ASTROPHYSICAL COSMOLOGY

Some issues in 2012

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11 July 2012

How did galaxies form?

How did supermassive black holes form?

What is the connection between supermassive black holes and galaxy formation?

Are there unexpectedly massive structures on the largest scales? Superclusters, voids...

What is the nature of dark matter?

Is dark energy just Einstein's Lambda?

What have we learnt in past 2 decades?

- Semi-analytical modelling c. 1990

  a recent example 2012NewA...17..175B

SAM parameters

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

Parameter	Value	R[eference]
[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[entations of] components are only listed where more than one non-null implementation currently exists within GALACTICUS.

Parameter	Value	Referen[ce]
[majorMergerMassRatio]	0.1	§4.9.1
[mergerRemnantSizeOrbitalEnergy]	1	§4.9.2
[mergerTreeBuildCole2000AccretionLimit]	0.1	§4.16
[mergerTreeBuildCole2000MassResolution]	$5 \times 10^9 M_\odot$	§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 have we learnt in past 2 decades?

- Semi-analytical modelling c. 1990

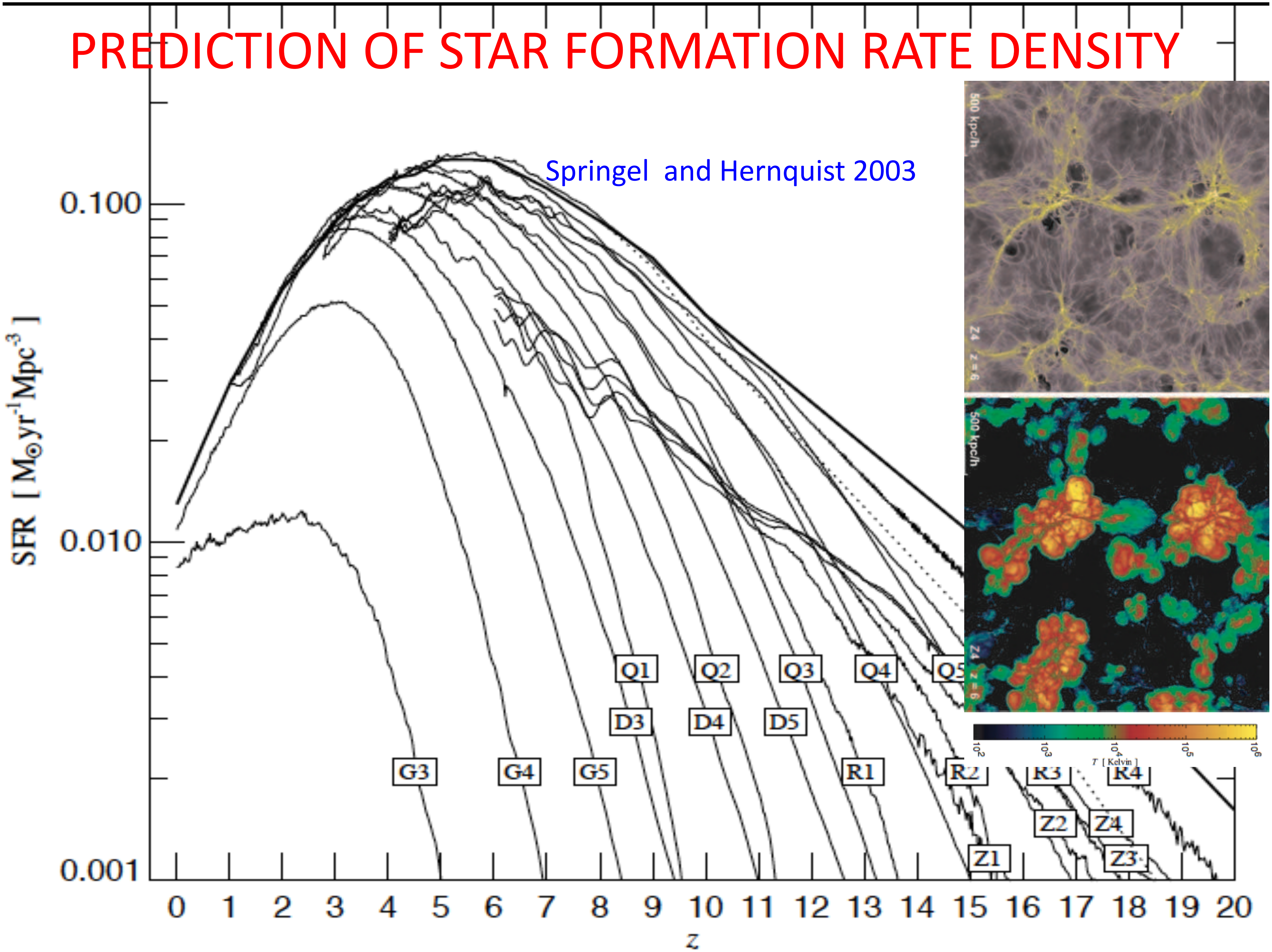
  a recent example 2012NewA...17..175B

- Hydrodynamical simulations

  a pioneering example 2003MNRAS.339..312S

PREDICTION OF STAR FORMATION RATE DENSITY

Springel and Hernquist 2003



What's missing?

A robust theory of star formation

and

Improved astrophysics

FEEDBACK

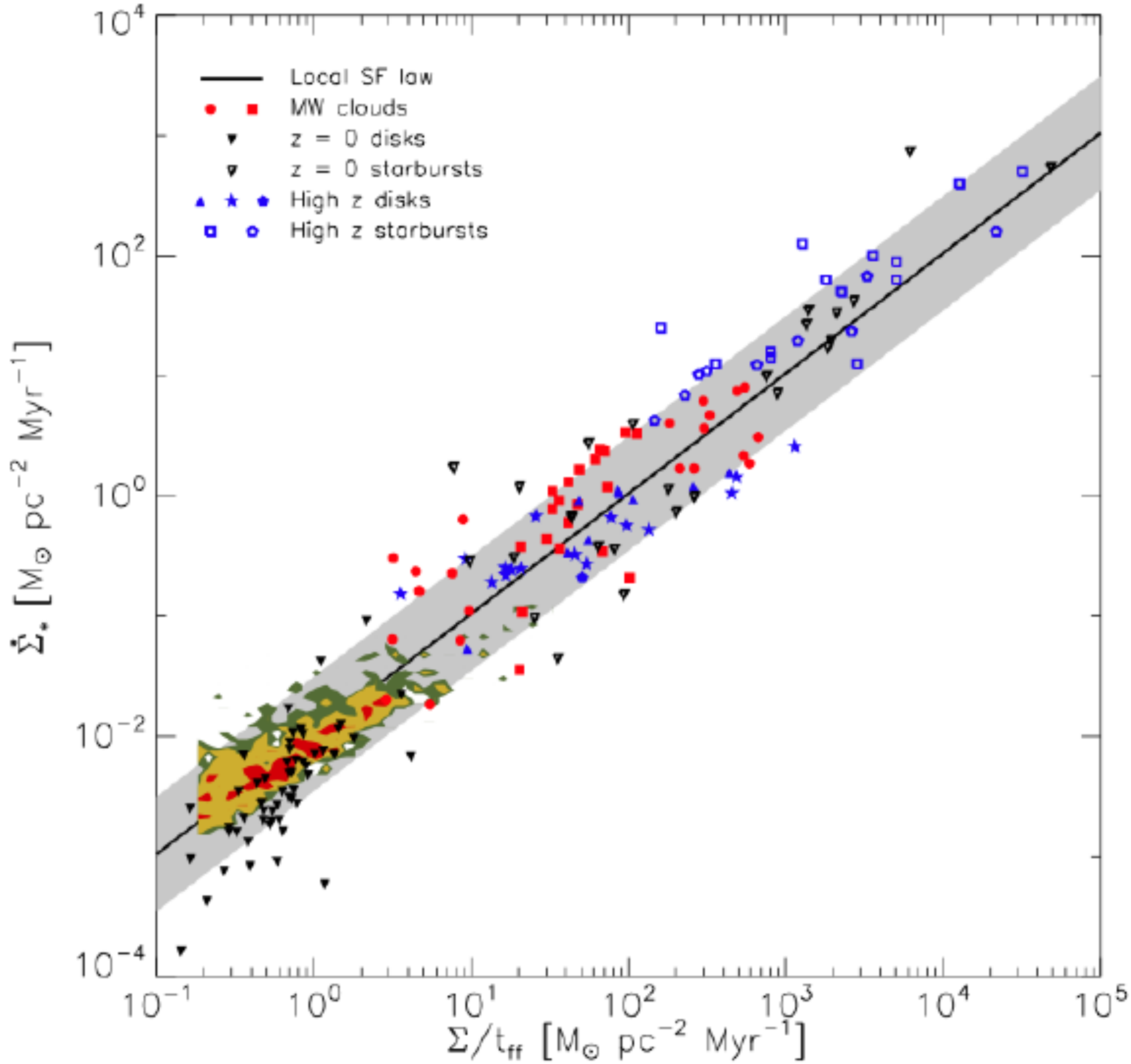
Controls how stars formed

Controls how galaxies formed

Controls how supermassive black holes formed

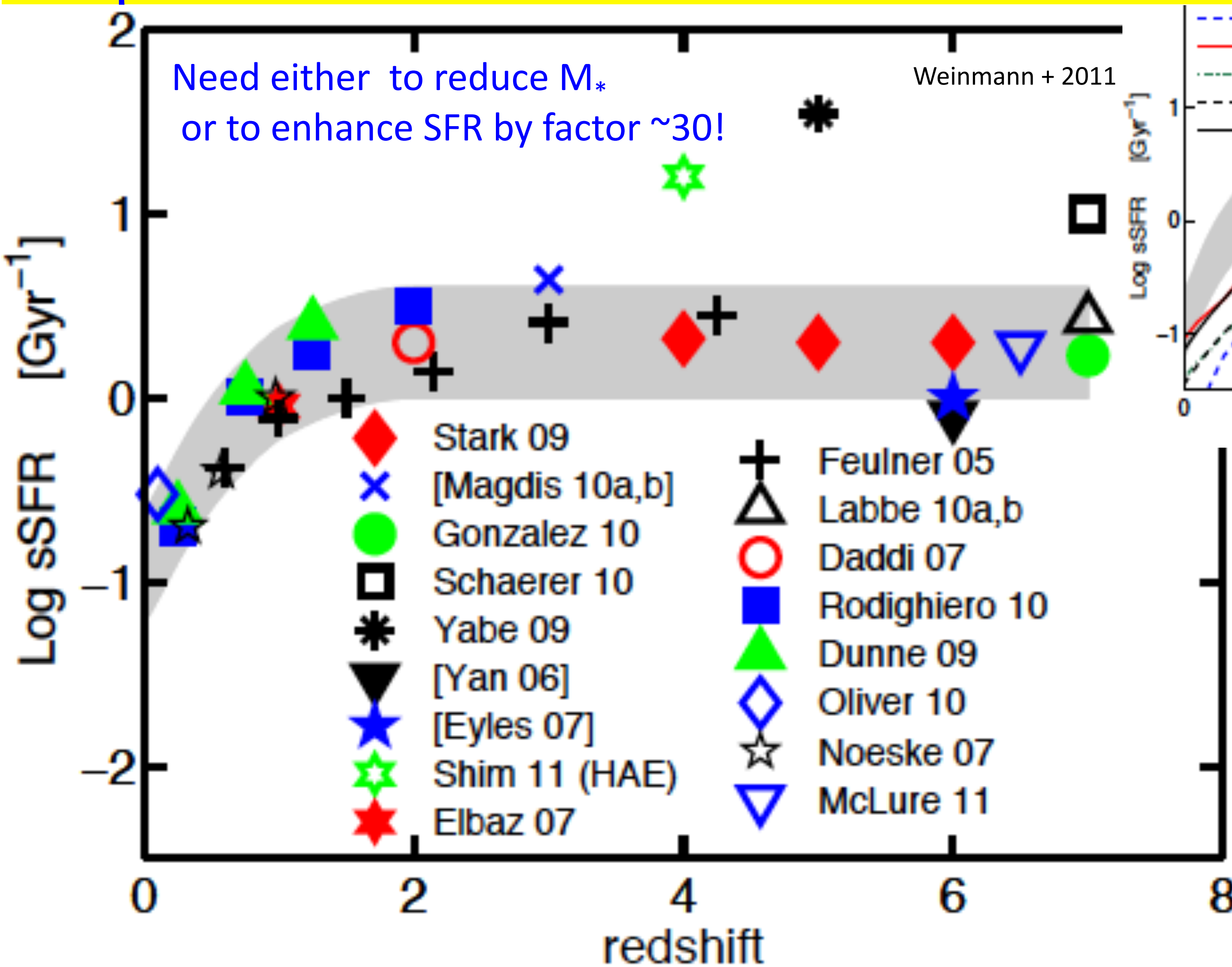
Controls the interplay of AGN and galaxy formation

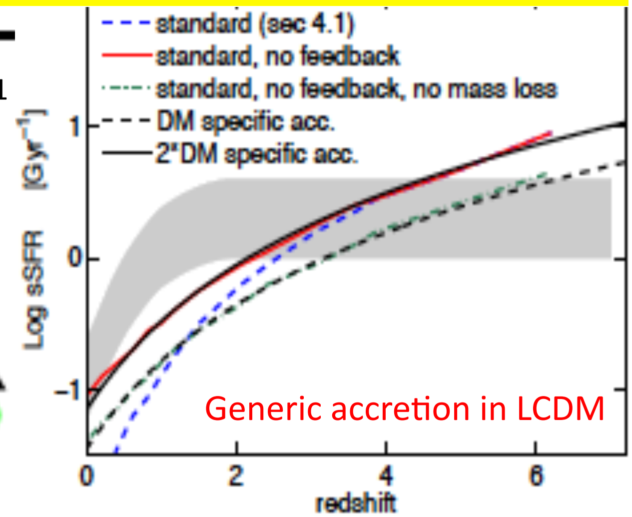
Star formation efficiency ϵ_{ff} =0.01 fits data for MW clouds



AGN and the SSFR?

specific star formation rate =SFR/stellar mass

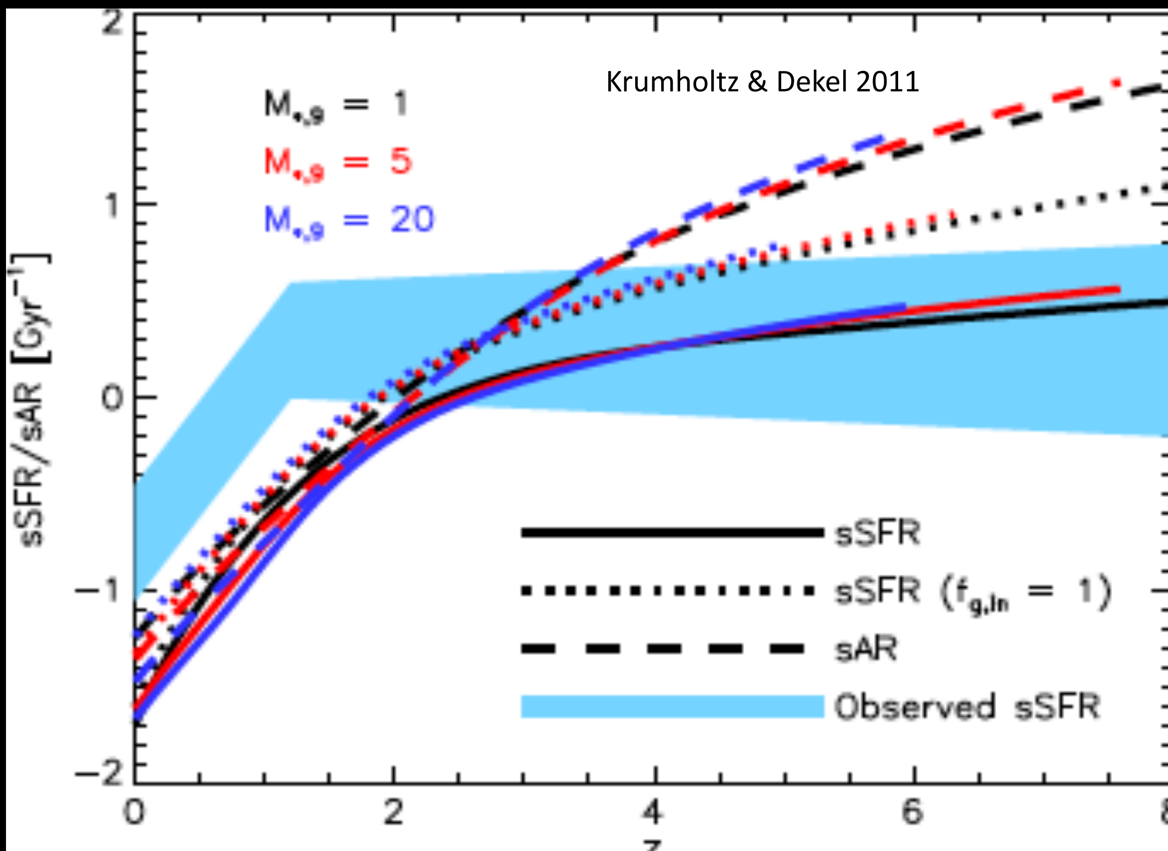




$$SFR = \varepsilon_{SN} M_{gas} / t_{ff}$$

$$\varepsilon_{SN} \sim Z$$

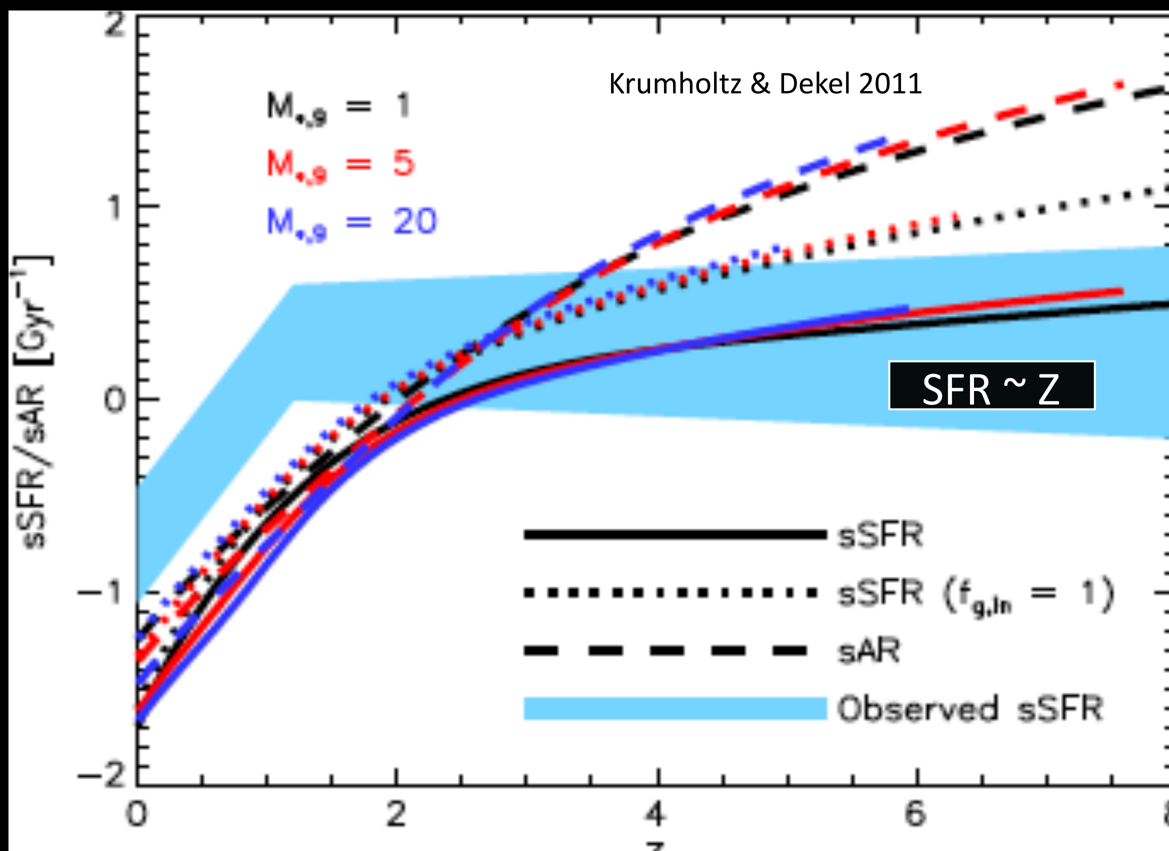
metallicity



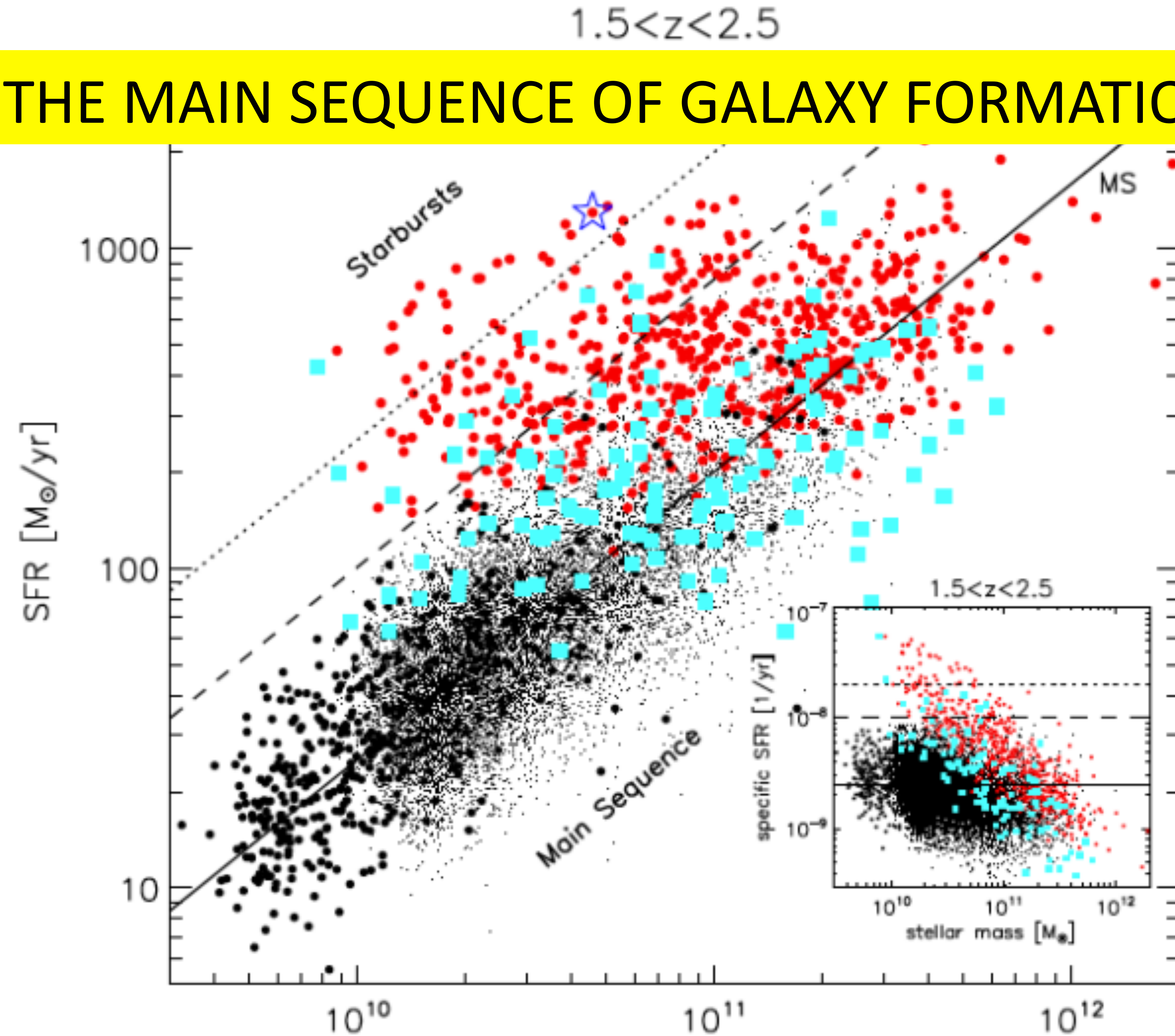
$SFR = \varepsilon_{SN} M_{gas} / t_{ff}$

- $SFR/M_* =$ constant means exponential SFR!
- Metallicity-dependent SFR is bad at low z: Z ↘ but M_{gas} ↗ with redshift

This is bad!

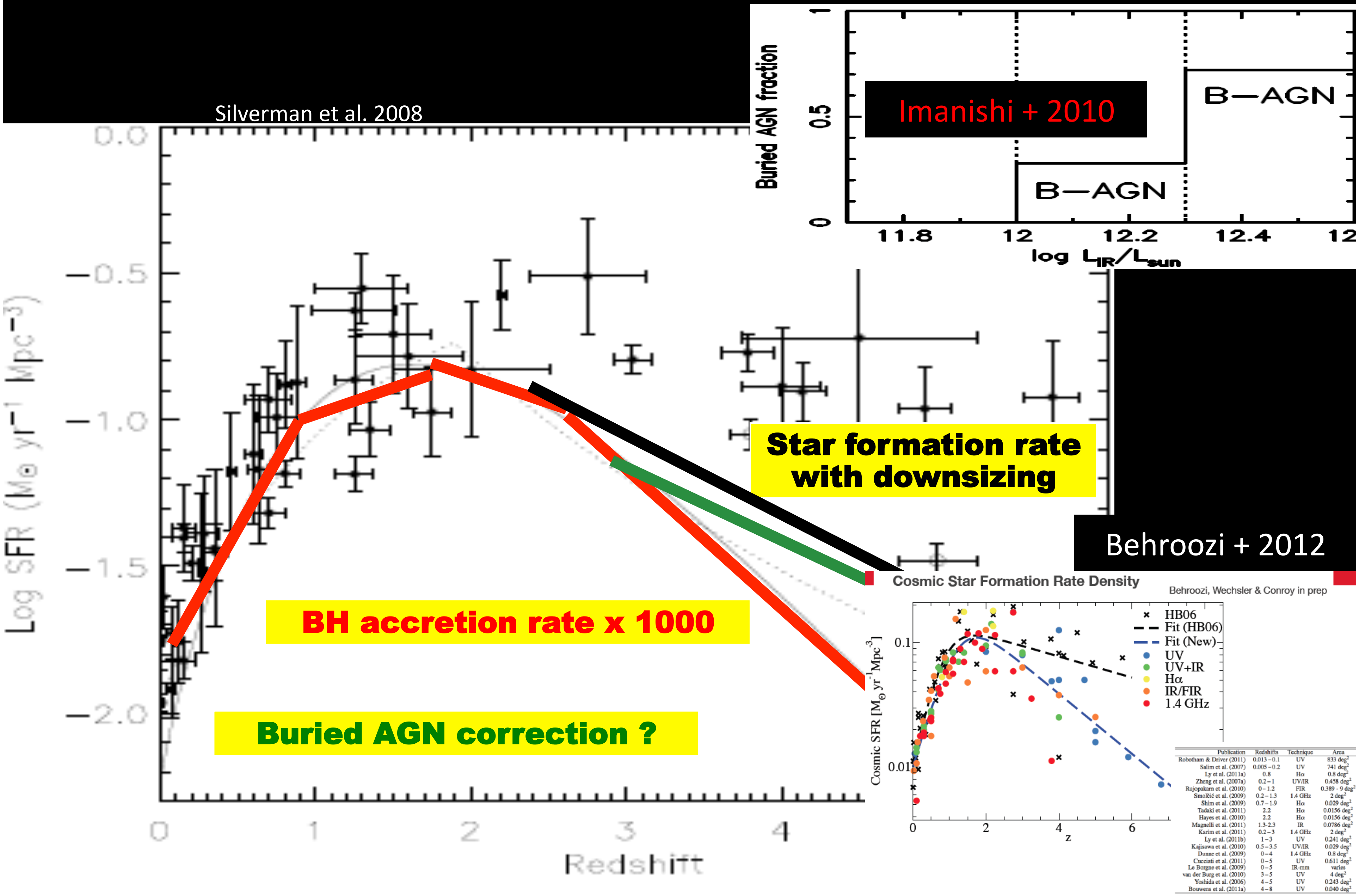


THE MAIN SEQUENCE OF GALAXY FORMATION



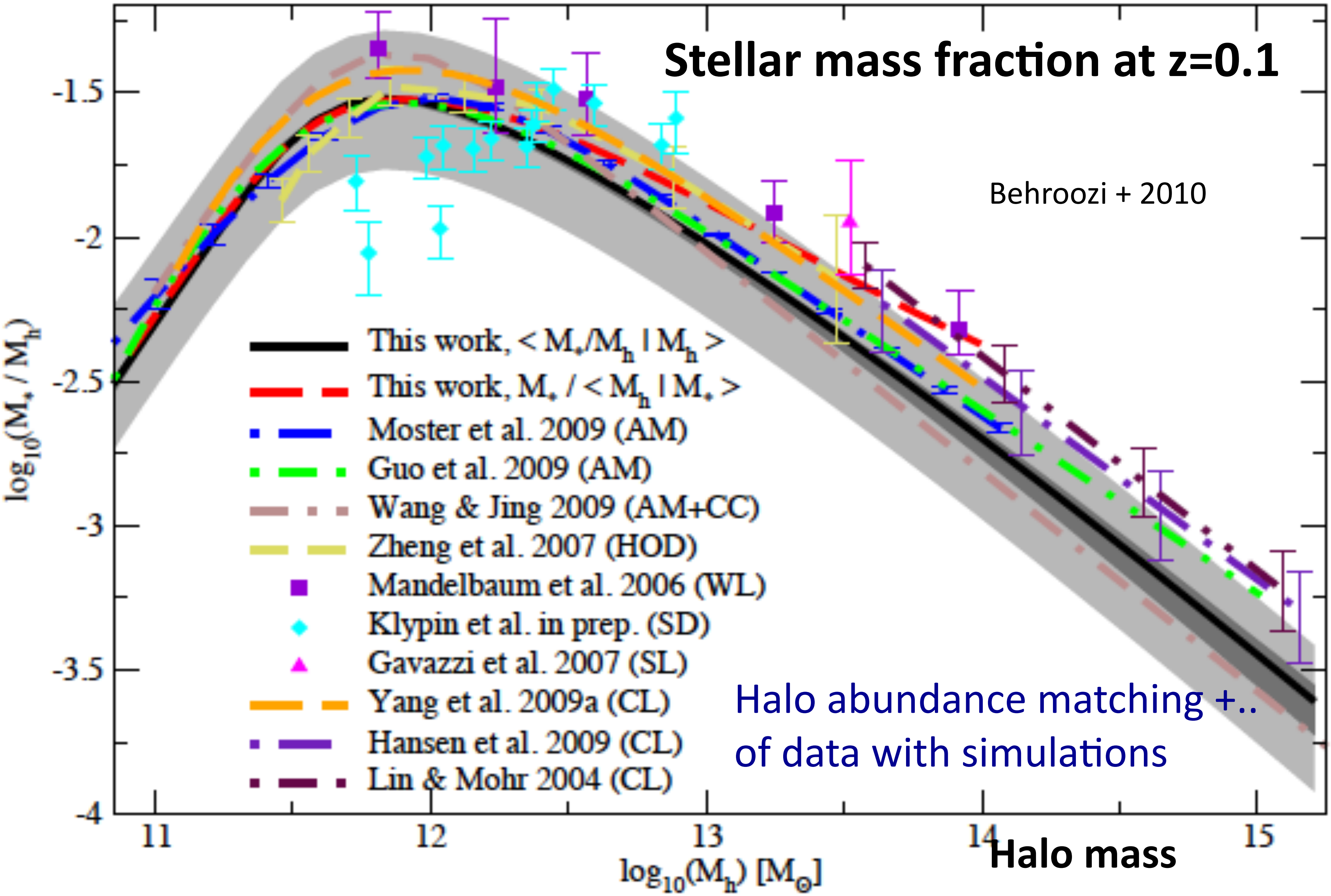
Rodighiero+2012

AGN feeding rate

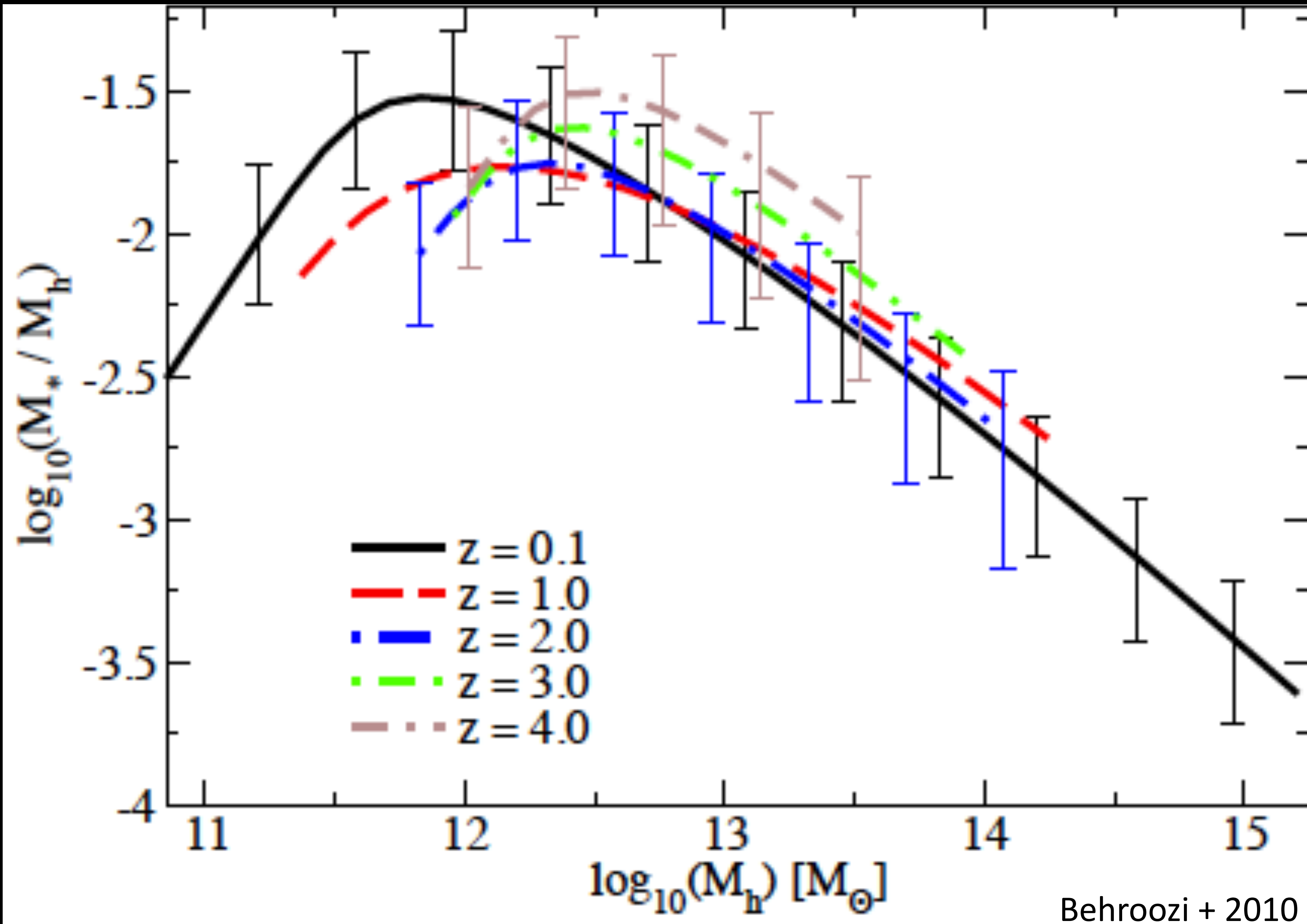


Publication	Redshifts	Technique	Area
Robotham & Driver (2011)	0.013 – 0.1	UV	833 deg^2
Salim et al. (2007)	0.005 – 0.2	UV	741 deg^2
Ly et al. (2011a)	0.8	Hα	0.8 deg^2
Zheng et al. (2007a)	0.2 – 1	UV/IR	0.458 deg^2
Rujopakarn et al. (2010)	0 – 1.2	FIR	0.389 - 9 deg^2
Smolčić et al. (2009)	0.2 – 1.3	1.4 GHz	2 deg^2
Shim et al. (2009)	0.7 – 1.9	Hα	0.029 deg^2
Tadaki et al. (2011)	2.2	Hα	0.0156 deg^2
Hayes et al. (2010)	2.2	Hα	0.0156 deg^2
Magnelli et al. (2011)	1.3-2.3	IR	0.0786 deg^2
Karim et al. (2011)	0.2 – 3	1.4 GHz	2 deg^2
Ly et al. (2011b)	1 – 3	UV	0.241 deg^2
Kajisawa et al. (2010)	0.5 – 3.5	UV/IR	0.029 deg^2
Dunne et al. (2009)	0 – 4	1.4 GHz	0.8 deg^2
Cucciati et al. (2011)	0 – 5	UV	0.611 deg^2
Le Borgne et al. (2009)	0 – 5	IR-mm	varies
van der Burg et al. (2010)	3 – 5	UV	4 deg^2
Yoshida et al. (2006)	4 – 5	UV	0.243 deg^2
Bouwens et al. (2011a)	4 – 8	UV	0.040 deg^2

THE NEED FOR OUTFLOWS



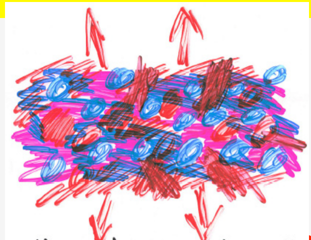
Even stronger outflows at z=4!



Behroozi + 2010

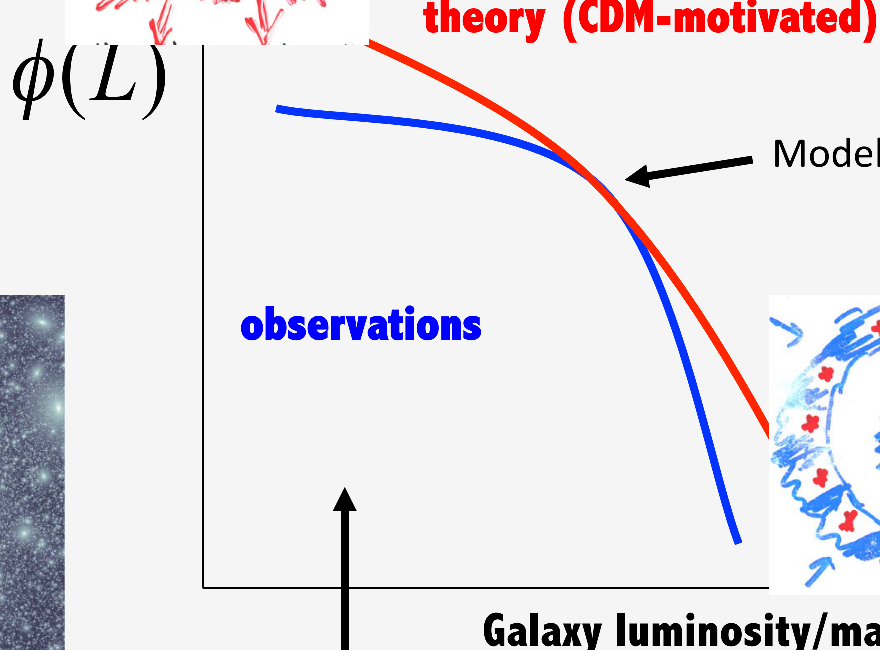
OUTFLOWS & THE DWARF & GIANT PROBLEMS

$$t_{cool} \sim \frac{nkT}{\Lambda(T)n^2}$$



$$M_{cooled-baryons} \sim \alpha_g^{-2}\alpha^3\left(\frac{m_p}{m_e}\right)\left(\frac{t_{cool}}{t_{dyn}}\right)T^{1+2\beta}$$

$$t_{dyn} \sim \frac{1}{\sqrt{Gm_p n}}$$

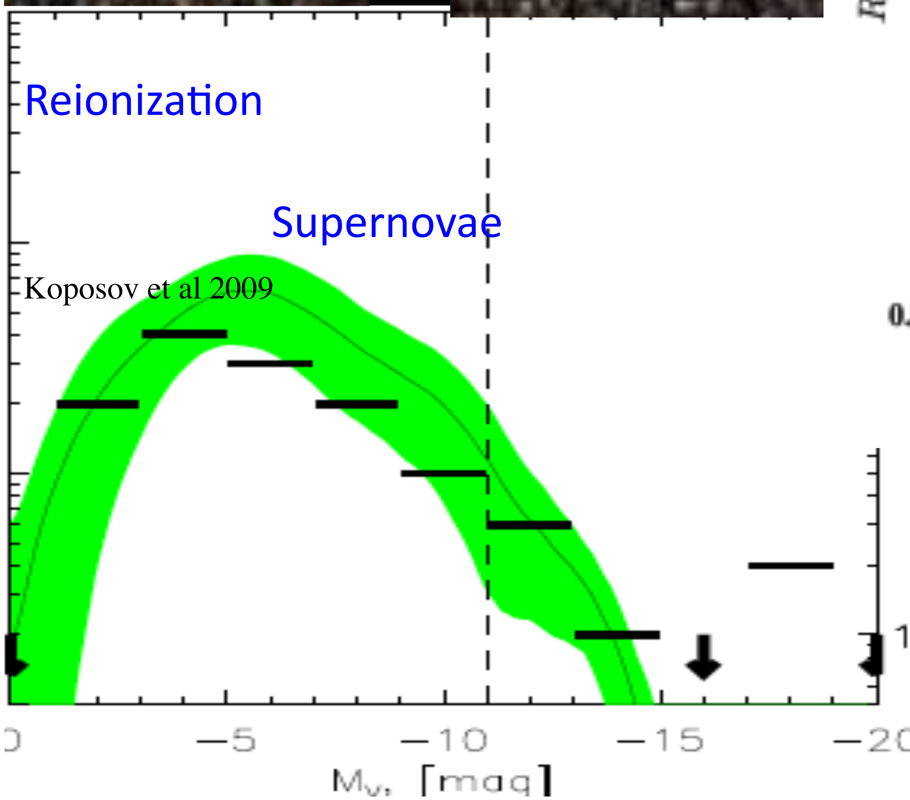


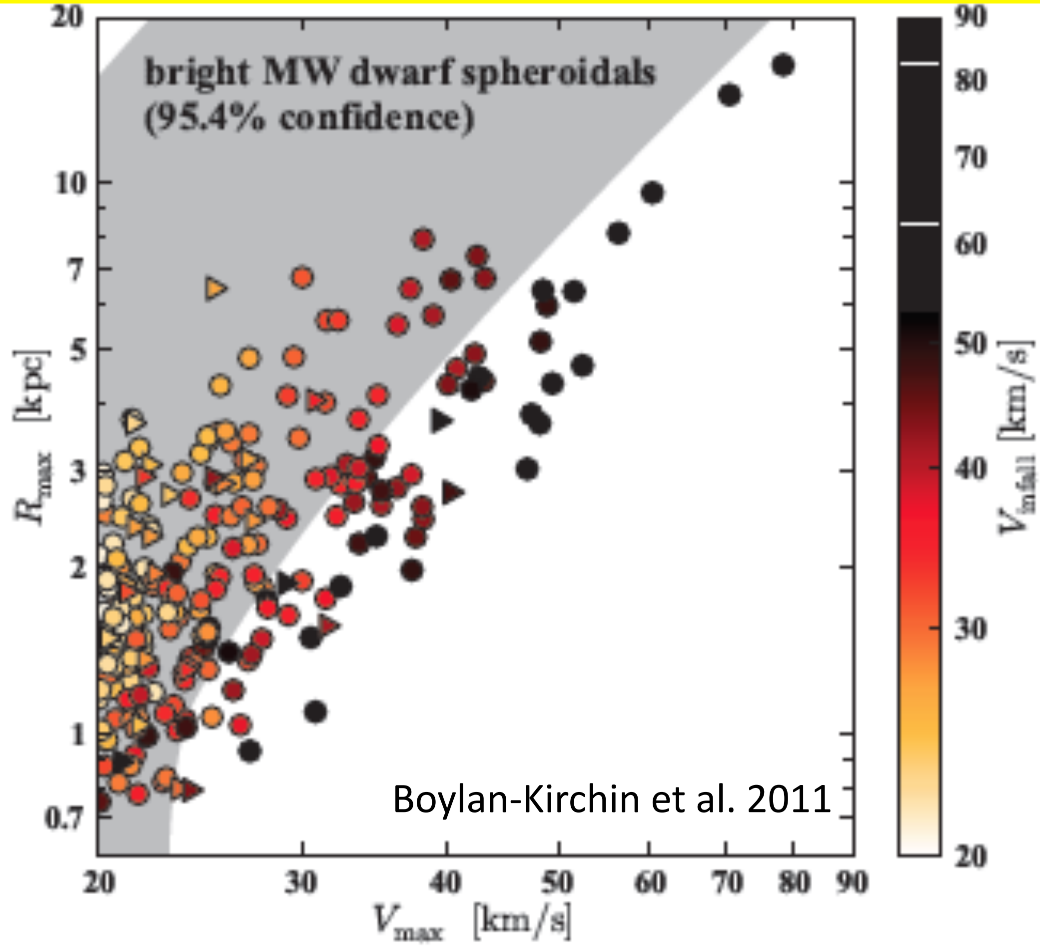
$$L_* \sim 3 \times 10^{10} Lsun$$

SuperNovae

ActiveGalacticNuclei

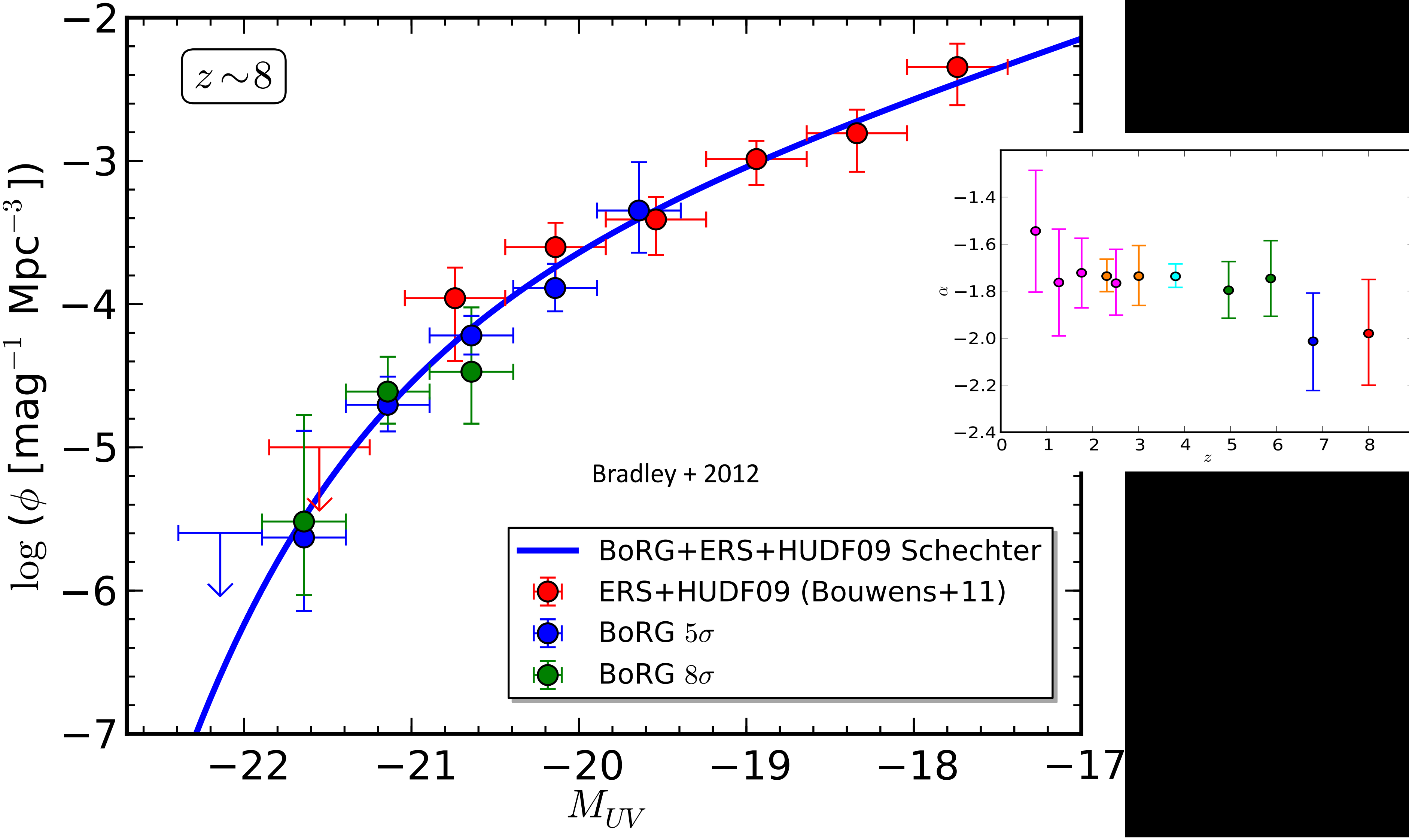
Fitting the mass function of low mass galaxies

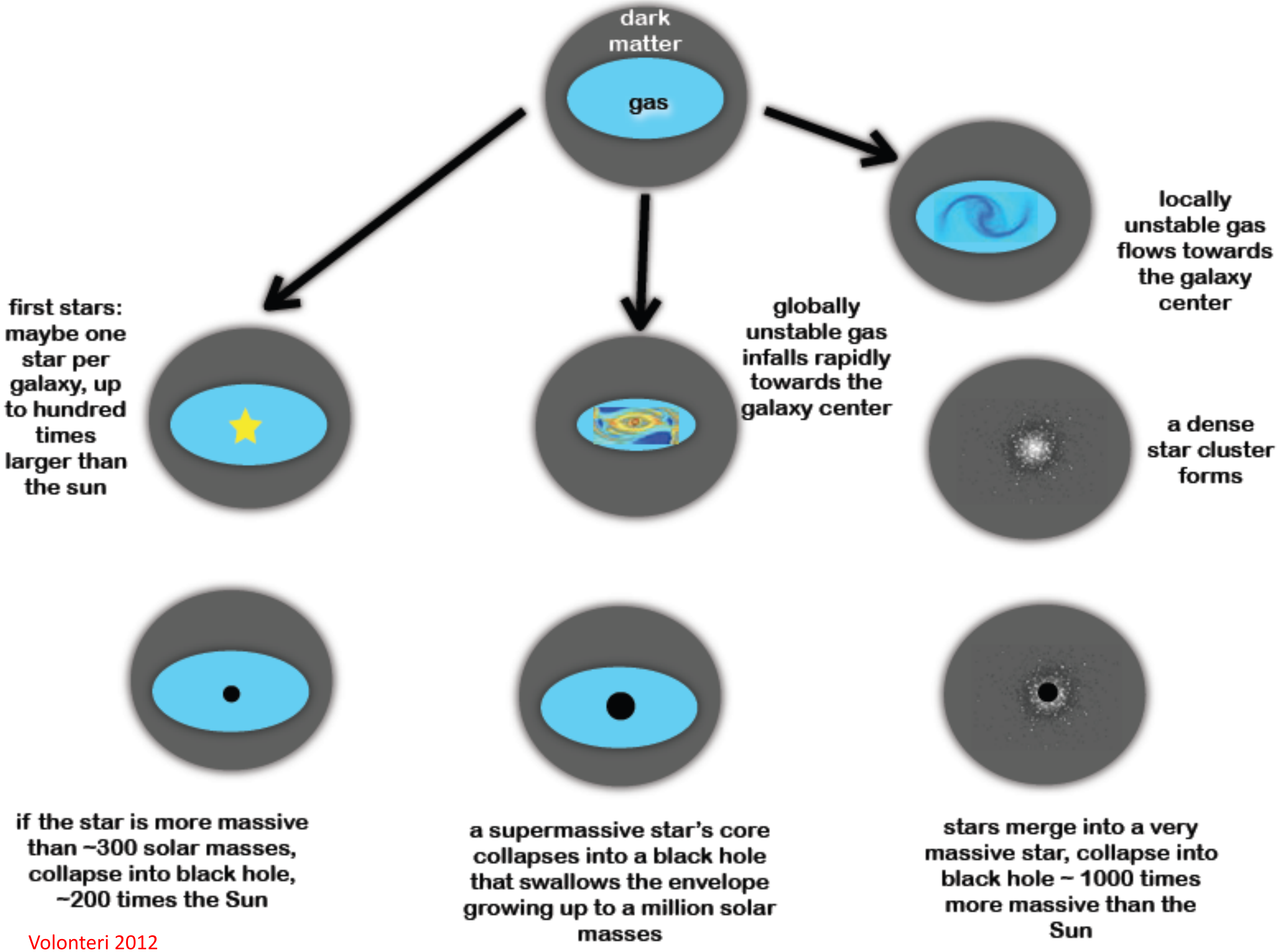




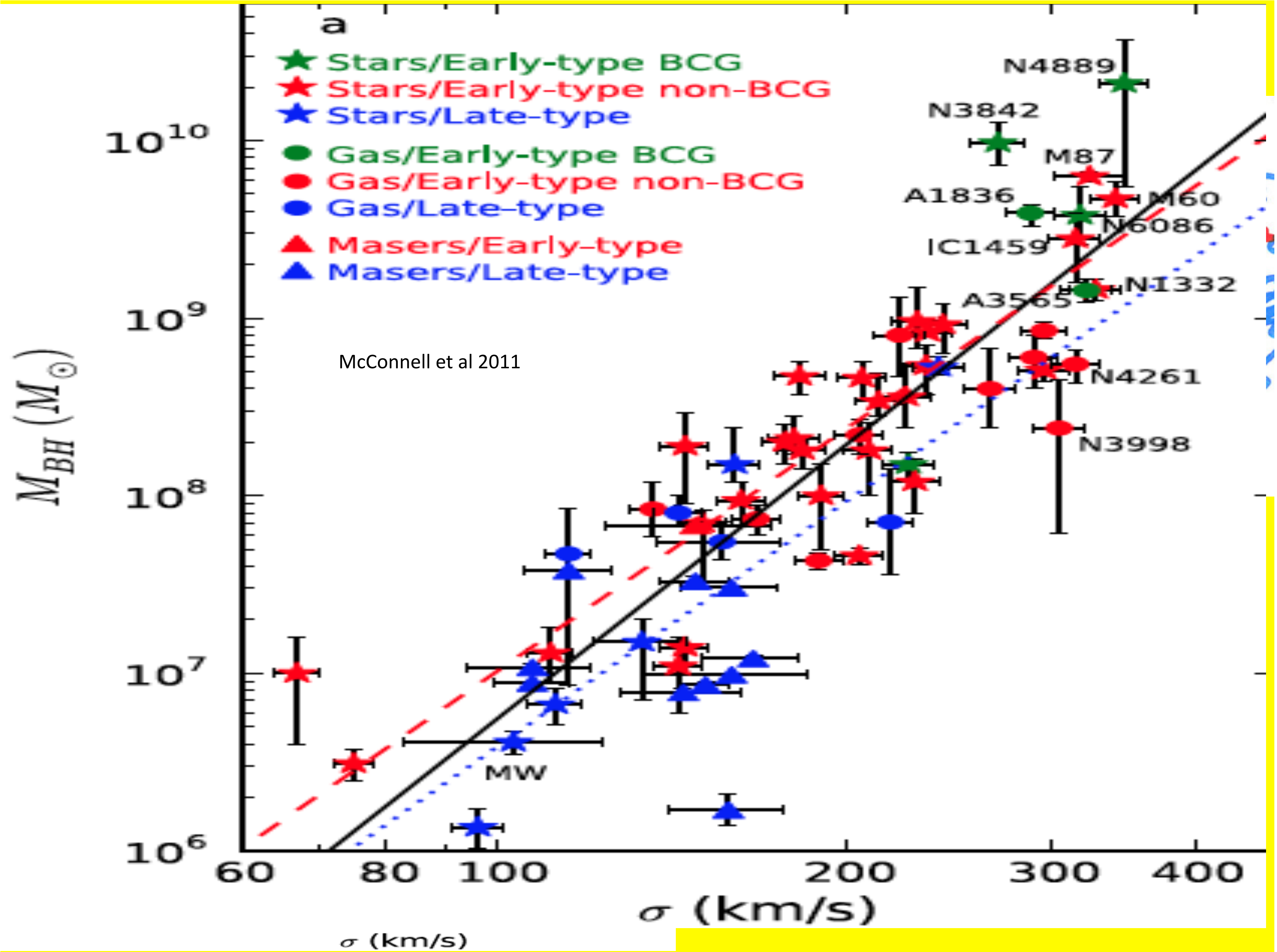
THE TOO BIG TO FAIL PROBLEM

THE GALAXY LUMINOSITY FUNCTION AT HIGH z





Volonteri 2012


a
Stars/Early-type BCG
Stars/Early-type non-BCG
Stars/Late-type
Gas/Early-type BCG
Gas/Early-type non-BCG
Gas/Late-type
Masers/Early-type
Masers/Late-type
N4889
N3842
M87
A1836
M60
N6086
IC1459
N1332
A3565
N4261
N3998
MW
McConnell et al 2011
$M_{BH}\ (M_\odot)$
10^{10}
10^9
10^8
10^7
10^6
60
80
100
200
300
400
σ (km/s)
σ (km/s)

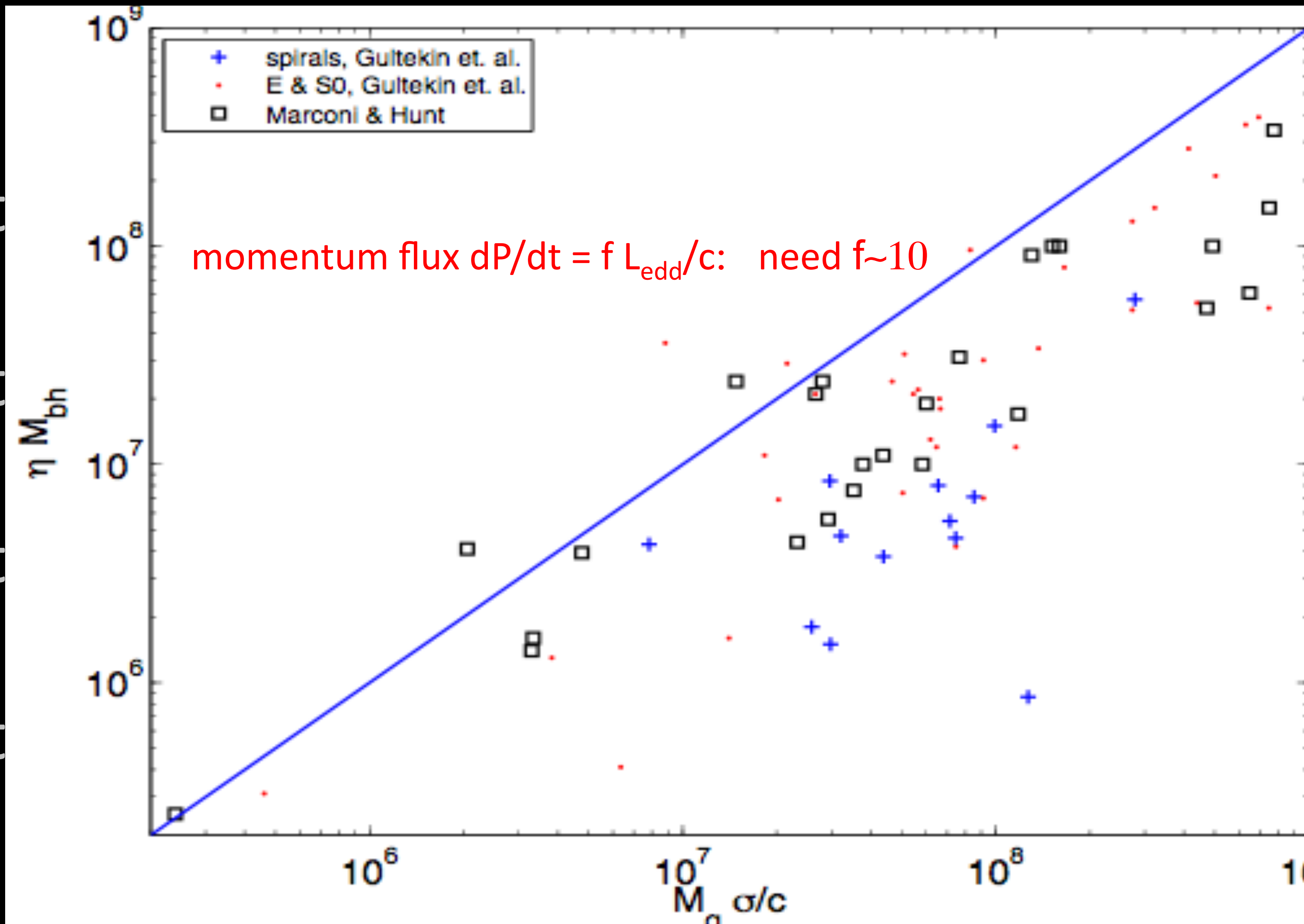
FEEDBACK

Cont

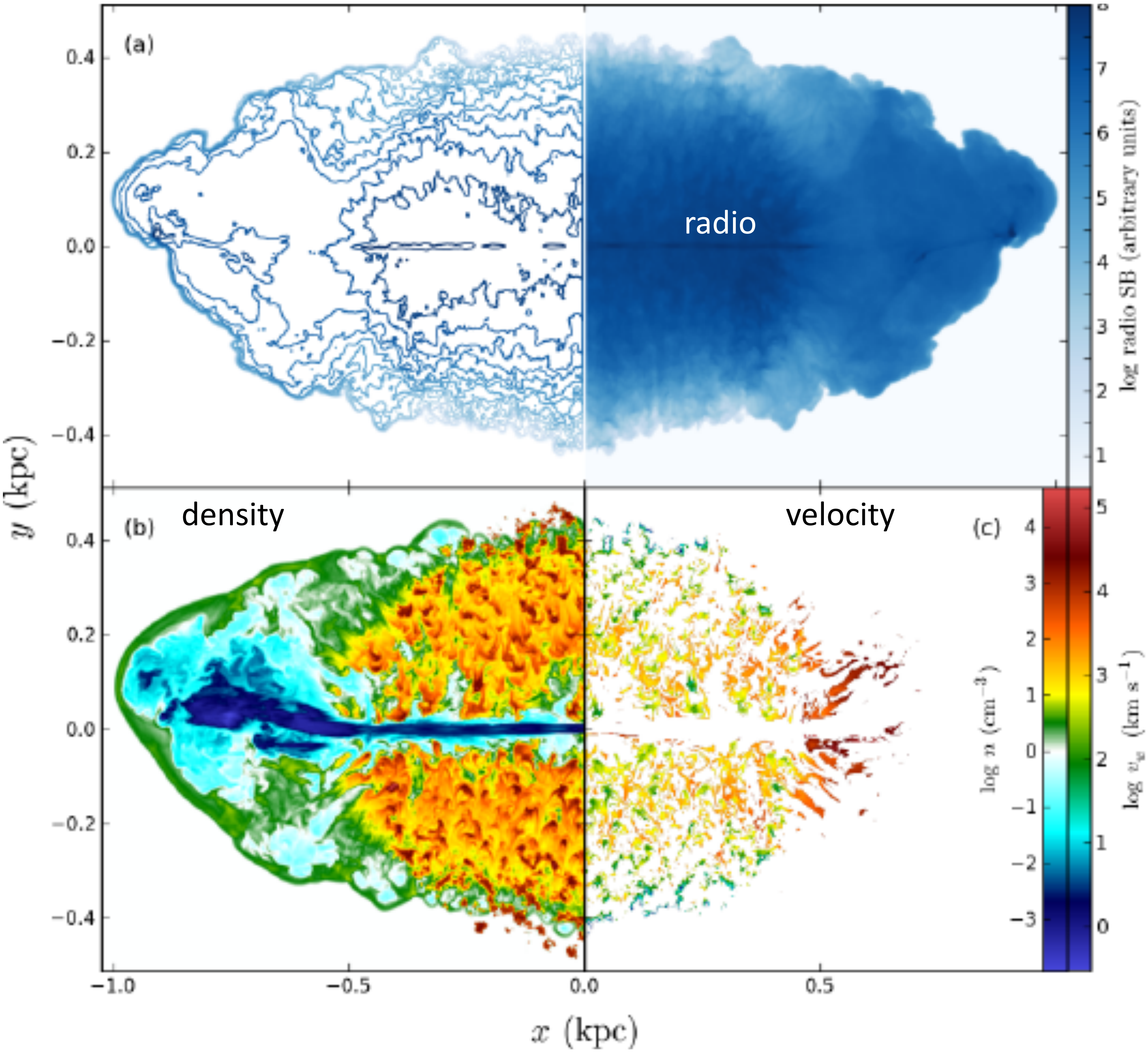
Cont

Cont

Cont … on

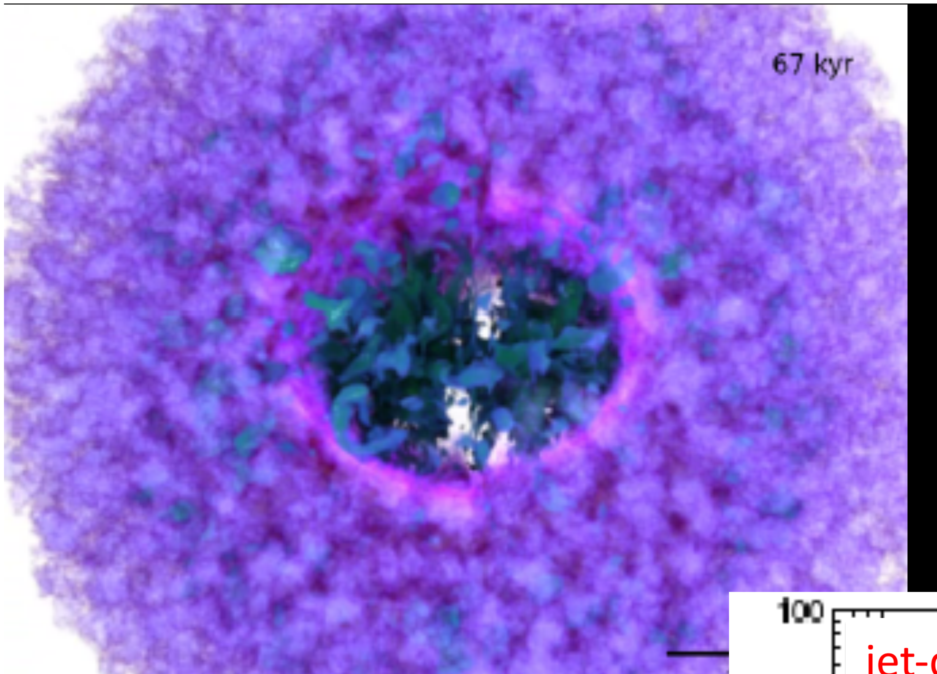


jet-driven wind provides M_{BH} - σ normalisation

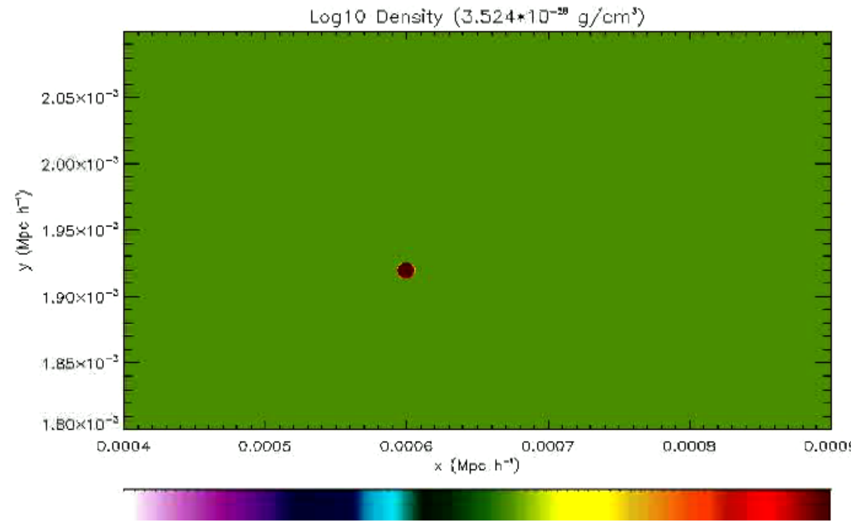


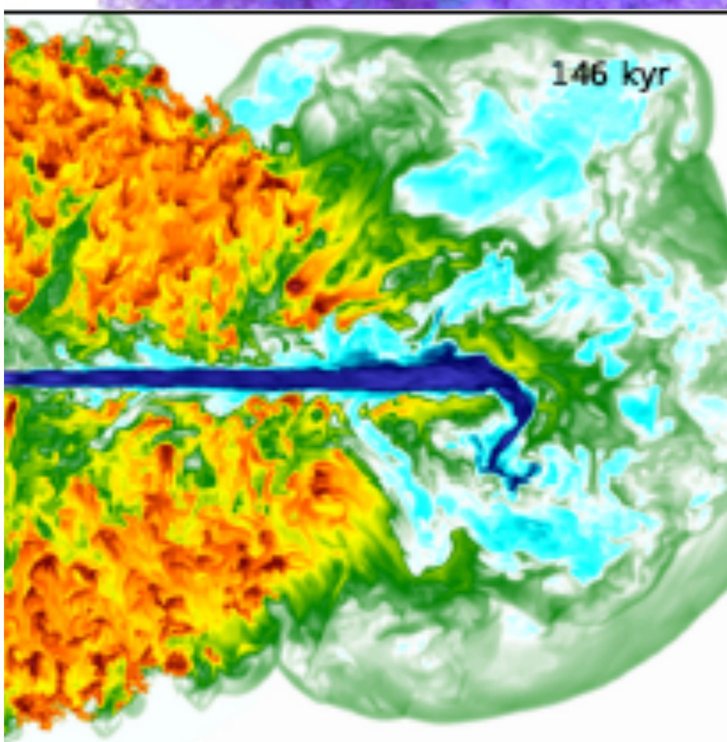
(a)
radio
log radio SB (arbitrary units)
(b)
density
velocity
(c)
log n (cm^{-3})
log v_x (km s^{-1})
y (kpc)
x (kpc)

Wagner + 2012

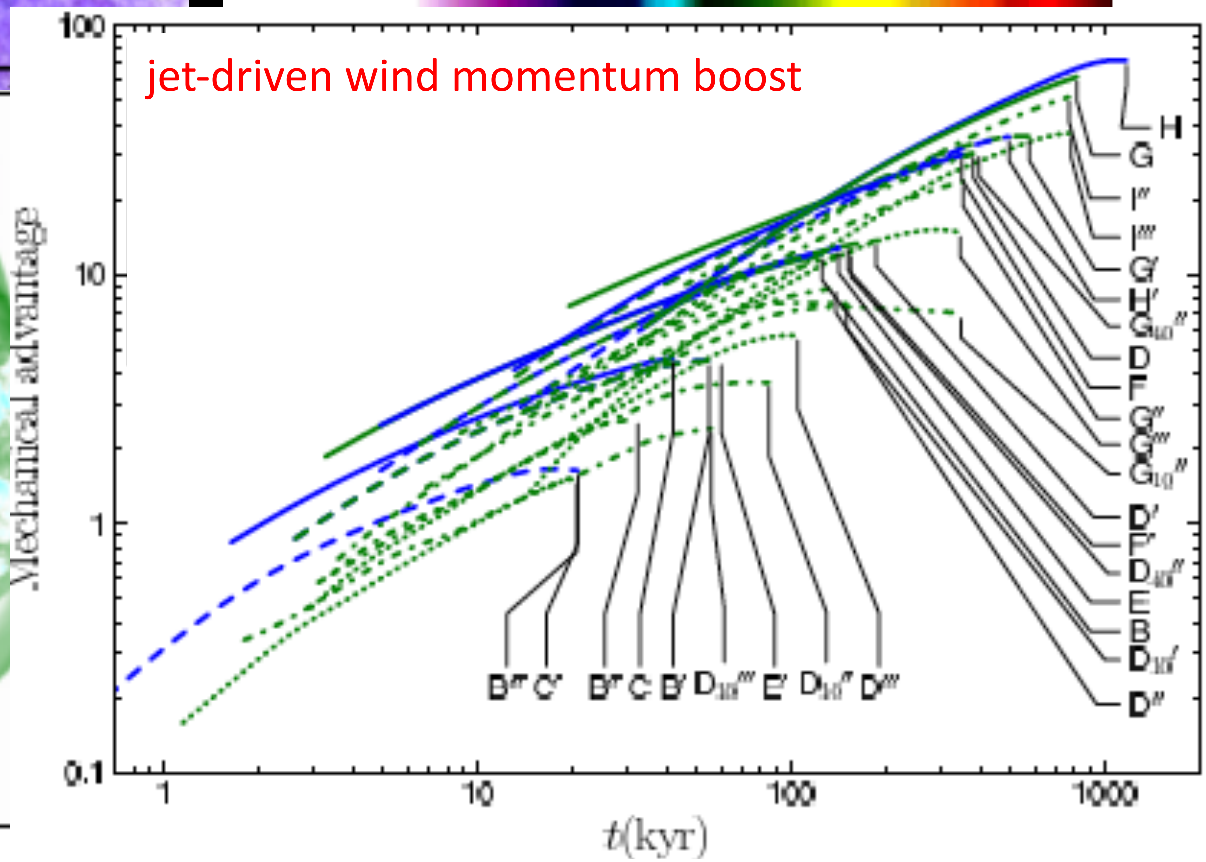


Antonuccio-Deloglou & JS 2010

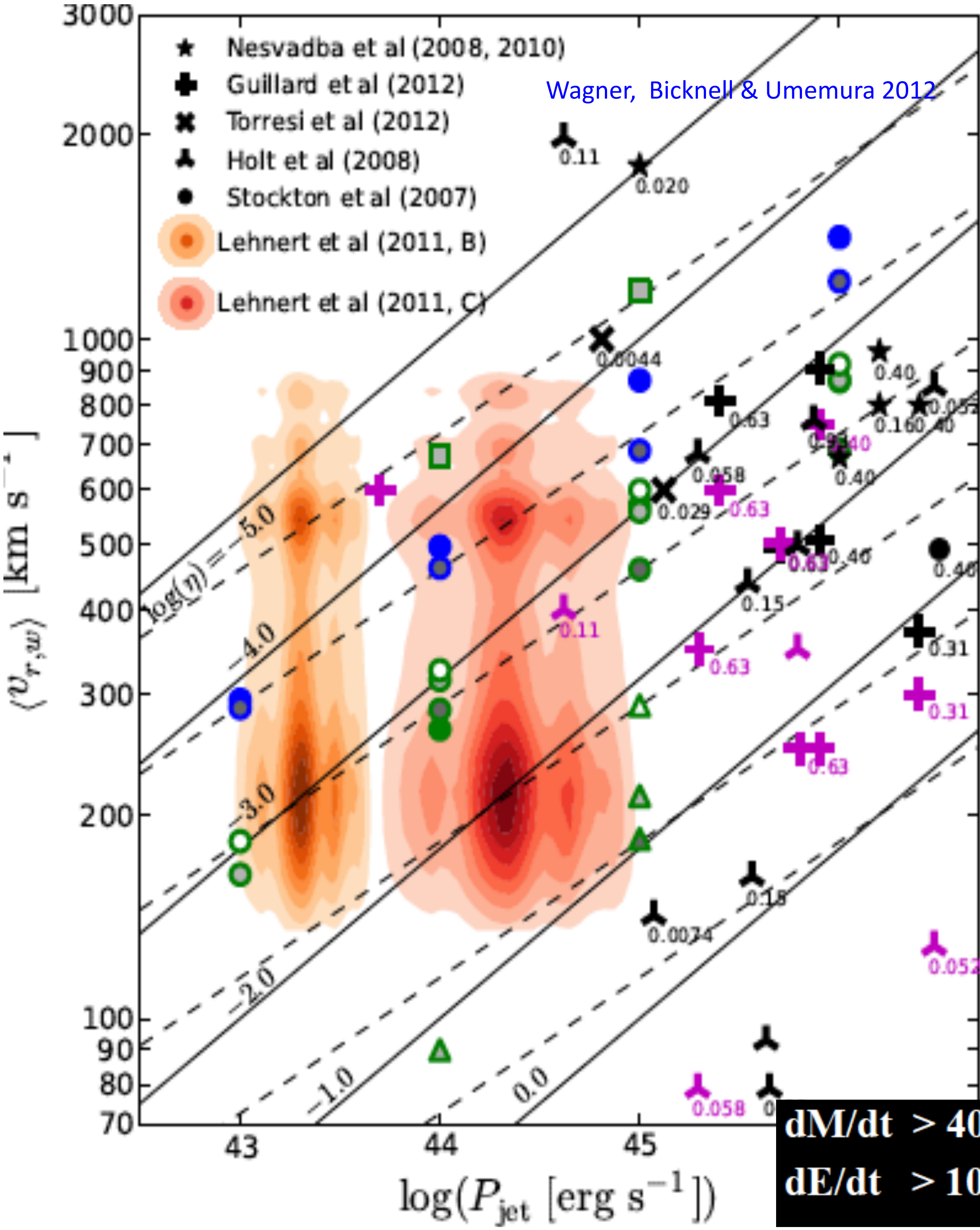


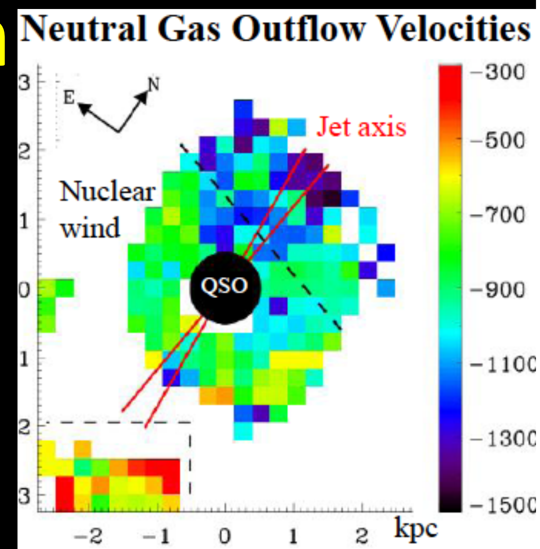


Wagner, Bicknell & Umemura 2012



Shock-entrained velocities are high

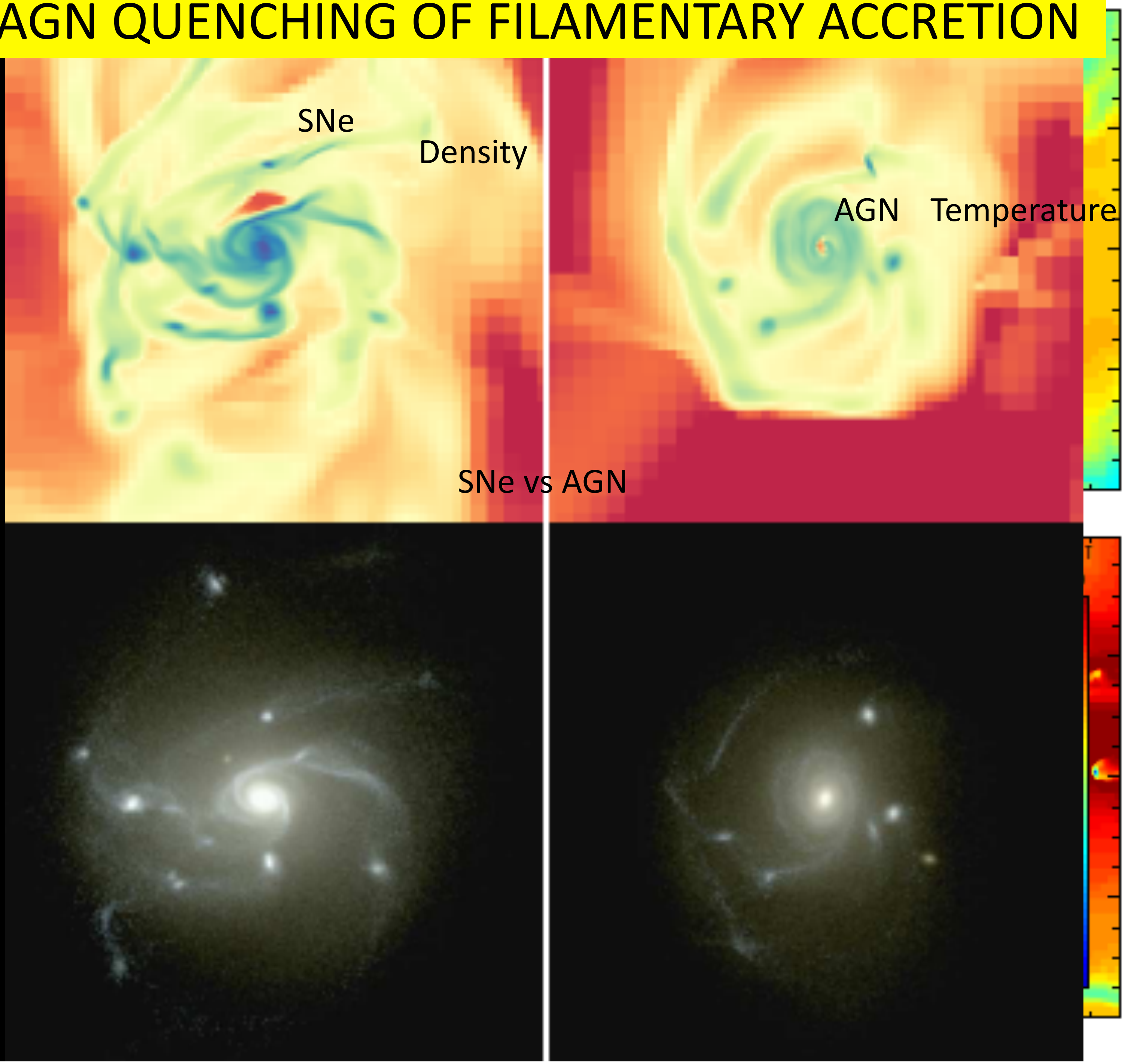




dM/dt > 400 M_{sun} yr^{-1} ~ 2.5 x SFR

dE/dt > 10^{44} ergs s^{-1} ~ 2.5 x dE_*/dt ~ 1% L_{AGN}

AGN QUENCHING OF FILAMENTARY ACCRETION

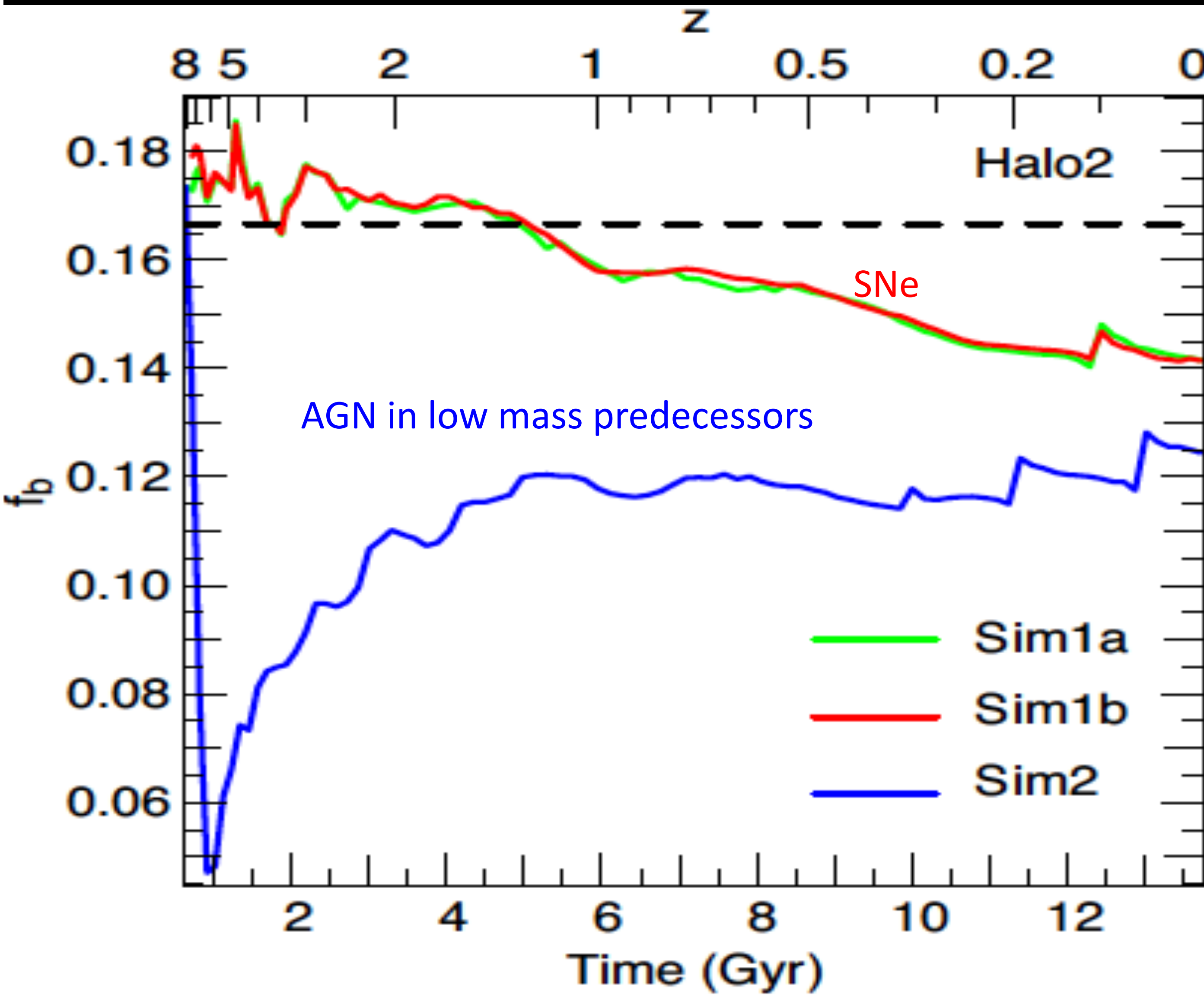


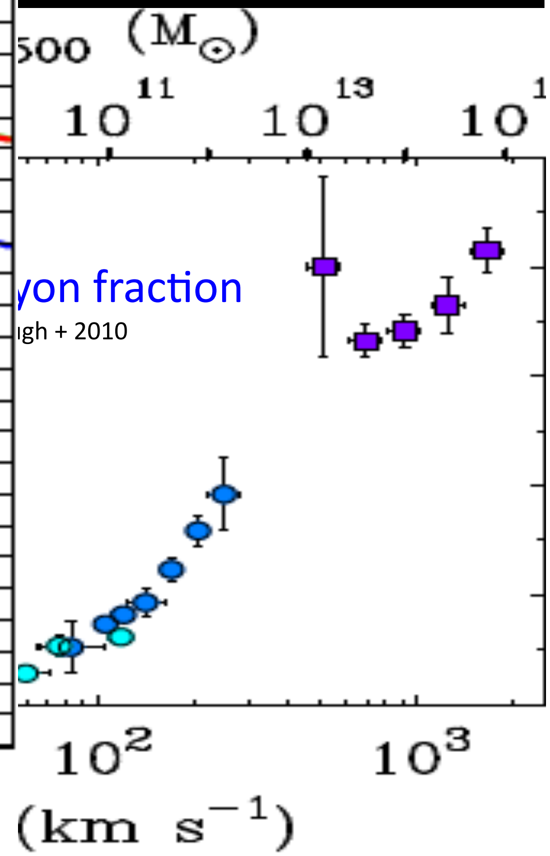
Dubois + 2012

AGN and BARYON EJECTION

Peirani + 2012

IMBH do the job!





how to enhance SFR: triggering by AGN

If AGN-driven outflows trigger star formation,

JS + C. Norman 2008

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

+ supernova heating

SFR = $\varepsilon M_{gas}/t_{ff}$

$$(p_{AGN}/p_g)^{1/2} \approx v_{jet}/\sigma$$

$$\varepsilon_{SN} = \sigma \; v_{cool} \; m_{*,SN} / E_{SN}$$

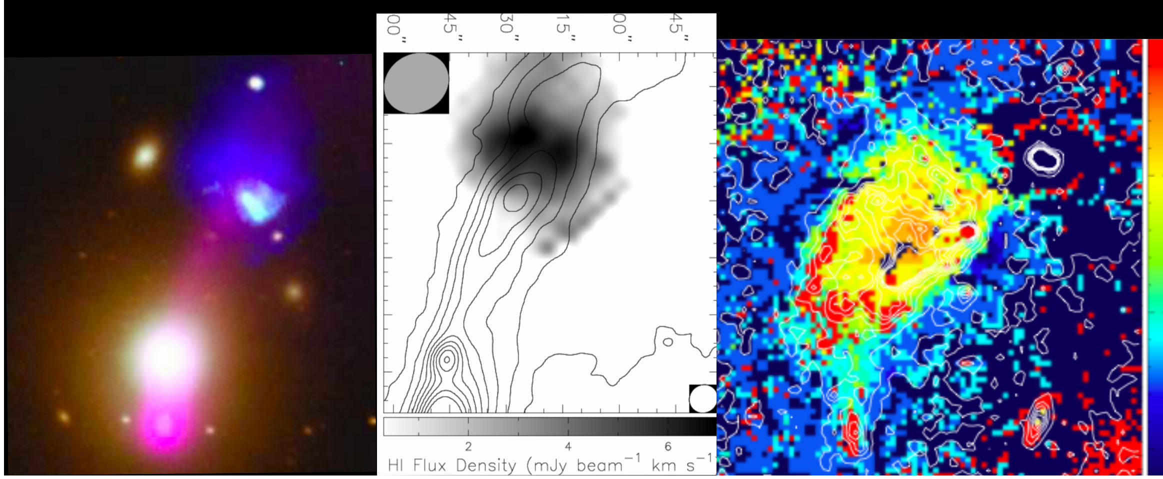
$$\dot{M}_* = (\epsilon_{SN}/\sigma) M_g (G p_g)^{1/2}$$

Klamer et al. 2006

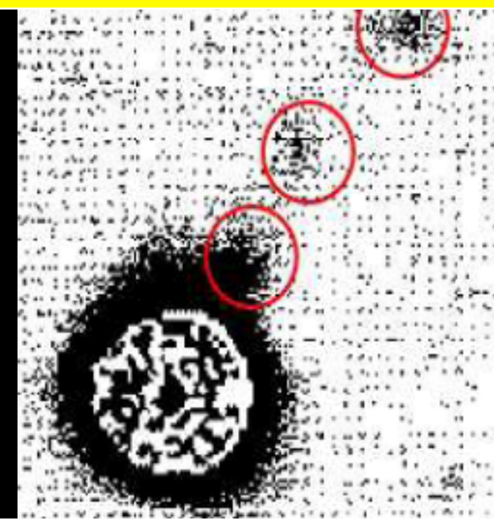
z = 4.7 quasar + CO

Minkowski's object

Croft et al. 2006



H_2 formation triggered by AGN



$$SFR = \varepsilon_{SN} M_{gas} / t_{ff}$$

- $SFR/M_* =$ constant means exponential SFR!
- Metallicity-dependent SFR is bad at low z: Z ↘ but M_{gas} ↗ with redshift

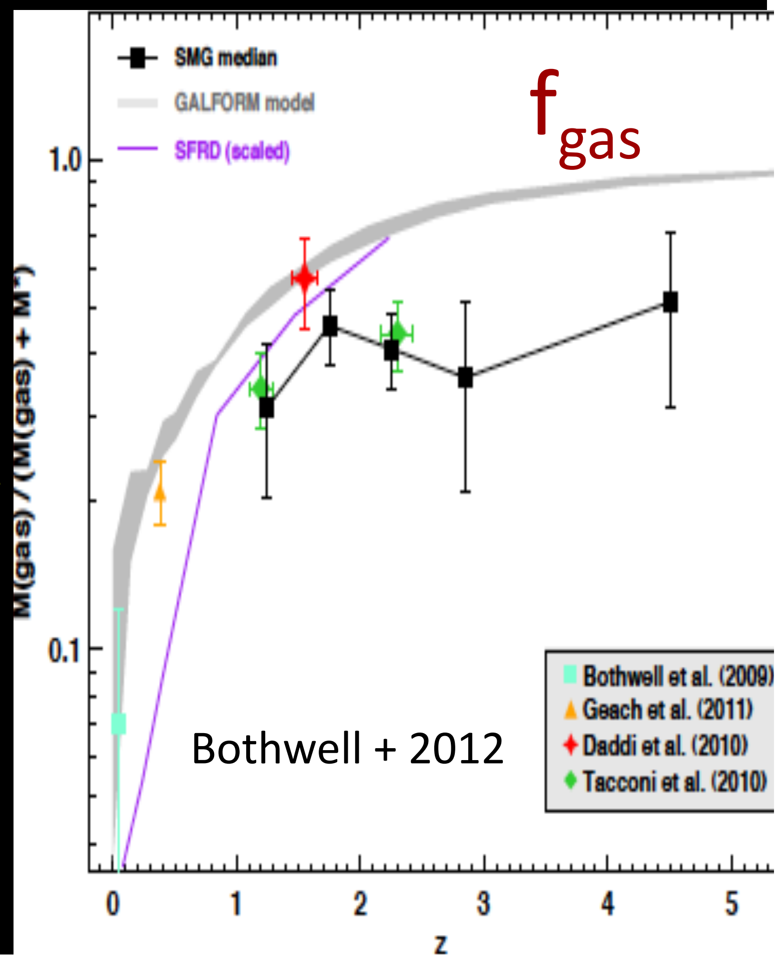
This is bad!

$$SFR=\varepsilon_{jet} M_{gas}/t_{jet}$$

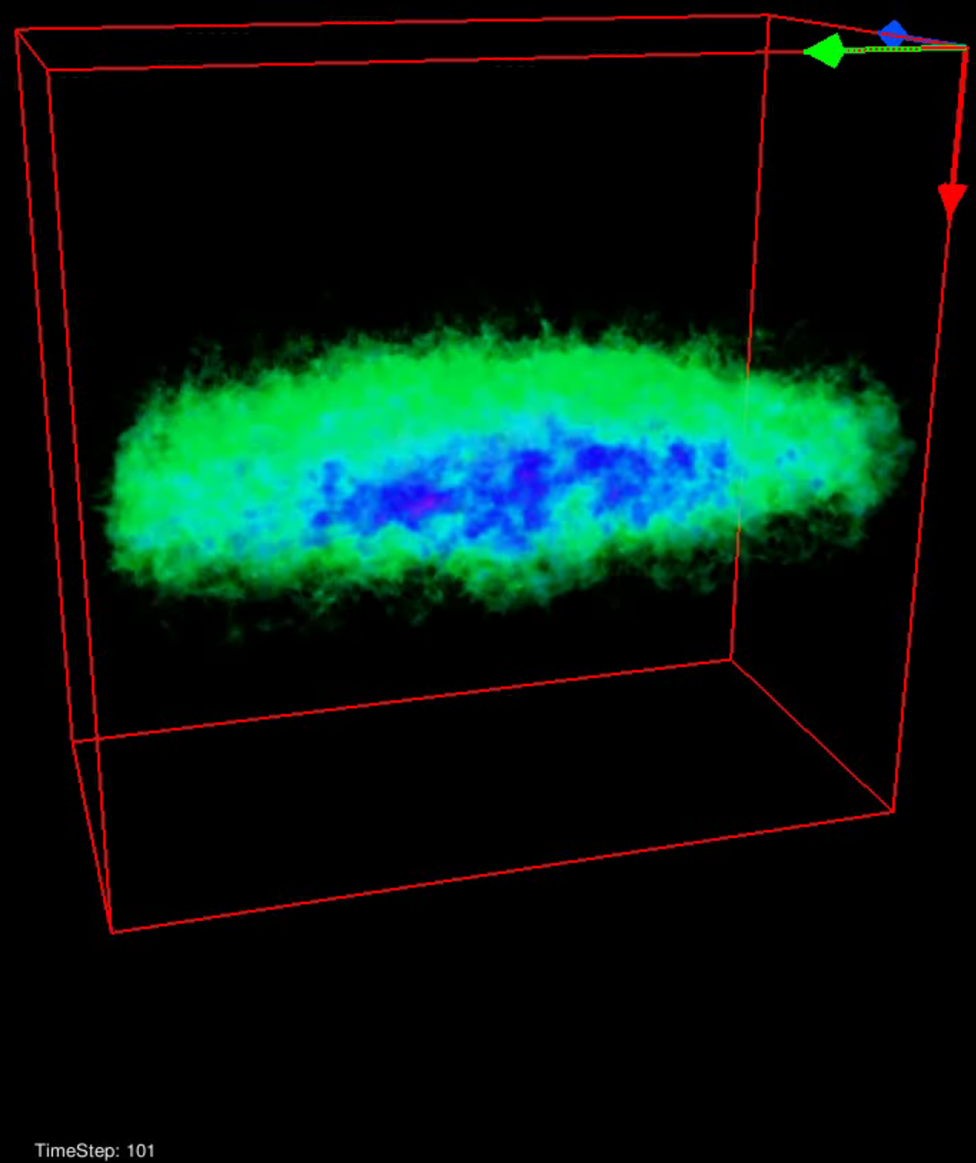
$$SSFR = f_{gas}\, \varepsilon_{jet} M_*/t_{jet} \sim \text{const at high z}$$
$$\sim f_{gas} \text{ at low z}$$

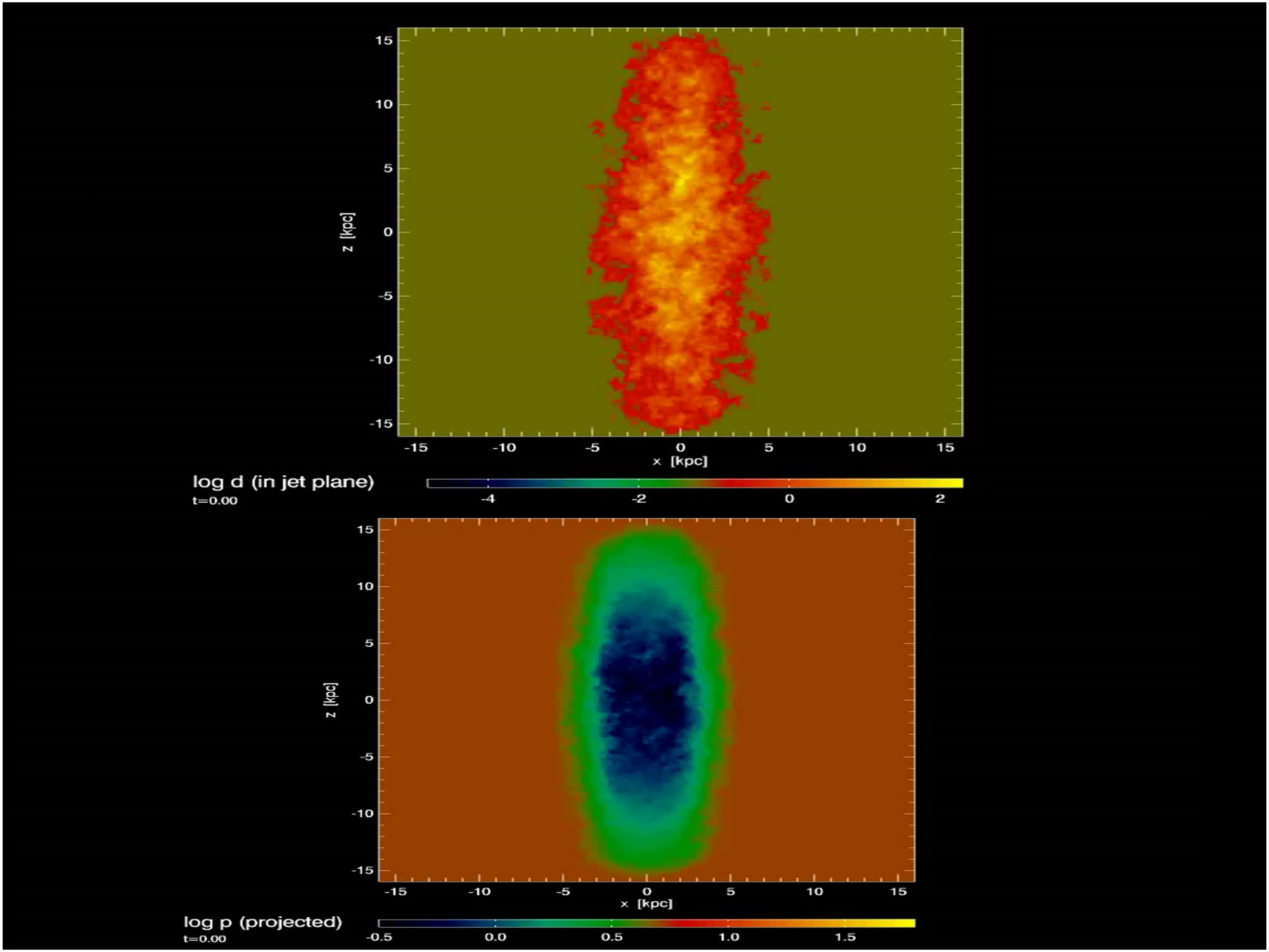
+ exponentially increasing, hence young and blue burst!

This is good!

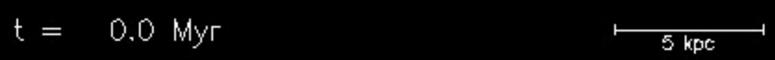


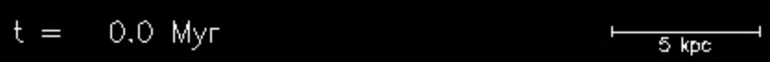
3-d N-body + hydro: RAMSES code (simulations by V. Gaibler, S. Khochfar, M. Krause, JS 2012)
100 pc resolution, 10 cm^{-3} SF threshold



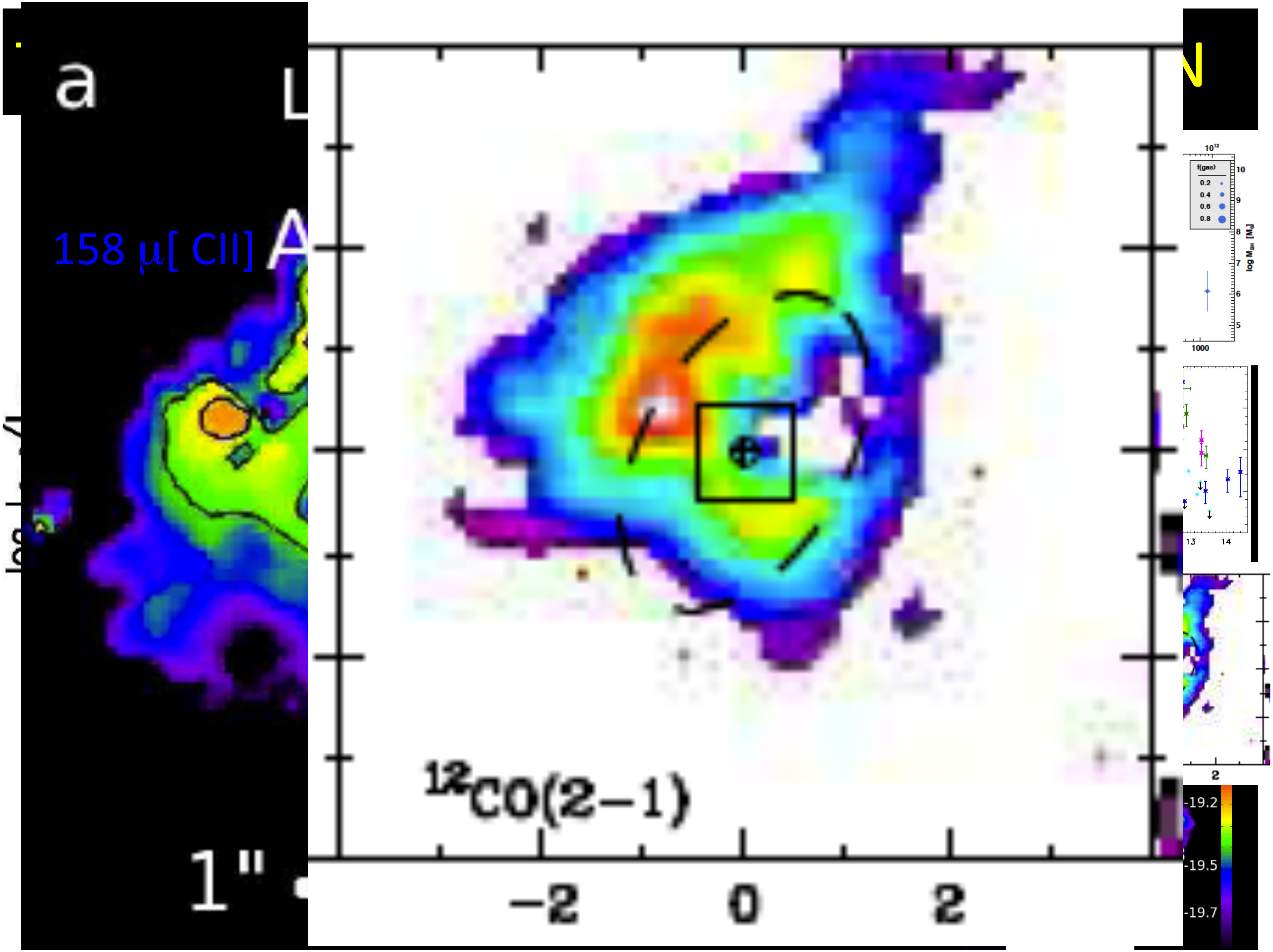

z [kpc]
x [kpc]
log d (in jet plane)
t=0.00
-4
-2
0
2
z [kpc]
x [kpc]
log p (projected)
t=0.00
-0.5
0.0
0.5
1.0
1.5

JET-INDUCED STAR FORMATION





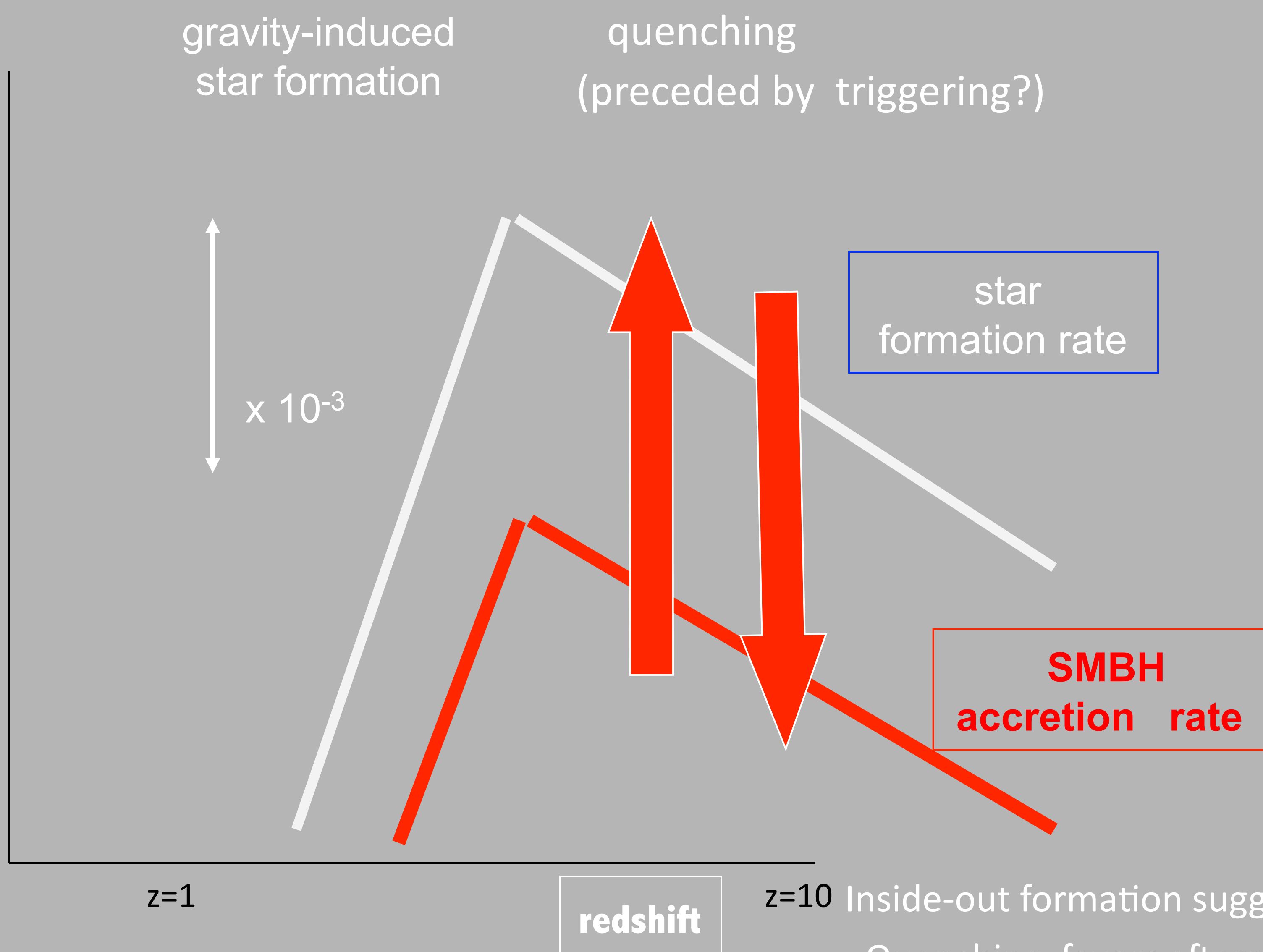
Star formation



a
158 μ[CII]
1"
12CO(2−1)
−2
0
2
f(gas)
0.2
0.4
0.6
0.8
log M_BH [M_⊙]
1000
13
14
-19.2
-19.5
-19.7

Active galactic nuclei:

aftermath, precursor or coeval to star formation?



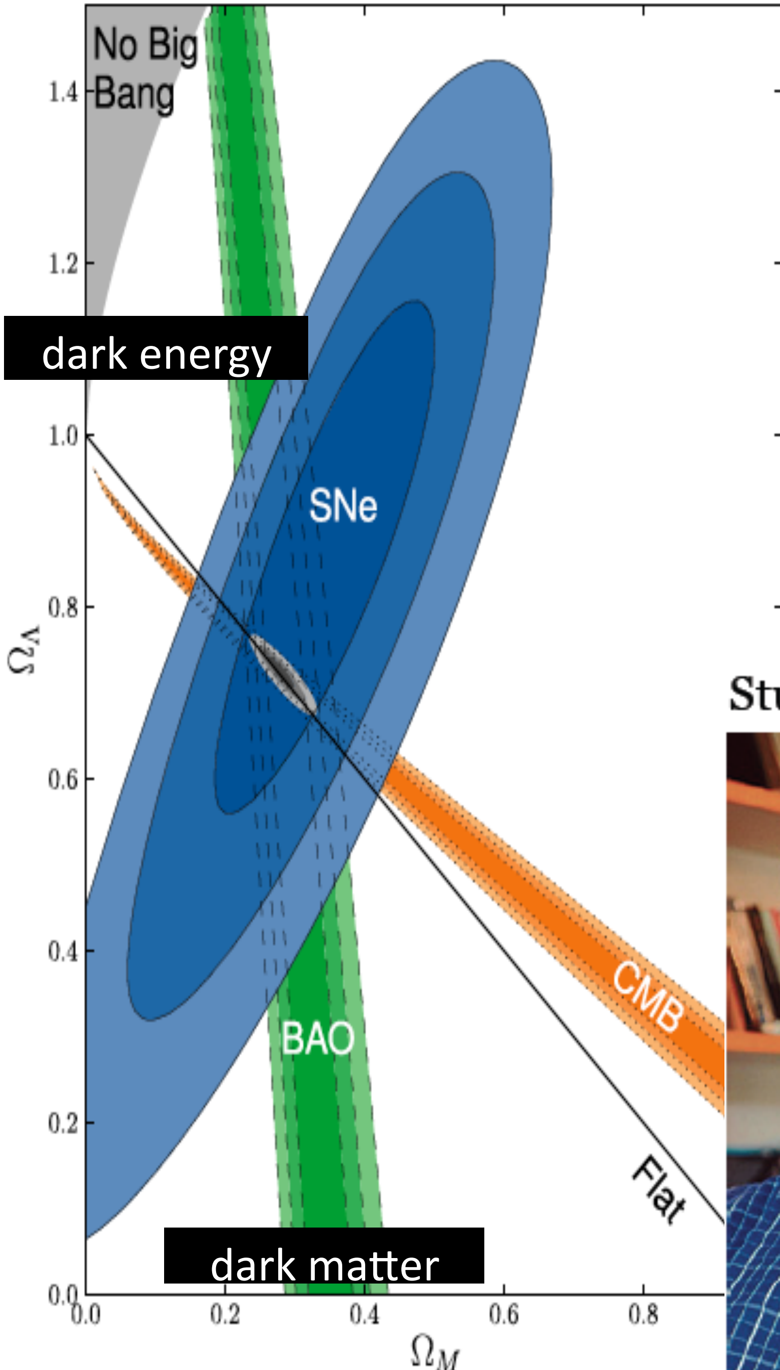
Inside-out formation suggests precursor

Quenching favors aftermath

THE THIN GALAXY PROBLEM

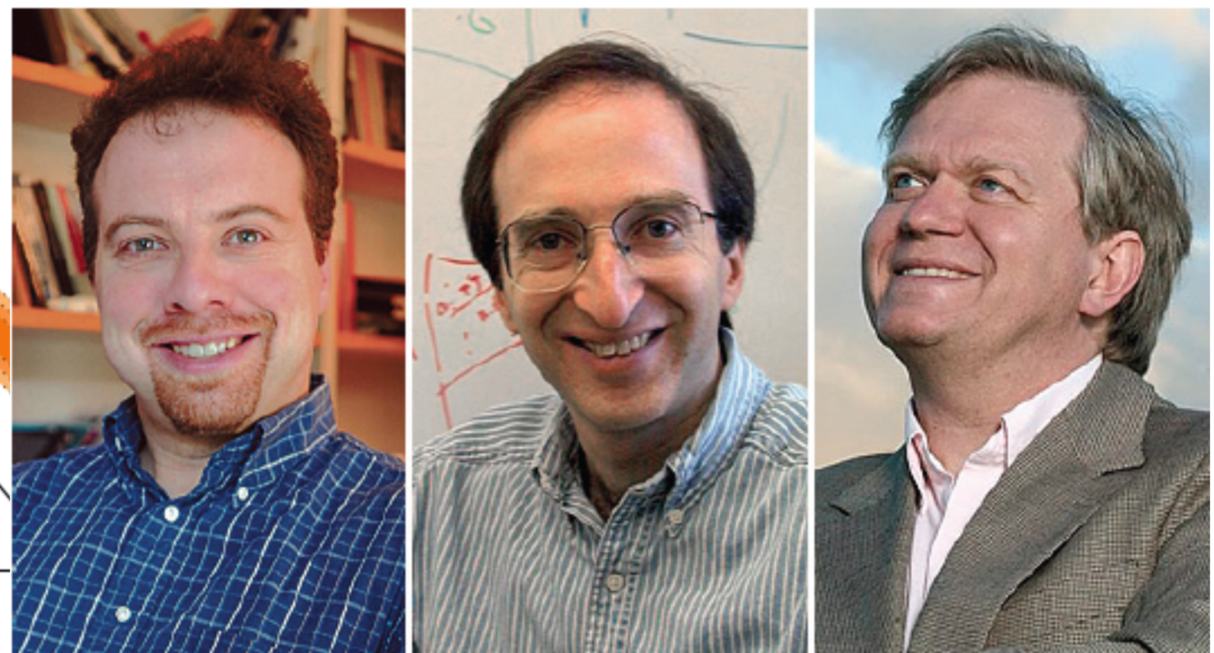
THE SUPERMASSIVE BLACK HOLE PROBLEM

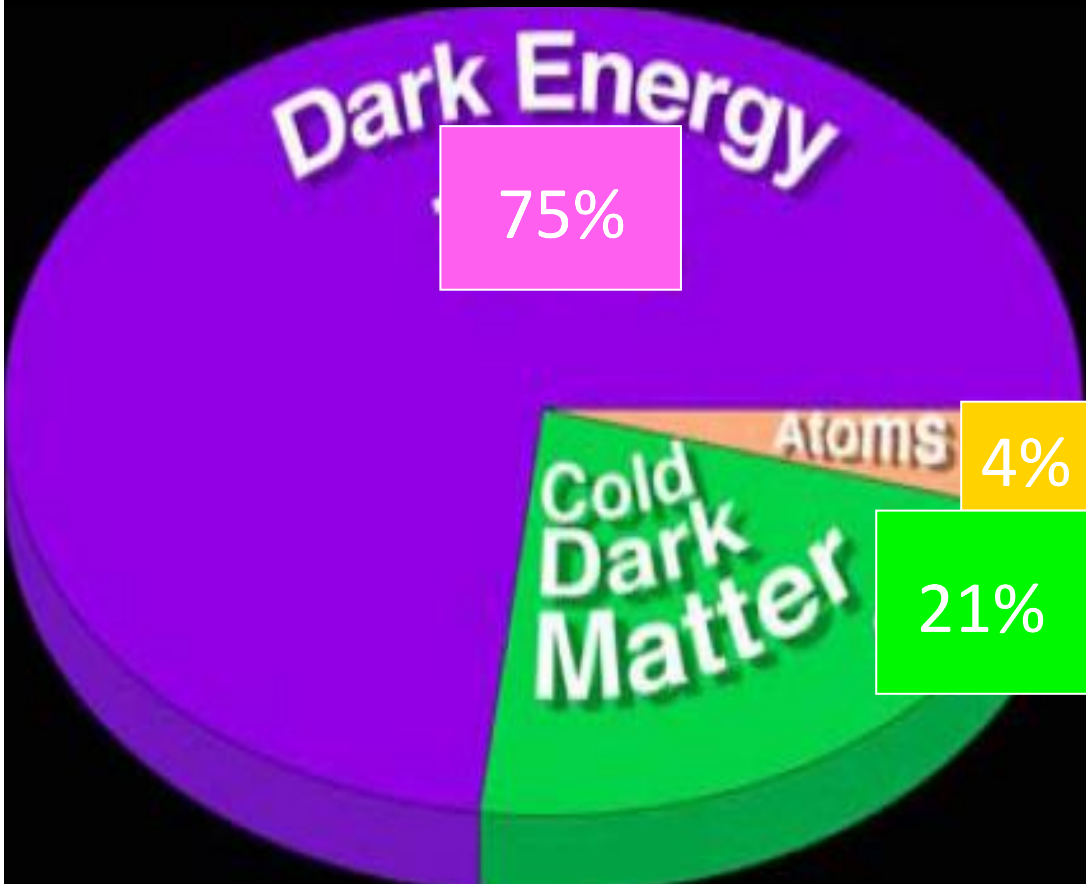
most of the mass-energy in the universe is dark!



Amanullah et al 2010

Studies of Universe's Expansion Win Physics Nobel





observe

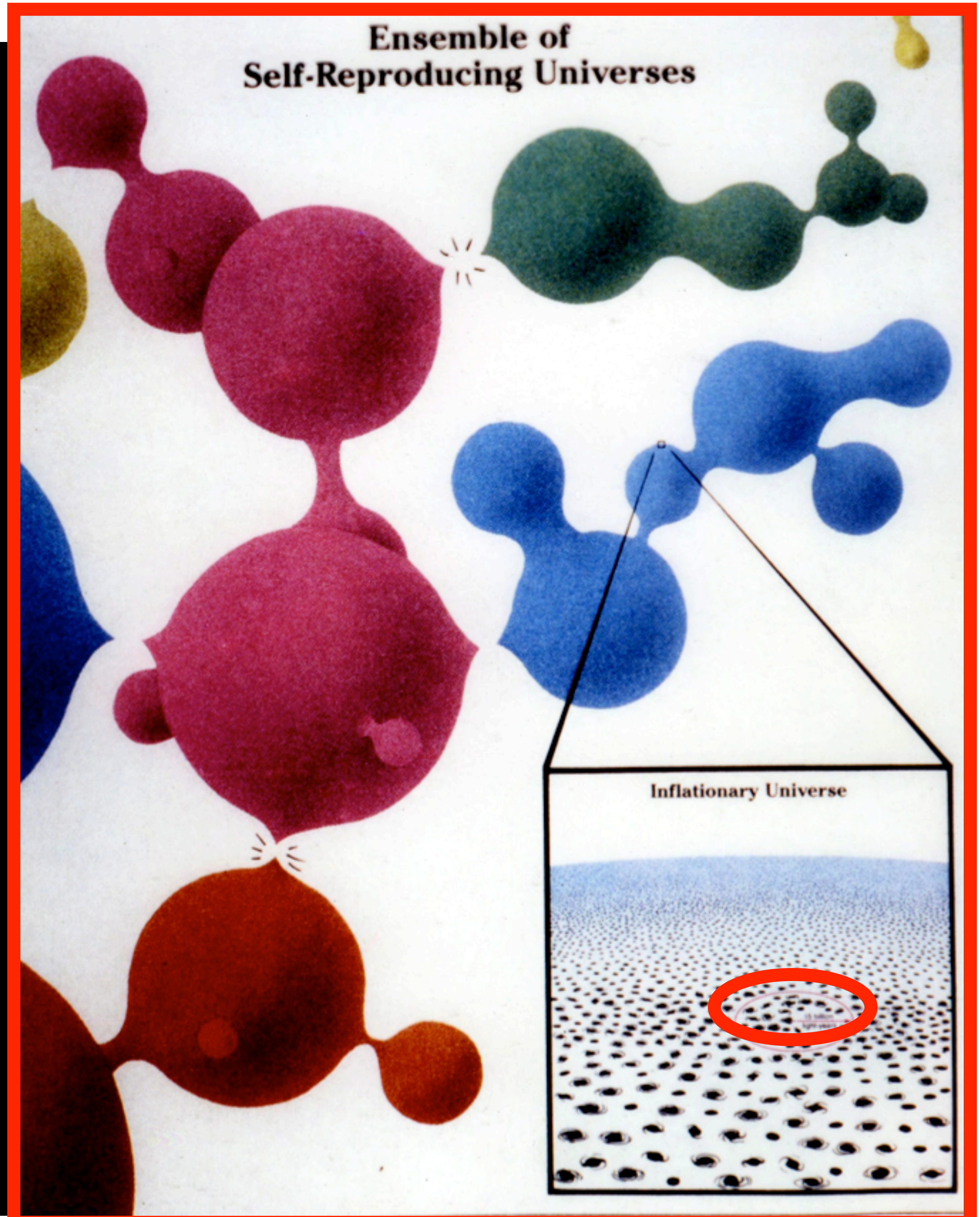
$$\rho_{\rm vac} \approx 10^{-10}\,\mathrm{eV}^4$$

predict

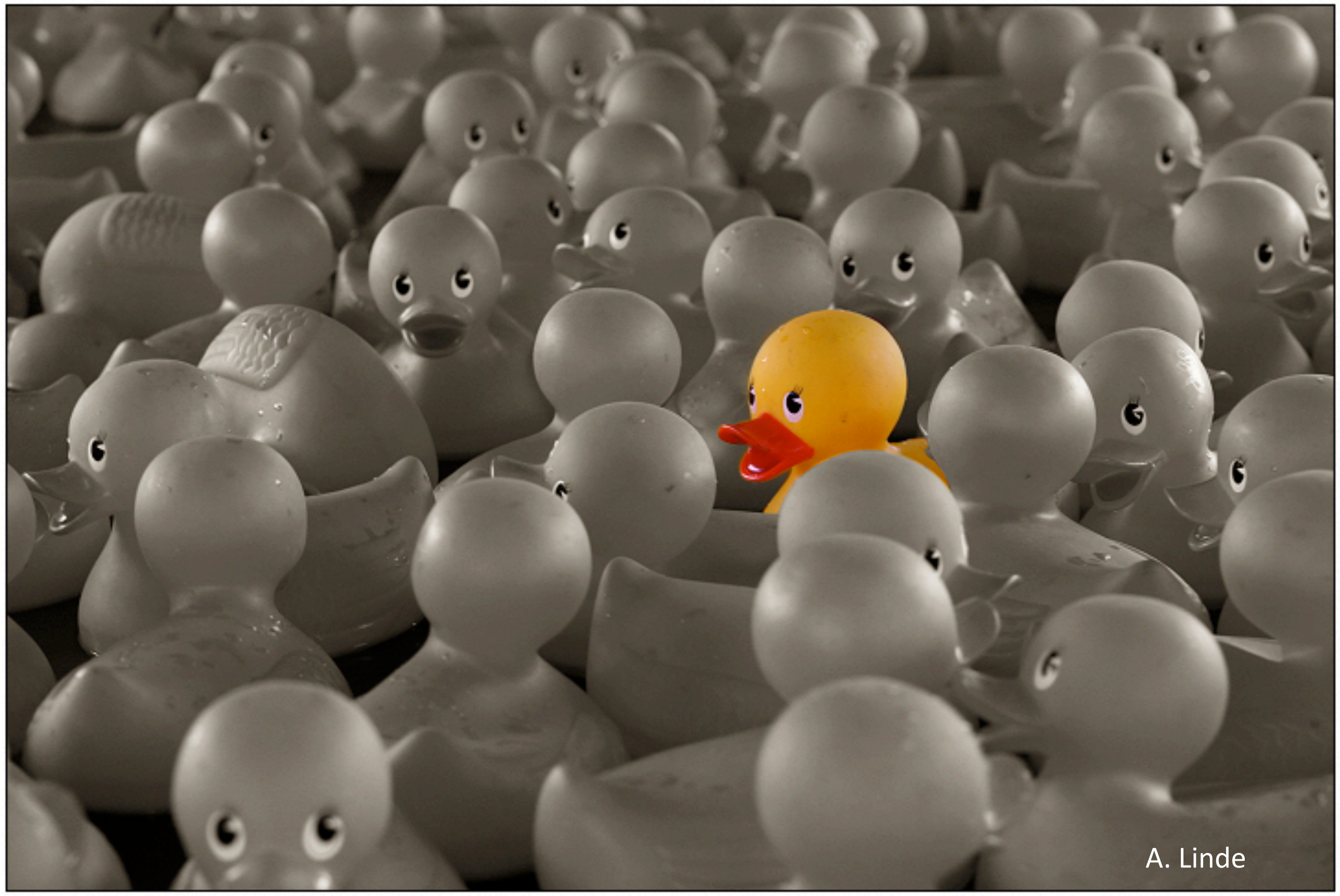
$$M \sim M_{Planck} = G^{-1/2} = 10^{28}\ \mathrm{eV} \;\Rightarrow\; \rho_{vac} \sim 10^{112}\,\mathrm{eV}^4$$

The worst prediction in physics!

Motivates multiverse explanation of why dark energy is so small

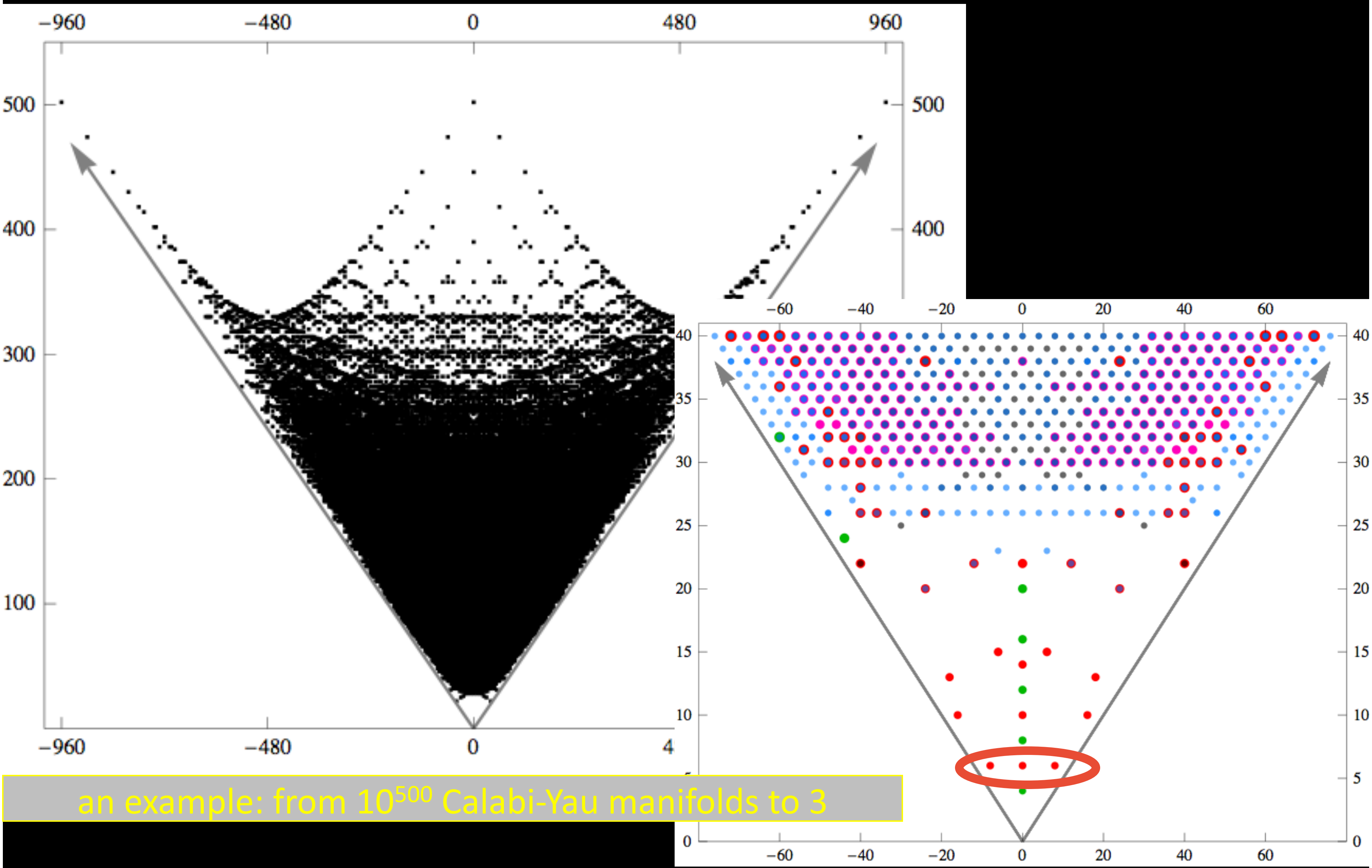


We live in one tiny pocket where the value of the cosmological constant is consistent with our kind of life — Leonard Susskind

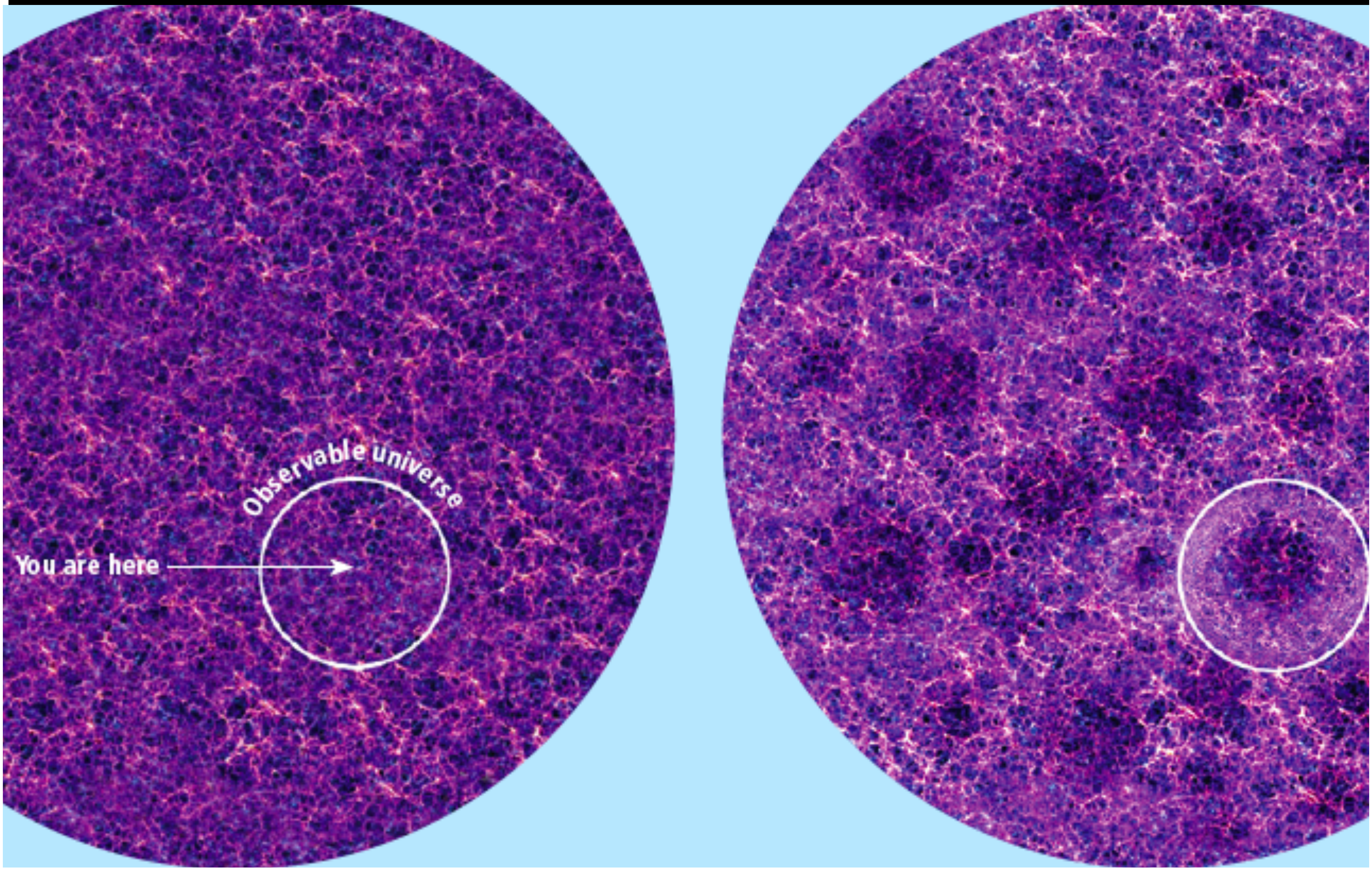


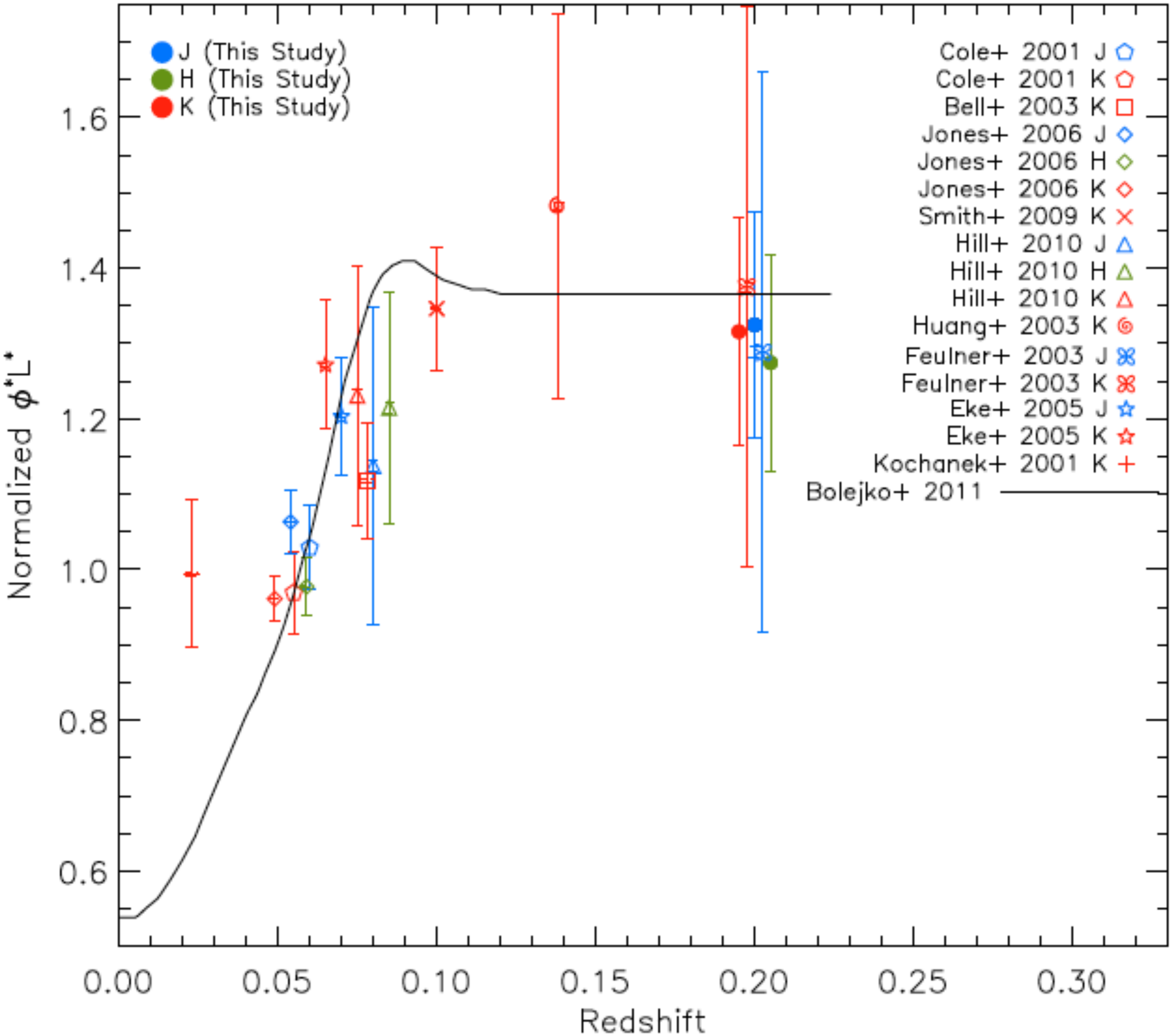
The multiverse theory can’t make any predictions … it can explain anything… — George Ellis

A physics solution?



an example: from 10^{500} Calabi-Yau manifolds to 3


Observable universe
You are here


J (This Study)
H (This Study)
K (This Study)
Cole+ 2001 J
Cole+ 2001 K
Bell+ 2003 K
Jones+ 2006 J
Jones+ 2006 H
Jones+ 2006 K
Smith+ 2009 K
Hill+ 2010 J
Hill+ 2010 H
Hill+ 2010 K
Huang+ 2003 K
Feulner+ 2003 J
Feulner+ 2003 K
Eke+ 2005 J
Eke+ 2005 K
Kochanek+ 2001 K
Bolejko+ 2011
Normalized φ*L*
Redshift
0.00 0.05 0.10 0.15 0.20 0.25 0.30
0.6 0.8 1.0 1.2 1.4 1.6

Keenan+2012

DARK MATTER IS AN URGENT PROBLEM

DETECTION IN MULTIPLE WINDOWS IS ESSENTIAL

- **hints from direct detection**
- **hints from γ rays**
- **may need to go to more complicated models**

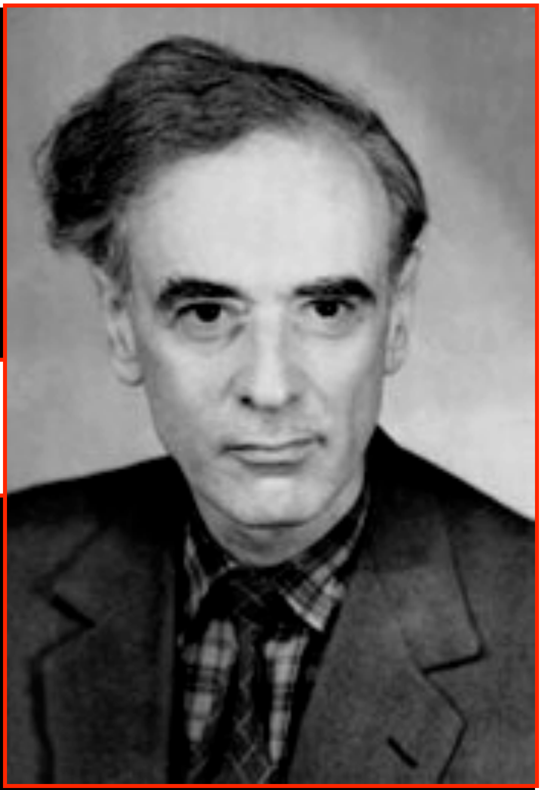
IF WE DETECT DM, NEED RESURRECTION VIA ASTROPHYSICS

IF WE FAIL, RESURRECTION VIA NEW FUNDAMENTAL PHYSICS

AS FOR DARK ENERGY: NO SOLUTION IN SIGHT.....

Landau on Cosmologists

Often in Error, Never in Doubt!

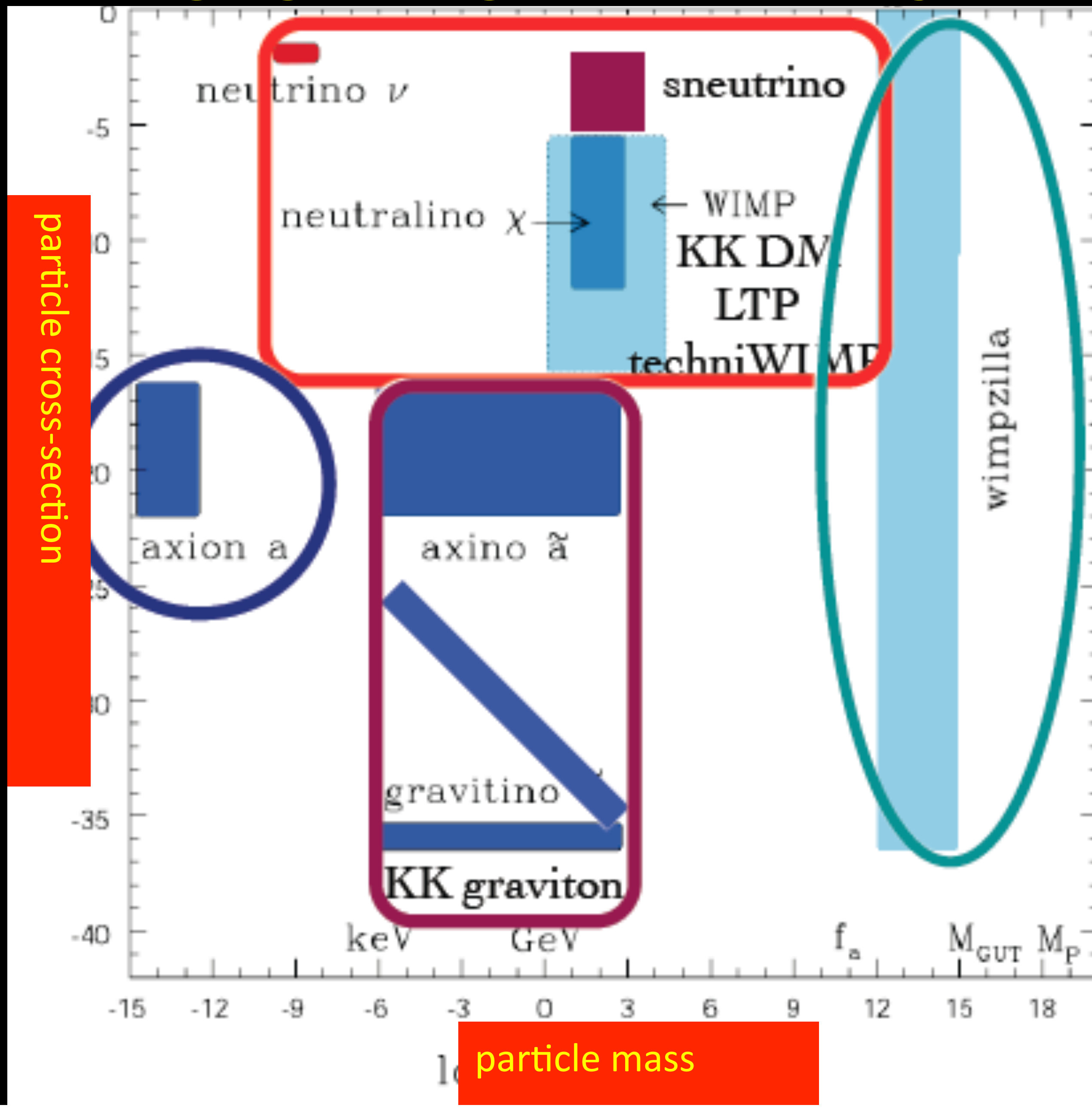


Alternatives:

we may hope for a fundamental physics theory of dark energy...........

or seek an astrophysical explanation

WIMPS or nonWIMPs



L. Roszkowski

FUTURE TELESCOPES

WILL RESOLVE THESE PROBLEMS…& SUPERCOMPUTERS WILL SIMULATE THEM