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Dust formation in the ejecta of the Type II-P supernova 2004dj

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From Dust to Rocky Planets
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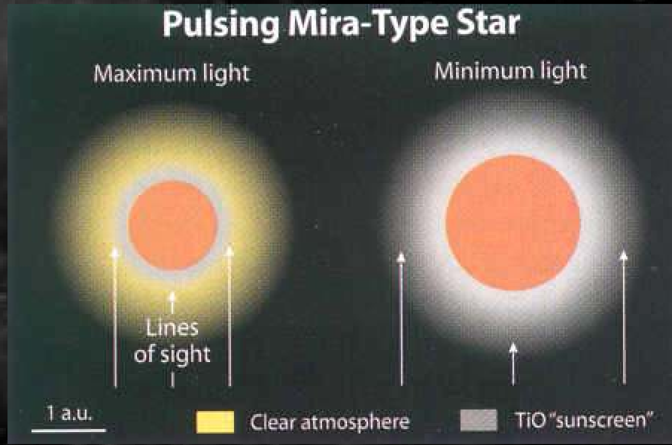
About the origin of the interstellar dust

- Grain condensation works only in special cases

Possible sources:

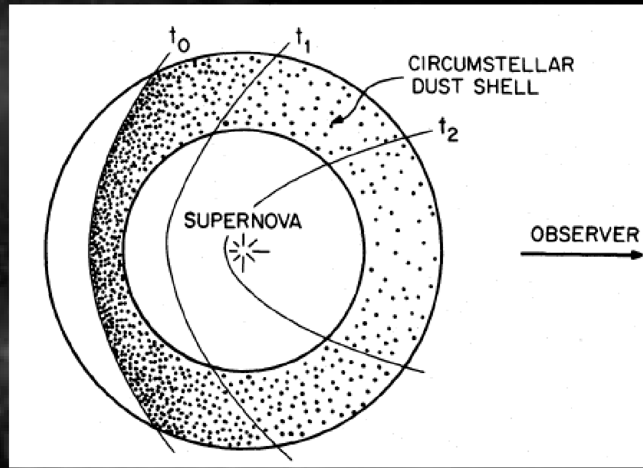
- Stellar winds of AGB stars (intensive convection)
- Quasar winds
- Core-collapse supernovae



- IR excess after explosion
- Sub-mm excess and strong polarisation by older SNRs
- Isotopic anomalies in meteorites
- Large dust amount of high-redshift galaxies

What do we see in mid-infrared?

- Thermal radiation of pre-existing CSM re-heated by the SN (IR echo)
- Newly-formed, warm dust in the ejecta (~3-500 days after explosion)
- Grain condensation in a cool dense shell (CDS) between forward and reverse shock waves

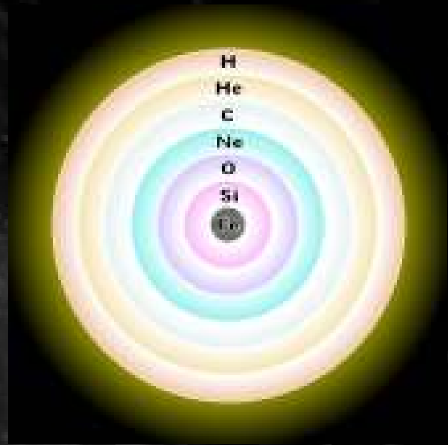


Other evidences of fresh dust:

- Strong decrease of optical fluxes and increase of MIR fluxes in the same time
- Attenuation / blueshift of optical emission lines

Current facts and theories

- Evidences of dust-formation only by a few SNe (long-term MIR observations are necessary), mostly by Type II-P ones (smaller v_{eject} of C, O, Si layers)



- Amount and size-distribution of grains depend on the environment (type) of the SN
- Observed dust masses (< 0.02 M_{Sun}) are much lower than predictions of models (0.1-1 M_{Sun}) → other sources of dust in the early Universe?
  - Note 1: difficulties by dust mass calculations (model dependencies, clumps, grain parameters, very cold dust)
  - Note 2: other possibilities (larger contribution of AGBs, top-heavy IMF, grain growth in the ISM)

SN 2004dj

- A Type II-P SN appeared in NGC 2403 (discovered by K. Itagaki)
- The closest (3,5 Mpc) and brightest (V = 11.2 mag) observed SN since SN 1993J
- Progenitor is a massive (12 M_{Sun} < M_{prog} < 20 M_{Sun}) star within the Sandage-96 star cluster
- Detailed analysis:

  Vinkó et al. 2006, MNRAS, 369, 1780

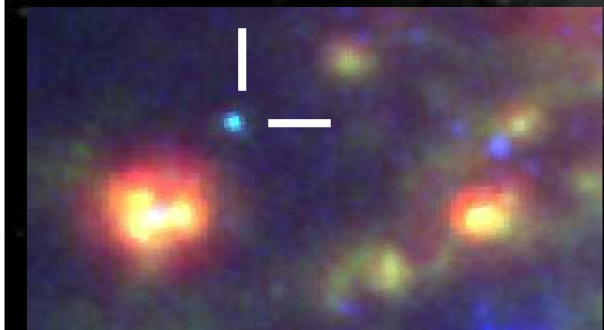
  Vinkó et al. 2009, ApJ, 695, 619

Mid-IR photometry of SN 2004dj

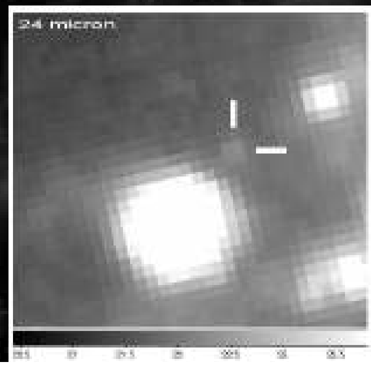
- Collection of public data of ***Spitzer IRAC*** (16 epochs) and ***MIPS*** (11 epochs) detectors between +98 and 1381 days after explosion
- Creating own mosaics from BCD images (IRACproc, DAT)
- Aperture photometry of the own mosaics (MOPEX, IRAF)

  PSF photometry of MIPS images (IDP3, IRAF/DAOPHOT)

  Check: photometry of PBCD images
- Generating SEDs
  - Dereddening of fluxes (E(B-V) = 0.1, Vinkó et al. 2006)
  - Subtraction of the contribution of S96 to flux values



Color-combined mid-IR image of the region around SN 2004dj (red: 24 μm, green: 8.0 μm, blue: 3.6 μm).



MIPS 24 μm image, 2004 Oct 12 (+103 days)

Mid-IR spectroscopy with *Spitzer/IRS*

- IRSStare/SL: 7 epochs between +115 and +868 days

  5.15 – 14.23 μm, R ~ 100

  Data reduction with SPICE → extracted, wavelength- and flux-calibrated, averaged spectra
- IRS PUI: 6 epochs between +510 and +1262 days

  13.0 – 18.5 μm (wide-band photometer)

  Aperture photometry with MOPEX

Imaging polarimetry with HST

- +425 day (PI: B.E.K. Sugerman, see Vinkó et al. 2009)
- HST/ACS HRC + F435W + POLUV (0, 60 and 120 degree)
- PSF photometry (DOLPHOT)
- Degree of polarization: p_{SN} = 0.5 %

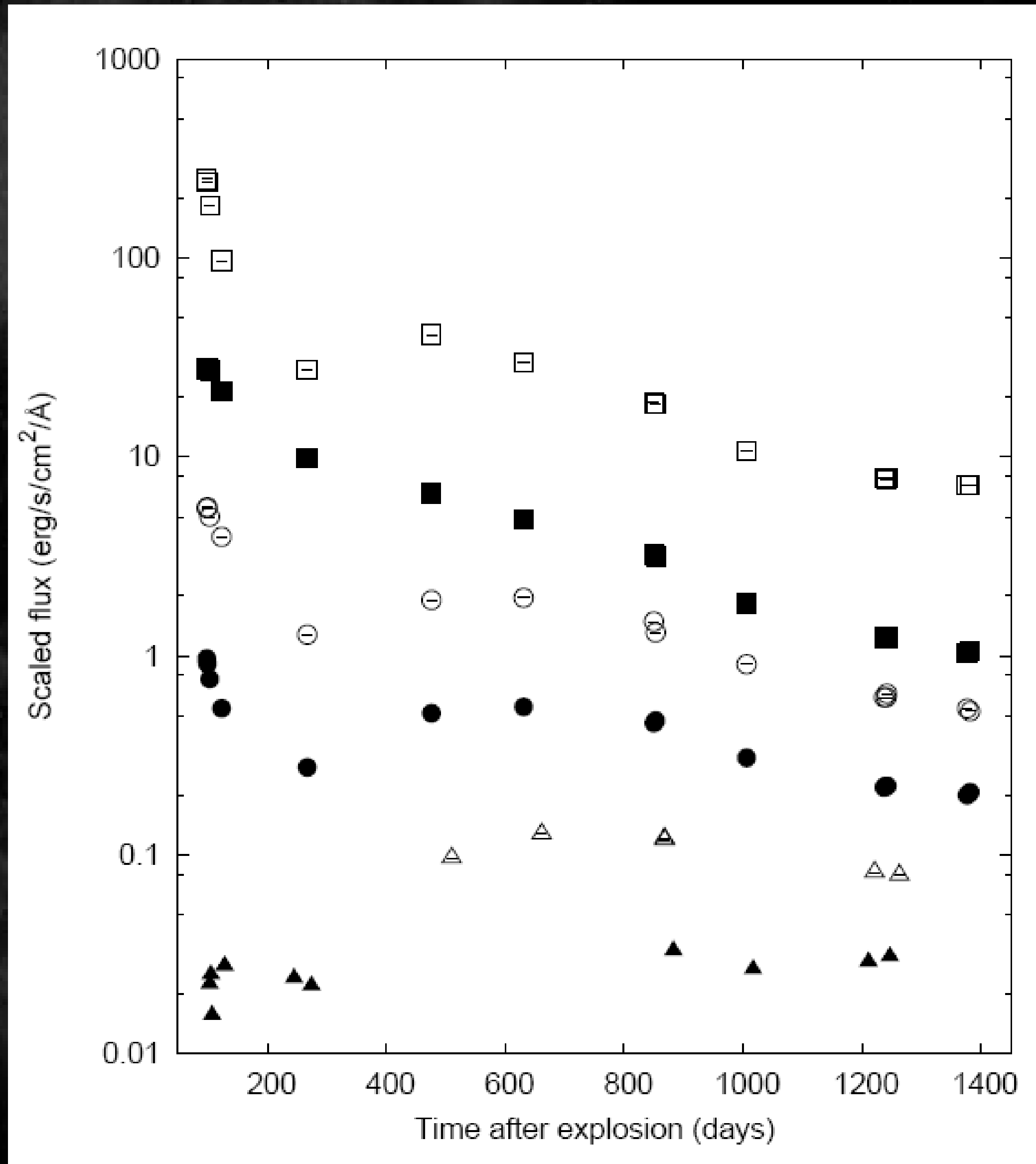
  (corrected for detector effects and ISM polarization)

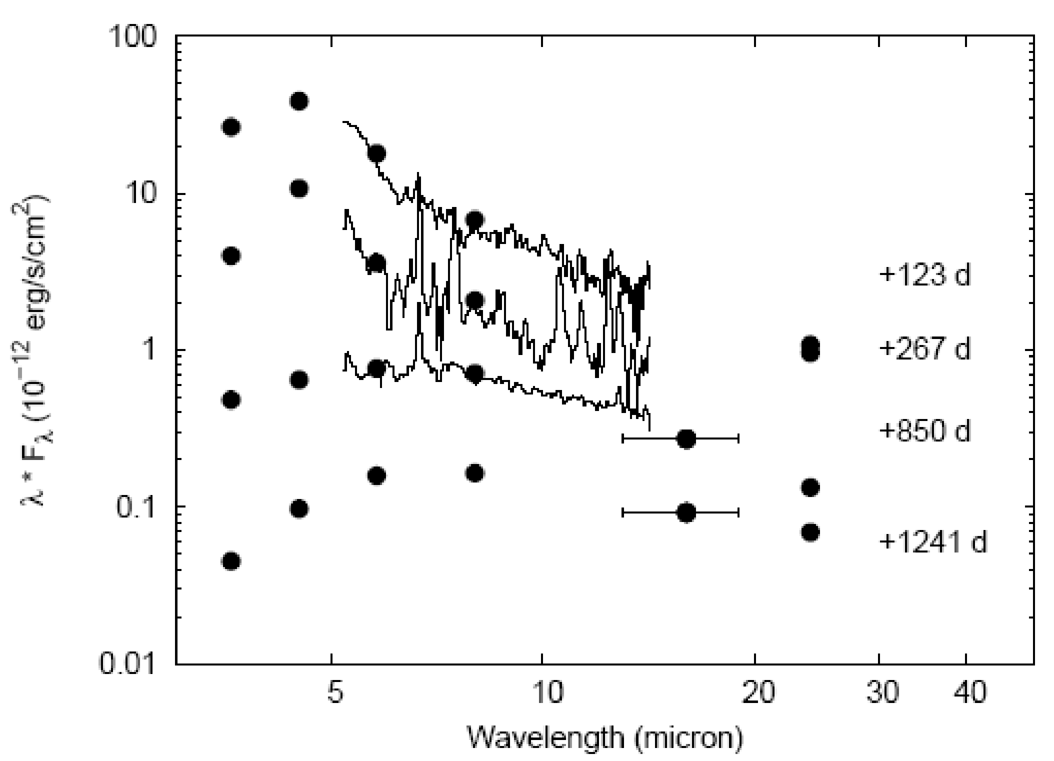
Light curves of SN 2004dj

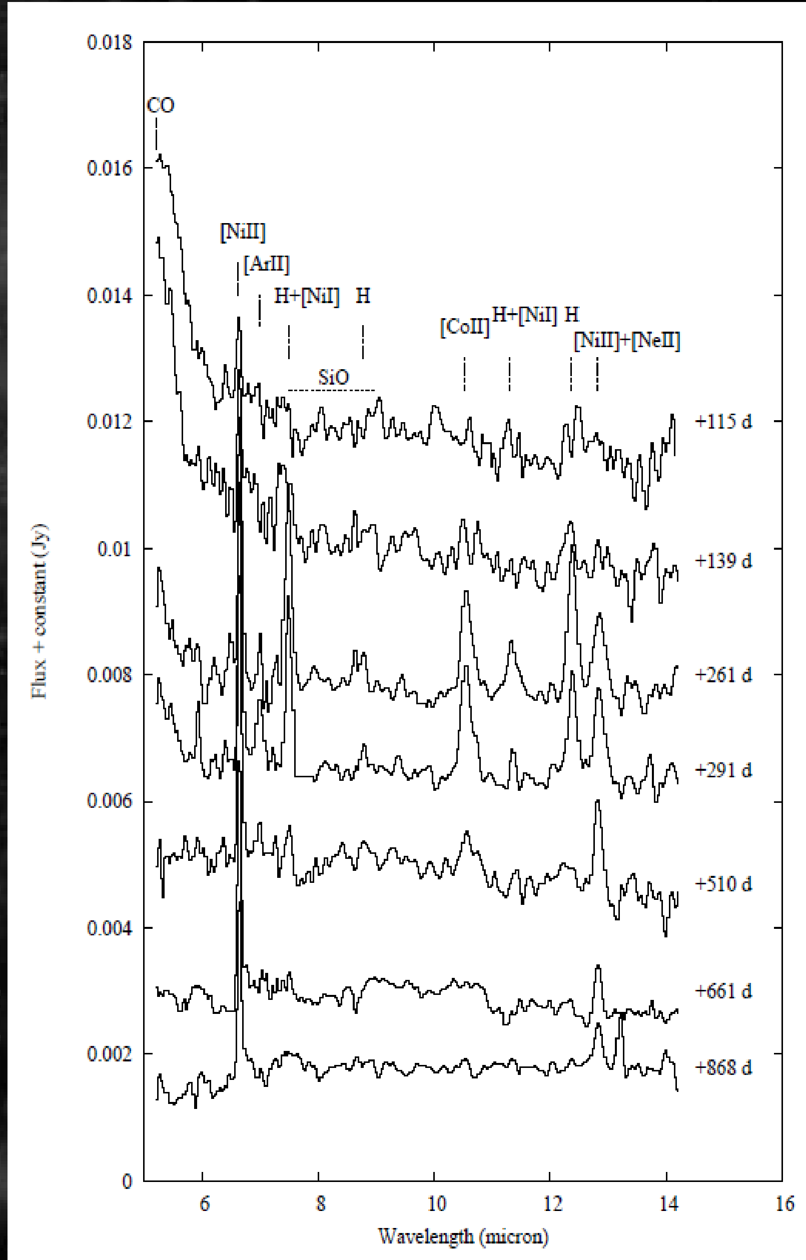
3.6 µm - open squares
4.5 µm – filled squares
5.8 µm - open circles
8.0 µm - filled circles
IRS PUI - open triangles
MIPS 24.0 µm - filled triangles

Time-shifted peaks
(later at longer wavelengths)
→ newly-formed dust

<u>No peak at 4.5 µm</u>:
1-0 vibrational band of CO at
4.65 µm (possibly)







MIR SEDs of SN 2004dj

IRS spectra of SN 2004dj in the nebular phase. The nebular lines disappeared during the ”bump” phase after +300 days → evidence of newly-formed dust

Models for dust

Analytic model (Meikle et al. 2007):

$$L_\nu = 2\pi^2 R^2 B_\nu(T)\left\{\tau_\nu^{-2}\left[2\tau_\nu^{2} - 1 + (2\tau_\nu + 1)e^{-2\tau_\nu}\right]\right\}$$

$$\tau_\nu = \frac{4}{3}\pi k \rho \kappa_\nu R \left(\frac{1}{4-m}\right)\left(a_{\max}^{4-m} - a_{\min}^{4-m}\right)$$

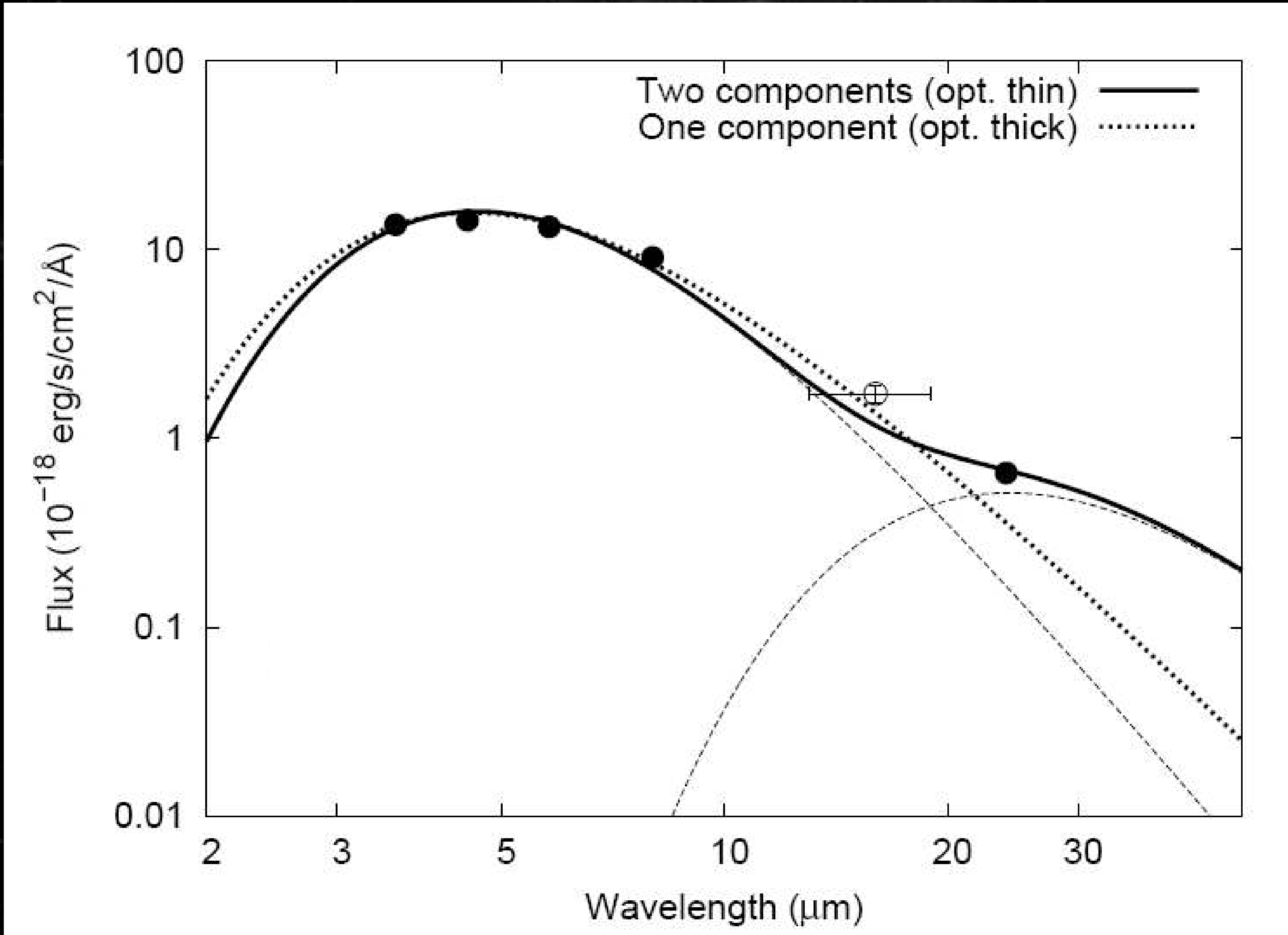
MRN-distribution (Mathis et al. 1977)

- Amorphous carbon grains
- m = 3,5, a_{min} = 0,005 µm; a_{max}= 0,05 µm
- Dust formation within a spherical shell
  (***R***: calculated from vmax ~ 3250 km s^{-1} of ejecta in nebular phase)
- Fitted parameters: ***T***, ***k***
- Total mass of dust:

$$M_d = \frac{4\pi R^2 \tau_\nu}{3\kappa_\nu}$$

(Lucy et al. 1989)

Mid-IR SED + analytic models (849-883 days)



Numerical models with MOCASSIN 3D radiative transfer code
(Ercolano et al. 2003, 2005)

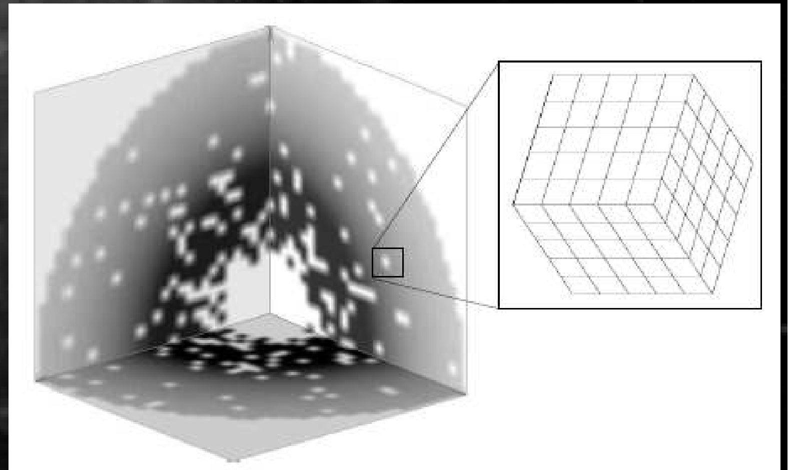
- Ray-tracing of energy packets in a shell containing specified medium (interactions)
- Cartesian grid

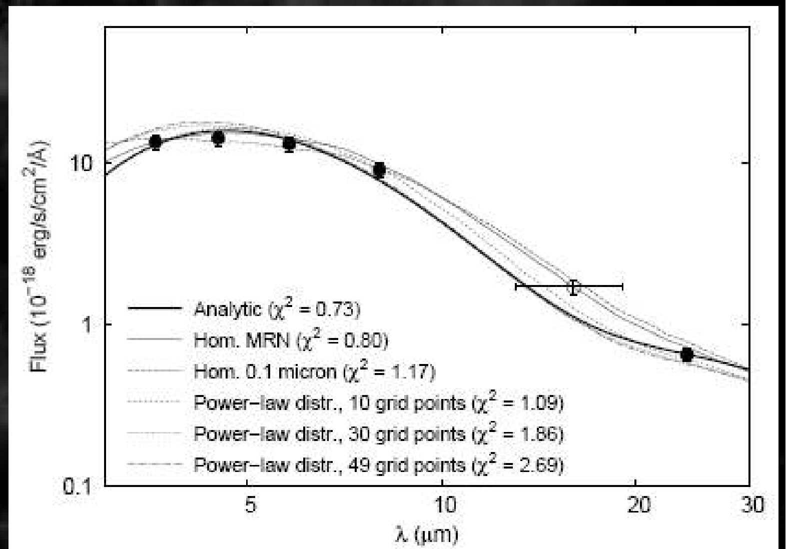
<u>Inputs</u>:

- Parameters of illuminating source
- Parameters of the shell (R_{in}, R_{out})
- Grain-size distribution (MRN, 0.005, 0.05, 0.1 μm)
- Average number density and density profile (homogenous, power-law)

<u>Outputs</u>:

- SED
- Total mass of dust





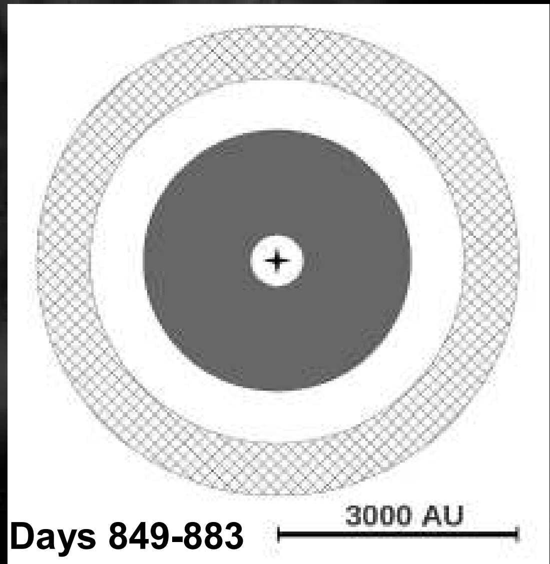
	Days 267-275	Days 849-883	Days 1006-1016	Days 1236-1246
R warm (10^{16} cm)	0.75	2.48	2.85	3.88
Rw/Rw in	3.5	5.0	5.0	8.0
T warm (K)	710	530	462	424
R cold (10^{16} cm)	1.5	4.3	4.6	6.2
T cold (K)	186	120	110	103

Total mass of dust (smooth distr.):

- 1 – 2 x 10^{-5} M_{Sun} (analytic)
- 2 – 6 x 10^{-4} M_{Sun} (num., homogenous)
- 1 – 5 x 10^{-5} M_{Sun} (num., n ~ R^{-7})

Cold component:

- v ~ 6400 kms^{-1}
- IR echo: not supported
- But: good agreement with the CDS model of Chugai et al. (2007)



Summary

- Detailed analysis of MIR light curves and spectra on SN 2004dj between +98 and +1381 days after explosion using public data of Spitzer
- Evidences for dust formation started between +400 - 500 days after explosion:
  - Significant brightening in MIR light curves around 500 days
  - Disappearance of the weak, optically thin lines from the *Spitzer*/IRS spectra during the same time
  - Detection of 0.5 % polarization from the SN ejecta in the optical (*HST F435W* filter) at +425 days
- Analytic and numerical modeling for observed SEDs
  - A warm (T~ 500 K), freshly formed and a cold (T ~ 110 K) component, the latter one possibly originated from CDS interactions
  - Minimal dust mass: 10^{-5} - 10^{-4} M_{Sun} (with clumpy distributions ~ 10^{-3} M_{Sun} , still much more less then in models


Thank You
for Your attention!