The Evolution of Metals and Dust in the high-z Universe

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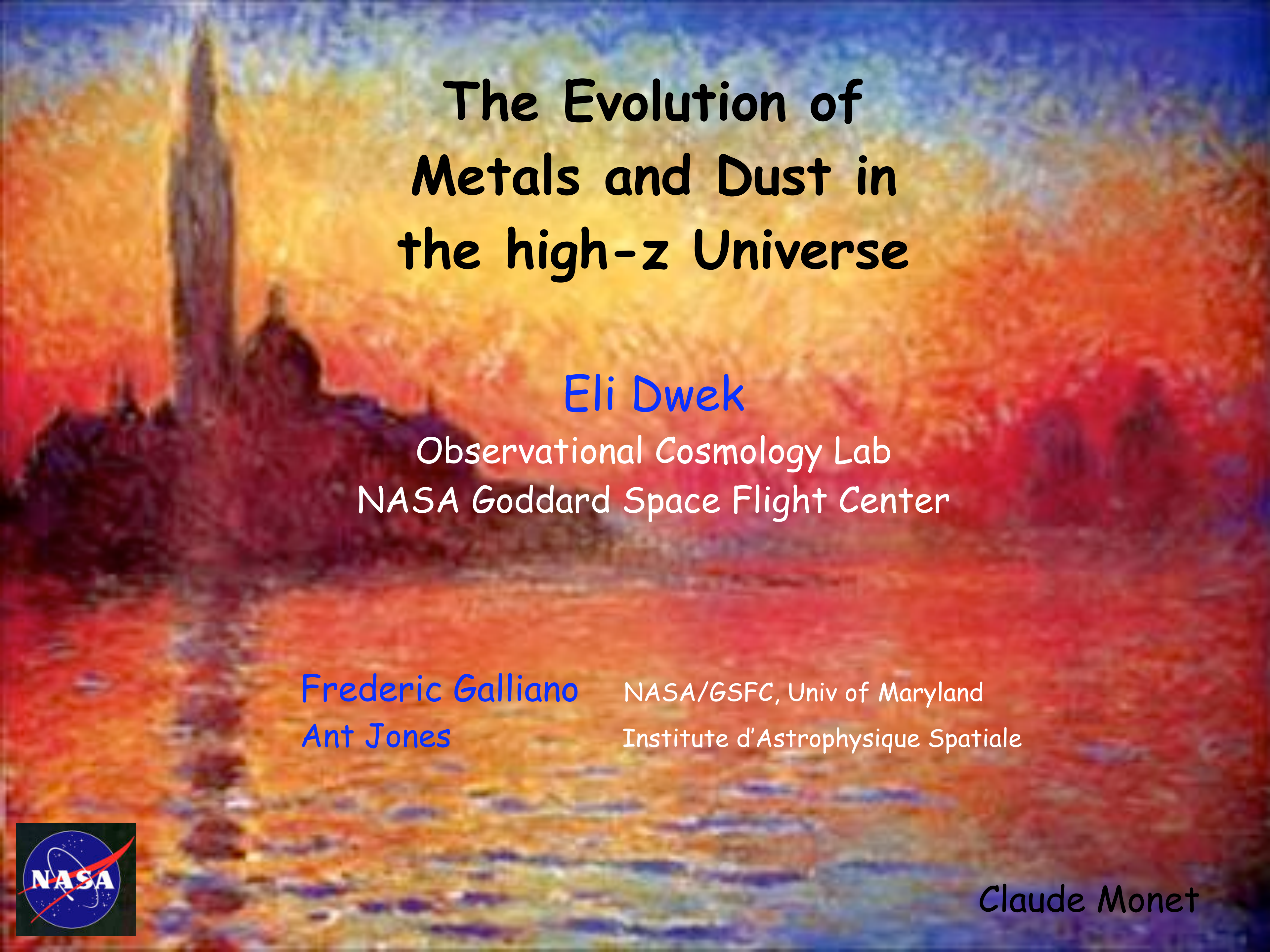


Claude Monet

Dust Formation at High Redshift SDSS J114816 ($z \approx 6.4$)

(Dwek, Galliano & Jones 2007 ApJ, 662, 927)

Age of the universe = 870 Gyr

Age of galaxy ≈ 400 Myr ($z_i = 10$)

IR luminosity ≈ 2×10^{13} L_{sun}

$M_{dust} \approx (0.9 - 4) \times 10^{8}$ M_{sun}

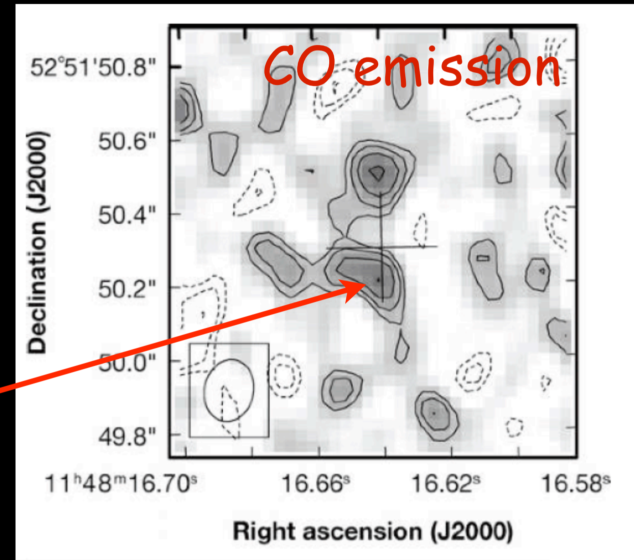
$M_{gas} \approx 2 \times 10^{10}$ M_{sun}

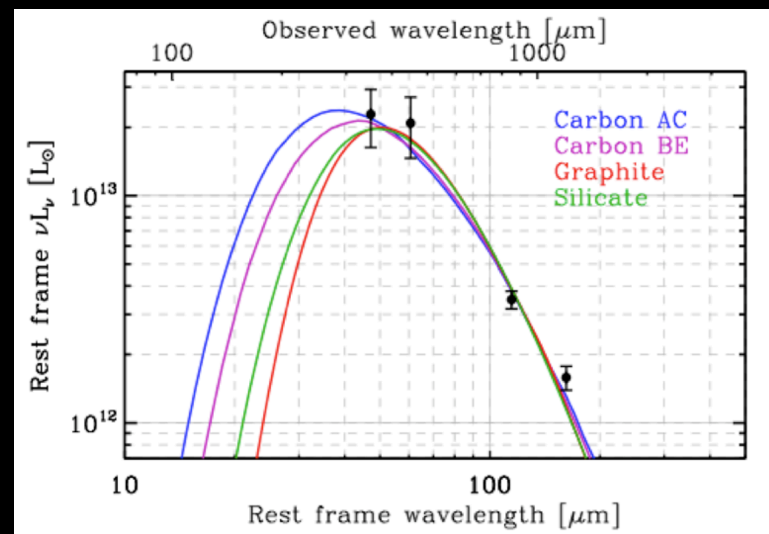
$M_{dyn} \approx 5 \times 10^{10}$ M_{sun}

$M_{dust}/M_{gas} \approx (0.5\text{-}1) \times 10^{-2}$

SFR ≈ 4000 M_{sun}/yr

AGN



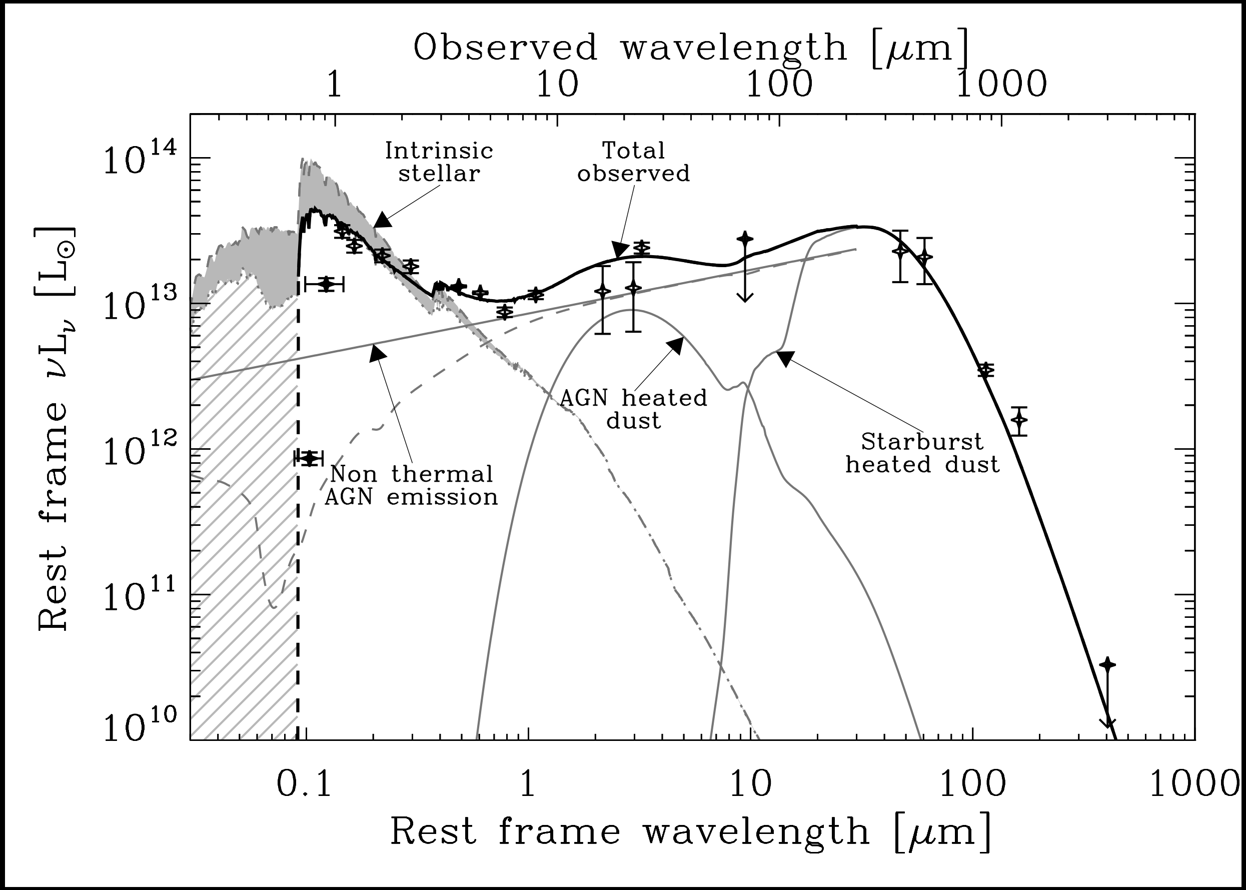


	graphite	silicate	carbon-B	carbon-A
	========	========	========	========
Mdust (Msun)	2.65e+08	4.91e+08	9.69e+07	9.26e+07
Tdust (K)	49.	47.	64.	74.
Ldust (Lsun)	1.89e+13	1.98e+13	2.41e+13	2.91e+13

The spectral energy distribution (SED) of J114816

Only a fraction of the UV/optical escapes → Submm surveys are important for probing the number of SF galaxies at high-z

(see poster by Staghun)



The Problem: How can a galaxy produce 2×10^8 M_{sun} of dust in only 400 Myr?

No problem:

- Dust could only have formed in core collapse SN
- SFR ≈ 4000 M_{sun}/yr → SN rate ≈ 30/yr (Salpeter IMF)
  Each SN must make only 0.02 M_{sun} of dust

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But there are 2 problems:

- SFR ≈ 400 M_{sun}/yr ⟶ SN rate ≈ 8/yr (top heavy IMF)
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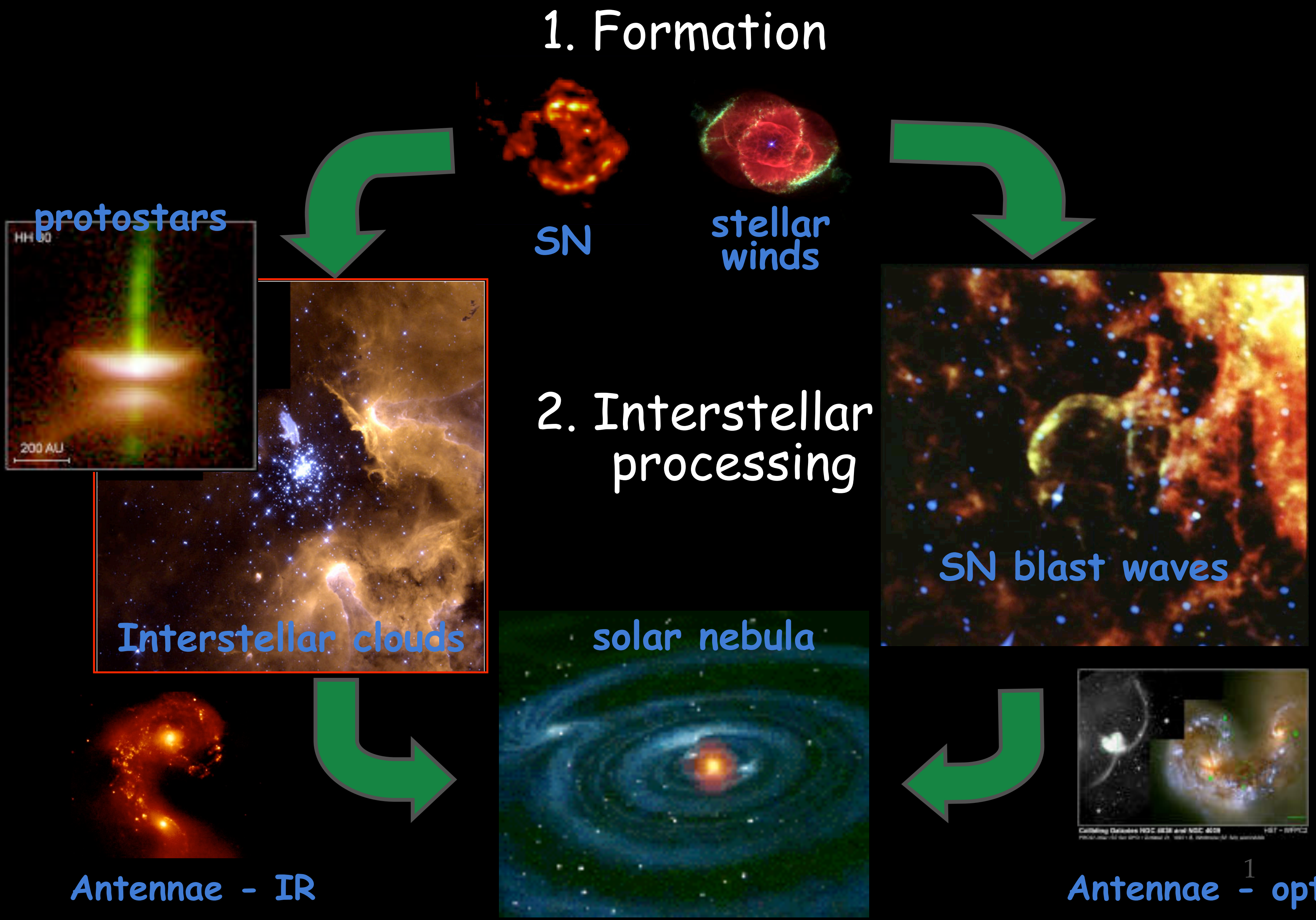
In a steady state: $\boxed{\text{dust yield in SN}} \approx \boxed{\text{dust-to-gas mass ratio}} \times \boxed{\text{ISM mass cleared of dust by a single SNR}}$

→ Yield ≈ 0.01 x 300 ≈ 3 M_{sun}

The cycle of dust in the ISM



A spherical cow may be a good representation of reality, provided you have a sufficiently limited point of view

How does the chemical evolution of dust differ from normal chemical evolution?

$$dN_A/dt = - \boxed{\text{astration}} + \boxed{\text{SNII, SNIa, WR, AGB, Novae}} + \boxed{\text{infall}} - \boxed{\text{outflow}}$$

How does the chemical evolution of dust differ from normal chemical evolution?

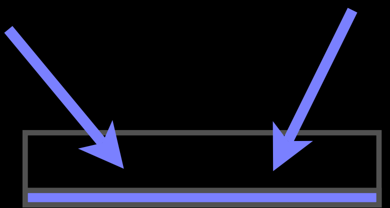
dN_A/dt = - astration + SNII, SNIa, WR, AGB, Novae + infall - outflow

dN_A/dt = - astration + SNII SNIa AGB WR, Novae

- destruction by SNR + accretion in clouds + infall - outflow

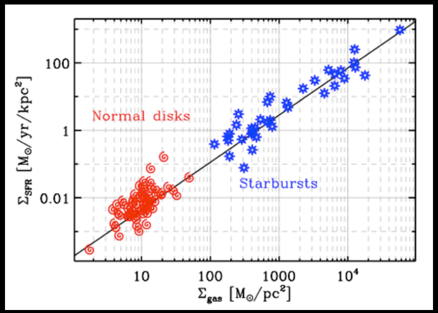
Chemical evolution parameters

- Chemical evolution model
  - ✦ infall model ....

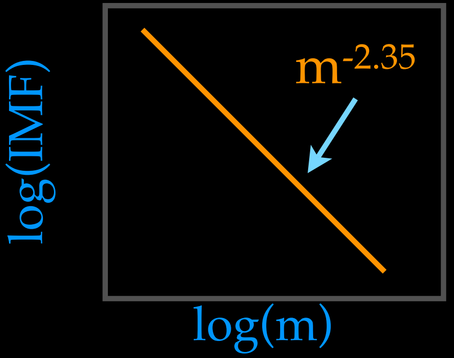


  - ✦ closed box ....

- SFR
  - ✦ Kennicutt law: SFR~$M^{1.4}$



  - ✦ analytical prescription
- Stellar IMF
  - ✦ Salpeter IMF (others)



- Nucleosynthesis yields
- Grain Formation/destruction

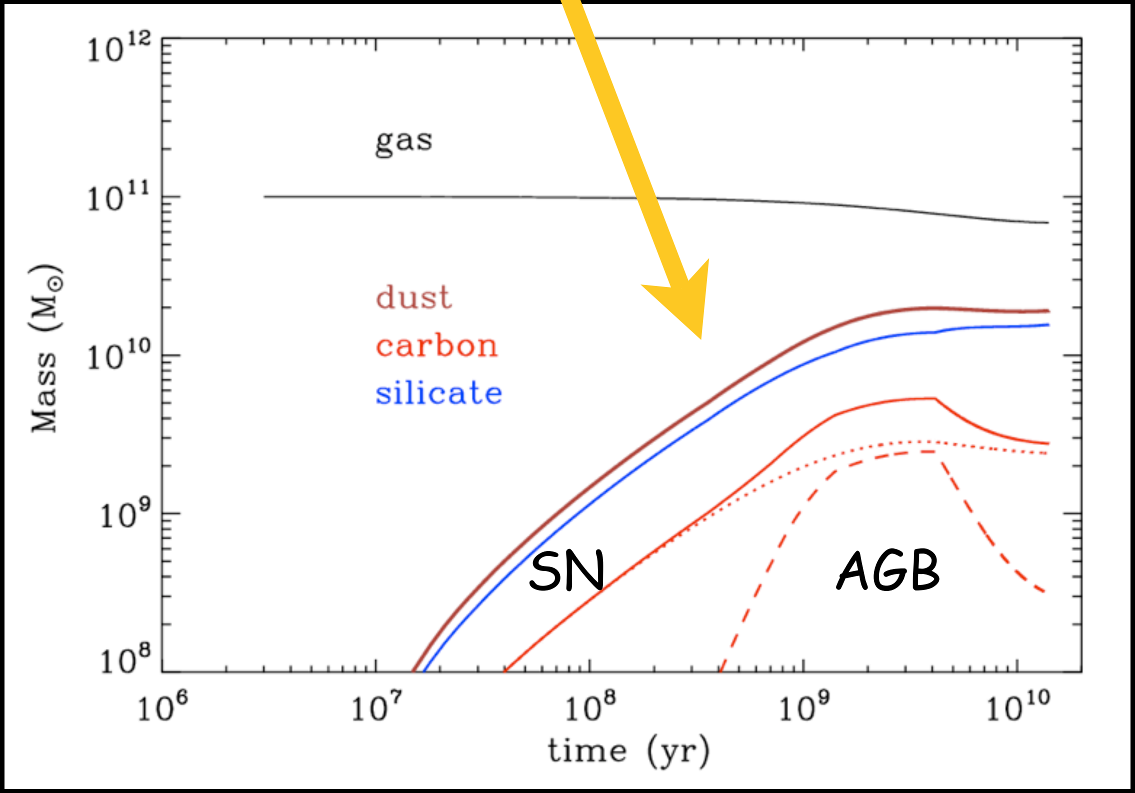
A simple dust evolution model

(Dwek 1998, Dwek, Galliano & Jones 2006)

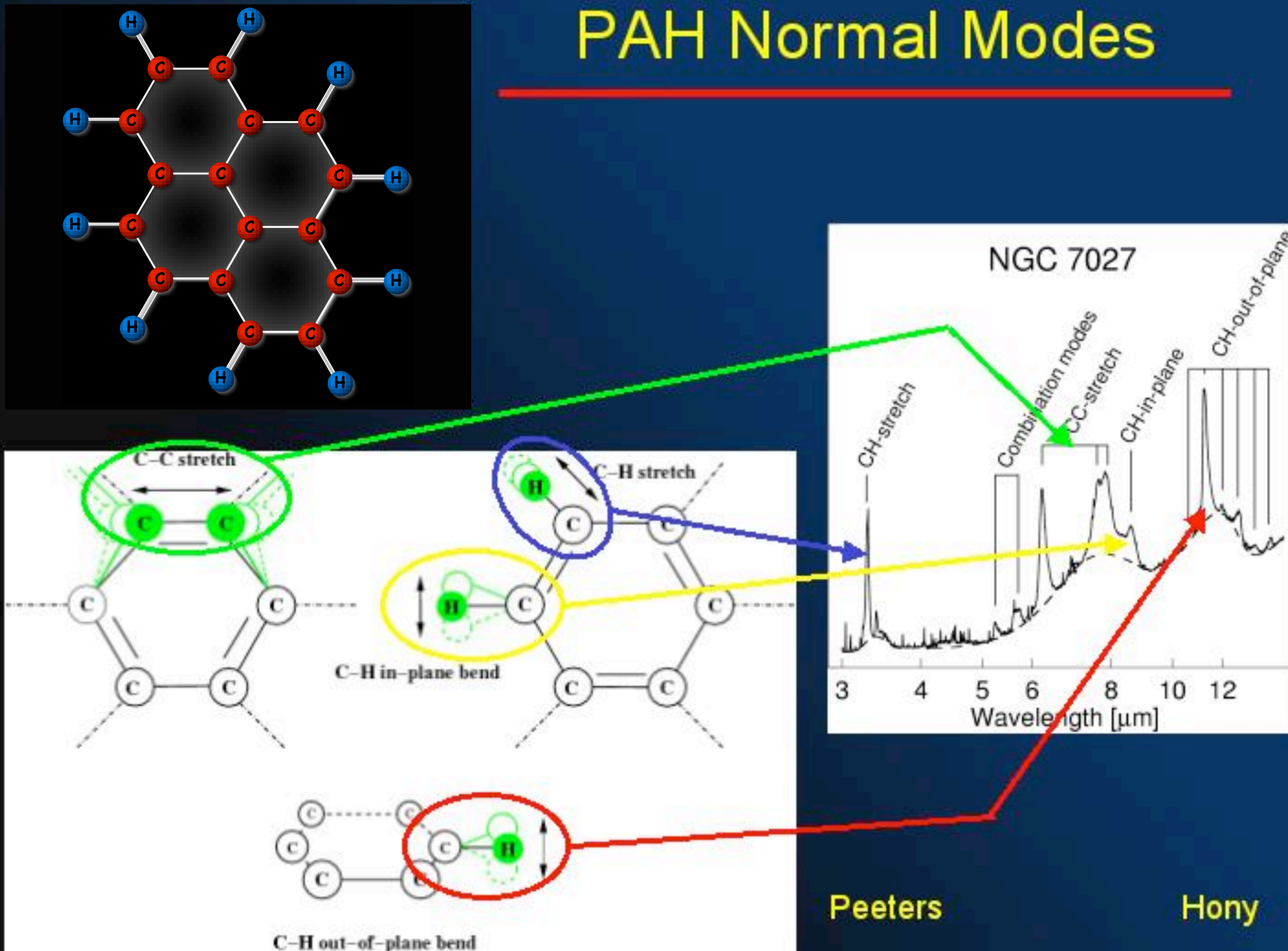
- Closed box model
- Condensation efficiencies = 1
- Destruction
  - m_g=300 M_{sun}
- IMF
  - Salpeter
    - M_{low} = 0.7 M_{sun};
    - M_{up} = 40 M_{sun}

Prediction

SN condensed dust and AGB dust have distinct evolutionary histories



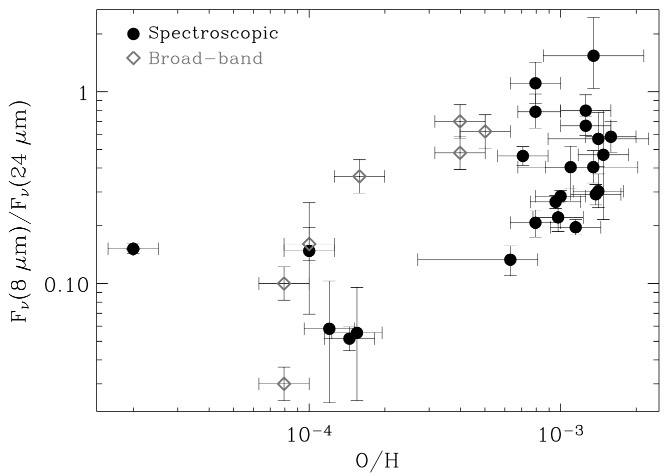
PAH Normal Modes



Peeters

Hony

A trend of PAH abundance with metallicity (time)



ISO (Madden et al. 2004)

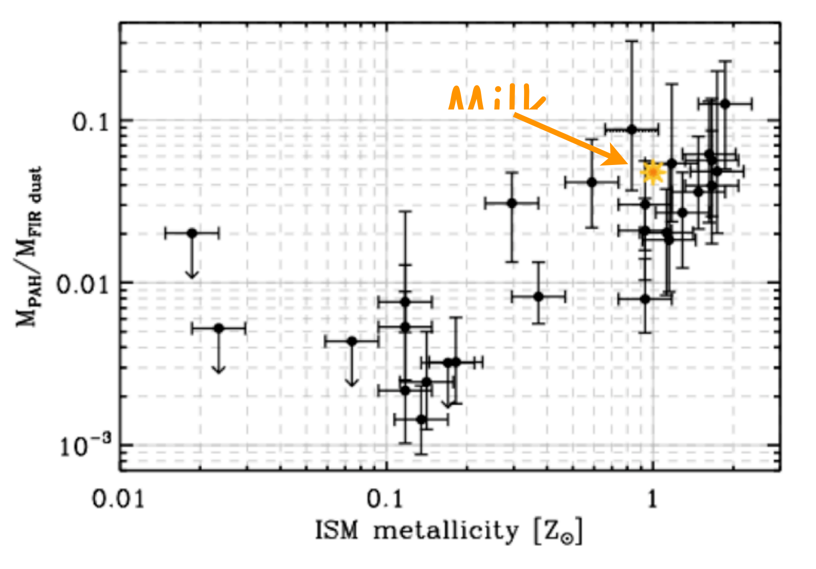
Spitzer (Engelbrecht et al. 2004)

Existence of metallicity cutoff

Correlation of PAH intensity with metallicity

Correlation of PAH intensity with metallicity is converted to PAH abundance versus metallicity

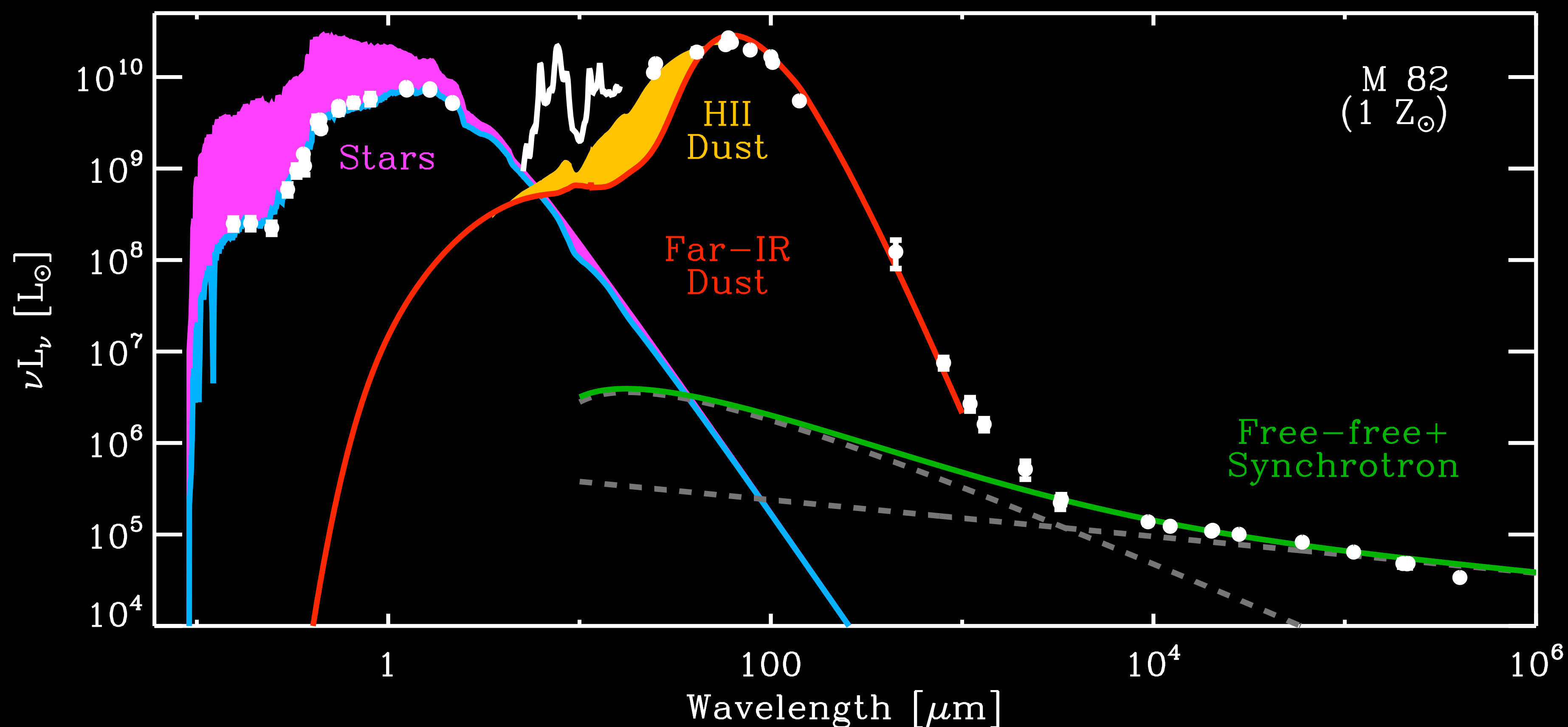
Galliano, Dwek & Chanial 2007, astro-ph



Final fit to galaxy's SED

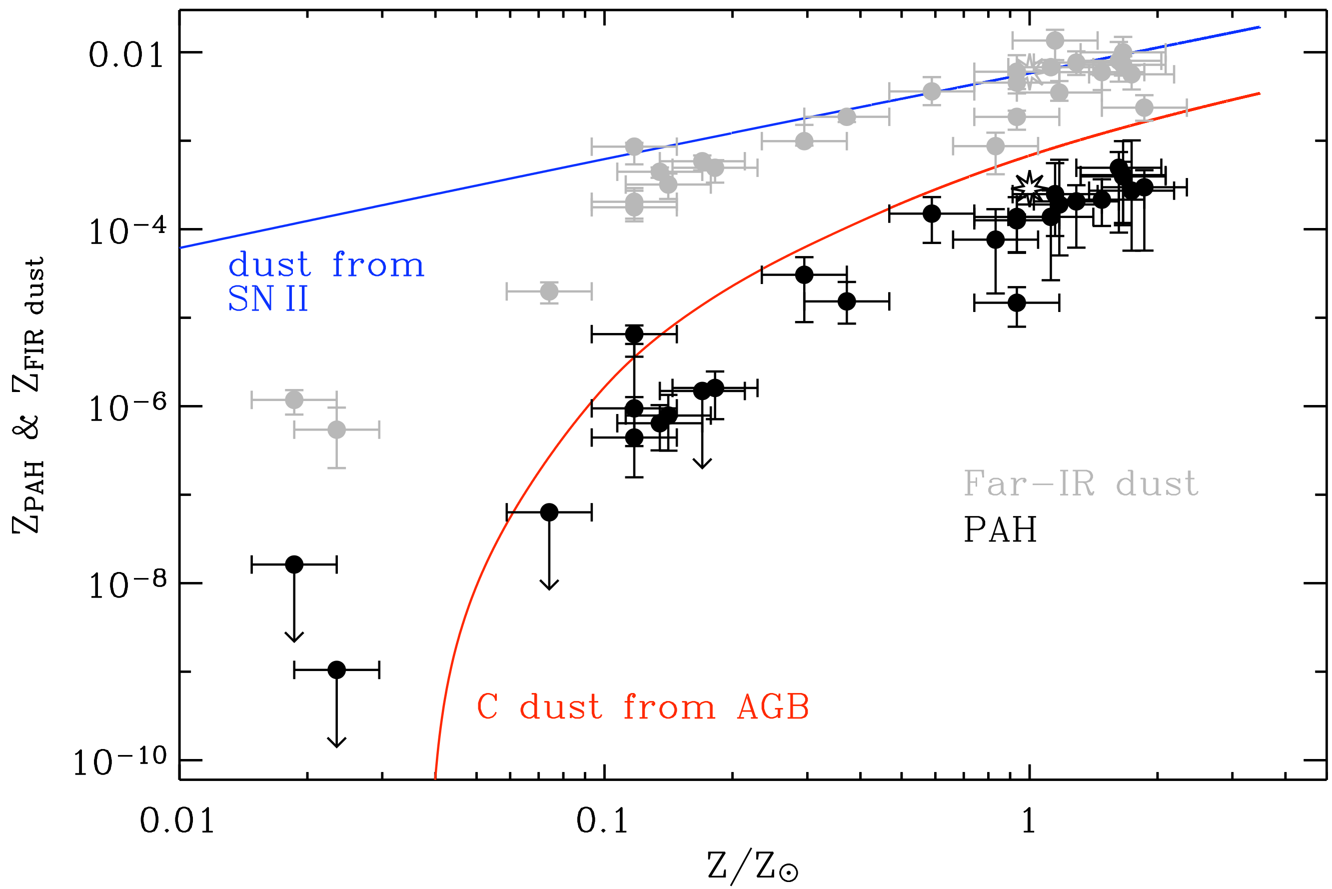
A fit to the dust emission from HI and HII regions is necessary in order to determine the ISRF that heats the PAHs

(Galliano, Dwek, & Chanial 2007)



The delayed injection of PAHs by AGB stars into the ISM:

A natural explanation for the PAH abundance trend with metallicity



Models are greatly simplified at high redshift

- Instantaneous recycling approximation
- The contributioon of AGB stars can be neglected
- Parameters for the closed box model:
    - the gas mass fraction
    - the mass of stars formed per SN event (M_{sn})
    - the mass of ISM gas cleared of dust by a single SNR (M_g)

- Same results are obtained for an infall model

Simple Chemical Evolution Model: Closed box model, no Infall/Outflow

The evolution of the gas

$$\boxed{\frac{dM_g}{dt} = -(1-R)\psi(t)}$$

SFR $\psi(t) = \psi_0 \left(\frac{M_g}{M_0}\right)^k$ Initial gas mass M_0

Evolution of gas mass fraction ($k=1$)

$$\boxed{\mu(t) \equiv \frac{M_g(t)}{M_0} = \exp\left[-(1-R)\left(\frac{\psi_0}{M_0}\right)t\right]}$$

The evolution of the dust

$$\boxed{\frac{dM_d}{dt} = -Z_d\,\psi(t) + Y_d\,R_{SN} - \frac{M_d}{\tau_d}}$$

$$Z_d \equiv \frac{M_d}{M_g}$$

$$R_{SN} = \frac{\psi(t)}{\langle m_{SN} \rangle}$$

$$\tau_d = \frac{M_g}{m_g\,R_{SN}}$$

General type $$\frac{dy}{dx} = f(x) + g(x)\,y$$

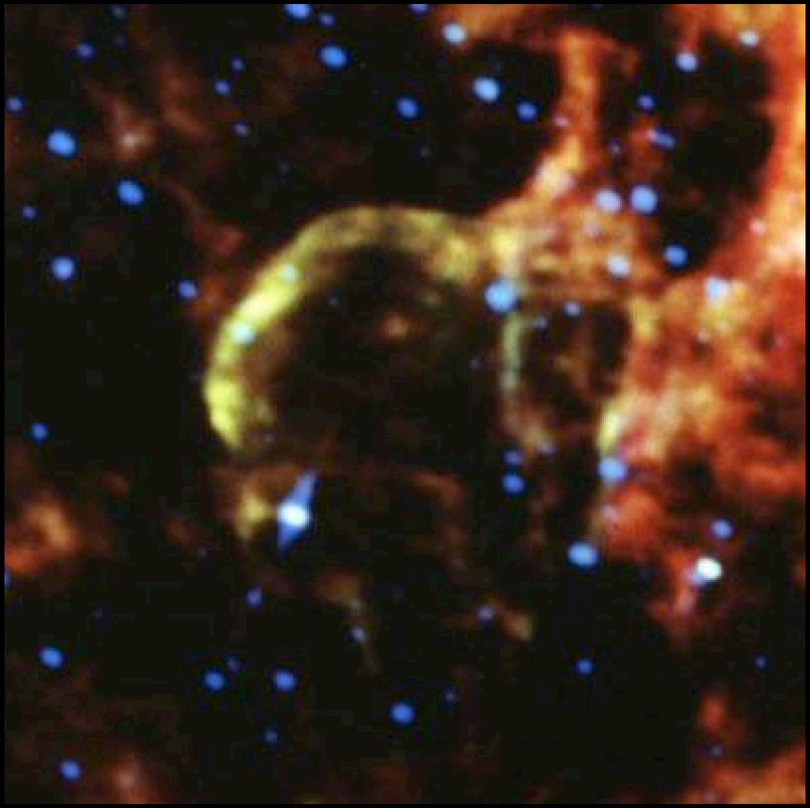
Solution $$M_d(t) = Y_d \left[\frac{M_0}{m_g + \langle m_{SN} \rangle\,R}\right] \mu\,(1 - \mu^{\nu})$$

$$\nu \equiv \frac{m_g + \langle m_{SN} \rangle\,R}{\langle m_{SN} \rangle\,(1 - R)}$$

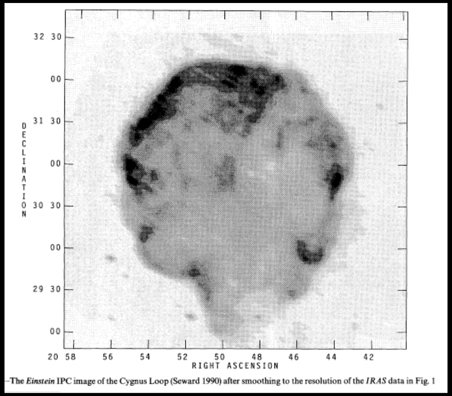
$$\boxed{M_d(t) = Y_d \left[\frac{M_g(t)}{m_g + \langle m_{SN} \rangle\,R}\right] (1 - \mu^{\nu})}$$

Supernovae destroy dust during the remnant phase of their evolution

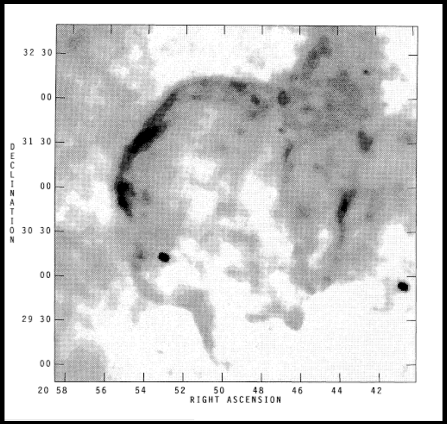
Cygnus Loop: IR emission from dust collisionaly-heated by the shocked gas



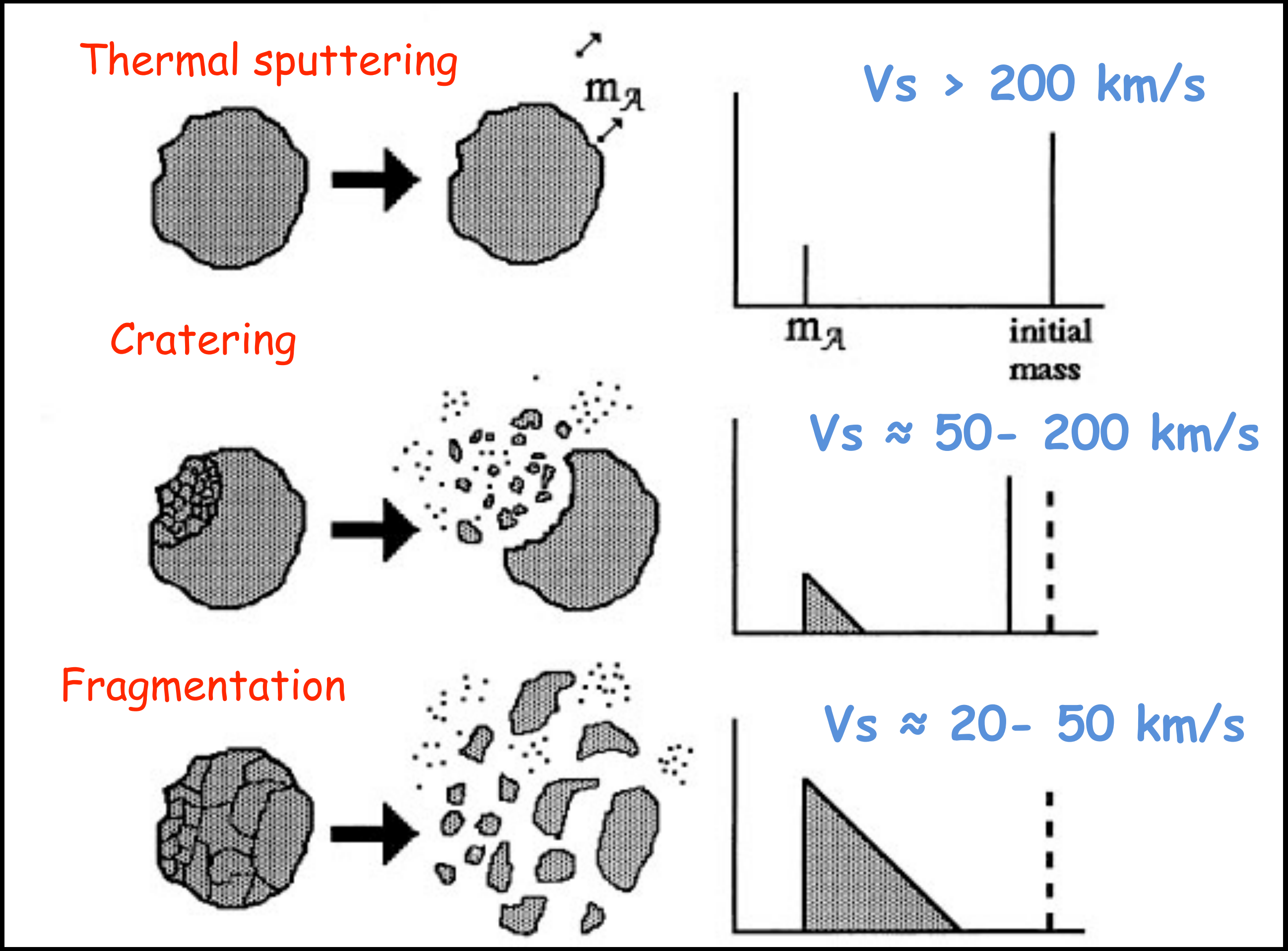
Cygnus Loop: X-rays (Einstein)



Cygnus Loop: Infrared (IRAS)



Grain Destruction Processes

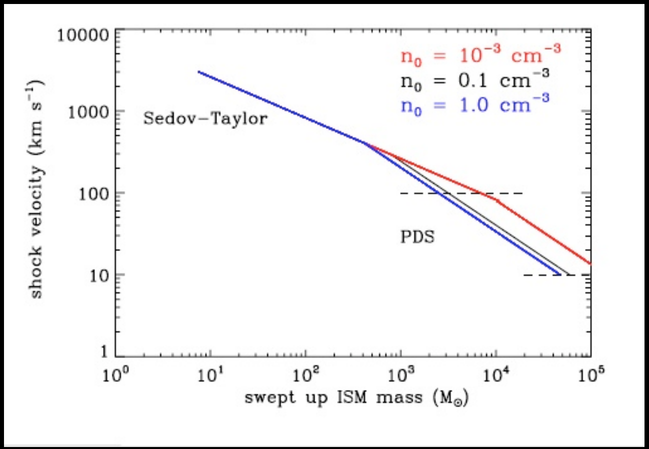


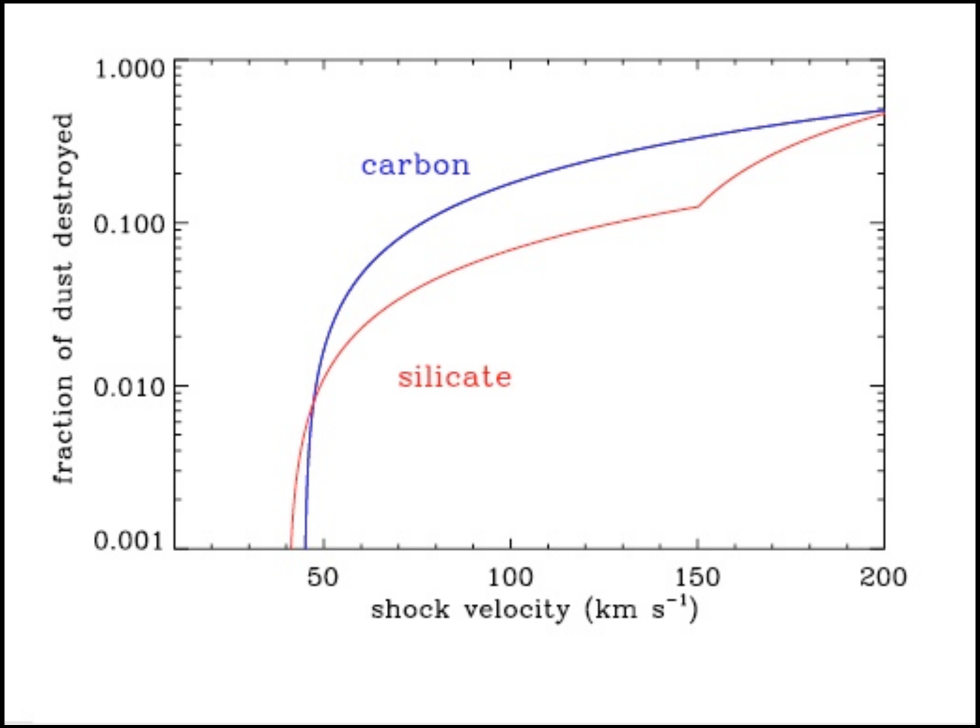
Grain destruction efficiencies

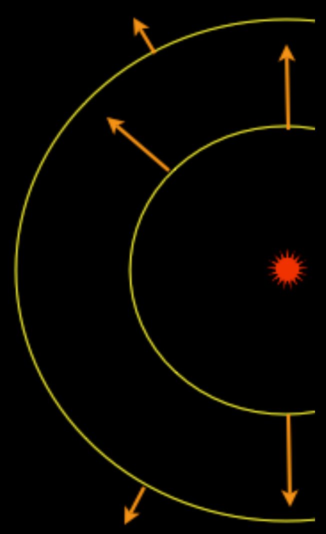
(Jones, Tielens, Hollenbach, & McKee 1994, 1996)

Mass of dust destroyed by a single SNR

$$M_d = Z_d \int_{v_0}^{v_f} f_d(v_s) \left(\frac{dM_{ISM}}{dv_s} \right) dv_s$$

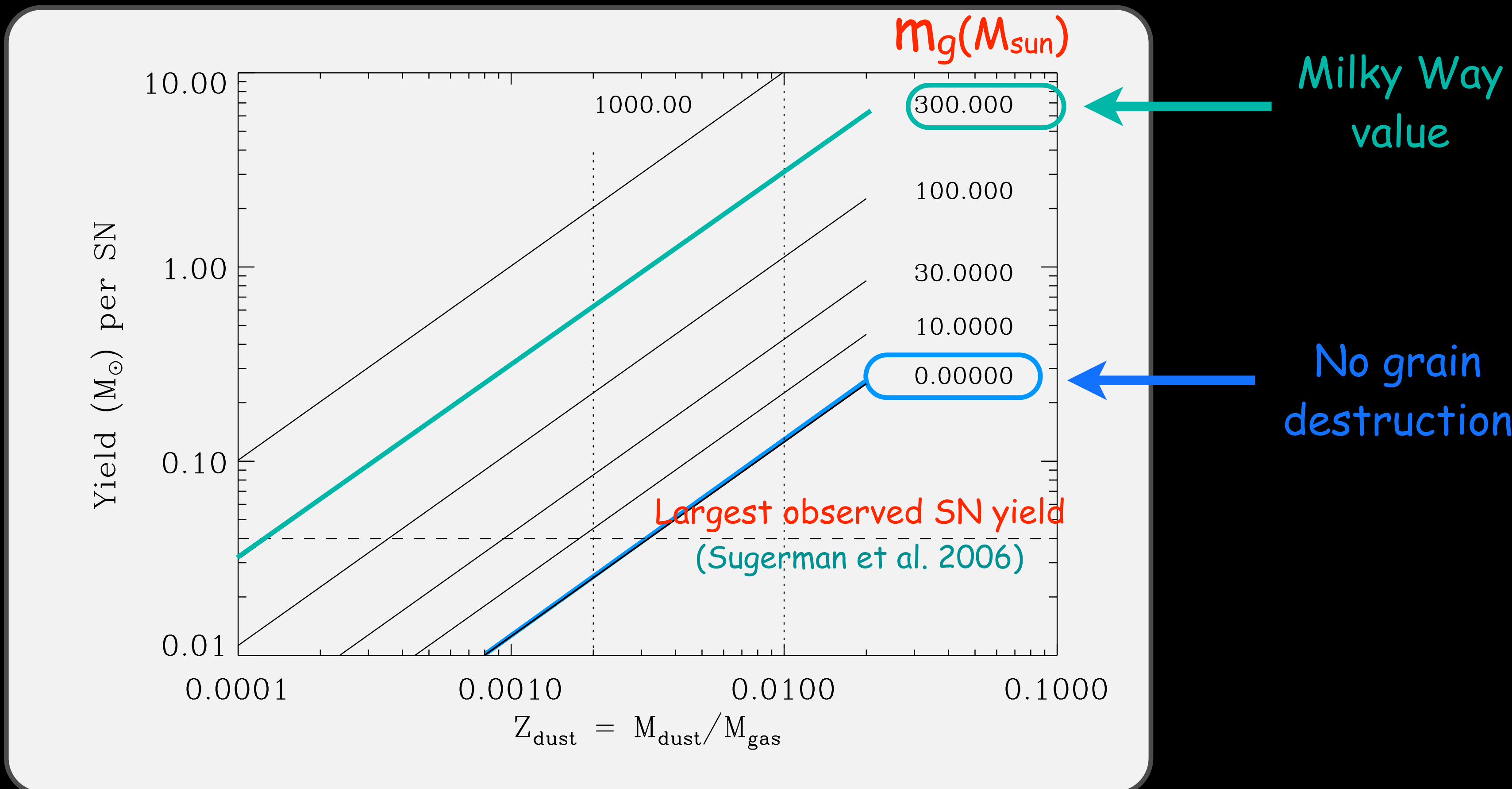






SN Yield Required to Produce an Observed Z_d

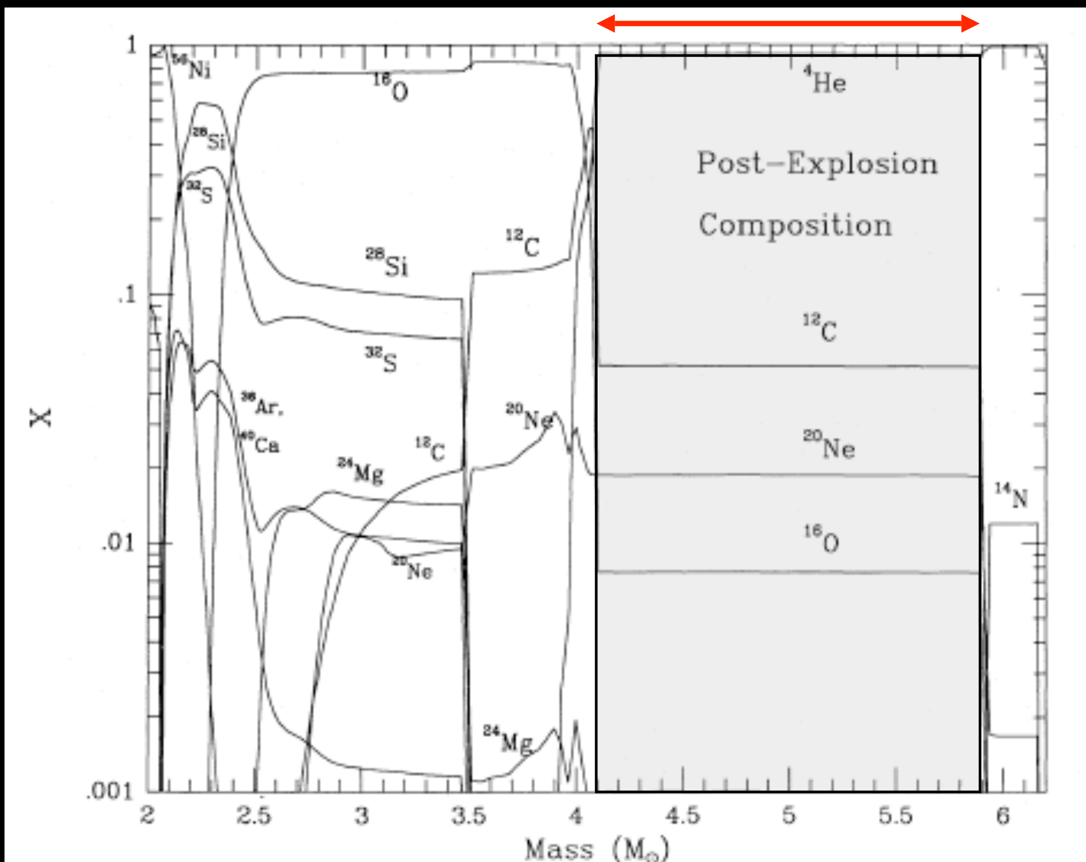
$$Y_d = Z_d(t)\left[\frac{m_g + \langle m_{SN}\rangle R}{1-\mu^{\nu}}\right]$$



SN 1987A Yield of Condensable Elements

25 Msun (Woosley & Weaver 1995)

C/O > 1



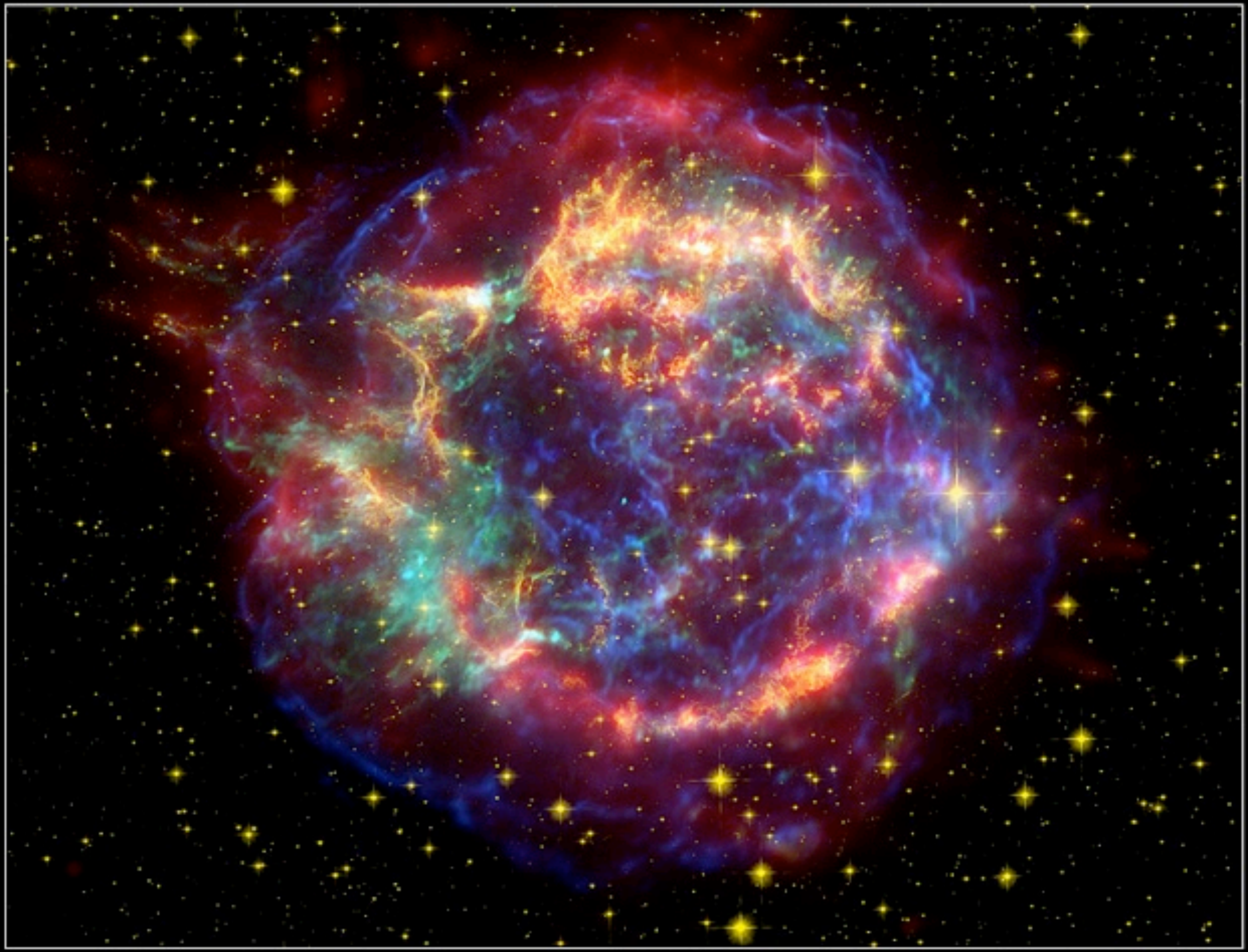
Element	$Y(M_{sun})$
C	0.1
O	0.4
Mg	0.02
Si	0.3
Fe	0.07

Dust ≈ 1 M_{sun}

Silicates: SiO_2

Carbon: C

Multiwavelength Observations of Cas A



Cassiopeia A Supernova Remnant
NASA / JPL-Caltech / O. Krause (Steward Observatory)
ssc2005-14c

Spitzer Space Telescope • MIPS
Hubble Space Telescope • ACS
Chandra X-Ray Observatory

Chandra
2.25-7.50 keV
1.65-2.25 keV

Opt - Hubble
IR - Spitzer

Dust mass
$\approx 10^{-2}\, M_{\odot}$

SCUBA 450 & 850 μm observations of Cas A: Evidence for massive amounts of cold dust?

(Dunne et al. 2003)

450 μm

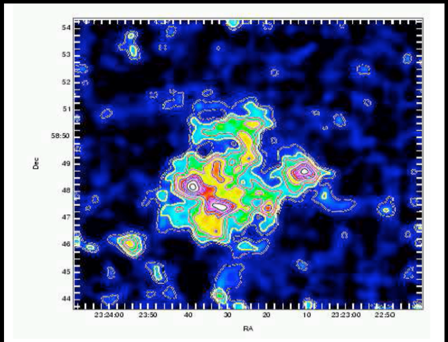


Figure 3: SCUBA 450μm map, smoothed with a 21″ gaussian. Colours and cont

850 μm

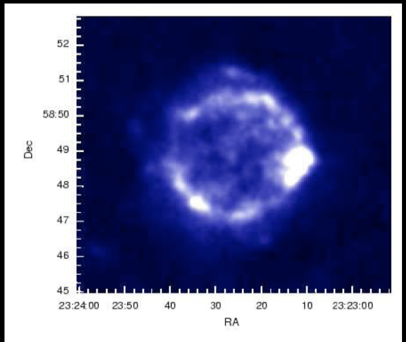
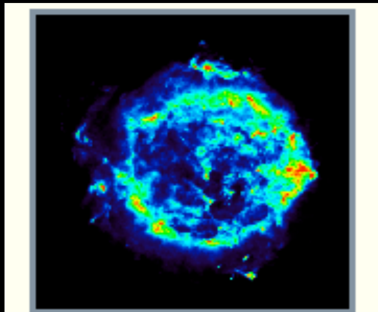


Figure 1: SCUBA 850μm image of Cas A at a resolution of 15 arcsec.



Radio: ©1992 NRAO

850 μm – synchr.

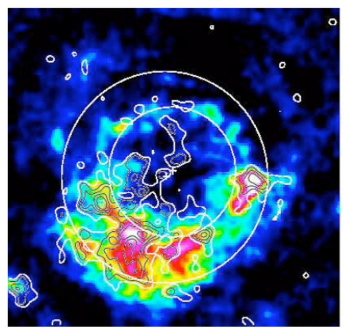


Figure 4: The 850μm emission once the synchrotron has been subtracted

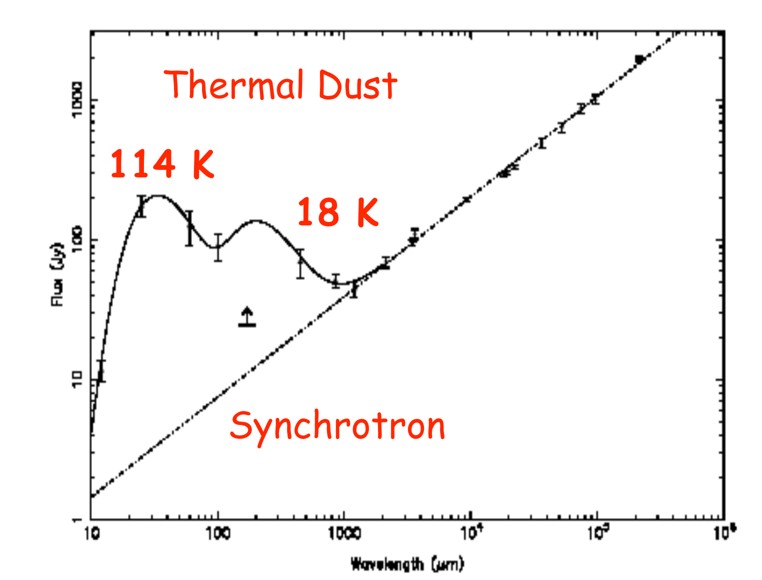


Figure 2: The SED of Cas A from the mid-IR to the radio. All fluxes a

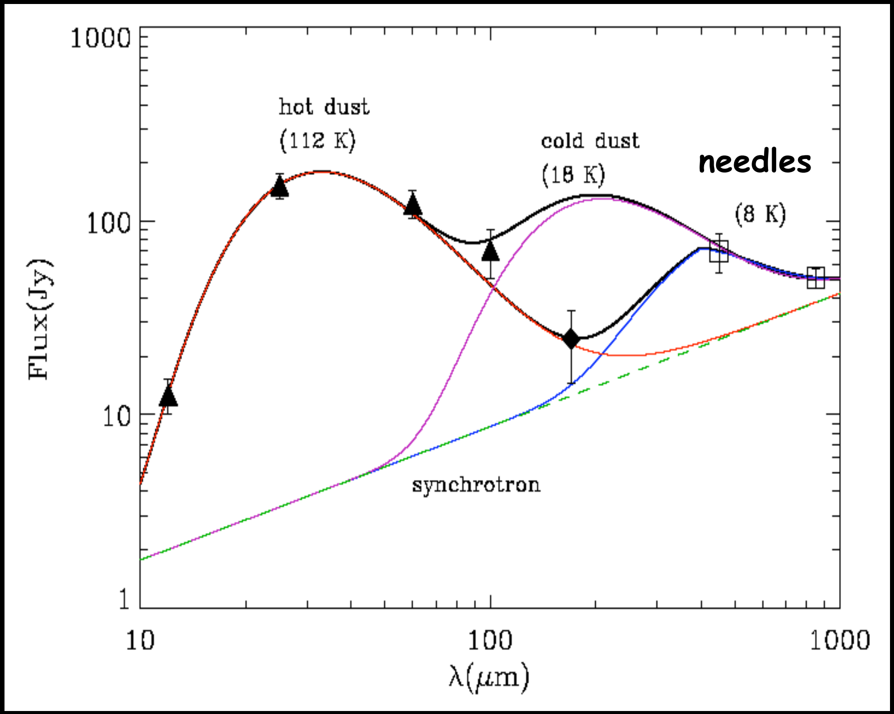
Dust Mass (M_{sun})

$M_{114\,K} \approx 10^{-3}$

$M_{18\,K} \approx 2\text{–}20$

Problems with the Dunne et al. interpretation:

(1) The 170 μm flux is an ISO detection (Tuffs et al.)



(2) Needles could alleviate the large mass of dust implied by the 450 μm SCUBA "detections" but .....

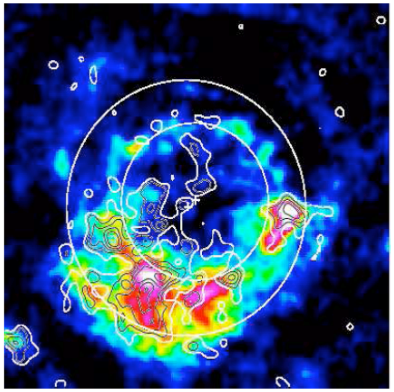


Figure 4: The 850μm emission once the synchrotron has been subtracted

(3) The 450 μm emission arises from a cloud along the LOS of Cas A

Conclusion: sofar there is no evidence that SNe make massive amount of dust

- Cas A: Spitzer has detected $\approx 10^{-2}\,M_\odot$ of dust in the ejecta (Rudnick et al. 2006)
- SN 2003gd in NGC 628:
  - Progenitor mass: $\approx 12\,M_\odot$
  - mass of condensable elements: $\approx 0.3\,M_\odot$
  - Observed dust mass: $\approx 0.04\,M_\odot$ (Sugerman et al. 2006)
- SN1987A
  - Detected dust mass $< 10^{-3}\,M_{sun}$
- Dust needs to survive its injection into the ISM
  - reverse shocks

Conclusions

- Massive amount of dust at high redshift requires an additional source of dust
- Dust accretion onto pre-existing dust cores in molecular clouds is most obvious source
  - Complex chemistry and accretion efficiency
    - Cosmic rays, minimum dust temperature ~ $T_{cmb} \approx 22$ K
  - Cycling between cloud-intercloud medium
    - ISM morphology, SN rates, cooling/heating of ISM

END