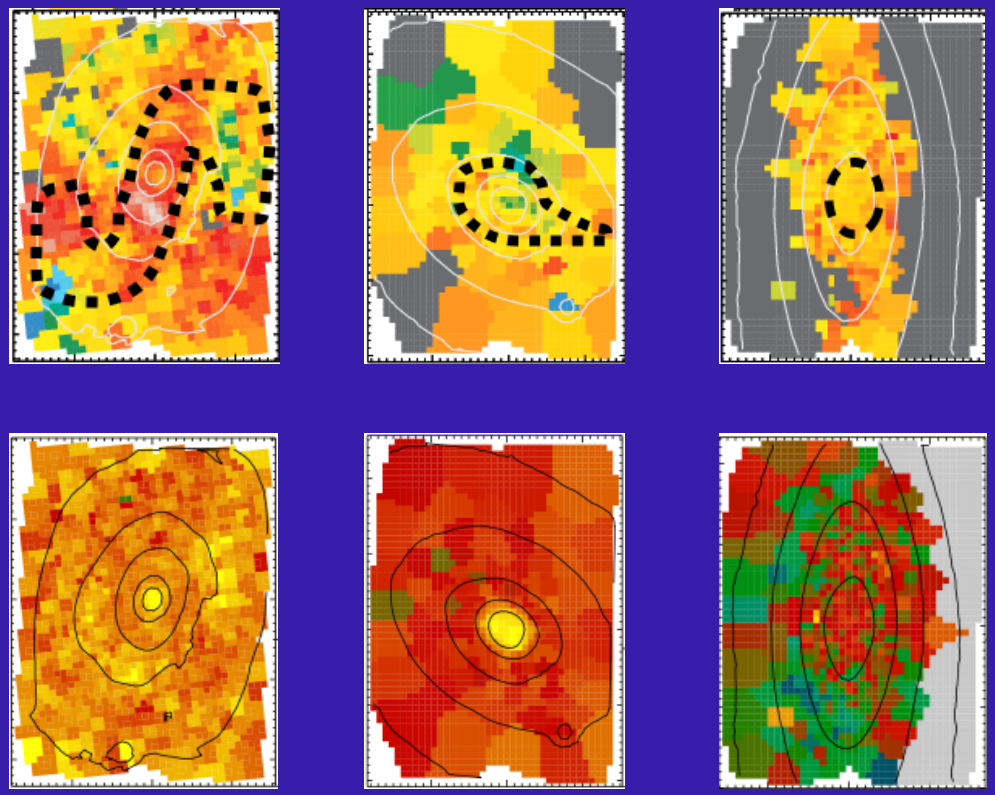
Type 2: Recently Star Forming

(Crocker et al. 09)

NGC3489 NGC4150 NGC4550



Ionised gas:

log(OIII/Hb)

-1.0 1.0

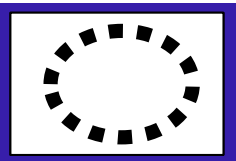
Starforming

Stellar population:

Hβ linestrength (A)

1.0 2.9

CO extent



- Ionization not dominated by young stars, but young stars are present

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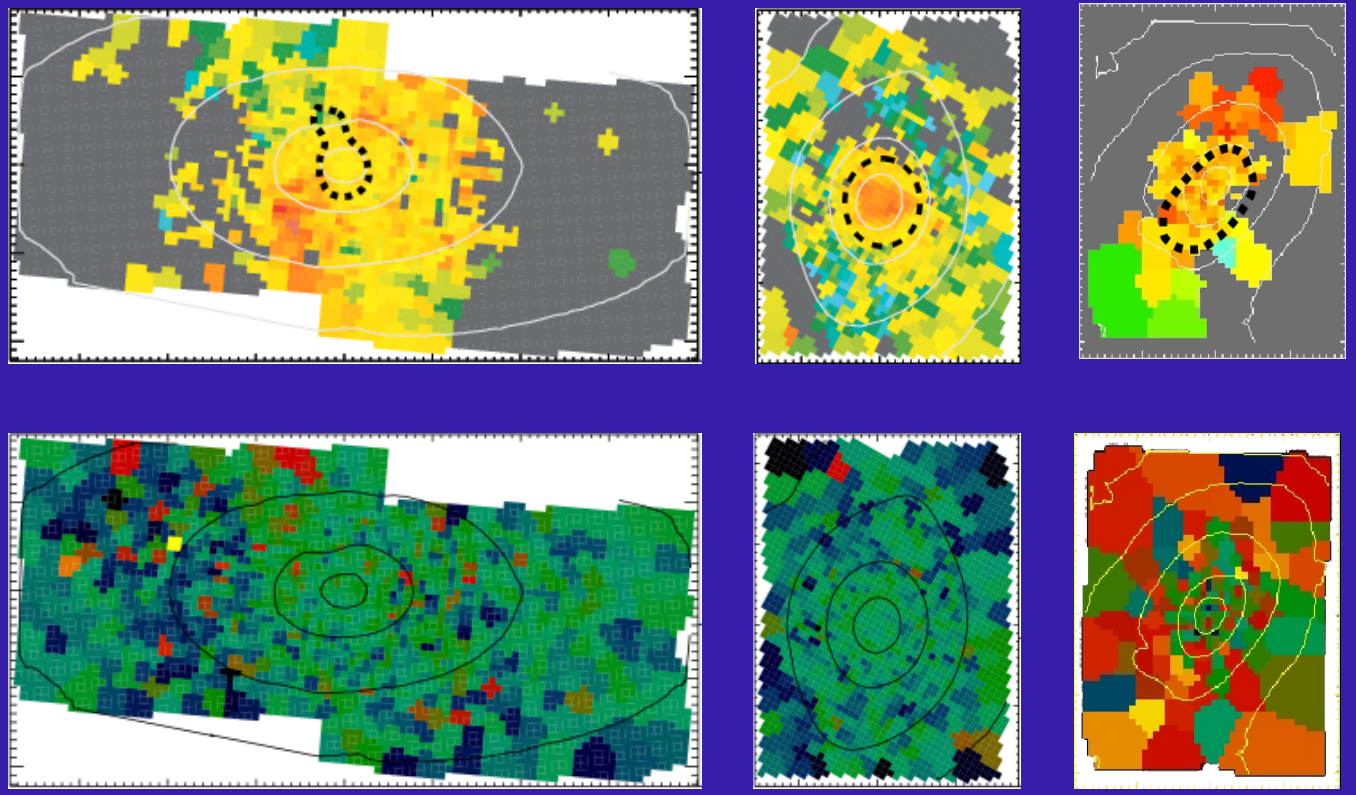
Type 3: Not Star Forming?

(Crocker et al. 09)

NGC2768 NGC4477 NGC2320



Ionised gas:

log(OIII/Hb)

-1.0 1.0

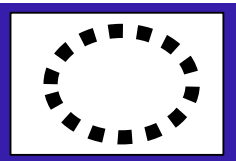
Starforming

Stellar population:

Hβ linestrength (A)

1.0 2.9

CO extent



- Ionization not dominated by young stars, and no young stars

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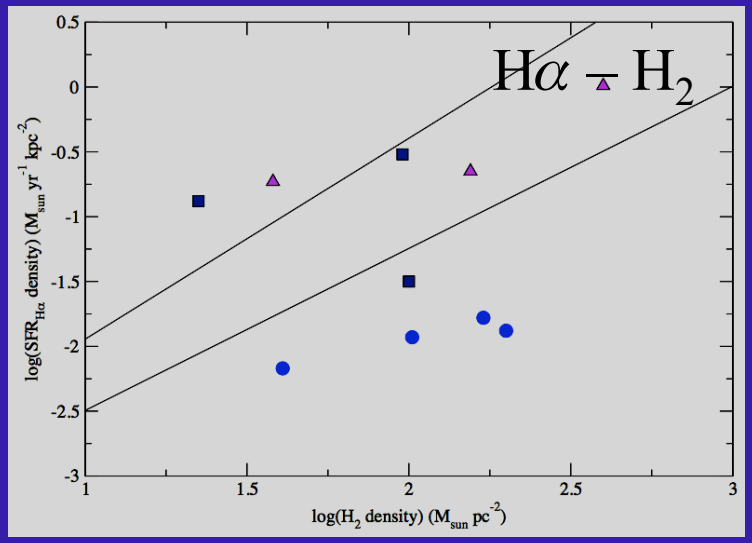
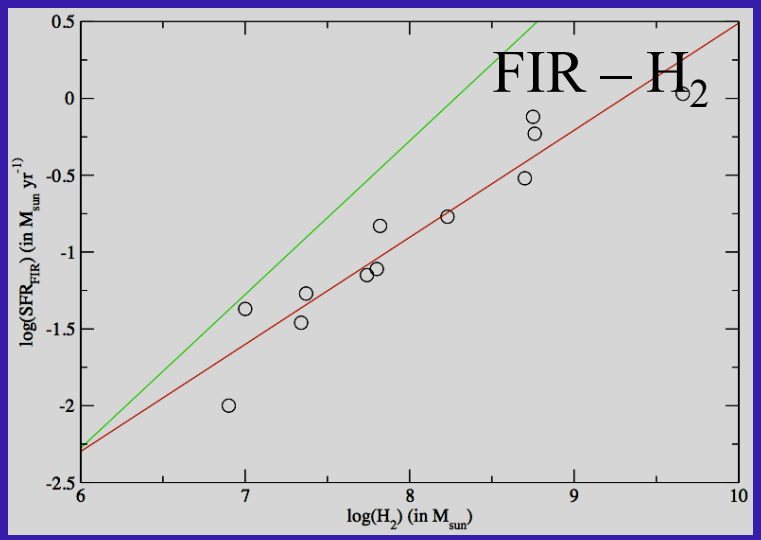
CO: Star Formation Laws

(Crocker et al. 09)





Atlas3D:

- Schmidt-Kennicutt - type laws not well respected:
  many galaxies have too low SFR
  (even SF-dominated ones!)
- FIR-radio correlation not well-respected:
  too many FIR-excess galaxies

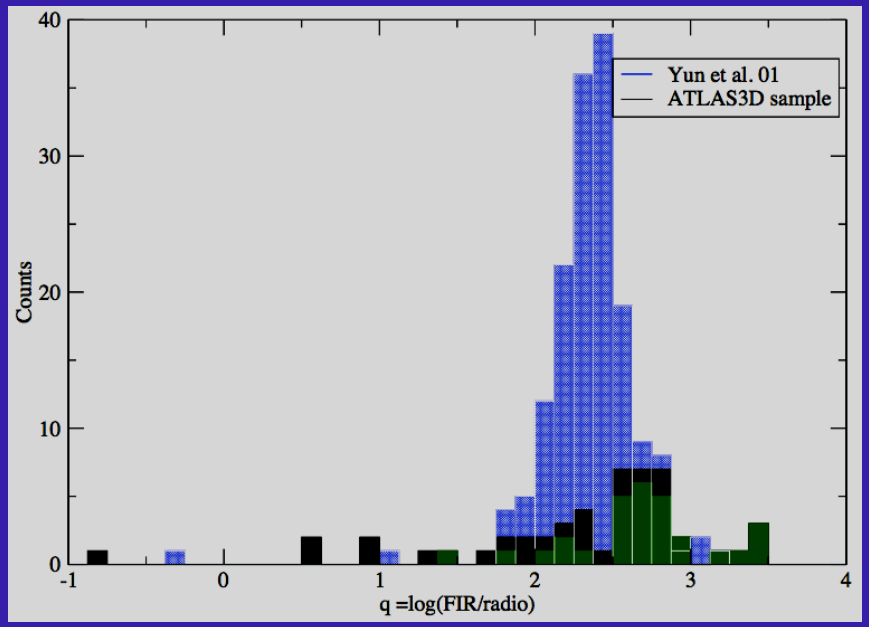
⇒ SF regime different from that in disk/starburst galaxies

⇒ Need to probe dynamics and physical conditions…

Martin Bureau, Oxford University

CO: Star Formation Laws

(Crocker et al. 09)



q = log (FIR / radio)

Atlas3D:

- Schmidt-Kennicutt – type laws not well respected:
  many galaxies have too low SFR (even SF-dominated ones!)
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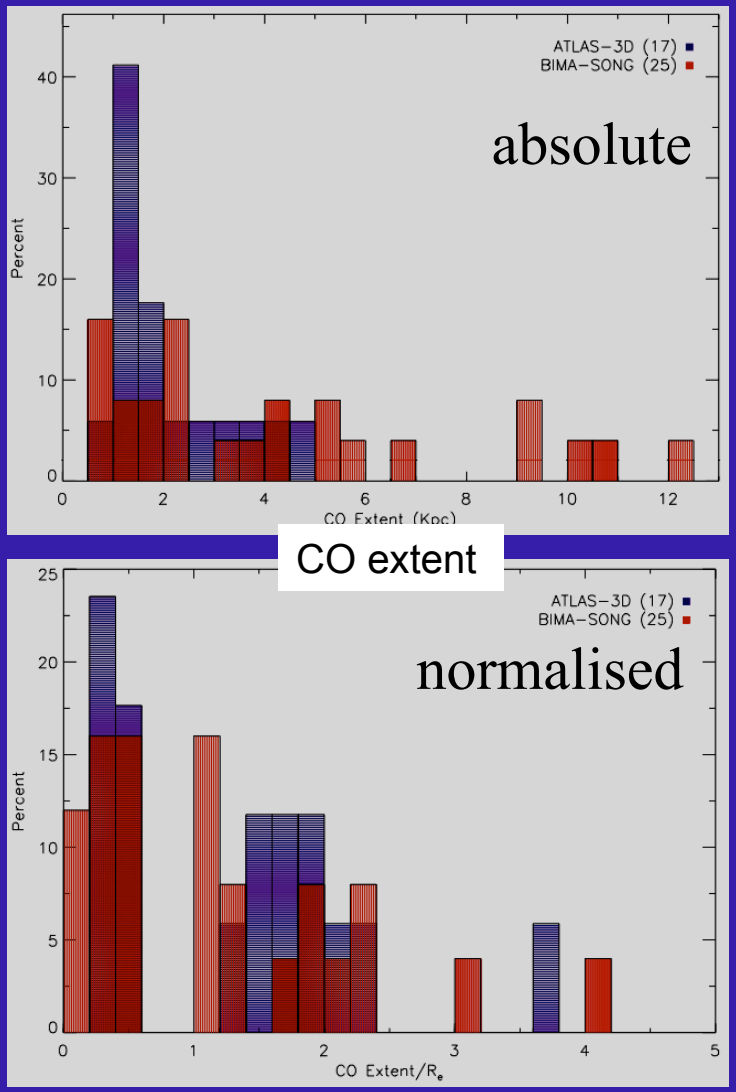
CO: Extent

(Davis et al., in prep)



Atlas3D (CARMA):

- BIMA-SONG spiral galaxy comparison sample (properly redshifted)
- H_2 extent smaller in E/S0s in absolute term
- H_2 extent similar in relative terms (R_e, R_{25}, M_K, …)

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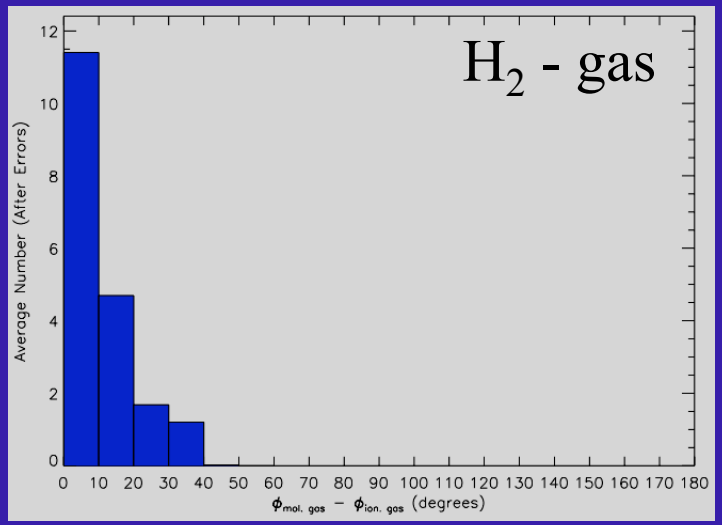
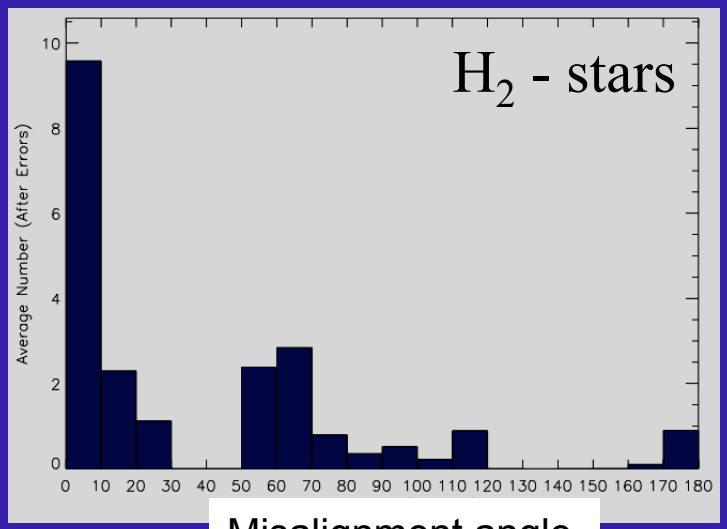
CO: Kinematic Misalignment

(Davis et al., in prep)





Atlas3D (CARMA):

- H_2 and ionised gas always aligned: common origin
- H_2 and stars often misaligned: external gas origin

- H_2 and stars always aligned in clusters/Virgo: purely internal gas origin (stellar mass loss)
- H_2 and stars randomly misaligned in field: external gas accretion rules

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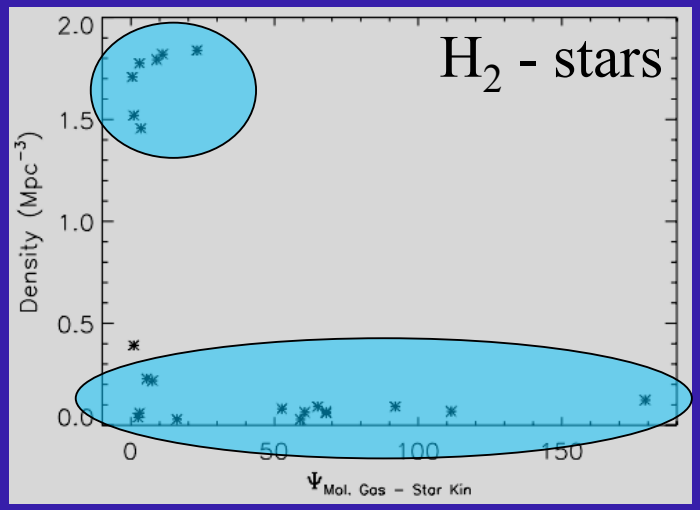
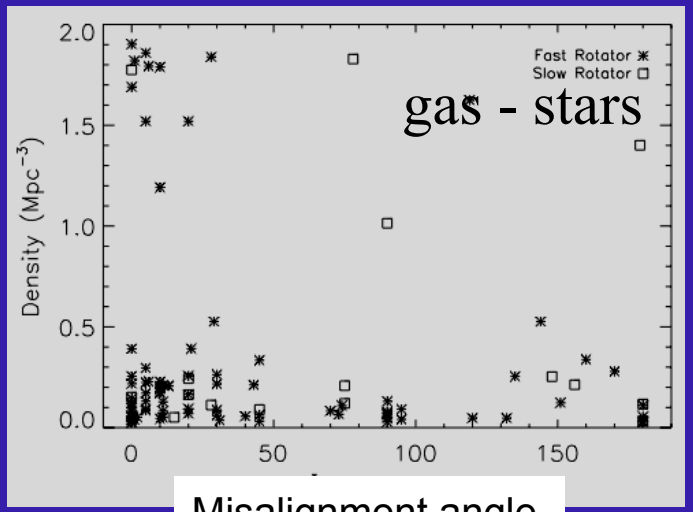
CO: Kinematic Misalignment

(Davis et al., in prep)





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- H_2 and stars always aligned in clusters/Virgo:
  purely internal gas origin
  (stellar mass loss)
- H_2 and stars randomly misaligned in field:
  external gas accretion rules

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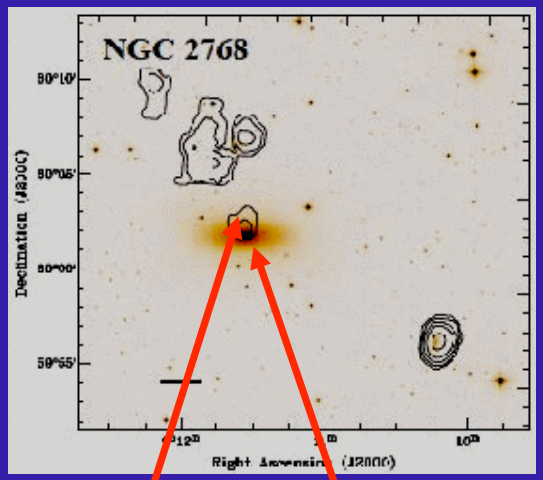
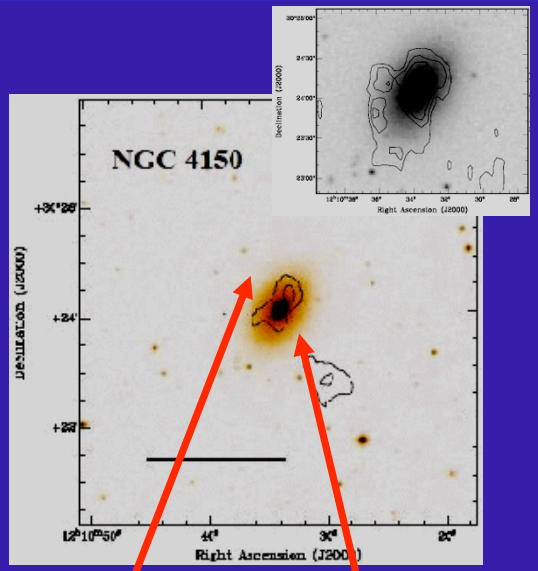
CO: External Accretion

(Young, Bureau, & Cappellari 08; Crocker et al. 08)

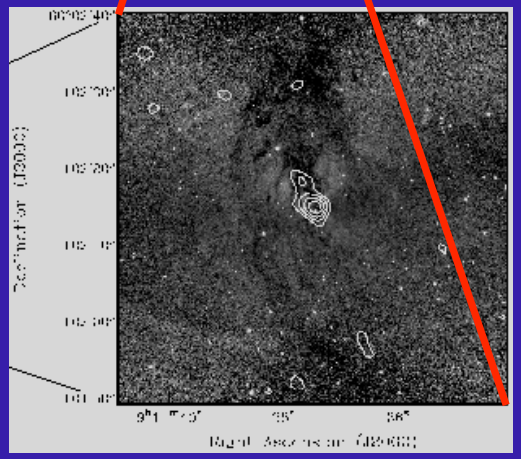
HI:

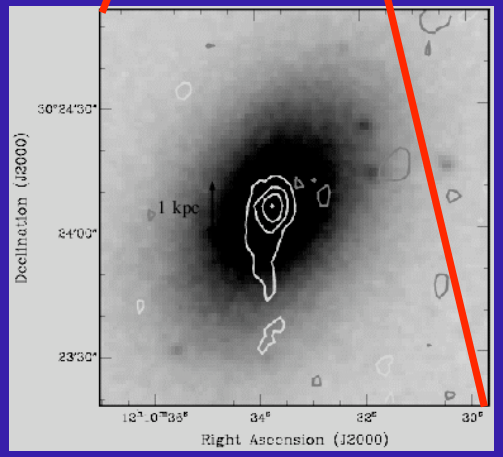




(Morganti et al. 06)

CO:





NGC2685, NGC2768:

- Generic accretion model for polar rings (although likely a polar disk)

Generally:

- Disturbed HI (Morganti et al. 06)
- Lack of strong correlations CO - optical

✗ Some galaxies with CO but no HI!

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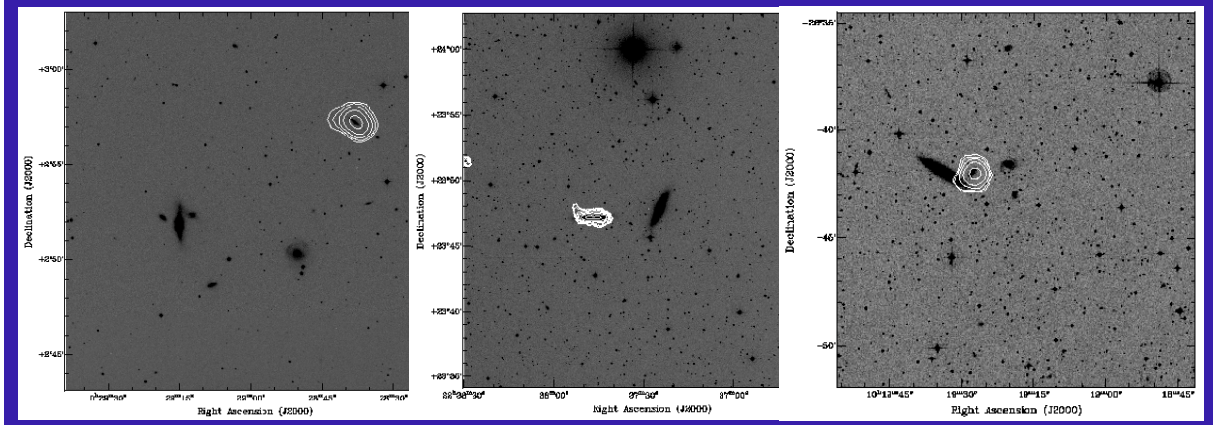
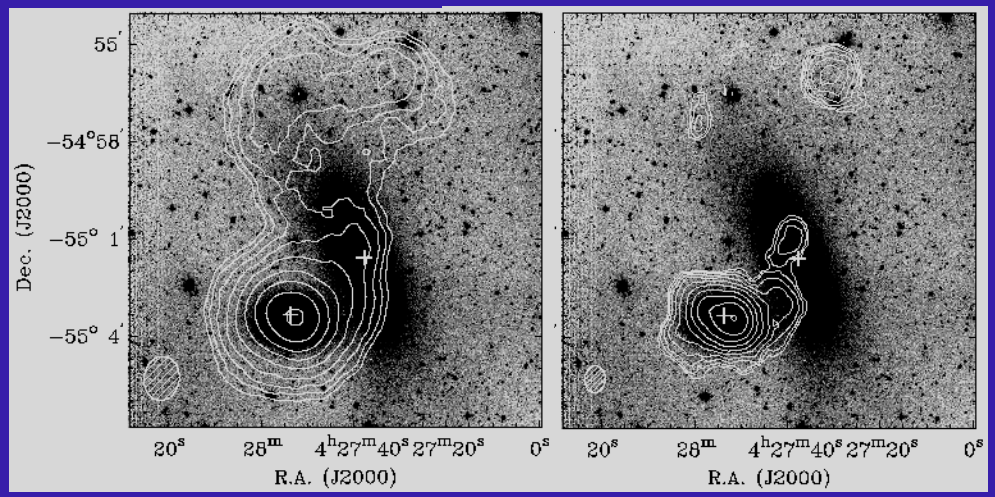
HI: NGC128, 3203, 7332, 1596

(Bureau & Chung 06; Chung et al. 06; Chung et al., in prep)

VLA + ATCA:





HI Structure:

- NGC128: Distant HI-rich companion
- NGC7332: Nearby HI-rich companion
- NGC3203: Interacting? HI-rich companion
- NGC1596: Interacting HI-rich companion

⇒ Circumstantial evidence for cold accretion and/or minor mergers

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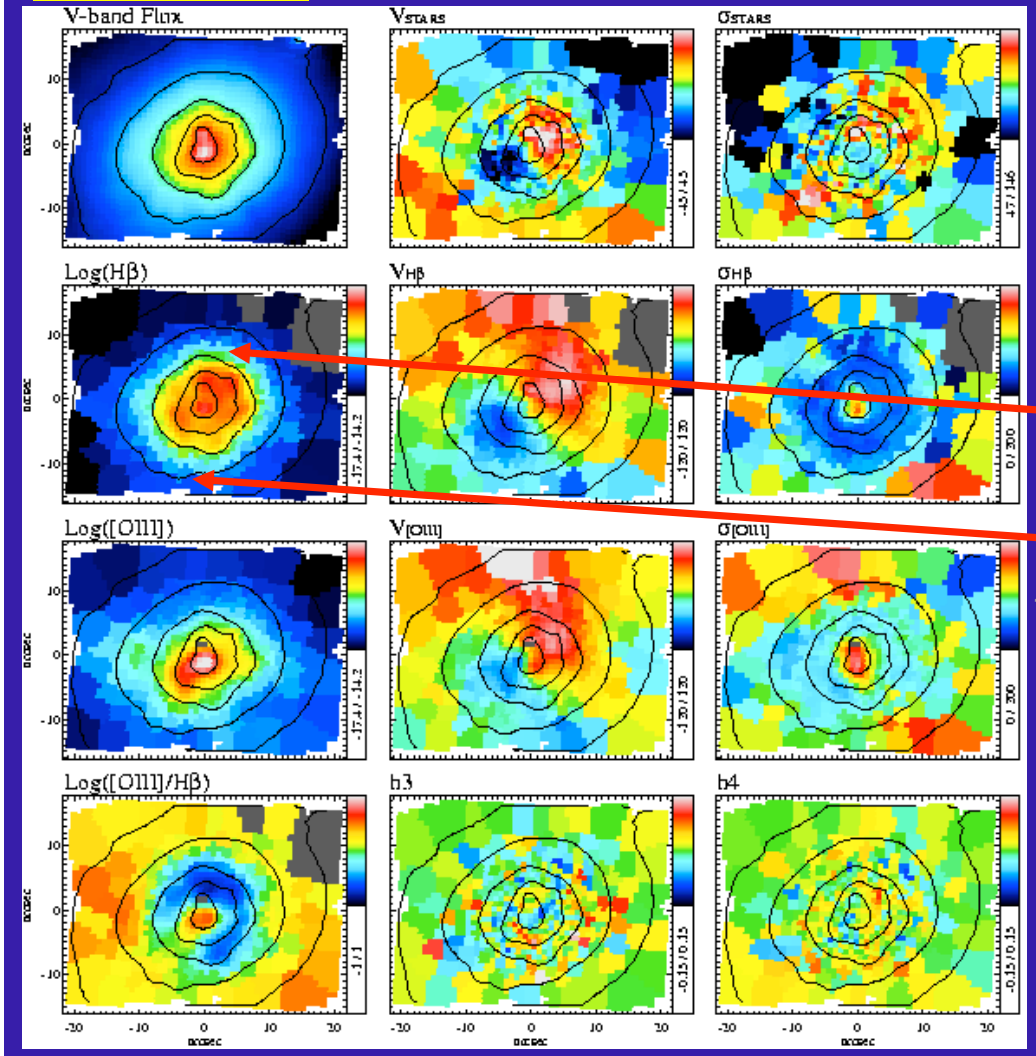
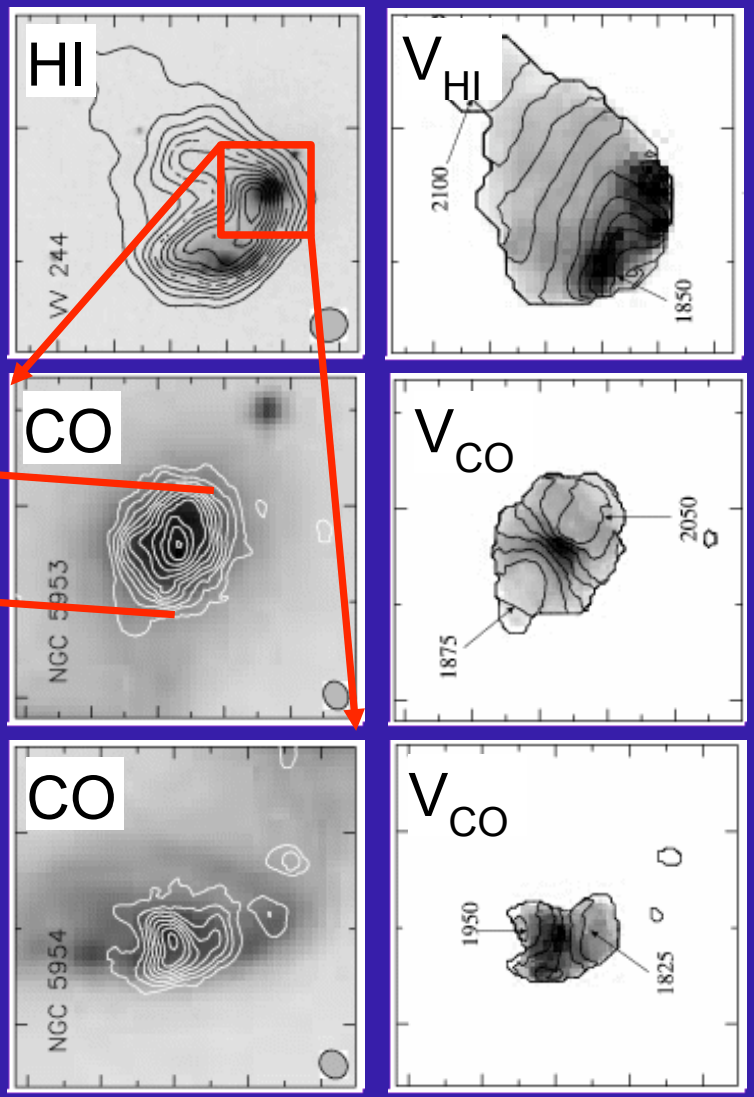
Textbook Case: NGC5953

(Jeong et al., in prep)

SAURON:



(Falcon-Barroso et al. 06)



(Iono et al. 05)

(Nordgren et al. 95)

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CO: Future

Atlas^{3D}:

- Complete volume-limited E/SO sample: Census
  - CARMA CO follow-up ongoing... 2-3 more terms
    (D array; Berkeley commitment; need broader bandwidth)
  - Further interferometric follow-up of individual objects
    (CARMA, SMA, PdBI; molecular outflows)
- Physical conditions in molecular gas:
  - IRAM 30m high-density tracers/molecular diagnostics:
    (^{13}CO, HCN, HCO+; density, opacity, kinetic temperature, …)
  - Interferometers… ALMA!

✗ Also obtaining optical IFU data for E/S0s with existing CO maps...

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Molecular Gas, Star, and Disk Formation in Local Early-Type Galaxies

Martin Bureau, Oxford University

CO
(L.M. Young, L. Blitz, F. Combes)
(Alison Crocker, Timothy Davis, Katey Alatalo)

GALEX
(Hyunjin Jeong, S. Yi)

Optical
(SAURON + Atlas3D teams)

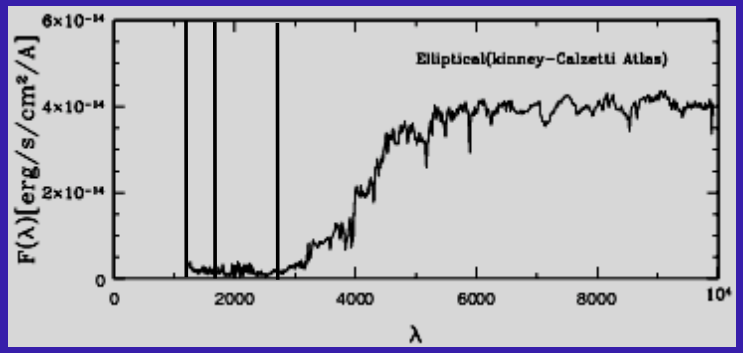
Plans:

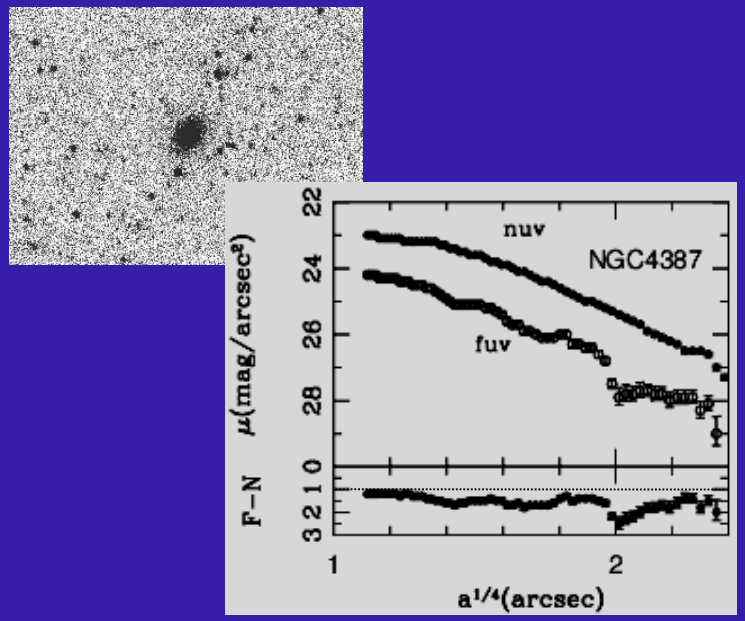
Optical/SAURON, UV/GALEX: Stellar populations in E/S0s
CO/30m: H_2 census (L, dynamics, environment)
CO/BIMA+PdBI+CARMA: H_2 origin, star formation
UV/GALEX, HI: Star formation, H_2 – HI relation
Summary

GALEX: UV Emission in E/S0s

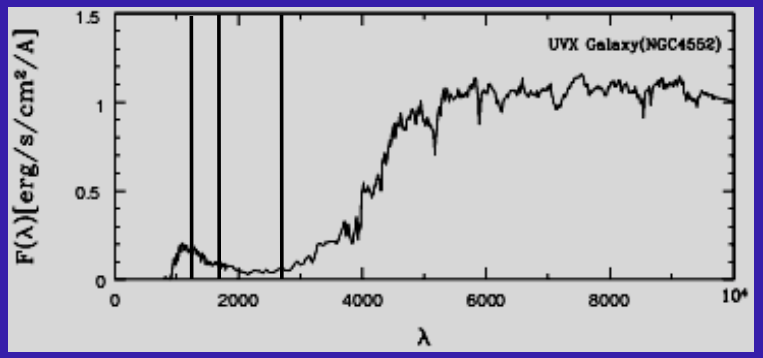
(Jeong et al. 09)

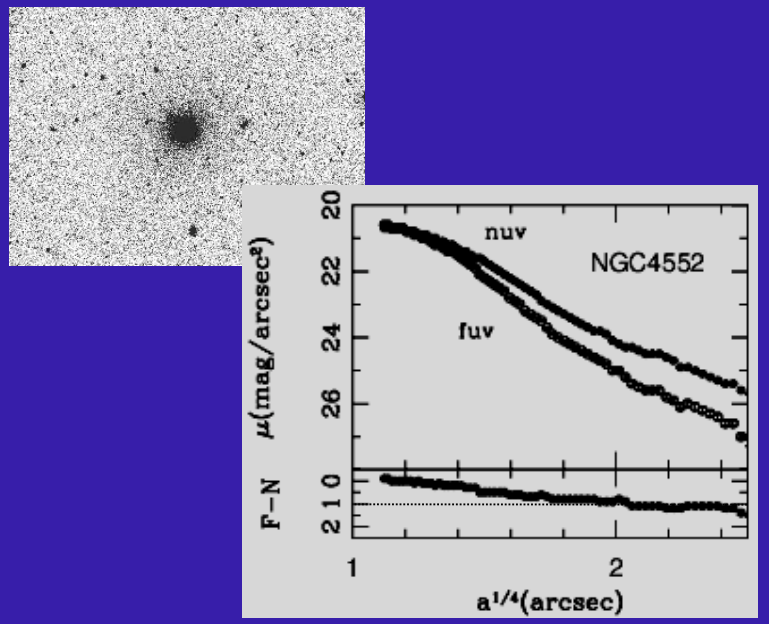
Normal:





UV Upturn:





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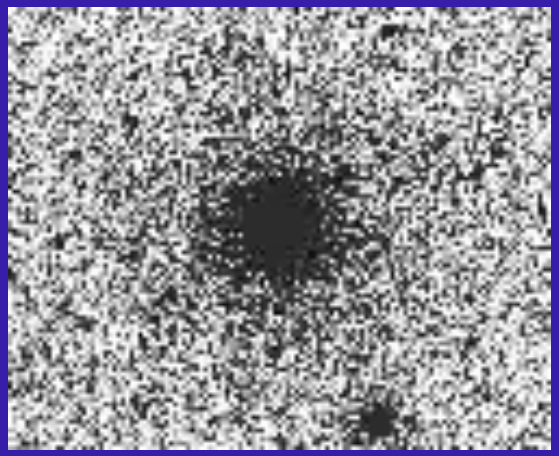
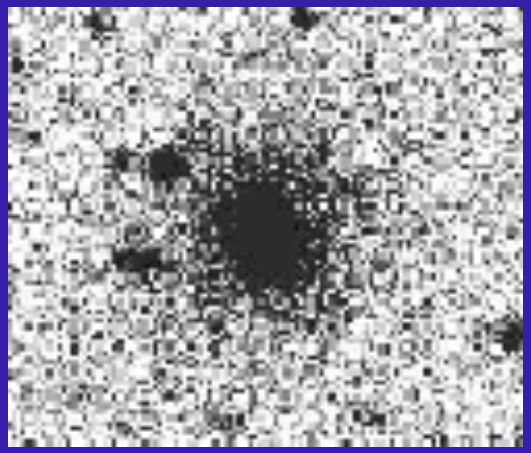
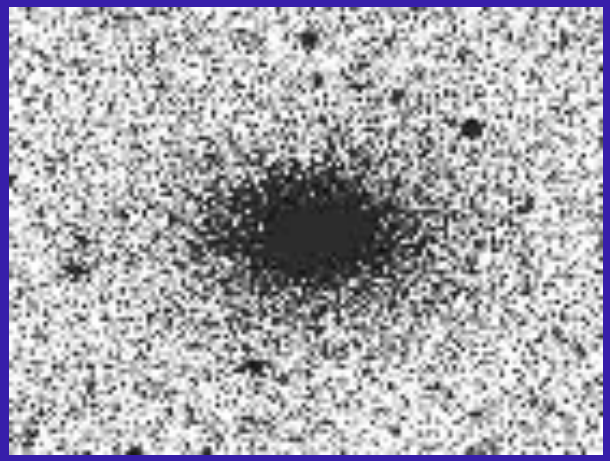
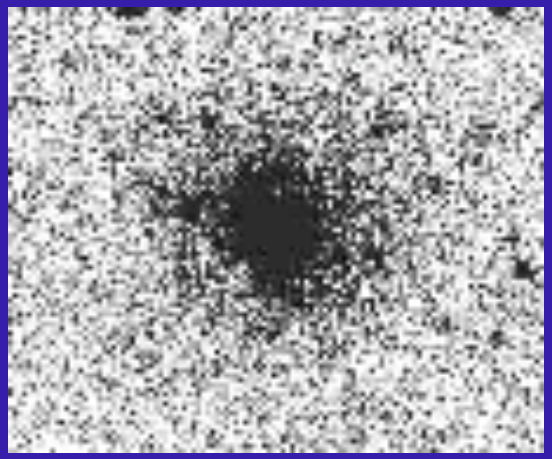
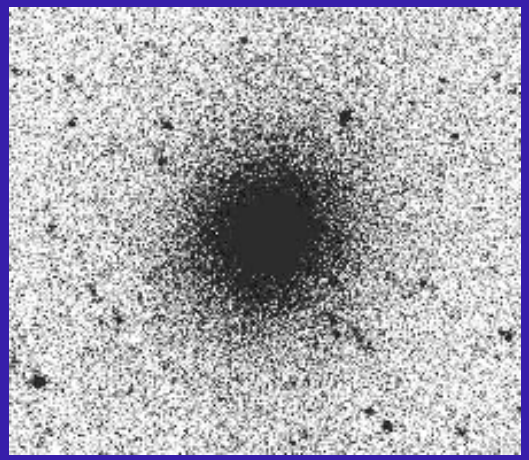
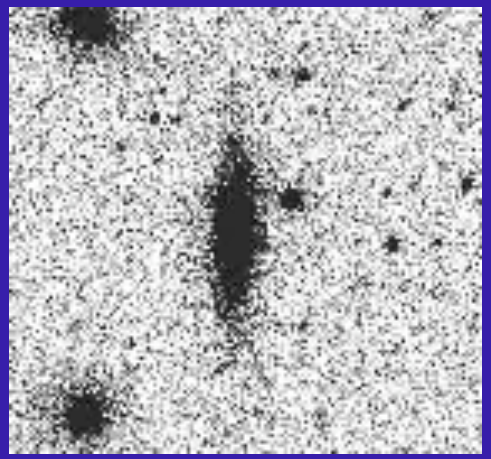
GALEX: Standard

(Jeong et al. 09)

UV Morphologies: Standard

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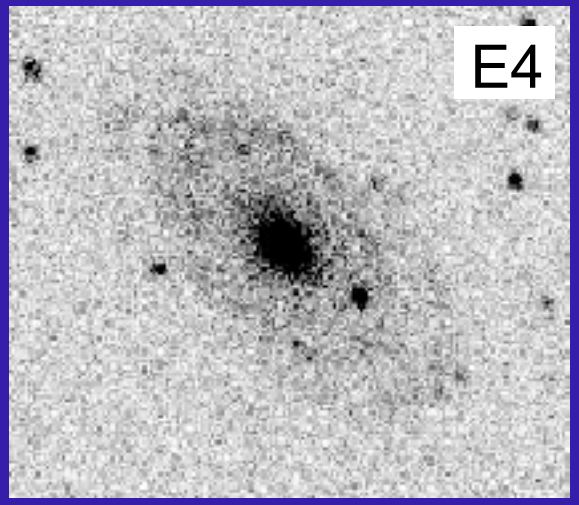
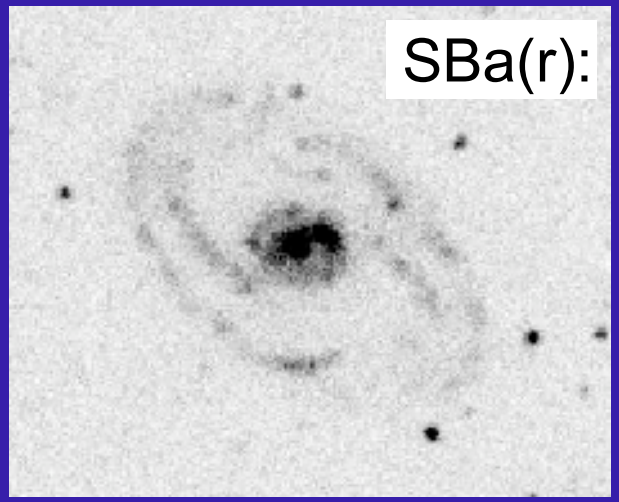
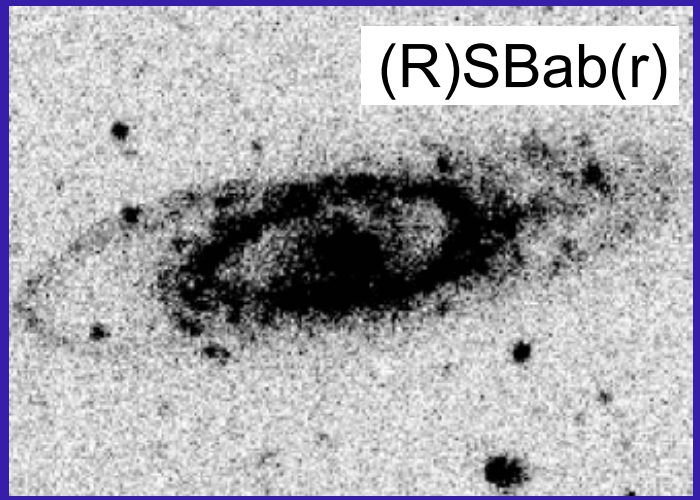
GALEX: Exceptional

(Jeong et al. 09)

UV Morphologies: Exceptional







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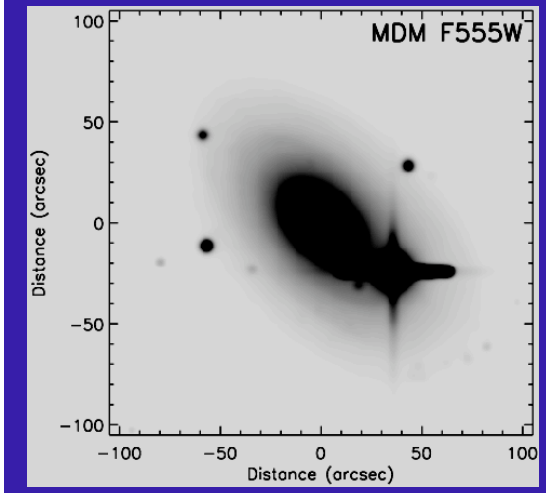
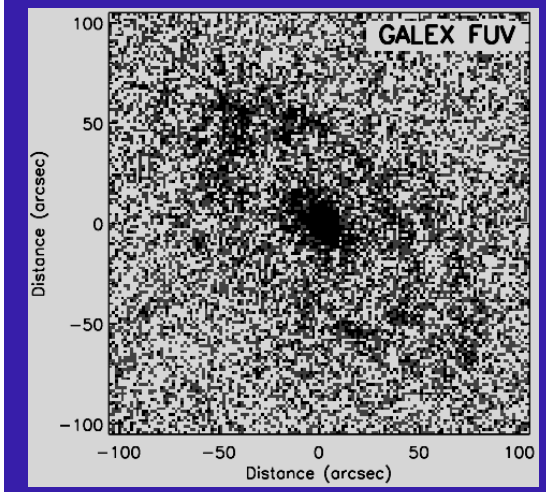
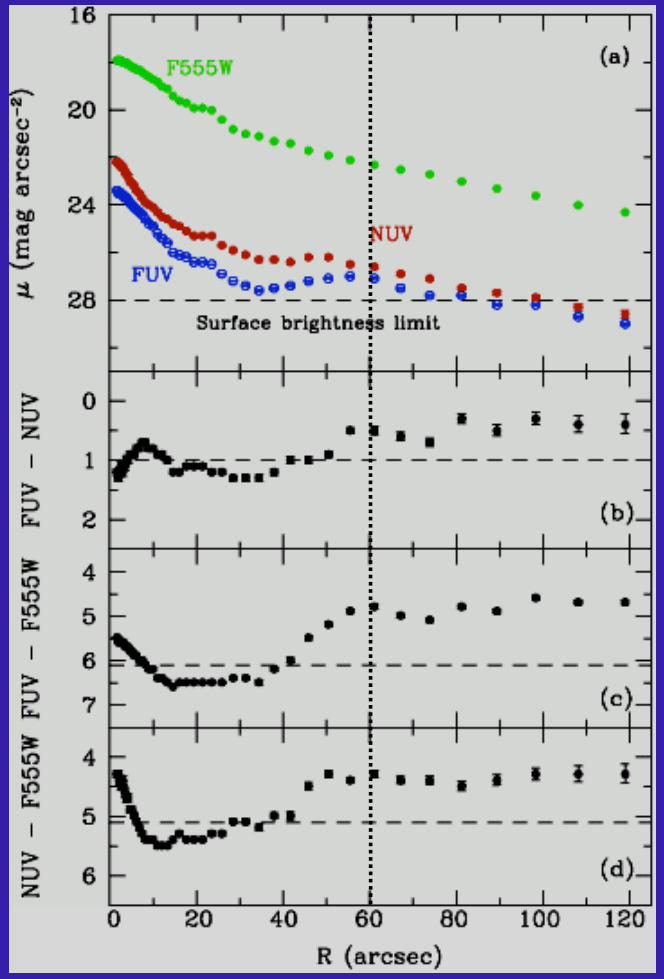
NGC2974: UV Morphology - Kin.

(Jeong et al. 07)

Optical-UV Imaging:







Distribution:

- Young stars and RSF (UV bright and blue) in centre + outer ring
- Possible larger partial ring

Barred Dynamics:

- [OIII] nuclear and inner rings
- Imply unique pattern speed

⇒ Bar-driven SF (single pattern speed)

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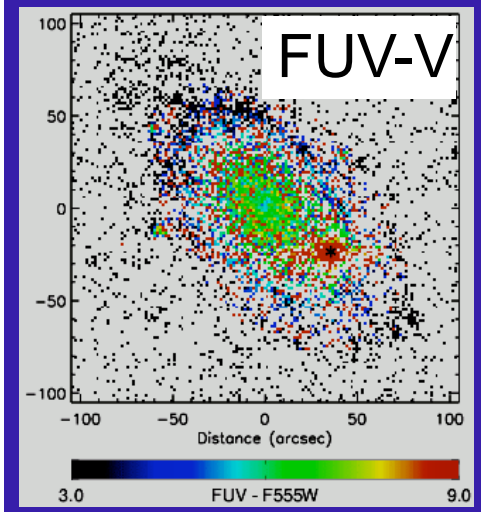
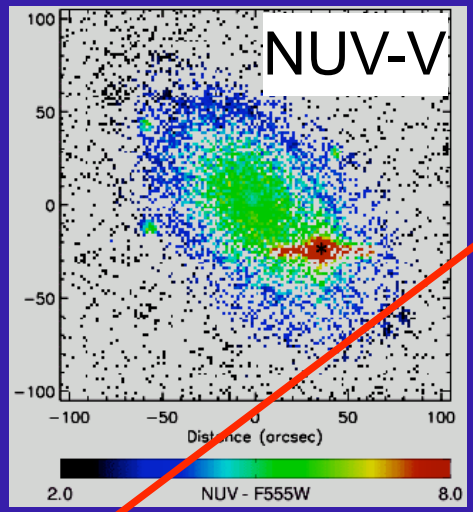
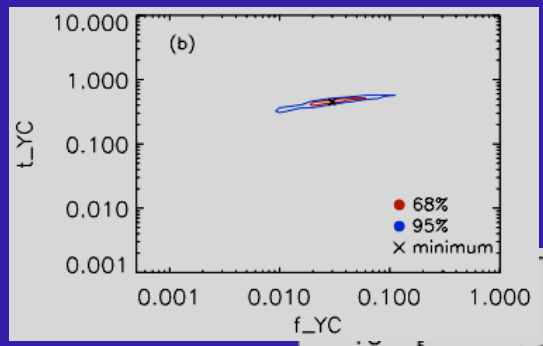
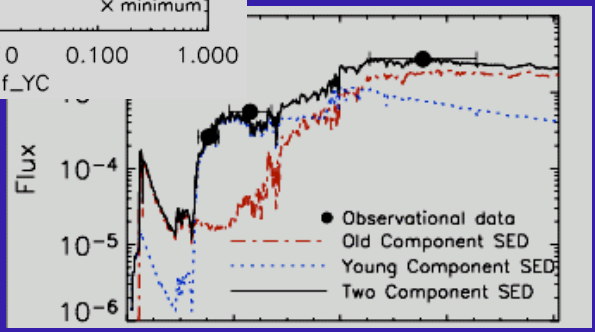
NGC2974: Stellar Pop. Modeling

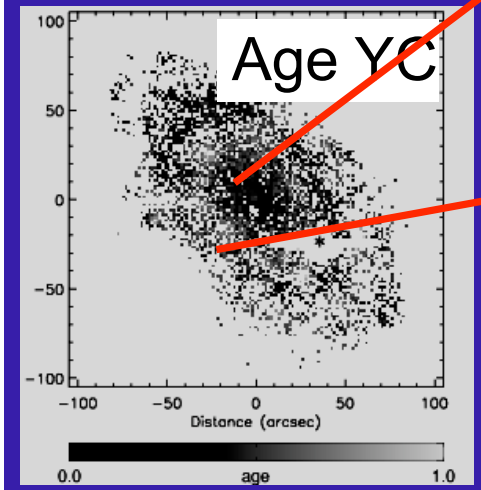
(Jeong et al. 07)

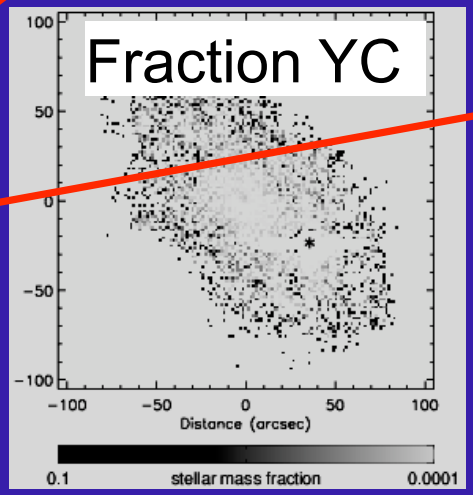


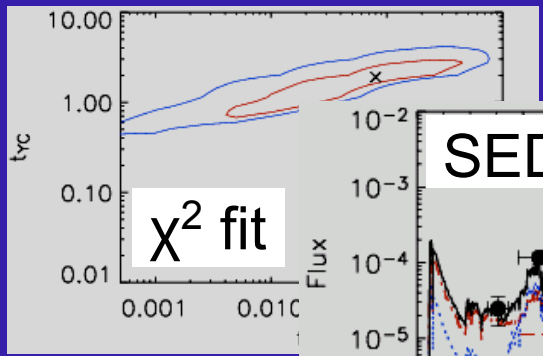


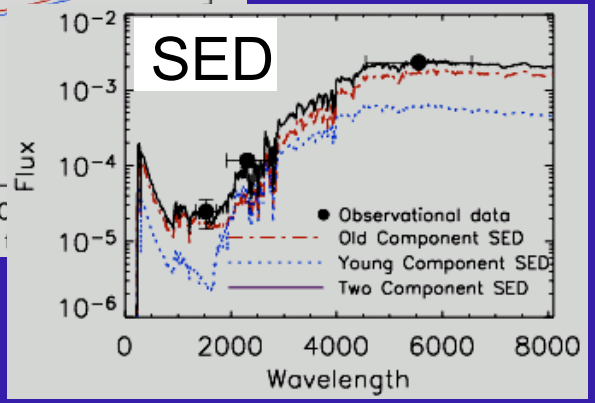












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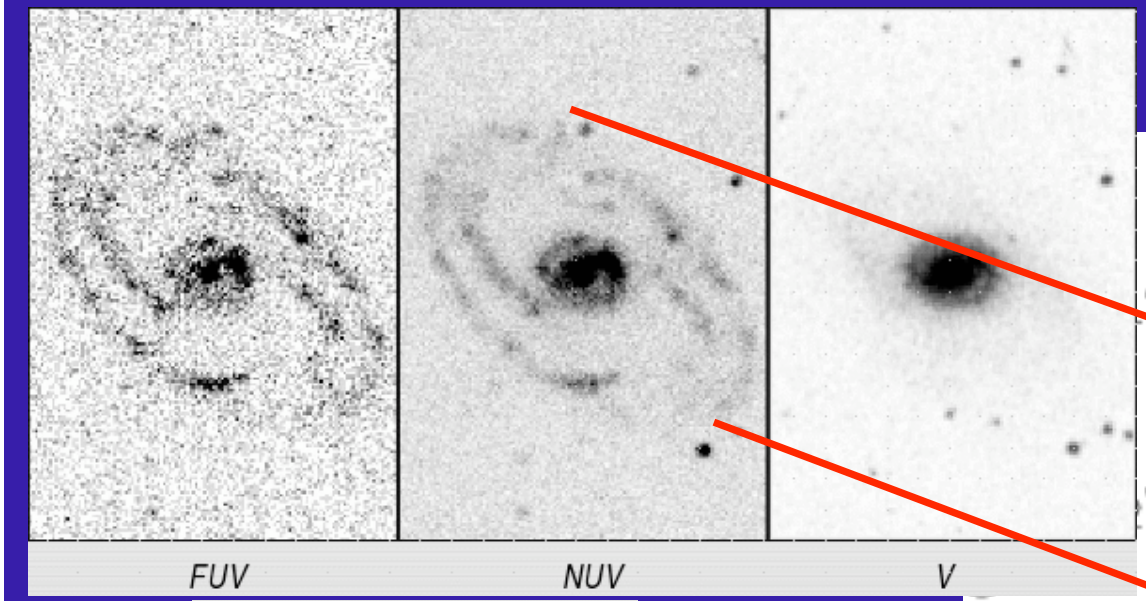
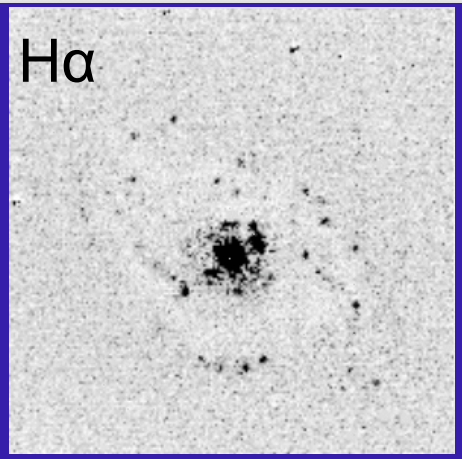
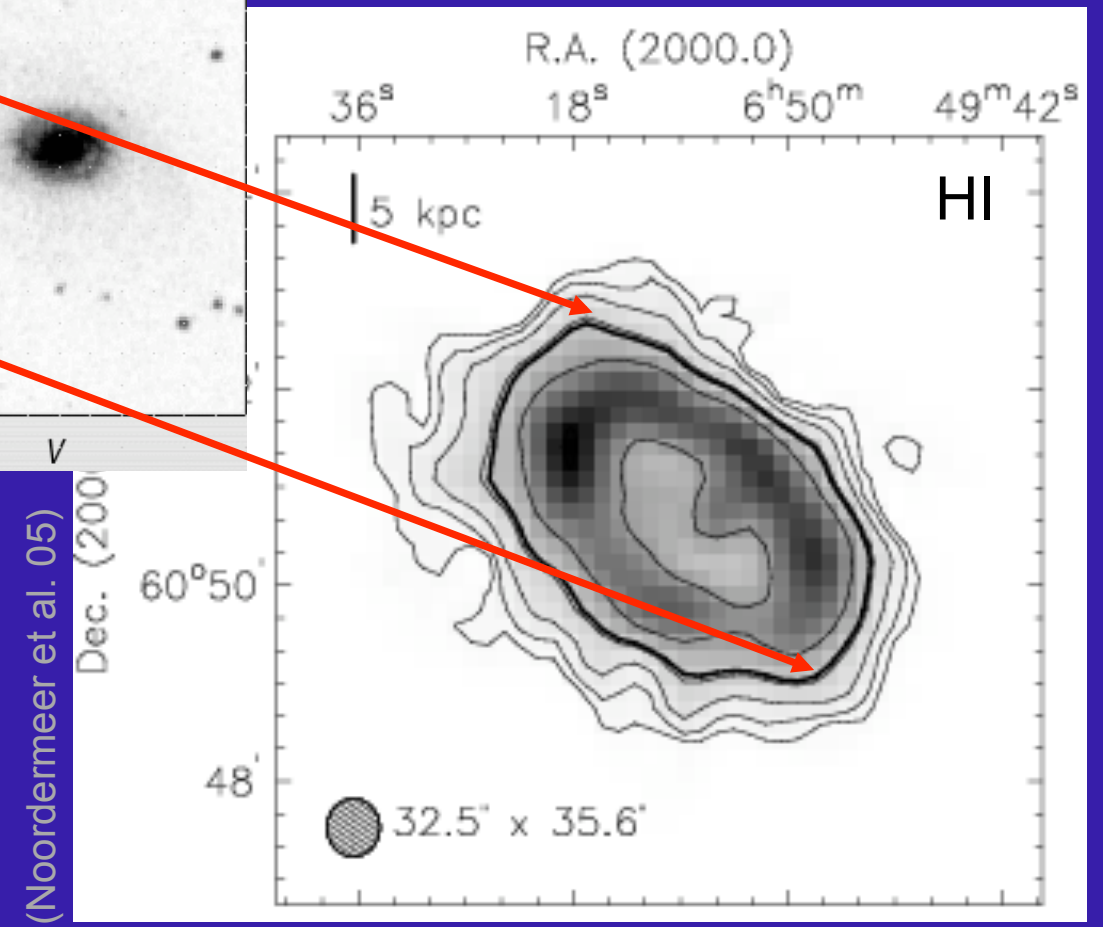
Other Cases: NGC2273

(Jeong et al., in prep)

GALEX-MDM:







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(Jeong et al., in prep)

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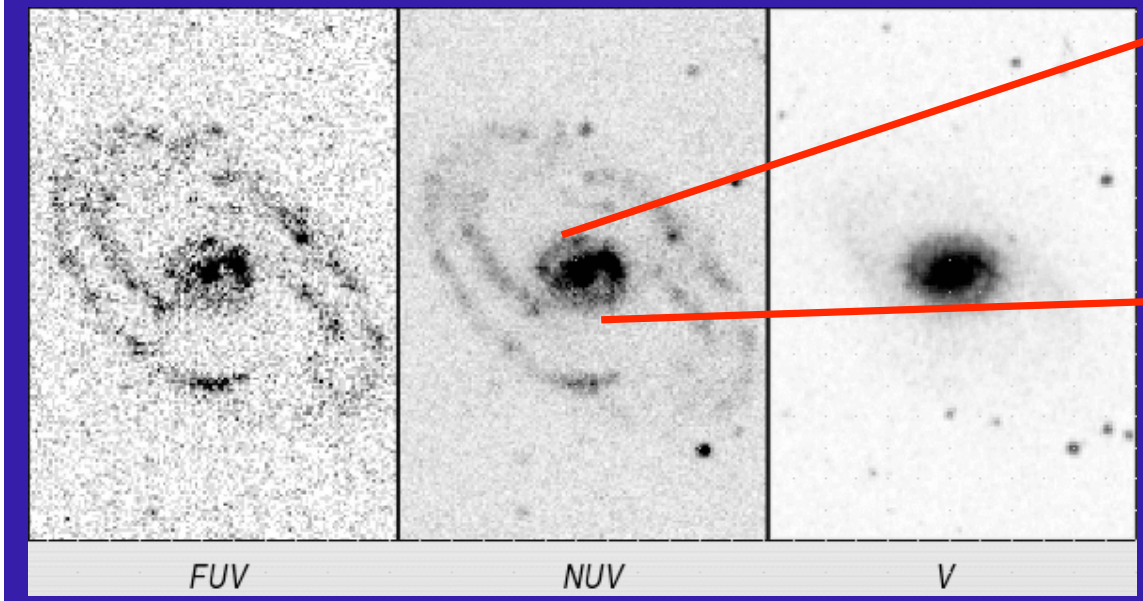
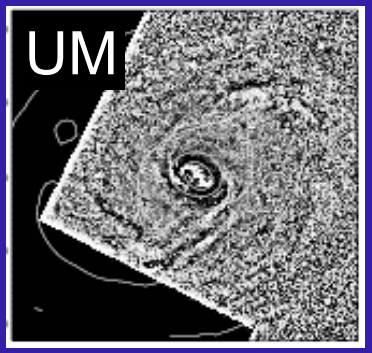
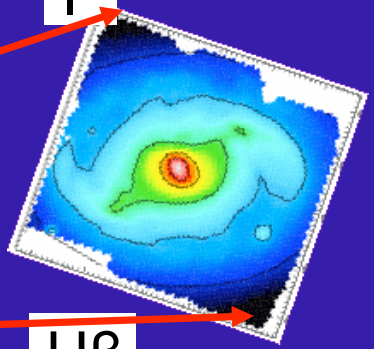
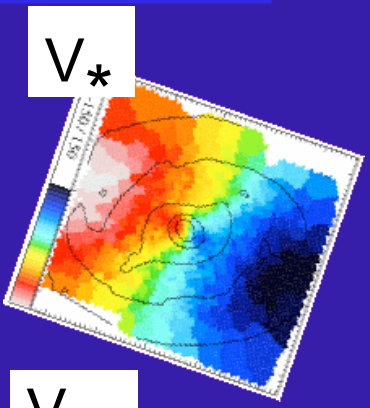




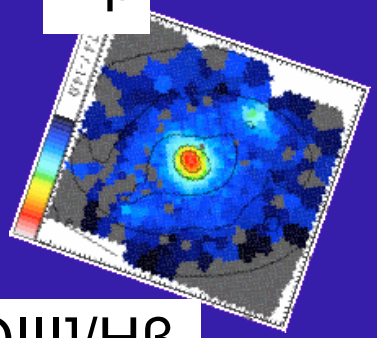
I



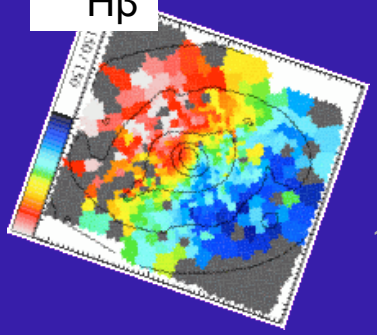
V_*



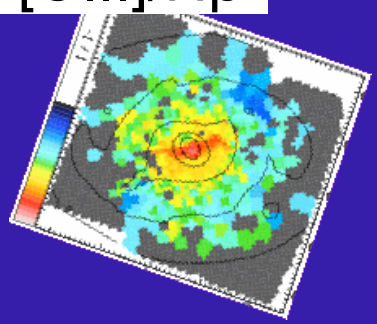
Hβ



$V_{H\beta}$



[OIII]/Hβ

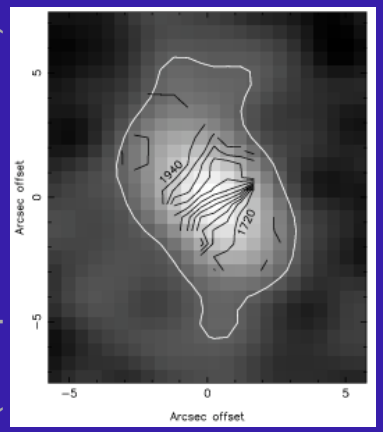


(Falcon-Barroso et al. 06)

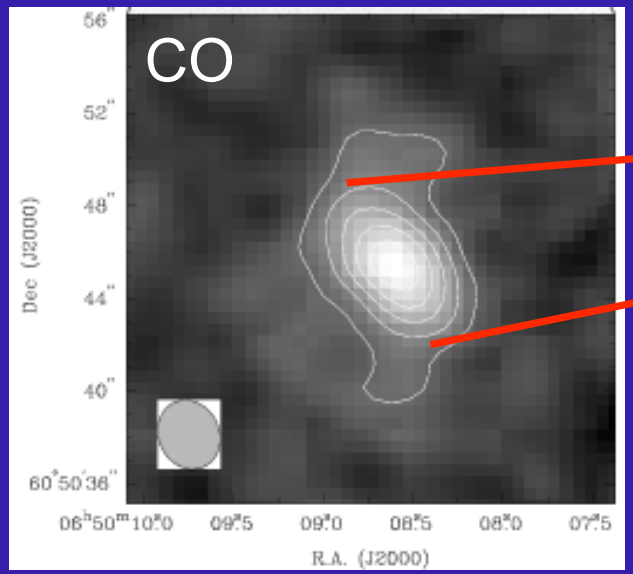
Other Cases: NGC2273

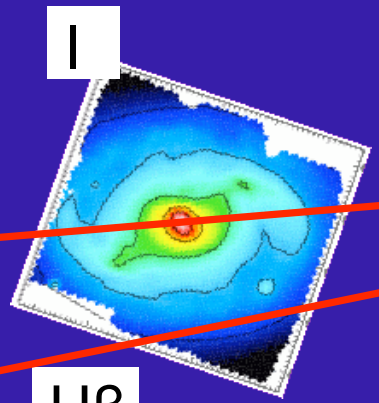
(Jeong et al., in prep)

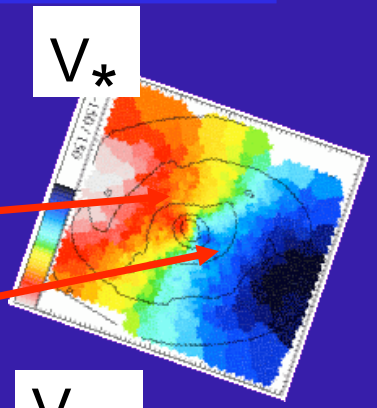
GALEX-MDM:

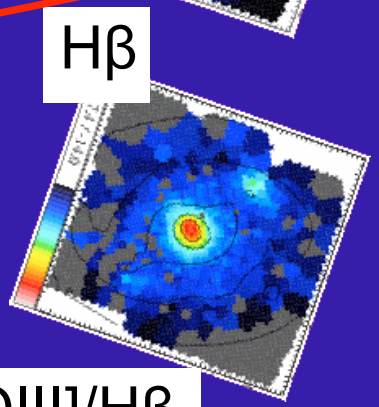


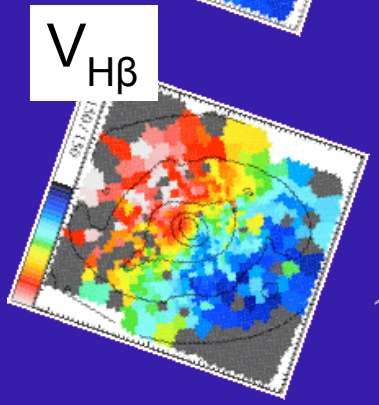
(Petitpas & Wilson 02)

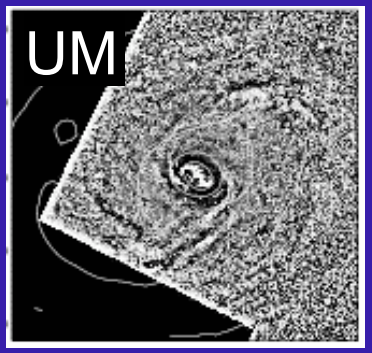


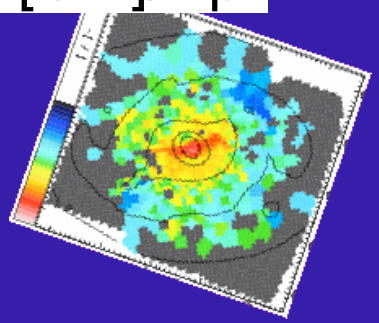












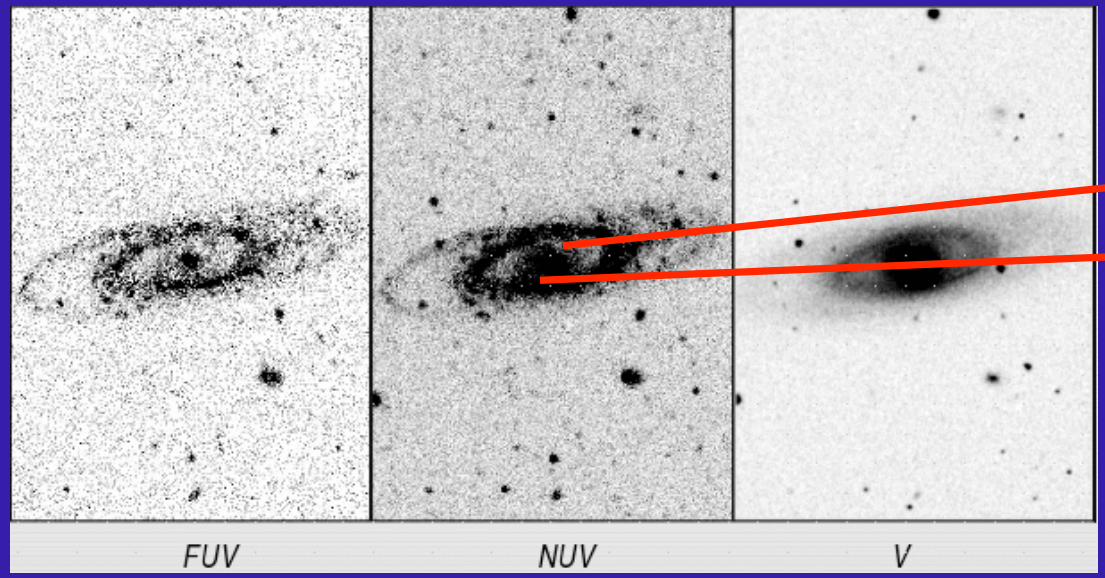
(Falcon-Barroso et al. 06)

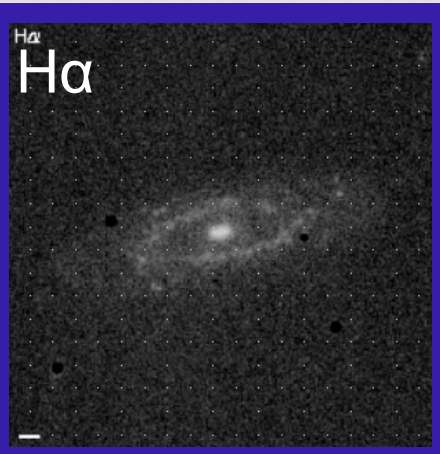
Martin Bureau, Oxford University

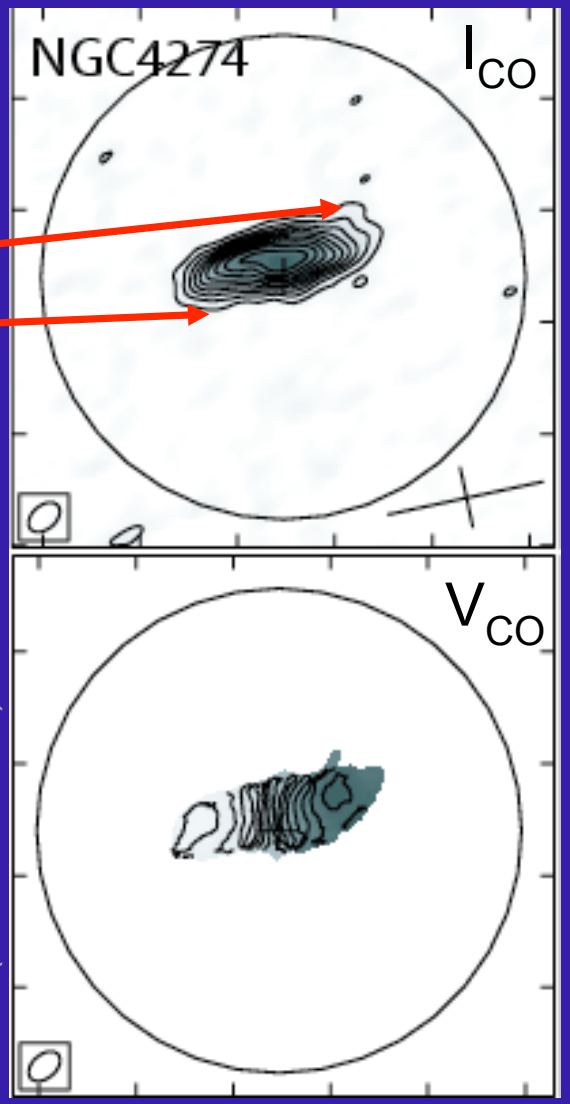
Other Cases: NGC4274

(Jeong et al., in prep)

GALEX-MDM:







(Koda et al. 05)

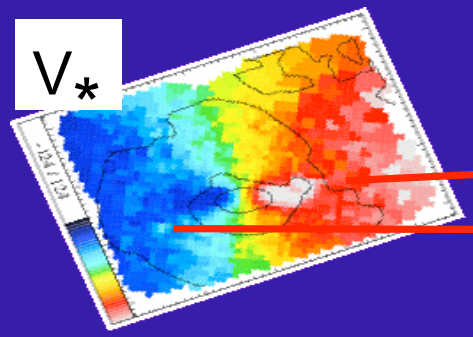
(Noordermeer et al. 05)

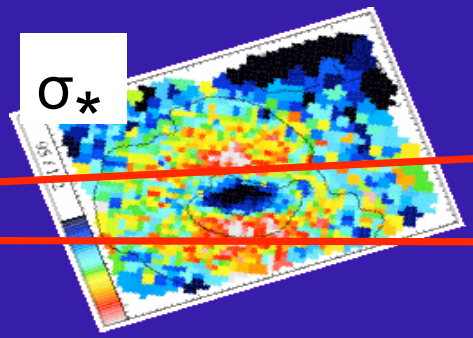
Martin Bureau, Oxford University

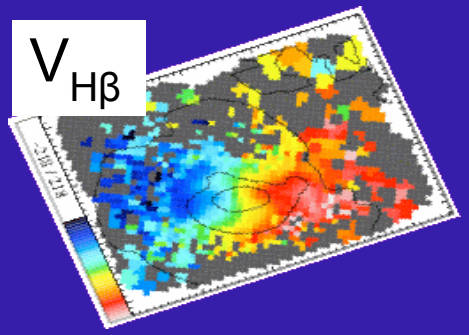
Other Cases: NGC4274

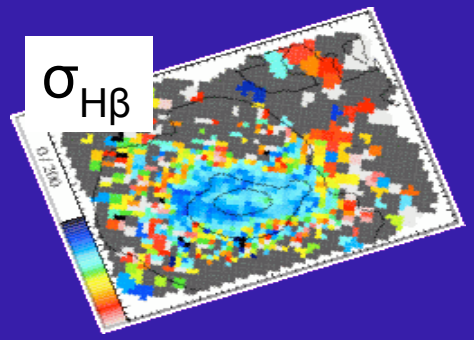
(Jeong et al., in prep)

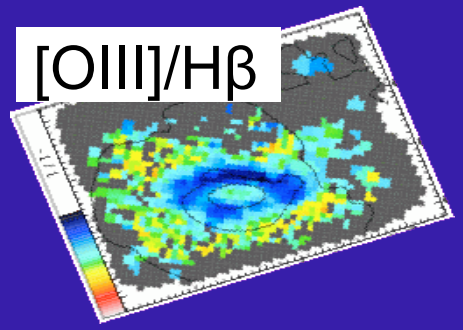
SAURON:



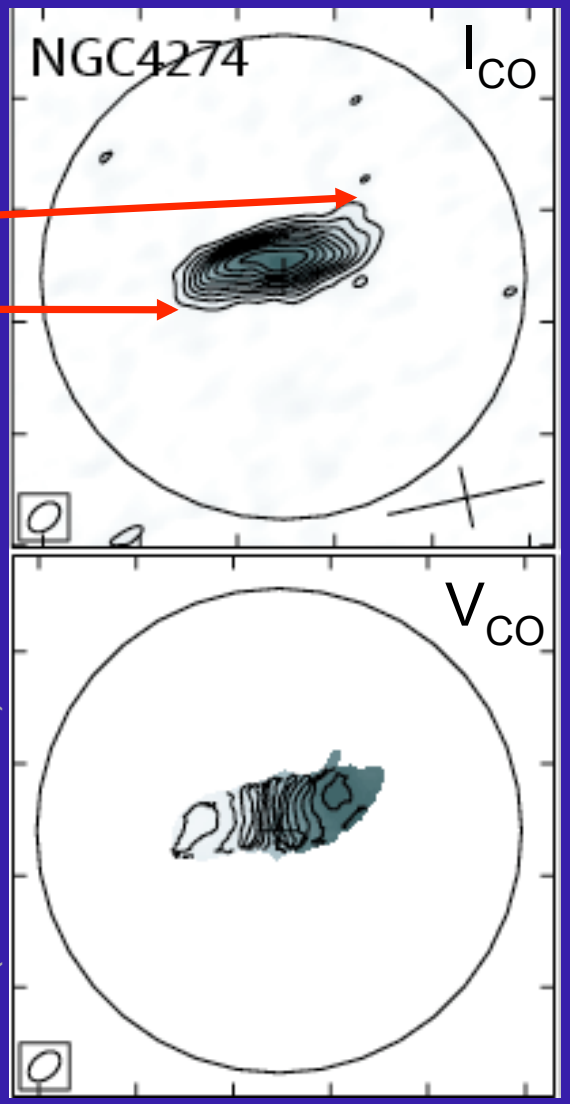








(Falcon-Barroso et al. 06)



(Koda et al. 05)

(Nordgren et al. 95)

Martin Bureau, Oxford University

Molecular Gas, Star, and Disk Formation in Local Early-Type Galaxies

Martin Bureau, Oxford University

CO
(L.M. Young, L. Blitz, F. Combes)
(Alison Crocker, Timothy Davis, Katey Alatalo)

GALEX
(Hyunjin Jeong, S. Yi)

Optical
(SAURON + Atlas3D teams)

Plans:

Optical/SAURON, UV/GALEX: Stellar populations in E/S0s
CO/30m: H_2 census (L, dynamics, environment)
CO/BIMA+PdBI+CARMA: H_2 origin, star formation
UV/GALEX, HI: Star formation, H_2 – HI relation
Summary

(Preliminary) Conclusions

- KDCs: - Young stars common in local E/S0s: ≅30%
  - Classic KDCs: Large, massive, homogeneously old, SR
    (early dissipational/late dissipationless major merger)
  - Compact KDCs: Small, lightweight, young, FR
    (recent minor merger/gas accretion)
- CO: - Common in local E/S0s: ≅23%; internal cluster, external field
  - Central disks: CO cospatial/corotating with gas/young stars
  - Central CRs: CO roughly cospatial with gas/young stars
    (generally less extended), unrelated to CRs ?
  - SF sequence? Current, recent, no/weak SF, ...
  - ✗ Still in exploratory phase, building up sample...
- UV: - Resolved UV-optical colors: Age, mass fraction of young stars
  - Recent SF correlated with stellar/ionised-gas/CO dynamics

Martin Bureau, Oxford University

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Great synergy
optical IFU – mm interferometry

Martin Bureau, Oxford University

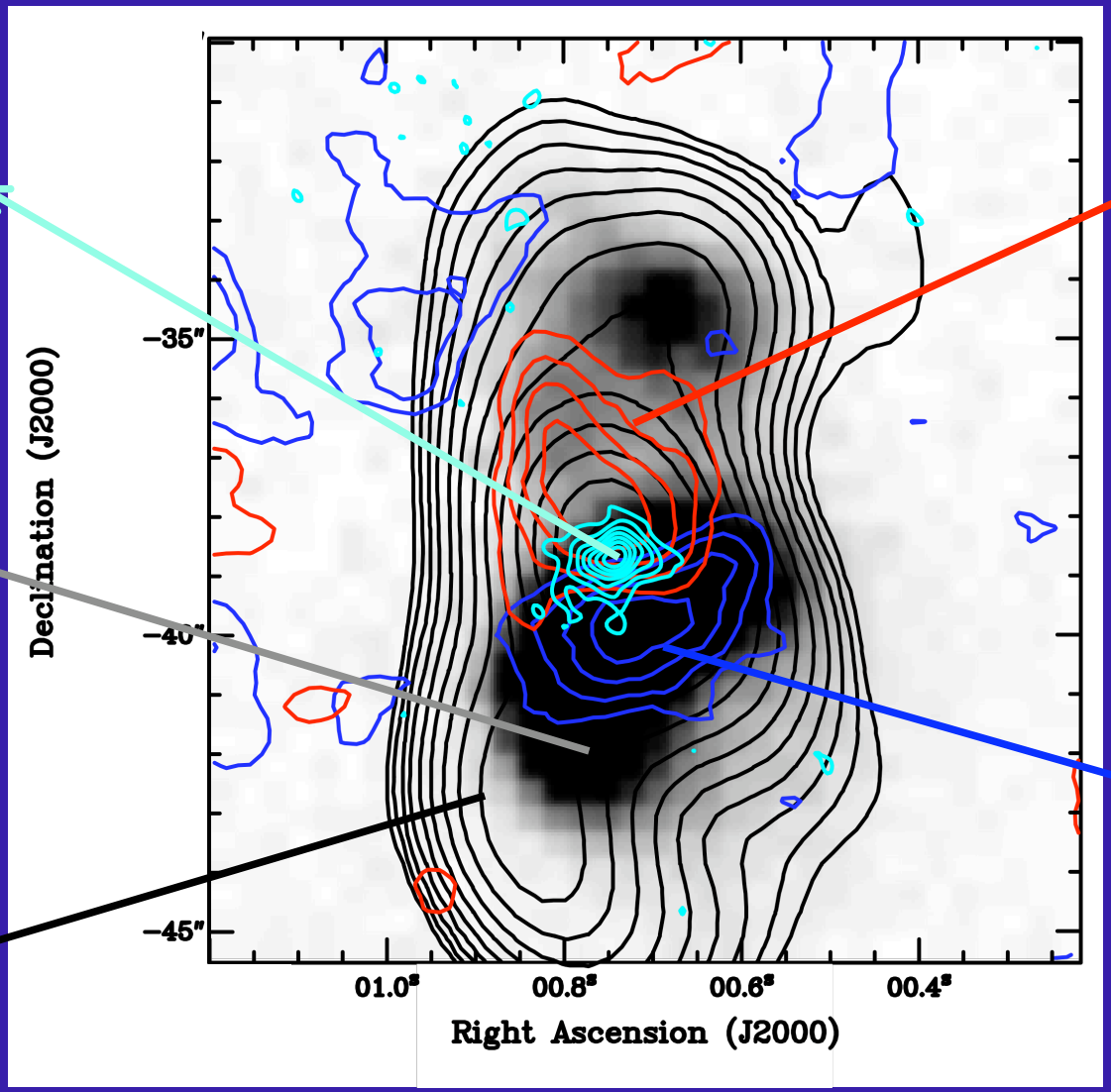
Molecular AGN-Driven Outflows

(Alatalo et al., in prep)

M_{H2} = 2x10^9 $M_\odot$ at $V_{systemic}$, within R = 150 pc

Narrow-band Hα

1.4 GHz radio continuum



Highly red-shifted H_2

Highly blue-shifted H_2

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