Running with the grain:

Consolidating physical and observational effects of dust with cosmological simulations

Dr James Trayford

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Dust in the Universe

- **Dust is probably most widely considered a nuisance…**

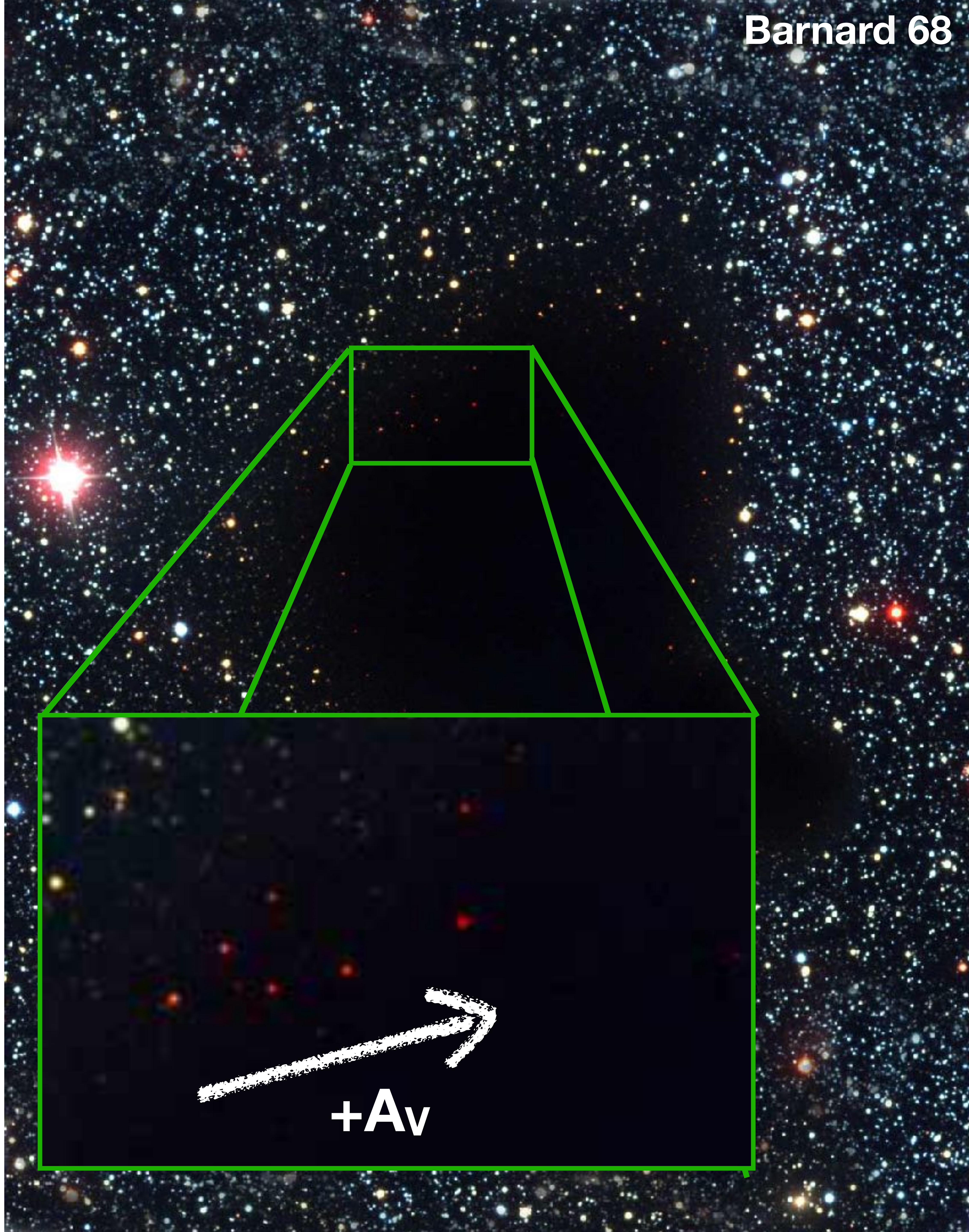
  Dust obscures starlight, greatly complicating the relationship between the optical properties and the intrinsic stellar properties of galaxies

- **However dust re-emits in the IR**

  Dust emission helps balance the energy budget, and encodes information of its own. Some galaxies are significantly brighter in IR (e.g. Sub-mm galaxies)

- **Dust also plays an outsized physical role in galaxies…**

  A substrate for molecule formation, a channel for cooling, a channel for heating, shields gas, interacts with gas, feels radiation pressure…



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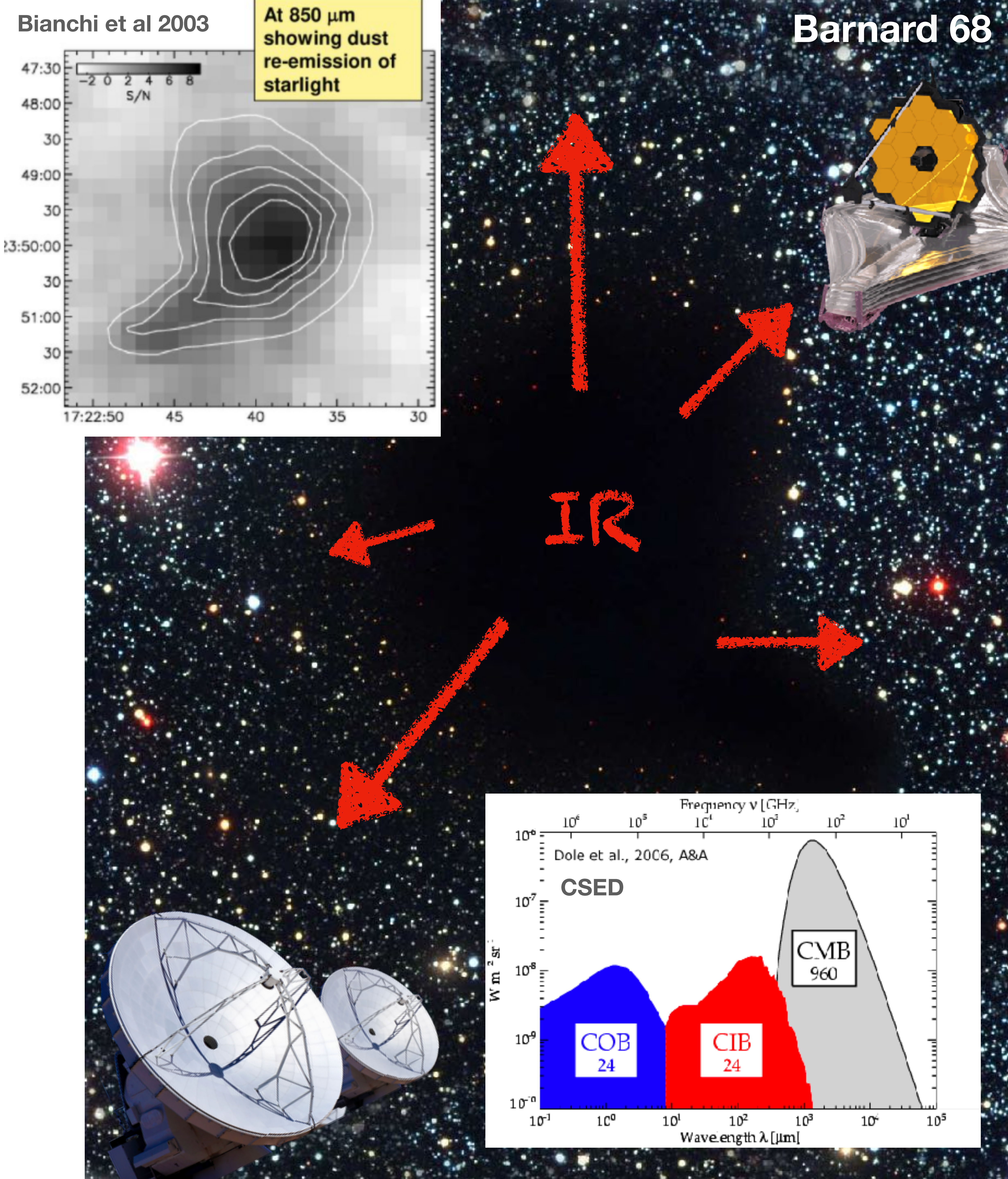

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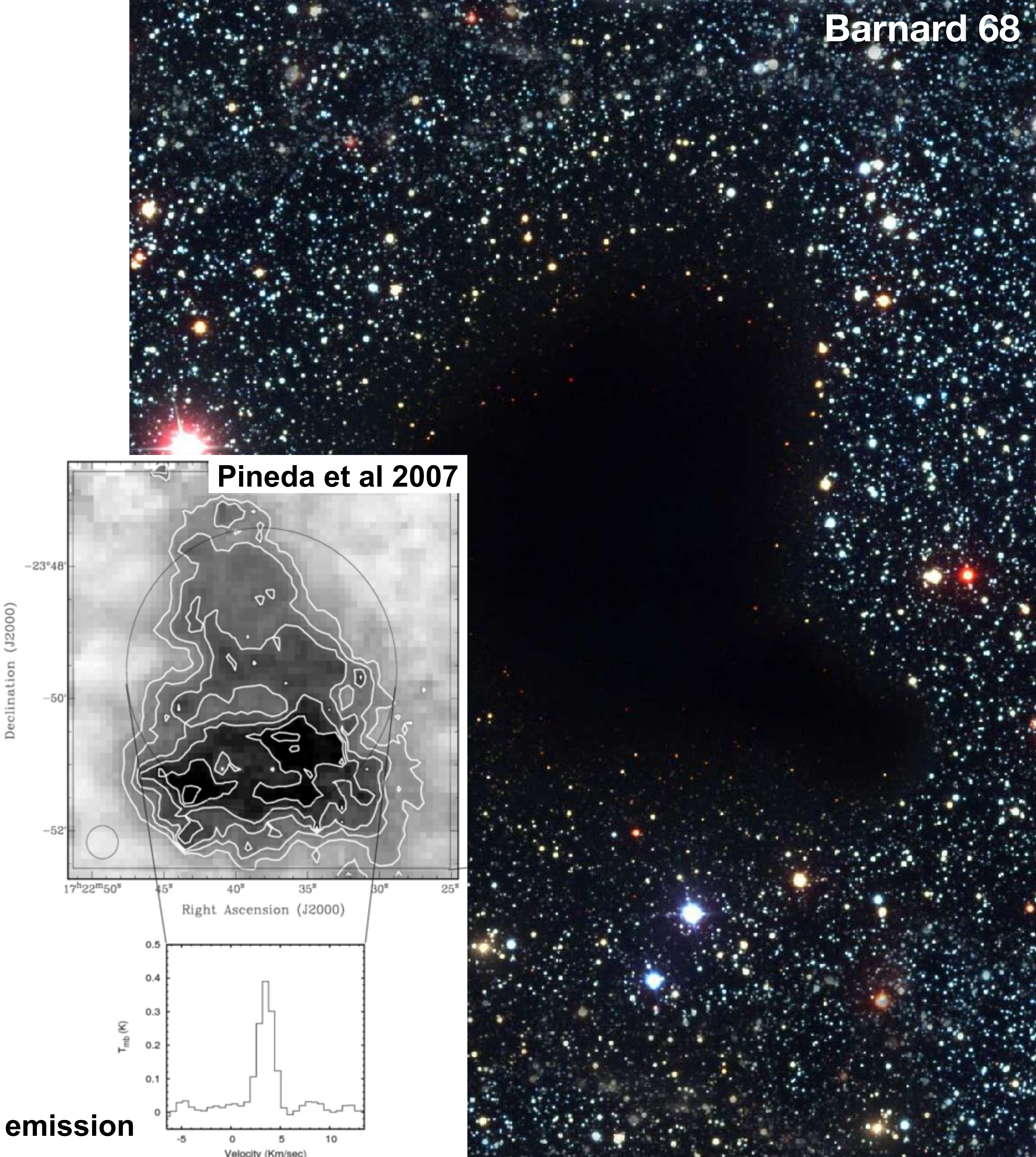
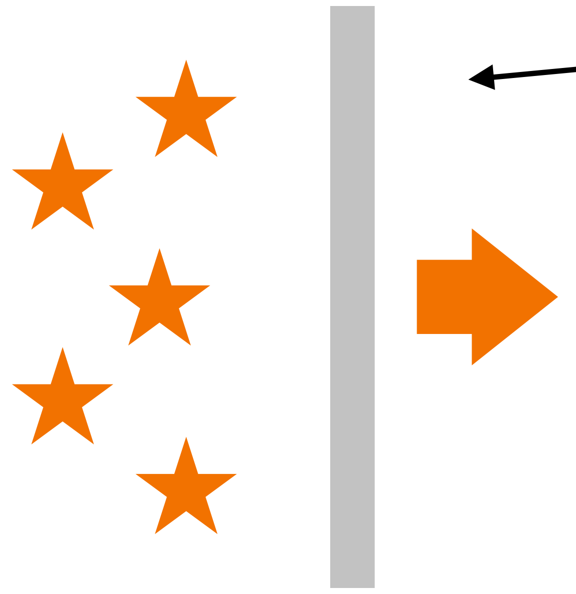


CO emission

How Does Dust Process Light in Galaxies?

Dust Extinction is dictated by the ***optical properties of grains themselves*** (*intrinsic scattering and absorption cross-sections)*



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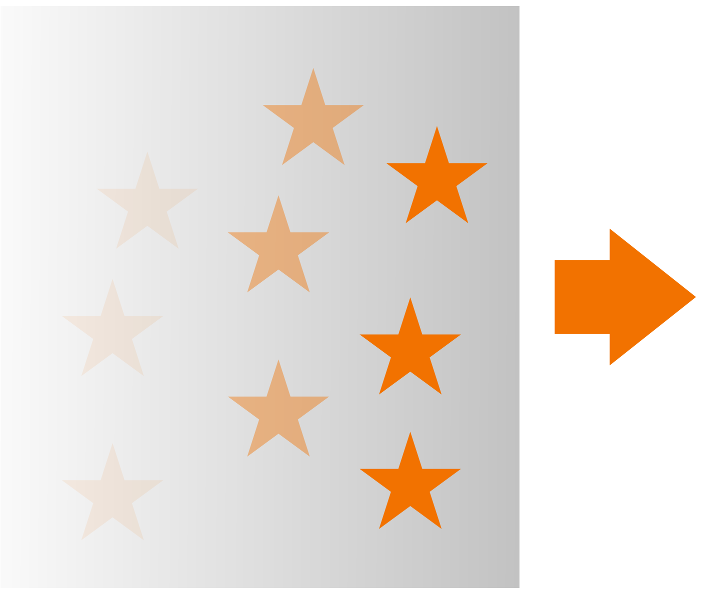
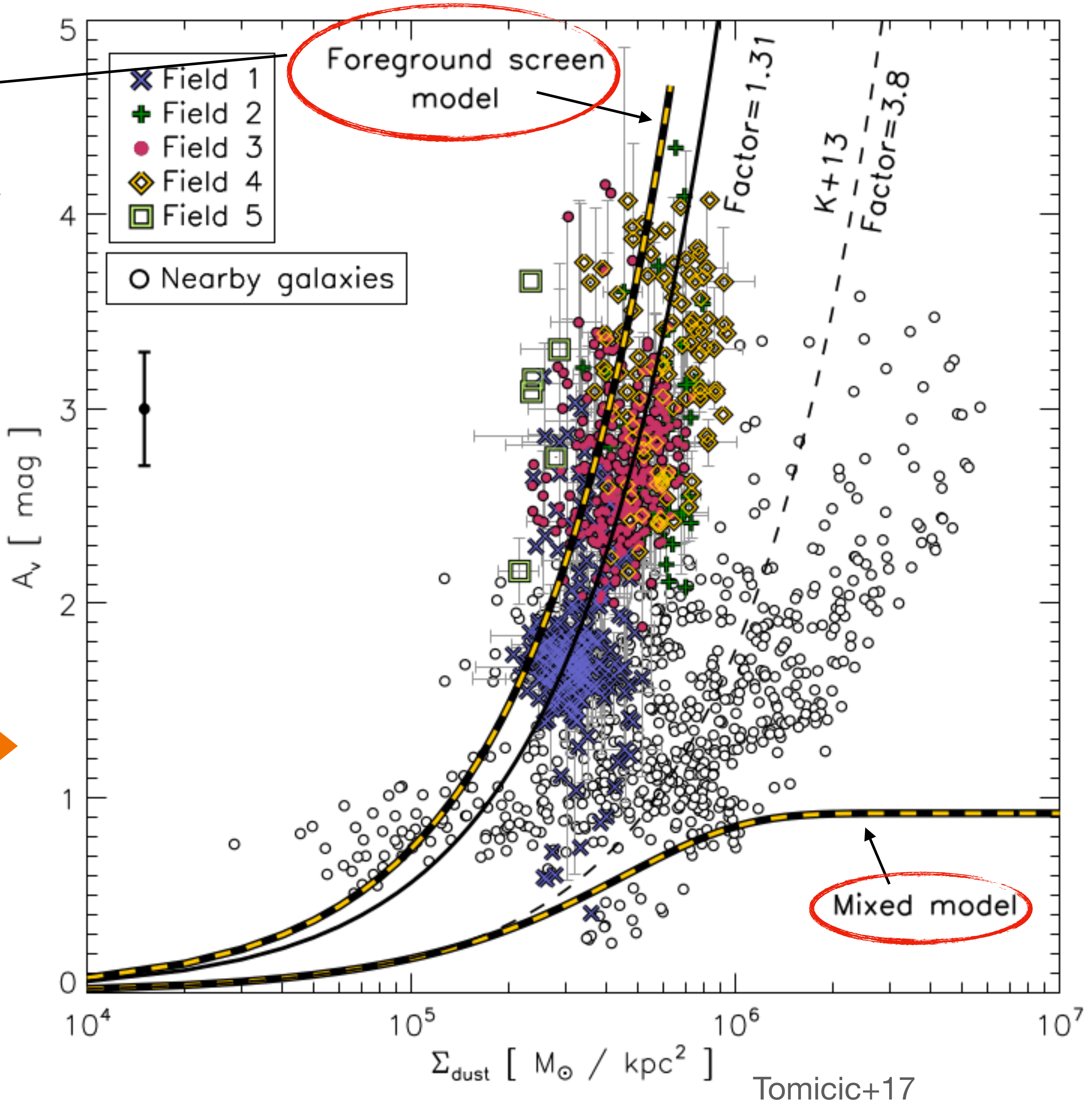
Dust Emission then depends on this Attenuation and the nature of dust grains



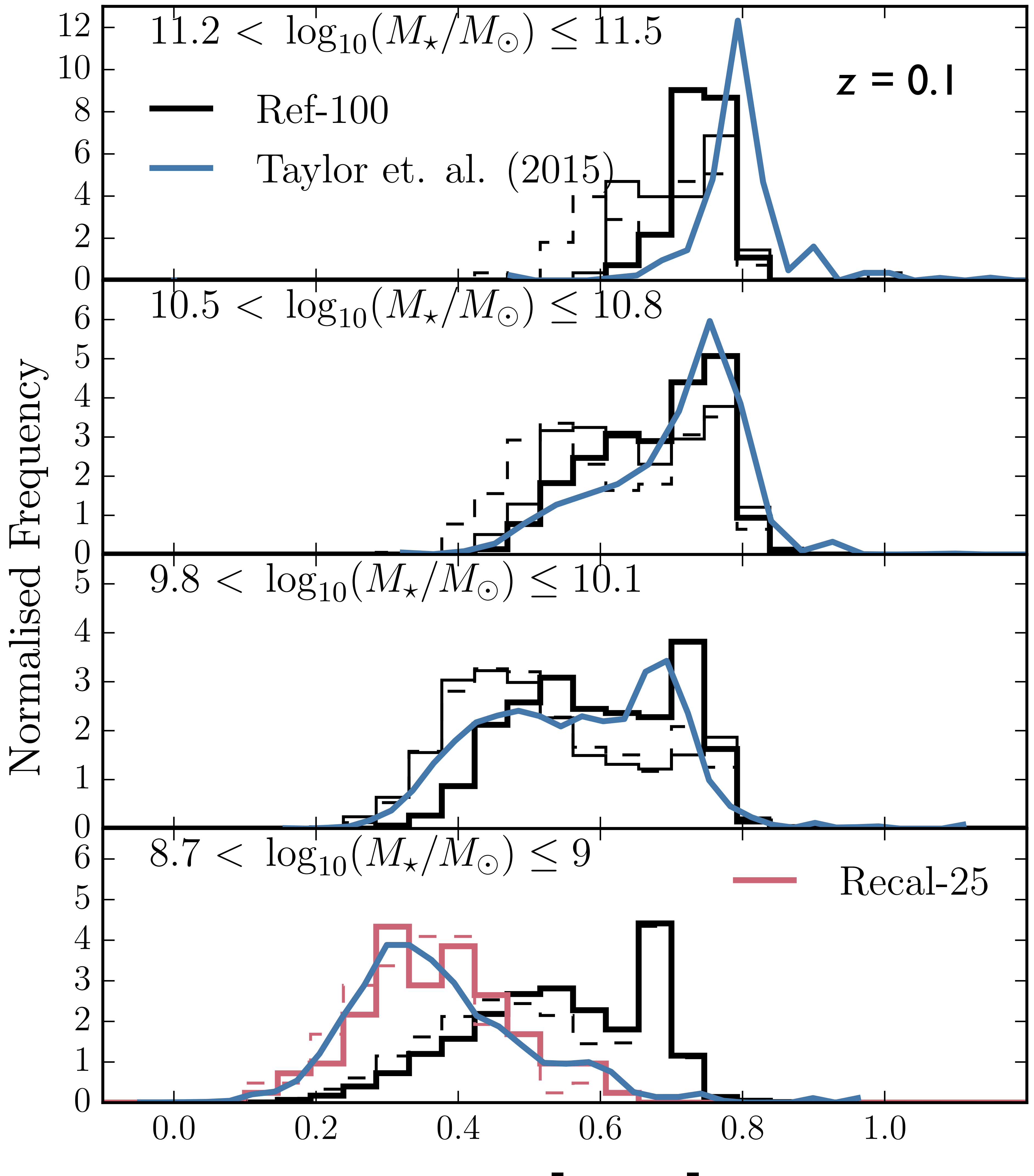
Extinction & Attenuation are only equivalent in the case of a point source and thin, intervening screen!

See e.g. Witt et al 1992



Tomicic+17

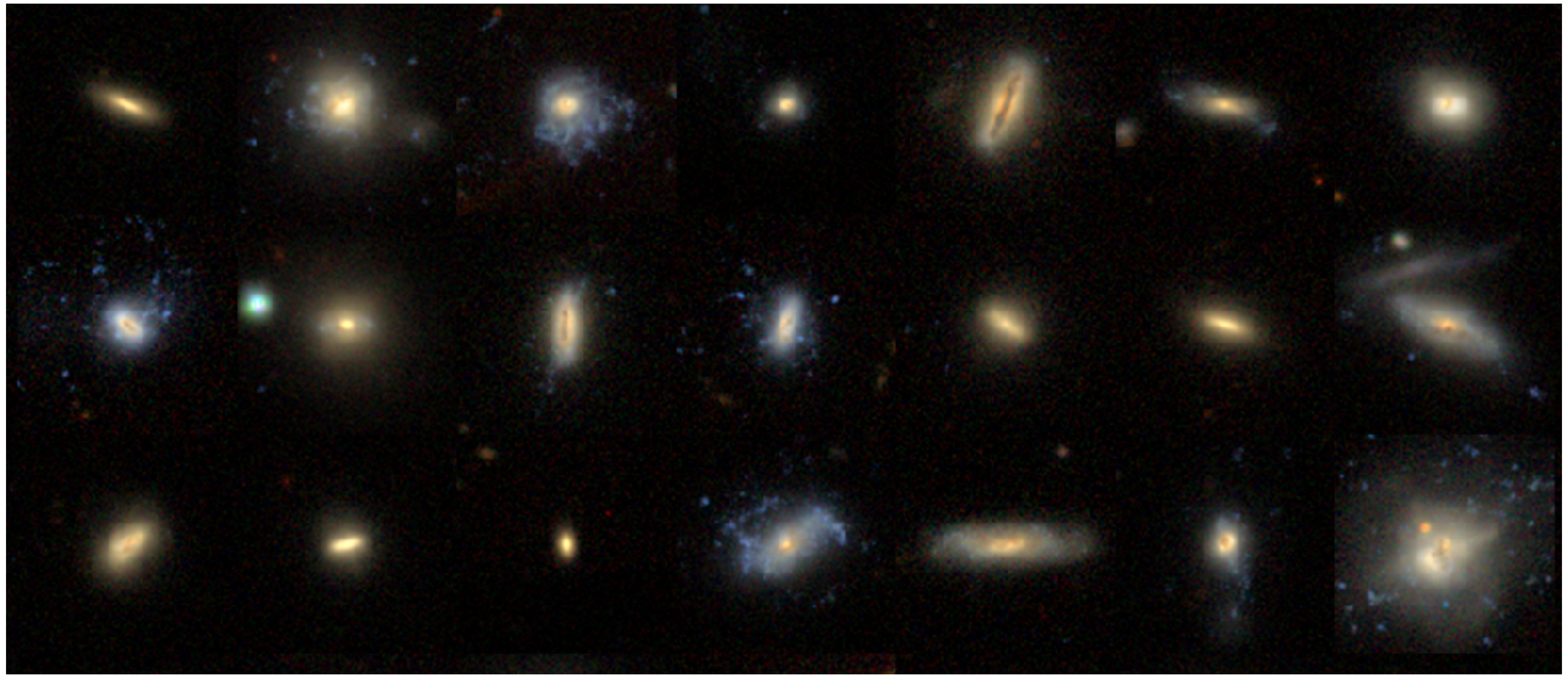
EAGLE & SKIRT



Trayford et al 2017

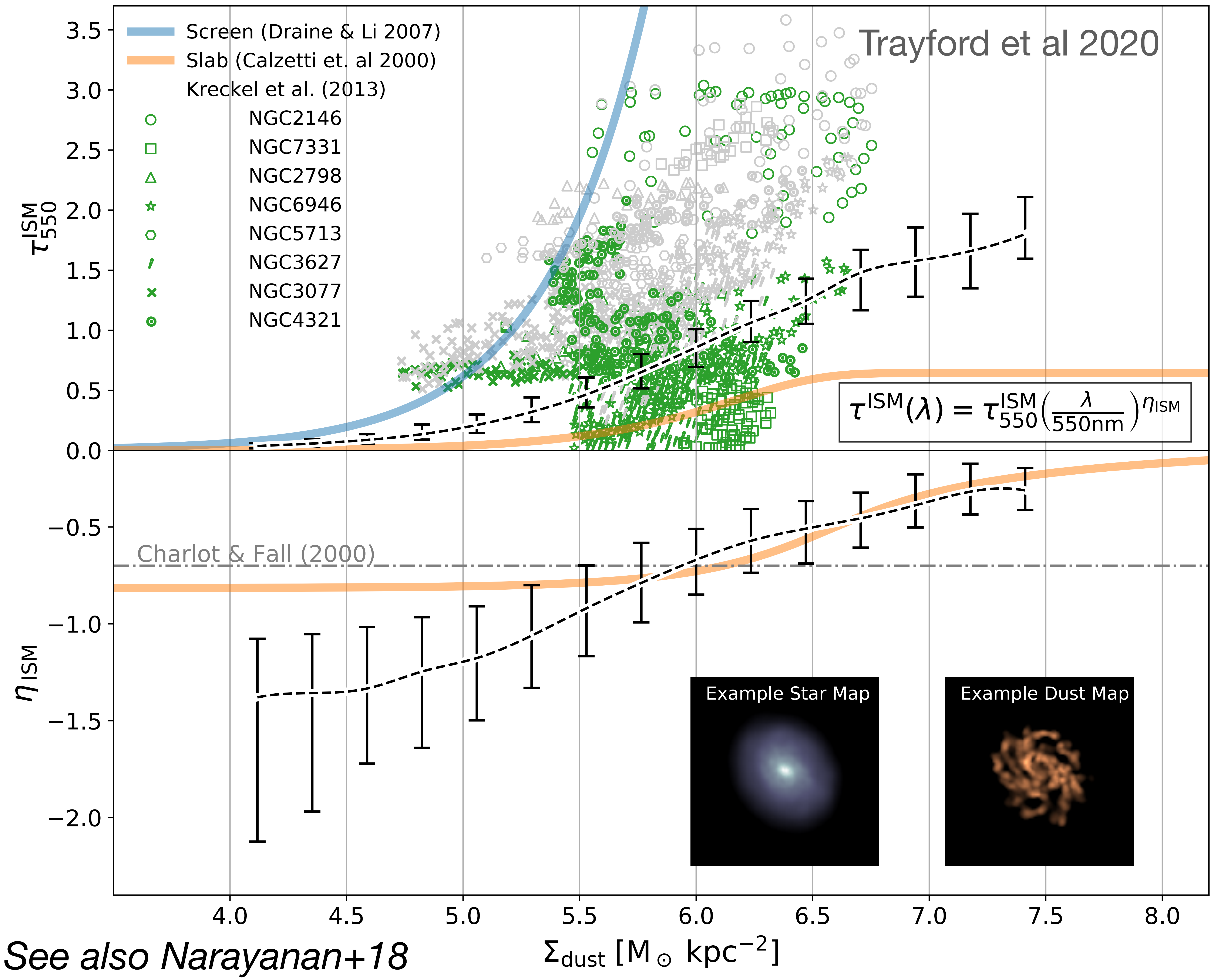
- ***SKIRT*** [1] radiative transfer used to model ***dust attenuation*** in ***EAGLE*** *(Schaye+15)* galaxies
- Attenuation varies a lot despite ***fixed grain model*** and ***dust-to-metal ratio*** - geometric effects!
- Accounting for this leads to a better match to ***galaxy colour bimodality*** and ***luminosity functions***

[1] skirt.ugent.be



Mock SDSS images of EAGLE galaxies created using full SKIRT radiative transfer

Parametrising ISM attenuation

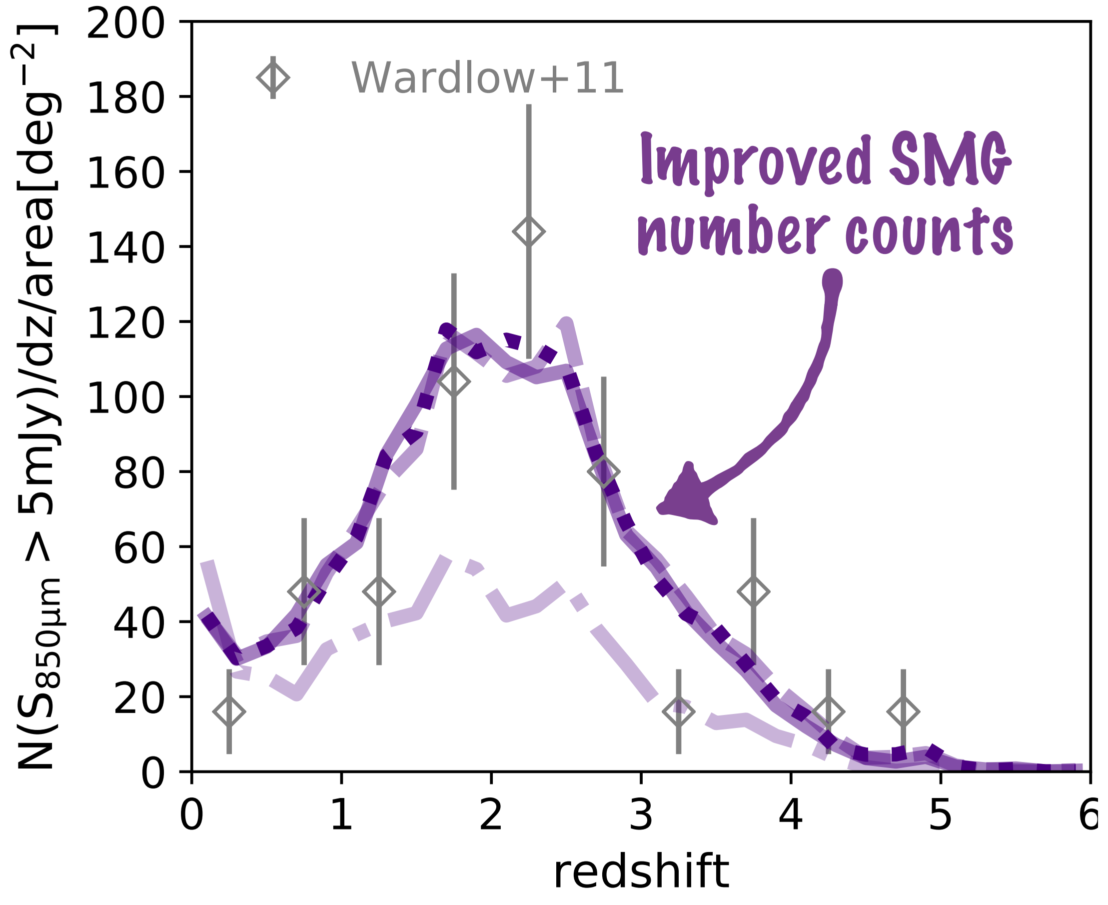


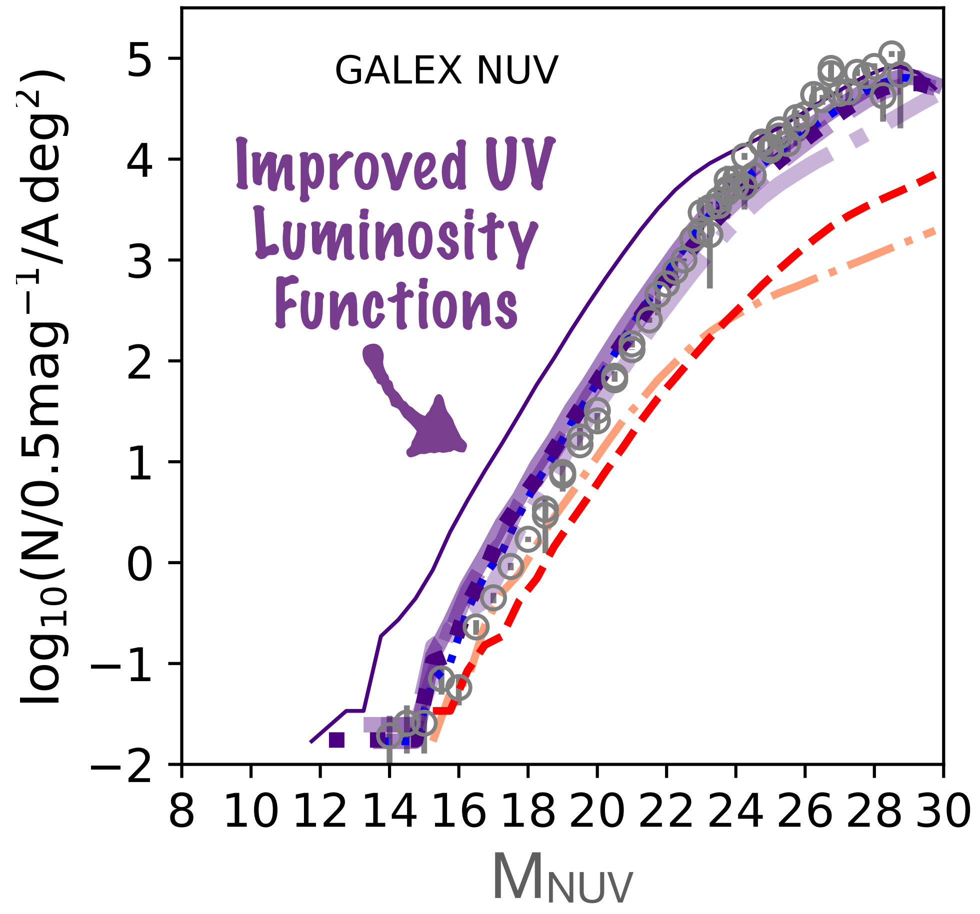
Can we harness the emergent morphologies of simulated galaxies to parametrise attenuation?

The **optical depth** and **wavelength dependence** of Charlot & Fall '00 ISM attenuation screen can be fit to ***dust surface density*** dependence in SKIRT+EAGLE

Explore different options for the ***birth cloud*** term, how does this affect overall attenuation?

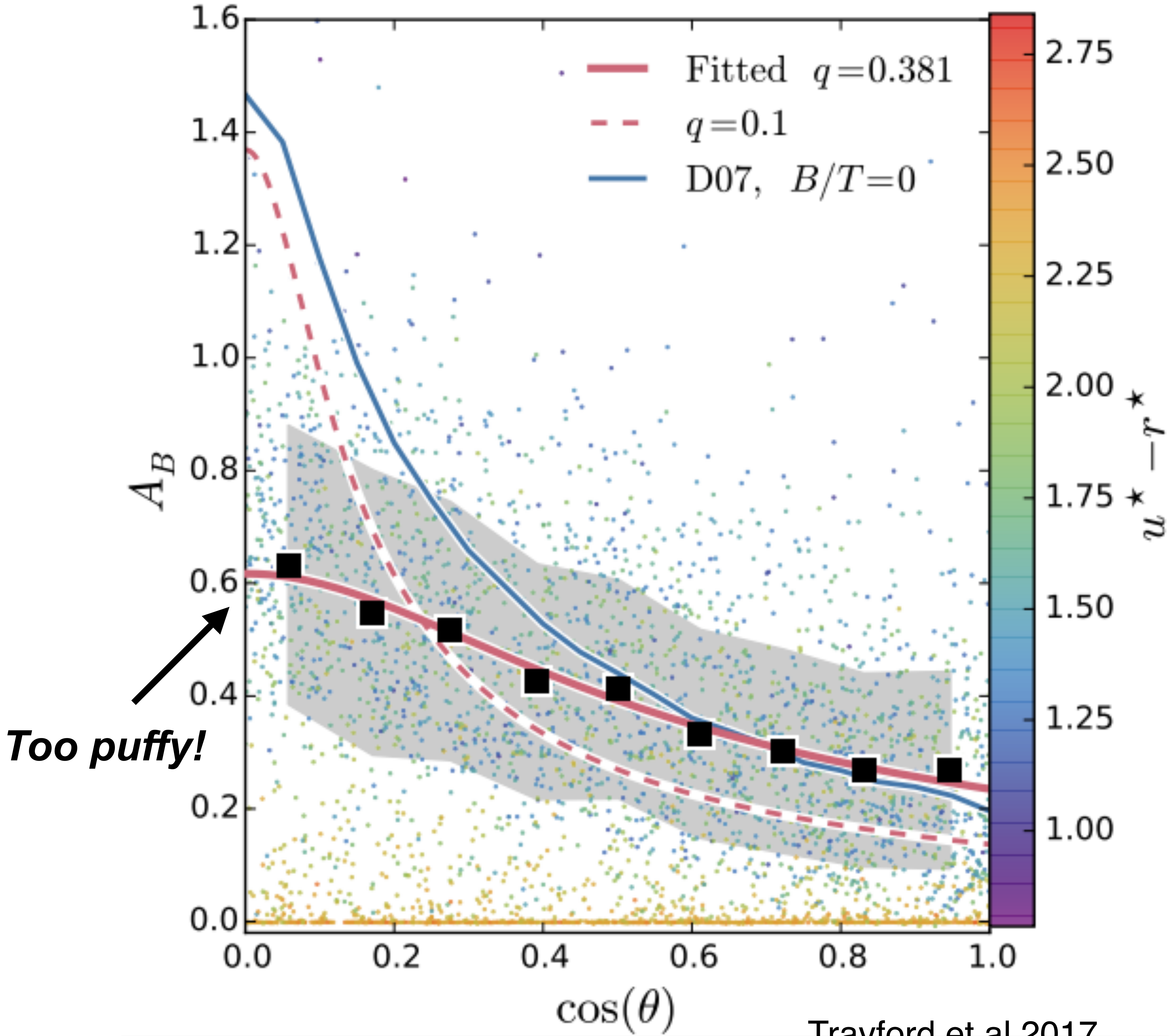
SHARK semi-analytic models (Lagos+19) demonstrated better UV and SMG agreement with SKIRT+EAGLE - like attenuation model





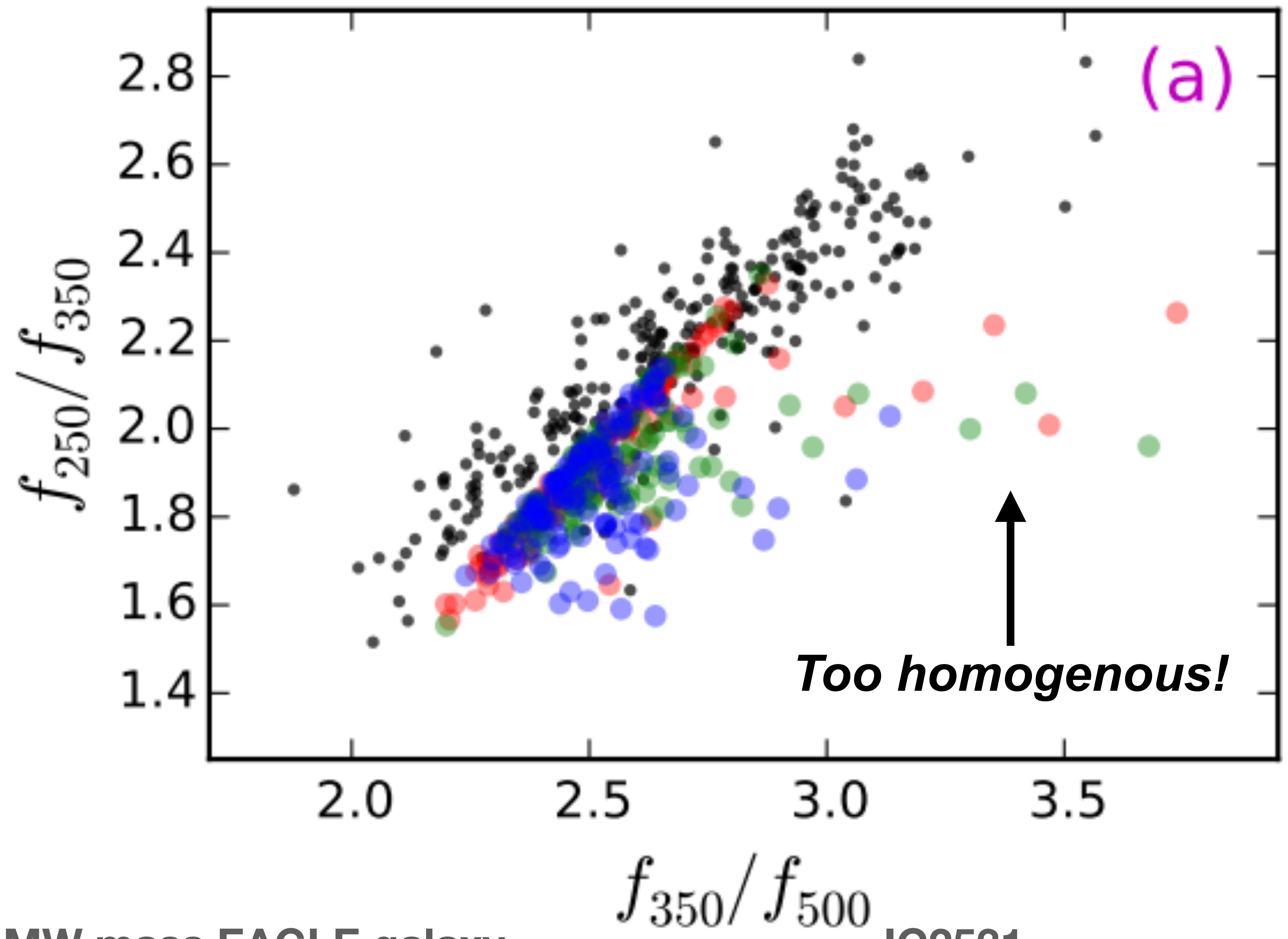
See also Narayanan+18

Resolution & Geometry Limitations

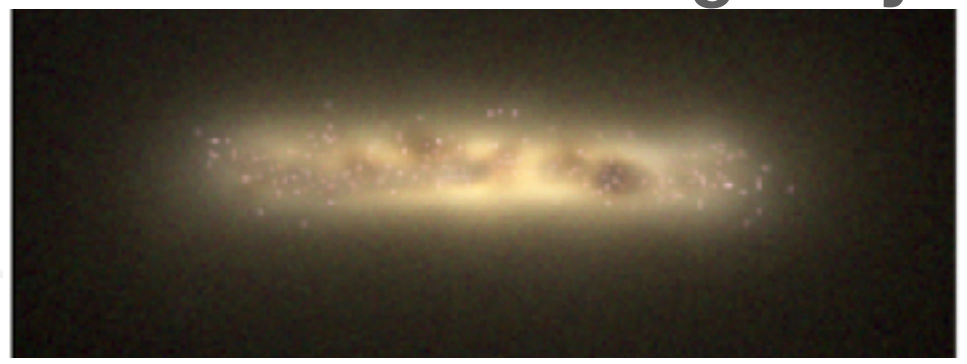


Trayford et al 2017

Camps et al 2016



MW mass EAGLE galaxy



IC2531

Dusty Galaxy formation in COLIBRE

skirt.ugent.be

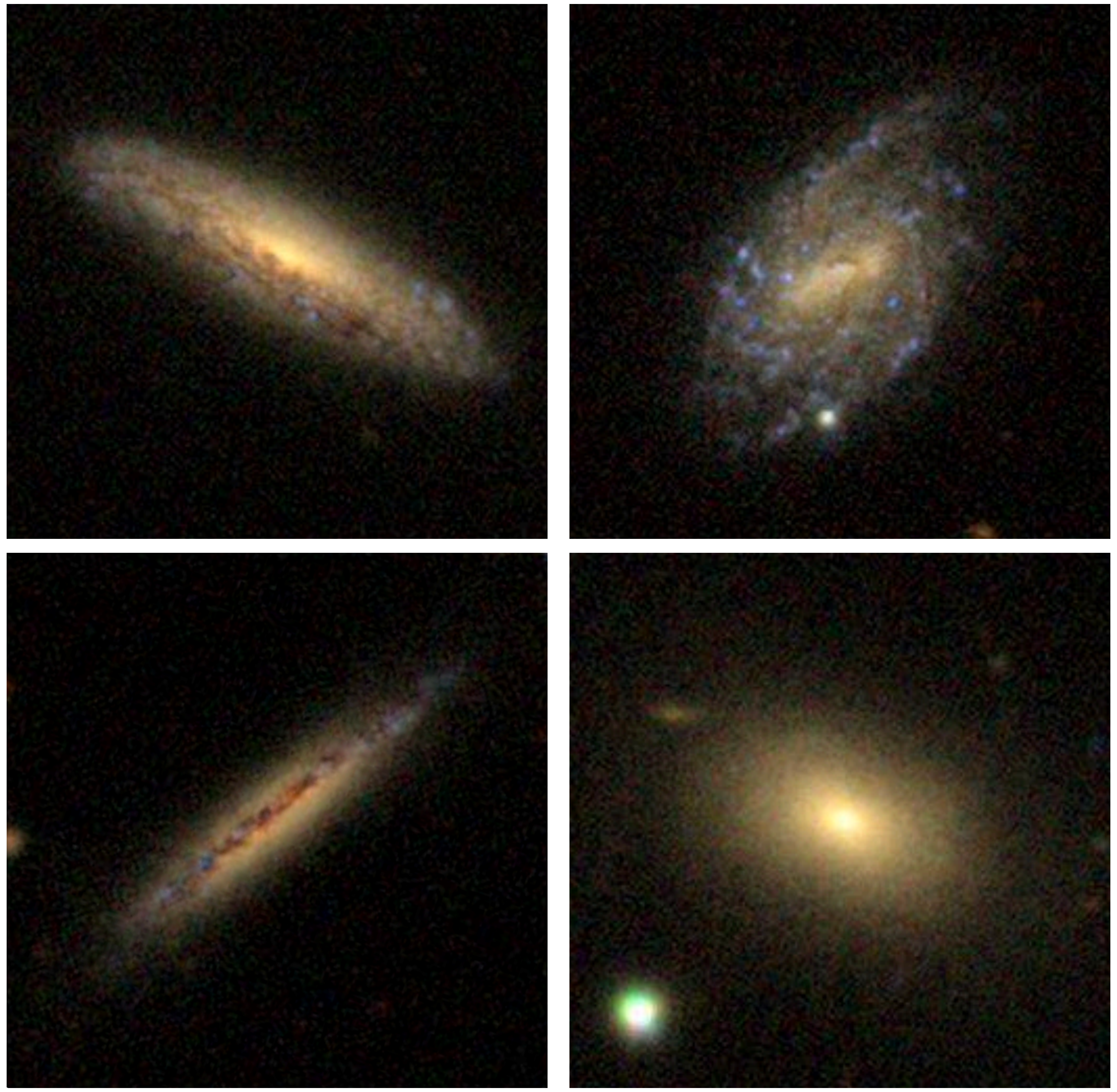
Many of these limitations require an enhanced, more detailed modelling of galaxy formation - enter the ***COLIBRE*** simulations.

COLIBRE should enable a clumpier, multiphase ISM with thinner discs

COLIBRE should simulate normal galaxies in a cosmological box at > EAGLE high-res resolution

COLIBRE should have the requisite physics to model at these resolutions (multi-phase gas, molecular processes, dust, etc)

Evgenii will talk more about COLIBRE on Friday!



SDSS-like images of some test galaxies

Grain Types

***Six* grain types are tracked…**

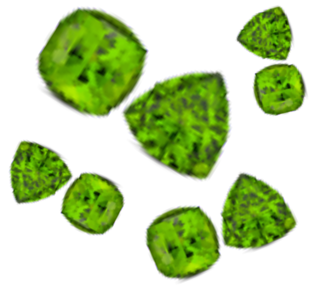
Carbonaceous grains → Graphite: C

~~Other grains~~
~~SiC, FeO, etc…~~

...3x Chemical species

Silicate grains → Olivine Grains → Forsterite: Fe_2SiO_4

Fayalite: Mg_2SiO_4



Pyroxene Grains → Enstatite: $Mg_2Si_2O_6$

Ferrosilite: $Fe_2Si_2O_6$

…& 2x Size bins

We use a two-size model, comprising large (0.1 micron) and small (0.01 micron) grains

Allow Mg and Fe species independence, less constraining on depletion patterns

Grain Evolution & The Dust Lifecycle

Seeding

- ***AGB winds*** *(e.g Dell'Agli+17)*
- ***SNII*** *(e.g Zhukovska+08)*

Growth

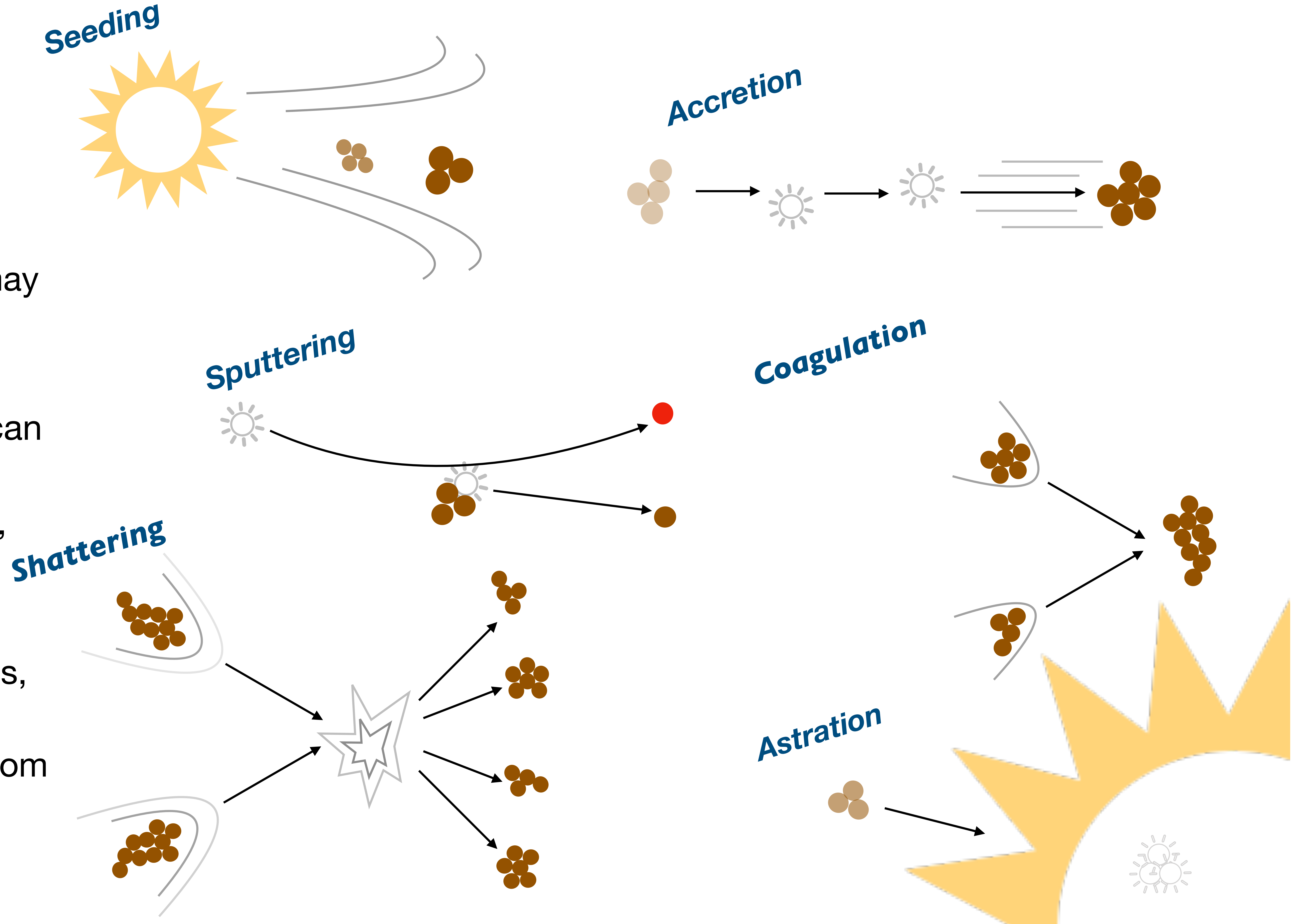
- ***Accretion***: In dense gas clouds, grains may grow by picking up material

Size Transfer

- ***Coagulation*** slow moving dust grains can stick together.
- ***Shattering*** faster moving grains collide, breaking into multiple smaller grains

Destruction

- ***Thermal sputtering:*** at high temperatures, gas-dust collisions erode dust grains
- ***Supernovae shocks:*** energetic shocks from supernovae may vaporise dust
- ***Astration:*** dust destroyed in stars



“Activating” Dust

With a model for the grain lifecycle, we can link the dust to the gas physics using the cooling module CHIMES *(Richings+14a,b, Ploeckinger & Schaye 2020)*

- **Depletion:** The deposition of gas-phase metals into dust modulates the level of metal-line cooling
- **Molecule Formation**: The molecular formation rates are affected by the availability of dust *surfaces*, and dust shielding
- **Cooling & Heating:** there are heating (e.g. photoelectric heating) and cooling (e.g. radiative cooling), again largely depending on dust surfaces

The ***size distribution*** of grains, with smaller grains providing higher rates.
Use a ***clumping factor*** to account for unresolved dense clouds

Summary

1. Dust weighs heavy in our understanding of galaxies Modulating both the observable radiation emerging from galaxies, and key ISM processes

2. Attenuation arises from grain properties & star-dust geometries the details of attenuation (and thus thermal re-emission) can be crucial for decoding observables, but is naturally very complex to inverse model accurately

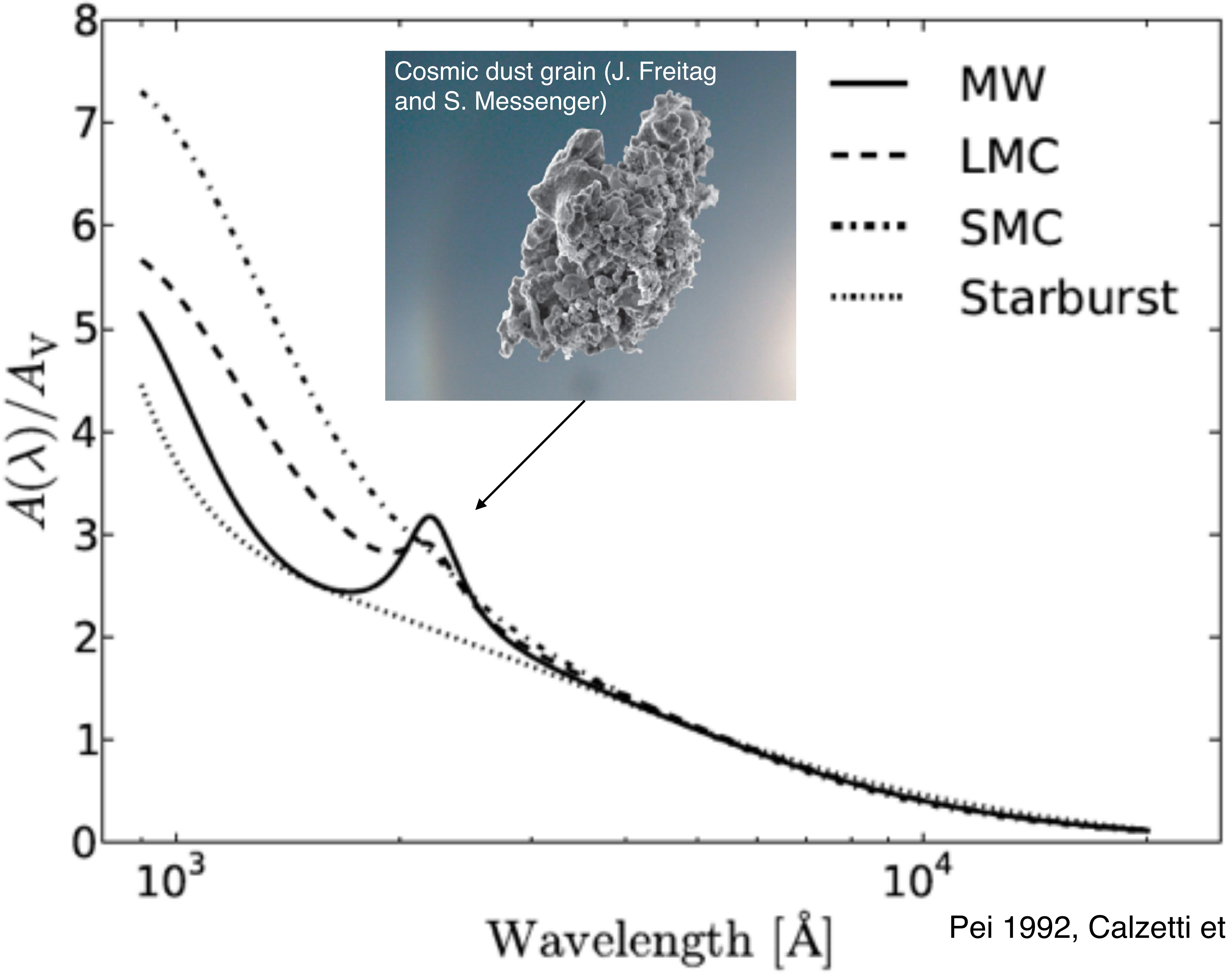
3. Multiphase, dust-inclusive simulations can be harnessed with a forward modelling approach particularly through the application of radiative transfer models, we can understand better the translation between observables and physical properties

Backup Slides

How Does Dust Process Light in Galaxies?

Extinction and ***Attenuation*** represent different things

Dust Extinction is dictated by the ***optical properties of grains themselves*** *(intrinsic scattering and absorption cross-sections)*



Pei 1992, Calzetti et al. 2000

How Does Dust Process Light in Galaxies?

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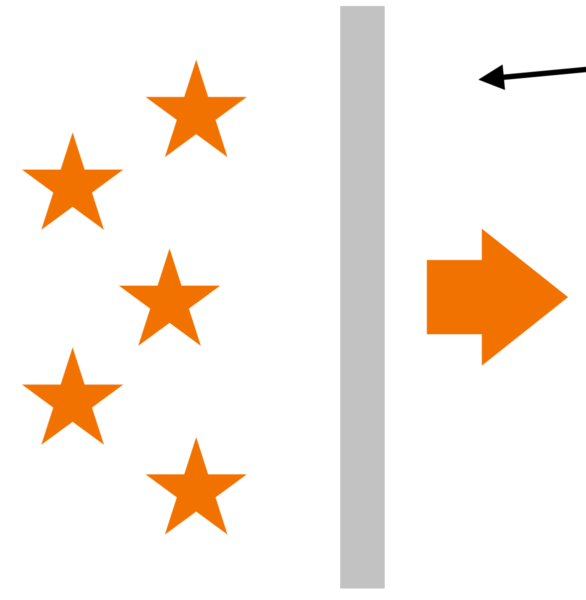
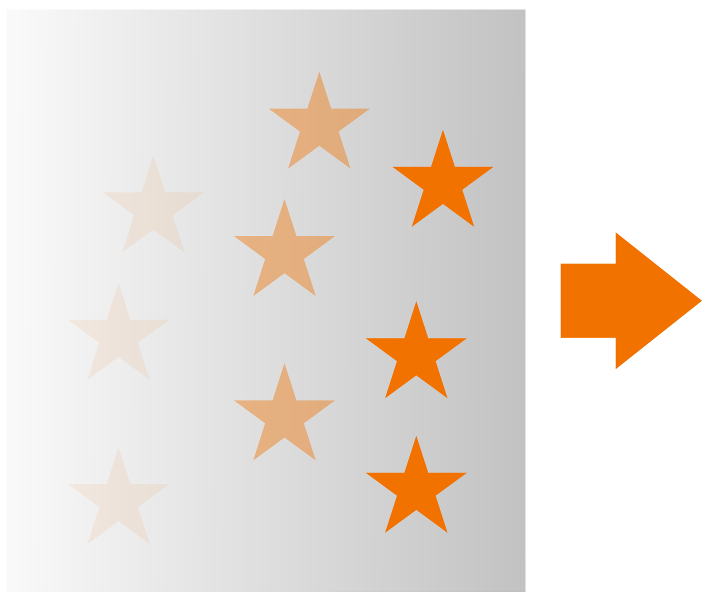


Dust Emission then depends on this Attenuation and the nature of dust grains



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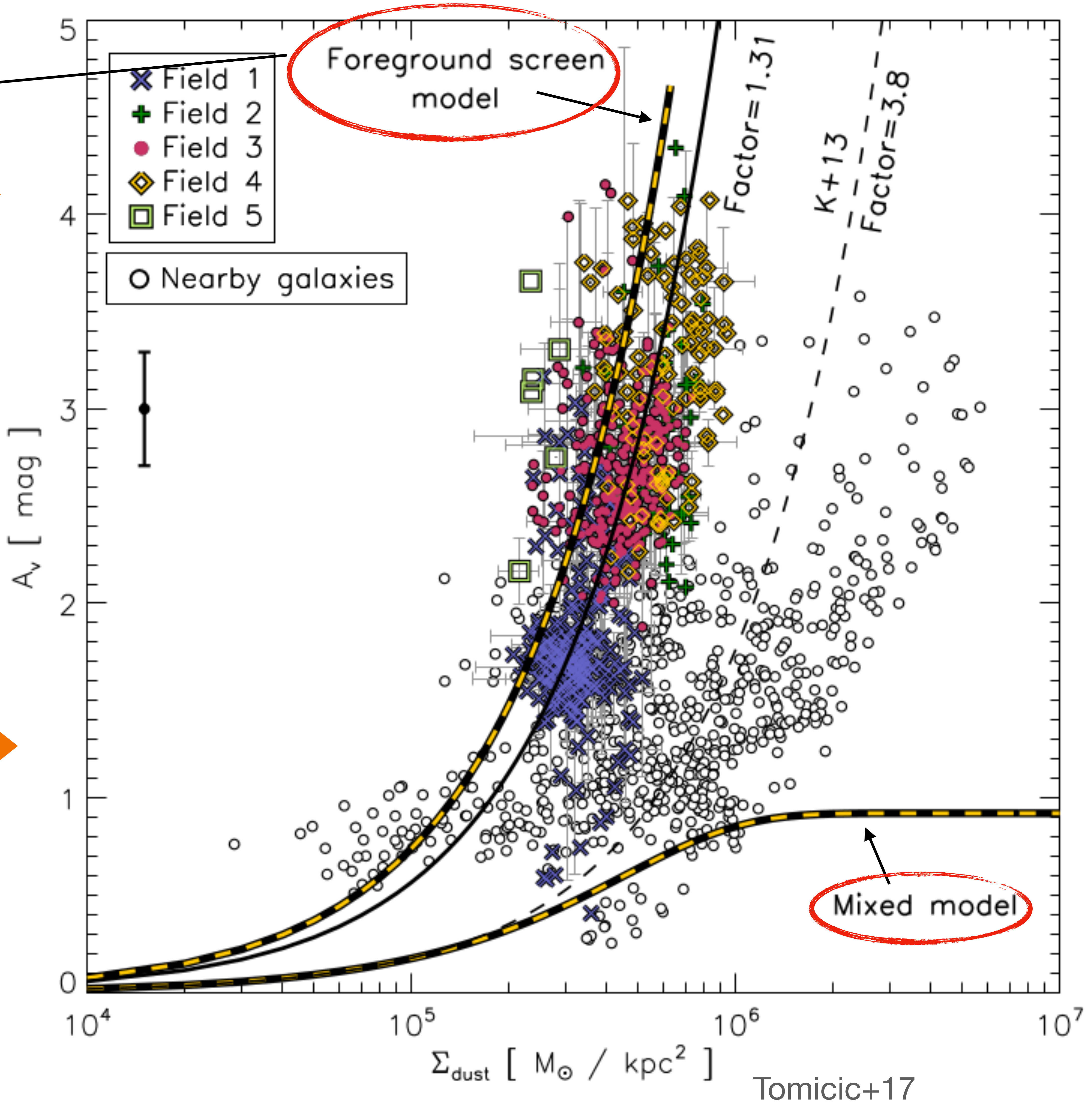
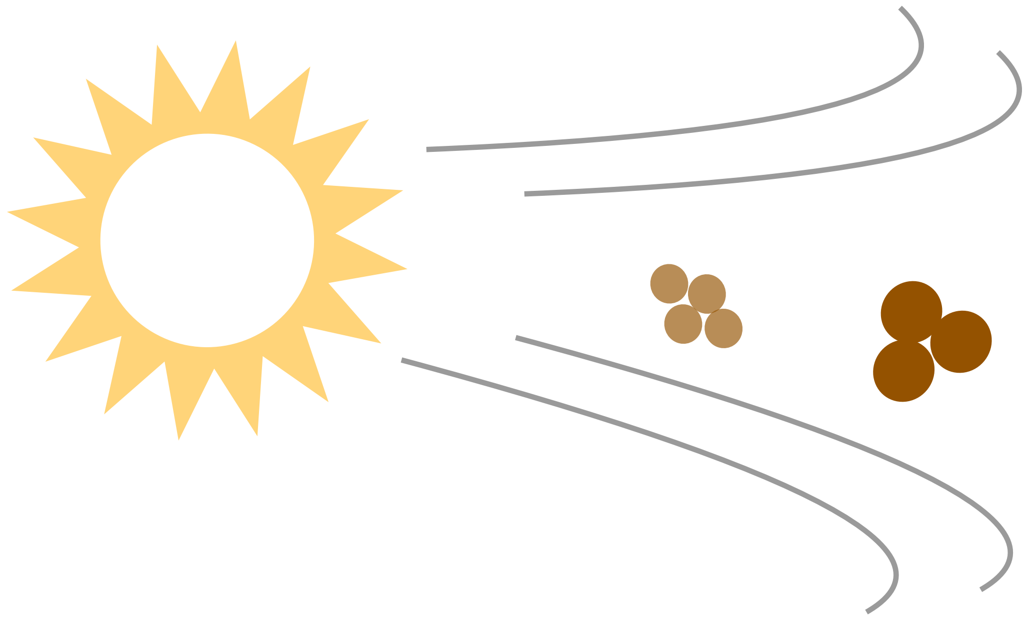


Tomicic+17

Grain Seeding

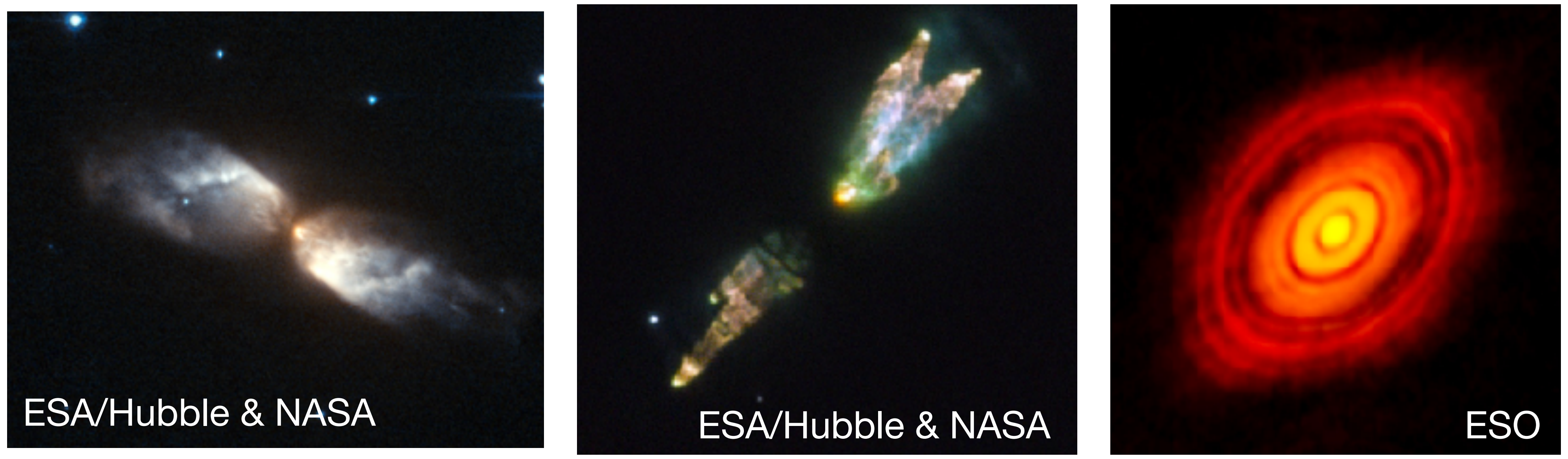


Grains thought to condense out of stellar ejecta

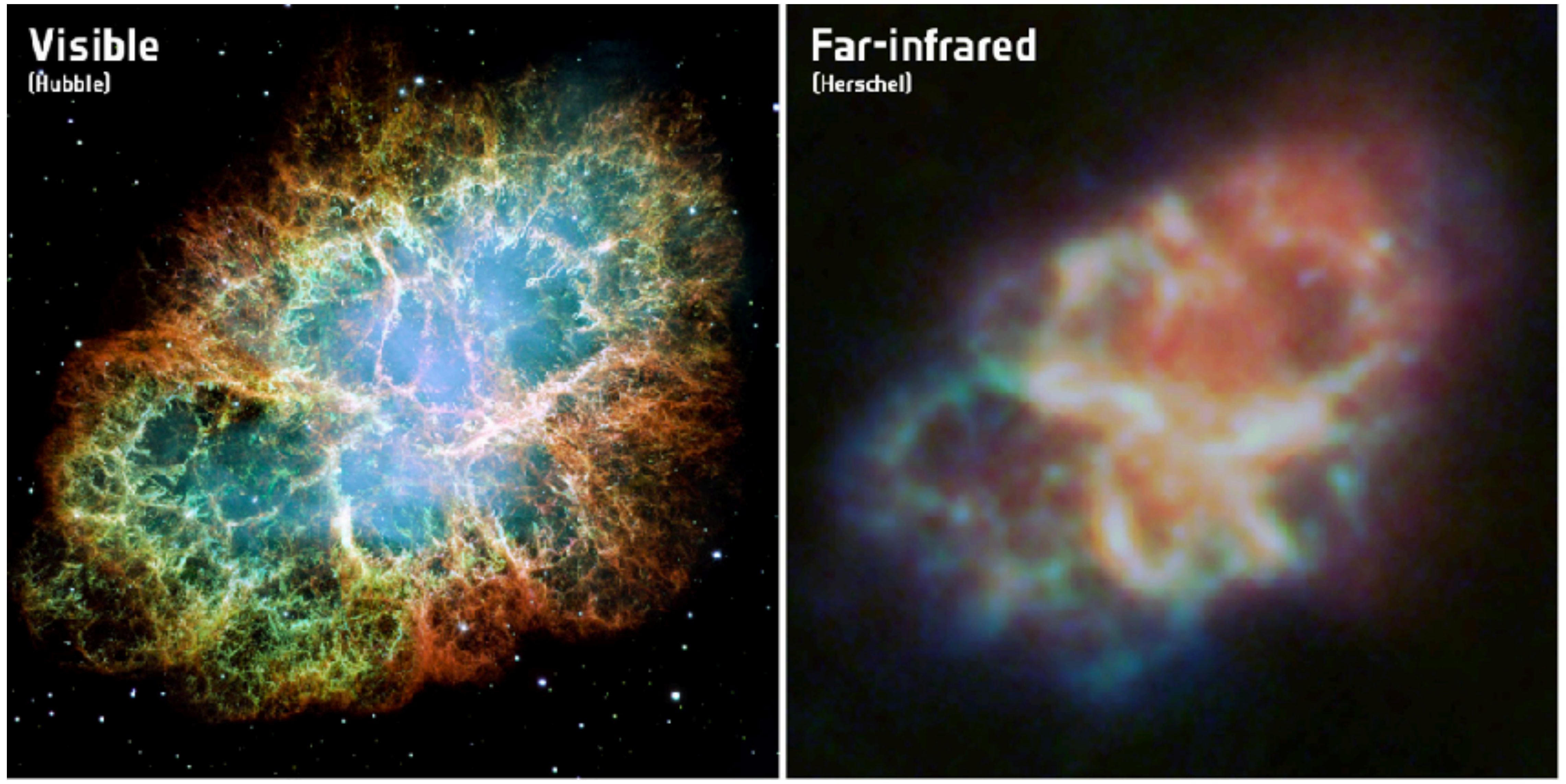
- ***AGB winds*** *(e.g Dell'Agli+17)*
- ***SNa ejecta***
  - SNII (e.g Zhukovska+08)
  - ~~SNIa~~ *(e.g Nozawa+11)*
- ***AGN?*** *(e.g Sarangi+19)*

Seeded grains are dominated by large sizes (~0.1 micron, e.g. Groenewegen+97, Yasuda+12, Asano+13b, Nozawa+07)

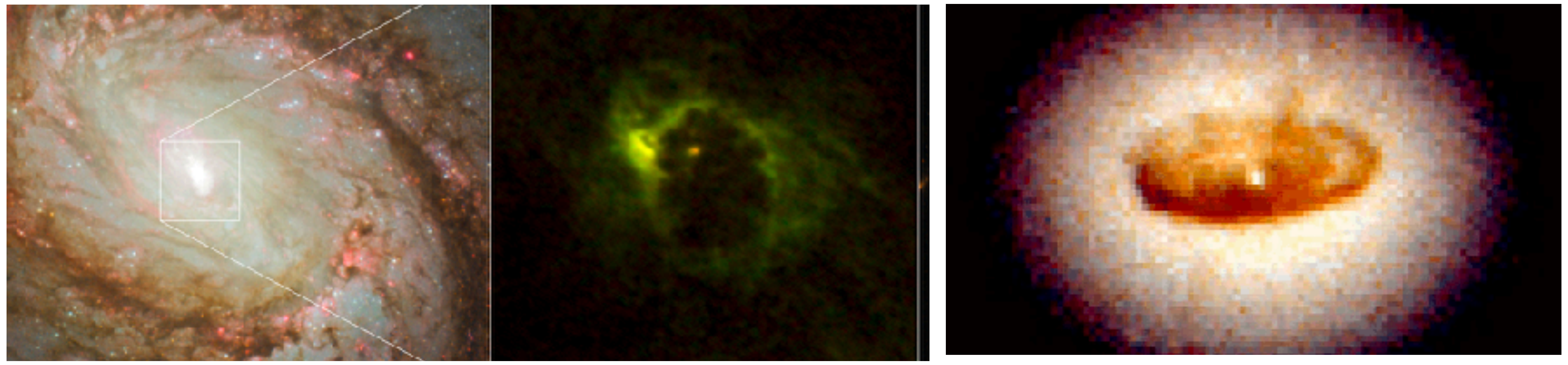
AGB / stellar yields



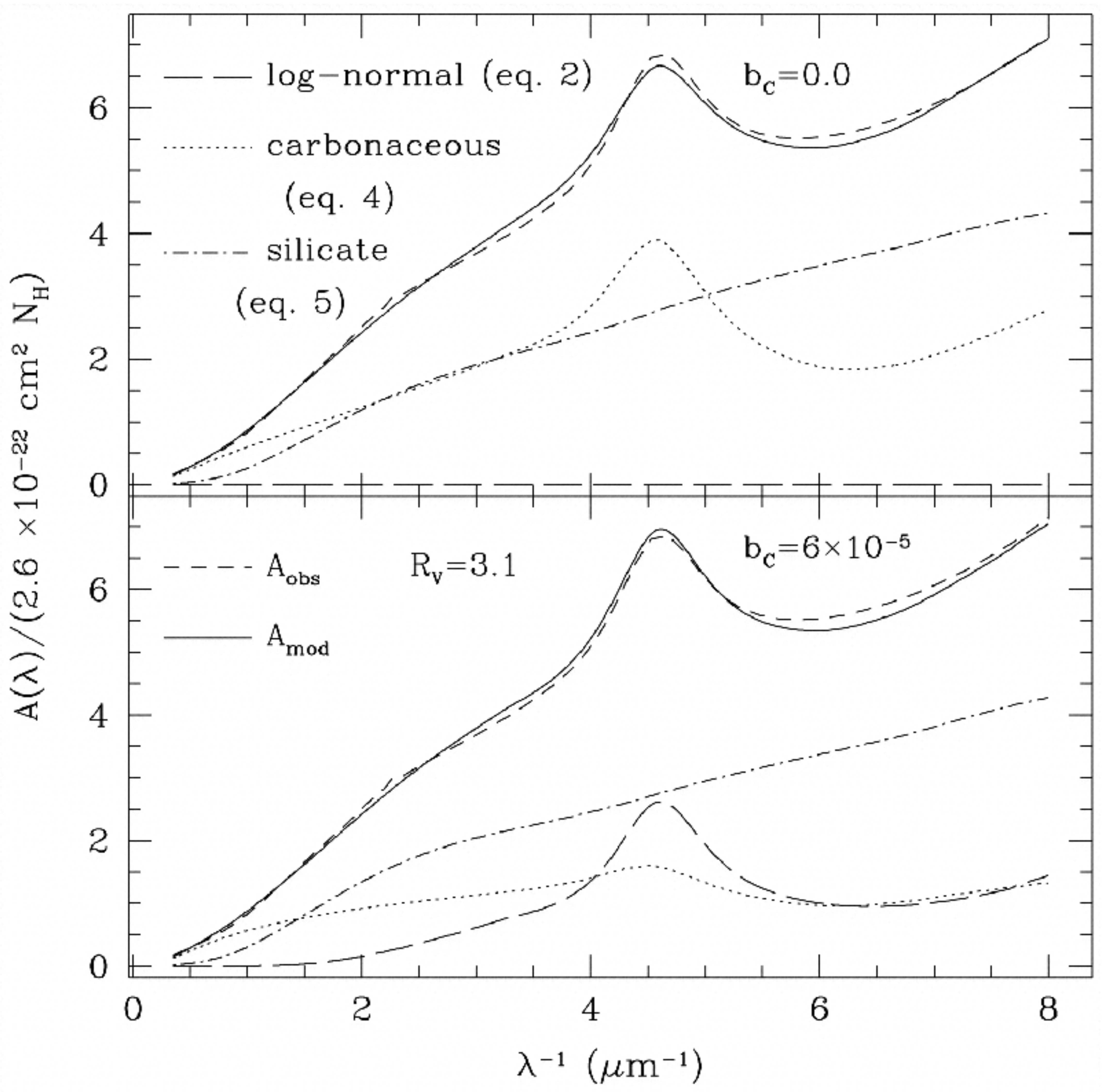
Supernova yields



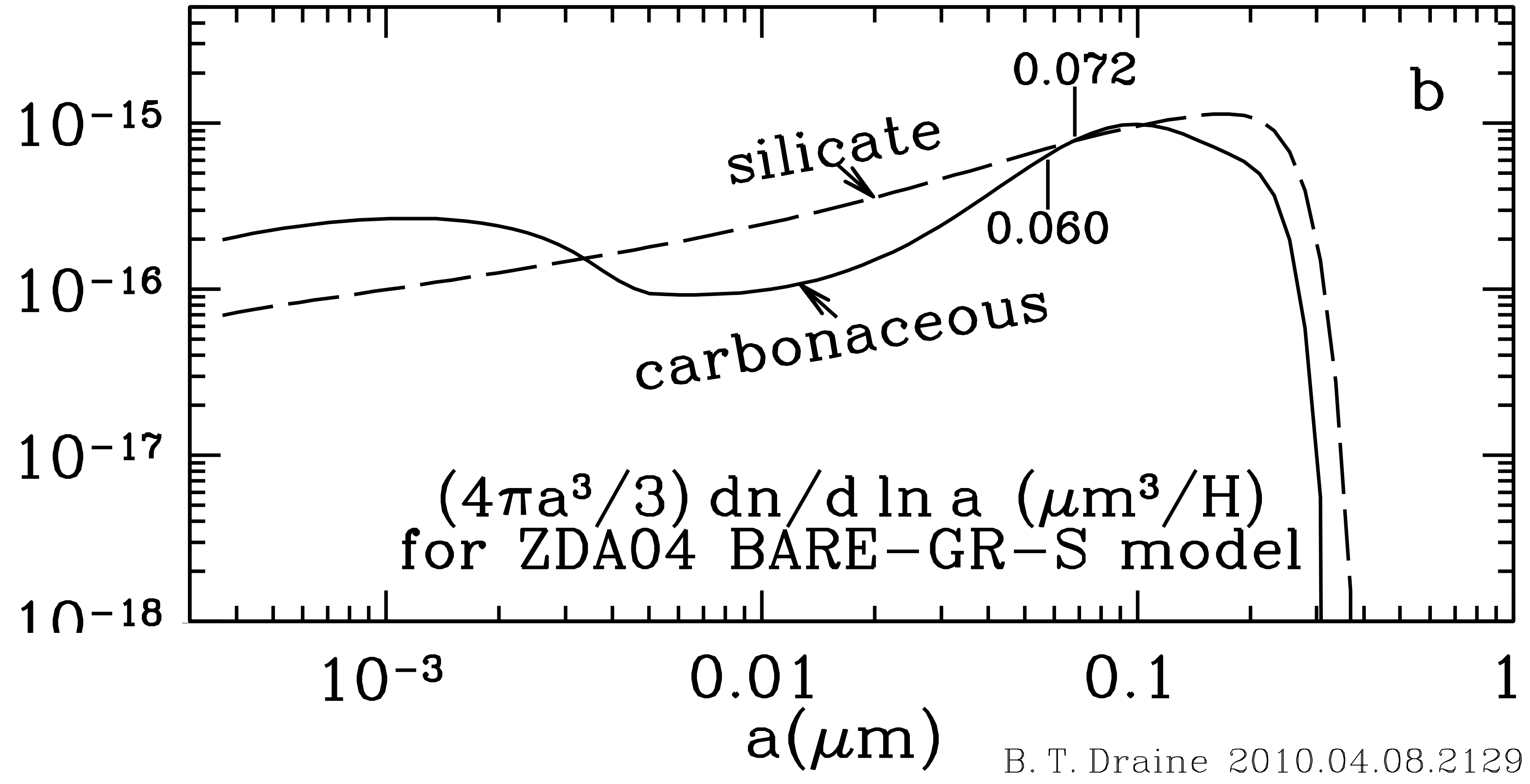
AGN?



Dust Sizes



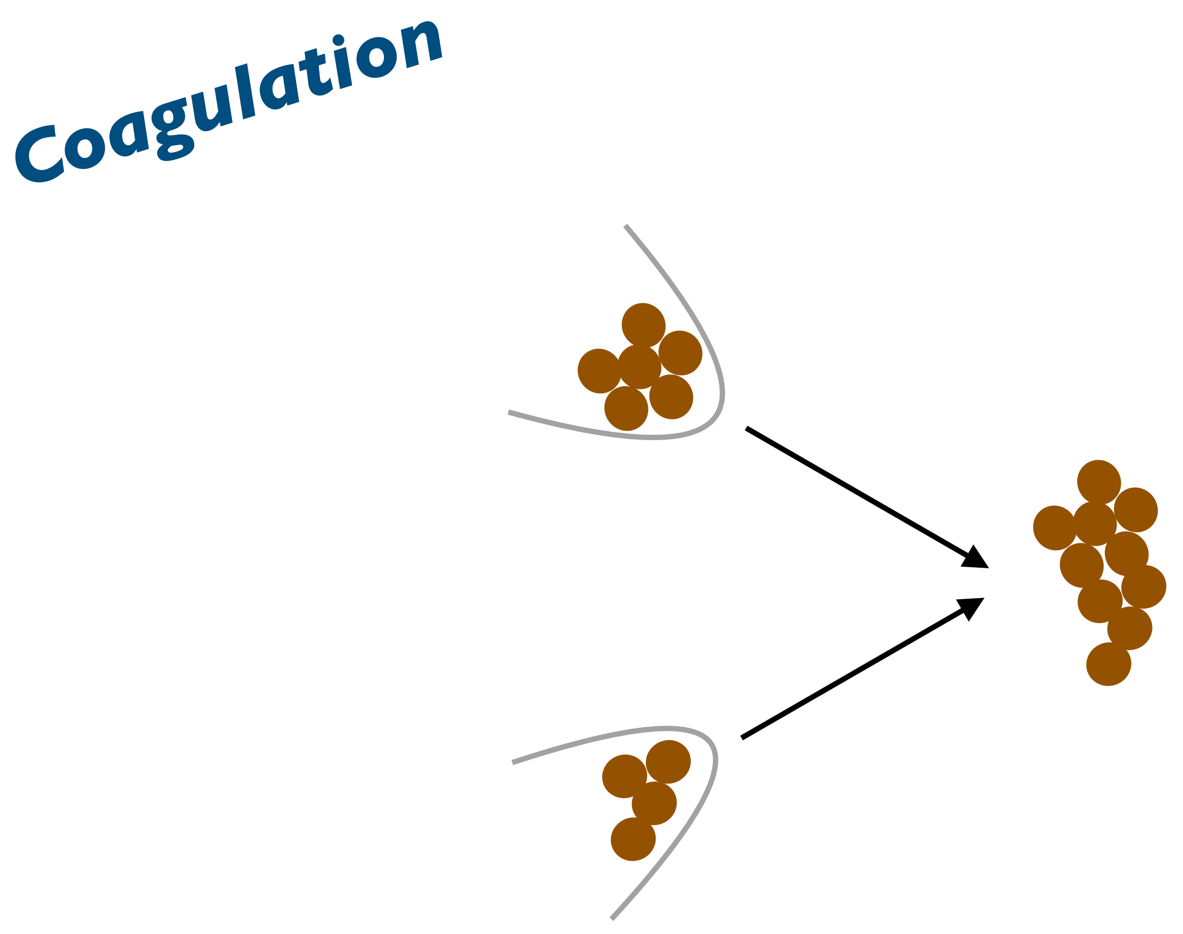
Extinction curves are a powerful constraint on the size distribution locally, which in turn encodes dust evolution



We experiment with single grain-size (0.1 micron)

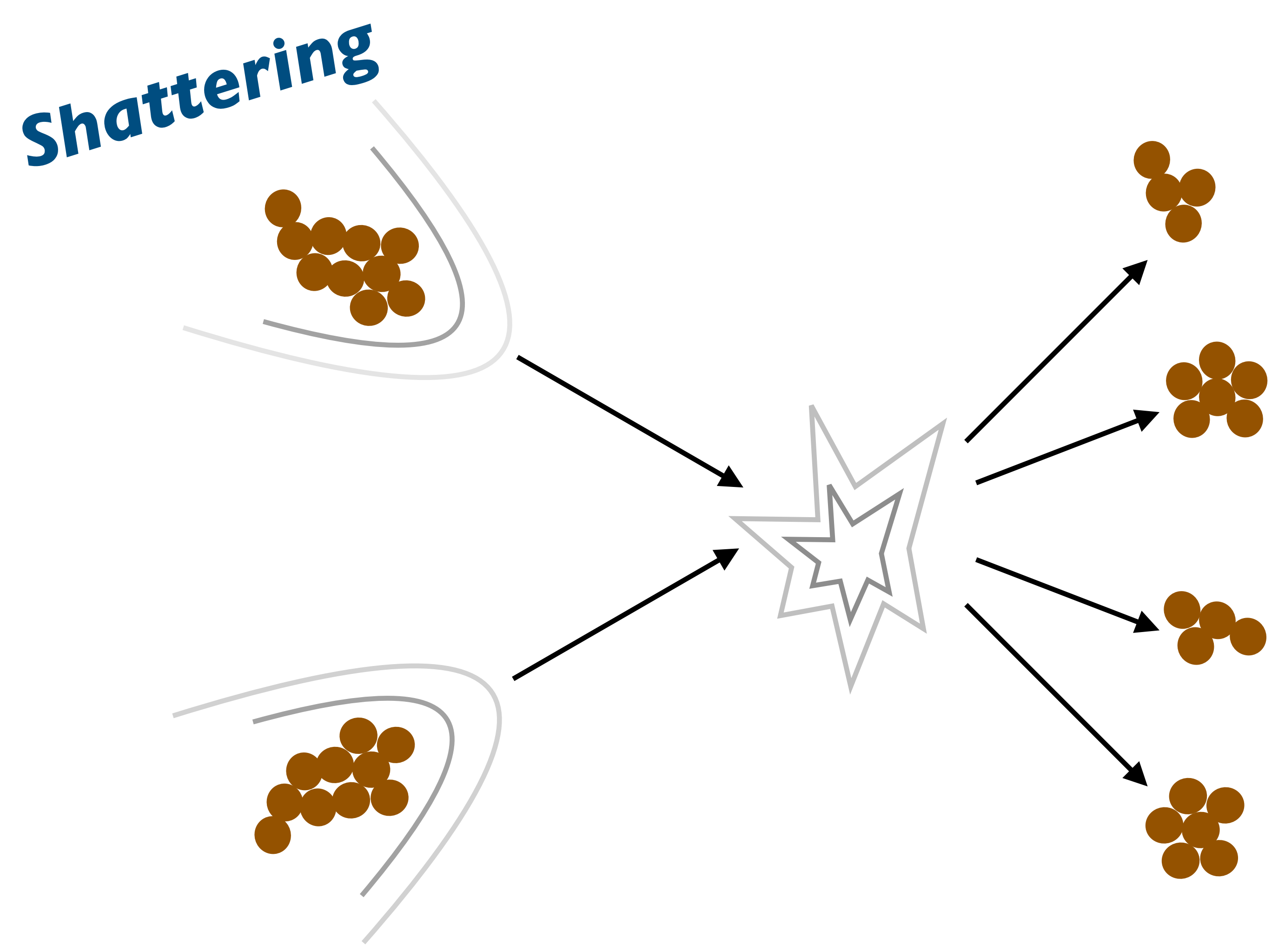
And two-size (0.1 micron and 0.01 micron)

Size Transfer



Grain agglomeration

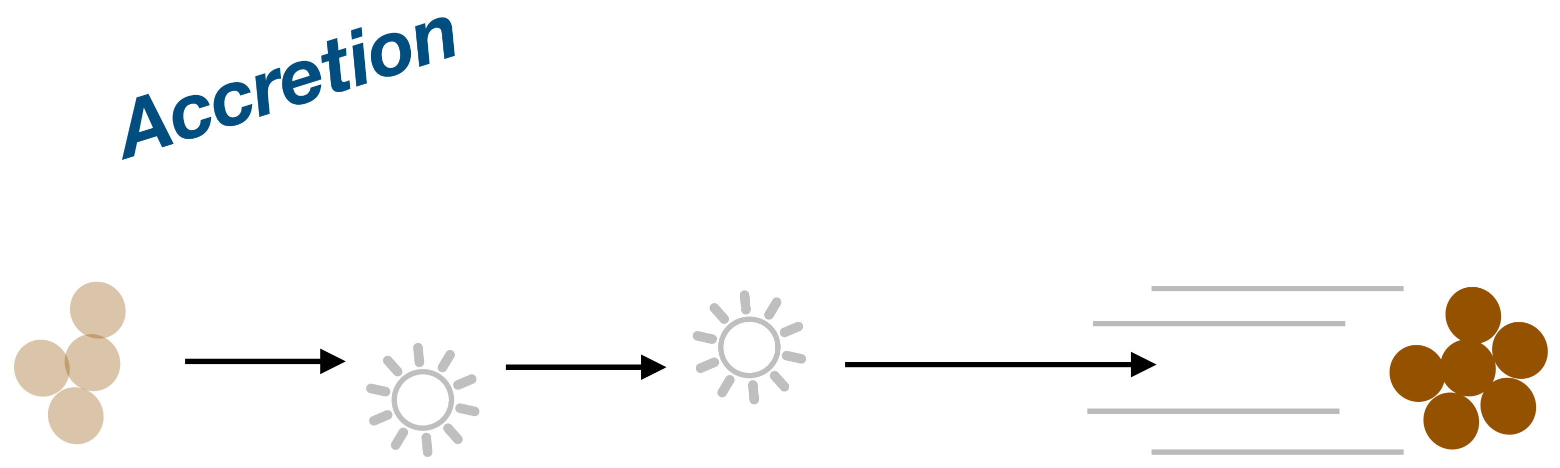
- ***Coagulation*** is when slow moving dust grains stick together. *(e.g Aoyama+17, Granato+21)*



Grain shrinkage

- ***Shattering*** is when faster moving grains collide, breaking into multiple smaller grains *(e.g Aoyama+17, Granato+21)*

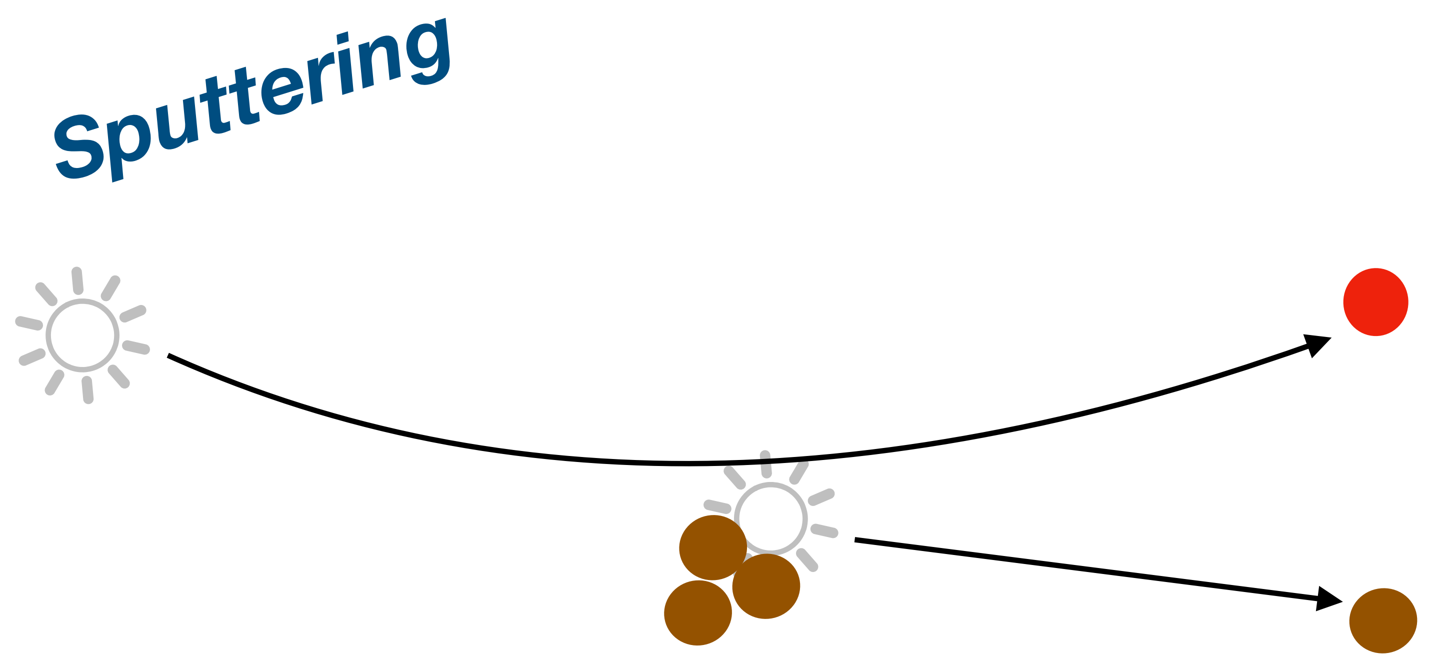
Grain Evolution



- **Sputtering** *(e.g. Tsai+95)*

$$\tau_{sput} \propto a\, n_H^{-1} \left[(T_{sput}/T)^{2.5} + 1\right]$$

a : grain radius
n_H : number density of H
T : local gas temperature



- **SNe destruction** *(e.g. Yamasawa+11)*

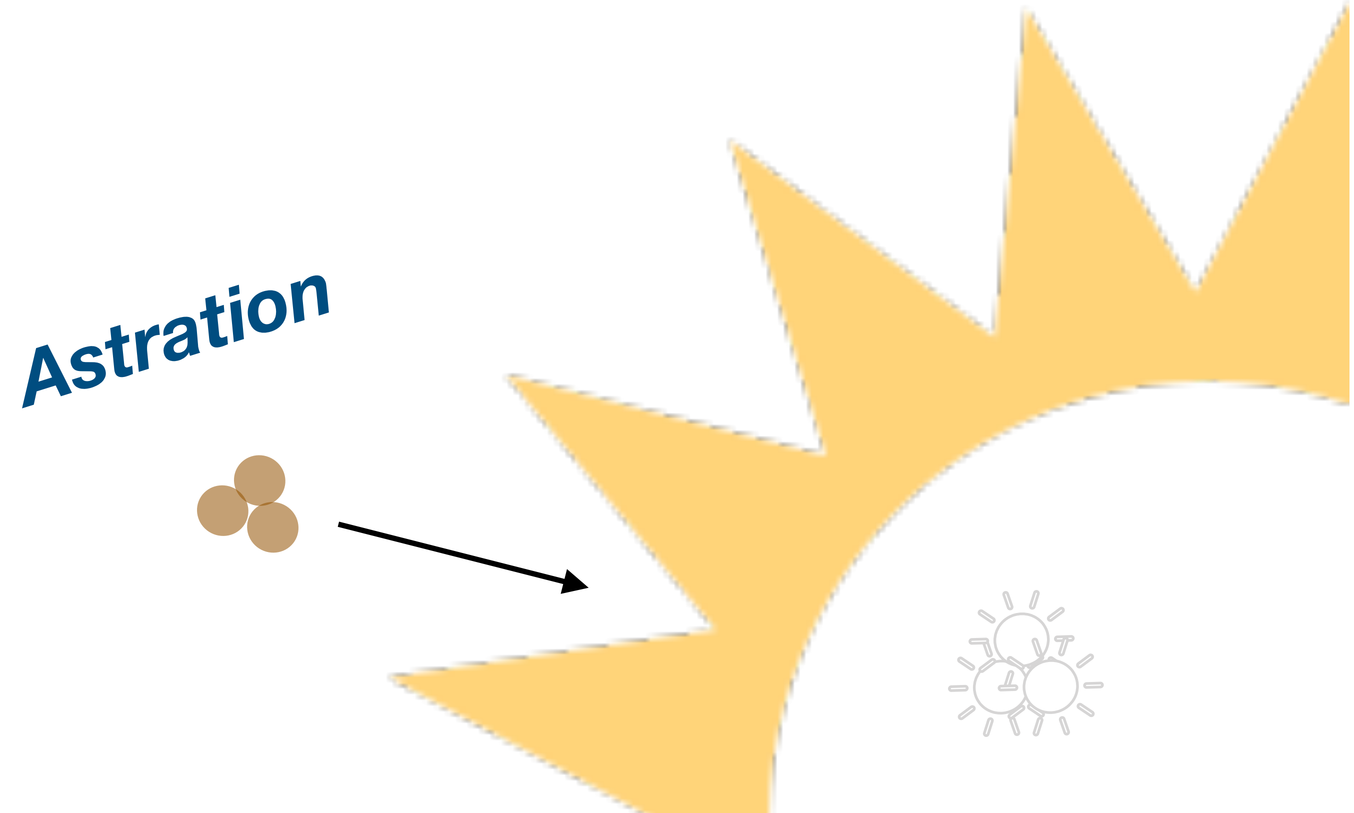
$$\tau_{SN} \propto \gamma^{*\,-1}\, m_g / m_{swept}$$

γ^* : specific SNe rate
m_g : gas particle mass
m_{swept} : mass swept by SN shock
(via n_H, Z; Yamasawa+11)

- **Accretion** *(e.g. Hirashita+13)*

$$\tau_{SN} \propto a\; n_H^{-1}\; T^{-0.5}\; X$$

X : abundance of ‘key’ element



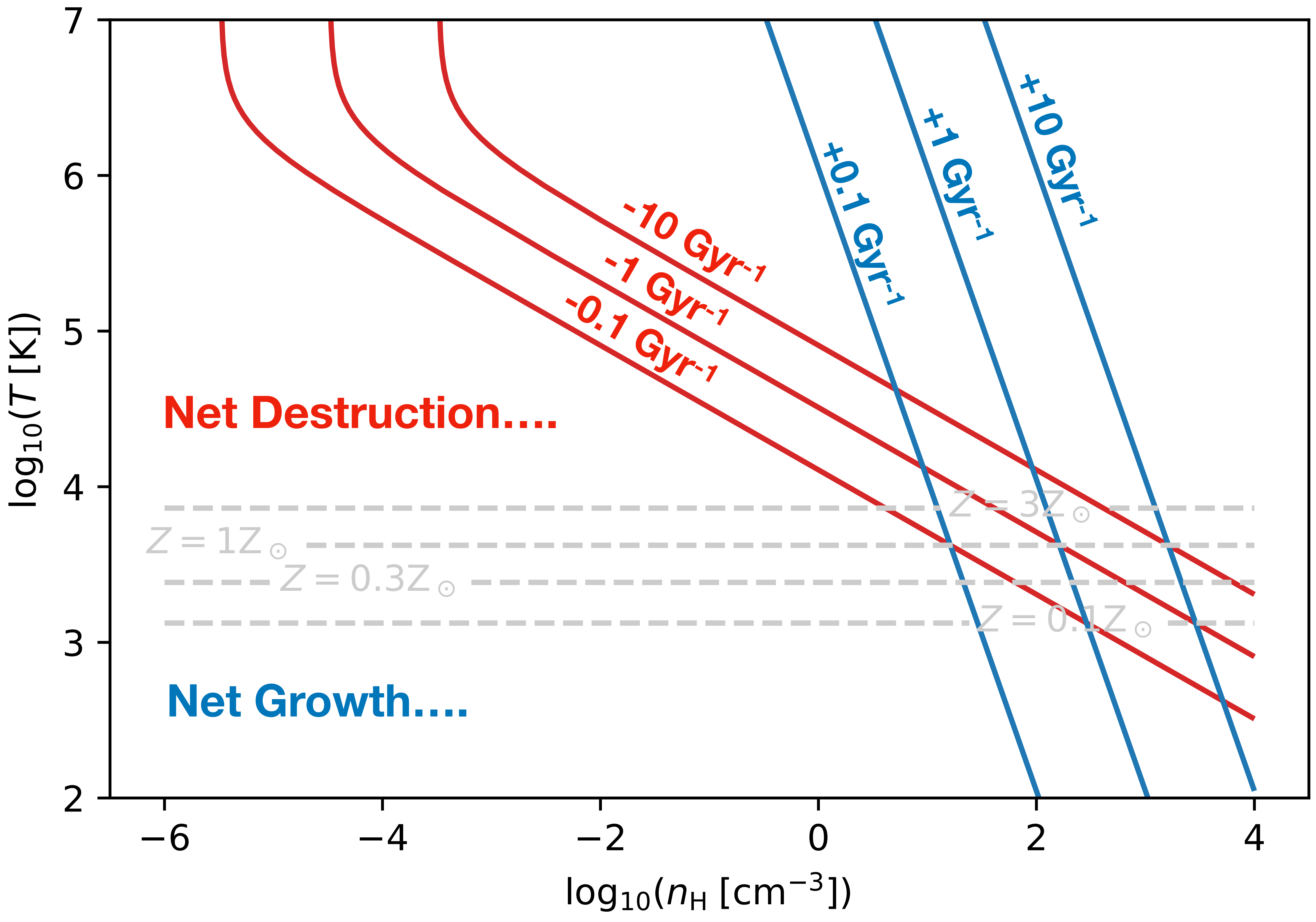
Grain Evolution

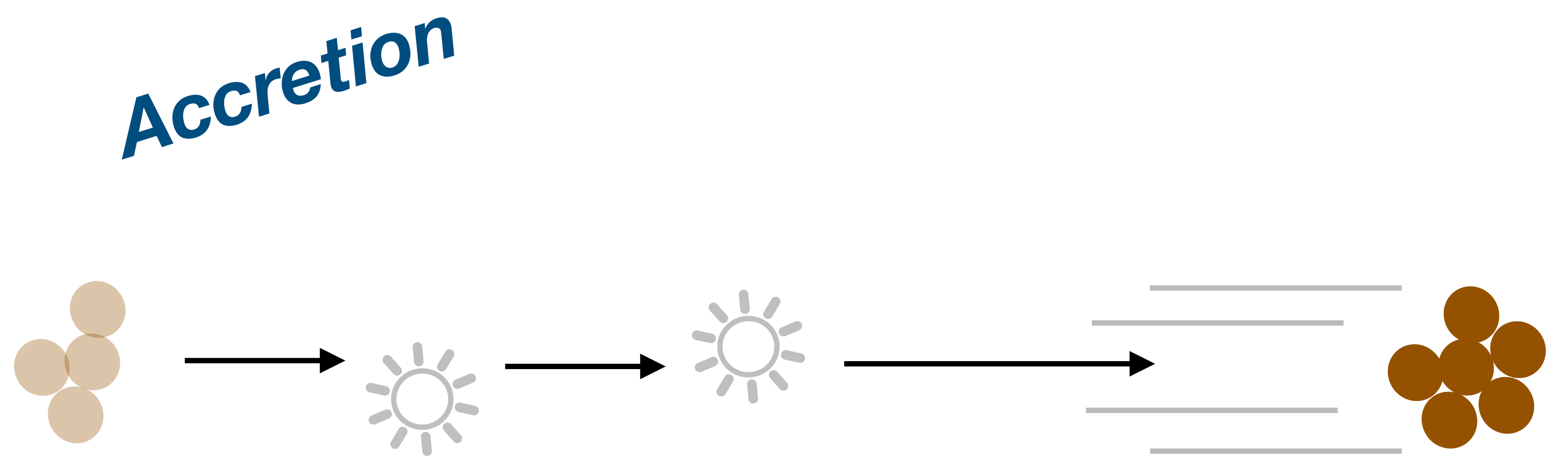
Seeding Mechanisms:
- AGB
- SNII

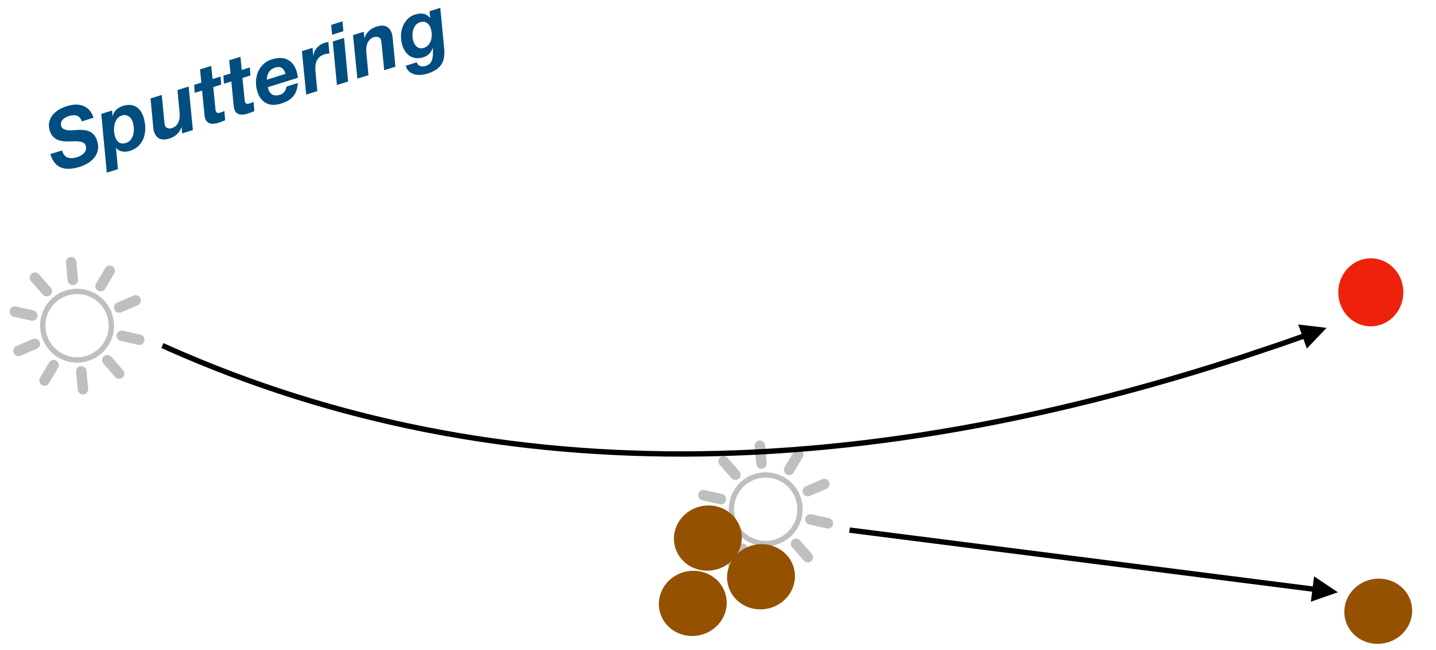
Destruction Mechanisms:
- Thermal Sputtering
- SN shocks
- Astration

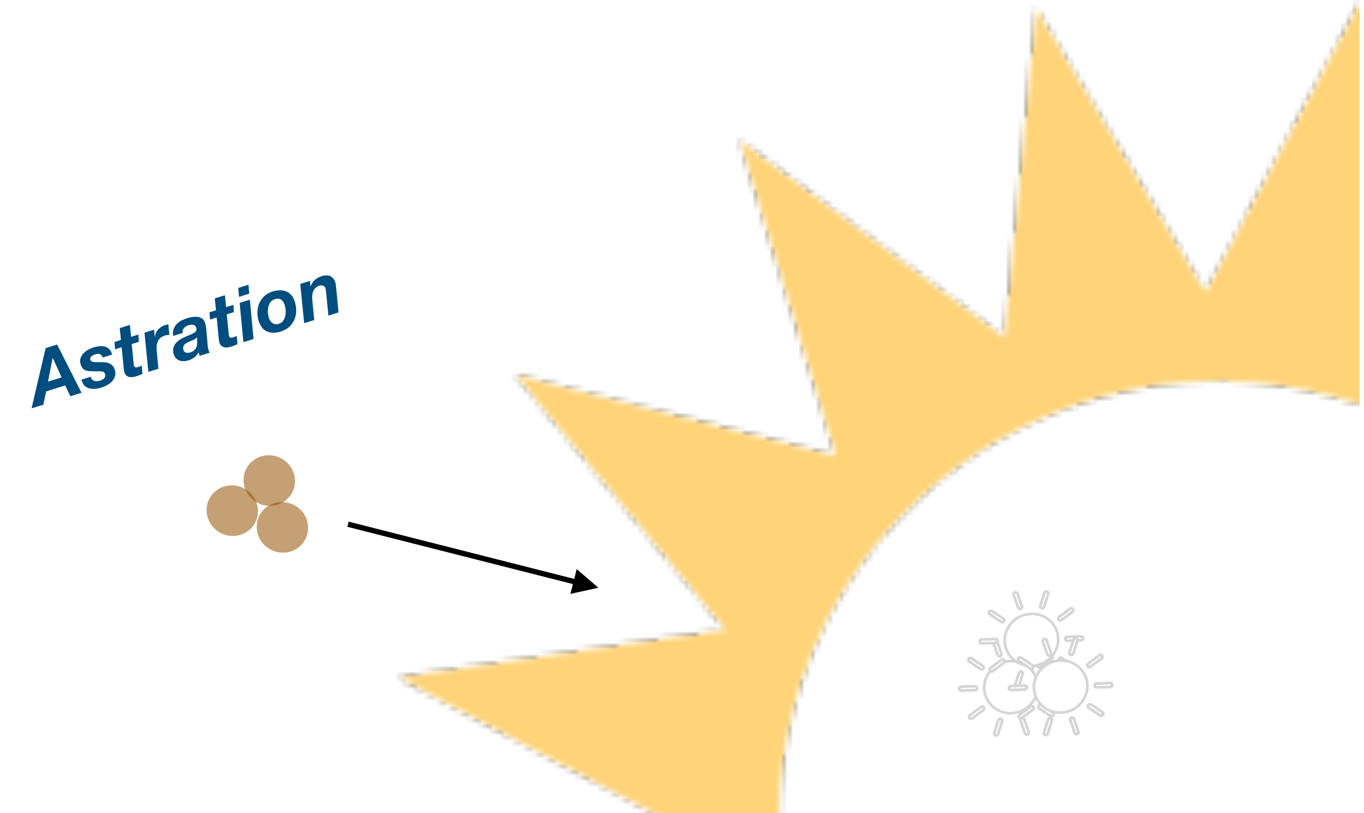
Growth Mechanisms:
- Accretion

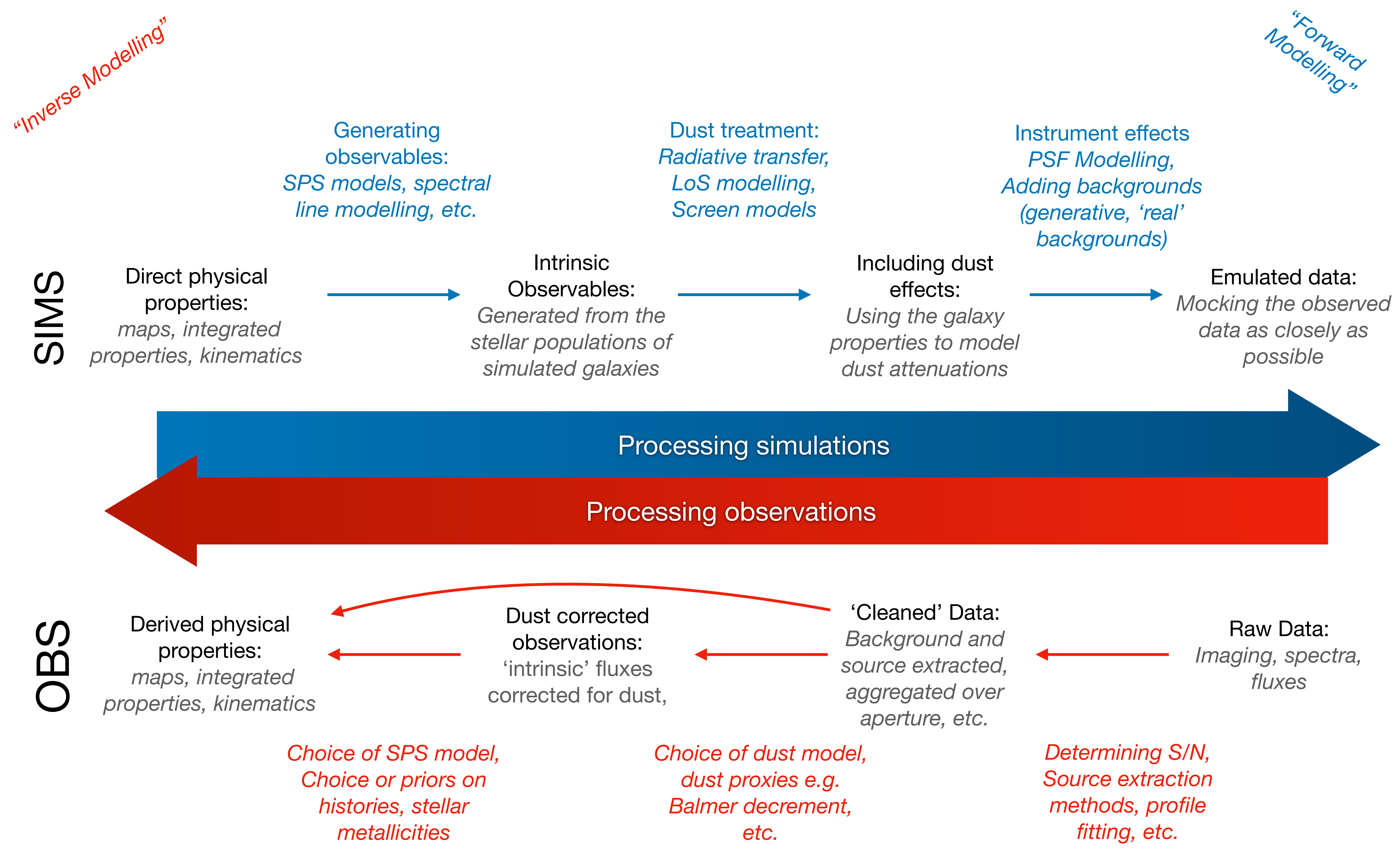
For large (0.1 micron) grains











"Inverse Modelling"
"Forward Modelling"
Generating observables:
SPS models, spectral line modelling, etc.
Dust treatment:
Radiative transfer, LoS modelling, Screen models
Instrument effects
PSF Modelling, Adding backgrounds (generative, 'real' backgrounds)
SIMS
Direct physical properties:
maps, integrated properties, kinematics
Intrinsic Observables:
Generated from the stellar populations of simulated galaxies
Including dust effects:
Using the galaxy properties to model dust attenuations
Emulated data:
Mocking the observed data as closely as possible
Processing simulations
Processing observations
OBS
Derived physical properties:
maps, integrated properties, kinematics
Dust corrected observations:
'intrinsic' fluxes corrected for dust,
'Cleaned' Data:
Background and source extracted, aggregated over aperture, etc.
Raw Data:
Imaging, spectra, fluxes
Choice of SPS model, Choice or priors on histories, stellar metallicities
Choice of dust model, dust proxies e.g. Balmer decrement, etc.
Determining S/N, Source extraction methods, profile fitting, etc.

A Two-Component Screen Model

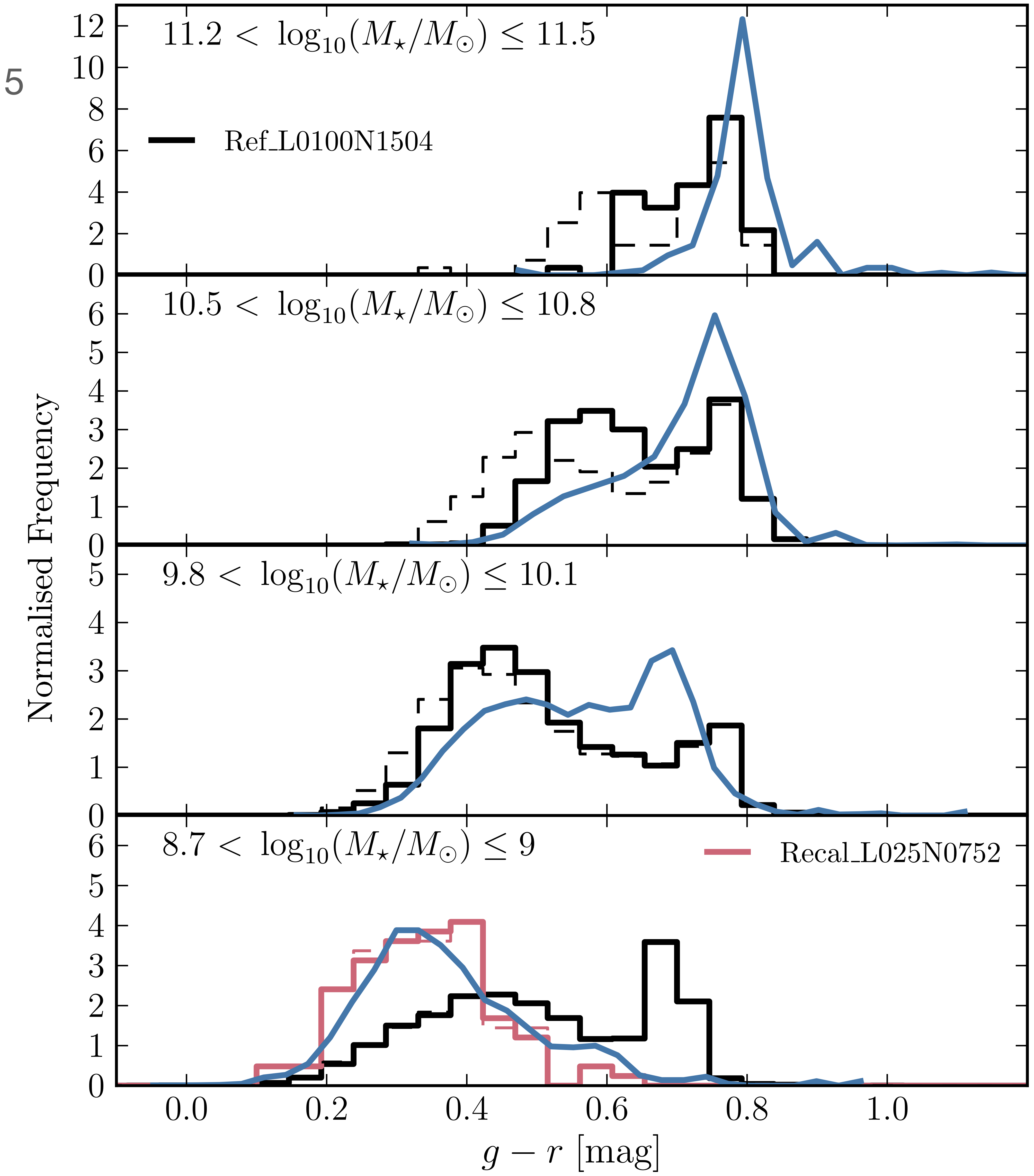
Trayford et al 2015

We assumed the two screen model of *Charlot & Fall 2000* for dust, assigning galactic ISM and Birth cloud optical depth

Scales with ISM metal mass and orientation for each galaxy

Constant

$$\tau(\lambda) = \begin{cases} \tau_{\mathrm{ISM}}\left(\frac{\lambda}{5500\mathrm{\AA}}\right)^{\eta_{\mathrm{ISM}}} & \text{for } t_{\mathrm{age}} > t_{\mathrm{disp}} \\ \tau_{\mathrm{ISM}}\left(\frac{\lambda}{5500\mathrm{\AA}}\right)^{\eta_{\mathrm{ISM}}} + \tau_{\mathrm{BC}}\left(\frac{\lambda}{5500\mathrm{\AA}}\right)^{\eta_{\mathrm{BC}}} & \text{for } t_{\mathrm{age}} \le t_{\mathrm{disp}} \end{cases}$$



See also Torrey et al 2015 (Illustris) for application of two-component screen to galaxy simulations

Forward Modelling - SKIRT

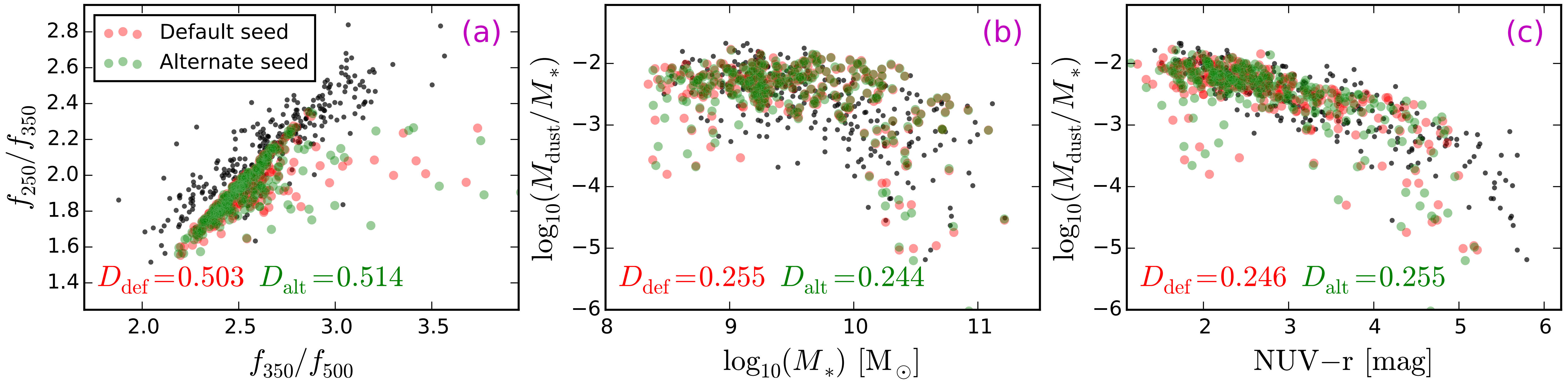
skirt.ugent.be

Radiative transfer provides the ***most representative*** way of forward modelling observables simulations.

- The ***SKIRT*** dust RT code was used to process ***EAGLE***, modelling the transfer of light through the **resolved ISM** (*Camps+16, Trayford+17*)
- MAPPINGS-III is used to represent **subgrid attenuation** calibrated to local IR (*Camps+16*)
- The ***resolved/sugbrid*** attenuation is similar to the ***ISM/birth-cloud*** formulation of Charlot & Fall 2000:

T_{max} : Hottest gas particles that contribute dust
f_{dust} : Fraction of metals locked-up in dust
f_{PDR} : Sphericallly-averaged cloud covering in MAPPINGS SEDs

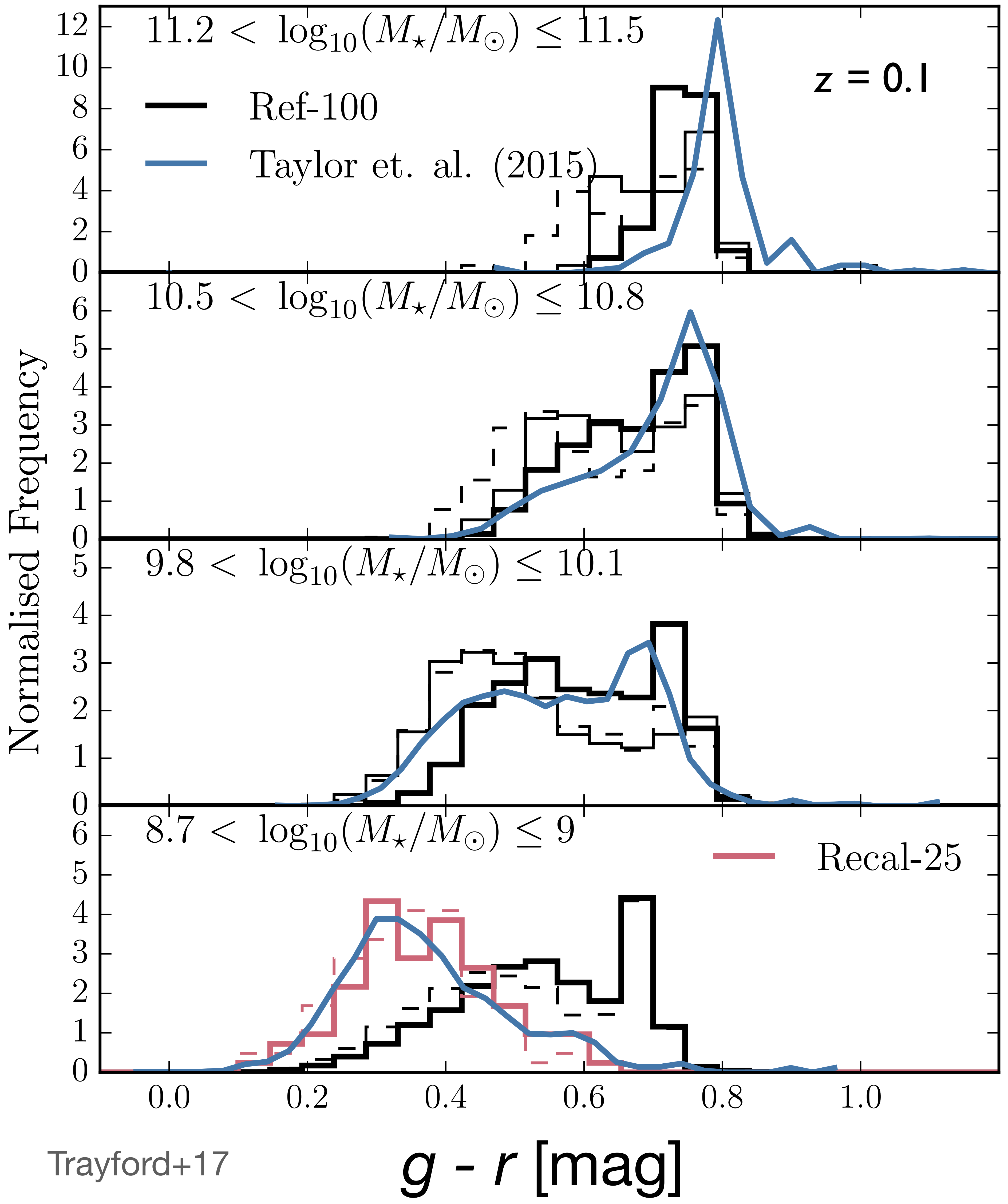
Camps et al 2016



T_{max} is preset to 8000 K to isolate ISM gas

Best values of f_{dust} = 0.3 and f_{PDR} = 0.1 are calibrated using the above relations.

Galaxy Bimodality

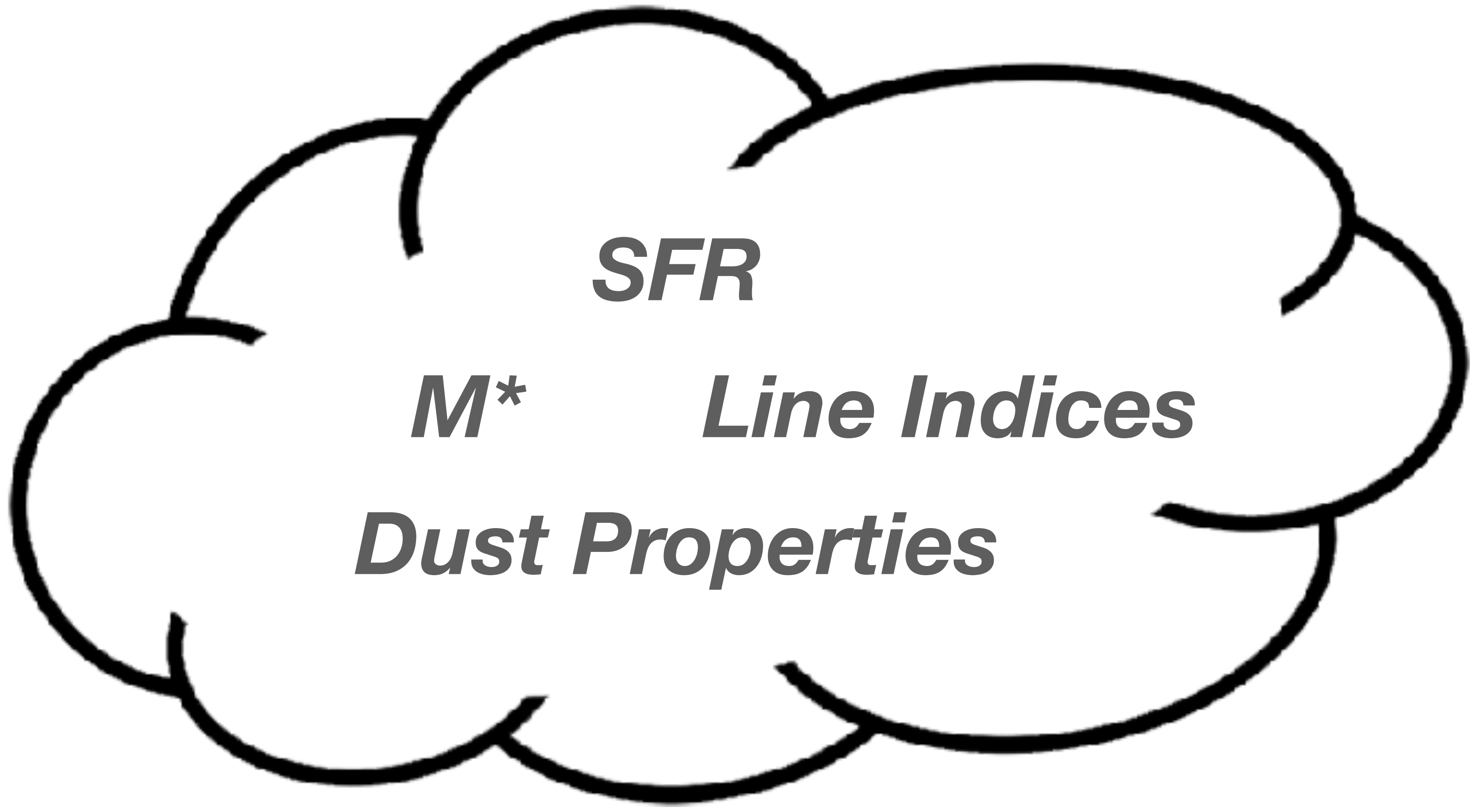


Trayford+17

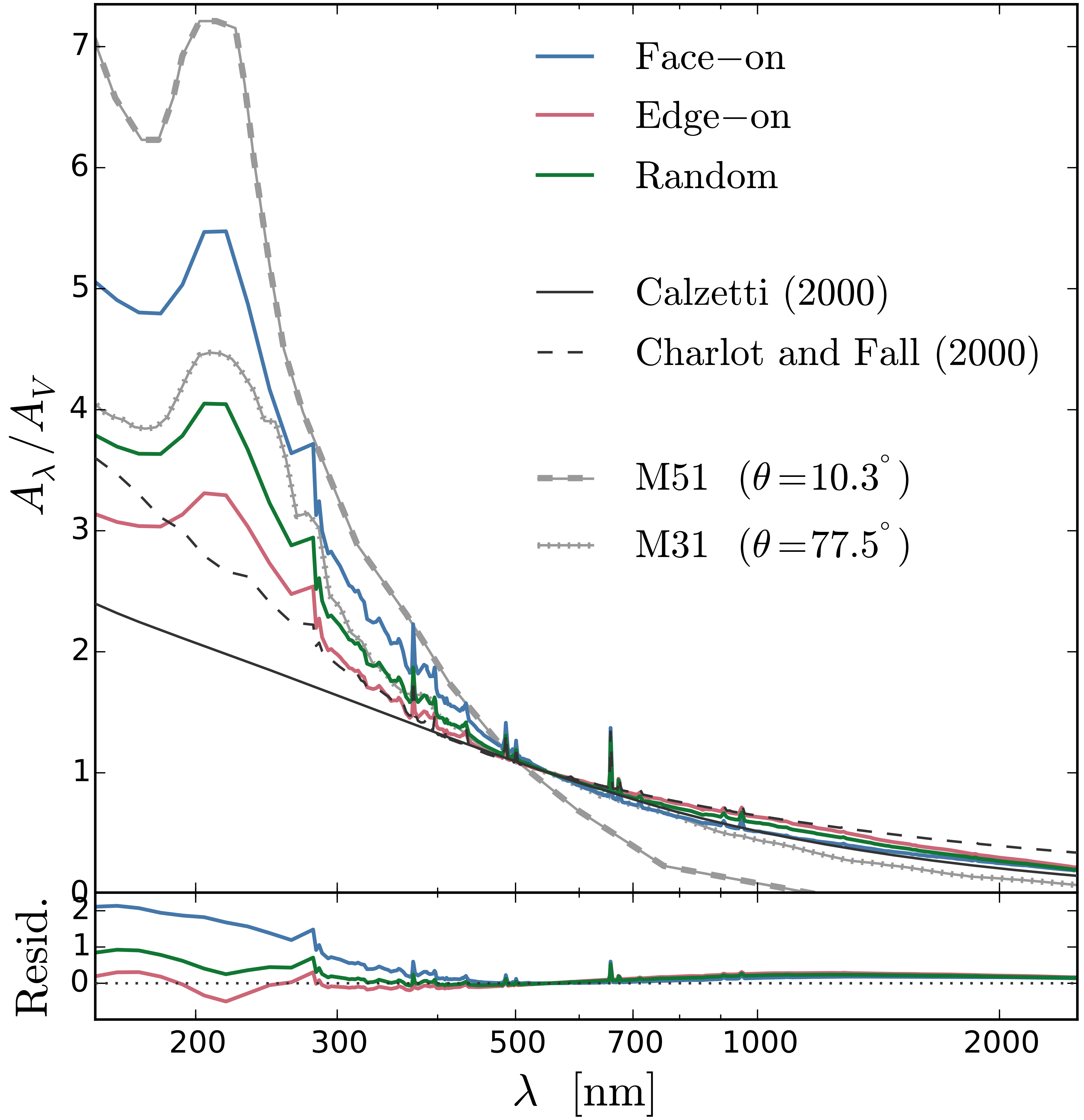
Mock SDSS images of EAGLE galaxies created using full SKIRT radiative transfer

Effective Attenuation Curves

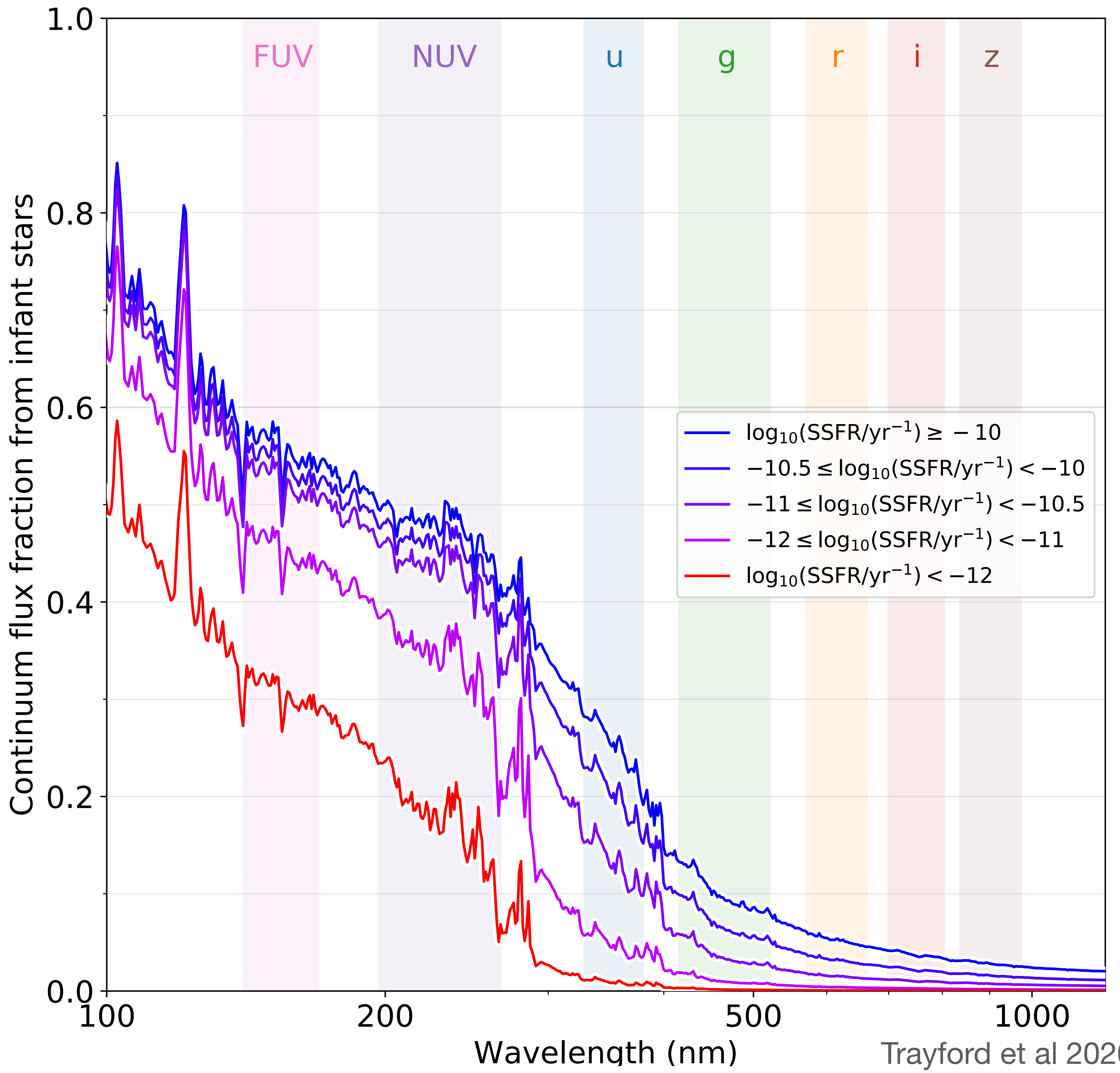
Systematic variations in attenuation curve has implications for recovering galaxy properties:



Can we parametrise the RT dust from EAGLE?

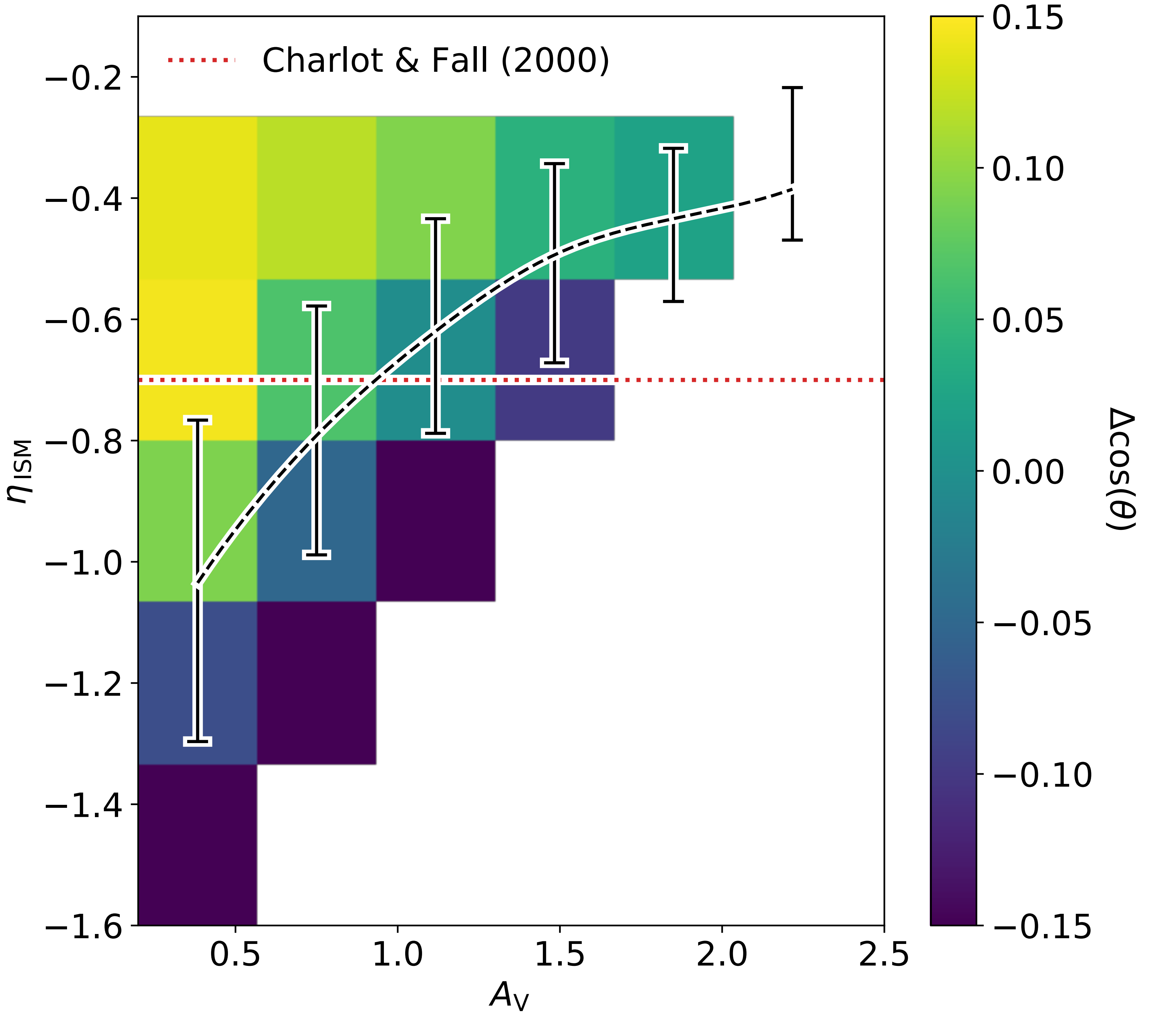


What about young stars?



Trayford et al 2020

Fading to grey

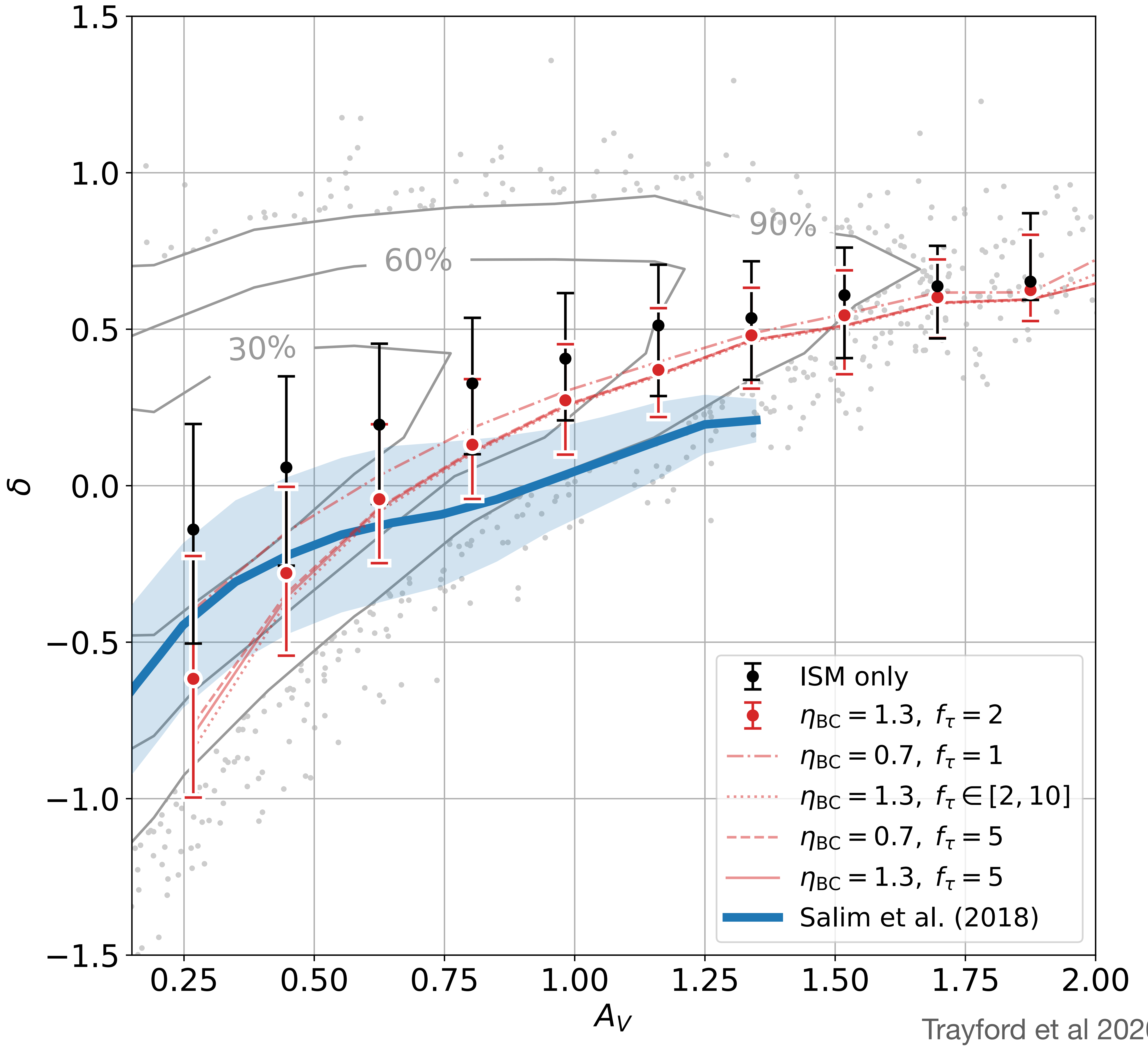


$$\tau(\lambda) = 0.4 \ln(10)\, E(B-V)\, k_{\rm SB}(\lambda) \left(\frac{\lambda}{5500\text{Å}}\right)^{\delta},$$

Calzetti curve

Slope modifier

See also IRX-Beta relations e.g. Narayanan+18 (MUFASA), Trcka+20 (EAGLE), Vijayan+21 (FLARES)

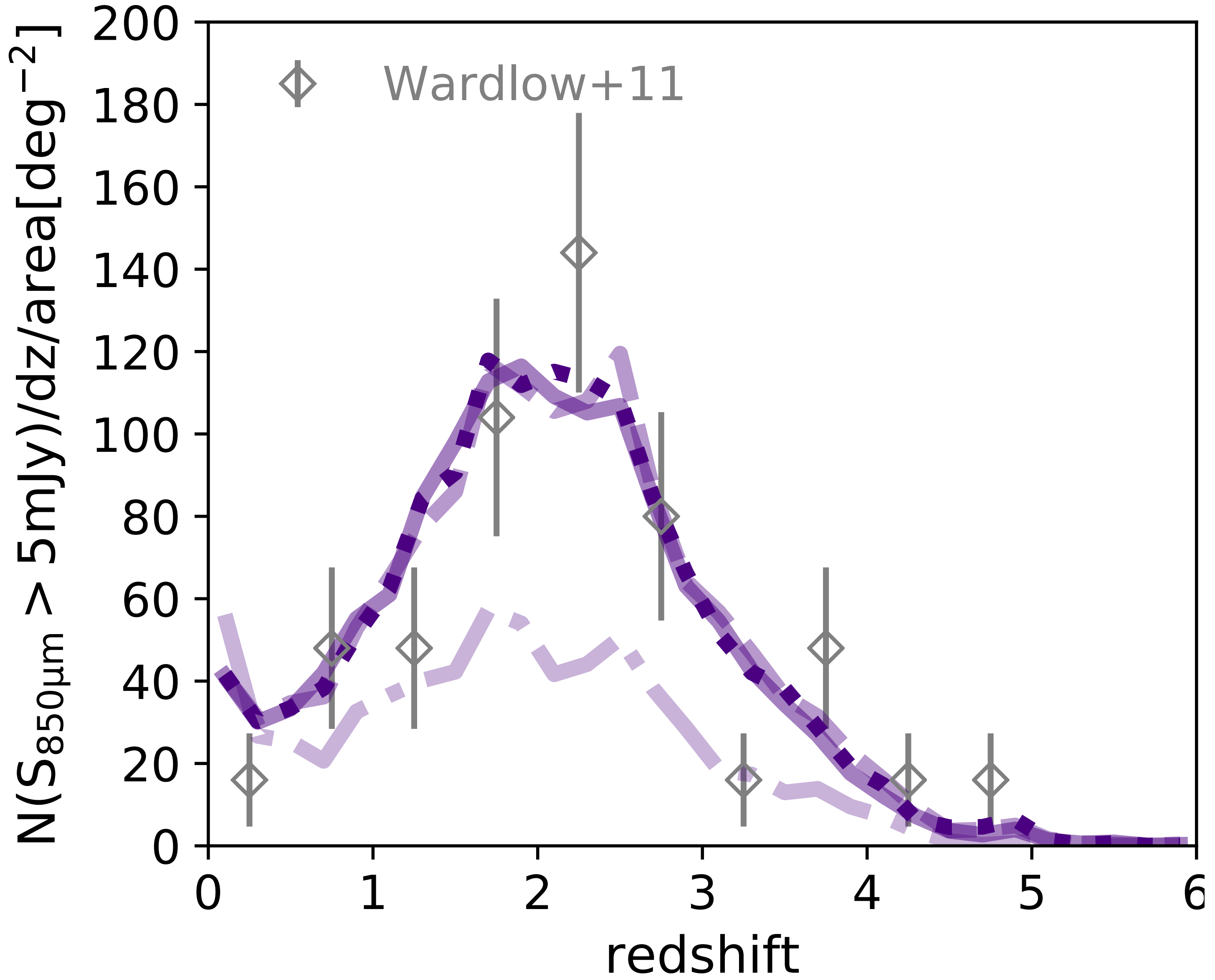


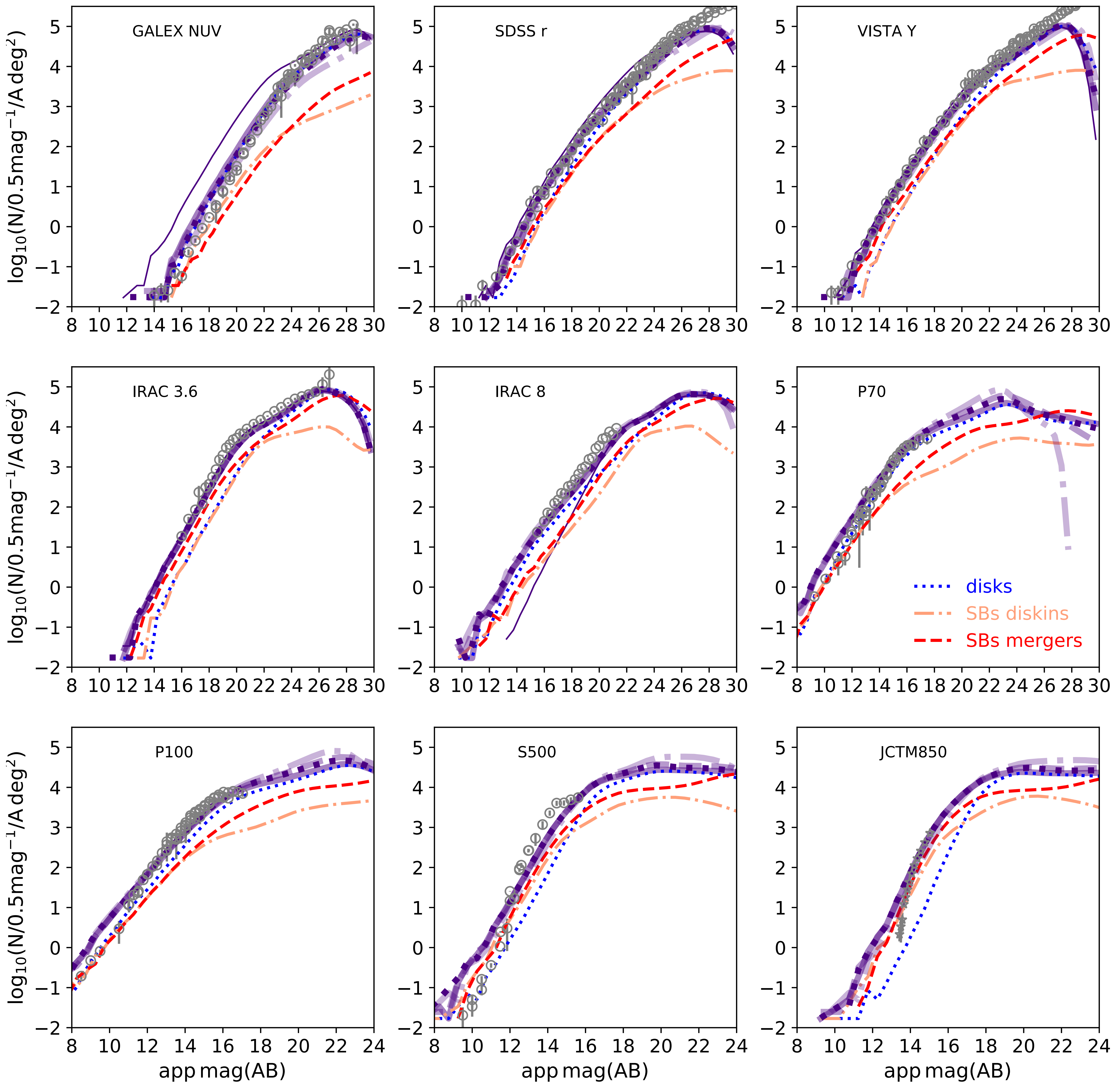
Trayford et al 2020

Applying this model to a SAM

- The SHARK SAM (Lagos+18c) adapted this, using the Charlot & Fall attenuation model, and the absorbed energy to parametrise Dale+14 dust emission templates.

- Evolving panchromatic SHARK data are presented in Lagos+19, where good agreement is in shown UV-IR, including SMG number counts





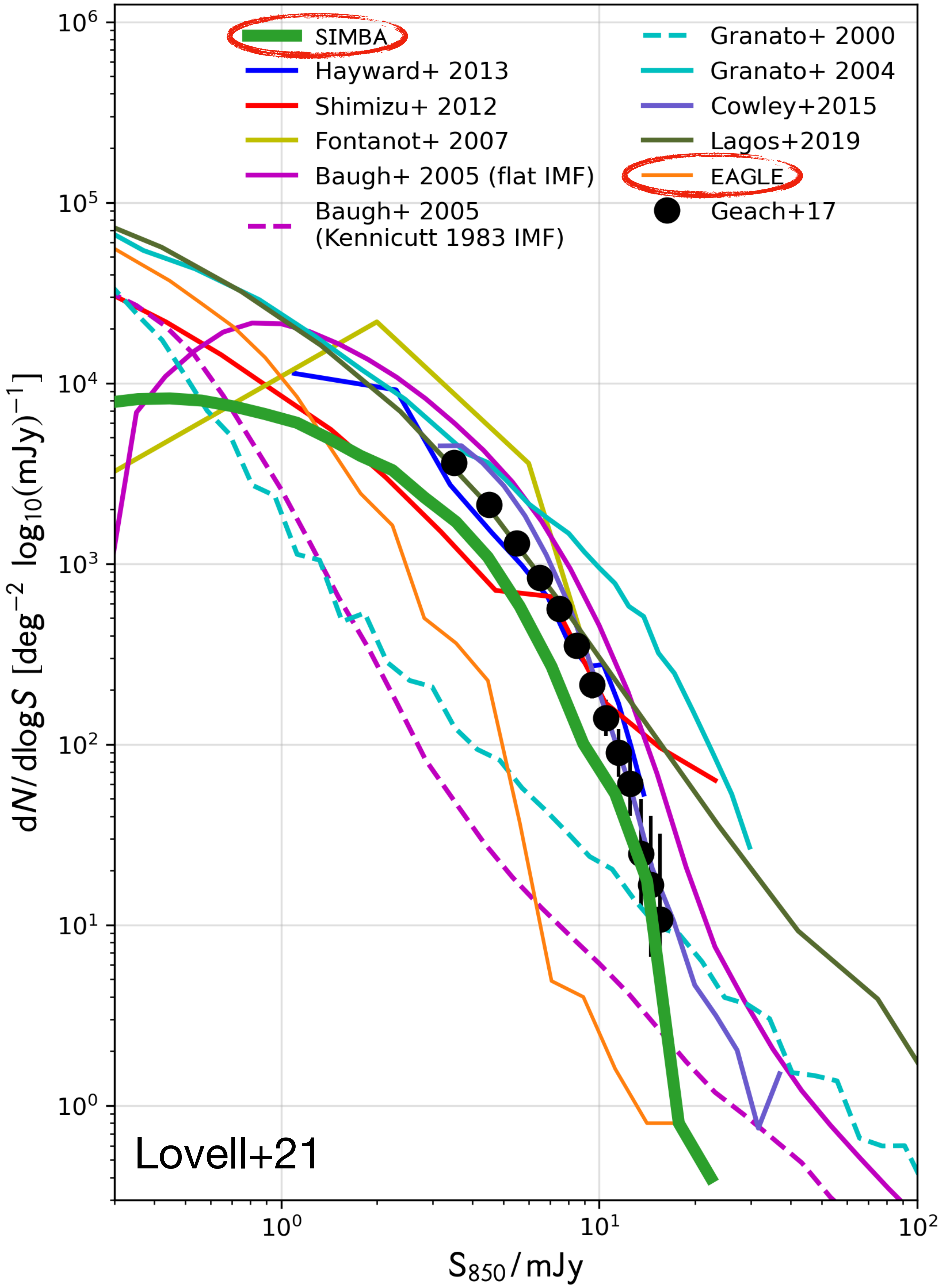
The EAGLE simulations

Despite caveats with SKIRT-EAGLE, this approach allows us to get at ***systematic trends that aren't captured by idealised models***, as demonstrated with SHARK.

Still there are improvements to be made:

- A uniform dust mix (i.e. *extinction*) and metallicity scaling is assumed for all galaxies and redshifts
- The artificially pressurised ISM means that density and thus attenuation is limited (e.g. Trayford+17 for discussion)
- Perhaps linked to both, the IR seems to diverge from a number of observations towards high redshift. *SMG number counts, CSED and IR evolution (McAlpine+18, Baes+18, Baes+19)*

e.g. Lovell et al 2021 show that the "burstier", larger volume SIMBA models with their self-consistent dust-to-metal ratios compare much better to SMG number counts.



Activating Dust

With a model for the grain lifecycle, we can link the dust to the gas physics using the cooling module (Richings+14a,b)

- **Depletion:** The deposition of gas-phase metals into dust modulates the level of metal-line cooling

- **Molecule Formation**: The molecular formation rates are effected by the availability of dust surfaces, and dust shielding

- **Cooling & Heating:** there are heating (e.g. photoelectric heating) and cooling (e.g. radiative cooling), again largely depending on dust surfaces

While large grains are typically considered subdominant in the ISM, Small grains play an outsized role in these processes due to their higher surface-to-volume ratio