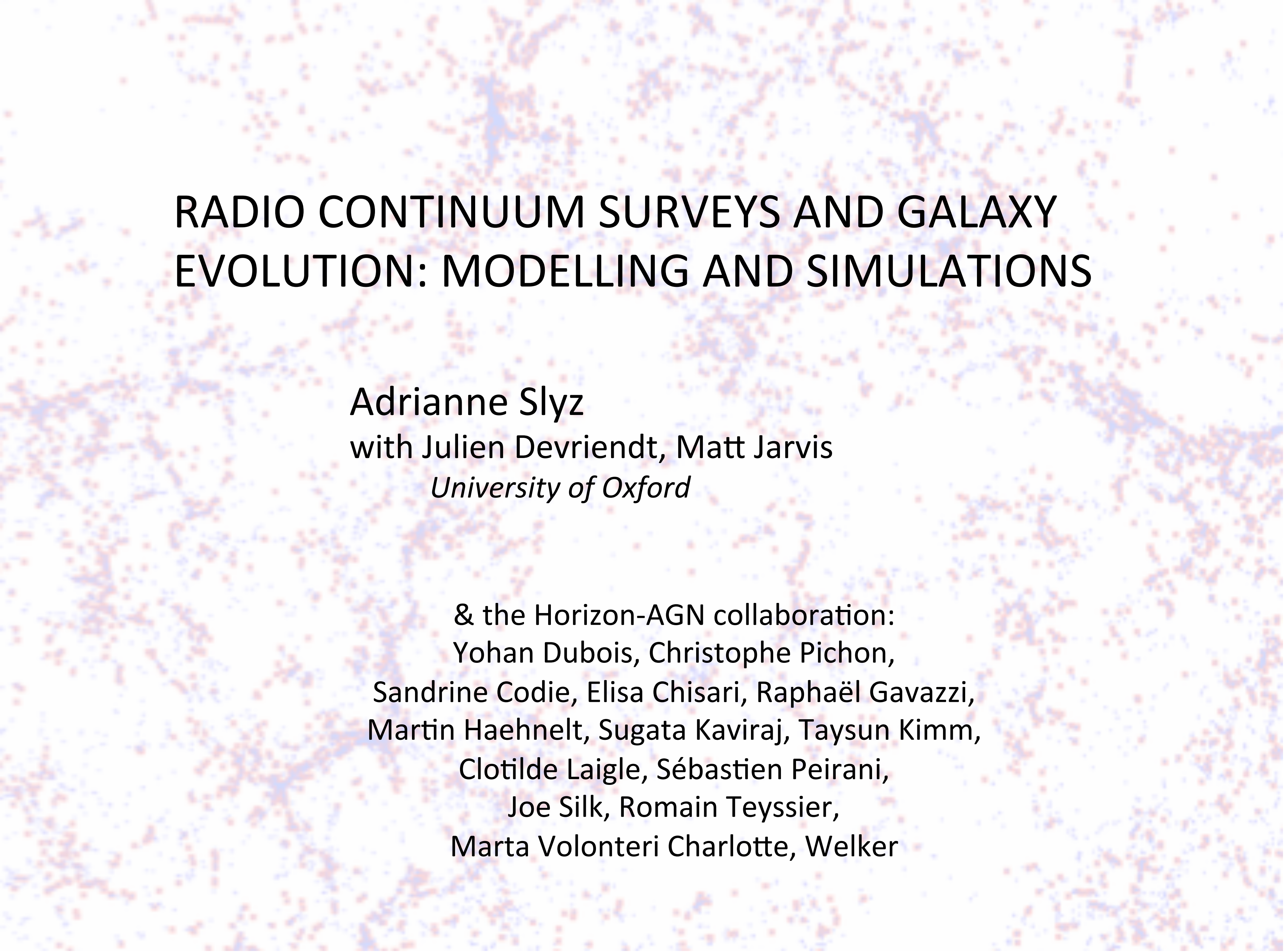


RADIO CONTINUUM SURVEYS AND GALAXY EVOLUTION: MODELLING AND SIMULATIONS

Adrianne Slyz
with Julien Devriendt, Matt Jarvis
University of Oxford

& the Horizon-AGN collaboration:
Yohan Dubois, Christophe Pichon,
Sandrine Codie, Elisa Chisari, Raphaël Gavazzi,
Martin Haehnelt, Sugata Kaviraj, Taysun Kimm,
Clotilde Laigle, Sébastien Peirani,
Joe Silk, Romain Teyssier,
Marta Volonteri Charlotte, Welker

SKADS Simulated Sky (S^3)

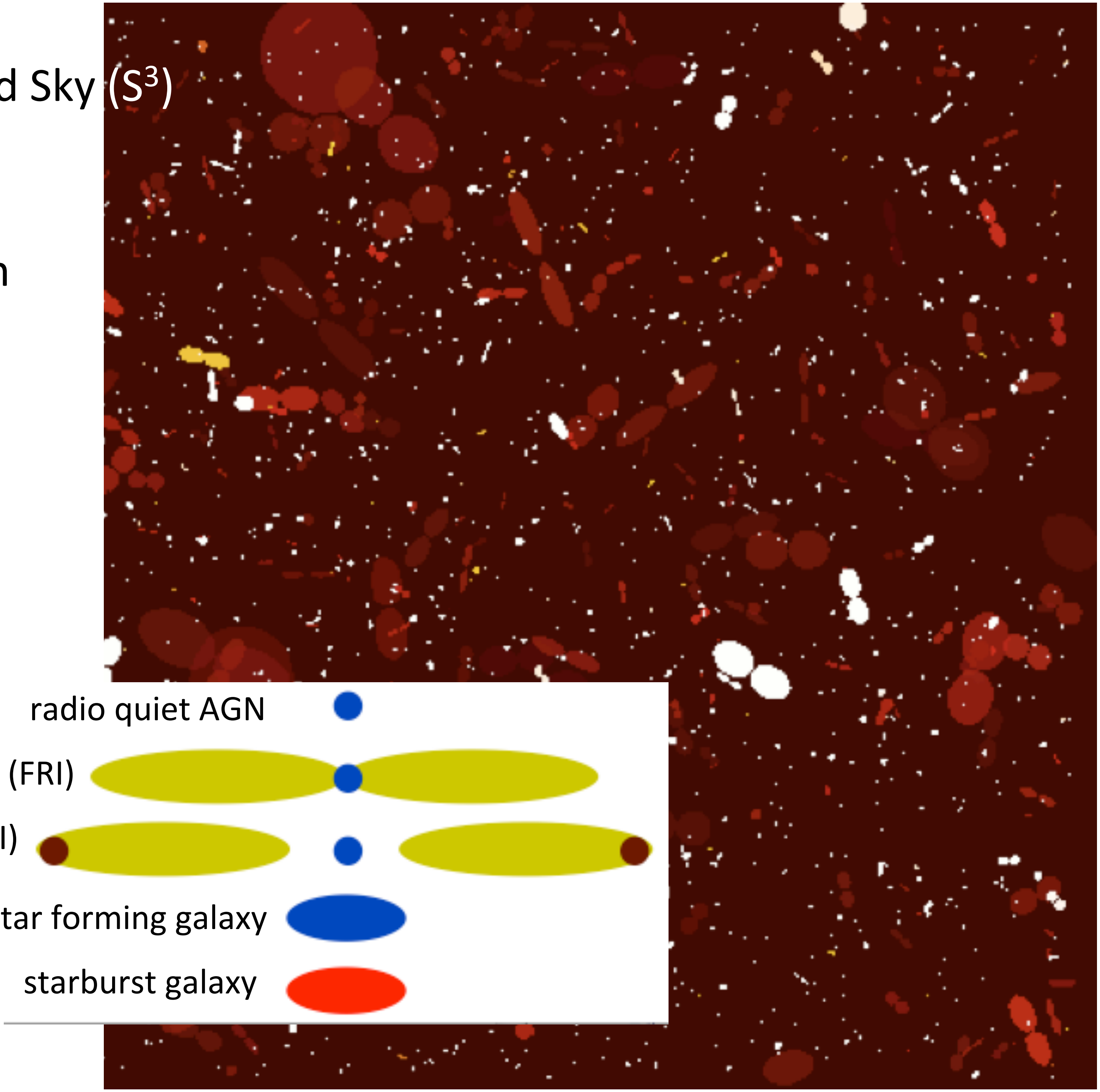
Semi-Empirical eXtragalactic radio continuum

Wilman et al. 2008

area: 20° X 20°

0 < redshift < 20

flux density > 10nJy

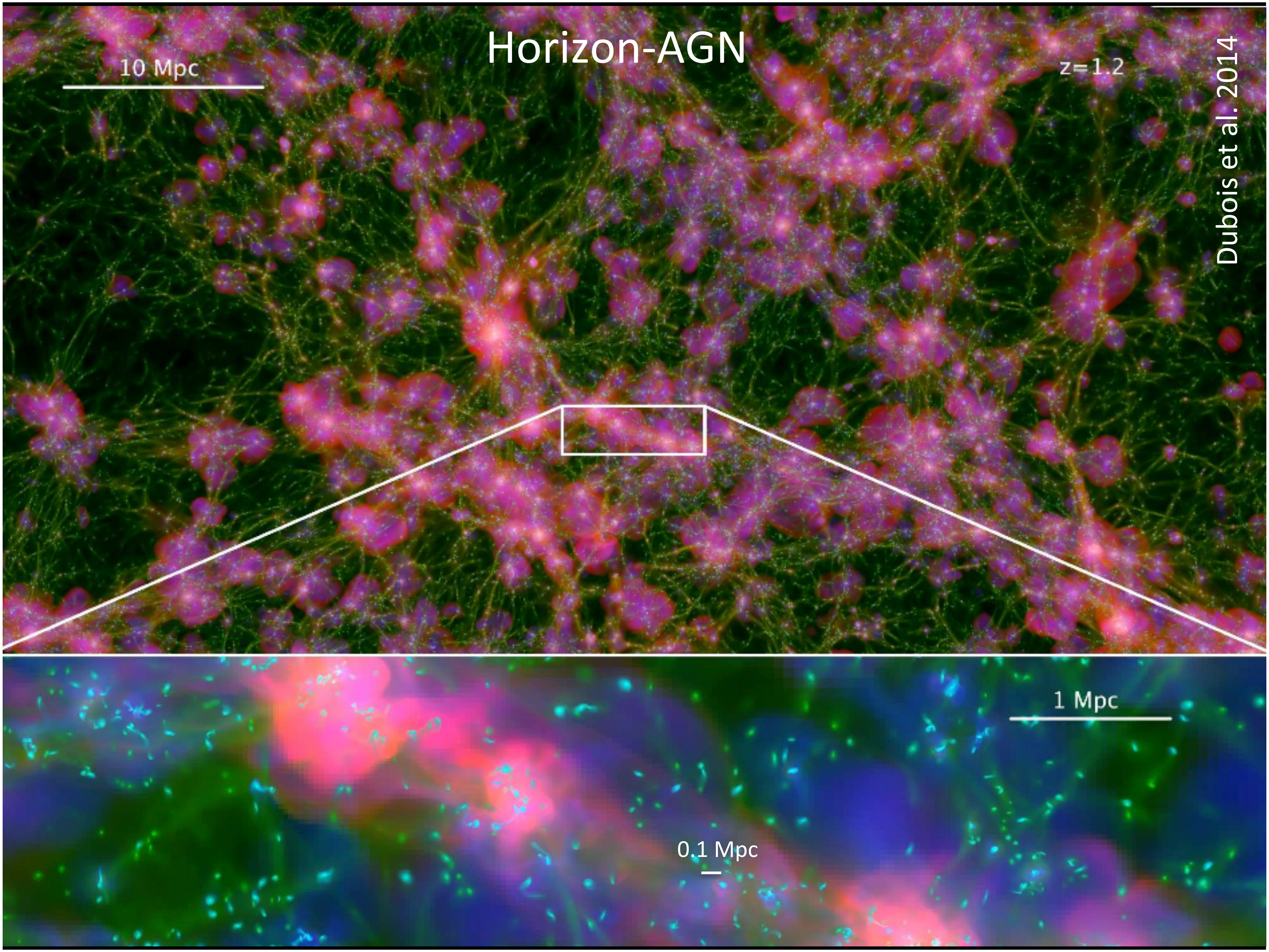


Limitations

use of extrapolated luminosity functions

lack of star forming/AGN hybrid galaxies

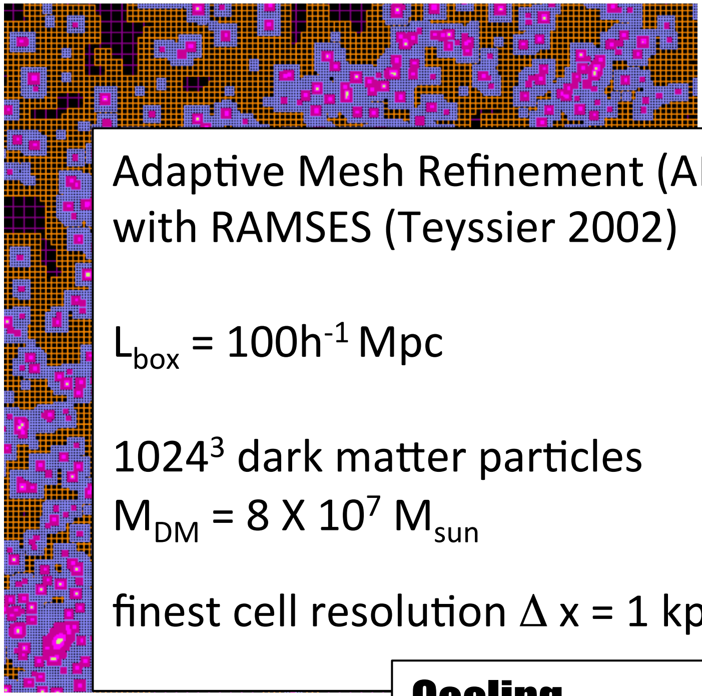
lack of small scale nonlinear clustering



Dubois et al. 2014

Horizon-AGN Simulation

http://www.horizon-simulation.org



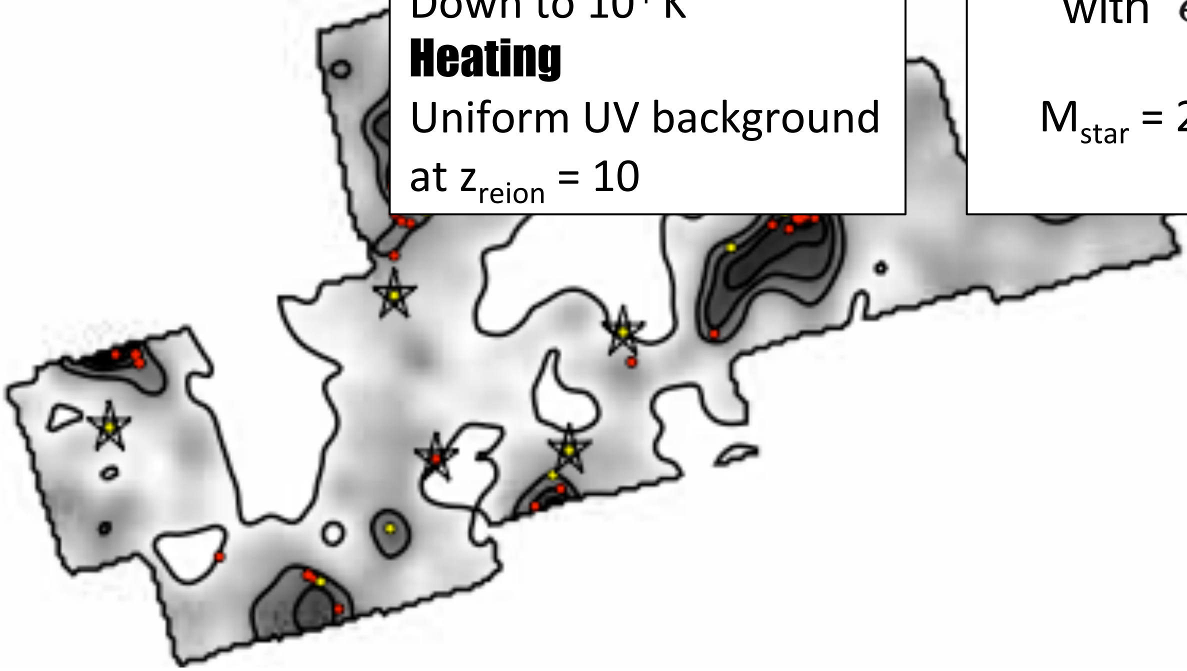
Adaptive Mesh Refinement (AMR) with RAMSES (Teyssier 2002)

$L_{box} = 100h^{-1}$ Mpc

1024^3 dark matter particles

$M_{DM} = 8 \times 10^7\ M_{sun}$

finest cell resolution $\Delta x = 1$ kpc



Cooling

Down to 10^4 K

Heating

Uniform UV background at $z_{reion} = 10$

Star formation

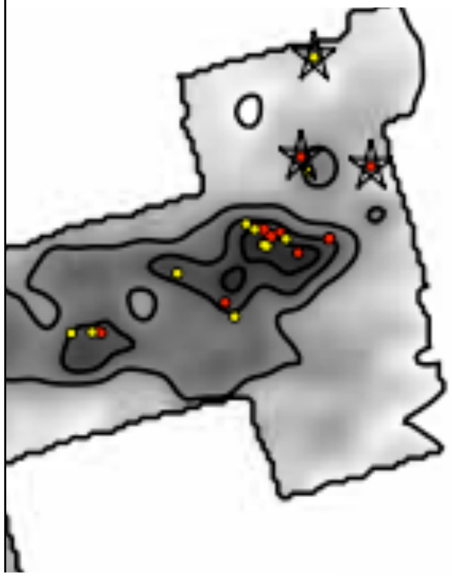
if $\rho > \rho_0$

($\rho_0 = 0.1$ H/cm^3)

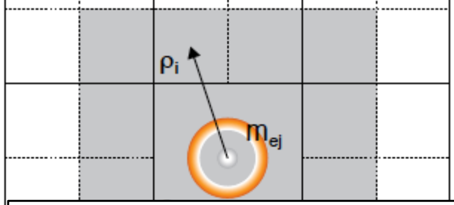
$$\dot{\rho}_* = \frac{\epsilon\,\rho}{t_{\mathrm{ff}}} \propto \rho^{3/2}$$

with $\epsilon = 0.02$

$M_{star} = 2 \times 10^6\ M_{sun}$



Stellar Feedback



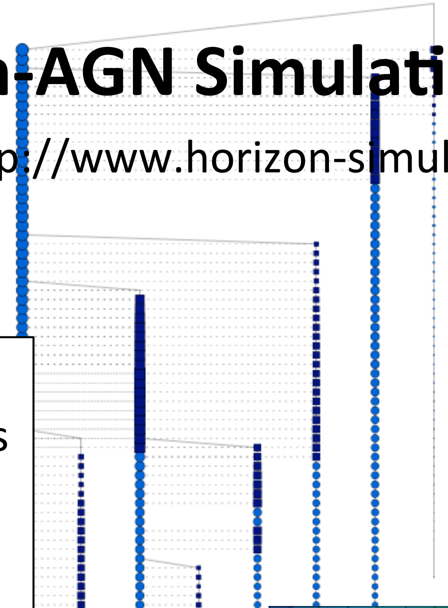
Assume Salpeter IMF

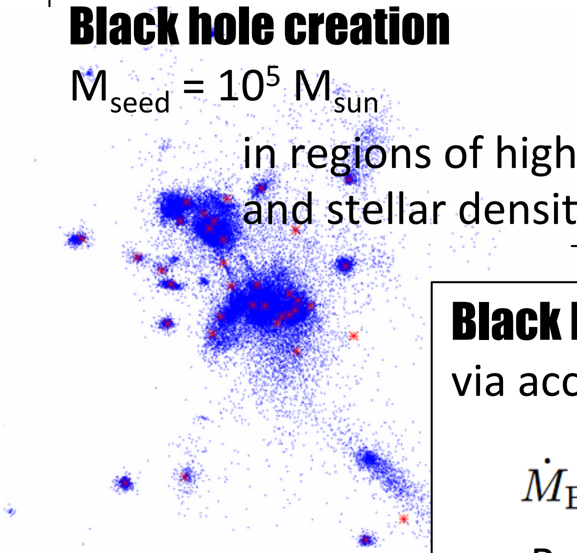
Stellar winds + SNII + SNIa

O, Fe, C, N, Si, Mg, H

Horizon-AGN Simulation

http://www.horizon-simulation.org





Black hole creation

$M_{seed} = 10^5 M_{sun}$

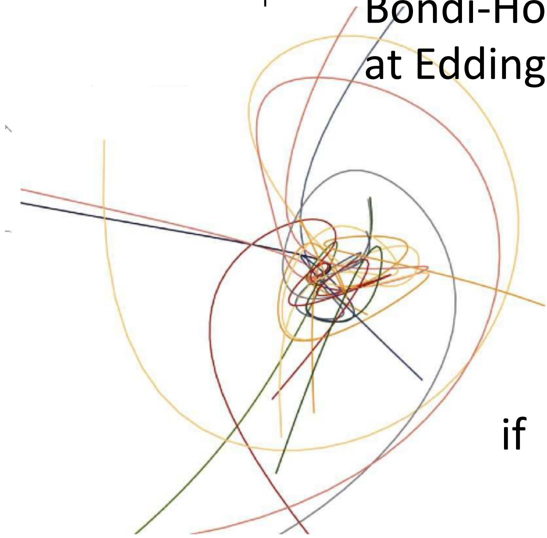
in regions of high gas and stellar densities

Black hole growth

via accretion and mergers

$$\dot{M}_{\rm BH} \propto \rho \frac{M_{\rm BH}^2}{c_{\rm s}^3}$$

Bondi-Hoyle capped at Eddington



Black hole feedback

2 modes: radio & quasar

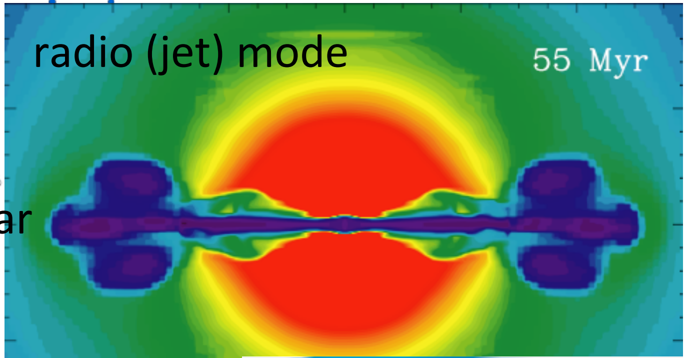
$$\chi = \frac{\dot{M}_{\rm BH}}{\dot{M}_{\rm Edd}}$$

if $\chi \leq 0.01$ then jet with

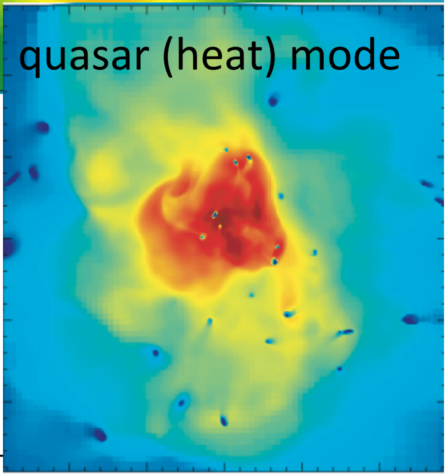
$$L_{radio} = 0.1 \dot{M}_{BH} c^2$$

if $\chi > 0.01$ then isotropic injection of thermal energy with

$$L_{quasar} = 0.015 \dot{M}_{BH} c^2$$

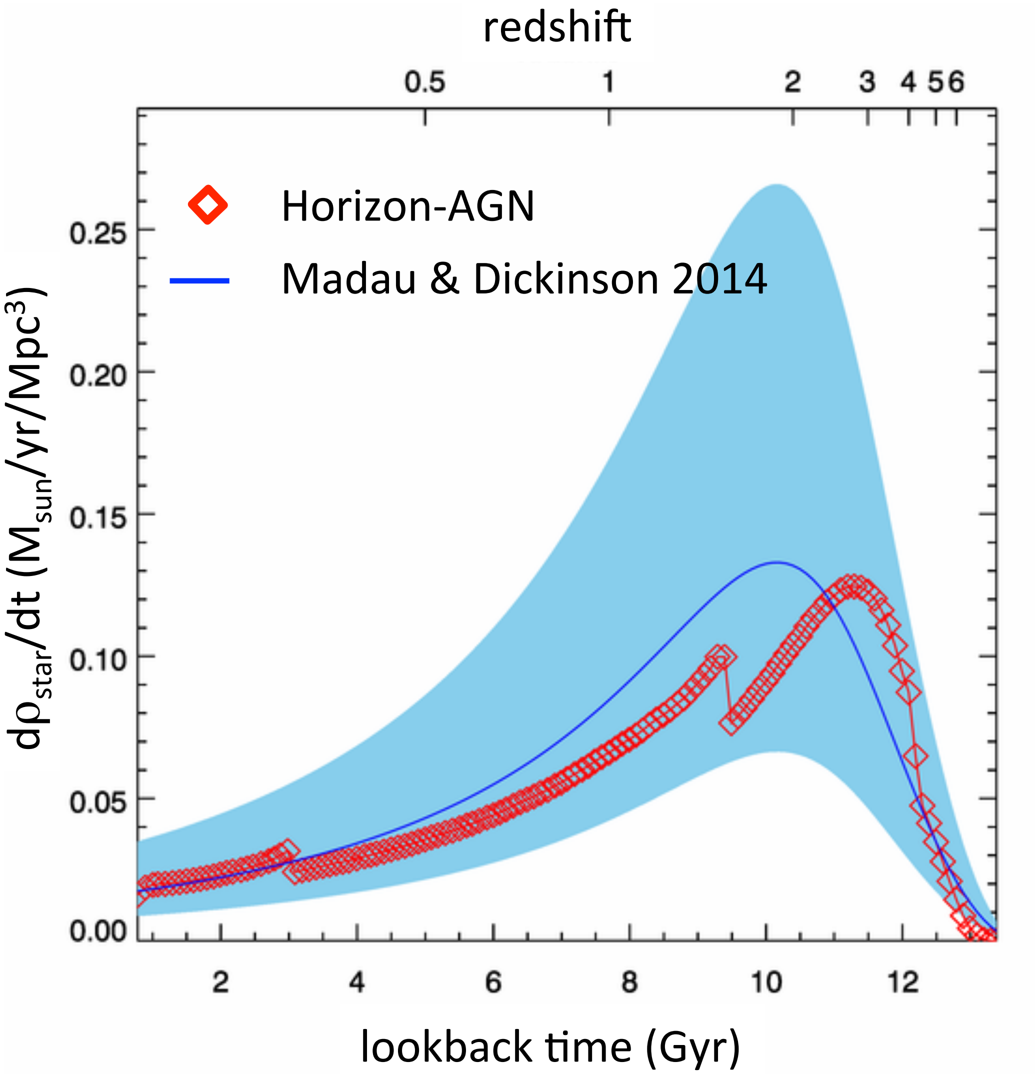


radio (jet) mode

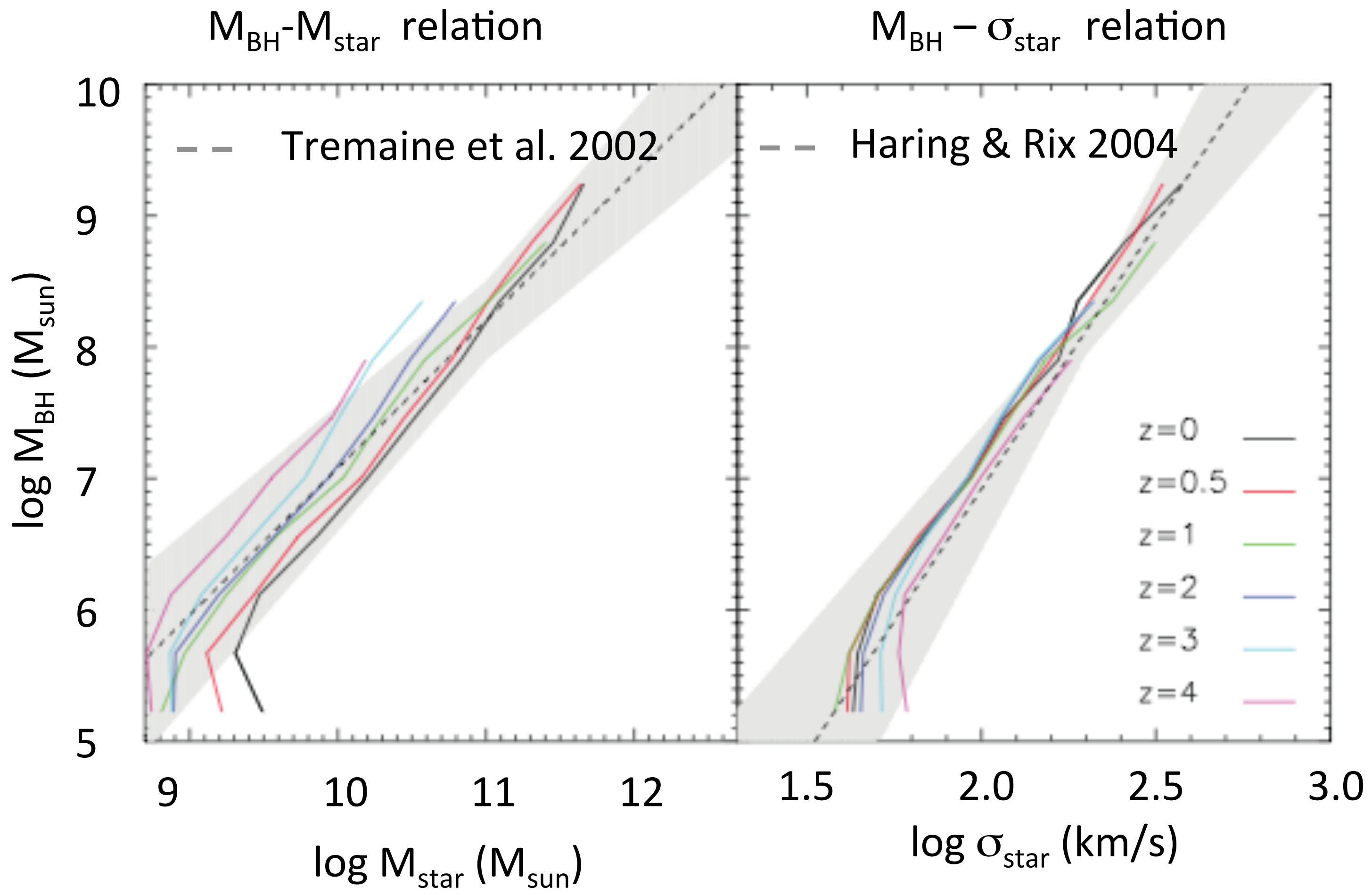


quasar (heat) mode

History of cosmic star formation rate density



Black hole scaling relations



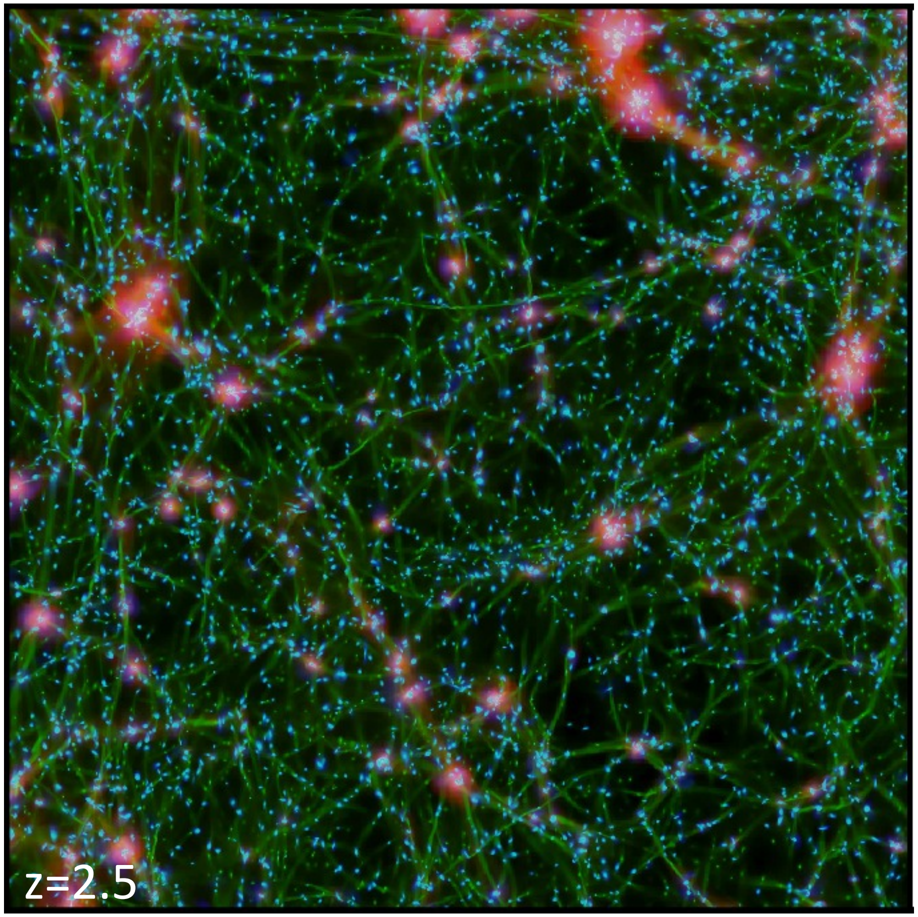
M_{BH}-M_{star} relation

$M_{BH} - \sigma_{star}$ relation

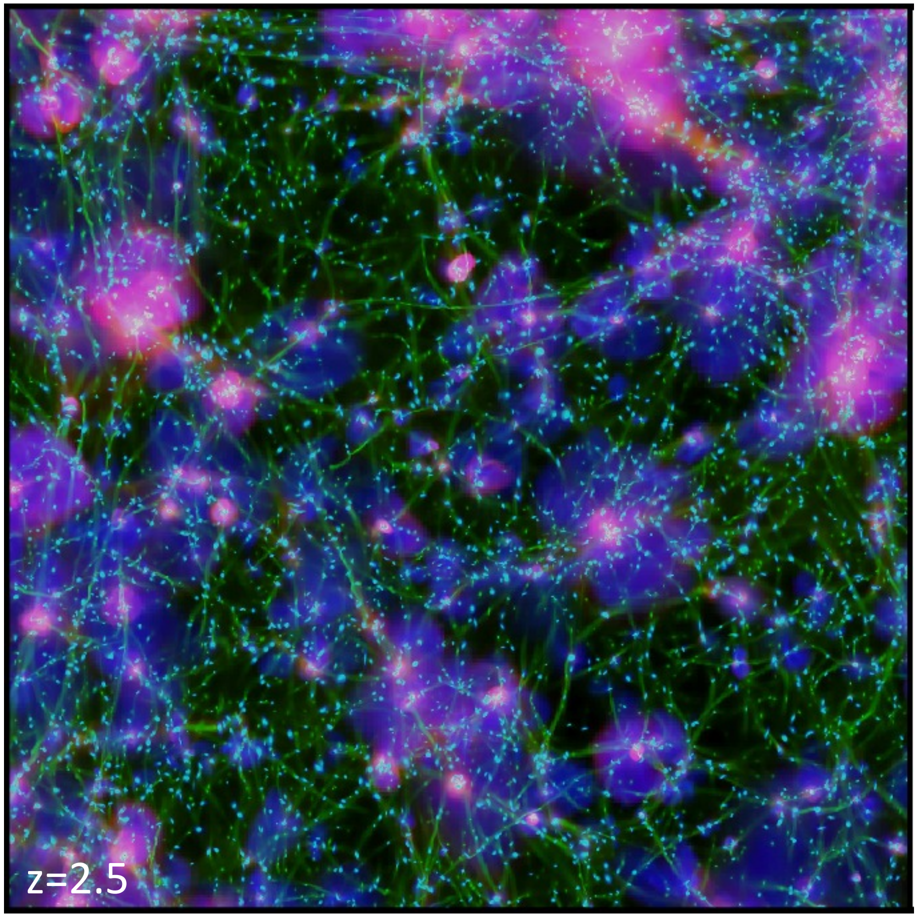
Dubois et al. 2012

What’s the role of AGN feedback?

Horizon no-AGN

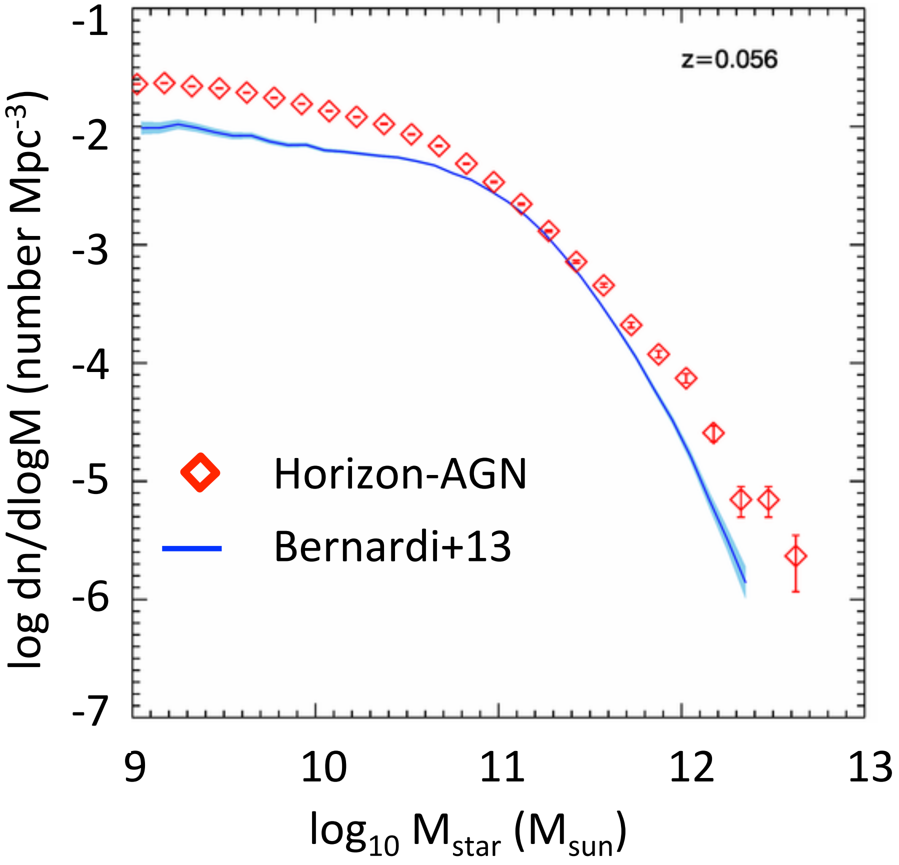


Horizon-AGN



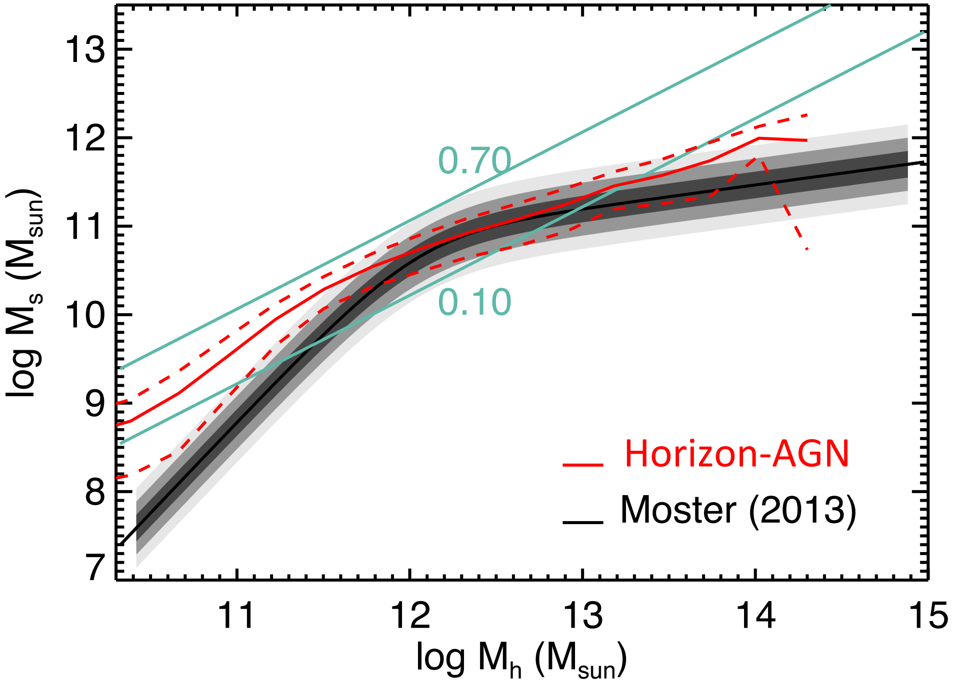
Stellar masses

Stellar mass function



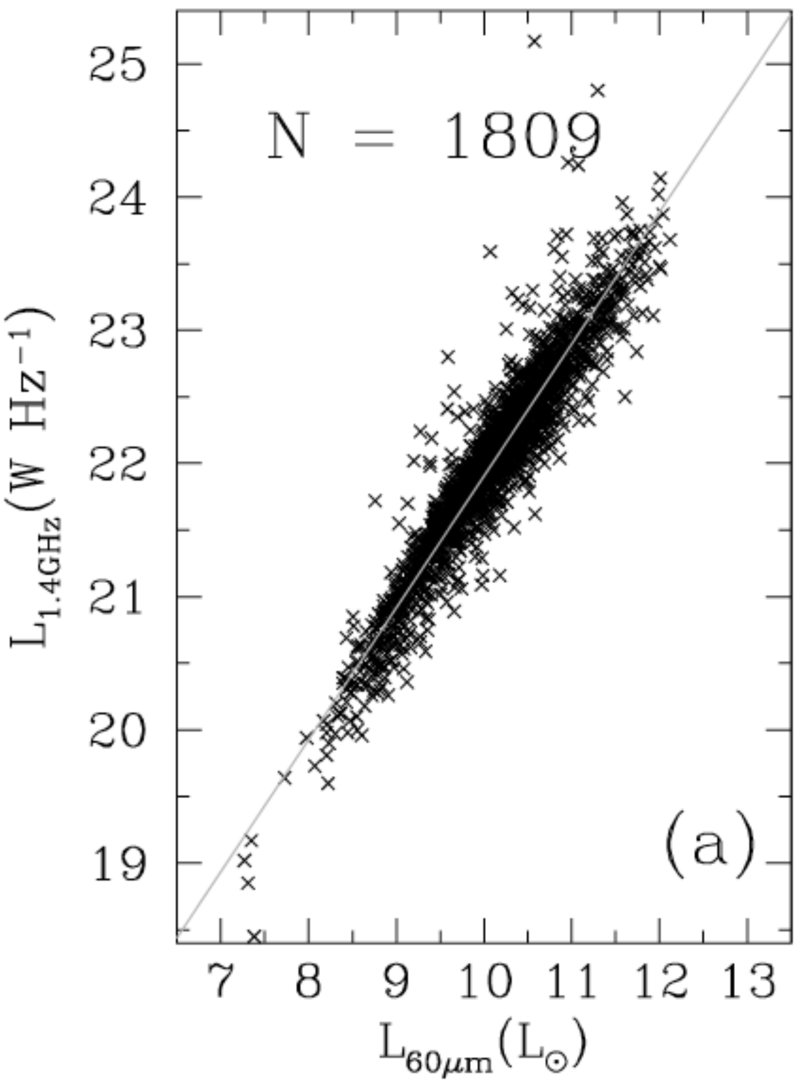
Kaviraj et al, in prep

Moster plot

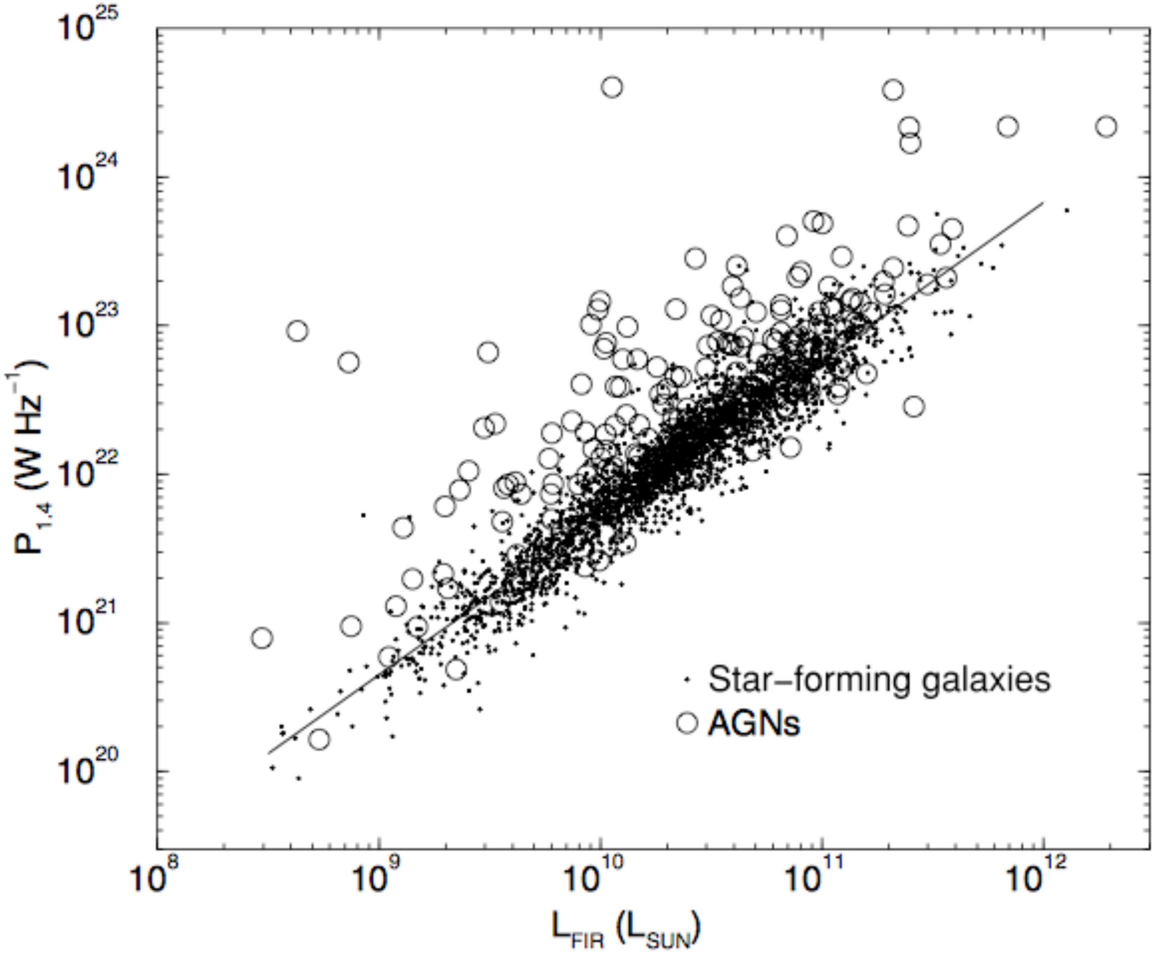


Dubois et al 2014

The FIR/Radio Correlation

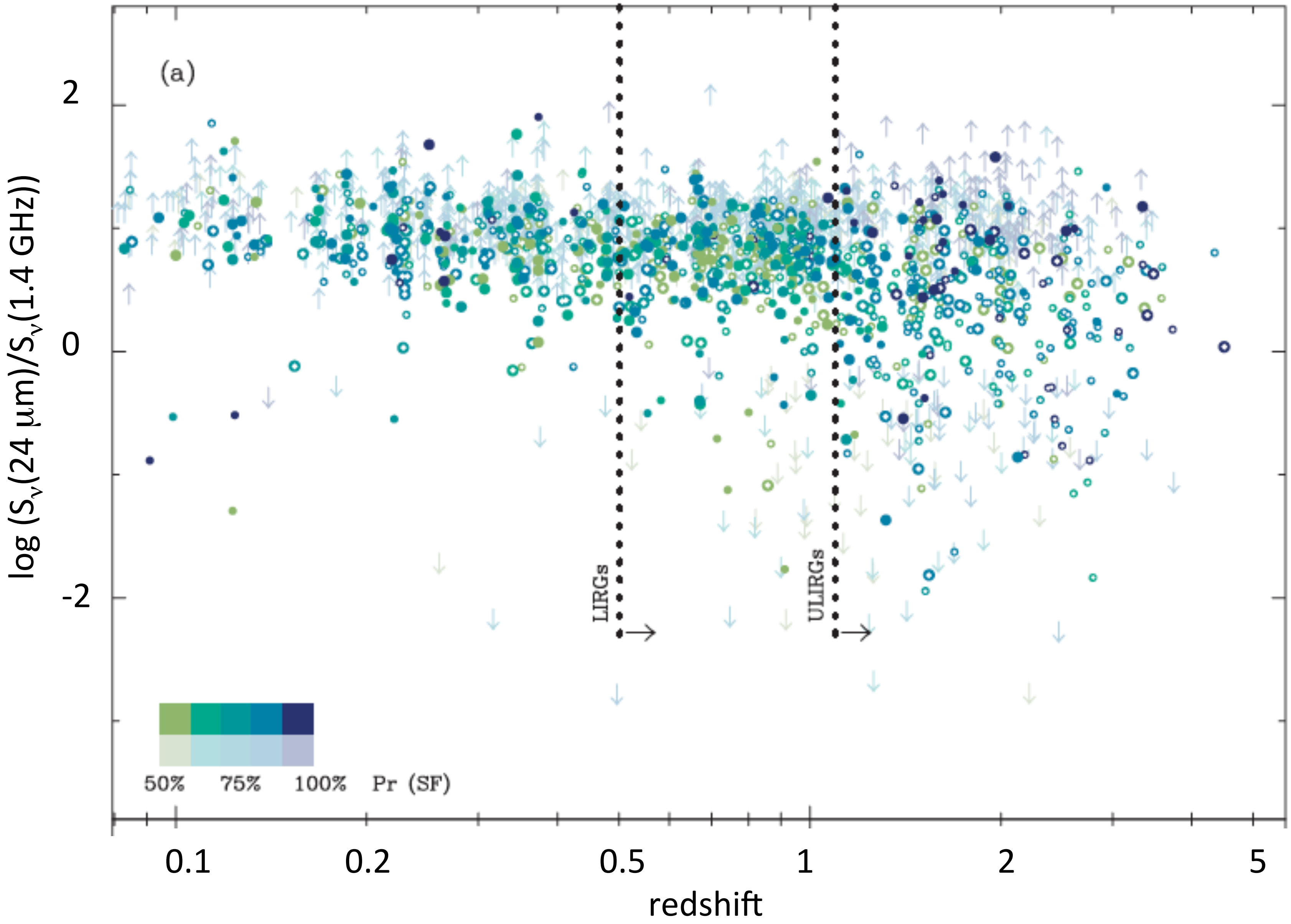


Yun, Reddy, Condon 2001



Mauch & Sadler 2007

Redshift evolution of radio-FIR correlation for star forming galaxies



Sargent et al. 2010

Model for radio emission from star formation

Condon 1992

Measure SFR (M ≥ 5 M_{sun})

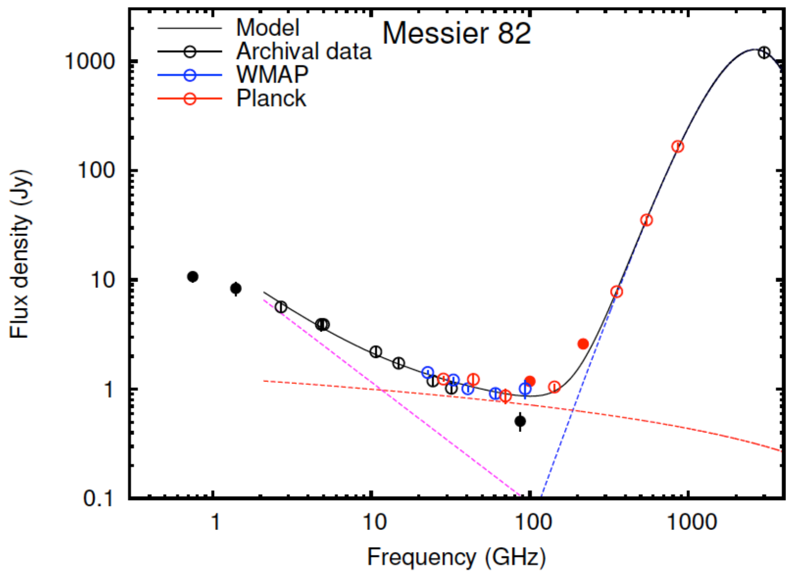
Nonthermal radio emission

$$\left(\frac{L_{\mathrm{N}}}{\mathrm{W\,Hz^{-1}}}\right) \sim 5.3\times10^{21}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-\alpha}\left[\frac{SFR(M\geq 5M_\odot)}{M_\odot\,\mathrm{yr^{-1}}}\right]$$

where alpha = 0.8

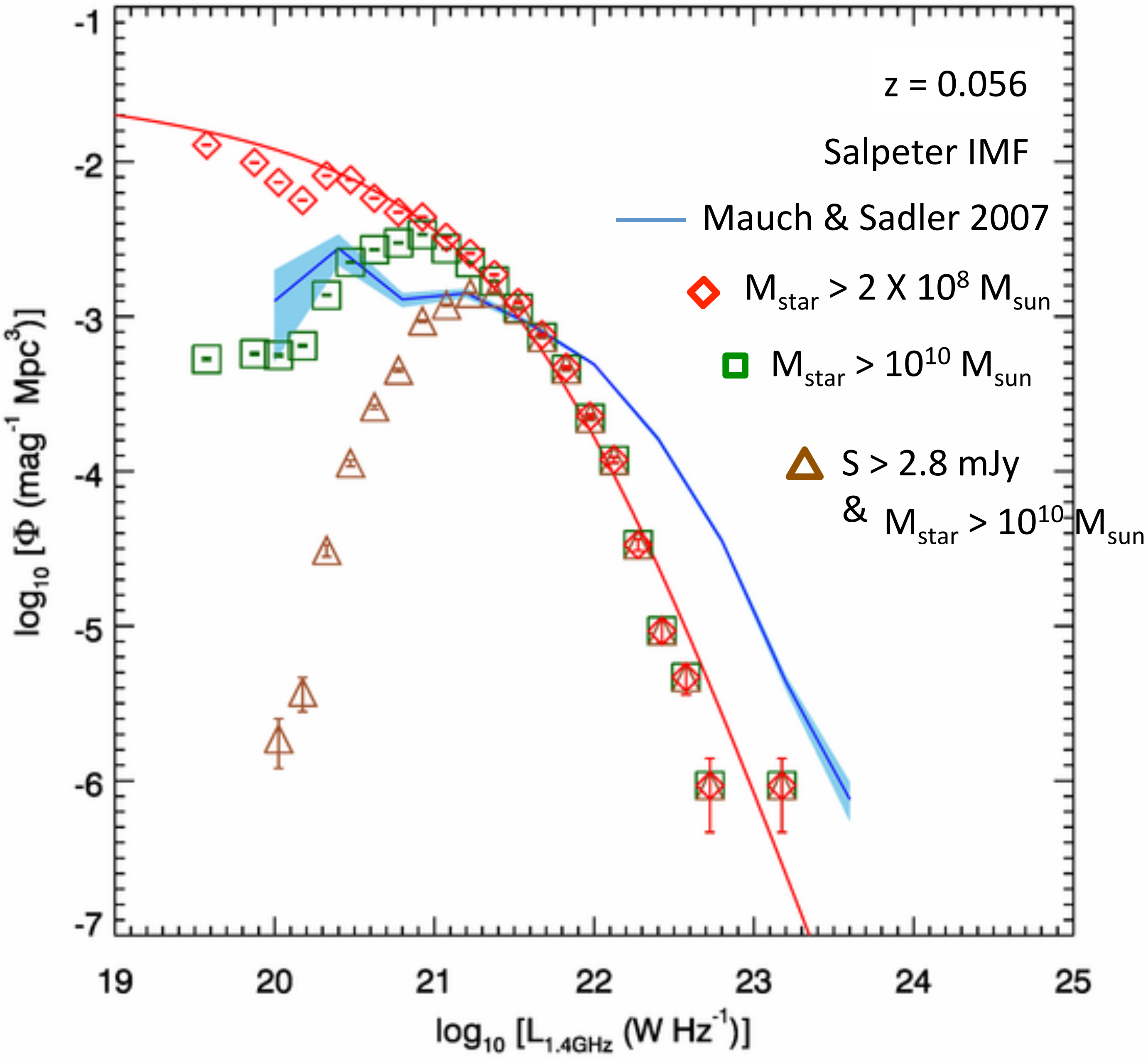
Thermal radio emission

$$\left(\frac{L_{\mathrm{T}}}{\mathrm{W\,Hz^{-1}}}\right) \sim 5.5\times10^{20}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.1}\left[\frac{SFR(M\geq 5M_\odot)}{M_\odot\,\mathrm{yr^{-1}}}\right]$$

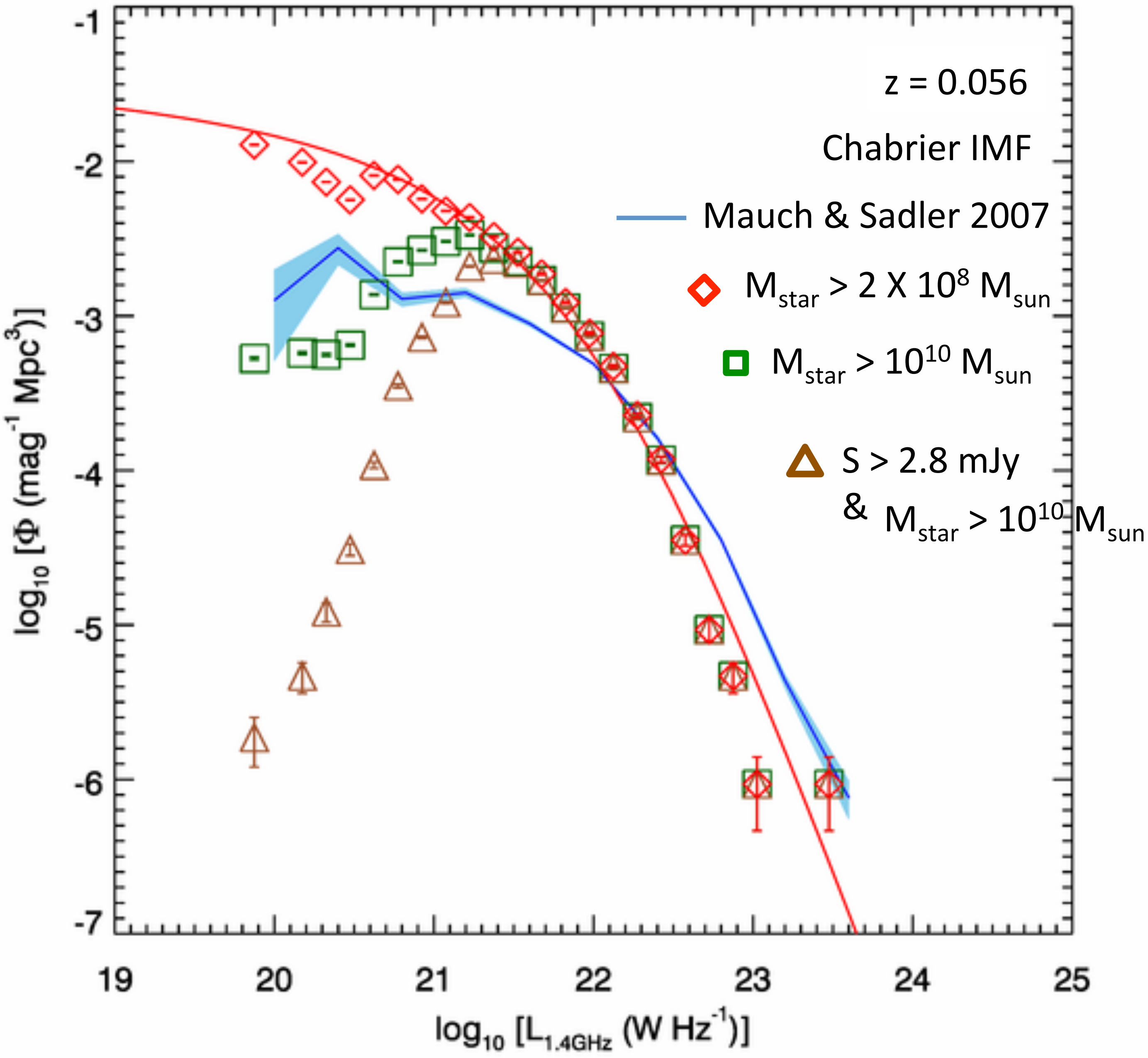


Peel et al. 2011

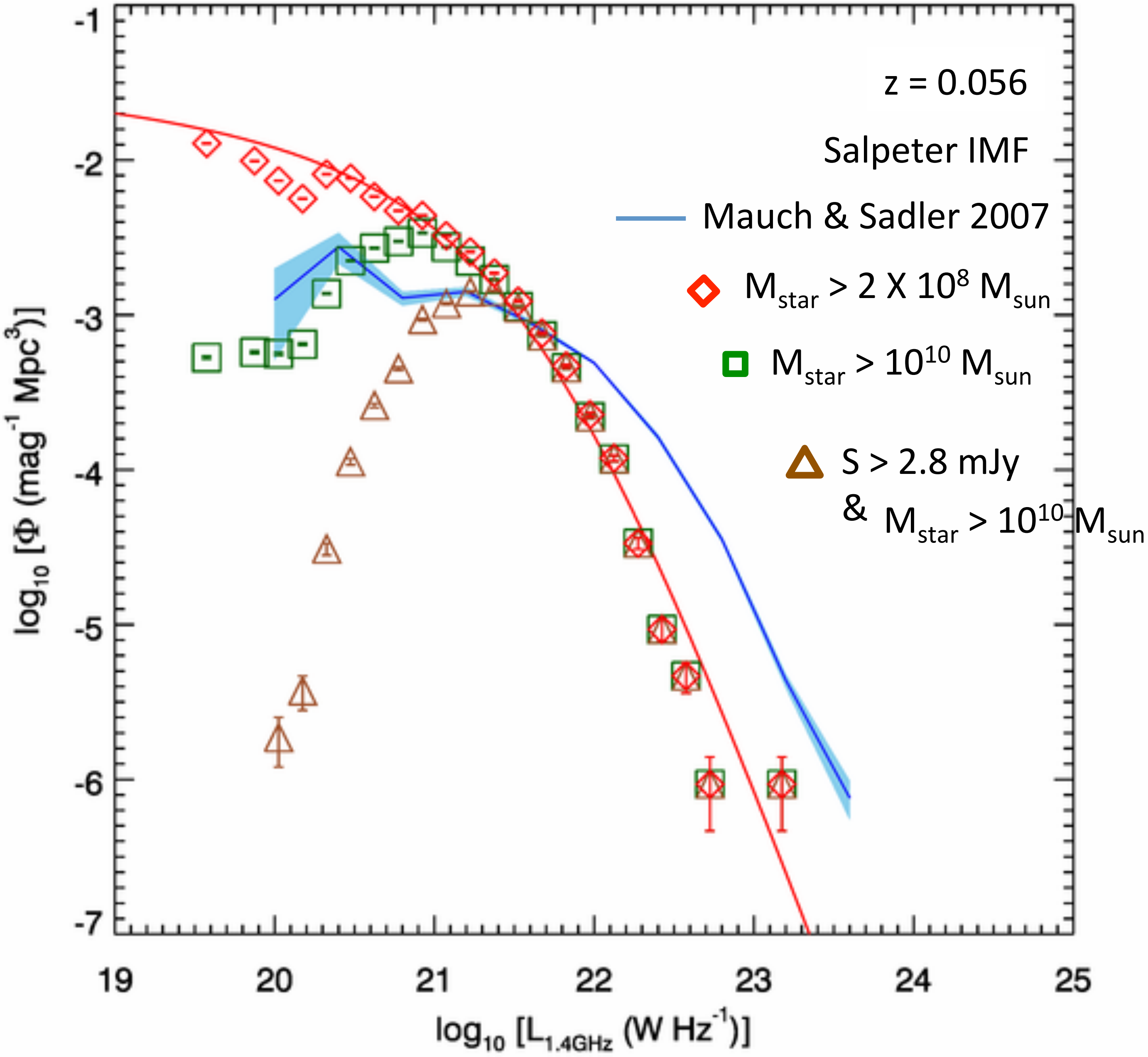
1.4 GHz SFG Radio Luminosity Function



1.4 GHz SFG Radio Luminosity Function



1.4 GHz SFG Radio Luminosity Function



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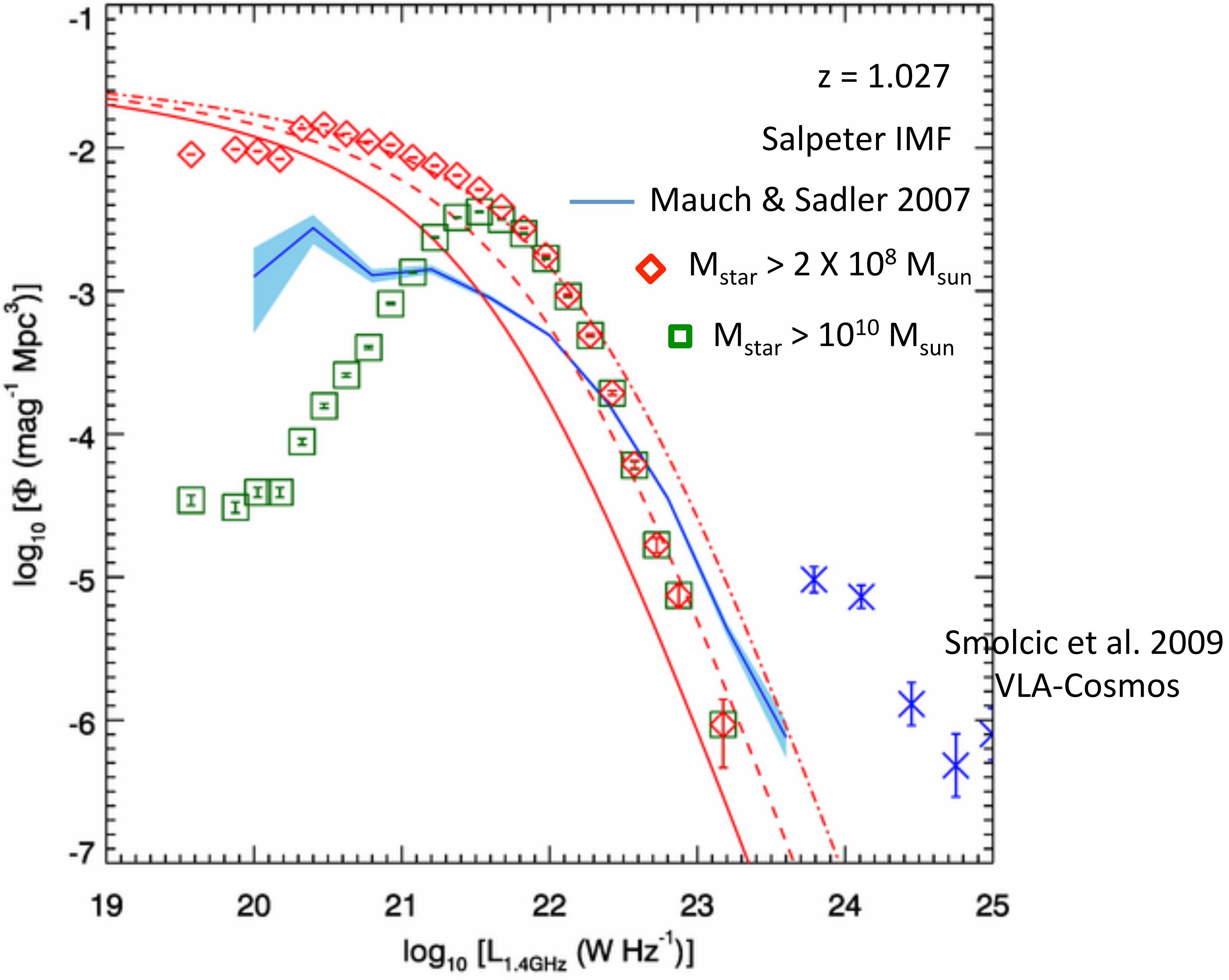
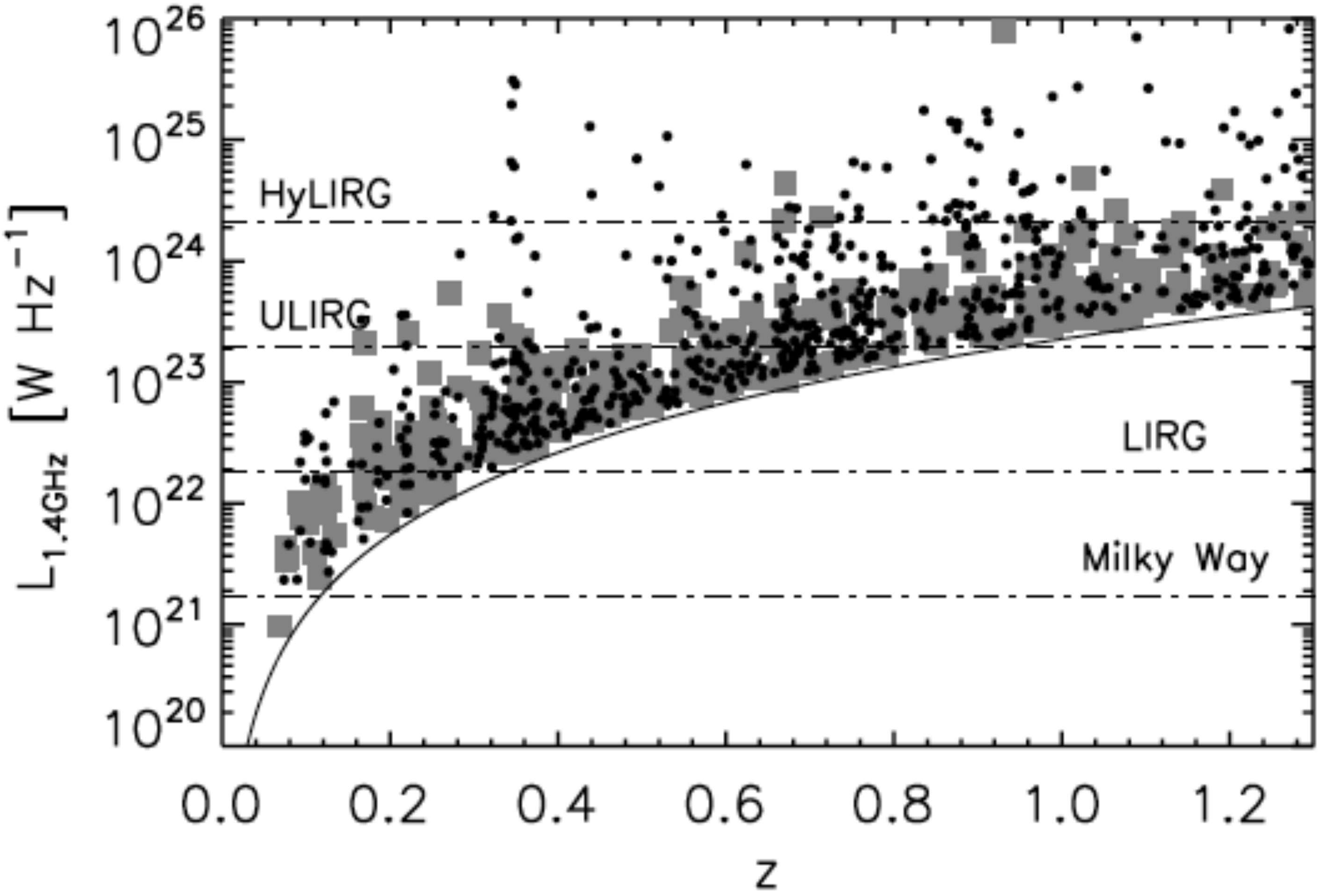


Smolcic et al. 2009
VLA-Cosmos

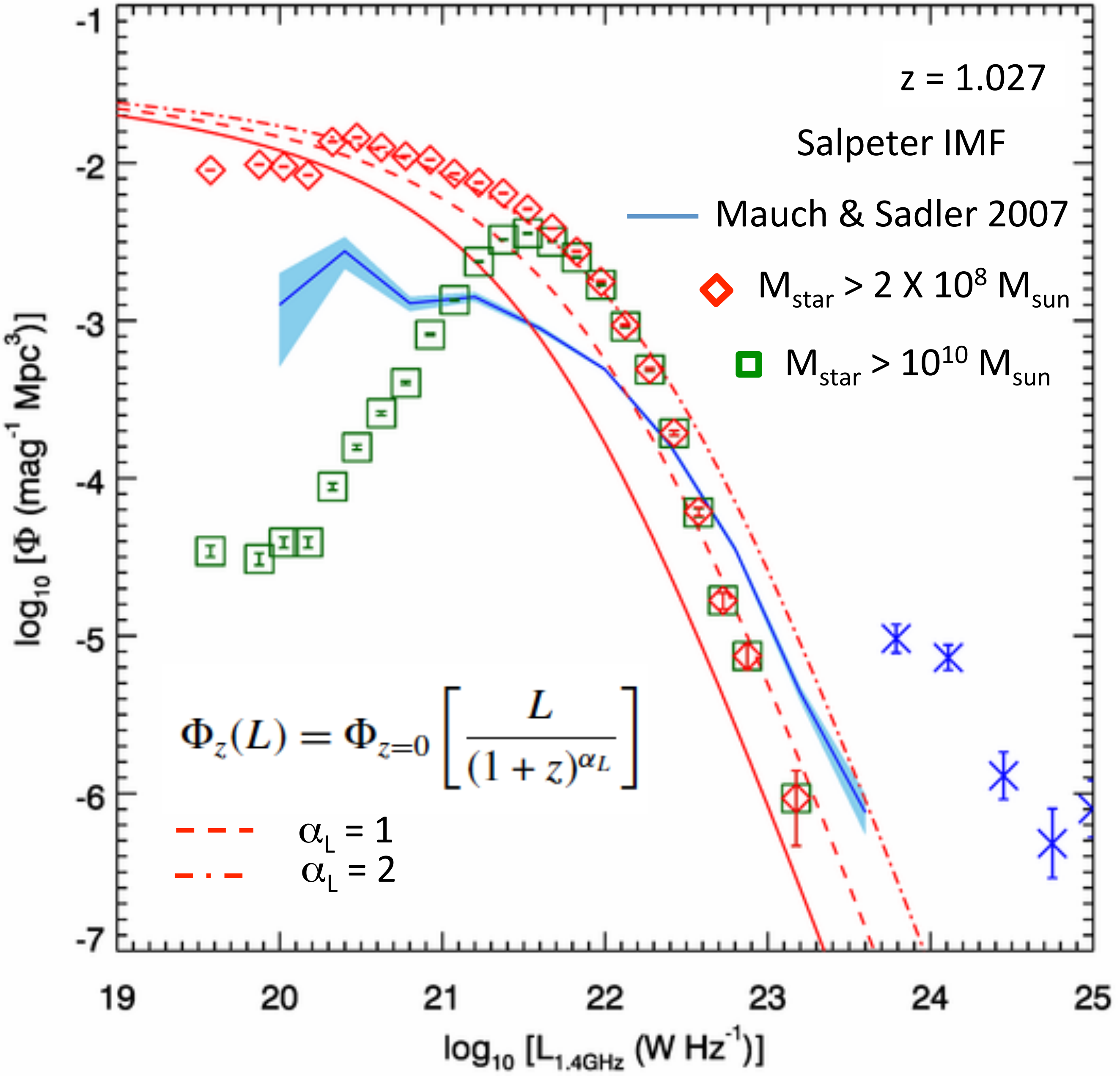
1.4 GHz Luminosity Function as a function of redshift



Grey squares: SF galaxies
Black dots: AGNs

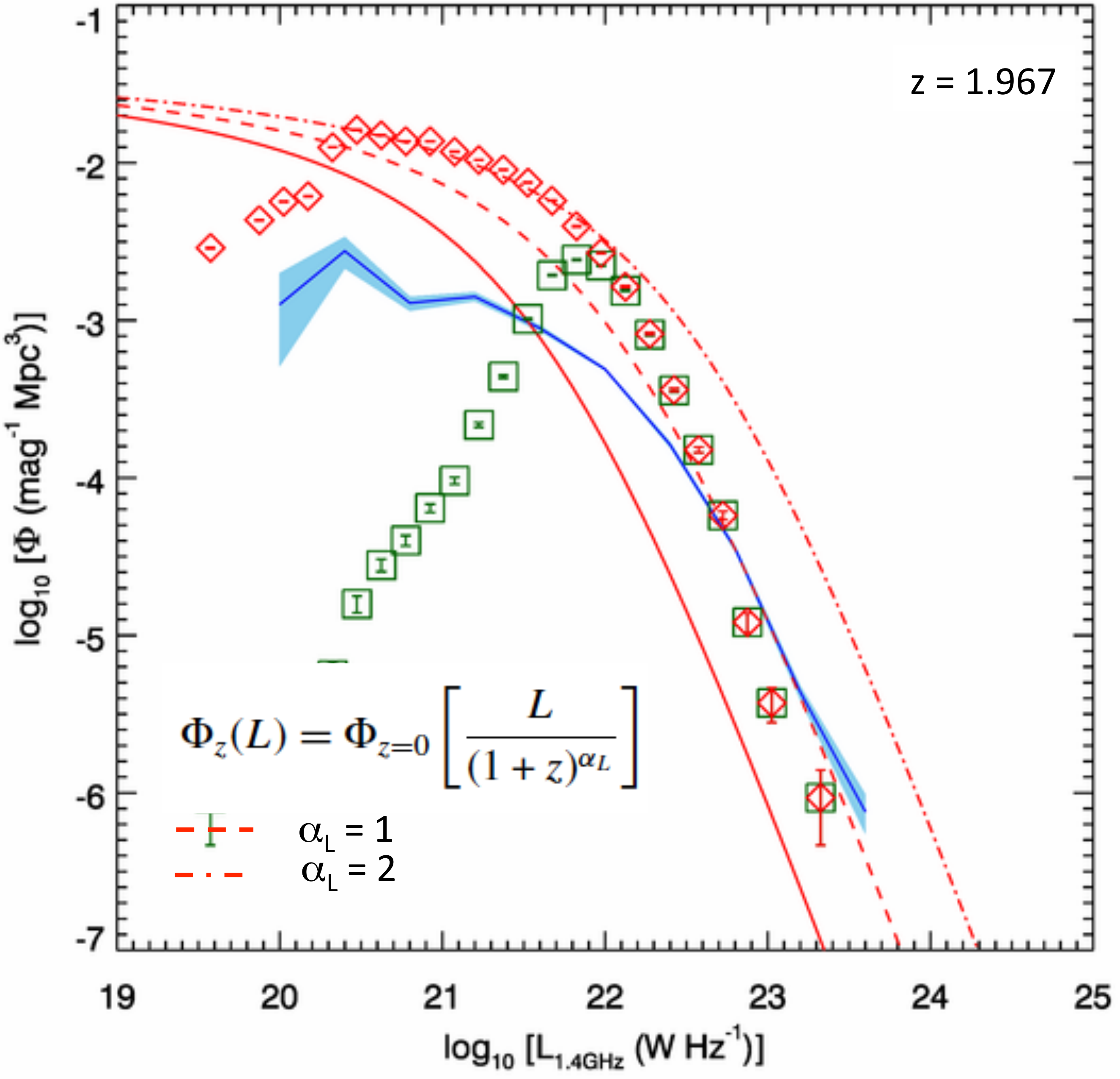
Smolcic et al. 2008

1.4 GHz SFG Radio Luminosity Function



$$\Phi_z(L) = \Phi_{z=0}\left[\frac{L}{(1+z)^{\alpha_L}}\right]$$

1.4 GHz SFG Radio Luminosity Function



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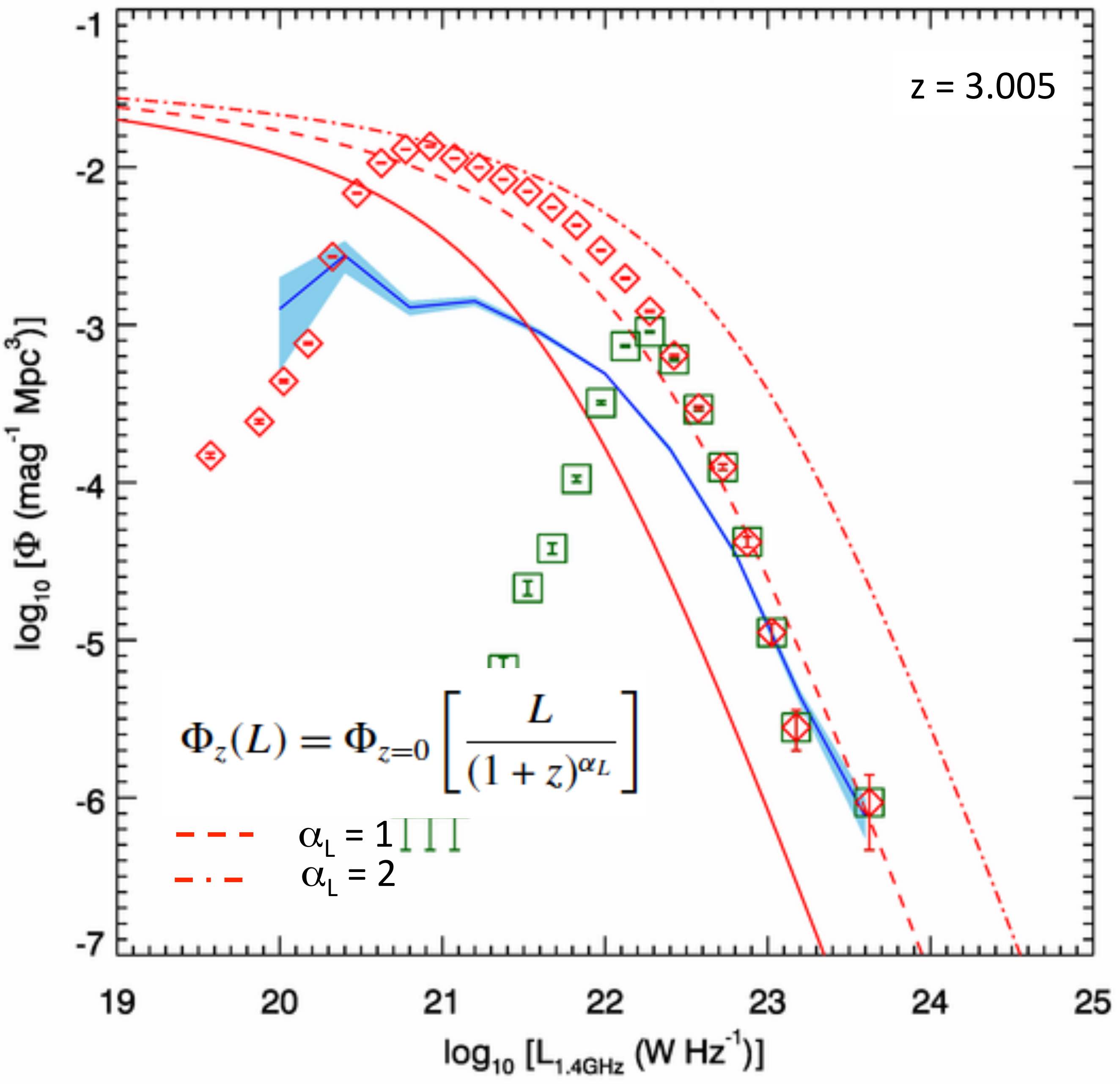

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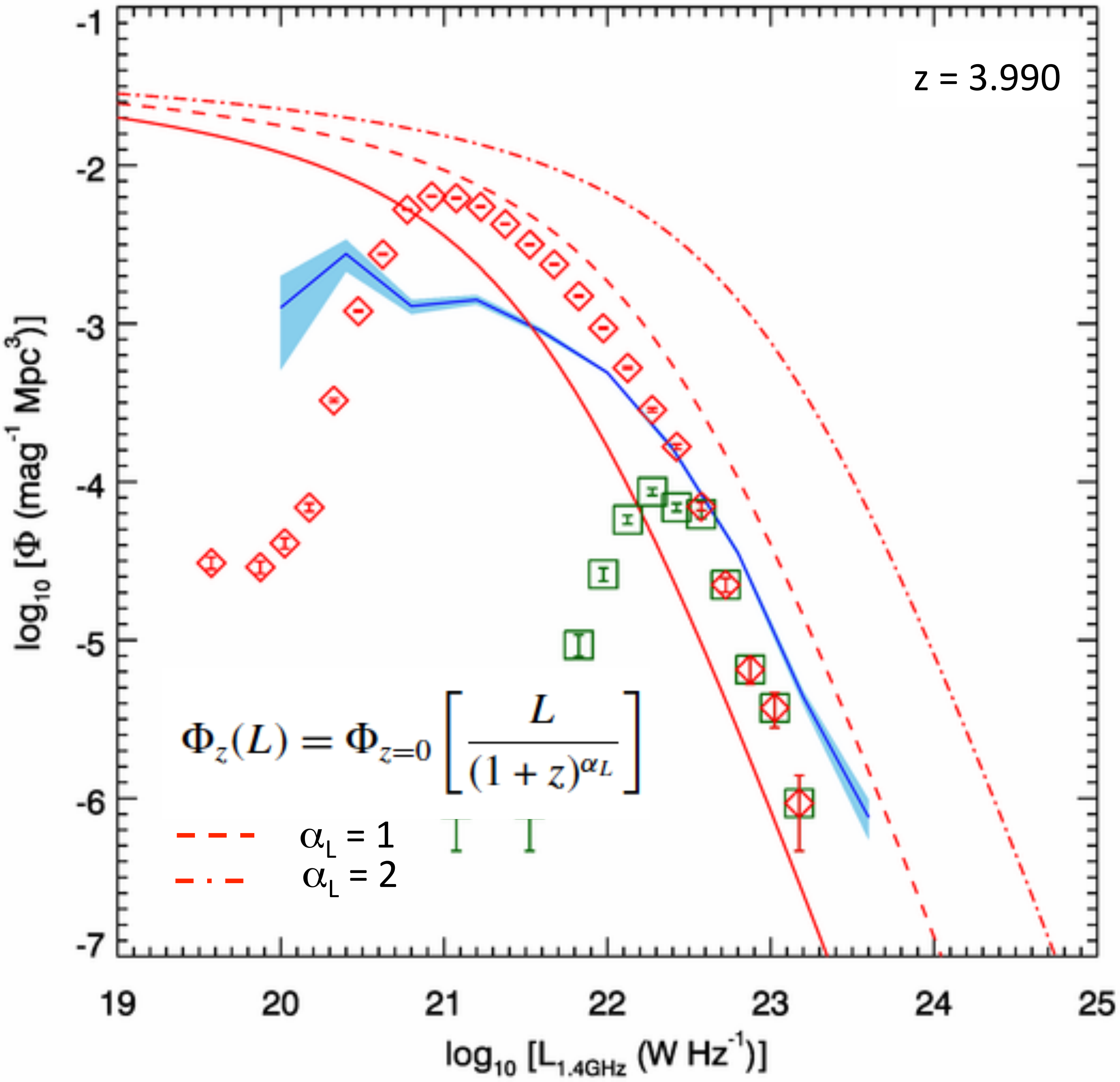

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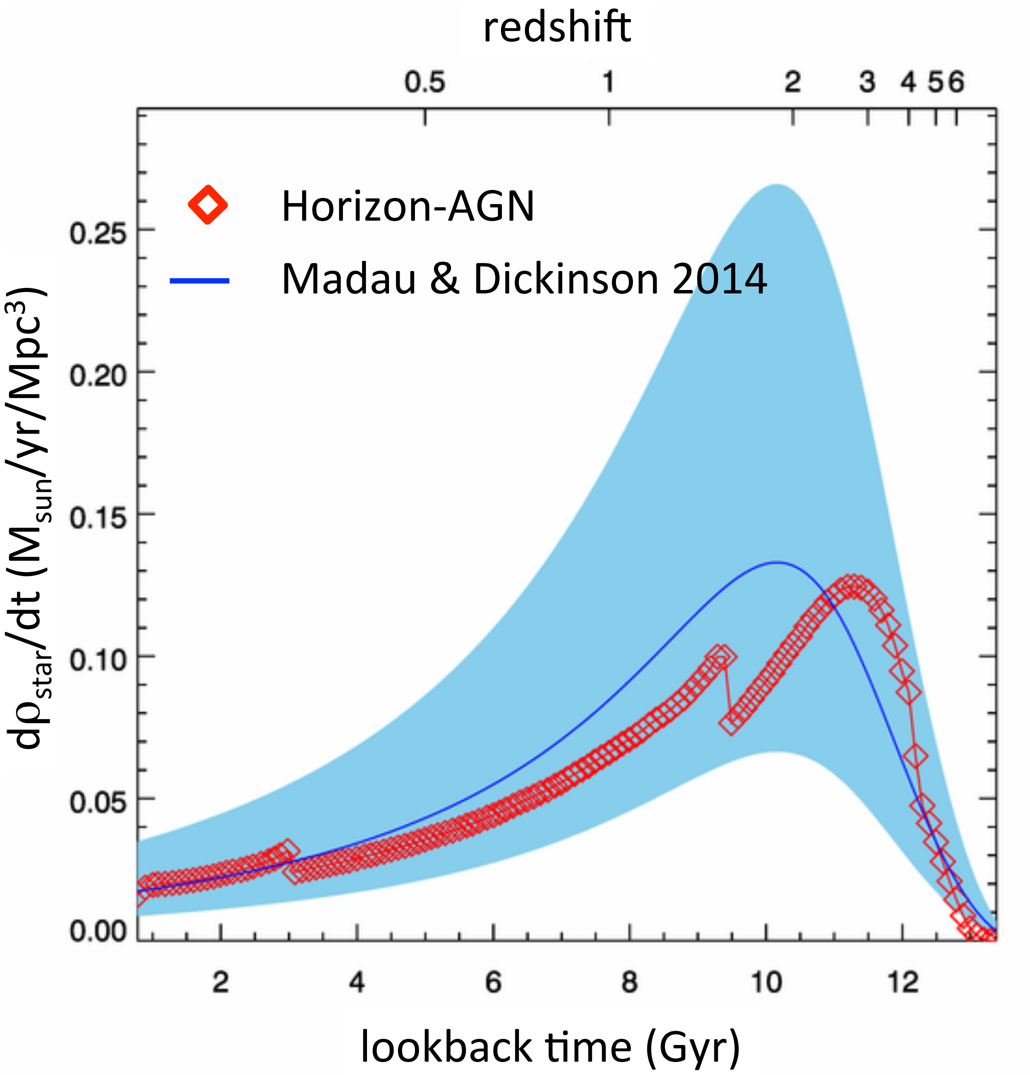
History of cosmic star formation rate density



Model for radio emission from AGN:
exploit analogy between X-ray binaries & AGNs

Kording, Jester, Fender 2008

X-ray binaries	AGNs
Hard state objects Flat radio spectra Stable, compact jets	**Low luminosity AGN** Accreting at low fraction of Eddington Flat spectrum radio core Energy output: jet
Intermediate state sources Unstable jets Ejections of highly relativistic blobs	**Radio Loud AGN** Accreting at high fraction of Eddington Energy output: radiation, extended radio lobes

Measure accretion
rate onto black hole

Compare to Eddington accretion

For low accretion
$\chi = \dot{M}_{acc}/\dot{M}_{edd} < \chi_{low}$
Low luminosity AGN

Use relationship between core radio luminosity & mass accretion rate (Kording, Fender, Migliari 2006)

$$\dot{M} \approx 4 \times 10^{17} \left(\frac{L_{\mathrm{Rad}}}{10^{30}\,\mathrm{erg\,s^{-1}}} \right)^{12/17} \mathrm{g\,s^{-1}}$$

let $L_{rad} \sim \nu L_\nu$ (assume a flat spectrum)
& solve for L_ν for a particular ν,
e.g. $\nu = 1.4$ GHz

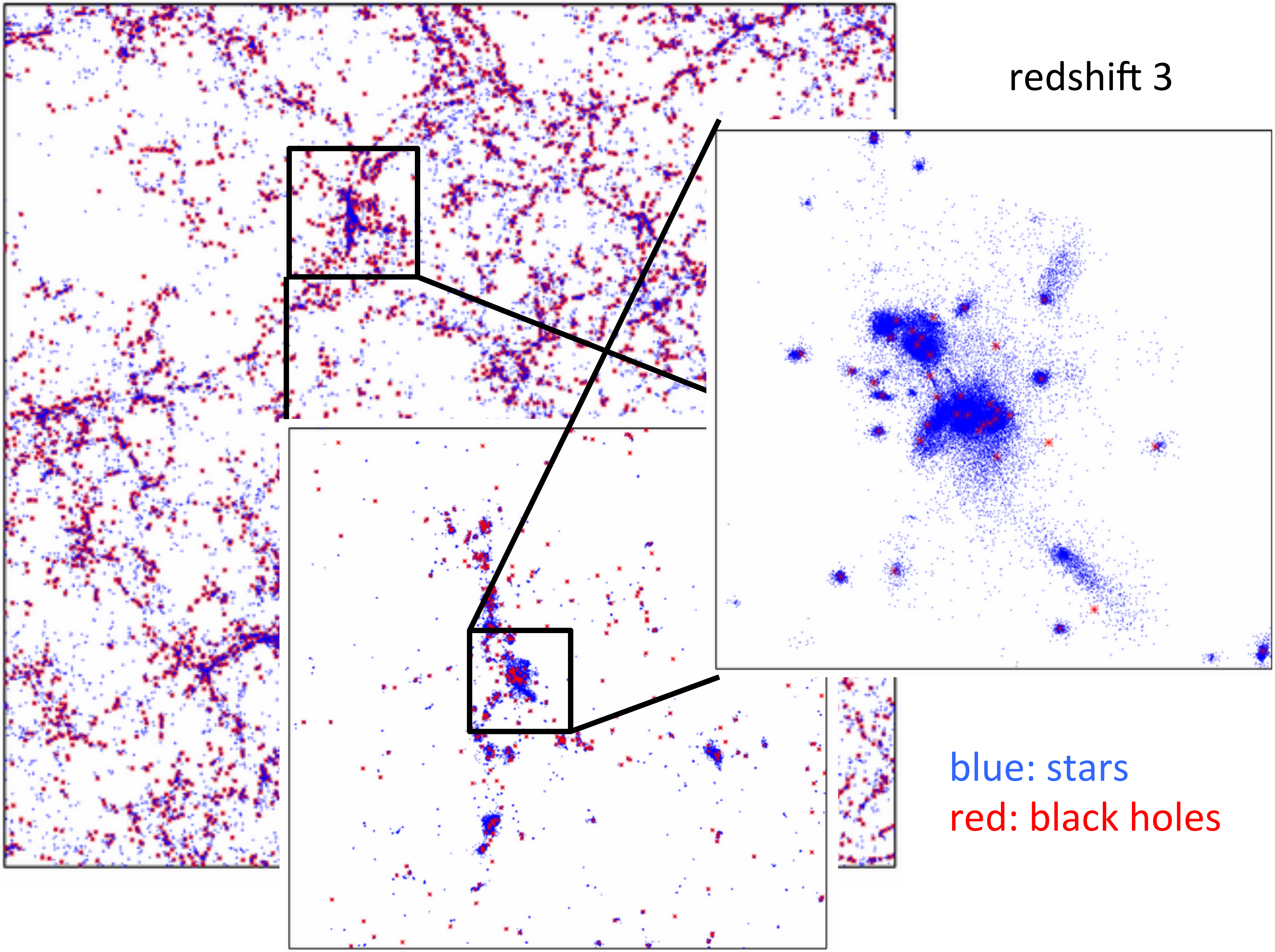
For high accretion
$\chi = \dot{M}_{acc}/\dot{M}_{edd} > \chi_{high}$
Radio Loud AGN

Use correlation between extended radio emission & mass accretion rate (Rawlings & Saunders 1991, Willott et al. 1999)

$$\log \dot{M}\,(\mathrm{g\,s^{-1}}) = \log L_{151}\,(\mathrm{W\,Hz^{-1}\,sr^{-1}}) - 0.15.$$

Kording, Jester, Fender 2008

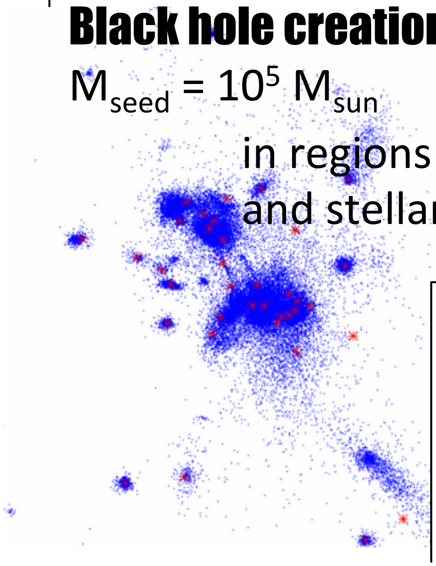
assuming $L_\nu = A\,\nu^{-0.7}$ (a steep spectrum)
solve for $L_{1.4} = L_{0.151}\,(1.4/0.151)^{-0.7}$



redshift 3

blue: stars

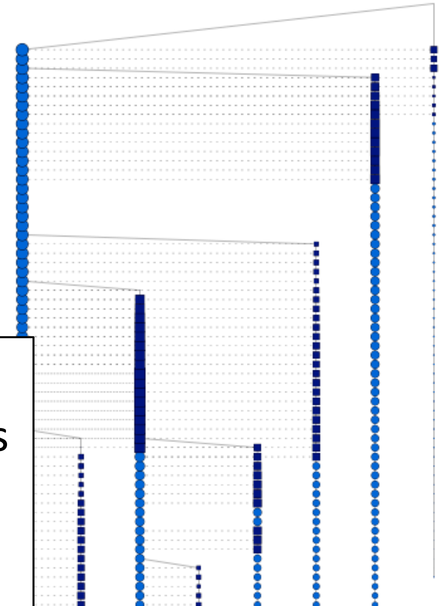
red: black holes



Black hole creation

$M_{seed} = 10^5 \, M_{sun}$

in regions of high gas and stellar densities

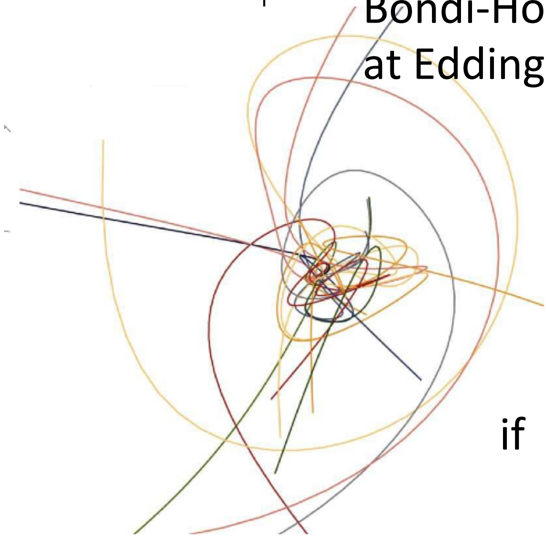


Black hole growth

via accretion and mergers

$$\dot{M}_{\rm BH} \propto \rho \frac{M_{\rm BH}^2}{c_{\rm s}^3}$$

Bondi-Hoyle capped at Eddington



Black hole feedback

2 modes: radio & quasar

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if $\chi \leq 0.01$ then jet with

$L_{radio} = 0.1 \, \dot{M}_{BH} \, c^2$

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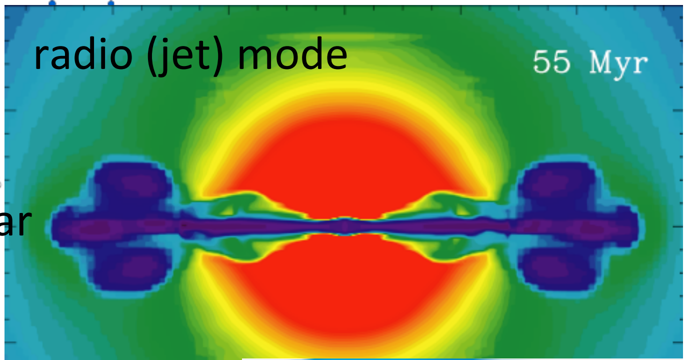
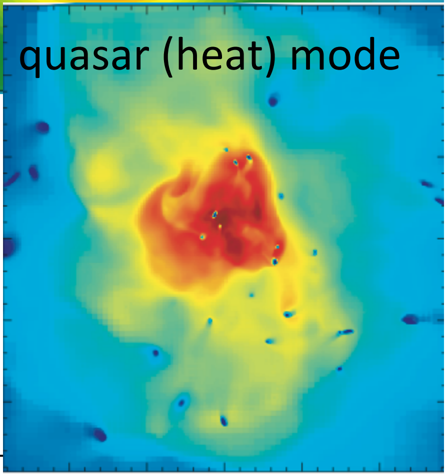


radio (jet) mode

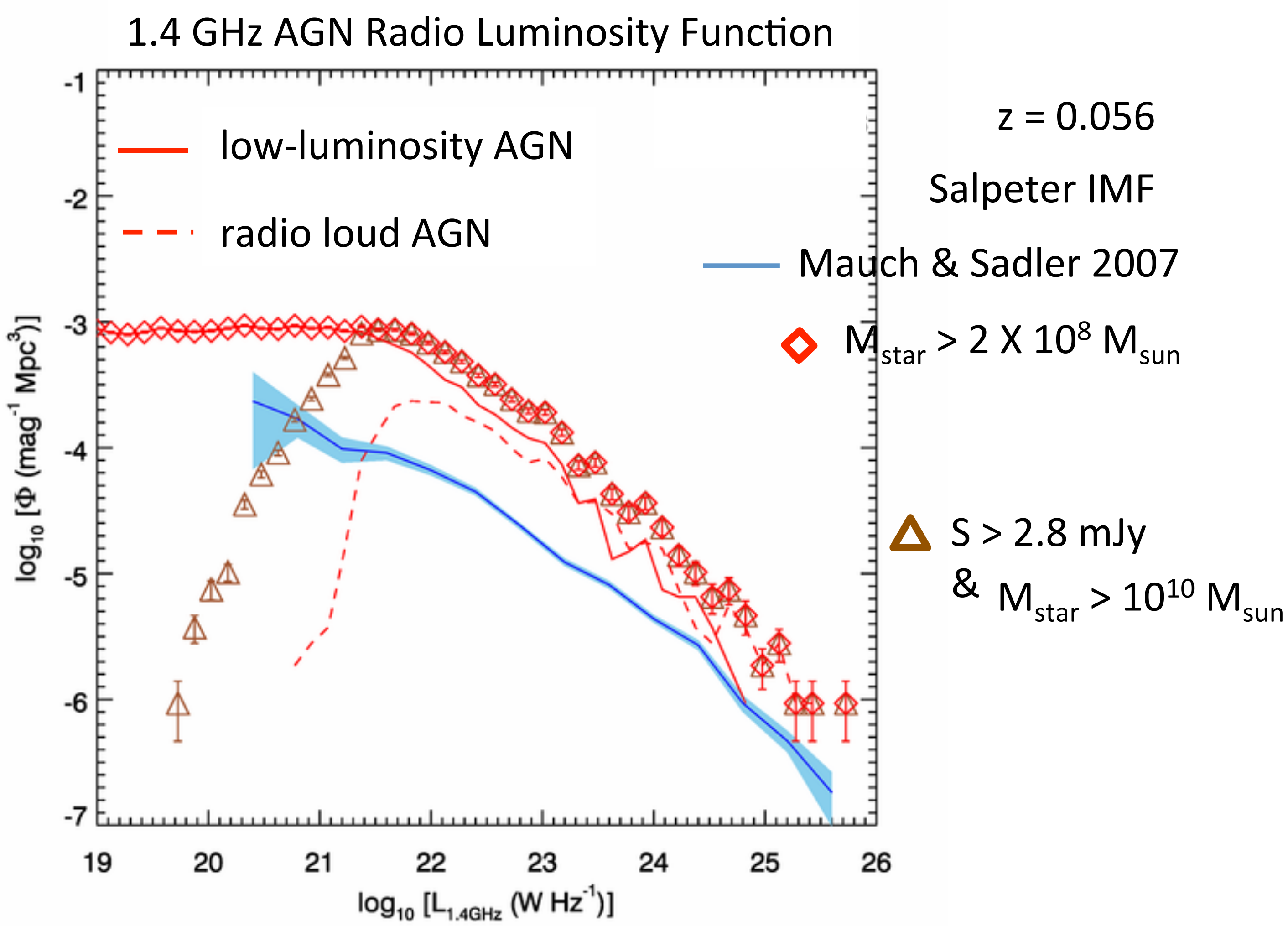


quasar (heat) mode

For low accretion
$\dot{M}_{acc}/\dot{M}_{edd} < \chi_{low}$
Low luminosity AGN

Model 1: $\chi_{low} = \chi_{high} = 0.01$

For high accretion
$\dot{M}_{acc}/\dot{M}_{edd} > \chi_{high}$
Radio Loud AGN



z = 0.056

Salpeter IMF

Mauch & Sadler 2007

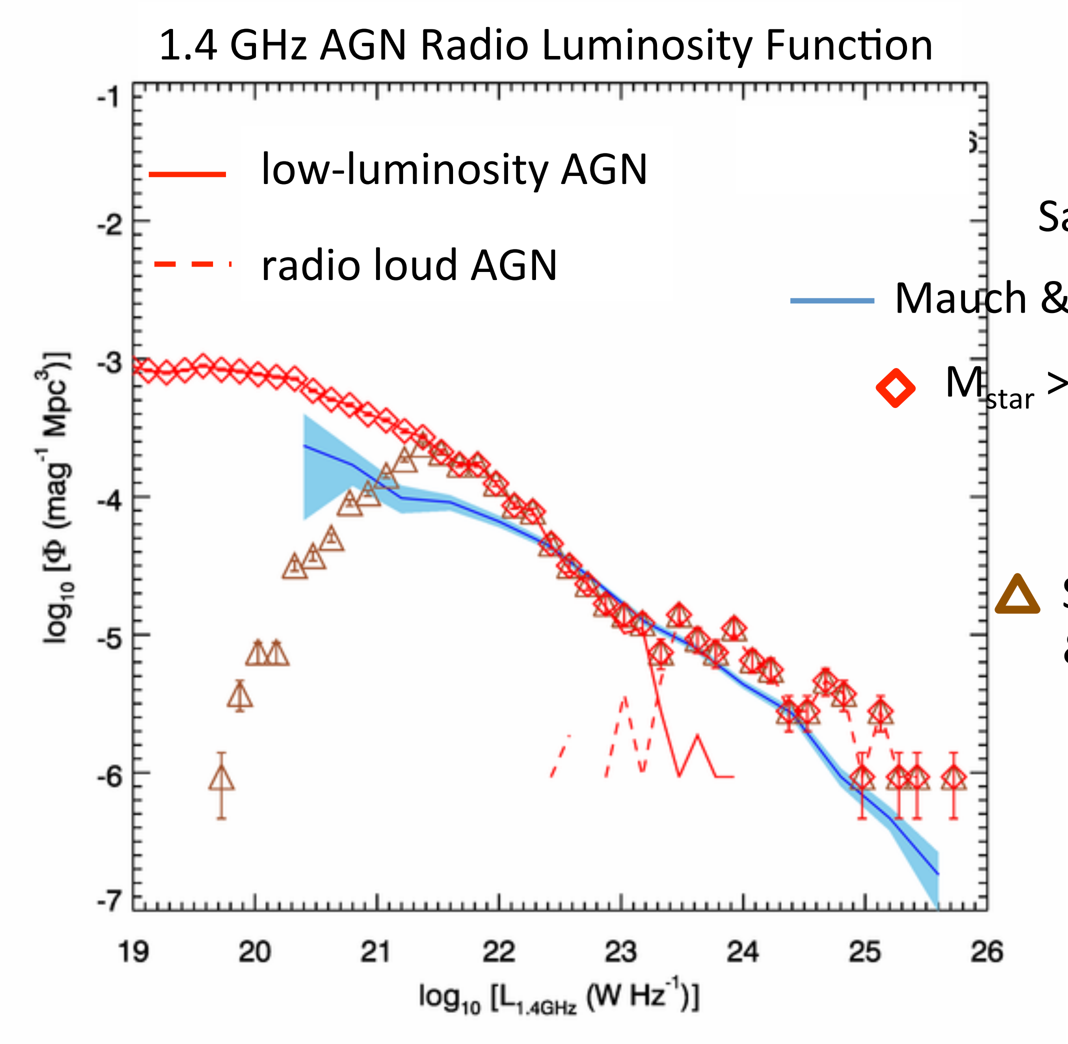
◇ $M_{star} > 2 \times 10^{8}\ M_{sun}$

△ $S > 2.8$ mJy
& $M_{star} > 10^{10}\ M_{sun}$

For low accretion
$\dot{M}_{acc}/\dot{M}_{edd} < \chi_{low}$
Low luminosity AGN

Model 2: $\chi_{low} = 0.001$, $\chi_{high} = 0.3$

For high accretion
$\dot{M}_{acc}/\dot{M}_{edd} > \chi_{high}$
Radio Loud AGN



z = 0.056

Salpeter IMF

Mauch & Sadler 2007

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Low luminosity AGN

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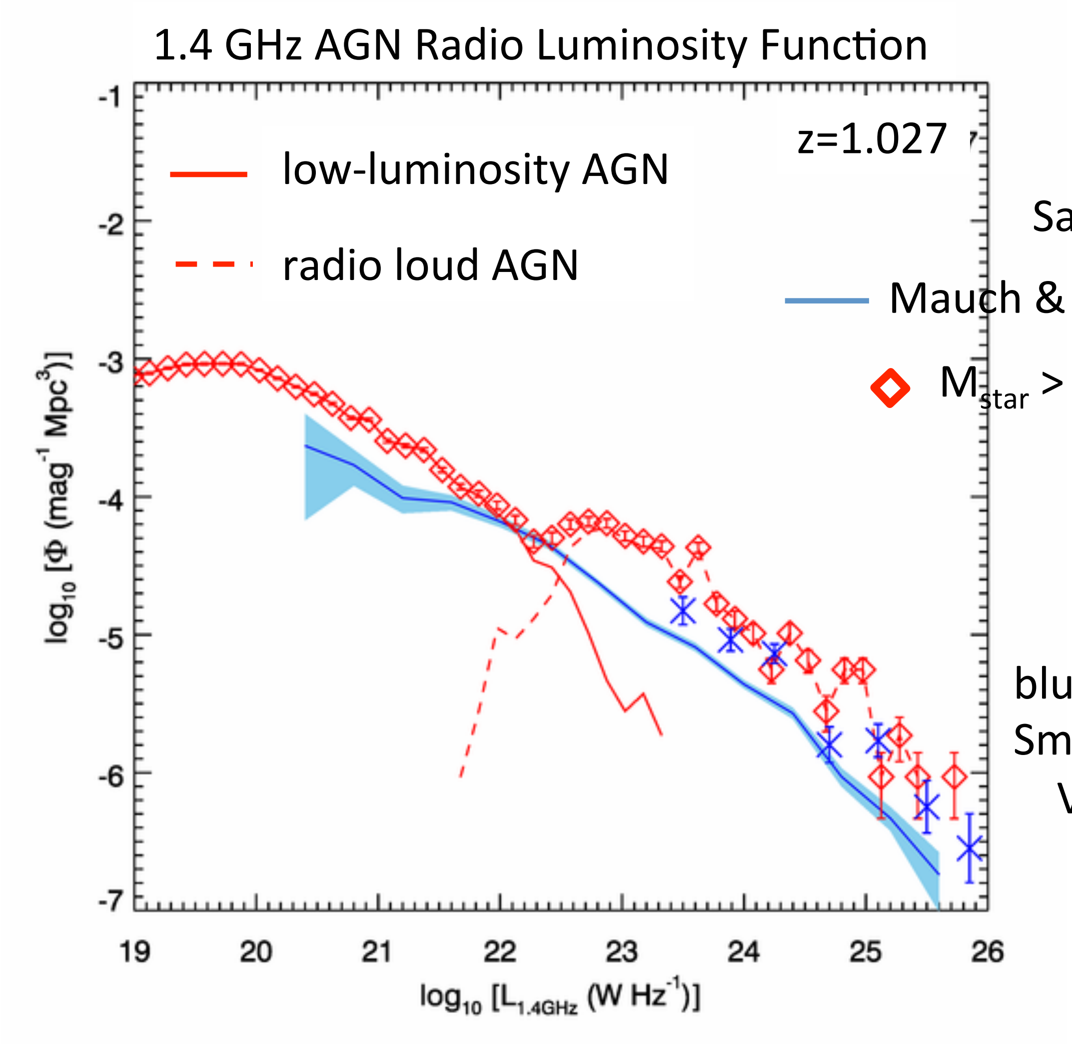
Radio Loud AGN


1.4 GHz AGN Radio Luminosity Function

Salpeter IMF

Mauch & Sadler 2007

◇ $M_{star} > 2 \times 10^{8} M_{sun}$

blue data points
Smolcic et al. 2009
VLA-Cosmos

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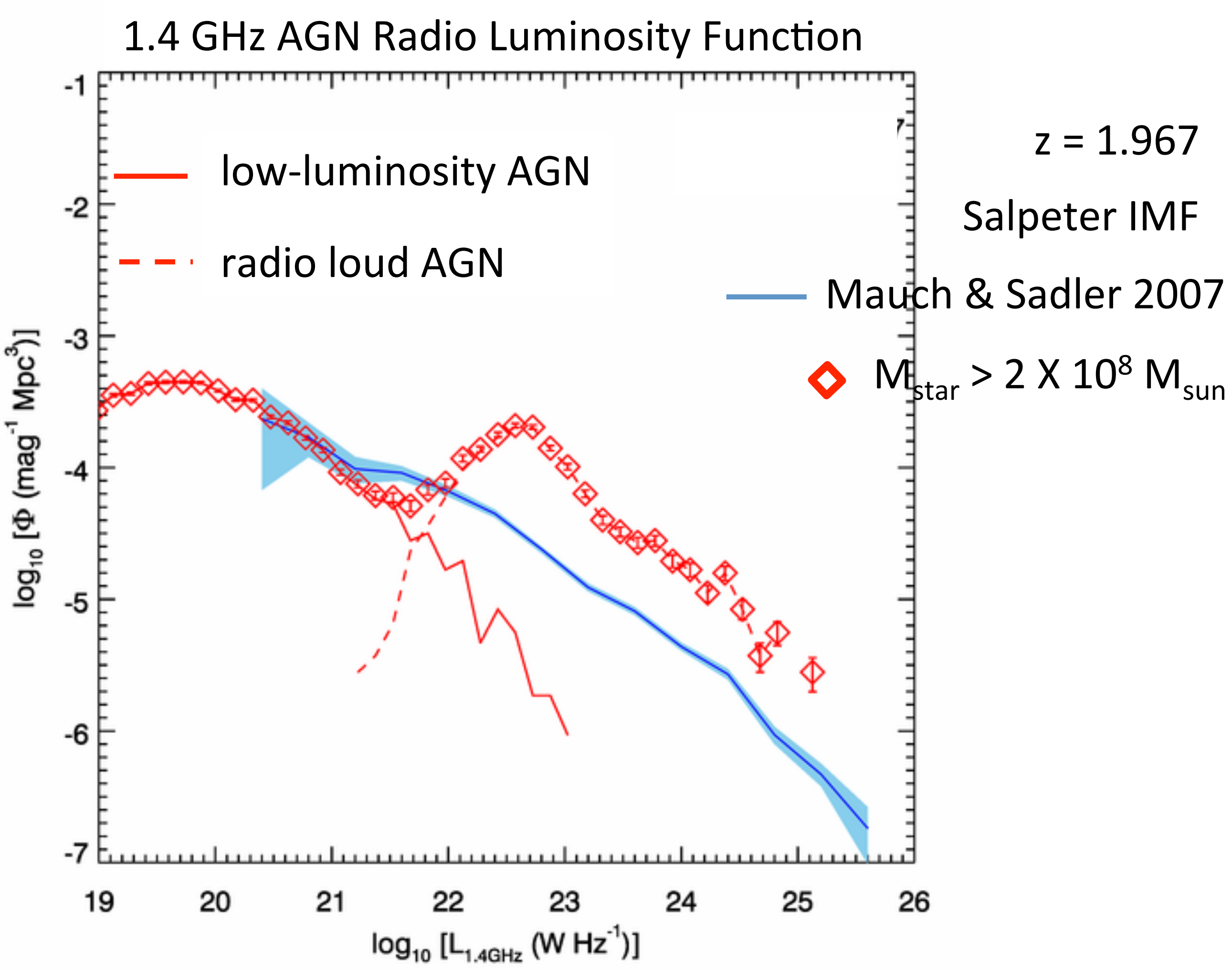
Radio Loud AGN



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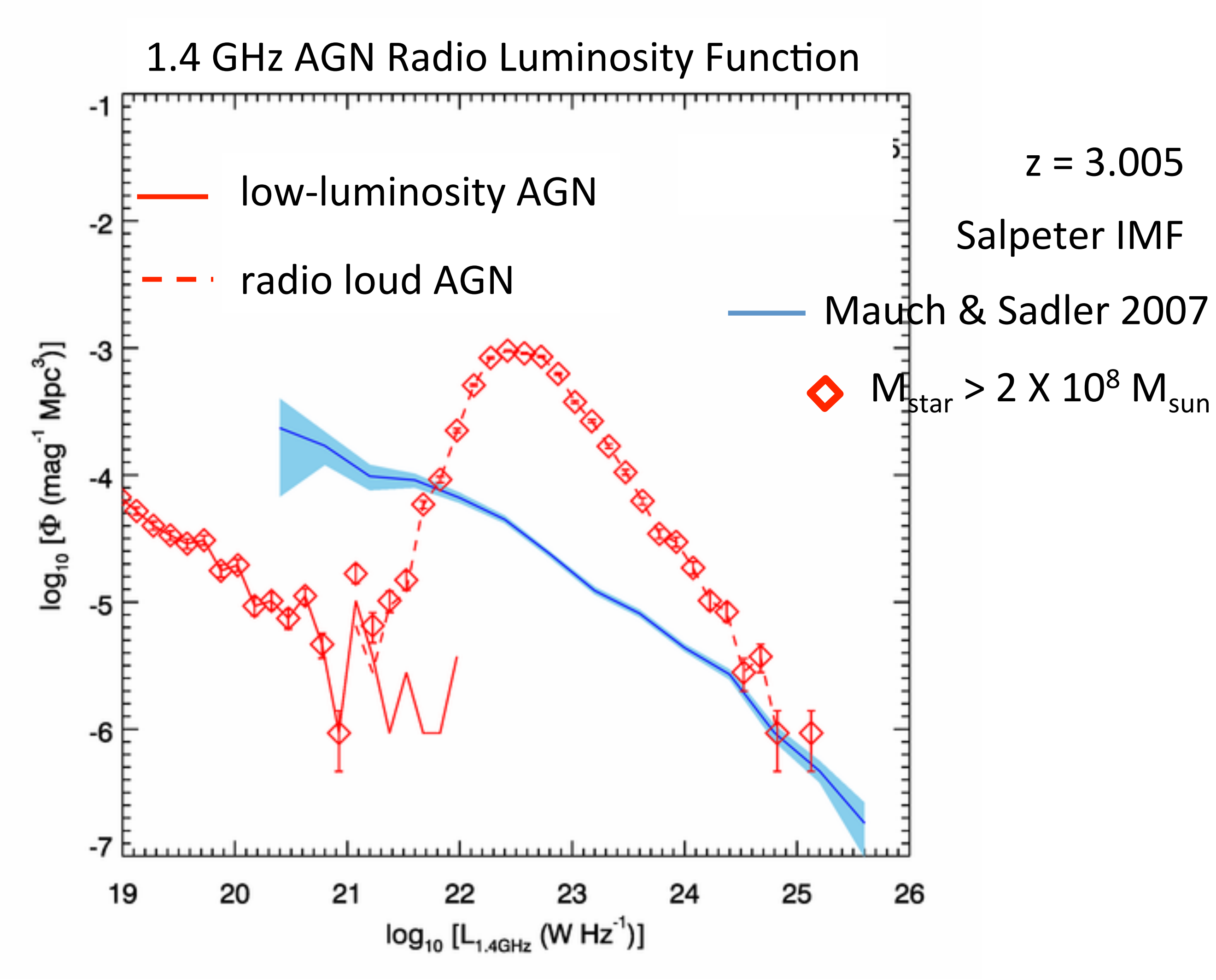
Radio Loud AGN

1.4 GHz AGN Radio Luminosity Function



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Low luminosity AGN

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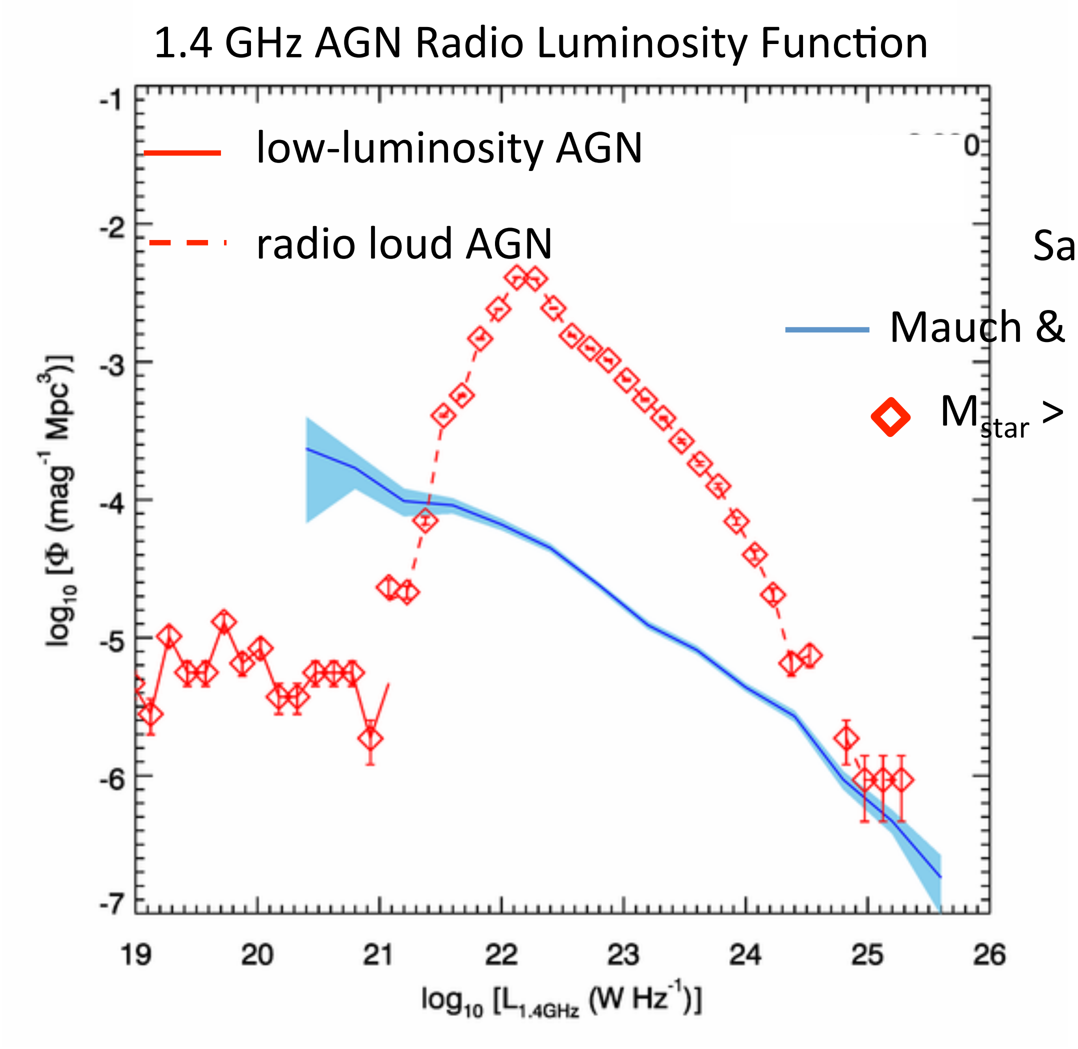
Radio Loud AGN



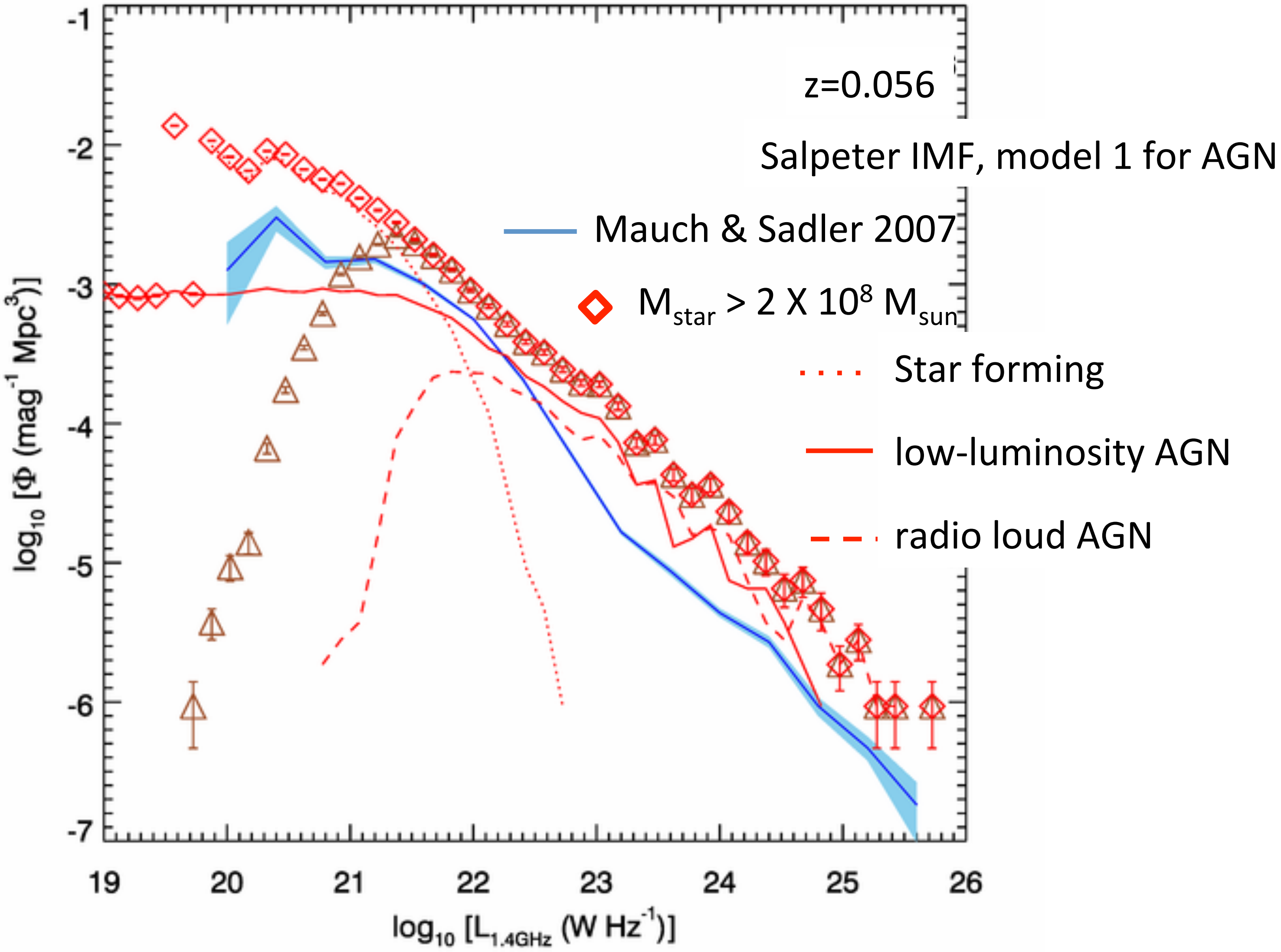
z = 3.990

Salpeter IMF

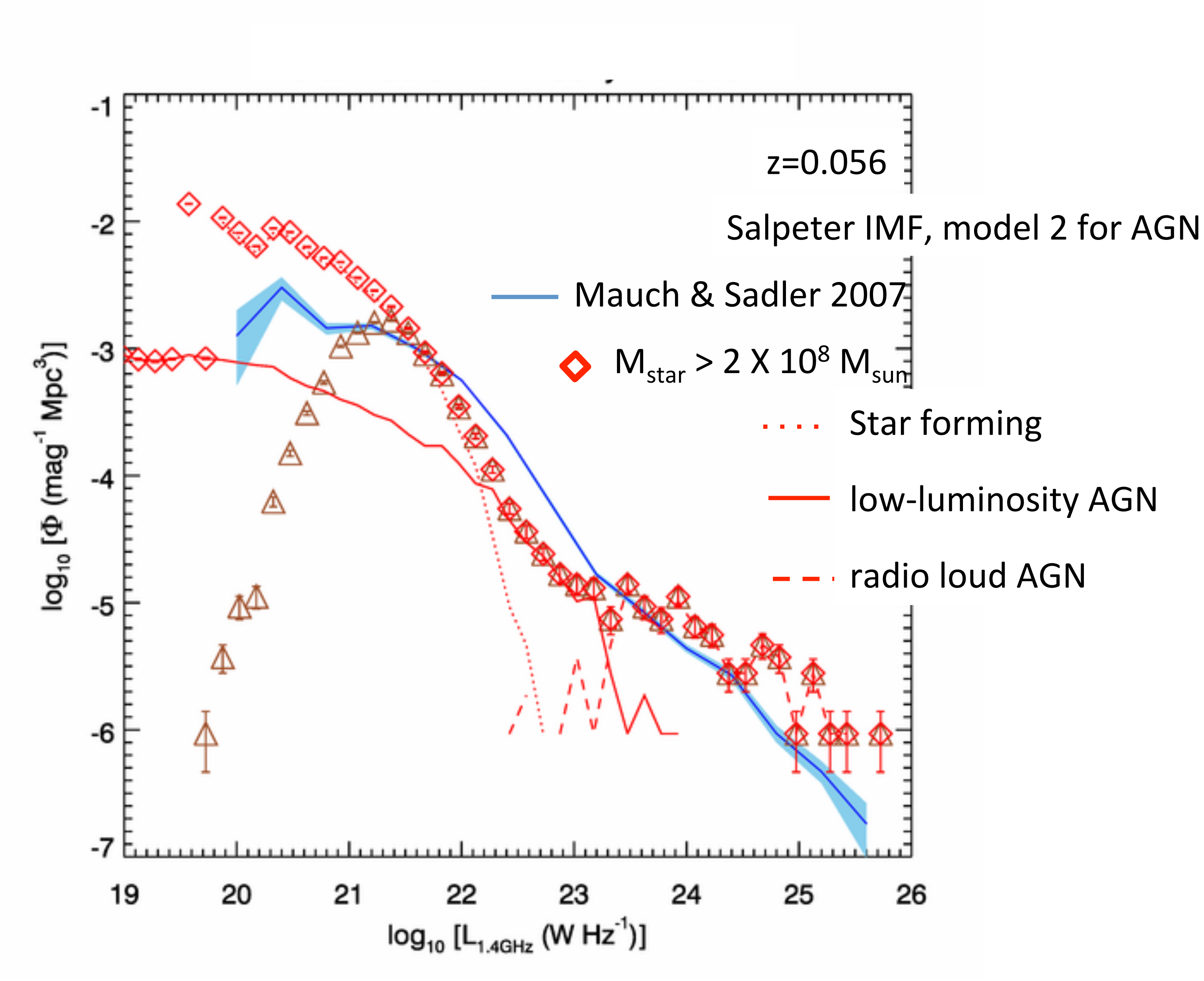
Mauch & Sadler 2007

$M_{star} > 2 \times 10^8 M_{sun}$

SFG + AGN 1.4 GHz Local Luminosity Functions (model 1)

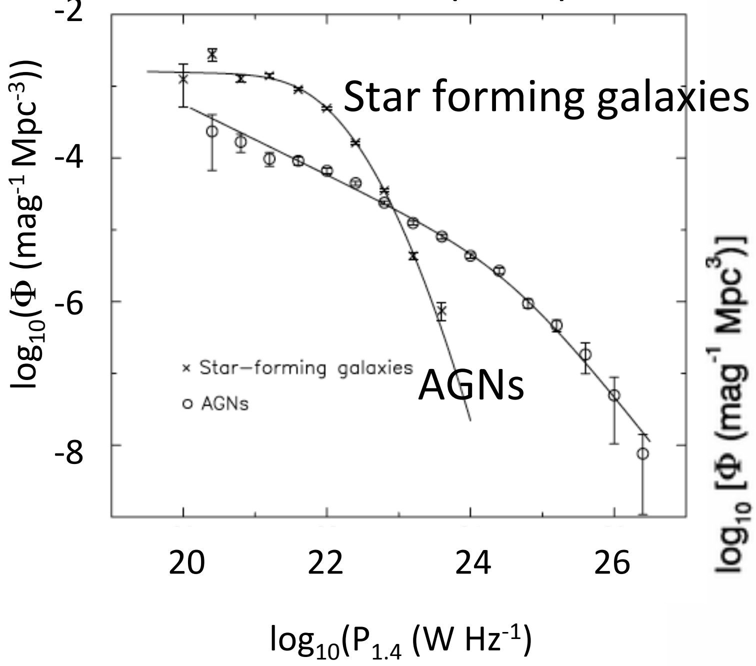


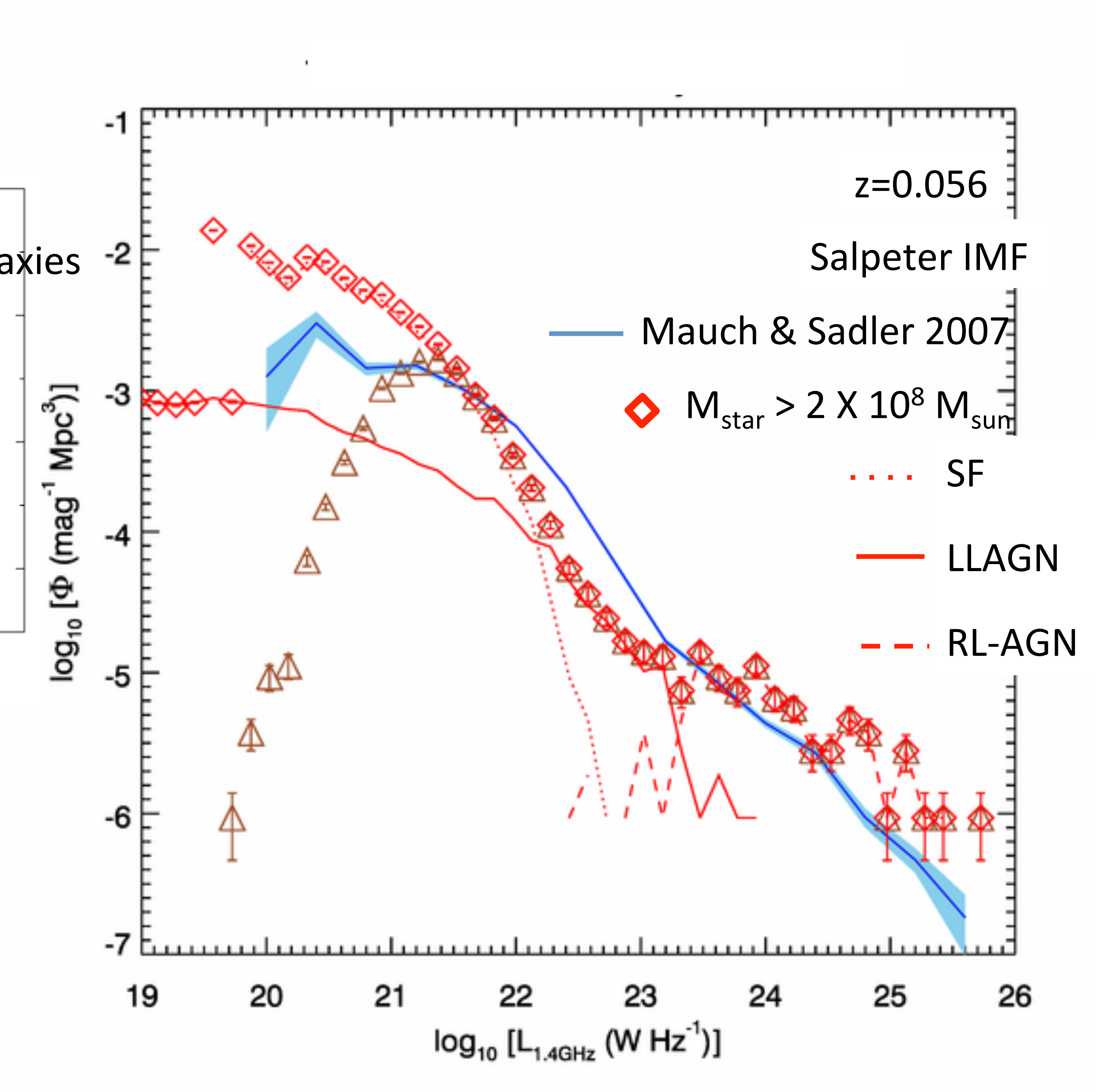
SFG + AGN 1.4 Ghz Local Luminosity Functions (model 2)



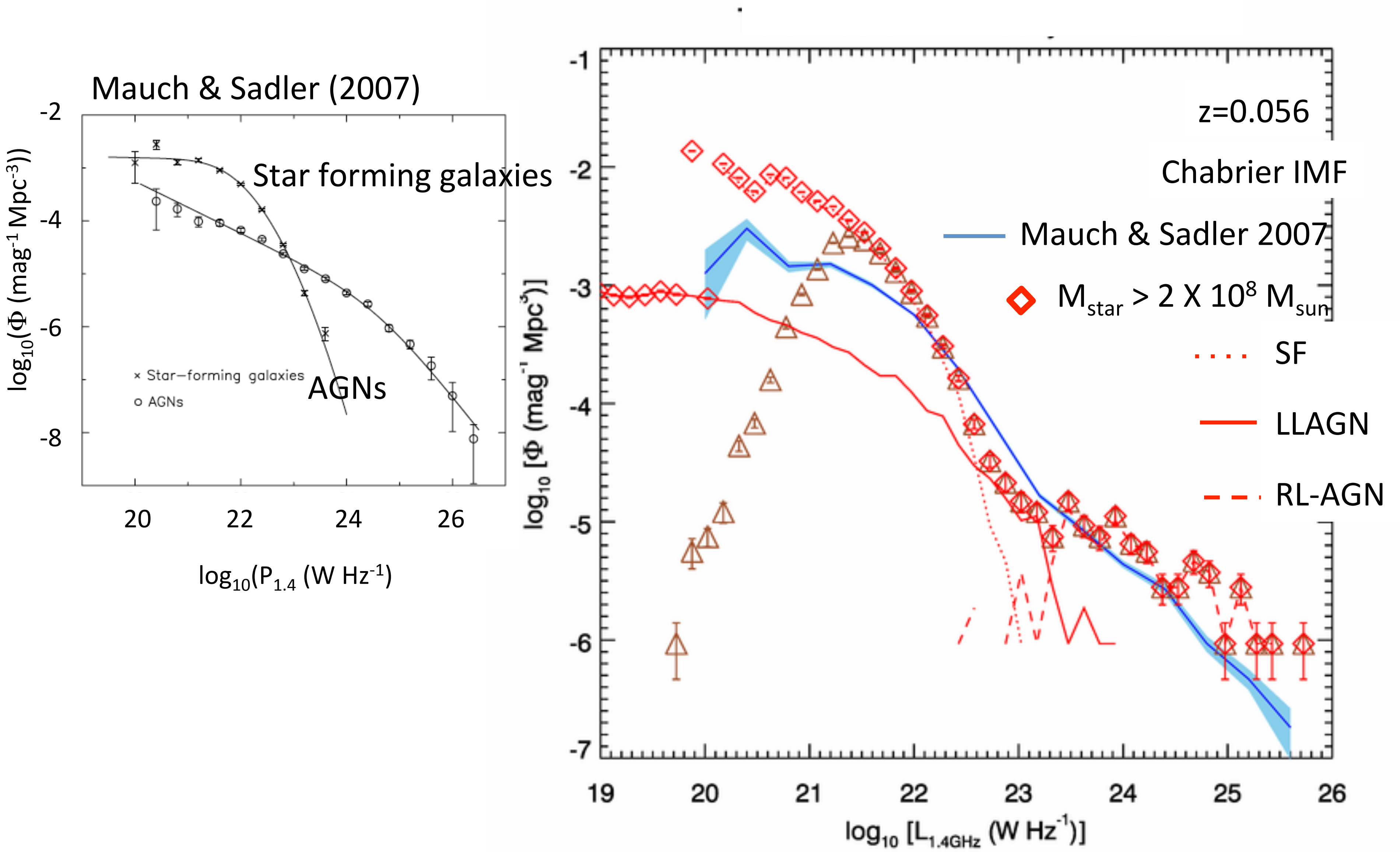
SFG + AGN 1.4 Ghz Local Luminosity Functions (model 2)

Mauch & Sadler (2007)





SFG + AGN 1.4 Ghz Local Luminosity Functions (model 2)



Mauch & Sadler (2007)

Summary

Hard problem because predictions rely on instantaneous quantities
(e.g. SFR, black hole accretion rate) in the simulations.
Much easier to get integrated quantities to match observations!

Hard problem because physics of radio continuum emission is complex!

Hard problem because very little known about how radio continuum emission depends on black hole accretion rate!

Luminosity evolution of radio continuum from star formation
depends on luminosity.

Choice of IMF changes prediction for radio continuum fueled by SF

Seem to need to suppress low luminosity AGN to get agreement with observations.