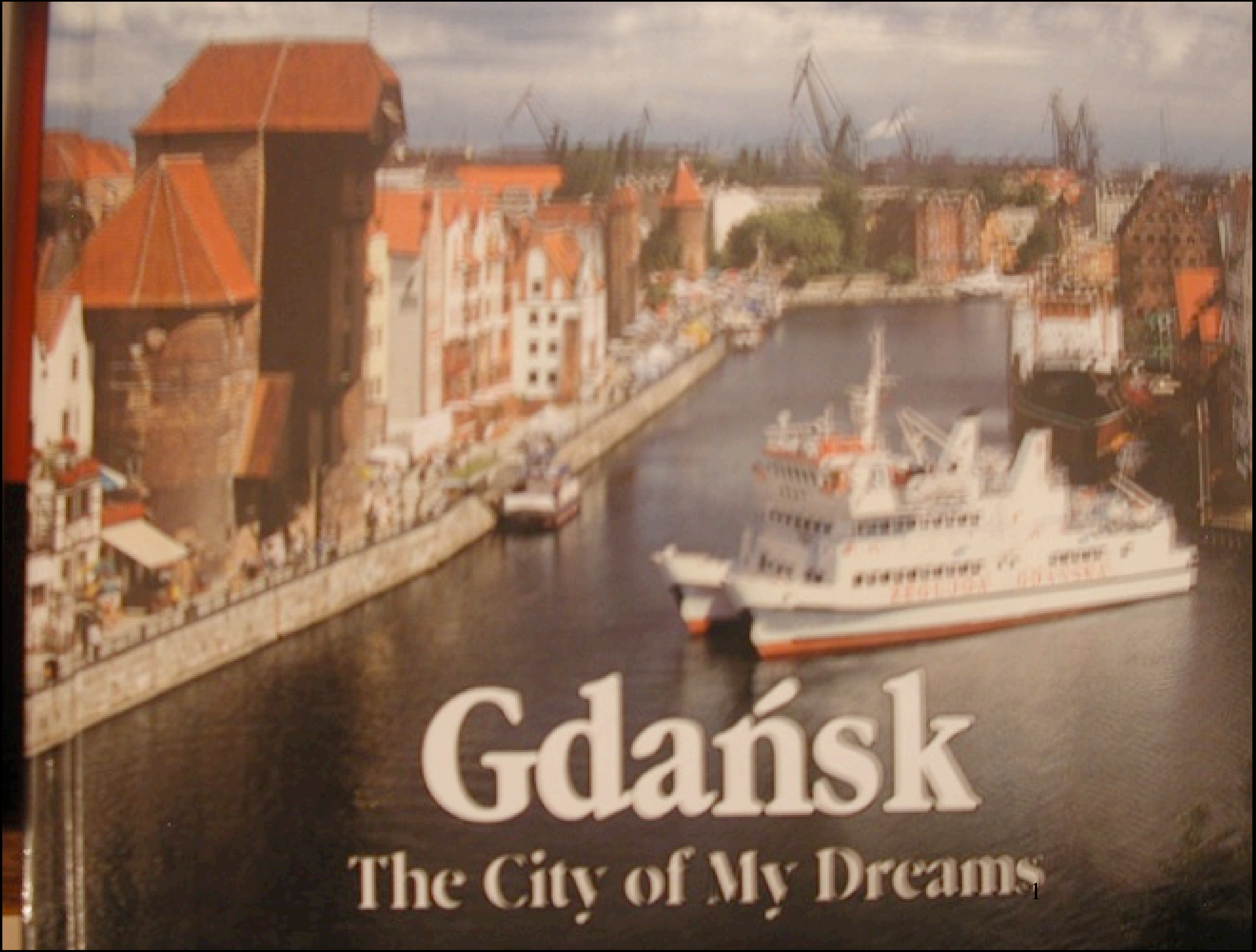


Gdańsk

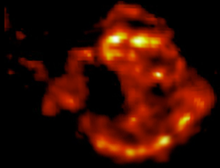
The City of My Dreams

The Evolution of Interstellar Dust

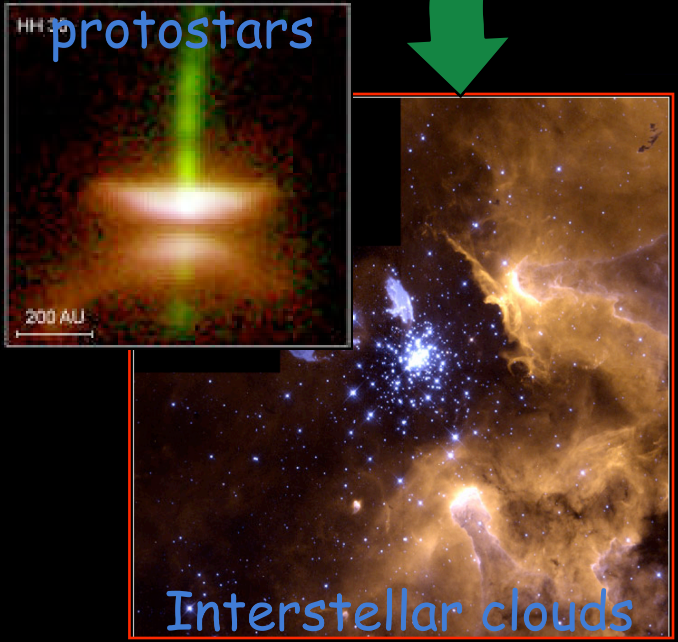
Eli Dwek

NASA/GSFC

1. Formation


SN

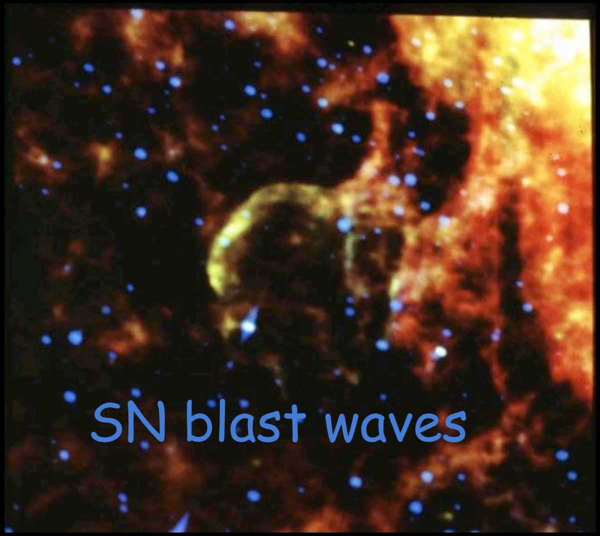

stellar
winds



protostars

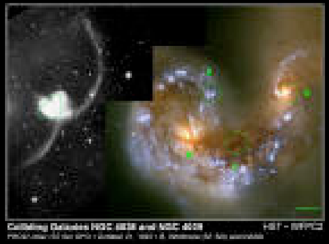
Interstellar clouds

2. Interstellar processing


SN blast waves


solar nebula


Antennae - IR


Antennae - opt

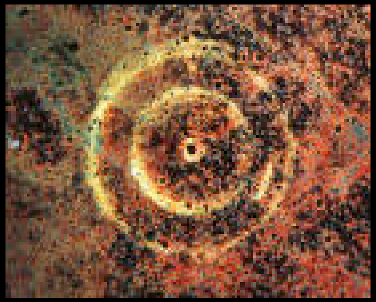
Lecture Outline

- What does interstellar dust look like today
- Sources of dust
  - Quiescent outflows
    - AGB winds, WR (fast) winds
  - Explosive ejecta
    - Supernovae, Novae
- Destruction and processing of dust
  - Interstellar shocks
  - Shocks in the sources (injection into ISM)
- Putting it all together in a SIMPLE evolutionary model
  - The evolution of carbon dust and PAHs

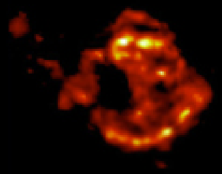
Manifestation of Interstellar Dust

extinction/obscuration
reddening of starlight

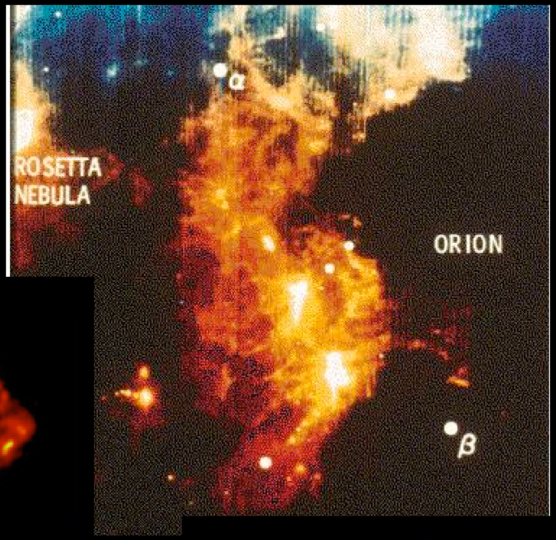
light echoes – SN 1987a
X-ray halos



Cas A

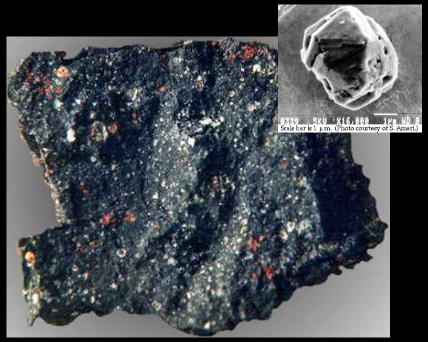


IR emission from
general ISM

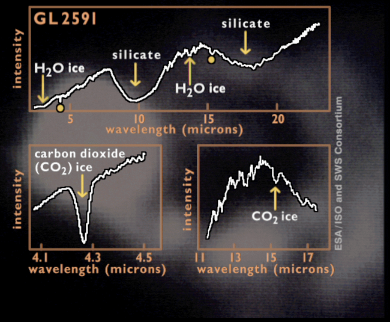


reflection/polarization
of starlight

presence in
meteorites & SS



Scale bar is 1 μm. (Photo courtesy of S. Amari.)



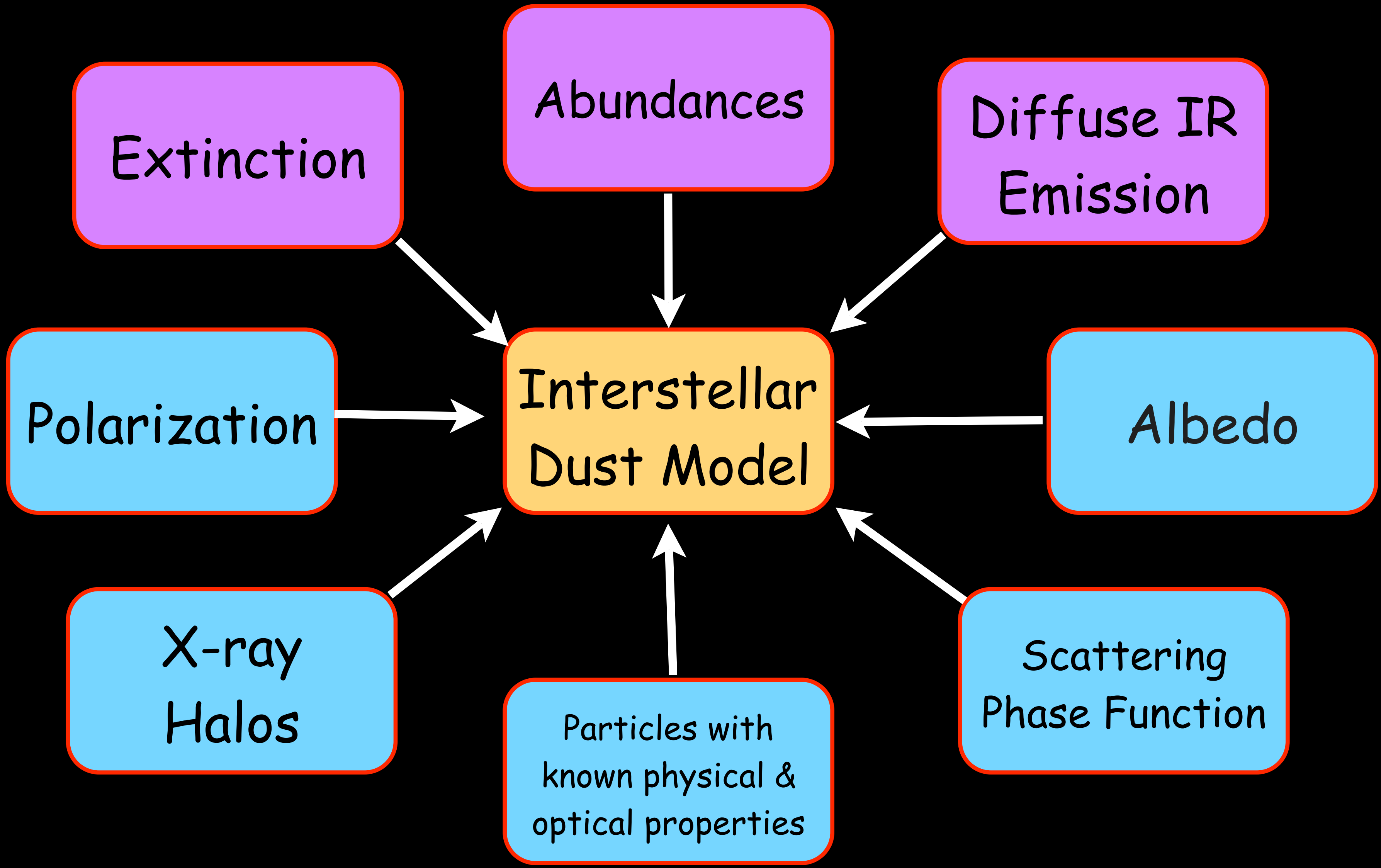
circumstellar-GL2591

Interstellar dust is completely characterized by

- Grain composition
- Abundance
- Size distribution
- Morphology

A complete evolutionary model should be able to explain the spatial and temporal behavior of these characteristics

Ideally, any interstellar dust model must be derived by simultaneously fitting all observational constraints



Extinction

Abundances

Diffuse IR Emission

Polarization

Interstellar Dust Model

Albedo

X-ray Halos

Particles with known physical & optical properties

Scattering Phase Function

Dust Models Consistent with

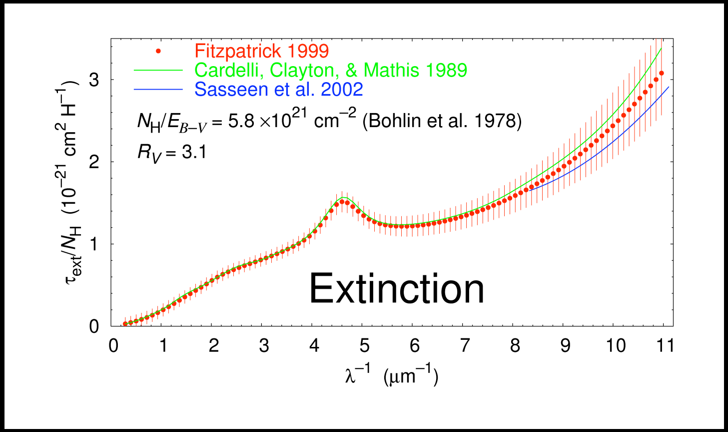
Extinction

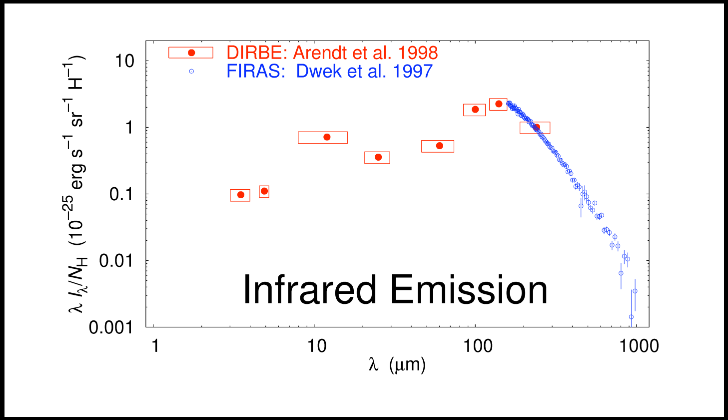
IR emission

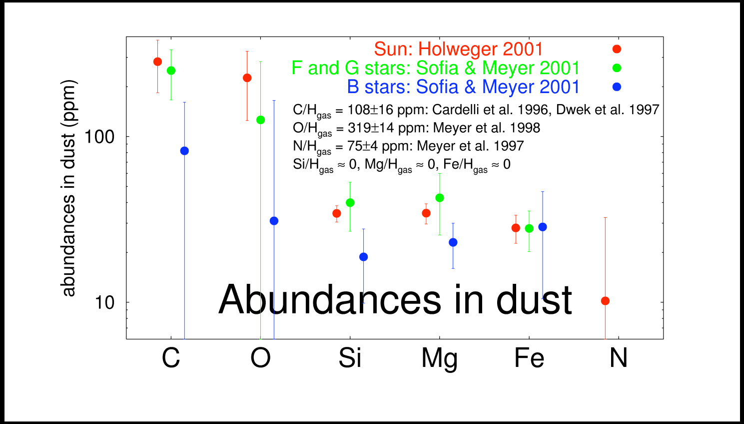
Abundances !

constraints.

(Zubko, Dwek, & Arendt 2004)







Bare dust

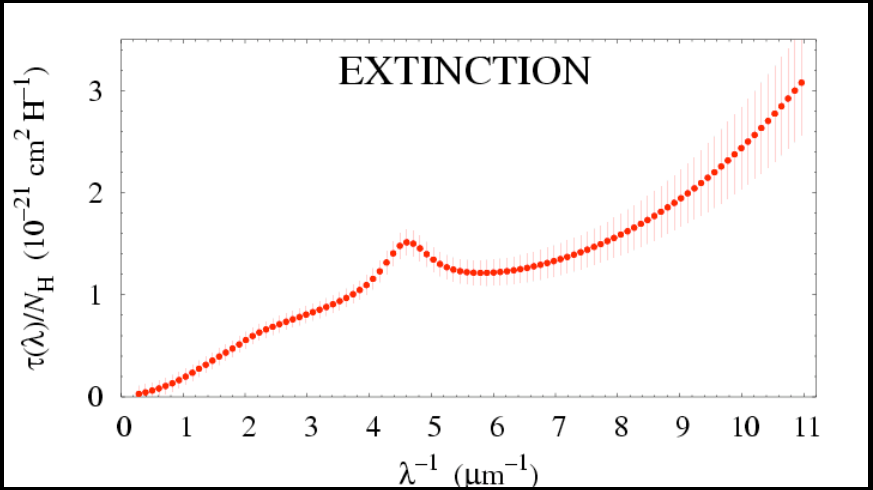
- PAHs
- Graphite
- Amorphous carbon (ACH2, BE, ACAR)
- Silicate ($MgFeSiO_4$)

Composite dust consisting of:

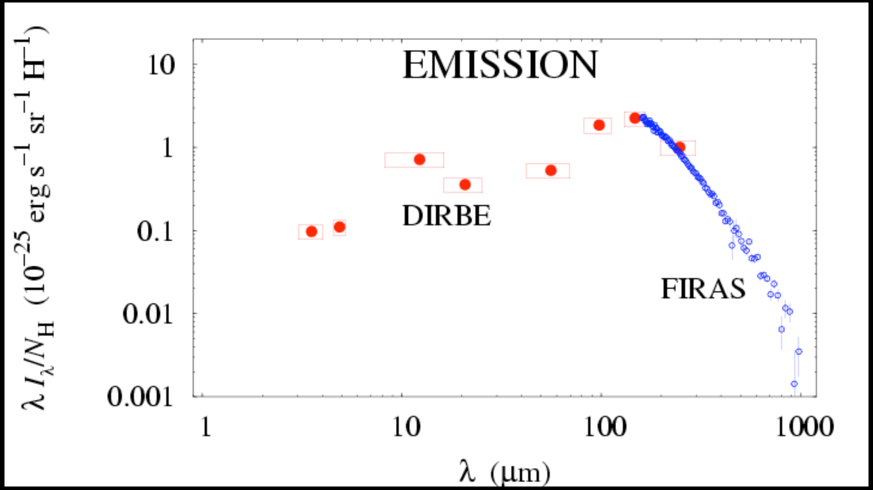
- Silicate ($MgFeSiO_4$)
- Organics ($C_8 H_8 O_4 H$)
- Water ice (H_2O)
- Voids (10 – 60%)

Observational Constraints on Dust in the Diffuse ISM

Fitzpatrick (1999), Cardelli et al. (1989), Sasseen et al. (2002)



Dwek et al. (1997)

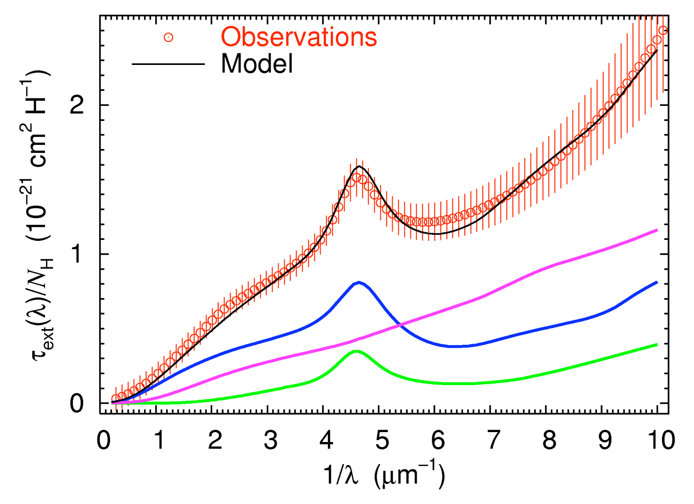


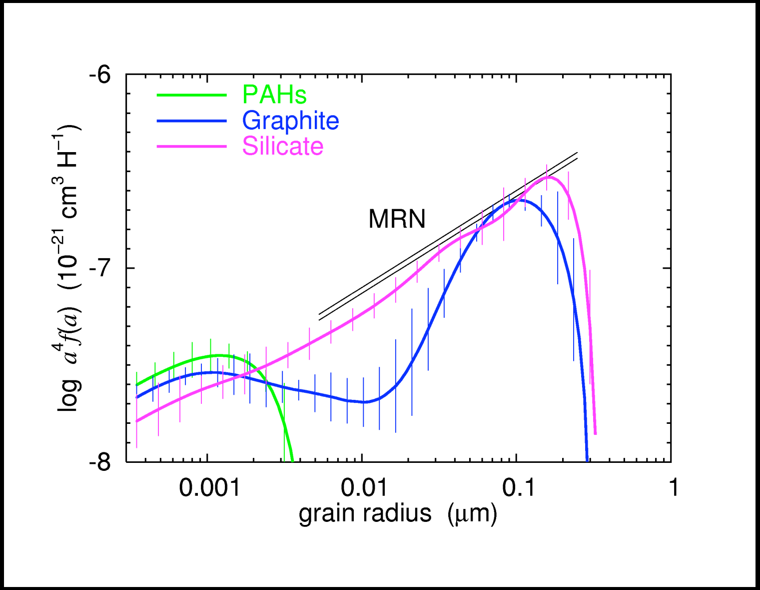
	Solar	F&Gstars	Bstars
C	391±98	358±82	190±77
(gas)		100±50	
O	545±100	445±156	350±133
Mg	35±5	43±17	23±7
Si	34±4	40±13	19±9
Fe	28±5	28±8	29±18
N	85±22	------	65±34

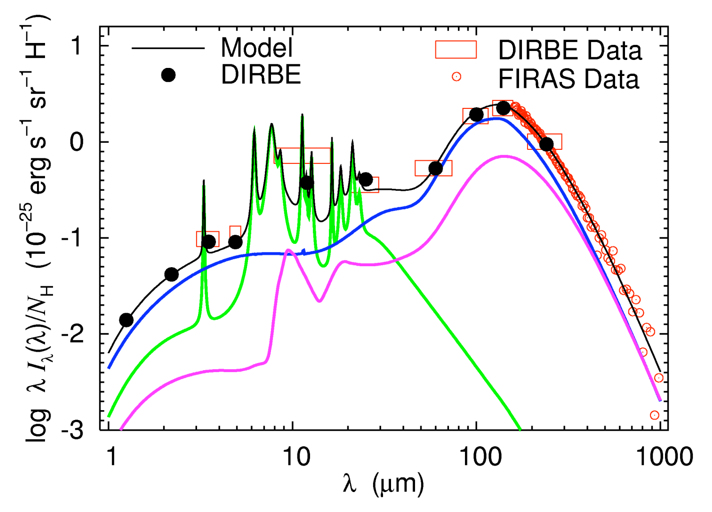
Sofia & Meyer, 2001, ApJ, 554, L211
ApJ, 556, L147

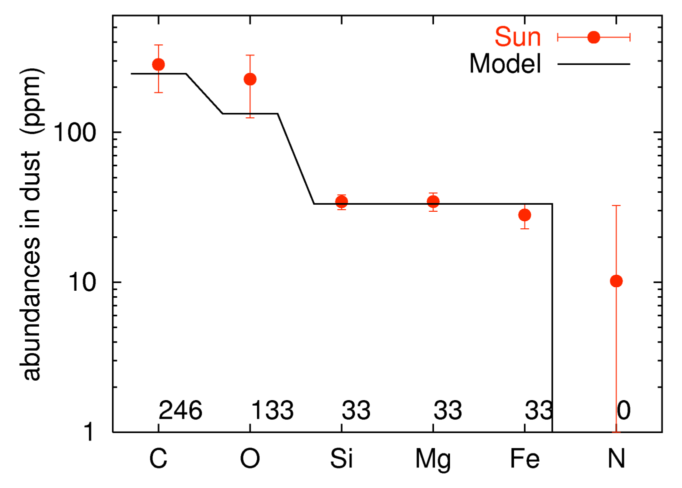
Carbon Crisis Snow & Witt (1995),
Mathis (1996), Dwek (1997)

Bare dust: PAH, Grf , Sil, - Solar abundances

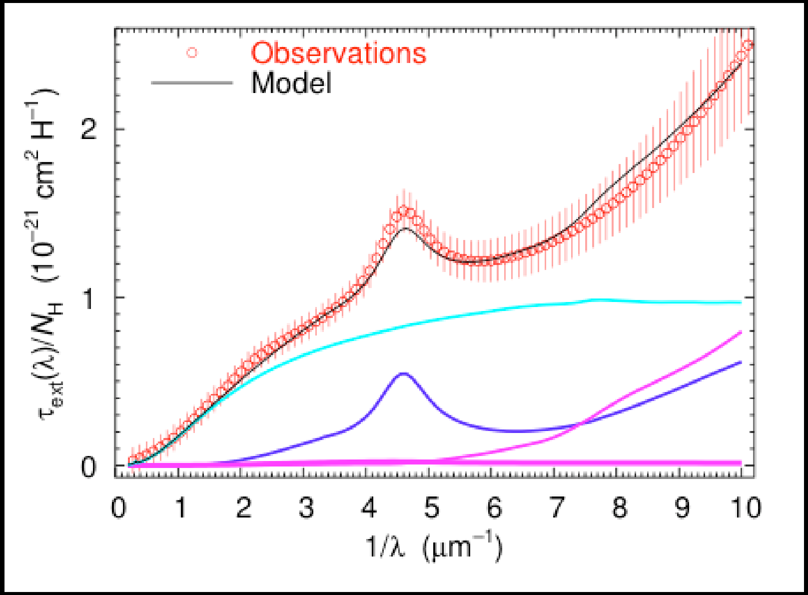


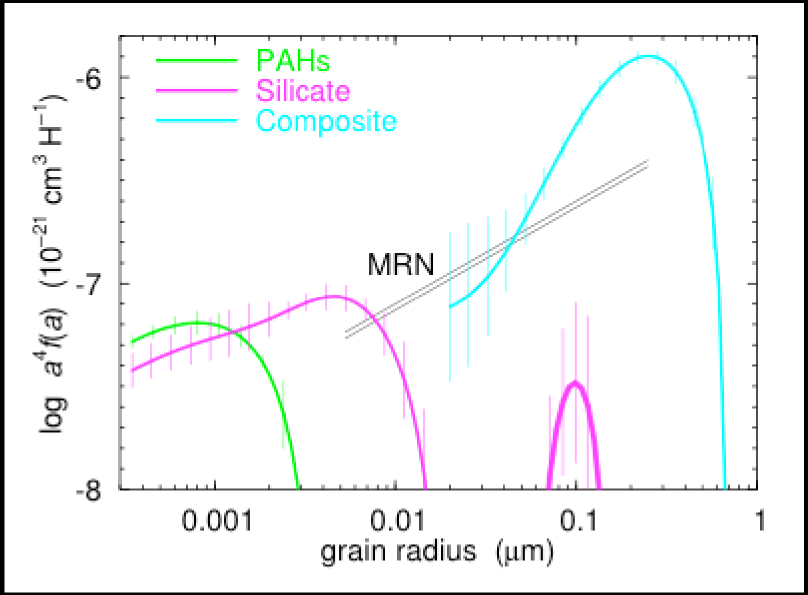


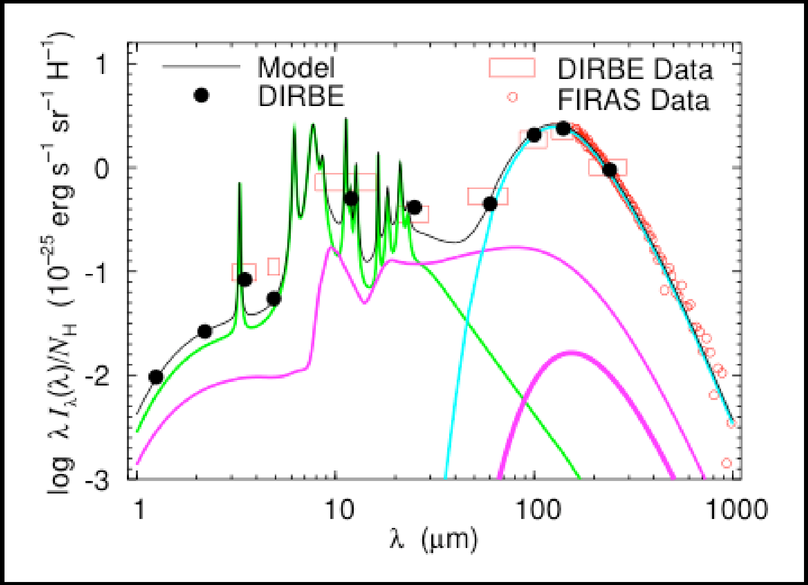


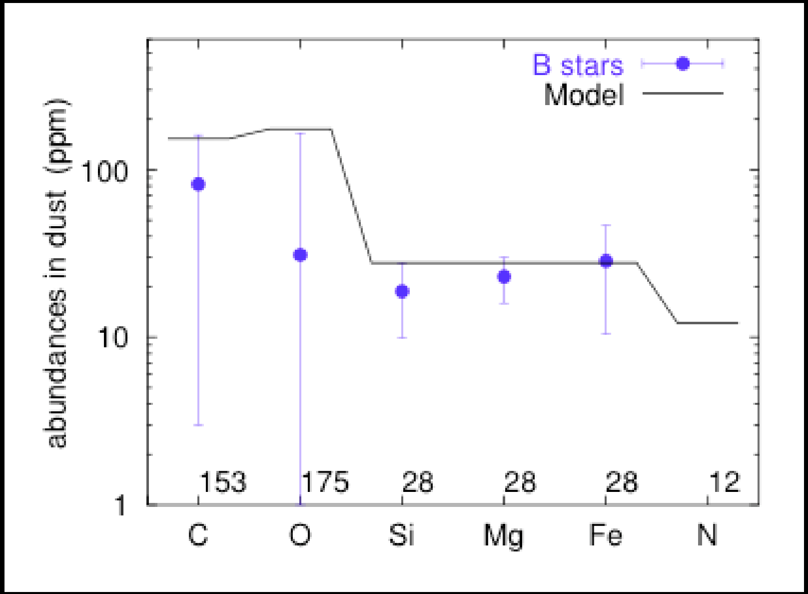


Composite dust: PAH, no C, Sil - B-star abundances

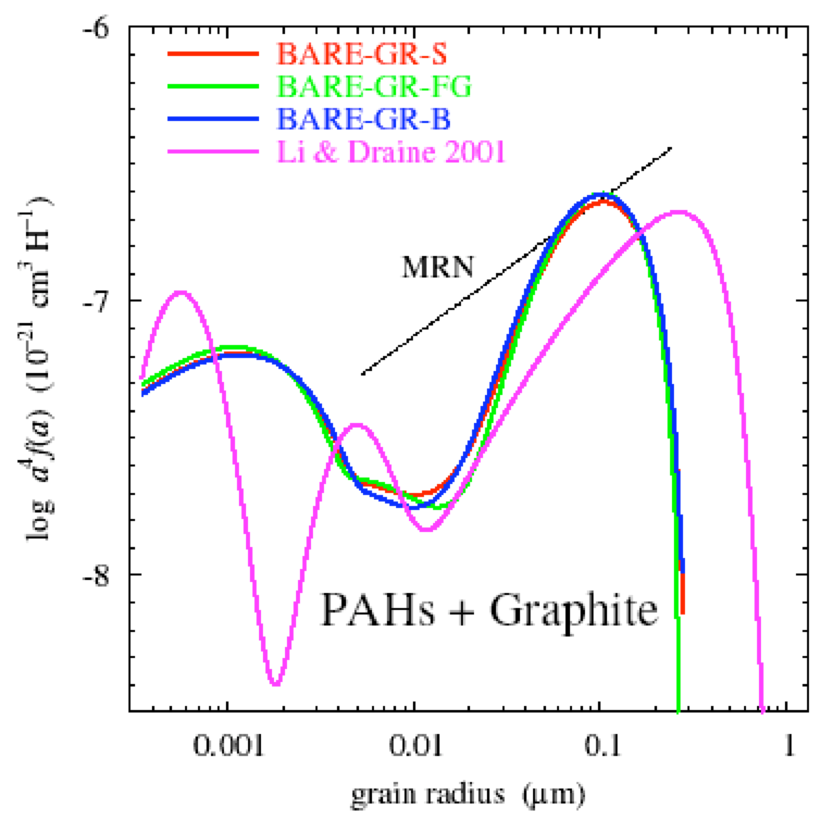


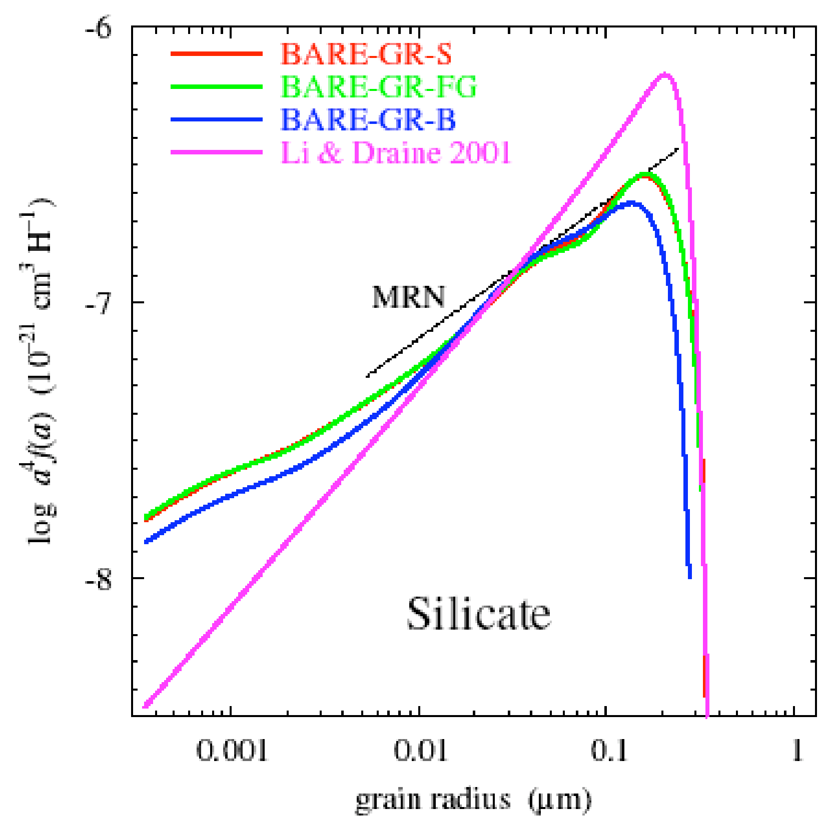






Comparison of Li-Draine to Zubko-Dwek-Arendt

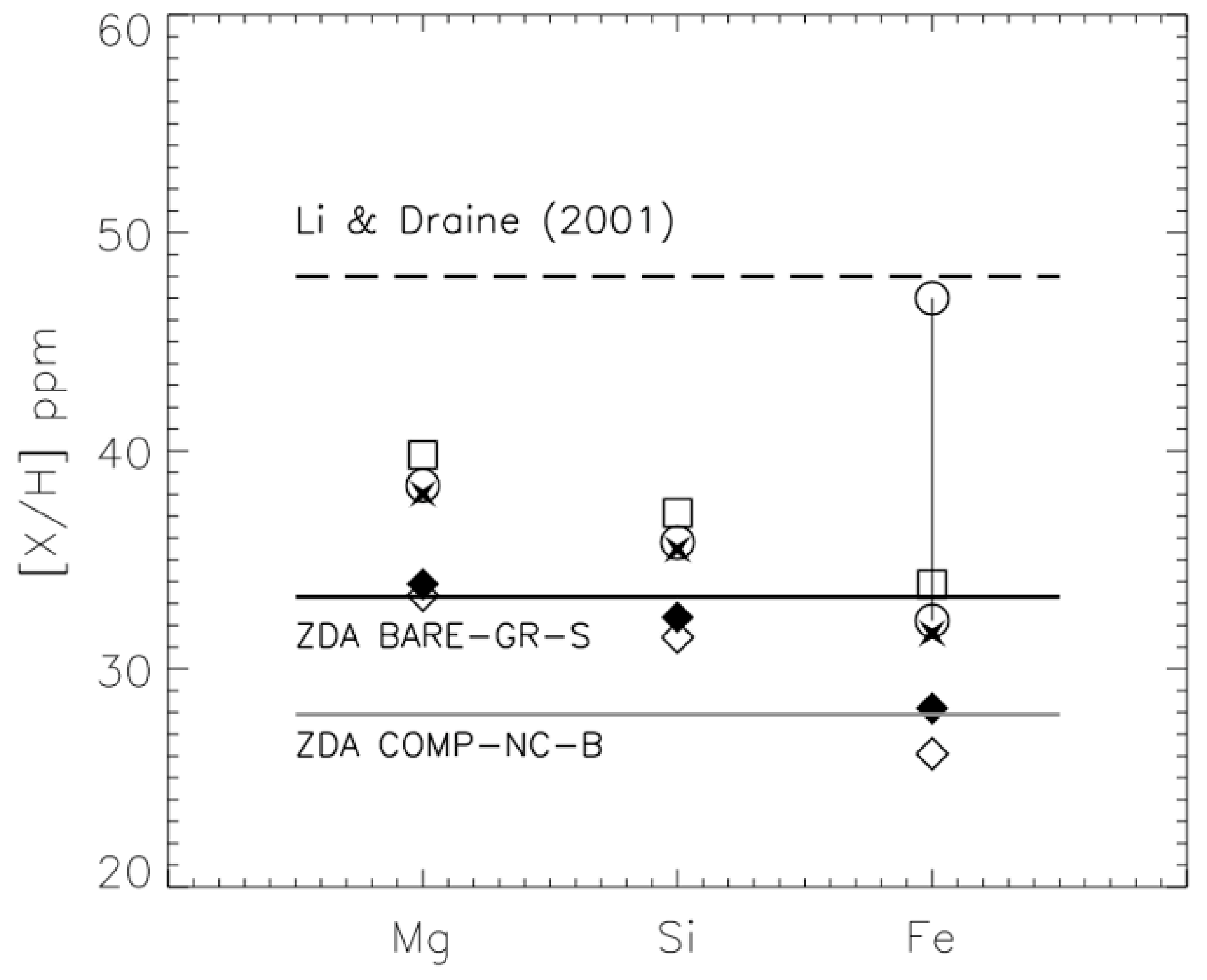




Li & Draine: C/H ≈ 230 ppm
Zubko et al: ≈ 250 ppm

Li & Draine: Si/H ≈ 50 ppm
Zubko et al: ≈ 33 ppm

Abundance Constrains in Various Dust Models



SUMMARY

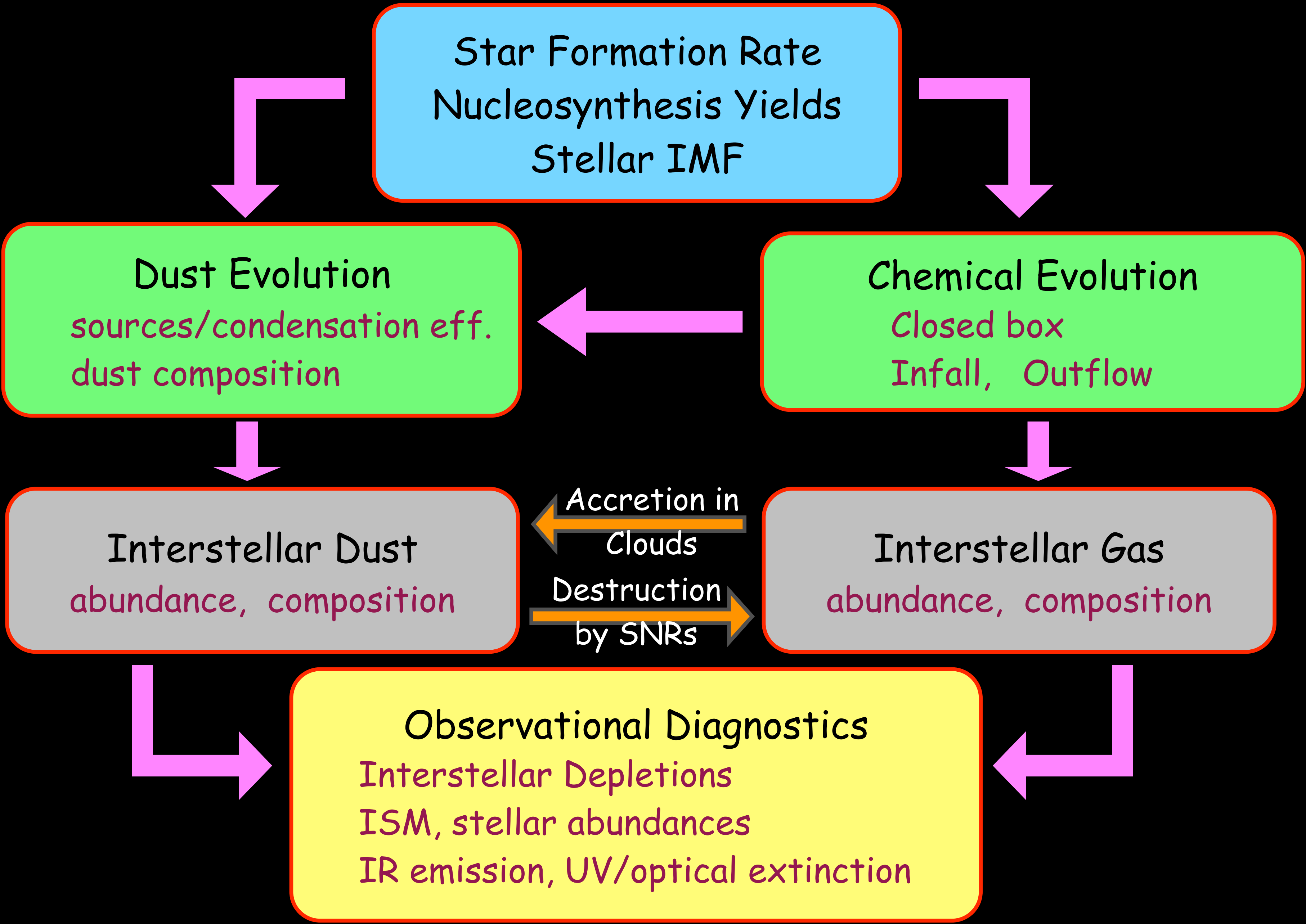
- In the local ISM, there are ~12 interstellar dust models that simultaneously satisfy the average interstellar extinction, diffuse IR emission, and IS abundances constraints

- "Canonical" abundances:

  Zdust ≈ 0.0073

  Zsil/Zcrb ≈ 0.0048/0.0025

Modeling the Evolution of Dust



Star Formation Rate
Nucleosynthesis Yields
Stellar IMF

Dust Evolution
sources/condensation eff.
dust composition

Chemical Evolution
Closed box
Infall, Outflow

Interstellar Dust
abundance, composition

Accretion in Clouds

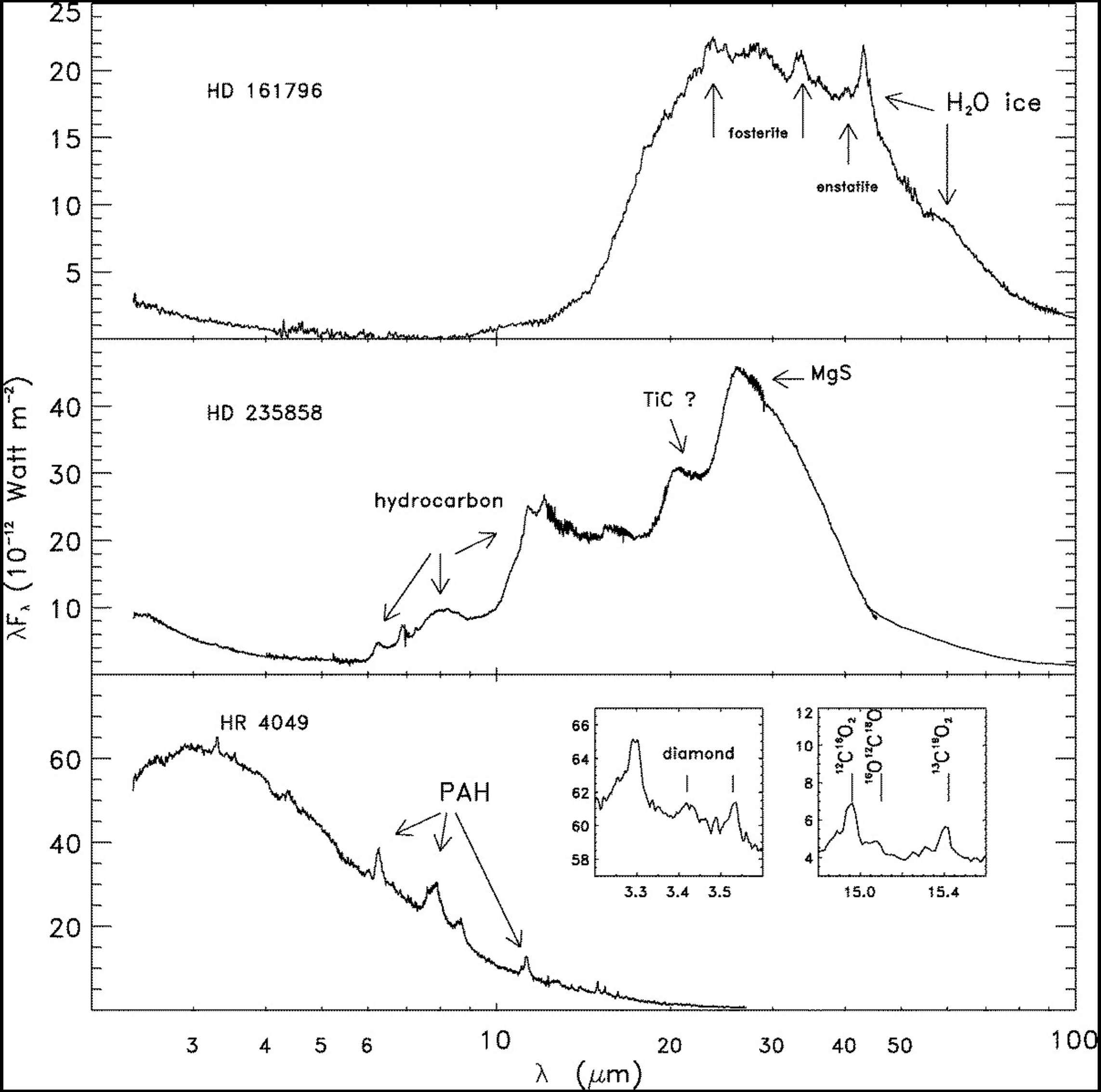
Destruction by SNRs

Interstellar Gas
abundance, composition

Observational Diagnostics
Interstellar Depletions
ISM, stellar abundances
IR emission, UV/optical extinction

Dust Formation in AGB stars

Dust sources: AGB stars



O-rich

$C/O < 1$

C-rich

$C/O > 1$

PAHs

$C/O > 1$

Mixed Chemistry in AGB stars

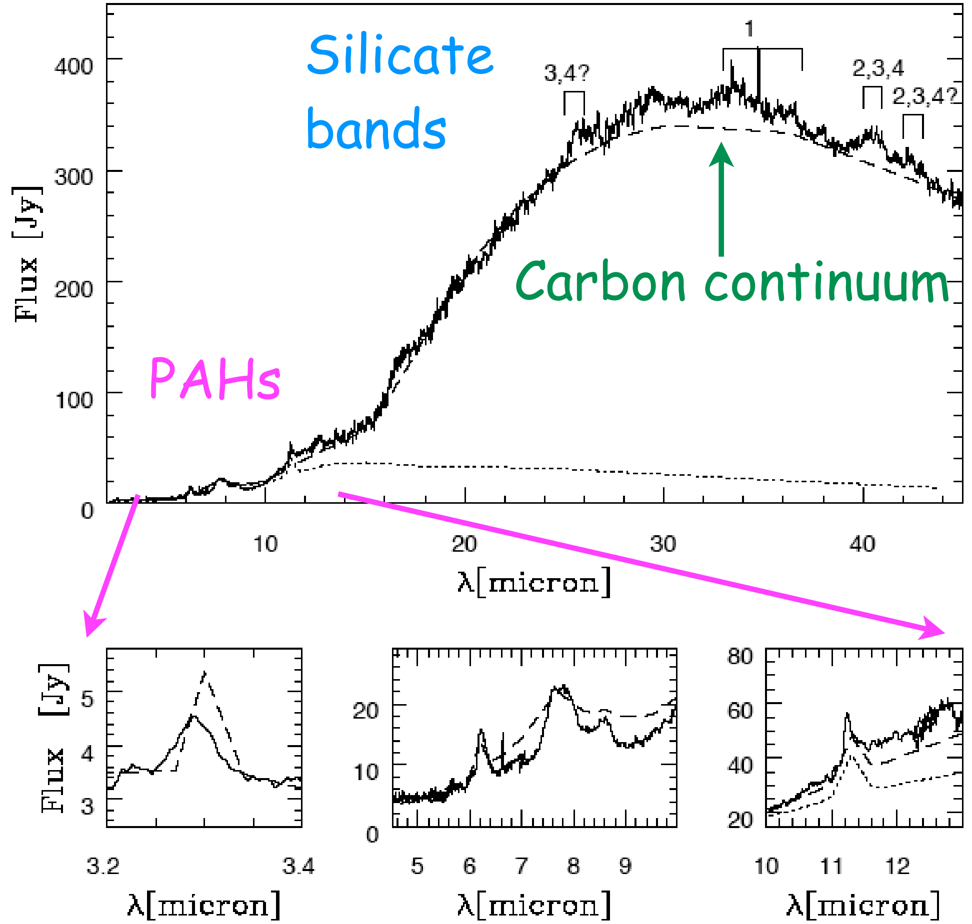


Fig. 7.— ISO/SWS spectra. The numbers show the identifications of crystalline silicate bands:'1' forsterite + plateau, '2' enstatite, '3' diopside, and '4' anorthite. Emission lines at 6.63 and 34.8 μm could be due to CI. The dashed line is the two-component model described in the text. The dotted line represents the continuum component of the model spectra due to the carbon grains only. The spectra of PAH features are enlarged in the bottom.

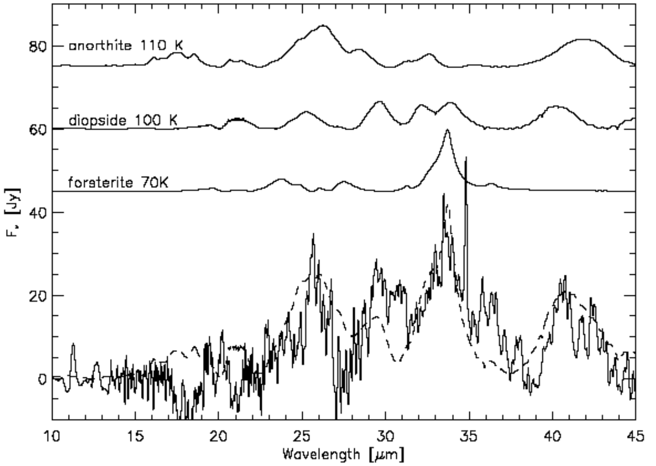


Fig. 9.— The continuum-subtracted ISO/SWS spectra (solid line). The dashed line shows the fitting of the crystalline bands (Molster et al. 2002b). The dust properties are measured by Koike et al. (1999, 2000); Chihara et al. (2003).

Mixed chemistry:

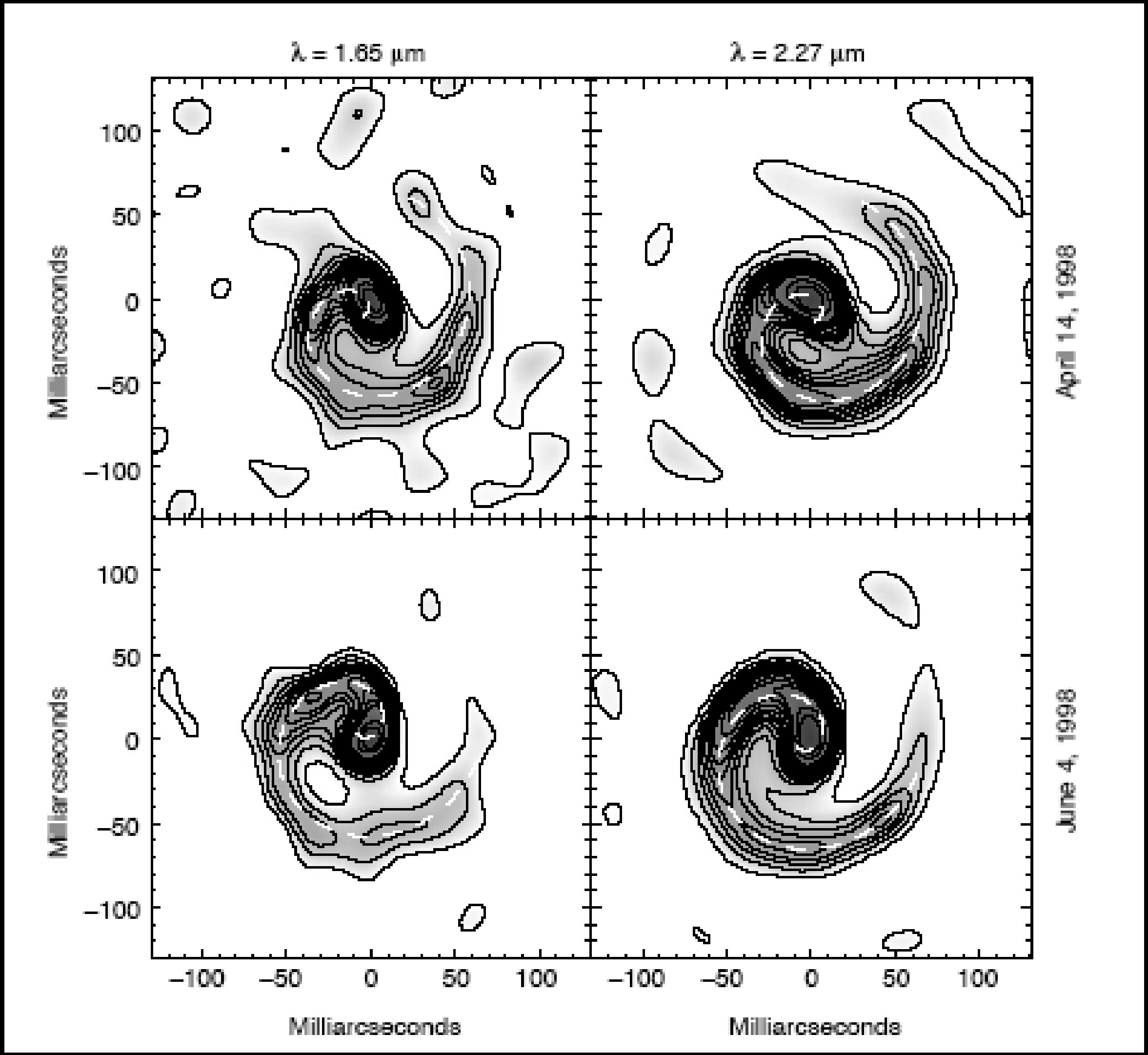
PAH and silicate features are present in the source Spectrum

- evolution from O- to C-rich?
- binary stellar system?

Dust Formation in Wolf-Rayet Stars

Dust sources: WR stars

(Tuthill, Monnier, & Danchi 1999)



Dust sources: WR stars

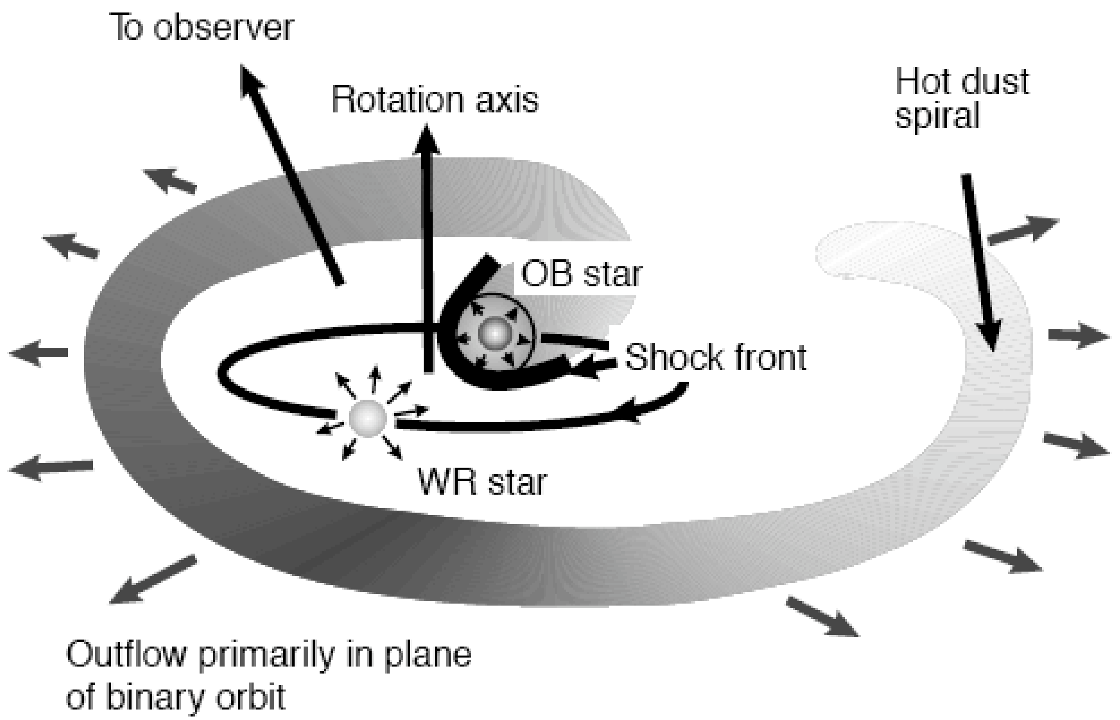


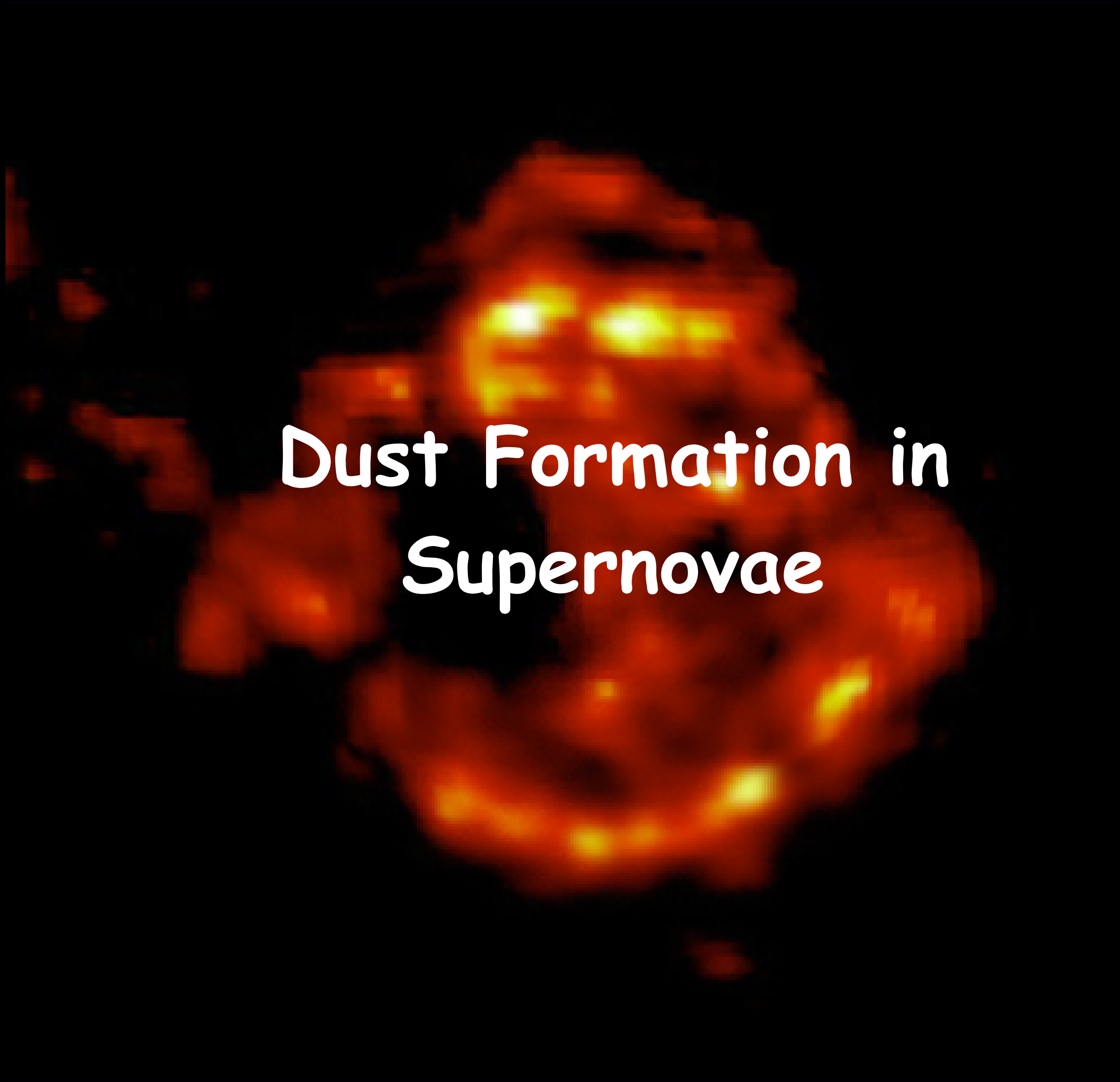
Figure 2 Schematic diagram of the WR104 binary system. The illustration shows the WR star, the OB companion, wind–wind collision front, and the resultant dust outflow plume (not to scale). The spiral shape is a consequence of material being swept radially outwards by the WR wind from a rotating dust nucleation zone associated with the shock front where the stellar winds collide.

Dust formation in the outflow from the WR star is induced by the wind-wind interaction with the OB companion

(Monnier, Tuthill & Danchi 2002)

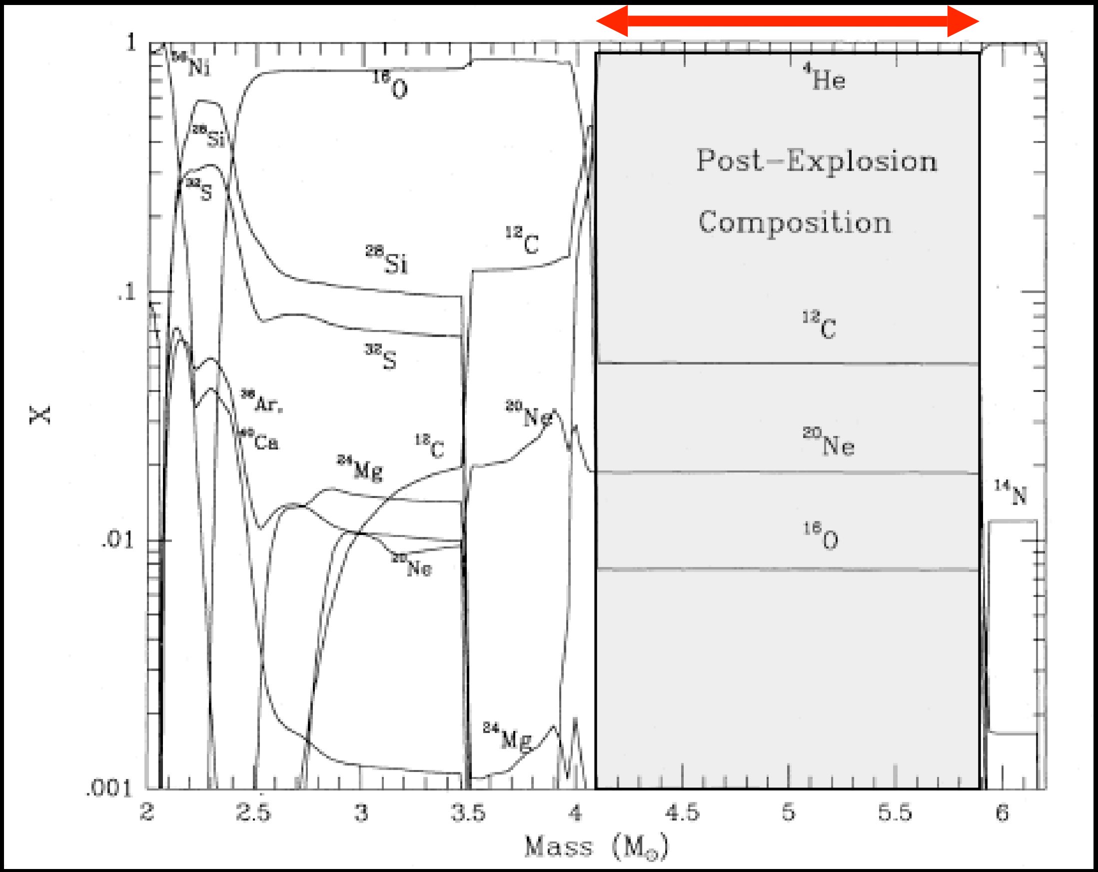
Dust formation only observed in WRCs

Dust Formation in Supernovae



SN 1987A Yield of Condensable Elements

C/O > 1



Element	Y(M_{sun})
C	0.1
O	0.4
Mg	0.02
Si	0.3
Fe	0.07

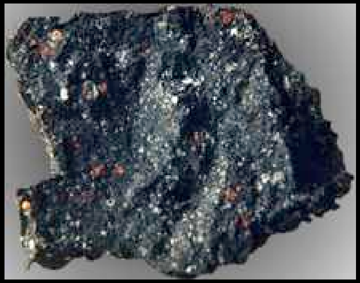
Dust ≈ 1 M_{sun}

Silicates: SiO_2

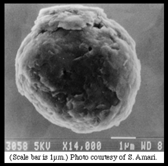
Carbon: C

Interstellar Grains in Meteorites

Murchison

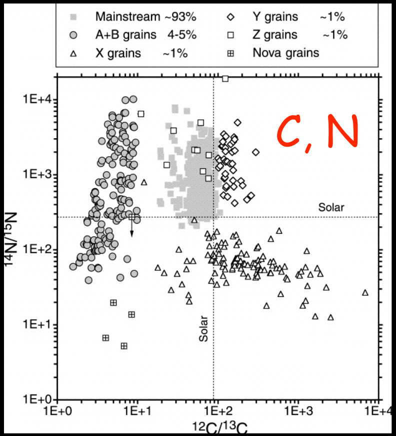


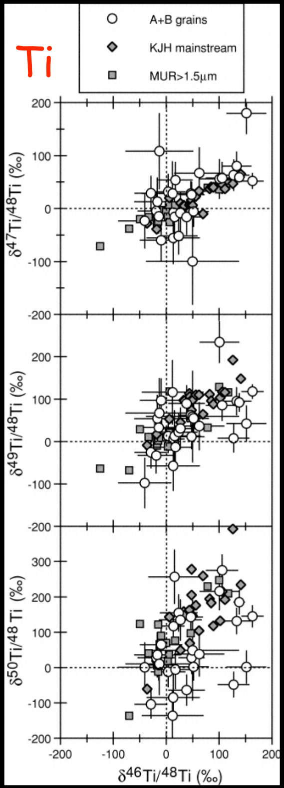
SiC
(Red Giants)



graphite

(Supernovae)


C, N


Ti

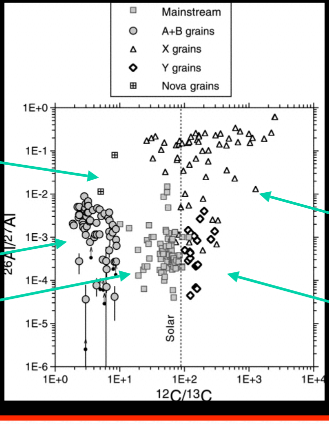
Al

Nova

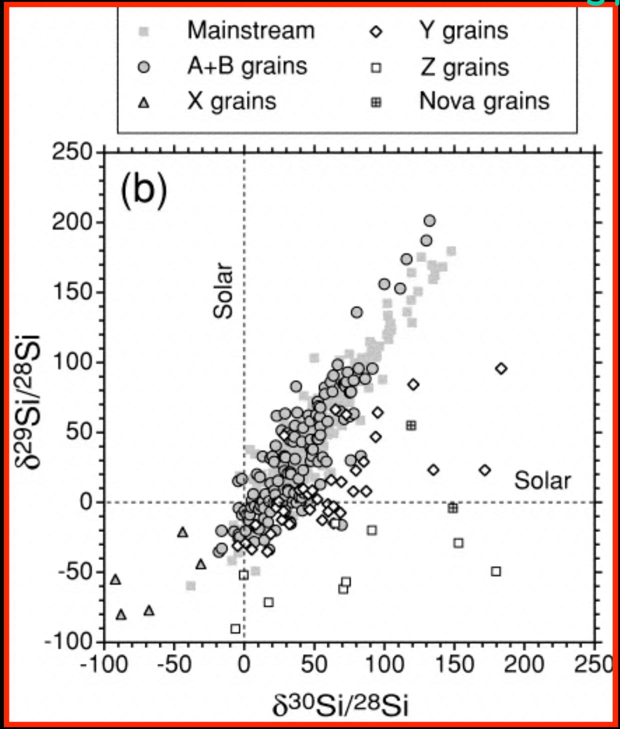
AGB stars

Supernova

AGB stars

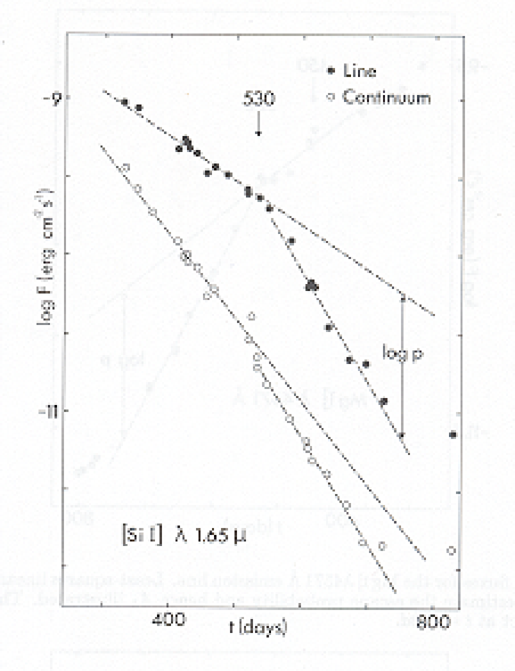


Si

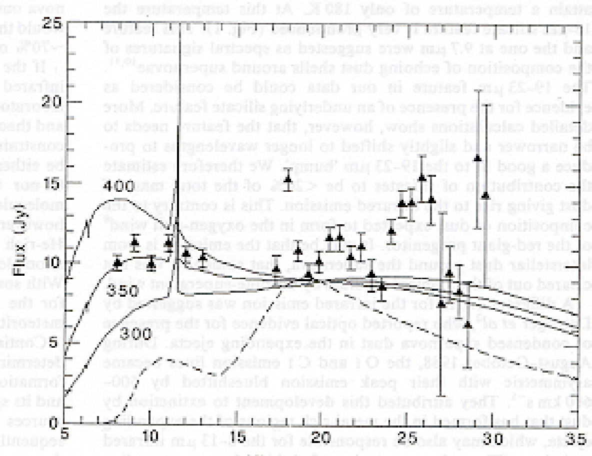


Dust Formation in SN 1987a

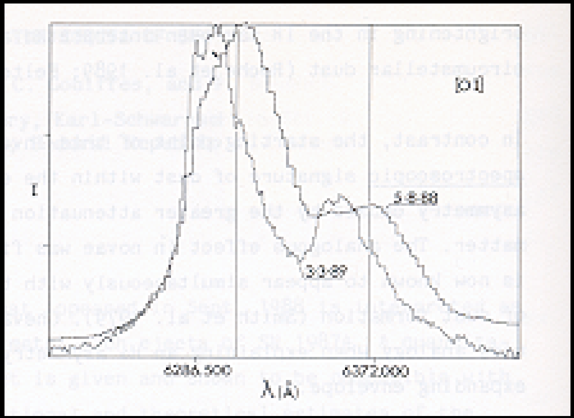
Si depletion
(Lucy et al. 1991)



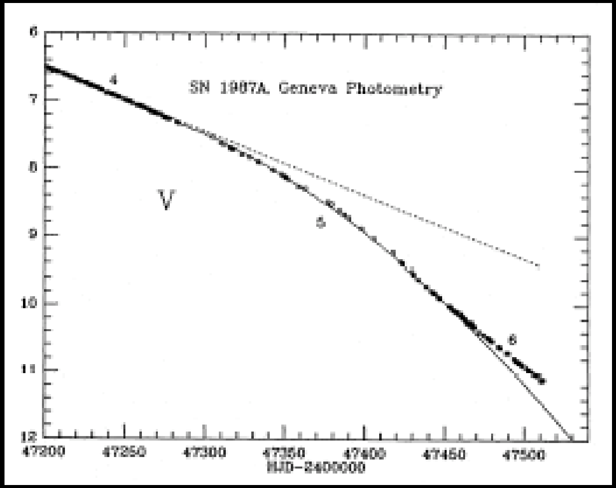
IR emission
(Moseley et al. 1989)



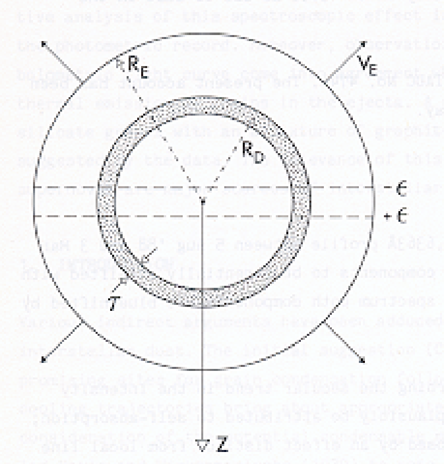
[OI] line extinction
(Lucy et al. 1989)



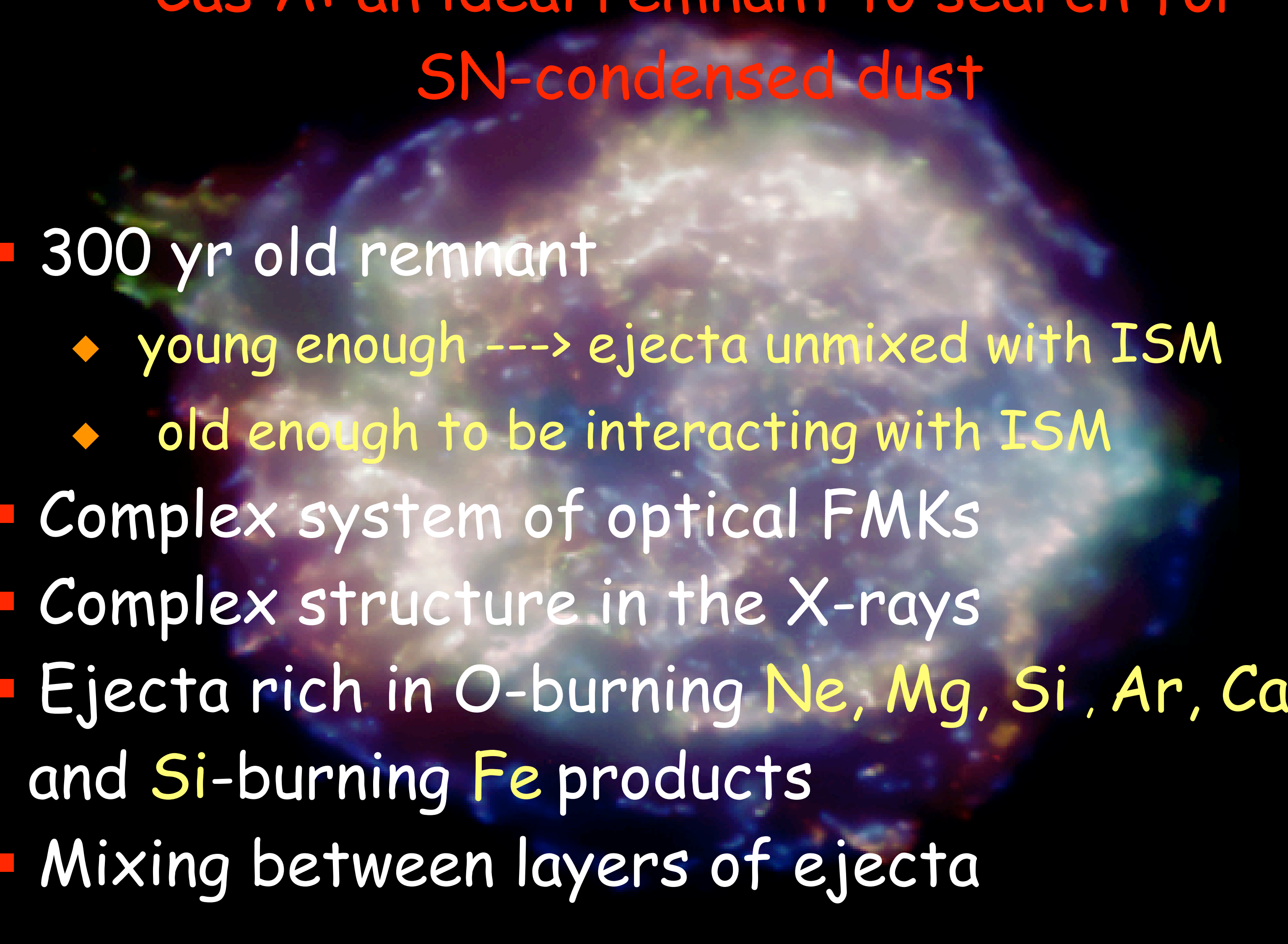
Light curve energetics
(Burki et al. 1989)



Model



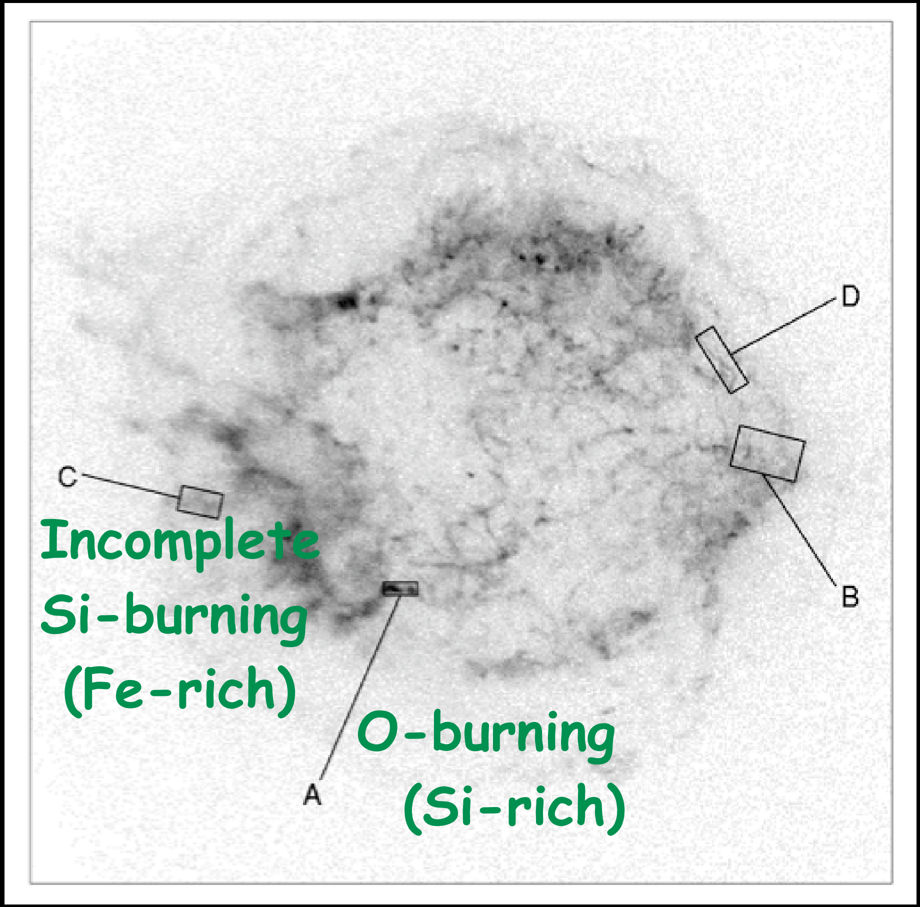
Cas A: an ideal remnant to search for SN-condensed dust



- 300 yr old remnant
  - young enough ---> ejecta unmixed with ISM
  - old enough to be interacting with ISM
- Complex system of optical FMKs
- Complex structure in the X-rays
- Ejecta rich in O-burning Ne, Mg, Si , Ar, Ca and Si-burning Fe products
- Mixing between layers of ejecta

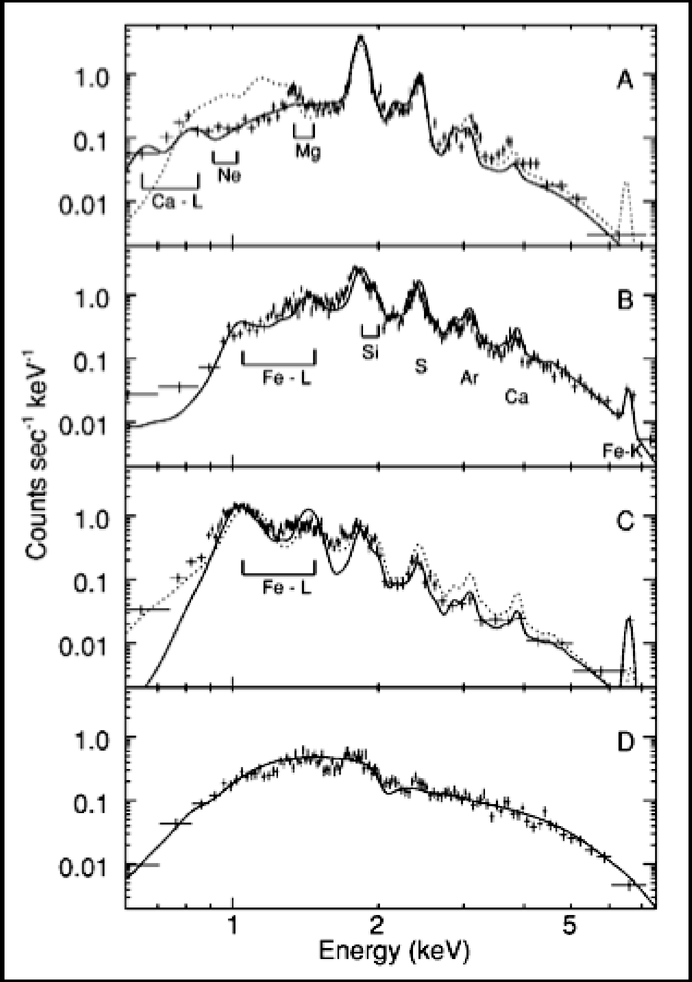
Mixing in Cas A

(Hughes et al. 2000)

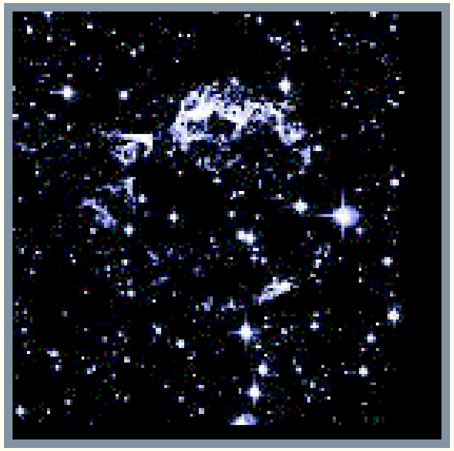


Incomplete Si-burning (Fe-rich)

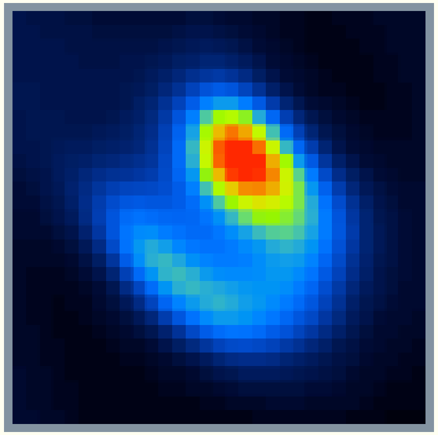
O-burning (Si-rich)



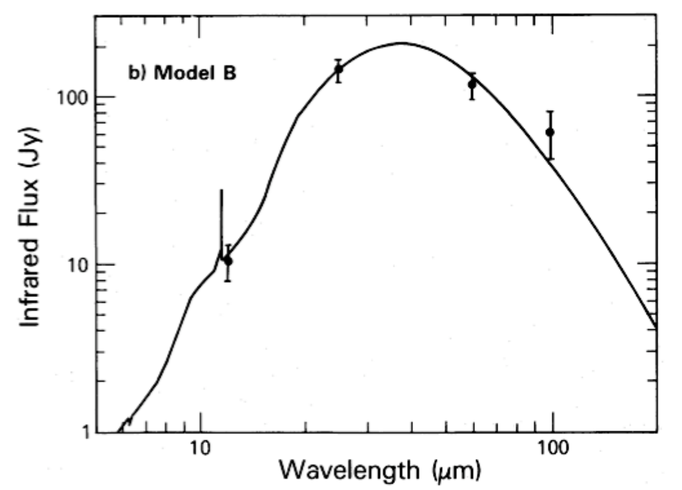
Multiwavelength Cas A

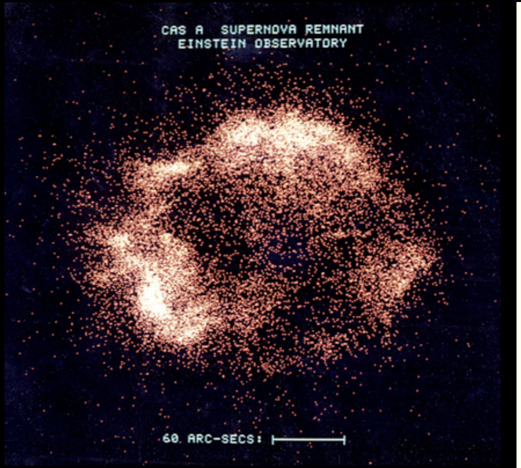


Visible: (Robert Fesen)

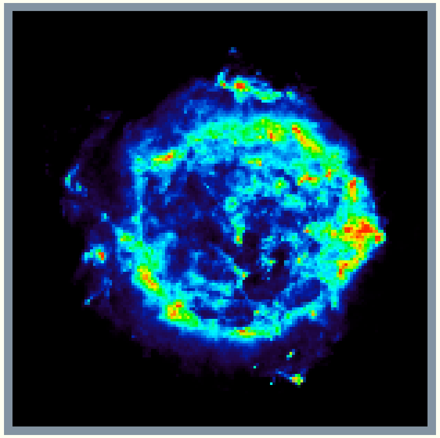


Far-Infrared: IRAS





Xray:



Radio: ©1992 NRAO

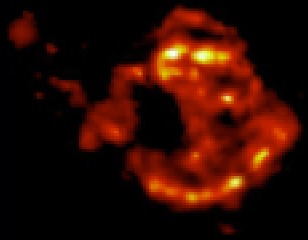
$T_{dust} \approx 100$ K

$M_{dust} \approx 10^{-3}\ M_{sun}$

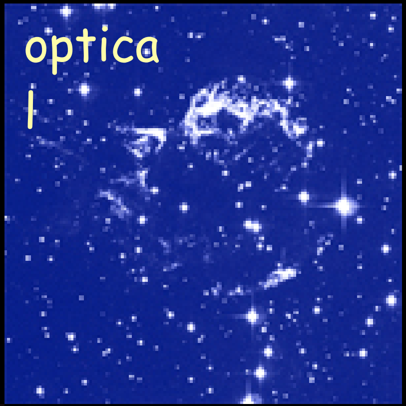
(Dwek et al. 1987)

Dust Formation in the Ejecta of Cas A

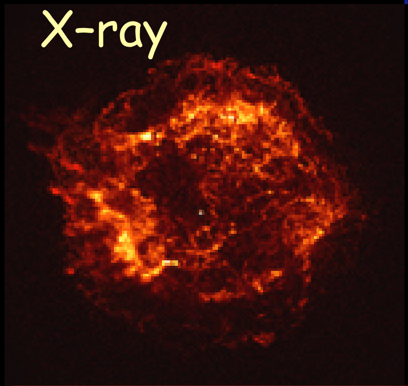
ISO - 11 μm
(Lagage et al.)



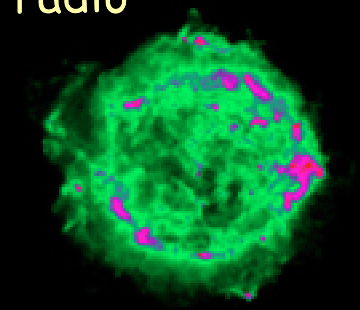
optical



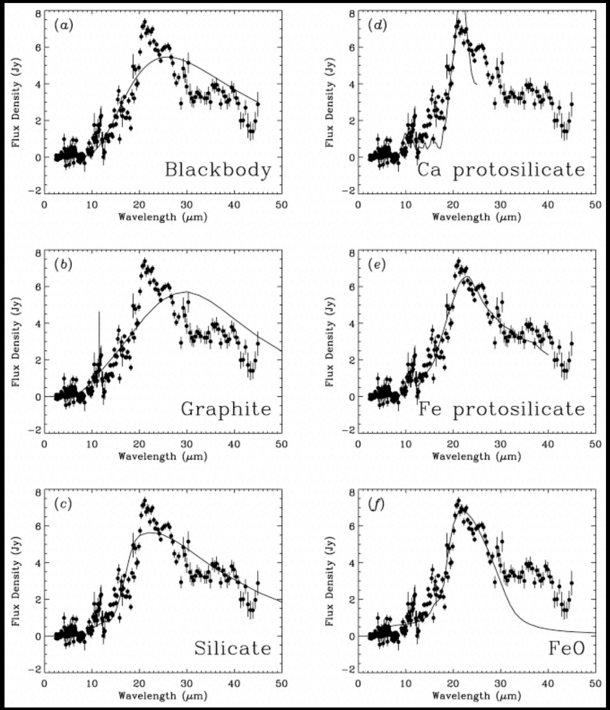
X-ray

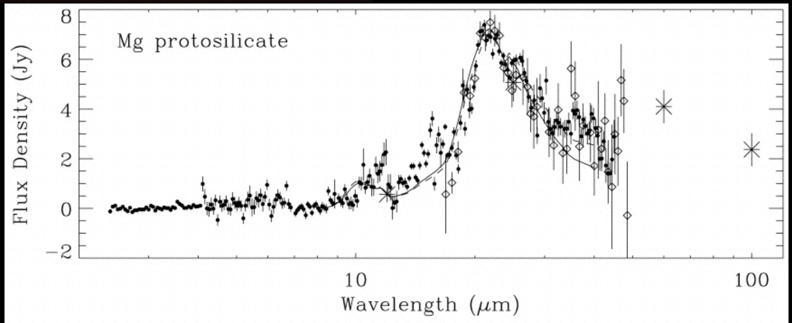


radio



Arendt, Dwek, & Moseley (1999)





Hot dust $\approx 10^{-3}\ M_{sun}$

Colder dust $\approx 0.2\ M_{sun}$

Conclusion

- So far there is no direct evidence that SN form massive quantities of dust (> 1 M_{sun})

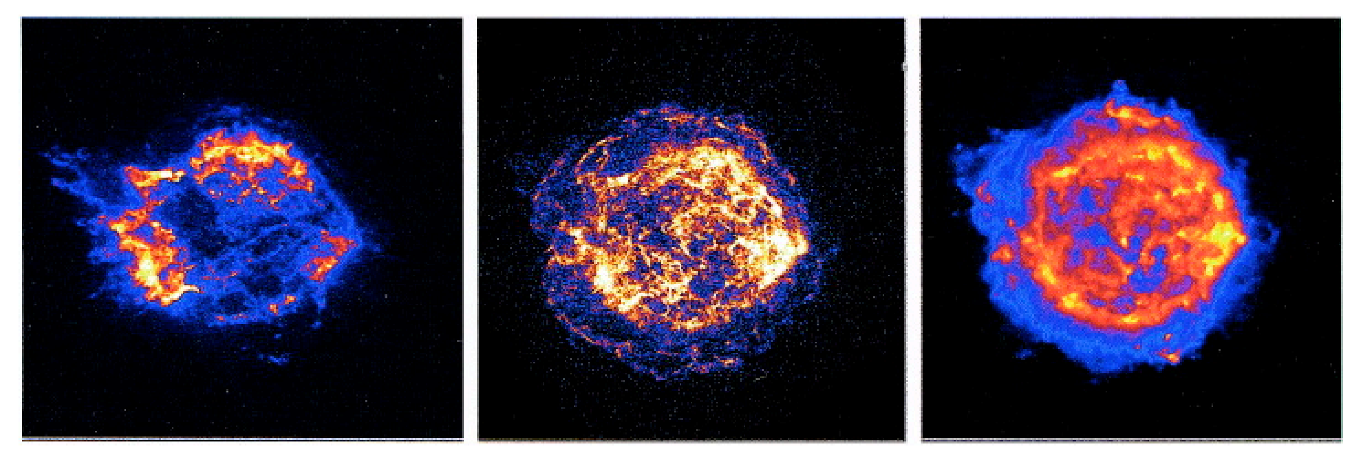
  in their ejecta

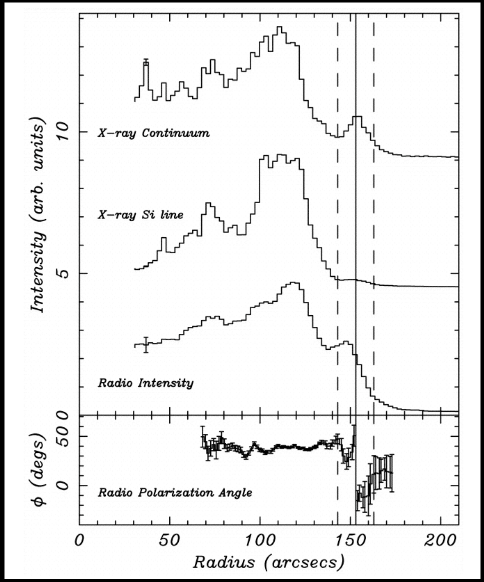
- Does any newly-formed dust survive the journey into the ISM?

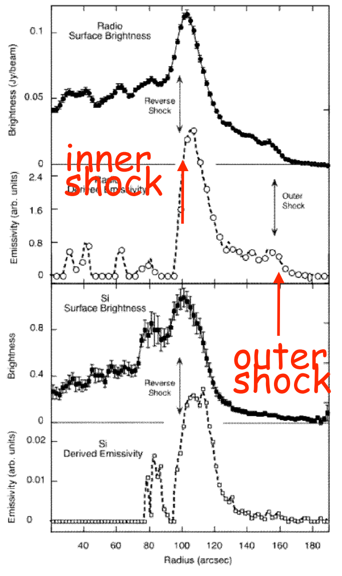
Detection of forward-reverse shocks in Cas A

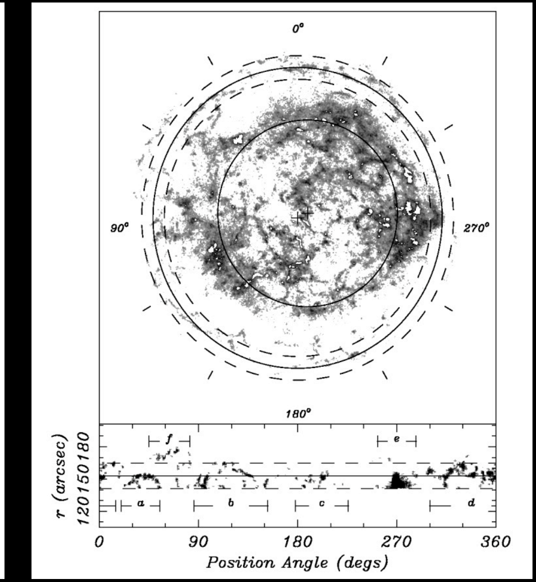
(Gotthelf et al. 2001)

SiX-Xcont Xcont 4-6 keV) Radio (4.4 GHz)





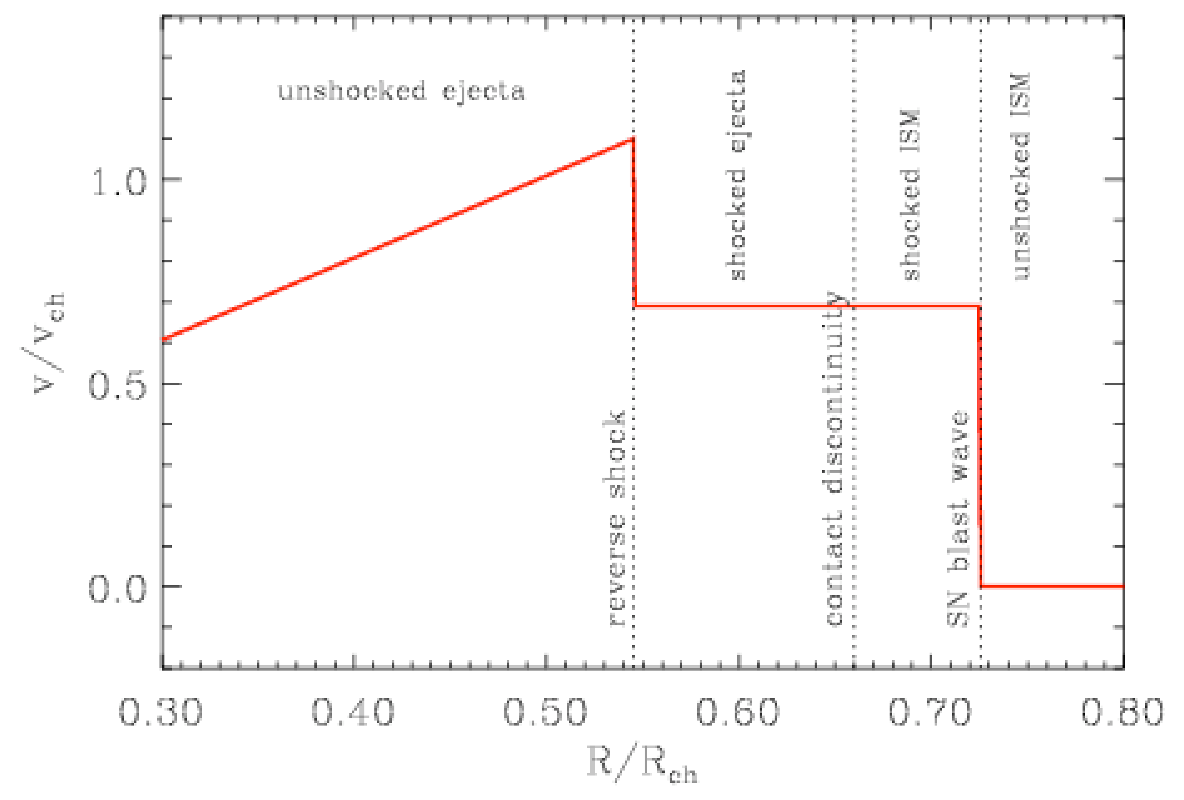




Does SN-condensed dust survive the journey into the ISM?

Velocity Profile of a Young SNR

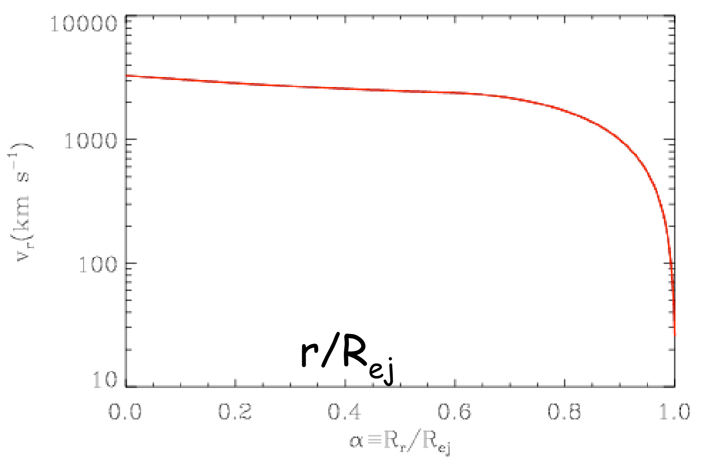
Truelove & McKee (1999)



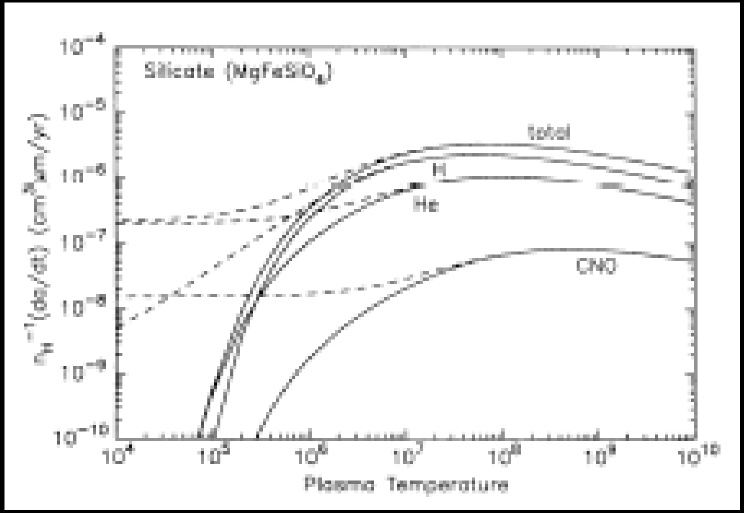
Grain Destruction by the Reverse Shock

(Dwek 2004, Dwek & Kozasa in prep.)

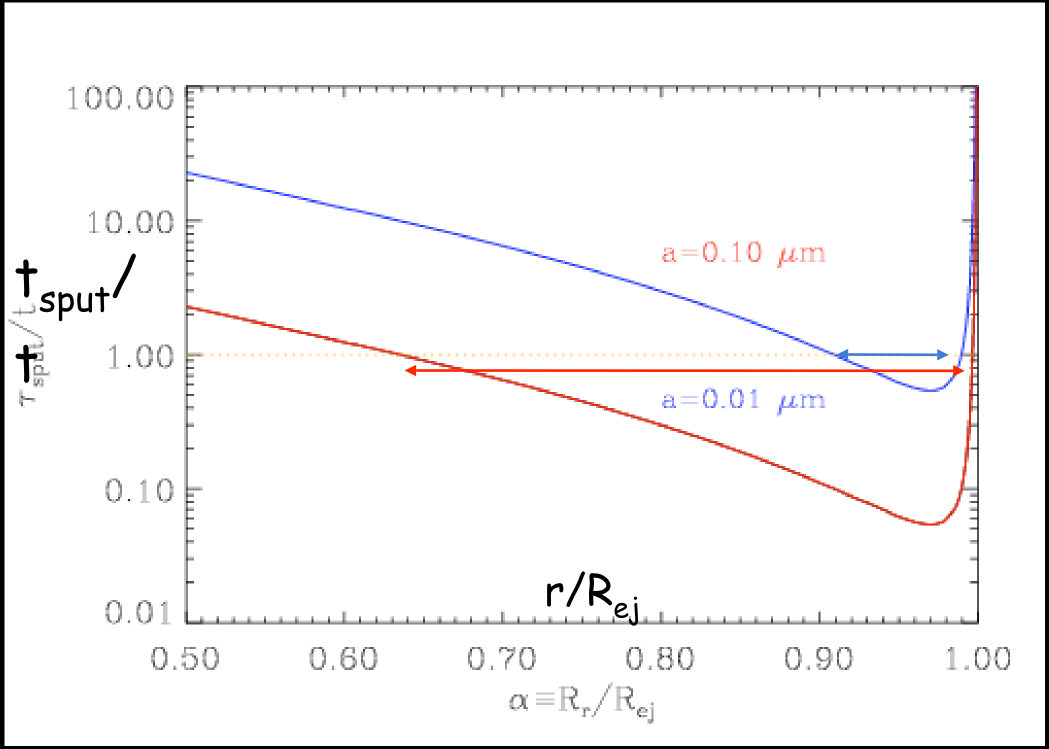
Velocity of the reverse shock



Thermal sputtering rate of silicate dust



Ejecta layers in which dust is destroyed



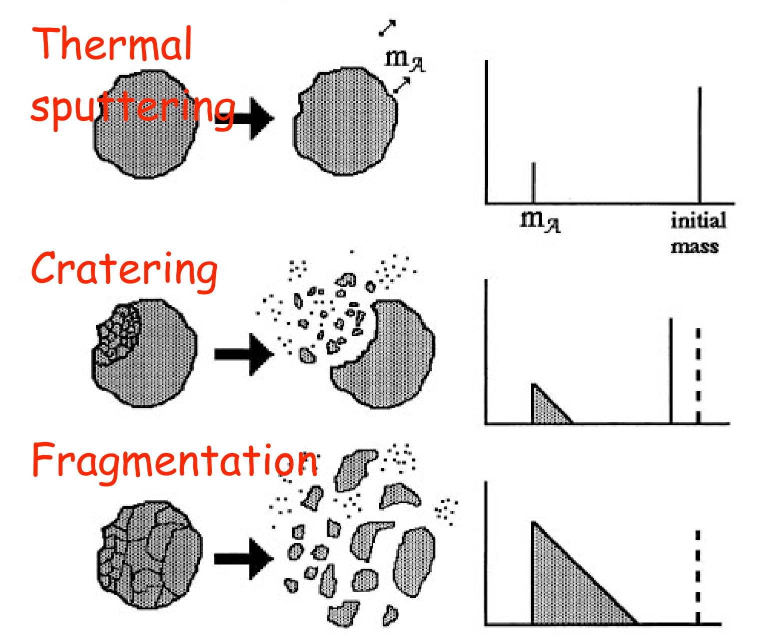
Sources of interstellar dust: Summary

- AGB, WR, SNII are all observed contributers to the population of IS dust
- Yields and abundances are very uncertain
- Source size distribution: commonly unknown
- Survival during injection into the ISM: unknown
- Source spectra show a wide variety of composition (silicates, carbonates, PAHs, ices)

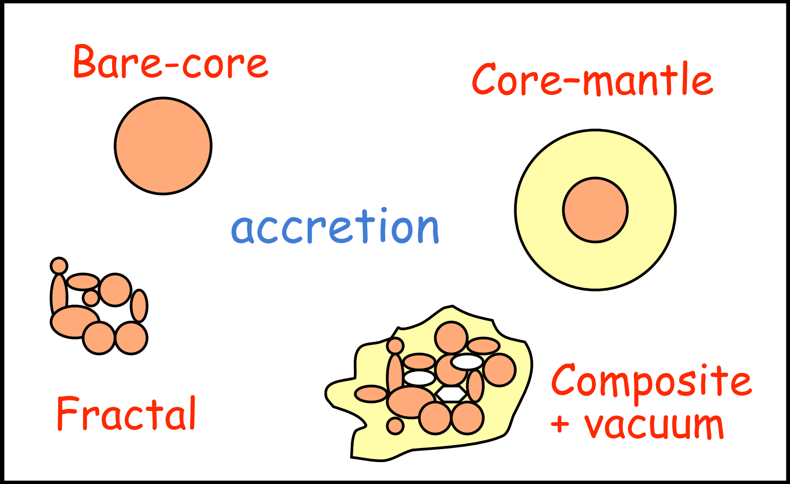
Dust Processing in the Interstellar Medium

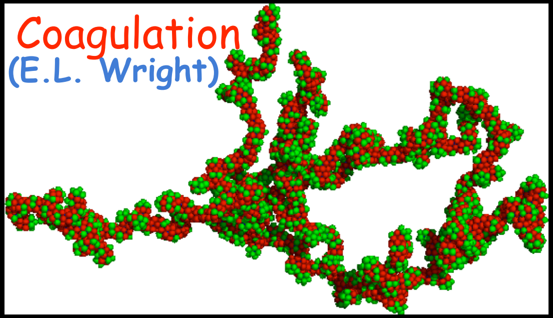
Grain Size Distribution

Grain destruction



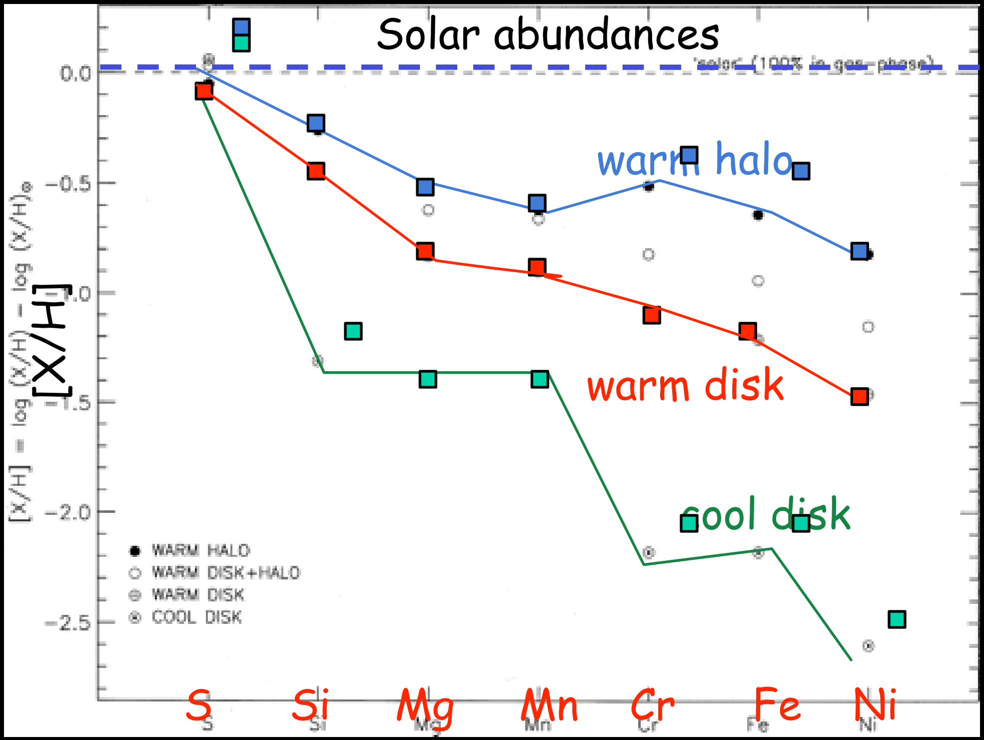
Grain growth





Elemental Depletions in Different ISM Phases

Savage & Sembach 1996, ARAA, 34, 279

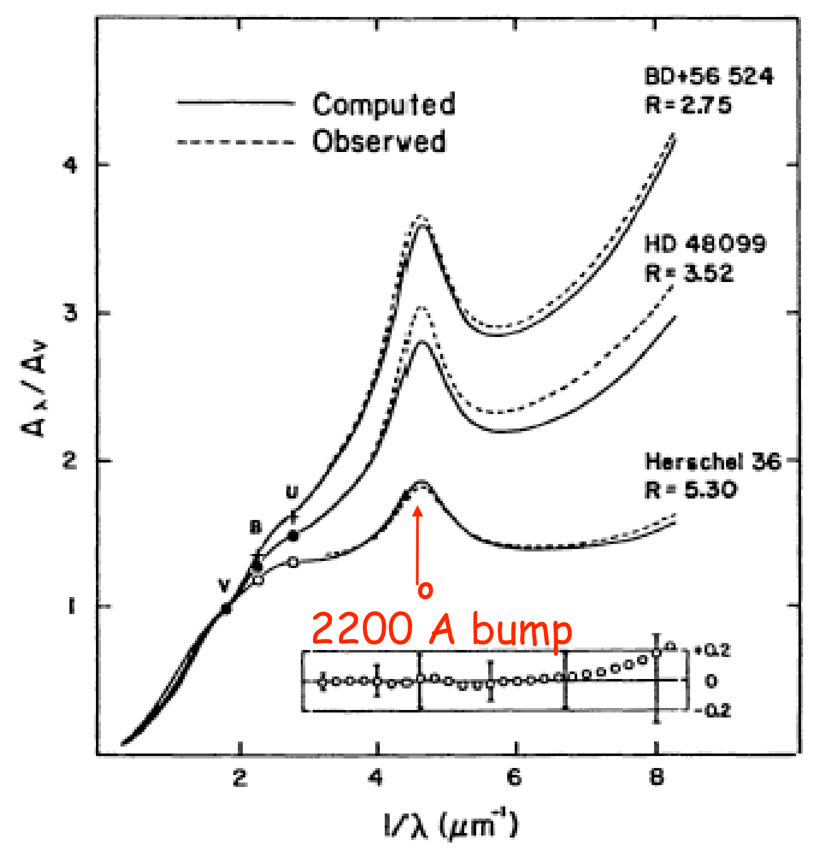


"The abundance pattern is consistent with a more severe destruction of dust in halo clouds than in disk clouds. This … may result from either more frequent or more severe shocking of halo clouds compared with the disk clouds".

Savage & Sembach (1996)

Variations of dust UV extinction: Evidence for coagulations?

Mathis 1990, ARAA,28, 37



$R_V = A_V/E(B-V)$

UV rise is related to the abundance of very small dust particles

Variations in R_V suggest Variations in the abundance of small grains

Graphite (Stecker & Donn 1965)

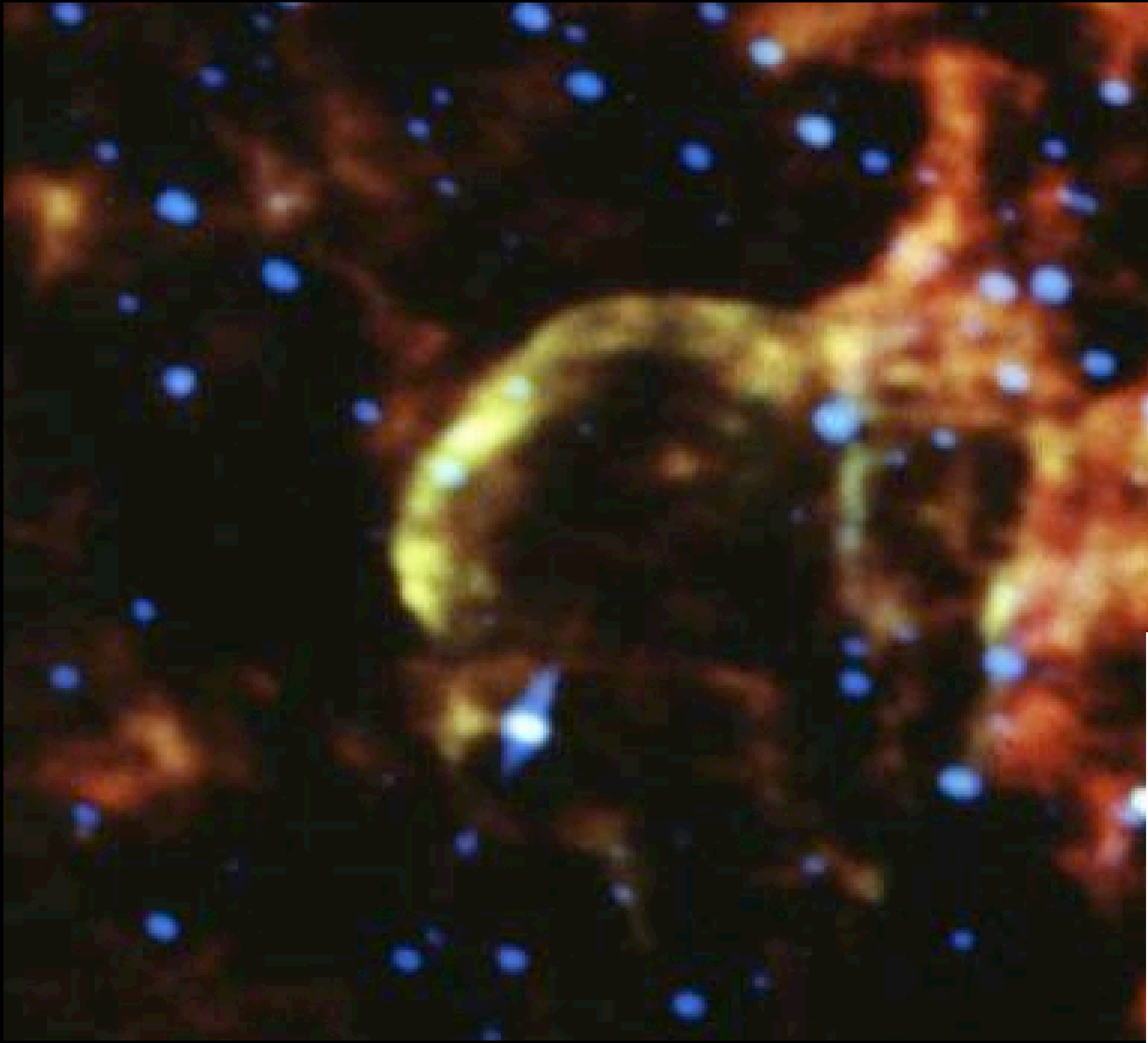
PAH (Joblin et al. 1992)

Hydrogenated amorphous-C (HAC) (Mennella et al. 1996)

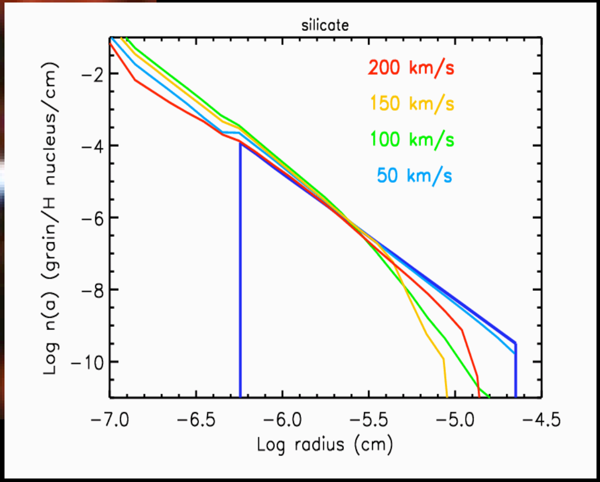
Coal (Papoular et al. 1996)

Grain destruction by SNRs

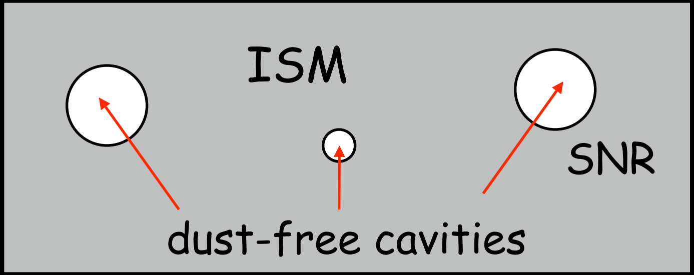
Cygnus Loop (IRAS)



(Jones 2003)



Lifetime of Interstellar Dust


ISM

SNR

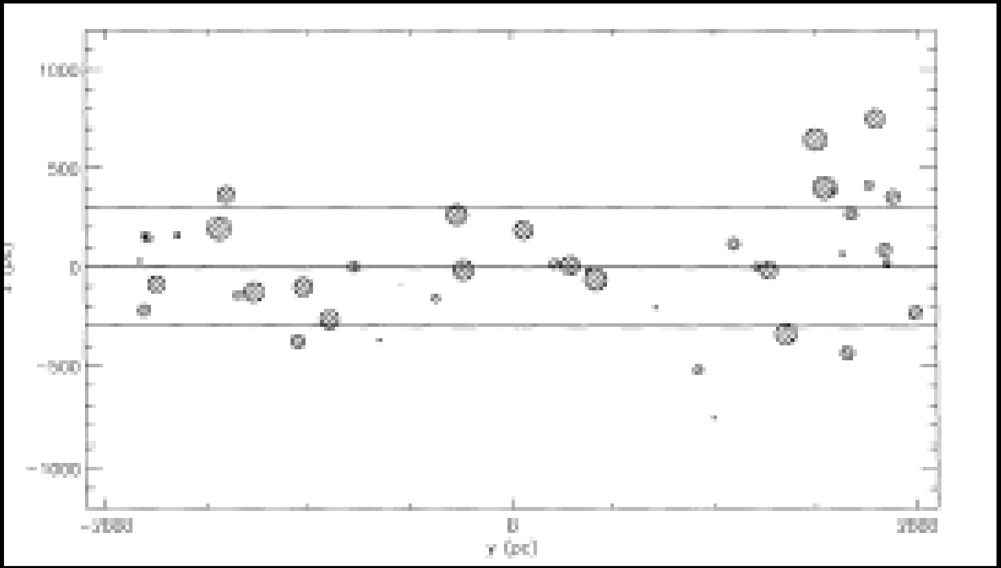
dust-free cavities

$$\frac{\text{dust in ISM}}{\text{dust destroyed in average SNR}} \Big/ \text{SN rate}$$

Dwek 1998

Isolated SNR

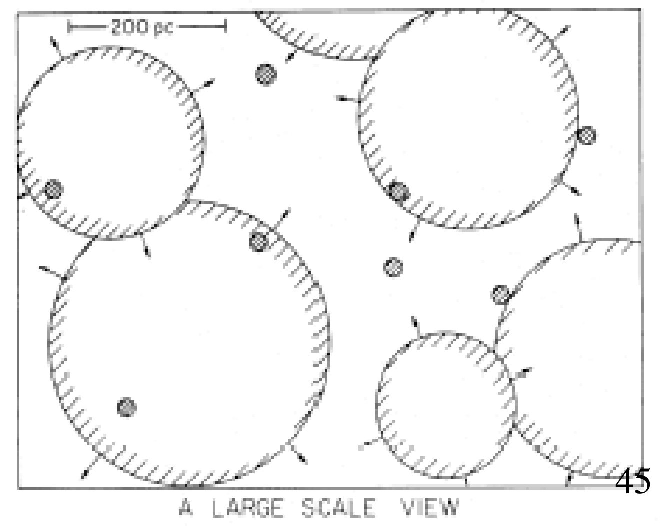
Slavin & Cox 1993



Overlapping SNR

McKee & Ostriker 1977

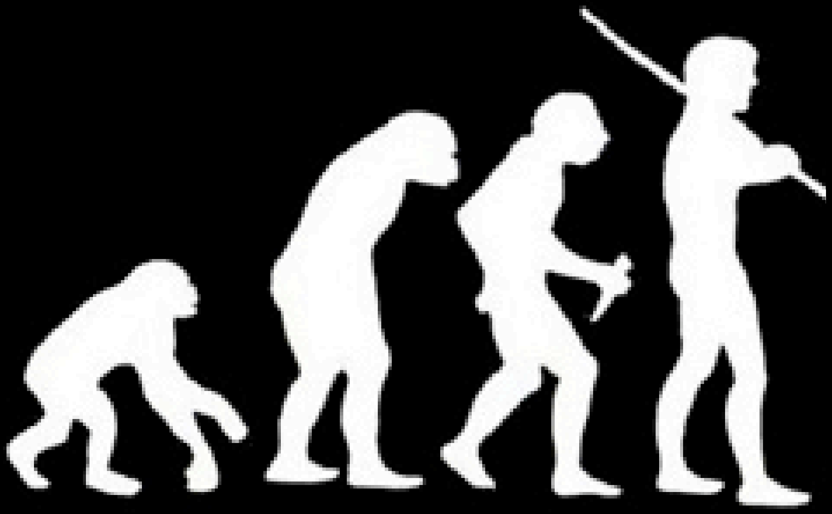
Jones et al. 1996



A Simple Model for the Evolution of Interstellar Dust

General Warning!

The danger of thinking that one can predict evolution

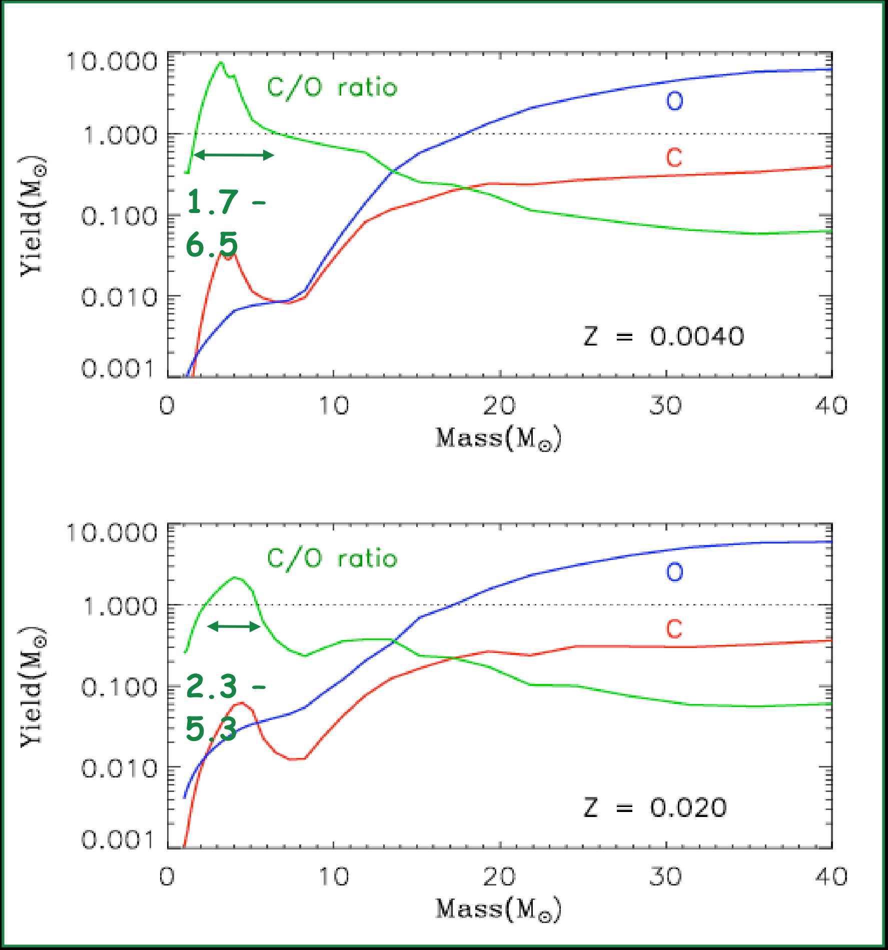


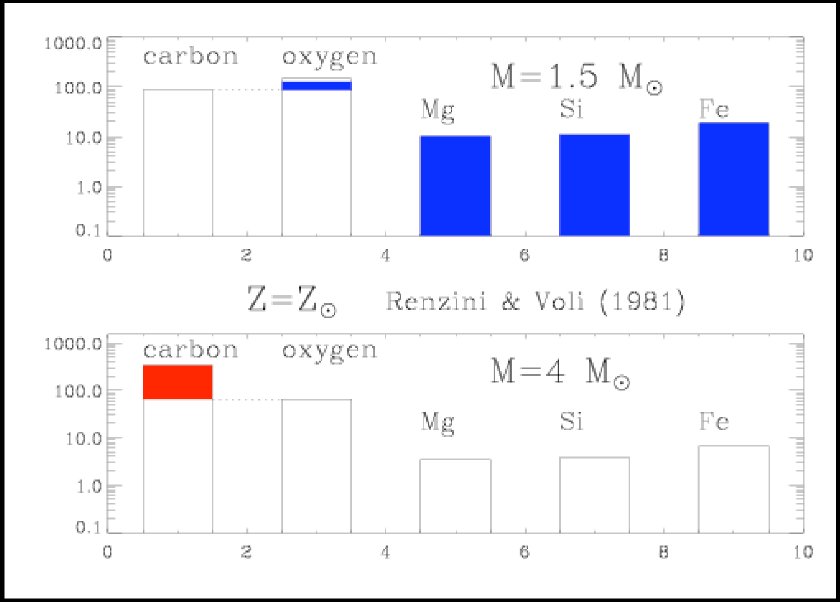
Yields of Silicate & Carbon Dust in Low-Mass Stars

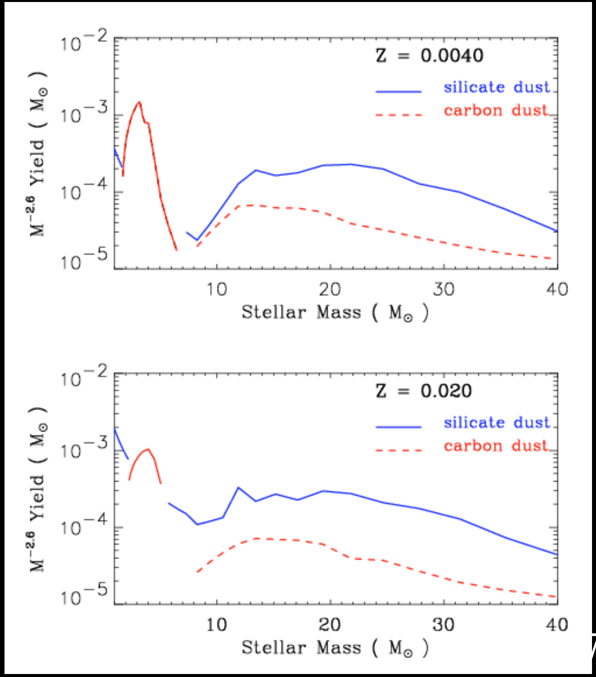
Dwek (1998)

$M < 8\ M_{sun}$
Renzini & Voli (1981)

$M > 8\ M_{sun}$
Woosley & Weaver (1995)





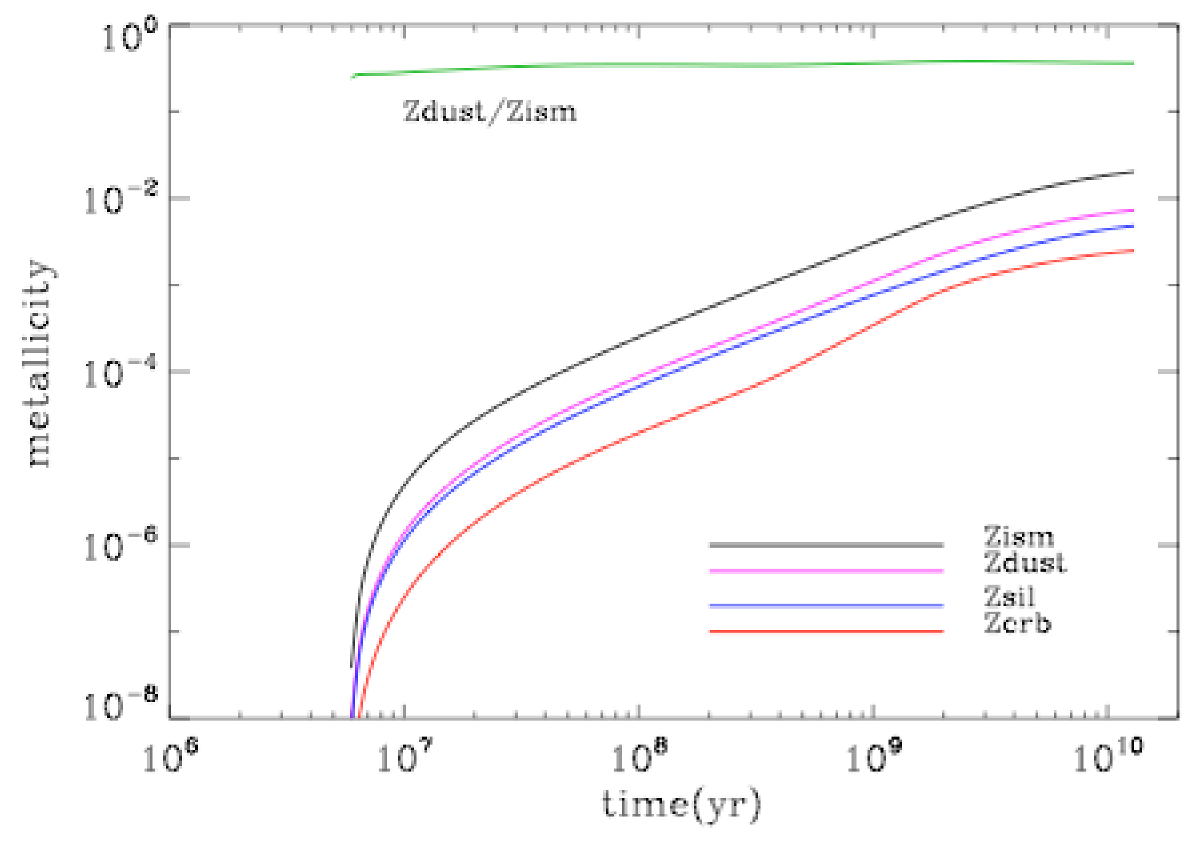


A “perfect” model

τ_{SFR} = 6x10^9 yr

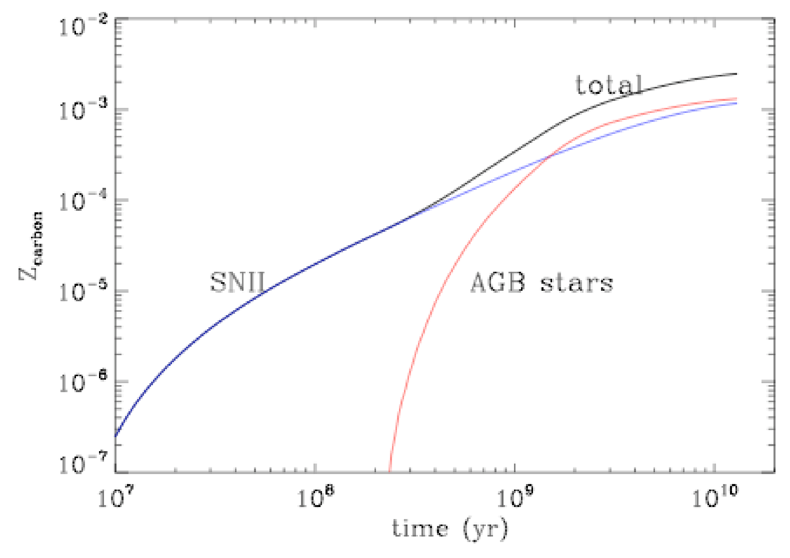
Yields: Marigo (2001)
Woosley & Weaver (1995)

- No grain destruction
- Ztot ≈ 0.02
- Zdust ≈ 0.0073
- Zsil/Zcrb ≈ 0.0048/0.0025



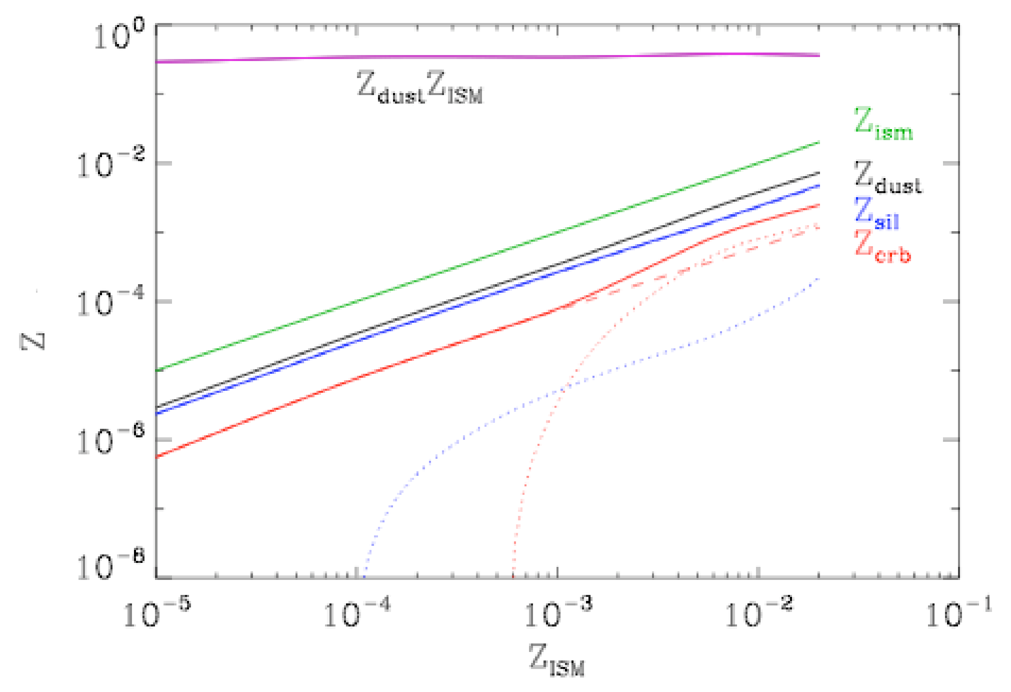
The evolution of carbon & silicate dust

no grain destruction - no accretion



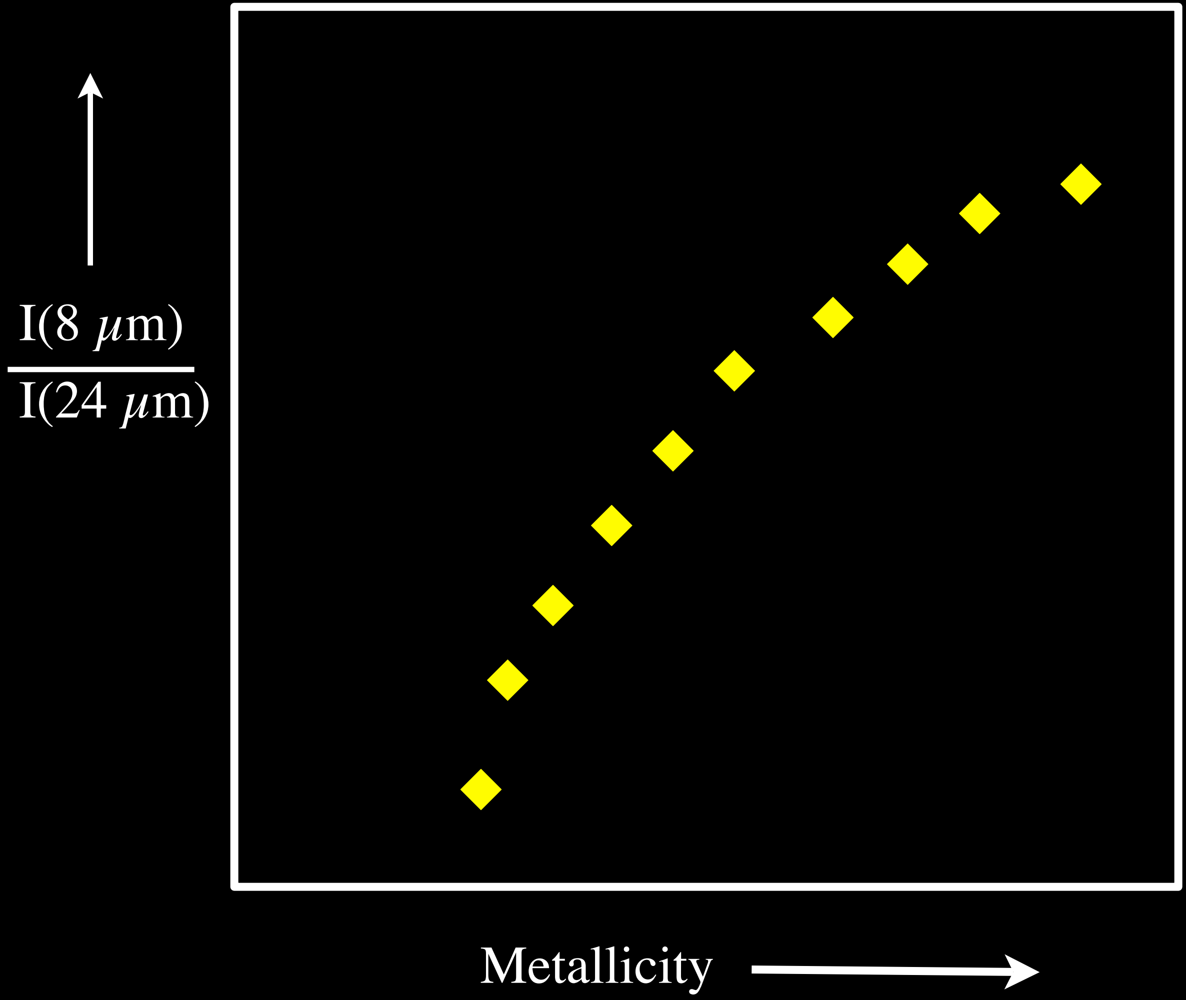
The evolution of carbon dust

The contribution of the different sources to the evolution of carbon and silicate dust



Spitzer Observations of PAH Emission in External Galaxies (schematic)

Can be explained by the delaided injection of PAHs into the ISM by AGB stars (Dwek 2004, Galliano & Dwek in prep.)



- I(8 μm) is a measure **of PAH emission**
- I(24 μm) arises from hot grains
- The flux ratio increases with Z
- There seems to be a threshold metallicity for PAH emission
- Ionization effects?

Summary

- The physics of the evolutionary processes are fairly well understood - microphysics generally well known .....
  - nucleation, sputtering, fragmentation, accretion
- Uncertainties when put in astrophysical context - macroscopics are very uncertain
  - the net yield of dust in the various sources
  - the net processing in the sources and the ISM
    - astrophysical dust differs from lab dust
    - source and ISM morphology are complicated
    - cycling of phases in the ISM -- role of SNR
- Approach to modeling:
  - Need to define the astrophysical system
    - local ISM, Galactic systems, the Universe (CCE)
  - Need to determine the observational constraints