Comparison of cosmological simulations and deep submillimetre galaxy surveys

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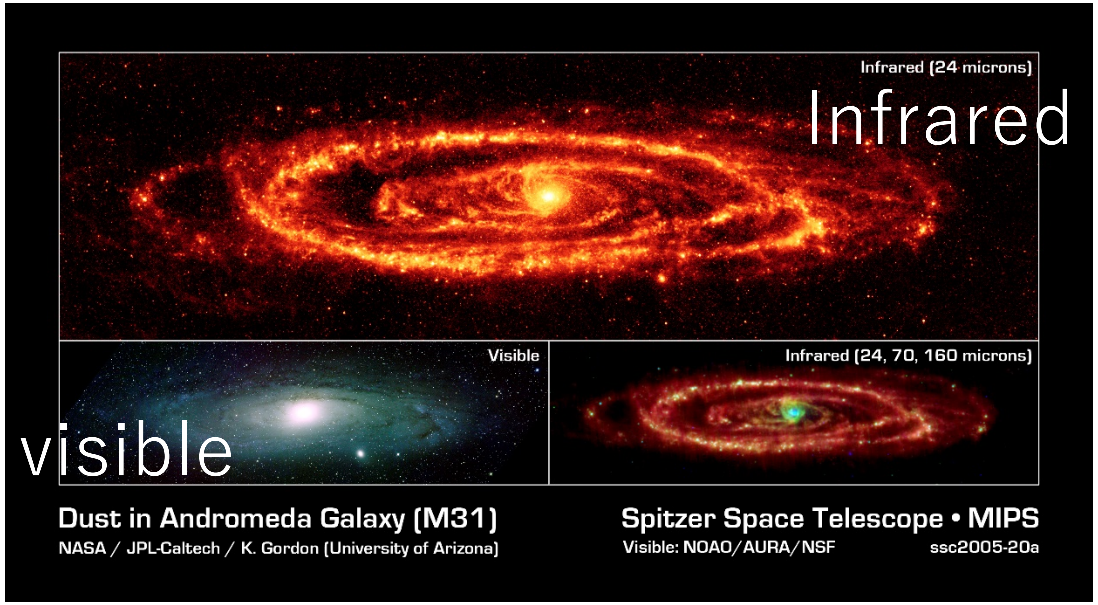
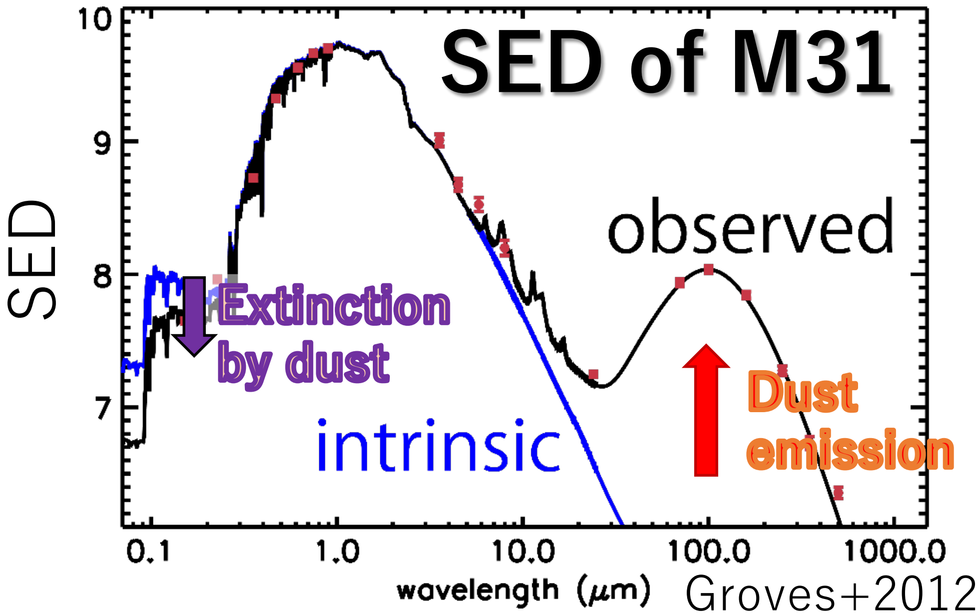
Based on
Aoyama et al. (2018) MNRAS, **478**(4), 4905 [**1802.04027**]
-> Aoyama et al. (2019) MNRAS, **484**(2), 1852 [**1809.10416**]

Importance of dust grains



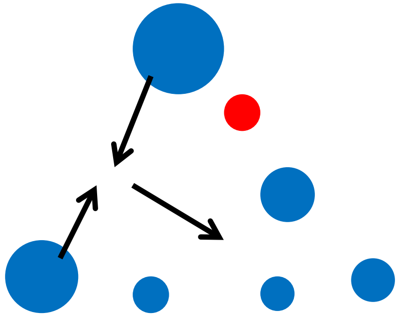


Groves+2012

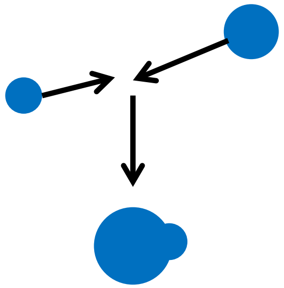
- Spectrum energy distribution (SED) is significantly modified by dust.
- **The modification is determined by dust spatial and size distribution in the galaxy.**
- **Not only spatial but also grain size distribution have to be predicted theoretically in order to estimate the star formation activity.**

Size distribution treatment
Hirashita 2-component model [1412.3866]

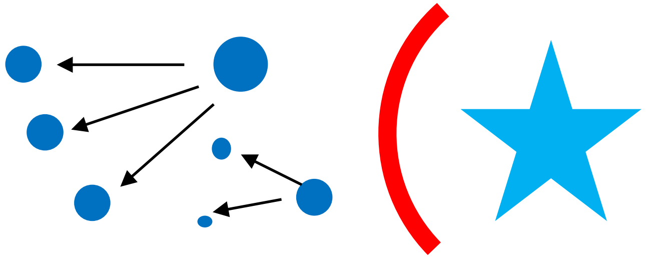
- Shattering (L↘ S↗)



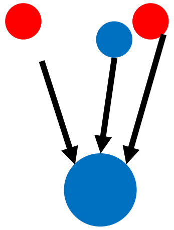
- Coagulation (L↗ S↘)

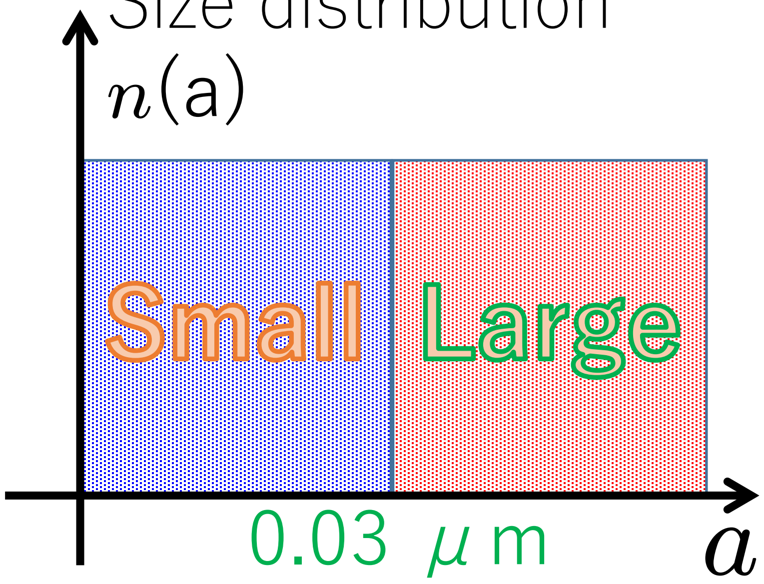


- Shock waves from SNe (L↘ S ↘)

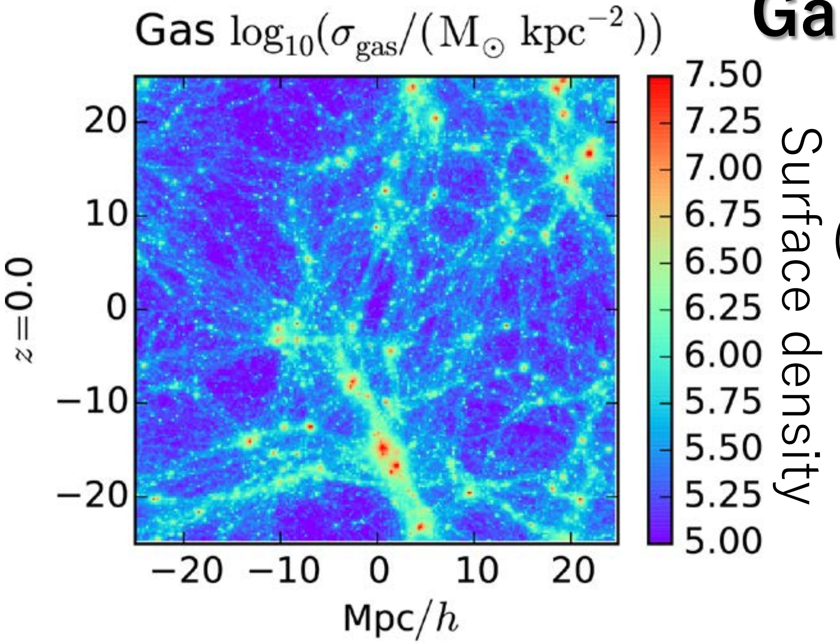


- Accretion (S↗)





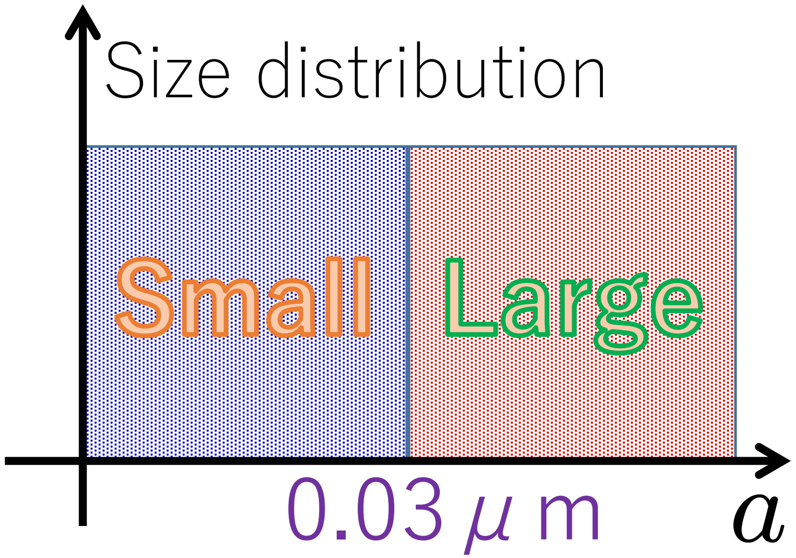
Research theory



simultaneously

Galaxy evolution ⟷ **Dust model**

Gas physical condition (density field $\boldsymbol{\rho}$, temperature $\boldsymbol{T}$, **Star Formation**)



- **Hydrodynamics of gas and star formation** are treated consistently with the gravitational evolutions of dark matter, etc.
- Formation of metals (ingredient of dust) is treated according to the star formation history.

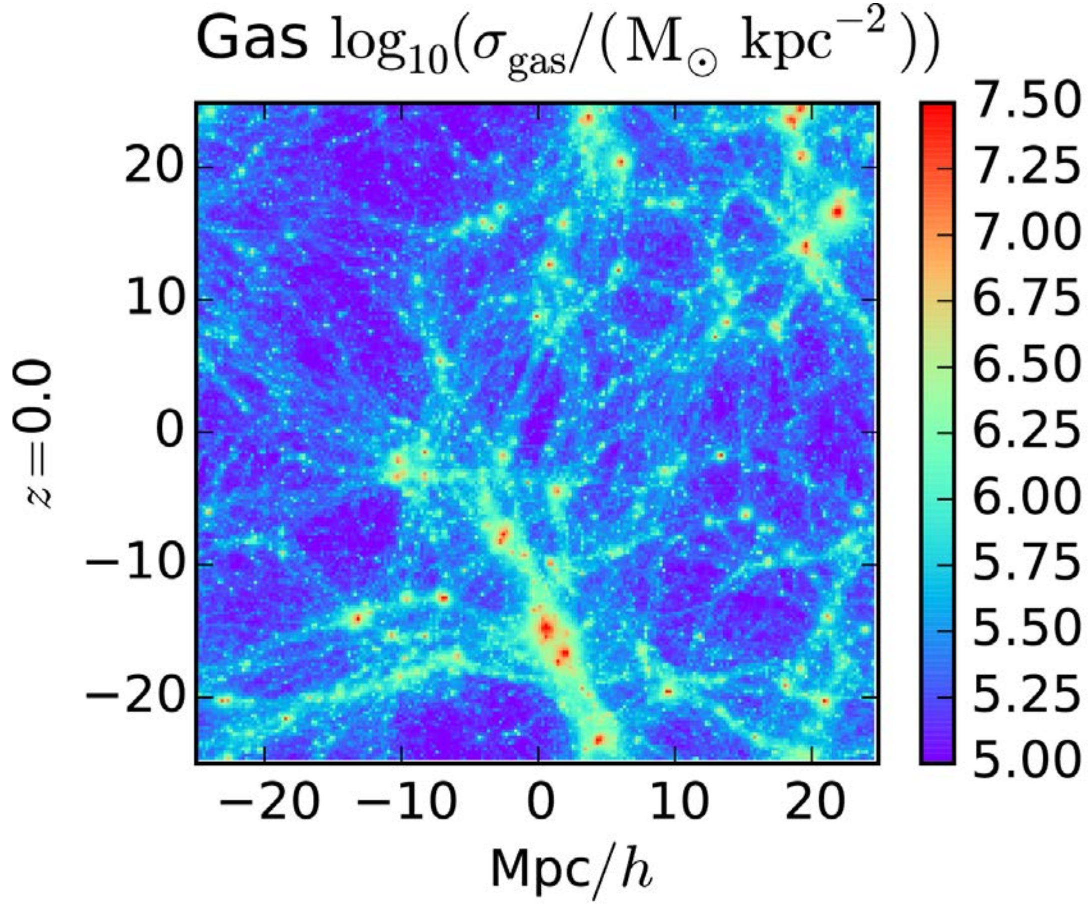
- Dust evolution is calculated by local density, temperature and dust abundances.
- **Accretion, coagulation, (growth) shattering (destruction) are implemented.**

Simulation

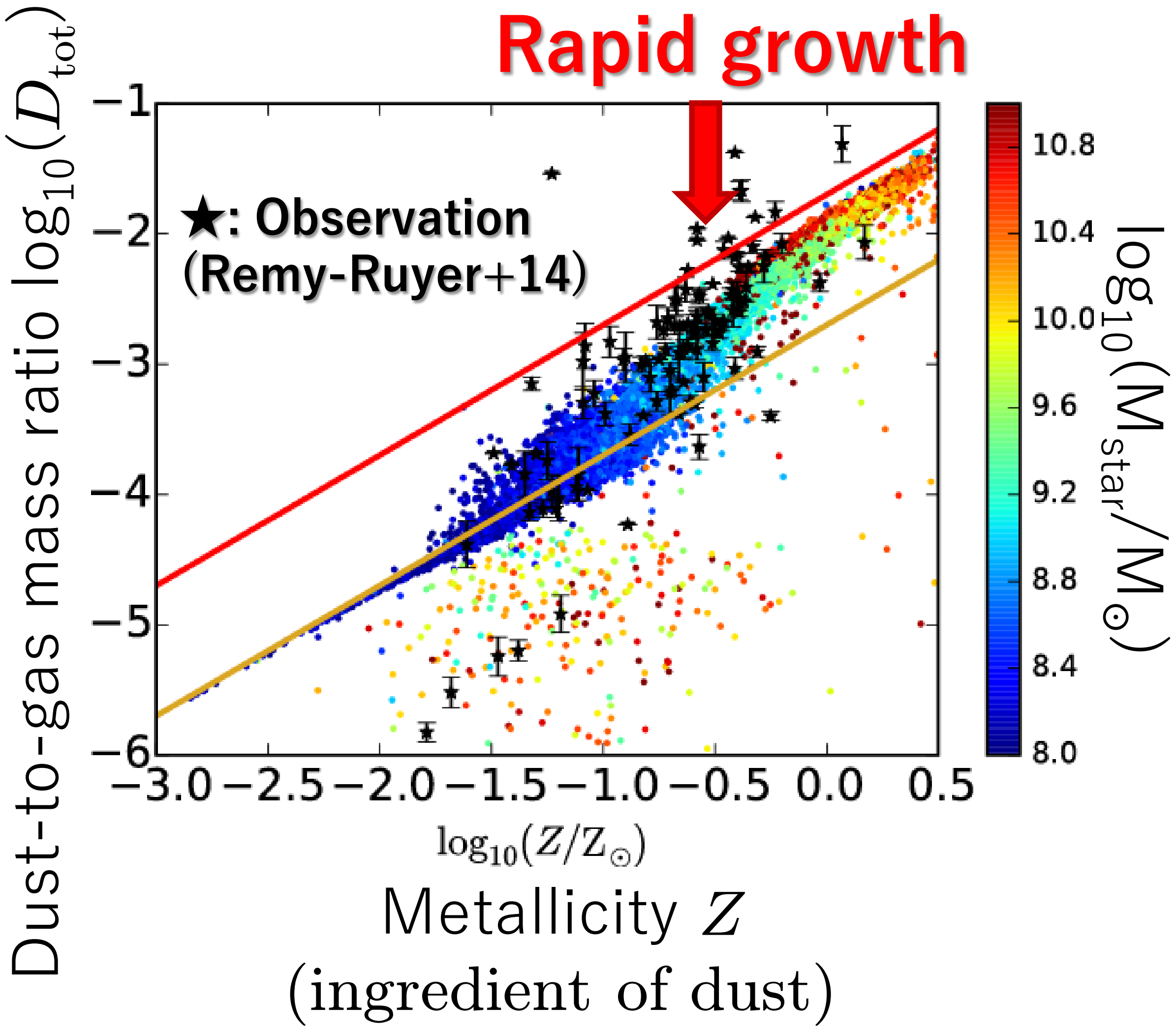
- Cosmological hydro-dynamical simulation with dust evolution (Hirashita model '15) is performed by GADGET3-Osaka.

- Star formation, early stellar and SNe feedback are consistently implemented.

- Planck cosmology (2015)
- Boxsize: 50 Mpc/h
- Resolution: 3 ckpc
- # of particles : 2×512^3



Results 1. D_{tot}-Z relation @ z=0



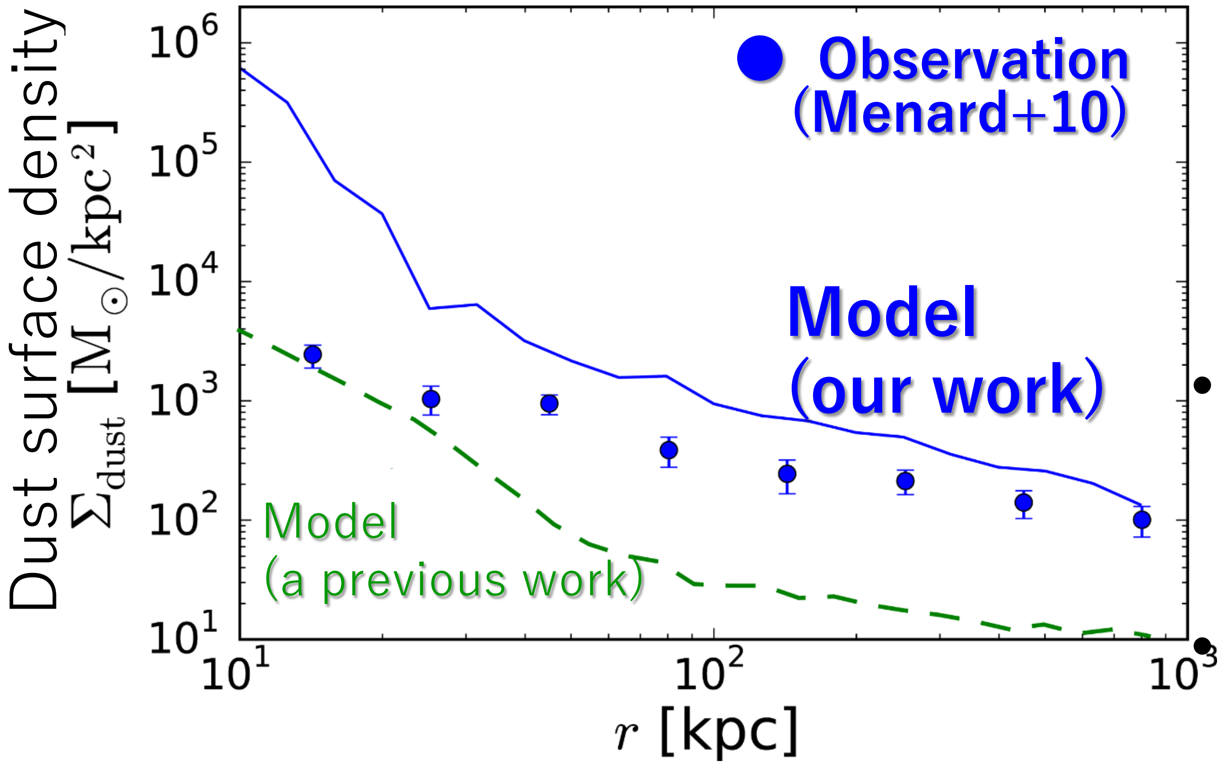
- Dust production is strongly associated with metal enrichment.

➢ The relation gives a strong test for dust evolution models. (Lisenfeld & Ferrara 1998; Dwek 1998)

- **We reproduce the rapid growth of dust at $Z/Z_\odot \sim 0.1$.**

➢ **Dust growth in ISM is confirmed to be successfully implemented.**

Results 3. large scale distribution of dust



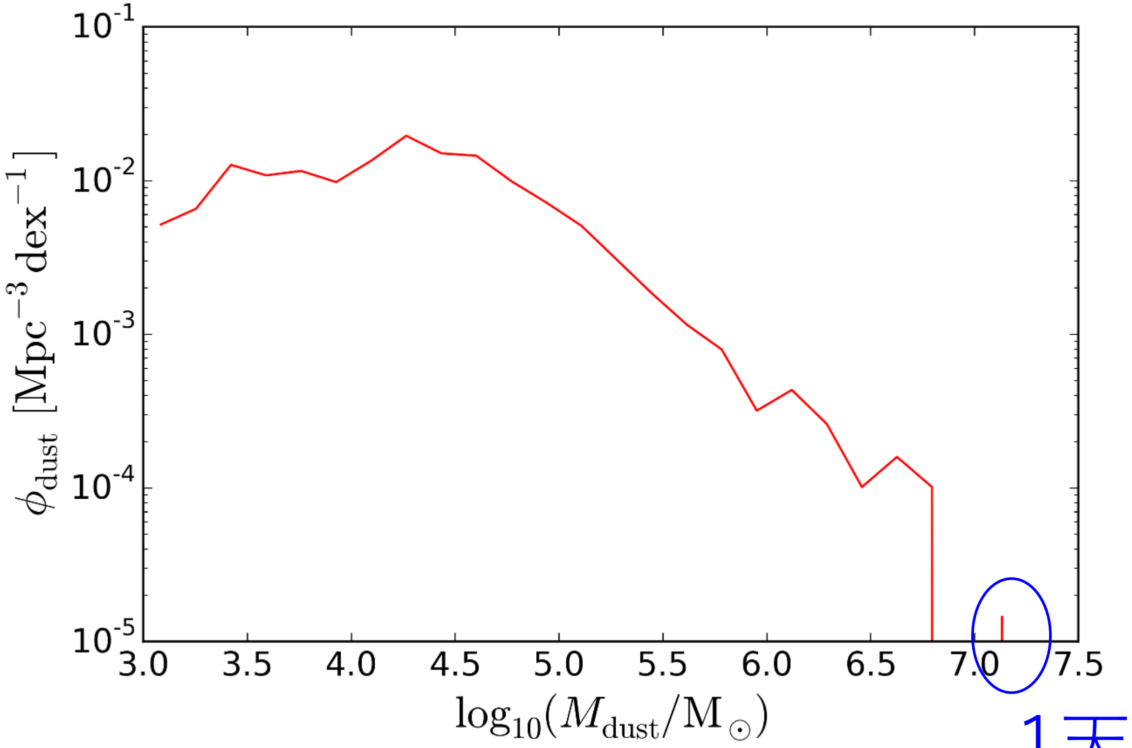
Distance from a center galaxy r

- Large scale distribution of dust reflects dust transport (stellar energy input) and dust evolution (especially, dust destruction in the hot gas in the galaxy halo).

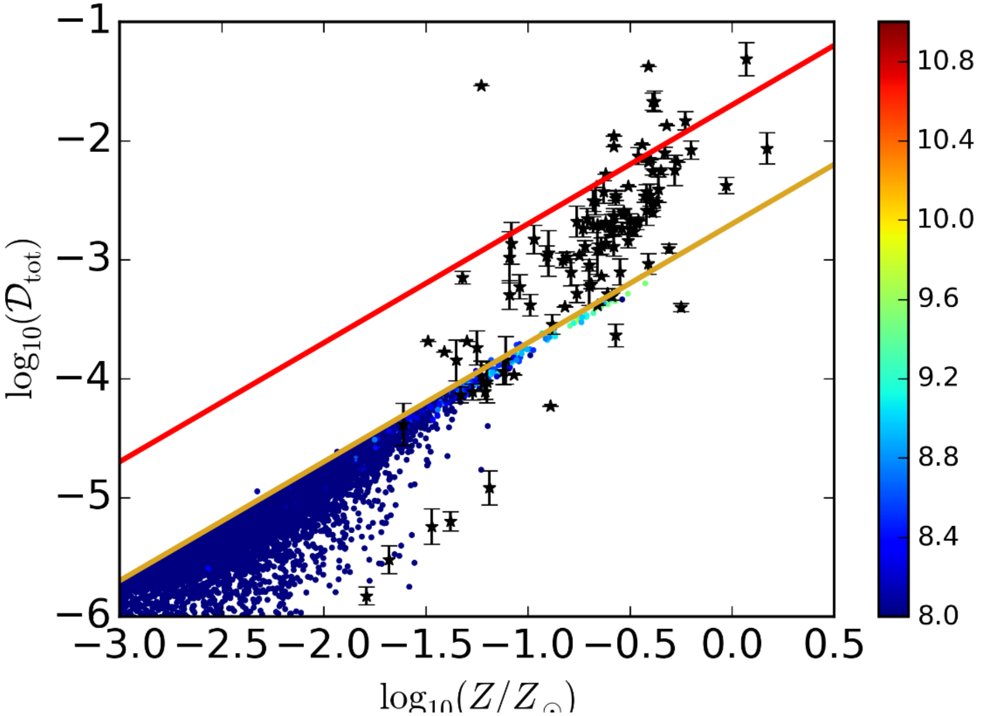
- Our model describes roughly observational one within 0.5 dex at $r > 30$ kpc.

- We succeeded in reproducing dust distribution in cosmological scale : **our consistent treatment of stellar energy input and dust evolution is essential.**

z≃7の宇宙 simulation with Hirashita15 model

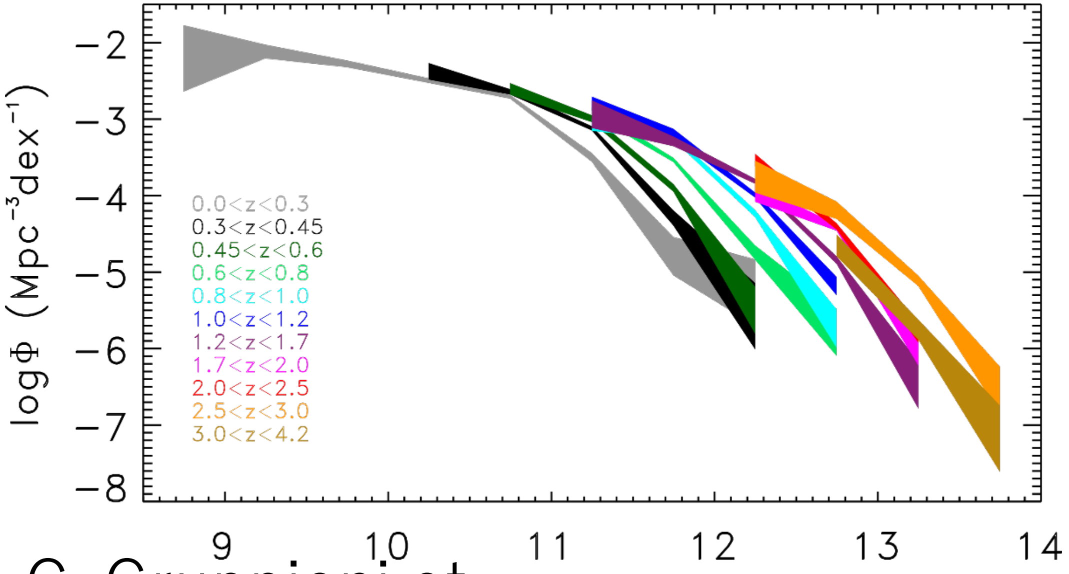


1天体
1個/(50Mpc/h)³



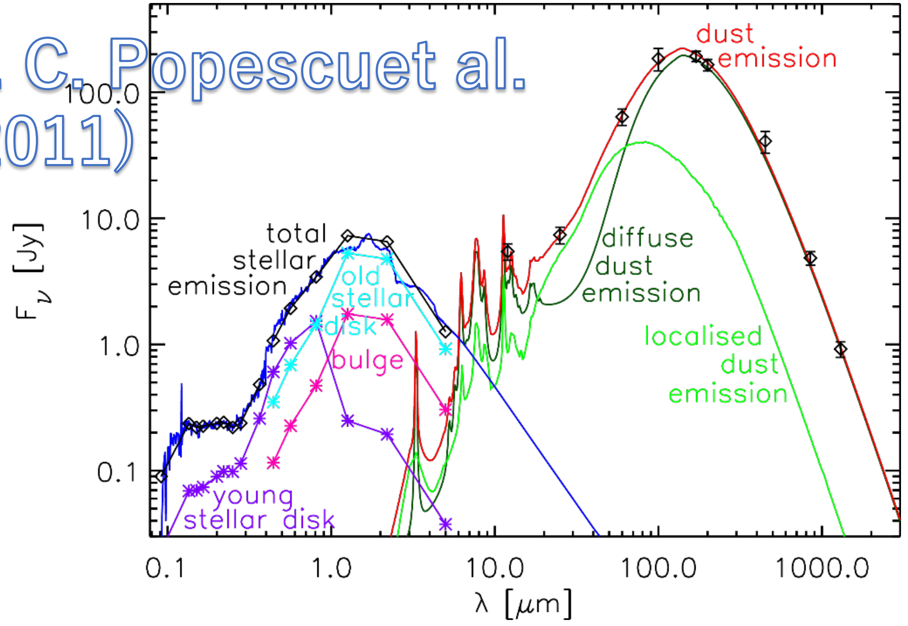
Introduction
Key quantities

- IR luminosity function $L_{\mathrm{IR}}(L_{\mathrm{IR}}, z)$
- Dust temperature T_{dust}
- $\mathrm{IRX} = \dfrac{L_{\mathrm{IR}}}{L_{\mathrm{UV}}(1650\text{Å})}$ (the ratio of IR to UV.)
- Slope of SED at UV @2000 Å β_{UV}



C. Gruppioni et al.(2013)[1302.5209]

C. C. Popescuet al. (2011)

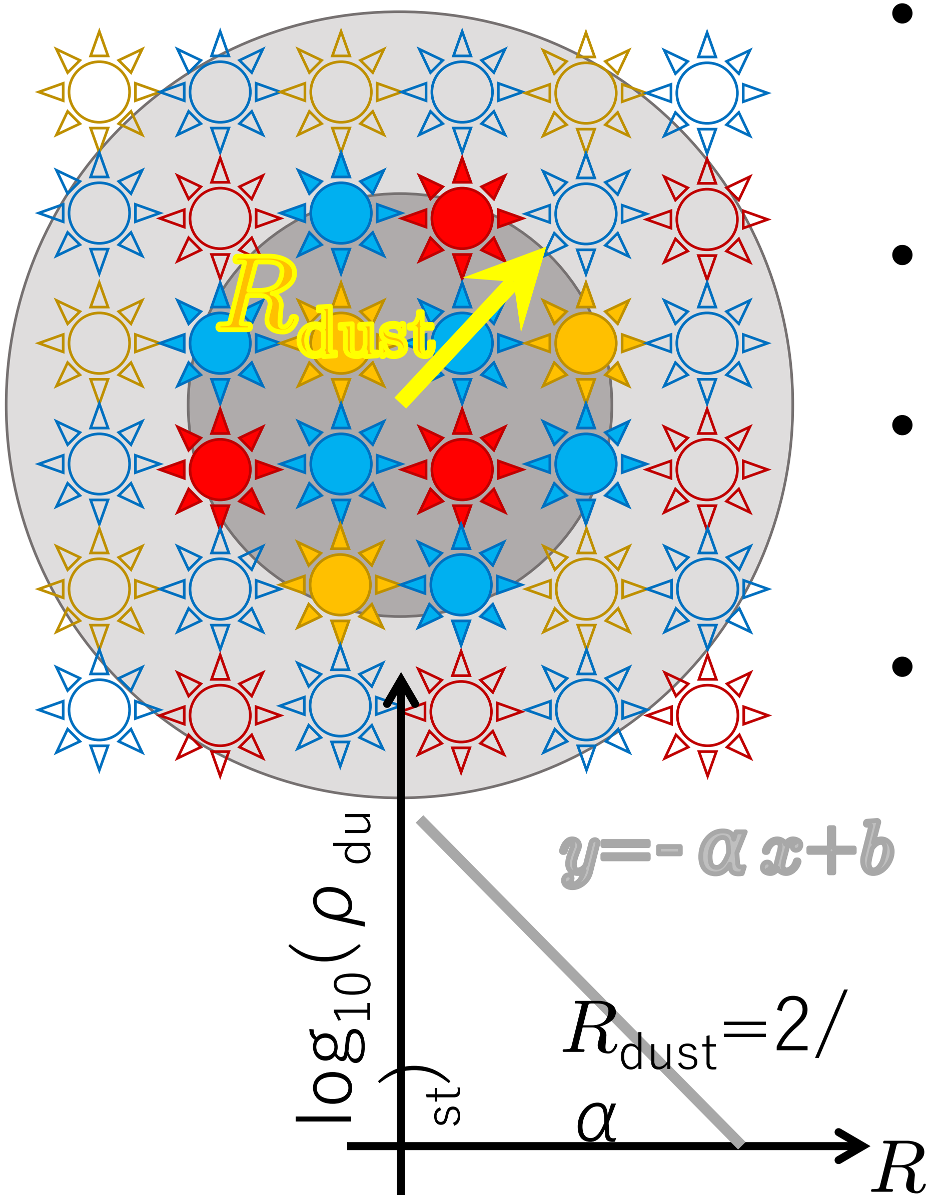


Infrared galaxies in the simulations

- We predict observed quantities related to dust grains (IR luminosity function, IR-β_{UV} relation etc.) at high-z Universe by simulations and reveal which processes are important for explaining observations.

- By comparing the predictions and corresponding observations and finding the discrepancies between them, we identify the reasons and try to improve the simulations and models.

Modeling of dust absorption and emission

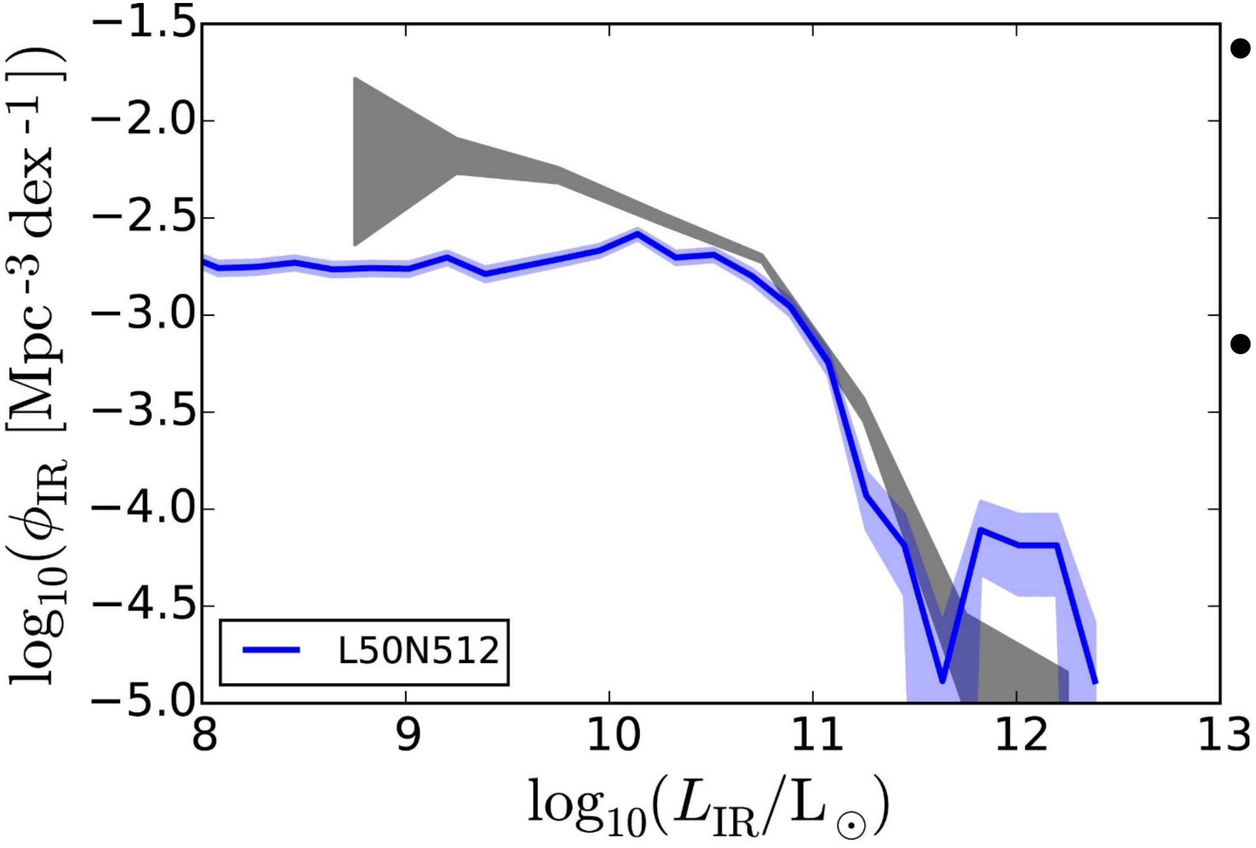


- We estimate the radius of IR emitting region $R_{\rm dust}$ by performing the exponential fitting of radial profile of dust mass density.
- We take into account stars and dust grains at $0 < R < R_{\rm dust}$.
- The intrinsic SEDs of stars are estimated by their age and metallicity based on Bruzual & Charlot (2003).
- The extinction is estimated based on the mixed geometry.

$$f_{\rm esc}(\lambda) = \frac{1 - \exp\left(-\tau(\lambda)\right)}{\tau(\lambda)}$$

Luminosity function at z=0

Gray shaded region: Herschel satellite
C. Gruppioni et al.(2013)



- We compare the LF with observation result with *Herschel*.
- Overall statistics is consistent with observation.

Luminosity function at z=0

Gray shaded region: Herschel satellite
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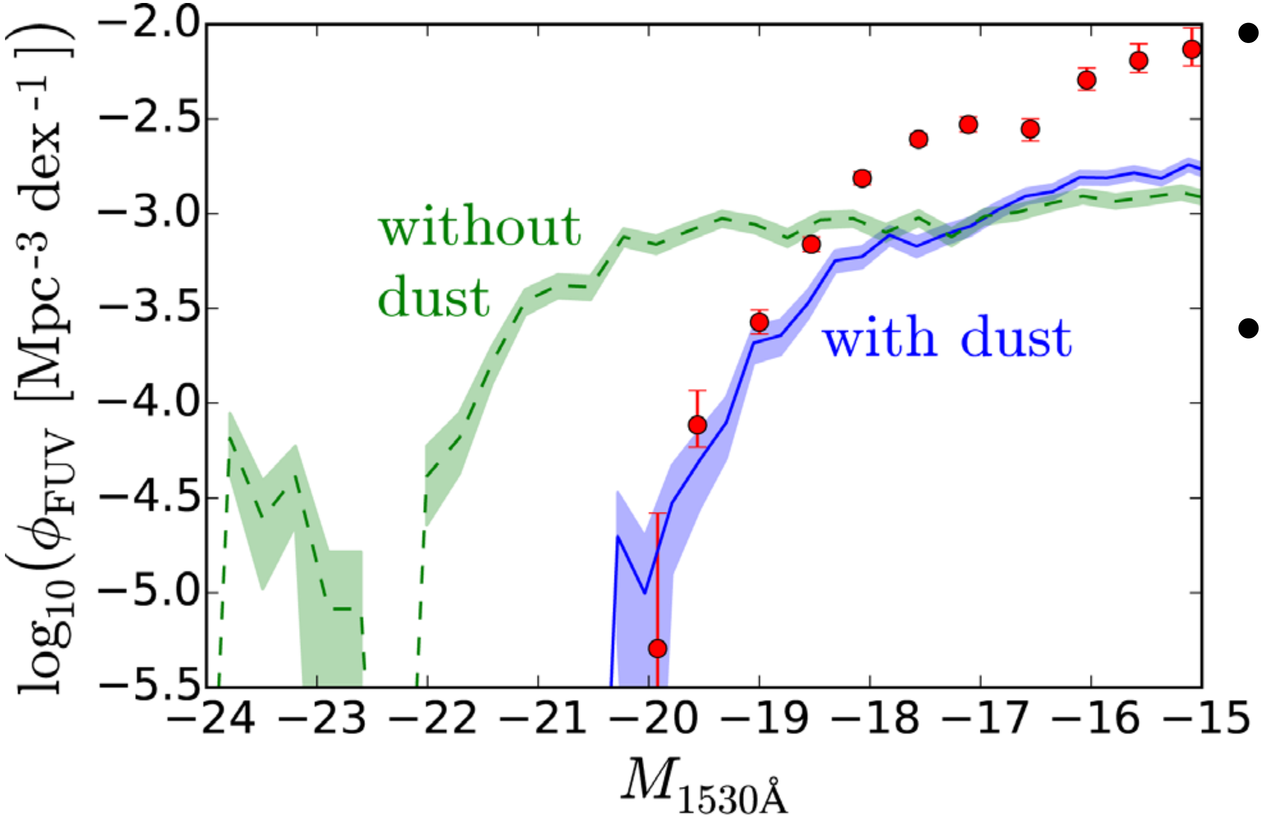

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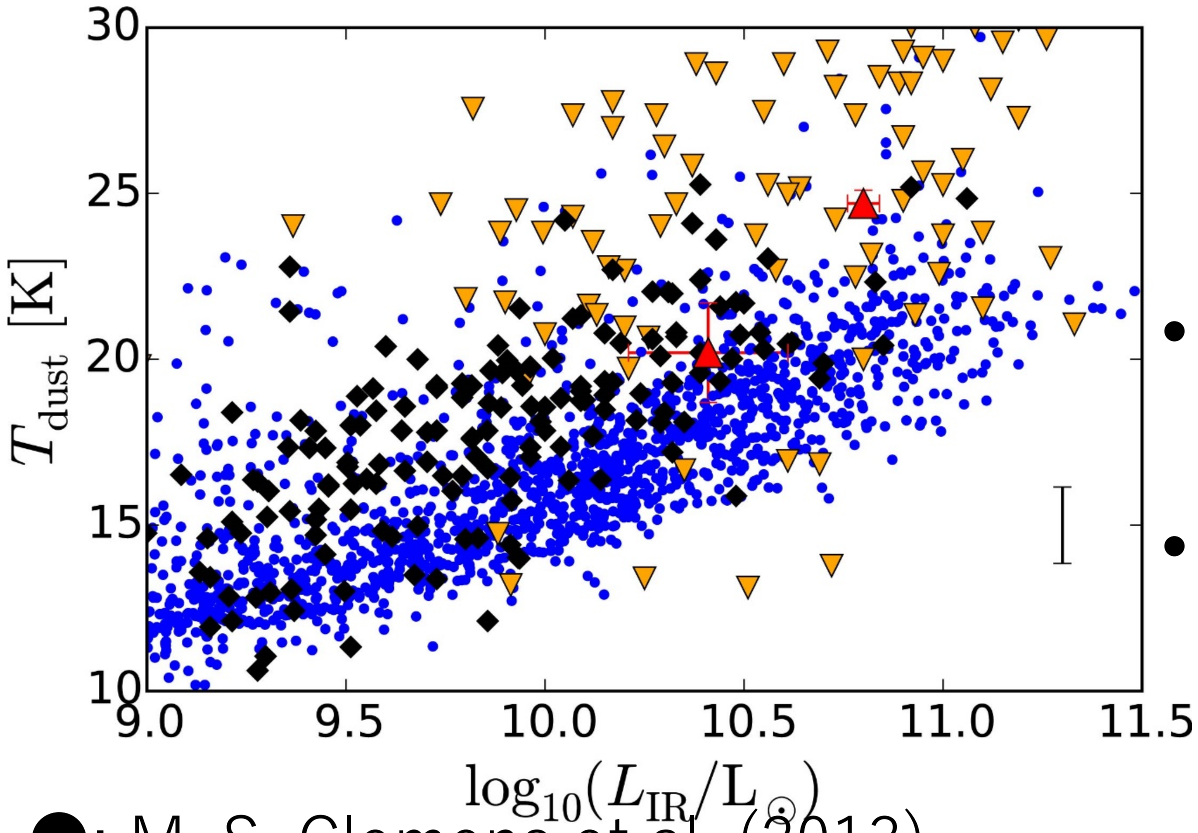
T_{dust}-L_{IR} at z=0



●: M. S. Clemens et al. (2013)

▼: A. Amblard et al.(2010)

▲: J. A. Zavala et al. (2018)

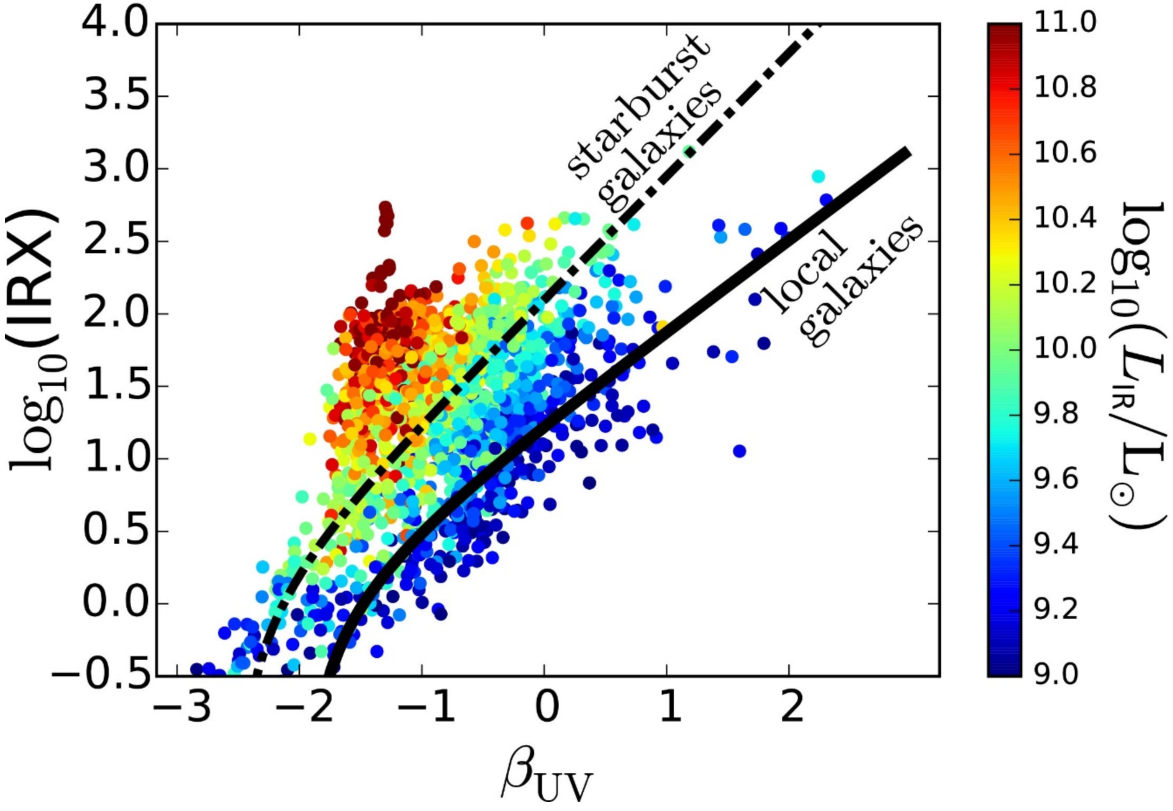
- Dust temperature is estimated by

$$T_{dust} = 7.5 \left(\frac{L_{IR}/L_\odot}{M_{dust}/M_\odot} \right)^{\frac{1}{6}} \ [K]$$

- Reproduced T_{dust}—L_{IR} relation

- It indicates that our dust model describes the IR luminosity and the dust optical depth (or dust surface density) consistently.

IRX- β_{UV} relation at z=0



- Observational relation are shown (dot-dashed; Kong et al. 2004, solid line; Takeuchi et al. 2012).
- We predict observational sequence.
- Affected by the assumed geometry of dust distribution. -> screen geometry could disperse these points.

STUDIES (SCUBA2)

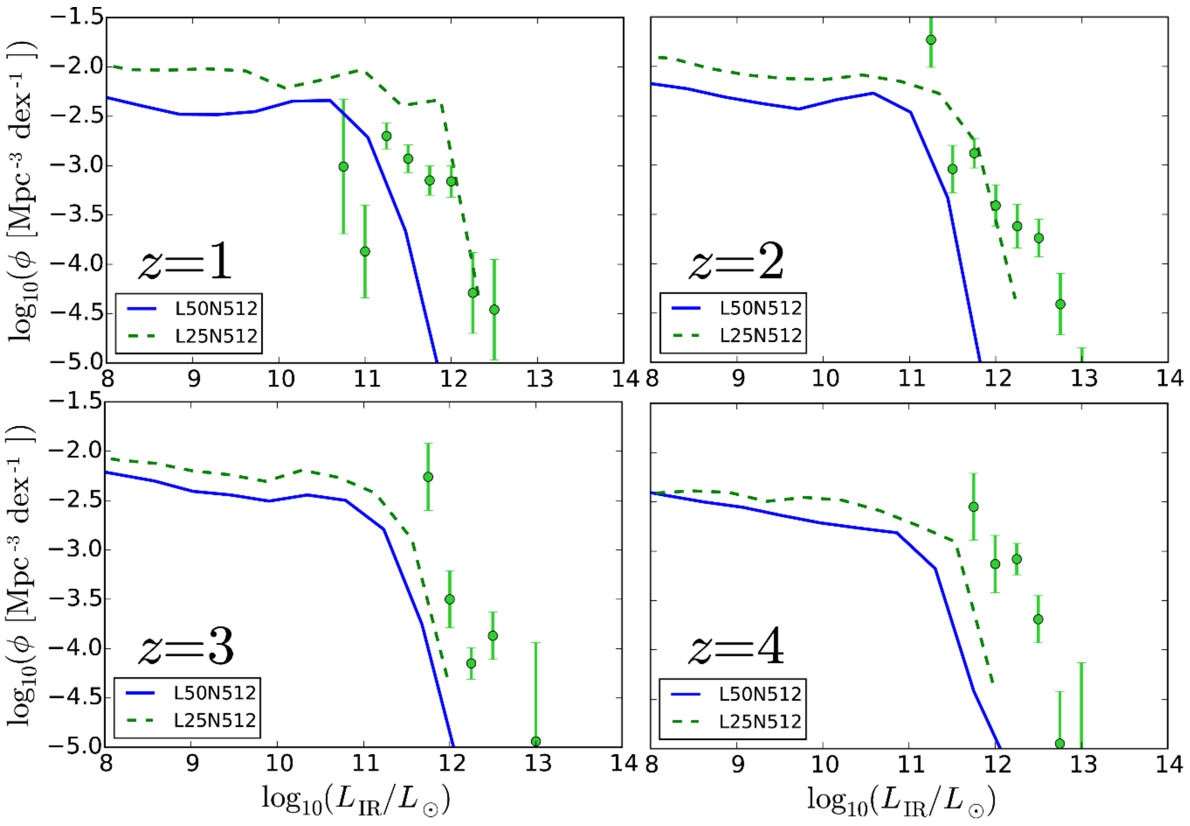
W-H. Wang et al. (2017), C-H. Lim in prep.

- λ =450, 850 μm
- Survey area: COSMOS-CANDELS region (151 arcmin^2)
- Noise level 0.91 mJy
- **Merit of JCMT**
- Taking advantage of the large aperture, fainter objects which *Herschel* cannot detect can be observed.
- Large survey area and 2 wavelengths.
- The integrated surface brightness down to 1mJy can account for up to 83^{+15}_{-16} % of COBE background.

JCMT

https://en.wikipedia.org/wiki/James_Clerk_Maxwell_Telescope

Luminosity function @high-z universe



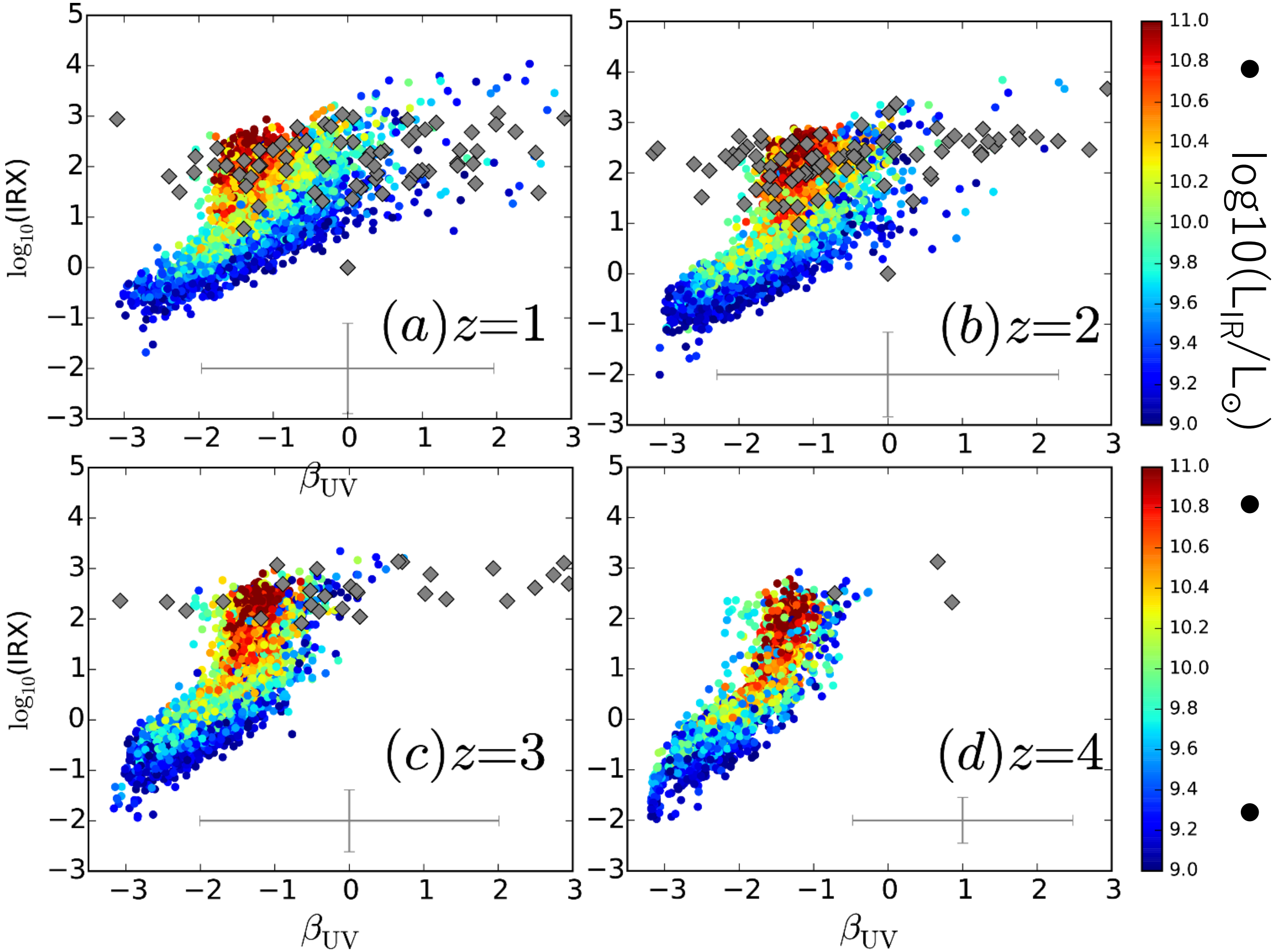
Solid L50N512 (Default)
Dashed L25N512

- Our snapshots are consistent with observation only at z≲1.
- When we performed a simulation whose spatial resolution is 2 times better, we can explain LF still up to z≃2.
- Hence resolution is not the reason for lack of IR luminous objects.

IRX- β_{UV}@high-z universe

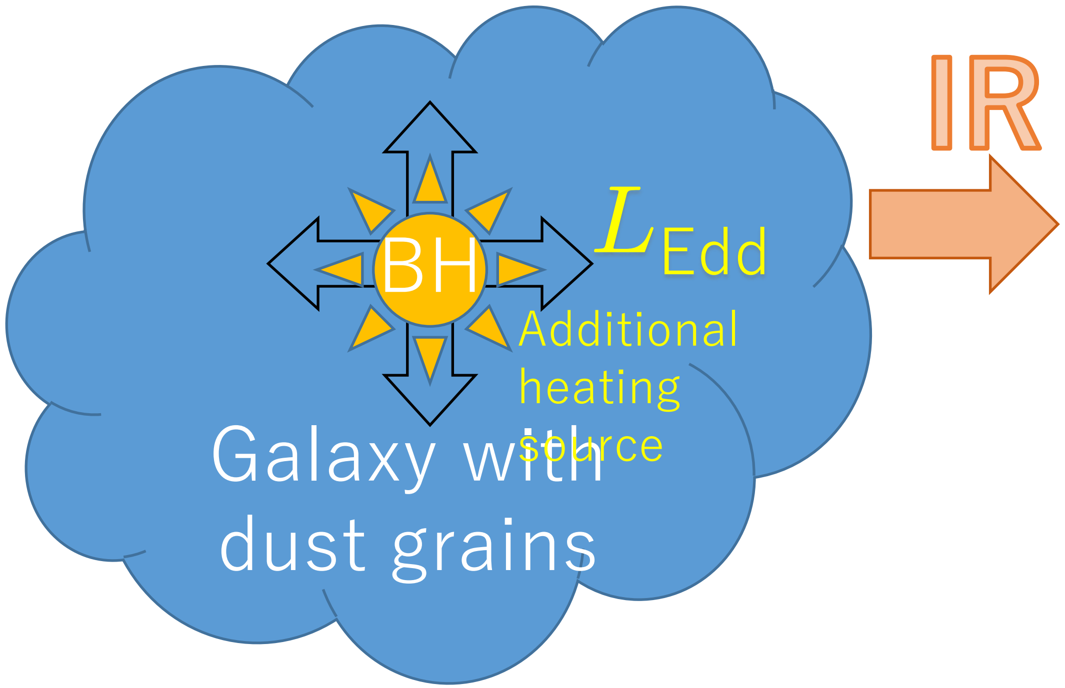
$$\mathrm{IRX} = \frac{L_{\mathrm{IR}}}{L_{\mathrm{UV}}(1650\text{Å})}$$

β_{UV}: Slope of SED at UV @2000 Å



- IRX- β_{UV} relation are explained by simulation results up to z≃3. Dust abundance and extinction are successfully treated even at high redshift (z ≲ 3).
- The observation uncertainty of β_{UV} becomes large because the targets are optically faint.
- At z≃4, some galaxies whose SEDs are very red cannot be explained.

Extra dust heating from SMBHs



- We assigned the super massive black holes randomly to identified galaxies.
- The mass is estimated by Magorrian relation (Haring & Rix (2004))

$$M_{\rm BH} = 10^{8.2} \left(\frac{M_{\rm bulge}}{10^{11}\ {\rm M}_\odot} \right)^{1.12} {\rm M}_\odot$$

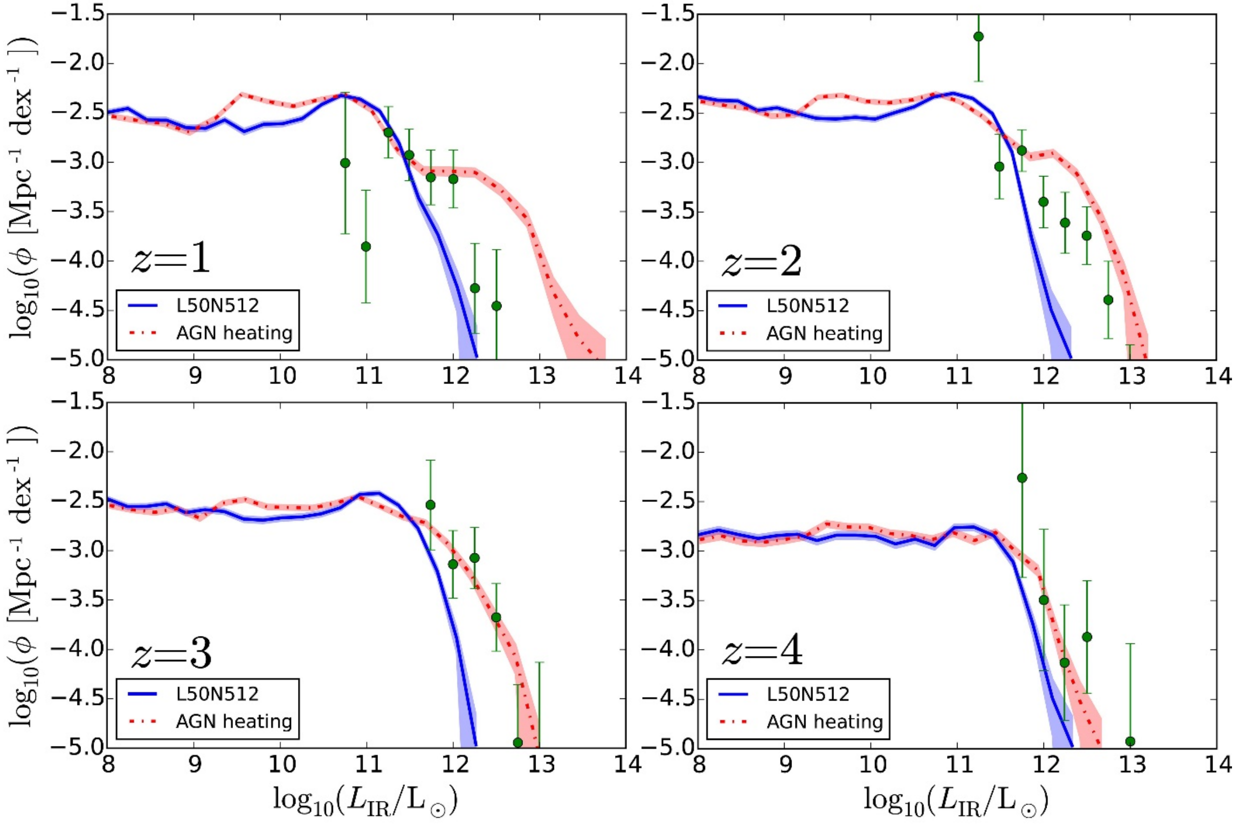
- The luminosities of SMBHs are supposed to be Eddington luminosity.

$$L = \frac{4\pi G M_{\rm BH} m_{\rm p} c}{\sigma_{\rm T}} = 5.07 \times 10^{12} \left(\frac{M_{\rm bulge}}{10^{11}\ {\rm M}_\odot} \right)^{1.12} {\rm L}_\odot$$

- The energy from SMBH is assumed to be completely absorbed by dust grain

Haering & Rix (2004) [astro-ph/0402376]

Additional heating of dust grains by AGN



Red : w/ AGN heating
Blue: w/o AGN

- We post-processed the additional dust heating from SMBHs. Maggorian relation (Haring & Rix (2004)) and Eddington luminosity is assumed. All photons are absorbed by dust.

- Almost all data points can be explained by AGN heating even in the high-z galaxies even at z>2.

Summary

- We analyze our simulation results (Aoyama et al. 2018a) and obtained IR luminosity function, dust temperature and IRX-β_{UV} relation.

- At z=0, our simulation can explain IR luminosity function, dust temperature and IRX-β_{UV} relation.
- At high redshifts, abundance of high luminous objects cannot be explained.
  It is not related to spatial resolution of simulations very much.
  (additional dust heating by AGN?)
- Our treatment of dust extinction and IR emission works well when we compare the observation data (STUDIES) in terms of IRX-β_{UV}.