Galaxy formation & evolution




Joseph Silk (Institut d'Astrophysique de Paris, Johns Hopkins University and Oxford University)

Herschel will be able to see through the opacity of cosmic dust and gas and observe structures and events far away that date back to the early Universe – such as the birth and evolution of early stars and galaxies – ten thousand million years ago, in an effort to determine exactly how it all started.

ESA press release 7 May 2009

1. state of field at the time of launch of Herschel

2. provide an overview of Herschel's actual contributions

What have we learnt in past 2 decades about galaxy formation?

Two examples

- Semi-analytical modelling began c. 1990

Here is a recent example (Benson 2012)

model parameters

Table 1: Values of parameters used in the example model. Parameters selecting between different im[…] components are only listed where more than one non-null implementation currently exists within GALACTIC[…]

Parameter	Value	R
[H_0]	70.2 km/s	
[Omega_0]	0.2725	
[Omega_DE]	0.7275	
[Omega_b]	0.0455	
[T_CMB]	2.72548 K	
[accretionDisksMethod]	ADAF	
[adafAdiabaticIndex]	1.444	
[adafEnergyOption]	pure ADAF	
[adafRadiativeEfficiency]	0.01	
[adafViscosityOption]	fit	
[adiabaticContractionGnedinA]	0.8	
[adiabaticContractionGnedinOmega]	0.77	
[barInstabilityMethod]	ELN	
[blackHoleSeedMass]	100	
[blackHoleWindEfficiency]	0.001	
[bondiHoyleAccretionEnhancementHotHalo]	1	
[bondiHoyleAccretionEnhancementSpheroid]	1	
[bondiHoyleAccretionTemperatureSpheroid]	100	
[coolingFunctionMethod]	atomic CIE Cloudy	
[coolingTimeAvailableAgeFactor]	0	
[coolingTimeSimpleDegreesOfFreedom]	3	
[darkMatterProfileMethod]	NFW	
[darkMatterProfileMinimumConcentration]	4	
[diskOutflowExponent]	2	
[diskOutflowVelocity]	200 km/s	
[effectiveNumberNeutrinos]	4.34	
[galacticStructureRadiusSolverMethod]	adiabatic	
[haloMassFunctionMethod]	Tinker2008	
[haloSpinDistributionMethod]	Bett2007	
[hotHaloOutflowReturnRate]	1.26	
[imfSalpeterRecycledInstantaneous]	0.39	
[imfSalpeterYieldInstantaneous]	0.02	
[imfSelectionFixed]	Salpeter	
[isothermalCoreRadiusOverVirialRadius]	0.1	

Table 1: *(cont.)* Values of parameters used in the example model. Parameters selecting between different implem[…] components are only listed where more than one non-null implementation currently exists within GALACTICUS.

Parameter	Value	Referen[…]
[majorMergerMassRatio]	0.1	§4.9.1
[mergerRemnantSizeOrbitalEnergy]	1	§4.9.2
[mergerTreeBuildCole2000AccretionLimit]	0.1	§4.16
[mergerTreeBuildCole2000MassResolution]	$5\times10^9 M_\odot$	§4.16
[mergerTreeBuildCole2000MergeProbability]	0.1	§4.16
[mergerTreeConstructMethod]	build	§4.14
[minorMergerGasMovesTo]	spheroid	§4.9.1
[modifiedPressSchechterFirstOrderAccuracy]	0.1	§4.15
[modifiedPressSchechterG0]	0.57	§4.15
[modifiedPressSchechterGamma1]	0.38	§4.15
[modifiedPressSchechterGamma2]	-0.01	§4.15
[powerSpectrumIndex]	0.961	§4.4.1;
[powerSpectrumReferenceWavenumber]	1 Mpc^{-1}	§4.4.1;
[powerSpectrumRunning]	0	§4.4.1;
[randomSpinResetMassFactor]	2	§3.7.2
[reionizationSuppressionRedshift]	9	§4.1
[reionizationSuppressionVelocity]	30 km/s	§4.1
[satelliteMergingMethod]	Jiang2008	§4.22.1
[sigma_8]	0.807	§4.4.1
[spheroidEnergeticOutflowMassRate]	1	§3.4.2
[spheroidOutflowExponent]	2	§4.23
[spheroidOutflowVelocity]	50 km/s	§4.23
[spinDistributionBett2007Alpha]	2.509	§4.6.3
[spinDistributionBett2007Lambda0]	0.04326	§4.6.3
[stabilityThresholdGaseous]	0.9	§4.7
[stabilityThresholdStellar]	1.1	§4.7
[starFormationDiskEfficiency]	0.01	§4.17
[starFormationDiskMinimumTimescale]	0.001 Gyr	§4.17
[starFormationDiskVelocityExponent]	-1.5	§4.17
[starFormationSpheroidEfficiency]	0.1	§4.17
[starFormationSpheroidMinimumTimescale]	0.001 Gyr	§4.17
[starveSatellites]	true	§3.2.2
[stellarPopulationPropertiesMethod]	instantaneous	§4.18
[summedNeutrinoMasses]	0	§4.4.2
[transferFunctionMethod]	Eisenstein + Hu	§4.4.2
[virialDensityContrastMethod]	spherical top hat	§4.4.5

Benson 2012

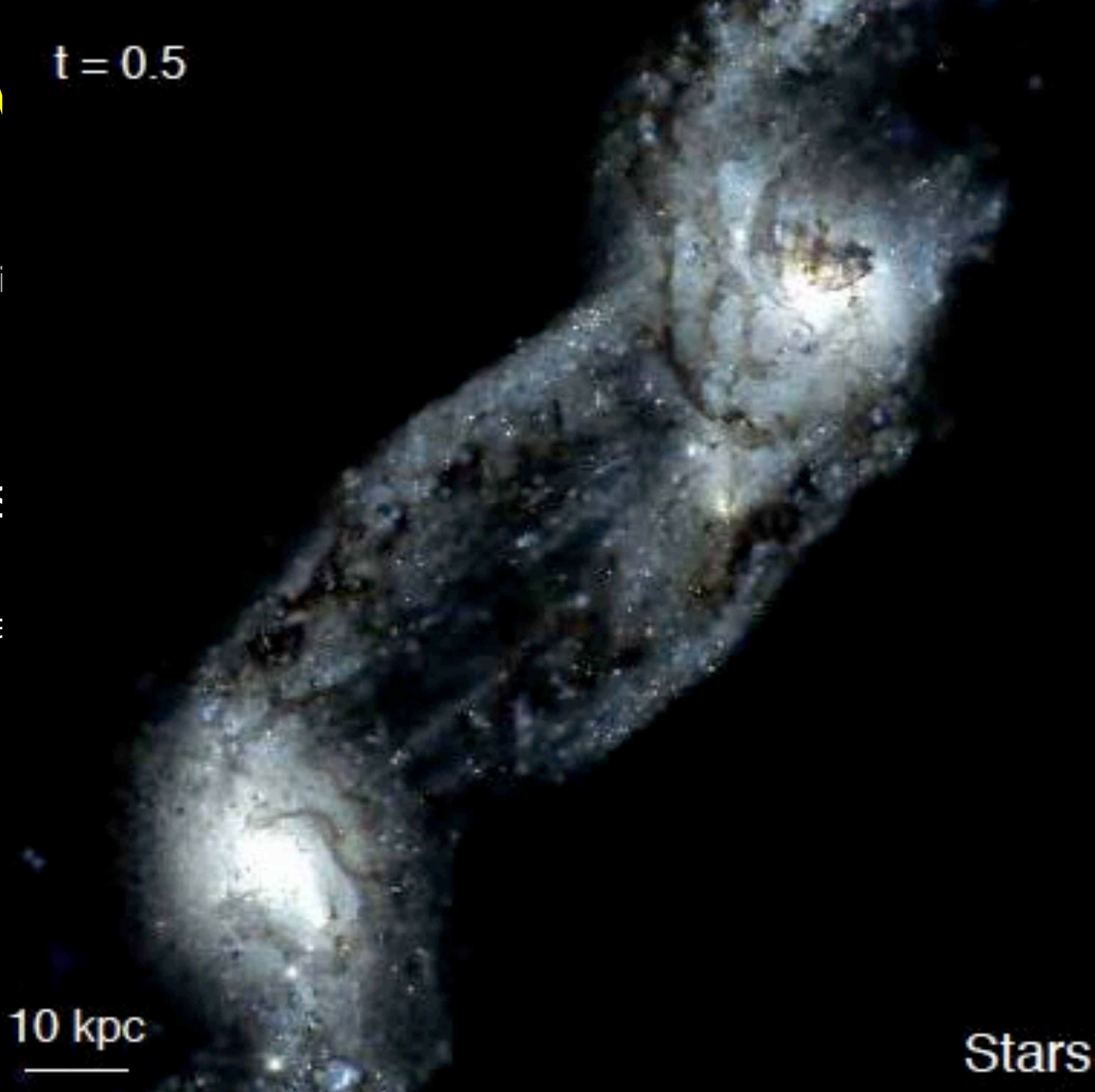
What hav

- Semi-anal

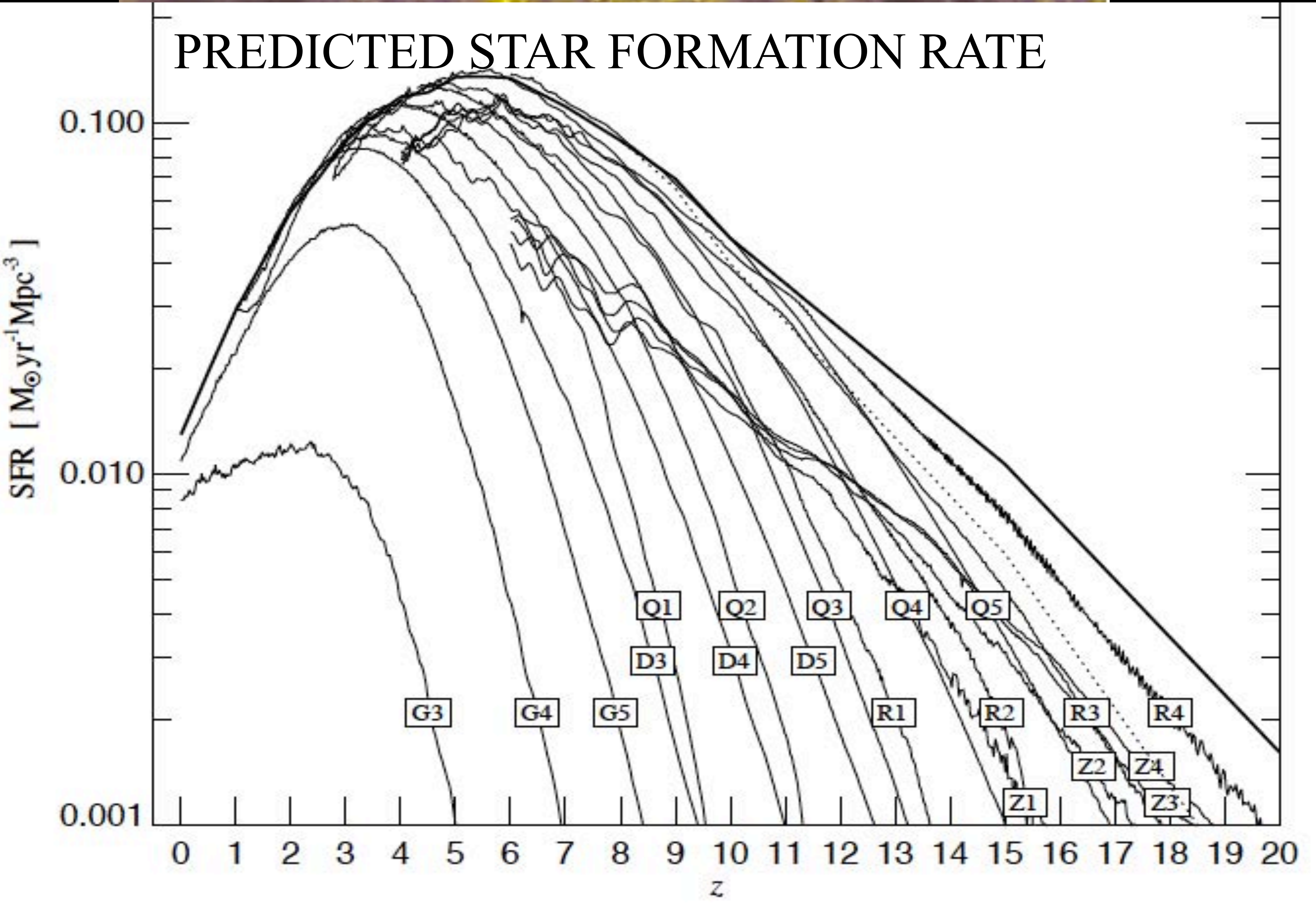
  Here i

- Hydrodyn
  in galaxie

1. Breathtaking ima



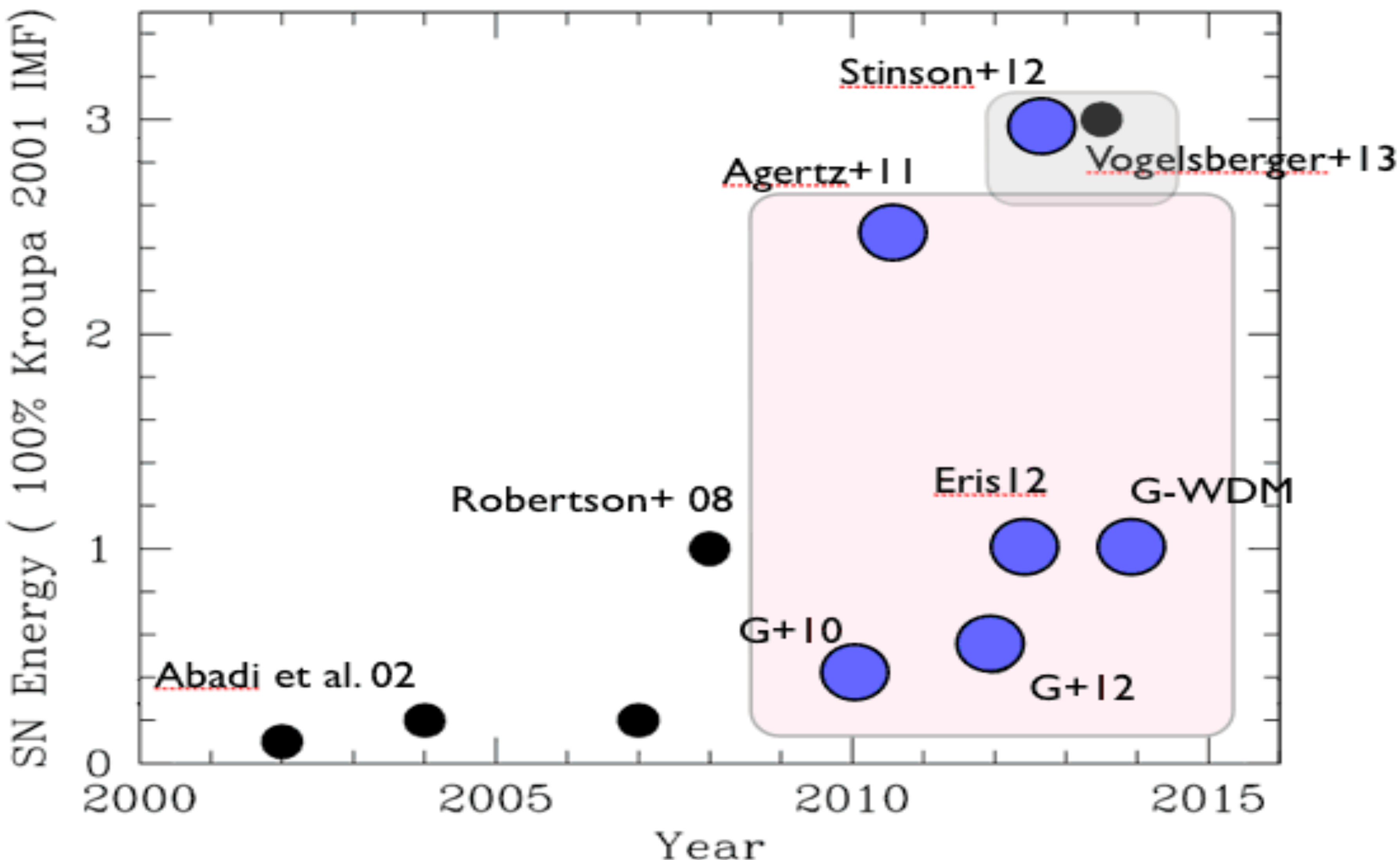
2. Here is a pioneering example (Springel & Hernquist 2003)



HAS MODELLING IMPROVED ?

FEEDBACK EFFICIENCY VS TIME

Governato 2013



What has HERSCHEL done for us?

- The dusty universe
- ULIRGS and mergers
- The galaxy main sequence
- Massive molecular outflows
- AGN and starbursts

Role of mergers

Dust evolution

AGN/star formation connection

Molecular outflows

GOODS–*Herschel*: an infrared main sequence for star-forming galaxies★

D. Elbaz[1], M. Dickinson[2], H. S. Hwang[1], T. Díaz-Santos[3], G. Magdis[1], B. Magnelli[4], D. Le Borgne[5], F. Galliano[1]

A *Herschel* view of the far-infrared properties of submillimetre galaxies★

B. Magnelli[1], D. Lutz[1], P. Santini[2], A. Saintonge[1], S. Berta[1], M. Albrecht[3], B. Altieri[4], P. Andreani[5,6], H. Aussel[7],

THE LESSER ROLE OF STARBURSTS IN STAR FORMATION AT $z = 2$

G. Rodighiero[1], E. Daddi[2], I. Baronchelli[1], A. Cimatti[3], A. Renzini[4], H. Aussel[2], P. Popesso[5], D. Lutz[5],

***Herschel*★-ATLAS: rapid evolution of dust in galaxies over the last 5 billion years**

L. Dunne,[1]† H. L. Gomez,[2] E. da Cunha,[3,4] S. Charlot,[5] S. Dye,[2] S. Eales,[2]

Enhanced star formation rates in AGN hosts with respect to inactive galaxies from PEP-Herschel★ observations

P. Santini[1,2], D. J. Rosario[1], L. Shao[1], D. Lutz[1], R. Maiolino[2], D. M. Alexander[3], B. Altieri[4], P. Andreani[5,6], H.

GOODS-*Herschel*: Ultra-deep *XMM-Newton* observations reveal AGN/star-formation connection★,★★

E. Rovilos[1,2], A. Comastri[1], R. Gilli[1], I. Georgantopoulos[1,3], P. Ranalli[1,3], C. Vignali[4,1], E. Lusso[5], N. Cappelluti[1],

GOODS-*Herschel*: radio-excess signature of hidden AGN activity in distant star-forming galaxies★

NUCLEAR ACTIVITY IS MORE PREVALENT IN STAR-FORMING GALAXIES

D.J. Rosario[1], P. Santini[2], D. Lutz[1], H. Netzer[3], F.E. Bauer[4,9], S. Berta[1], B. Magnelli[5], P. Popesso[1],

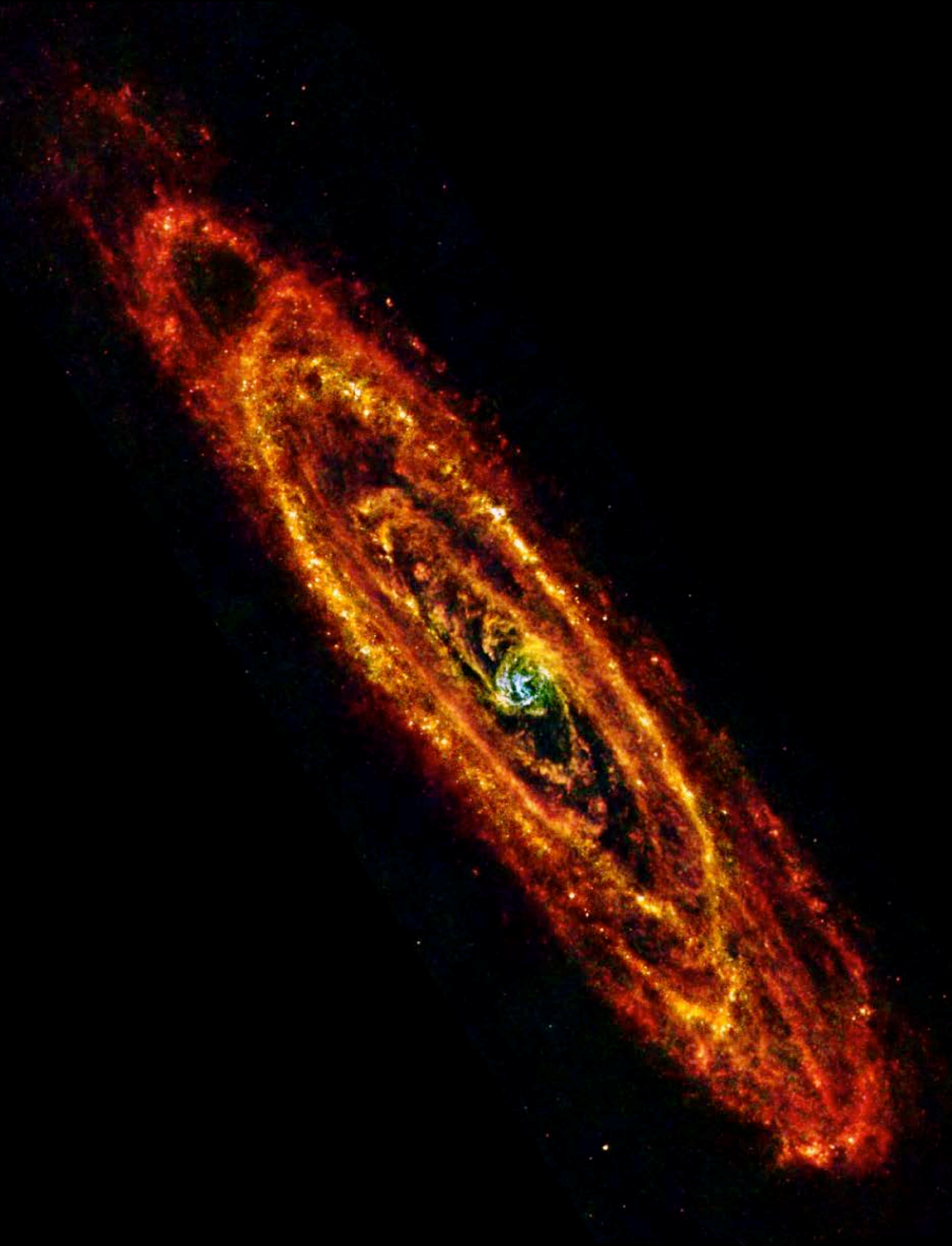
Fast Molecular Outflows in Luminous Galaxy Mergers: Evidence for Quasar Feedback from *Herschel*

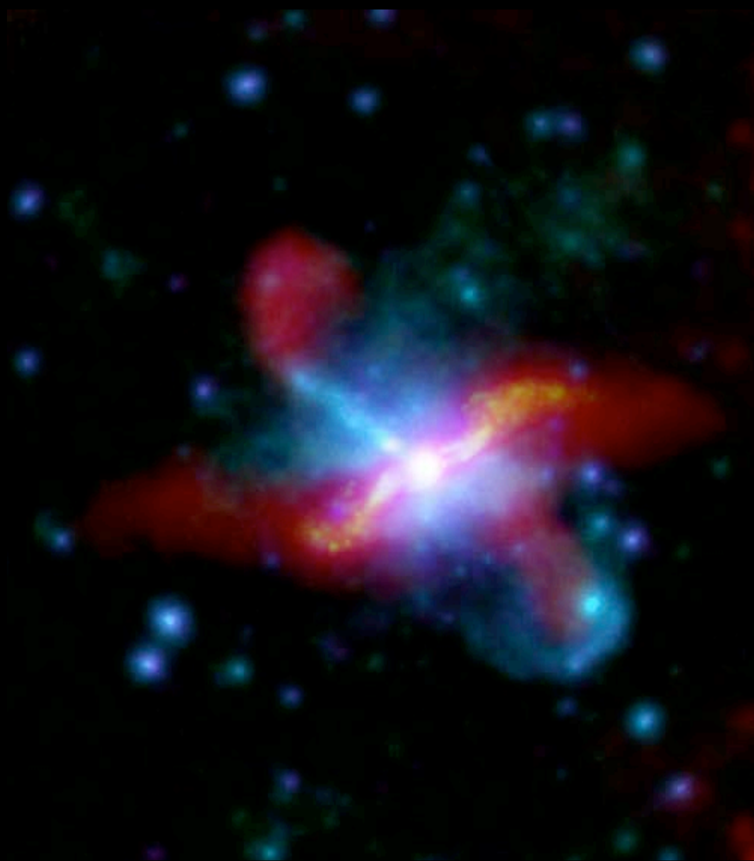
S. Veilleux[1,2,3], M. Meléndez[1], E. Sturm[3], J. Gracia-Carpio[3], J. Fischer[4], E.

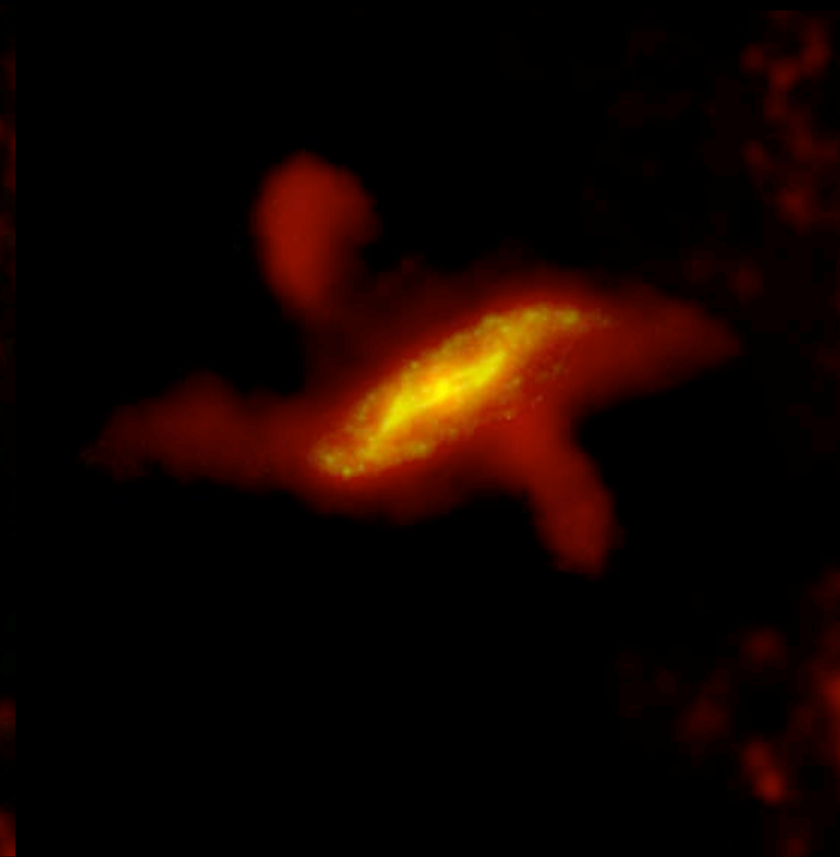
DIAGNOSTICS OF AGN-DRIVEN MOLECULAR OUTFLOWS IN ULIRGS FROM HERSCHEL-PACS OBSERVATIONS OF OH AT 119μM

W.W. Spoon[1], D. Farrah[2], V. Lebouteiller[3,1], E. González-Alfonso[4], J. Bernard-Salas[5], T. Urrutia[6],

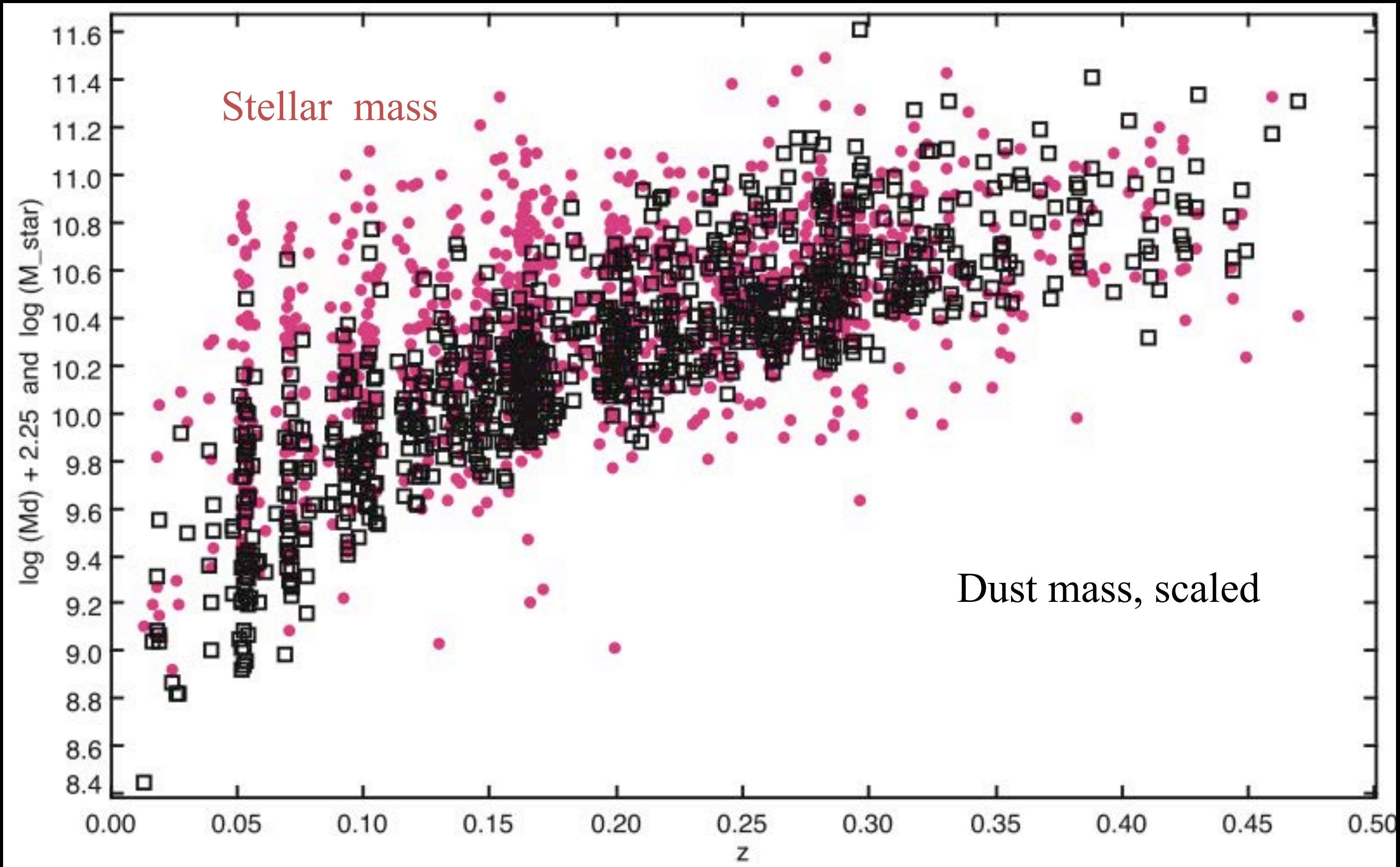
Dust evolution



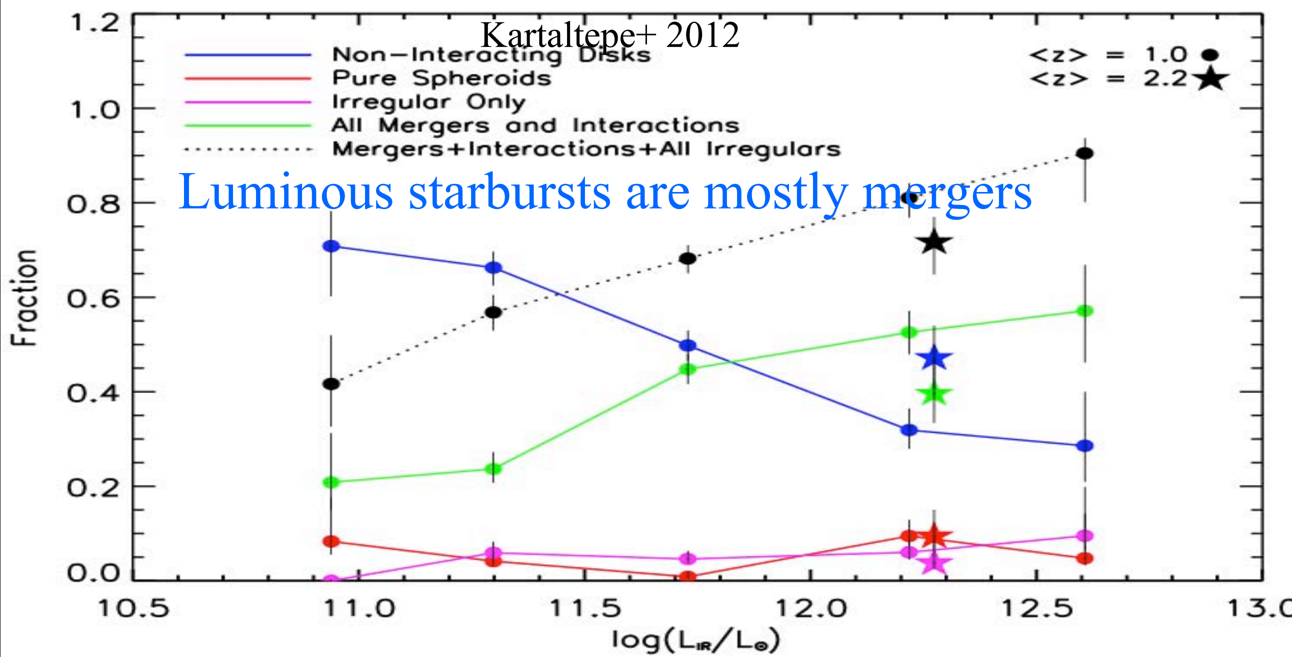


Dust-to-gas ratio

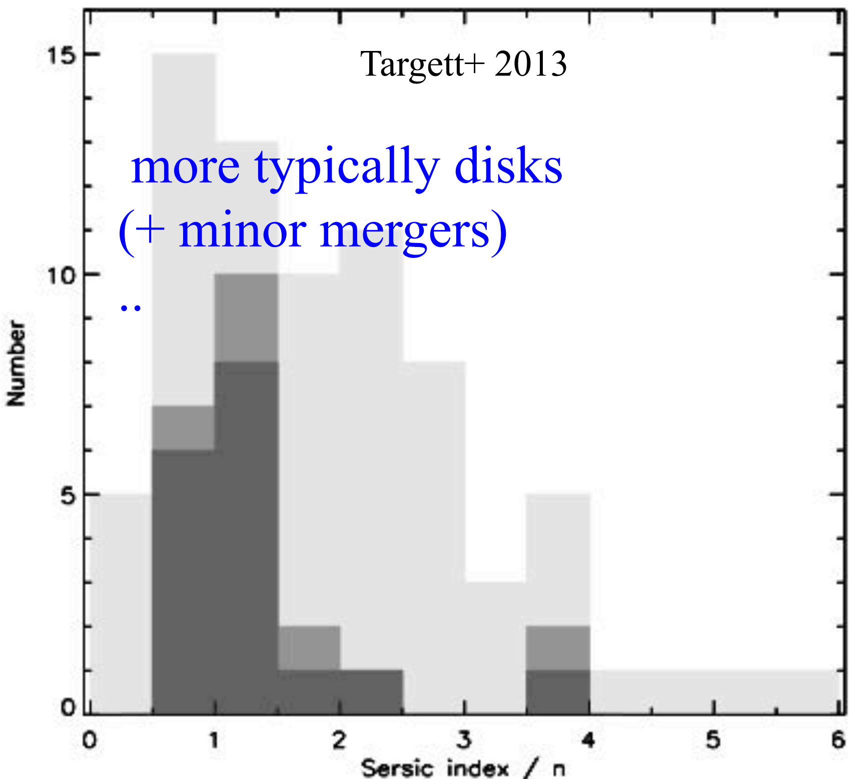


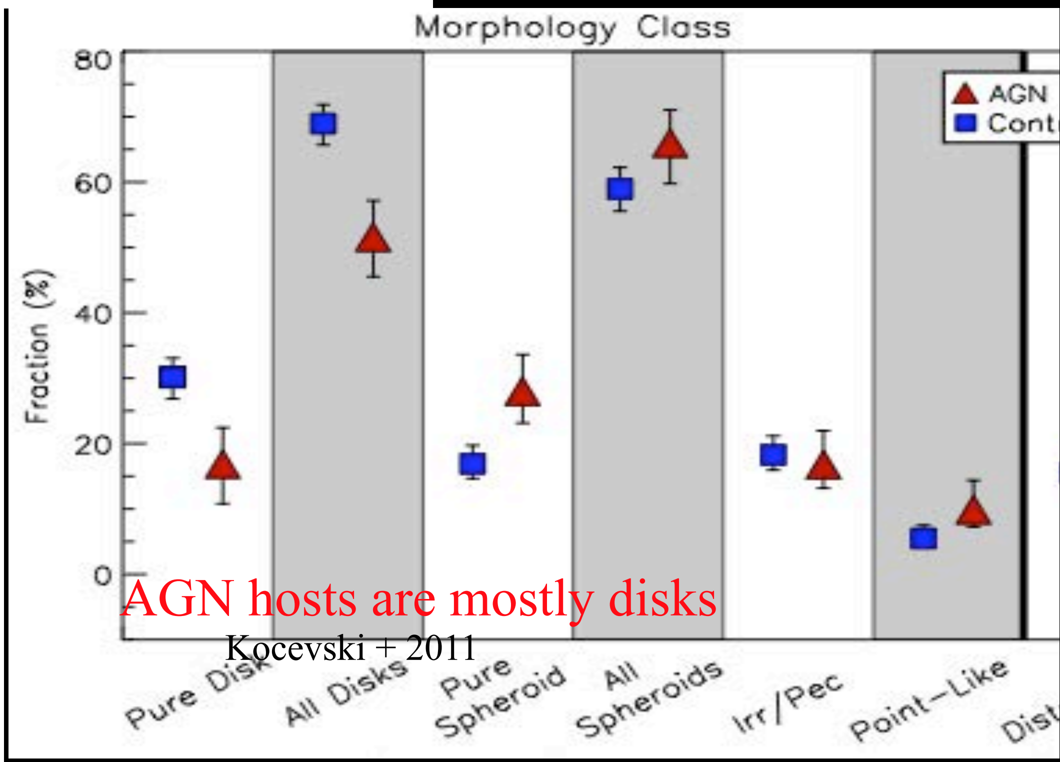
Dunne + 2011

Role of mergers

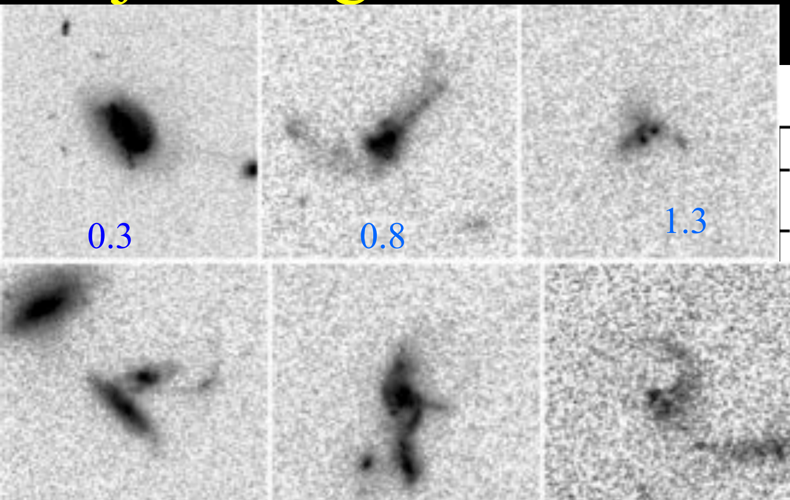

Kartaltepe+ 2012
Non−Interacting Disks
Pure Spheroids
Irregular Only
All Mergers and Interactions
Mergers+Interactions+All Irregulars
<z> = 1.0
<z> = 2.2
Luminous starbursts are mostly mergers
Fraction
log(L_IR/L_⊙)

at z~2

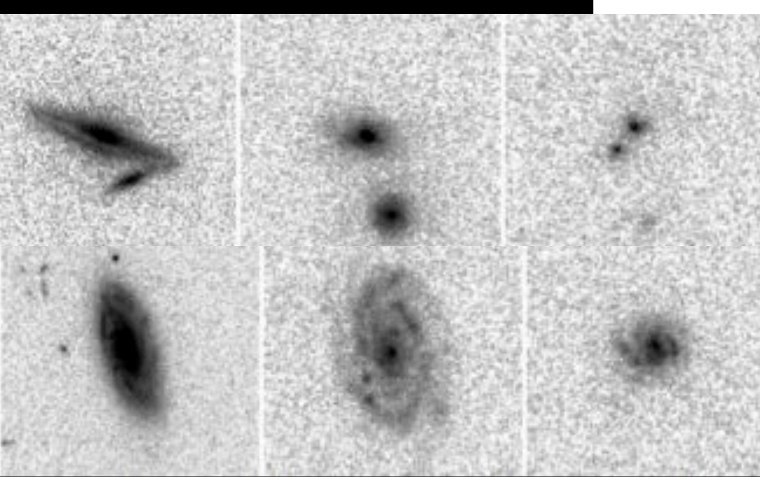

Targett+ 2013
more typically disks
(+ minor mergers)
..
Number
Sersic index / n

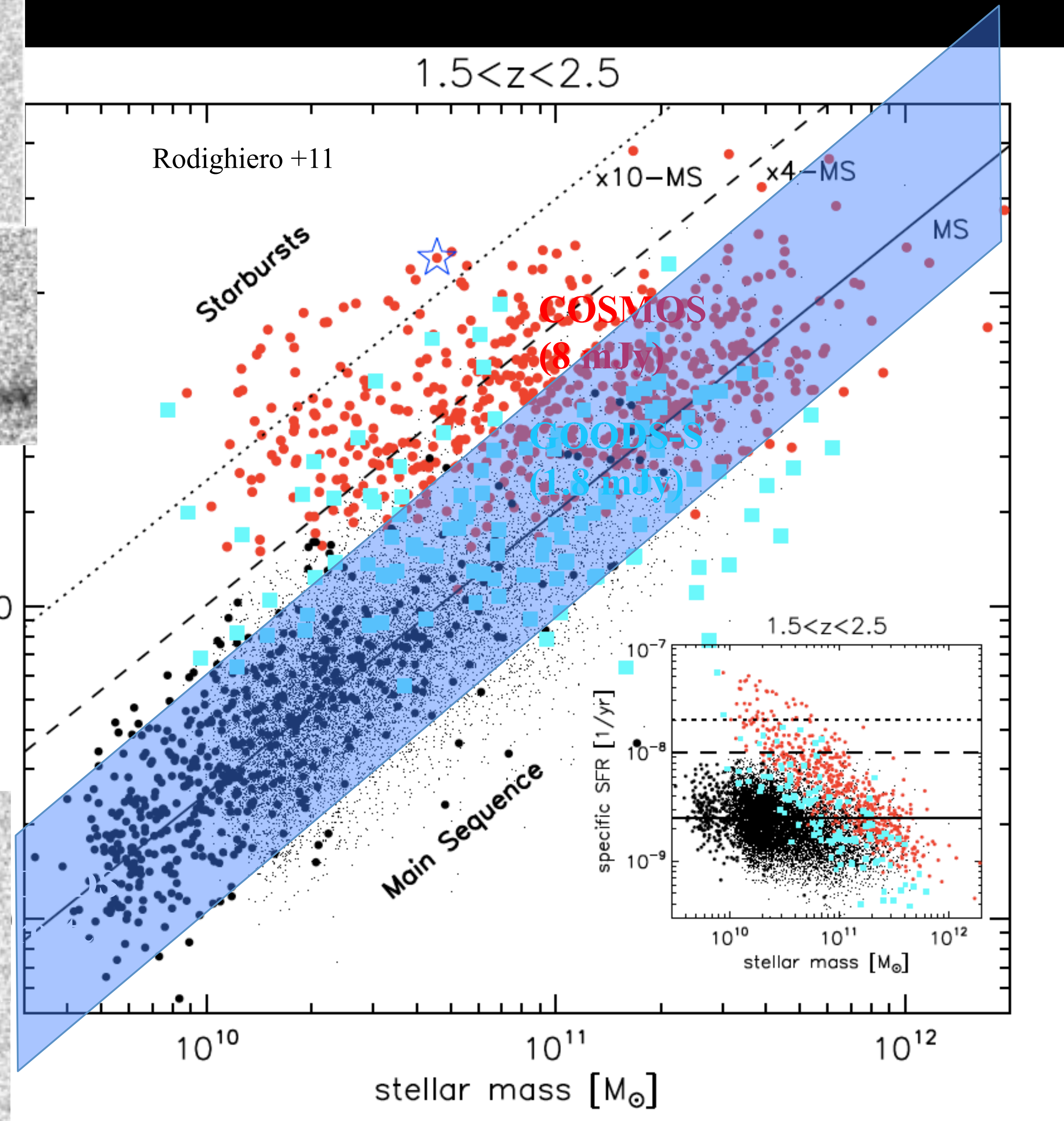

Morphology Class
AGN
Cont
Fraction (%)
Pure Disk
All Disks
Pure Spheroid
All Spheroids
Irr/Pec
Point-Like
AGN hosts are mostly disks
Kocevski + 2011

Major mergers are minor contributor in forming most stars



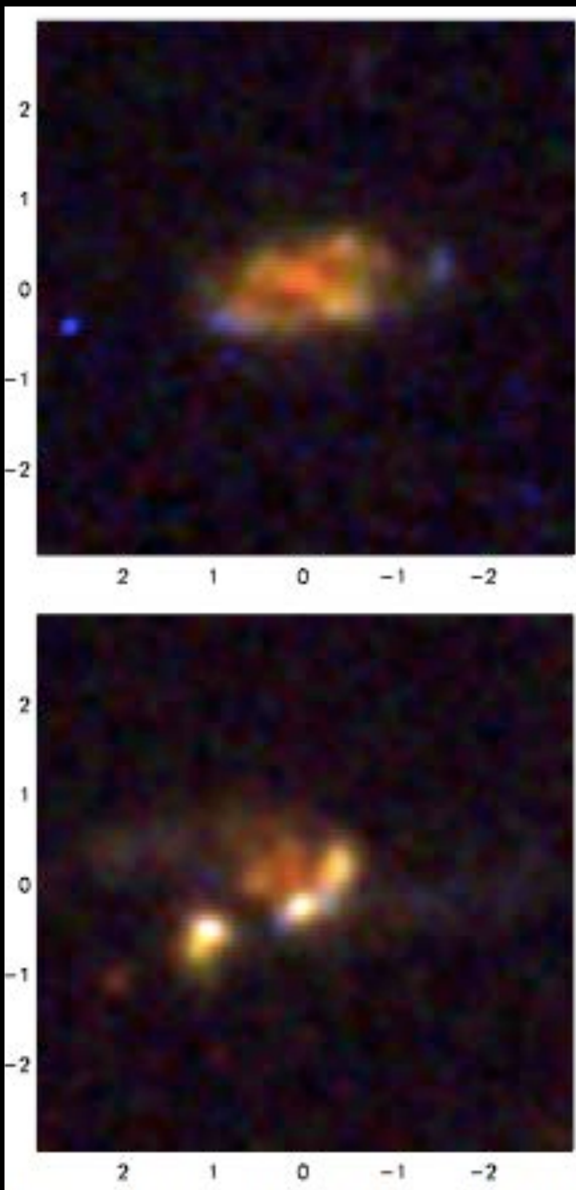
Hung + 2013

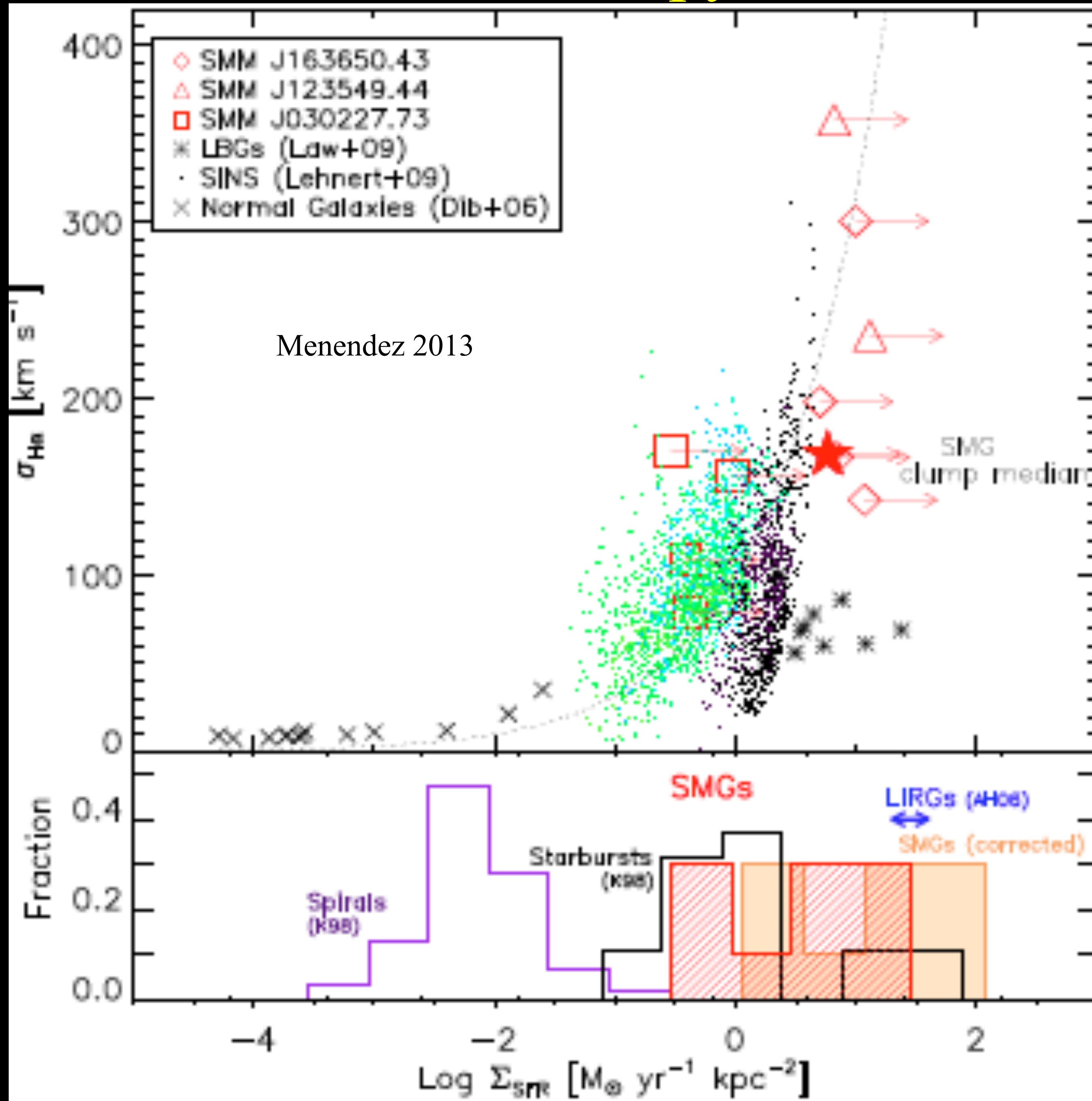




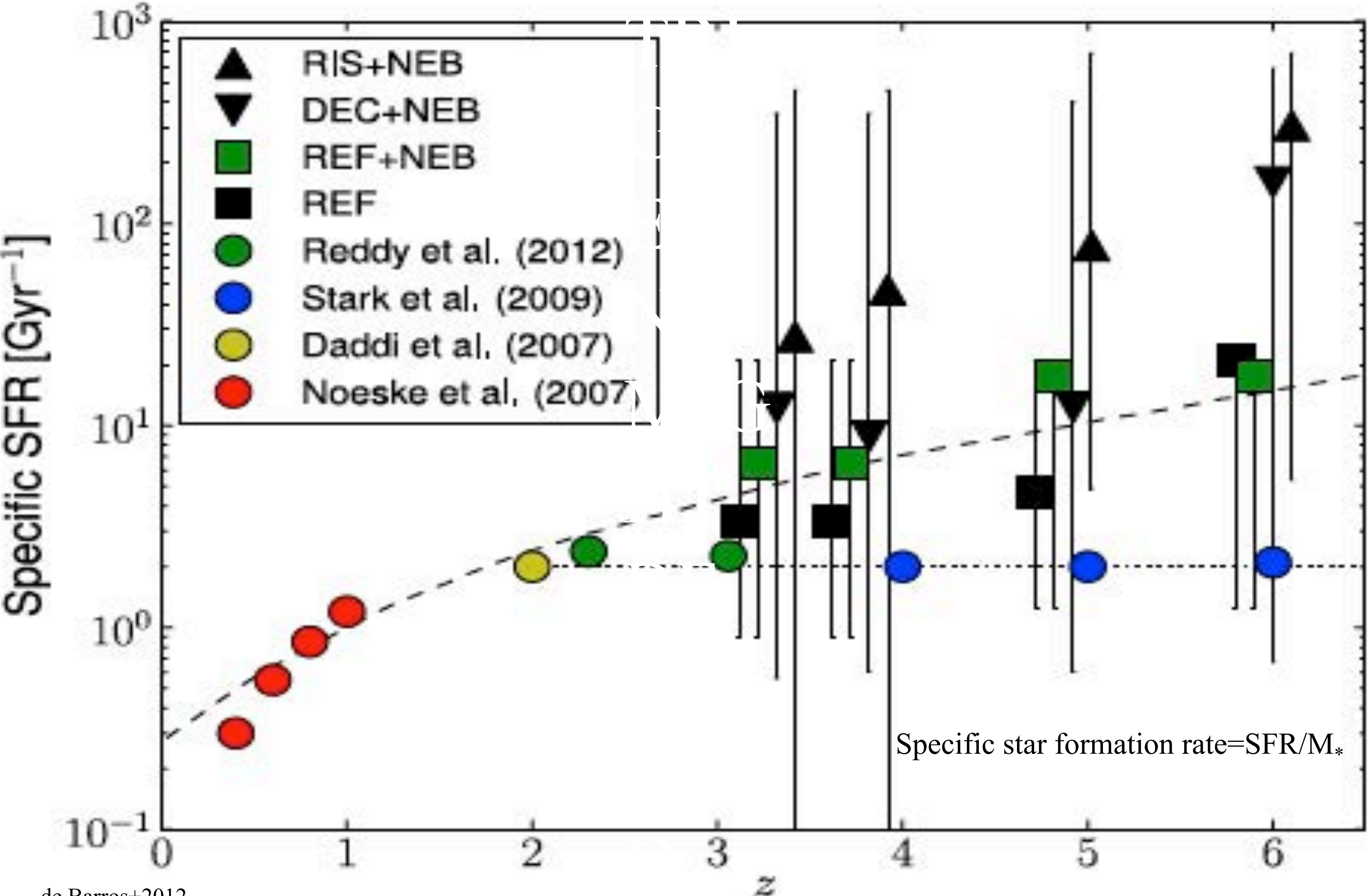
elevated star formation rate in clumpy disks

z~2 Targett + 2013





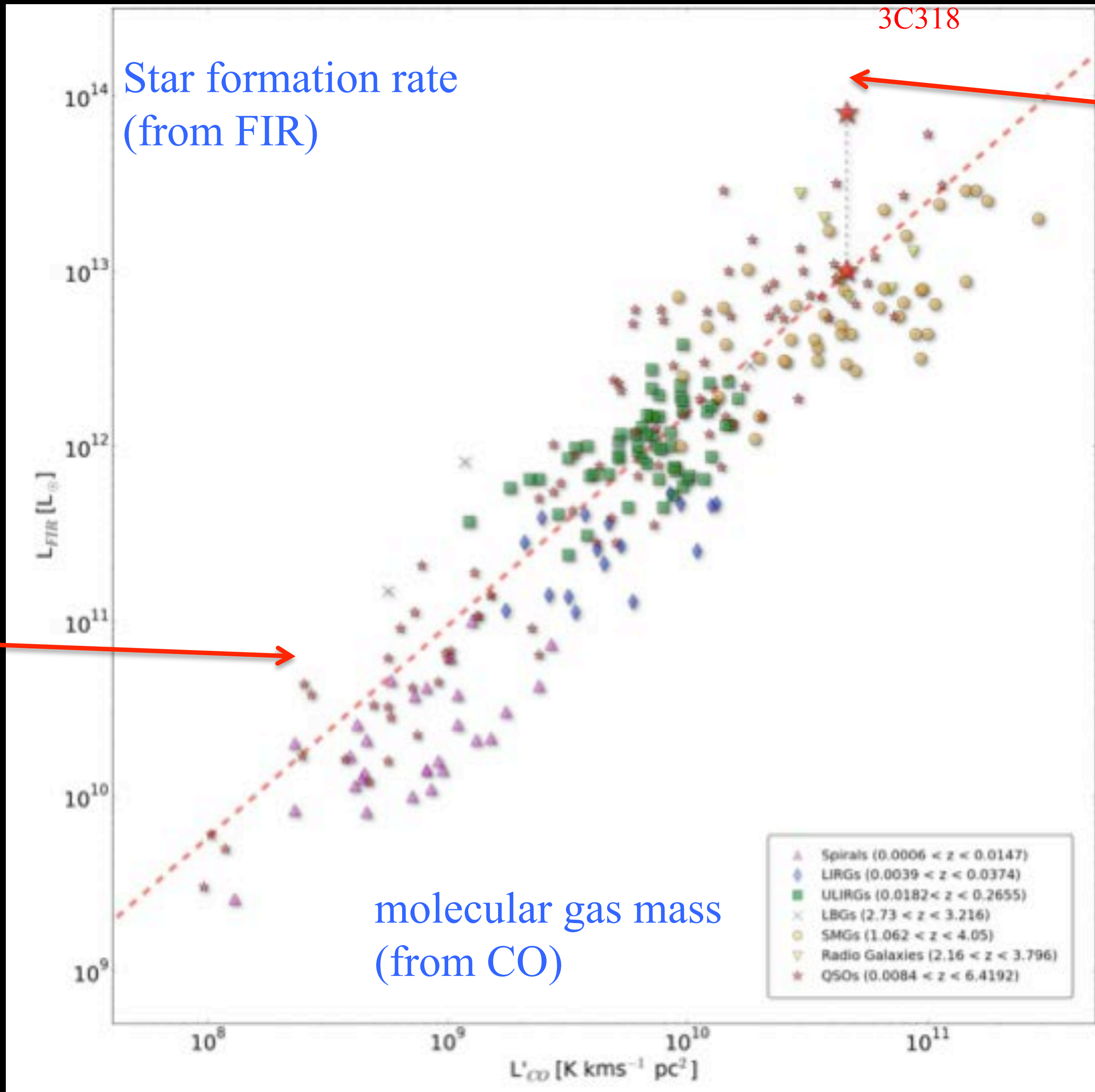
A second mode of star formation might be needed



de Barros+2012

Molecular outflows

Short gas depletion times with luminous AGN?



Gas depletion time ~20 Myr

SFR~$10^3 M_O$/yr

M_{H2}~$4.10^{10} M_O$

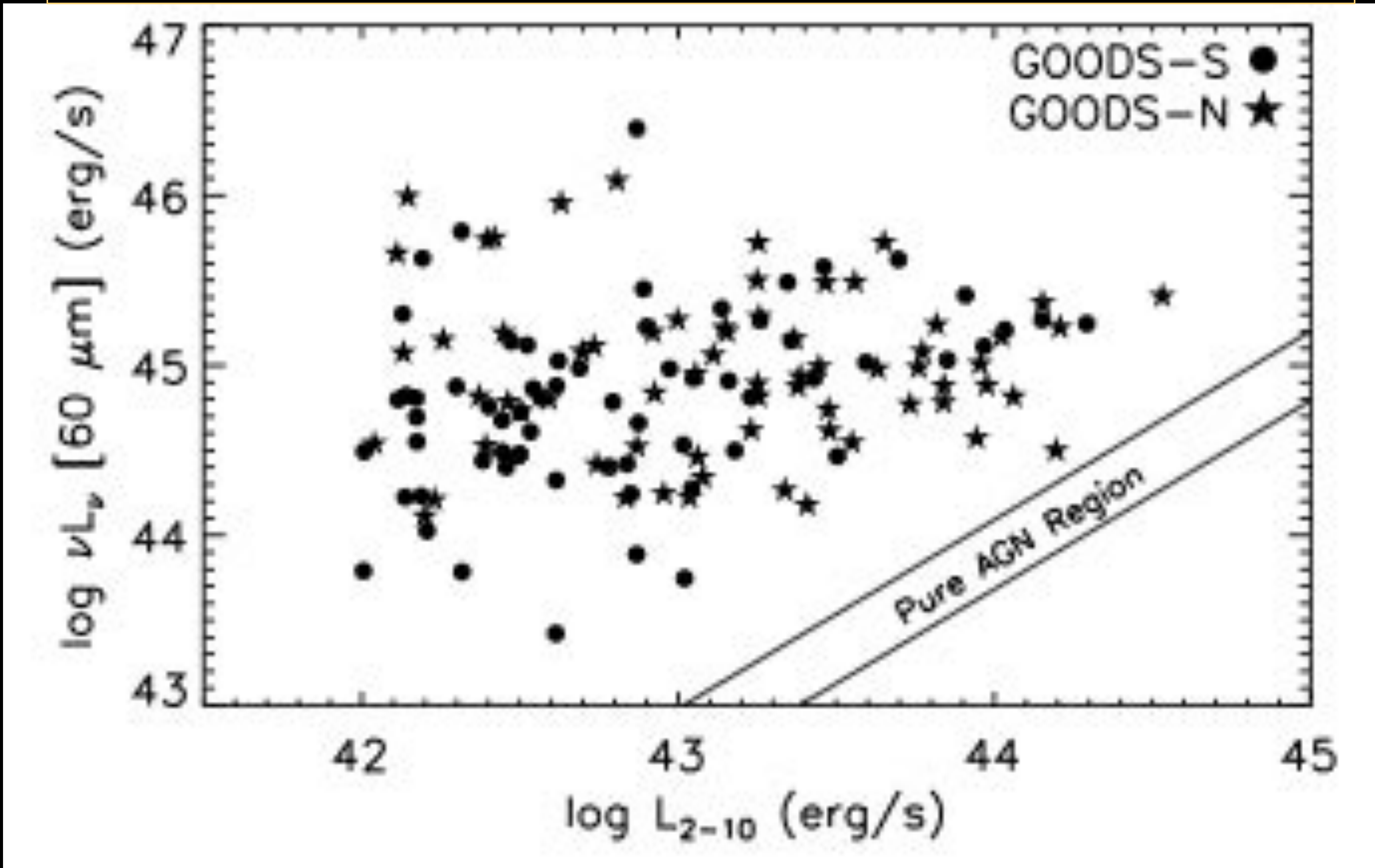
Gas depletion time ~200 Myr

Heywood+ 2013

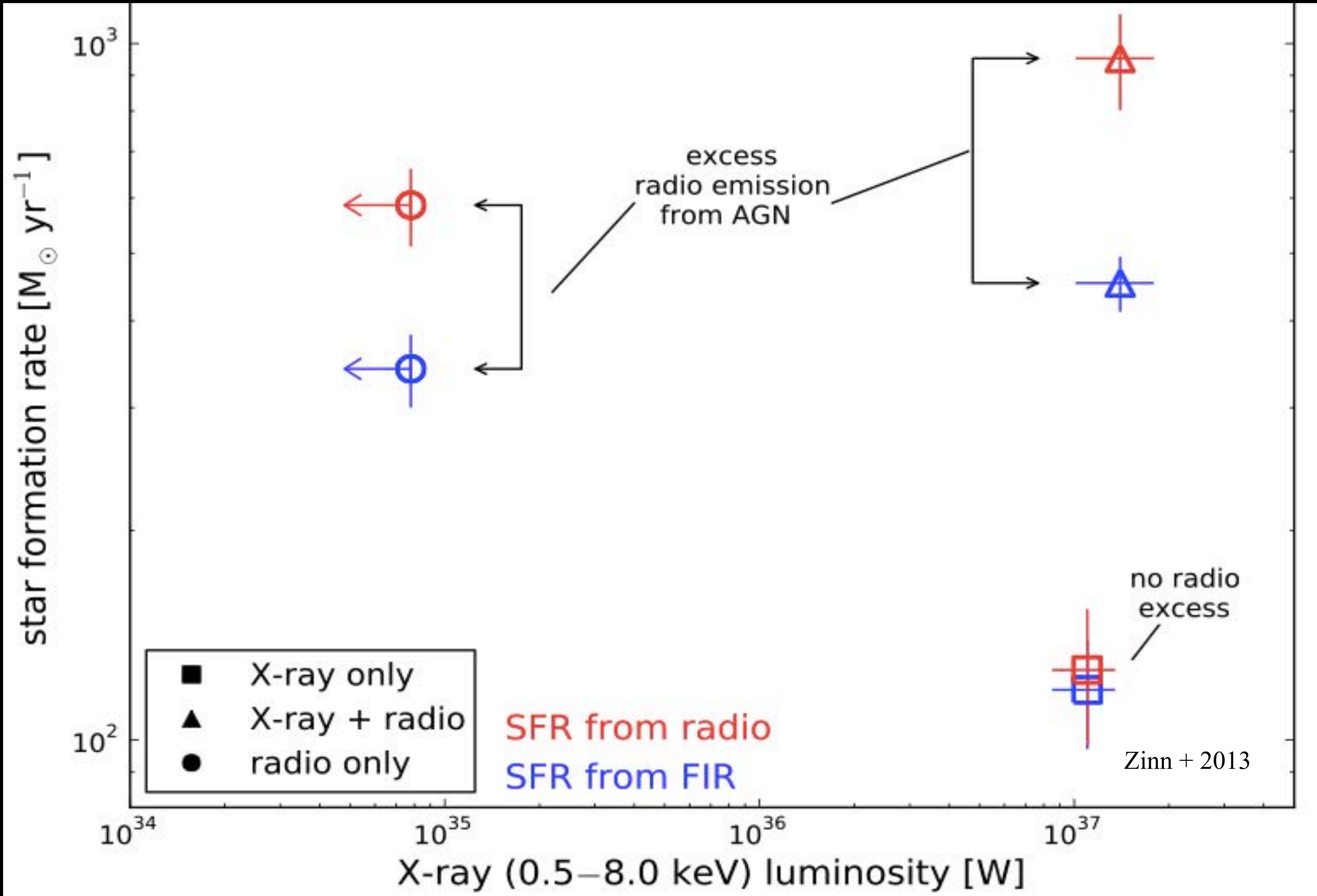
AGN/star formation connection

AGN have enhanced SF

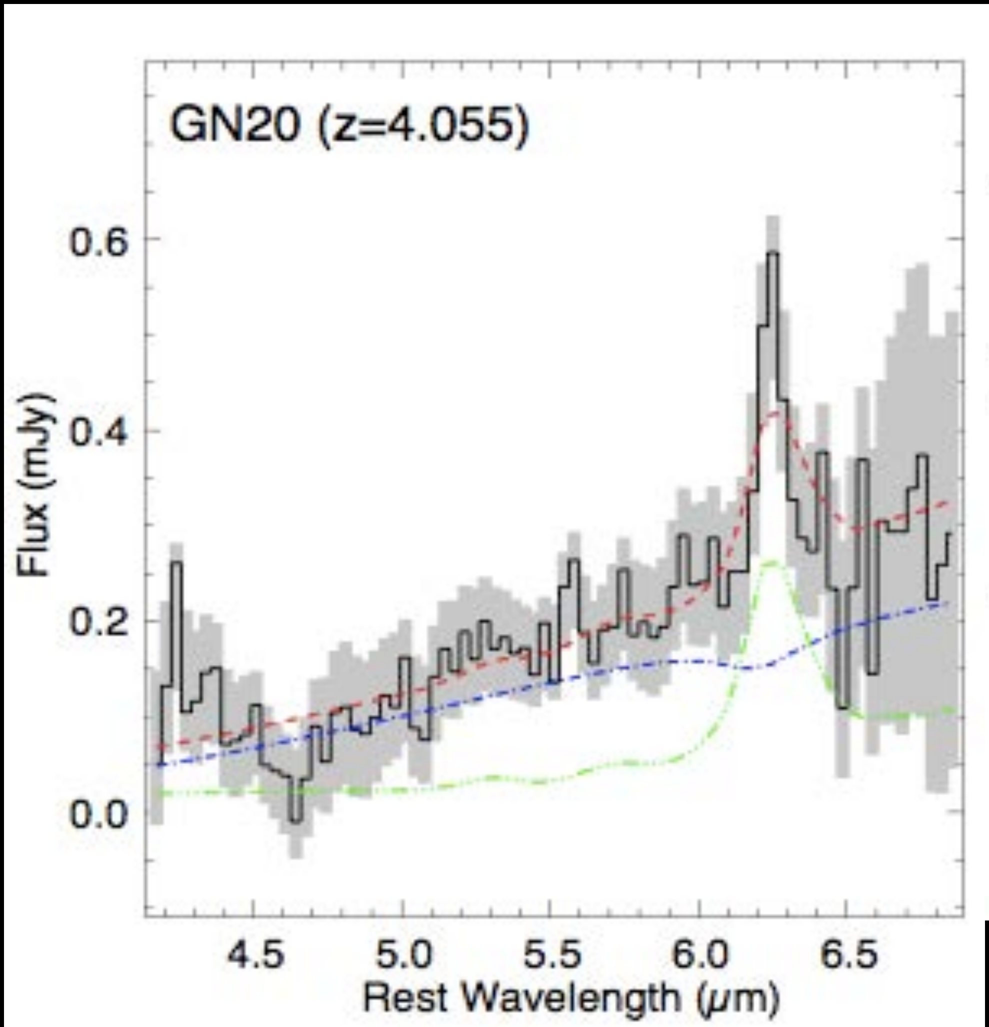
Rosario + 13

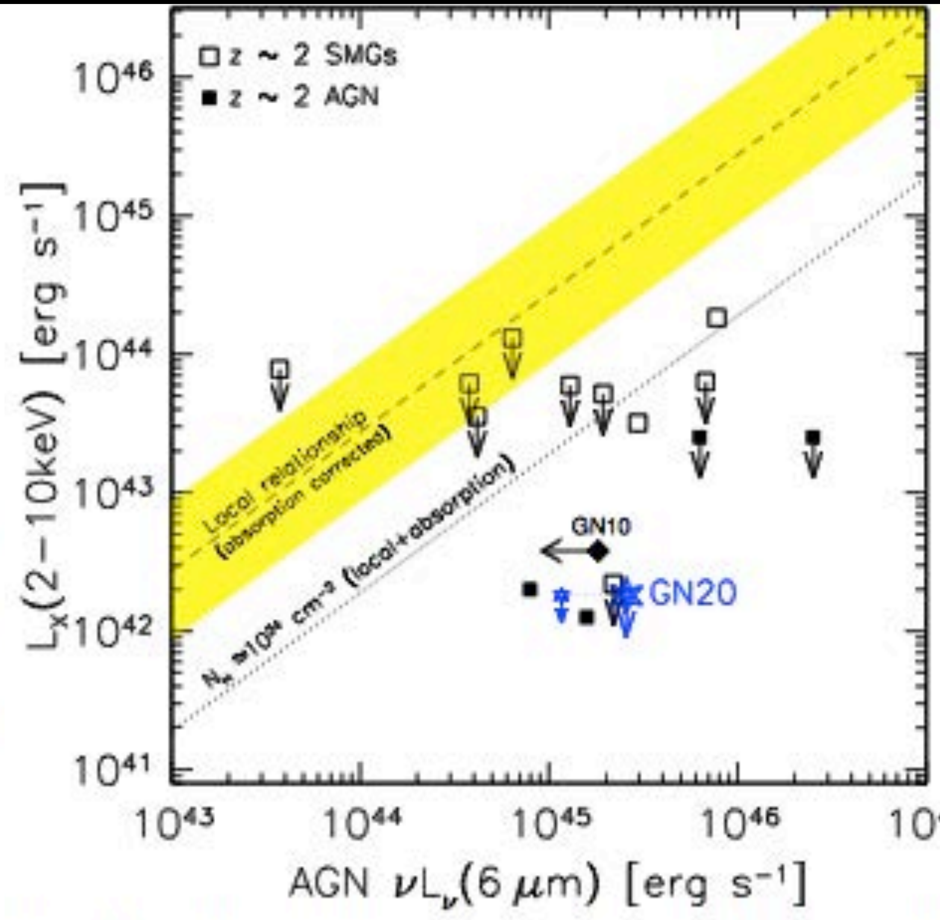


Radio jets induce excess star formation



X-ray obscured AGN seen in FIR

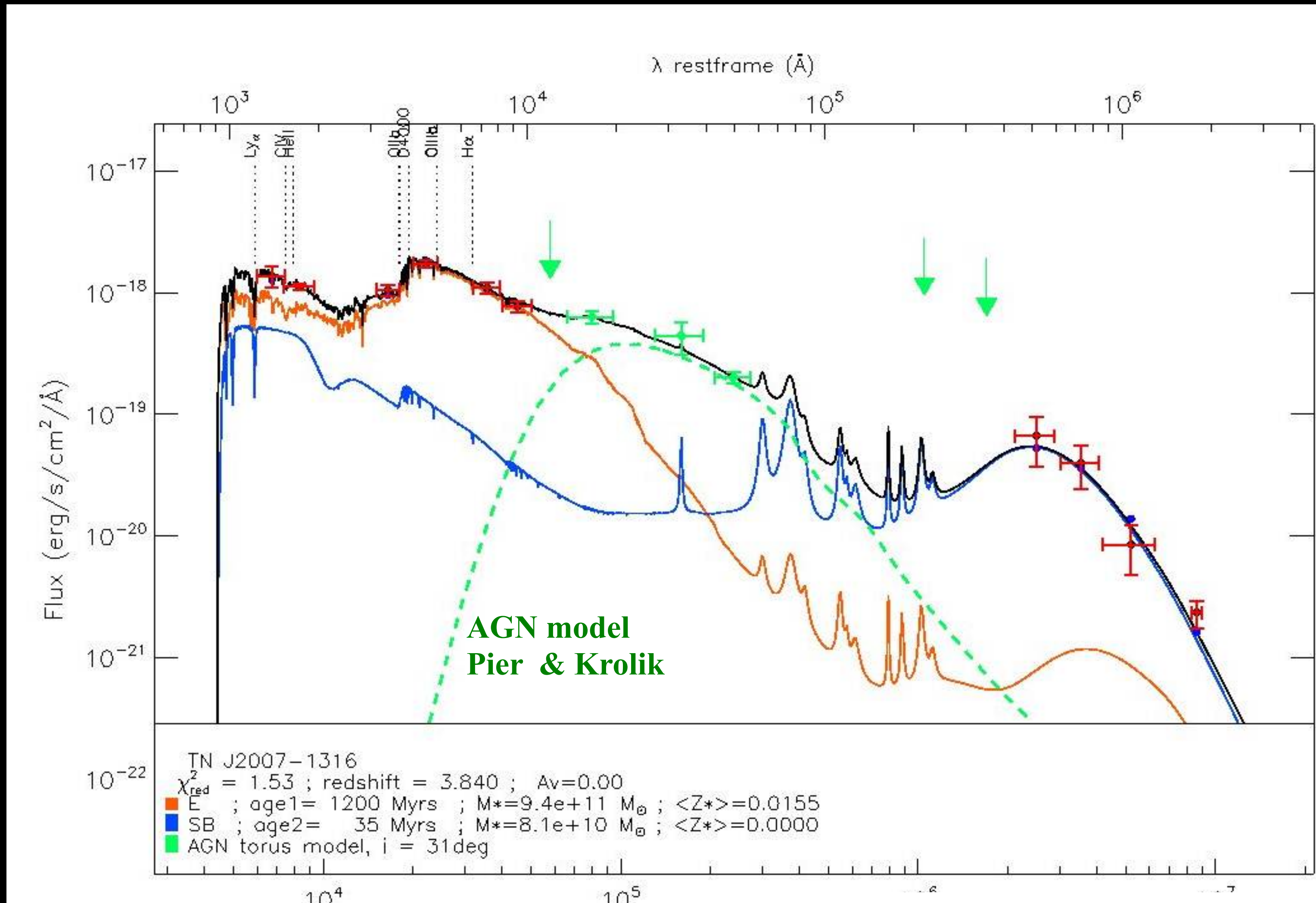




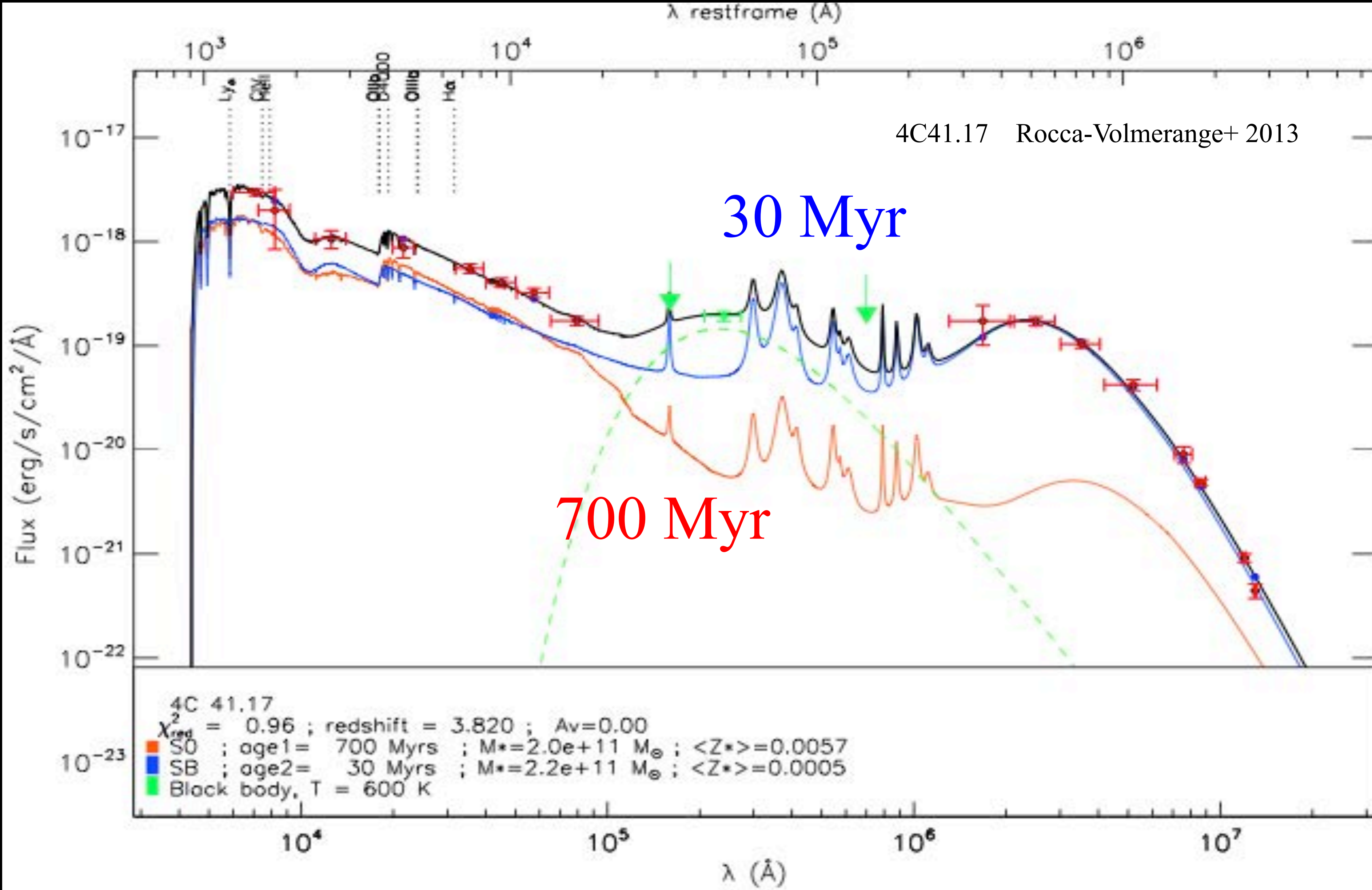
SMG at z=4 SFR =1700 M_{sun}/yr (PAH)

Reichers + 2013

TN J2007-1316 (z=3.8) :
Elliptical at age 1.2 Gyrs (red)
Starburst at age 35 Myrs (blue)



Rocca-Volmerange et al, 2013



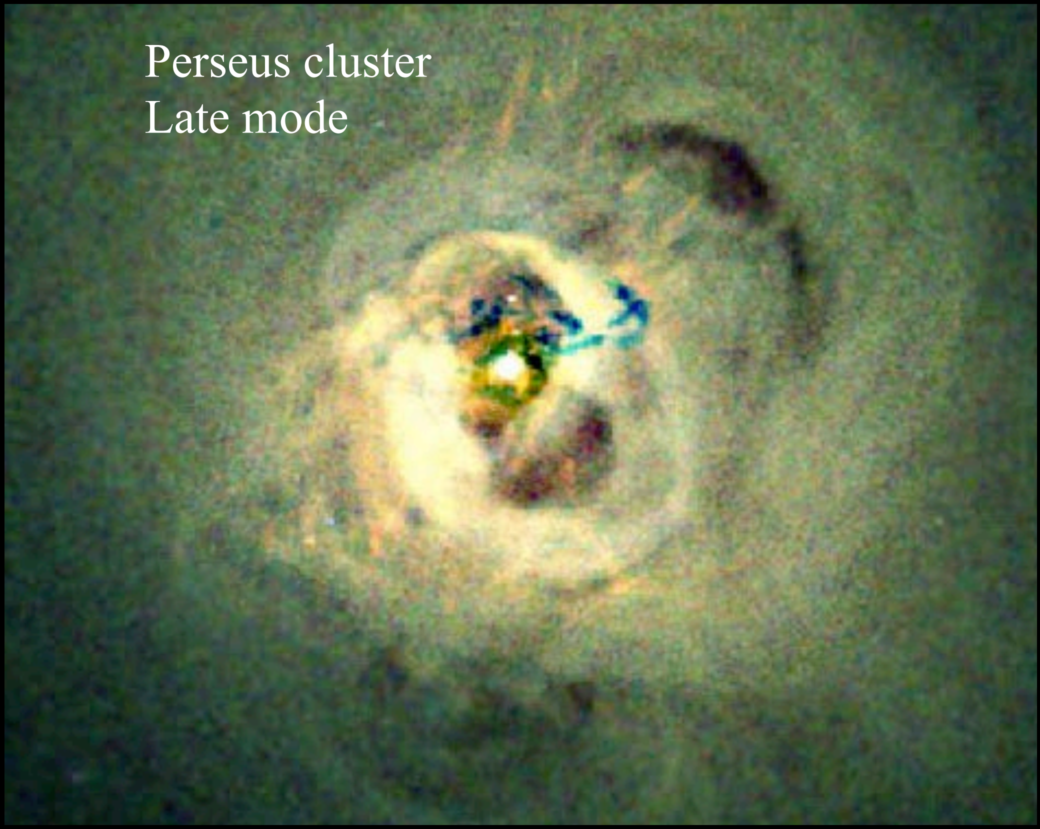
A 30 million year 10^{11} M_{sun} starburst in a radio galaxy

how to quench SFR: by AGN

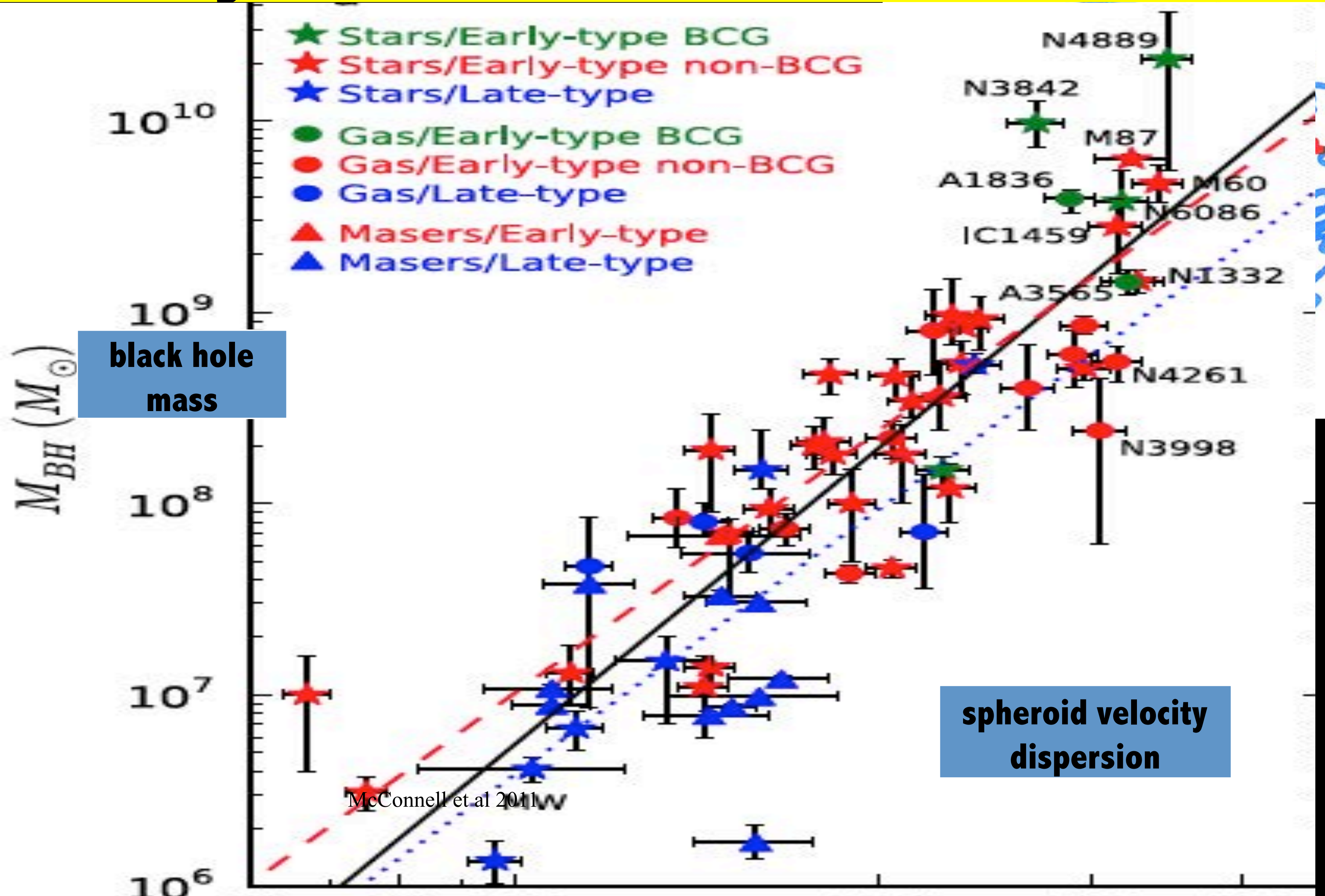
SUPERMASSIVE BLACK HOLES

10^5 to 10^{10} solar masses

Supported by theory but observational evidence is sparse



Early mode: SMBH accretion



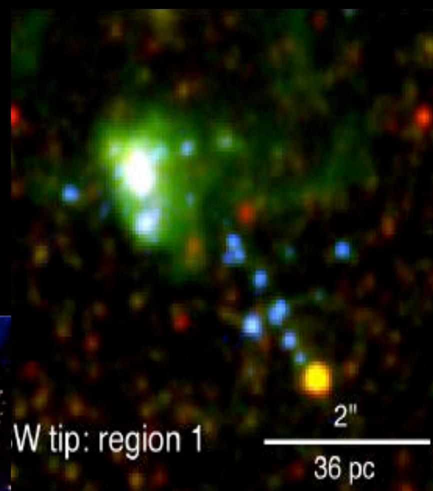
how to enhance SFR: triggering by AGN

If AGN-driven outflows trigger star formation,

JS + C. Norman 2009

star formation rate boost factor ~ v_{cocoon}/σ ~10-100

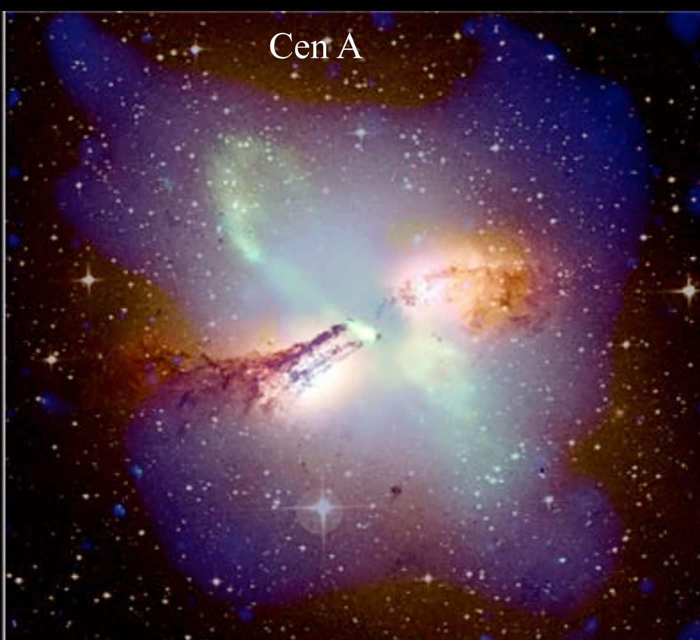
+ supernova heating

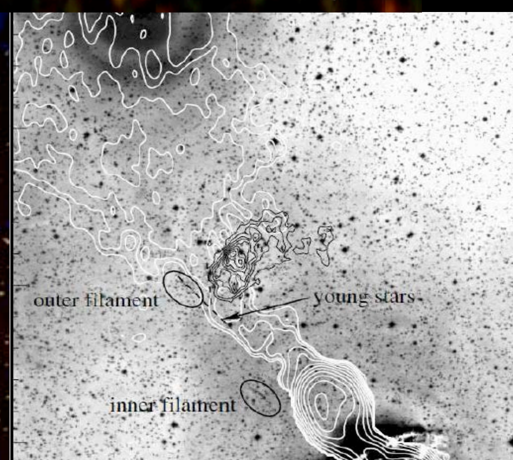


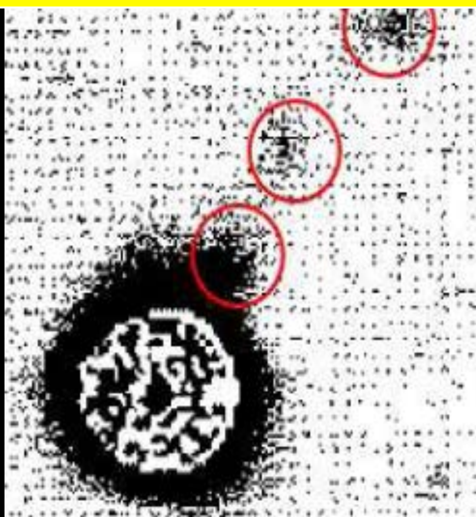
Klamer et al. 2006

z = 4.7 quasar + CO

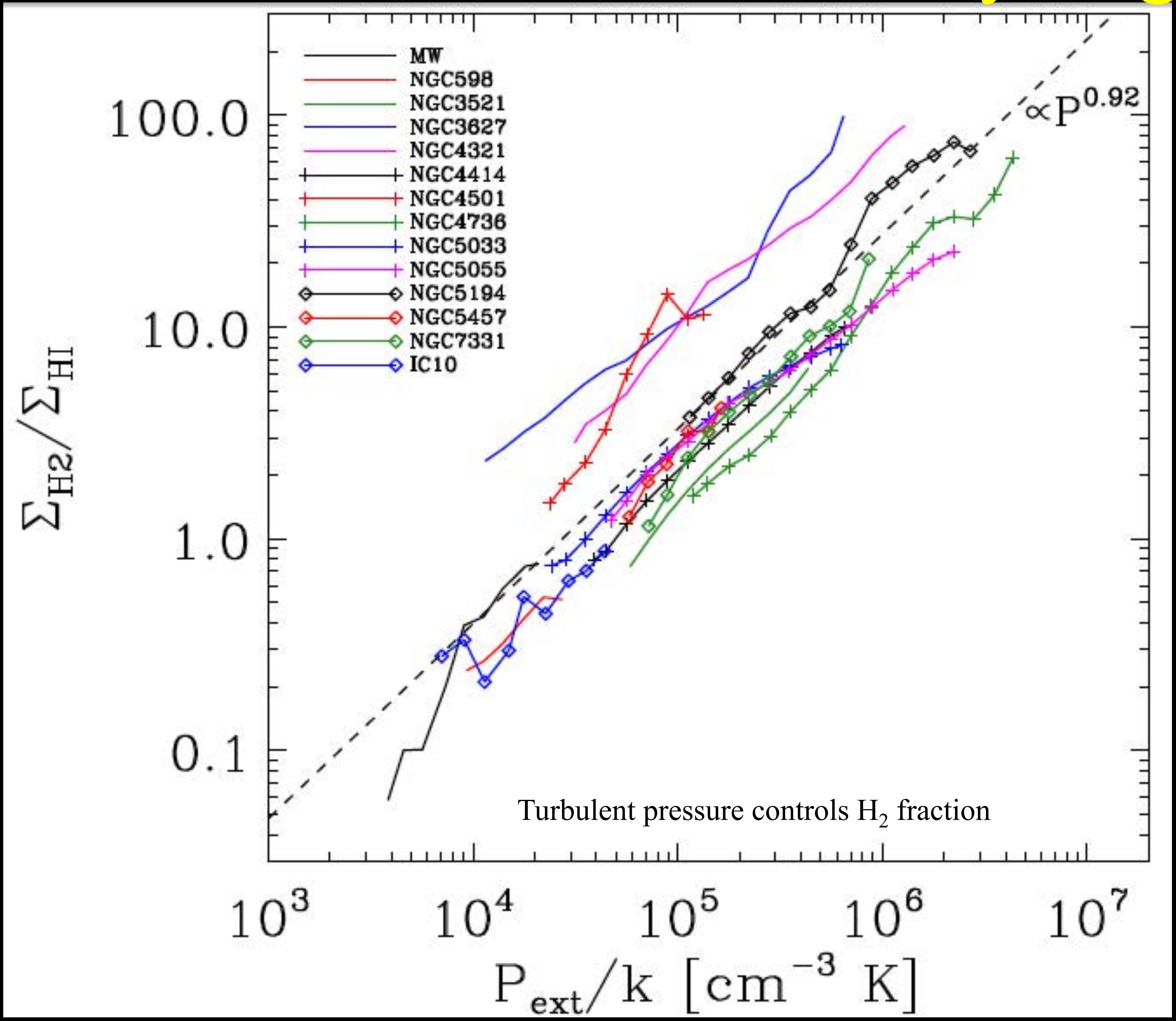
H_2 formation triggered by AGN







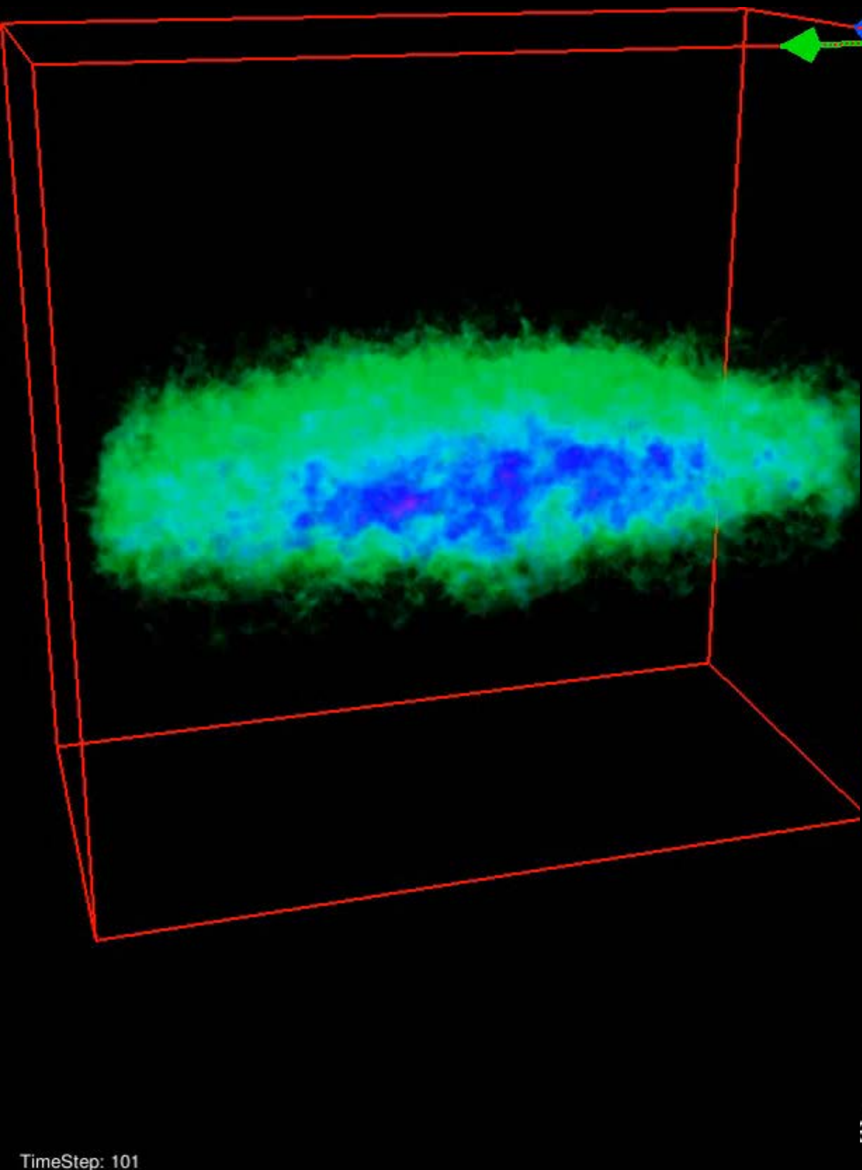
Role of molecular hydrogen

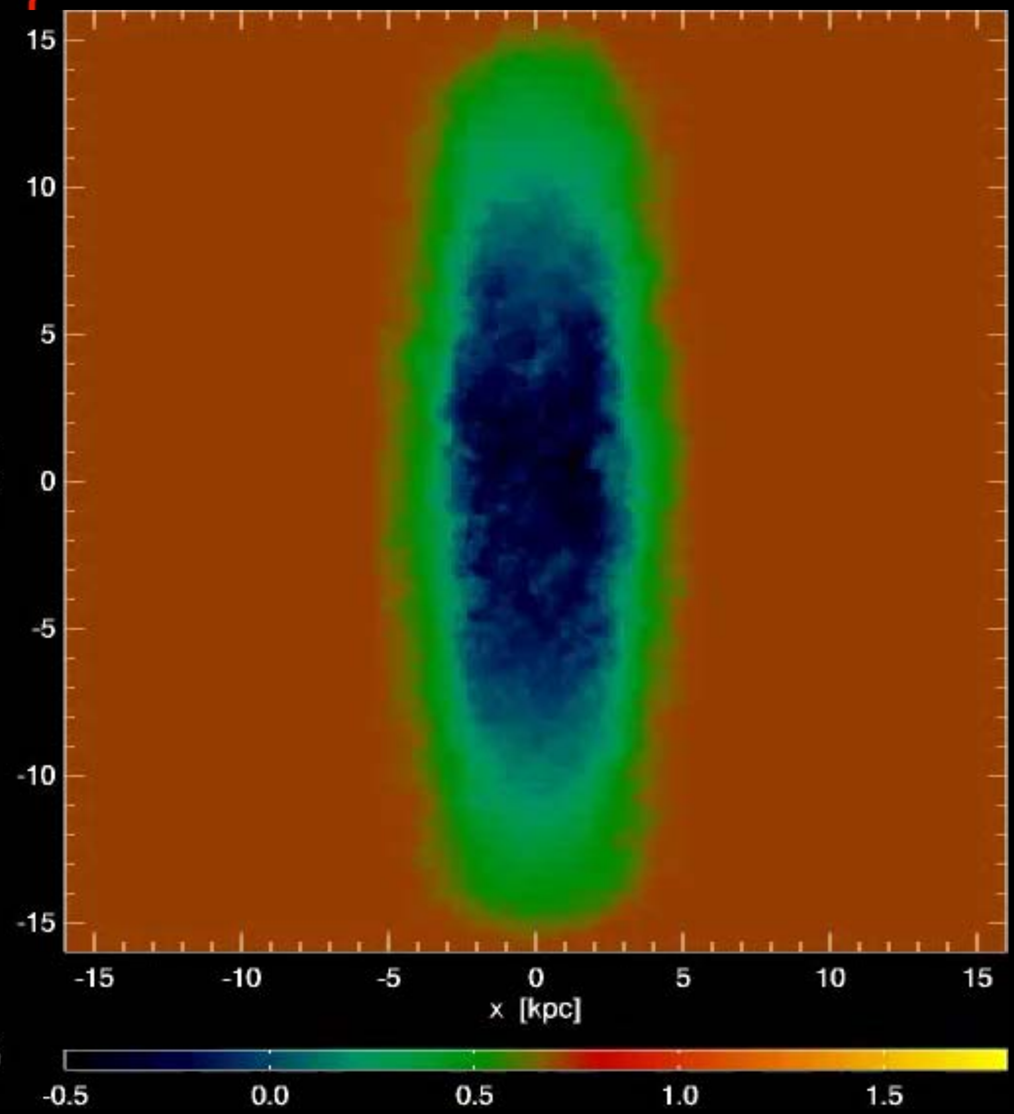


Blitz & Rosolowsky 2007

3-d N-body + hydro: RAMSES code
100 pc resolution, 10 cm^{-3} SF threshold

(simulations by V. Gaibler, S. Khochfar, M. Krause, JS 2012)





JET-INDUCED STAR FORMATION

t = 0.0 Myr

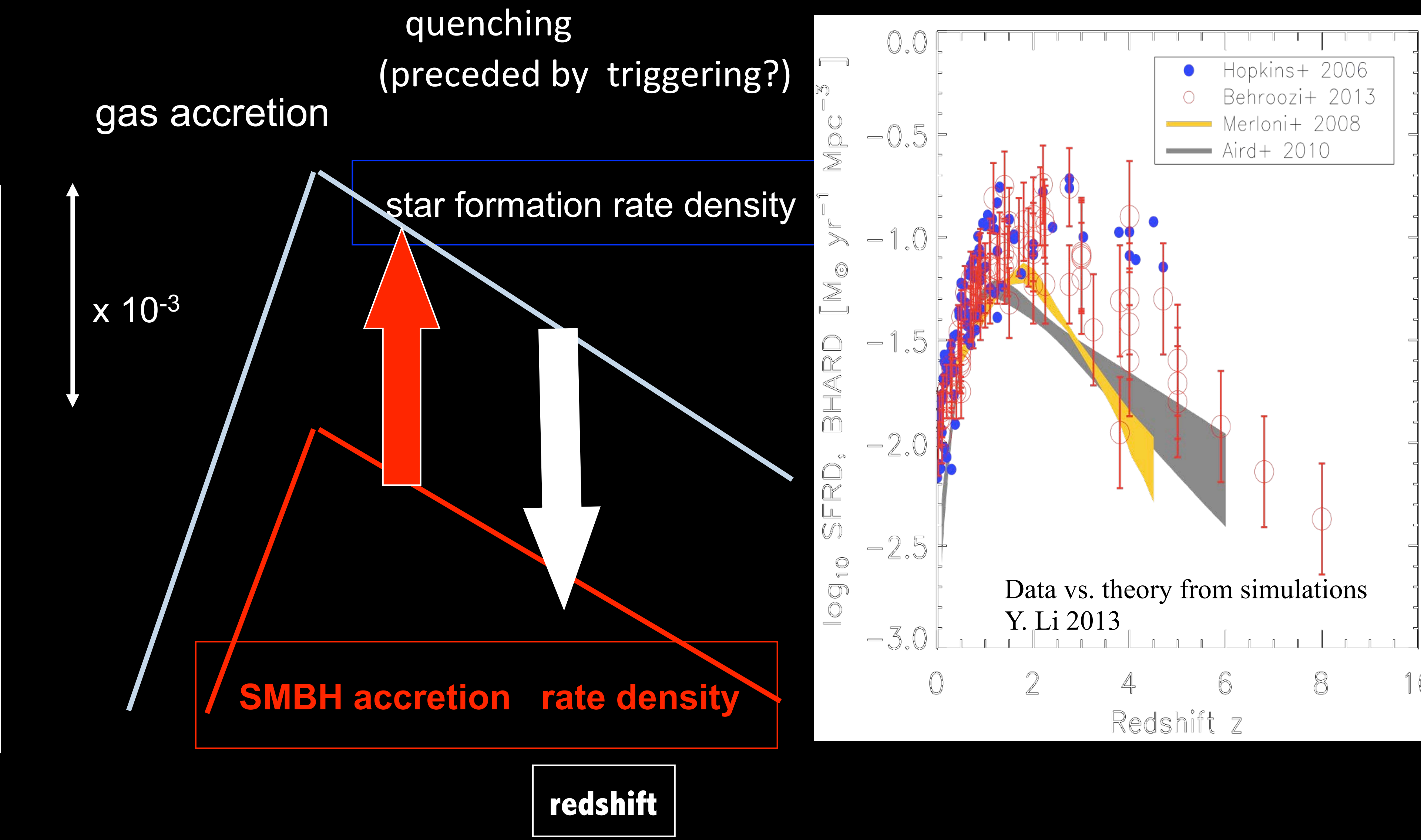
5 kpc

t = 0.0 Myr

5 kpc

Star formation

AGN and galaxy formation: the case for coevolution



SUMMARY

Herschel has given us a new perspective on the distant universe

But we still understand neither star formation in extreme conditions nor massive black hole formation

Is it the "same as usual" but with eg more gas, or is there a new mode of star formation appearing at high z?

HERSCHEL HAS SET THE SCENE FOR ALMA