On dust obscured simulations

Gian Luigi Granato (INAF-OATS)

Plan:

- Generalities on dust in astrophysics
- Radiative transfer problem in dusty ISM for cosmological simulations
- A few applications of our solution: GRASIL3D
- Incorporating dust evolution in simulations

Collaborators: too many to mention here ☺

Will see later…

LACEGAL

What is cosmic "dust"?

The *Interstellar Medium* (ISM), provides 5–10% of the baryonic mass of local galaxies in form of gas mixed with tiny solid particles: dust grains

Grain size ranges from a few Å (PAH molecules) to 1-10 μm

Composition: two main chemical groups: carbonaceous (graphite and/or amorphous C) and silicate (Mg+Fe+Si+0, eg olivine) grains

Typically from 0.5 to 1% of ISM mass is in dust, but about ½ of heavy elements are *depleted* to dust

Dust is an interesting active element of ISM life: heats or cool the gas, catalyses the formation of molecules, increases the importance of radiation pressure…..

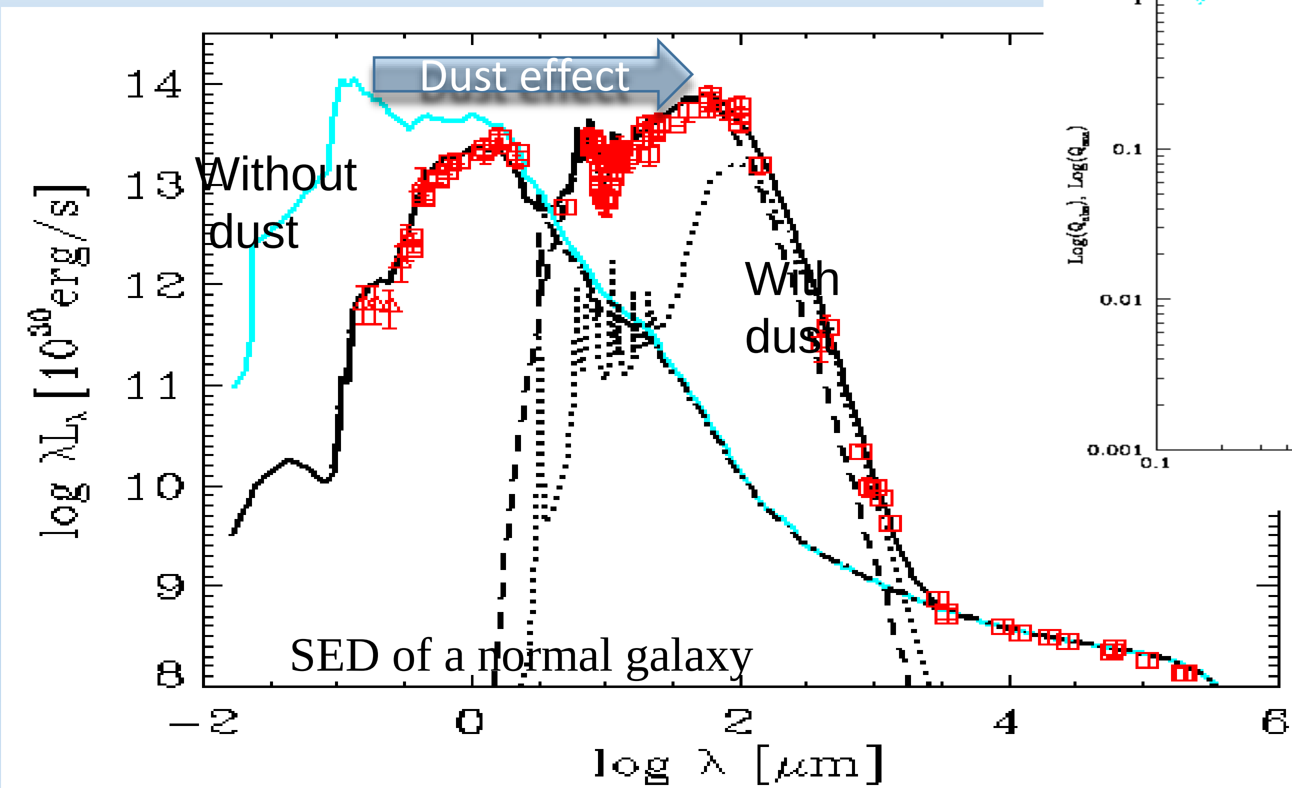
Problem: due to its effective interactions with the radiation field, dust strongly affects the perception of astrophysical objects

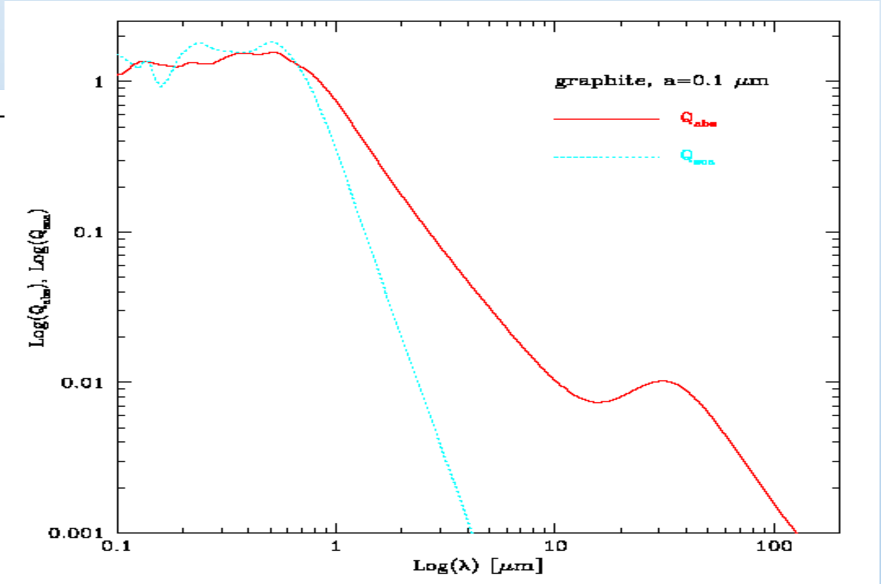
Effects of "dust" on the SED

Dust particles interact with photons (absorb, scatter, polarize) emitted by stars or other primary sources.

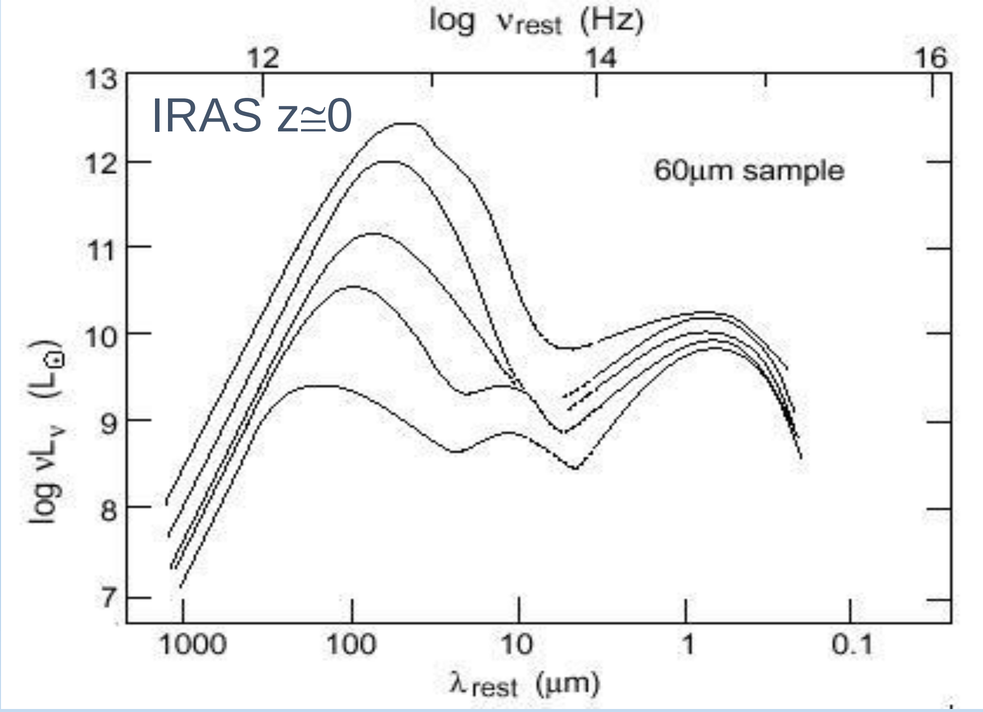
This is particularly effective in optical-UV ($\lambda < 1\ \mu m$).

The energy is thermally reradiated at $\lambda >$ a few μm. This is because grains are destroyed at T > 1000-2000 K





- In the local universe about 30% of primary radiation emitted by stars (and AGNs) is dust reprocessed. Important but maybe not dramatic.
- However reprocessed fraction is an increasing function of SF ($\Rightarrow$ plausibly of z), approaching 100% in strong starbursts. Twofold reason:
    1. The higher the specific SF of a galaxy, the more abundant the ISM;
    2. youngest and brightest stars tend to live close to densest ISM environments (i.e. the parent molecular clouds);



Adapted from Sanders & Mirabel 1996

Dust reprocessing in simulations

Thus, now it is (or should be) clear that a direct comparison of galaxy models with many observations calls for a radiative transfer treatment of reprocessing in the dusty ISM.

This is a complex, time-consuming and to some extent uncertain numerical task.

As for simulations, it is by now practically feasible only in post-processing.
A few tolls already exist for this:

1. SUNRISE (Jonnson+ 2006,2009);
2. RADISHE (Chakrabarti + 2008, 2009);
3. SKIRT (the new version: Baes+ 2011; Steinacker+ 2013);
4. Art2 (+2007, 2008; Yajima+ 2012);
5. GRASIL3D (Dominguez-Tenreiro+ 2014)

However, all but 5 (and possibly 1), are un-satisfactory, due to the following…

Dust reprocessing in simulations

Cosmological simulations do not provide enough information to perform sensible dust radiative transfer (RT).

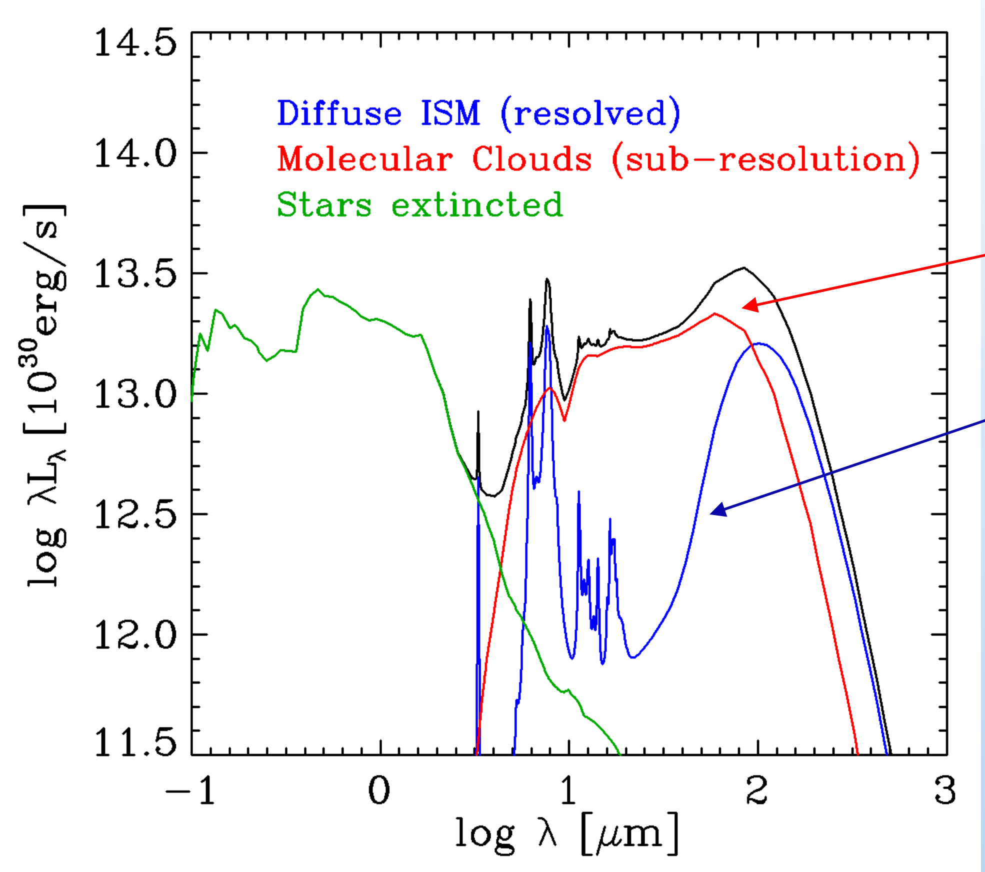
Most of the reprocessing occur on the unresolved scales of Molecular Clouds, ($M < 10^5 - 10^6\, M_\odot$; $R < 50\, pc$), i.e. orders of magnitude below typical resolution;

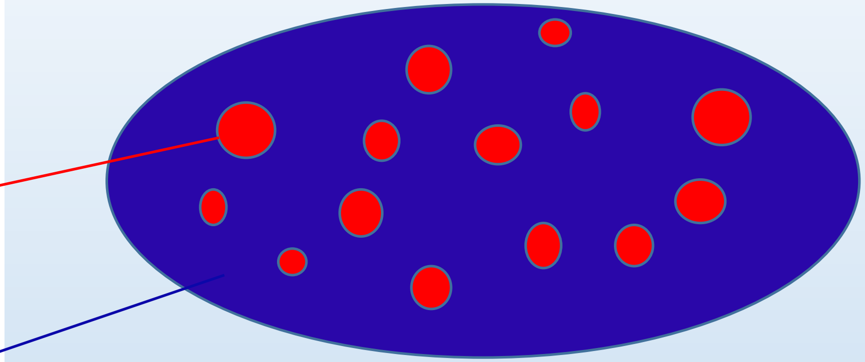
Thus further "sub-resolution" RT modelling is unavoidable (and associated free parameters).

Orion Nebula visible light

Orion Nebula visible + sub-mm (orange)

Dust reprocessing in simulations





The GRASIL3D infrared SED is the sum of two components:

- a cooler one due to diffuse ISM (cirrus), computed using the resolved density fields of dusty gas and stars
- a warmer one due to unresolved Molecular Clouds (MCs), computed with additional sub-resolution modelling (2 to 4 parameters)

A quick review of applications of GRASIL3D dusty radiative transfer to cosmological simulations
(in chronological order)

- Obreja+2014, MNRAS (8 zoom simulations of ET galaxies. Evolution of M*-SFR and M*-Z relations)
- Granato+2014, MNRAS (Galaxies clusters zoom in. Proto-cluster stage)
- Buck+2017, MNRAS accepted (100 high resolution zoom simulations. Nature of clumpy disks at high-z)
- Santos+2017, A&A accepted (dwarf galaxies in the CLUES local group zoom simulation. The diversity of IR-submm emission.)
- Goz+2017, MNRAS submitted (MUPPI small cosmological box)

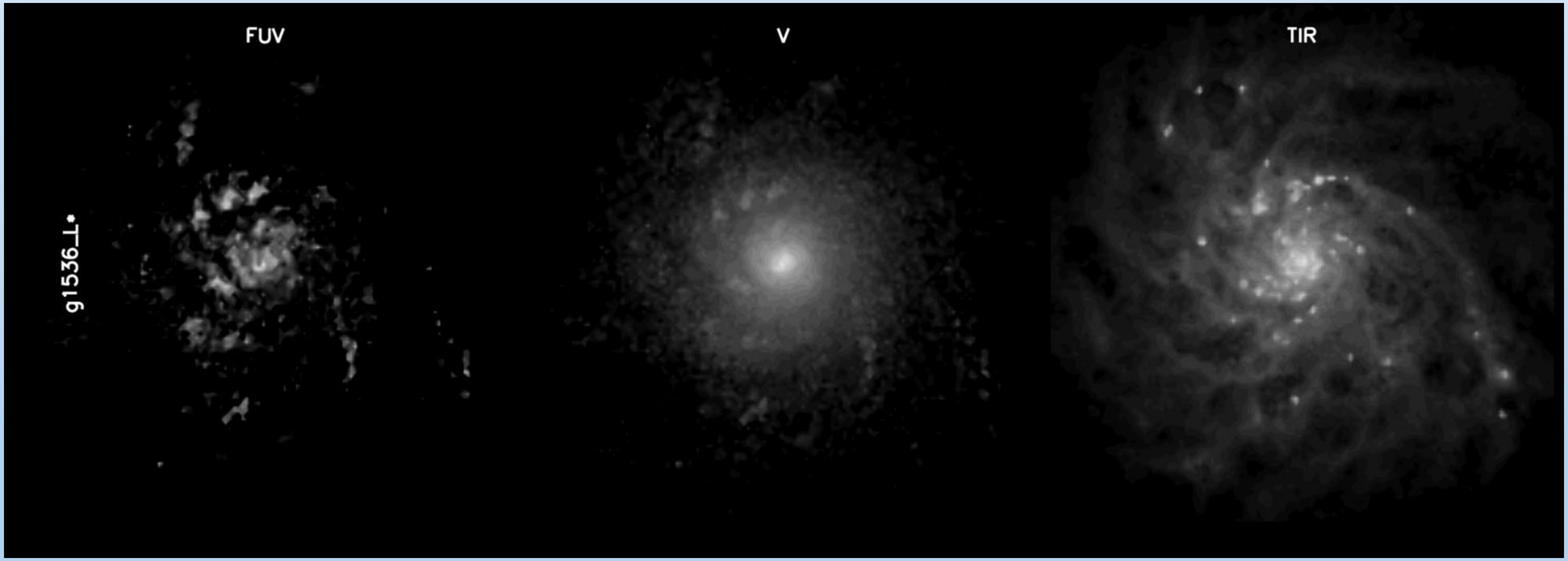
1° sample application of GRASIL3D: Obreja+ MNRAS 2014

The main sequence and the fundamental metallicity relation in MaGICC Galaxies: evolution and scatter

A. Obreja,[1★] C. B. Brook,[1] G. Stinson,[2] R. Domínguez-Tenreiro,[1] B. K. Gibson,[3,4] L. Silva[5] and G. L. Granato[5]

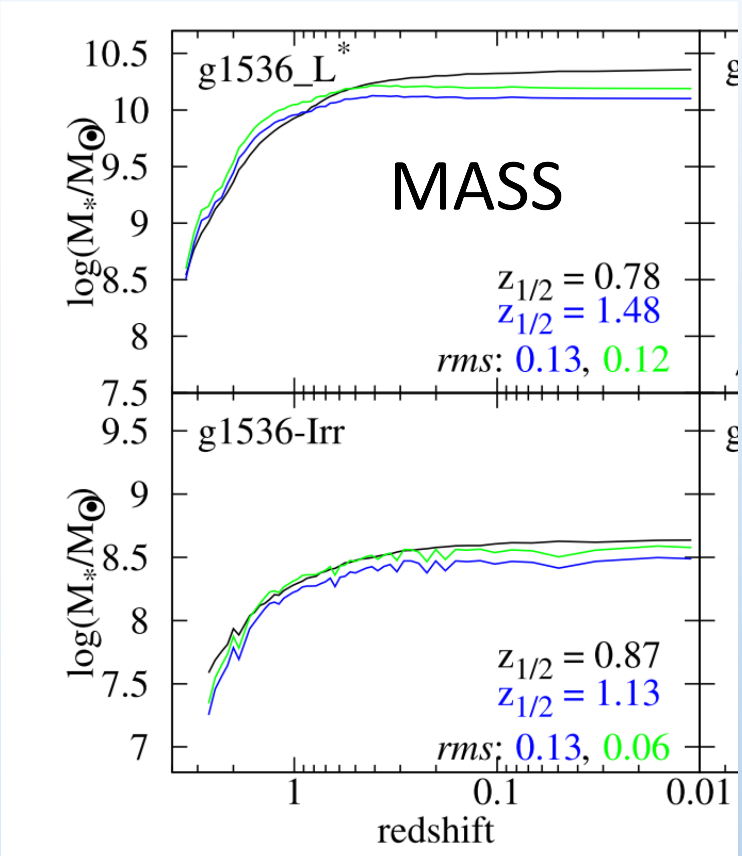
Based on 8 zoom simulations of early type galaxies

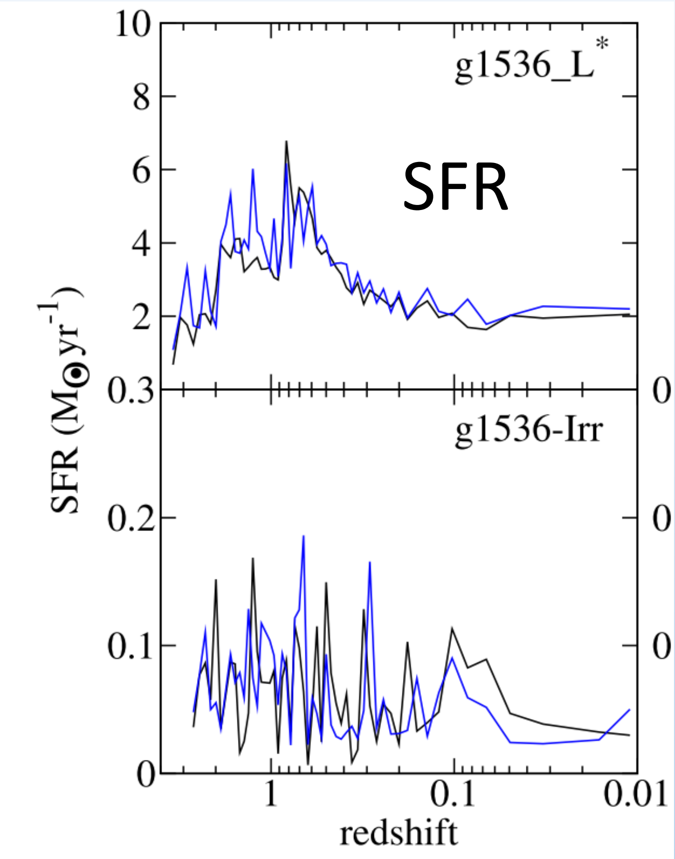
Far UV | Visible | Total infrared



Images of a mock galaxy , as predicted by the RT code GRASIL3D

1° sample application of GRASIL3D: Obreja+ MNRAS 2014





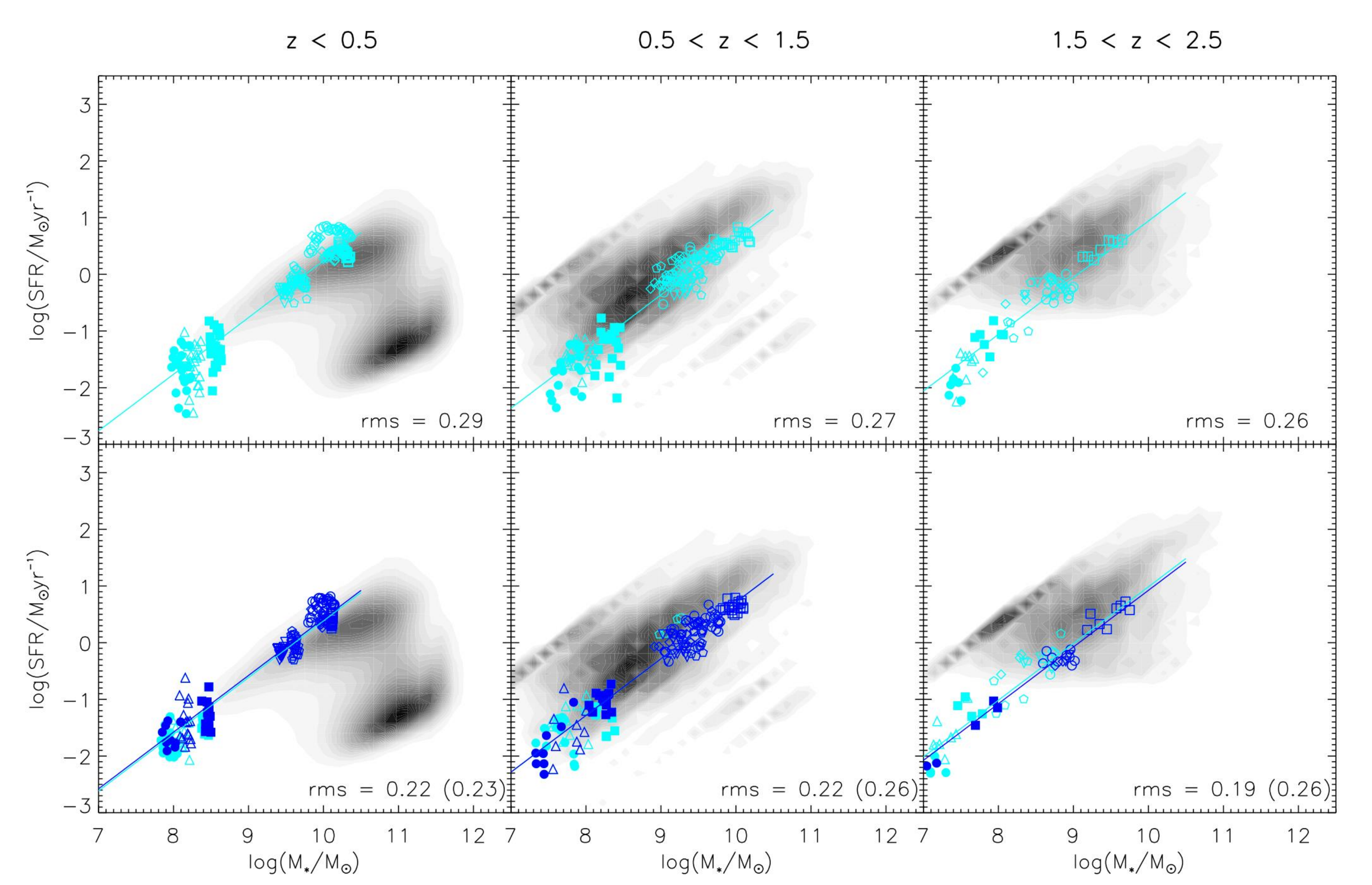
Mock galaxies “data”, computed by post-processing MaGICC simulations with GRASIL3D, have been used to asses the reliability of estimators of galaxy mass and SFR, commonly used with real data.

The agreement between these “light-weighted” (green and blue) and intrinsic “mass-weighted “(black) quantities is in general acceptable.

1° sample application of GRASIL3D: Obreja+ MNRAS 2014

Mass-weighted ("true" quantities directly from sims)

Light-weighted (estimated as for data after G3D rad. transfer)



The evolution of M_* – SFR
(grey regions data Wuyts+2011)

2° sample application of GRASIL3D: Granato+ MNRAS 2015

Monthly Notices
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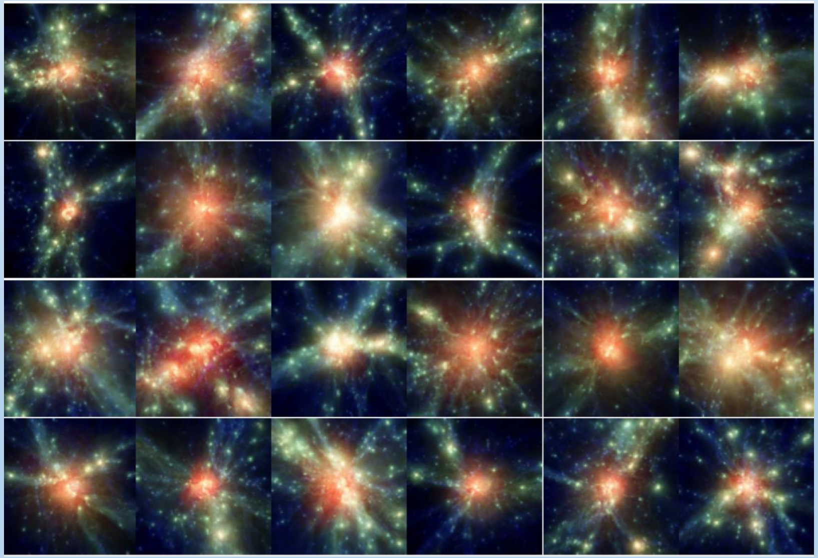
MNRAS **450,** 1320–1332 (2015) doi:10.1093/mnras/stv676

The early phases of galaxy clusters formation in IR: coupling hydrodynamical simulations with GRASIL-3D

Gian Luigi Granato,[1★] Cinthia Ragone-Figueroa,[1,2] Rosa Domínguez-Tenreiro,[3] Aura Obreja,[3] Stefano Borgani,[1,4] Gabriella De Lucia[1] and Giuseppe Murante[1]

DIANOGA SET: 24 most massive clusters (M_{200} > 1e15 h^{-1} $M_\odot$ at z=0) selected from Parent gravity only sims, box 1 Gpc h^{-1}, re-simulated at higher resolution in boxes of about 60 Mpc, including baryonic physics



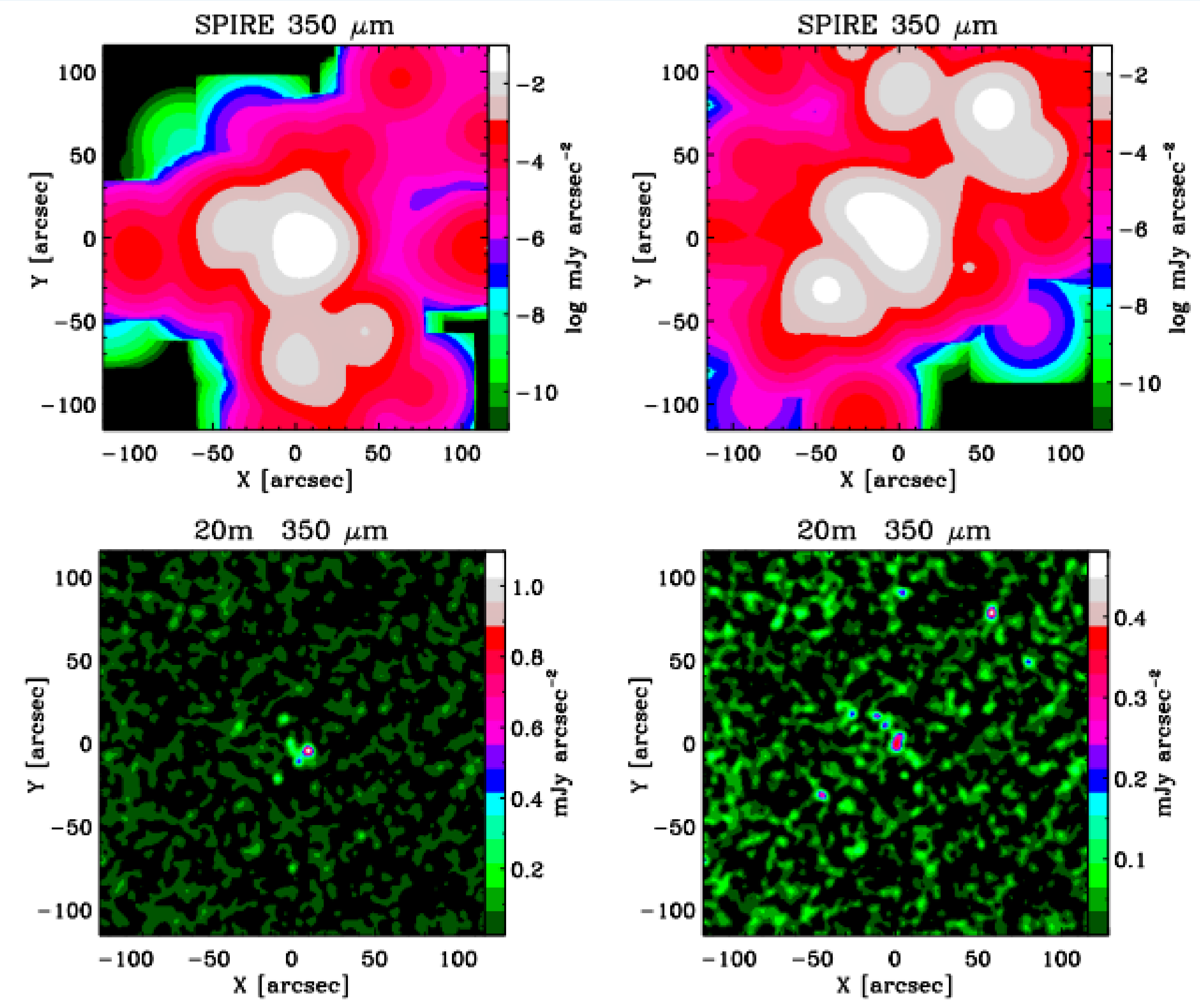
The proto-cluster regions of 2 Mpc (~ Planck beam) from snapshots at z 0.75 to 4 (where SF and thus dust reprocessing is high), postprocessd with GRASIL3D to produce images and SEDs

2° sample application of GRASIL3D: Granato+ MNRAS 2015

The two brightest simulated clusters at z=2 and $350\ \mu m$ with some telescope effects (top 25 arcsec, bottom 3 arcsec)

Only white spots slightly above Herschel survey limit

At odd with hints from observations (e.g. Clements+2014; Planck collaboration XXVII 2015)



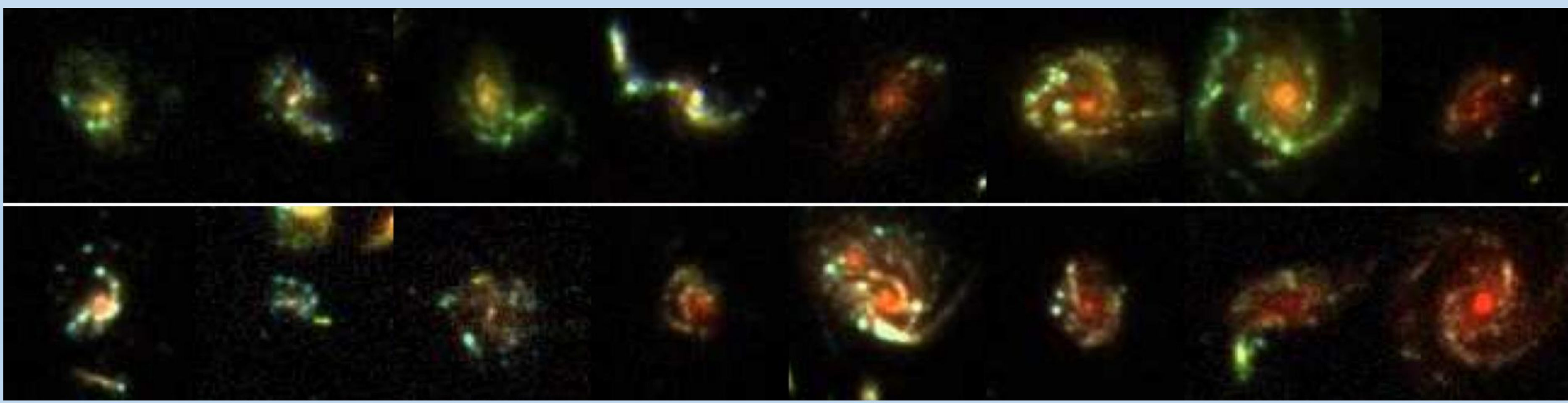
3° sample application of GRASIL3D: Buck+ MNRAS 2017

NIHAO XIII: Clumpy discs or clumpy light in high redshift galaxies?

Tobias Buck[1,2]*, Andrea V. Macciò[3,1]†, Aura Obreja[3], Aaron A. Dutton[3], Rosa Domínguez-Tenreiro[4], Gian Luigi Granato[5]

19 hi-res sims of disc galaxies from the NIHAO suite post-processed with GRASIL3D in order to investigate the nature, the formation and the evolution of giant clumps **observed** in the discs of high z (1−3) star forming galaxies.

These clumps attracted a lot of attention both from an observational and a theoretical point o view



Observations: Guo+2015, CANDELS field

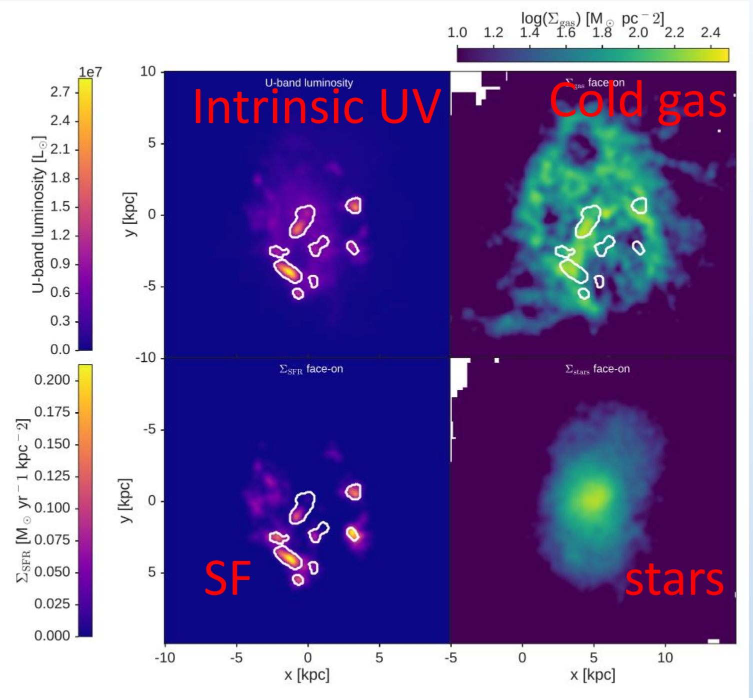
3° sample application of GRASIL3D: Buck+ MNRAS 2017

In high-z simulated galaxies, giant clumps are evident in Star Formation, cold gas and intrinsic UV light, while the stellar distribution is smooth

UV images computed taking into account RT in the dusty ISM show clumps, but they are often displaced, due to dust attenuation on one hand and clumpy gas distribution on the other hand

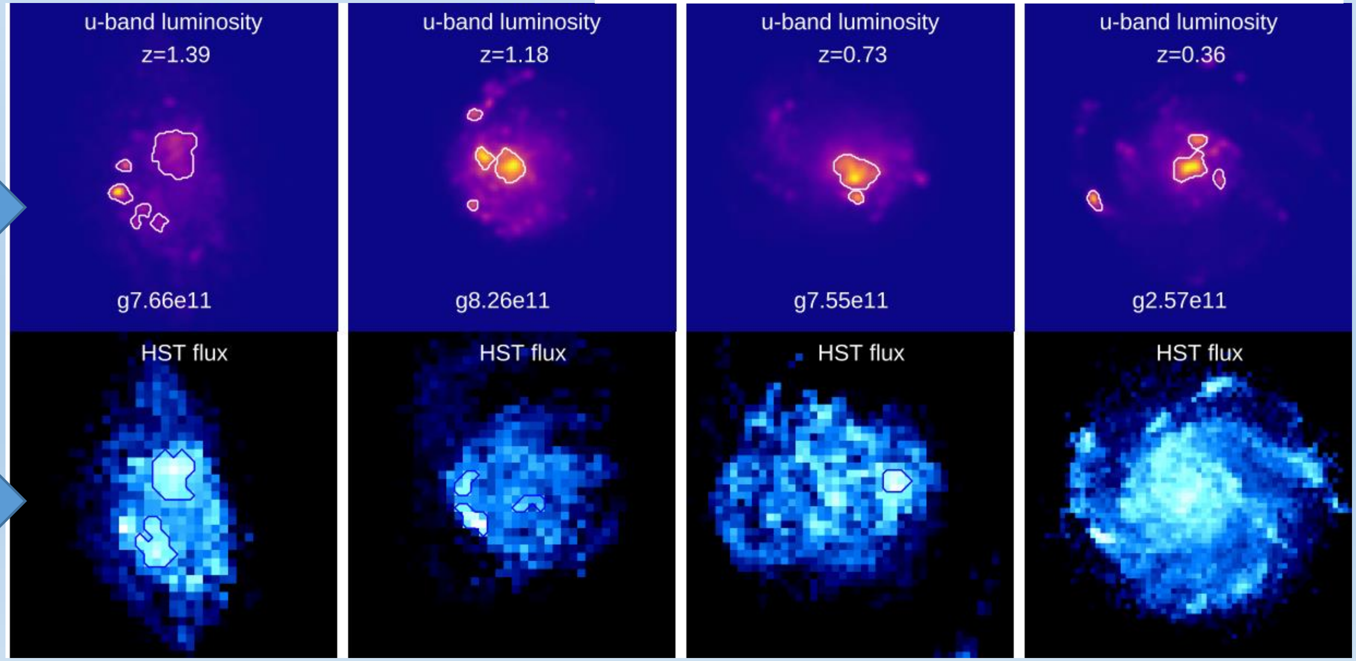
Radiative Transfer is essential to properly compare with observations

Clumps are shortly lived, do not spiral inward and do not contribute to the bulge build-up



Intrinsic UV (no dust RT)

Radiative Transfer UV



4° sample application of GRASIL3D: Santos+ A&A 2017

On the diversity of the IR-submm emission patterns of dwarf galaxies: CLUES from hydrodynamical simulations

Isabel M.E. Santos-Santos[1]★, Rosa Domínguez-Tenreiro[1], Gian Luigi Granato[2], Chris B. Brook[1], Aura Obreja[3]

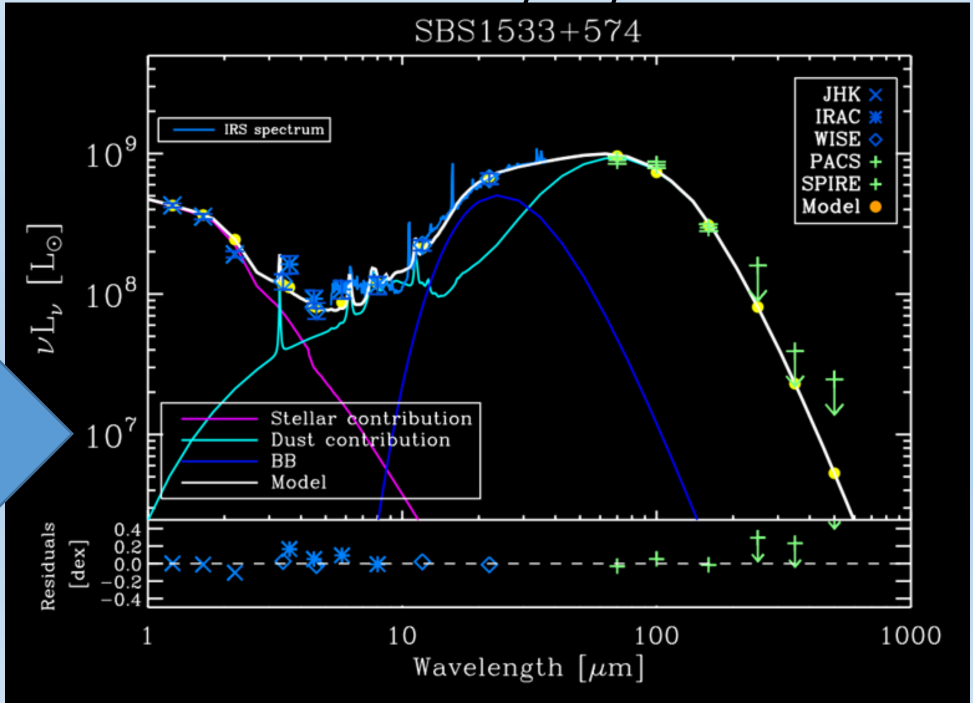
Computation of the SED of 27 dwarf galaxies from the Constrained Local UniversE Simulations (CLUES).

The purpose: to investigate the origin of the peculiar features of low mass-low metallicity galaxies in the IR/sub-mm range:

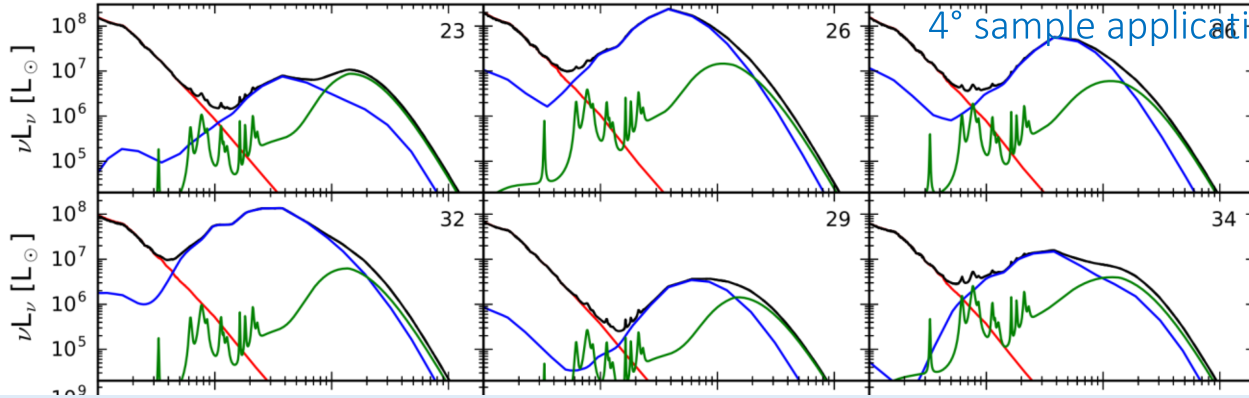
- broader IR peak;
- flatter sub-mm/FIR slope;
- weaker PAH emission bands;

To reproduce these features, simple empirical SED models usually advocate ad-hoc assumptions, such as additional components and dust optical properties.

Rémy-Ruyer+ 2015



4° sample application of GRASIL3D: Santos+ A&A 2017



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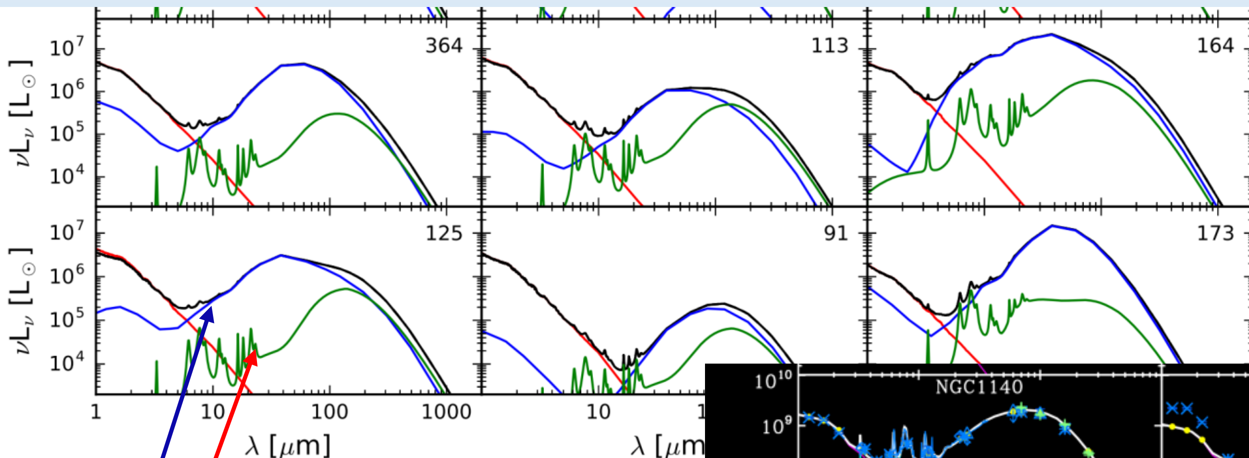
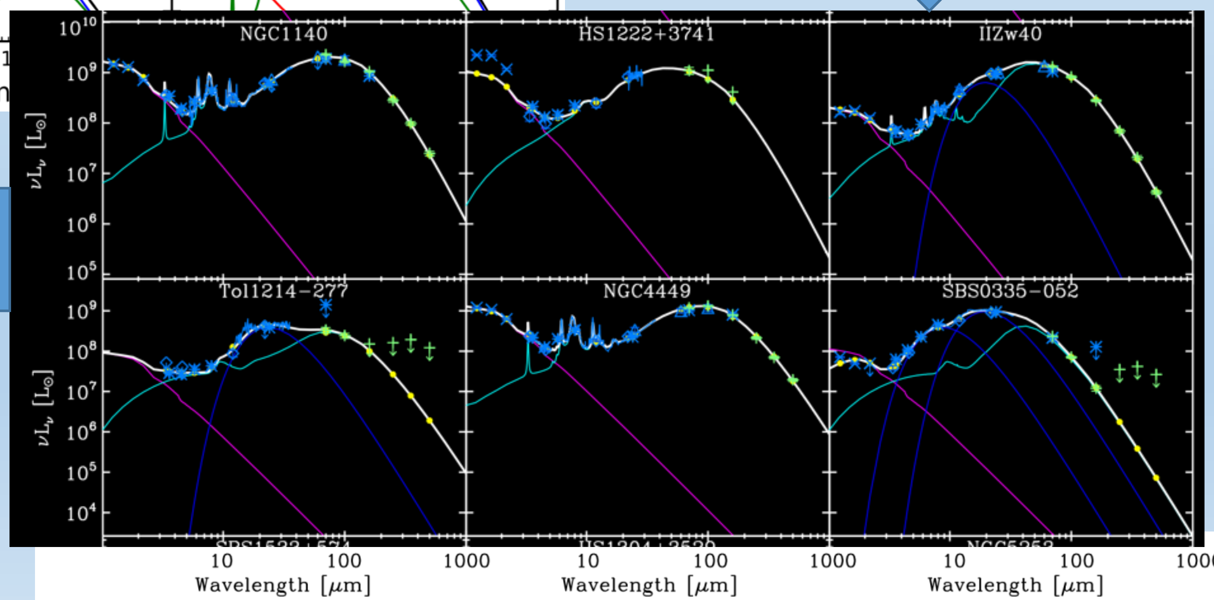
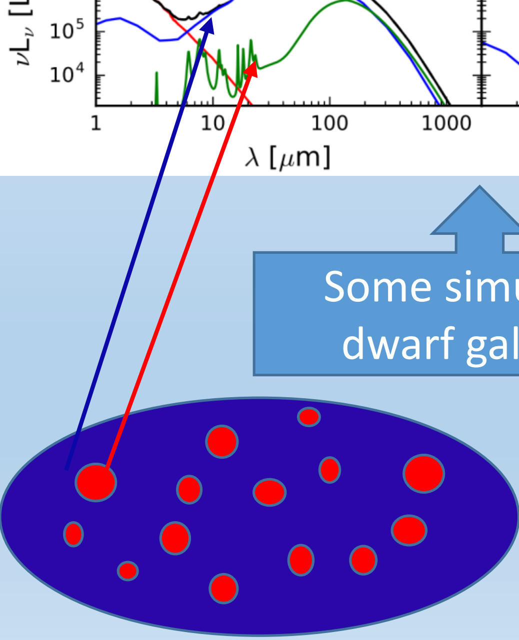


The SEDs of simulated dwarf galaxies naturally reproduce the varied features of real ones.
They are shaped by the variable separation and relative intensity of the MC and cirrus dust emission component

Some observed dwarf galaxies



Some simulated dwarf galaxies

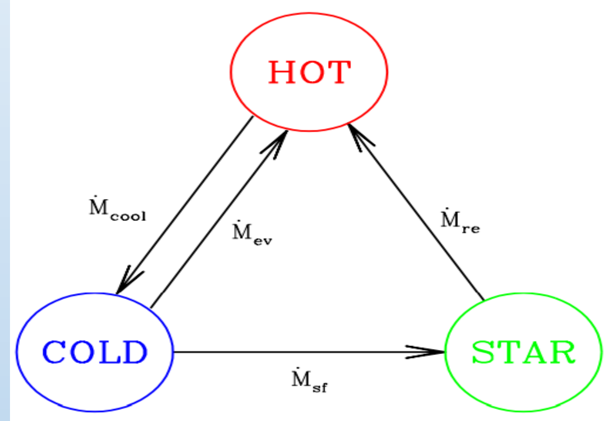


5° sample application of GRASIL3D: Goz+ MNRAS submitted

Panchromatic Spectral Energy Distributions of simulated galaxies: results at redshift $z = 0$

David Goz[2], Pierluigi Monaco[1,2], Gian Luigi Granato[2], Giuseppe Murante[2], Rosa Domínguez-Tenreiro[3], Aura Obreja[4], Marianna Annunziatella[1] and Edoardo Tescari[5,6]

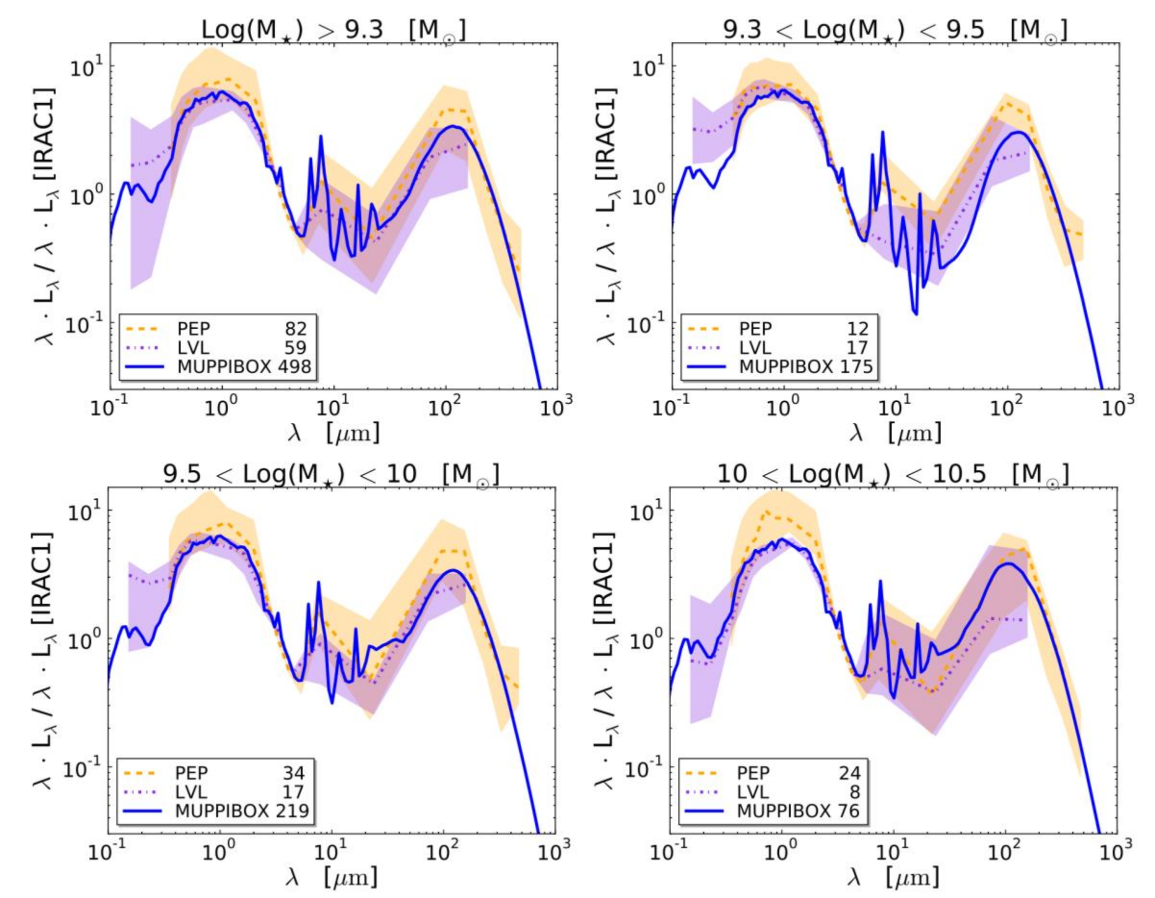
A small (25 Mpc/h) cosmological box simulated using the sophisticated sub-grid model for SF and stellar feedback MUPPI (Multi Phase Particle Integrator; Murante+ 2015).

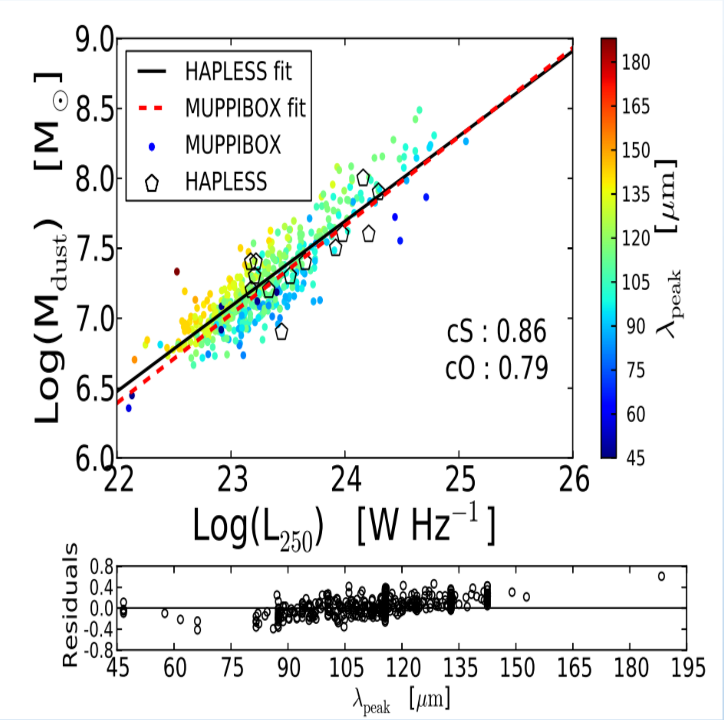


Multiphase particles, phases evolution treated during the simulation with methods similar to those of semi-analytic models.

The 968 galaxies with M > 2e9 h^{-1} $M_\odot$ at z=0 post processed with GRASIL3D. The resulting mock Spectral Energy Distributions statistically compared with those of well studied local samples: Local Volume Legacy (LVL) (Cook+ 2014a), PACS Evolutionary Probe (PEP) (Gruppioni et al. 2013).

5° sample application of GRASIL3D: Goz+ MNRAS submitted



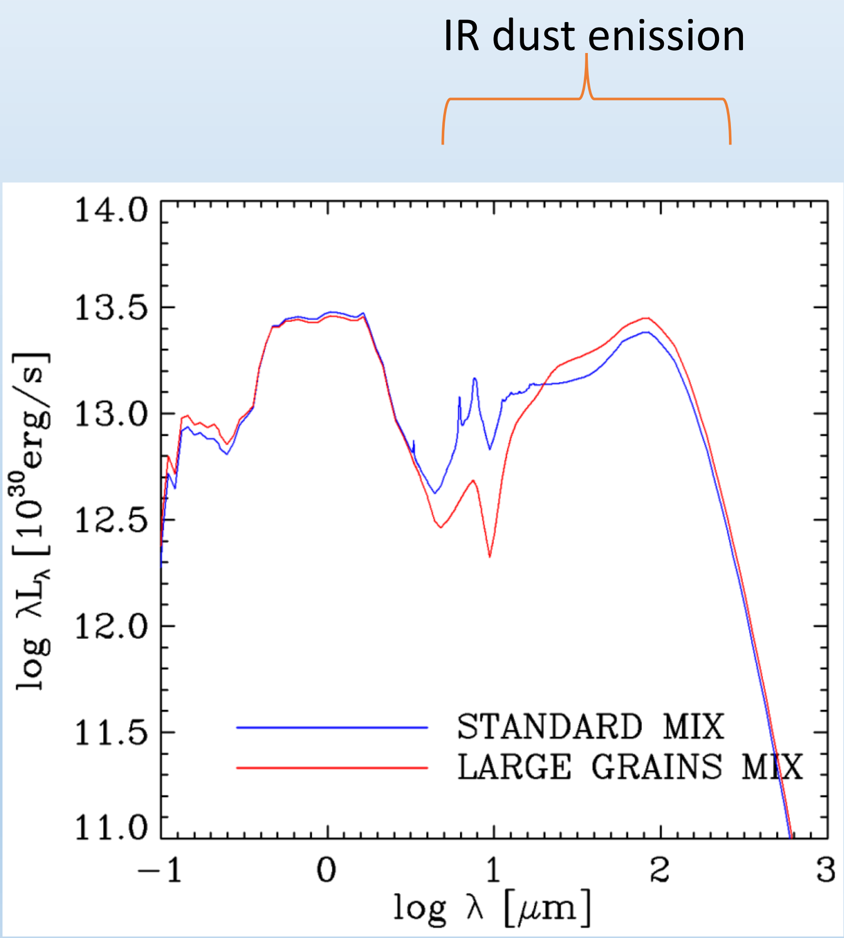


In general the SED of simulated galaxies resembles those of observed ones. When differences appears, they can be tracked to tension in predicted physical properties, e.g. metallicity in the lowest mass bin.

Observed correlations between IR luminosities and physical properties are also in general well reproduced.

Next step: including a treatment of evolution of dust properties in the simulation

- The radiative effects of dust strongly depend on the physical and chemical properties of dust grains
- Most computations adopt models of the dust grain mixture (composition and size distribution) derived to explain some "average" properties of MW dust
- However it is expected and observed that these properties change from galaxy to galaxy and even within different environments of the MW



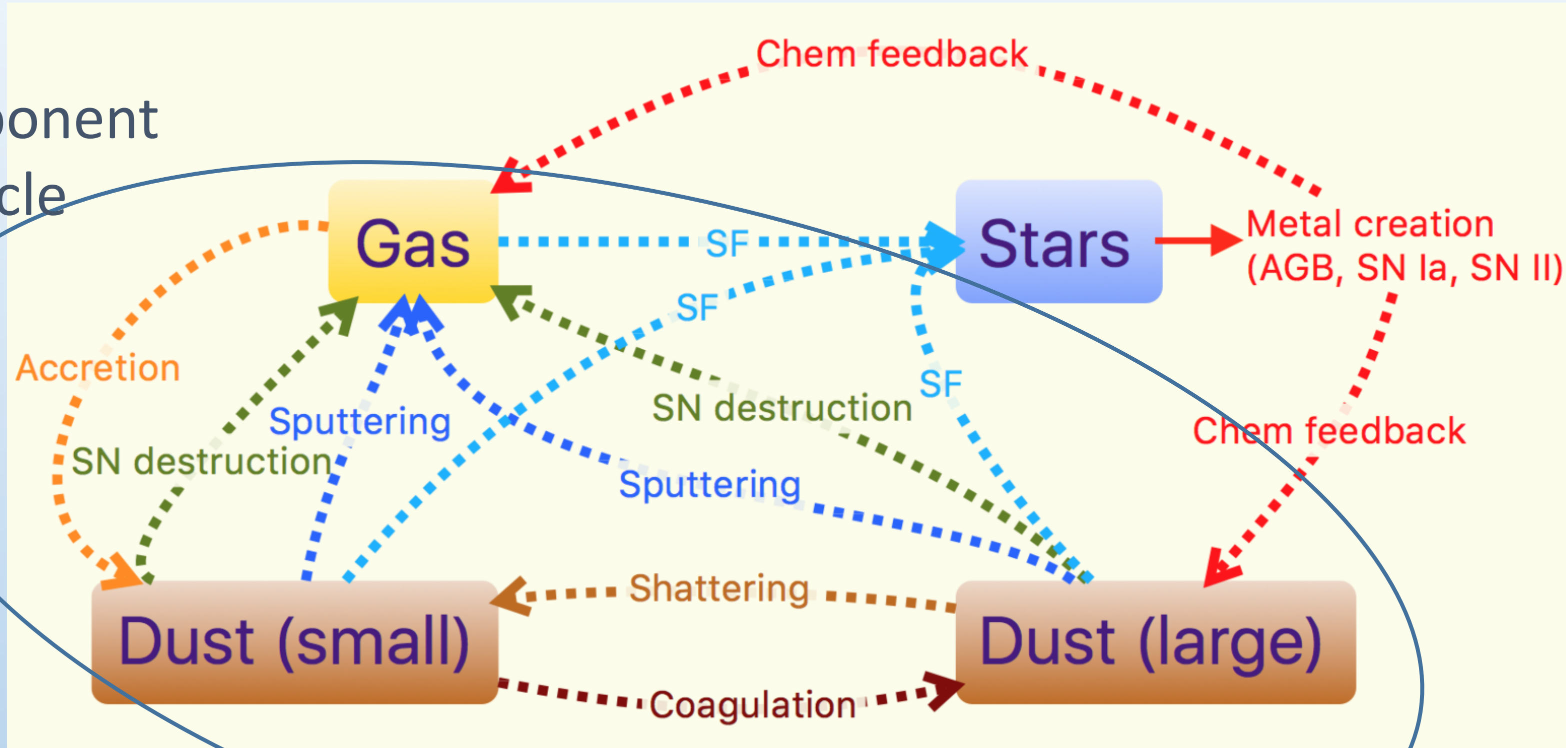
Next step: including a treatment of evolution of dust properties in the simulation

- Since Dwek 1998, there have been sparse attempts to construct galaxy models accounting for production & evolution of dust grains in the ISM (to predict dust-to-gas ratio, dust chemical properties, or sometimes also size distribution.)
- Most work was done in the context of monolithic chemical evolution models (a somewhat natural extension of chemical evolution equations)
- Now the "theory" begins to be applied to simulations (few attempts as of yet.)
- We recently completed an implementation of dust evolution in our version of P-Gadget3. So far, it is the most complete efforts. (PI Eda Gjergo, INAF Phd student.)

Modeling Dust Evolution in P-GADGET3

Eda Gjergo[1,2], Gian Luigi Granato[1], Cinthia Ragone-Figueroa[1,3], Giuseppe Murante[1].

Multicomponent "gas" particle



- Evolution of "gas" particles over code time-steps with SAM methods;
- We predict abundances of small and large, carbon and silicate dust grains (2x2=4 dust abundances)

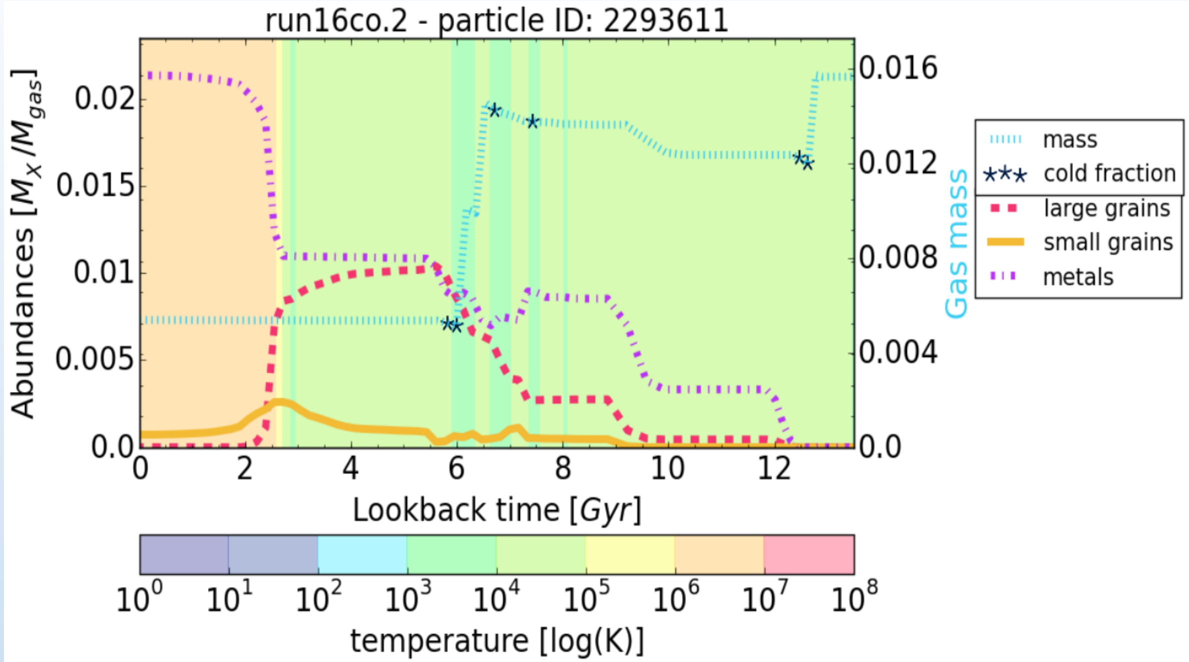
Process	Small grains	Large grains	Total
Stellar ejecta	Δ	$\nearrow$	$\nearrow$
Accretion	$\nearrow$	Δ	$\nearrow$
Shattering	$\nearrow$	$\searrow$	$\longrightarrow$
Coagulation	$\searrow$	$\nearrow$	$\longrightarrow$
SN destruction	$\searrow$	$\searrow$	$\searrow$
SF	$\searrow$	$\searrow$	$\searrow$
Sputtering	$\searrow$	$\searrow$	$\searrow$

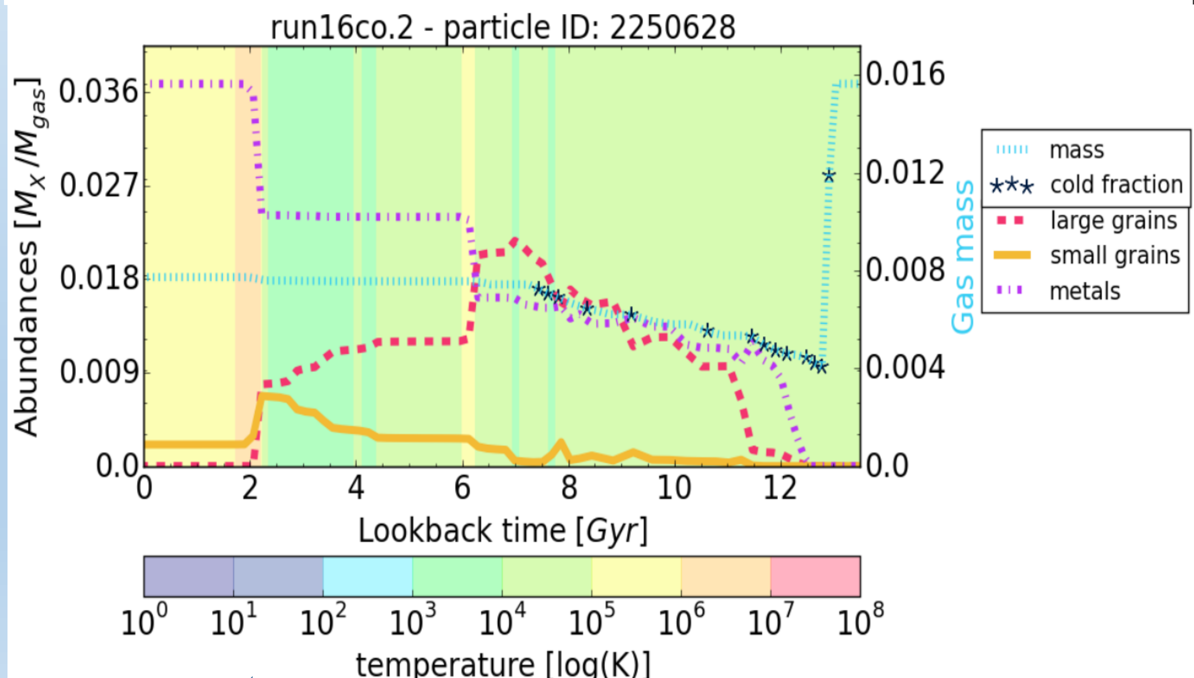
Examples of evolution of the various components in 2 gas particles

At times the dust abundance grows more than the metallicity due to the important role of accretion in the ISM

When particles are dense and star forming, small grains disappears due to efficient coagulation. If not, shattering can win.

Thermal sputtering destroys grains at T>1E6vK

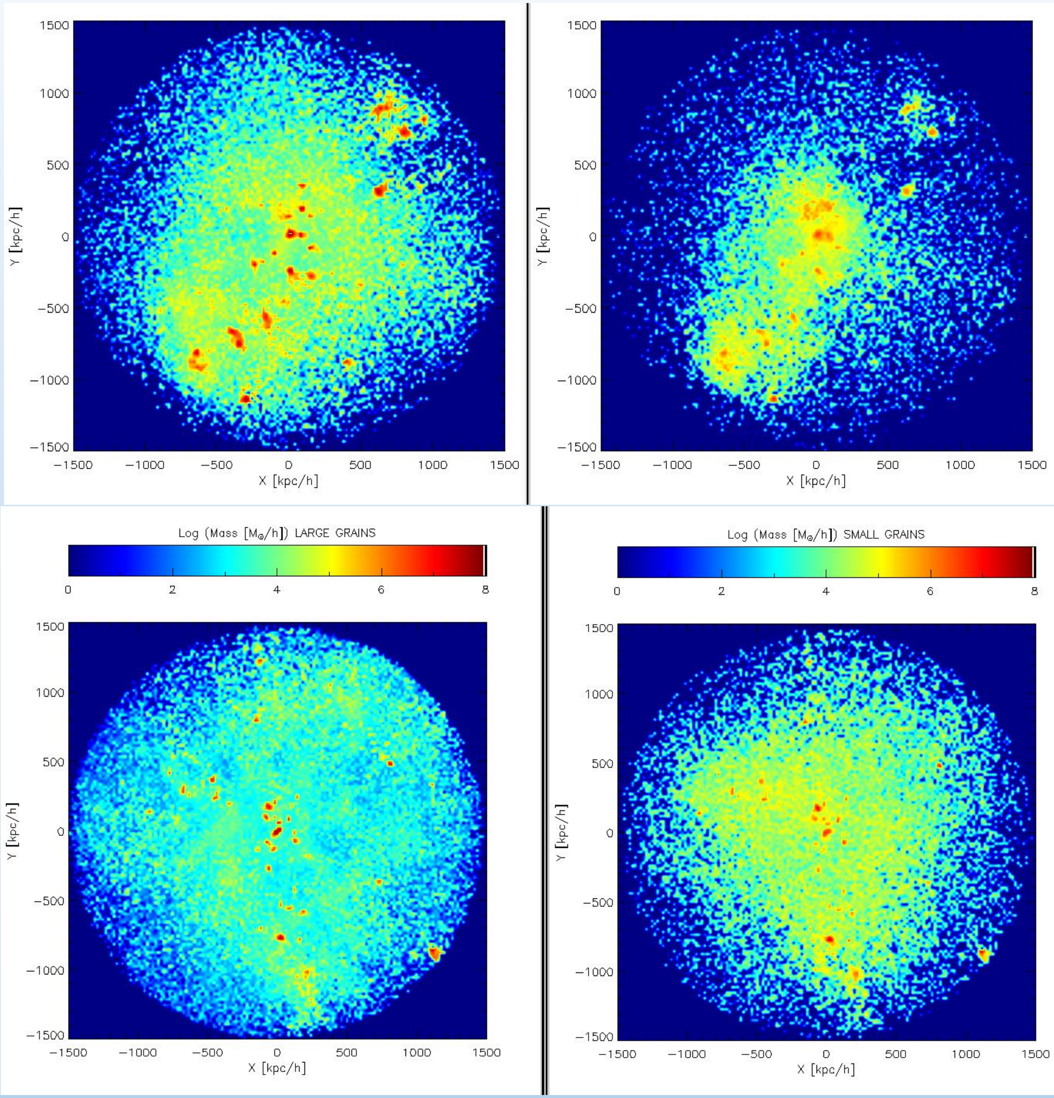




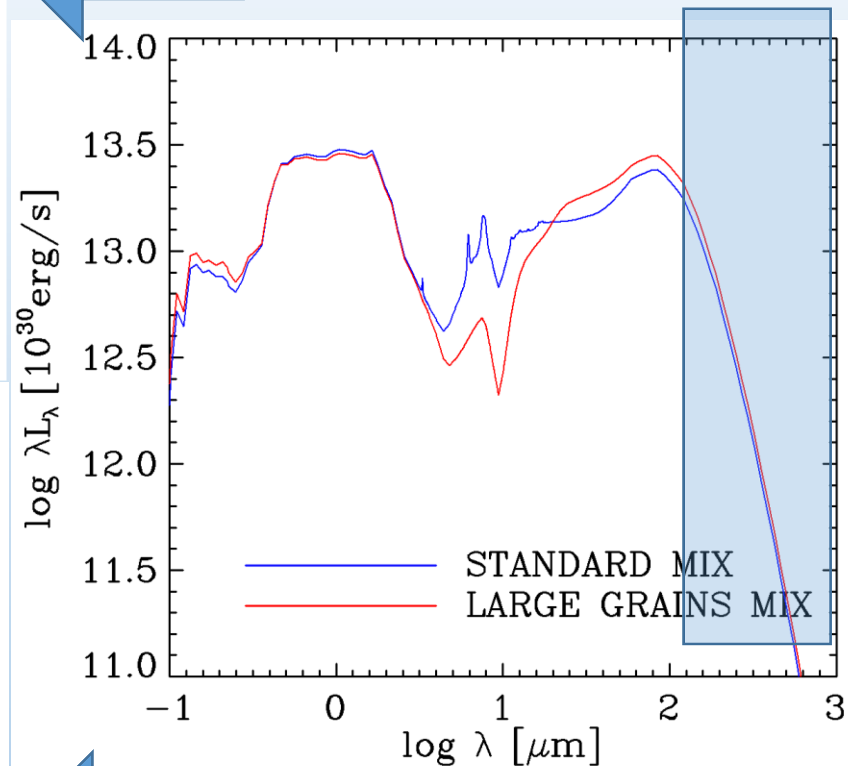
arrow of time

DUST MASS DENSITY MAPS WITHIN Rvir

IR dust emission



Z=1



Z=0

LARGE GRAINS

SMALL GRAINS

Small grains abundant only at late time

SED below 100 μm is affected

Conclusion

A proper treatment of dust effects in galaxy formation simulations is in its infancy, but it is strongly required

Don’t be lazy: some tools to play with are already available

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