宇宙論的銀河形成モデルの構築

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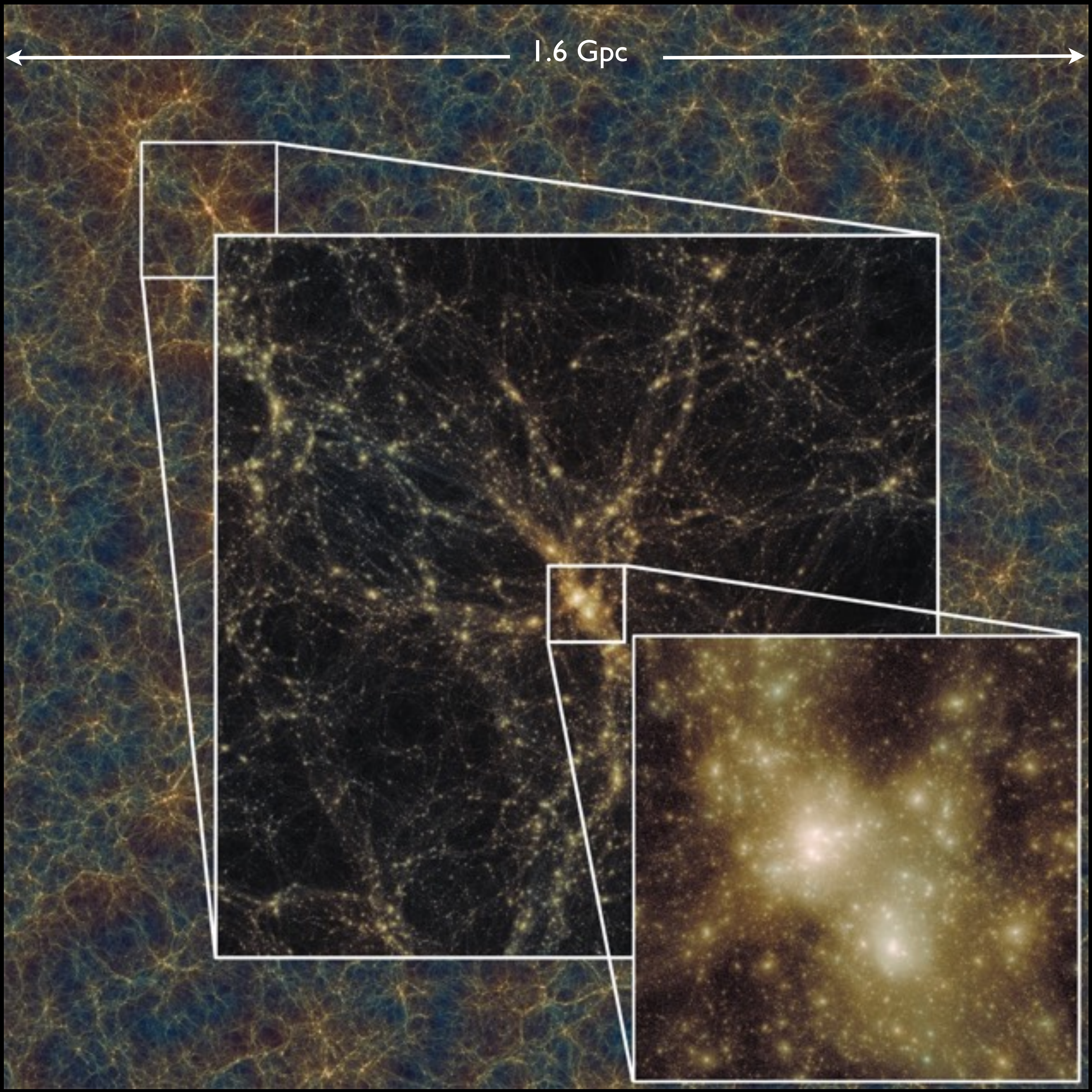
概要

- Nagashima et al. (2005) の準解析的銀河形成モデルをアップデートした
- 何がまだわからないのかがわかってきた

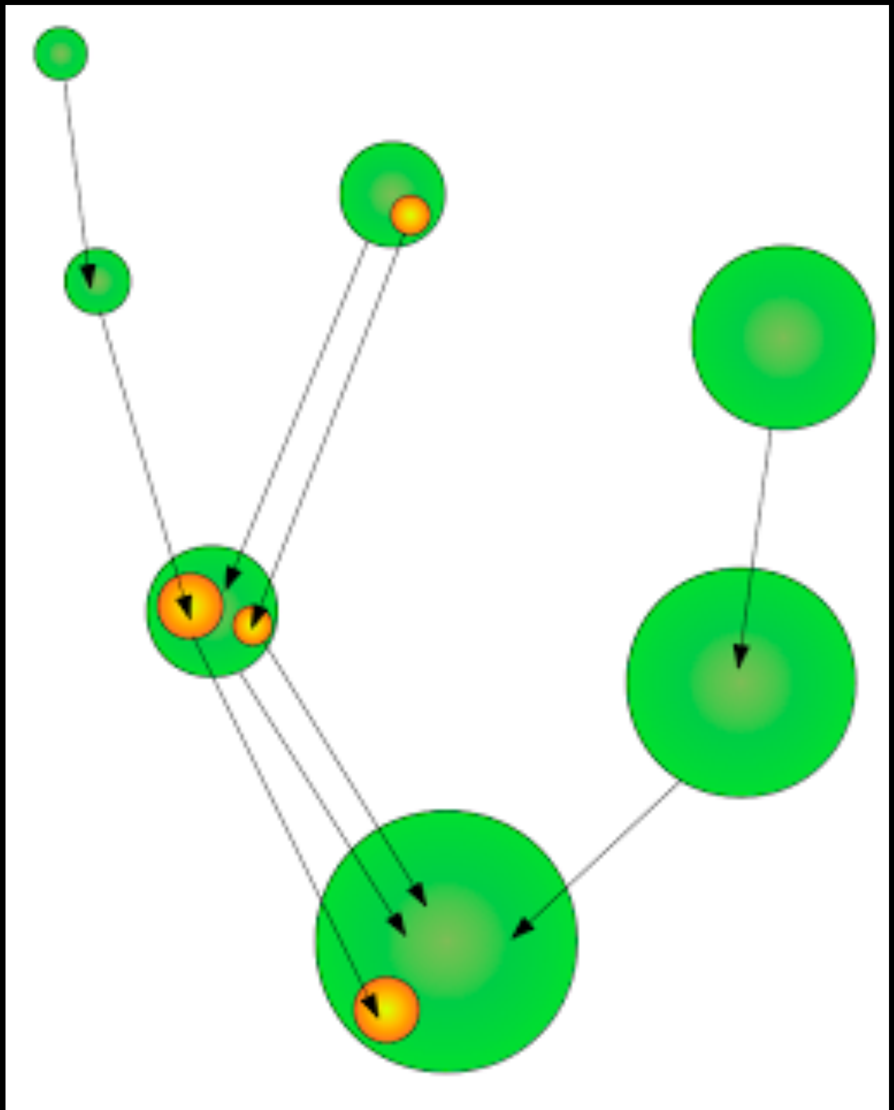
Model

- The NEW numerical galaxy catalog (ν^2GC; Makiya et al 2015 in prep.)
- "Semi-analytical model"
  - ダークマターの形成進化は N-body simulation で計算 (Ishiyama et al. 2015)
  - バリオン進化は解析的モデルで解く (gas cooling, star formation, feedback, metal enrichment...)
  - local の光度関数, HI mass function に合うようにパラメータ決定
- 新しくなったところ
  - 世界最大規模のダークマターの N-body simulation
  - AGN feedback
  - UV feedback
  - MCMC fitting

Cosmological dark matter simulation (Ishiyama et al. 2015)

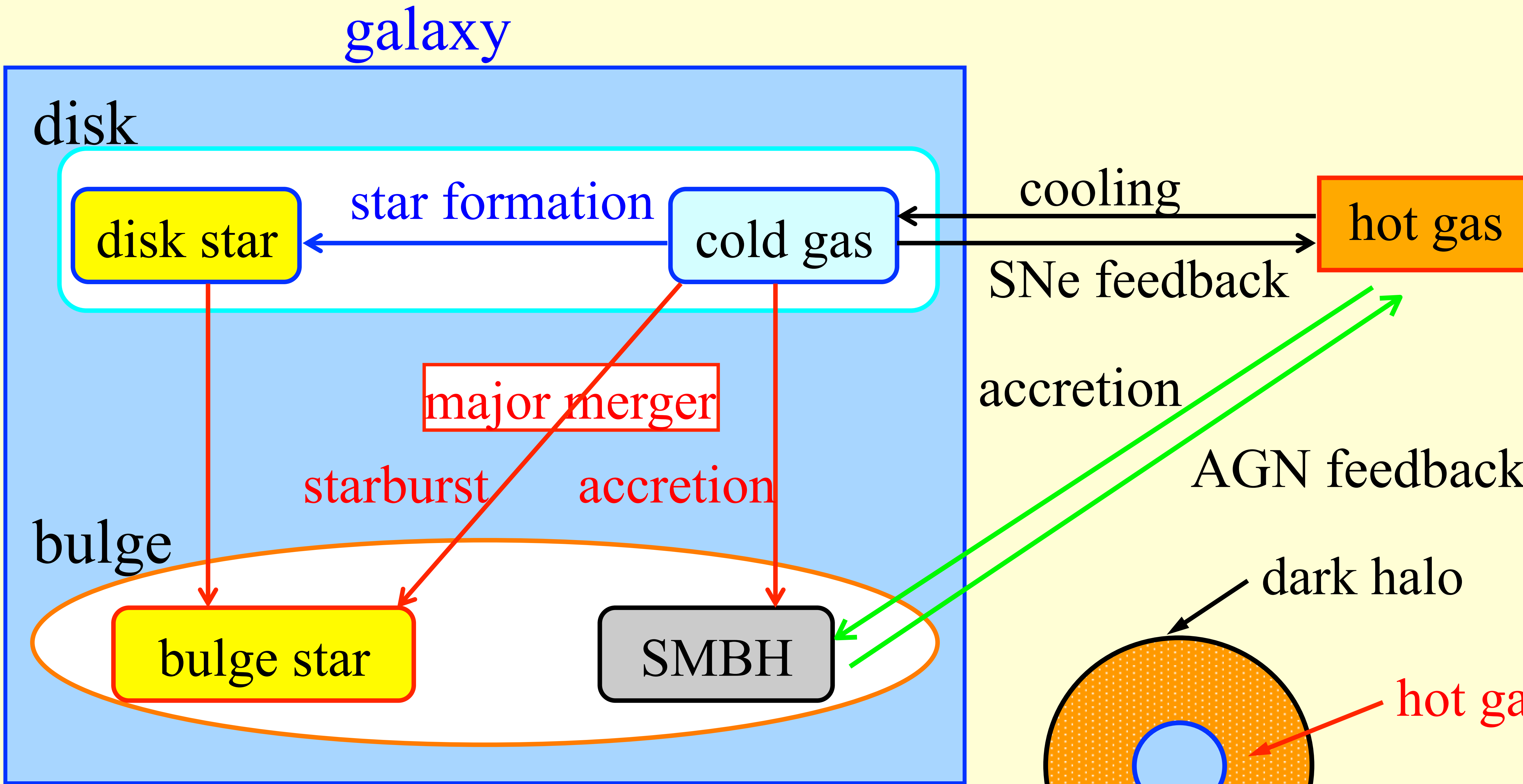


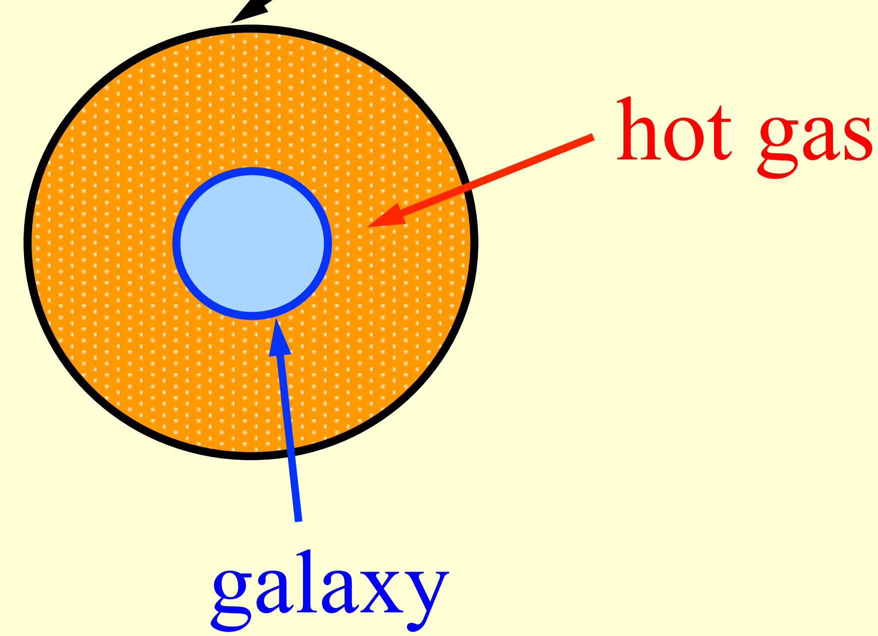
Merger tree



(Galacticus blog より)

ν²GC における銀河進化計算のおおまかな流れ





*galaxy = disk + bulge
disk = disk star + cold gas
bulge = bulge star + black hole
* hot gas ; diffuse gas, virial temperature

スライド by榎さん

Baryon physics

- gas cooling
  - 温度, 金属量, ガス密度の関数として cooling rate を計算
  - ガスの温度分布や H_2 形成などは考えない
- star formation and supernova feedback
  - 星形成タイムスケールは銀河の dynamical time の関数
  - 星形成に応じて金属量進化, ダストも生成 (Mdust ∝ Mgas × Zcold)
  - SN feedback で cold gas を吹き飛ばす
    - 小さい銀河ほど feedback がよく効く

Baryon physics

- galaxy merger
  - satellite galaxy が力学的摩擦で中心に落ち central galaxy と合体
  - 合体する銀河の質量比が同程度の場合には major merger が起きる => starburst + bulge formation
- SMBH evolution / AGN feedback
  - 全ての銀河は seed black hole を持つ
  - major merger の際に, 一定の割合で cold gas が central SMBH に降着 => SMBH と bulge の共進化
  - SMBH が成長すると AGN によって gas cooling が抑制される

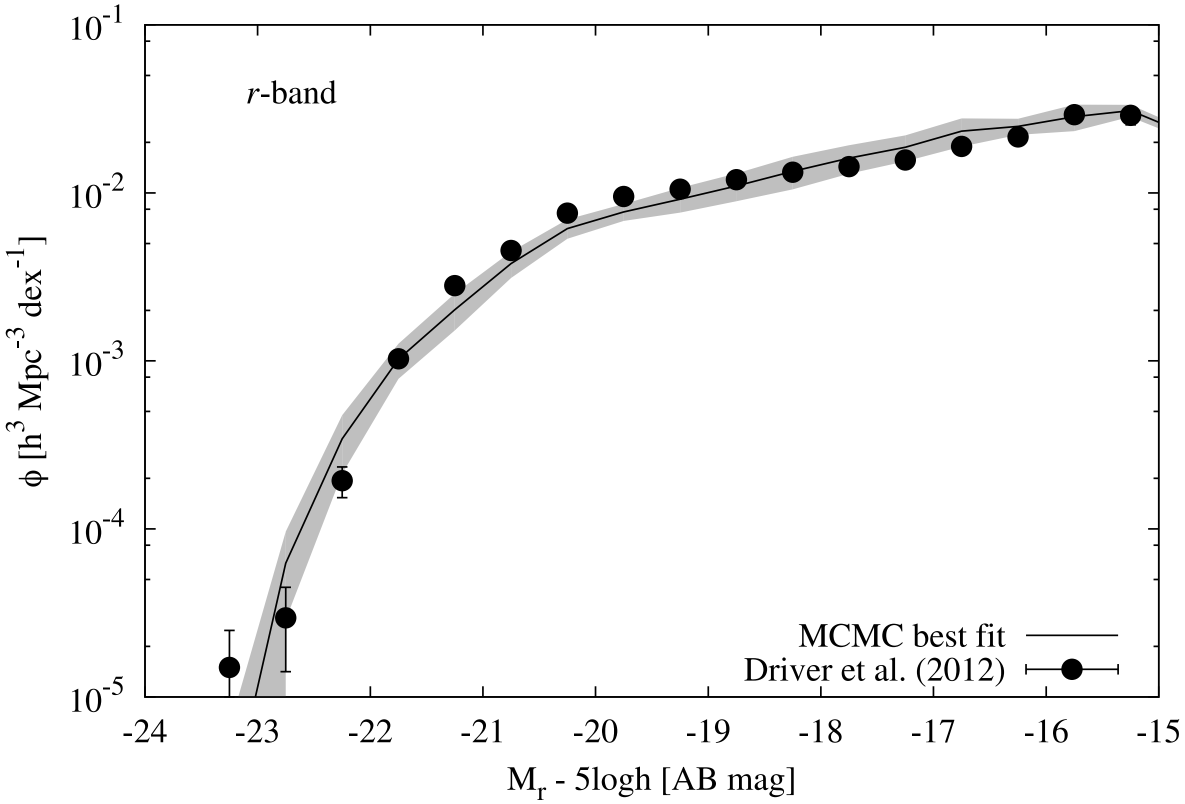
パラメータまとめ

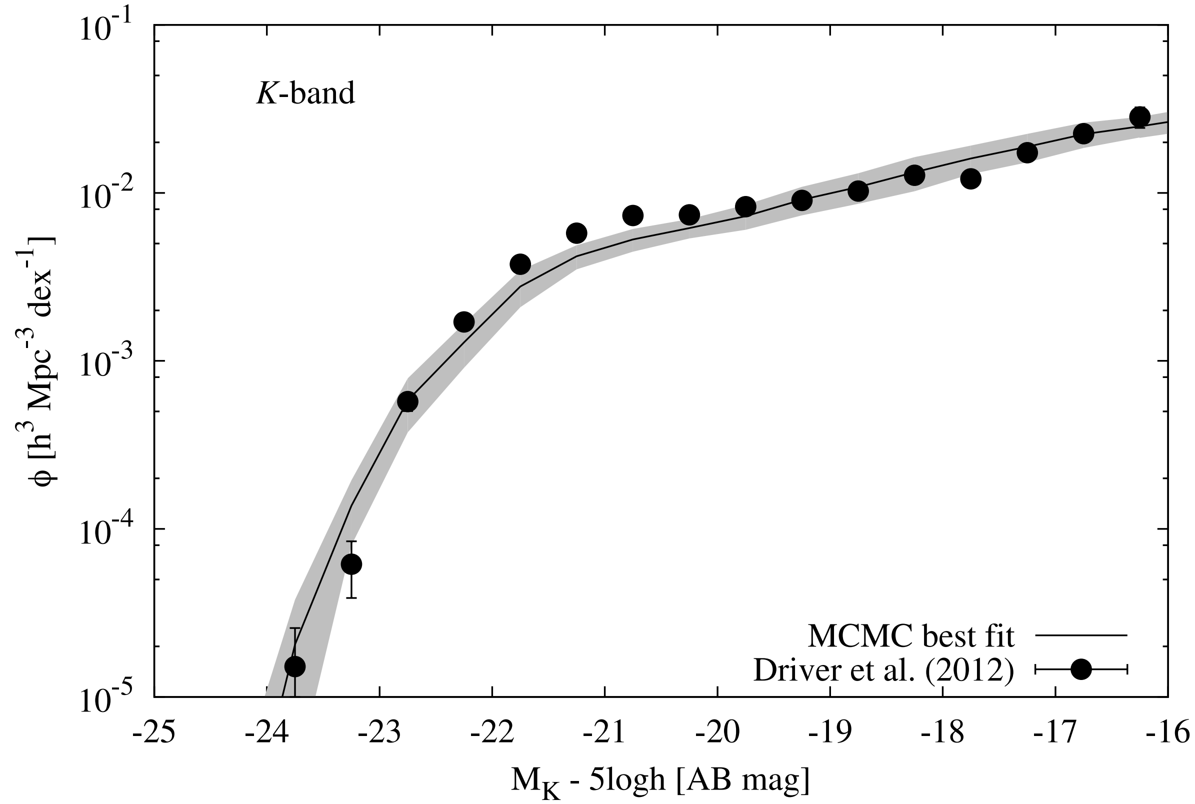
	best-fit	1σ error	meaning
$\alpha_{\rm star}$	-1.178	0.163	star formation-related
$\varepsilon_{\rm star}$	0.170	0.011	star formation-related
$\alpha_{\rm hot}$	2.996	0.168	SN feedback-related
$V_{\rm hot}$ (km/s)	171.23	7.561	SN feedback-related
$\alpha_{\rm cool}$	6.110	0.250	AGN feedback-related
$\log_{10}(\epsilon_{\rm SMBH})$	-0.240	0.157	AGN feedback-related
$M_{\rm seed}(M_{\odot})$	10^5 (fix)	–	seed blackhole mass
$f_{\rm BH}$	0.01 (fix)	–	fraction of the mass accreted onto SMBH during major merger
τ_{V0}	2.5e5 (fix)	–	coefficient of dust extinction
$f_{\rm bulge}$	0.1 (fix)	–	major/minor merger criterion
$f_{\rm mrg}$	0.7 (fix)	–	coefficient of dynamical friction timescale
$f_{\rm diss}$	1.0 (fix)	–	energy loss fraction
ρ	0.0 (fix)	–	redshift dependence of disk size
γ	1.0 (fix)	–	redshift dependence of dust optical depth

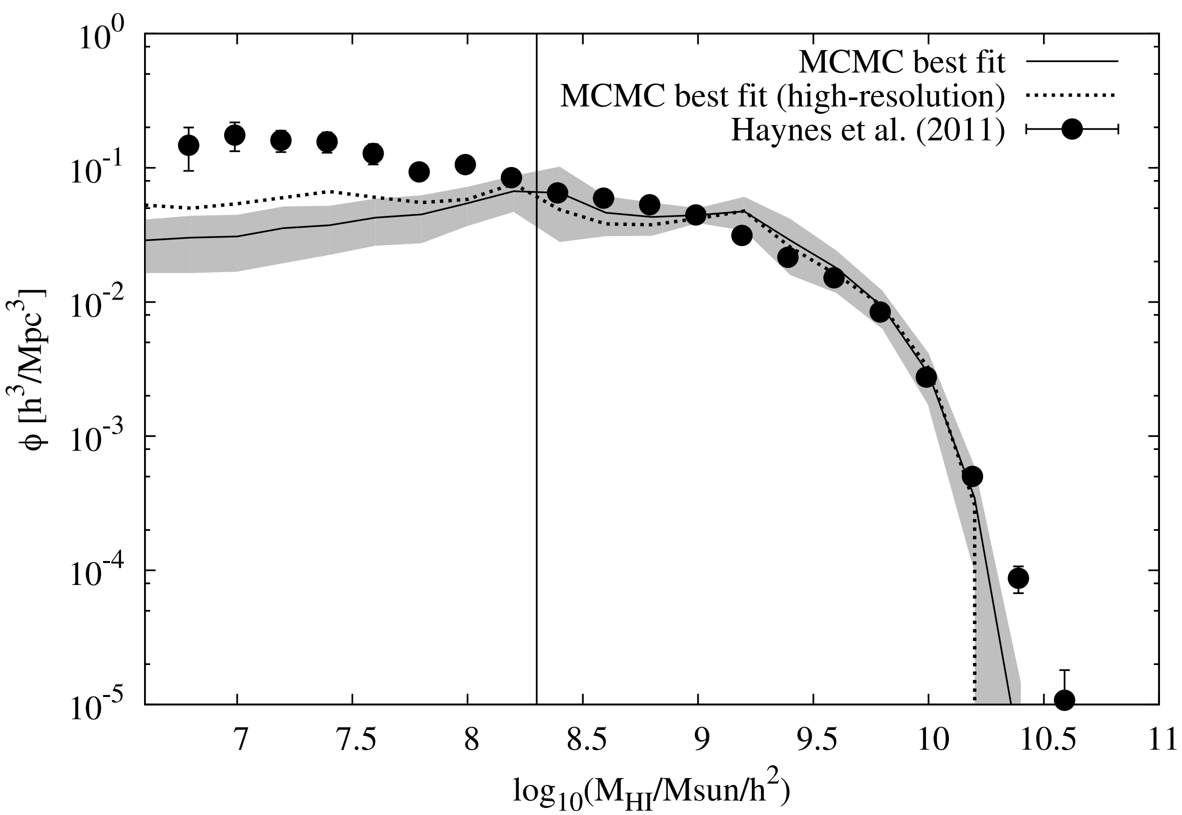
Table 2. PARAMETERS

- パラメータの決め方
  - Markov-Chain Monte Carlo 法を用いる
  - local の r-band 及び K-band 光度関数, HI 質量関数に合わせる

local LFs and HI mass function

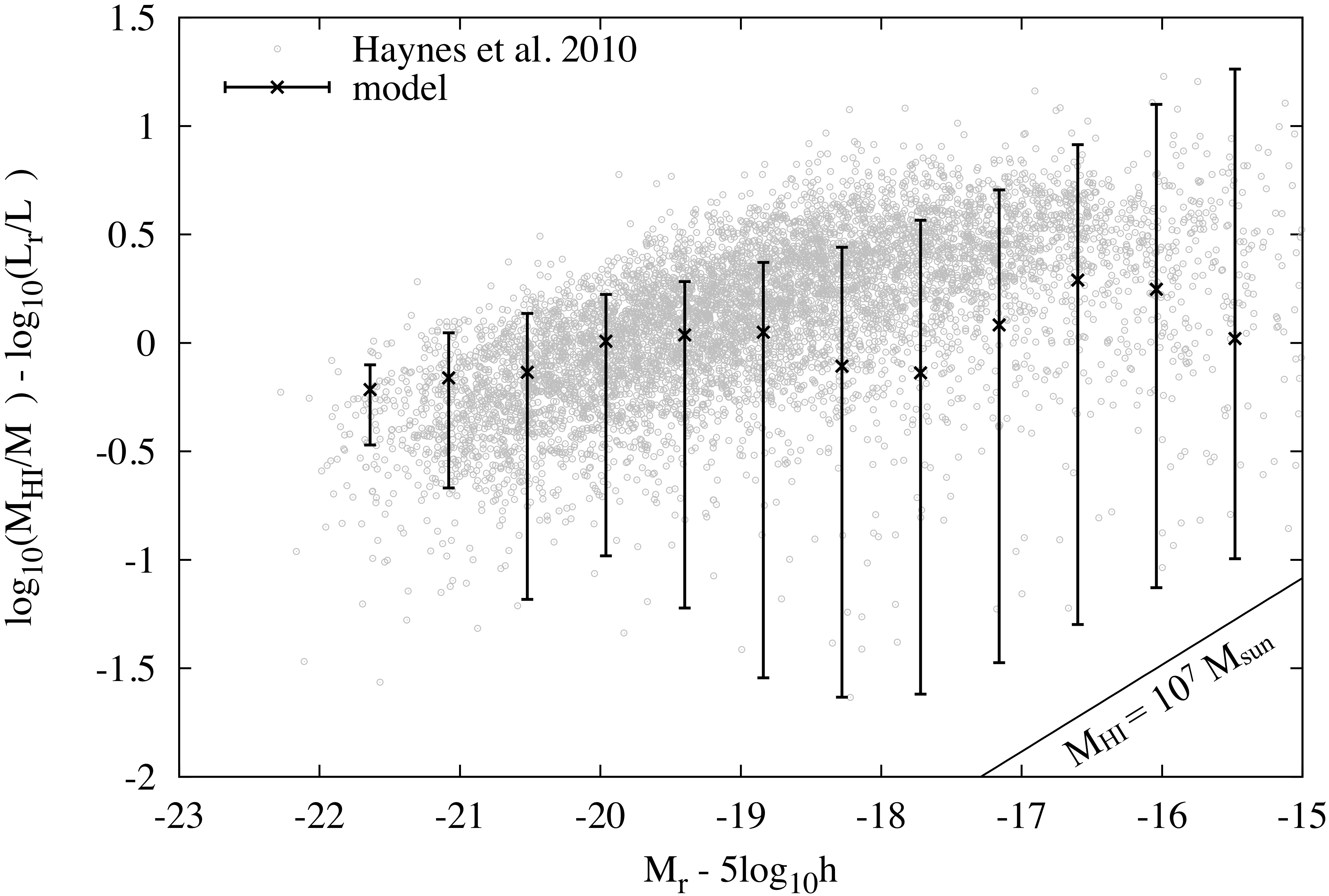






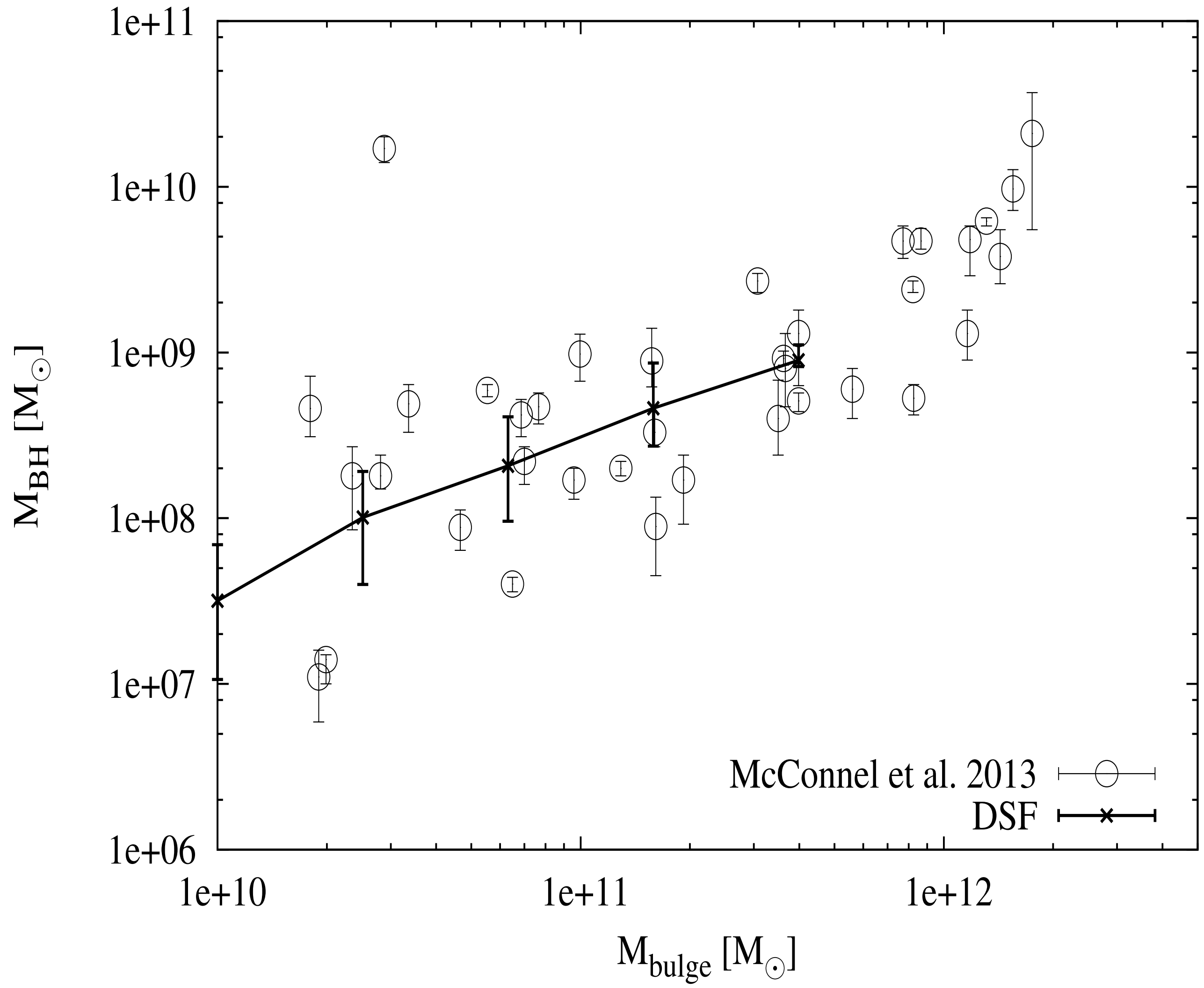
- 光度関数と HI 質量関数を同時に再現できた
- (HI 質量関数の faint-end は怪しい？)

Cold gas mass relative to *r*-band mag

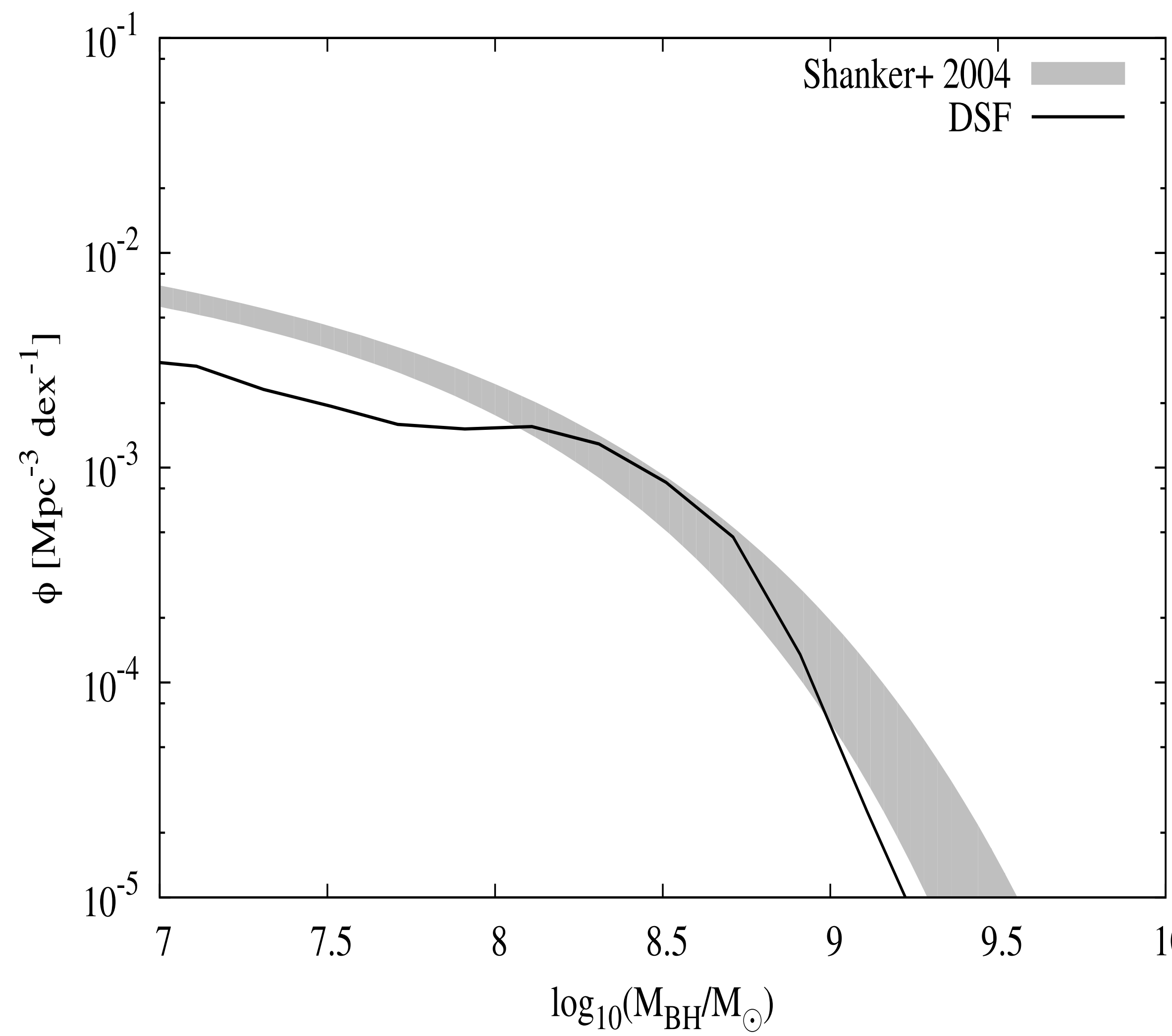


暗い銀河でガスを飛ばし過ぎ？

local SMBHs



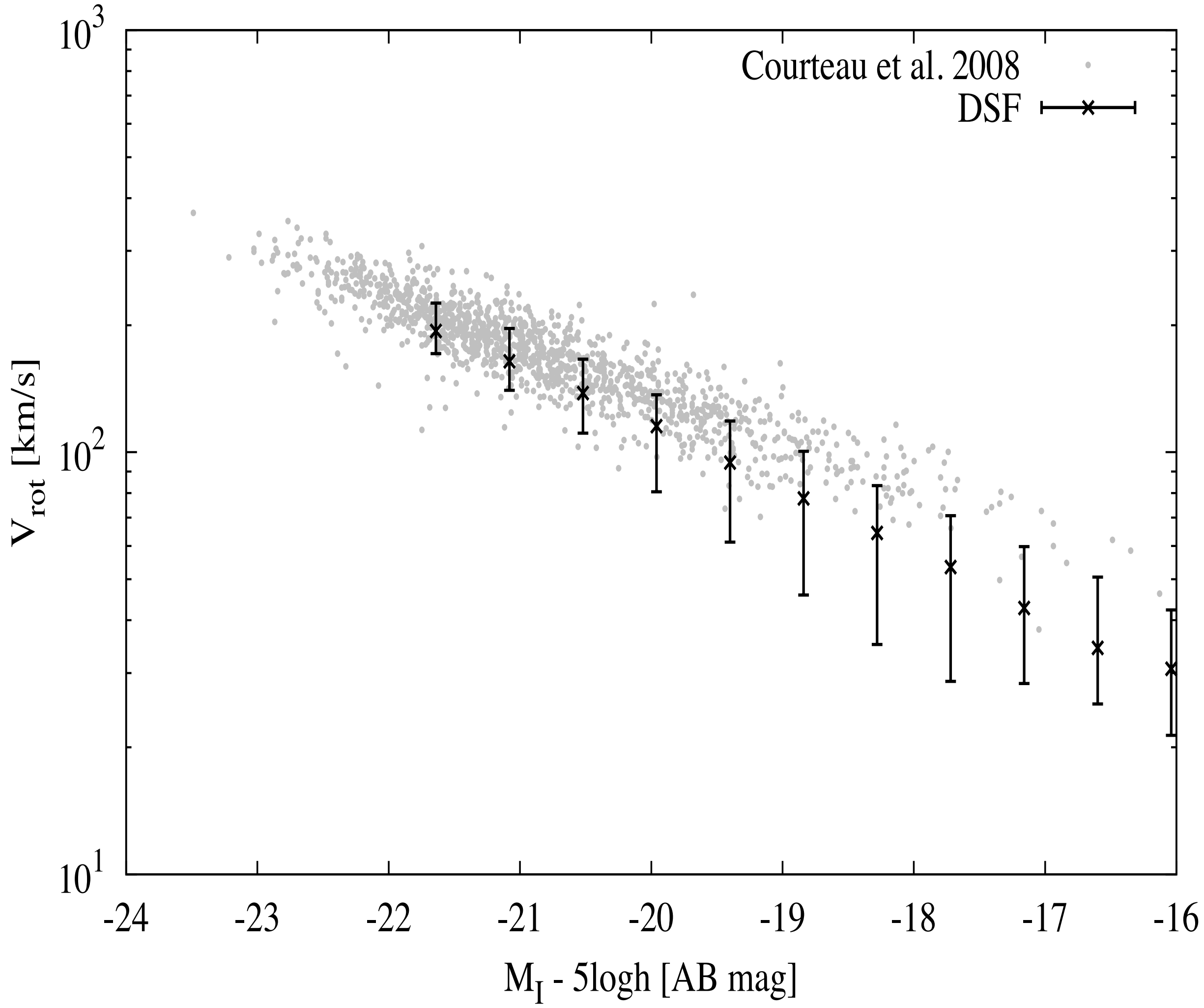
M_{bulge}-M_{BH} relation



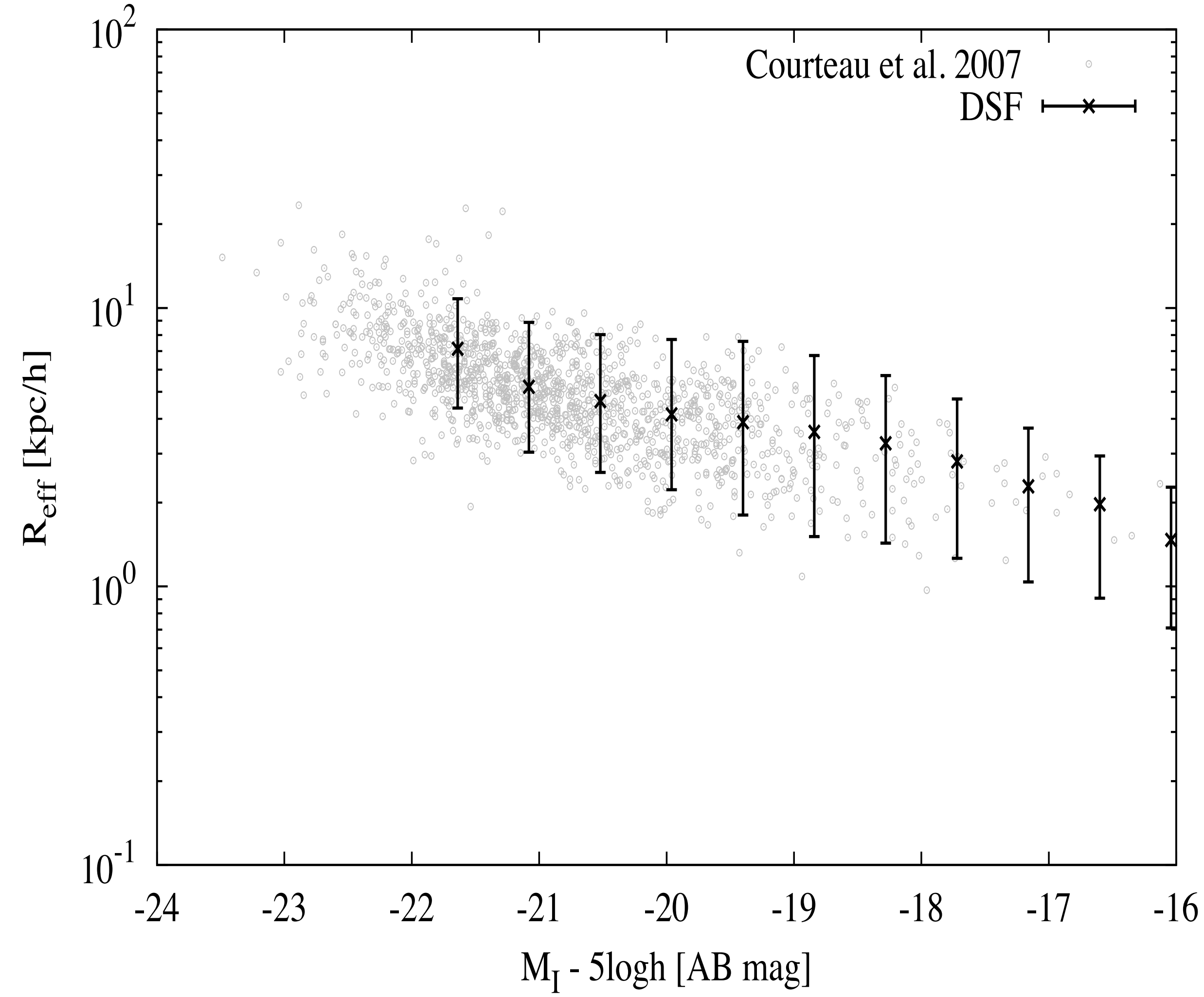
SMBH mass function

- major merger 時に cold gas の ~1% を SMBH に落とせば観測を再現する

Size and rotation velocity of galaxy disk



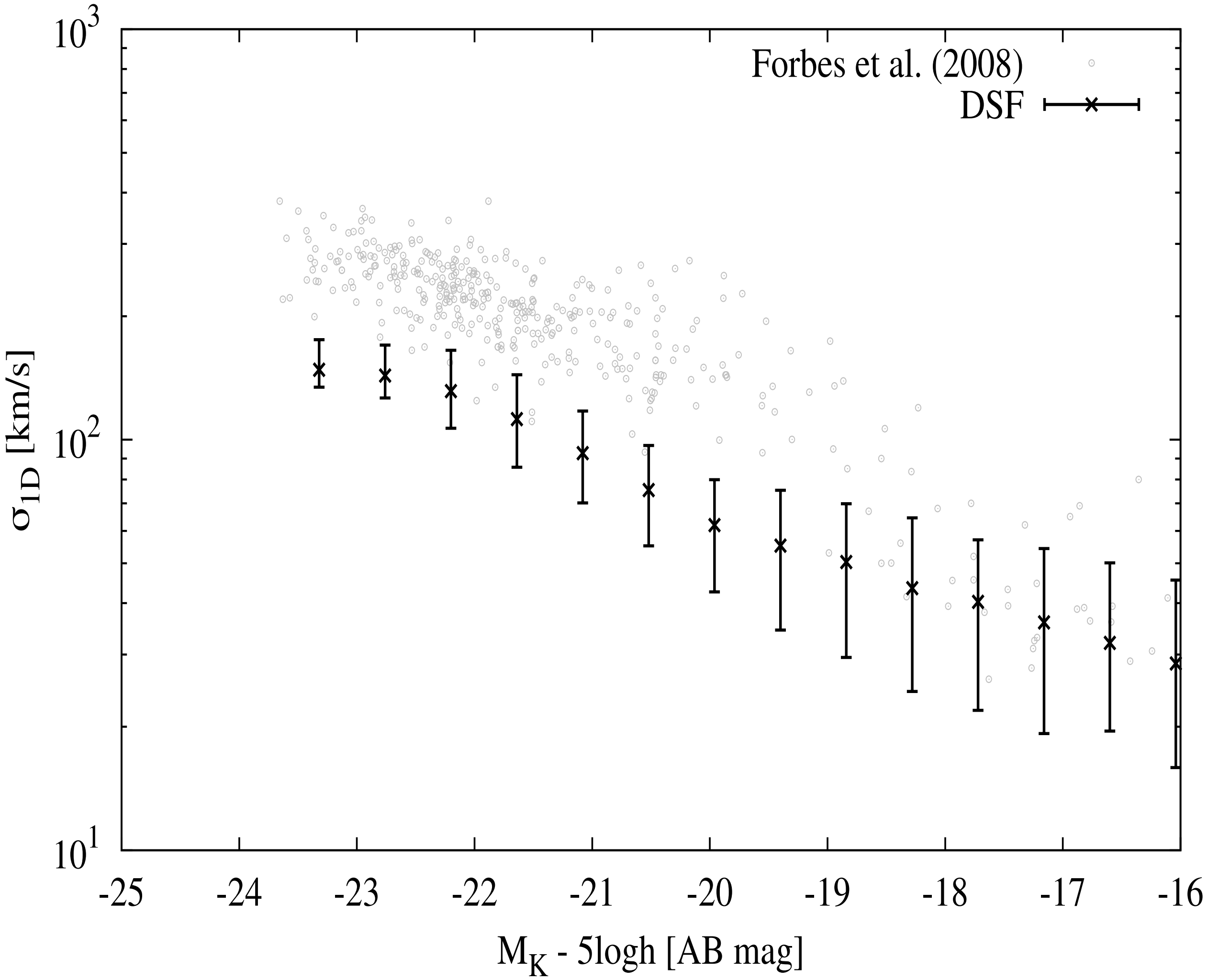
Tully-Fisher relation



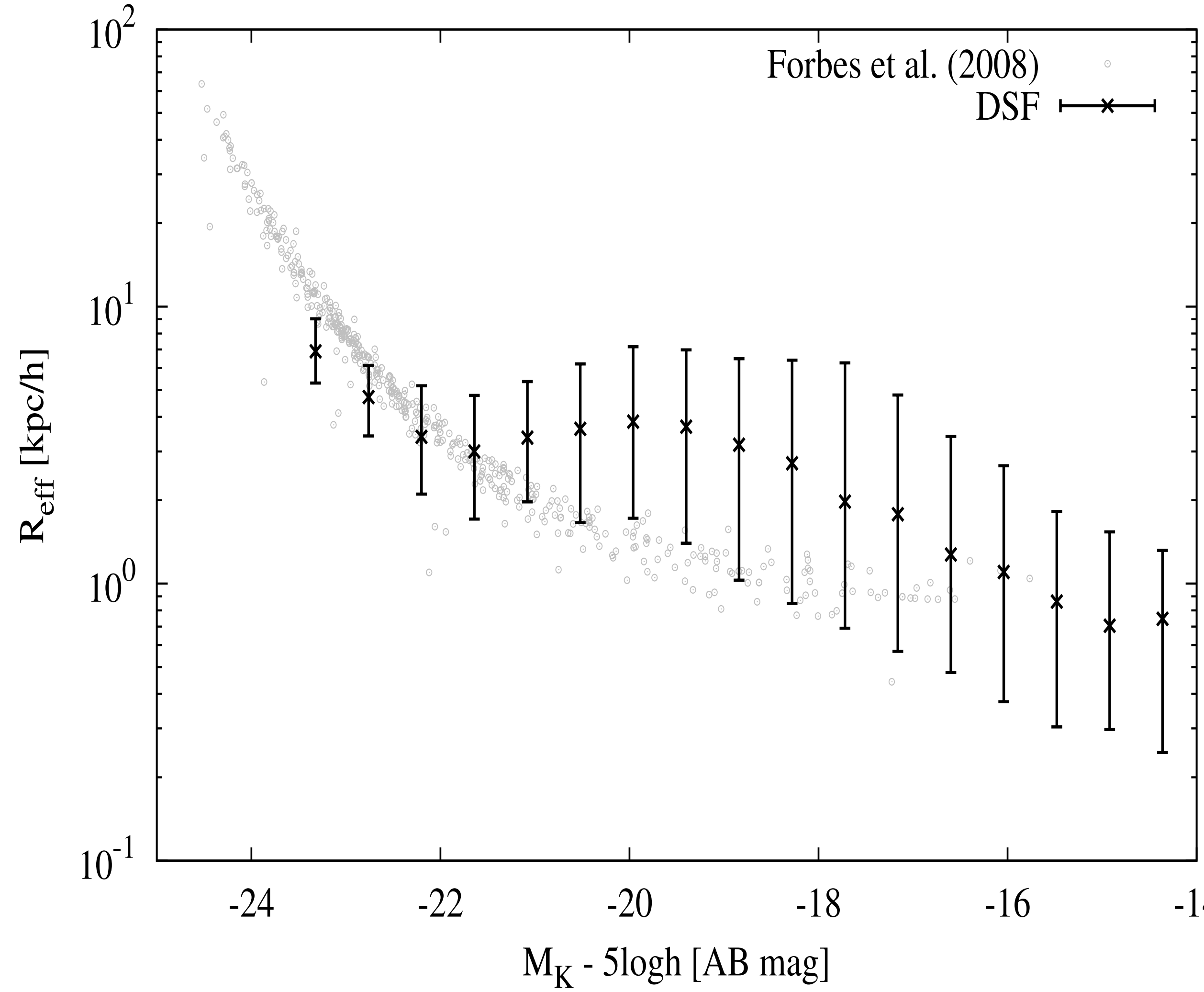
Size-magnitude relation

- ダークマターハローの virial size と circular velocity から銀河円盤のサイズと回転速度を決定
- 力学応答によるサイズ進化も考慮

Size and velocity dispersion of bulge



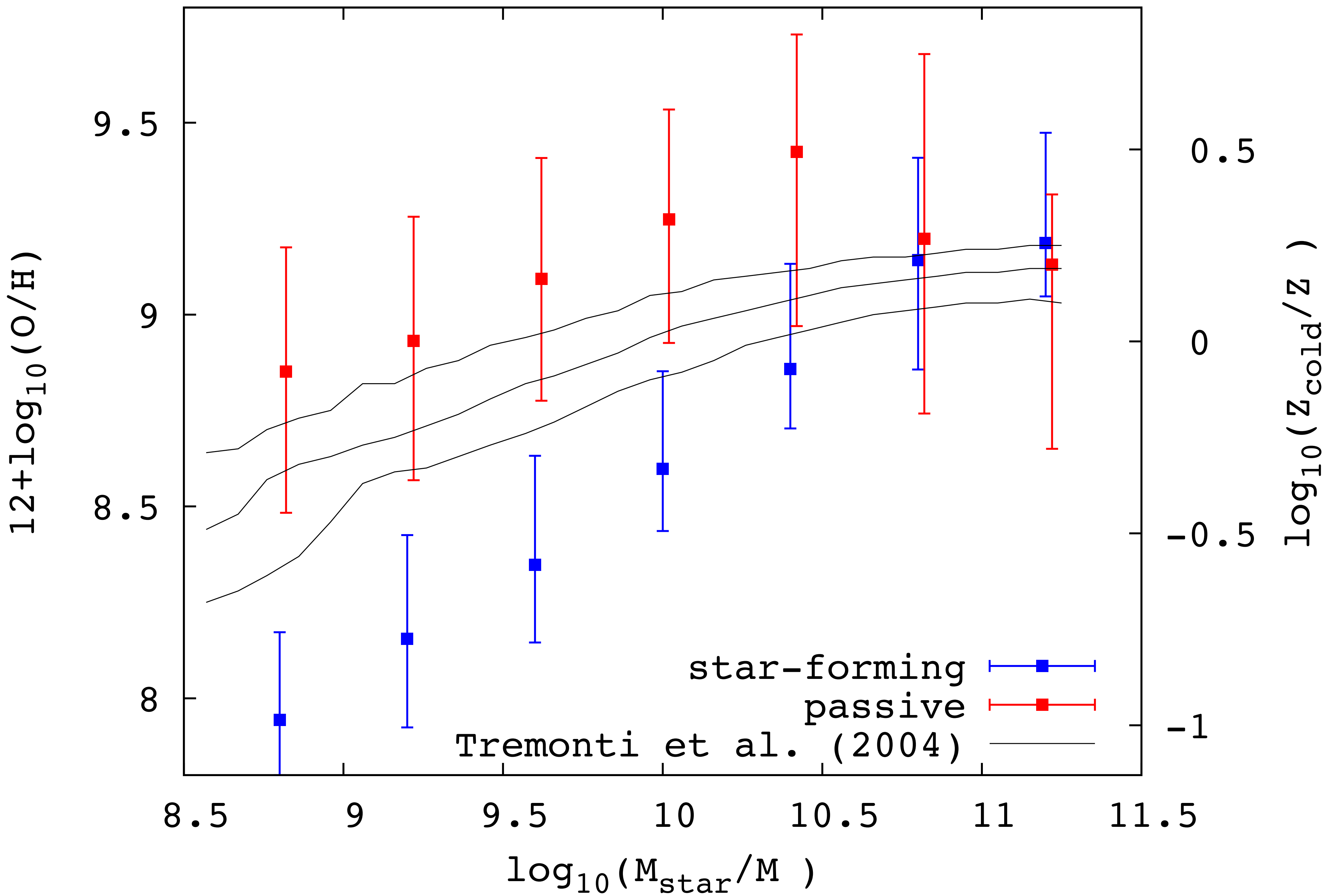
Faber-Jackson relation



Size-magnitude relation

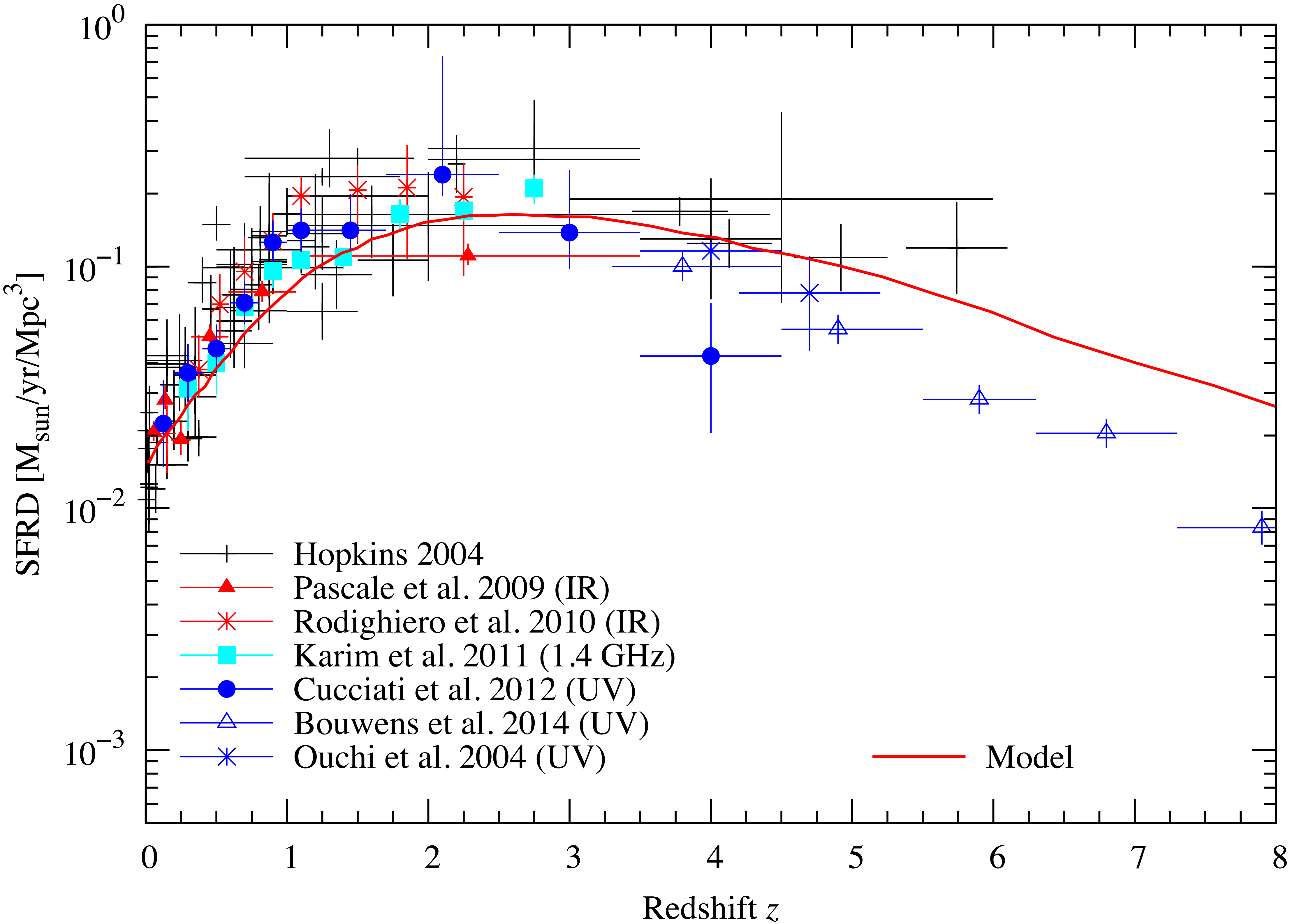
- major merger 前後のエネルギー保存からサイズと速度分散を計算
- 明るい側でどちらも観測より小さい => M/L が間違っている？

Mstar-Zcold relation

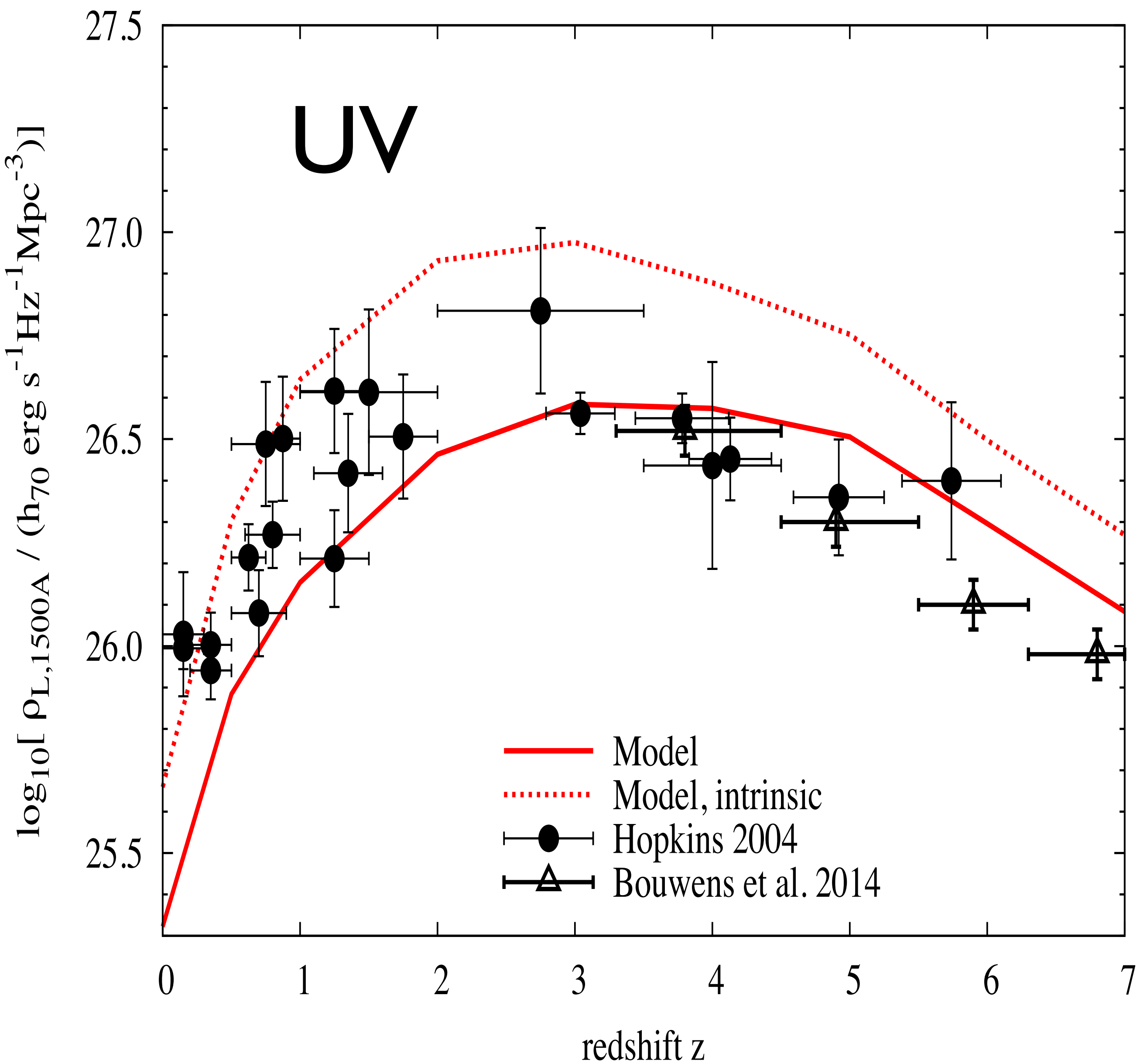


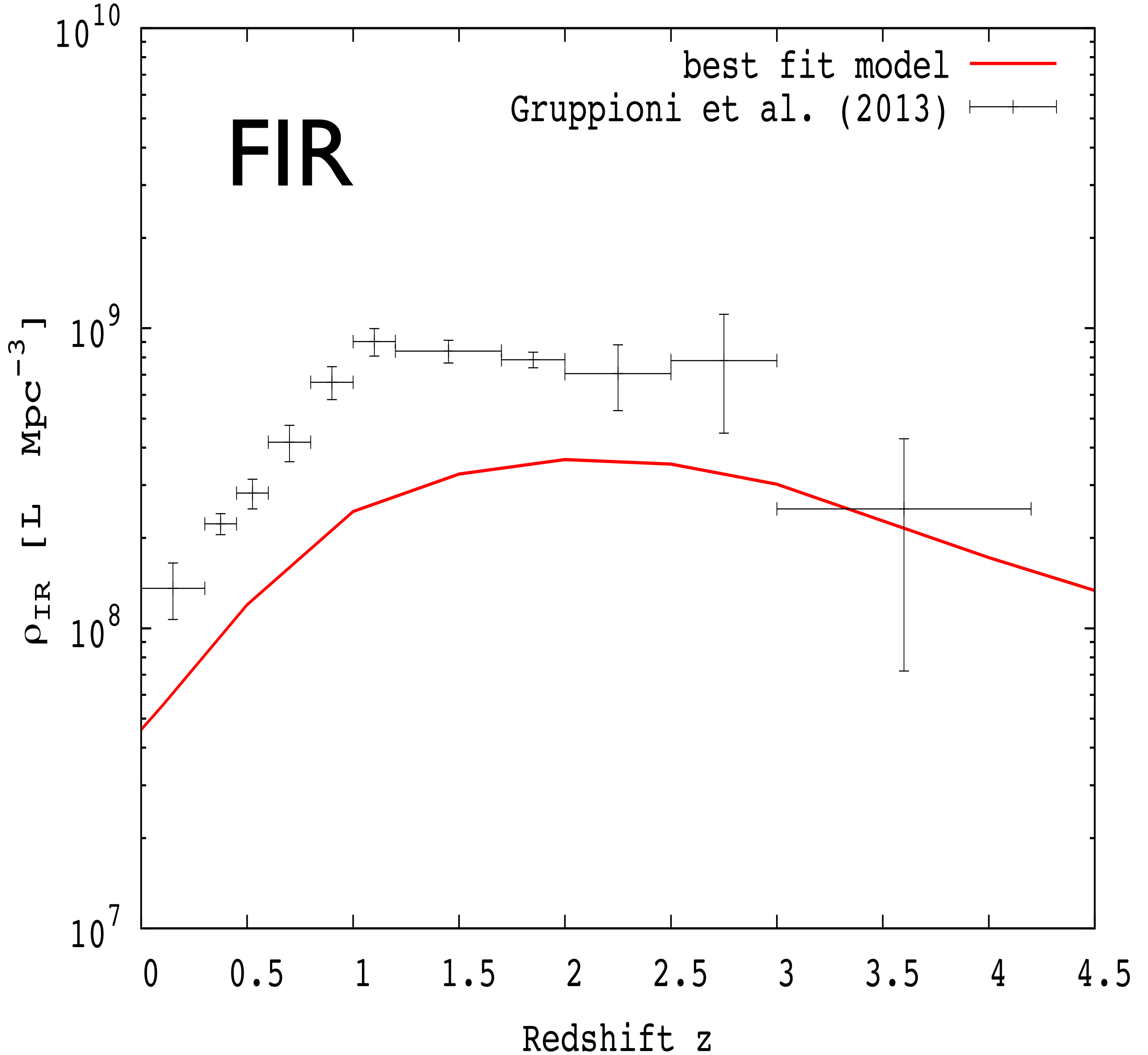
- 小さい銀河ではメタルが足りない
- SN feedback を効かせすぎ？

Cosmic star formation history



UV and IR luminosity density





- UV は観測を再現するが IR は factor ~2--3 足りない
- もっと SFR を上げる？ top-heavy IMF？ AGN？

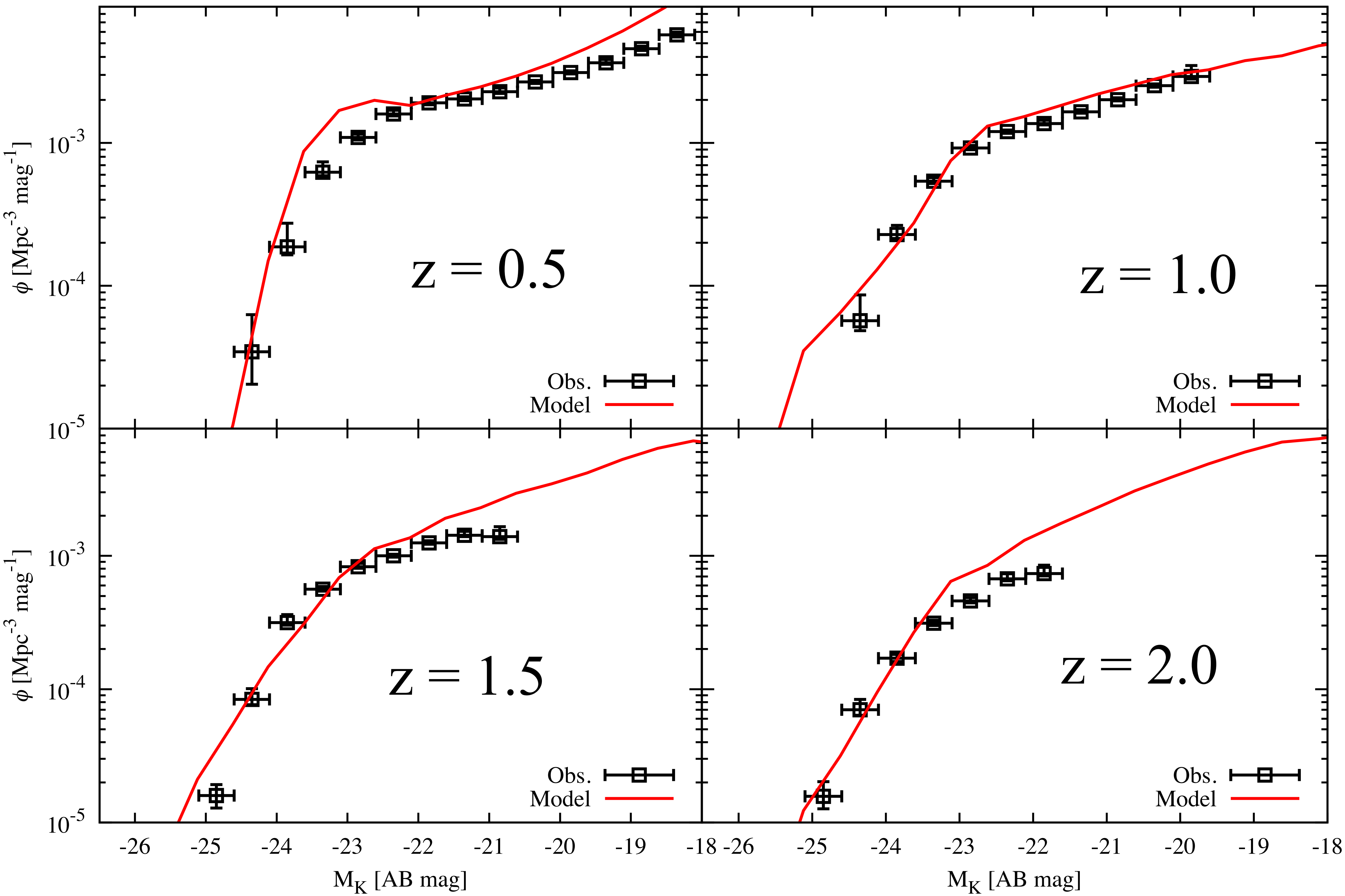
まとめ

- local LF や cosmic SFR density evolution は概ね再現
- 未解決問題
  - 暗い銀河で cold gas が少ない
  - MZ relation
  - バルジ形成機構
  - ダスト生成 / ダスト放射機構
- 星成分は大体よし、ガスやメタルやダストはまだ理解が甘い

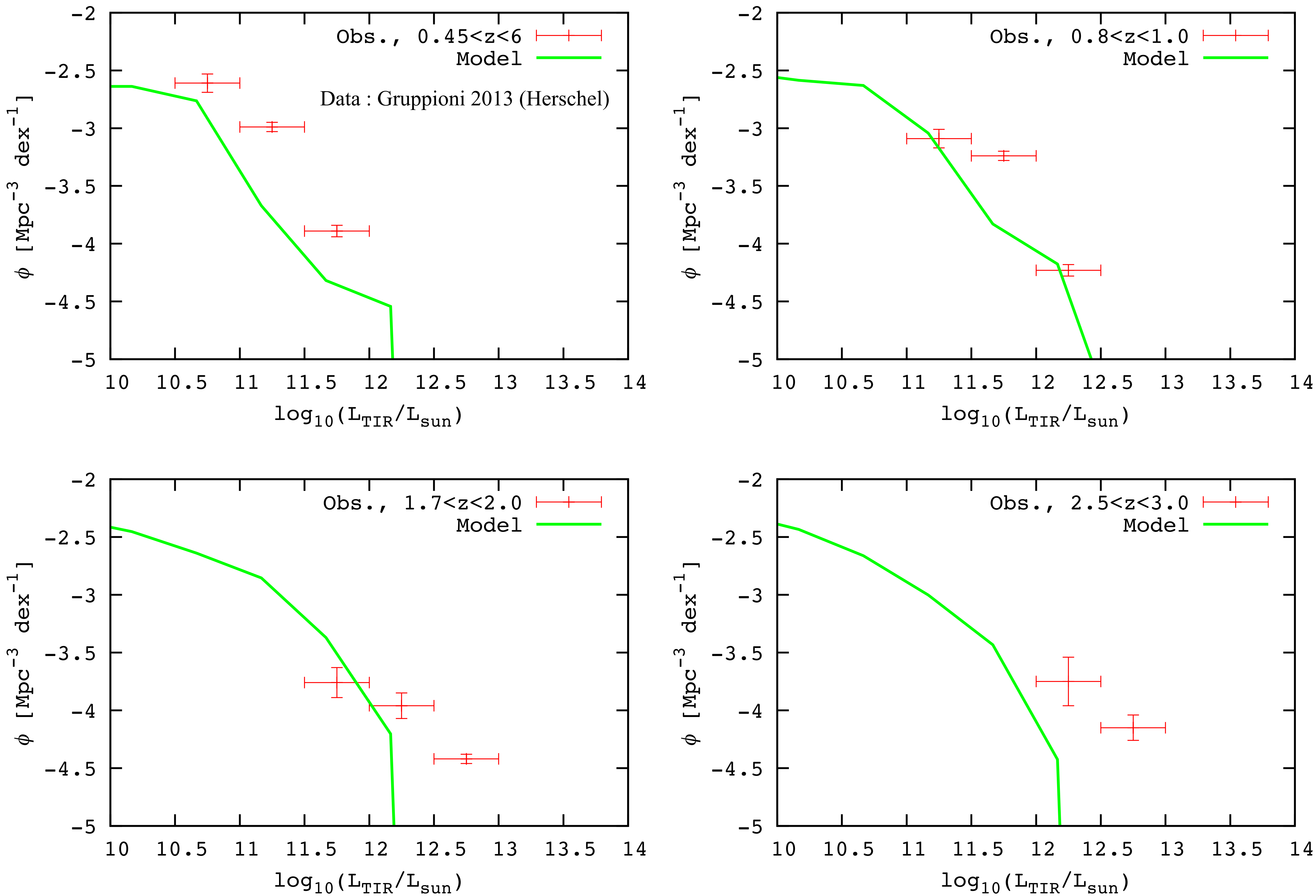
Table 1. Details of the ν^2GC simulations. N is the number of simulated particles, L is the comoving box size, m is the particle mass resolution $M_{\rm min}$ is the mass of the smallest halos, the total number of halos, and $M_{\rm max}$ is the mass of the largest halo in each simulations. The smalles halos consist of 40 particles. In the last two columns, values at z=0 are presented except for the ν^2GC-H3 simulation, which was stopped at $z = 4$

Name	N	$L(h^{-1}{\rm Mpc})$	$m(h^{-1}M_\odot)$	$M_{\rm min}(h^{-1}M_\odot)$	#Halos	$M_{\rm max}(h^{-1}M_\odot)$
ν^2GC-L	8192^3	1120.0	2.20×10^8	8.79×10^9	$421,801,565$	4.11×10^{15}
ν^2GC-M	4096^3	560.0	2.20×10^8	8.79×10^9	$52,701,925$	2.67×10^{15}
ν^2GC-S	2048^3	280.0	2.20×10^8	8.79×10^9	$6,575,486$	1.56×10^{15}
ν^2GC-SS	512^3	70.0	2.20×10^8	8.79×10^9	$103,630$	6.58×10^{14}
ν^2GC-H1	2048^3	140.0	2.75×10^7	1.10×10^9	$5,467,200$	4.81×10^{14}
ν^2GC-H2	2048^3	70.0	3.44×10^6	1.37×10^8	$4,600,746$	4.00×10^{14}
ν^2GC-H3	4096^3	140.0	3.44×10^6	1.37×10^8	$44,679,543 (z = 4)$	$1.15 \times 10^{13} (z = 4)$

Stellar mass functions

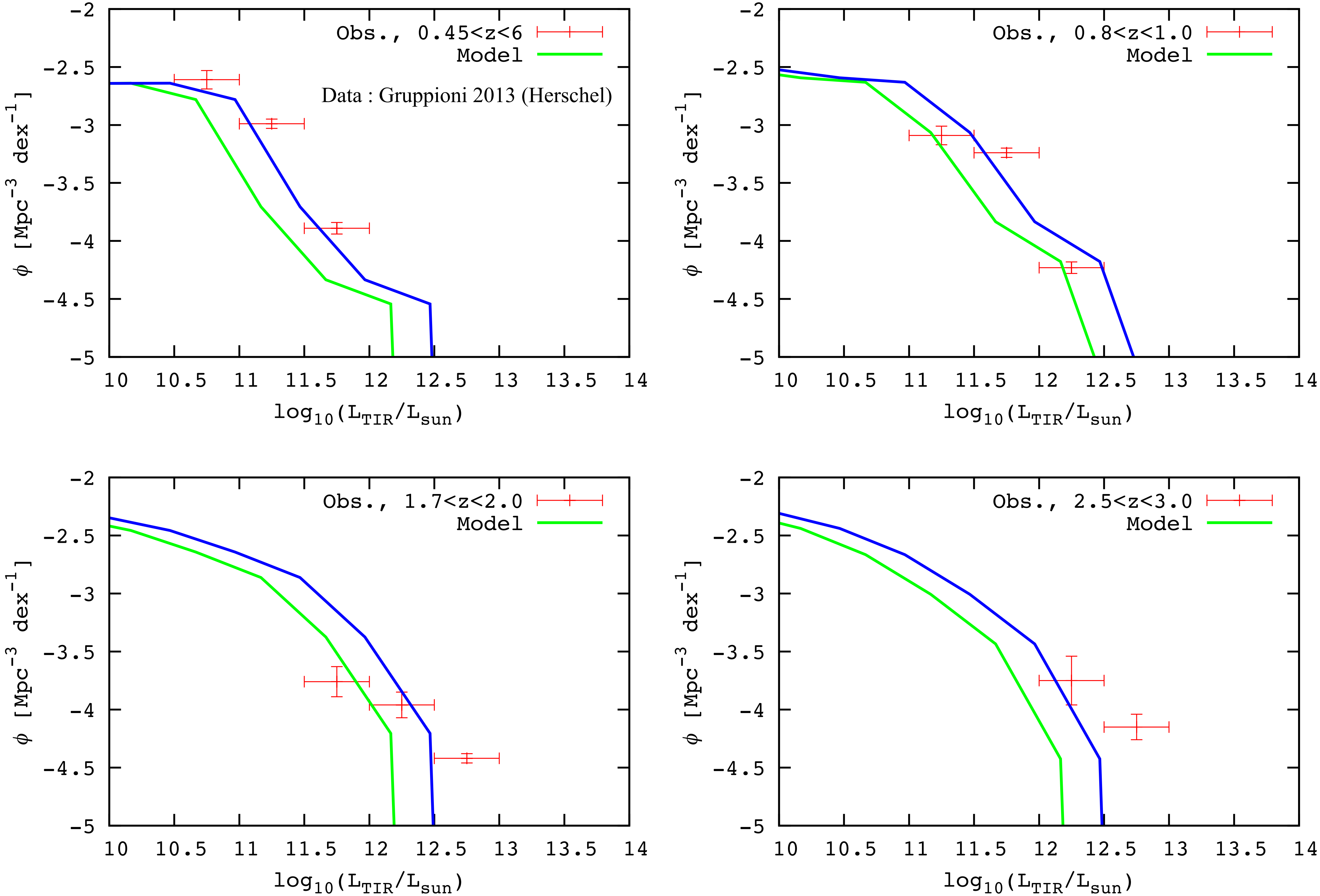


TIR luminosity functions



モデル銀河は全体的に IR で暗い…

TIR luminosity functions

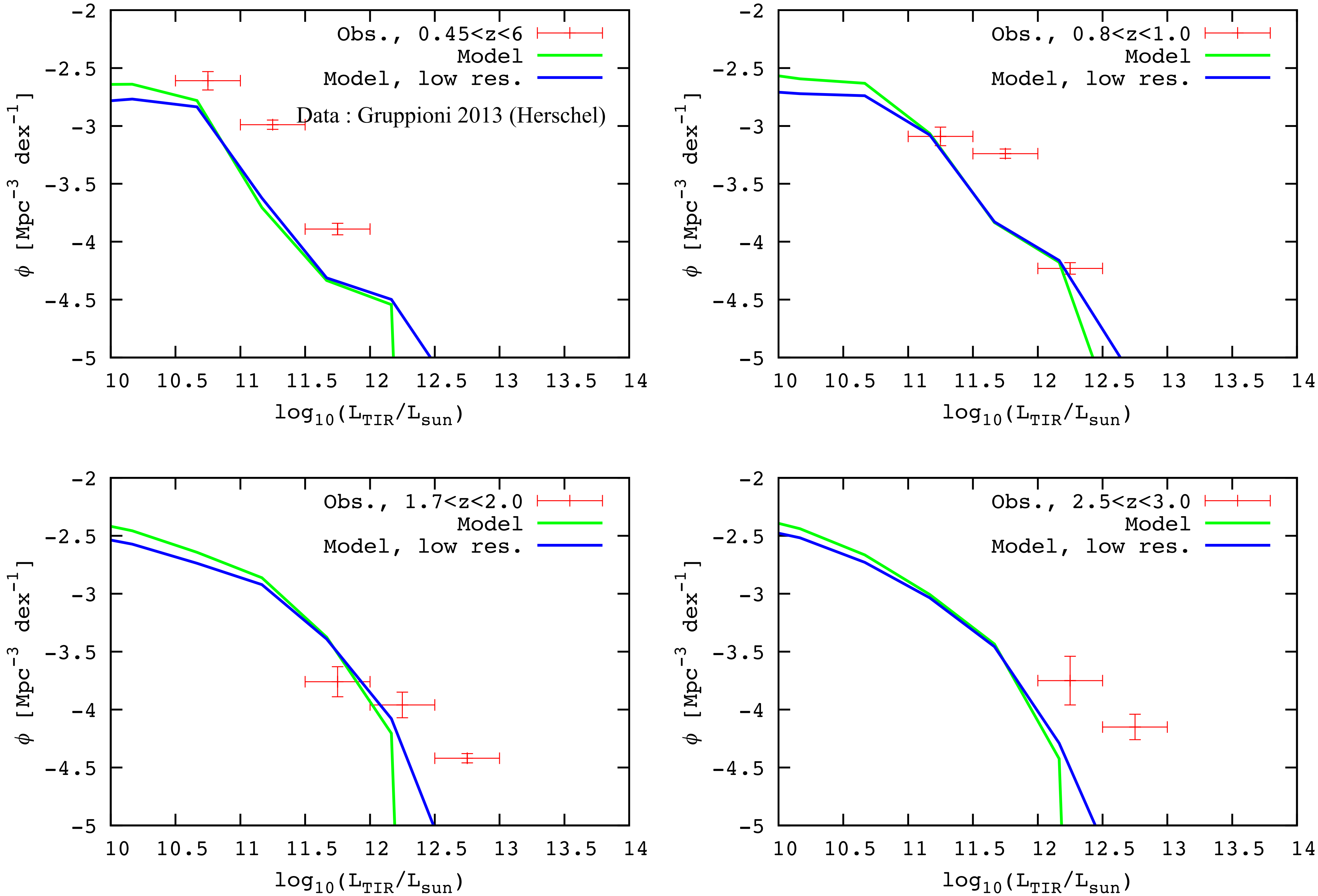


大体２倍くらい暗い

Why?

- 観測の空間分解能の影響？
  - 観測データは複数のソースをまとめて見ている？
- AGNの寄与？
  - モデルにはまだ入っていない
  - ULIRG 的な天体は AGN dominated
- top-heavy IMF?
  - SFR を変えずに UV photon を増やせる

TIR luminosity functions

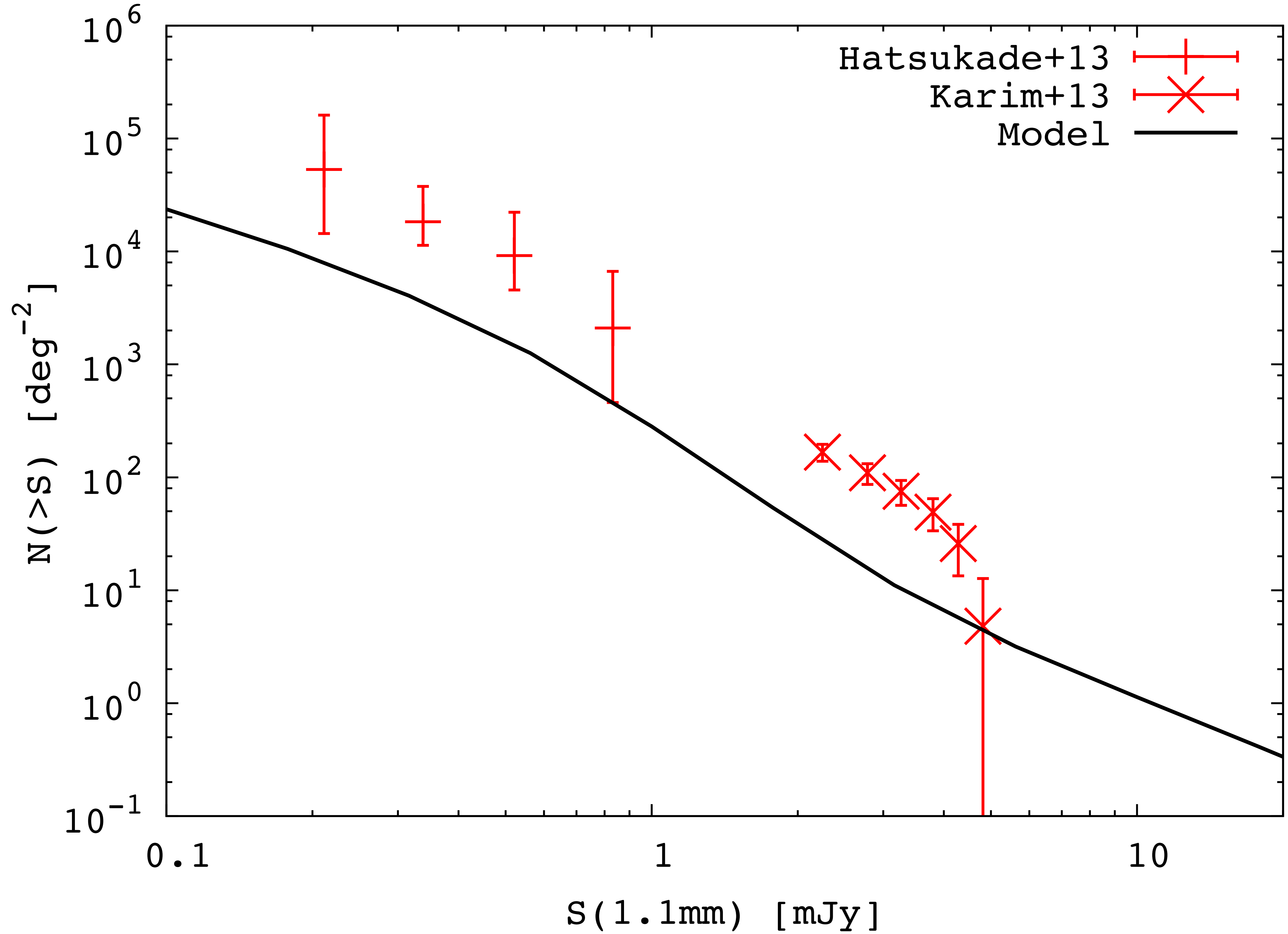


- 青線 : 空間的になましてLFを計算
- それほど効かない

TIR LF は合わないがとりあえず

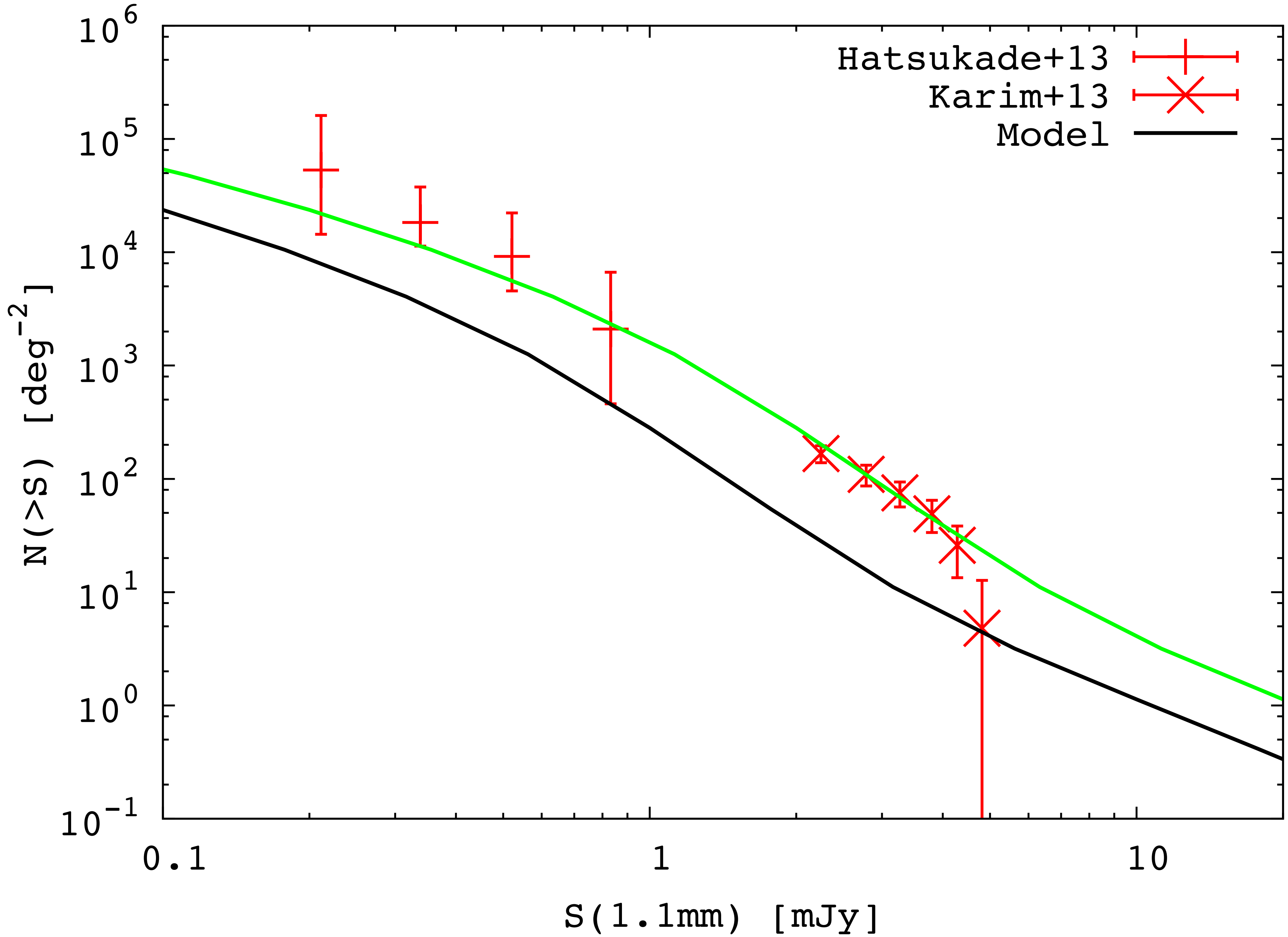
SMGs の計算をしてみる

Number count of 1.1mm sources



- やはり SMGs も暗い

Number count of 1.1mm sources

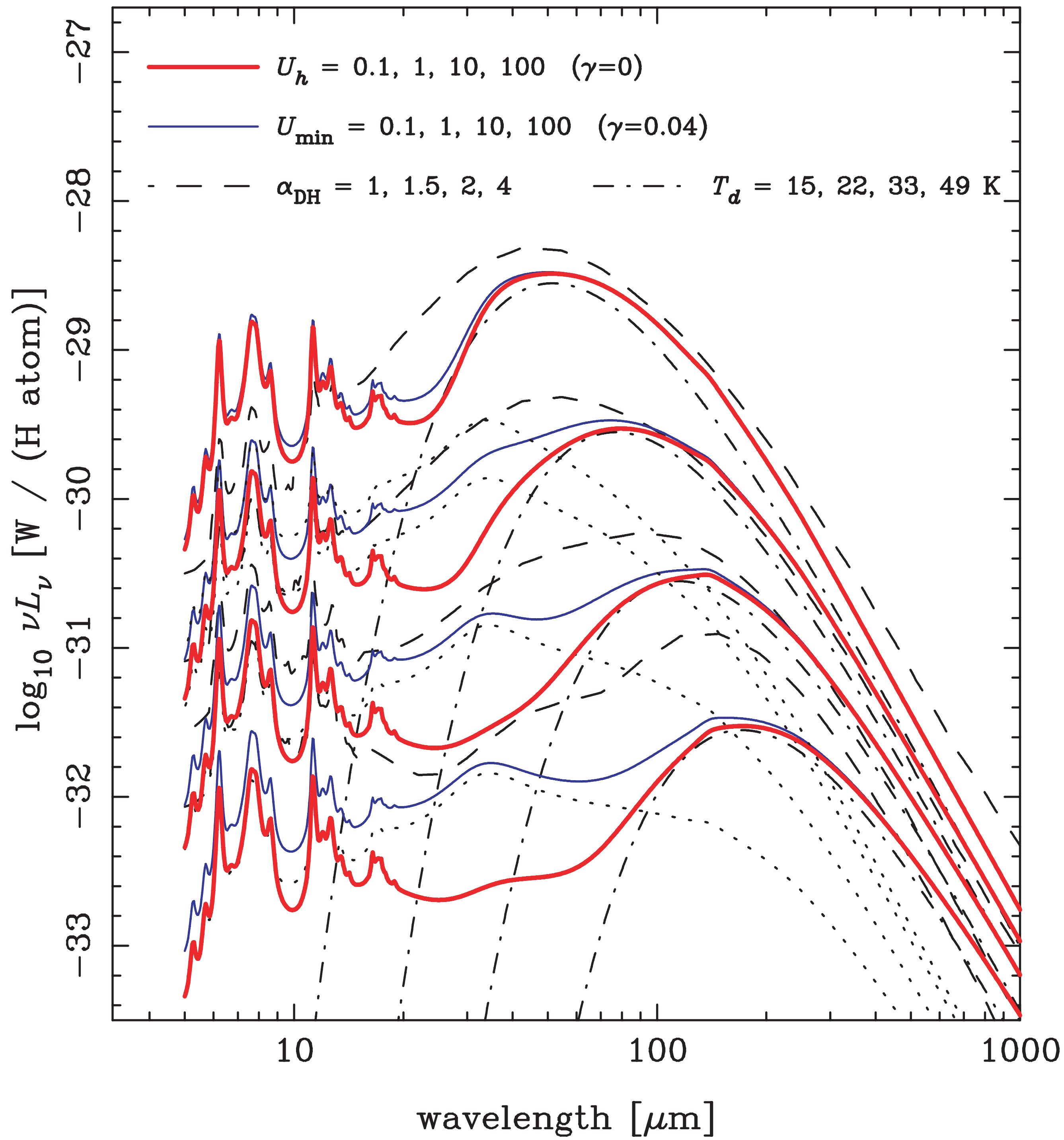


- 緑線 : $L_{\rm TIR}$ を手で２倍にして計算
- ぴったり合う => SED model は良さそう

Evolution of disk size and L-$T_{\rm dust}$ relation

- At fixed SFR:
  - large size => low $\tau_{\rm dust}$ and low $L_{\rm TIR}$
- At fixed $L_{\rm TIR}$
  - large size => low $T_{\rm dust}$ and high submm flux
- effective radius of $L \sim L_*$ galaxies scales as $r \propto (1+z)^{-1}$ (e.g., Ono+ 2013)
- モデル銀河は同じ $L_{\rm TIR}$ でも high-z ほどダスト温度が高温になる

Physical dust model by Draine & Li (2007)



L_{TIR}-T_{dust} relation for SMGs and local SF galaxies

Hwang et al. (2010)

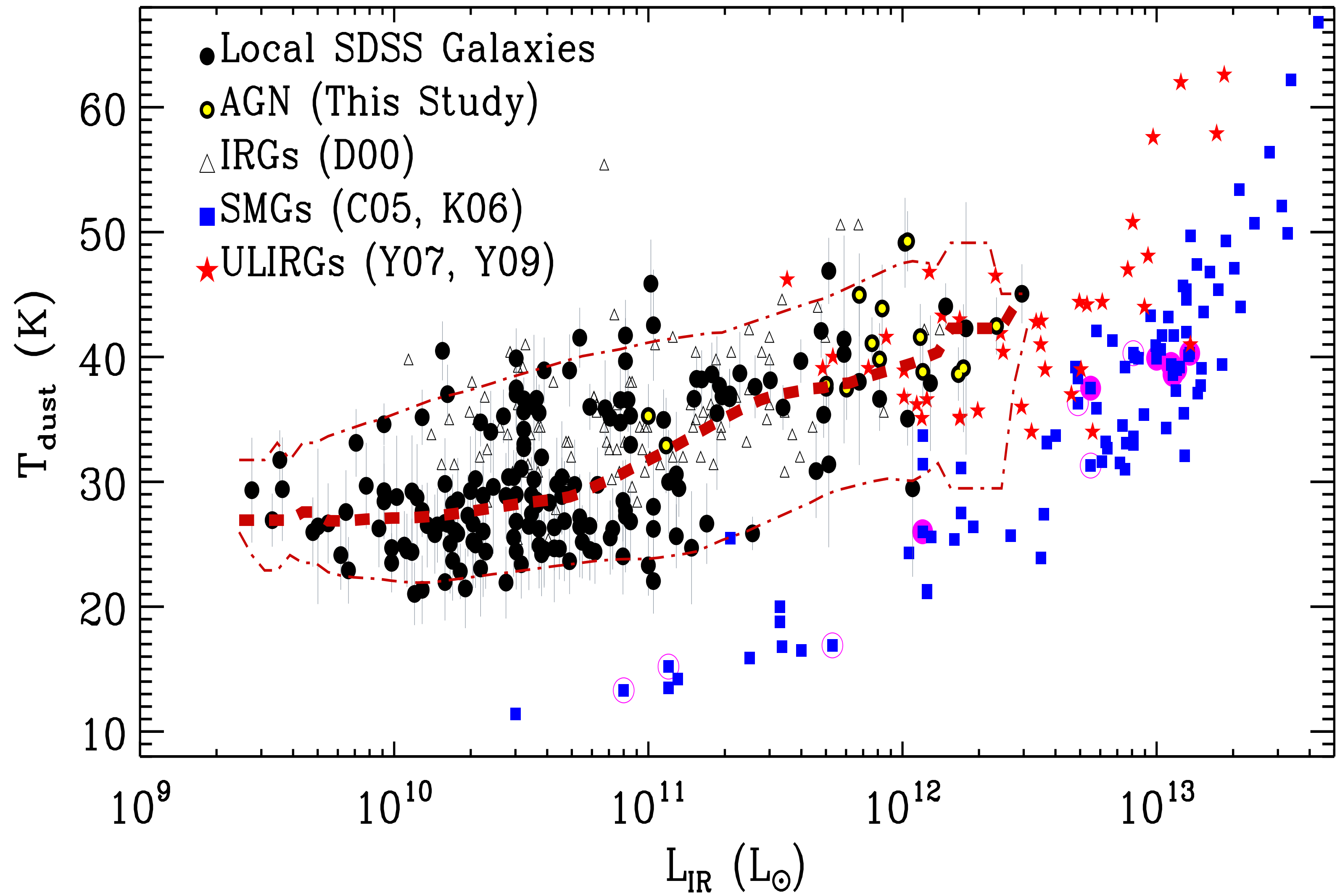


Figure 3. T_{dust} vs. L_{IR} for galaxies in SDSS. Galaxies hosting AGN are indicated by yellow symbols. The thick dashed line is a smoothed median trend of T_{dust} for local SDSS galaxies by excluding those with AGN, and the dot-dashed lines are its envelope that includes 90% of the galaxies above and below the median. The known local infrared galaxies (IRGs) (D00: Dunne et al. 2000), SMGs (C05: Chapman et al. 2005, K06: Kovács et al. 2006) and ULIRGs (Y07: Yang et al. 2007, Y09: Younger et al. 2009) are plotted with triangles, squares and star symbols, respectively Among the SMGs in common between this study and C05, those having no neighbouring sources (clean) are denoted by large filled circles, while those possibly contaminated by neighbouring sources (blended) are denoted by large open circles.

SMGs are systematically cold?

Size of SMGs

(Iono et al. 2009)

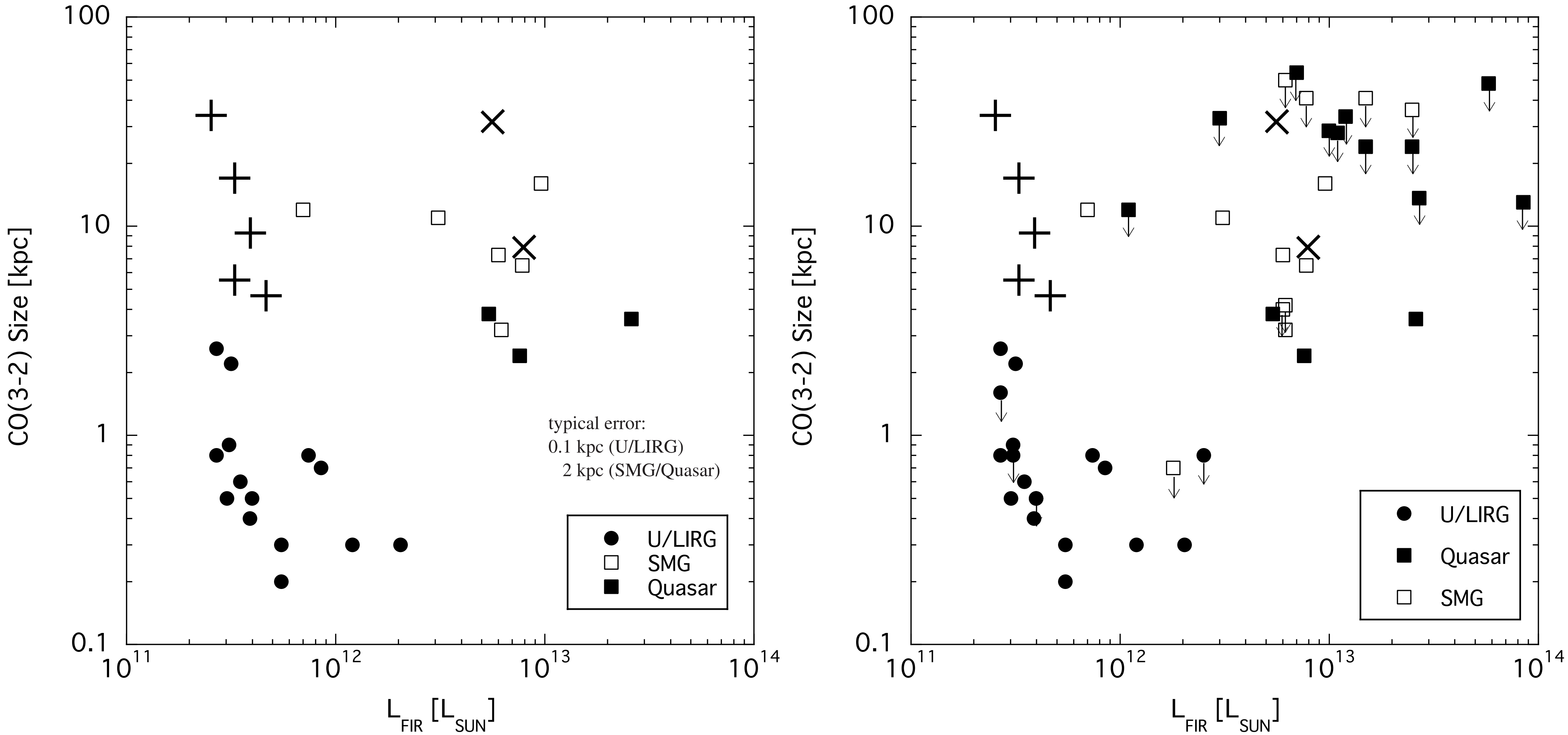
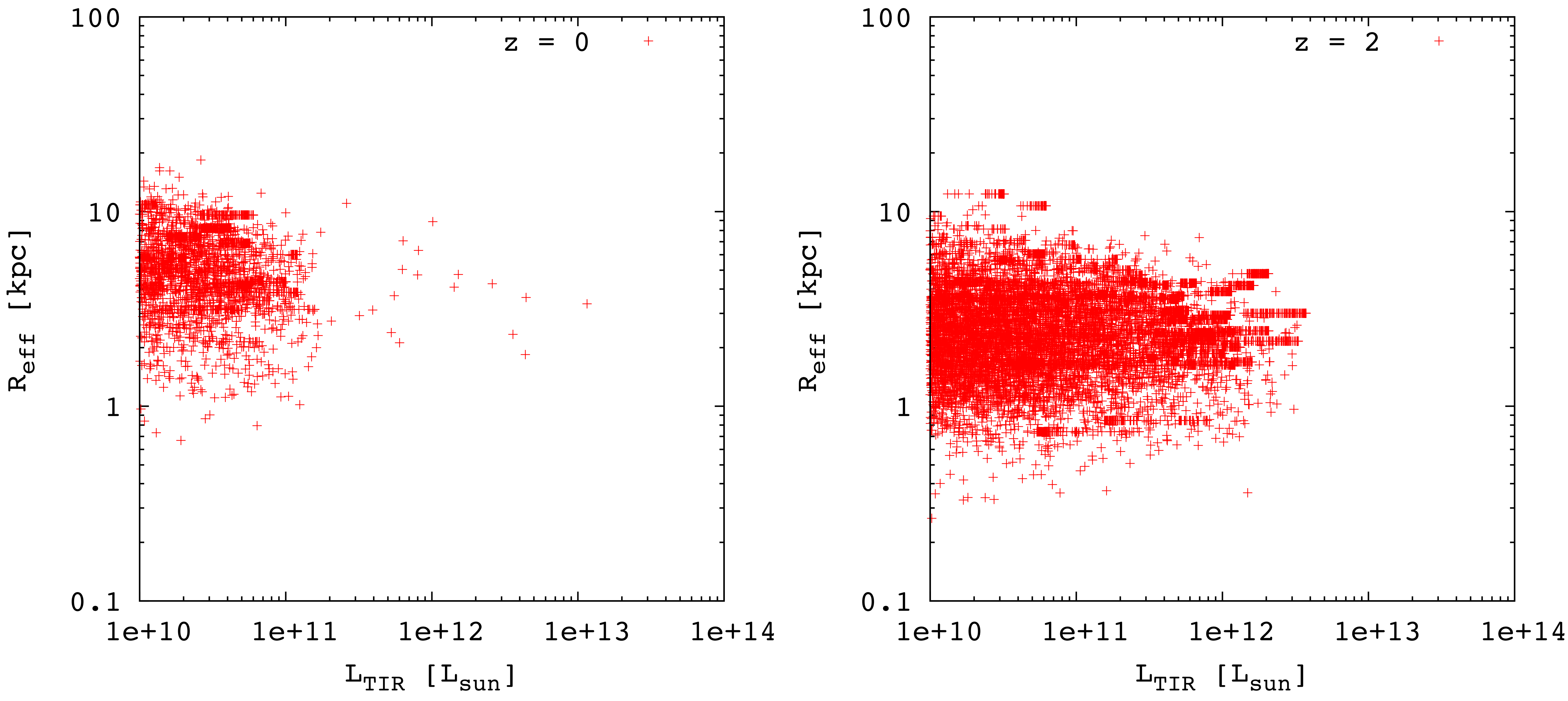


Figure 4. Left: the CO (3–2) size plotted against the FIR luminosities. The CO (3–2) minor axis was used for all sources. We note that some of the LIRGs (especially the low luminosity ones) are widely separated merging pairs, and here we have used the source sizes of each CO (3–2) component. Typical error bars are ∼0.1 kpc for the U/LIRGs and ∼2 kpc for the high-redshift sources. We also plot the separation of the widely separated pairs for LIRGs (+) and SMGs (x). Right: same as left but with the galaxies with only upper limits to the source size included for completeness.

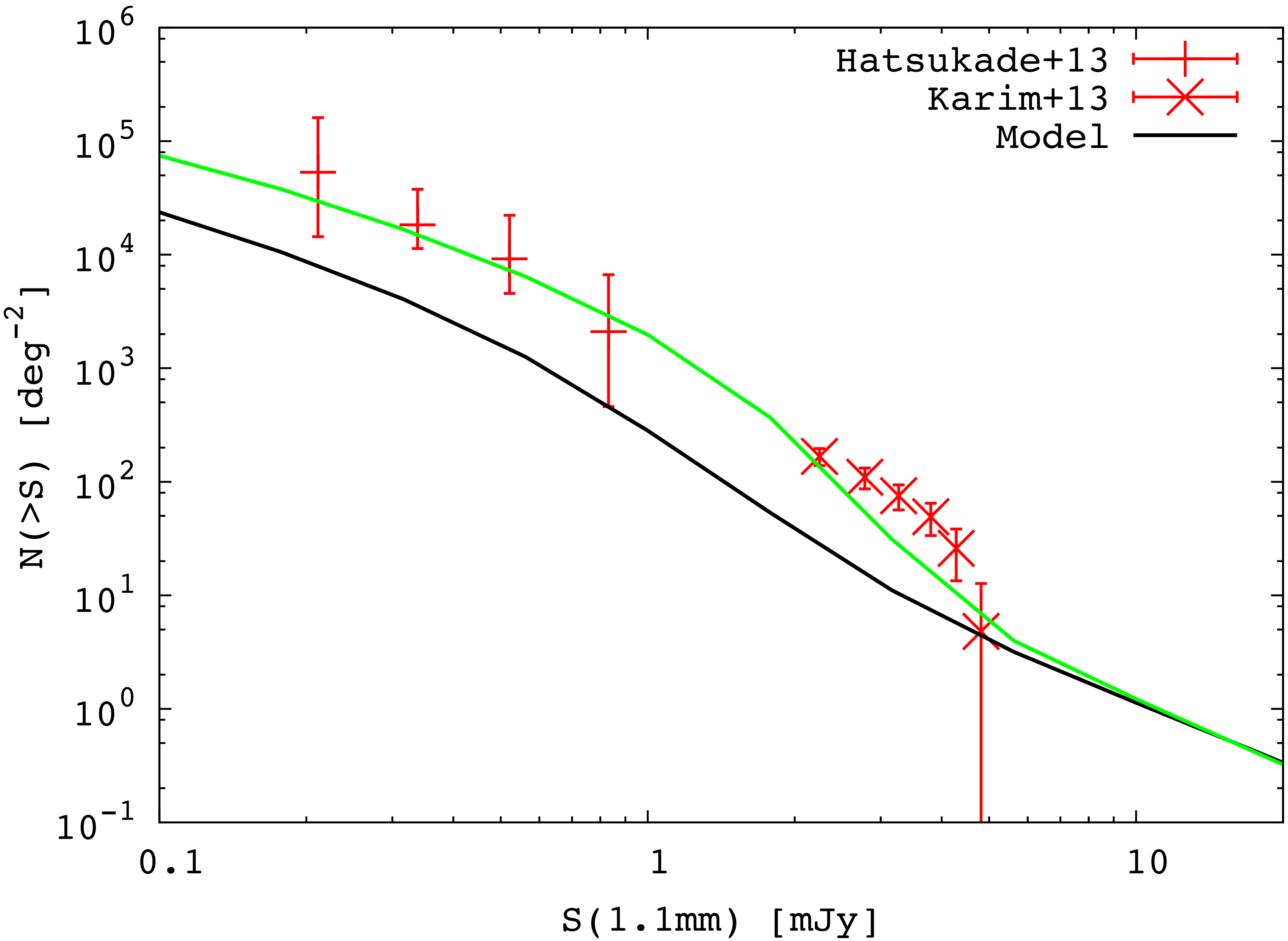
- SMGs have ~10kpc star forming region?
- ALESS sources are < 10kpc (Hodge et al. 2013)

Size of model galaxies



- モデル銀河の disk size は小さい

Number count of 1.1mm sources (no size-evo. model)



- 緑線 : 銀河サイズに(1+z)を掛けてサイズ進化を打ち消したモデル
- 低温になった分 submm flux が上がり観測に合うようになる
    - この場合 L_{TIR} を合わせると SMGs が明るくなりすぎる

SMGs size estimated by ALMA

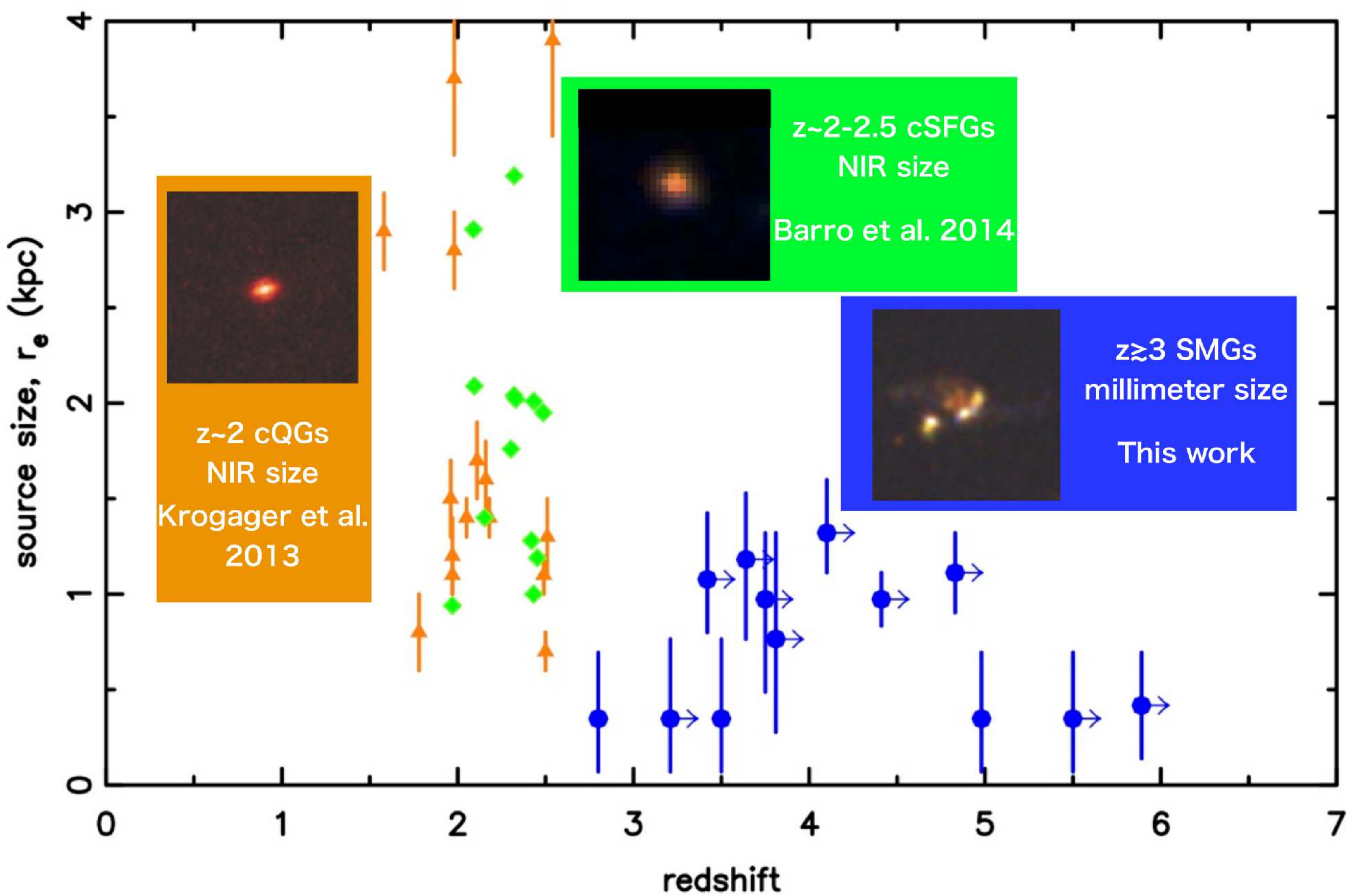


Fig. 4.— Relationship between redshift and sizes for $z \gtrsim 3$ SMGs, $z \sim 2$ cQGs and $z \sim 2$–2.5 cSFGs. We plot the 1100-μm size – that of the starburst nuclei – for $z \gtrsim 3$ SMGs (this work). We plot the NIR size – that of the stellar component – for cQGs (Krogager et al. 2013) and cSFGs (Barro et al. 2014). Color images of a SMG and a cQGs are taken from Toft et al. (2014); that of a cSFG is from Nelson et al. (2014). This plot illustrates that $z \gtrsim 3$ SMGs have a compact starburst region which could generate the compact, high-density stellar components of cQGs or cSFGs. Errors in the measured sizes of cSFGs are small (~ 0.05 kpc) (Barro et al. 2014). (Ikarashi et al. 2015)

ALMA で見ると SMGs は小さい (モデル銀河と同程度)

Summary

- 銀河形成モデルにダスト放射機構を組み込んだ
- モデル銀河は全体的に暗く TIR LF を再現できず
  - Cosmic SFR density や SMF は大体合っている
  - SFR をあと~二倍増やす？
  - IMF を top heavy にして UV photon だけ増やす？
- SMGs のサイズや $T_{\rm dust}$ の進化は number count の予想に顕著な影響を持つ

観測に期待すること

- AGN と SF の切り分け
- galaxy merger と AGN activity の関係
- 金属量進化
  - Mdust / Mgas ratio の redshift 進化が見たい
- 赤外で明るい銀河のサイズ進化