Dust Properties of Galaxies in the Early Universe

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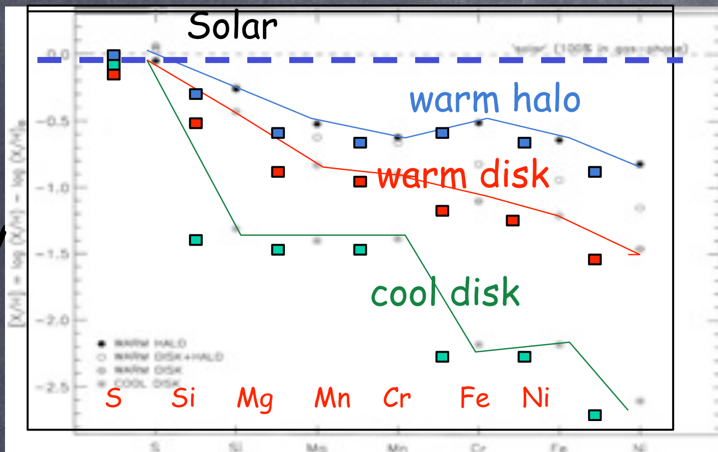
Frontiers in Star Formation:

A Conference in honor of Dr. Richard Larson,

Yale Univ, October 26-27, 2012

Motherhood Statement

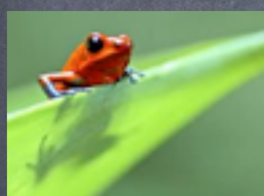
elemental depletions

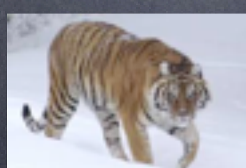
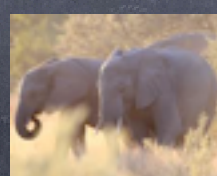


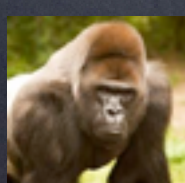
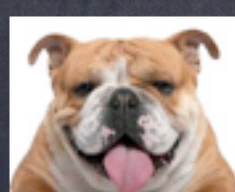
All dust in the universe must contain the following refractory elements

S, Mg, Si, Fe, Ca, Ti, Ni

So is dust the same all over?




All Life on earth (universe?) must be based on carbon chemistry

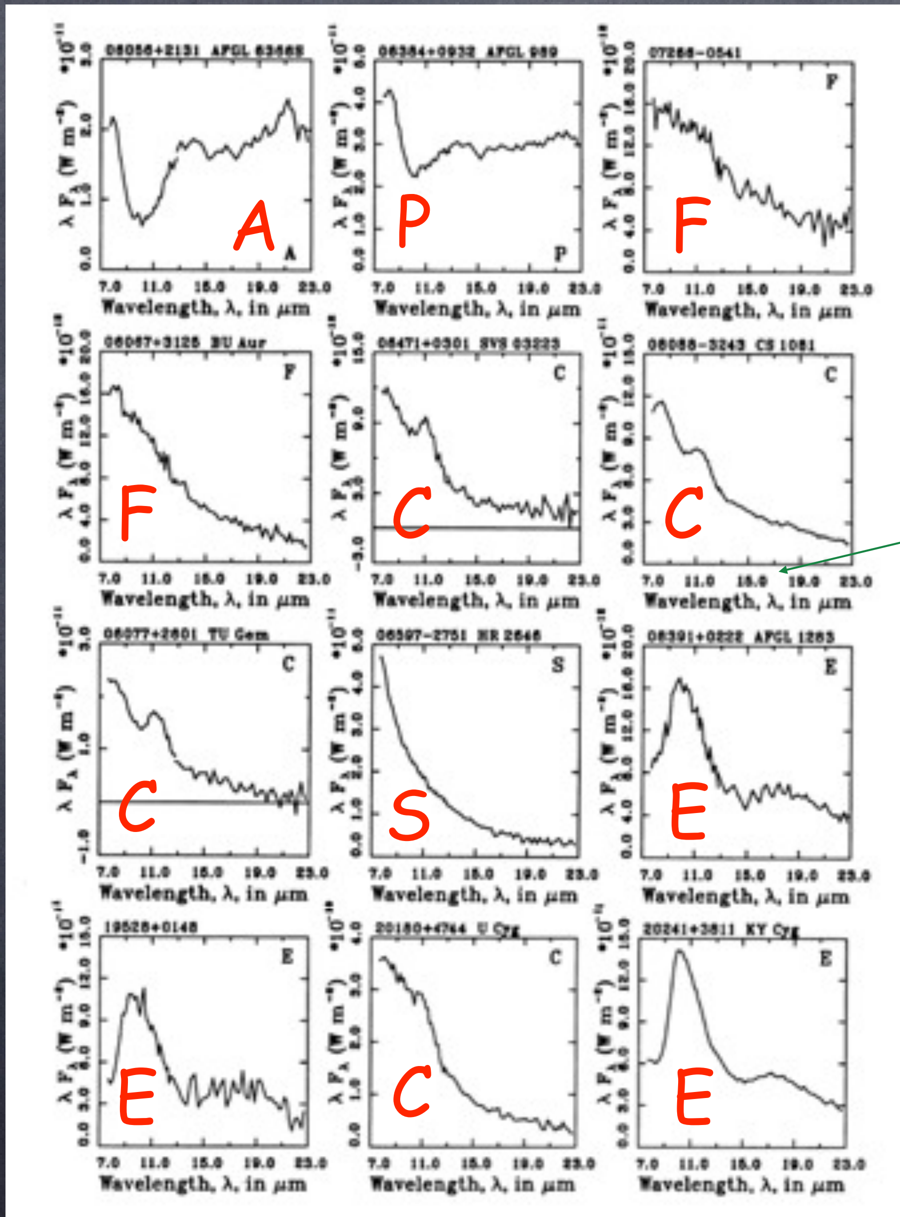
There is a huge variety of life forms!

Dust properties

- Composition
- Size distribution
- Abundance

Detailed observations of Galactic
sources reveal a very
rich variety of dust mineralogy
and composition

Dust Formation in Quiescent Outflows

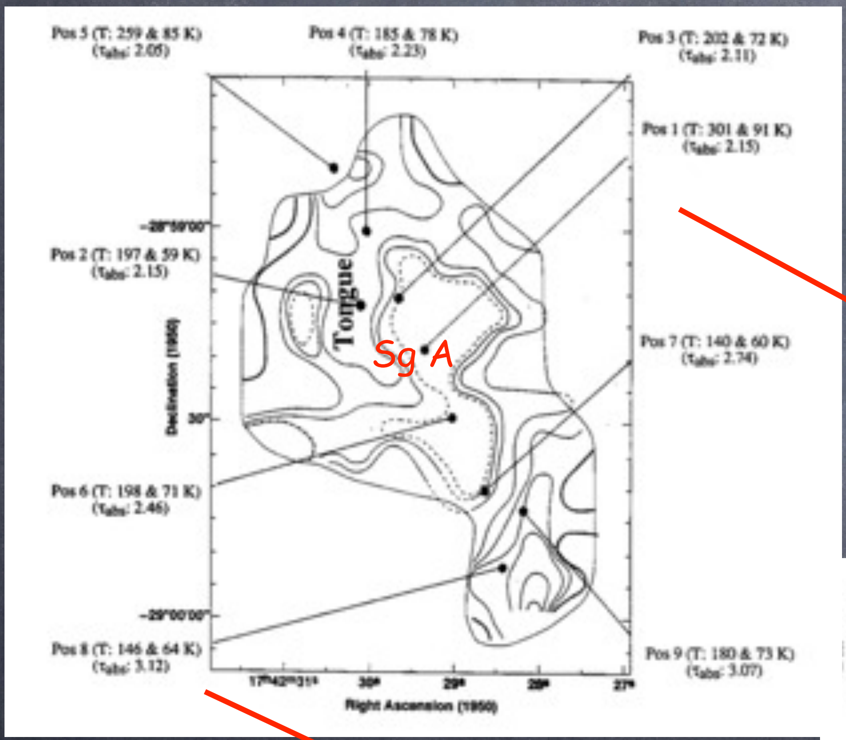


(IRAS satellite)

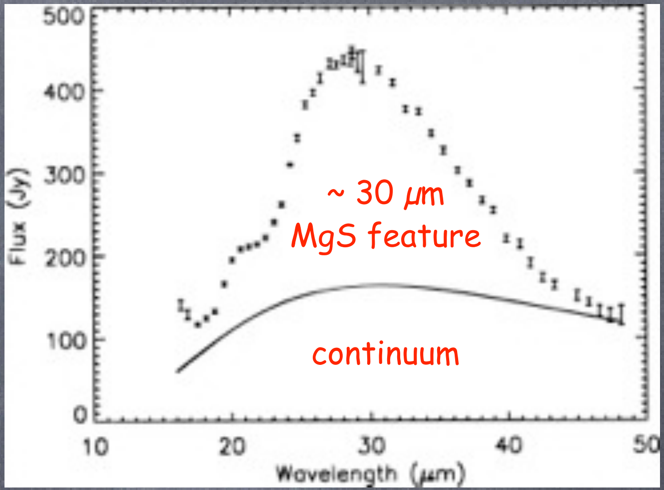
- **A** silicate absorption (9.7, 18 μm)
- **C** SiC emission (11.3 μm)
- **E** silicate emission (9.7, 18 μm)
- **F** featureless spectrum (C?)
- **P** PAH spectrum (7.6, 11.3 μm)
- **S** stellar black body

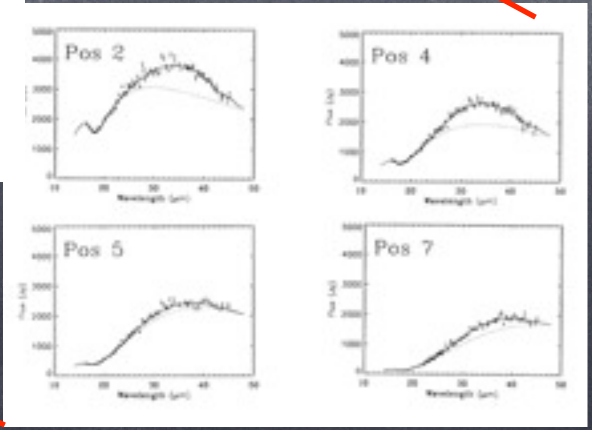
MgS Formation in Stellar Outflows (KAO)

Galactic center   Chan et al. 1997



IRAS 22272+5435

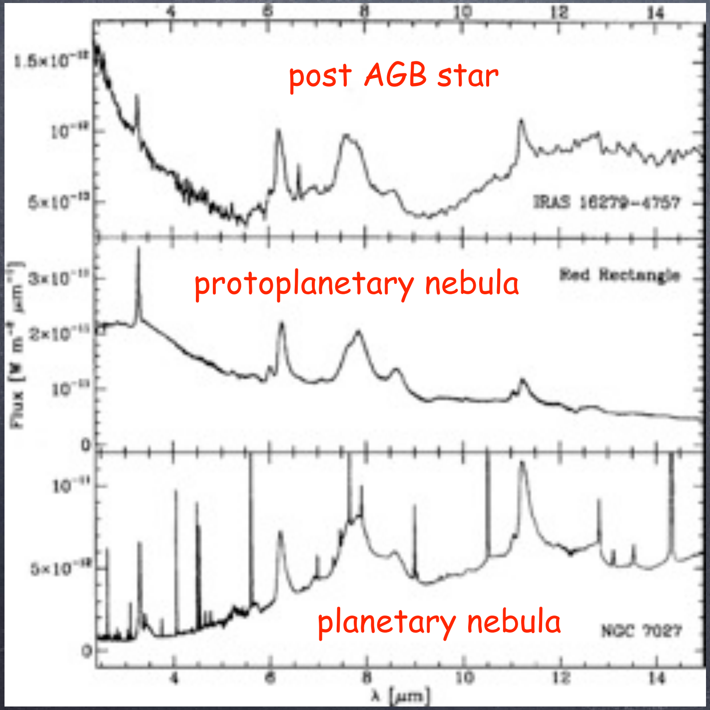




Dust composition in circumstellar Shells, YSO, and ULIRGS

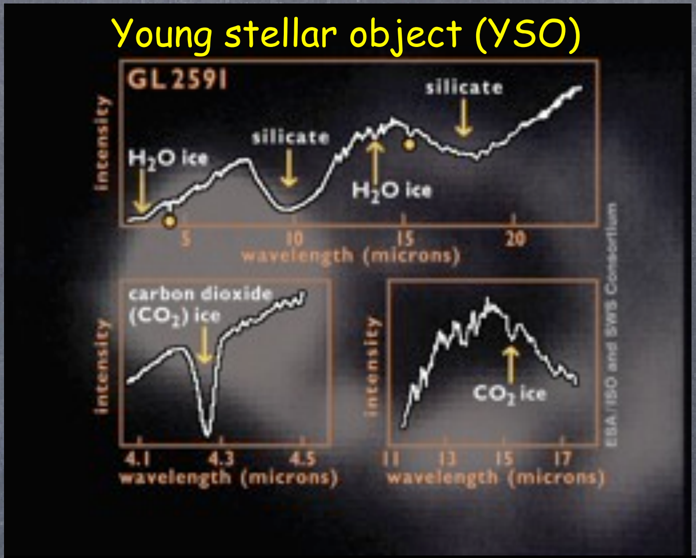
(Spitzer/ISO satellite)

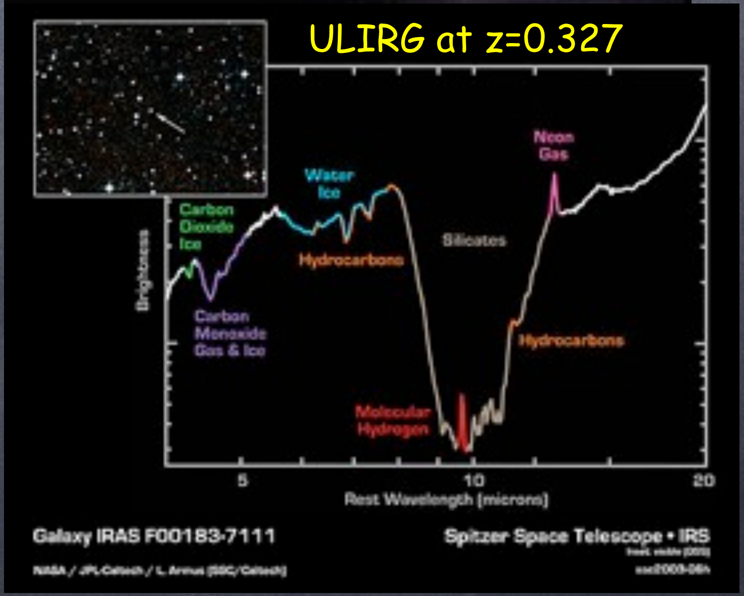
PAH macromolecules



H_2O, CO_2, CH_4 ices,

hydro-C, PAHs, silicate





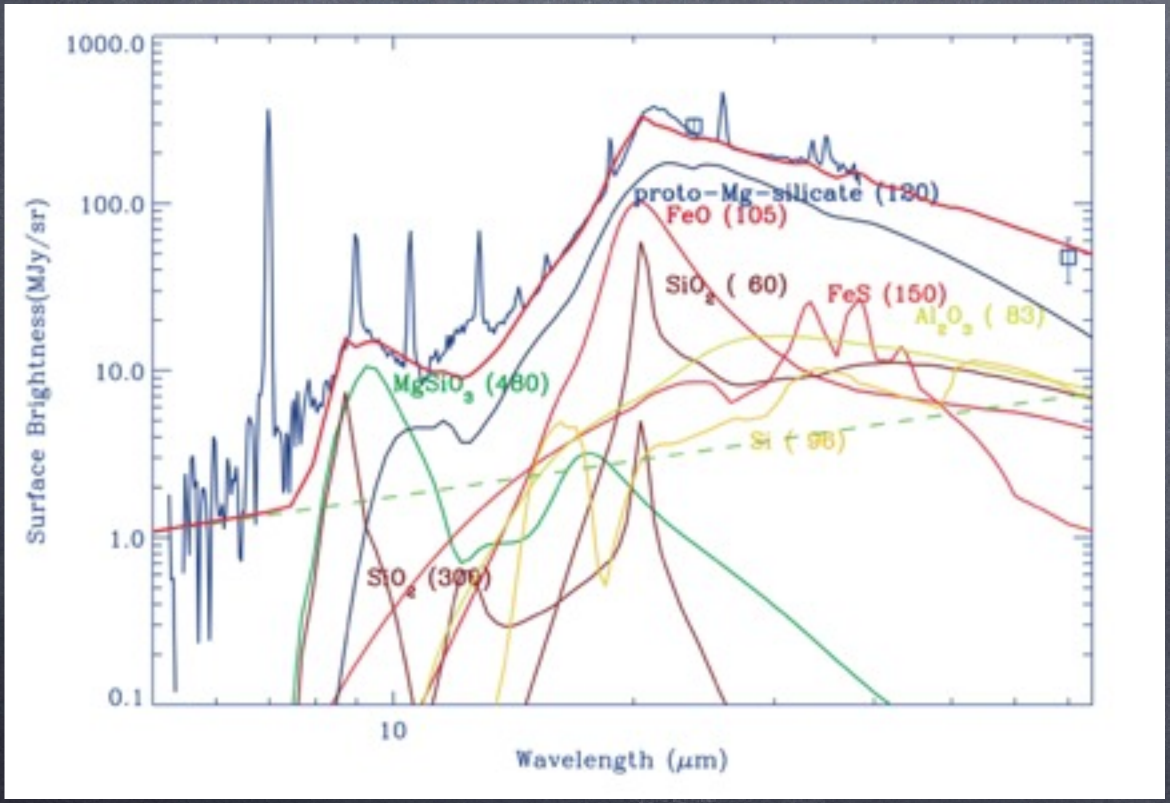
IR emission and dust composition from of Cas A

(Rho et al. 2008)

Chandra

HST

Spitzer



Compositions used:

proto-silicates

FeO

FeS

Al_2O_3

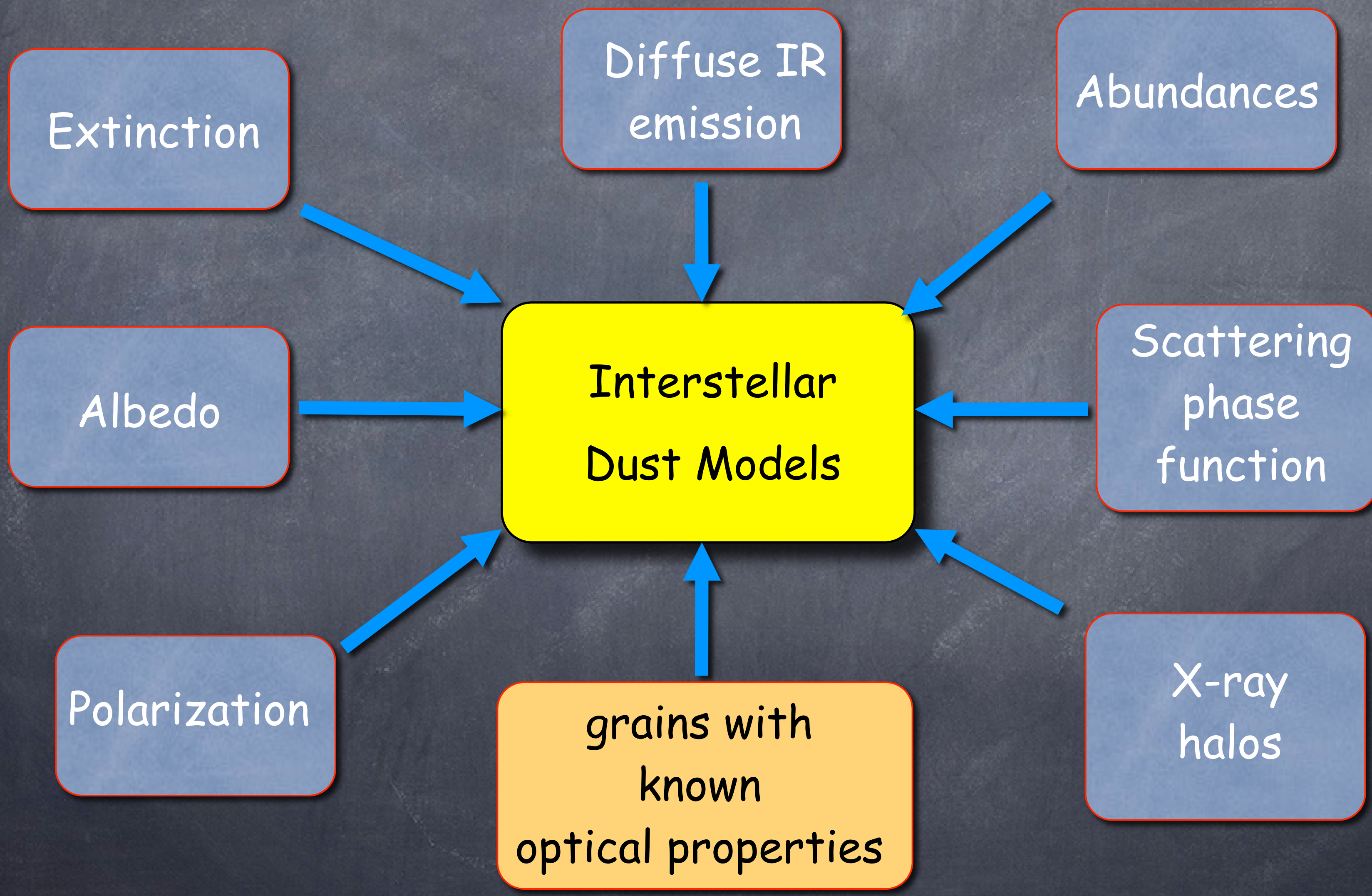
Silica

SiO_2

Mg_2SiO_3

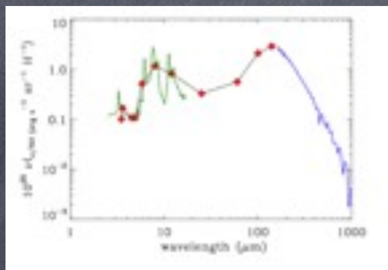
But interstellar dust models require only two basic dust types

What is an interstellar dust model? One that complies with all these observational constraints



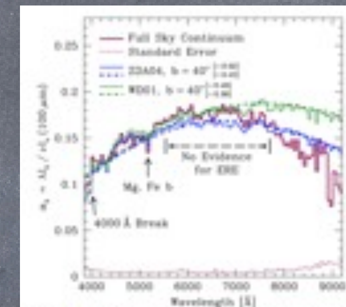
Modeling interstellar dust

diffuse IR emission

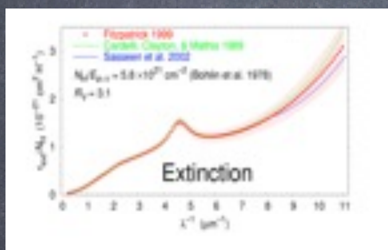


inversion program

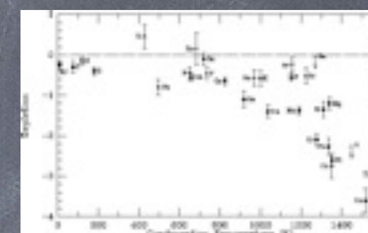
diffuse scattering



interstellar extinction

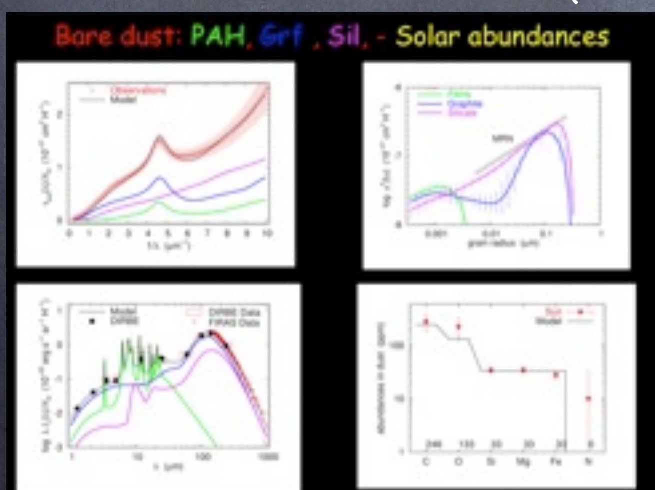


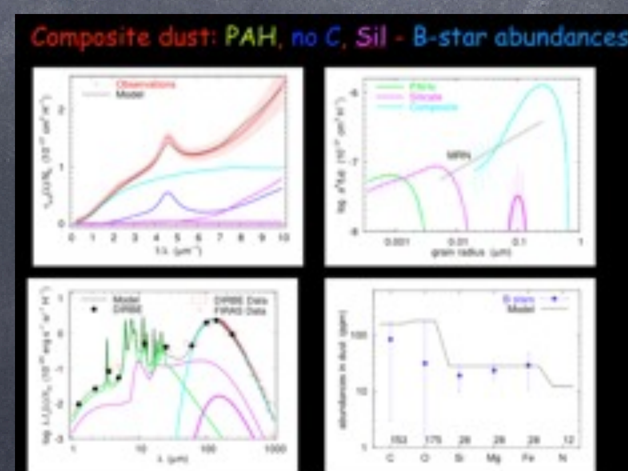
interstellar depletions



interstellar dust model!

(Zubko et al. 2004)





Where has all the variety gone?

AGB stars
- A-carbon
- PAHs
- silicates
- MgS

Supernovae
- proto-silicates
- FeO
- FeS
- Al_2O_3
- Silica
- SiO_2
- Mg_2SiO_3

Molecular clouds
- A-carbon
- PAHs
- silicates
- water and methane ices
- organic material

interstellar processing
minor contributors
lack of spat/spec resolution
?

extinction/emission
Diffuse MW ISM
Xternal galaxies
- A-carbon
- PAHs
- silicates
- graphite?

Why do we expect dust in high-z galaxies to be different from dust in the local universe?

- Sources evolve, and so must dust composition (Dwek 1998)
- Interstellar process may be different in the early universe

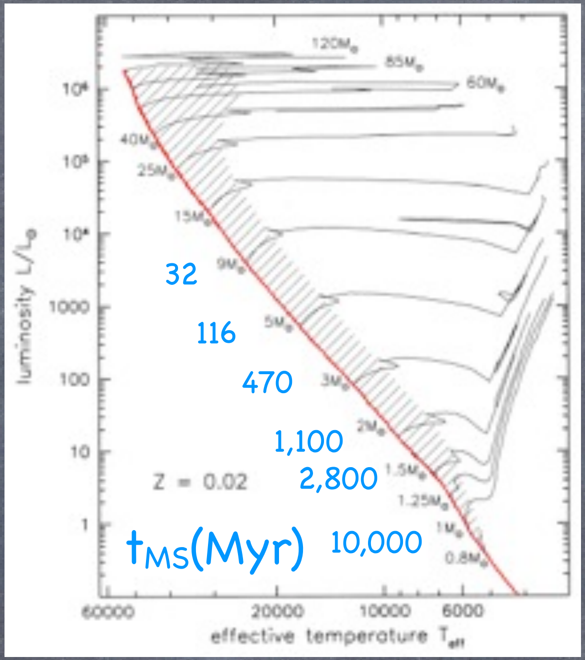
Galactic age an important factor

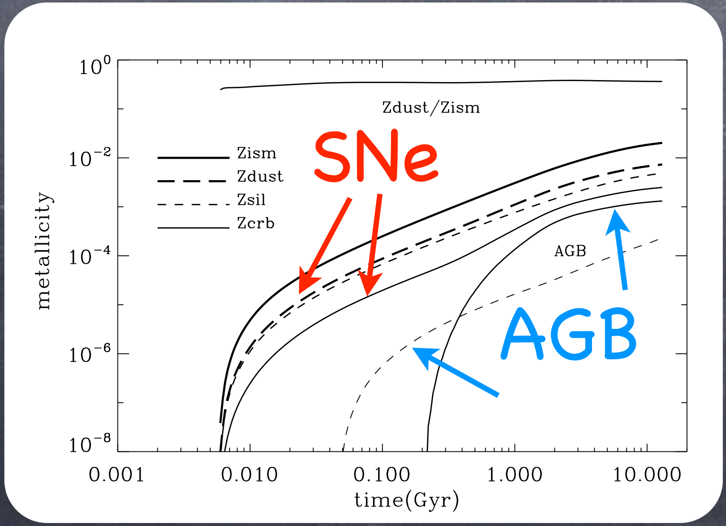
A young galaxy
age < 400 Myr
$z \geq 6$

AGB stars have not yet evolved off the MS

SNe are only sources of condensed dust

WR stars?





An old galaxy
age > 1 Gyr
$z \leq 5$

AGB stars may then be the most important sources of condensed dust

What observations do we have from which we can learn about the nature of dust in the high redshift universe?

- extinction curve
  - stars, shadowing galaxies, Quasars, GRBs
- average IR emission
- metallicity constraints
- dust sources?
  - WR stars, SNe, AGB stars, ISM

Is dust in high-z galaxies mostly SN-condensed dust?

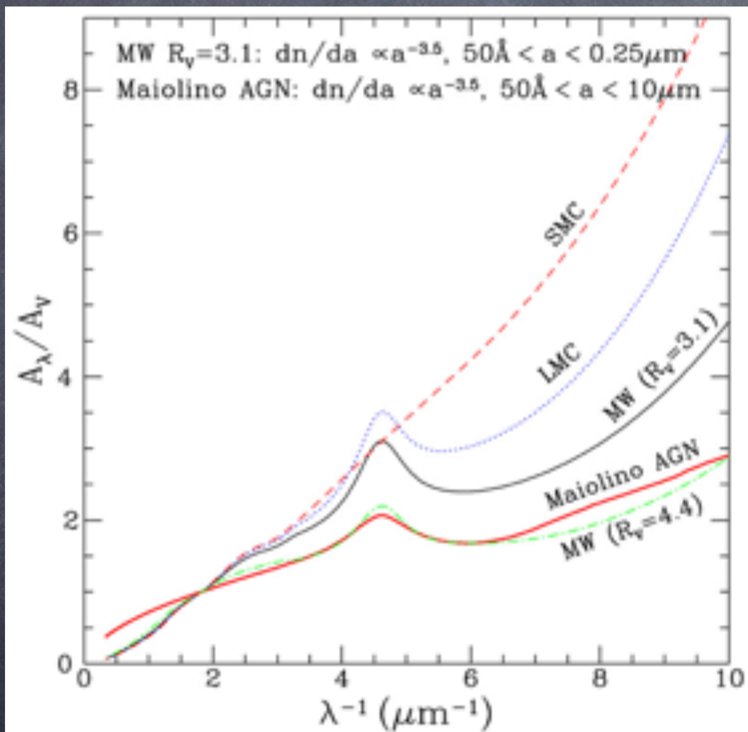
Is there any evidence for the following trend?

SN condensed dust

AGB condensed dust

What can we learn from extinction measurements?

MW - LMC - SMC extinction



There is a gradual change in:

(Pei 1997)

- the strength of the 2175 Å bump
- the slope of the UV extinction (Rv)
- the silicate graphite/PAH abundance ratio

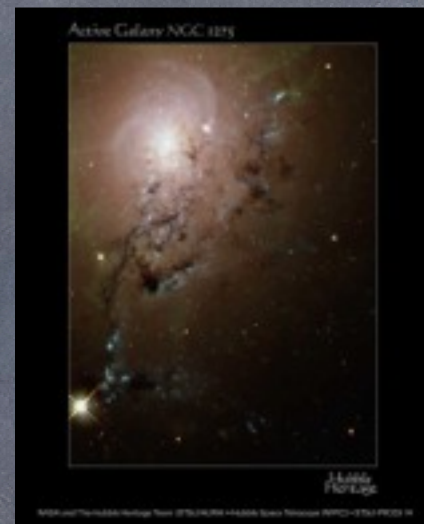
Extinction in backlit local galaxies

Keel 1983

Foreground galaxy: NGC 3314 (Sc)
Background galaxy (Sb)

B, V, R, I photometry show patchy extinction with
$R = A_V/(B-V) \approx 3.5$

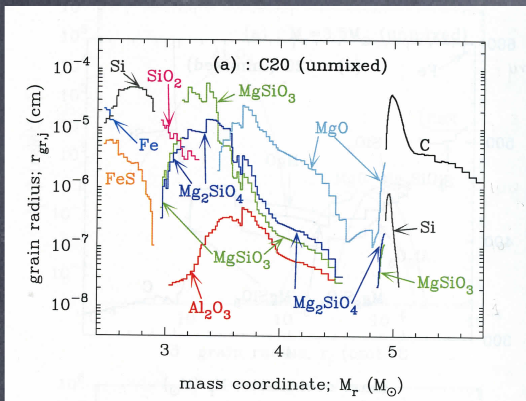
Active galaxy: NGC 1275

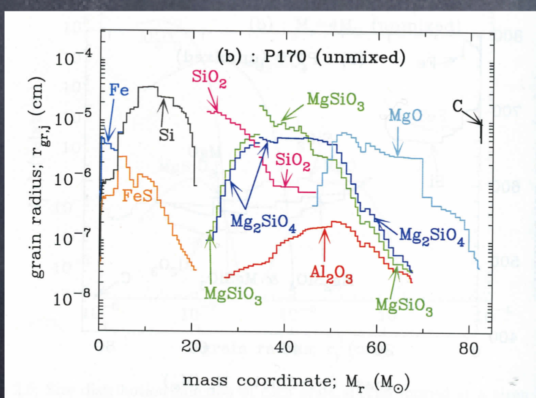


Patchy dust lanes with variable extinction

Dust from primordial CCSN

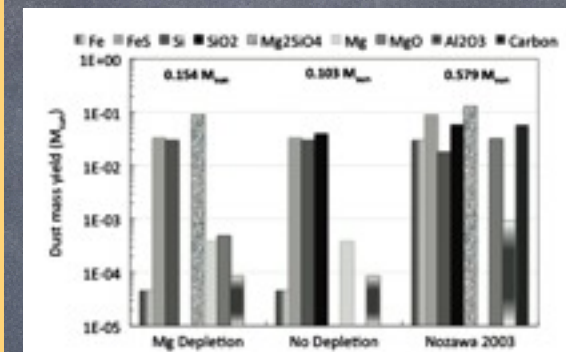
Nozawa et al. 2003

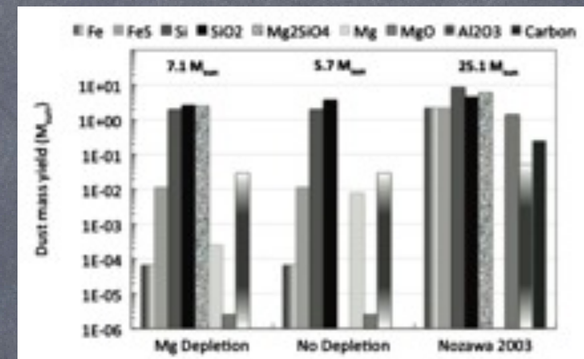




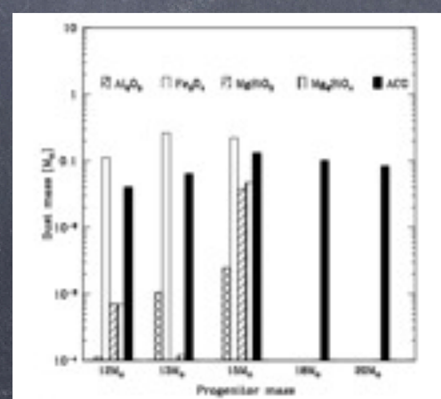
Cherchneff & Dwek 2010

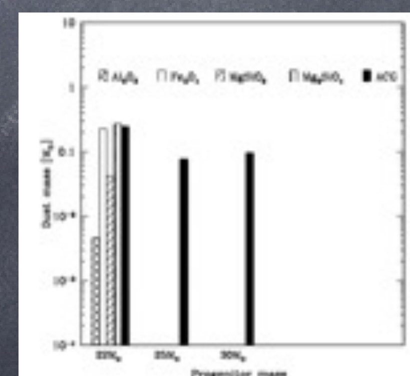
Fe, FeS, Si, SiO_2, Mg_2SiO_4, Mg, MgO, Al_2O_3, CRB





Todini & Ferrara 2001



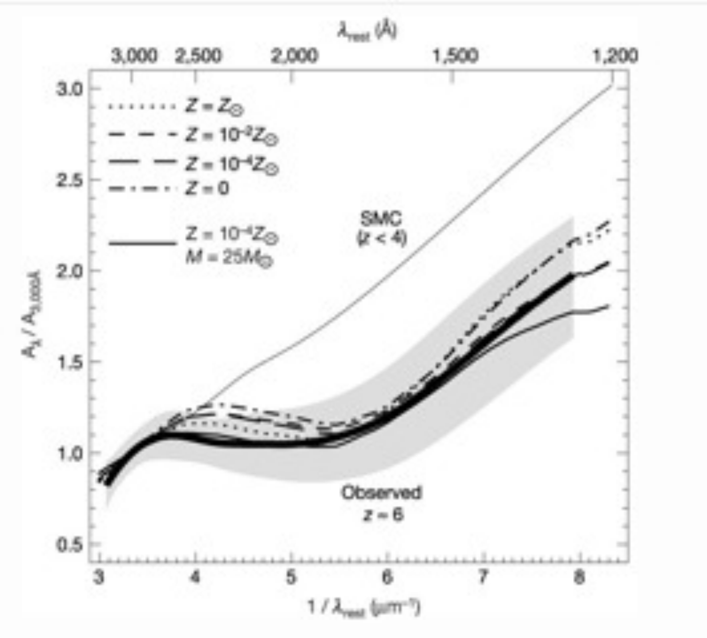


Extinction towards high-z (> 6) quasars

Maiolino et al. 2004

BAL quasar at z=6.19

Extinction has a distinct S shape, requiring SN-condensed dust

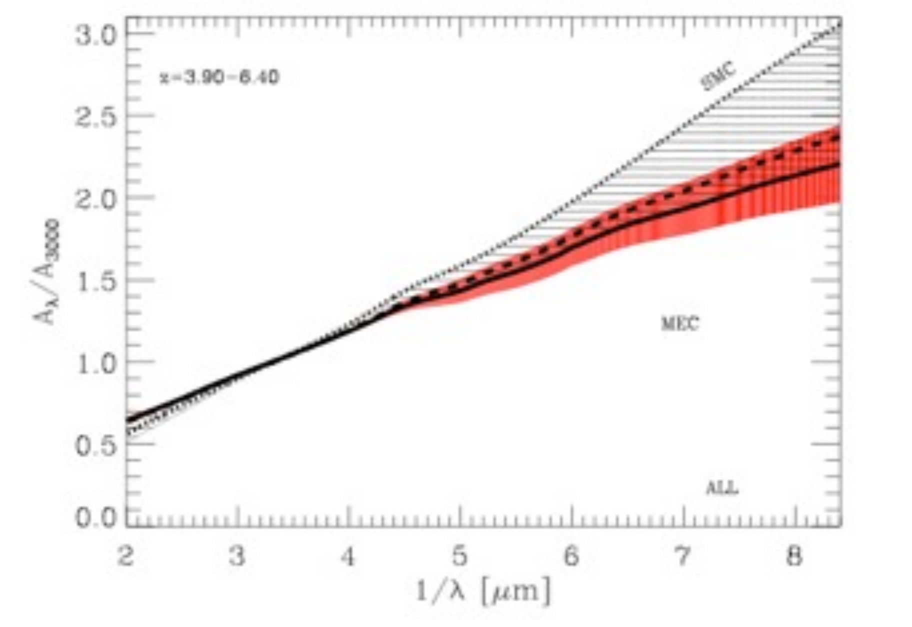


Gallerani et al. 2010

Analysis of 33 quasars with z = 3.9−6.4

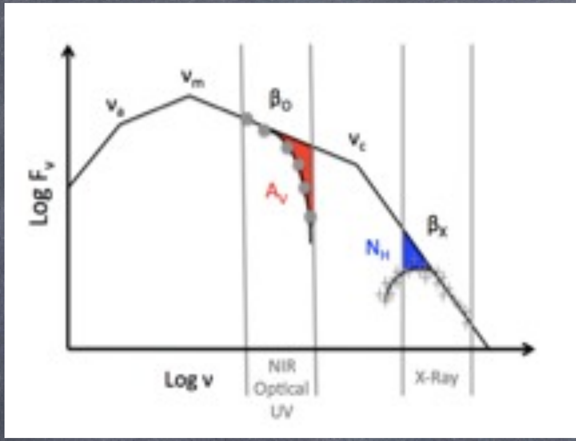
The ext curve is flatter than those in quasars with z < 2.2.

However, due to uncertainties it is consistent with SMC dust

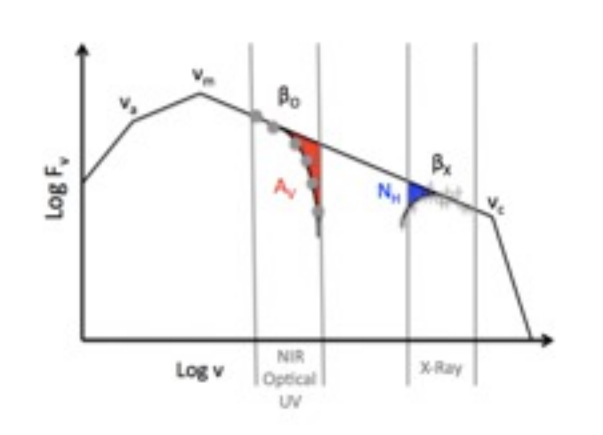


Dust properties inferred from GRBs

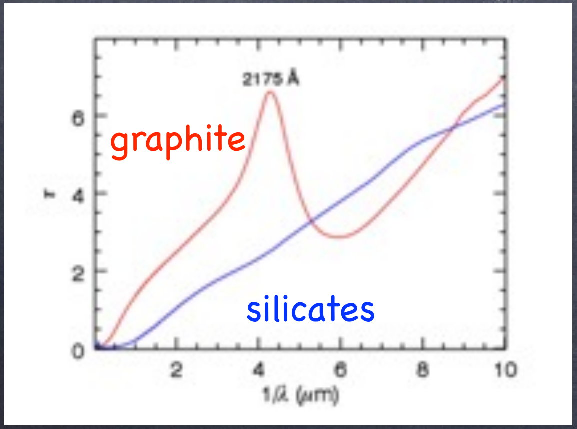
Compton cooling:
$f \approx$ UV-X



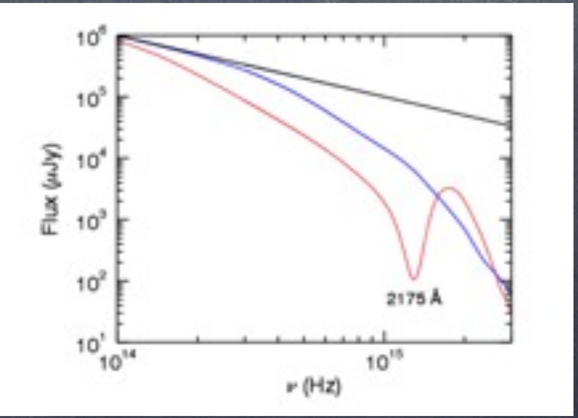
compton cooling:
f > X



extinction curves
silicates, graphite

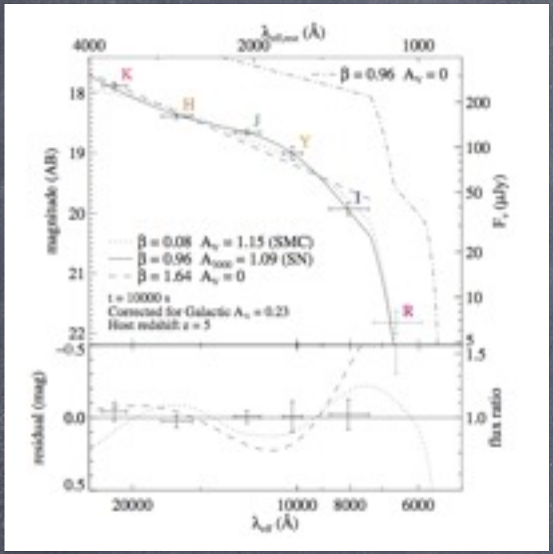


effects on GRB spectrum



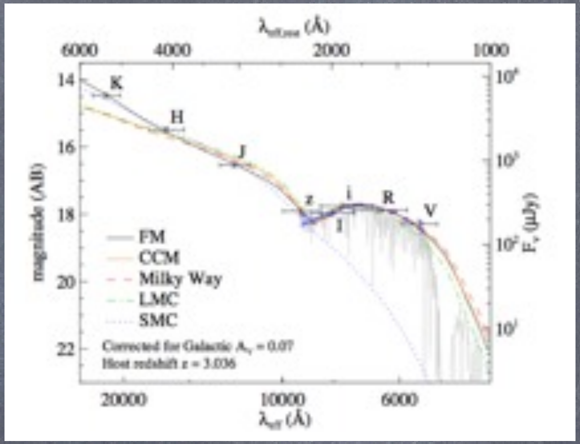
Dust properties inferred from GRBs

GRB 071025 (z=4.4-5.2)
(Perley et al. 2010)



SN dust with
Maiolino ext law

GRB 080607 (z=3.036)
(Perley et al. 2011)



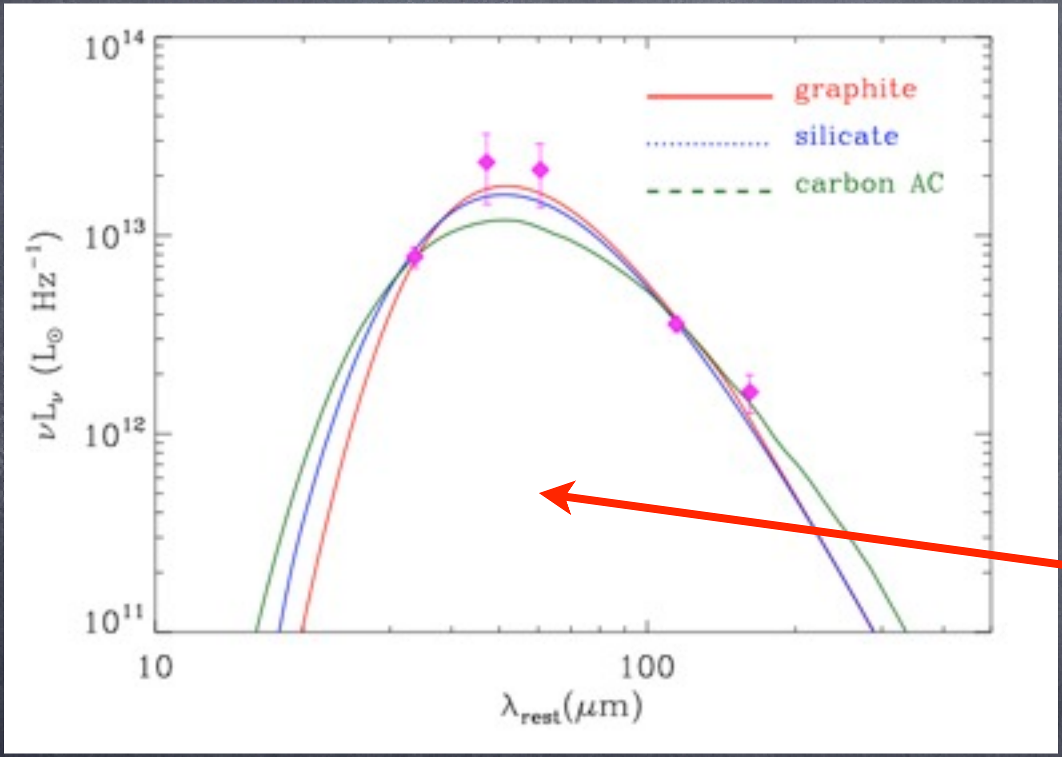
diffuse MW dust with
Fitzpatrick-Massa ext law

transition from SN to AGB dominated dust?

What can we learn from IR emission spectra?

Spectral FITS to the FIR Flux of J1148+5251

z=6.4



Dust Masses

3×10^8 M_{sun}

4×10^8 M_{sun}

1×10^8 M_{sun}

$L_{FIR} \approx 2 \times 10^{13}$ L_{sun}

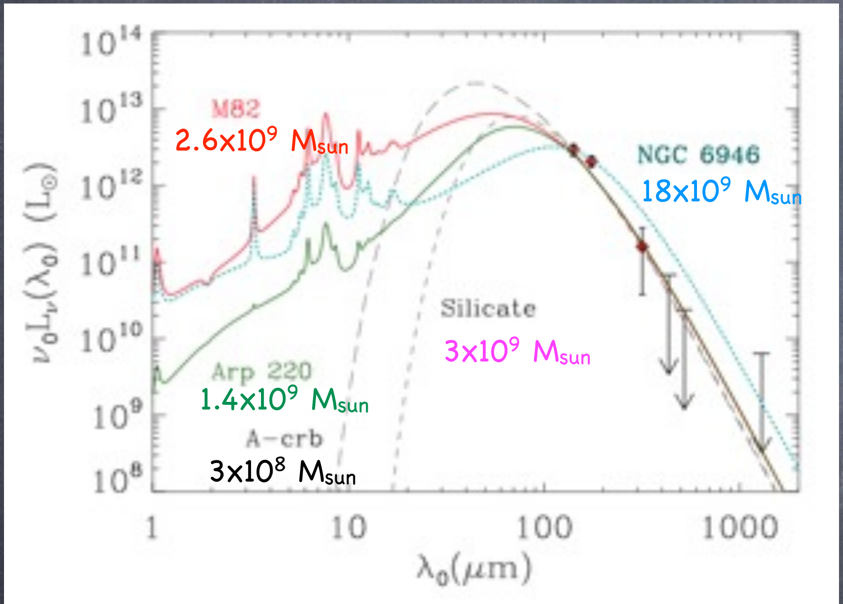
Milky Way: $M_{dust} \approx 3 \times 10^7$ M_{sun}

The Far-IR SED of AzTEC-3

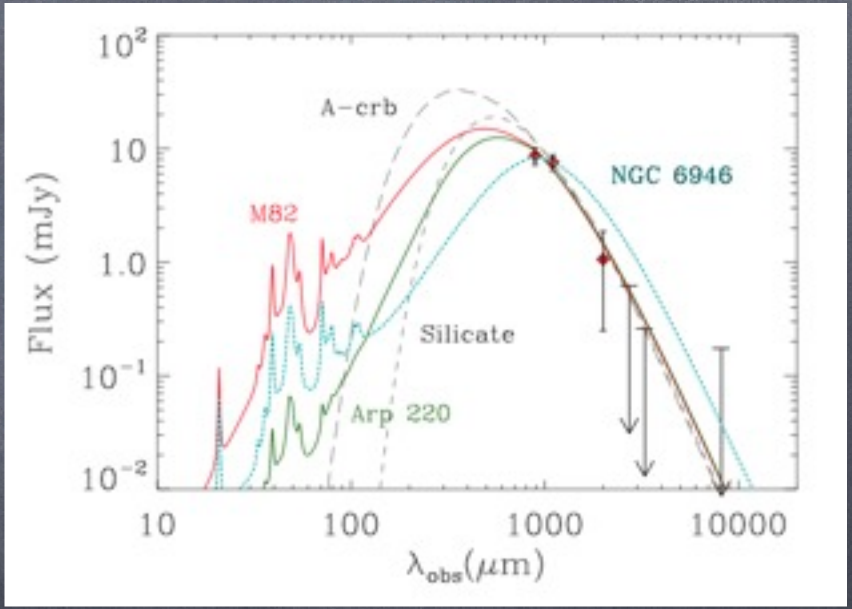
z=5.1

(Galaxy templates from Galliano, Dwek, & Chanial 2008)

spectrum in rest-frame



observed spectrum



recent 350 μm observations suggest that the spectrum of AzTEC-3 is "hot"

$M_{dust} \approx 3\times10^8\ M_{sun}$

What is the origin of the dust in these high-z galaxies?

J1148 may be an “old” galaxy, so that AGB stars could be important dust sources

(Valiante et al. 2009)

The star formation history of high-z quasars in hierarchical galaxy merger models

(Li et al. 2007)

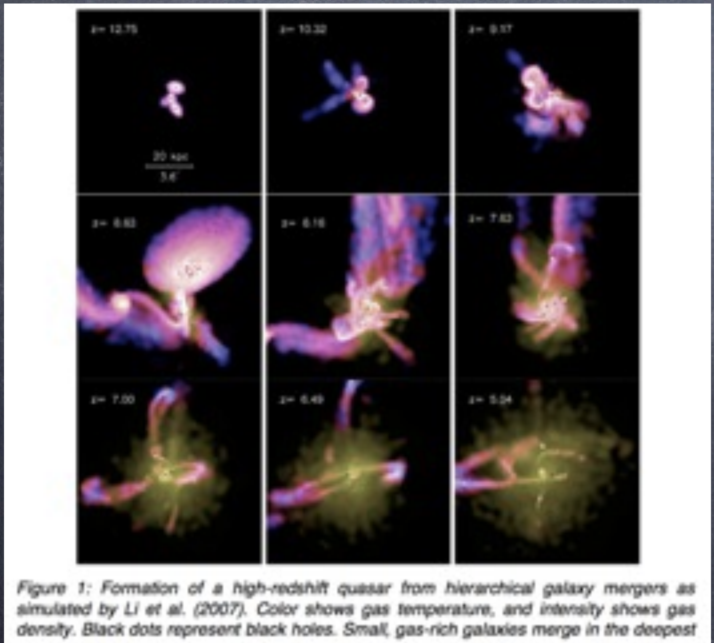
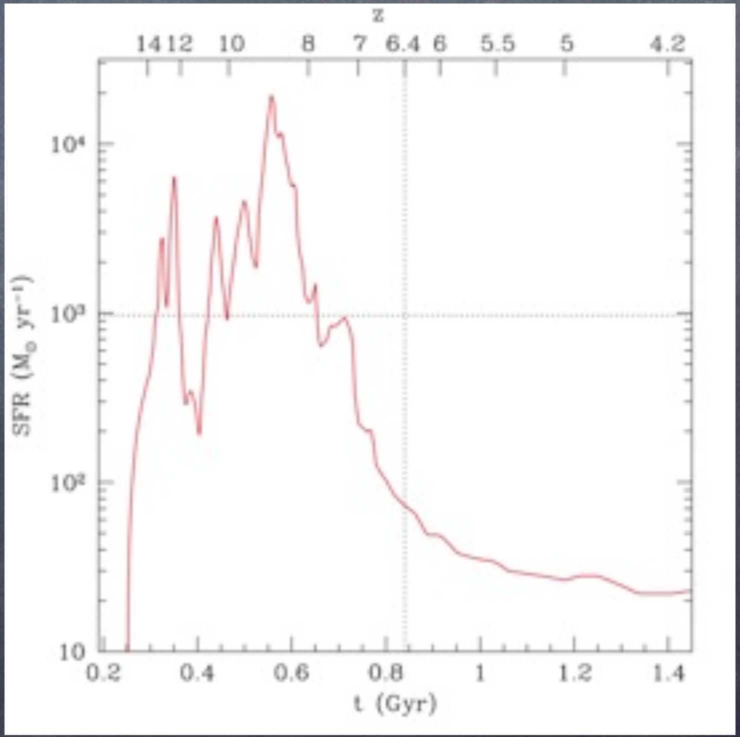
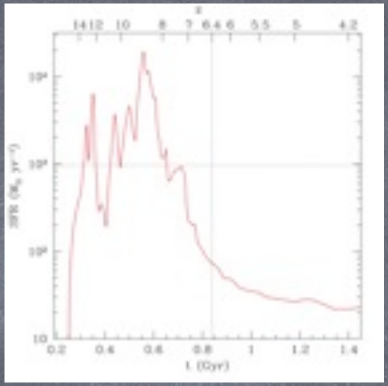


Figure 1: Formation of a high-redshift quasar from hierarchical galaxy mergers as simulated by Li et al. (2007). Color shows gas temperature, and intensity shows gas density. Black dots represent black holes. Small, gas-rich galaxies merge in the deepest

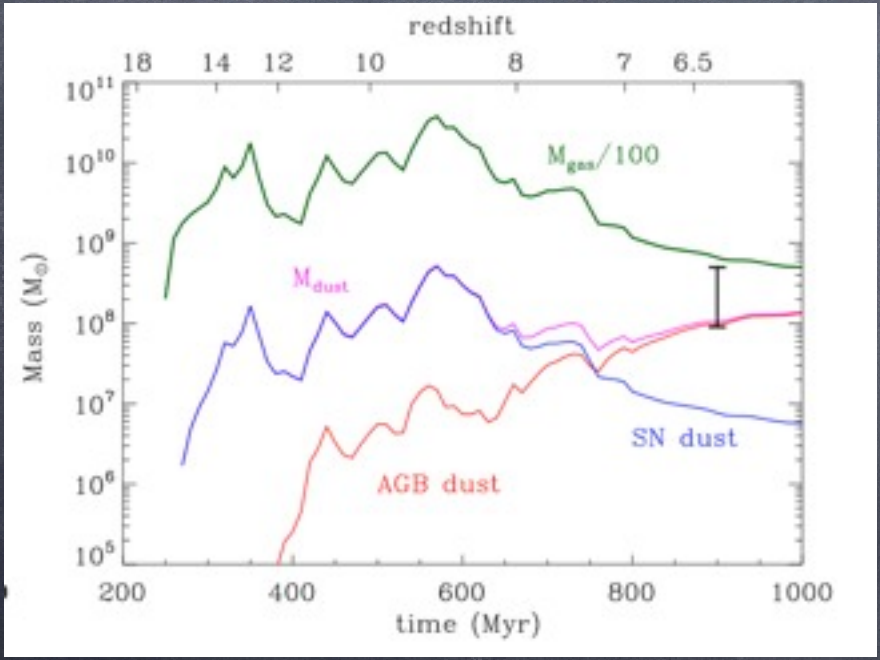


The Evolution of Dust in J1148+5251

(Dwek & Cherchneff 2010)



Schmidt-type SFR-M_{gas} relation

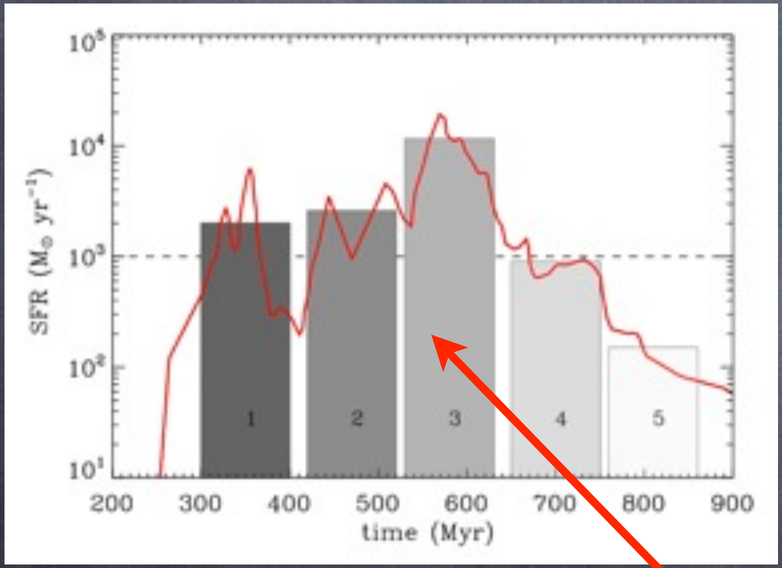


AGB are the main source of dust in J1148

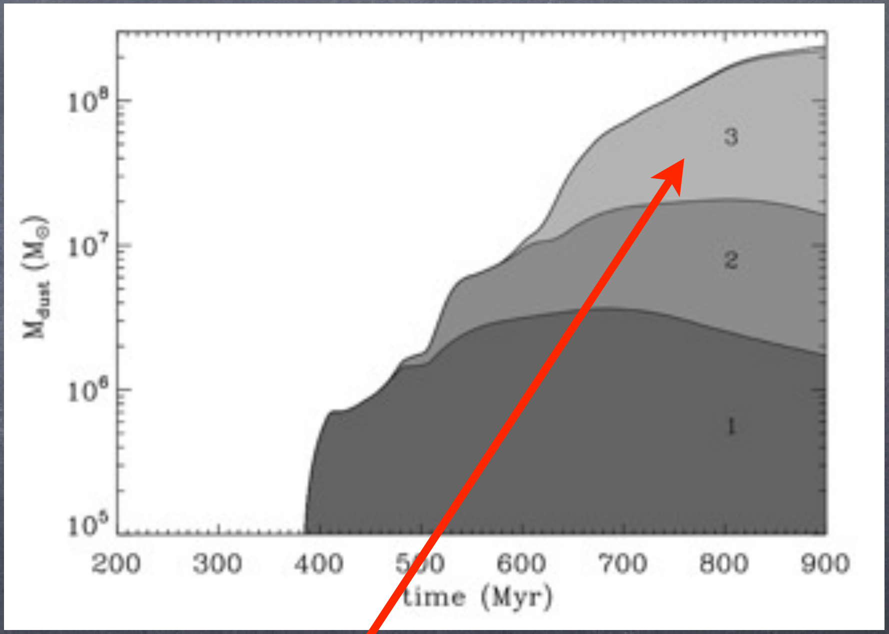
No need for grain growth in molecular clouds

The Contribution of Successive Bursts of Star Formation

Approximation the merger history with discrete bursts



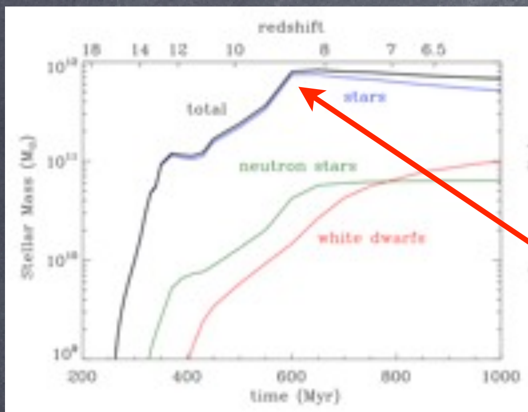
The cumulative contribution of the bursts to the dust mass



Most of the observed dust was produced by AGB stars that formed during burst # 3

The problem with the merger model

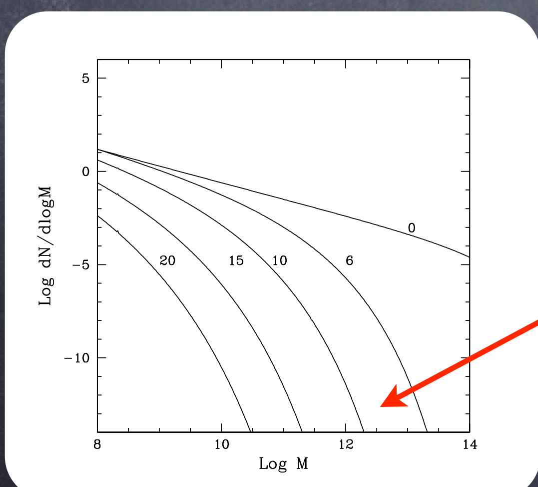
Stellar mass production (PEGASE)



7×10^{11} M_{sun} objects must have formed at $z \approx 8.5$

violates the dynamical mass limit

Press-Schechter (PS) formalism: comoving number density of collapsed halos (Mpc^{-3})



$M_{halo} \approx 4 \times 10^{12}$ M_{sun}

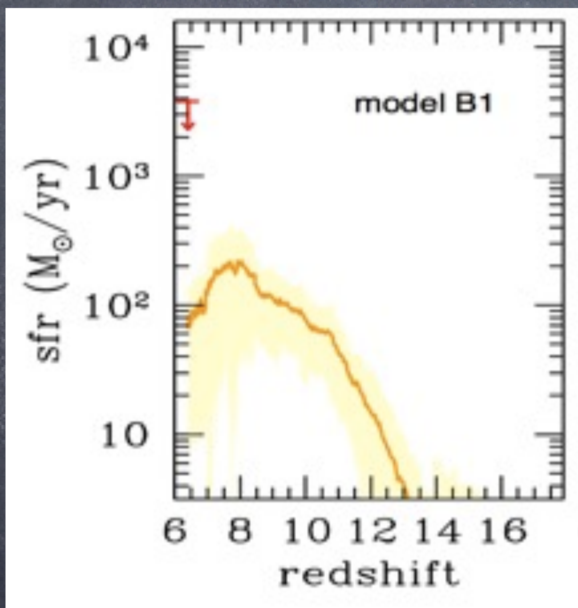
- PS formalism predicts that the number density of such objects is $\approx 10^{-12}$ Mpc^{-3}
- But the comoving number density of $z \approx 6$ QSOs is $\approx 10^{-9}$ Mpc^{-3}

J1148 a VERY rare object

The evolution of dust in J1148+5251

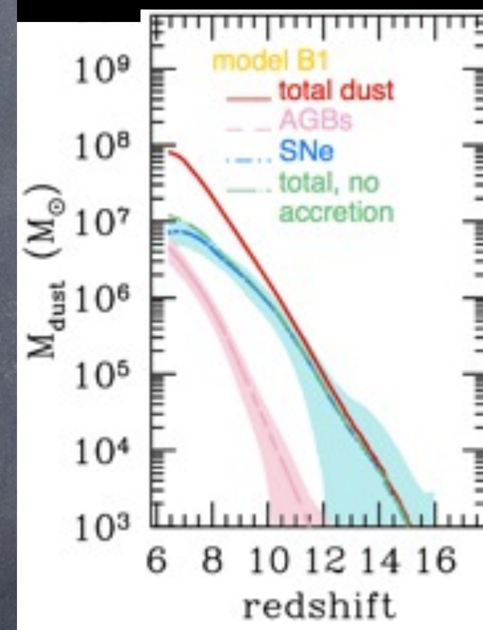
(Valiante et al. 2011)

Using a different
(less stochastic) SFR



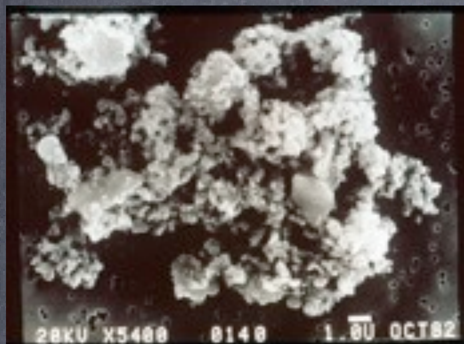
One finds that:
Accretion in ISM is the most
important source of dust in J1148

[redacted]

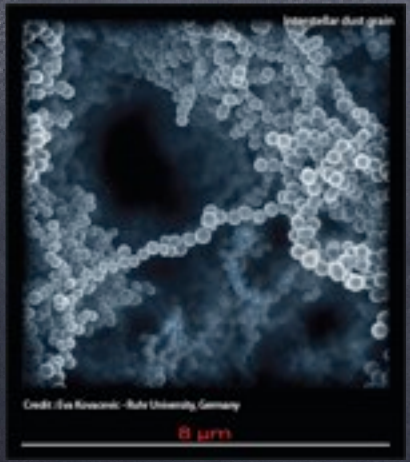


Beautiful illustration of how the star formation
history affects the dust origin

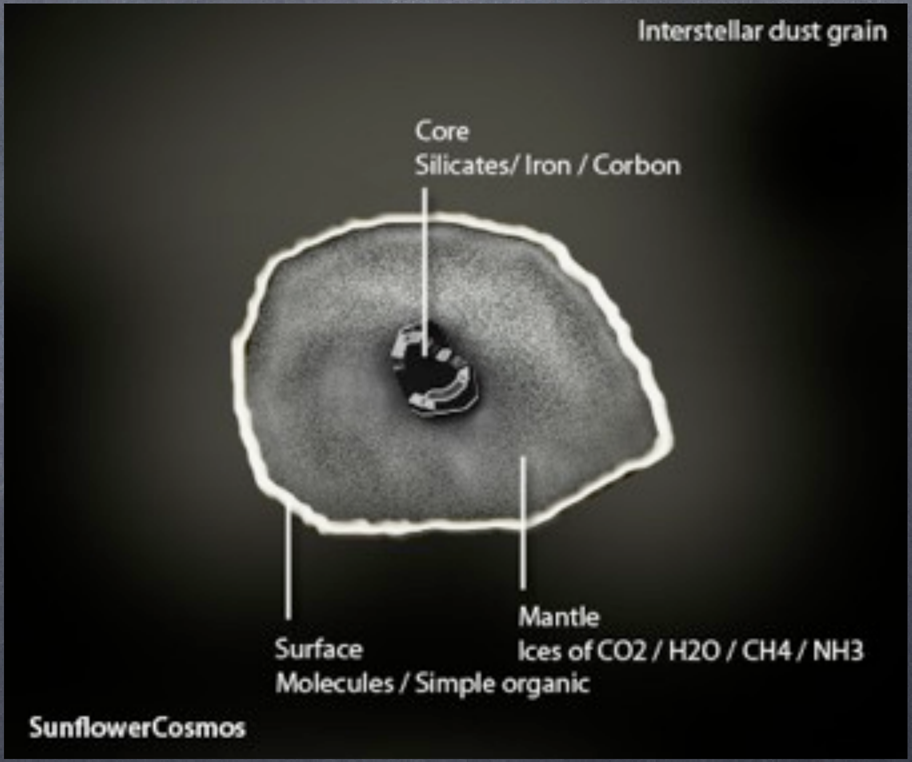
Grain processing in clouds



Coagulation



Accretion



Why is an ISM origin not the silver bullet?

- Problems with accretion model:
  - hard to maintain silicate-carbon dust separation in the ISM
  - cold accreted mantle will have different optical properties than those used in dust models
- Problems with coagulation model:
  - will have mixed silicate-carbon dust agglomorate
  - optical properties very different from those used to model IS dust
- GRAIN DESTRUCTION EFFICIENCIES MAY HAVE BEEN SEVERY OVERESTIMATED

Interstellar Dust Candidates

- Silicates
  - (MgFeSi) O_4
  - Ca, Al, Ti (?)
  - protosilicates
  - MgS
  - Fe needles
- Carbon
  - graphite
  - Amorphous carbon
  - (HAC, Be, Coal ....)
  - PAHs
- Ices
  - CO_2, H_2O, NH_4
- Vacuum

Summary

- Sources reveal a large variety of dust morphology and composition
  - silicates, oxides, sulfides, carbonaceous dust, organic refractories, ices ....
- Interstellar models consisting of spherical, bare silicate, graphite (or amorphous-C, and PAHs are successful in modeling the average dust properties in the local diffuse ISM and Xternal galaxies

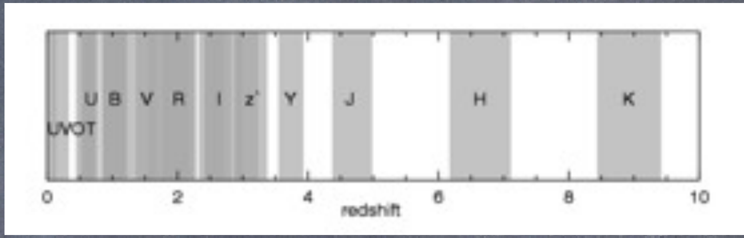
Summary - Future Prospects

- There are hints for a progression of

  SN-dust ====> AGB-dust with redshift

- Blazar photometric UV-NIR observations

Optimal filter for observing the 2175Å feature as a function of blazar redshift



- Need more spatial/spectral resolution
  - JWST:
    - 2175 Å absorption feature
    - PAH and aromatic features (3-13 μm) to $z \approx 2$


END