Molecular Gas and Star Formation in Early-Type Galaxies

Martin Bureau, Oxford University

CO
(Katey Alatalo, Estelle Bayet, Leo Blitz, Francoise Combes,
Alison Crocker, Timothy Davis, Melanie Krips, Lisa Young)

Optical
(SAURON + Atlas^{3D} teams)

Plans: SAURON+Atlas^{3D}: E/S0 formation, residual SF, surveys
CO: E/S0 H_2 incidence, distribution, kinematics, origin, BHs
CO: E/S0 SF tracers, sequence, laws, ISM
Summary and future

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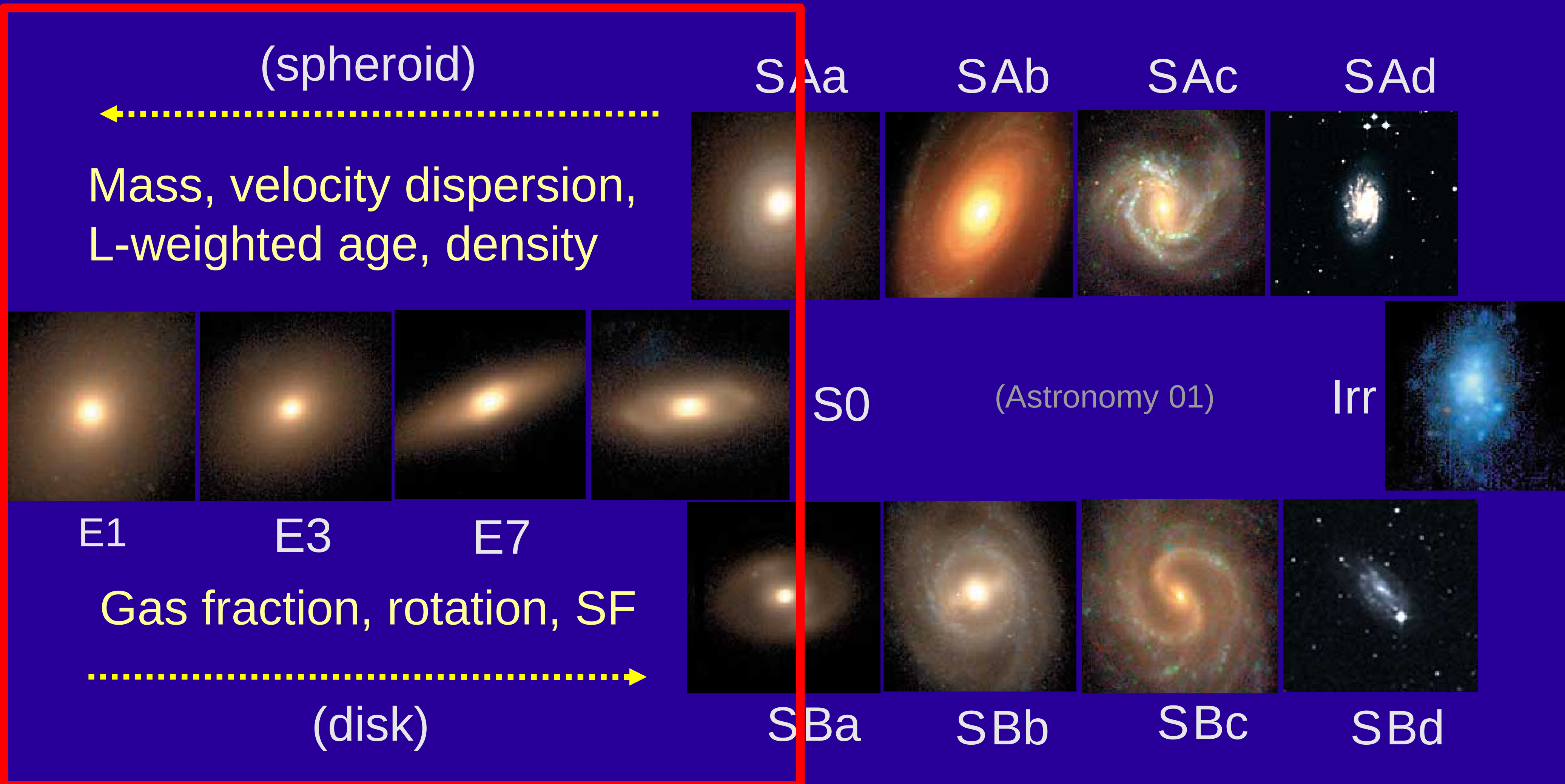
Hubble Sequence



Sauron + Atlas^{3D}

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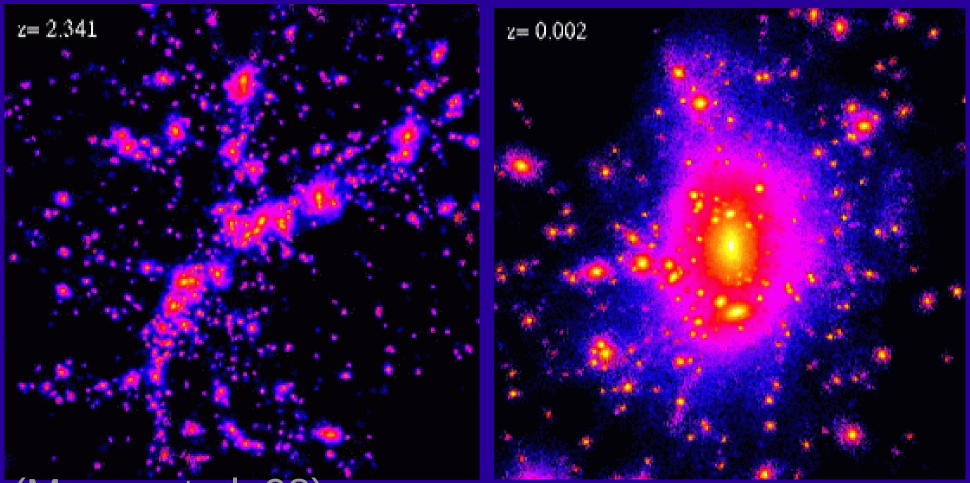
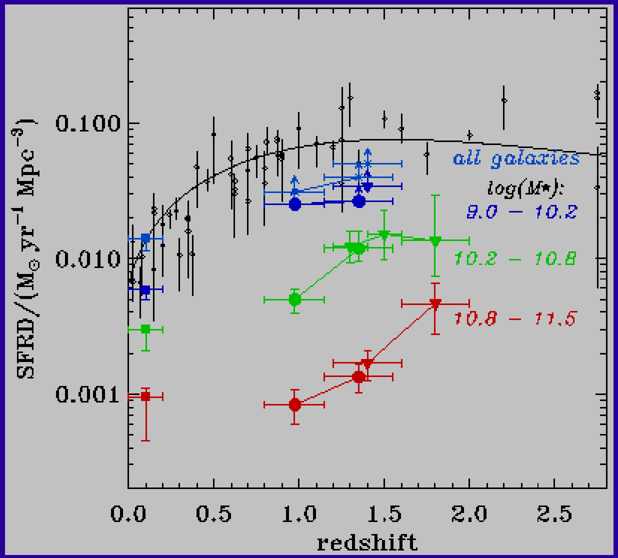
(SAURON+Atlas^{3D}): Broad Aims



(Moore et al. 98)



(Juneau et al. 05)

Goals:

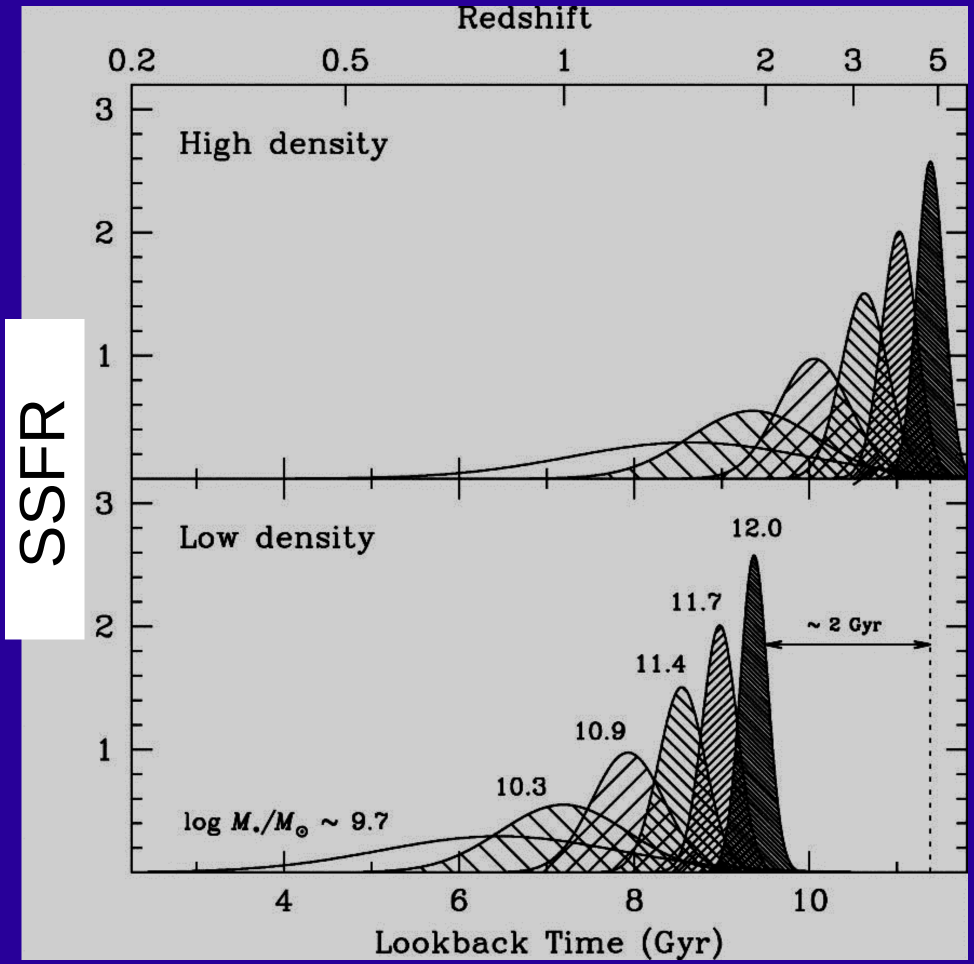
- Mass assembly history
  (stars, gas, dark matter)
- Chemical enrichment history
  (age, metallicity, SFH)

Context:

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

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

Hierarchical Context



(Thomas et al. 05)

Downsizing:

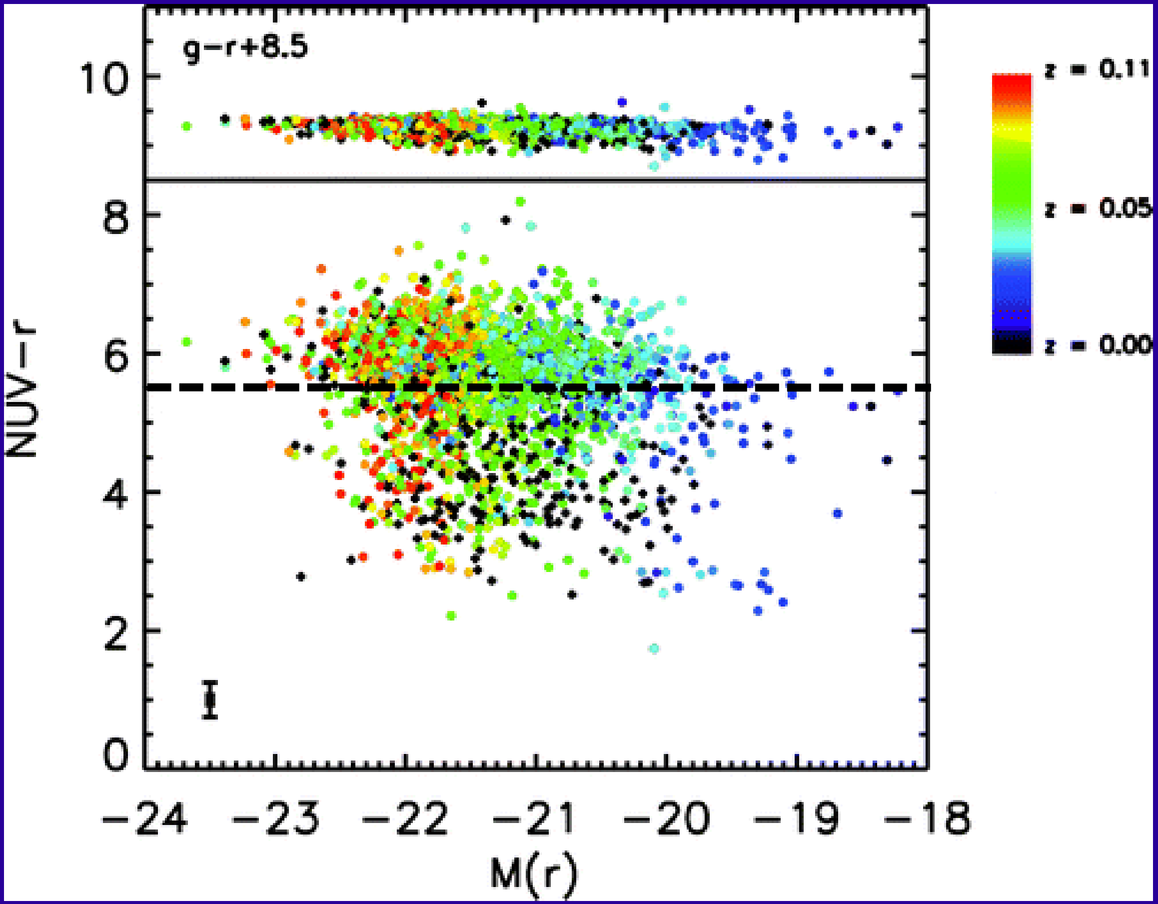
- Star formation history anti-hierarchical …
- More massive galaxies form their stars earlier and faster (age, metallicity, α-elements)
- Star formation earlier overall in denser environments

⇒ Are the star formation and mass assembly histories of early-type galaxies truly over at $z = 0$?

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

SAURON: Stellar Linestrengths

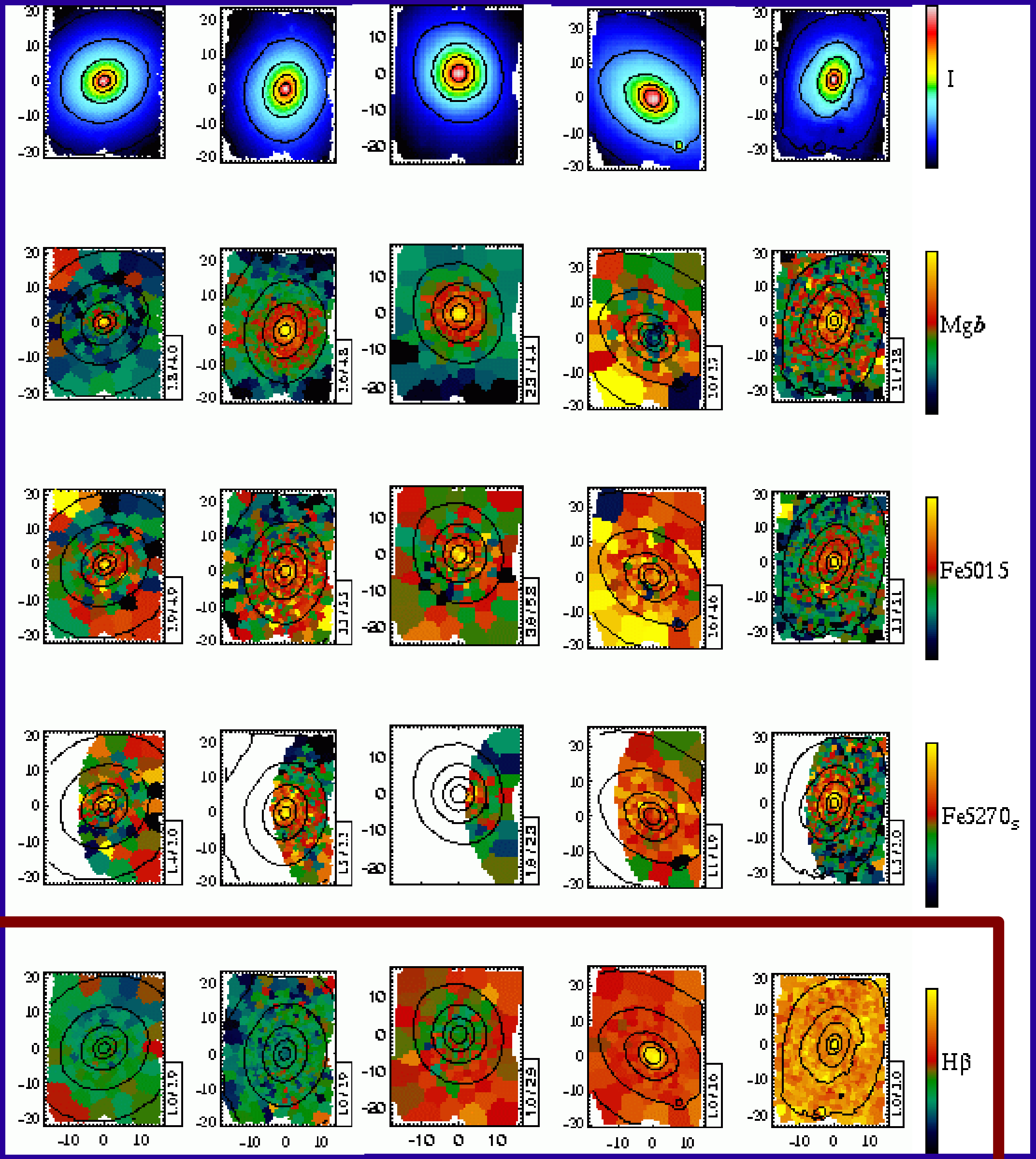
(Kuntschner et al. 06, 10; McDermid et al. 06)

<u>Main results:</u>

- Standard:
  Homogeneously old,
  decreasing metallicity
- Occasional:
  Young core/body,
  varied metallicity

<u>KDC Dichotomy:</u>

- Small, young, distinct
  (in fast rotators; dissipation?)
- Large, homogeneously old
  (in slow rotators)



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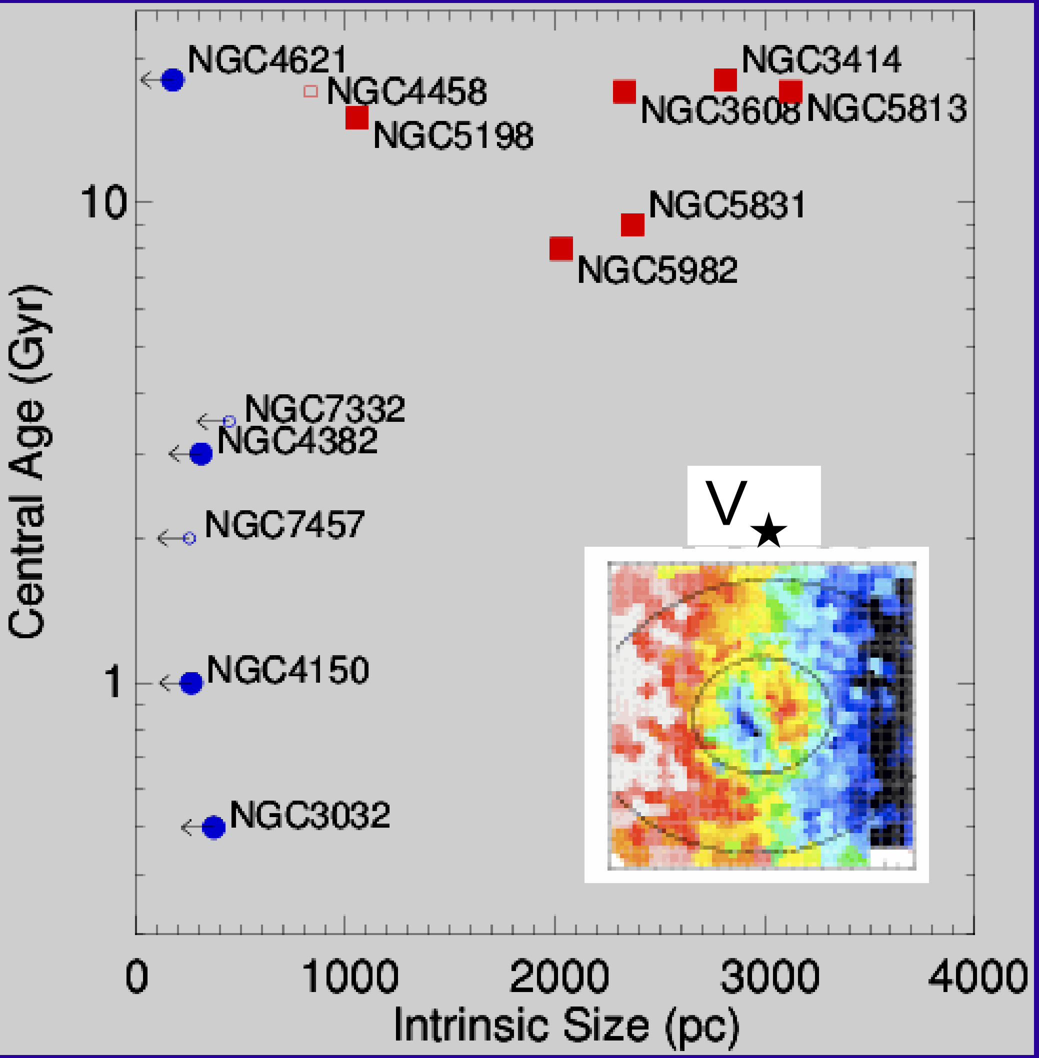

KDC Dichotomy:

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Molecular Gas and Star Formation in Early-Type Galaxies

~~red and dead~~

~~dynamically simple… boring~~

<u>Where</u> <u>When</u> <u>How</u> <u>Why</u>

does star formation take place in ETGs ????

(What are the origin, dynamics, physical conditions, chemistry, … of the molecular gas ?)

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Complete Survey of ETGs

(Cappellari et al. 2011)

Science goals:

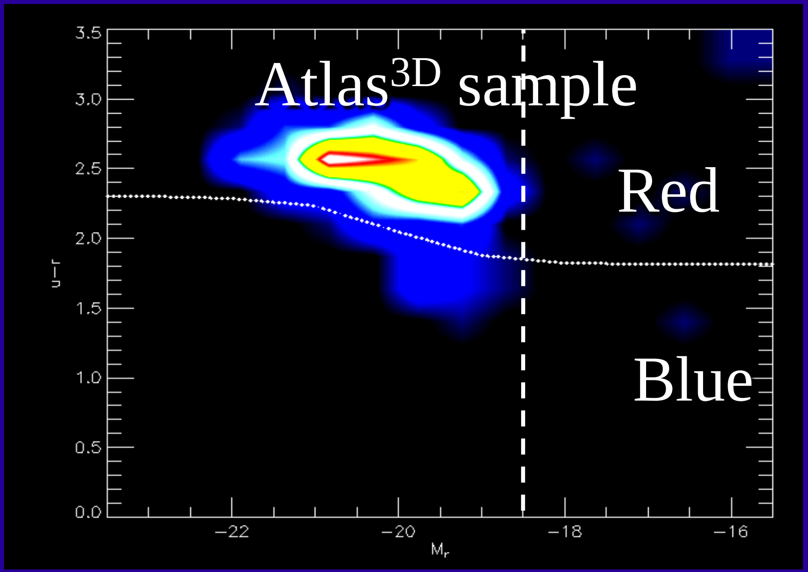
- Distribution of fast + slow rotators
- Fraction of wet + dry mergers
- Role of SF + AGN feedback
- ✧ Strong low-z constraints for simulations

Sample selection:

- $M_K < -21.5$
- D < 41 Mpc
- $|\delta\text{-}29^\circ| < 35^\circ$, $|b| > 15^\circ$
- All E/S0s, no spiral structure

Atlas[3D]

g-r



M_r

⇒ 260 galaxies

Complete Survey of ETGs

(Cappellari et al. 2011)

Datasets:

- Optical integral-field spectroscopy: WHT/SAURON
- Optical photometry: Multi-bands (SDSS, INT), deep (CFHT)
- Single-dish CO: IRAM 30m (^{12}CO(1-0, 2-1))
- CO interferometry: CARMA (^{12}CO detections only; 40+ galaxies)
- HI interferometry: WSRT (~150 galaxies excl. Virgo), ALFALFA
- Archival data: Chandra, XMM, GALEX, HST, Spitzer, 2MASS, …

Simulations:

- Cosmological, binary mergers, individual galaxies, SAMs, …

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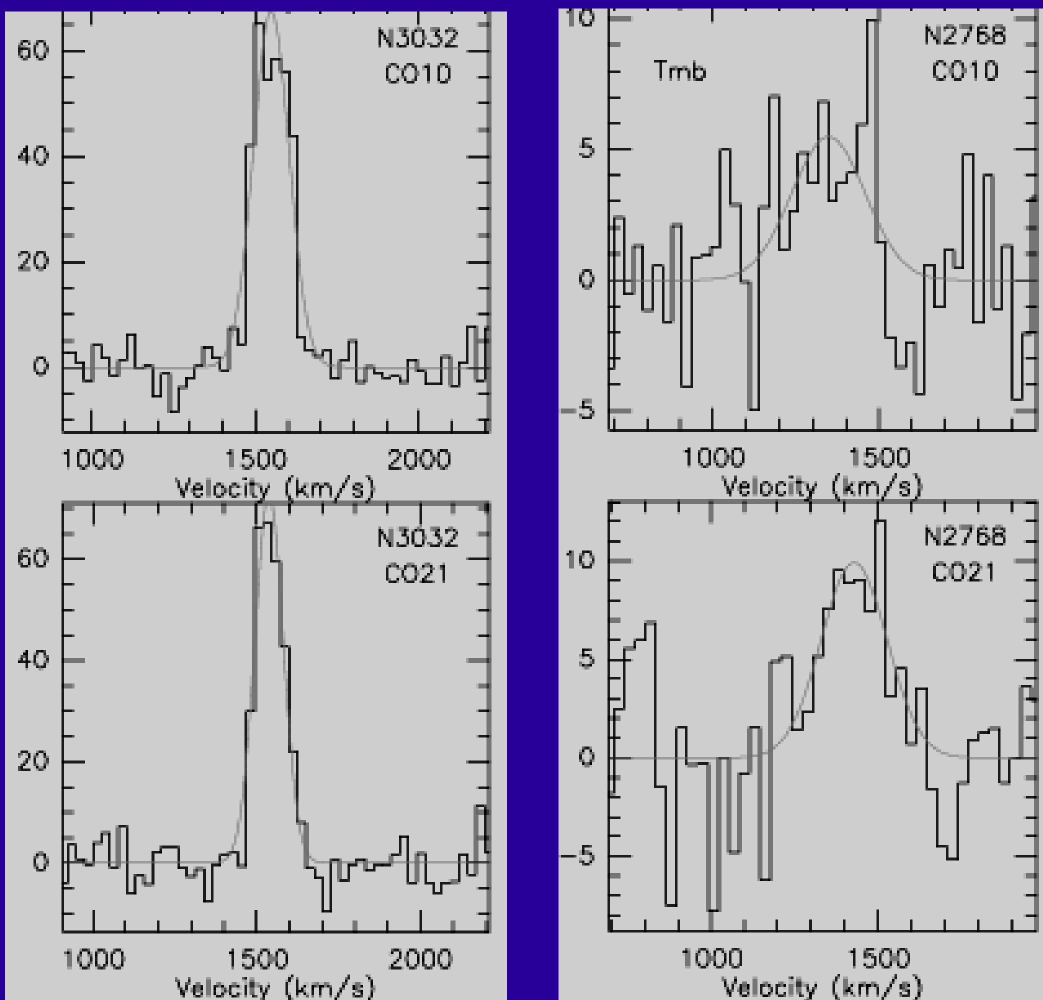
Summary and future

CO: Single-Dish Survey

(Combes, Young & Bureau 07; Young et al. 11,13)

High S/N: Low S/N:



IRAM 30m Survey:

- CO(1-0,2-1), 23/12" FWHM
- 260 Atlas^{3D} E/SOs
- Sensitivity: 3 mK (30 km s^{-1})
  3×10^7 $M_\odot$

Results:

- 22% detection rate
- $M_{H2} = 10^{7.1-9.3}$ $M_\odot$
- CO(2-1)/CO(1-0) ≈ 1 – 2

⇒ Independent of most structural, dynamical, environmental parameters…

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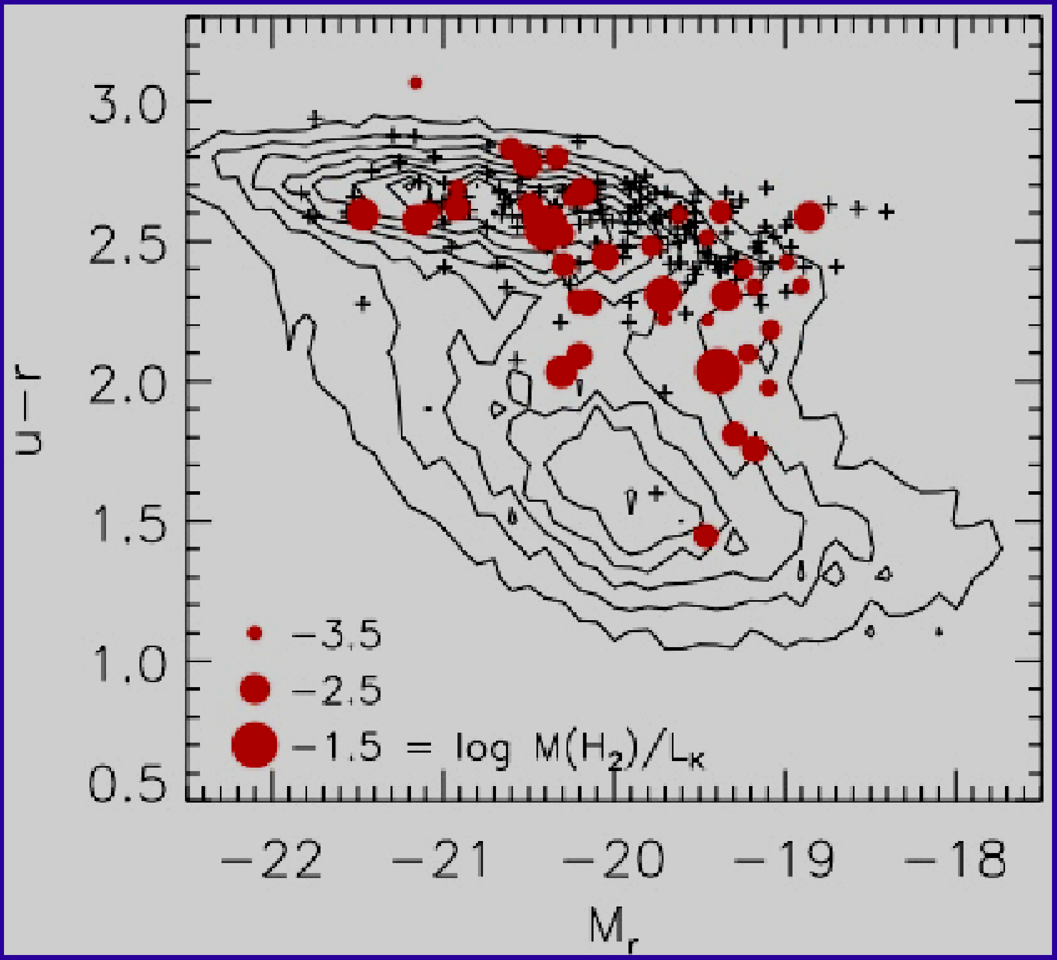
(Combes, Young & Bureau 07; Young et al. 11,13)

Optical CMD + CO



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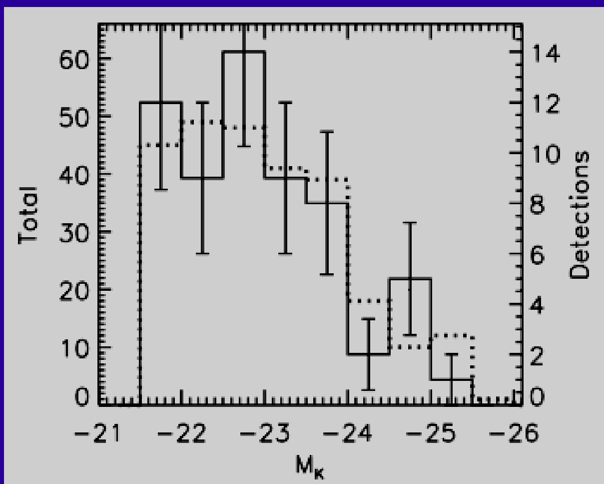
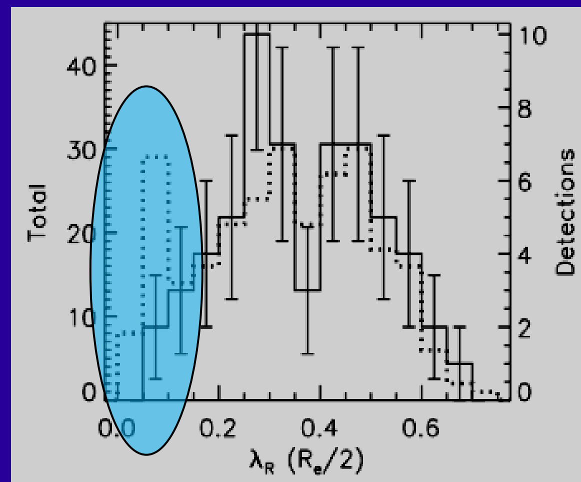
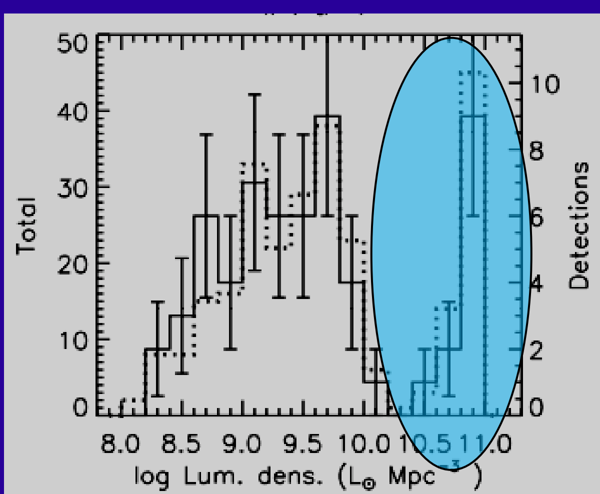
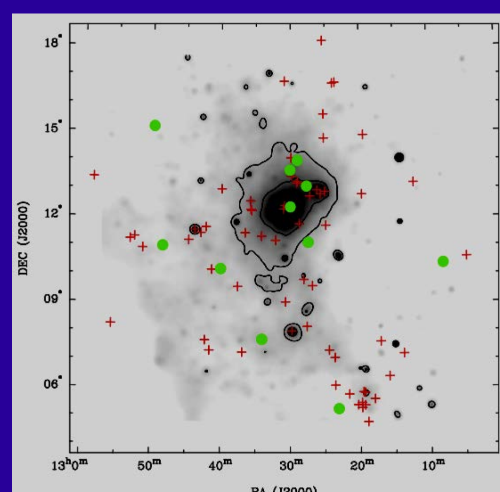
CO: Single-Dish Main Results

(Young et al. 11)









IRAM 30m Results:

- Detection rate largely independent of:
  - Luminosity
  - Dynamics ($\bullet_R$)
  - Environment (Virgo)
  - …
- ✧ Slow-rotator H_2 poor
- Expected correlations with linestrengths (but no simple CO-SF relation; SF sequence?)

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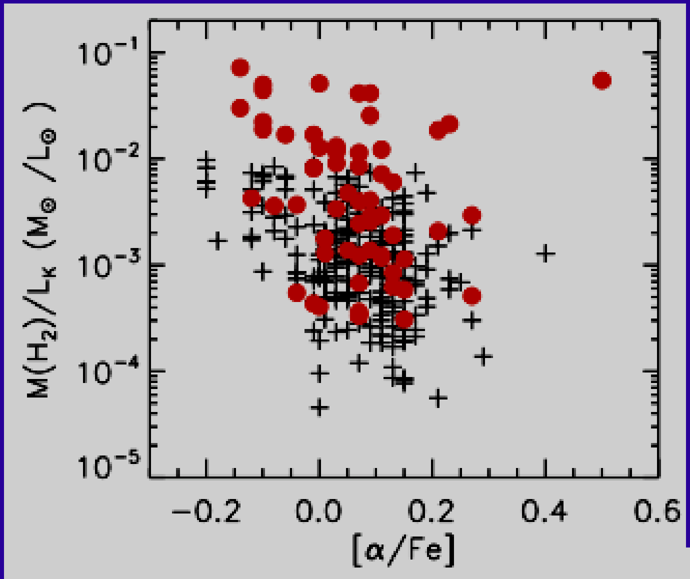

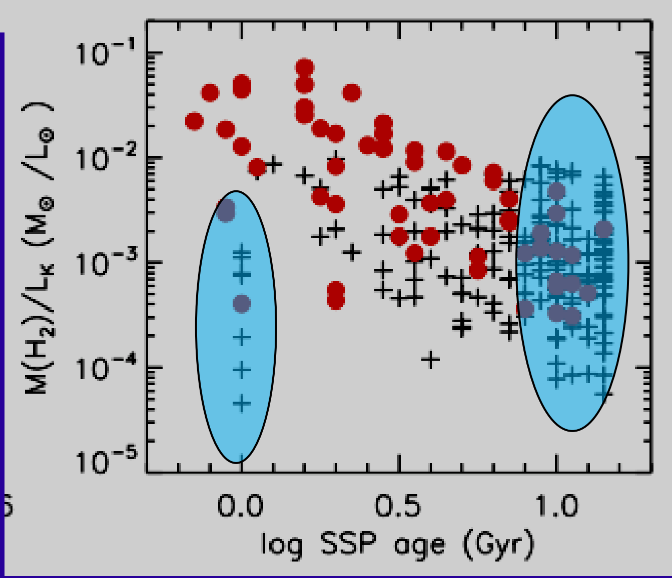

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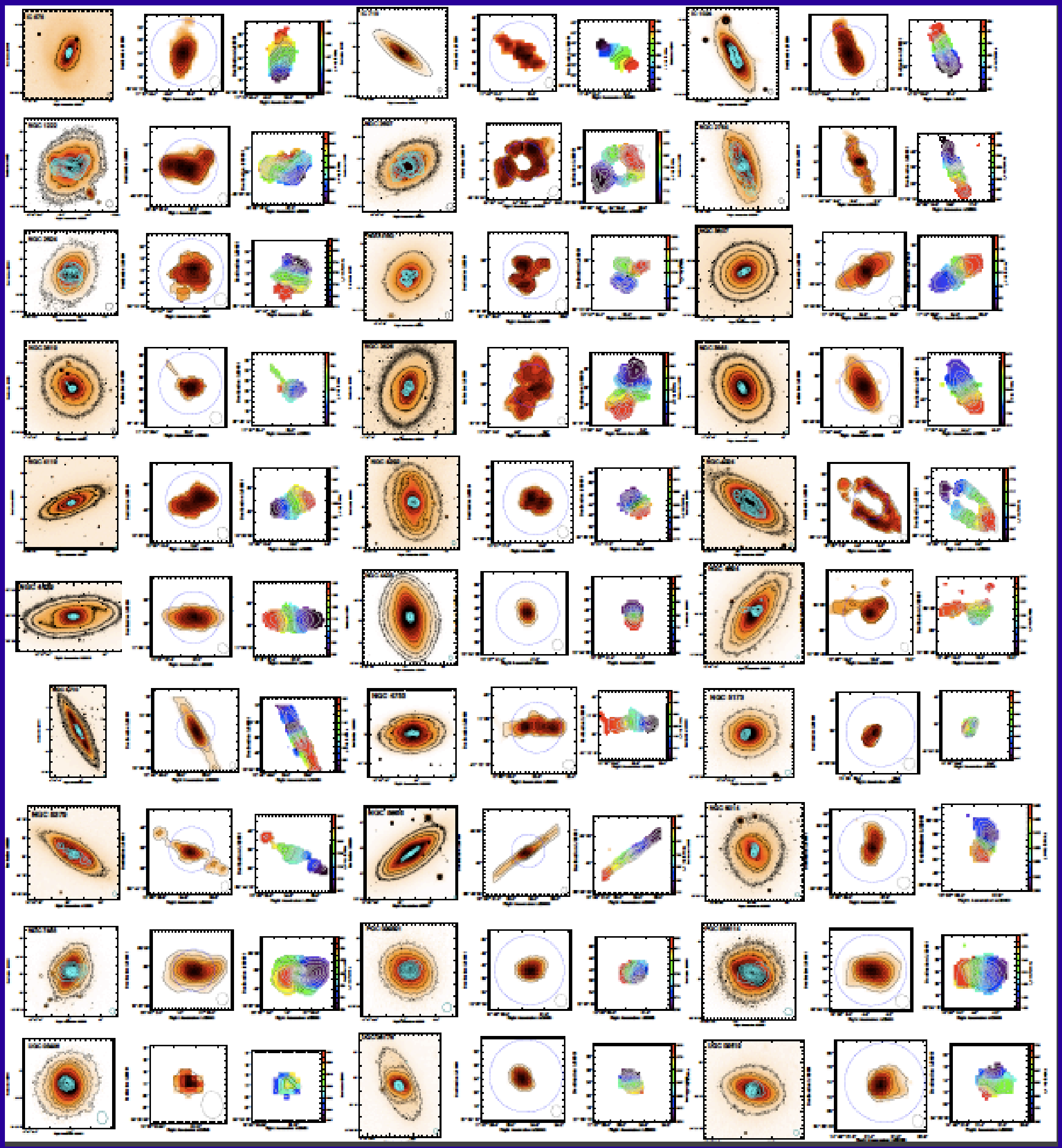
CO: Morphology

(Alatalo et al. 2012; Davis et al. 2012)



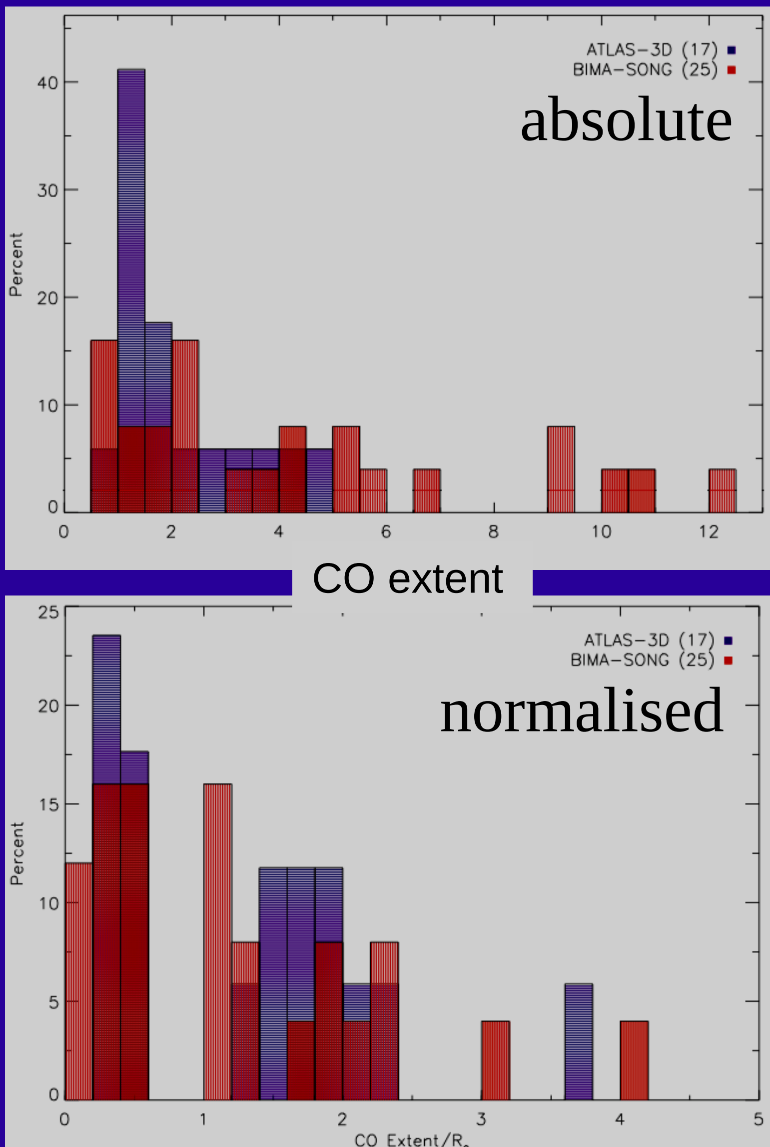
Atlas^{3D} (CARMA):

- > 40 objects so far (CARMA, PdBI, BIMA)

- Centrally-concentrated H_2 (physical size)
- Diverse morphologies (disks, rings, bars, …)
- Regular kinematics (CO best circular velocity and thus mass tracer)

CO: Extent

(Davis et al. 2012)



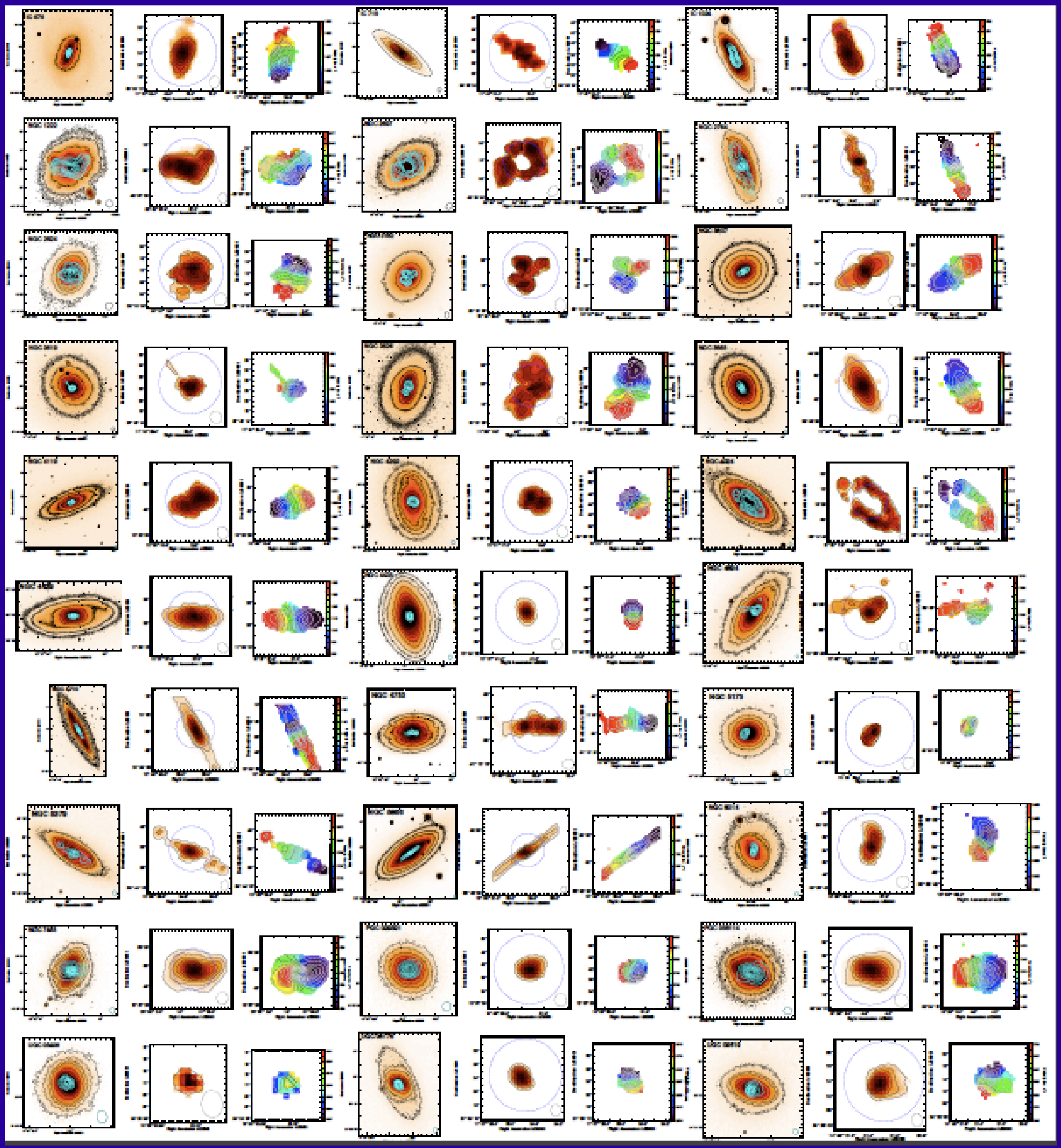
Atlas[3D] (CARMA):

- 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, …)

CO: Morphology

(Alatalo et al. 2012; Davis et al. 2012)



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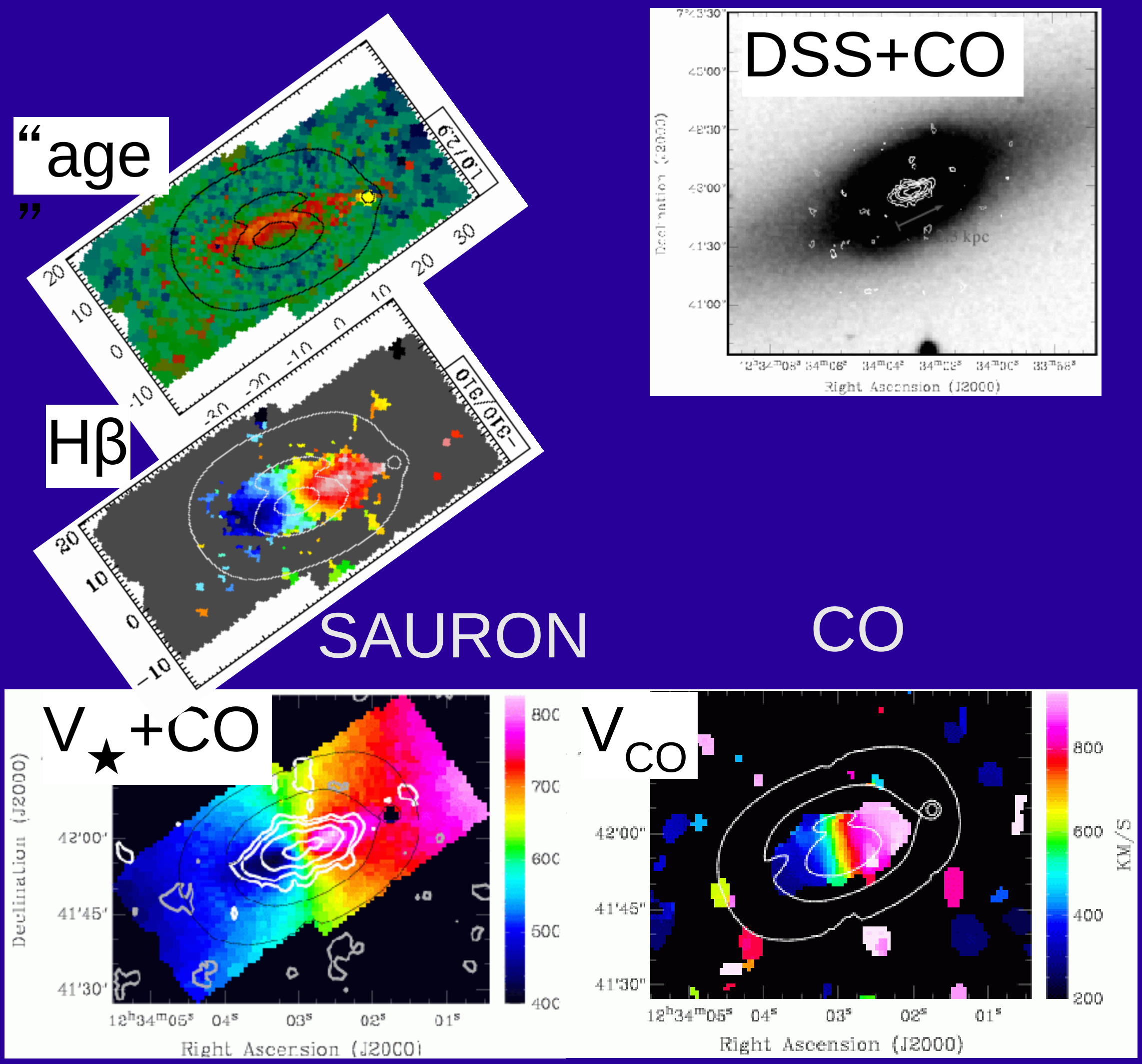
CO: Central Disks

(Young, Bureau & Cappellari 08; Crocker et al. 08, 09, 11)

BIMA-SAURON Data: NGC4526



Central Disks:

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

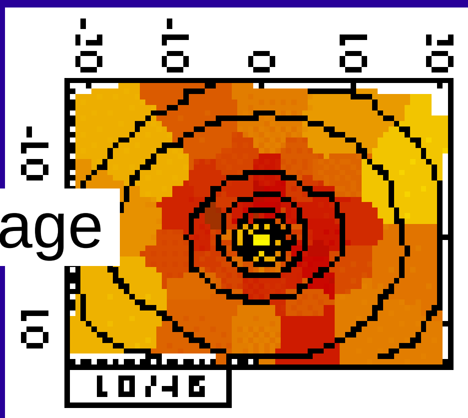
CRs:

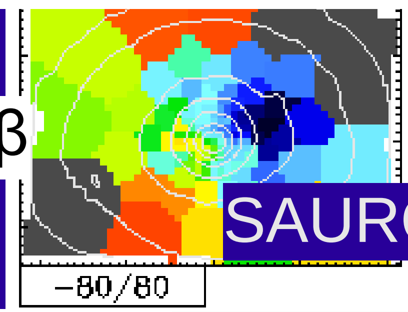
- CO roughly cospatial with young stars and CR/gas (generally less extended)
- CO and stars/gas kinematics not always related ? (triggered SF?)

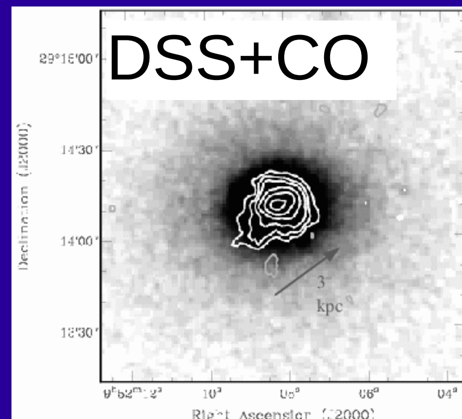
CO: Central Disks

(Young, Bureau & Cappellari 08; Crocker et al. 08, 09, 11)

BIMA-SAURON Data: NGC3032







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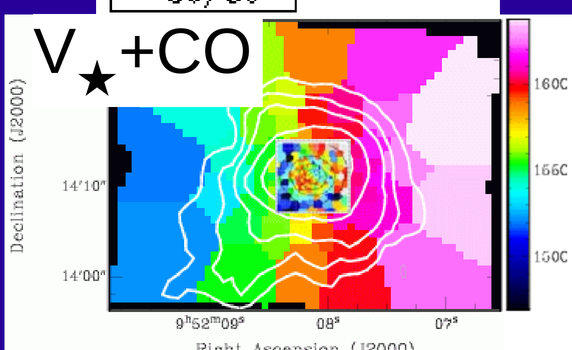

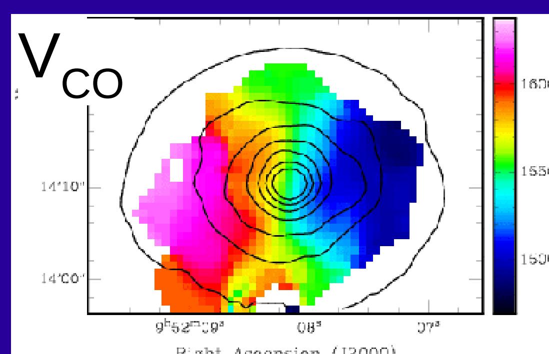

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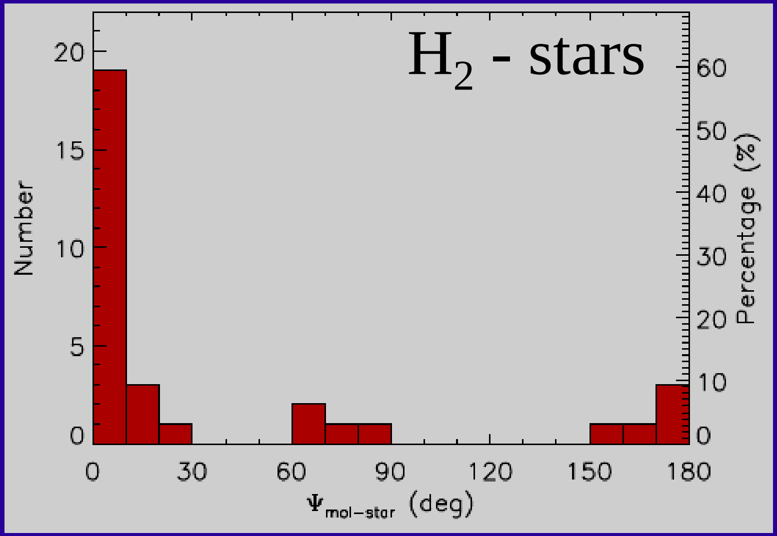
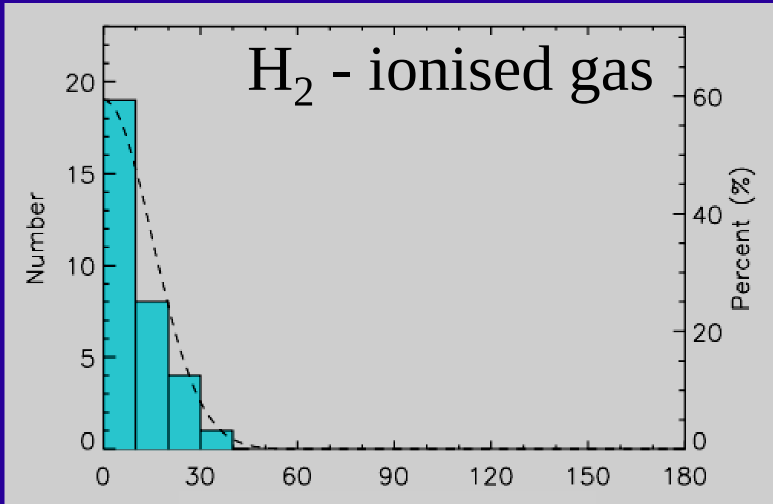
CO: Kinematic Misalignment

(Davis et al. 11)





Misalignment angle

Atlas^{3D} (CARMA):

- H_2 and stars often misaligned:
  > 35% external
  < 65% internal gas origin
- H_2 and ionised gas always aligned: common origin

- H_2 and stars always aligned in clusters/Virgo:
  internal gas origin
  (stellar mass loss, leftover)
- H_2 and stars very often misaligned in field:
  significant external gas accretion

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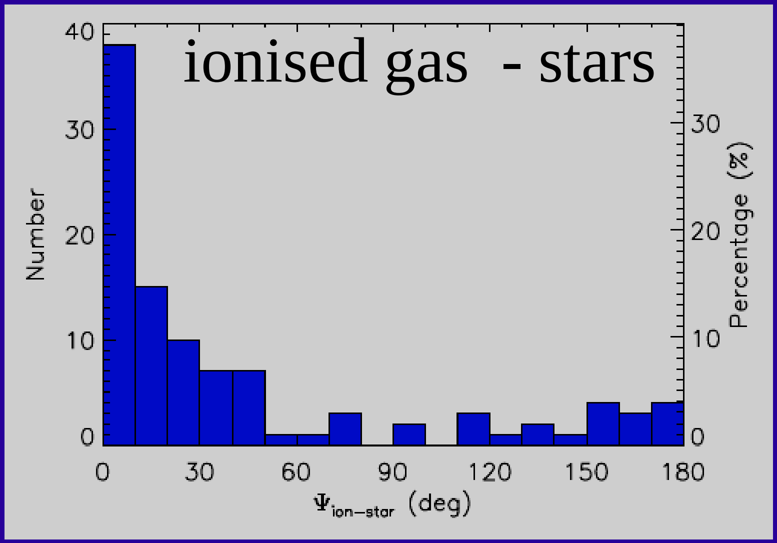

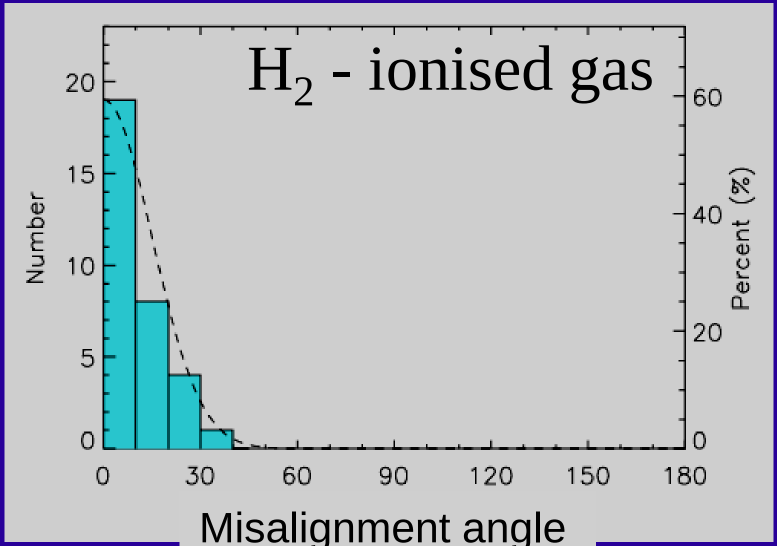

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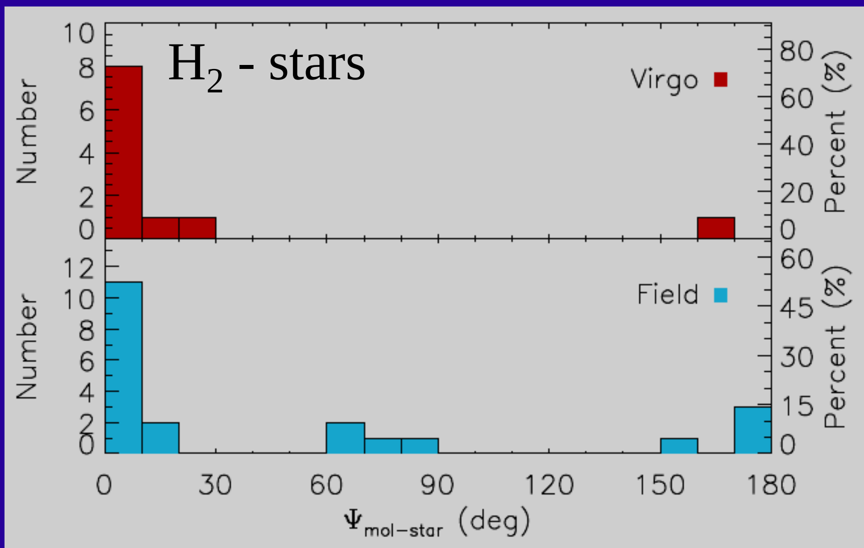

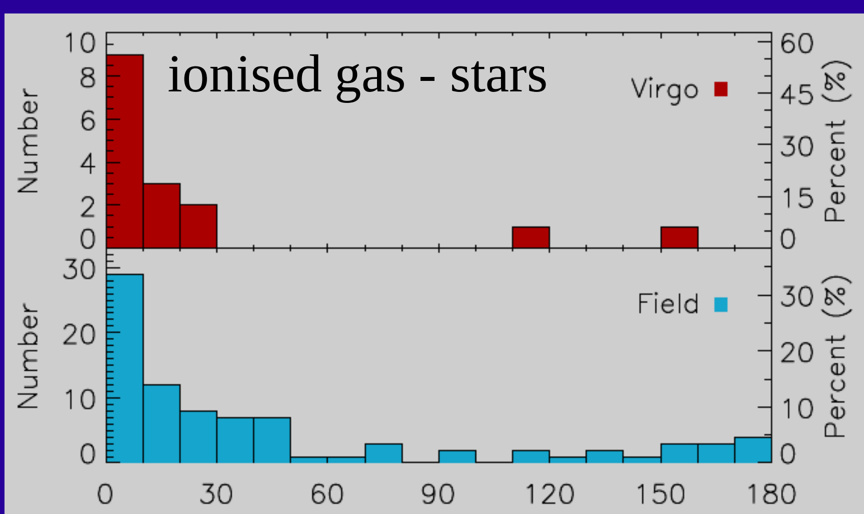

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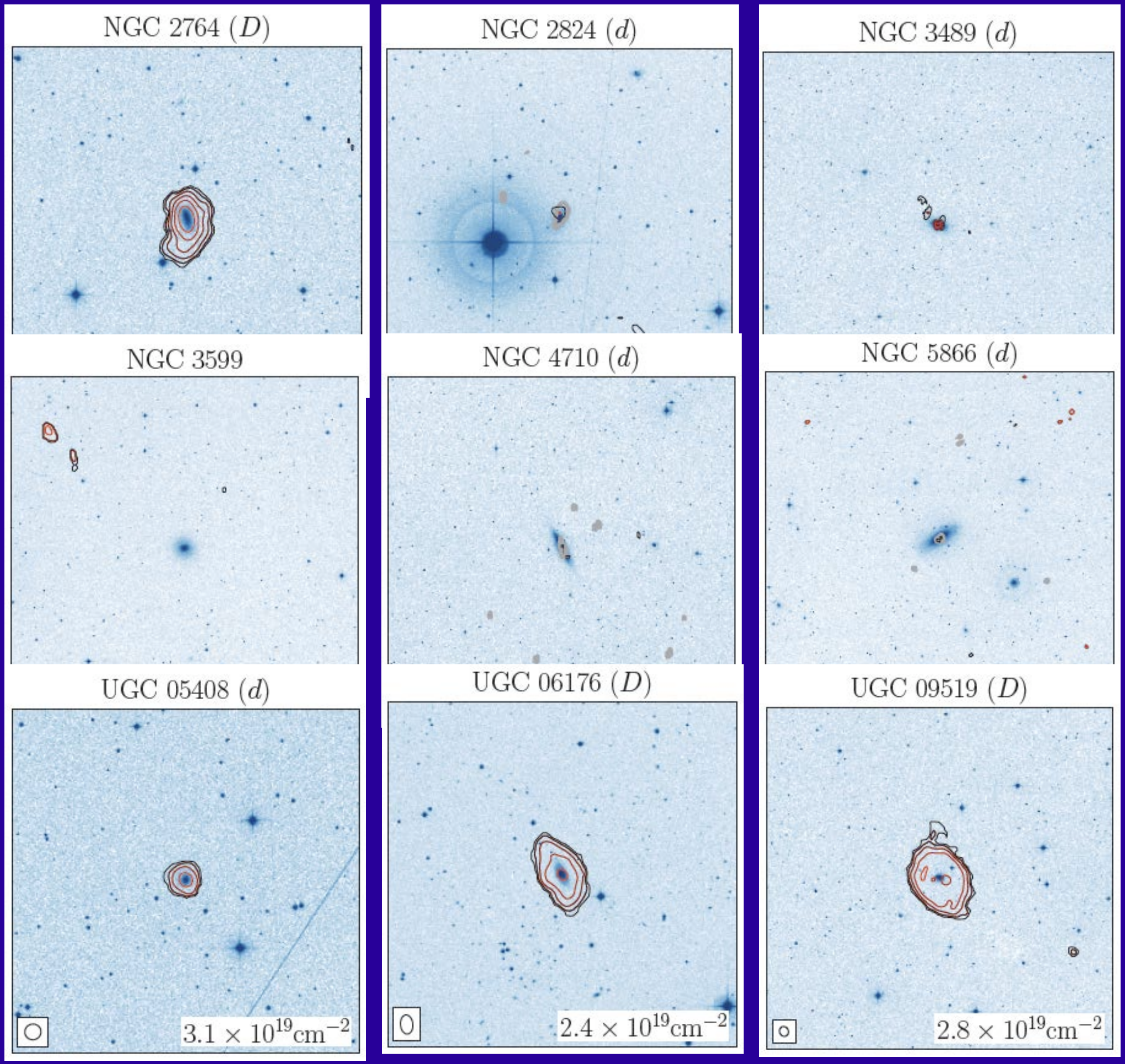
CO: HI imaging

(Morganti et al. 06; Oosterloo et al. 10; Serra et al. 12)

WSRT: Undisturbed HI



HI facts:

- CO detections:
  ≈50% undisturbed,
  moslty isolated
  ≈50% disturbed,
  clear companions

⇒ HI (and CO) of external origin in at least half of CO-rich ETGs

⇒ Circumstantial evidence for cold accretion and/or minor mergers (gas-rich dwarfs ?)

CO: HI imaging

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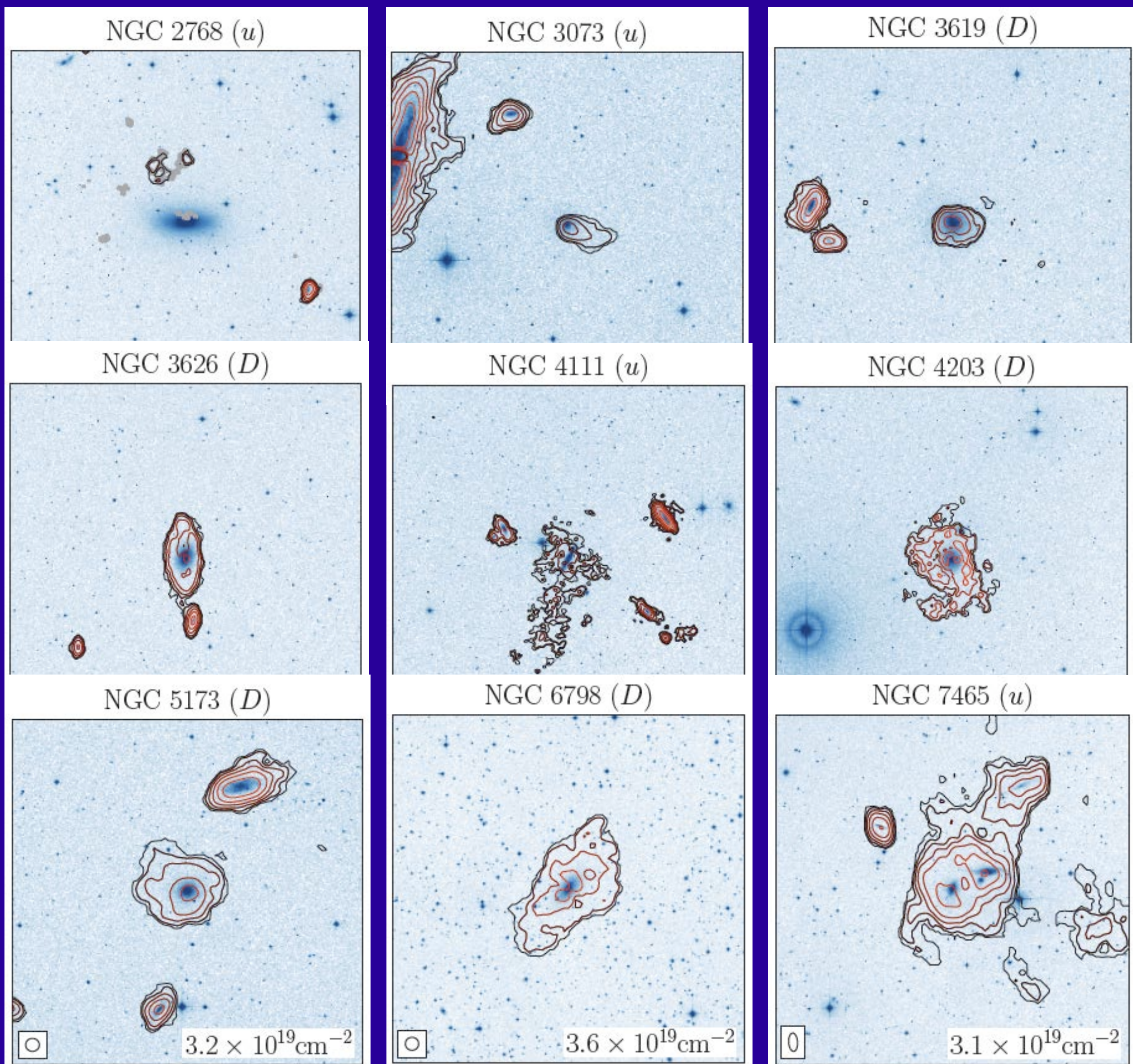
WSRT: Disturbed HI



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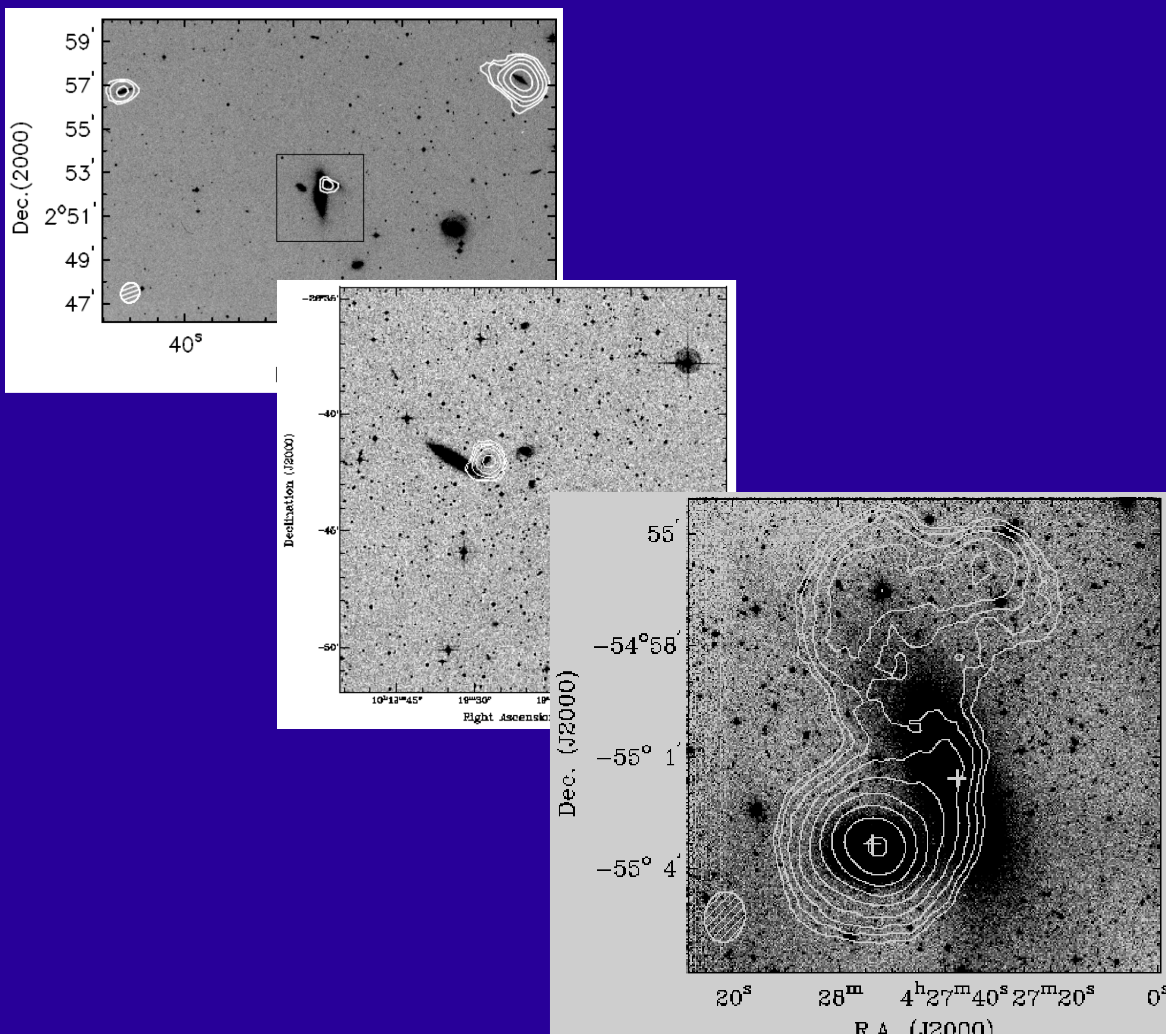
Gas Counter-Rotation: S0s

(Bureau & Chung 06; Chung et al. 06, 12)

VLA + ATCA:



Ionised Gas:

- Literature compilation:
  15±4% total
  23±5% with gas

⇒ Accretion of external gas non-negligible in at least half of S0s

HI:

⇒ Circumstantial evidence for cold accretion and/or minor mergers
(gas-rich dwarfs ?)

Gas Accretion: Timescales

Hand-waving argument:

$$
\begin{aligned}
t_{gas\_depletion} &< t_{torque} \\
&< \text{few } t_{dynamical} \\
&< \text{few } 3\text{x}10^{7} \text{ yr} \\
&< 100 \text{ Myr}
\end{aligned}
$$

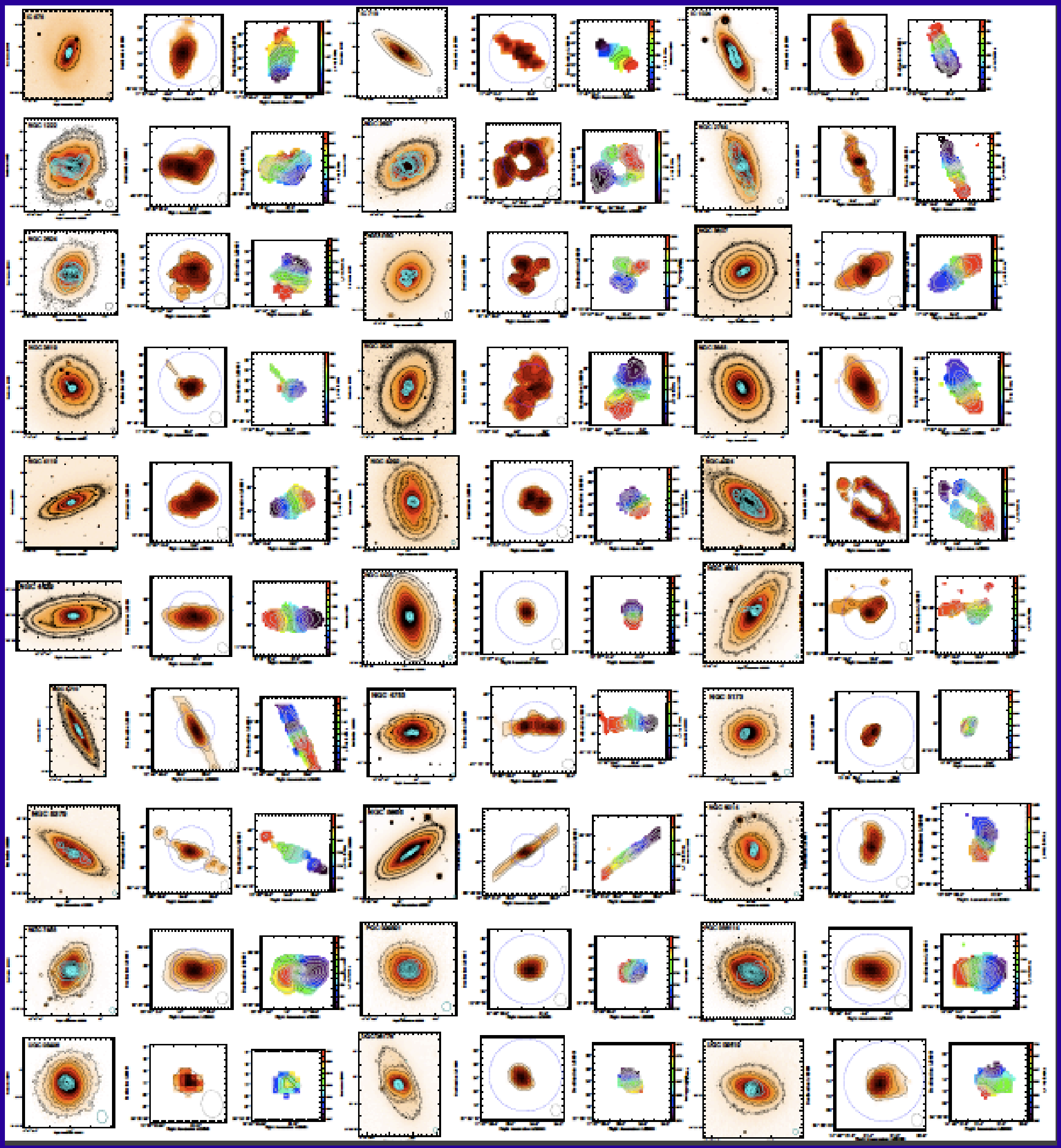
$$
\begin{aligned}
t_{gas\_replenishment} &\approx t_{gas\_depletion} \;/\; \text{detection\_rate} \\
&< \text{few } t_{dynamical} \;/\; 0.22 \\
&< 0.5 \text{ Gyr}
\end{aligned}
$$

⇒ Rapid gas replenishment (gas accretion, mergers)

✗ Problem: $t_{gas\_depletion}$ expected to be 1-2 Gyr …

CO: Morphology

(Alatalo et al. 2012; Davis et al. 2012)



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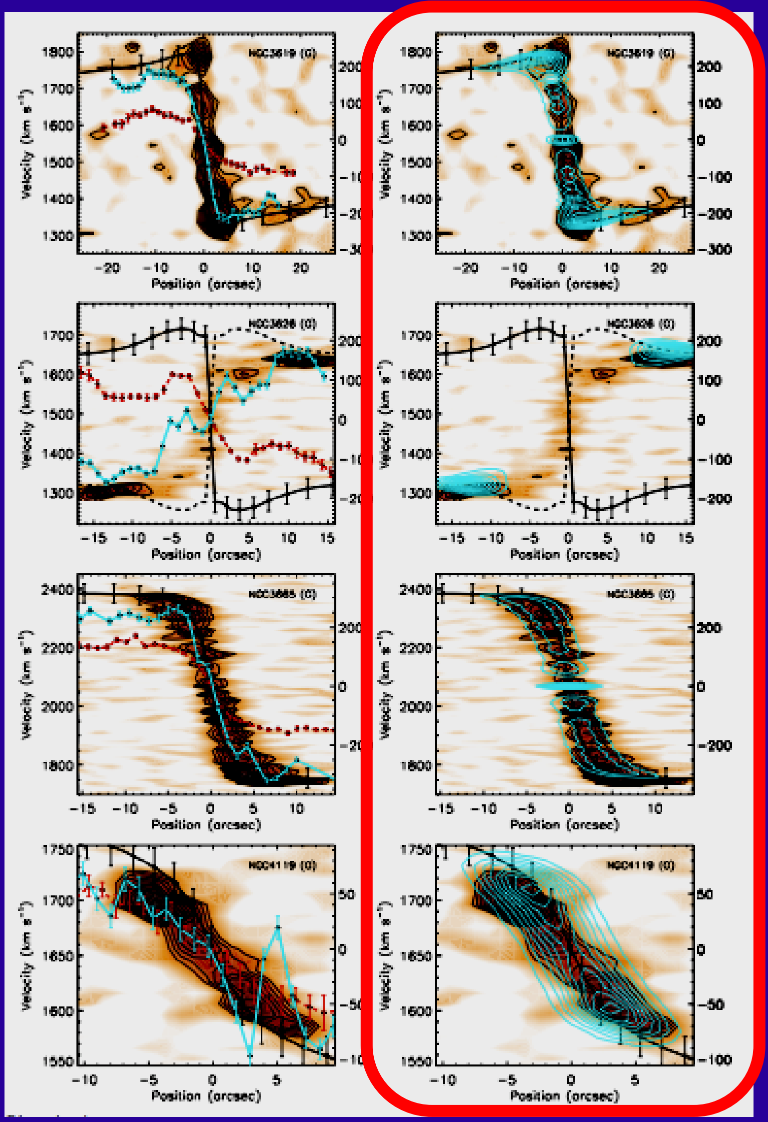
CO: Kinematics tracer

(Davis et al. 2012a)



CO vs. V_c:

- CO rotating faster (colder) then ionised gas (and stars)
- Nearly perfect tracer of the circular velocity

⇒ Best (and excellent) tracer of dynamical mass

✗ : CARMA CO (1-0)

: Modeled CO (1-0) from JAM model

--- : SAURON JAM model

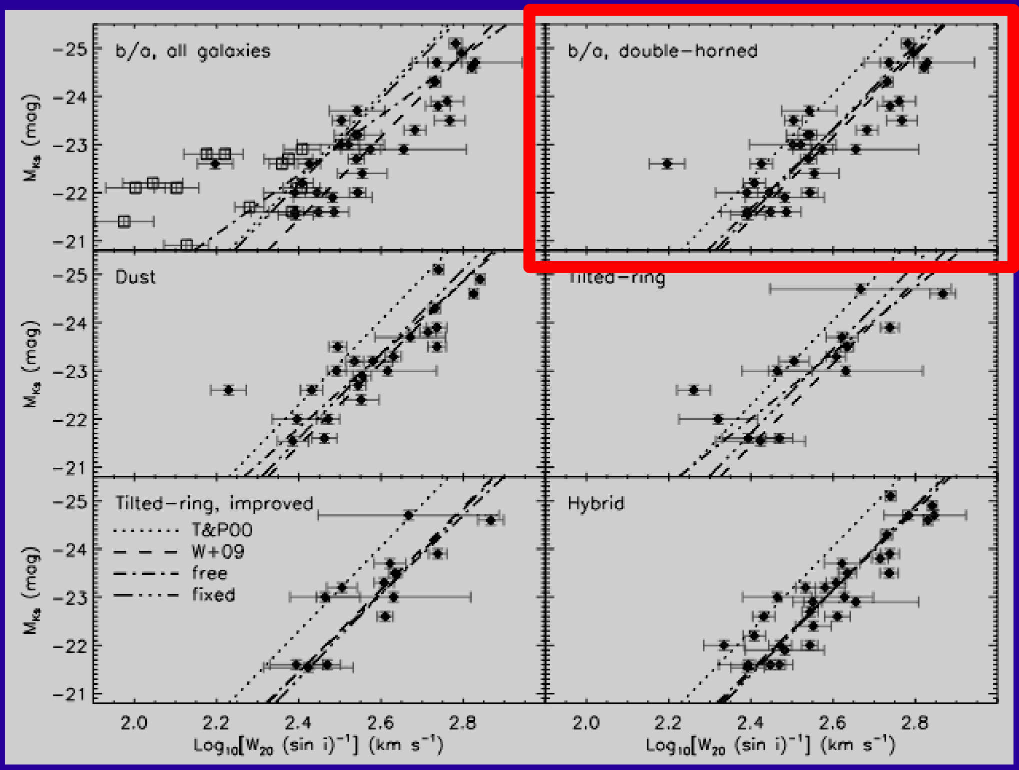
+ : SAURON stars

+ : SAURON ionised gas

CO: Tully-Fisher Relation

(Davis et al. 2011)

CO Tully-Fisher relations:



Tully-Fisher:

- High-mass end traditionally available only through stellar dynamical modelling: hard, time-consuming
- Many (potential) pitfalls to CO-derived velocities: simple workarounds, easy to improve

⇒ Stellar / Jeans T-F recovered

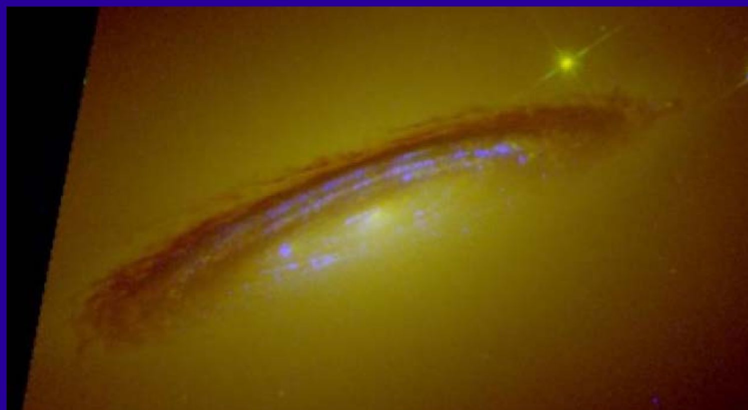
⇒ CO appears to work with no or minimum efforts !

⇒ Great prospect to probe M/L (z) with ALMA…

CO: Black hole mass

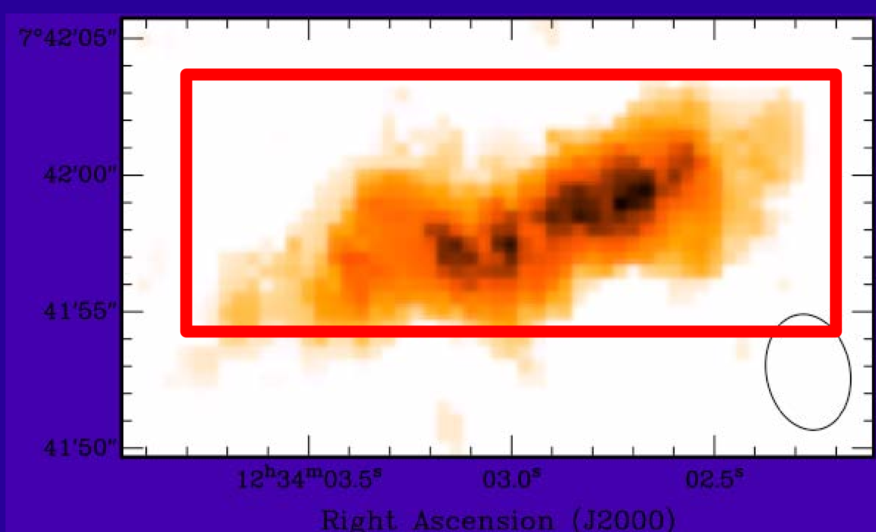
(Davis et al. 2013)

HST WFC3 NUV-optical data:



(Kaviraj et al. ??)

BIMA low-res (4.5”) data:



NGC4526:

- High resolution (0.25”) CARMA CO(2-1) data
- Regular (central) disk kinematics
- Free M/L_* and $M_\bullet$

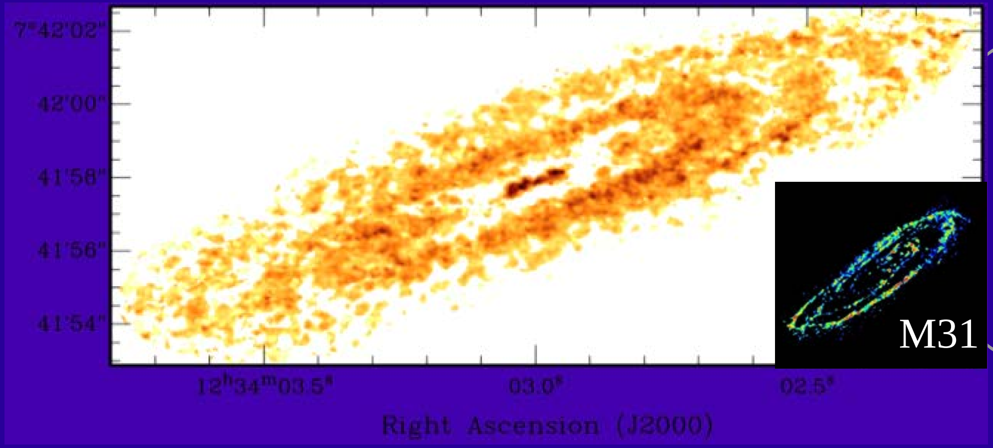
⇒ Strong constraints on $M_\bullet$
($M_\bullet = 4.1 \times 10^8\ M_\odot$)
(consistent with $M_\bullet$ - σ)

⇒ Great prospects across Hubble sequence with ALMA…

CO: Black hole mass

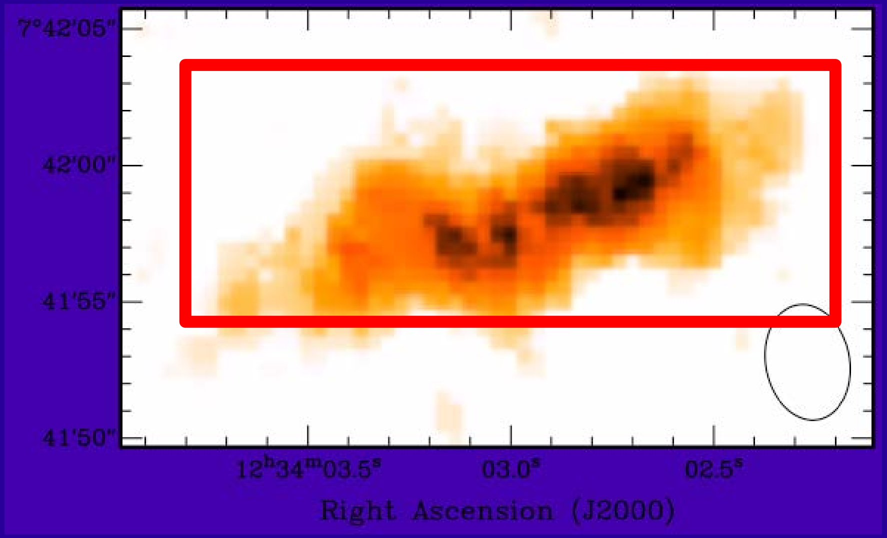
(Davis et al. 2013)

CARMA high-res (0.25" = 20 pc) data:



(Nieten et al. 06)

BIMA low-res (4.5") data:



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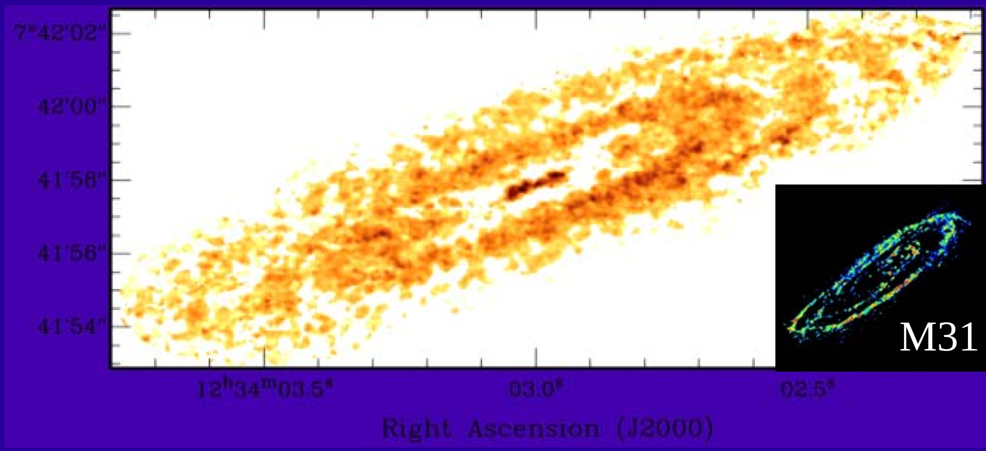
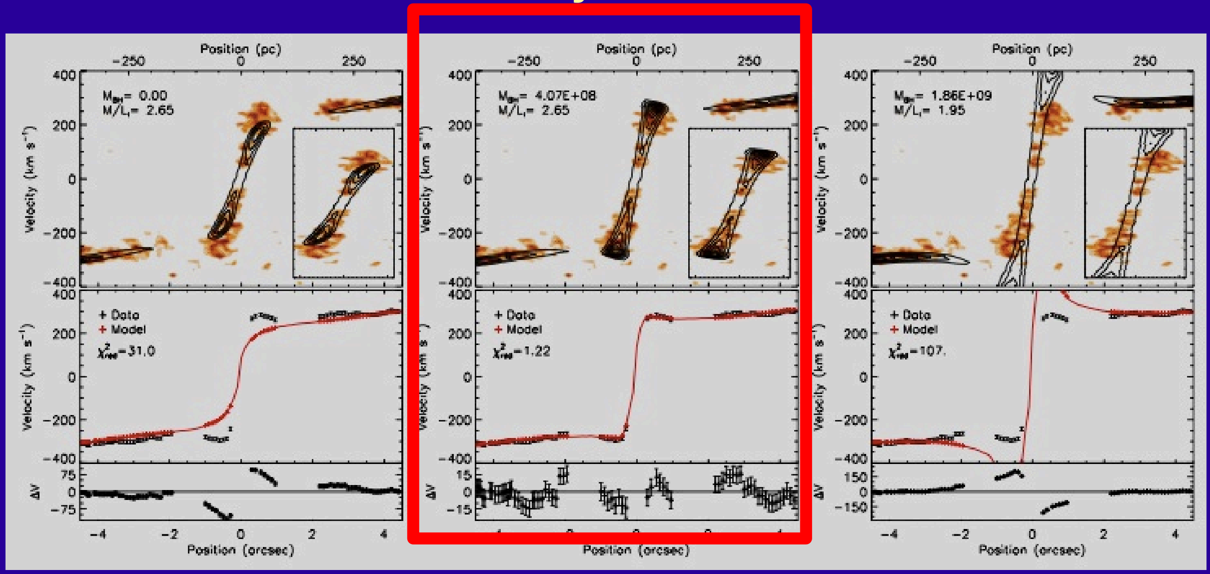


(Nieten et al. 06)

Model PVD and major-axis trace:



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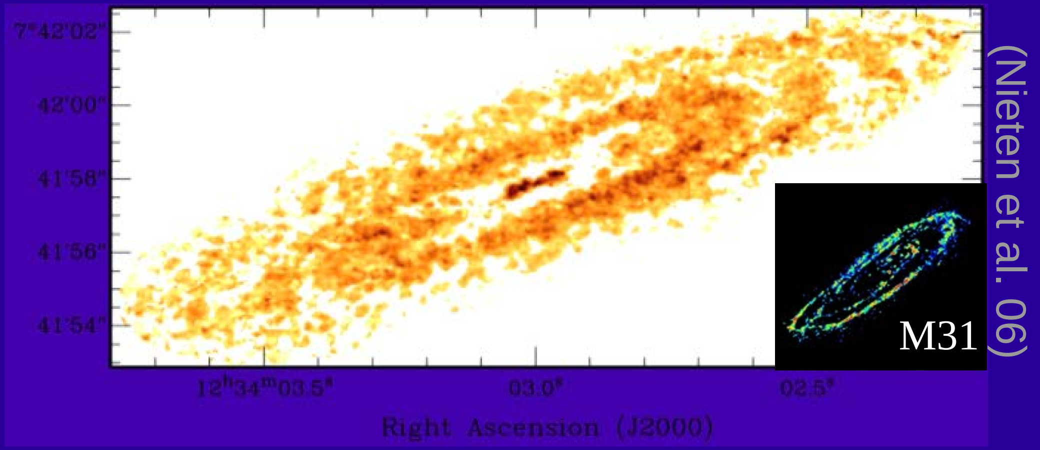
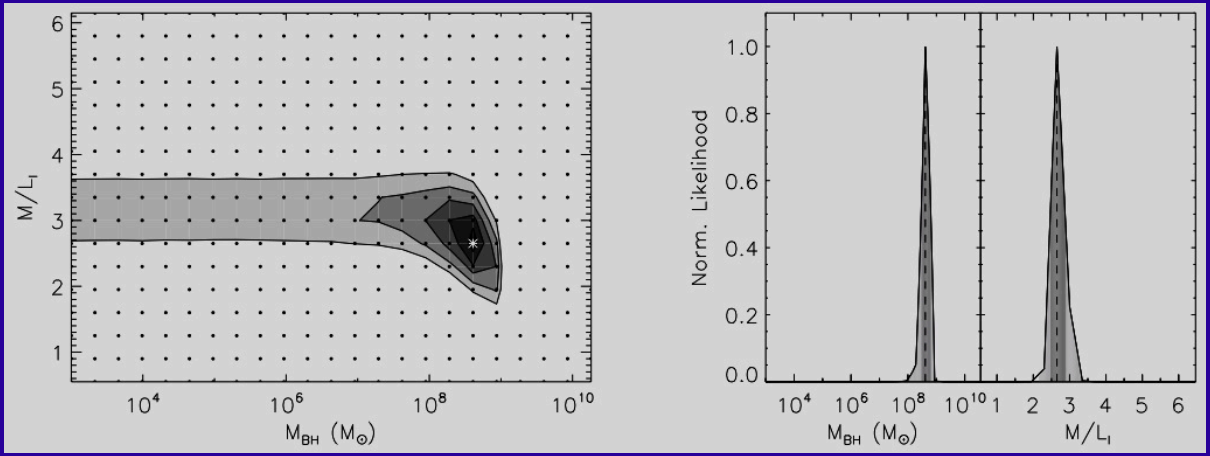


BH mass χ^2 and likelihood:



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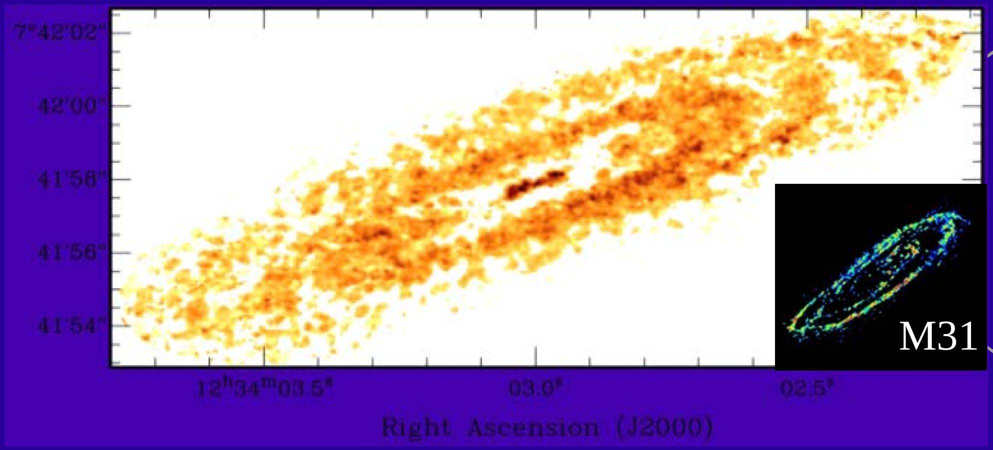
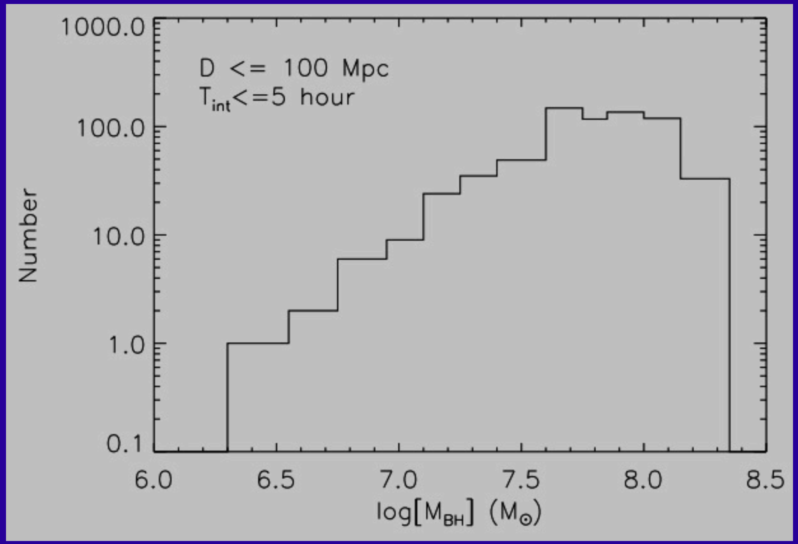


(Nieten et al. 06)

ALMA BH mass measurement prospects:



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Molecular Gas and Star Formation in Early-Type Galaxies

Martin Bureau, Oxford University

CO
(Katey Alatalo, Estelle Bayet, Leo Blitz, Francoise Combes,
Alison Crocker, Timothy Davis, Melanie Krips, Lisa Young)

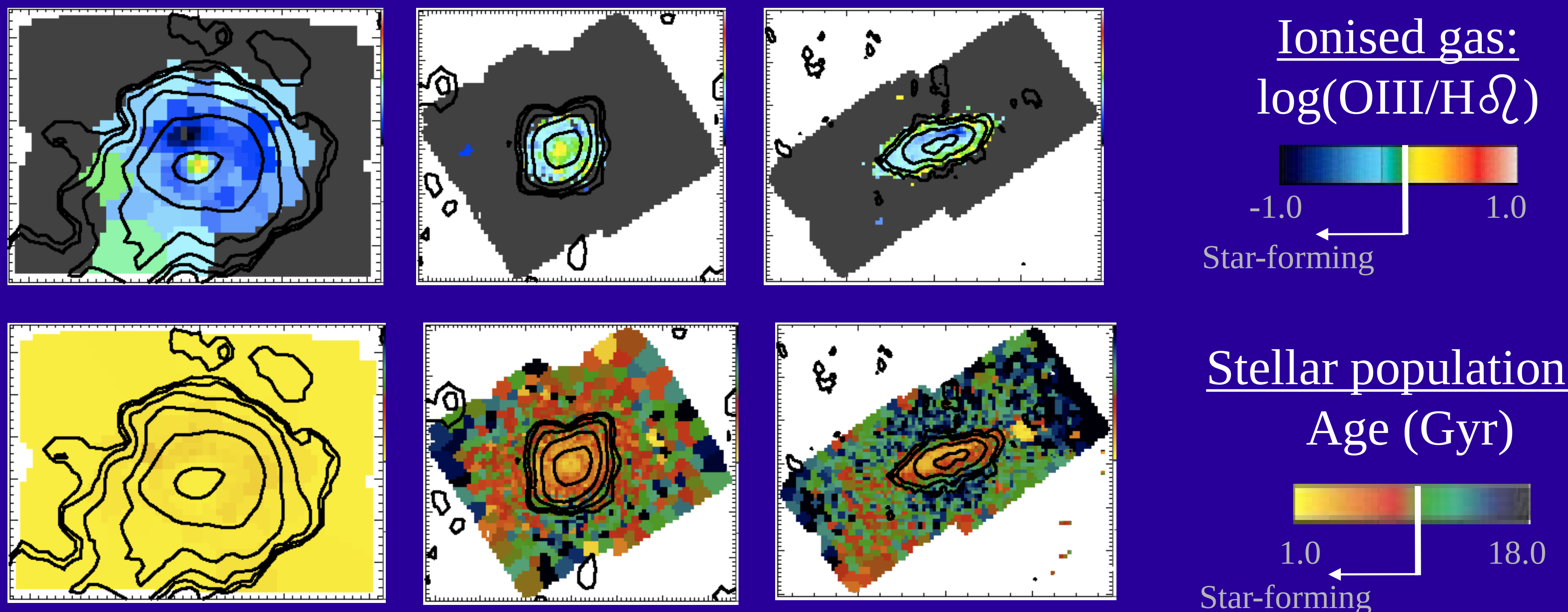
Optical
(SAURON + Atlas^{3D} teams)

Plans: SAURON+Atlas^{3D}: E/S0 formation, residual SF, surveys
CO: E/S0 H_2 incidence, distribution, kinematics, origin, BHs
CO: E/S0 SF tracers, sequence, laws, ISM
Summary and future

Type 1: Currently Star-Forming

(Crocker et al. 11)

NGC3032 NGC4459 NGC4526

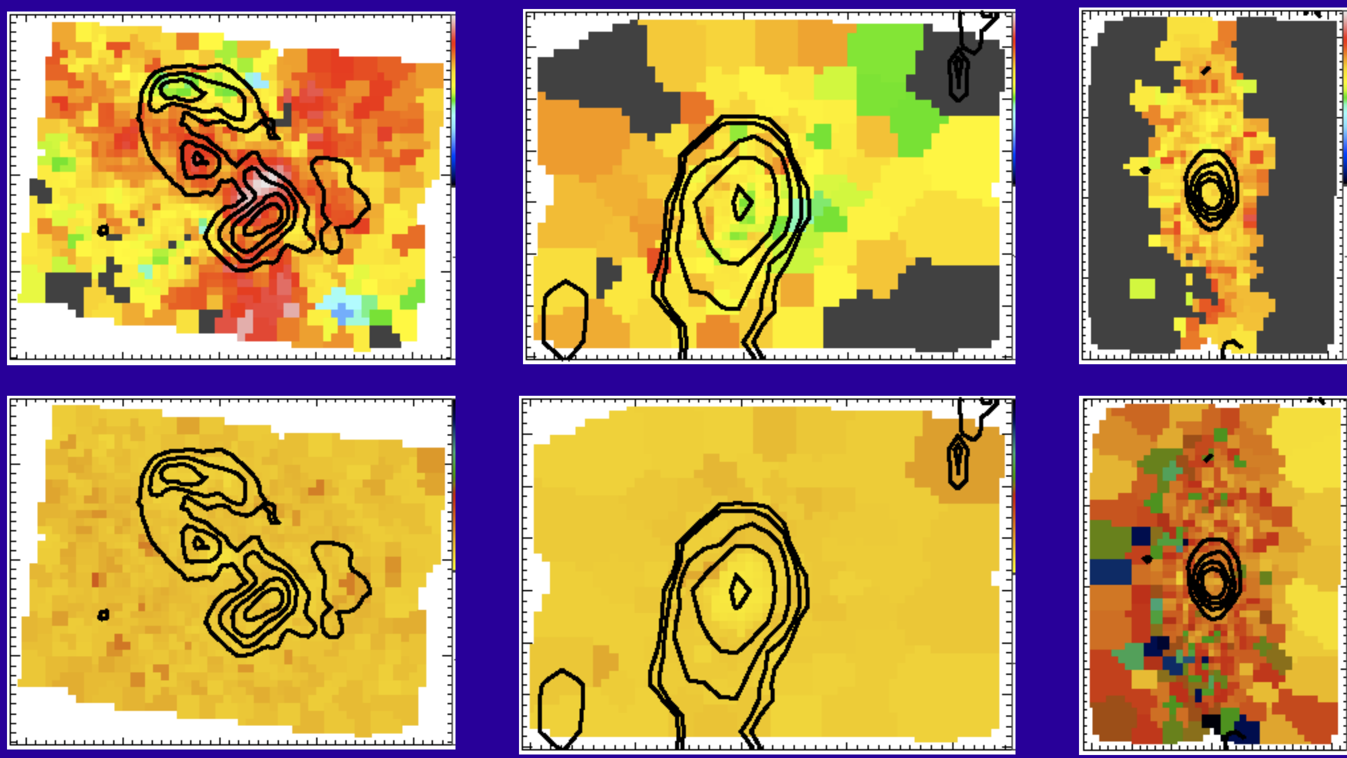


- Ionization dominated by young stars, and young stars are present

Type 2: Recently Star-Forming ?

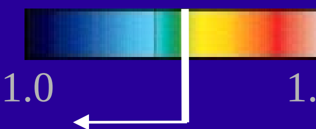
(Crocker et al. 11)

NGC3489 NGC4150 NGC4550



Ionised gas:

log(OIII/Hβ)

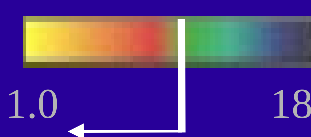


-1.0 1.0

Star-forming

Stellar population:

Age (Gyr)



1.0 18.0

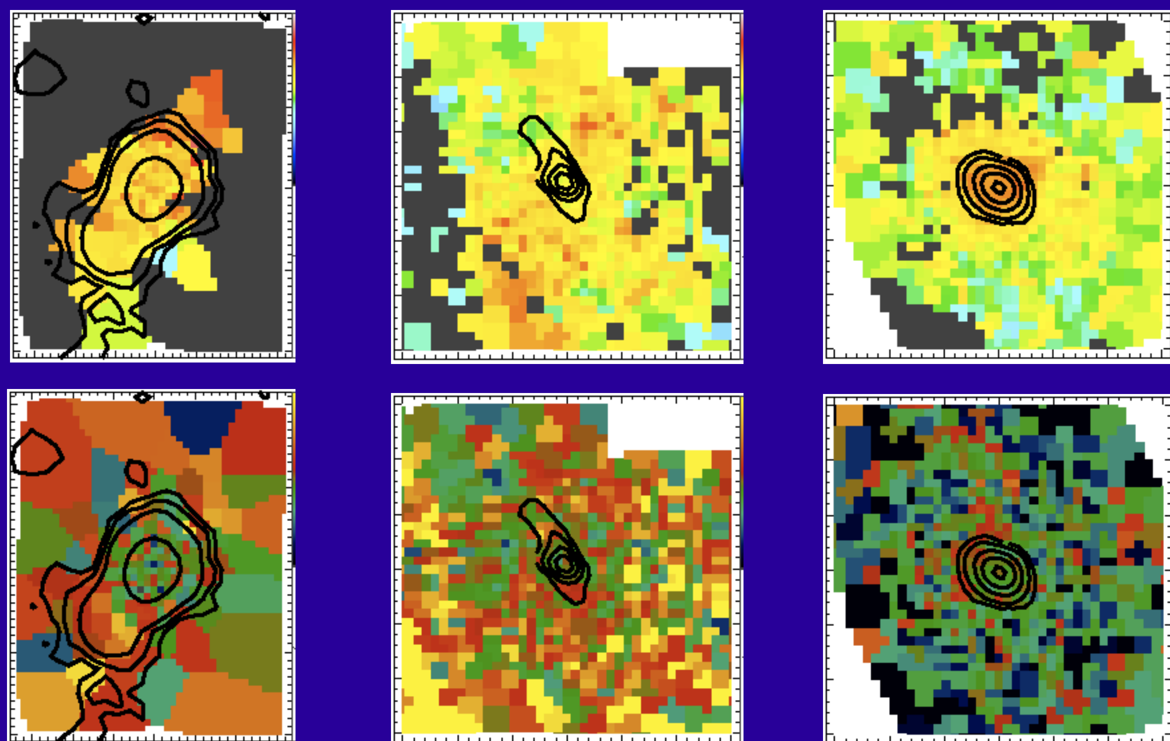
Star-forming

- Ionization not dominated by young stars, but young stars are present (pervasive)

Type 3: Not Star-Forming ?

(Crocker et al. 11)

NGC2320 NGC2768 NGC4477



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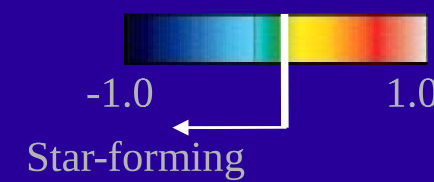

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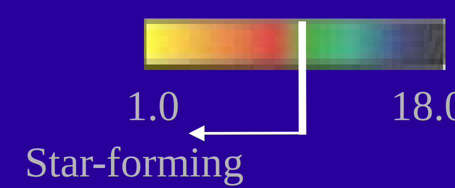
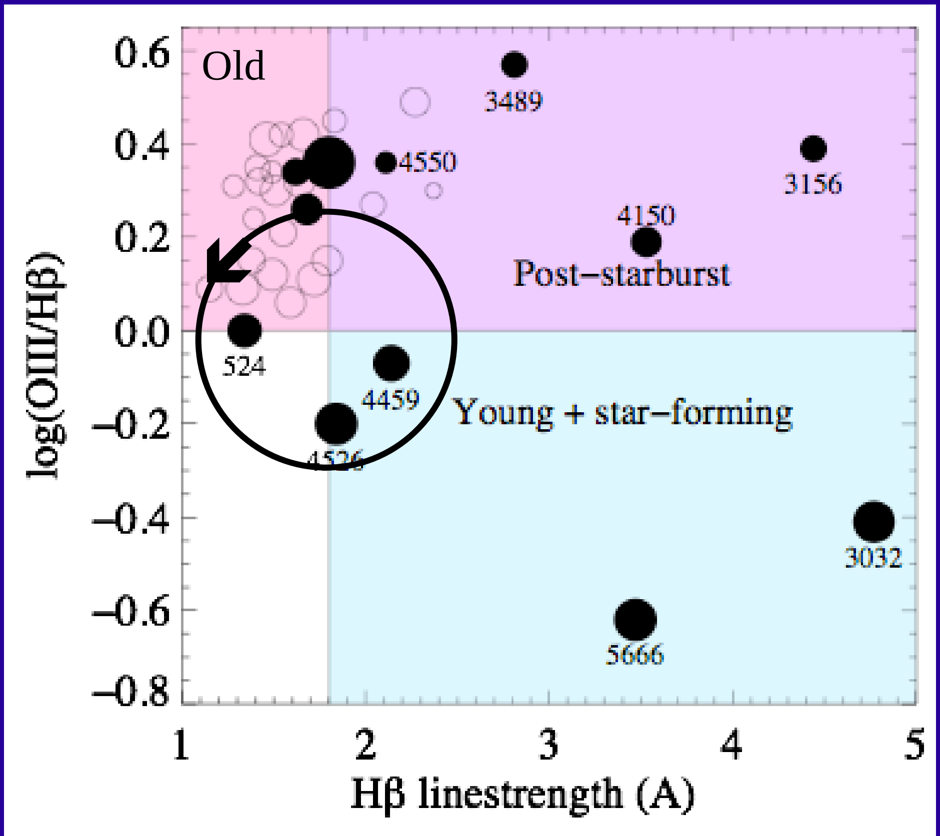


- Ionization not dominated by young stars, and young stars are not present

CO: Star Formation Laws

(Crocker et al. 11)



SAURON:

- Star formation sequence ?
- Possible offset from Schmidt-Kennicutt law (≈ 1σ ; lower SFE)
- TIR enhanced over 8 and 24 ❍m
- FIR – radio correlation not respected: too many FIR-excess

⇒ SF possibly slightly different from that in disk/starburst galaxies

⇒ Need to probe gas dynamics and physical conditions…

SF Physics: Differences

Dynamics:

- Toomre's Q :

$$Q \quad \alpha \quad \sigma \ \kappa \ / \ \Sigma$$

σ velocity dispersion
(effective sound speed)
κ epicyclic frequency
(function of V_c or Φ)
Σ surface density

⇒ Much more freedom in ETGs than in disk galaxies
(esp. central vs. outer parts)
(high κ, decreased disk self-gravity)

⇒ Morphological quenching ?
(Kawata et al. 07; Martig et al. 09,...)

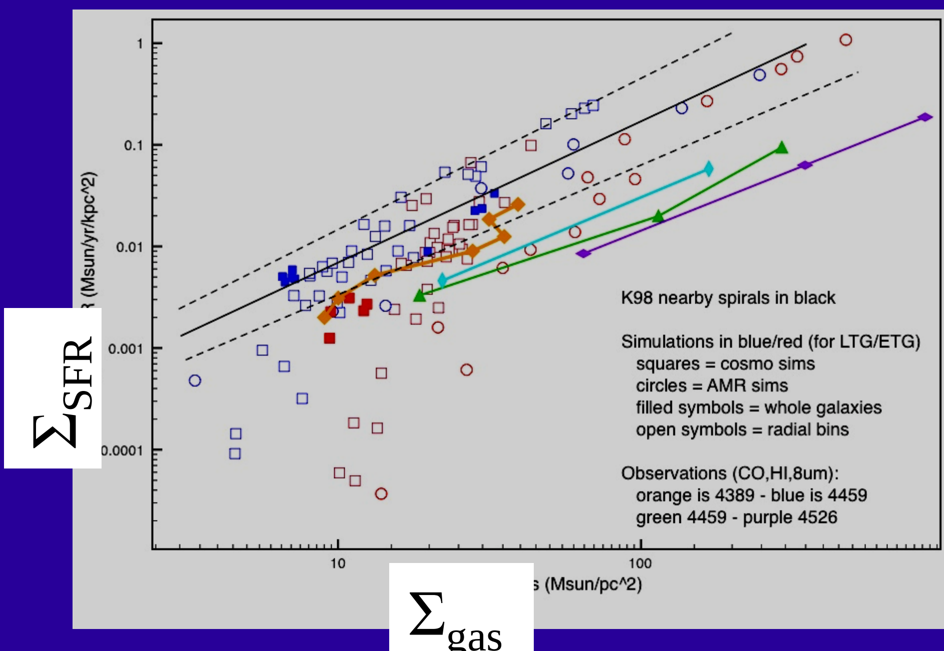
Physical Conditions:

- Stellar populations:
  Old (> 8 - 10 Gyr)
  High metallicities (> $Z_\odot$)
  Non-Solar abundances ([α/Fe])
  …
- Radiation Field:
  Frequent hot gas (10^6 K)
  Frequent AGN
  UV-upturn (dep. on Z, age)
  …

⇒ Different abundances, excitation
⇒ SFR indicators contaminated…

CO: Star Formation Laws

(Crocker et al. 11; Martig et al. 2012)



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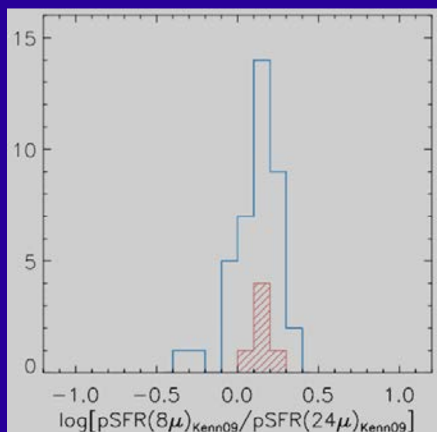
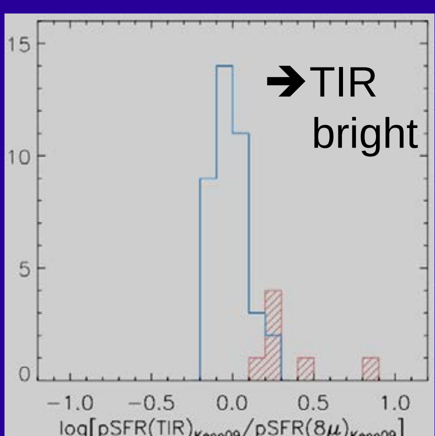
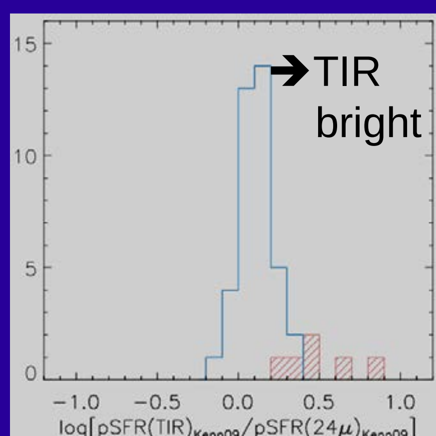
(Crocker et al. 11)

E/S0s vs SINGS spirals:







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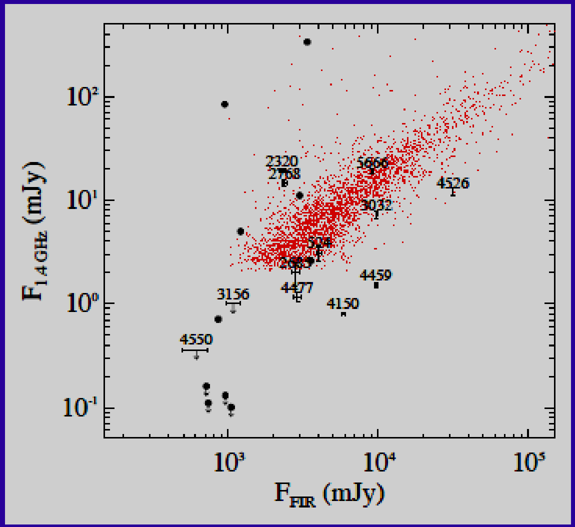
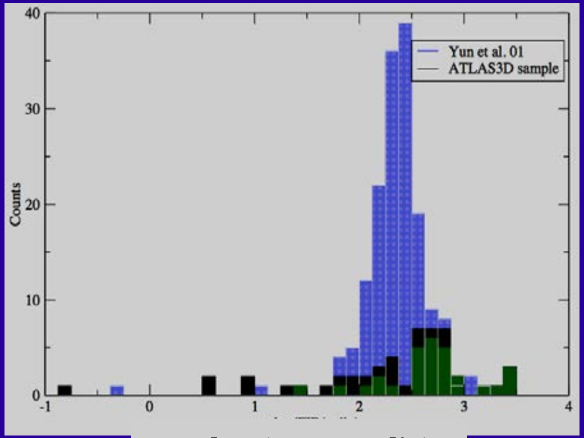
E/S0s vs Condon et al. (2002):





q = log (FIR / radio)

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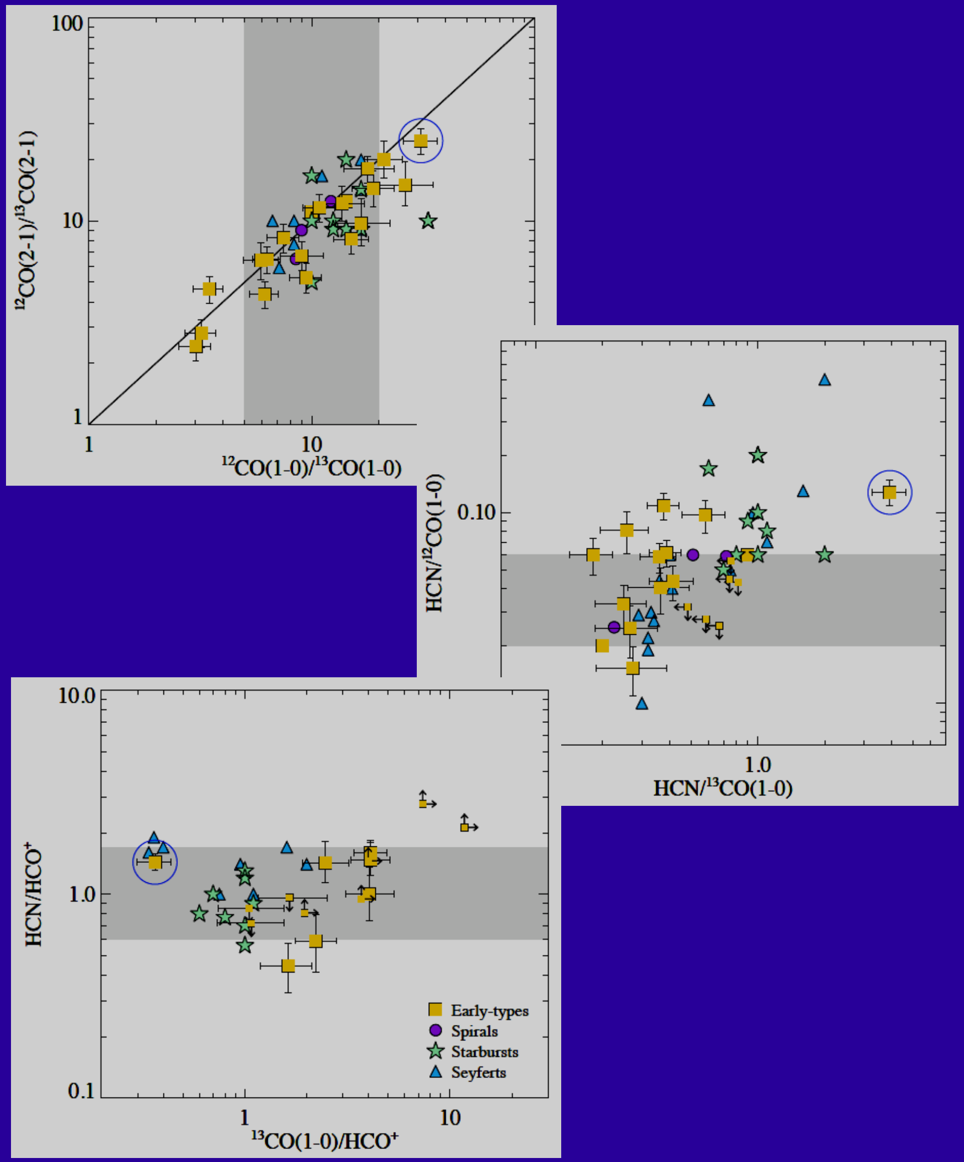
CO: Line Diagnostics

(Krips et al. 10; Crocker et al. 12)



CO-Brightest Galaxies:

- Ratios: ^{12}CO/^{13}CO occ. low
  HCN/^{13}CO low
  HCN/HCO$^+$ often high

⇒ ^{13}CO occasionally enhanced,
HCO$^+$ often suppressed

* Usual IR-CO and IR-HCN trends

- Corr.: M_{H2}/M_{HI}, f_{60}/f_{100}, dust morph.
  Star L_K, age, metallicity, …

⇒ Consistent with downsizing?

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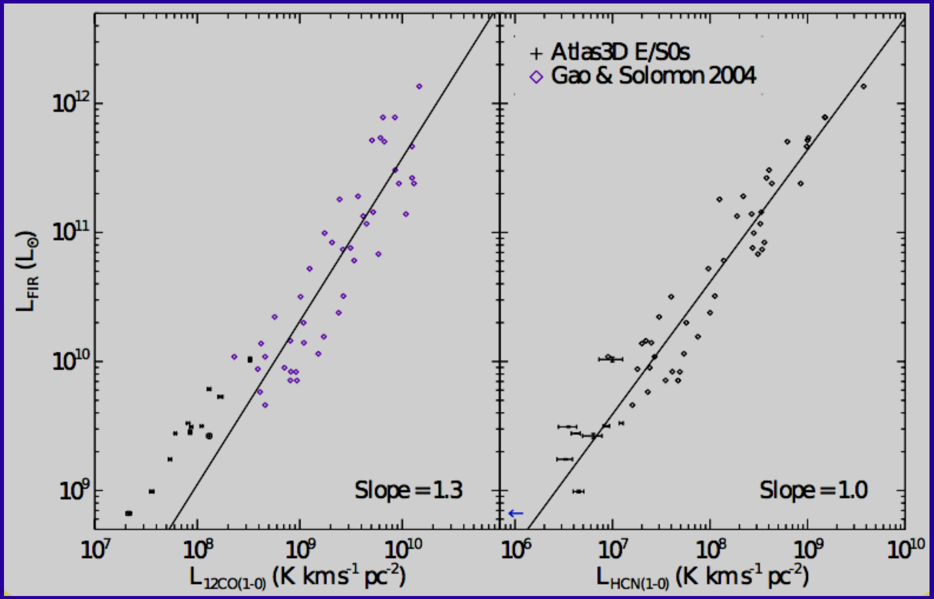

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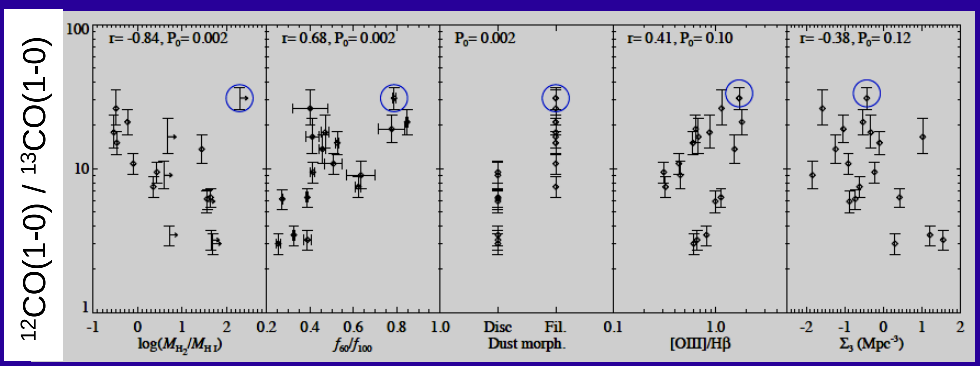

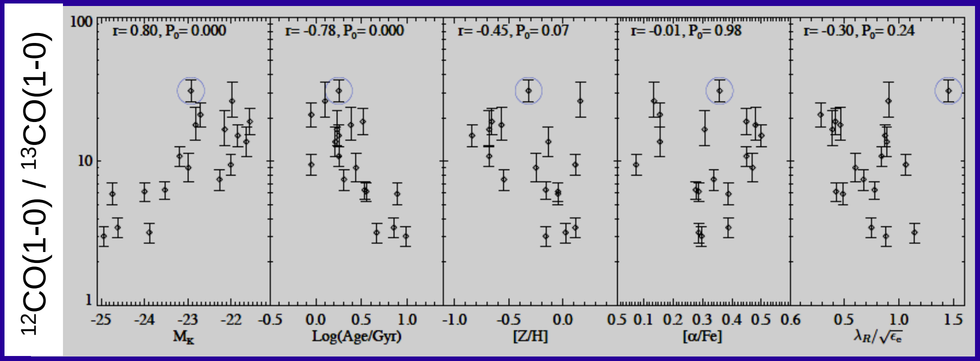

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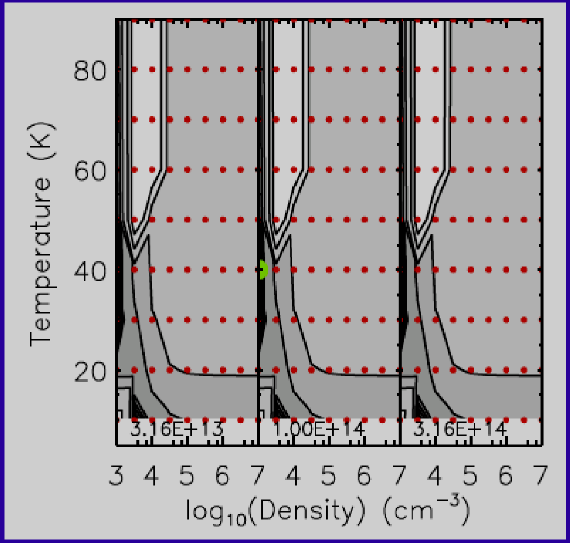
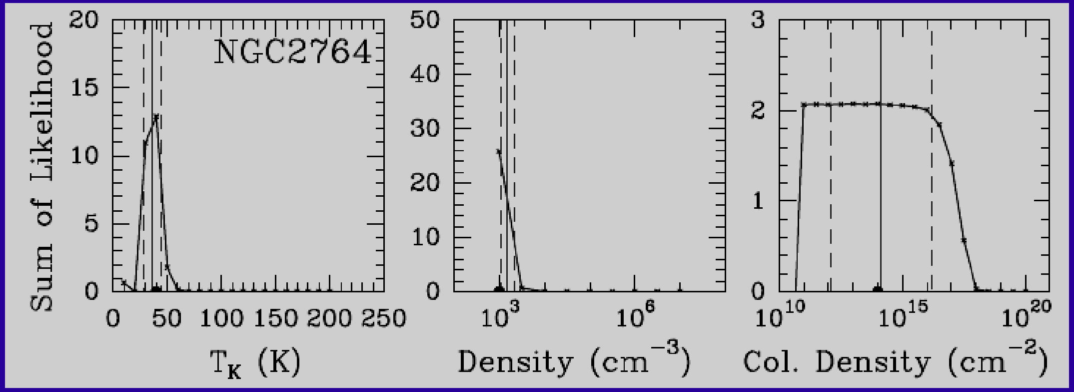
CO: Line Modeling

(Bayet et al. 12)

χ^2:



Likelihood:



LVG Modeling:

- Usual models but:
  - High metallicities (> $Z_\odot$)
  - Non-Solar abundances ([α/Fe])
  - …
  - Frequent hot gas (10^6 K)
  - Frequent AGN
  - UV-upturn (dep. on Z, age)
  - …

CO: Line Modeling

(Bayet et al. 12)

Physical Conditions:

- "CO" gas: T_K = 10 - 110 K
  $n(H_2)$ = 10^{3-4} cm^{-3}
  $N(CO)$ = 10^{11-19} cm^{-2}

⇒ Similar to Milky Way SF?

- "HCN" gas: Unconstrained

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  …

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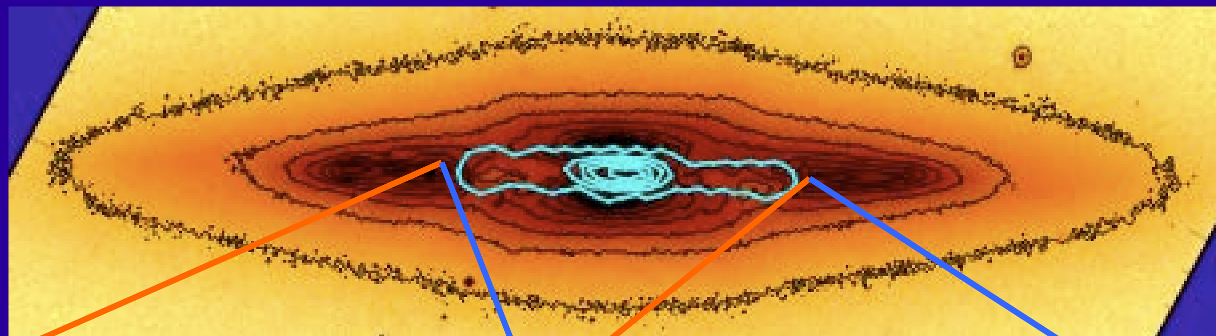
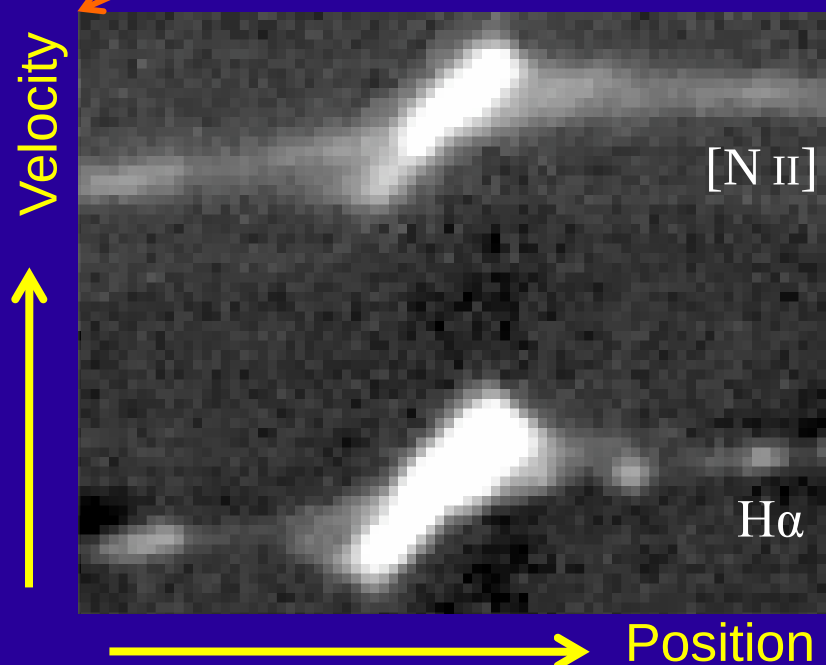
NGC4710: Line Diagnostics

(Topal et al., in prep)

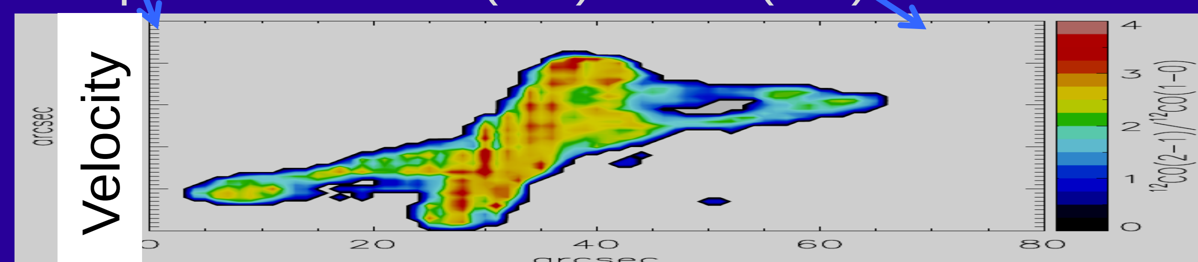


Optical PVD:

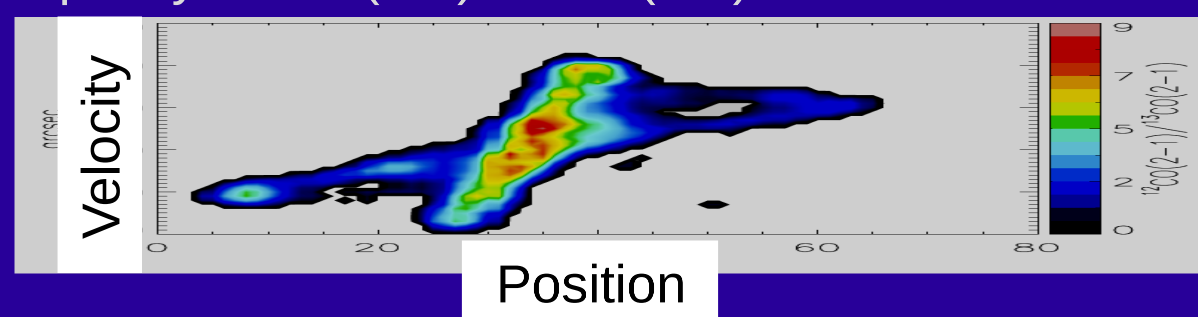


CO PVD:

Temperature: $^{12}CO(2-1)$ / $^{12}CO(1-0)$



Opacity: $^{12}CO(2-1)$ / $^{13}CO(2-1)$



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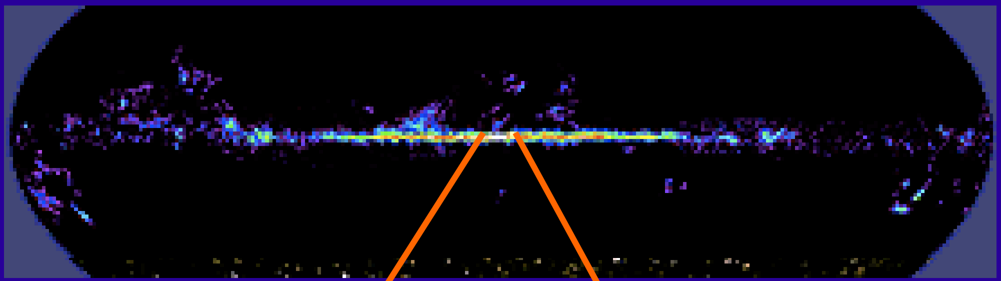
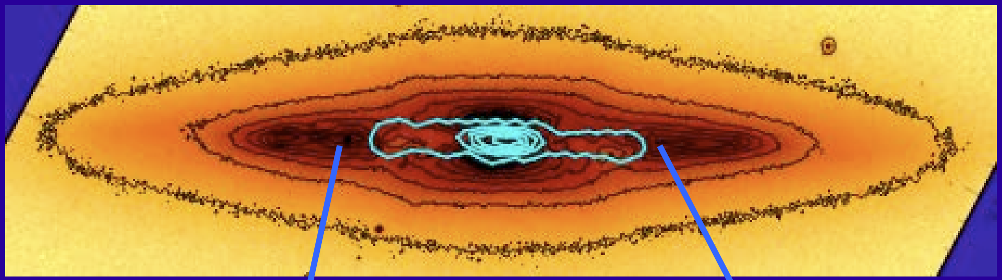
NGC4710: MW similarities

(Topal et al., in prep; Torii et al., in prep)





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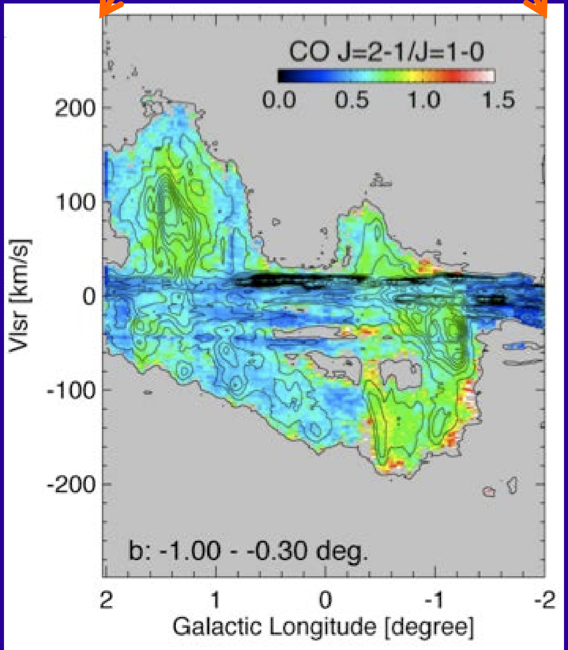
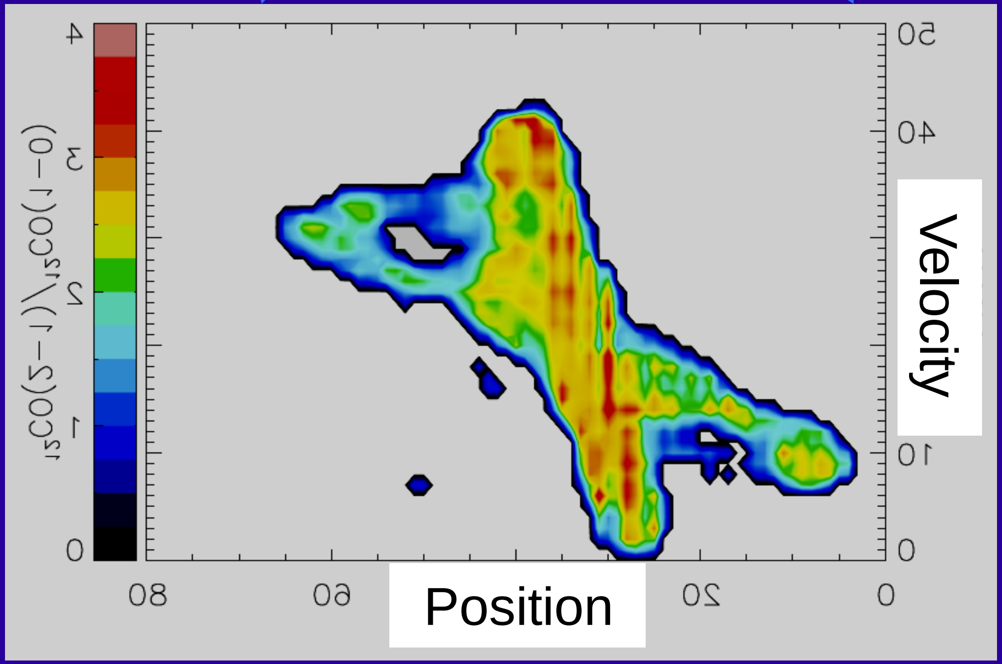


Velocity

Position

CO PVD:

Temperature: ^{12}CO(2-1) / ^{12}CO(1-0)



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CO: E/S0 H_2 incidence, distribution, kinematics, origin, BHs

CO: E/S0 SF tracers, sequence, laws, ISM

Summary and future

Conclusions

CO: - Atlas^{3D}: Unprecedented 3D survey/database (optical, CO, HI, …)

- Common in local E/S0s: ≅22%; independent of most properties
- Distribution: Centrally-concentrated; "self-similar" to spirals
- Decoupled structures: Co-spatial/co-rotating with gas/young stars
- Origin: Internal in clusters, 50% external in field
  Probable minor mergers/cold accretion
- SF: Sequence (current, recent, no/weak SF) ?, E/S0s FIR-bright
  E/S0s great laboratory to study SF laws, possible offset from K-S law
- ISM: ^{13}CO enhanced, HCO^+ suppressed; correlated with galaxy properties
  First determination of physical properties, great future

✗ Ending exploratory phase; starting spatially-resolved multiple line studies

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Great synergy

optical IFU – mm interferometry

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