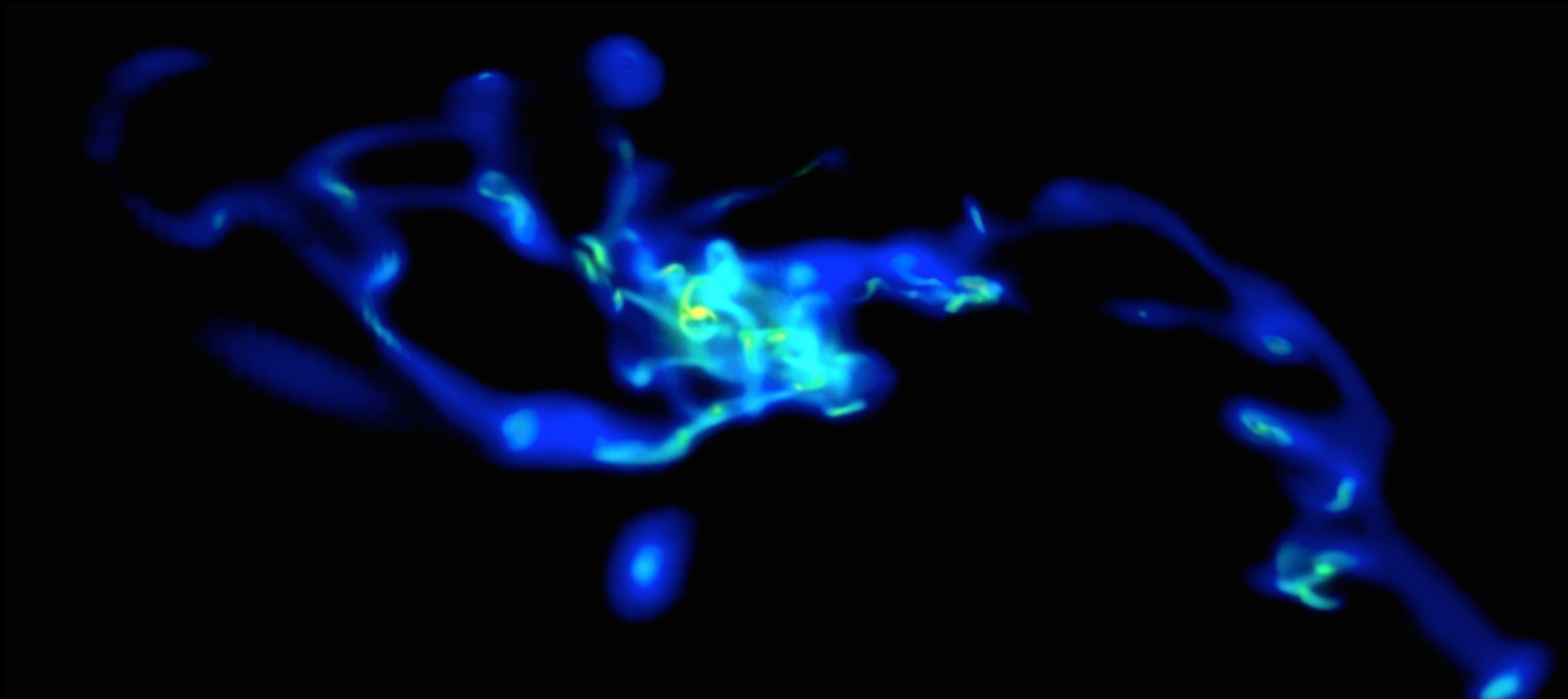
Disk and mergers
from low to high redshift

ISM properties, Star Formation and Black Hole growth



Frederic Bournaud - CEA Saclay

with

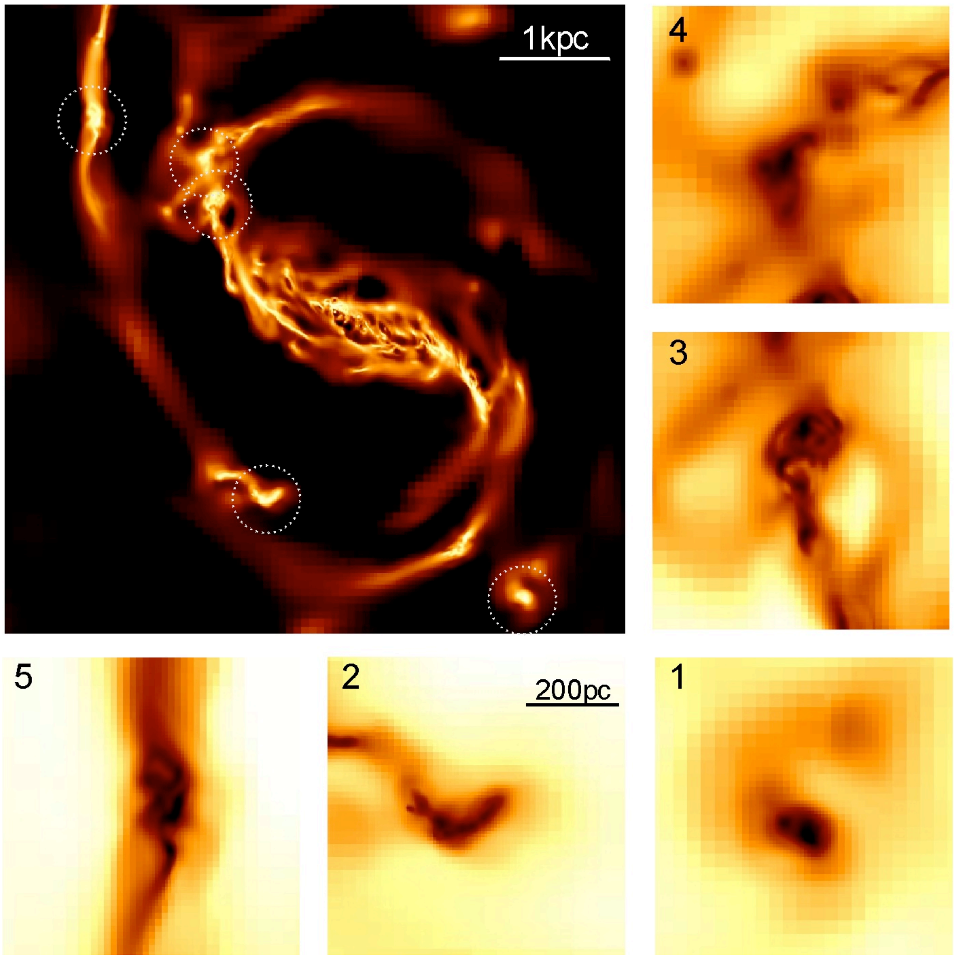
Damien Chapon, Alison Crocker, Emanuele Daddi, Avishai Dekel, Bruce Elmegreen, Debbie Elmegreen, Stephanie Juneau, Chiara Mastropietro, Leila Powell, Romain Teyssier …

Galaxy models with resolved dense gas clouds

hydro resolution of 100pc => $T>10^4$K => Mach<1 subsonic ISM

hydro resolution of 10pc => $T<10^3$K => Mach>1 but 2D

hydro resolution of 1pc => T~100K , 3D supersonic turbulence



Here a disk at 0.8pc, AMR,
cooling curve down to 100K,
with star formation and feedback

We now resolve where SF clouds are,
how dense they are, their main substructures,
etc…

Moderate density gas

explicitely resolved

Dense gas clouds
and sub-clouds at $n > 10^5 cm^{-3}$

sub-resolution scheme:
fixed SFE in high-density gas

Star formation

Bournaud, Elmegreen, Tessyier et al. 2010 MNRAS 409 1088

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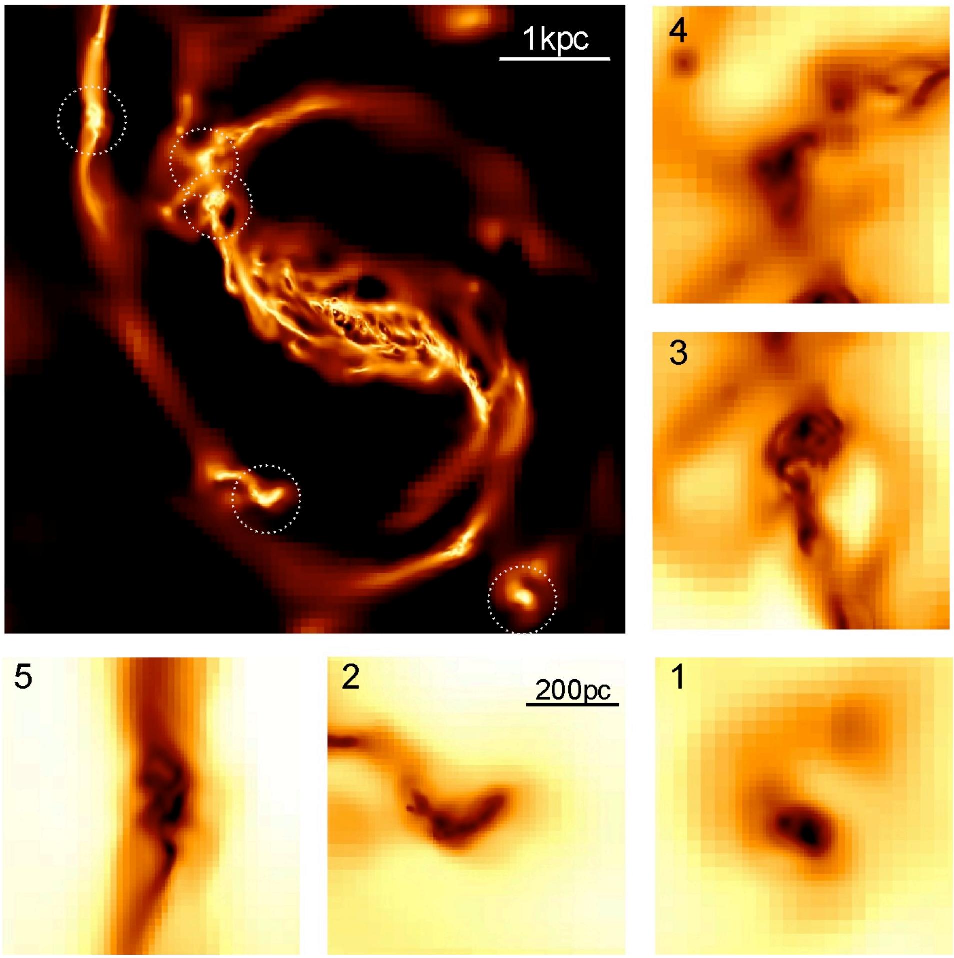

Don't ask for big samples (yet)

(~1Mhours CPU per simulations)

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sub-resolution scheme:
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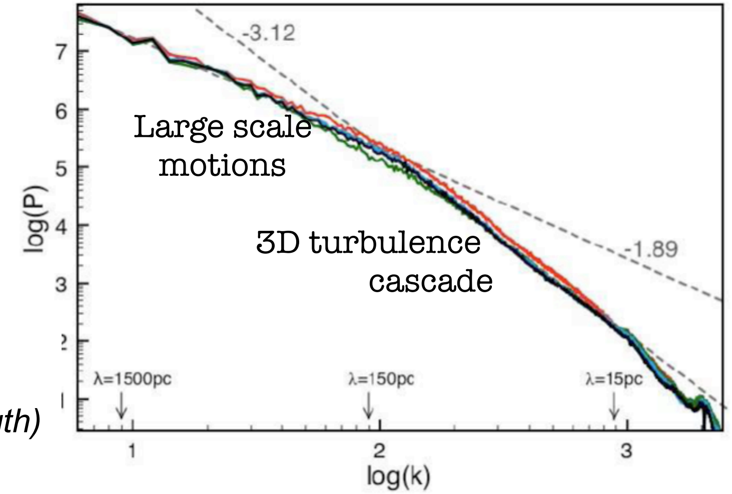
Resolving star-forming clouds in simulations

- *Density power spectrum: double power-law , similar to real ISM*

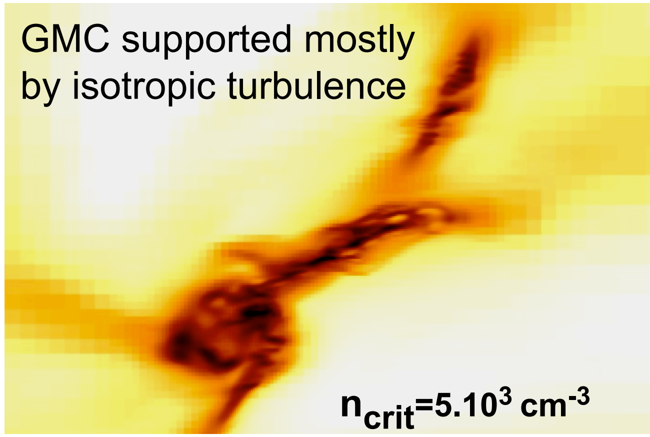


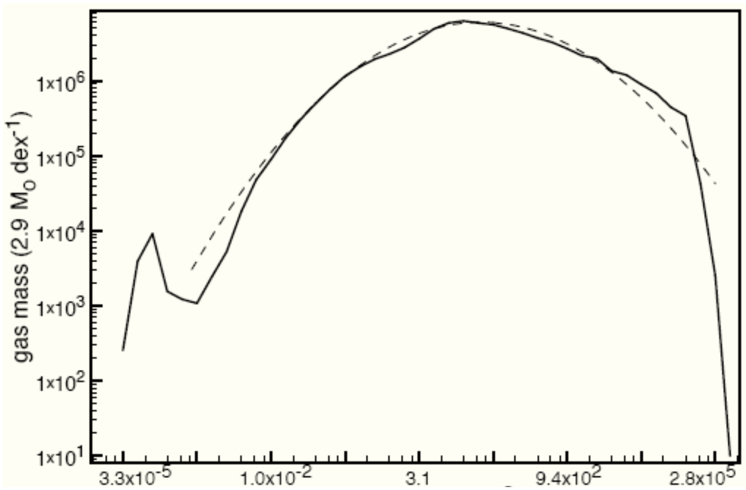
As observed:
Elmegreen+93
Dutta+09
Block+10

3D turbulence cascade initiated at the disk scale height (~ mean Jeans length)

- *Single GMC and entire galaxy PDFs are log-normal* →

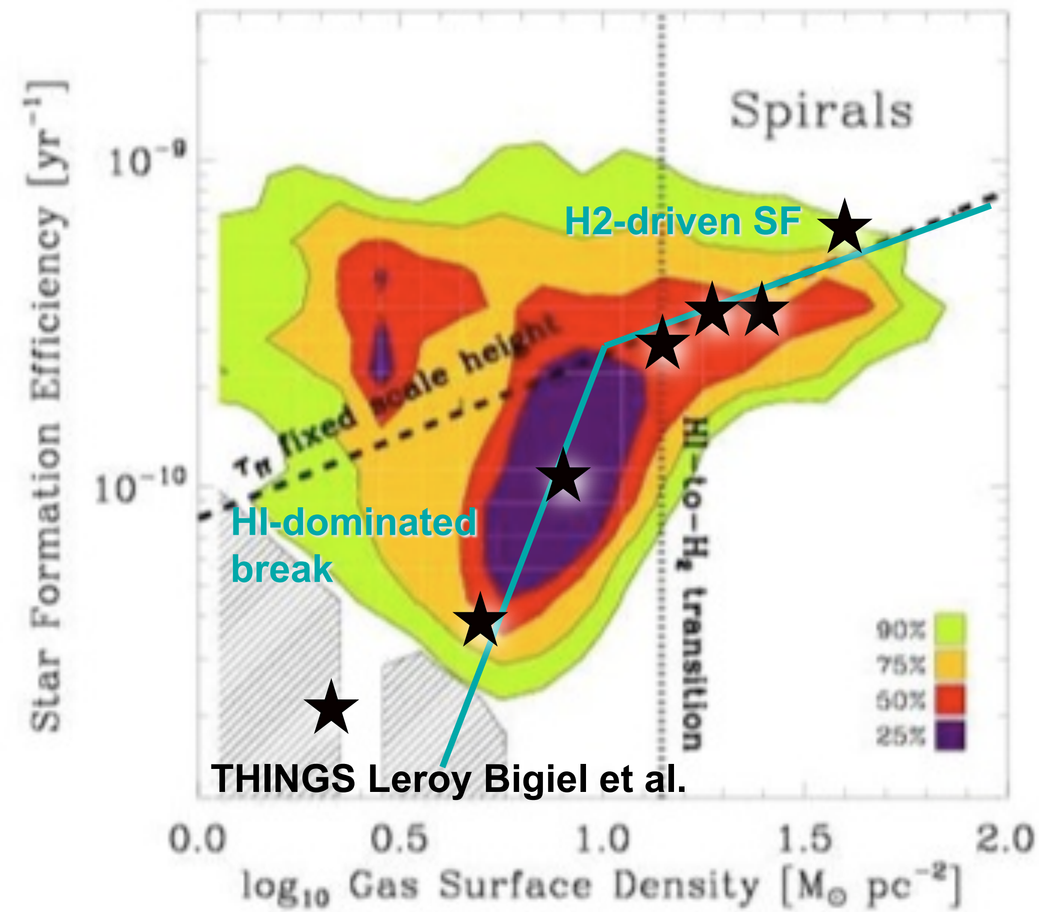
As observed:
Alves, Lada, Lombardi et al.

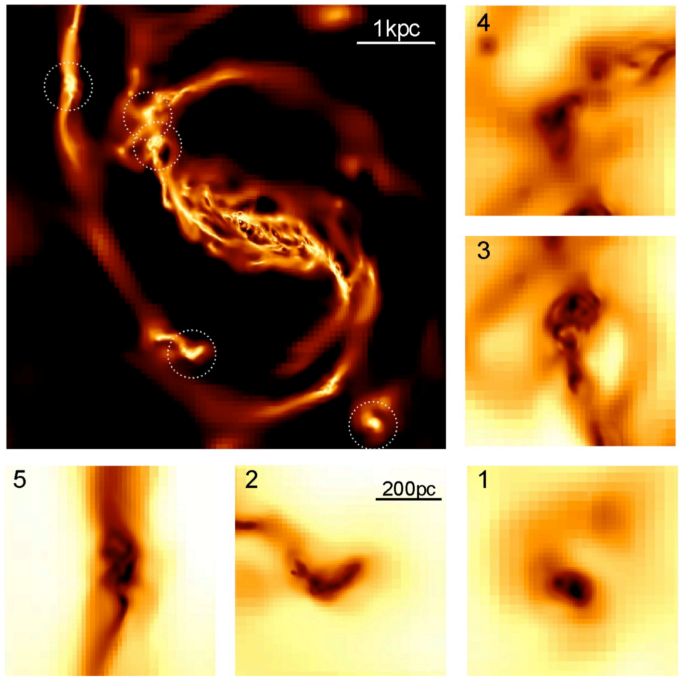




+ Bournaud 2010; IAUS270

Is only H_2 important in star formation?





Coincidence or causal link?

The simulation has no molecule prescription…

Yes, SF takes place in dense gas, but molecular physics may not be important in controlling large-scale star formation (at least this plot is not observational evidence for it)

What about merger-induced starbursts?

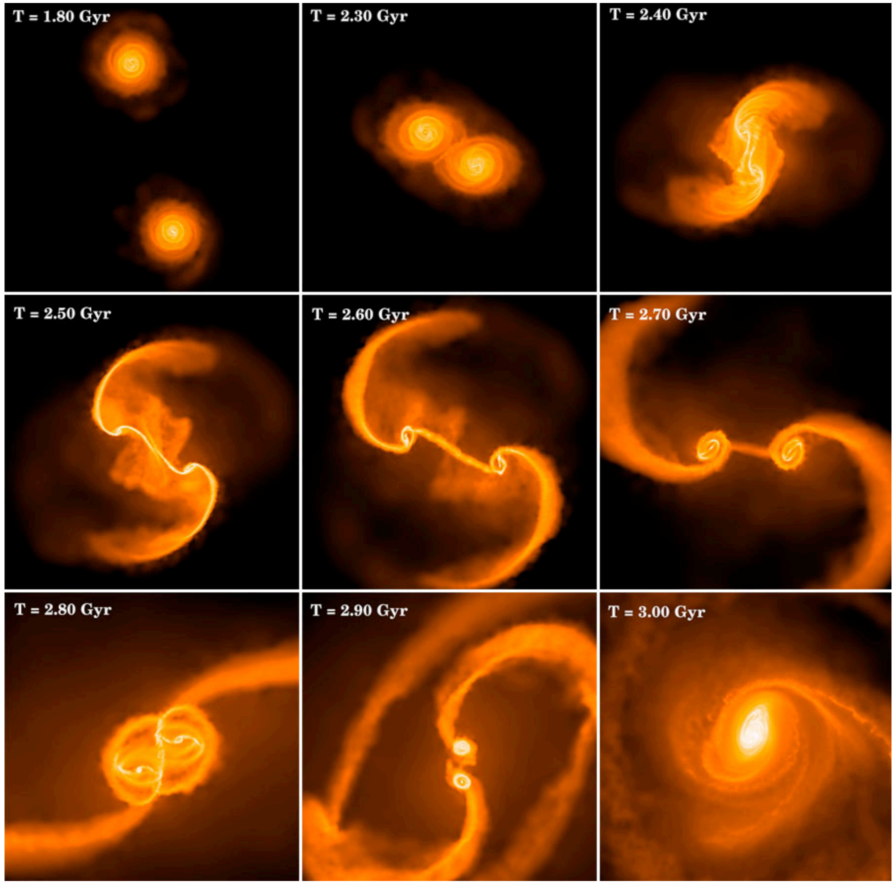
Usual explanation:

Interaction

=> Gravity torques

=> Central gas inflow

=> Nuclear starbursts



Toomre & Toomre 70's
Barnes & Hernquist 1991-92
Cox et al.
Mihos et al.
Dubinski et al. …

SF in mergers is *not* as simple as nuclear inflows

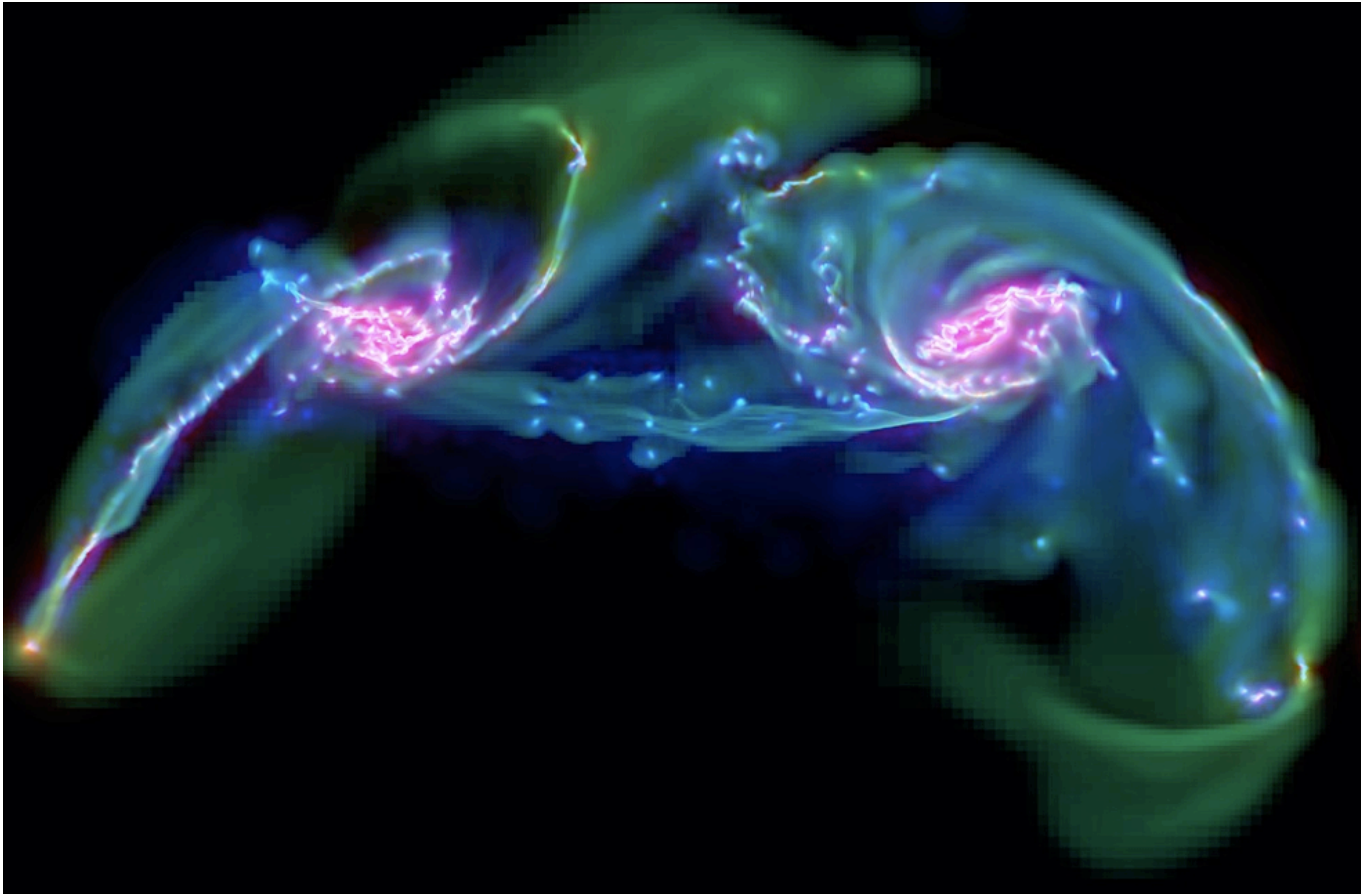
Antennae starburst: 1/3rd nuclear, 1/3rd SSCs, 1/3rd overlap **(Wang+04)**

In fact, merger-induced starbursts are:

- not just nuclear
- spatially-extended
- often in big clusters/HII regions
- stronger than predicted by models

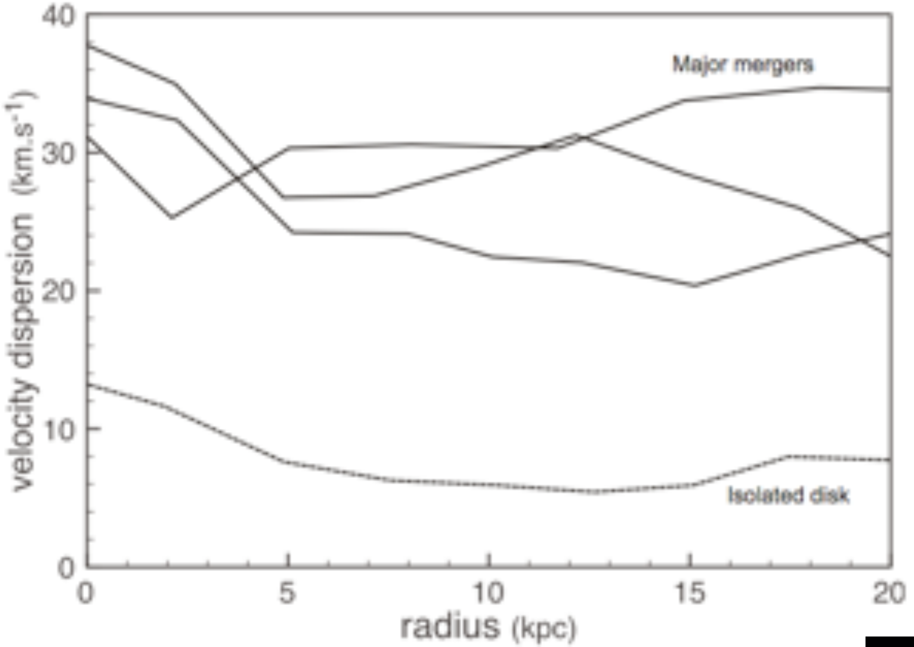
Barnes 2004, Chien & Barnes 2010 -- Di Matteo et al. 2007-2008 -- Smith, Struck, Duc, Brinks etc..

Resolved star formation in mergers



AMR merger simulations with resolutions from 12pc (Teyssier+10) and now up to 4pc

Increased turbulence in interacting galaxies

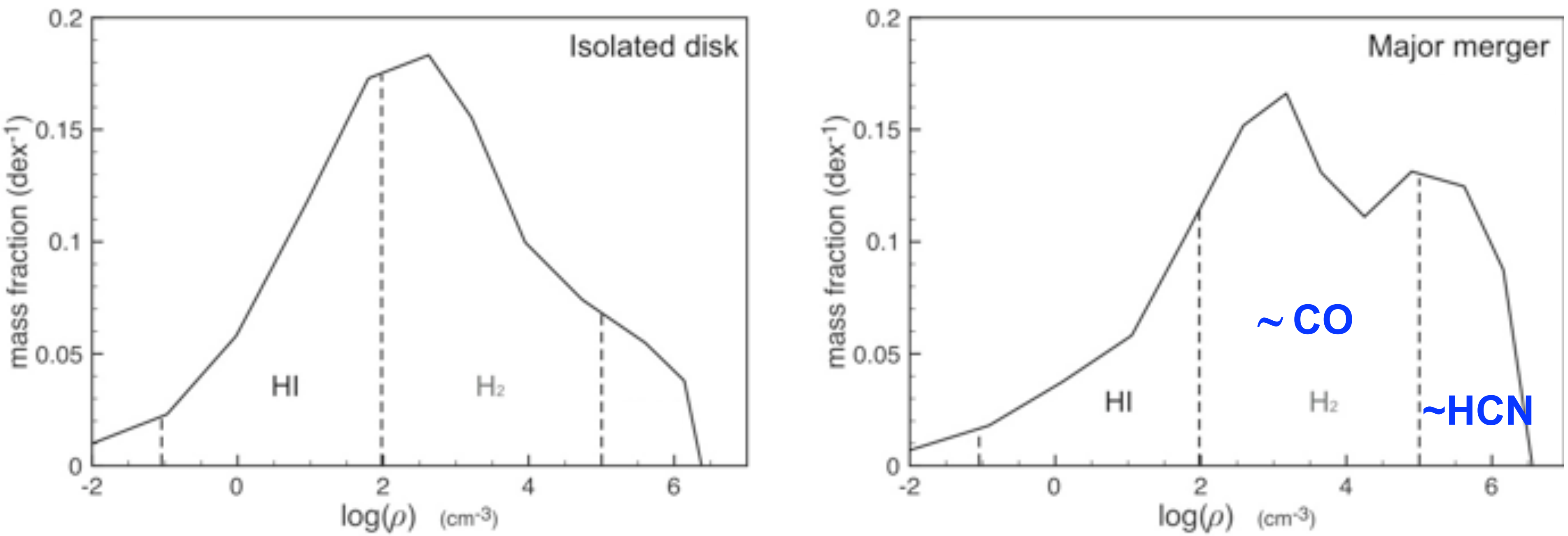


ISM turbulence gets 3-4 times larger in major interactions and mergers…

…as observed
(Irwin 94, Elmegreen 95)

⇒ Can increase L_{Jeans} and make larger clouds/clusters, but not only…

Dense gas excess in starbursting mergers

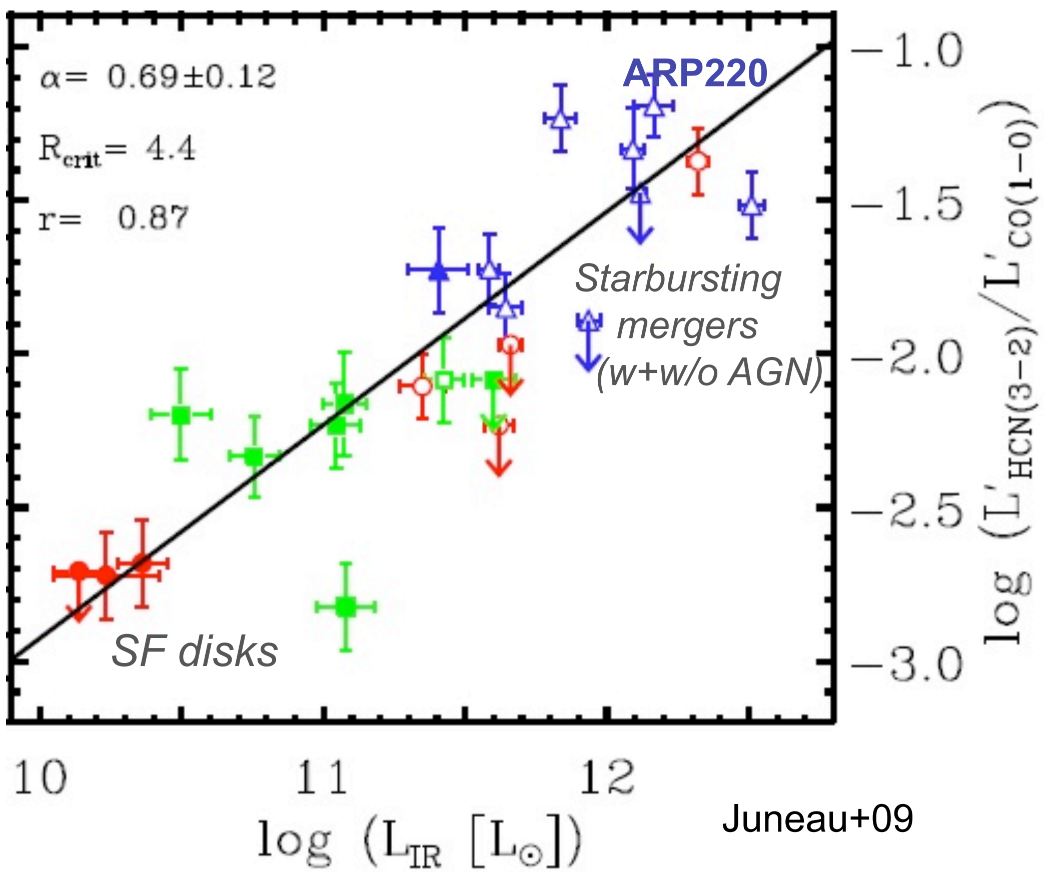


Interaction triggers non-circular motions, compression fronts throughout disks
=> cascade to all scales below ~kpc
=> local shocks (Mach>1)
=> gas compression in dense clouds with fast cooling
=> new self-gravitating cold SF clouds

- Why non log-normal PDF? Stirring is as fast as dissipation timescale
- Note also that dissipation timescale grows if the Mach number increases

Bournaud 2011 IAUS271 (arXiv1012.5227)**, Powell et al. in prep**

Dense gas excess in starbursting mergers



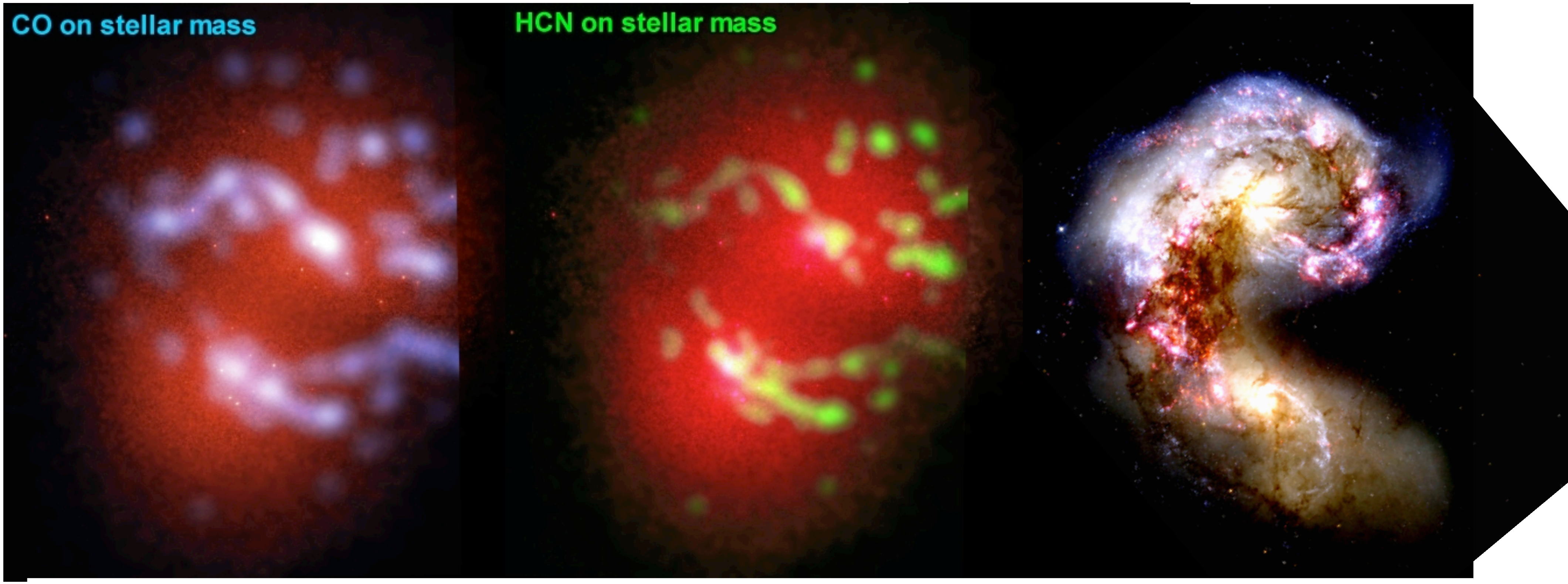
- Observations of HCN, HCO+..
- Dense gas excess in nearby (U)LIRGs (=starbursting mergers)
- Not associated to AGN chemistry effect, but rather to ISM dynamics

=> This observation can explain the deviation from a single SF mode at fixed local SFE

*BUT in our models it results from nuclear inflows **and** triggered turbulence/fragmentation*

Gao & Solomon 2004 ; Juneau et al. 2009 ; Gao et al. 2001 ; Engel et al. 2010 ; Boquien et al. 2011

Dense gas excess in starbursting mergers

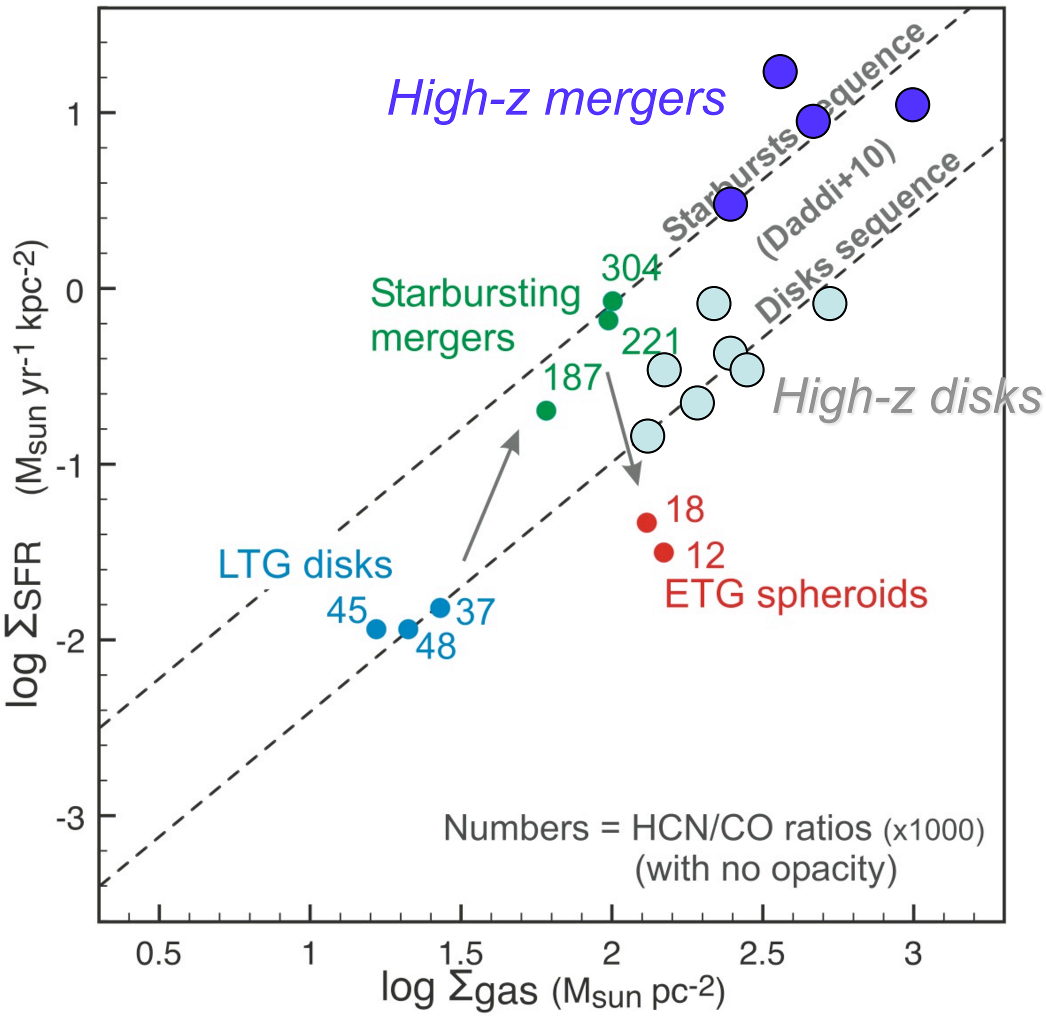


High dense gas fractions not only in the nuclei,
Also in the outer super star clusters, esp. If formed in compressive tidal fields.

« Extended » starburst triggering

LVG modelling on AMR simulations - Mastropietro et al. in prep

Modes of star formation in the Universe



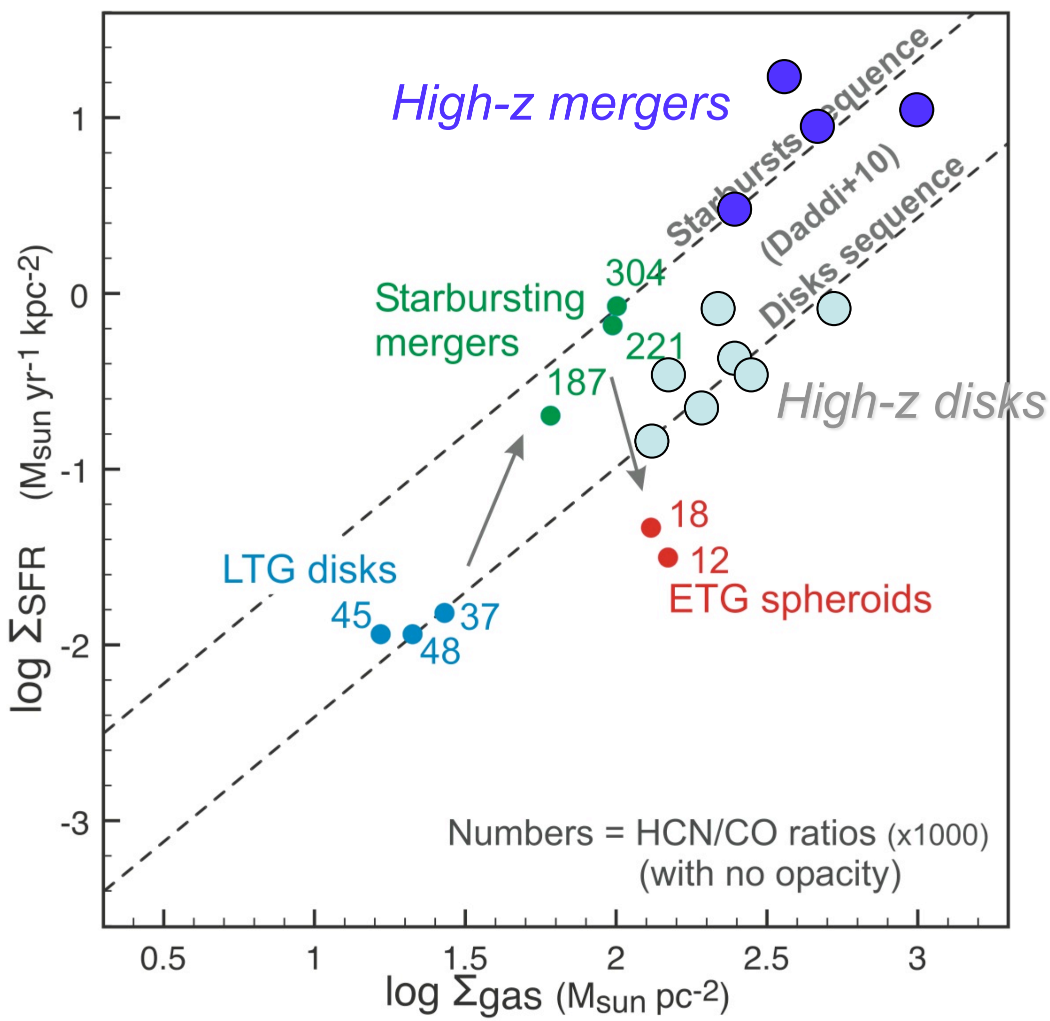
- This SF mode in mergers can increase the grand averge Σ_{SFR} much more rapidly than Σ_{gas}

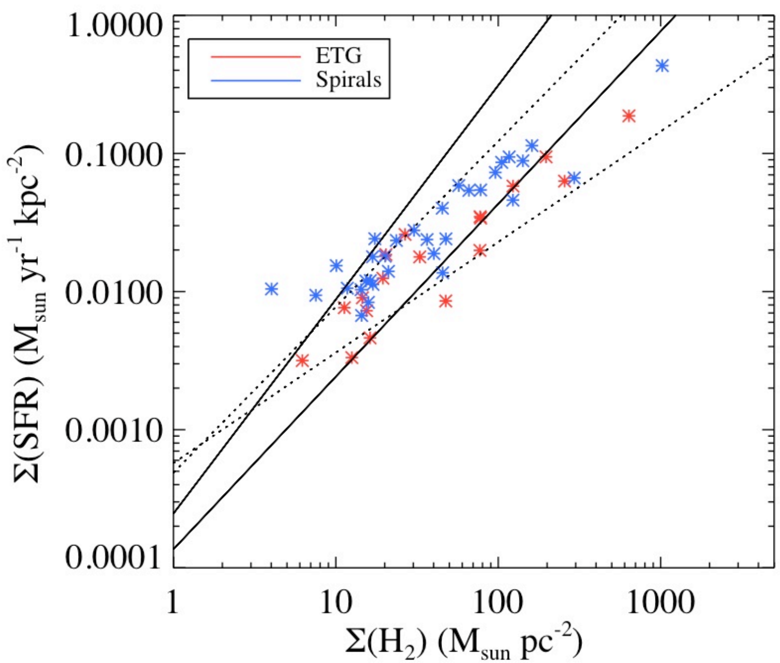
- There is no « bimodality »

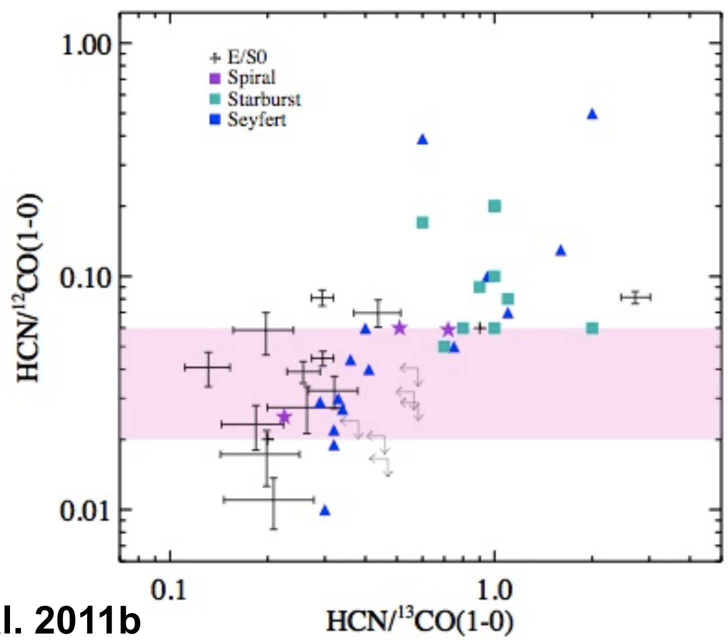
- Apparent « 2 laws » resulting from selecting the most starbursting mergers
(ULIRGs, SMGs, models at peak SFR)

Daddi et al., Genzel et al, 2010 - observed « two modes » of SF

Modes of star formation in the Universe







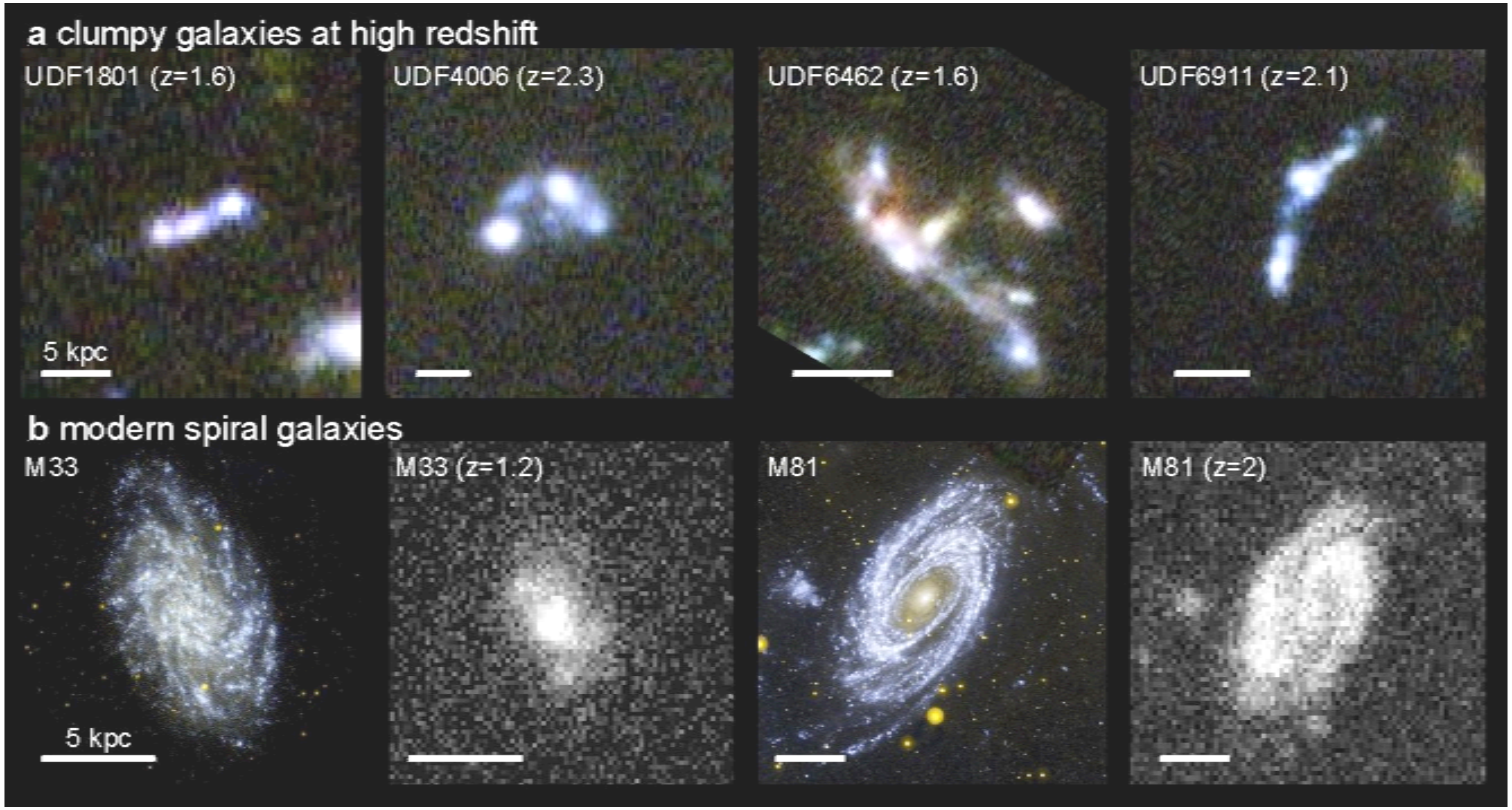
Spheroid-dominated galaxies could have lower SFE, and low HCN/^{13}CO

Crocker et al. 2010,11 (ATLAS3D) - see also Saintonge et al. 2011b

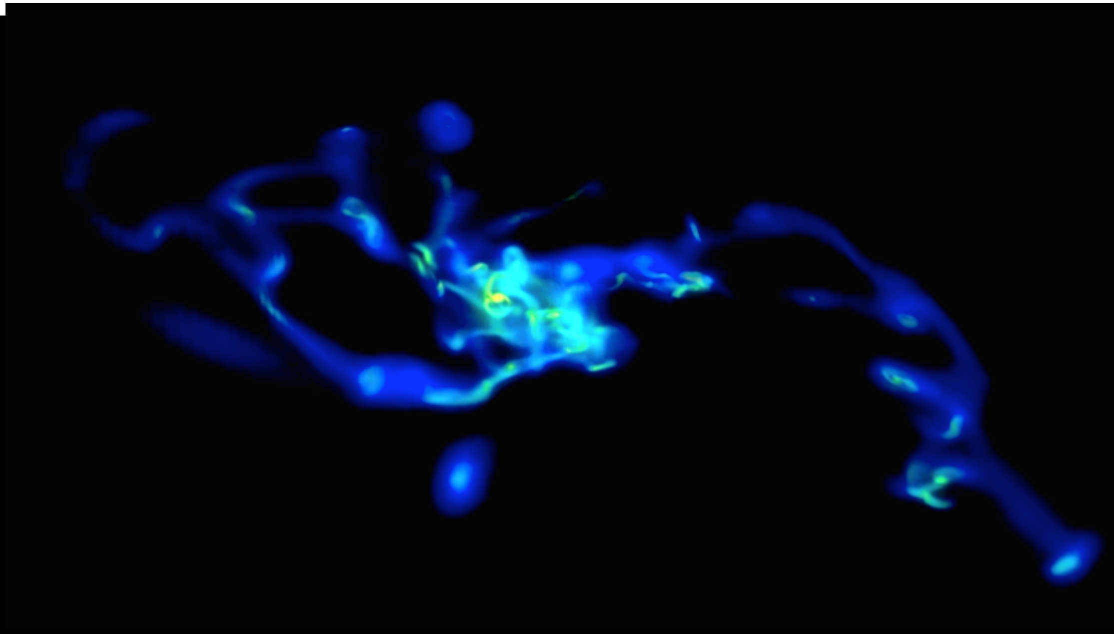
Star-forming galaxies at high-redshift

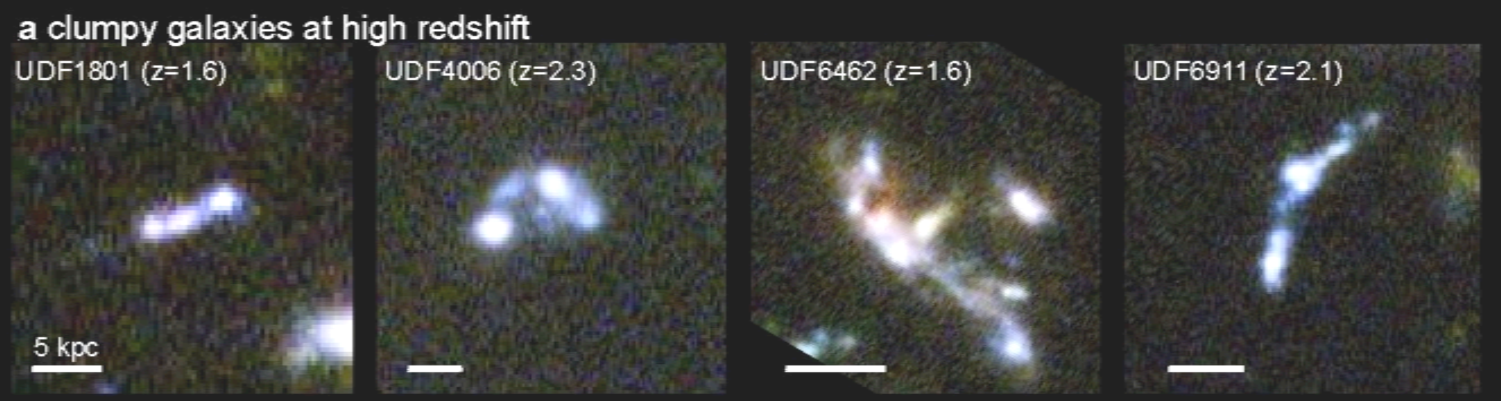
Optical surveys *(mostly Hubble Ultra Deep Field - UDF):*

- SF at z>1 is mostly in clumpy disks - not violent mergers
- SF clumps much more massive than local GMCs **(10^{7-9} M_{sun} , ~1kpc)**
- Formed internally because of morphology, photometry, kinematics



Cowie et al. 96 - Elmegreen, Elmegreen et al. 2004-2010 - Conselice et al. 2007





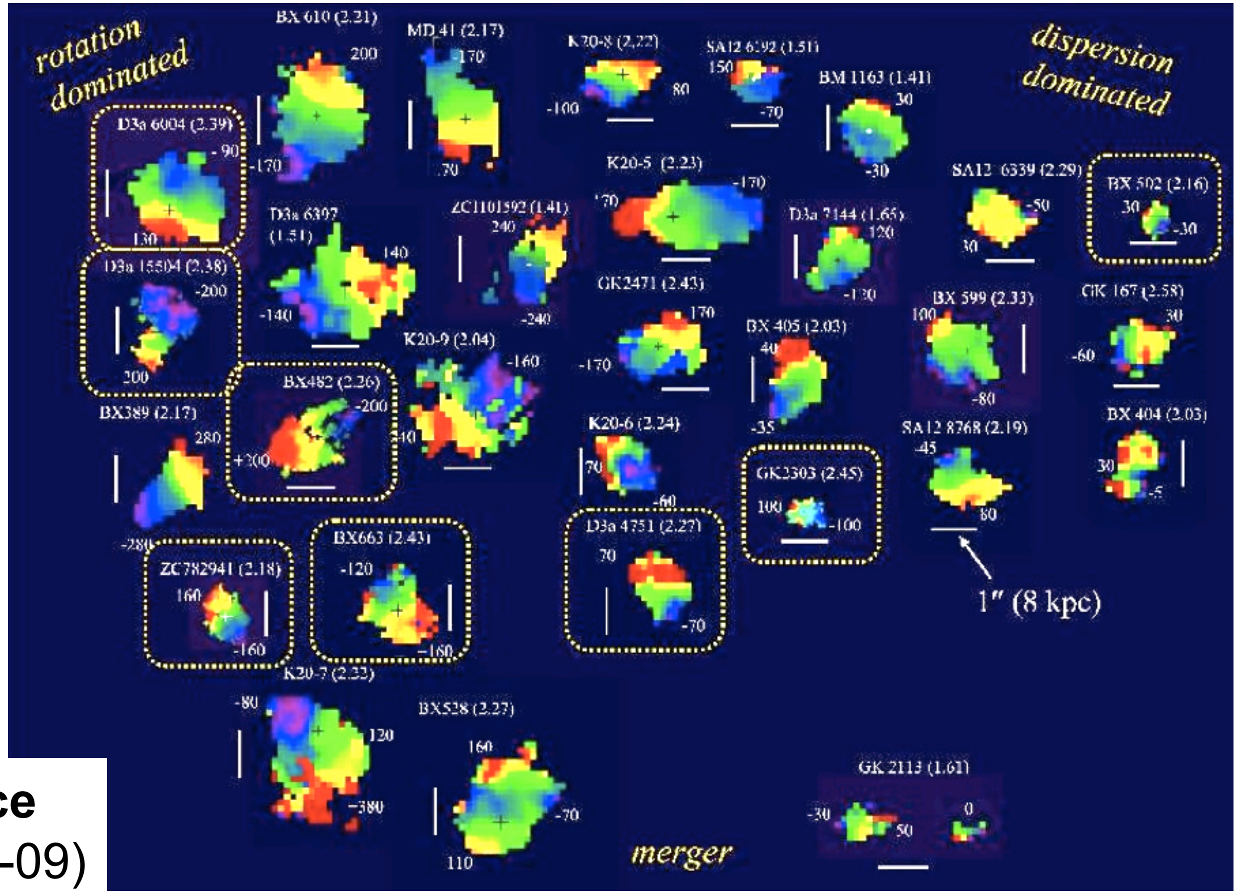
These are mostly gas-rich disks, that are violently unstable because of high gas fractions (~50%), with high SFR due to rapid infall of gas (probably cold streams)

Star-forming galaxies at high-redshift

Spectroscopic surveys of ``normal'' SF-ing galaxies:

- Majority of rotating disks - some mergers and dispersion-dominated
- Strong turbulence

  σ~50km/s
- Big Hα clumps with M_{dyn} up to 10^9 M_{sun}
- Kinematical disturbances from clumps



***and* morphological evidence**
(Elmegreen & Elmegreen 2005-09)

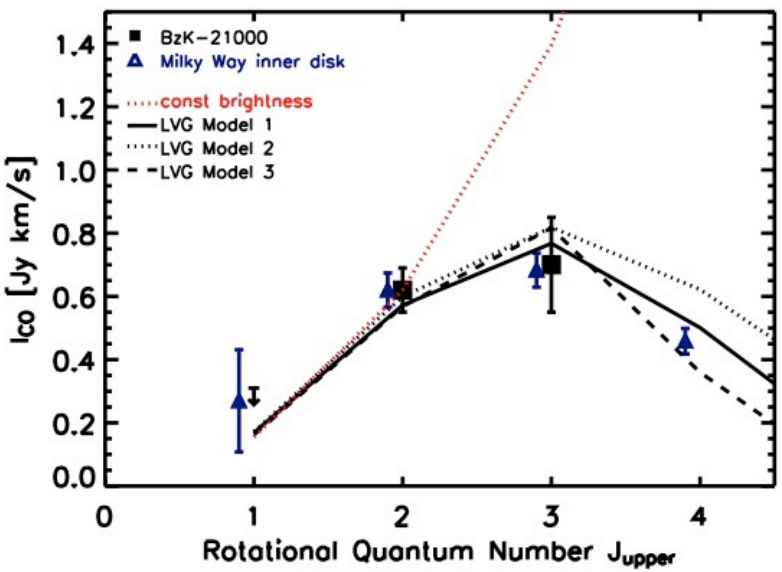
Förster-Schreiber et al. 06,09, Genzel et al., Shapiro et al. 08 - Bournaud Daddi et al. 08 - Epinat et al. 09

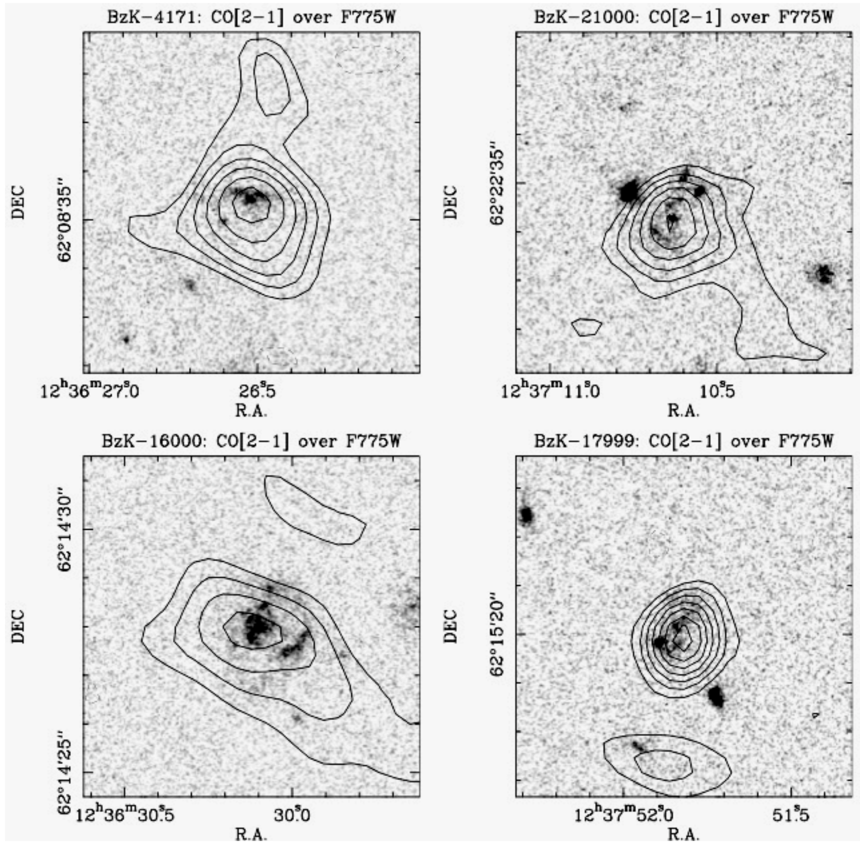
Star-forming galaxies at high-redshift

CO surveys of ``normal” SF-ing galaxies:

- High gas fractions ~ 50% of the baryons

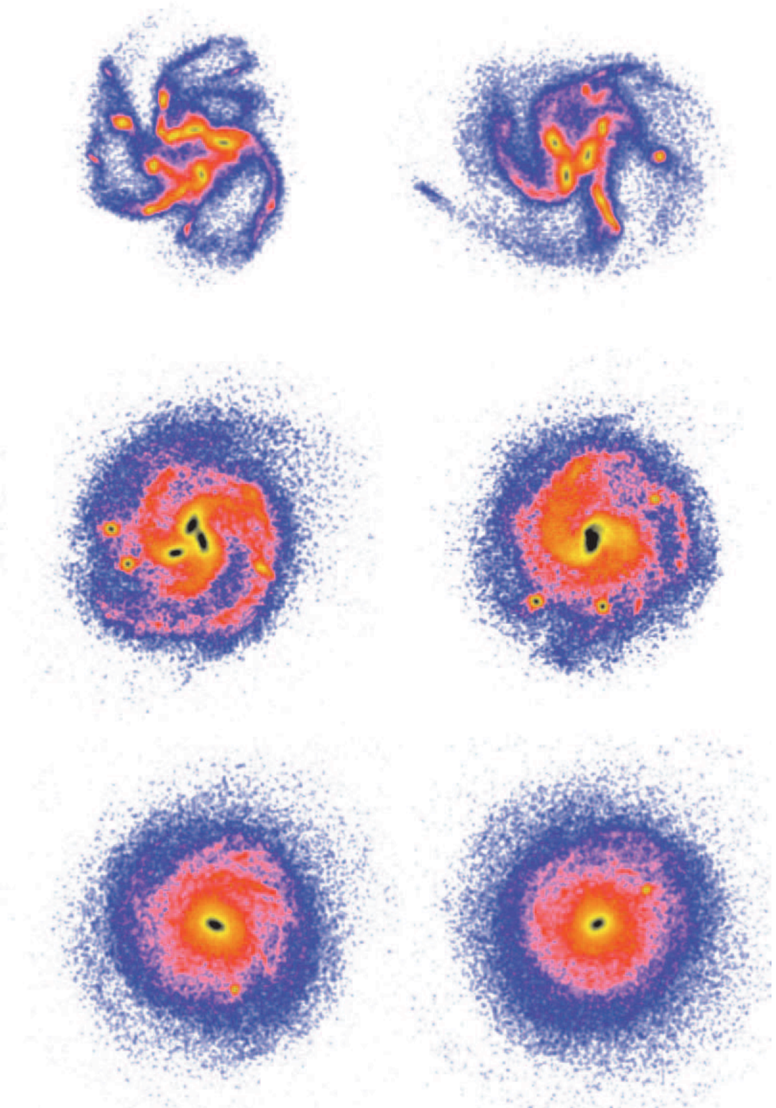
- Dynamical masses *and* CO SEDs support MW-like excitations and conversion factors





Daddi et al. 2007, 2008, 2010 - Dannerbauer et al. 2009 - Tacconi et al. 2010 - Saintonge et al. in prep

Giant clump instabilities, clump migration, bulge formation



1 Gyr of internal evolution - BEE07

Typical z~2 disk, gas-rich

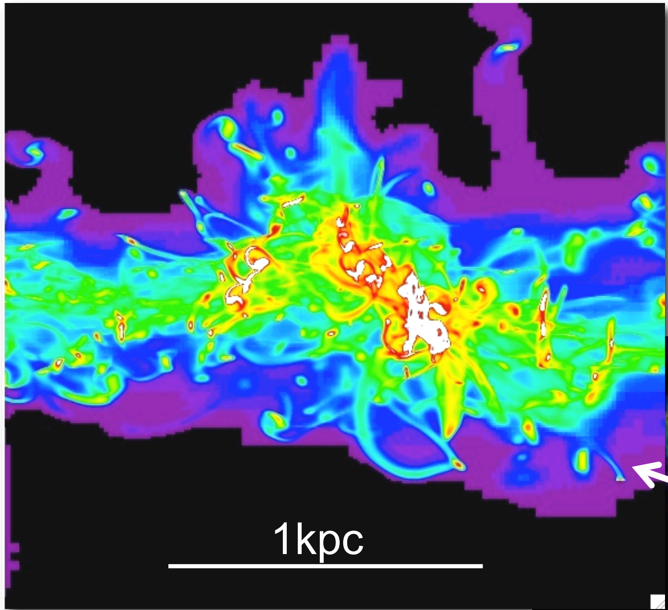
Gravitationally unstable $Q_{(gas+stars)} < 1$
Fragmentation into giant SF clumps

Clump migration (dyn friction+torques)

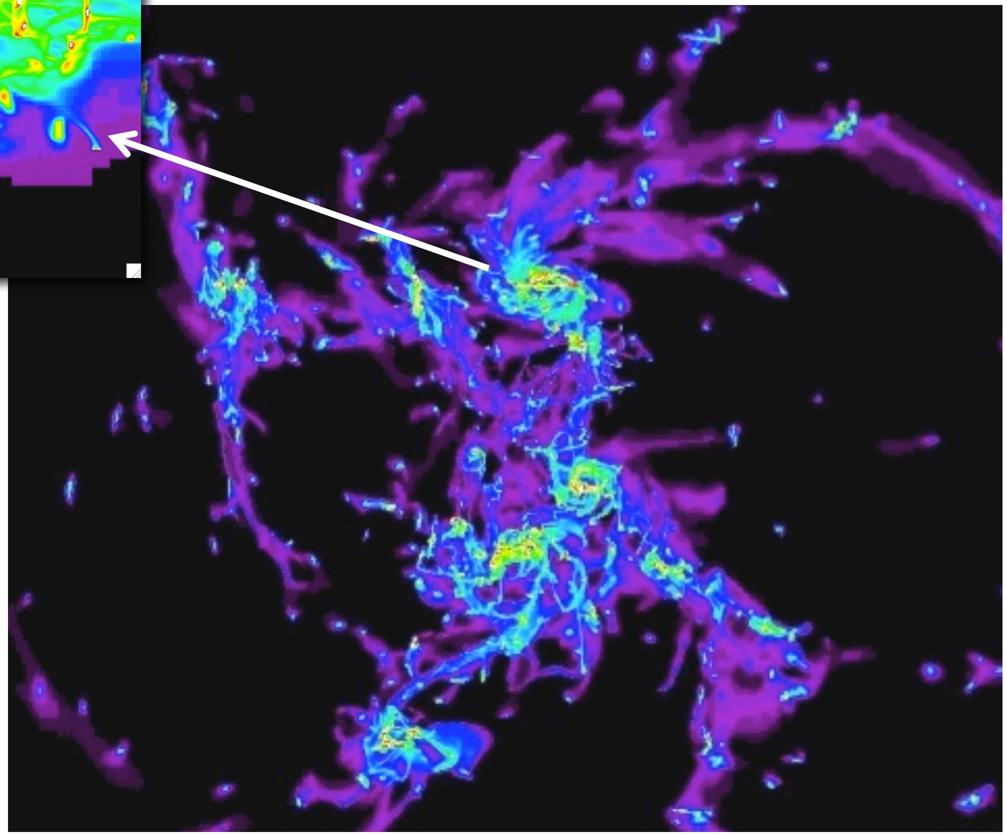
Coalescence in a central bulge
+ exponential spiral disk

Bournaud, Elmegreen & Elmegreen 2007-09, Noguchi 99, Immeli+04

Self-regulated, low SFE disks at high-redshift



Giant clumps rotate and fragment,
Develop internal turbulent support,
$\Sigma_{SFR}/\Sigma_{gas}$ remains moderately high



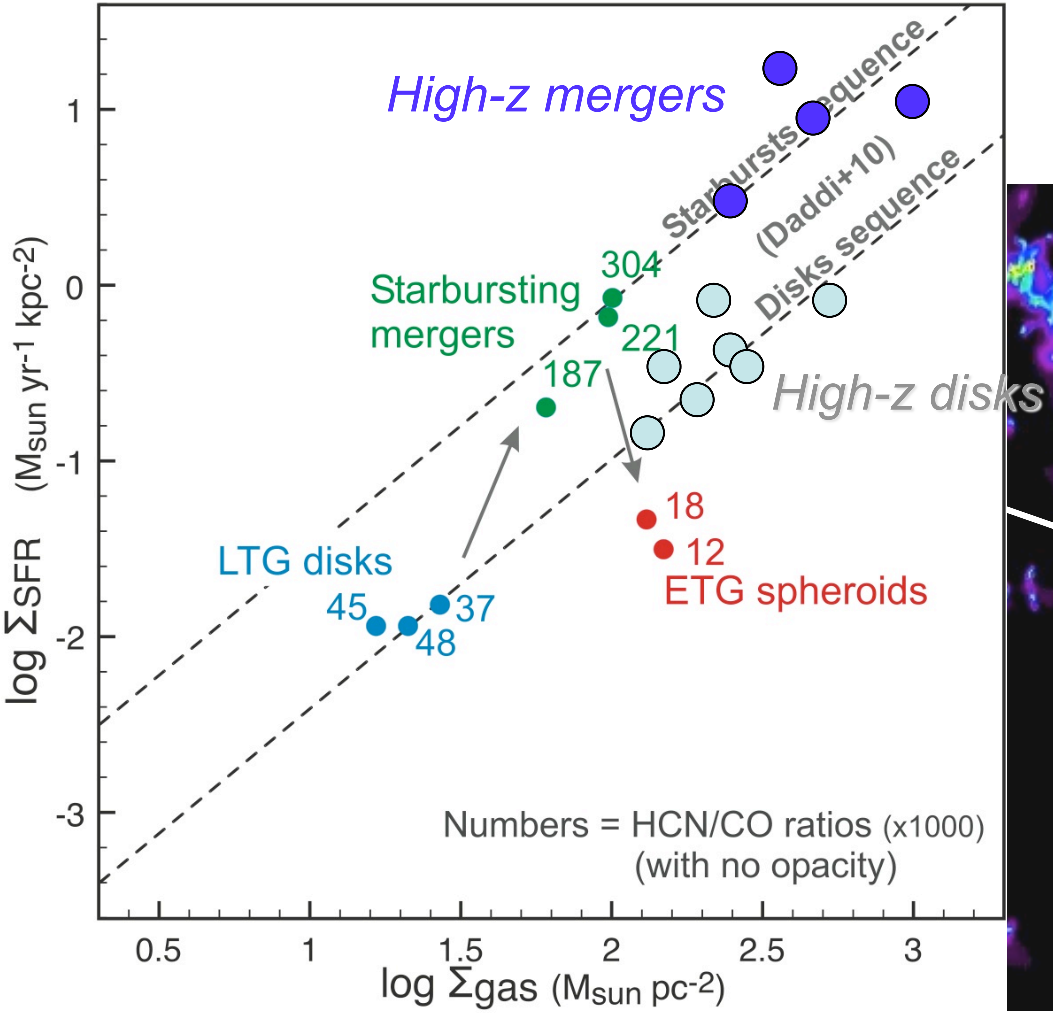
SFR~100M_o/yr in 5-10 giant clumps

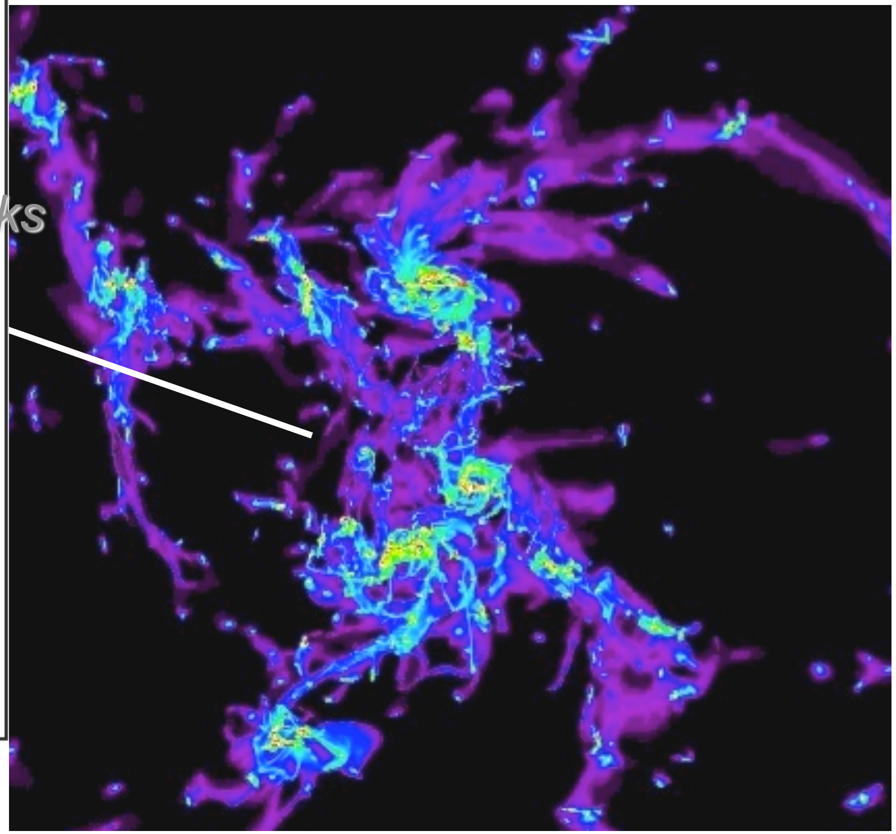
Each giant clump:
1kpc, $10^{8\text{-}9}$ Mo

Sub-clumps:
20pc, 10^{6} Mo

Clump rotation : 30-50 km s^{-1}
Clump dispersion : 50-70 km s^{-1}

Self-regulated, low SFE disks at high-redshift

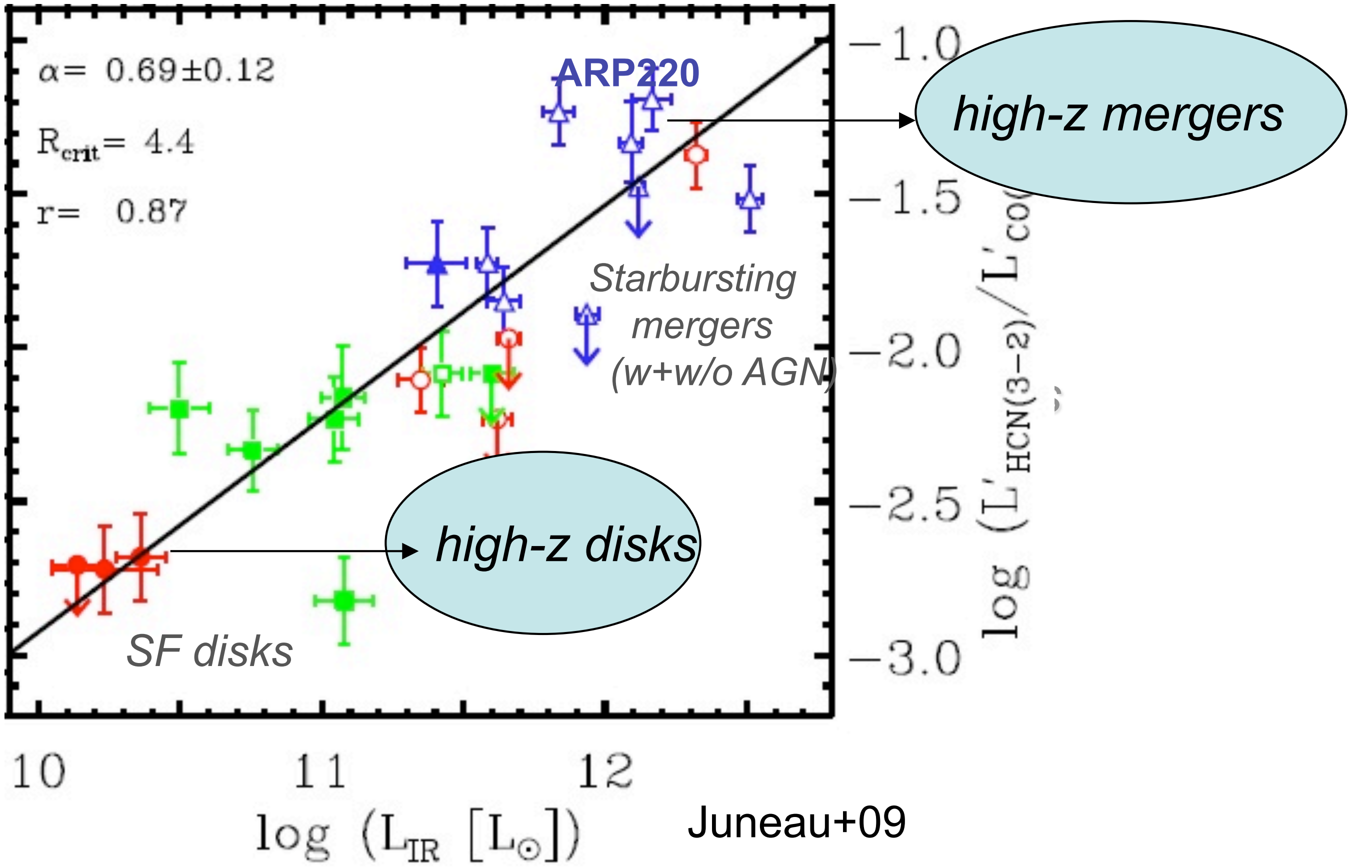




Density PDF is log-normal (unlike mergers, even if SFR is high)

Molecular gas properties (X_{CO}, HCN/CO) should be close to disk-like,
not ULIRG-like even if ULIRG-like SFR

Self-regulated, low SFE disks at high-redshift



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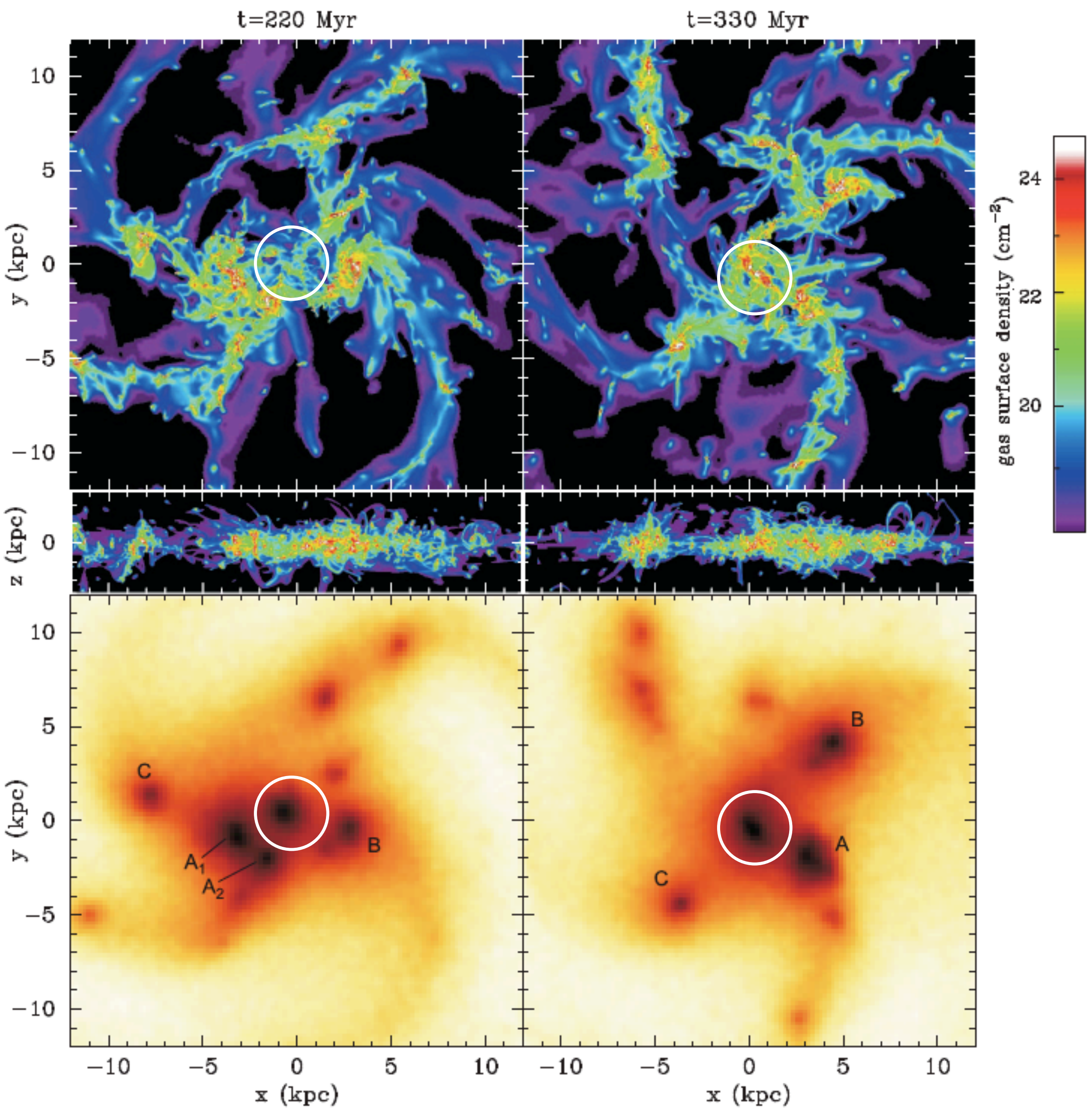
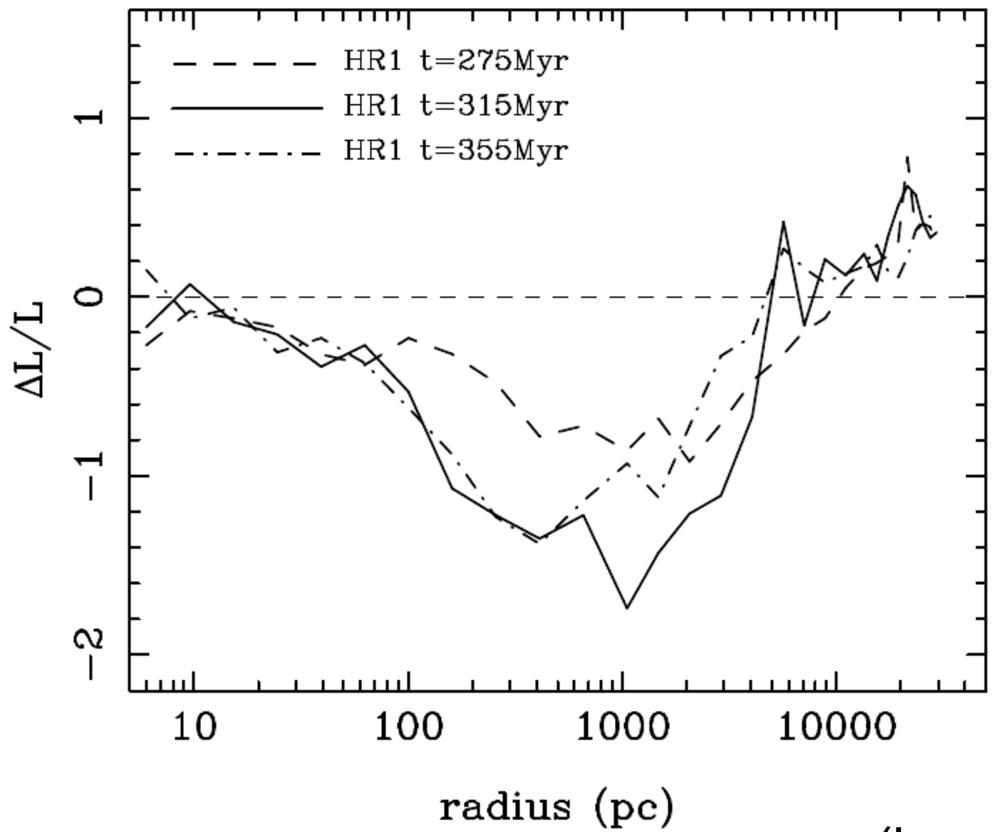
Global gas inflow (not just from giant clump migration)



- Idealized model starting with bulge + gas-rich disk
- Initial bulge gas-poor
- *Torques and turbulent dissipation initiate an inflow of gas*
- Inflow even before the giant clumps migrate to the bulge
- Note high central surface densities of gas

Bournaud Dekel Teyssier + 2011

Gravitational torquing of inter-clump gas

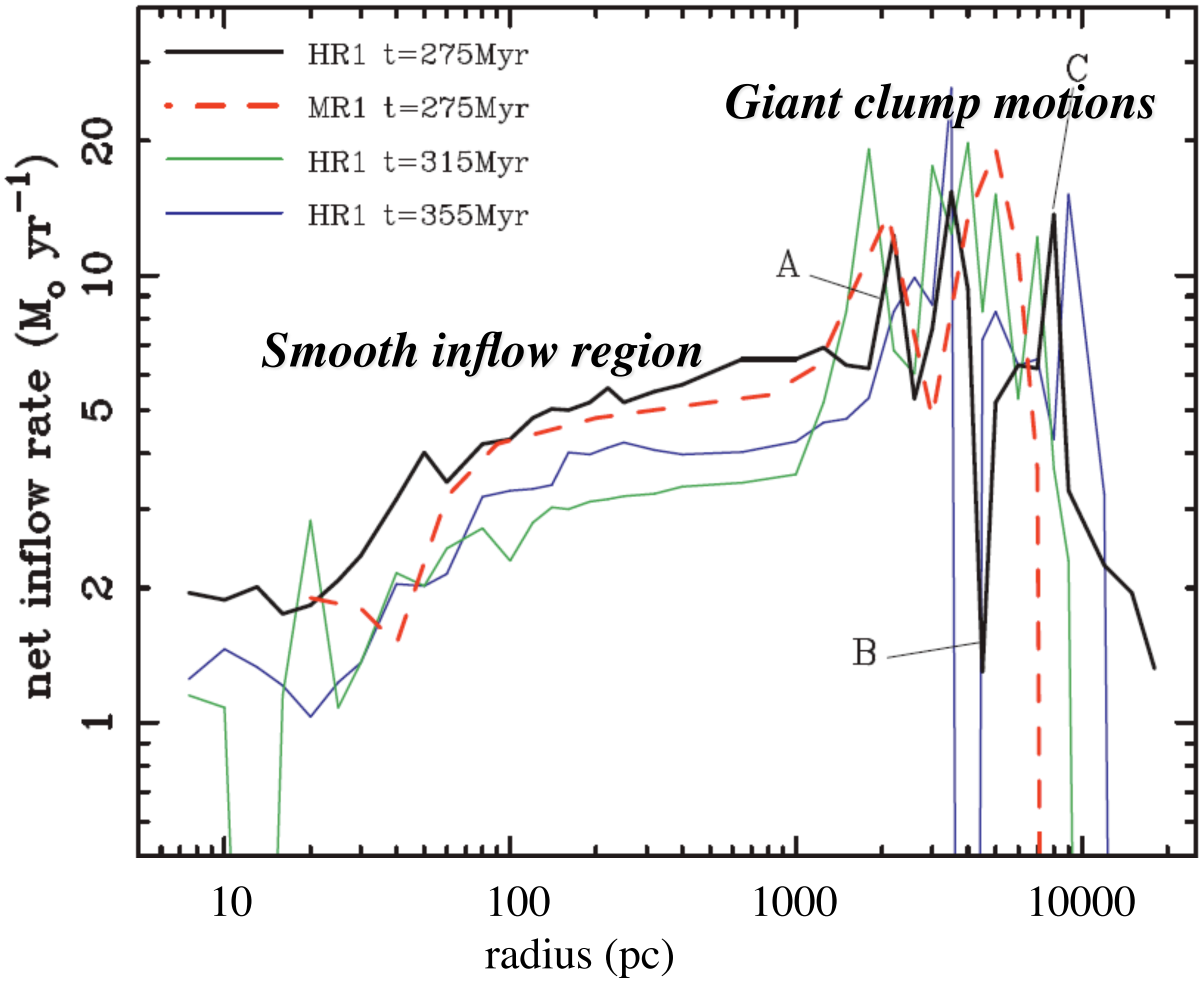


- Clumps are at their own corotation, without ILR in general
- Mass inside clump distance undergoes negative gravity torques
- relative angular momentum variation:
  up to -100% per rotation period

(bars at z~0 would make 5-10% at best)

Bournaud Dekel Teyssier + 2011

Inflow rate onto the AGN



- inflow rate ~few Mo/yr

- not affected when feedback is varied

- persists at very small radii

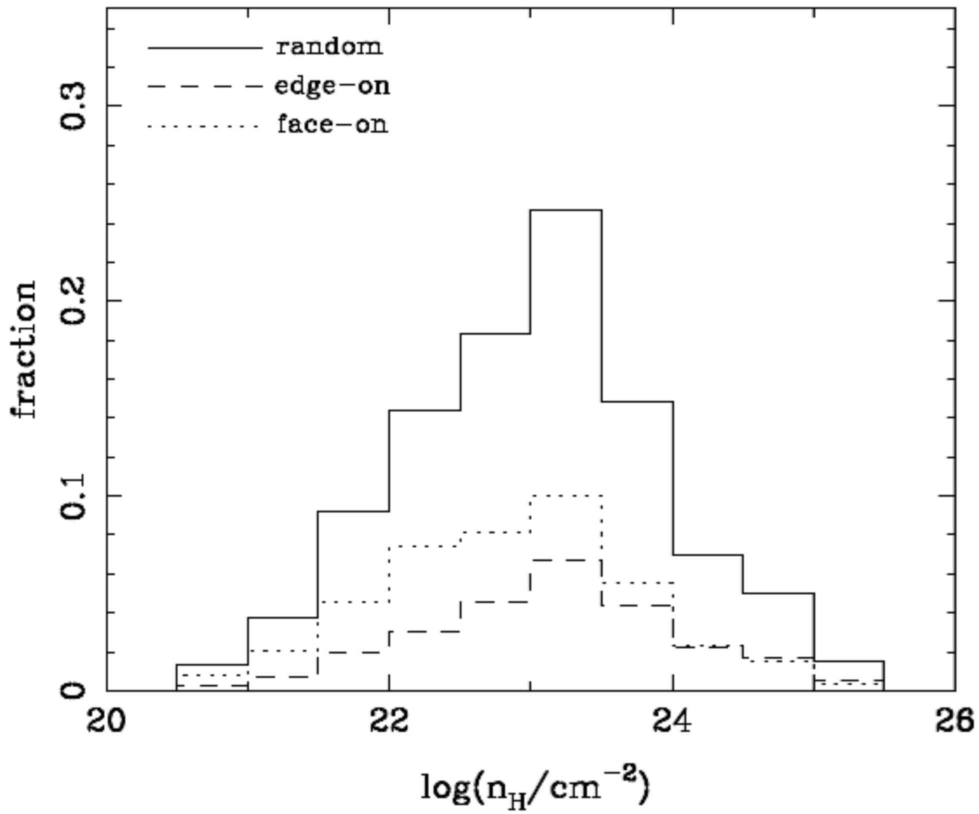
Inflow radial velocity could be 10-20 km s^{-1}

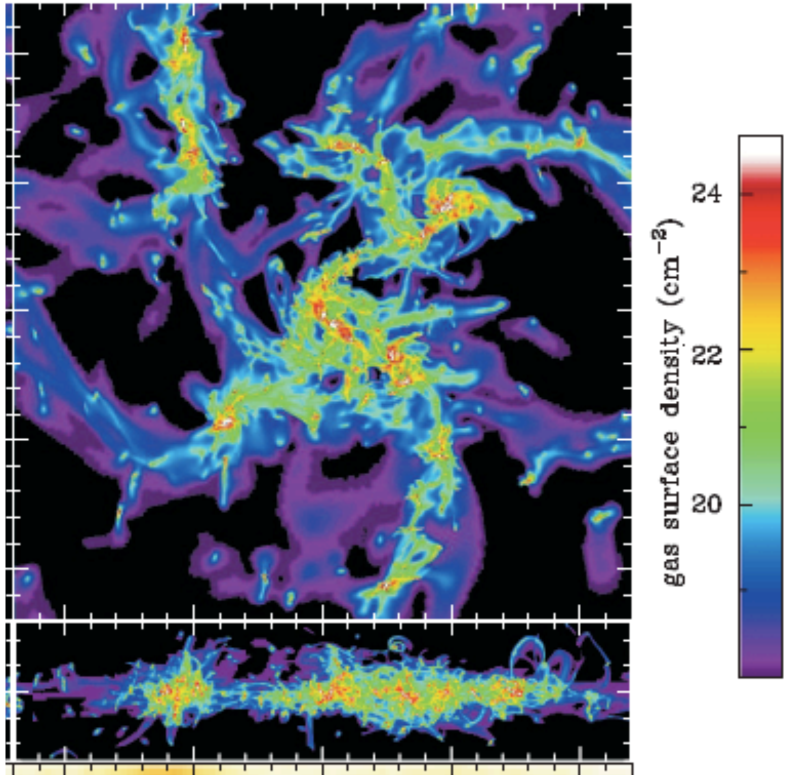
Bondi Hoyle accretion may bring ~1% of the central $1M_o$/yr onto the SMBH which would be enough to reach the Maggorian relation

Bournaud Dekel Teyssier + 2011

« Disk instability AGNs » : modest L_X *and* obscuration

- average L_X **~ 10^42 erg/s** for $M_{stars} \sim 10^{11}$, but lasting 2-3Gyrs
- highly **obscured** by ISM distribution, can be Compton Thick

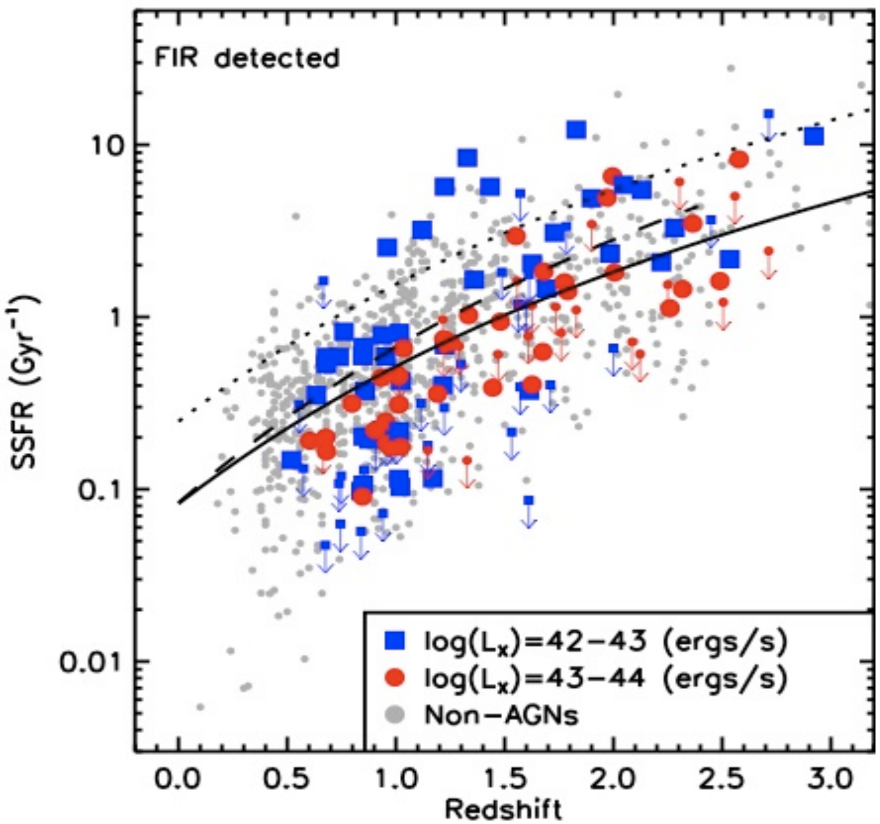




It is not easy to see an AGN in a gas-rich star-forming disk galaxy

Bournaud Dekel Teyssier + 2011

Star Formation in AGN hosts (1<z<3)



Mullaney et al. 2011 (arxiv1106.4284)

AGN host morphologies are not suggestive of merger-induced activity

Grogin et al. 2005
Gabor et al. 2009
Schawinski et al. 2011
Kocevski et al. 2011

X-ray CDFS AGNs are mostly in « Main Sequence » galaxies, « normally star forming » galaxies (1<z<3), as opposed to merger-induced starbursts.

… at z>1, these should be mainly gas-rich (unstable?) disks.

Can we directly observe AGN in unstable disks?

At z~2: - Mostly weak and obscured AGNs, hardly observable even 4Ms CDFS

- Narrow line diagnostics not calibrated (and lines are in the IR..)

At z~0.5-1:

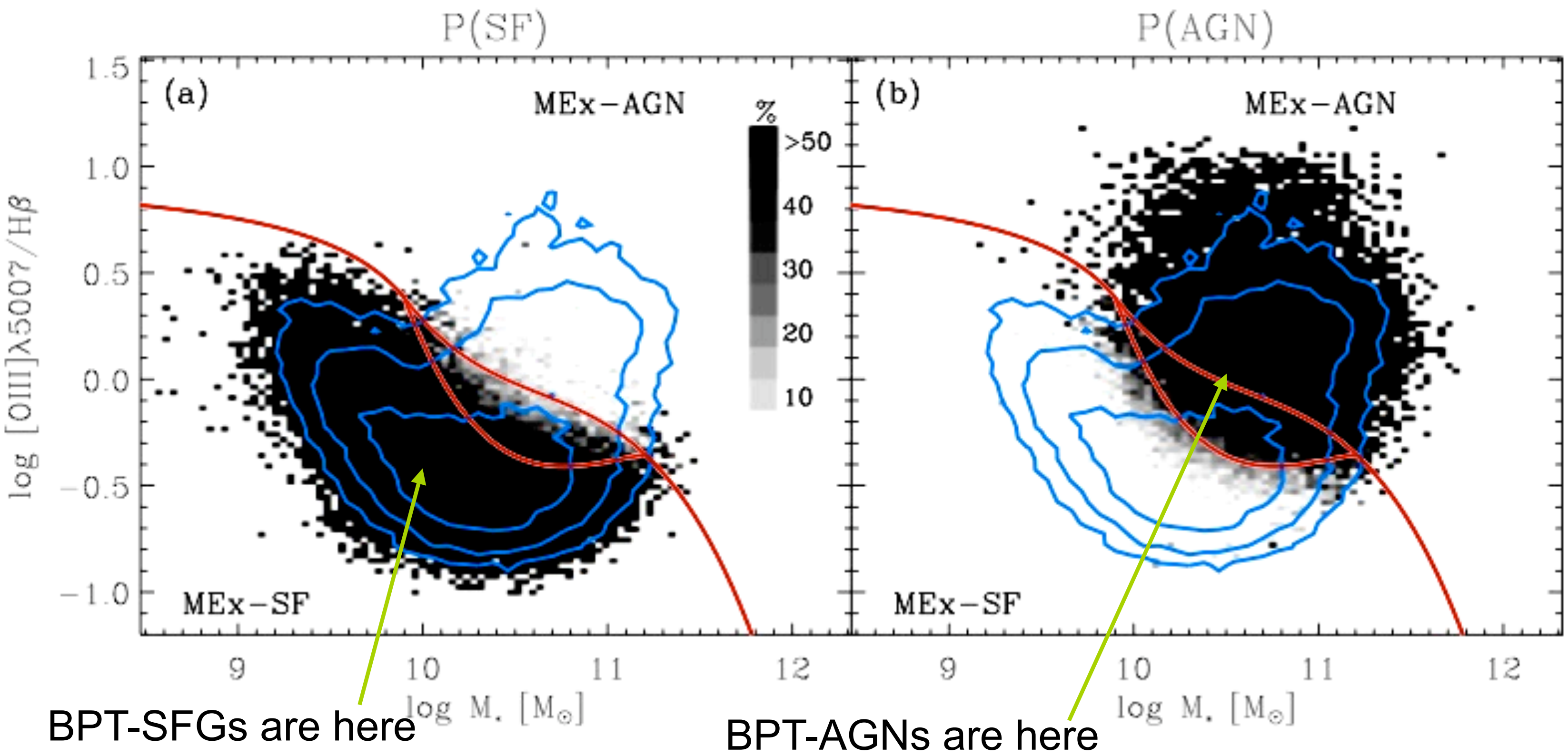
- This is the end of violent disk instabilities but there are some left

  (not in very massive galaxies, but in MW-like progenitors)

- Weak and obscured AGNs may be in reach of X-ray stacking

- Narrow line diagnostics *can* be used (calibrated + optical lines)

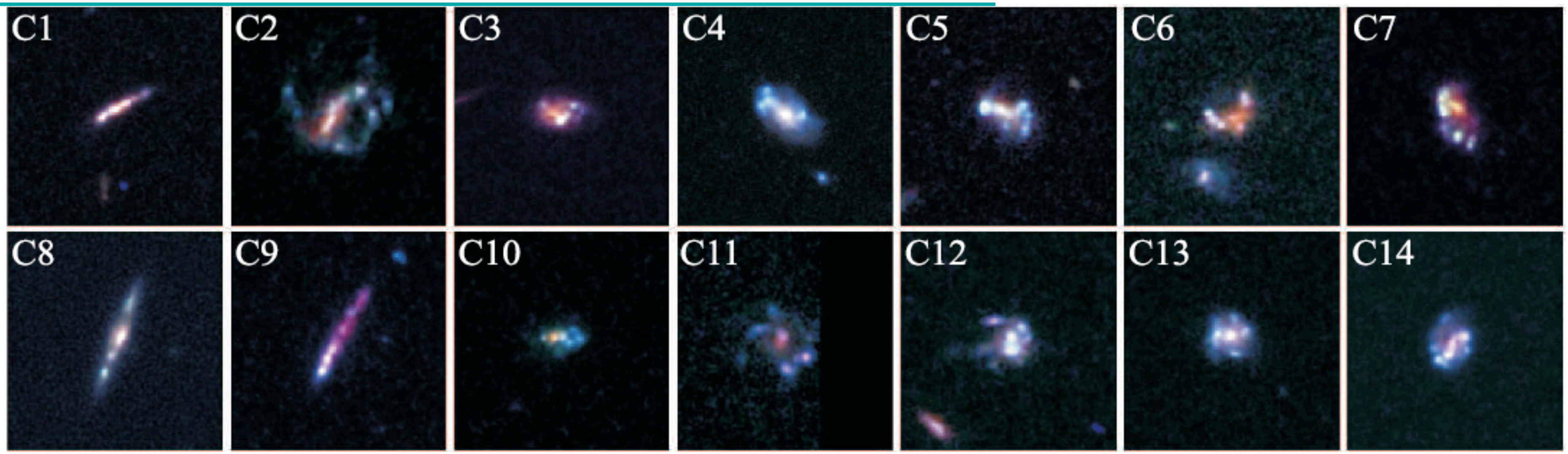
Mass-excitation AGN diagnostic (MEx)



- *Useable with optical spectra up to z~1*
- *Tested against X-rays up to z~1*
- *Empirical dividing lines* and *statistical calibration « P(AGN) vs P(no-AGN) »*

Juneau, Dickinson, Alexander & Salim 2011

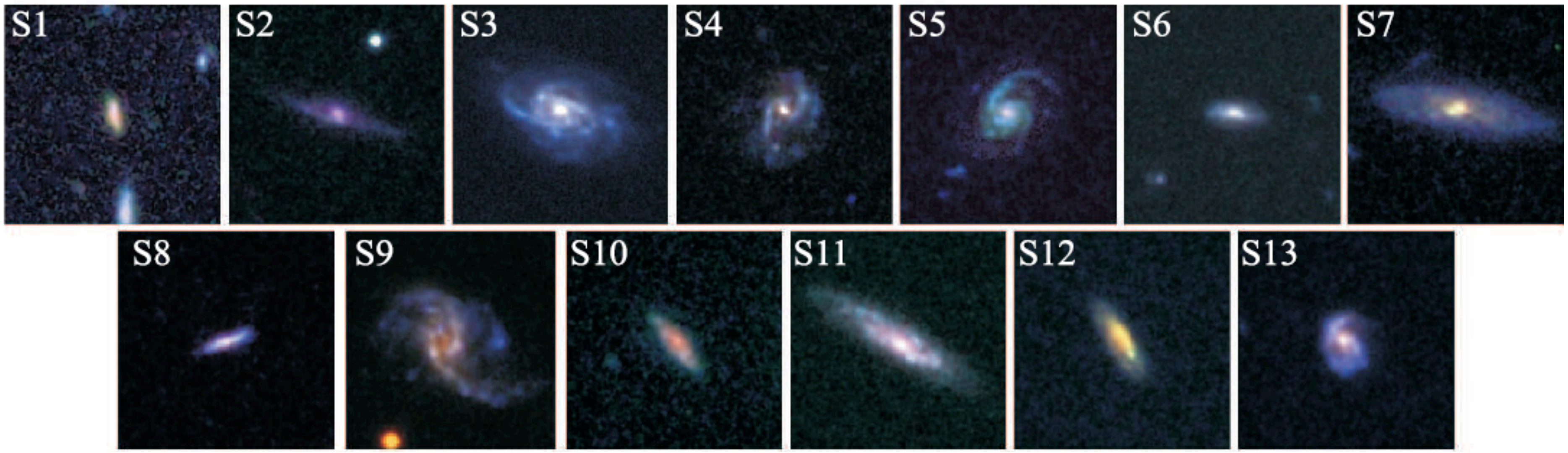
Goods-South Clumpy/Stable disks at z~0.7



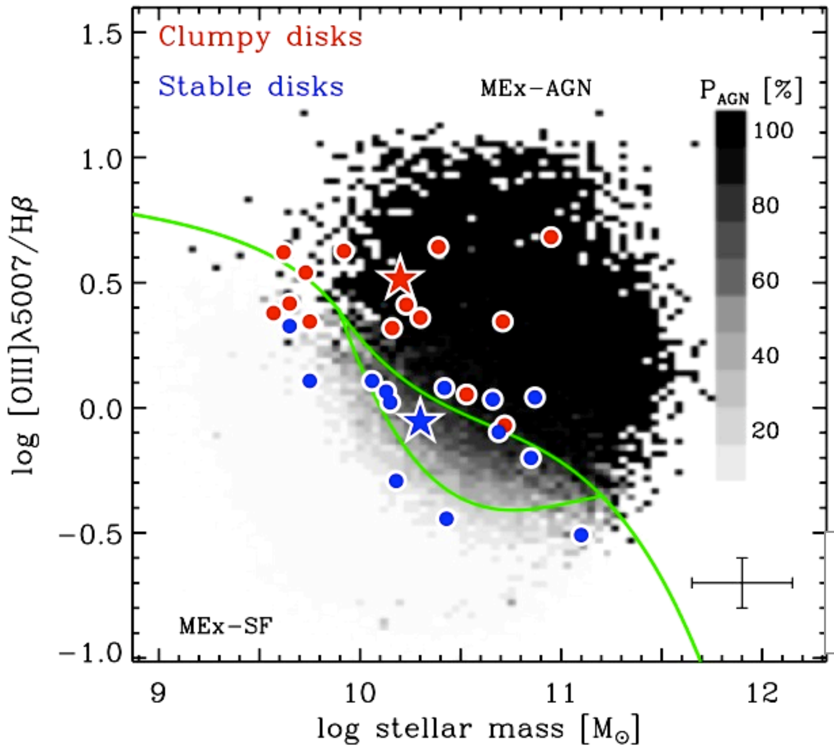
Very clumpy - violently unstable - high sSFR and f_{gas}

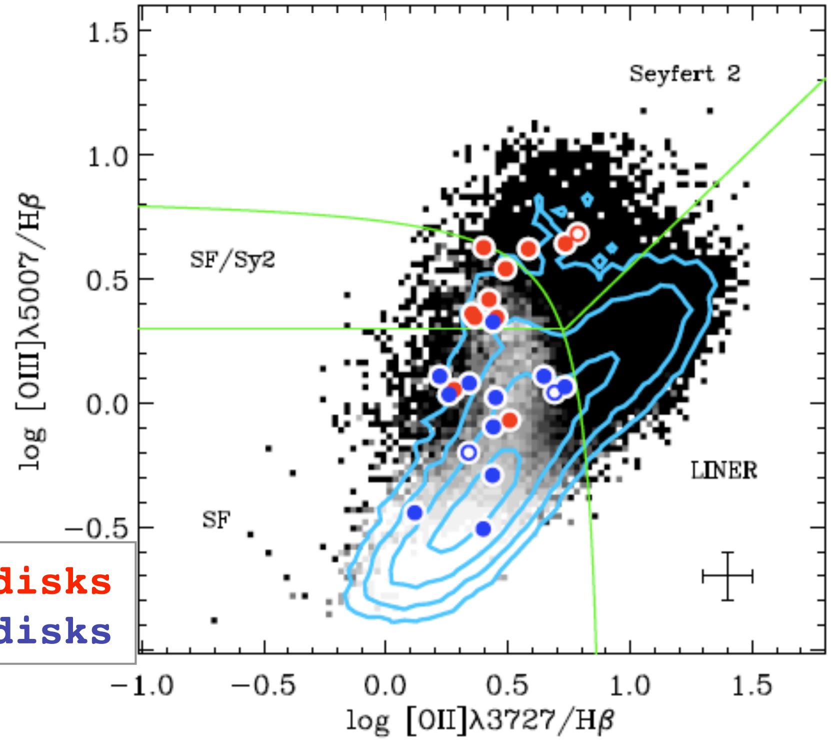
In Goods-South, redshift and mass-matched, M*~ few 10^{10}

More Stable - arm/bar-dominated, low sSFR and f_{gas}

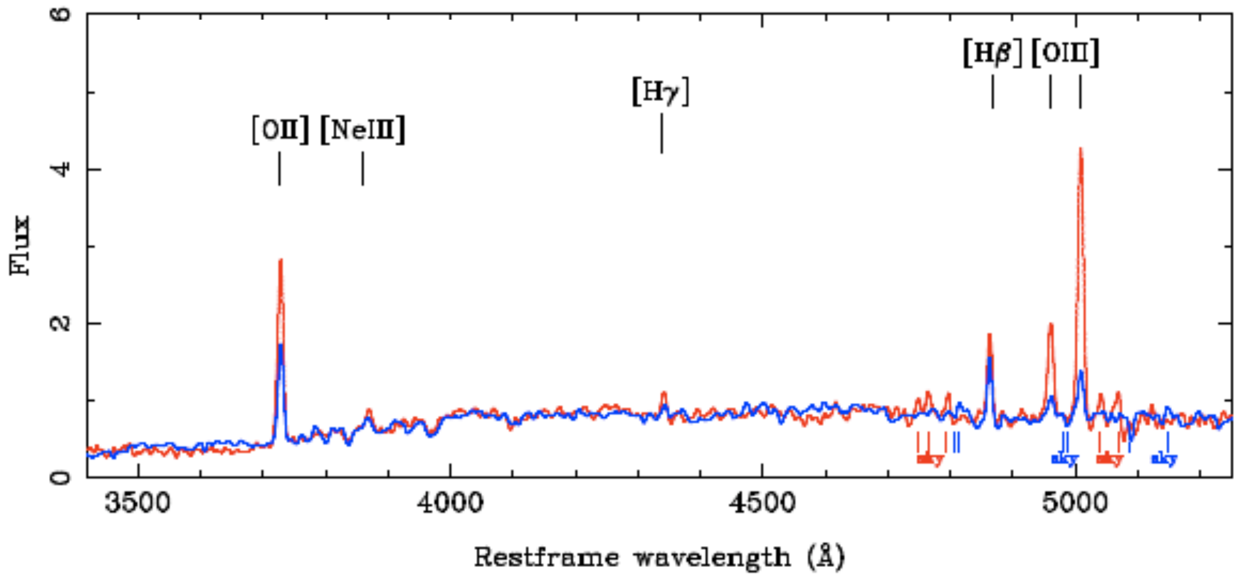


Optical spectra diagnostics





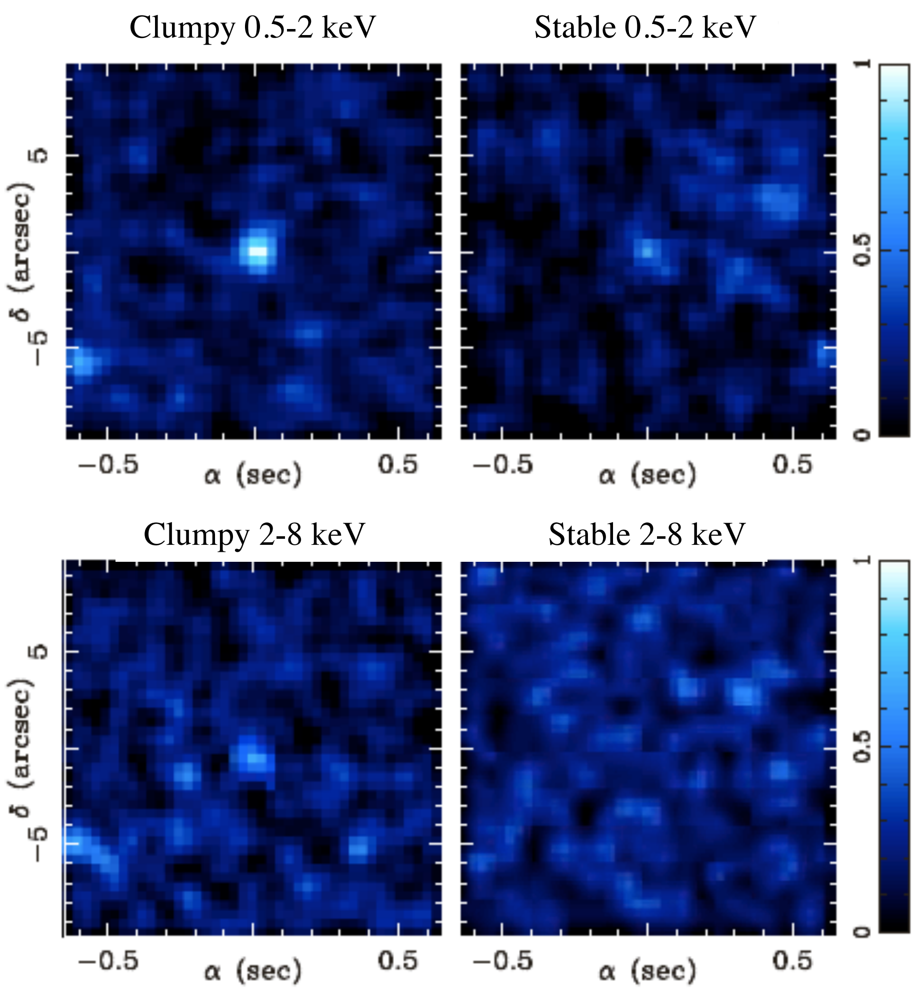
Clumpy disks
Stable disks



- **High [OIII]/Hβ**
- **Low-Z SF unlikely**
- **P(AGN)>>50%**

Bournaud Juneau et al. 2011

X-ray stacking



- Soft and hard X-ray excess in clumpy unstable sample

- Could it just be X-ray Star Formation?

Clumpy types have somewhat higher sSFR

But also somewhat lower stellar masses

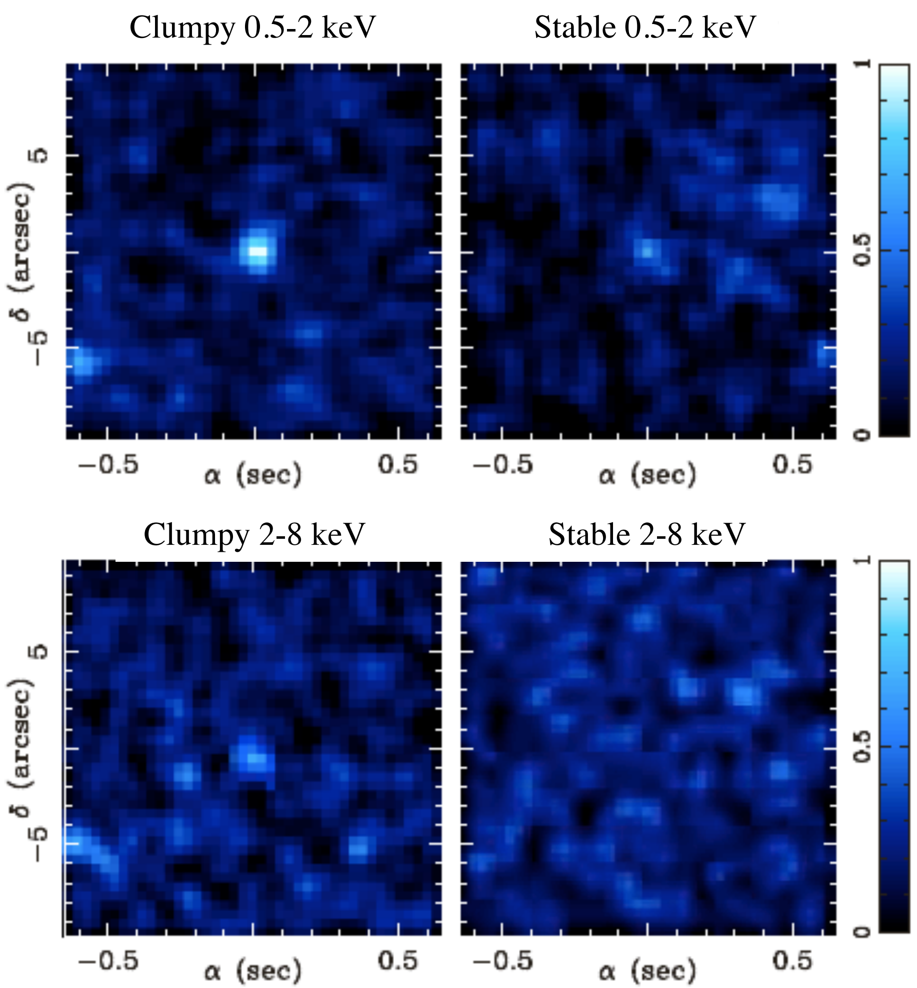
('downsizing' of cold stream accretion and disk instability)

And not higher absolute SFRs

(even a bit lower)

Bournaud Juneau et al. 2011

X-ray stacking



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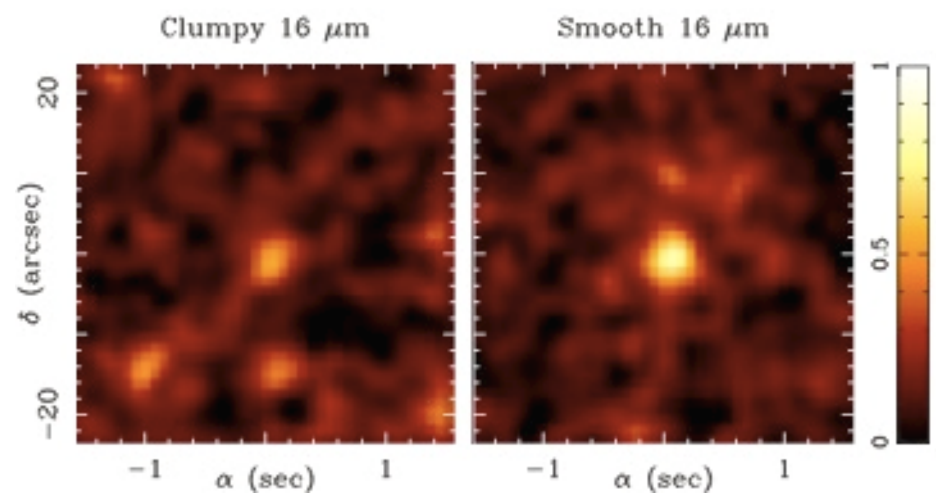

So, the Mex was right!

Bournaud Juneau et al. 2011

Conclusions

- SF laws are not universal, because properties of ISM turbulence change

- Dense gas ratios could trace dynamical state (disk, meger, spehroid)

- Starbursts in mergers are not exclusively nuclear,
  Rapid stirring of ISM turbulence changes the SFE throughout

- At high redshift, disks are very gas-rich, gravitationally unstable,
  but self-regulate their star formation efficiency through strong turbulence:
  high SFR, but not 'starburst' - don't call them 'ULIRGs'

- Giant clumps may survive feedback and coalesce into bulges

- The instability is much stronger than at z=0

- Rapid inflows can feed an AGN -- and this is observed.