What we would like to know about the evolution of interstellar dust

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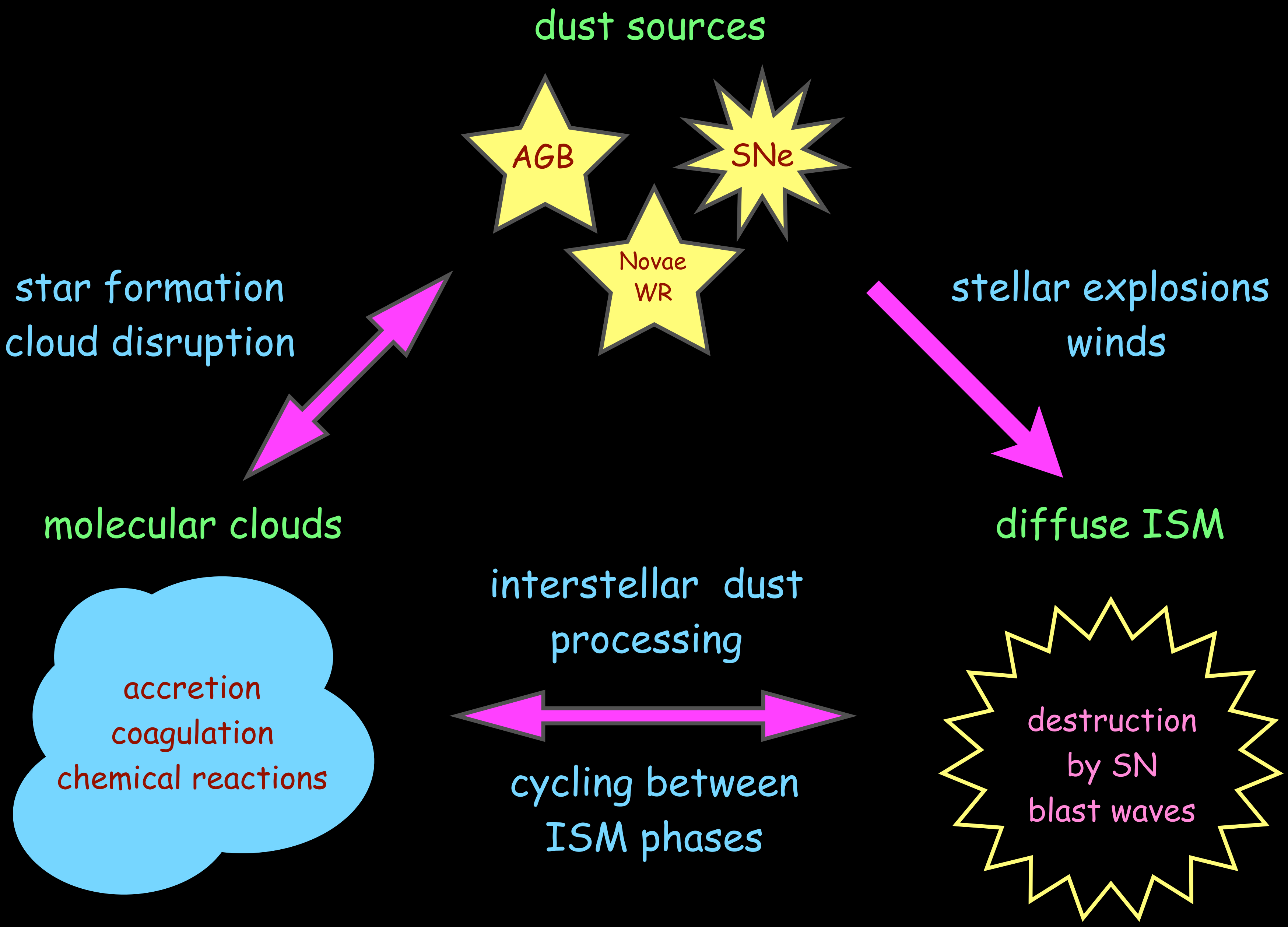
SOFIA 2010 Workshop - Asilomar

A Billion Years in the Life of a Dust Particle



dust sources

AGB

SNe

Novae
WR

star formation
cloud disruption

stellar explosions
winds

molecular clouds

diffuse ISM

interstellar dust
processing

accretion
coagulation
chemical reactions

cycling between
ISM phases

destruction
by SN
blast waves

Fundamental Scientific Questions

Eye popping

Sensational

Jaw dropping

General Scientific Goal

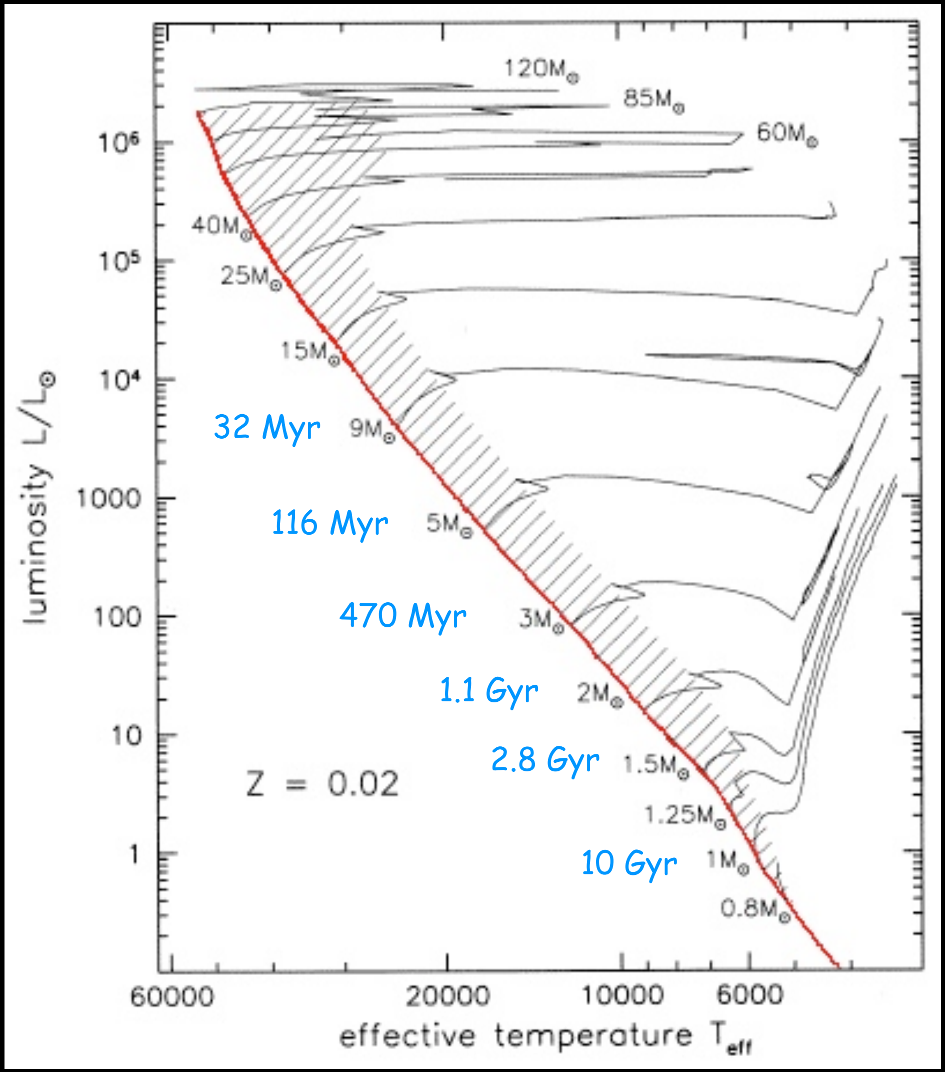
Understanding the origin and evolution of dust in the universe

Fundamental questions addressed by studies of SNe and SNRs

- How much dust is produced in the explosive ejecta of supernovae?
- What is its composition and size distribution?
- Does this dust survive its injection into the ISM?
- How are certain meteoritic isotopic anomalies produced?
- How efficiently are SNRs destroying and processing interstellar dust?
- How efficiently is the SN-dust mixed into the ISM?
- Can shock induce the nucleation/growth of dust in very dense circumstellar shells?

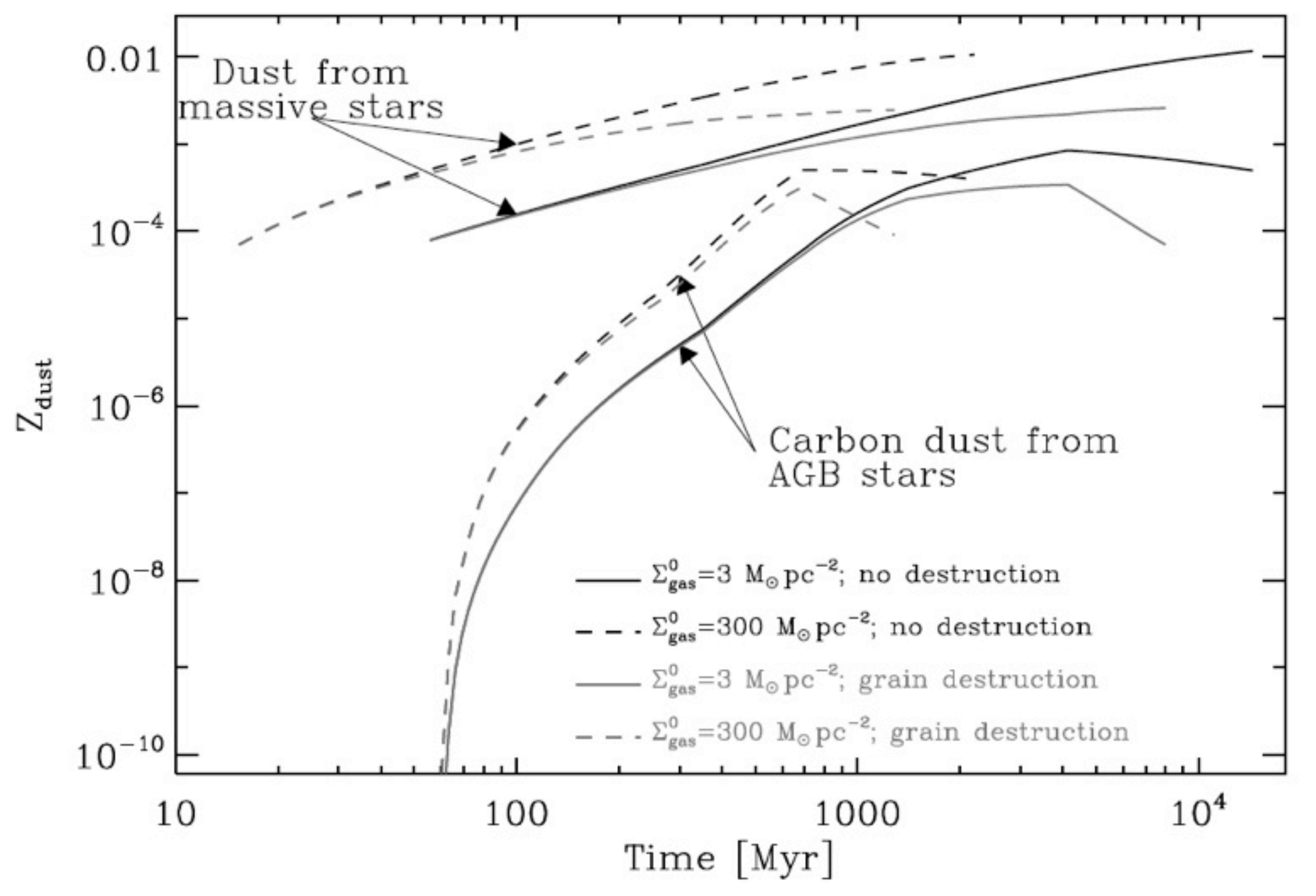
The local universe

The dust composition MUST evolve !

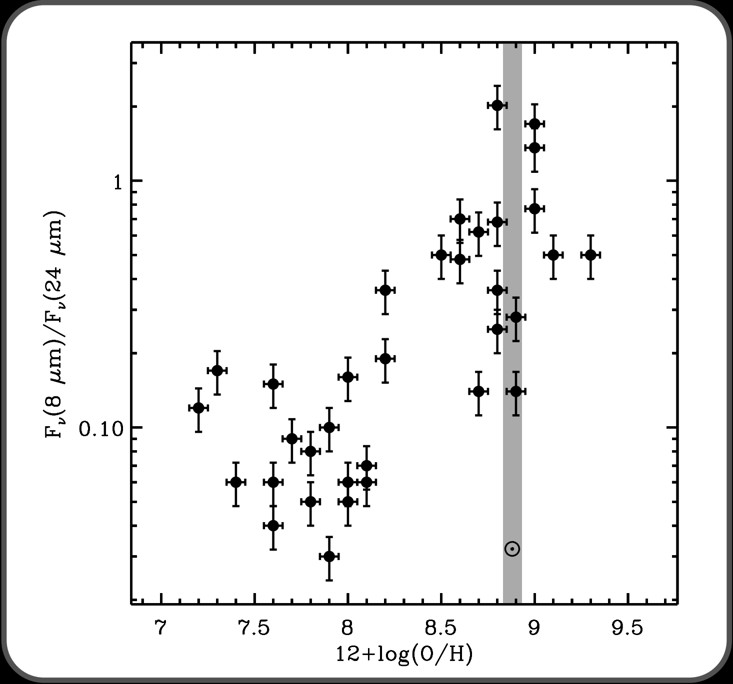


- SN are the primary sources of silicate dust
    - they return their processed ejecta “promptly” back to the ISM
- AGB stars (Msun ≈ 1-8 M_{sun}) are the primary sources of carbon dust
    - they return their processed material a considerable time after their birth
        - The IMF-averaged mass of a carbon star is ~ 3 M_{sun}
- The dust composition will therefore change over time
    - extinction, composition, IR emission will therefore depend galactic age
- How can we observationaly test it?
    - find proxy for AGB dust
    - observe galaxies at different ages or metallicities

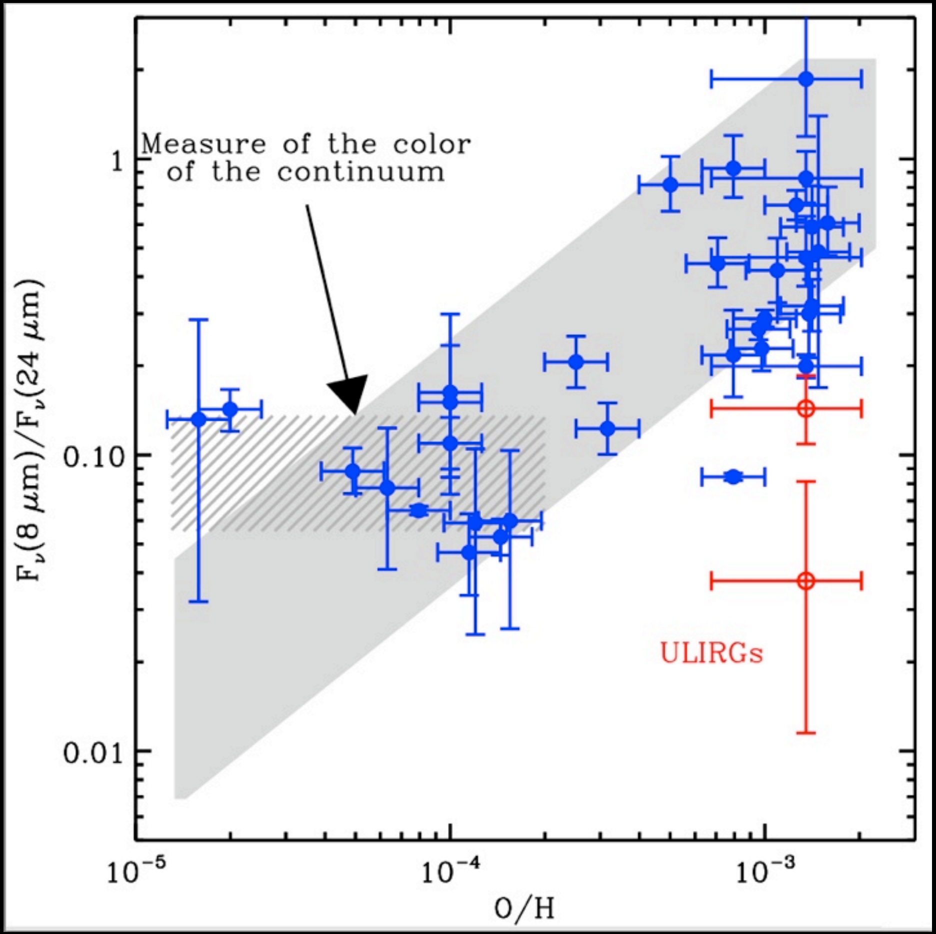
The evolution of SN- and AGB-condensed dust



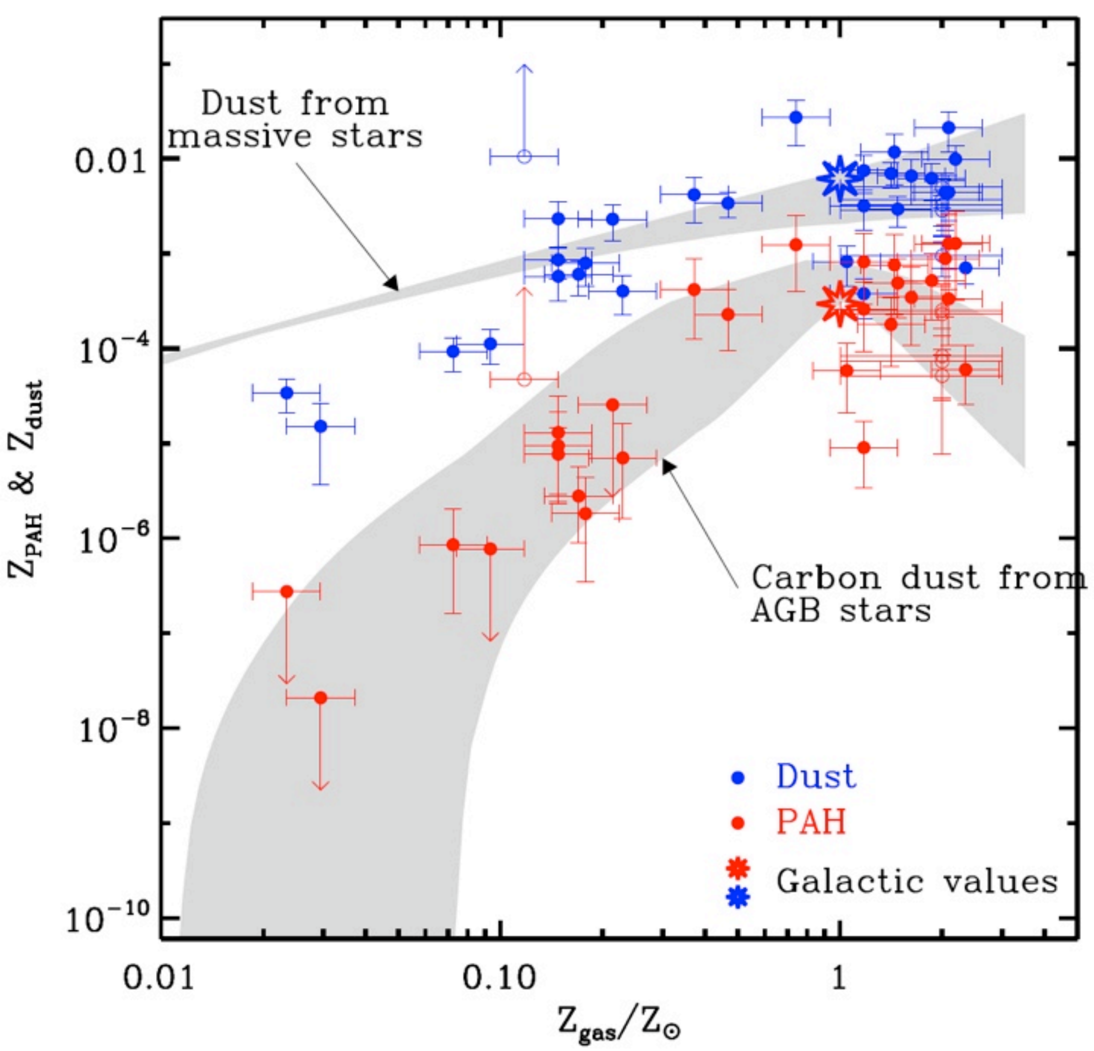
The trend of “PAH emission” with metallicity (Engelbracht et al. 2005)



Updated trend of “PAH emission” with metallicity (Galliano et al. 2005)



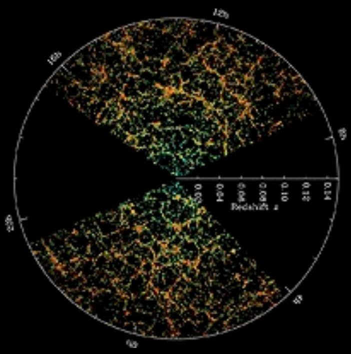
Comparison of dust evolution models to observations



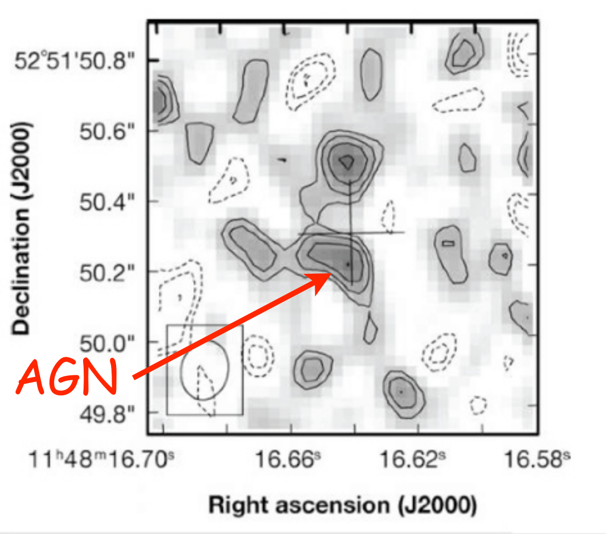
The high-z universe

2.5 m

What is the Origin of Dust in the high redshift quasar SDSS J114816+5251 ?



Detected in a search for i (7481 Å) dropouts in
the Sloan Digital Sky Survey
(Fan 2003)
Follow-up spectroscopy
z = 6.4



$$M(H_2) = 1.6 \times 10^{10}\ M_\odot$$

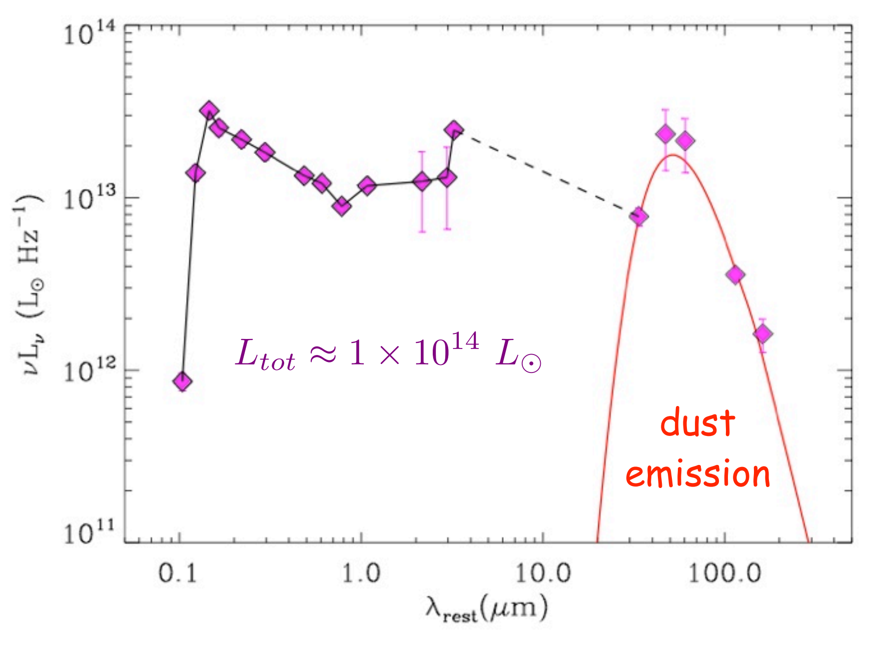
$$M_{dyn} = (4.5 - 5.5) \times 10^{10}\ M_\odot$$

$$M_{BH} = 3 \times 10^{9}\ M_\odot$$

$$M_{bulge} = 5 \times 10^{11}\ M_\odot$$

The Spectral Energy Distribution of J1148

Searches for lensing effects were negative



Dust Mass in J1148

(1–4)x10^8 M_{sun}

Milky Way

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

- ✦ Star formation rate, FIR

(Kennicut relation)

$$\psi(\frac{M_\odot}{yr}) = 1.7 \times 10^{-10}\ L_{FIR}(L_\odot)$$

$$\psi \approx 3000\ M_\odot\, yr^{-1}$$

However the SRF can be much lower if the AGN contributes significantly to the FIR luminosity

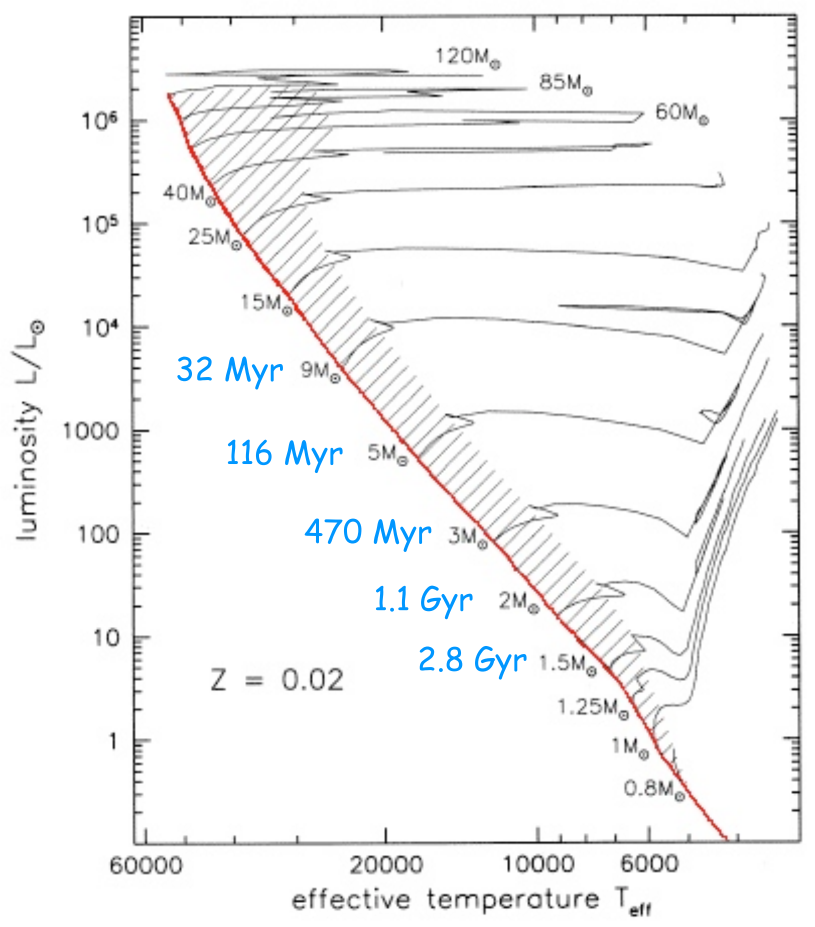
- ✦ Star formation rate, L(CO)

$$\psi \approx 3000\ M_\odot\, yr^{-1}$$

Can SN produce the required mass of dust?

Age of the universe: 890 Myr

z = 10 Univ = 490 Myr, Gal age = 400 Myr
z = 20 Univ = 190 Myr, Gal age = 700 Myr
z = 30 Univ = 100 Myr, Gal age = 790 Myr



NO PROBLEM!

SN rate ≈ 20 per yr

in 400 Myr → ≈ 10^9 SNe

Each SN needs to make
3×10^8 / 10^9
≈ 0.03 M_{sun} of dust

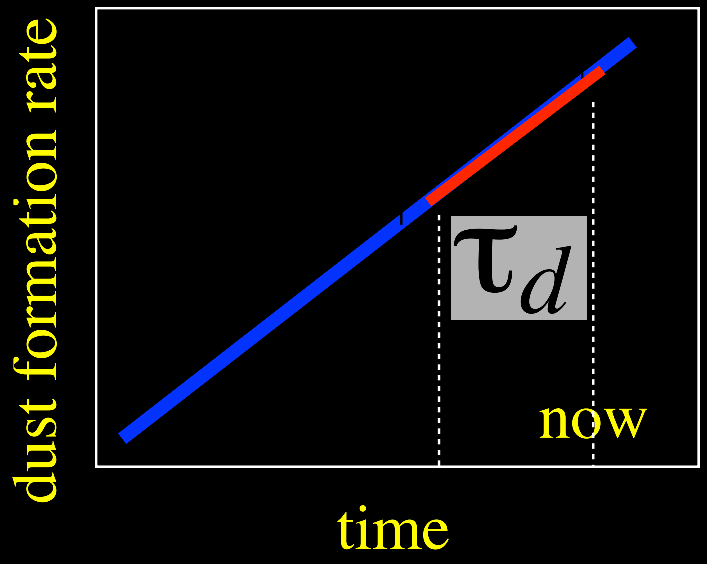
These calculations neglect:

(1) the effect of grain destruction

(2) the finite effective SF time

How much dust must a SN produce to account for the observed dust mass in J1148+5251?

Mass of dust = dust production rate X dust lifetime



$$M_d = (Y_d\, R_{SN}) \times \tau_d$$

$$\tau_d = \frac{M_d}{< m_d >\ R_{SN}}$$

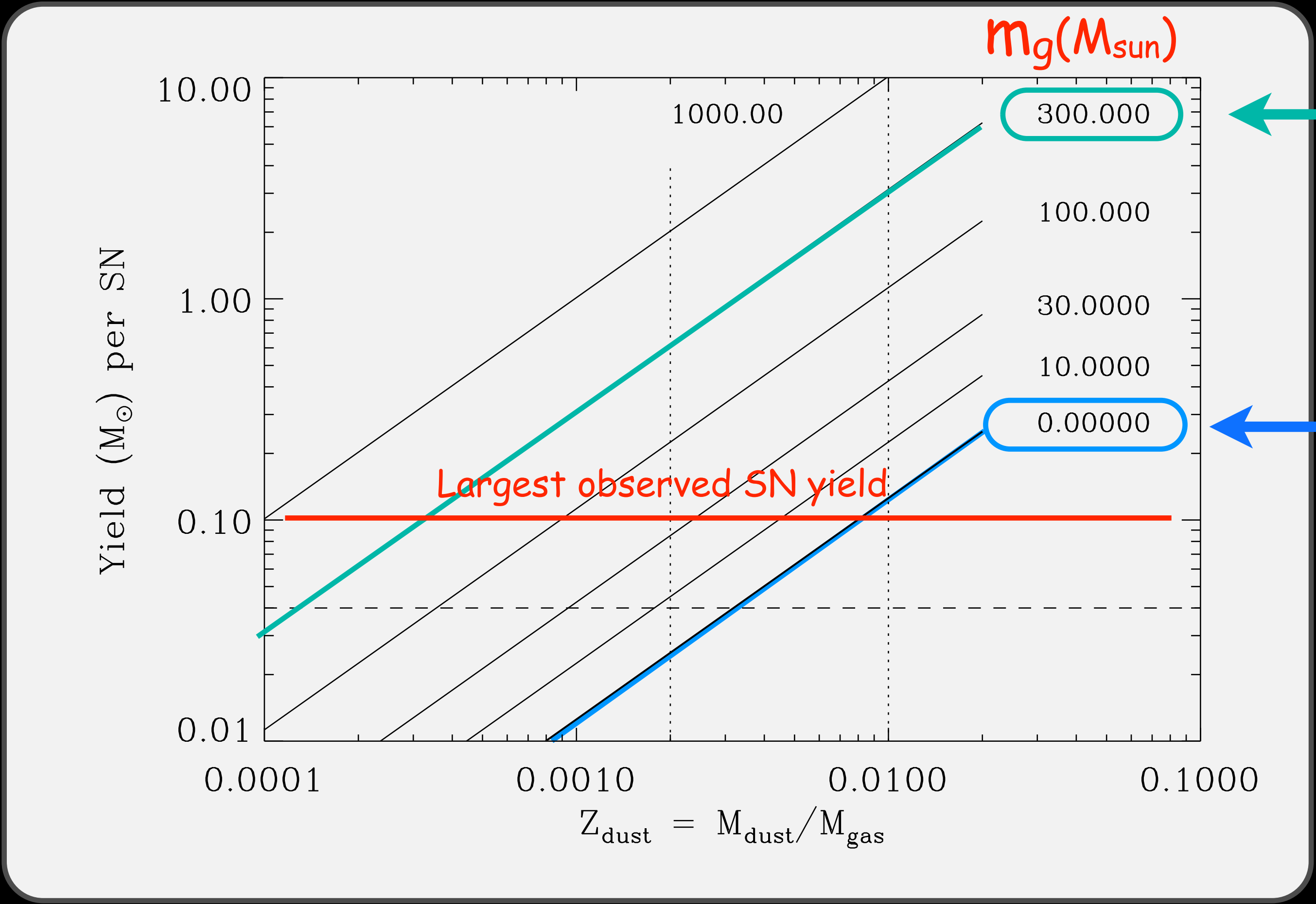
$$\Rightarrow \boxed{Y_d \approx < m_d >}$$

Milky Way:

$$\tau_d \approx 400\ Myr \longrightarrow < m_d > \approx 3\ M_\odot$$

SN Yield Required to Produce an Observed Dust-to-Gas Mass Ratio, Z_d

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



Milky Way value

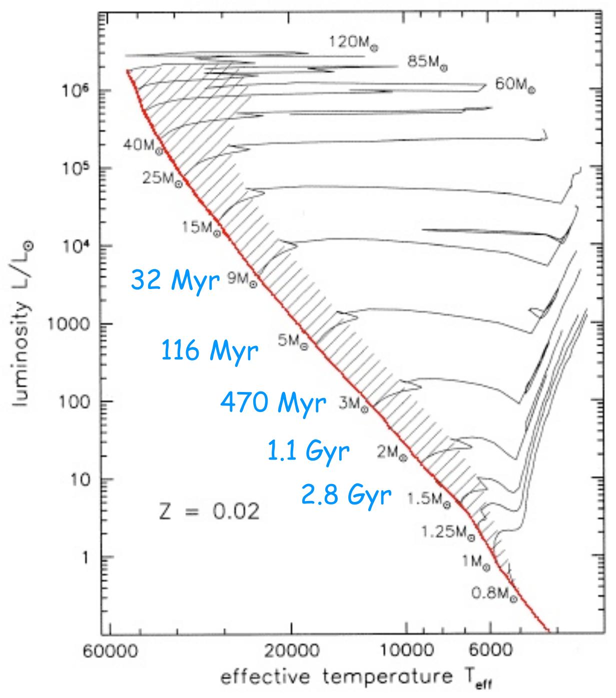
No grain destruction

Can AGB stars produce the inferred dust mass?

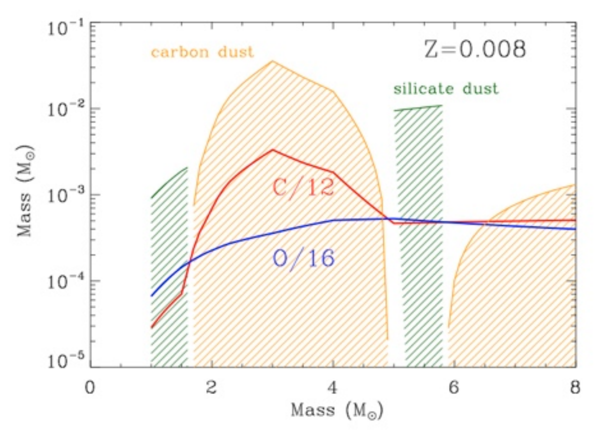
Average mass of dust producing AGB star

At z=6.4 the age of the universe is 890 Myr

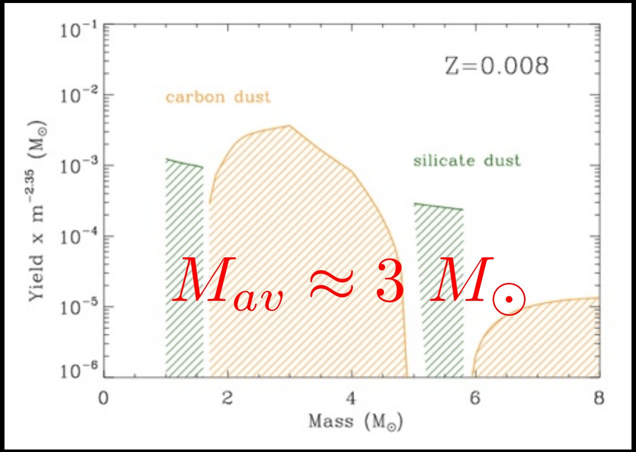
z = 10 Univ = 490 Myr, Gal = 400 Myr
z = 20 Univ = 190 Myr, Gal = 700 Myr
z = 30 Univ = 100 Myr, Gal = 790 Myr



Dust yield in AGB stars



IMF-averaged dust yield



$$M_{av} \approx 3\ M_\odot$$

Galaxy needs to be significantly older than ≈ 500 Myr

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

(Li et al. 2007)

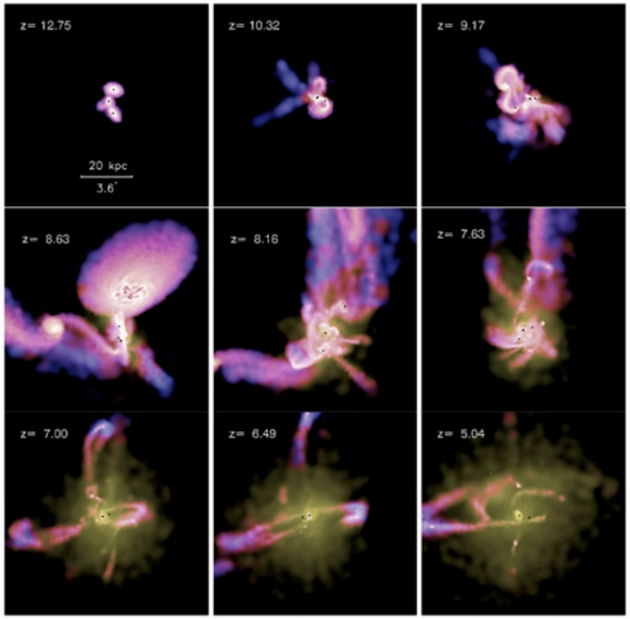
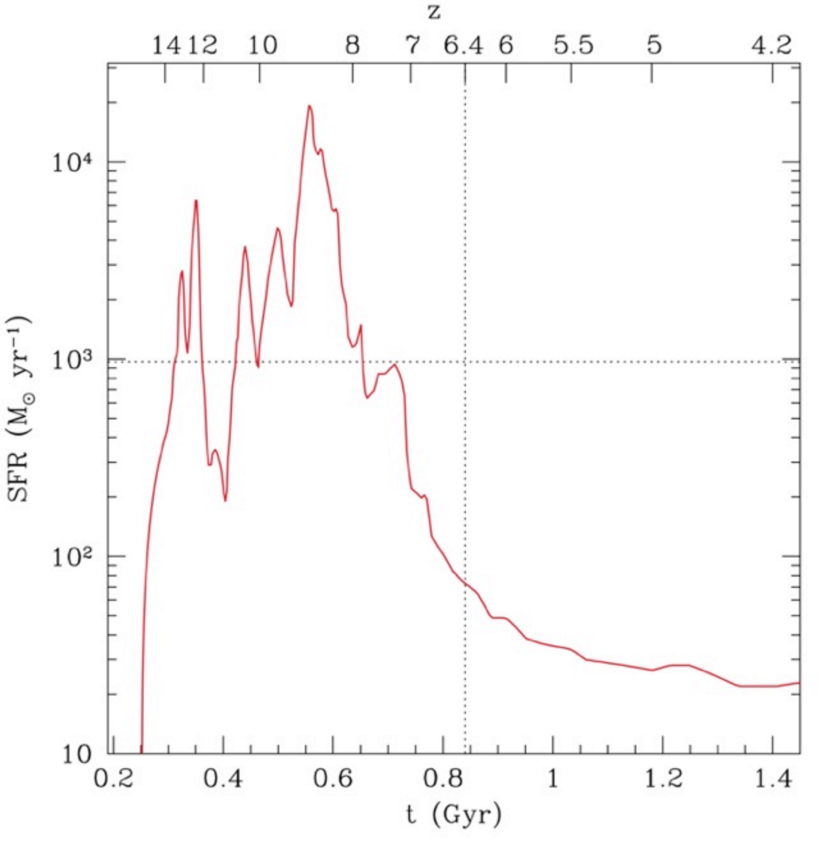
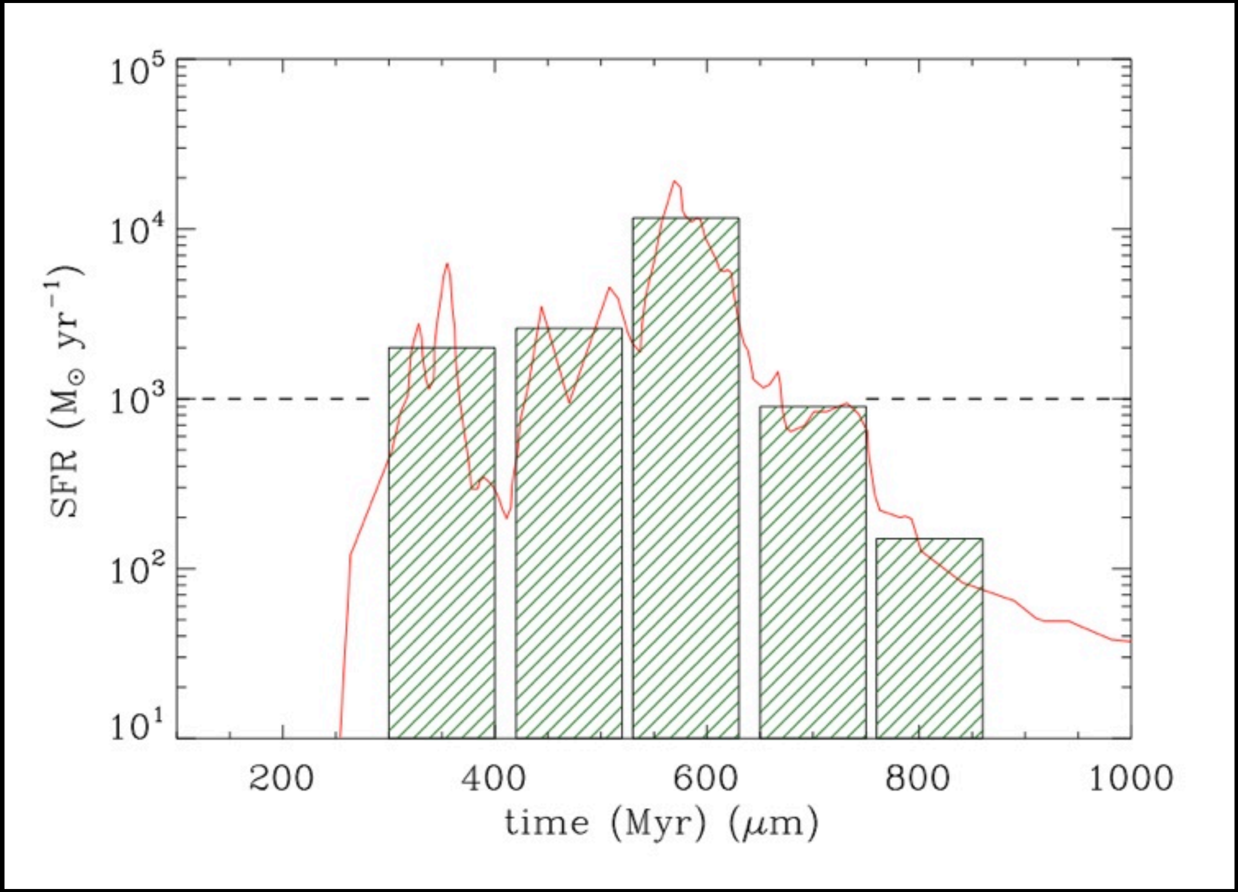


Figure 1: Formation of a high-redshift quasar from hierarchical galaxy mergers as simulated by Li et al. (2007). Color shows gas temperature, and intensity shows gas density. Black dots represent black holes. Small, gas-rich galaxies merge in the deepest

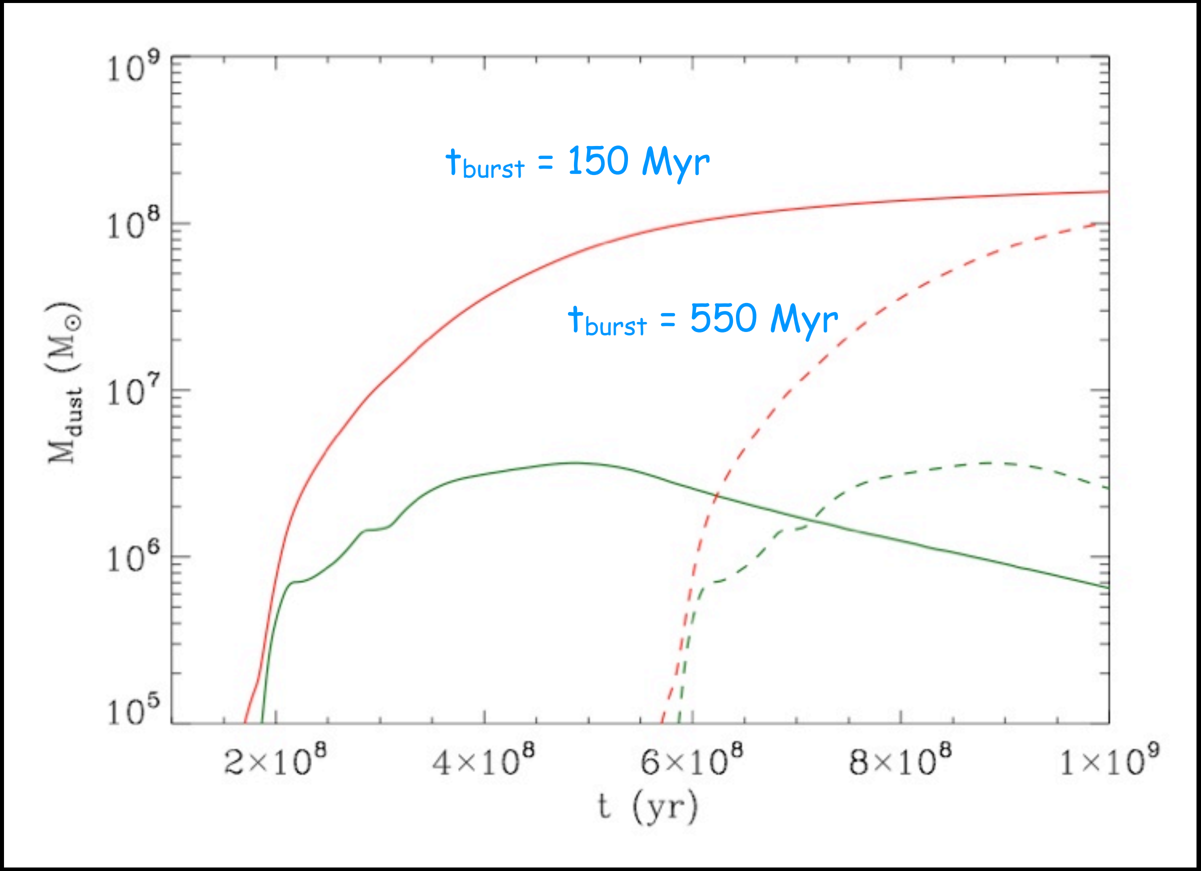


The SF history can be approximated by a series of discrete bursts



Evolution of AGB dust

- Single 100 Myr duration burst
- SFR = 1000 M_{sun}/yr
- Salpeter IMF (M_{low}=1 Msun)
- Dust lifetime = 10 Myr

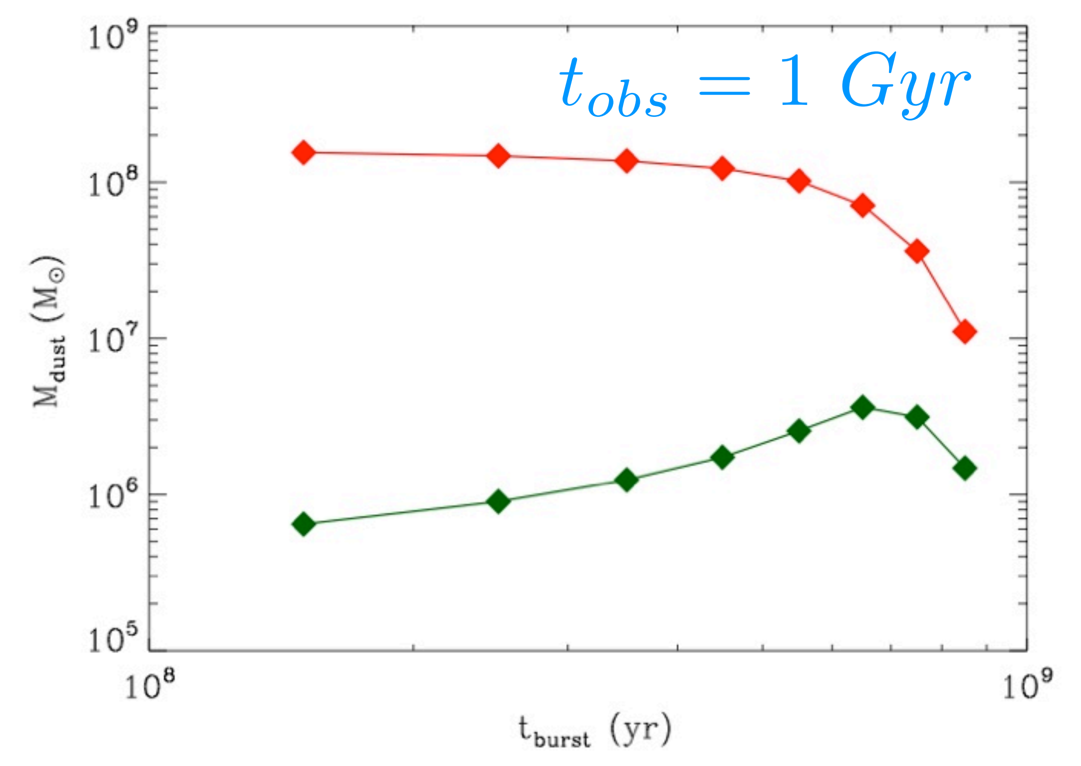


—— no grain destruction

- - - - - - - - with grain destruction

Bursts contribution to dust reservoir at t = 1000 Myr

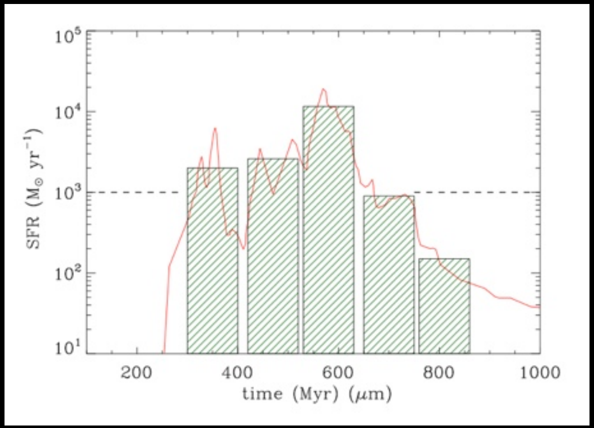
- Single 100 Myr duration burst
- SFR = 1000 M_{sun}/yr
- Salpeter IMF (M_{low}=1 Msun)
- Dust lifetime = 10 Myr

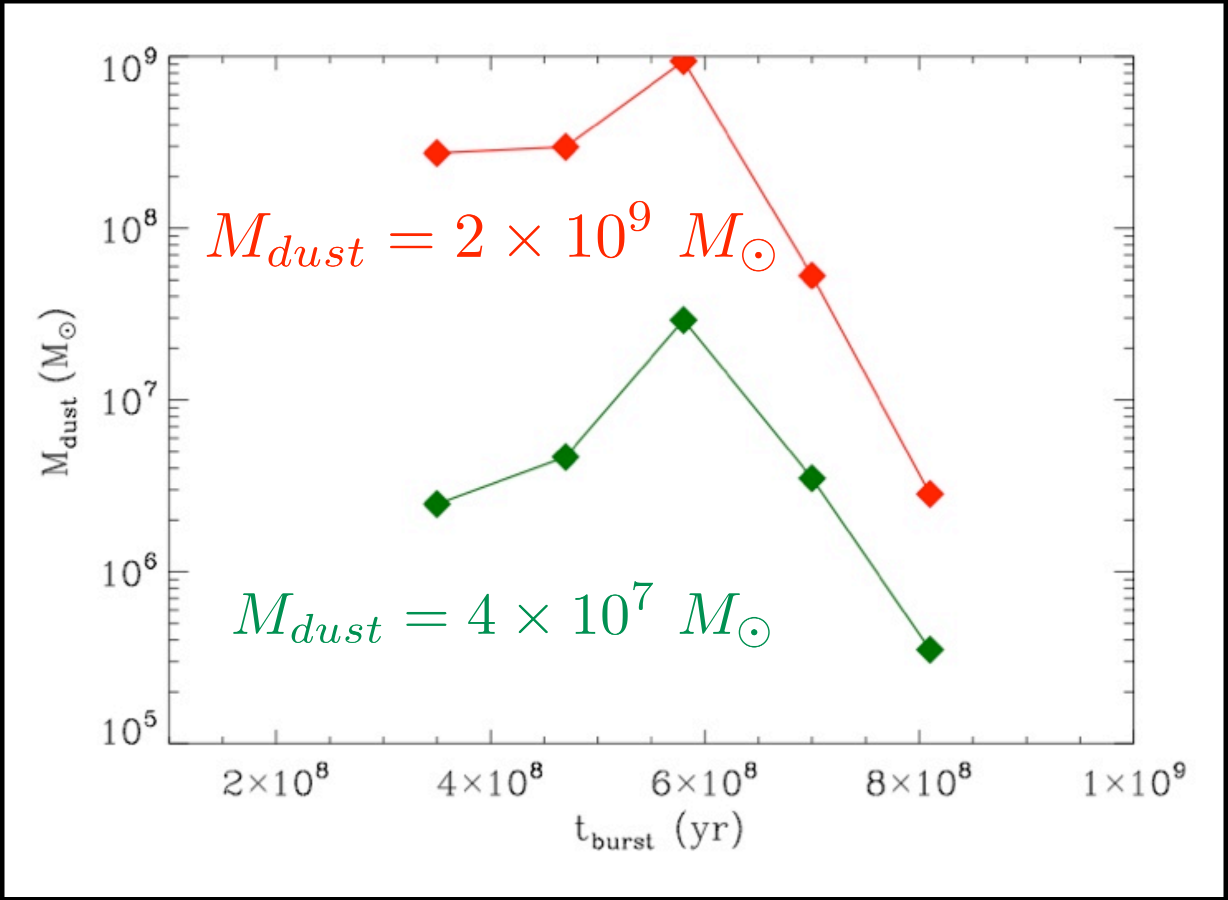


no grain destruction

with grain destruction

Bursts contribution to dust reservoir at t = 1000 Myr





$$M_{dust} = 2 \times 10^9 \ M_\odot$$

$$M_{dust} = 4 \times 10^7 \ M_\odot$$

— no grain destruction

- - - with grain destruction

Dust must be reconstituted in molecular clouds

- Lifetime of clouds must be larger than accretion time
- IR emission must primarily originate from molecular clouds
- The composition of dust in the diffuse ISM should bear traces of the processing in MCs

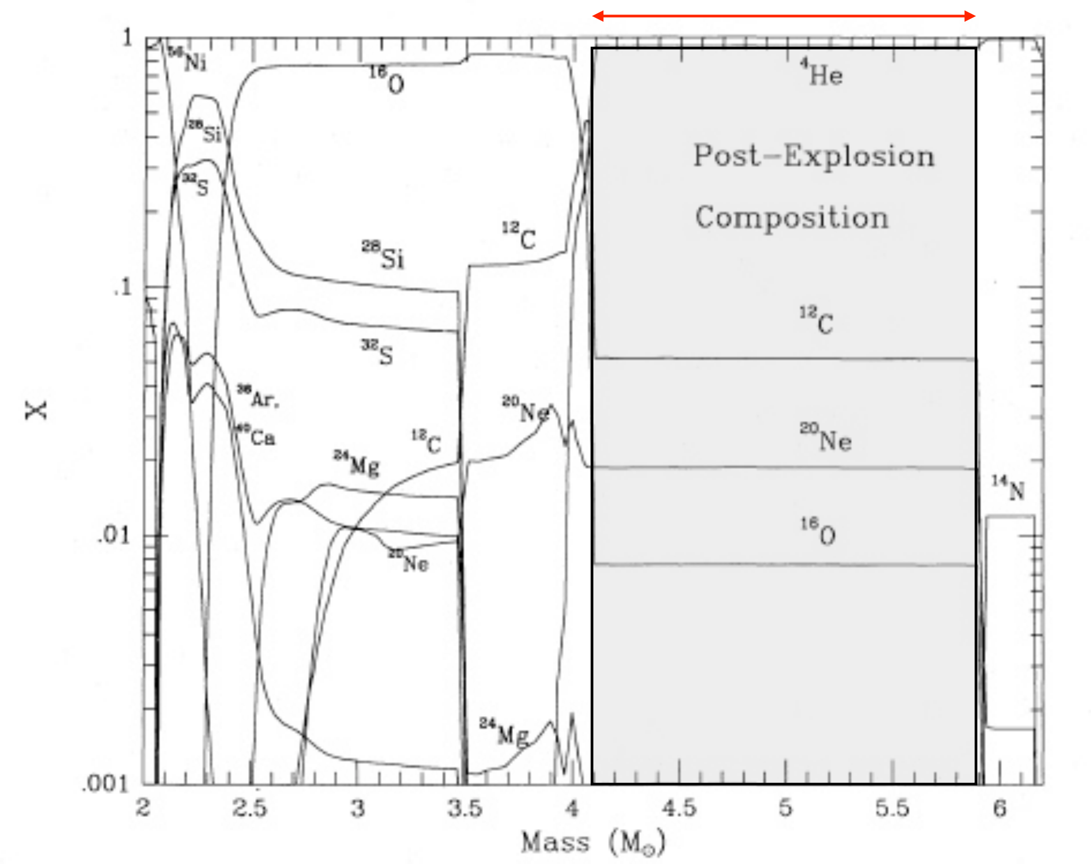
Supernovae and their Remnants can provide some answers

- Supernovae:
  - The most energetics events in the ISM: 10^{51} erg
  - Major source of chemical enrichment in the ISM
    - heavy elements - dust
  - Probes of ISM structure, composition
- Supernova Remnants
  - Laboratories for studying dust-gas physics
    - heating / cooling of dusty plasmas
    - PAH and dust processing in ejecta, circumstellar/ interstellar medium
    - dust formation in shocks
  - Play important role in the cycling between ISM phases

Supernovae as Dust Factories

SN1987A 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 $\approx 1\ M_{sun}$

Silicates: SiO_2

Carbon: C

Dust Formation in Novae & Supernovae
UV/opt - IR spectra method

(Gehrz 1988)

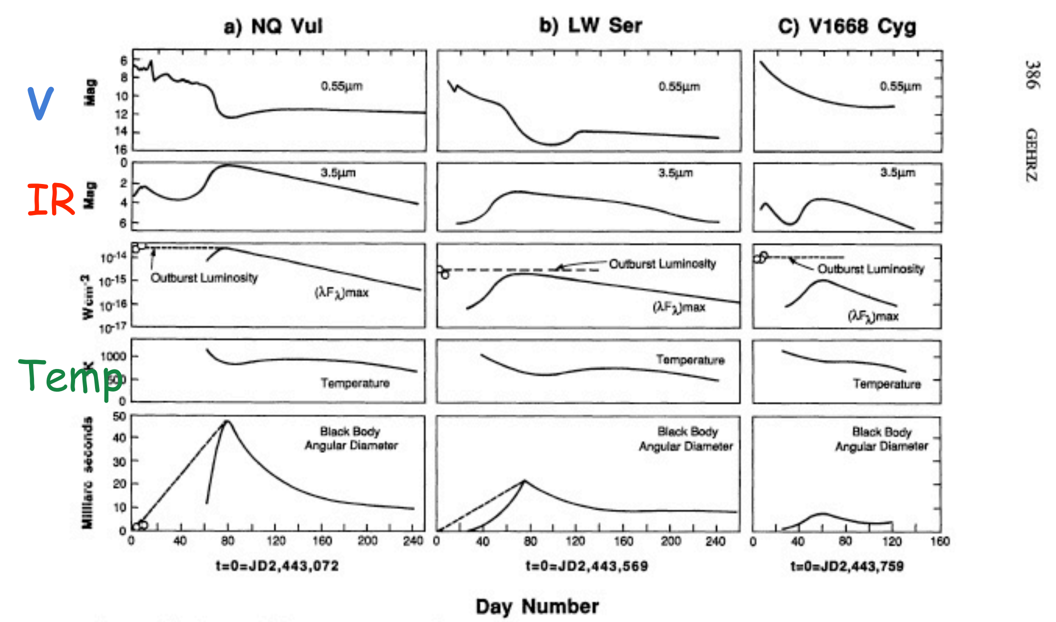
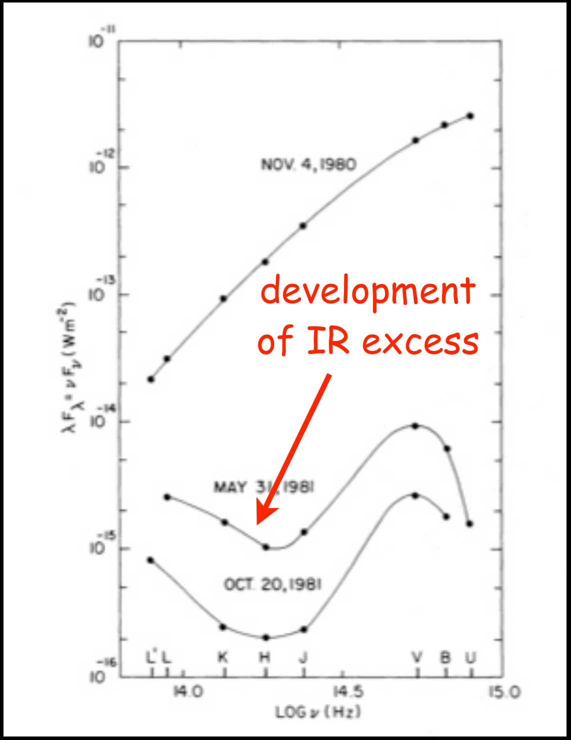


Figure 1 Temporal development of three recent novae that formed dust shells: (*a*) NQ Vul (168), (*b*) LW Ser (after 95), and (*c*) V1668 Cyg (after 97). When optically thick shells form (*a* and *b*), the visual light plunges as the thermal emission rises and the outburst luminosity is eventually reradiated in the infrared. In the optically thin case (*c*), the visual light is unaffected by the dust formation. In both cases, the dust first appears at a temperature of 1000–1200 K. The temporal behavior of the shell temperature and the blackbody angular diameter can be explained if it is assumed that the grains sputter or evaporate following the period of maximum grain growth as the shell expands.

SN1980k

(Dwek et al. 1983a)



development of IR excess

The rise in the IR could be an echo

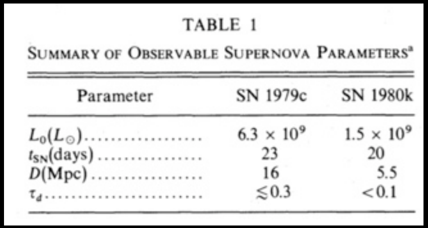
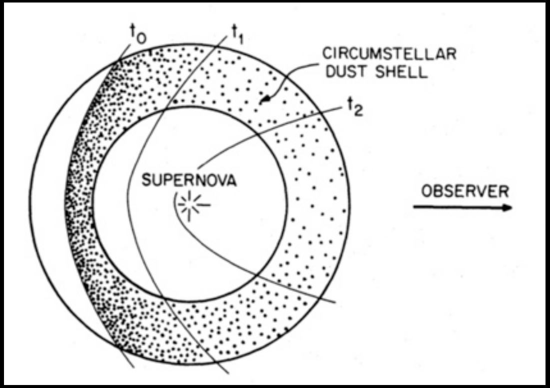


TABLE 1

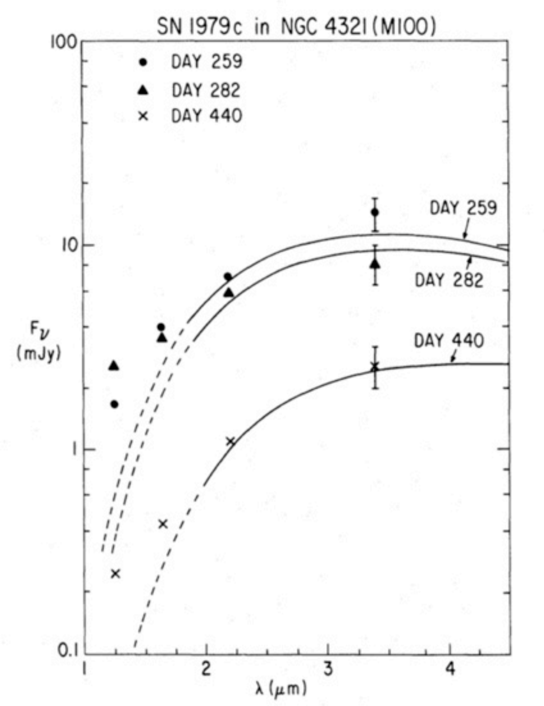
SUMMARY OF OBSERVABLE SUPERNOVA PARAMETERS[a]

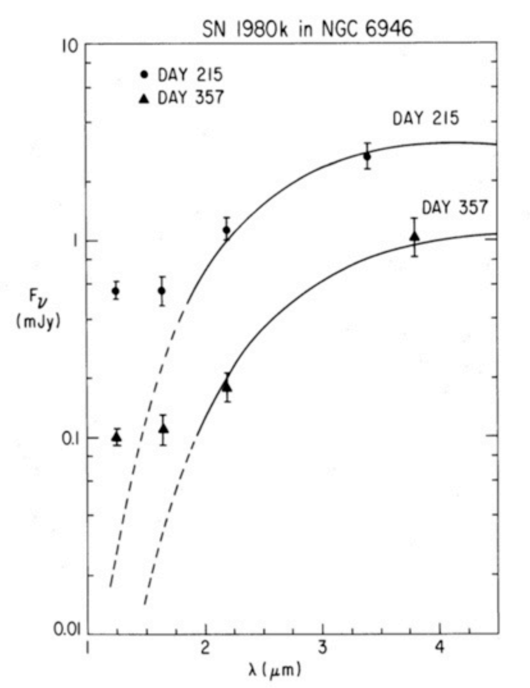
Parameter	SN 1979c	SN 1980k
$L_0(L_\odot)$	6.3×10^9	1.5×10^9
t_{SN}(days)	23	20
D(Mpc)	16	5.5
τ_d	$\lesssim 0.3$	< 0.1



definitely NOT
dust formation

maybe
dust formation

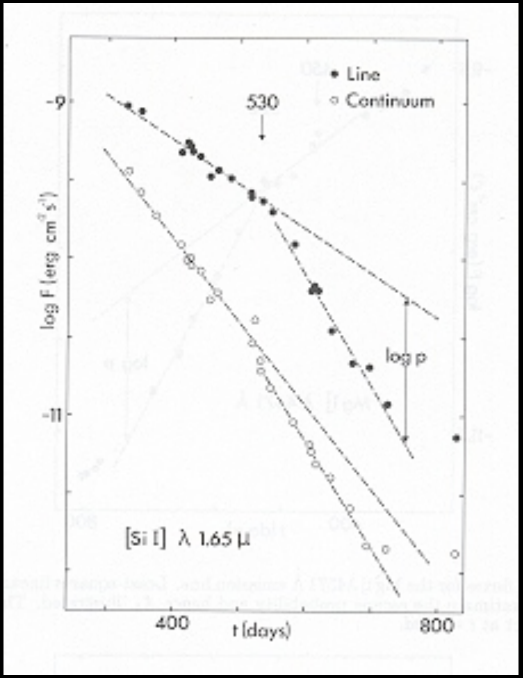




Dust Formation in SN 1987a

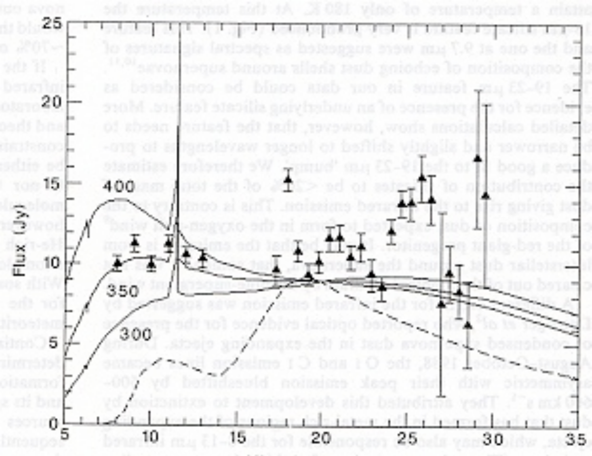
Observed only
≈ 10^{-3} M_{sun} !

Si depletion
(Lucy et al. 1991)

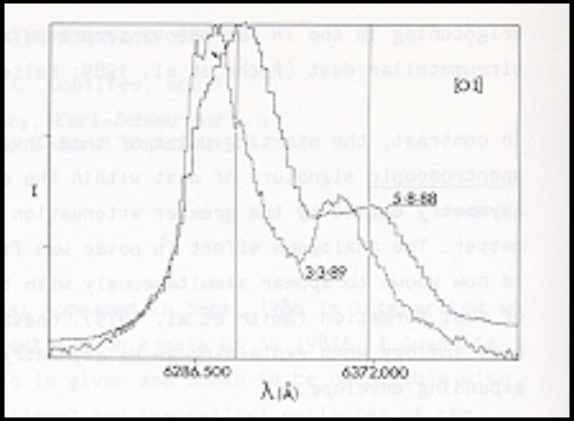


However, the Si depletion could be an ionization effect

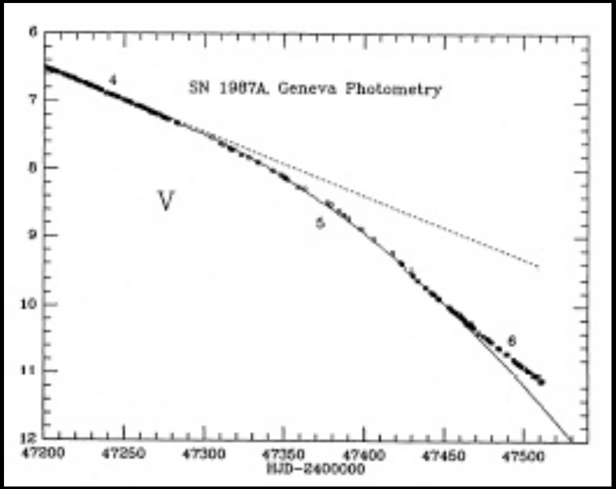
IR emission
(Moseley et al. 1989)



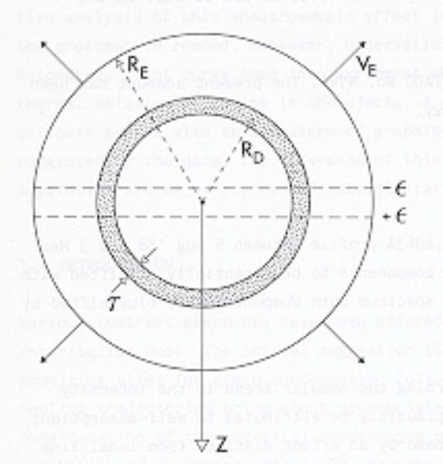
[OI] line extinction
(Lucy et al. 1989)



Light curve energetics
(Burki et al. 1989)



Model



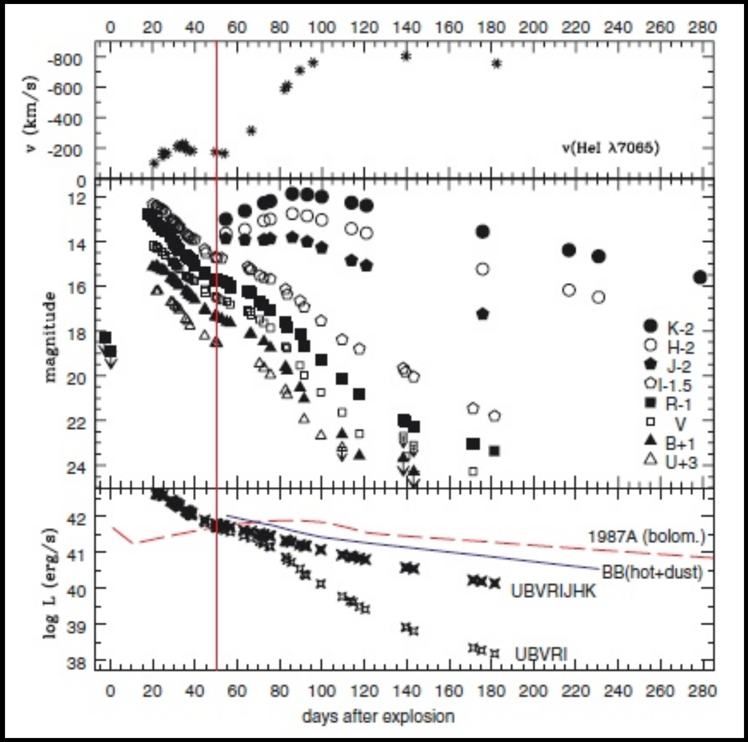
Dust Formation in SN2006jc
UV/optical decline - IR spectra method

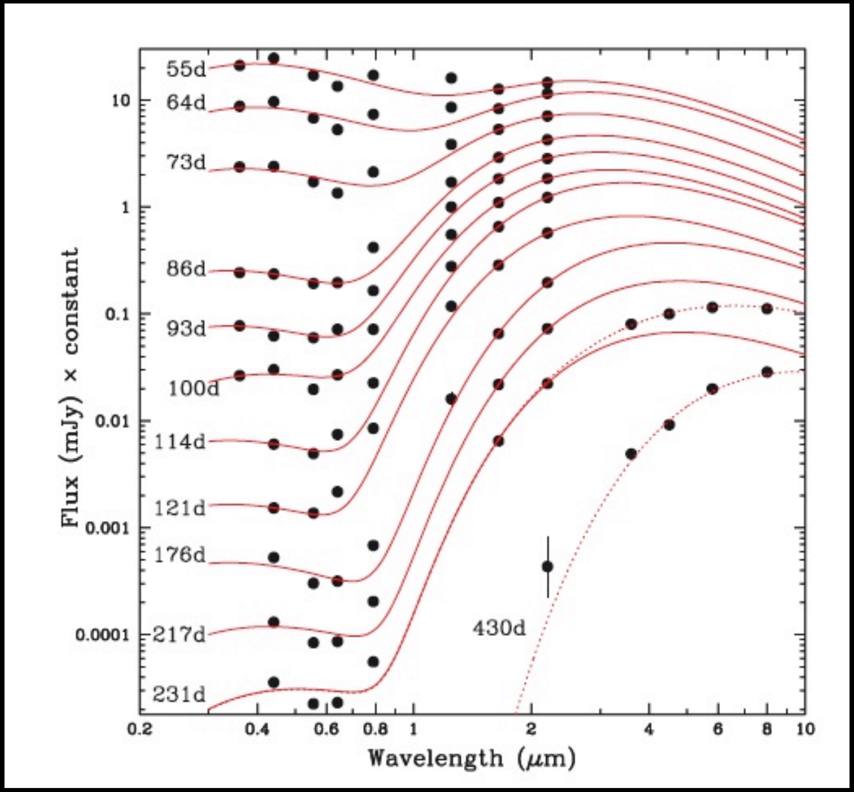
UGC 4904
D=26 Mpc

(Mattila et al. 2008)

UV/optical decline
coincident with rise in IR

The changing IR spectrum



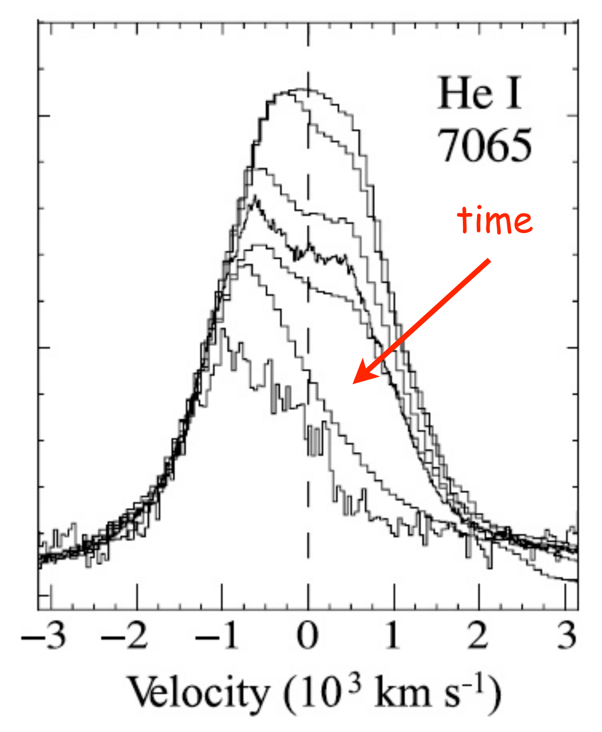


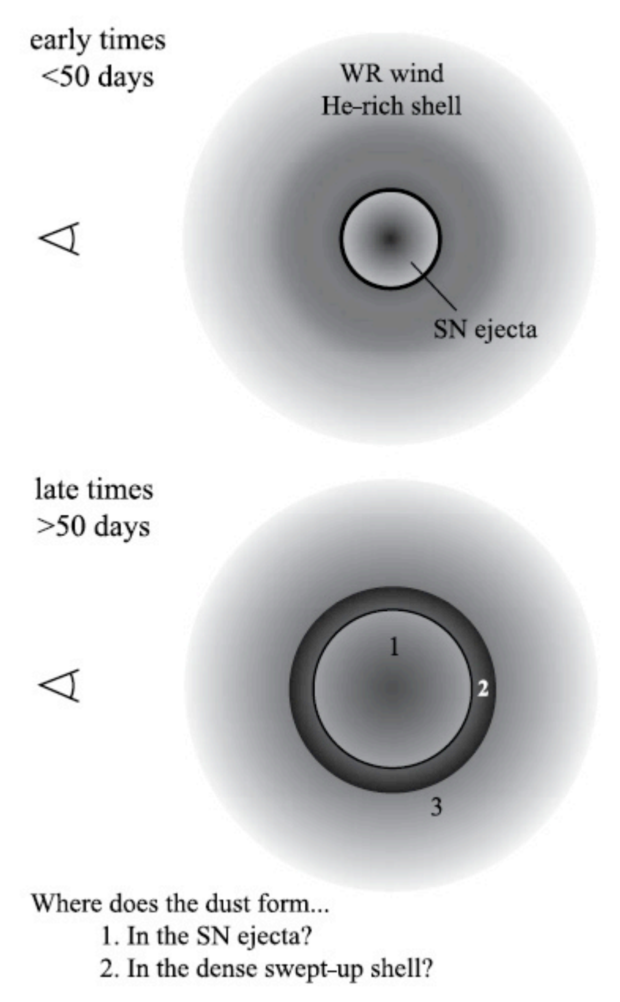
Dust Formation in SN2006jc
Line absorption - IR spectra method

UGC 4904
D=26 Mpc

(Smith et al. 2008)

redshifted (receeding) part of the spectral line is absorbed

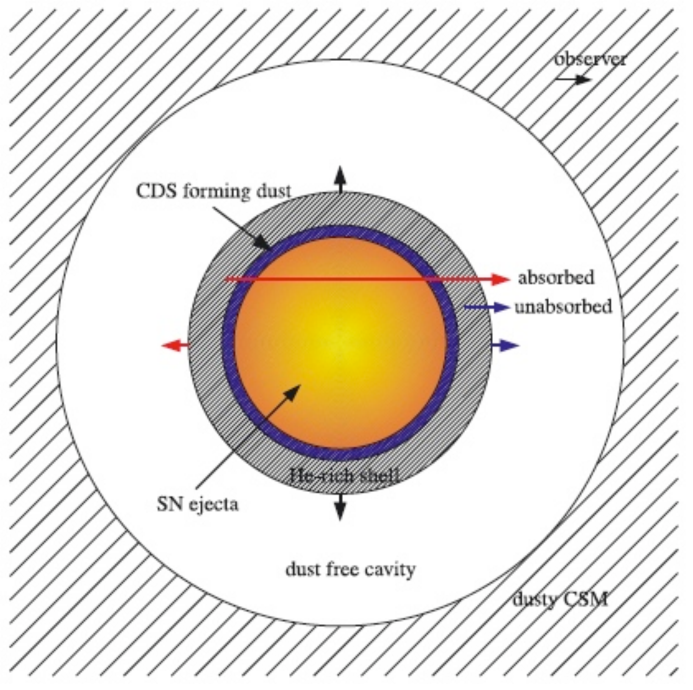




Where does the dust form...
1. In the SN ejecta?
2. In the dense swept-up shell?

Dust Formation AND echo in SN2006jc

(Mattila et al. 2008, Smith et al. 2008)



Two IR emission components

- Early rise in IR emission from newly-formed dust
  - dust formed in a cool dense shell that was compressed by the expanding SN blast wave
  - requires massive pre-SN wind
- Late rise in IR emission from pre-existing circumstellar dust
  - IR echo

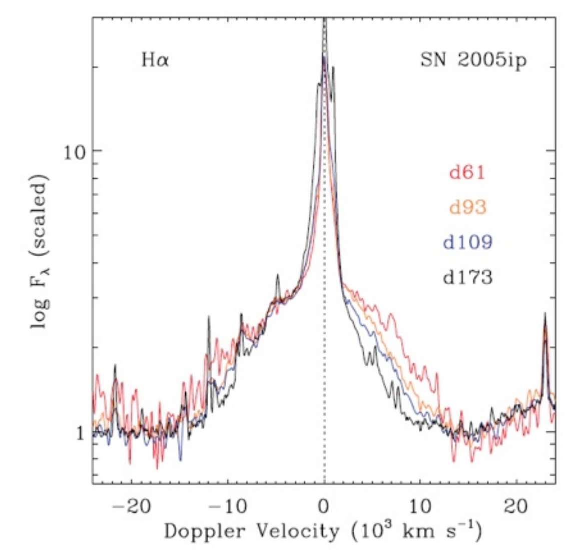
Dust Formation and IR echo in SN2005ip
Line absorption - IR spectra method

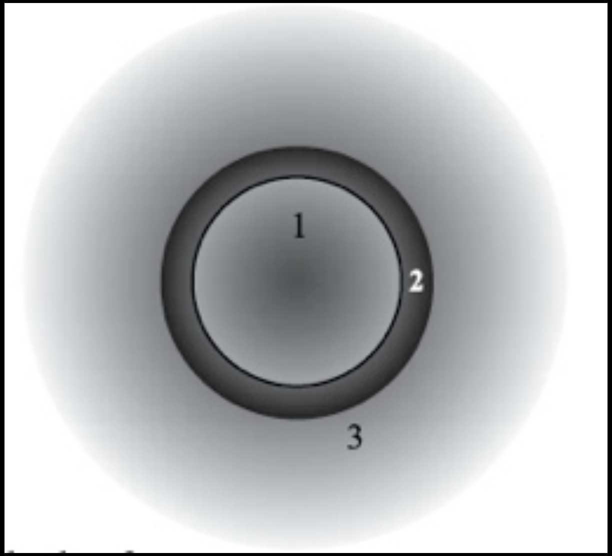
NGC 2906
D=34 Mpc

(Fox et al. 2009, 2010; Smith et al. 2009)

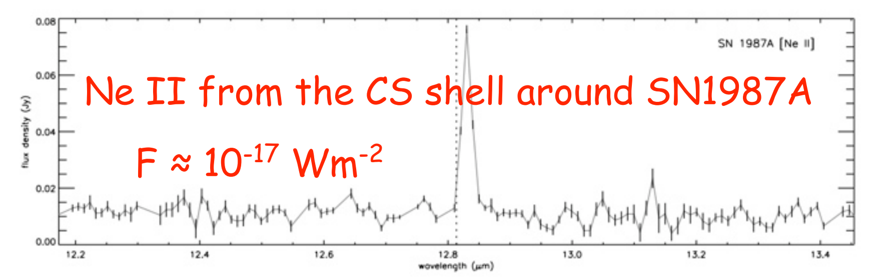
- Dust is formed in a cold dense shell between the forward and reverse shock - region 2
- Dust also formed in ejecta - region 1
- All dust is heated by the cooling postshock gas
- Bulk of IR emission is an echo

redshifted (receeding)
part of the ~ 10,000 km/s Ha
line is absorbed by dust in region 1



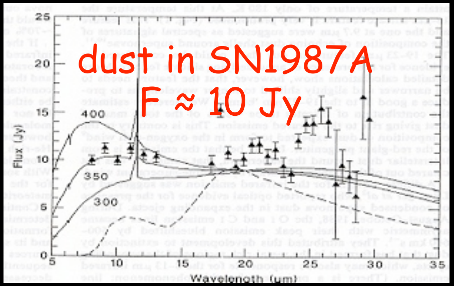


SOFIA Capabilities for the detection of SN condensed dust in Xgalactic SNe



Ne II from the CS shell around SN1987A

F ≈ 10^{-17} Wm^{-2}



dust in SN1987A

F ≈ 10 Jy

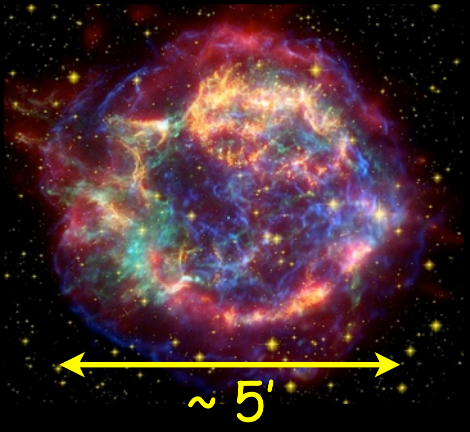
- Hi-resolution observation of [Ne II] 12.8 μm line with EXES
  - R = 5,000-10,000
  - EXES line sensitivity ≈ 10-^{17} Wm^{-2}
    - Can observe 0.1-1 M_{sun} of Ne up to D ≈ 30 Mpc
  - the 12 μm optical depth is ≈ 10
    - M_{dust} ≈ 0.001 Msun
    - R_{shell} ≈ $2x10^{15}$ cm (v=500 km/s, t=1 yr)
    - Line is optically thick for 0.1–1 M_{sun} of Ne in the ejecta
- Low-resolution spectra of PAH and dust continuum emission FORCAST
  - R ≈ 10 - 100
  - FORCAST continuum sensitivity ≈ 0.1 Jy
    - Can observe dust up to D ≈ 0.5 – 1 Mpc (Andromeda)

Young, Unmixed Supernova Remnants

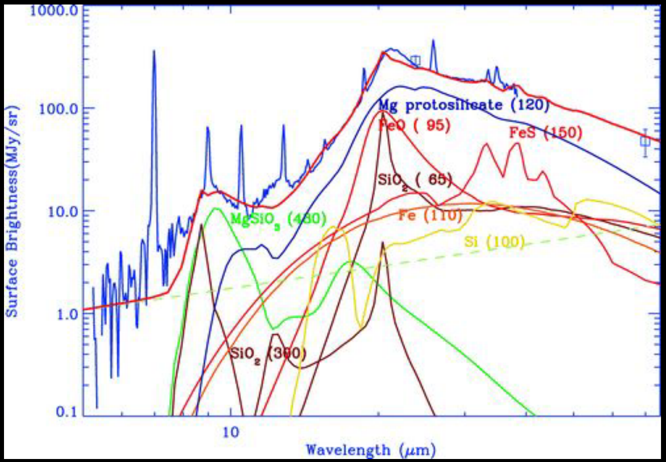
Sites of SN-condensed dust

Dust Formation in Cas A

Hubble/Spitzer/Chandra

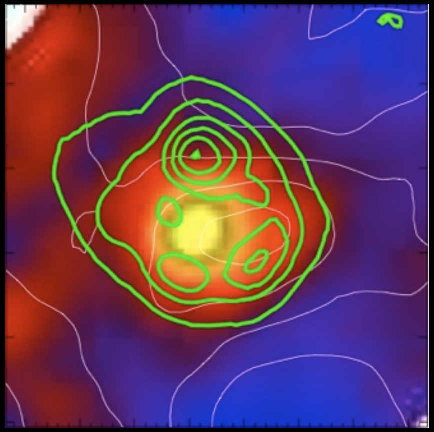


Observations

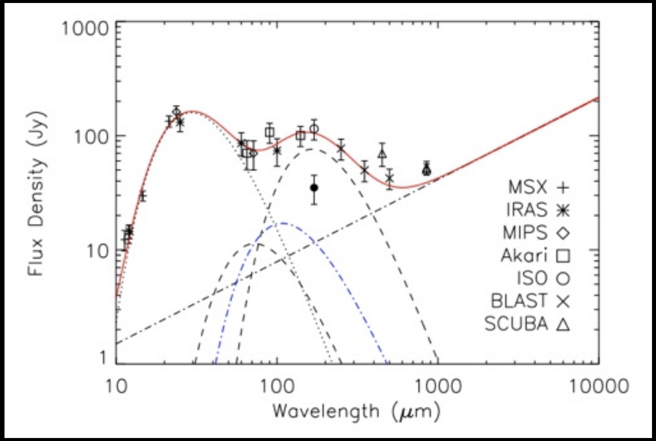


Spitzer spectra of Cas A
≈ 0.02–0.04 M_{sun}
of dust

(Rho et al. 2008)



Akari 90 μm image
Akari 65 μm
BLAST 250 μm



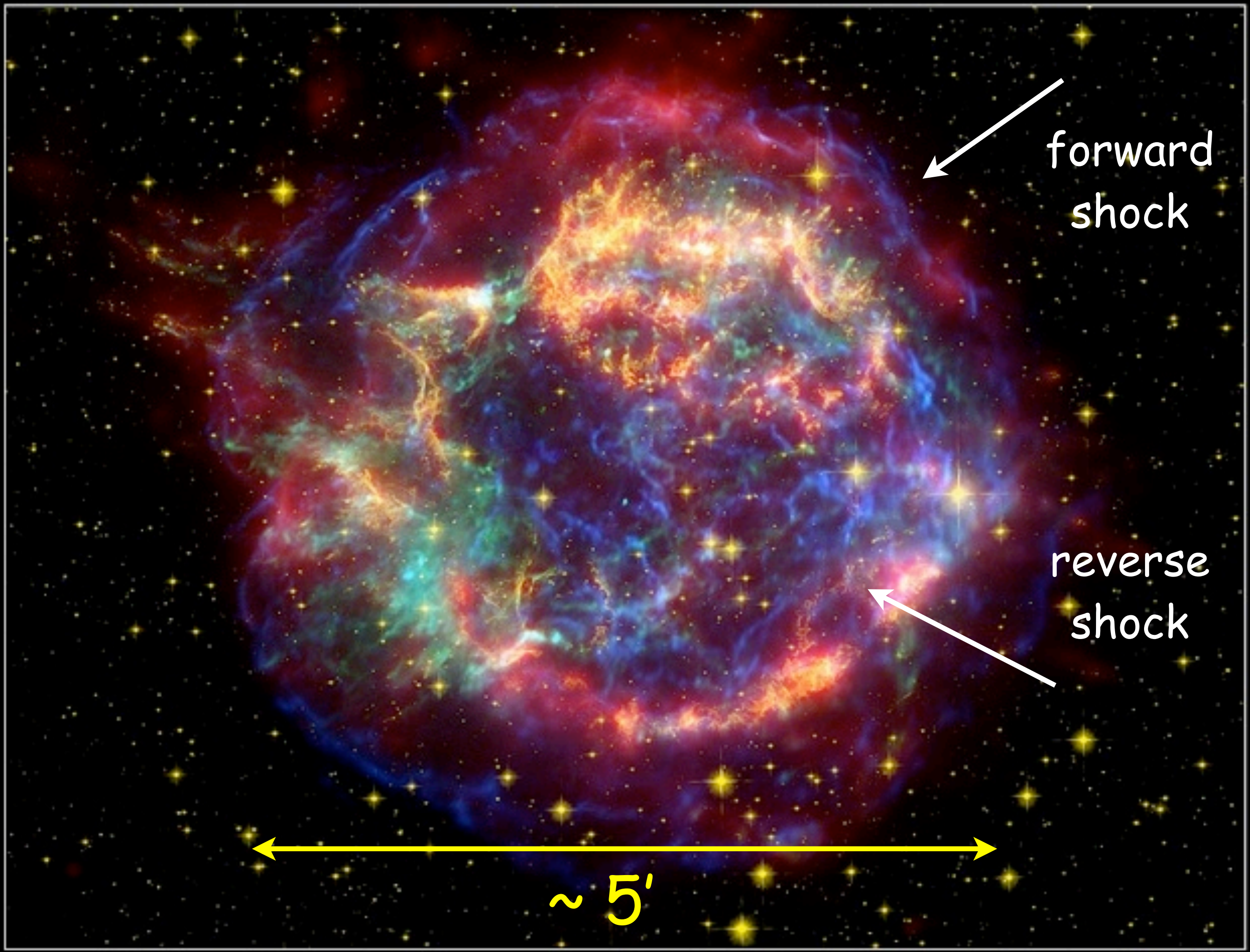
Akari/BLAST search for
warm (~ 35 K) dust
≈ 0.06 M_{sun}

(Sibthorpe et al. 2009)

Herschel Observations of
cool dust
≈ 0.08 M_{sun}

(Barlow et al. 2010)

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

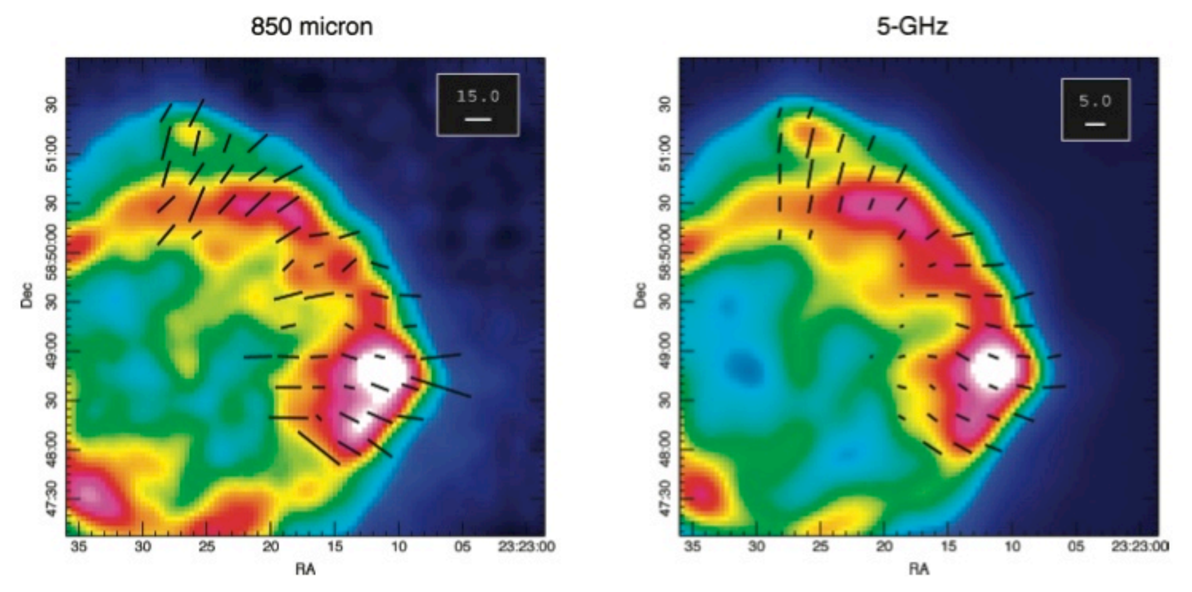
Chandra
2.25-7.50 keV
1.65-2.25 keV

Opt - Hubble
IR - Spitzer

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

Polarized dust emisison form Cas A

(Dunne et al. 2009)



- polarized submm emission from dust ($f_{pol} \approx 30\%$)
- significantly higher level than the polarized synchrotron emission
- highly efficient grain alignment
- metallic dust needles?

Supernova Remnants

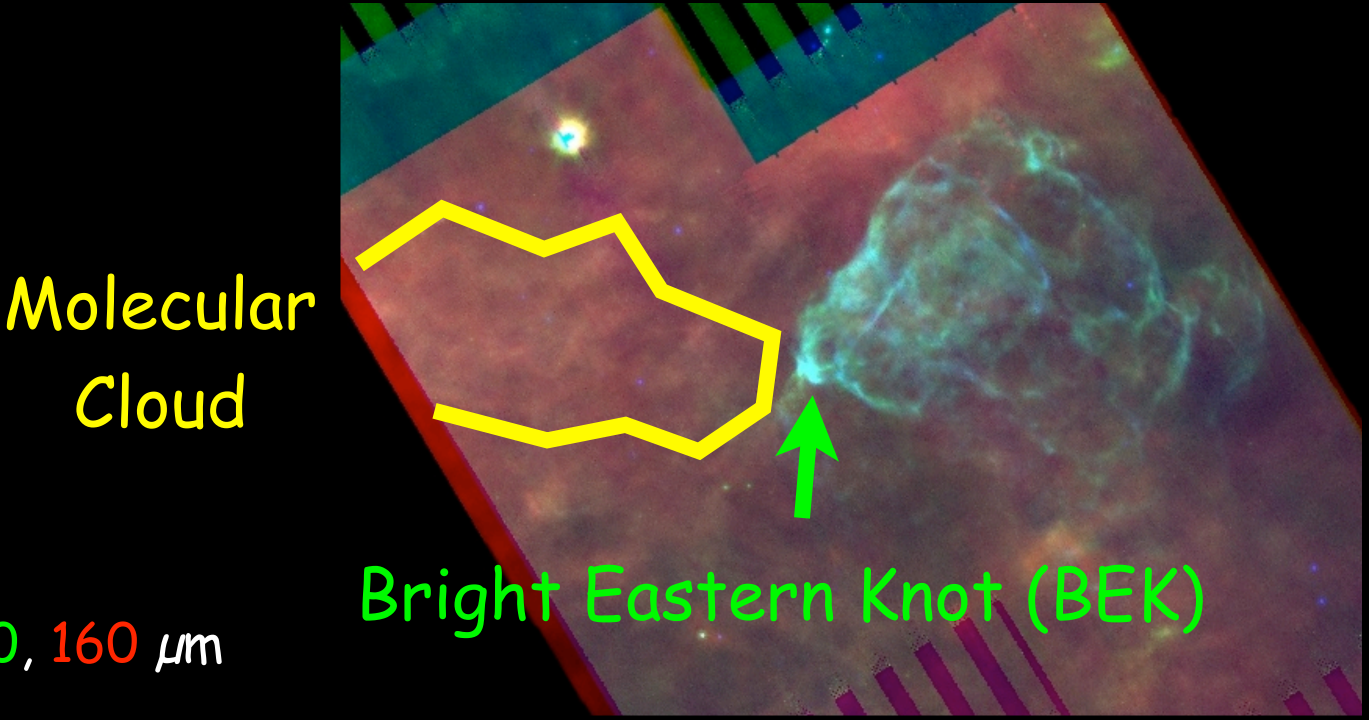
Interstellar laboratories
for studying:

(1) physical processes in dusty plasmas
(2) grain destruction/processing

Grain destruction in the ISM

Spitzer observations of Puppis A

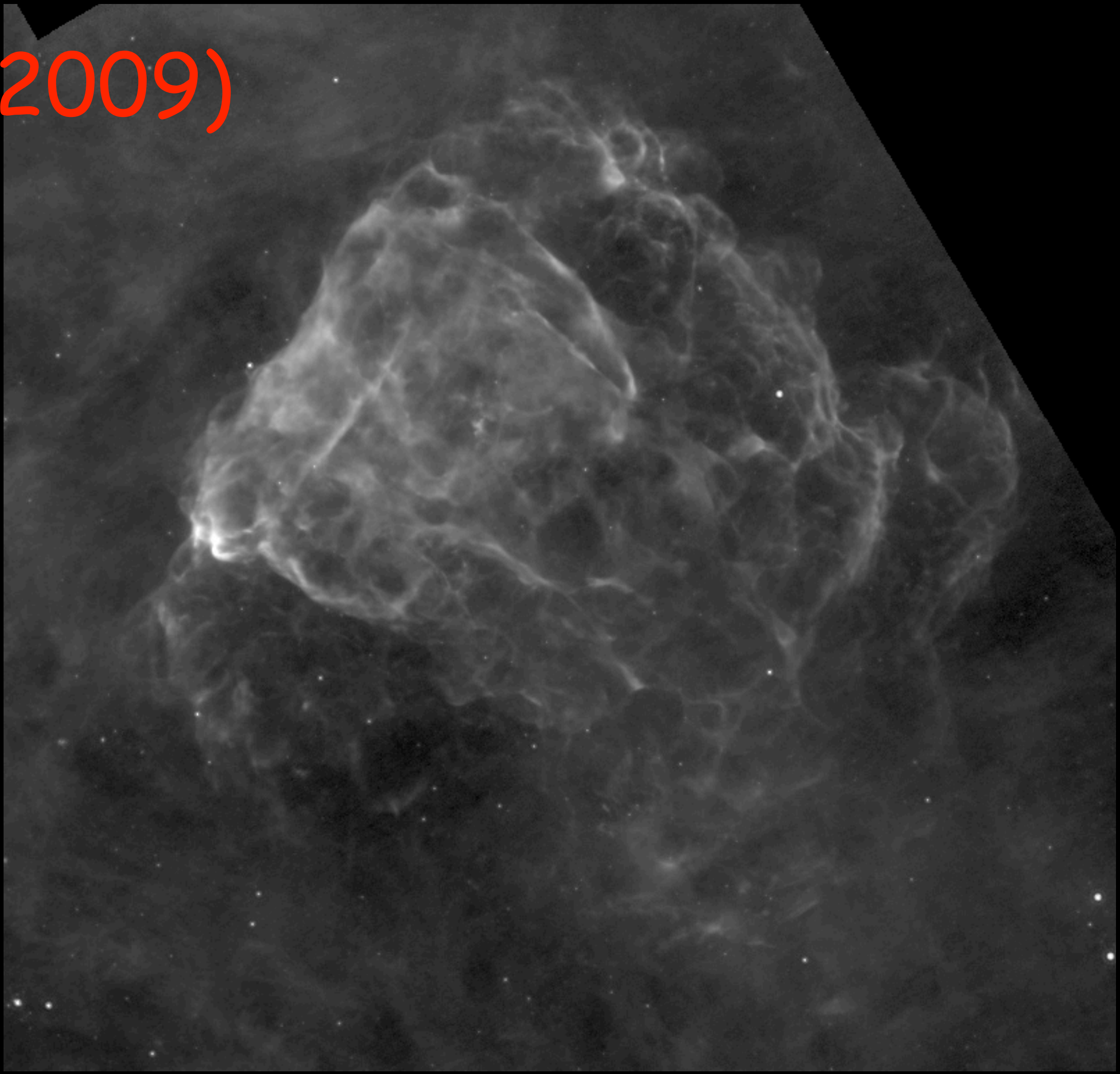
Arendt et al. 2010



- 24, 70, 160 μm

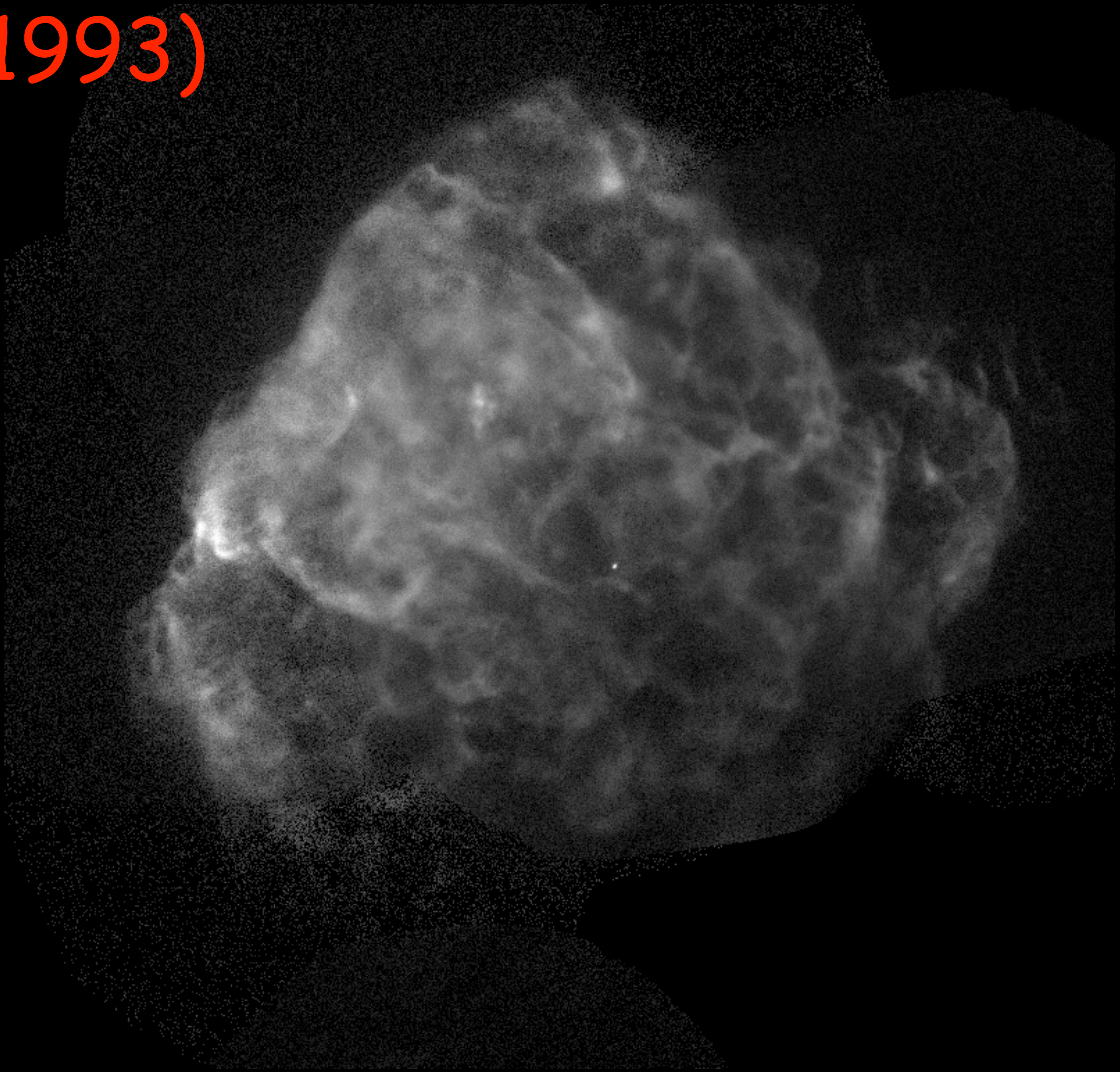
Spitzer (2009)

MIPS 24 µm

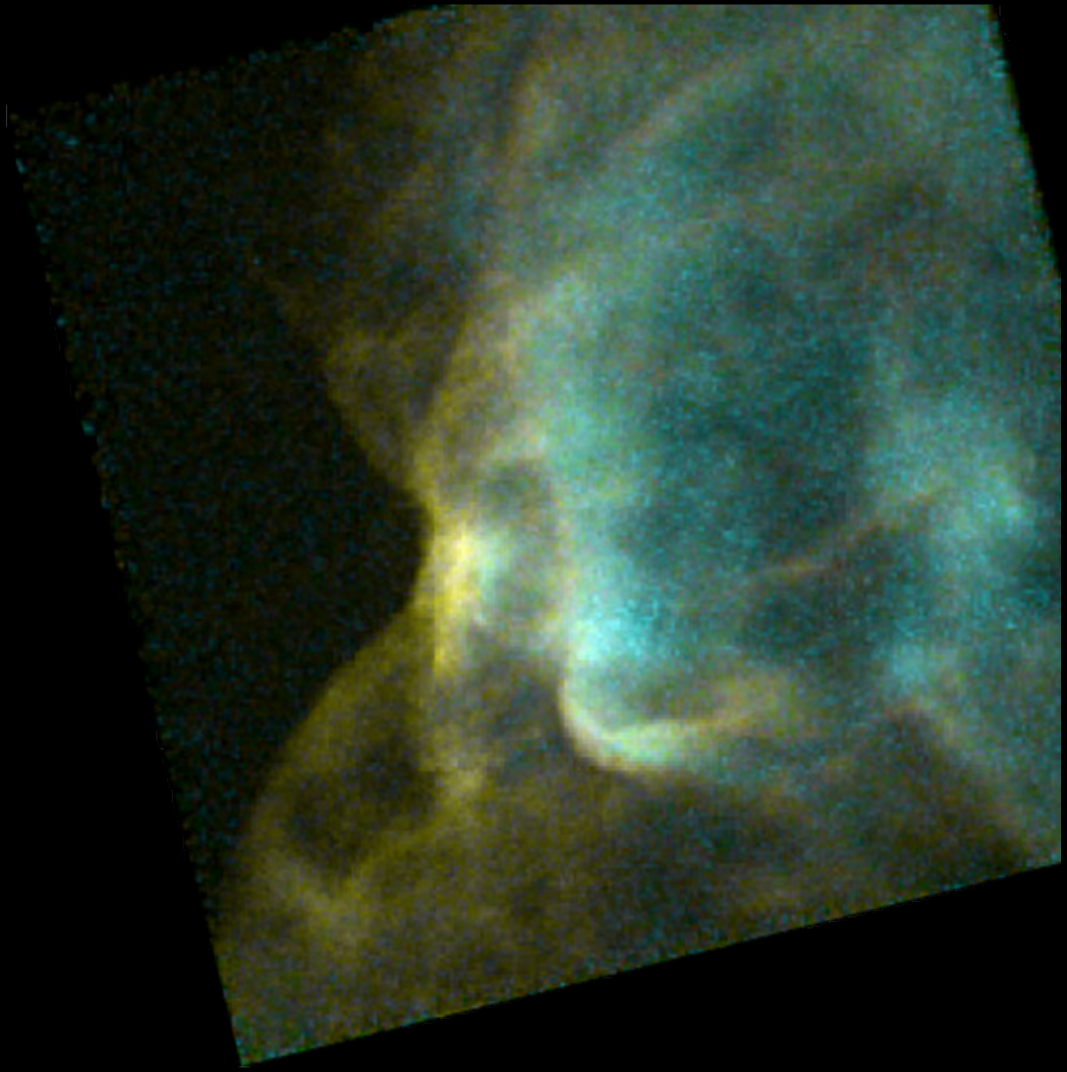


ROSAT (1993)

HRI ~1 keV



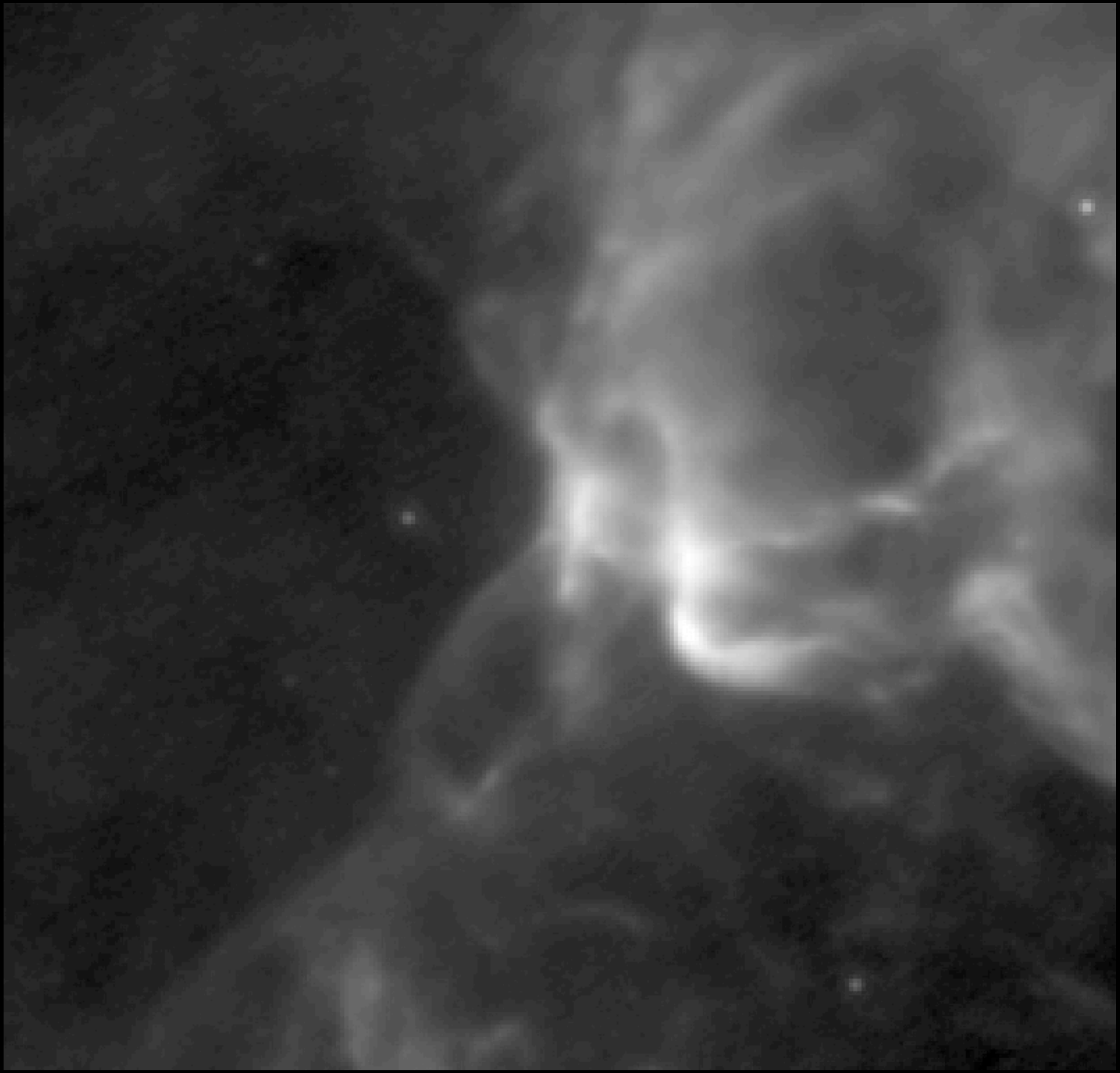
Chandra



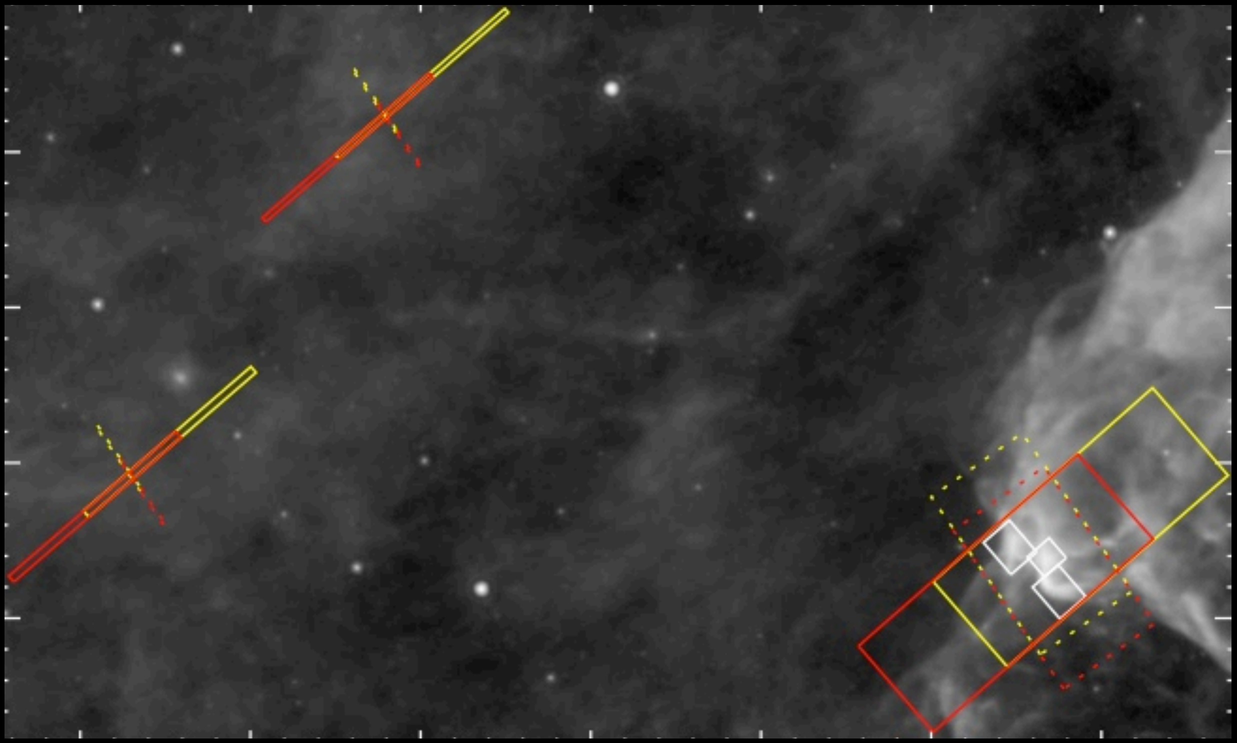
- 0.4-0.7 keV, 0.7-1.2 keV, >1.2 keV

Hwang et al.
(2005)

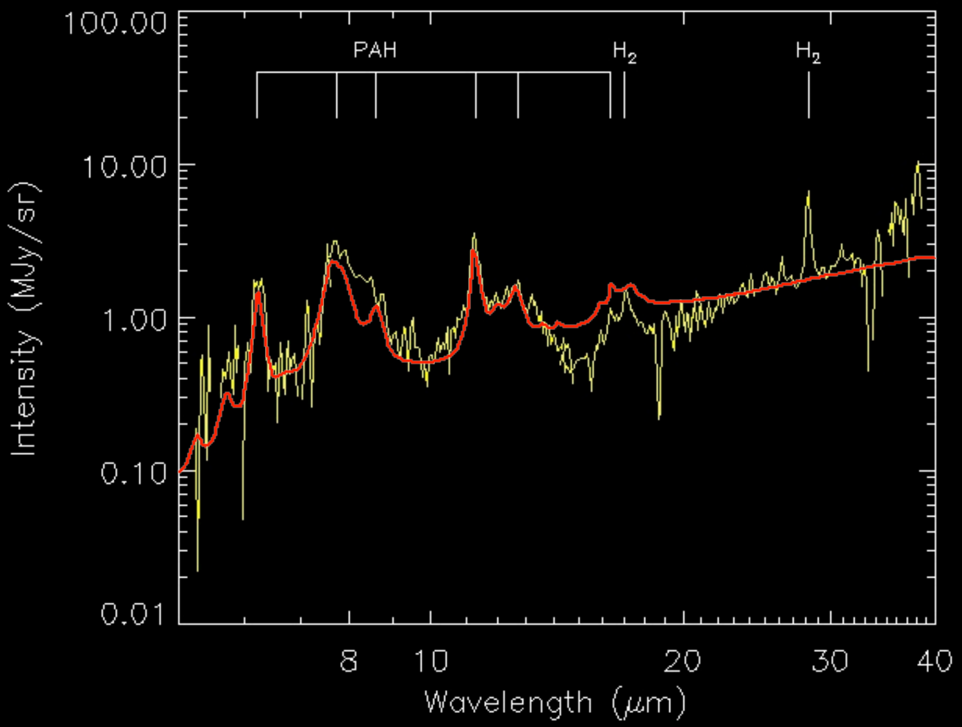
Spitzer



- MIPS 24 μm



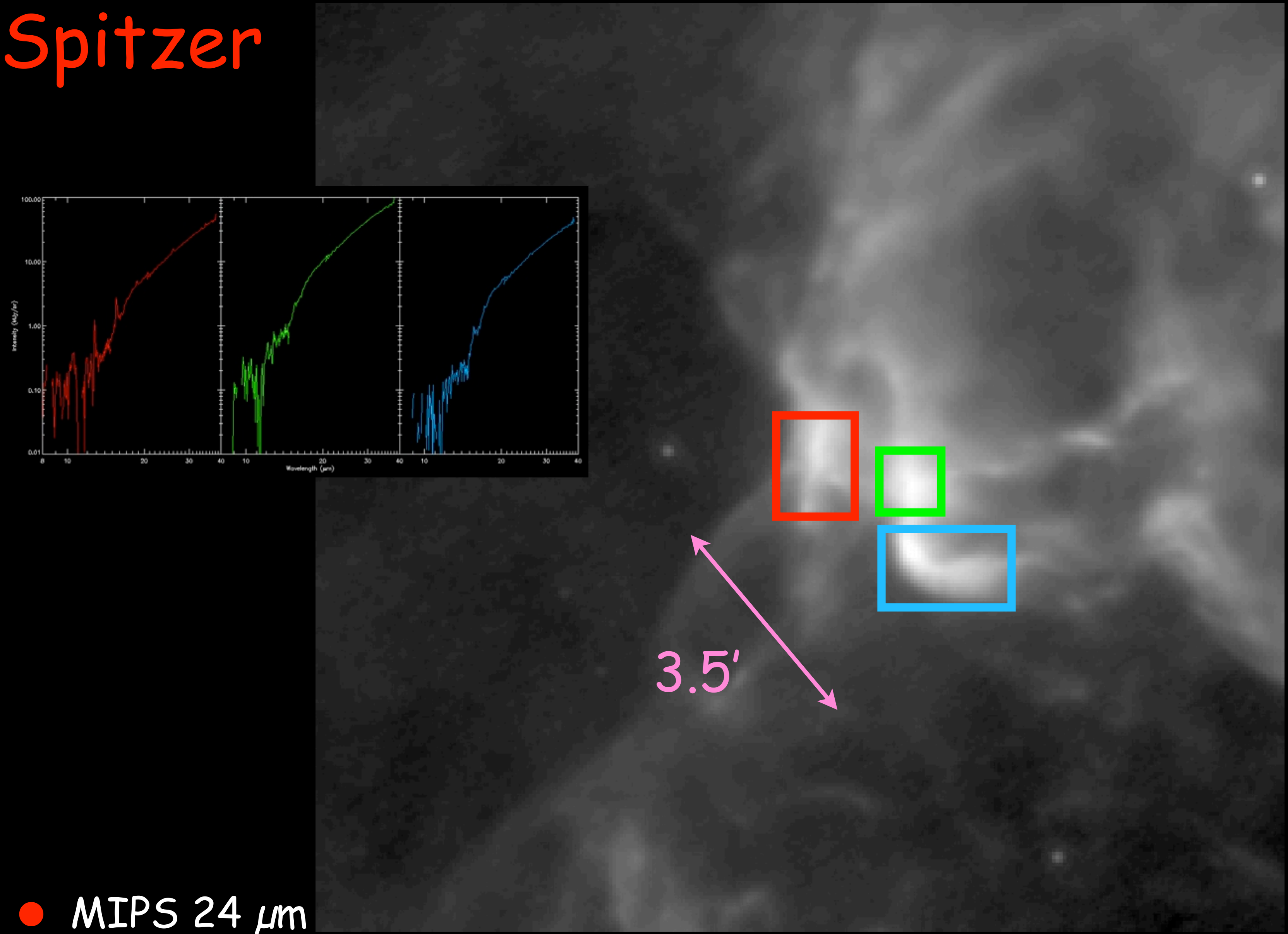
Molecular Cloud Spectrum



1.0 x ISRF (Zubko et al. 2004)

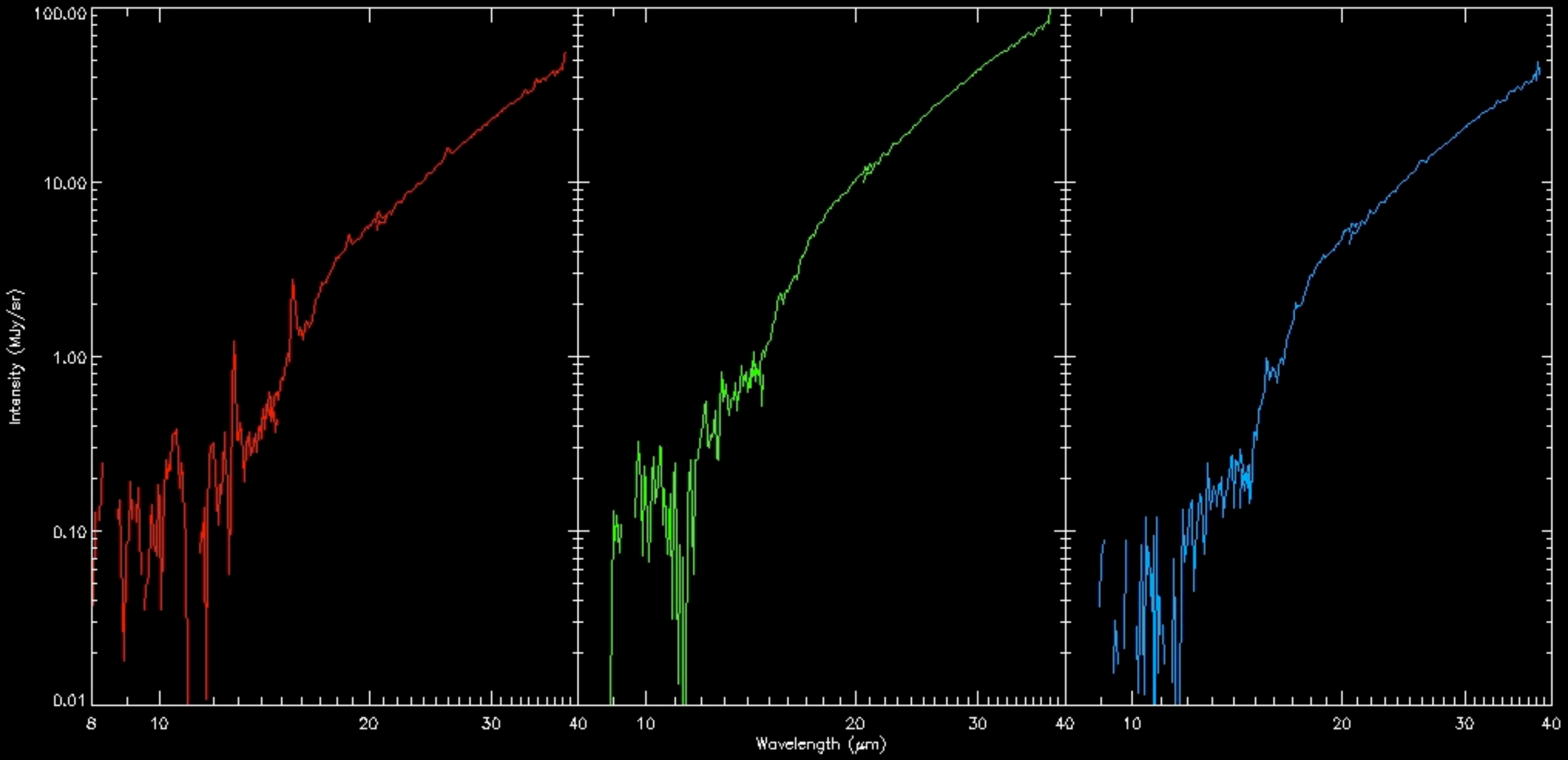
- PAH features
- H_2 lines

Spitzer



- MIPS 24 μm

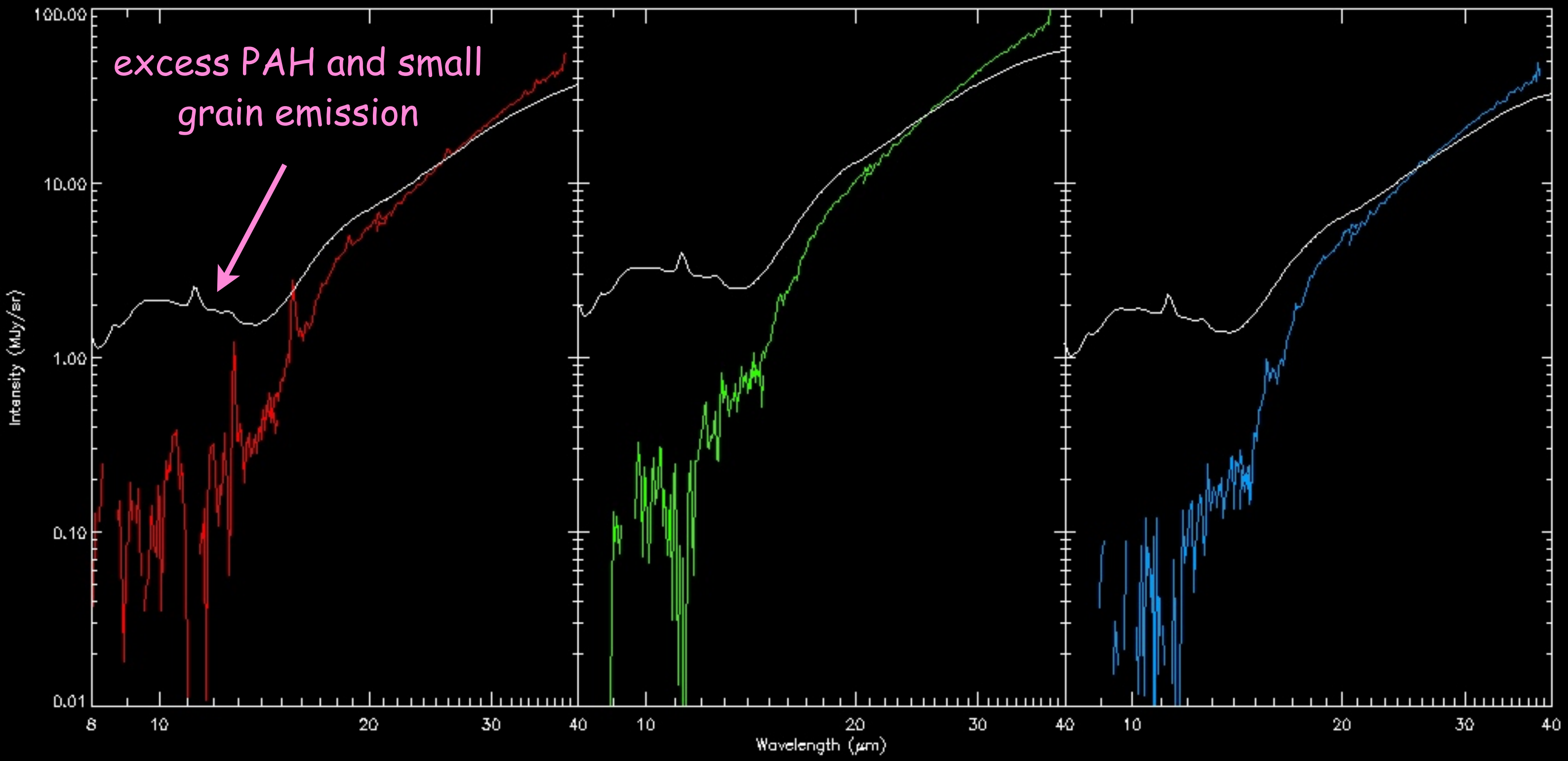
Bright Eastern Knot Spectra



- Strong continuum with 20μm silicate feature
- Ionic lines, poorly correlated with continuum

Bright Eastern Knot Spectra

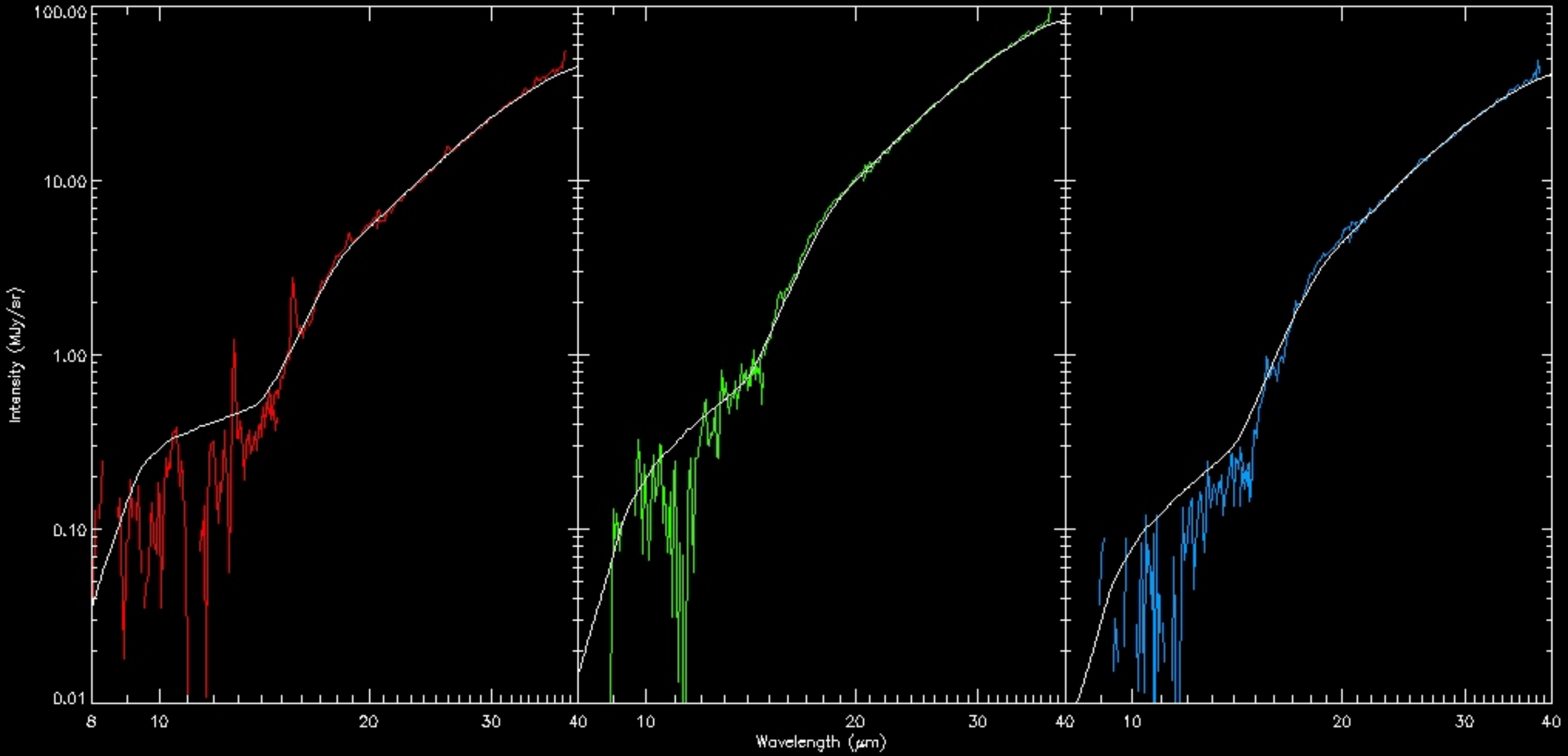
$n_e = 4.0\ \mathrm{cm}^{-3} \quad T_e = 3.2\times10^6\ \mathrm{K}$



- Collisionally heated ISM dust is a poor fit.
- Excess from PAHs and hot (small) grains

Bright Eastern Knot Spectra

$n_e = 4.0\ \mathrm{cm}^{-3}$ $T_e = 3.2\times10^6$ K

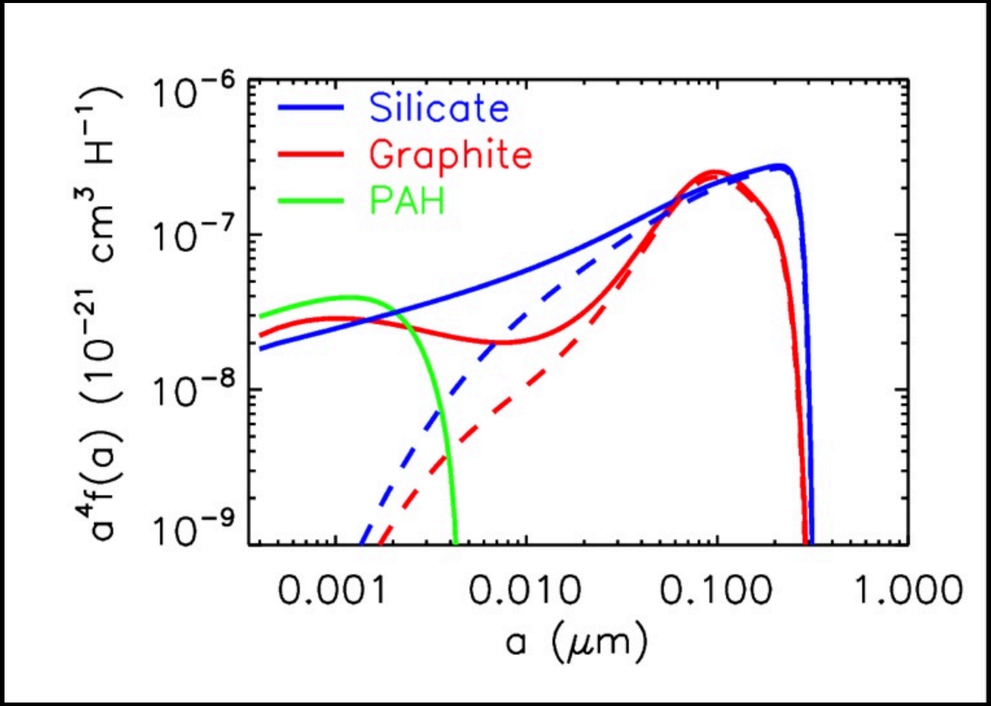


- Collisionally heated ISM dust is a good fit
- requires $a_{sput} \approx 20$Å

Grain destruction in Puppis A

——— pre-shock

- - - - post-shock



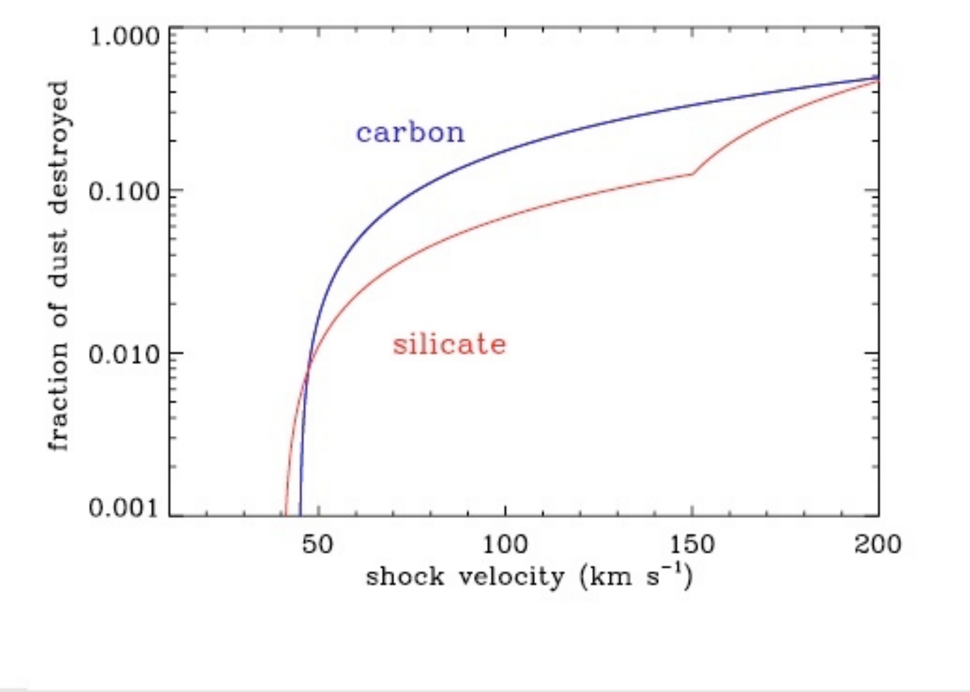
About 30% of the dust mass is destroyed in the ~ 500 km/s shock

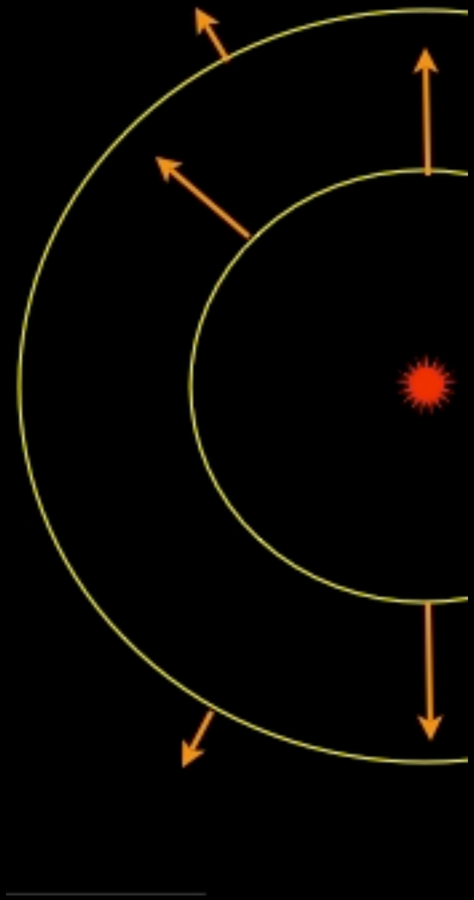
Grain destruction efficiencies

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

Mass of dust destroyed by a single SNR

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



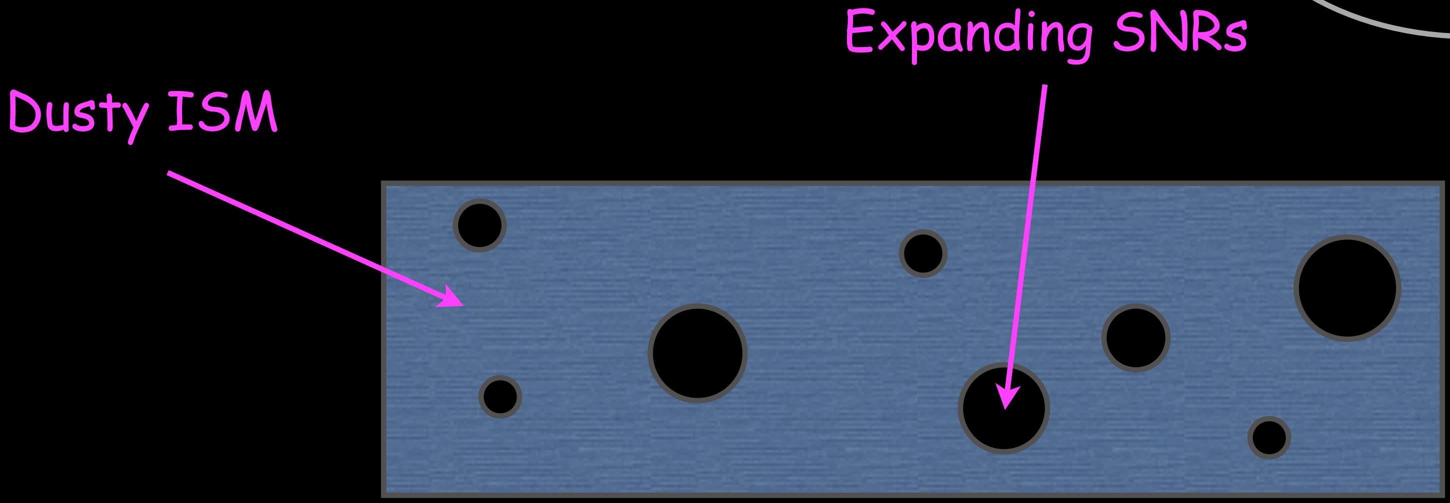


The dust lifetime

$$\tau_d(t) \equiv \frac{M_d}{m_d\, R_{SN}}$$

m_d

The mass, locked up in dust, that is returned to the gas phase by a single SNR



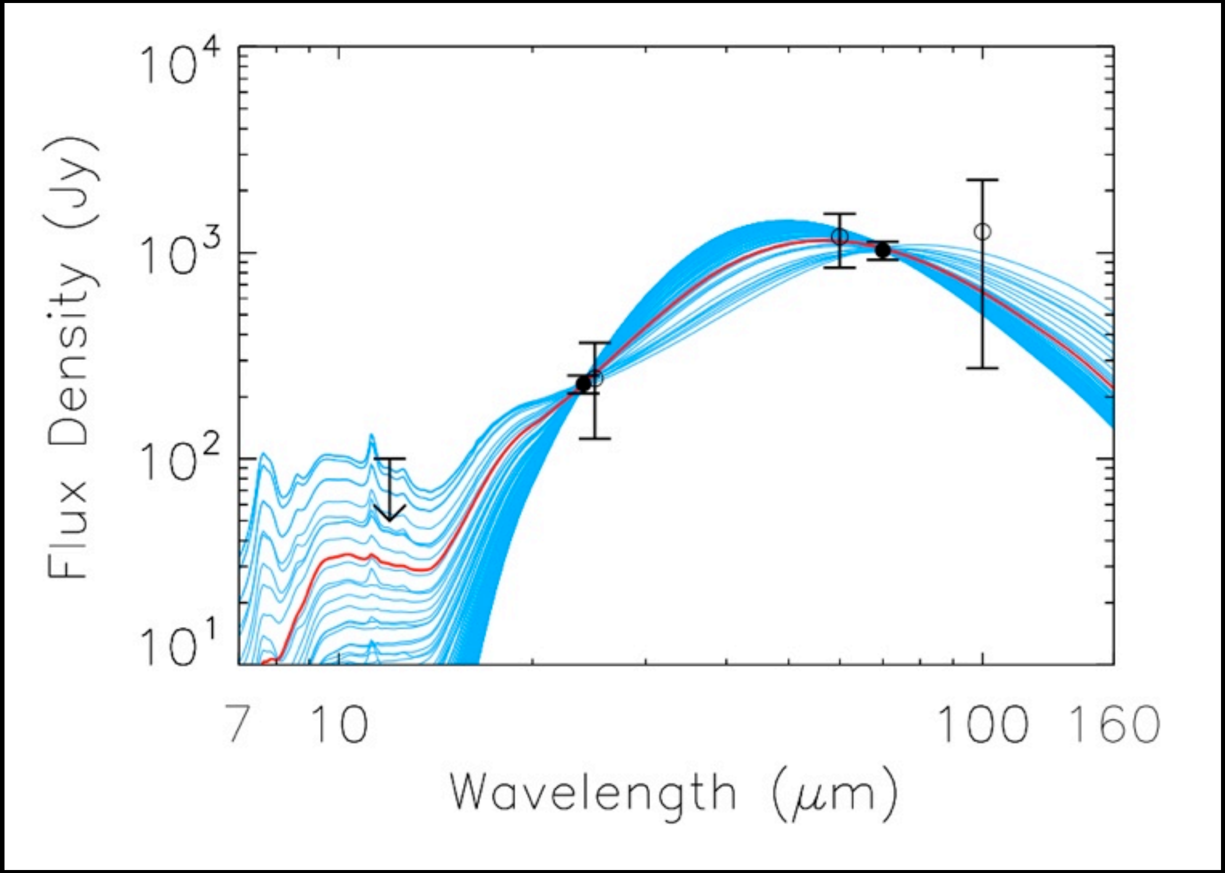
- For the MW galaxy:

✦ $M_d \approx 3\times10^7\ M_{sun}$ $R_{SN} \approx 0.02\ yr^{-1}$ $m_d \approx 3\ M_{sun}$

$\tau_d \approx 500$ Myr

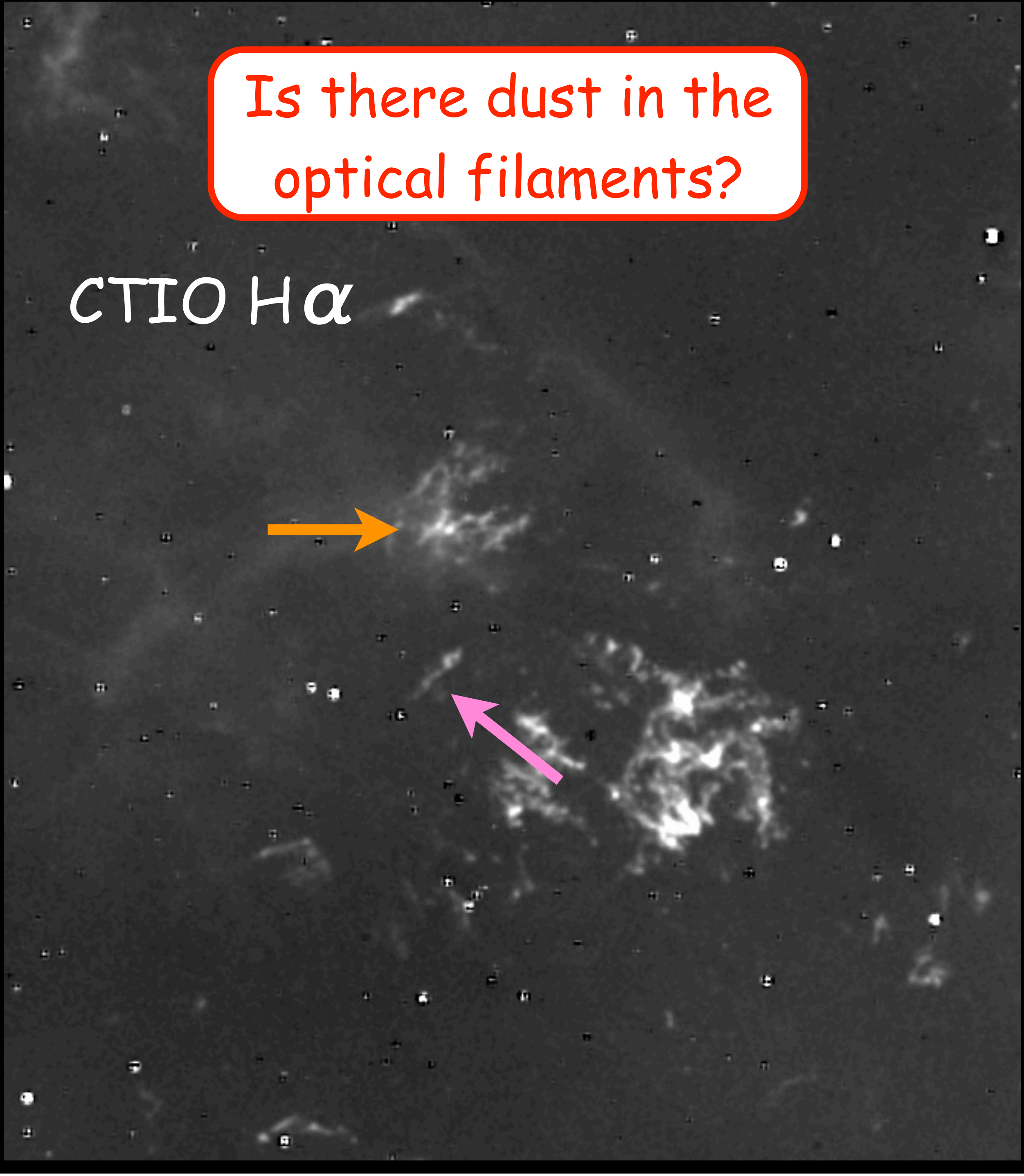
Total flux from Pup A

Need to know the total flux in order to calculate the global amount of grain destruction



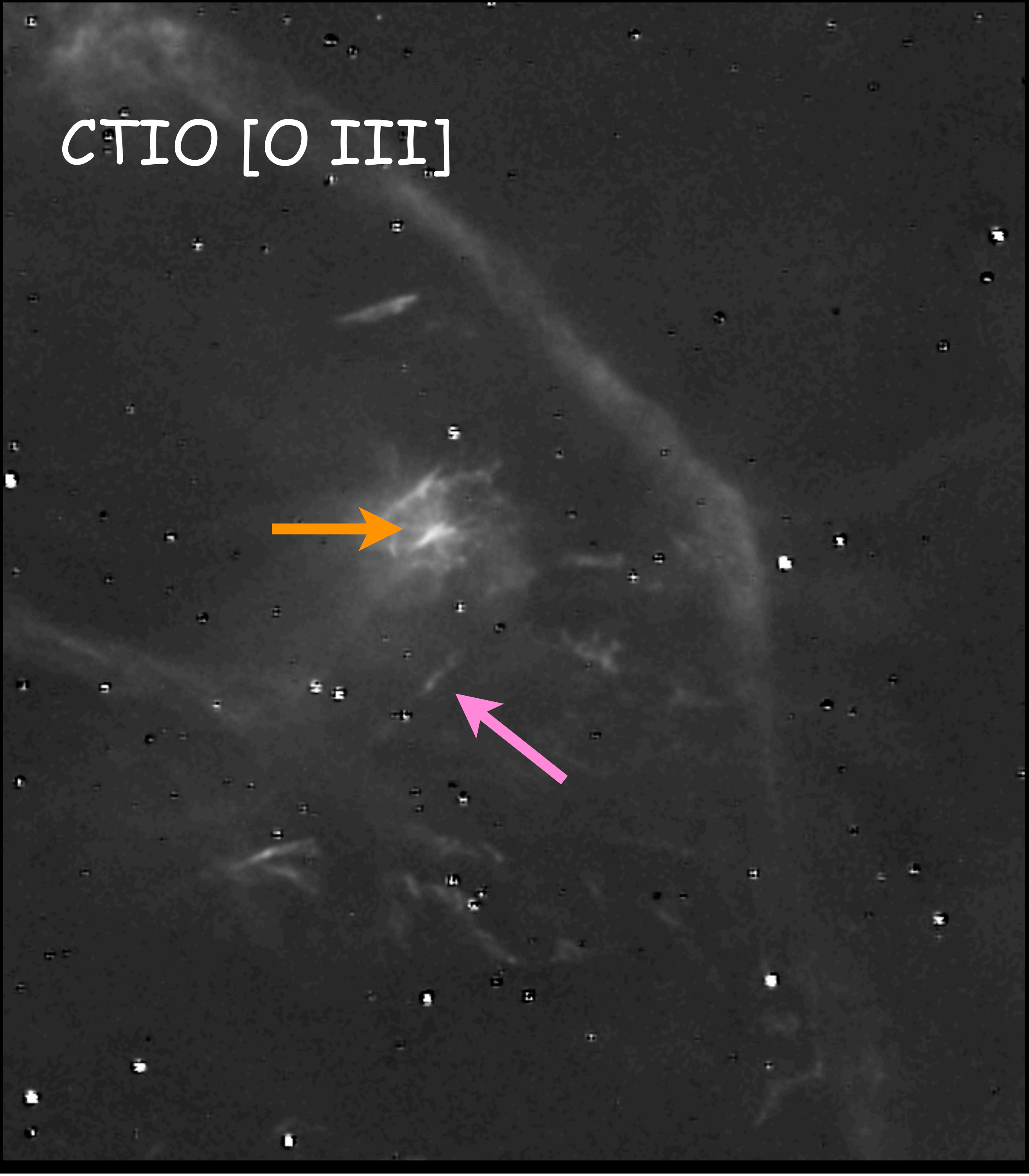
Total flux from Pup A

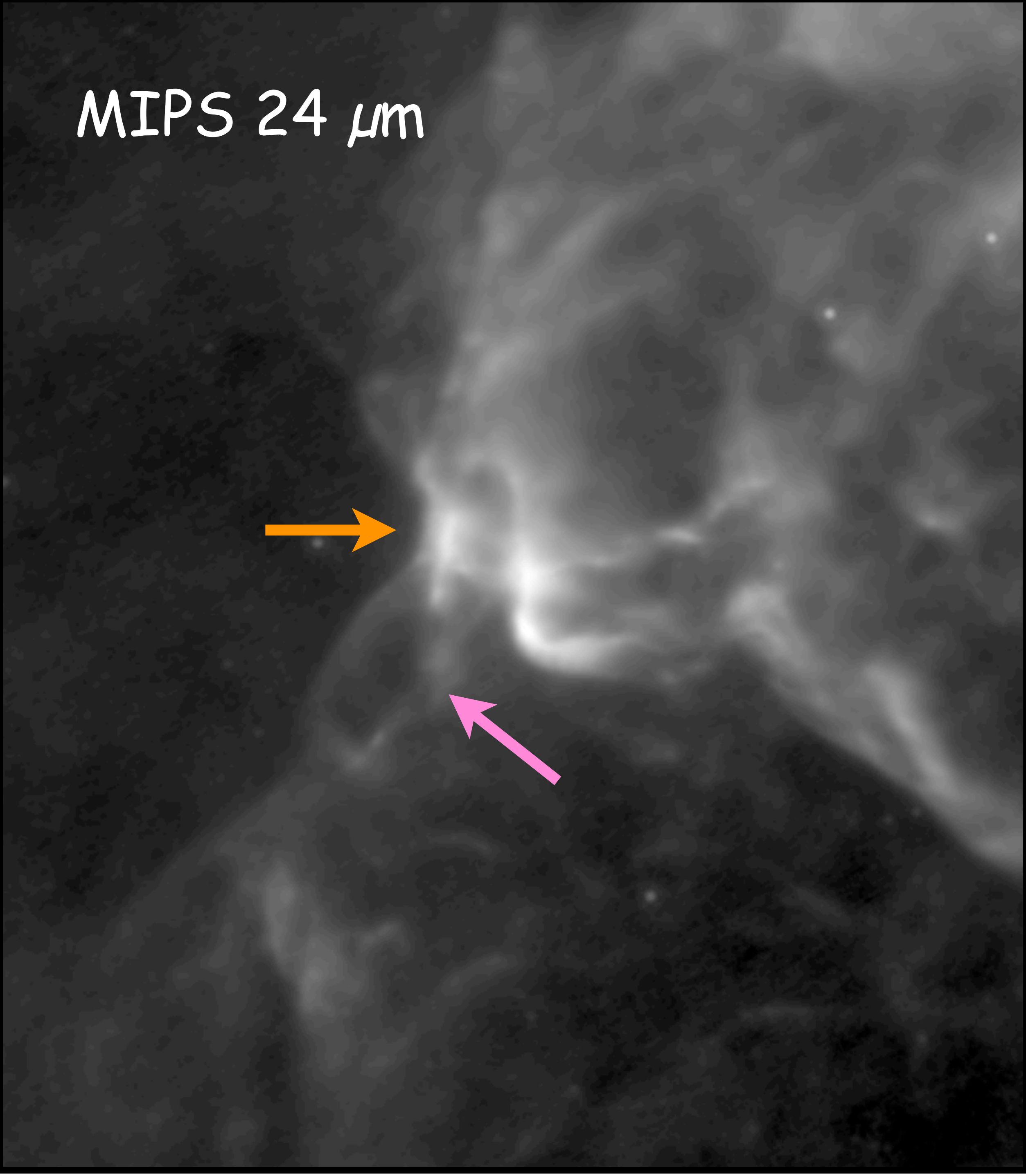
- Need short wavelengts 5-15 μm spectra
  - constrain small grain population, needed to estimate the global amount of grain destruction
- need more photometric data (HAWC)
  - long wavelengths to constrain large grains (warm dust) which is the bulkof the mass
- SOFIA has higher spatial resoltion compared to IRAS, so error bars will be smaller (confusion)
- Need background dominated (> 160 μm) image to serve as a spatial remplate for removing background at shorter wavelengths

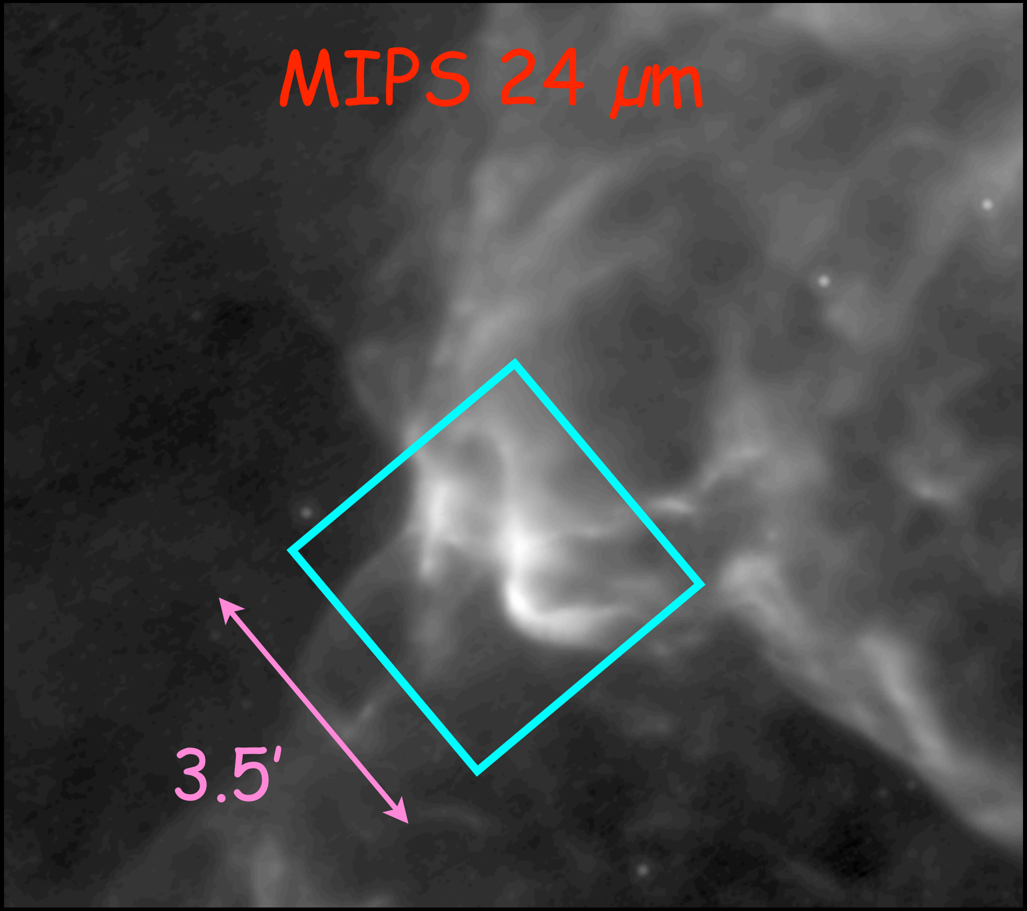


Is there dust in the optical filaments?

CTIO Hα


CTIO [O III]


MIPS 24 μm



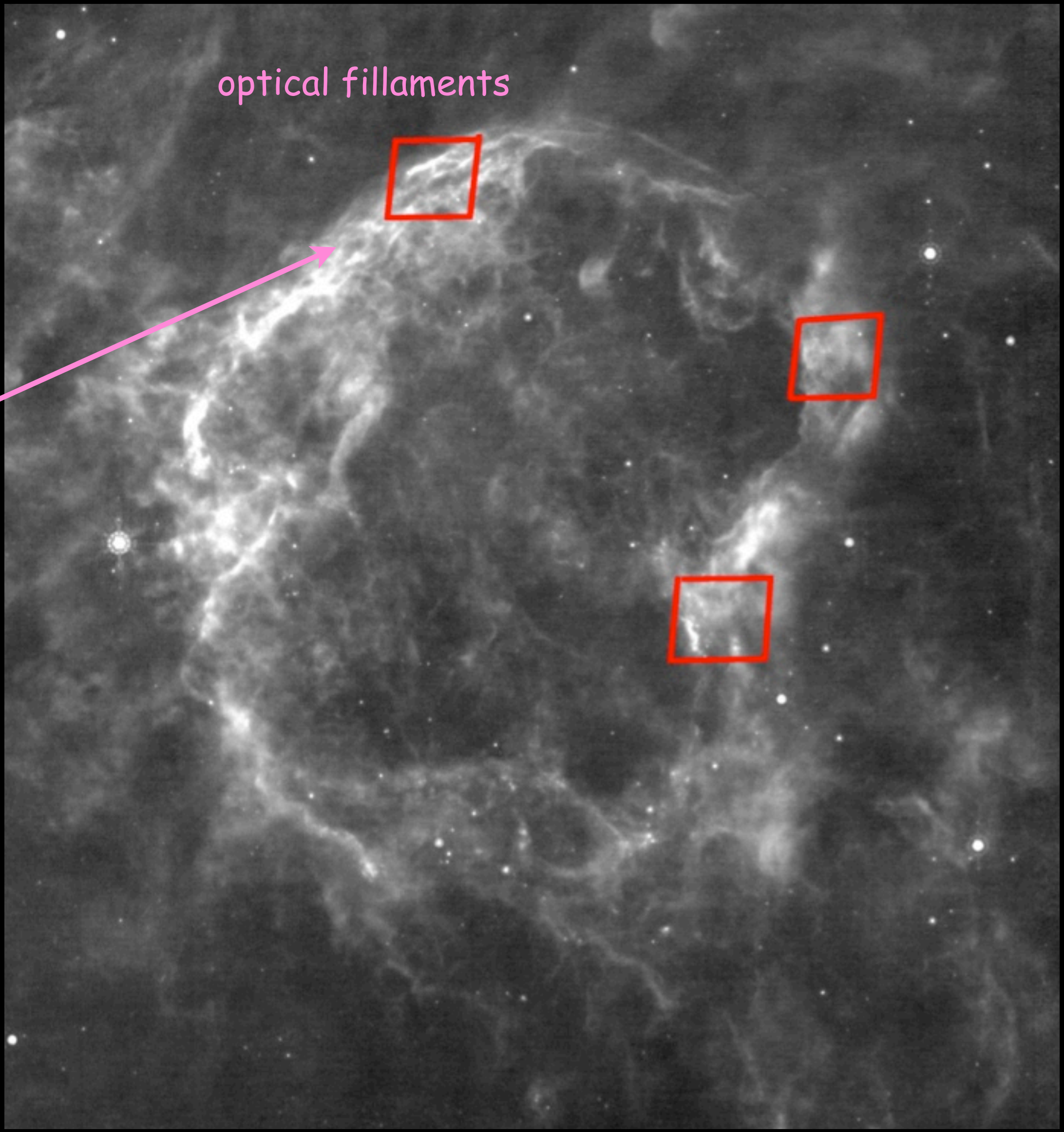
SOFIA can produce a 70 μm at the same resolution as the Spitzer 24 μm image.

This will allow to create 24/70 μm color maps to identify the presence of dust in the optical filaments

IC443

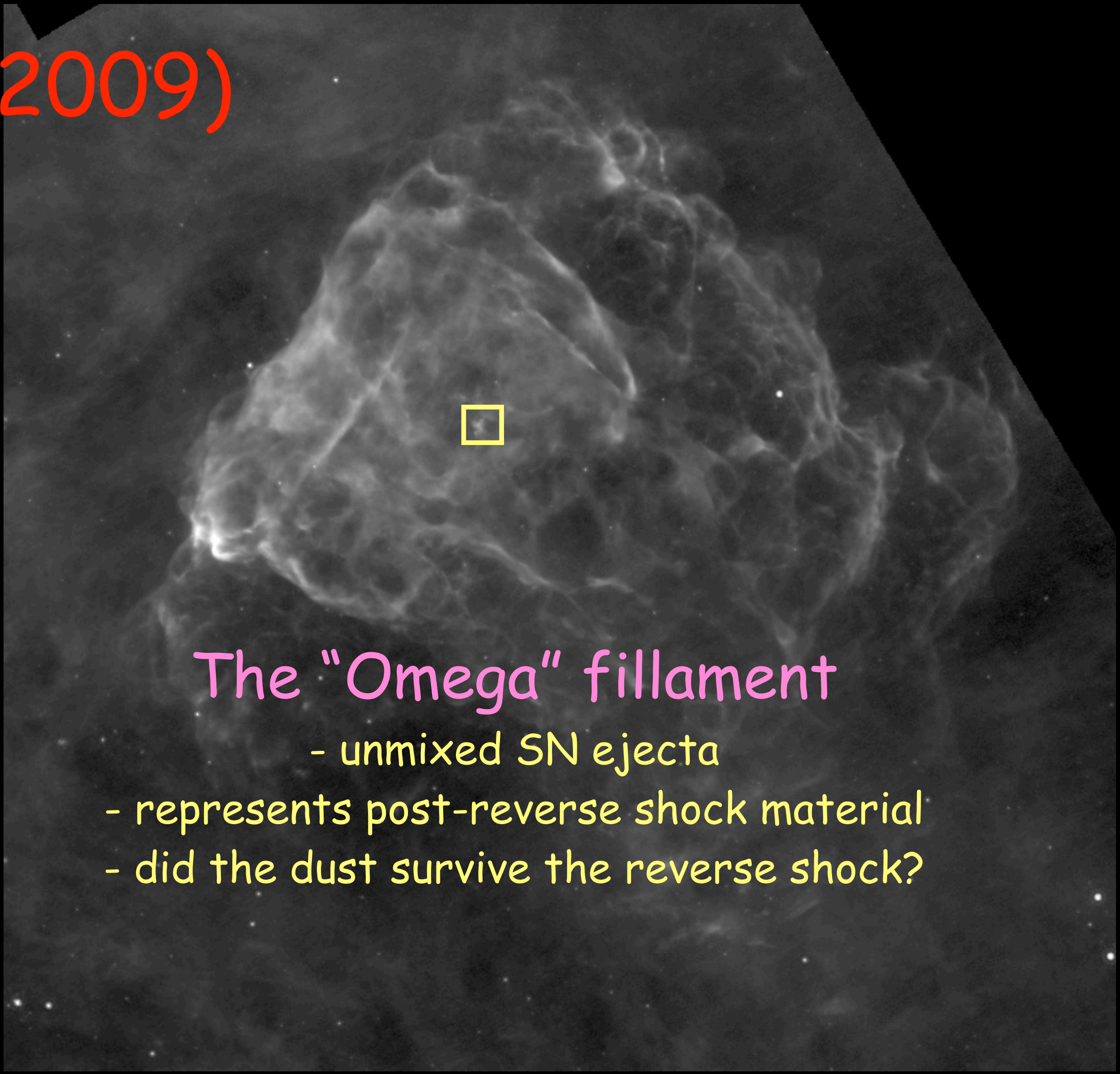
MC interaction
Rho et al. 2001

- Different regions sample different shock velocities and different ISM densities
- previously unobserved



Spitzer (2009)

MIPS 24 μm

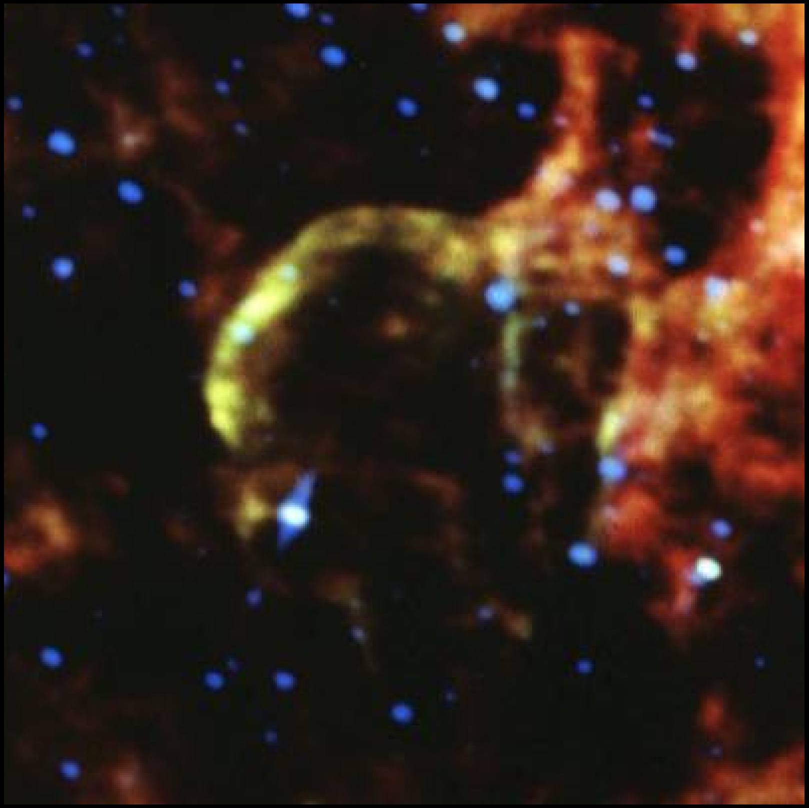


The “Omega” fillament

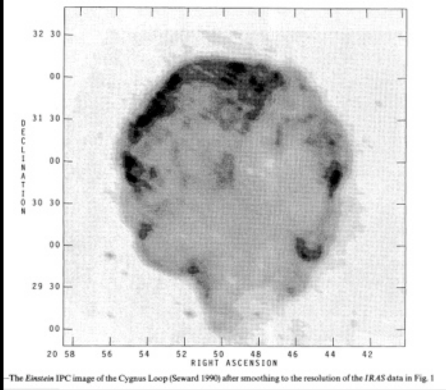
- unmixed SN ejecta
- represents post-reverse shock material
- did the dust survive the reverse shock?

Grain Destruction in the Cygnus Loop

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

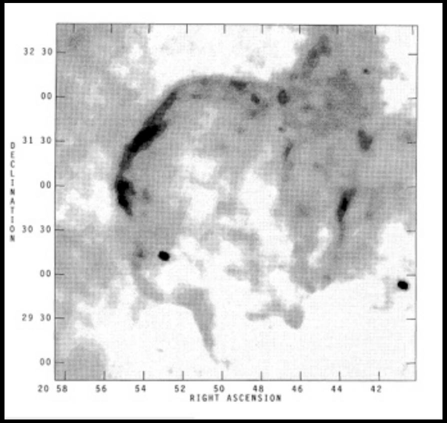


Cygnus Loop: X-rays (Einstein)



—The *Einstein* IPC image of the Cygnus Loop (Seward 1990) after smoothing to the resolution of the *IRAS* data in Fig. 1

Cygnus Loop: Infrared (IRAS)



Grain Destruction in the Cygnus Loop

(Sankrit et al. 2010)

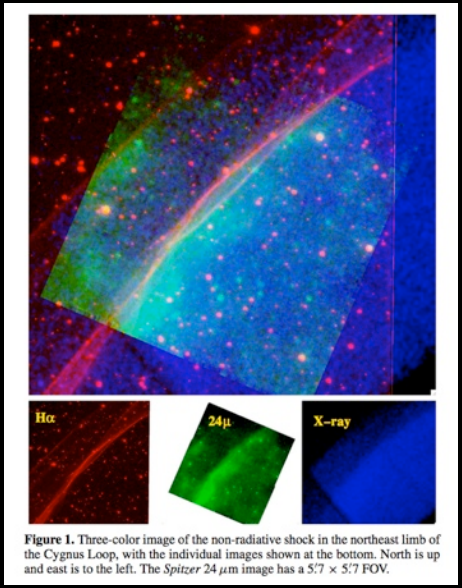
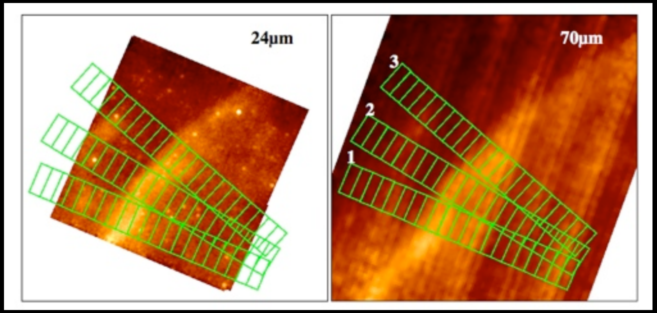
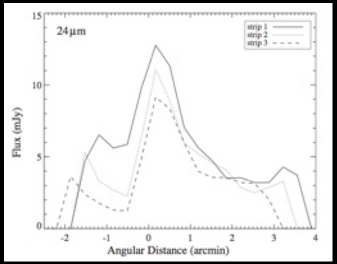
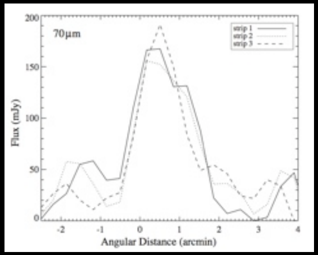


Figure 1. Three-color image of the non-radiative shock in the northeast limb of the Cygnus Loop, with the individual images shown at the bottom. North is up and east is to the left. The *Spitzer* 24 μm image has a 5.′7 × 5.′7 FOV.

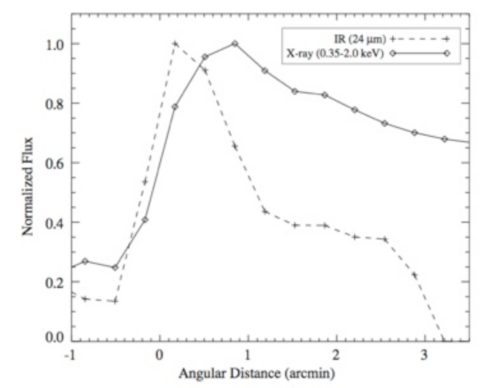






Color changes across the shock F_{70}/F_{24} μm flux ratio increases downstream

smaller grains are destroyed



The IRX = F_{IR}/F_x flux ratio decreases behind the shock

evidence for grain destruction

From models:
35% of the dust mass is destroyed in the ~ 400 km/s shock

Summary of Some Unknowns

What do we still need to know?

(Highly abbreviated list)

(1) Grain destruction

microphysics scale

galaxy scale

- sputtering
- grain-grain collisions

astrophysical shocks
SN1987A

supernova remnants
Puppis A

ISM

(2) Dust formation

Laboratory data

astrophysical environments
AGB, SNe, WR

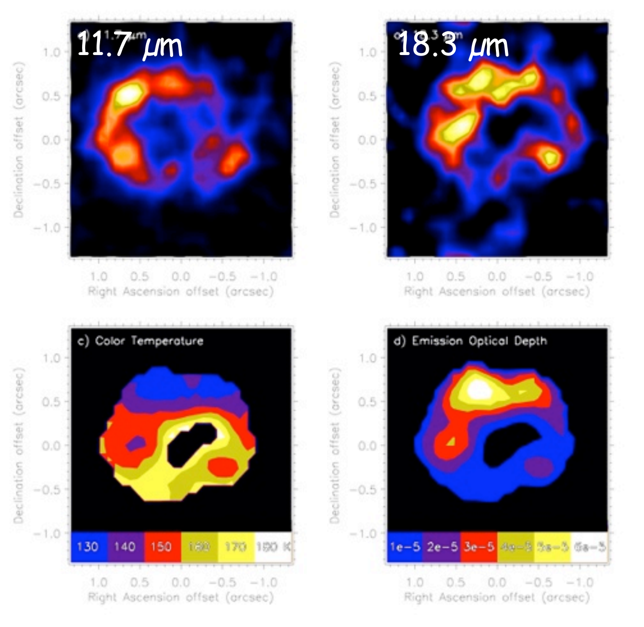
additional sources?
AGN, ISM

Continuous Monitoring of SN1987A

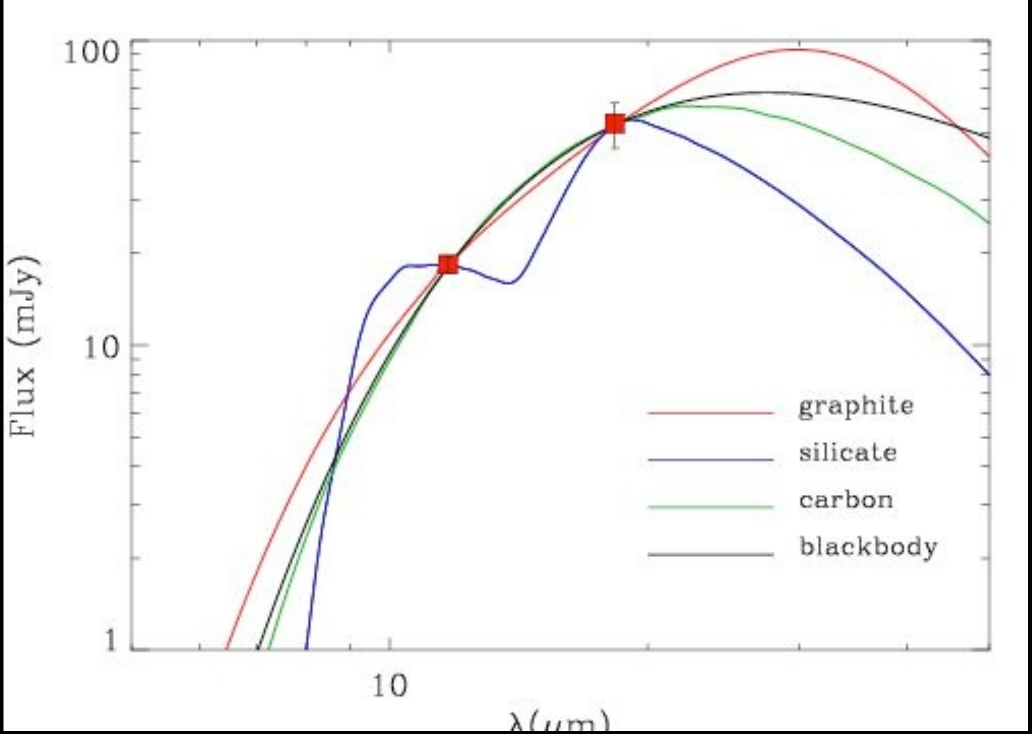
Southern hemisphere campaign

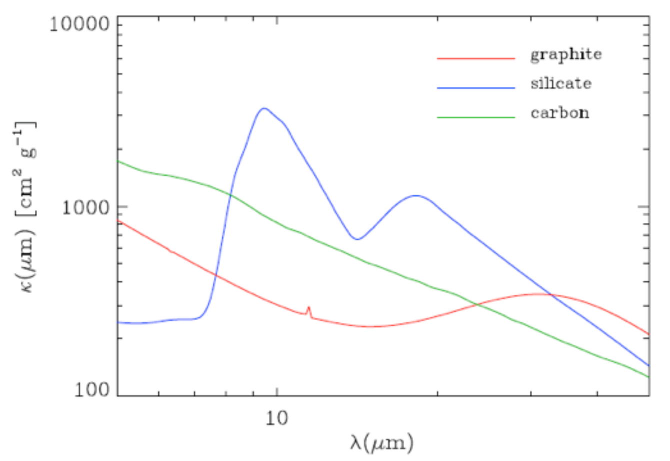
- Interaction of SN blast wave with the equatorial ring
- Interaction of the reverse wave with teh SN ejecta

Shock-heated circumstellar dust



T-ReCS observations resolve the ring, but with only two wavelengths, cannot provide constraints on dust composition



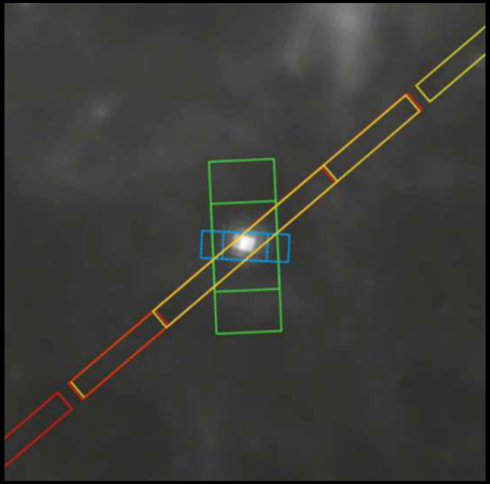


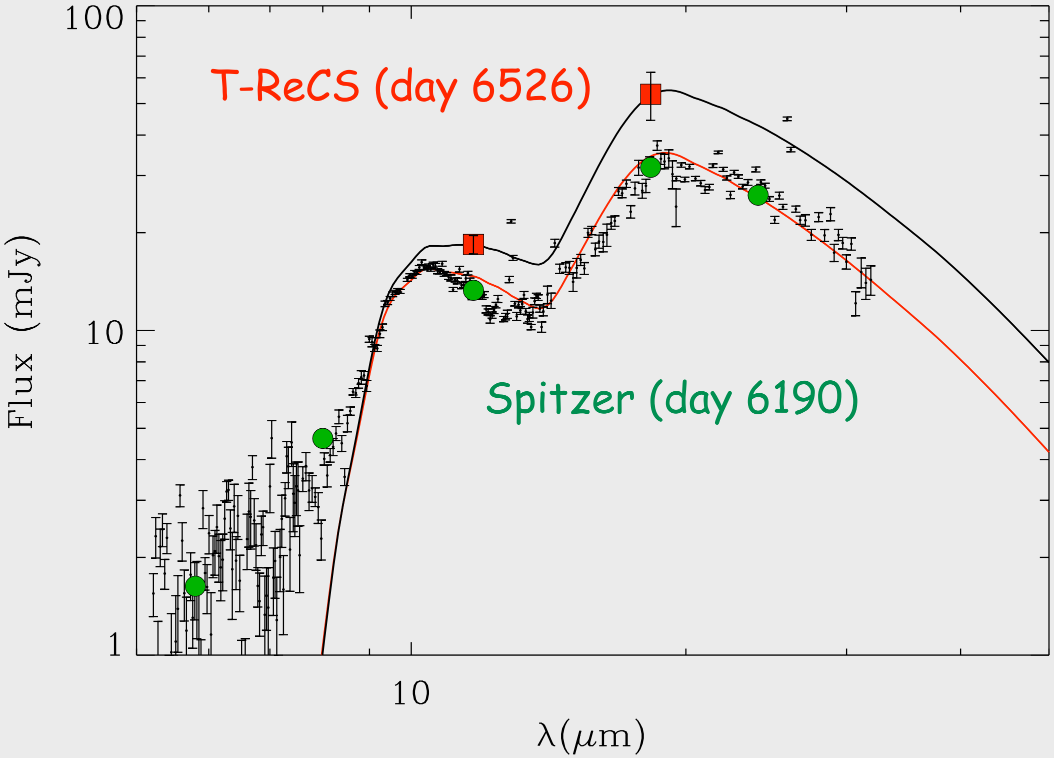
Shock-heated circumstellar dust

Spitzer – MIPS 24 μm (day 6184)
IRAC 3.6–8 μm (day 6130)
IRS 12–37 μm (day 6190)

Shock-heated silicate dust
$T_{dust} \approx 180 \pm 15$ K
$M_{dust} \approx (1\text{–}2) \times 10^{-6}\ M_{sun}$

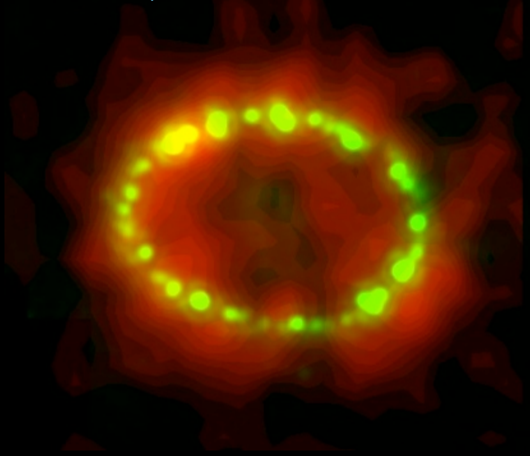
Spitzer observations
day 6190
(Gehrz, Polomski)



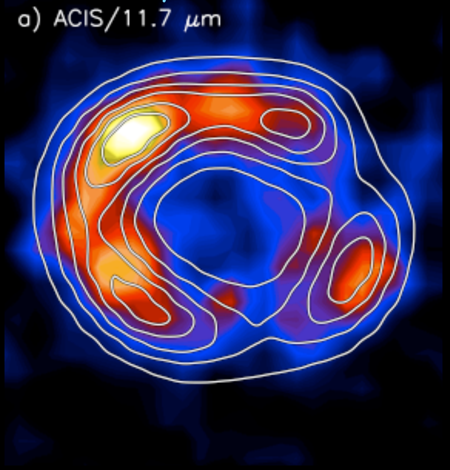


What is the origin of the IR emission?

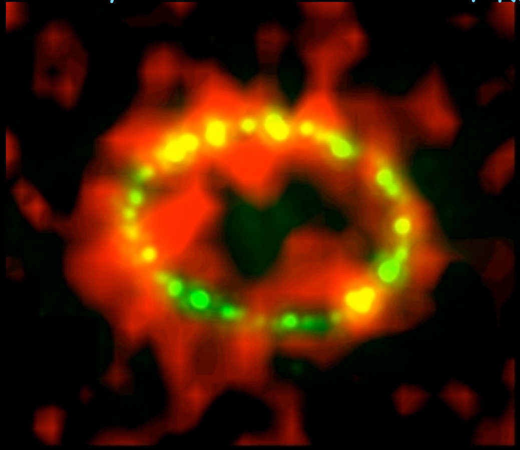
T-ReCS 11.7 μm + HST F625W



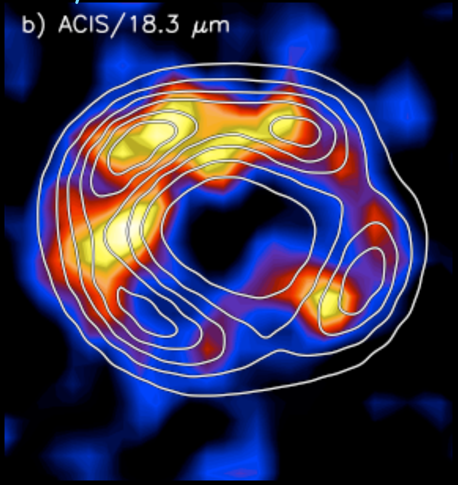
T-ReCS 11.7 μm + Chandra/ACIS



T-ReCS 18.3 μm + HST F625



T-ReCS 18.3 μm + Chandra/ACIS

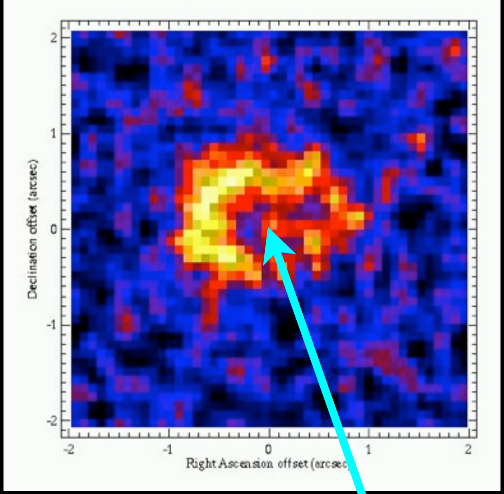


- T-ReCS (Bouchet et al. 2006)
  - $T_{dust} \approx 180$ K
- Is the dust emission associated with optical knots?
  - dust can only be radiatively heated to $T_{dust} \approx 120$ K
  - the optical depth of the ring is too low to explain the large (~1) IR/opt ratio
- Is the dust emission associated with the X-ray emission?
  - dust can easily be collisionally-heated to $T_{dust} \approx 180$ K

IR origin more consistent with collisionally-heated dust

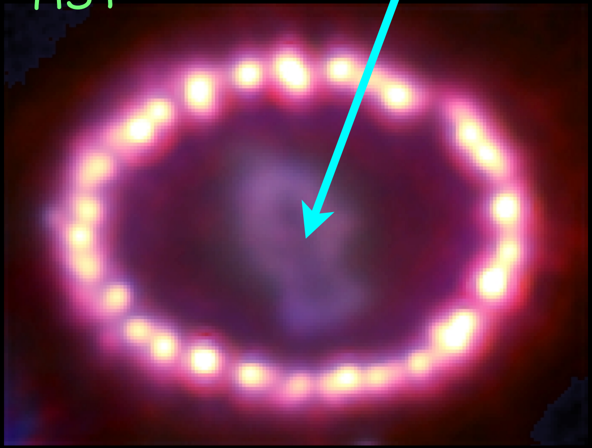
Inner debris and ring of SN1987A

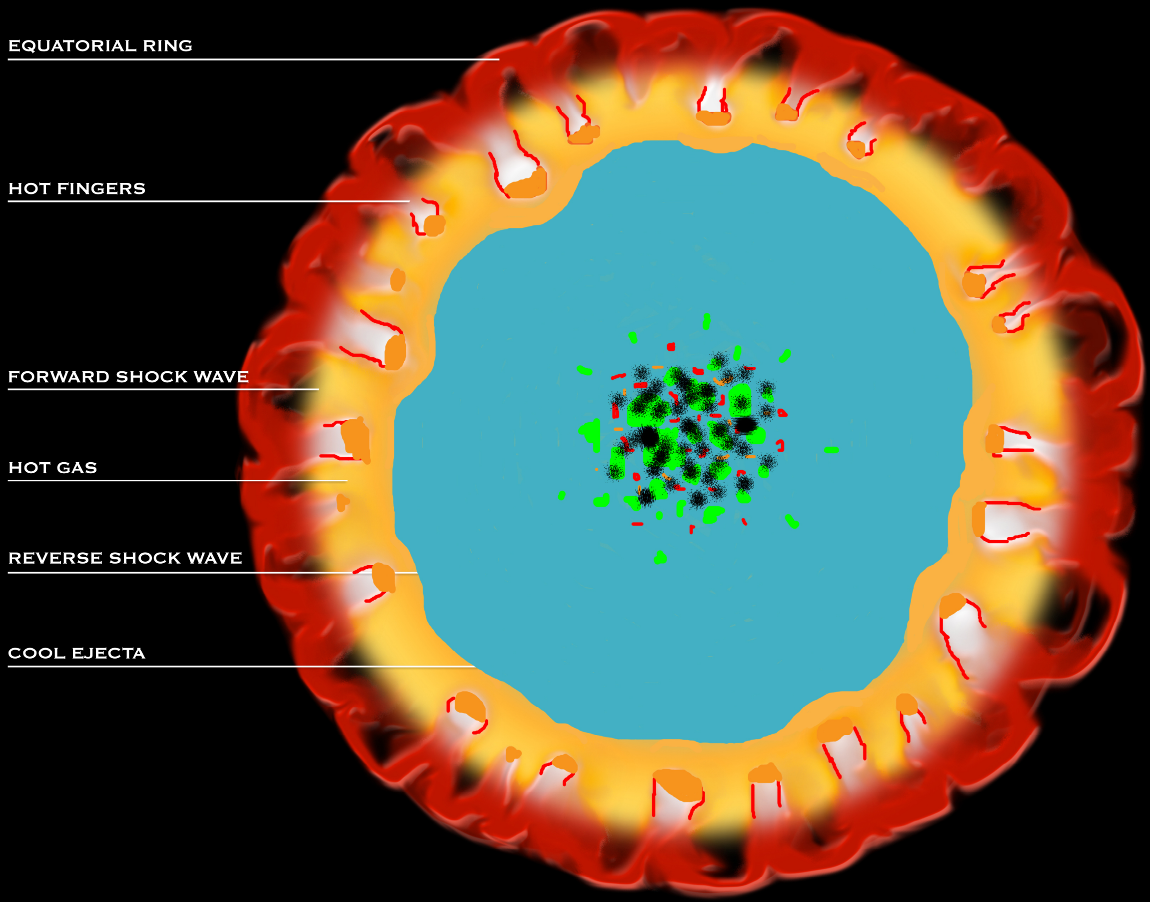
Gemini-S 10 μm - day 6067
(Bouchet et al 2004)



ejecta

HST





EQUATORIAL RING

HOT FINGERS

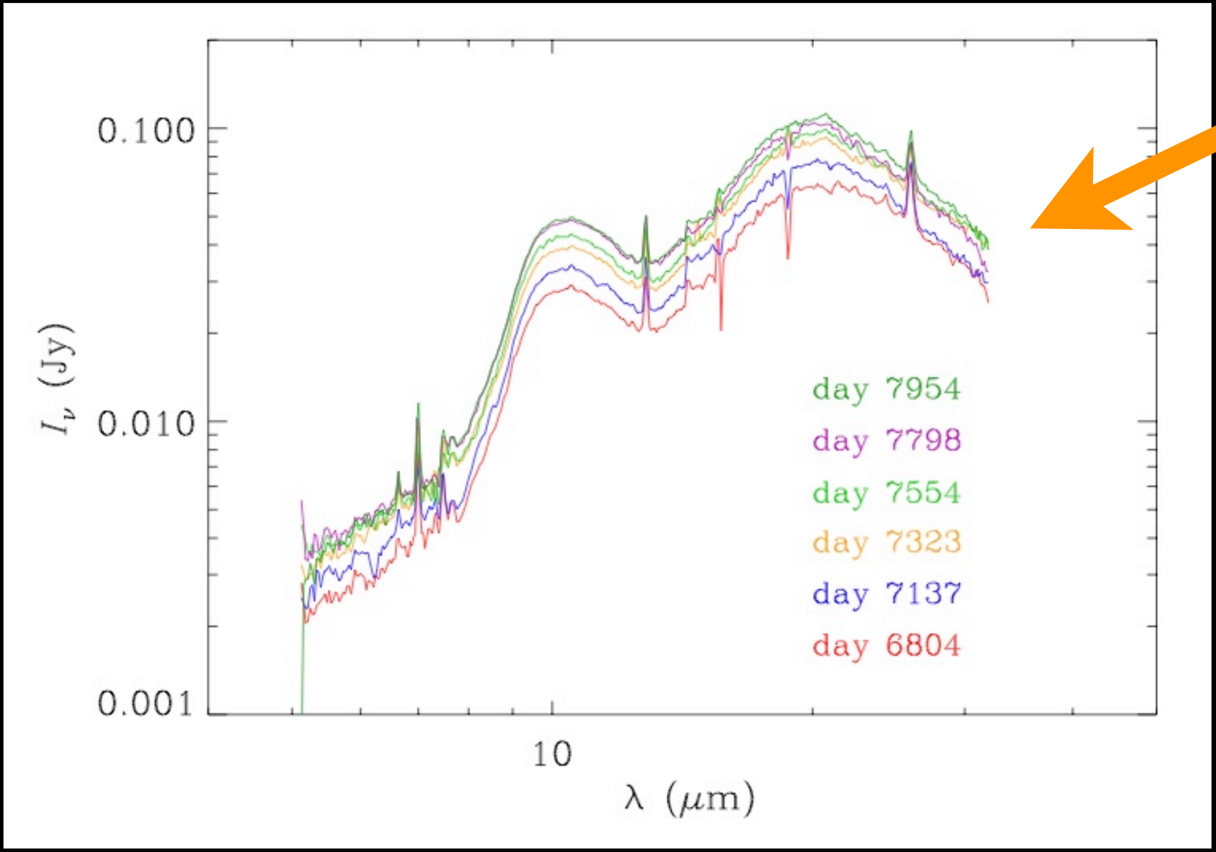
FORWARD SHOCK WAVE

HOT GAS

REVERSE SHOCK WAVE

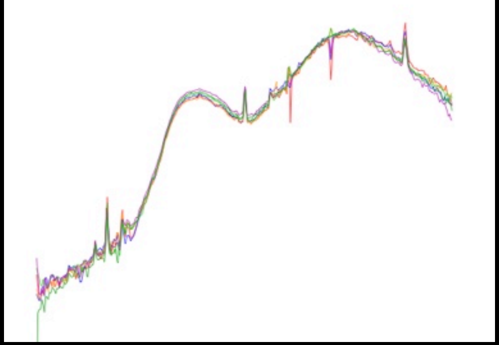
COOL EJECTA

The Evolution of the Infrared Spectrum

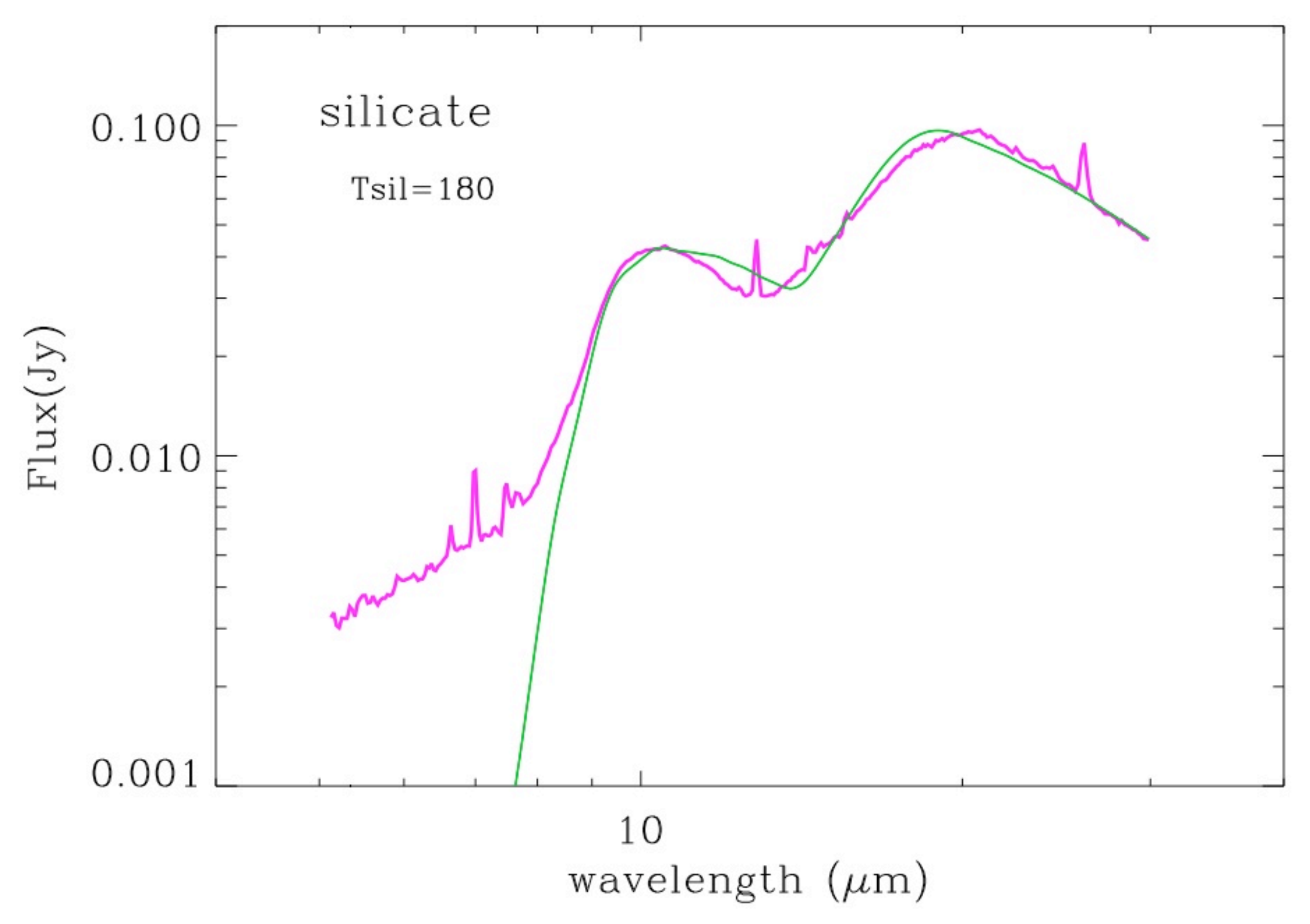


The spectrum has evolved in intensity

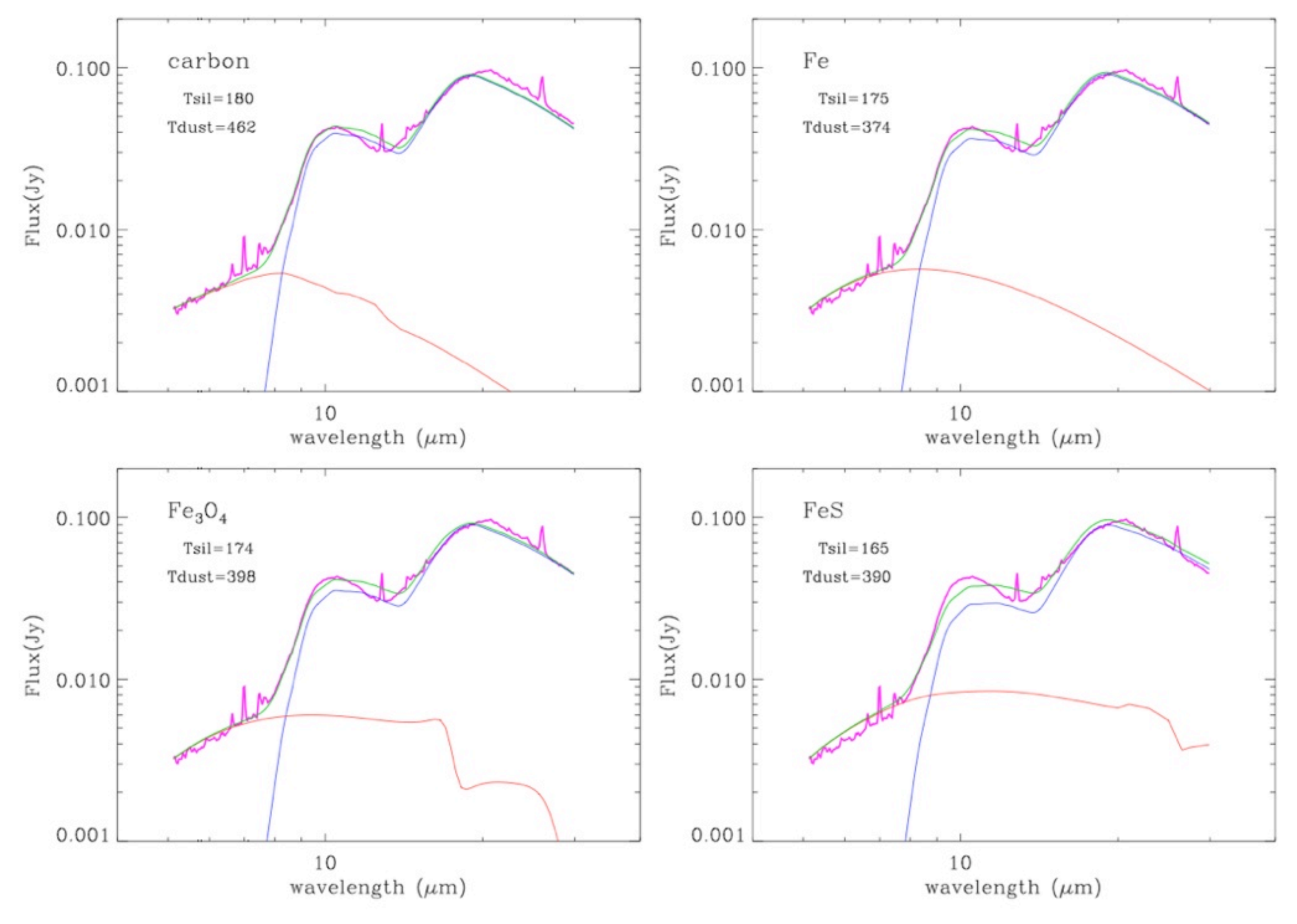
but has maintained a fixed spectral shape for over ~ 1800 d !



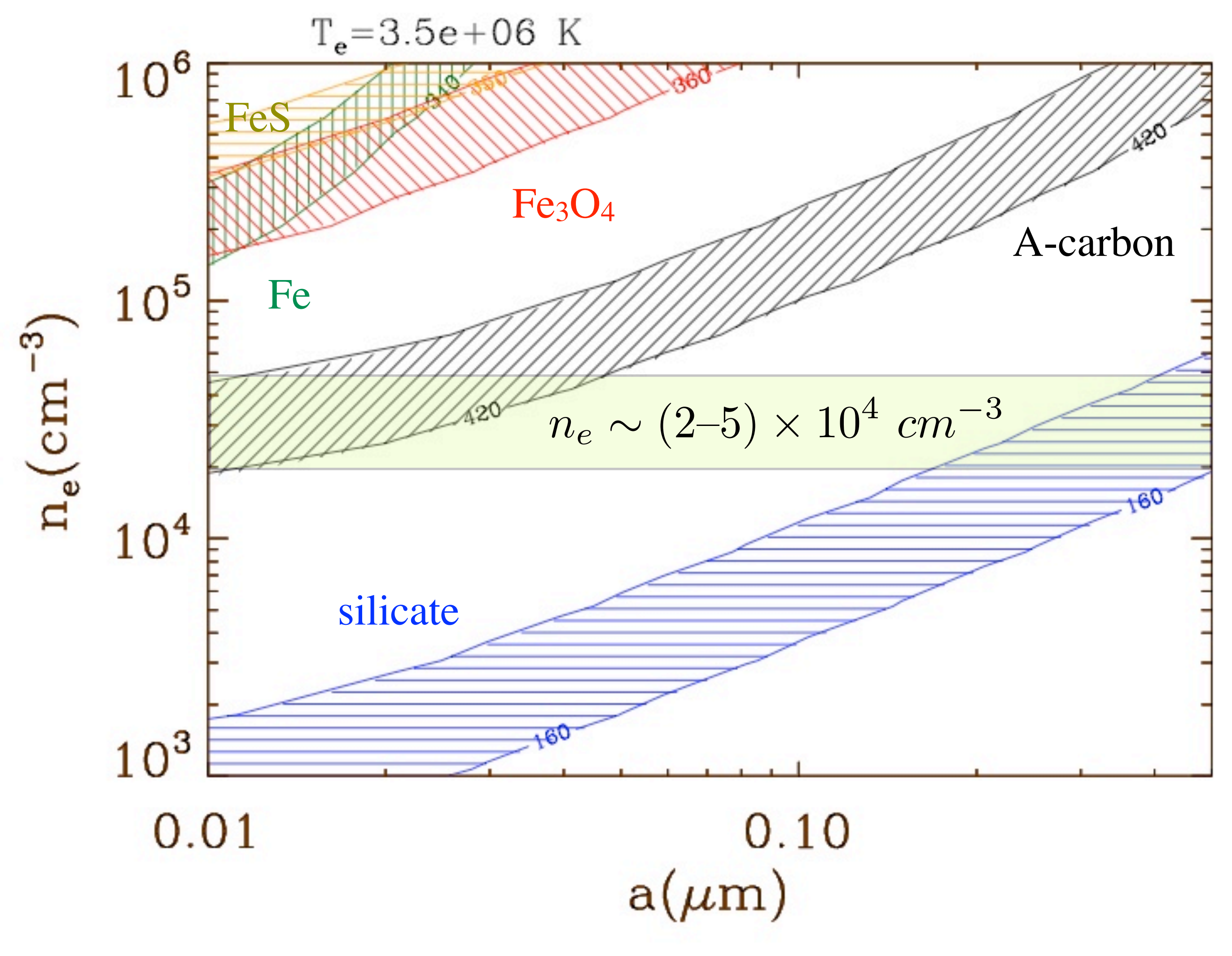
IR Emission from Collisionally-heated silicate grains



Two-temperature fits to the IR spectrum of SN1987A

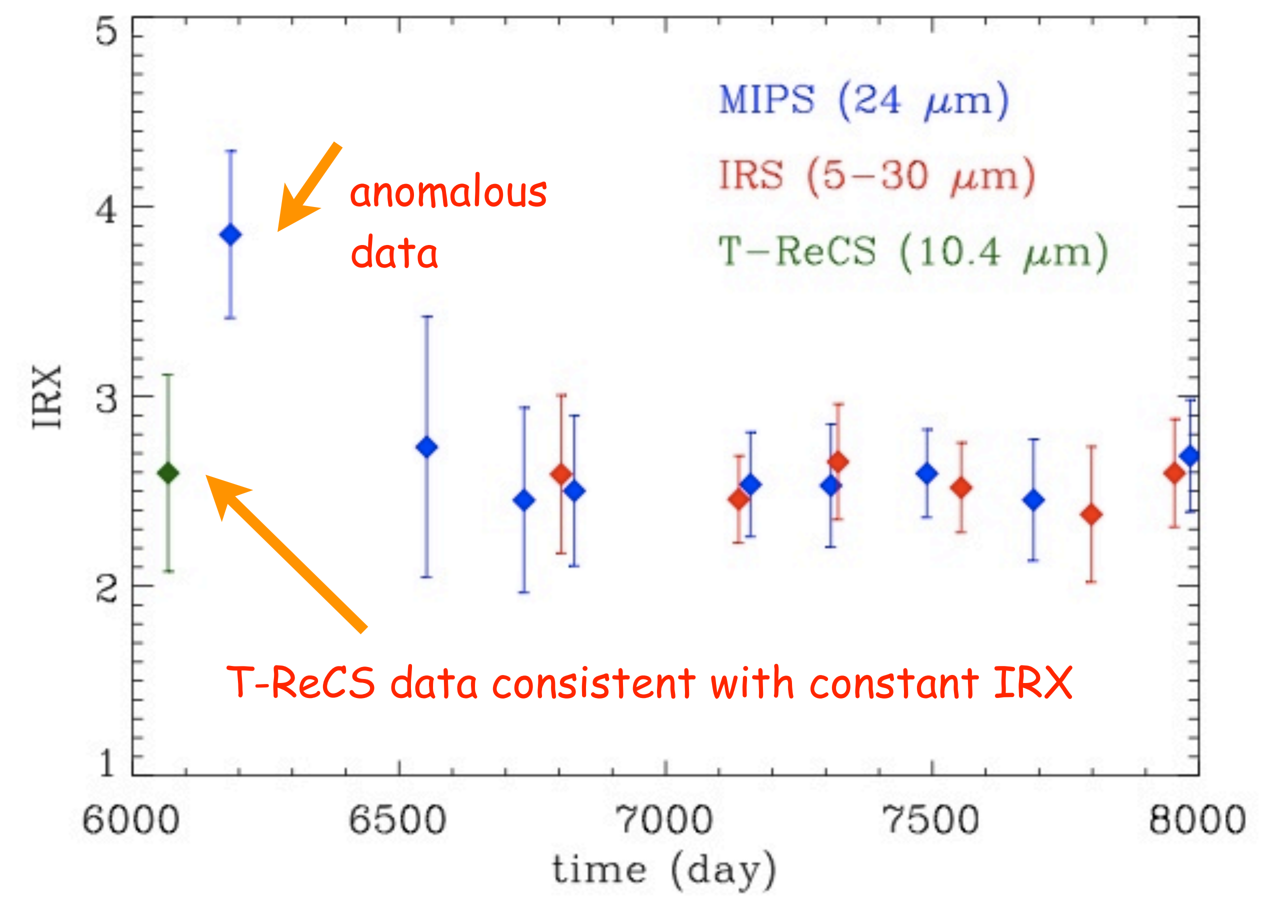


Electron density required to simultaneously heat the silicate and the second dust component to their respectively observed temperature



The Evolution of IRX

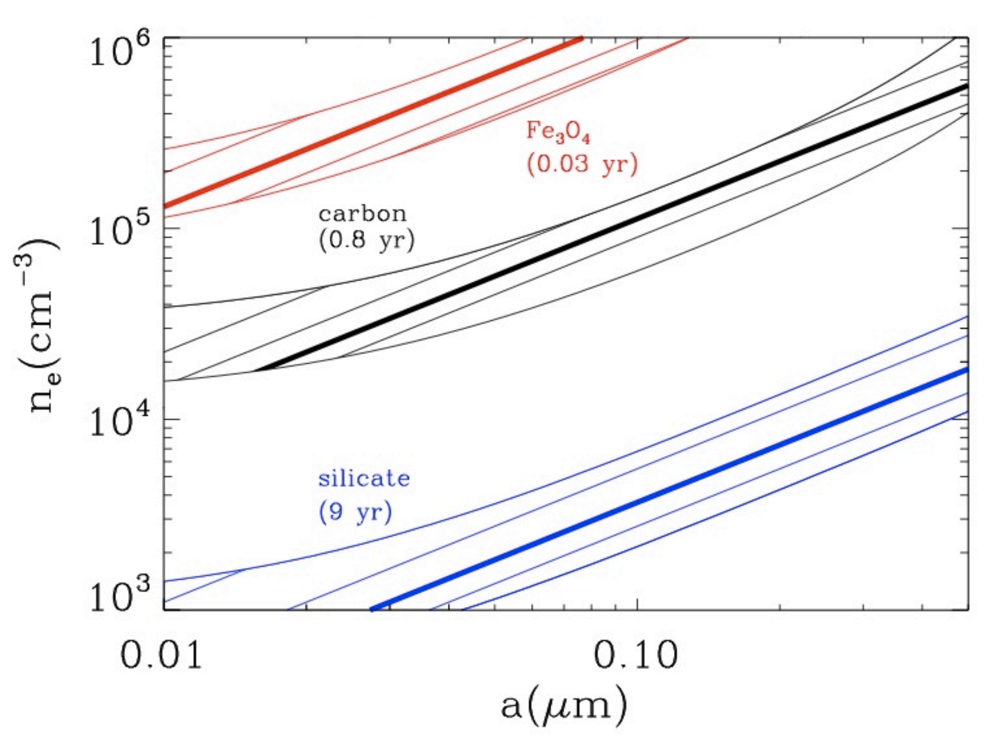
IRX is constant: NO grain destruction
or subsequent gas cooling

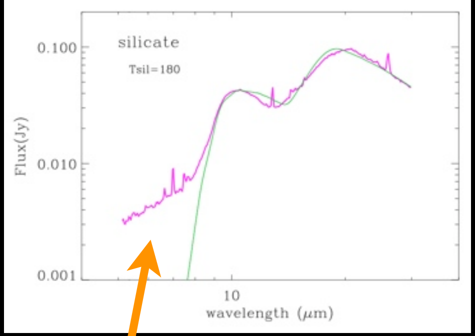


anomalous data

T-ReCS data consistent with constant IRX

Destruction timescales of the different dust components





What is the origin of the secondary dust component?

SN-condensed dust that is heated by the reverse shock?

Summary of Science Goals

- Grain destruction in SNRs
  - fill in the shock velocity and ISM density phase spaces
    - multiple remnants, different location in remnants
    - different ISM environments
  - observe pre-and post-shock IR spectra
- Survival and mixing of SN dust
  - identification of SN ejecta at different ages and in different environments (optical, X-ray)
- Global picture of remnant evolution in a dusty ISM
  - mapping of remnants of different ages and in different ISM phases
- Abundances of heavy elements
  - sputtered refractories

Required capabilities

- Grain destruction in SNRs -
  - Wavelengths ~ 5 - 40 μm with $R \geq 100$

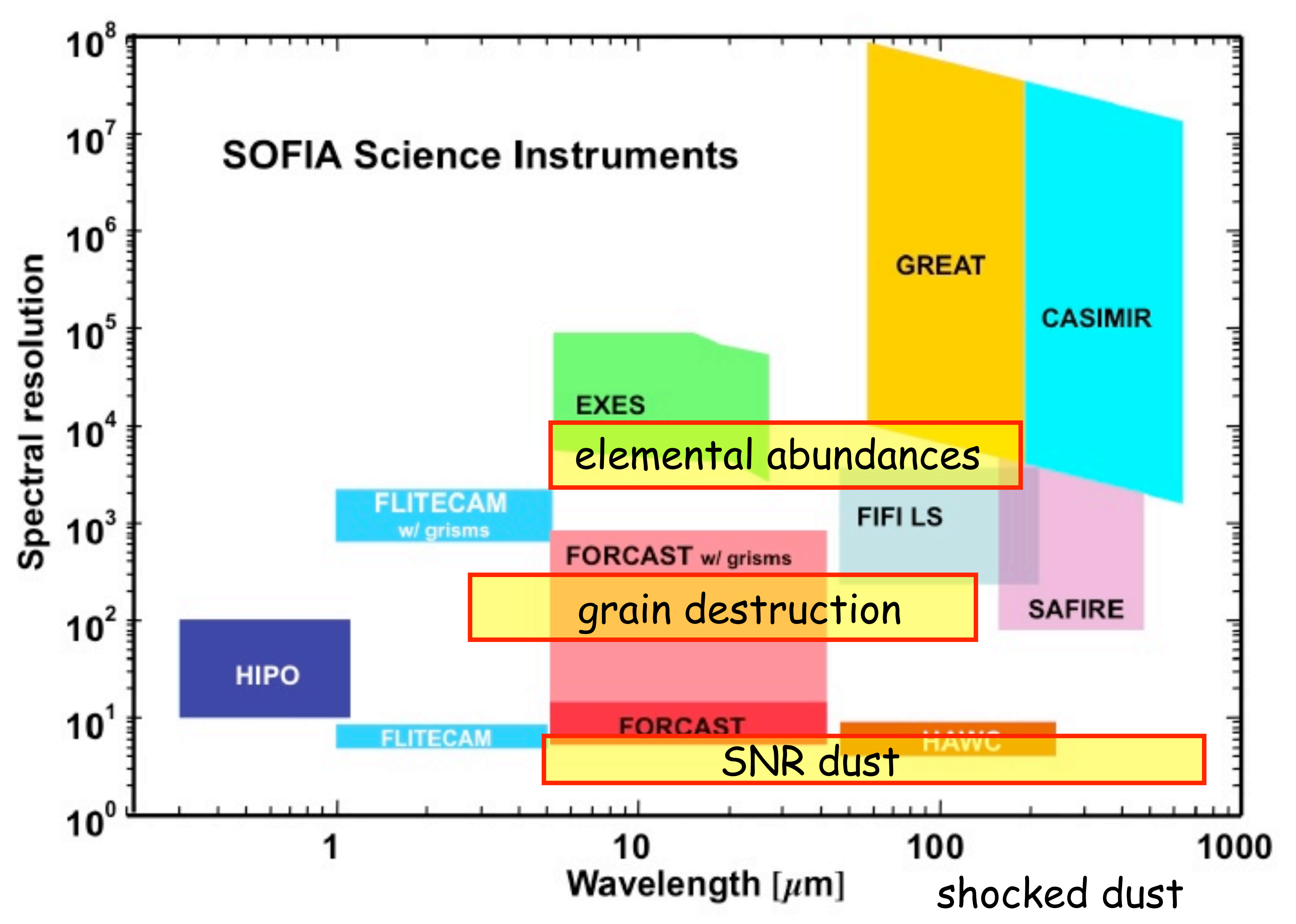
    FORCAST with grism
  - Wavelengths ~ 40 – 300 with $R \approx 10$

    HAWC
  - FOV ≈ 5′x5′
- Return of refractory elements to gas phase
  - Wavelengths ~ 5 - 160 μm with $R \geq 1000$

    EXES
- Survival and mixing of SN dust
  - same as (1)
- Global picture of remnant evolution in a dusty ISM
  - Wavelengths ~ 10 – 300 μm with $R \approx 10$

    FORCAST, HAWC
  - FOV ≈ 1x1 deg^2 (or larger)

    ?



elemental abundances

grain destruction

SNR dust

shocked dust

END

The Crab Nebula

- Higher spatial resolution will provide the dust SED in the filaments
- Dust is heated by nebular synchrotron emission

SOFIA Capabilities for studying grain processing in SNRs

- Hi-resolution observation of [Ne II] 12.8 μm line with EXES
  - R = 5,000-10,000
  - EXES line sensitivity ≈ 10^{-17} Wm^{-2}
    - Can observe 0.1-1 M_{sun} of Ne up to D ≈ 30 Mpc
  - the 12 μm optical depth is ≈ 10
    - M_{dust} ≈ 0.001 Msun
    - R_{shell} ≈ 2×10^{15} cm (v=500 km/s, t=1 yr)
    - Line is optically thick for 0.1–1 M_{sun} of Ne in the ejecta
- Low-resolution spectra of PAH and dust continuum emission FORCAST
  - R ≈ 10 - 100
  - FORCAST continuum sensitivity ≈ 0.1 Jy
    - Can observe dust up to D ≈ 0.5 – 1 Mpc (Andromeda)

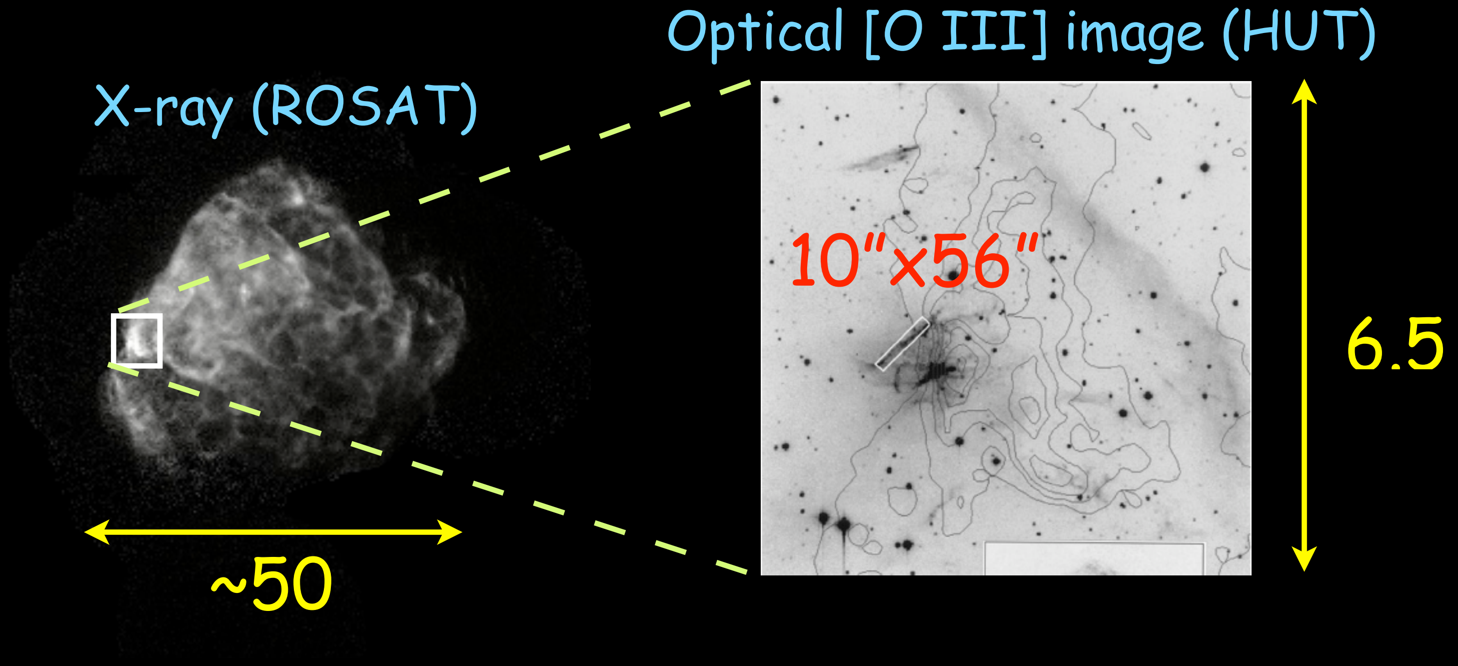
total flux from Pup A

- Need short wavelengts 5-15 μm spectra
  - constrain small grain population, needed to estimate the global amount of grain destruction
- need more photometric data (HAWC)
  - long wavelengths to constrain large grains (warm dust) which is the bulkof the mass
- SOFIA has higher spatial resoltion comparedto IRAS, so error bars will be smaller (confusion)
- Need background dominated (> 160 μm) image to serve as a spatial remplate for removing background at shorter wavelengths

SOFIA can produce a 70 μm at the same resolution as the Spitzer 24 μm image.

This will allow to create 24/70 μm color maps to identify the presence of dust in the optical filaments

Grain destruction in Puppis A



Spatial resolution of ~ 10″ needed to resolve optical filaments

Spectral resolution of $R \approx 100 - 200$ from ~ 3 — 200 μm to resolve PAH features and dust crystaline structure

Spectral resolution of $R \approx 1000 - 3000$ from ~ 3 - 200 μm for sputtered gas species: [OI]63μm, [CII]158μm, [FeII], [SIII], [SiII] , numerous H_2 lines (5.5, 6.1,......17.0, 28.3 μm)

Supernovae: Key Issues

- The abundance of newly synthesized heavy elements
- The composition, abundance, and size distribution of SN-condensed dust
- The nature of the progenitor star
- The morphology of the ambient circumstellar/ interstellar medium

Supernova Remnants:
Key Issues

- The physics of dusty plasmas
  - Dust heating via gas-grain collisions
  - Plasma cooling via gas-grain collisions
  - Grain destruction by thermal/kinetic sputtering
- The physics behind radiative shocks: PAH and dust processing/gas physics and chemistry
  - Sputtering, vaporizing and shattering grain-grain collisions
  - Dust formation/reconstitution in dense shocked environments

Sources of interstellar dust

- What are the major sources of interstellar dust?
  - massive stars
    - winds, explosive ejecta
  - low mass stars, protostars, AGN, shocks
- What is their relative importance as dust sources?
- What is the composition, abundance and size distribution of the dust in the different sources?
  - Novae and AGB show complex Si-rich AND C-rich dust - separate ejection, incomplete CO formation
- Does the newly-condensed dust survive the injection into the ISM?

Dust processing in the interstellar medium

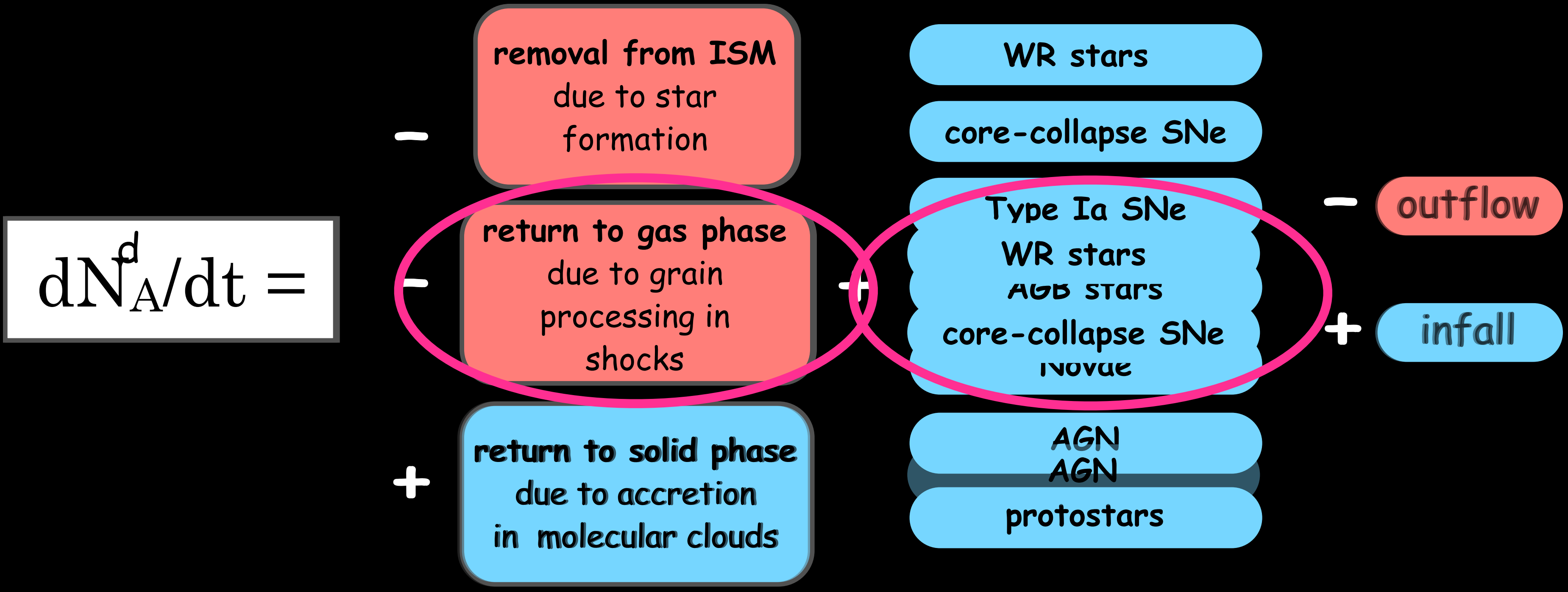
- How (in)homogeneous is the dust in the ISM?
  - how does the newly-formed dust mix into the ISM?
  - how do molecular clouds disperse into the ISM?
- What happens to dust in the ISM?
  - where does all the chemical, physical, radiative processing of the dust take place?
  - why don't we see composite grains, or a wider variety of dust in the diffuse ISM?
- What is the grain destruction efficiency in the ISM

What we would like to know about interstellar dust - 3

- What are the carriers of the various dust features?
  - 2200Å , ERE, UIB, 30 μm,
- What are the physical characteristics of dust?
  - composition (bare/composites)
  - density (solid, porous)
  - size distribution
  - crystaline state
  - shape
  - heat capacity
  - magnetic properties

At high redshift models can be considerably simplified

(Dwek, Galliano & Jones 2007)



$dN^d_A/dt =$

- **removal from ISM** due to star formation

- **return to gas phase** due to grain processing in shocks

\+ **return to solid phase** due to accretion in molecular clouds

\+

WR stars

core-collapse SNe

Type Ia SNe

WR stars

AGB stars

core-collapse SNe

Novae

AGN

AGN

protostars

\- outflow

\+ infall

At high redshift models can be considerably simplified

(Dwek, Galliano & Jones 2007)

The evolution of dust

$$dN^d_A/dt =$$

−

removal from ISM
due to star
formation

−

return to gas phase
due to grain
processing in
shocks

+

return to solid phase
due to accretion
in molecular clouds

+

WR stars

core-collapse SNe

Type Ia SNe

WR stars

AGB stars

core-collapse SNe

Novae

AGN

AGN

protostars

− outflow

+ infall

Dust yield in SNe

- Higher spatial and spectral resolution (compared to IRAS) have increased the inferred dust mass
    - ✦ the gobal SED could be separated into distinct (colder) dust component, requiring more mass
- Increased spatial resolution (compared to Spitzer) will allow comparison with individual optical knots
    - ✦ will enable use of detailed stochastic heating model which may result in a further increase in the derived dust mass

HAWC Spectral Passbands

SOFIA

Wavelength range: **50 - 240 µm**

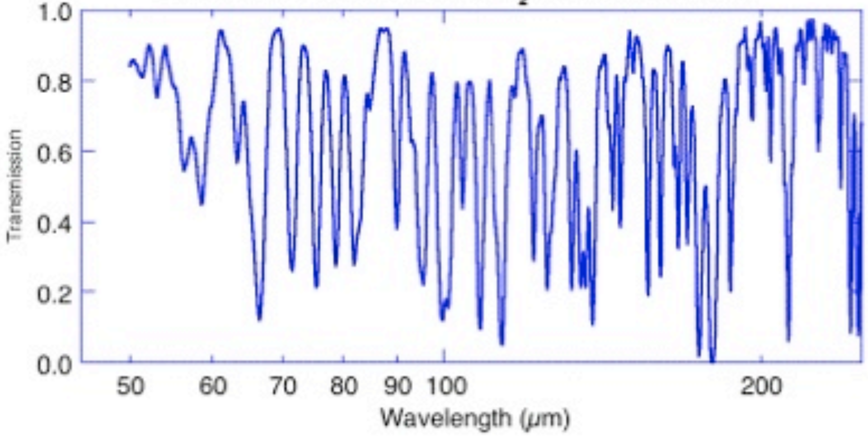
Four bandpass filters:

Band No.	λ_0	$R = \lambda_0/\Delta\lambda$
1:	53 µm	10
2:	88 µm	10
3:	155 µm	6.7
4:	215 µm	5

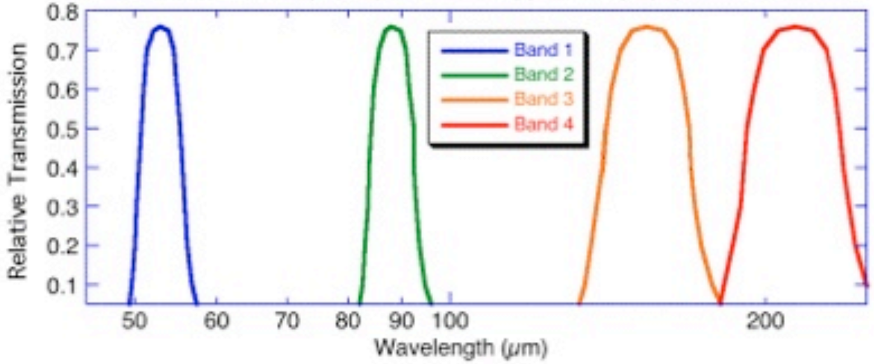
Each passband is observed separately; time to change passbands is roughly 2 minutes.

Reimaging optics provide a match to the diffraction limit in each passband (details provided on page 3).

Atmosphere transmission at 41,000 ft., 40° elevation, 7.3 µm zenith H_2O, 1 µm resolution



HAWC Filter Transmission Profiles



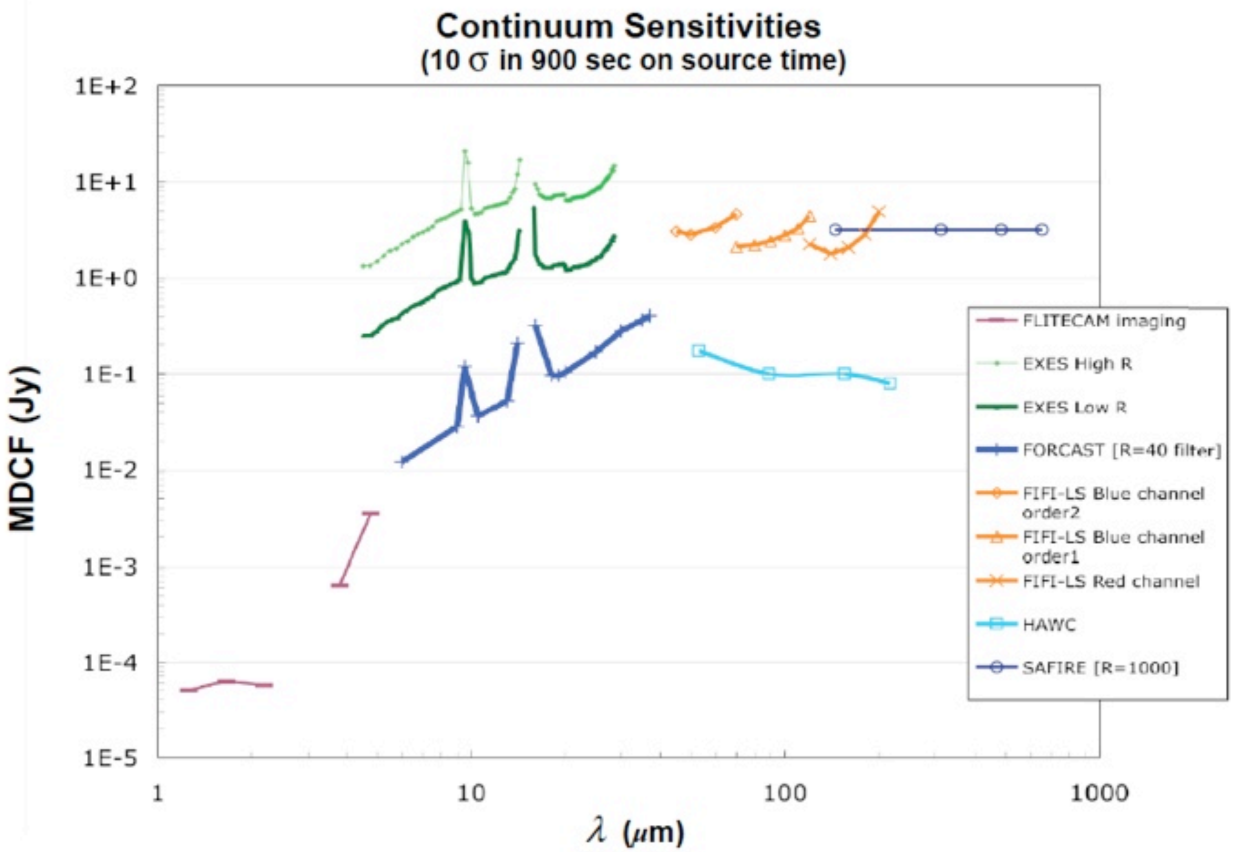


Figure 1-9. The continuum sensitivity of SOFIA instruments expected at the time of full operational capability. Shown is the 10 σ minimum detectable continuum point source flux densities (MDCF) in Janskys for 900 seconds of integration on source. Observing and chopper efficiency have not been included.

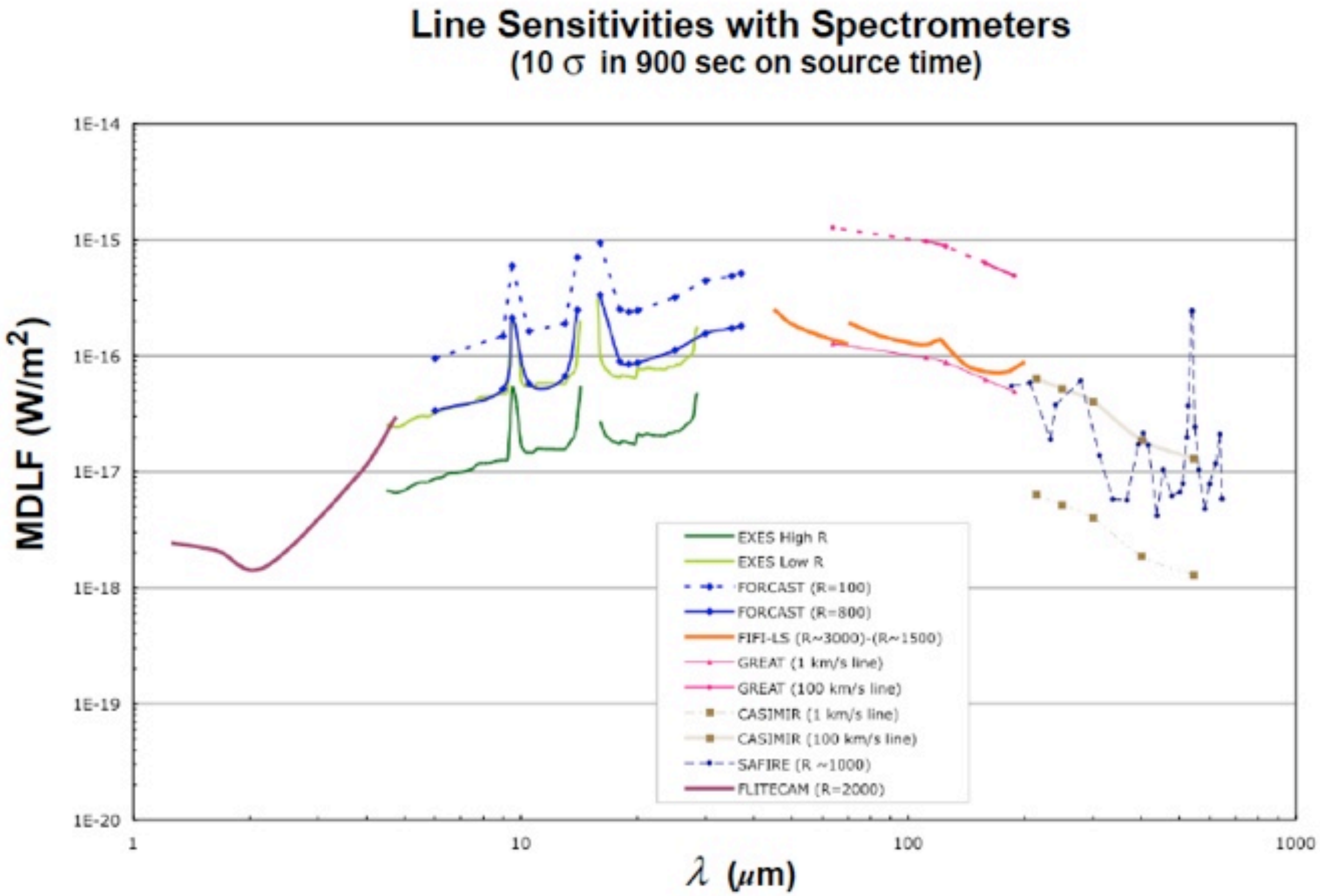
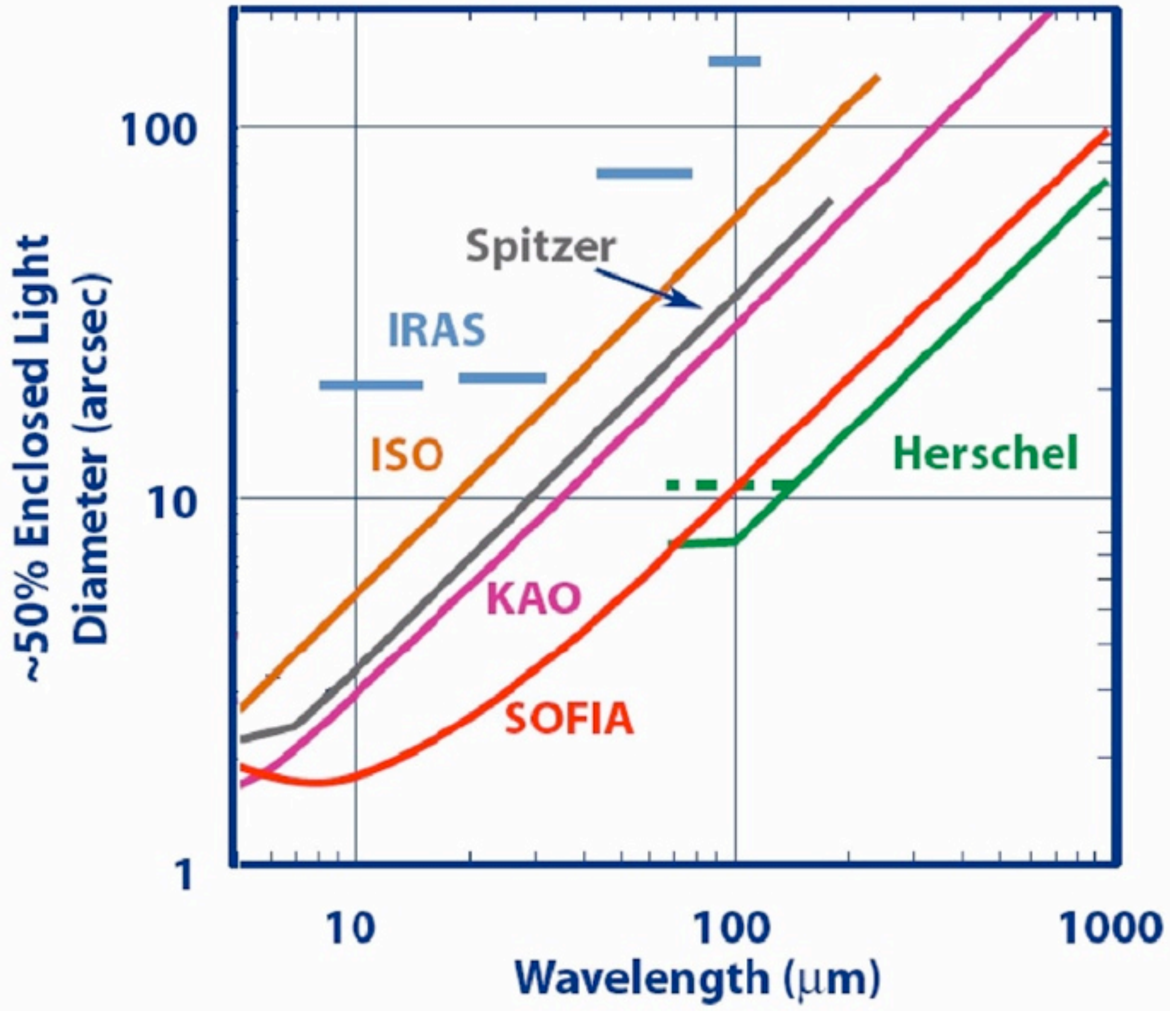
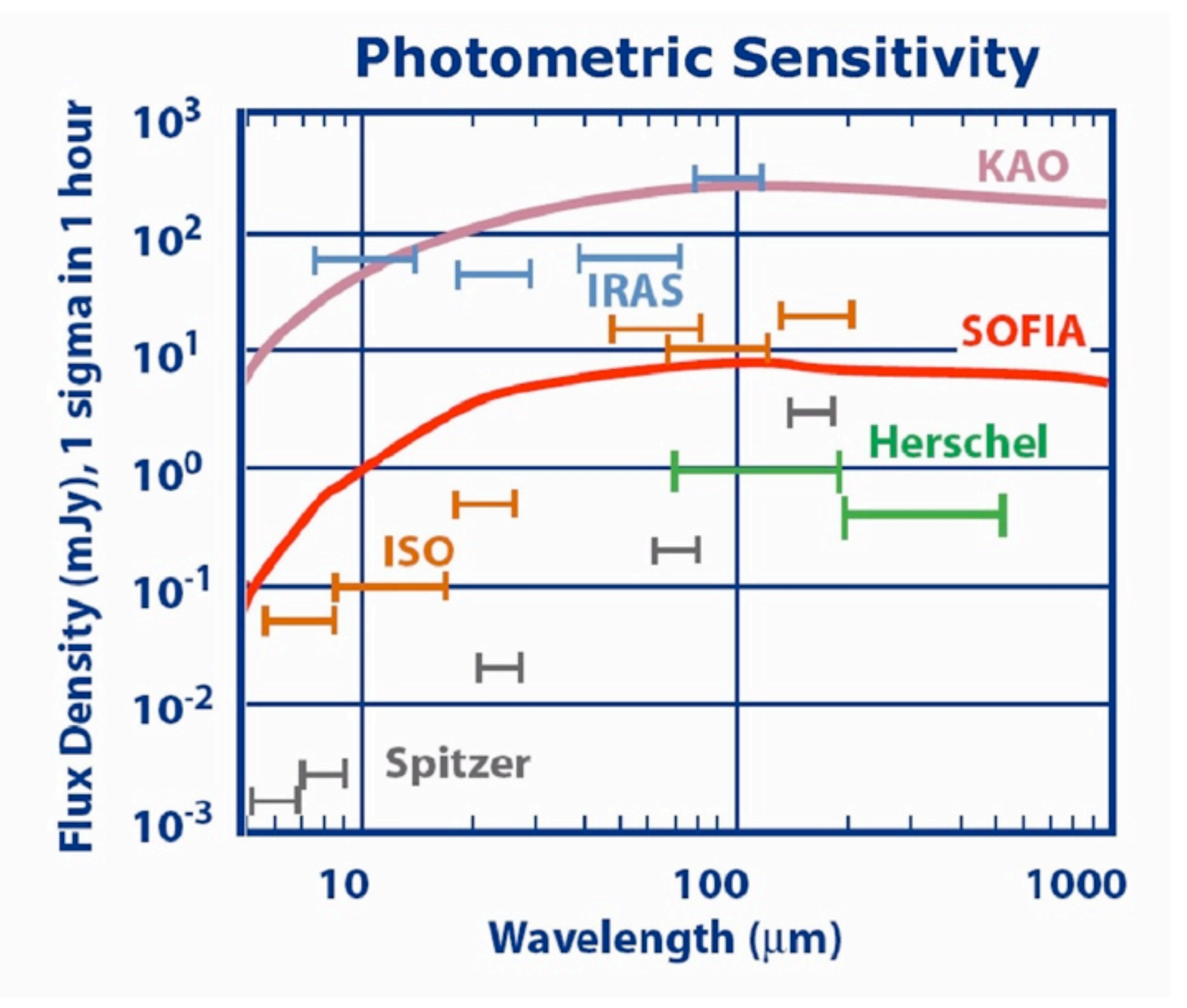


Figure 1-10. *The expected line sensitivity of SOFIA spectrometers at the time of full operational capability. Shown is the 10 σ minimum detectable line flux (MDLF) in watts per meter squared for 900 seconds of integration on source. Observing and chopper efficiency have not been included.*

Angular Resolution





Photometric Sensitivity
Flux Density (mJy), 1 sigma in 1 hour
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
KAO
IRAS
SOFIA
Herschel
ISO
Spitzer
10
100
1000
Wavelength (μm)

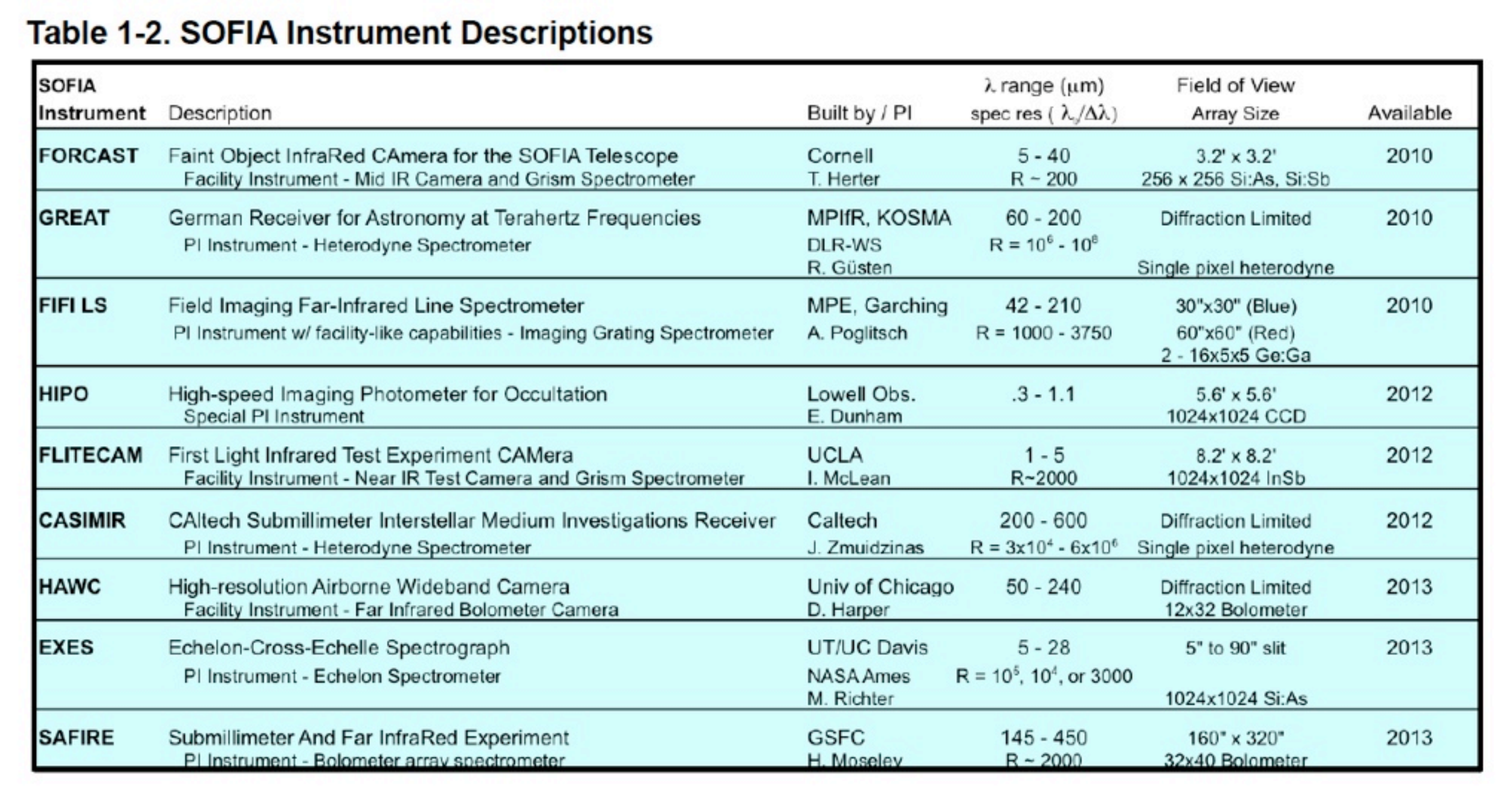
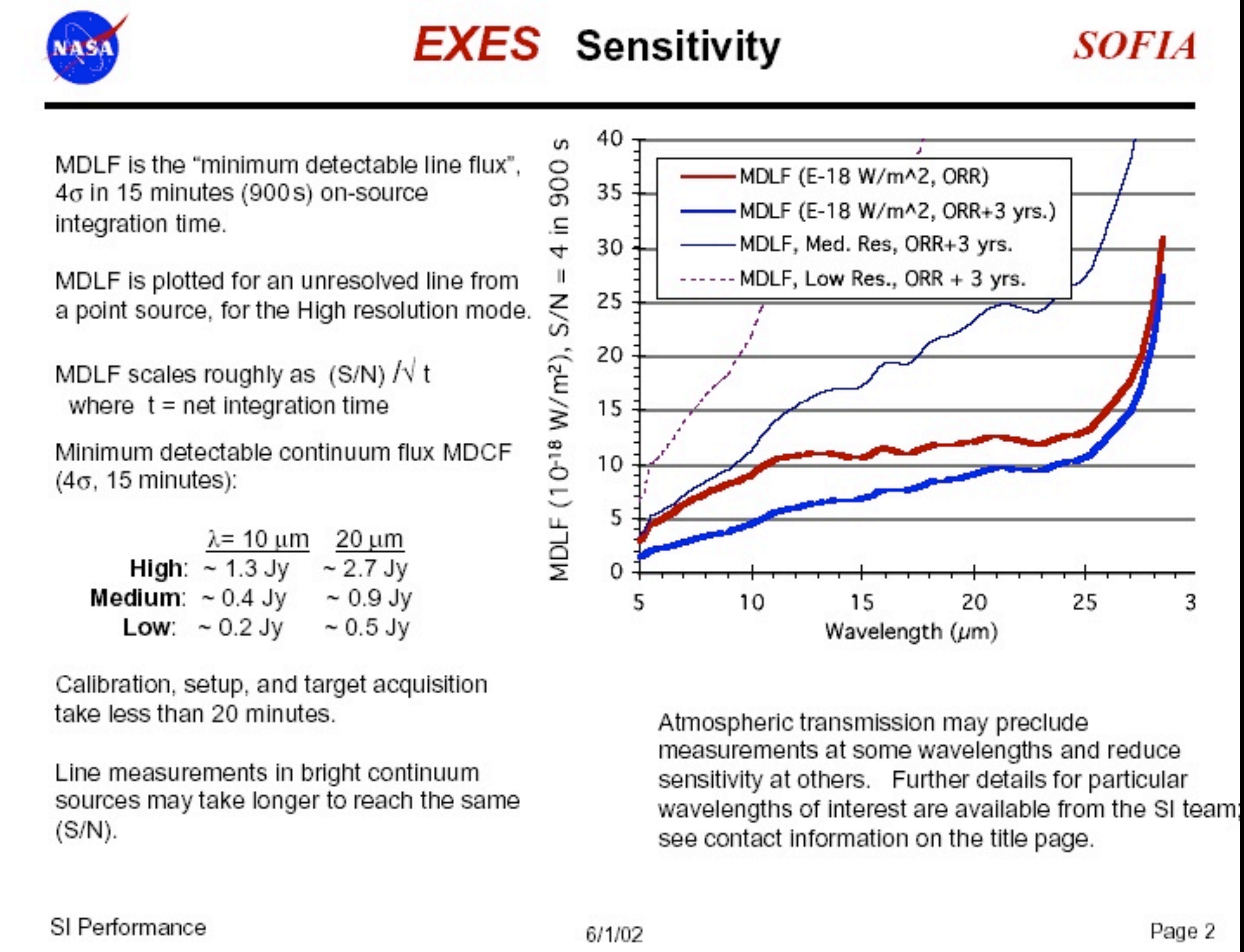


Table 1-2. SOFIA Instrument Descriptions

SOFIA Instrument	Description	Built by / PI	λ range (μm) spec res ($\lambda_o/\Delta\lambda$)	Field of View Array Size	Available
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope Facility Instrument - Mid IR Camera and Grism Spectrometer	Cornell T. Herter	5 - 40 R ~ 200	3.2' x 3.2' 256 x 256 Si:As, Si:Sb	2010
GREAT	German Receiver for Astronomy at Terahertz Frequencies PI Instrument - Heterodyne Spectrometer	MPIfR, KOSMA DLR-WS R. Güsten	60 - 200 R = 10^6 - 10^8	Diffraction Limited Single pixel heterodyne	2010
FIFI LS	Field Imaging Far-Infrared Line Spectrometer PI Instrument w/ facility-like capabilities - Imaging Grating Spectrometer	MPE, Garching A. Poglitsch	42 - 210 R = 1000 - 3750	30"x30" (Blue) 60"x60" (Red) 2 - 16x5x5 Ge:Ga	2010
HIPO	High-speed Imaging Photometer for Occultation Special PI Instrument	Lowell Obs. E. Dunham	.3 - 1.1	5.6' x 5.6' 1024x1024 CCD	2012
FLITECAM	First Light Infrared Test Experiment CAMera Facility Instrument - Near IR Test Camera and Grism Spectrometer	UCLA I. McLean	1 - 5 R~2000	8.2' x 8.2' 1024x1024 InSb	2012
CASIMIR	CAltech Submillimeter Interstellar Medium Investigations Receiver PI Instrument - Heterodyne Spectrometer	Caltech J. Zmuidzinas	200 - 600 R = 3×10^4 - 6×10^6	Diffraction Limited Single pixel heterodyne	2012
HAWC	High-resolution Airborne Wideband Camera Facility Instrument - Far Infrared Bolometer Camera	Univ of Chicago D. Harper	50 - 240	Diffraction Limited 12x32 Bolometer	2013
EXES	Echelon-Cross-Echelle Spectrograph PI Instrument - Echelon Spectrometer	UT/UC Davis NASA Ames M. Richter	5 - 28 R = 10^5, 10^4, or 3000	5" to 90" slit 1024x1024 Si:As	2013
SAFIRE	Submillimeter And Far InfraRed Experiment PI Instrument - Bolometer array spectrometer	GSFC H. Moseley	145 - 450 R ~ 2000	160" x 320" 32x40 Bolometer	2013



EXES Sensitivity

SOFIA

MDLF is the “minimum detectable line flux”, 4σ in 15 minutes (900 s) on-source integration time.

MDLF is plotted for an unresolved line from a point source, for the High resolution mode.

MDLF scales roughly as $(S/N)/\sqrt{t}$
where t = net integration time

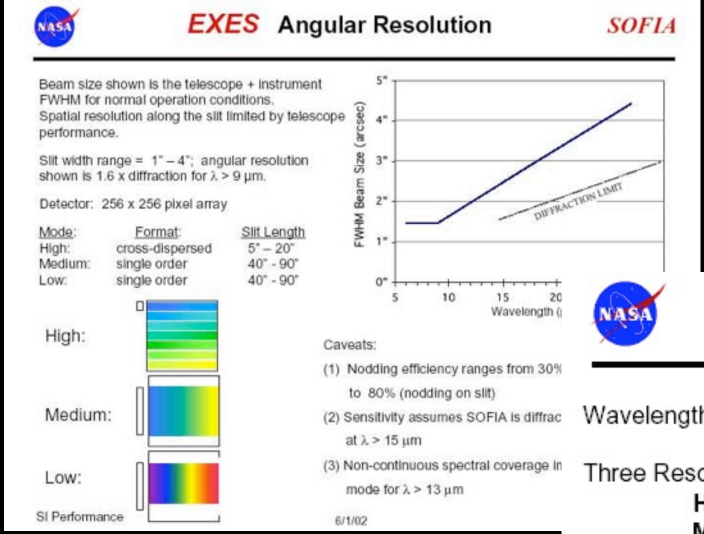
Minimum detectable continuum flux MDCF (4σ, 15 minutes):

	λ = 10 µm	20 µm
High:	~ 1.3 Jy	~ 2.7 Jy
Medium:	~ 0.4 Jy	~ 0.9 Jy
Low:	~ 0.2 Jy	~ 0.5 Jy

Calibration, setup, and target acquisition take less than 20 minutes.

Line measurements in bright continuum sources may take longer to reach the same (S/N).

Atmospheric transmission may preclude measurements at some wavelengths and reduce sensitivity at others. Further details for particular wavelengths of interest are available from the SI team; see contact information on the title page.



EXES Angular Resolution

SOFIA

Beam size shown is the telescope + instrument FWHM for normal operation conditions.
Spatial resolution along the slit limited by telescope performance.

Slit width range = 1" – 4"; angular resolution shown is 1.6 x diffraction for λ > 9 µm.

Detector: 256 x 256 pixel array

Mode:	Format:	Slit Length
High:	cross-dispersed	5" – 20"
Medium:	single order	40" - 90"
Low:	single order	40" - 90"

Caveats:

(1) Nodding efficiency ranges from 30%
to 80% (nodding on slit)

(2) Sensitivity assumes SOFIA is diffrac
at λ > 15 µm

(3) Non-continuous spectral coverage in
mode for λ > 13 µm

SI Performance

6/1/02

EXES Spectral Resolution

SOFIA

Wavelength range: **5 - 28 µm**

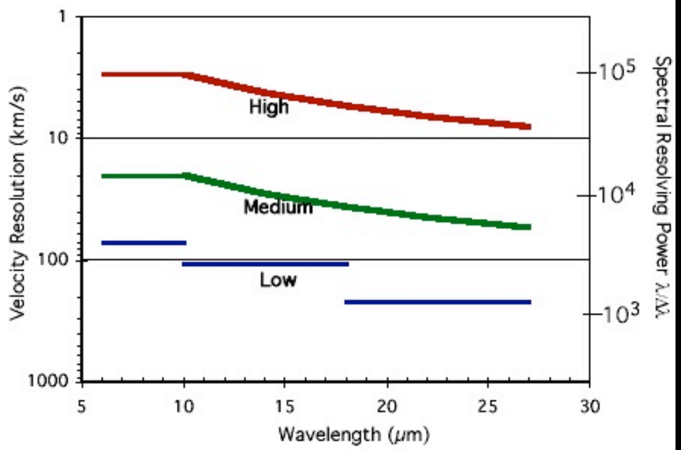
Three Resolving Powers:

High: ~ 10^5
Medium: ~ 10^4
Low: ~3000

The resolving power plotted corresponds to the FWHM of the instrument line spread function for a monochromatic line from a point source.

Wavelength changes require about 3 minutes.

Resolution change requires about 3 minutes.



Free spectral range :

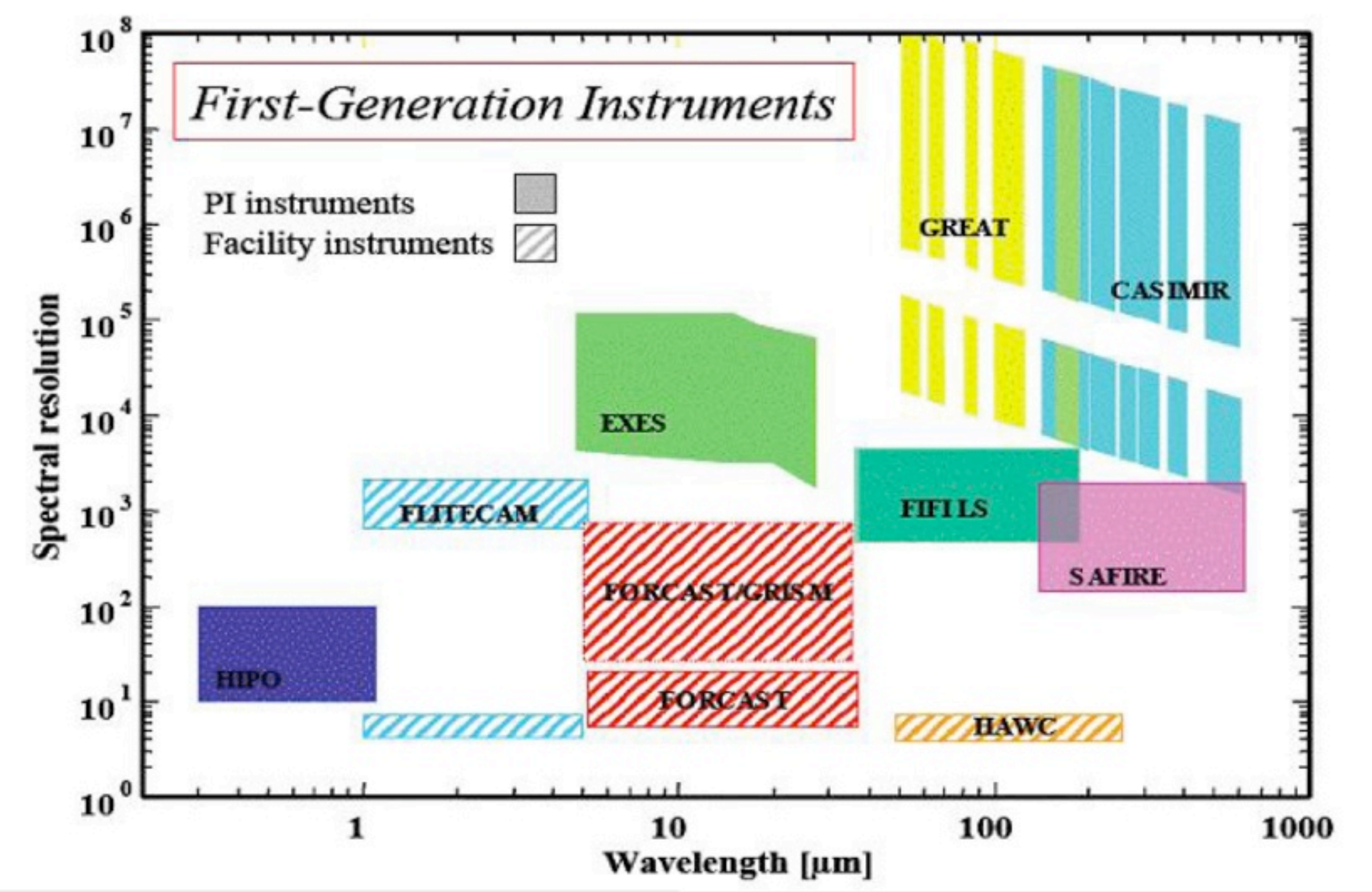
High: 1500 km/sec (echelle mode)
Medium: 1500 km/sec
Low: 6000 km/sec

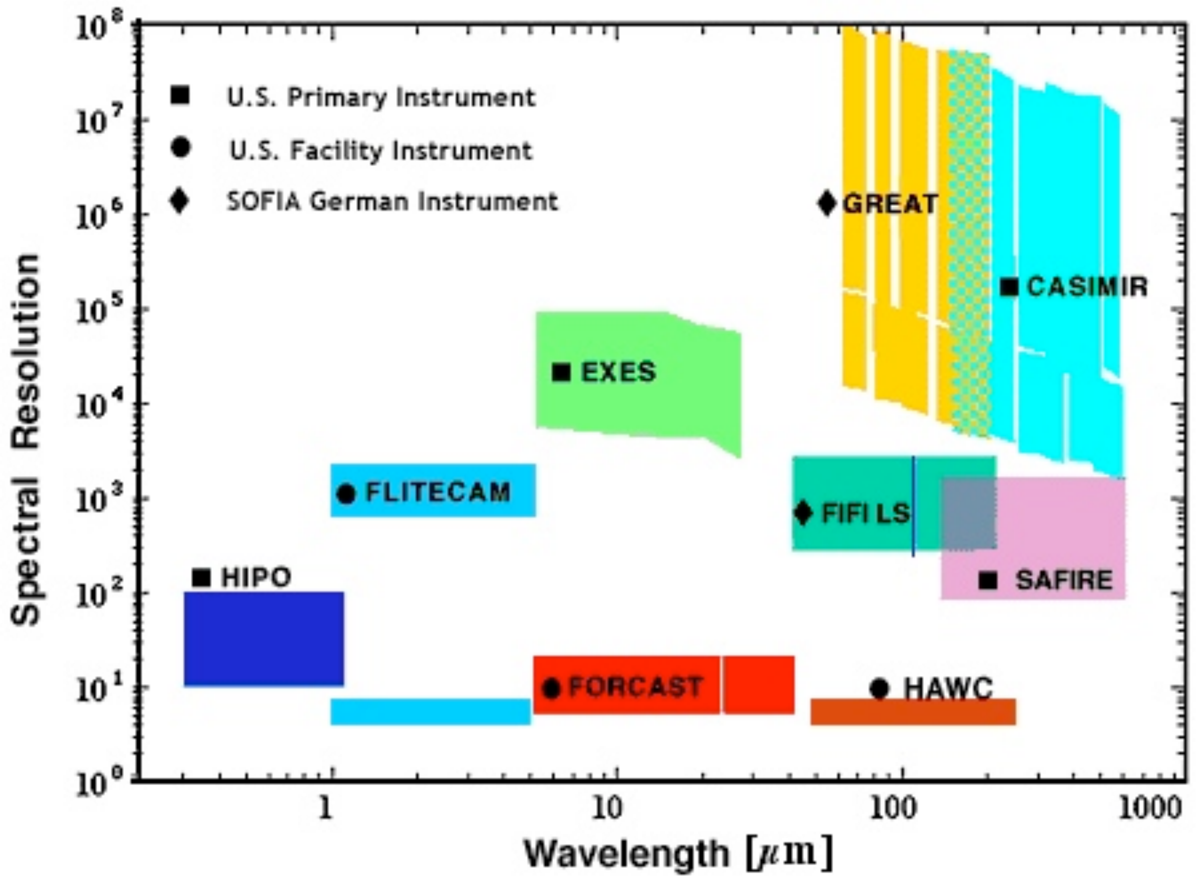
SI Performance

6/1/02

Page 1

Dust evolution with SOFIA

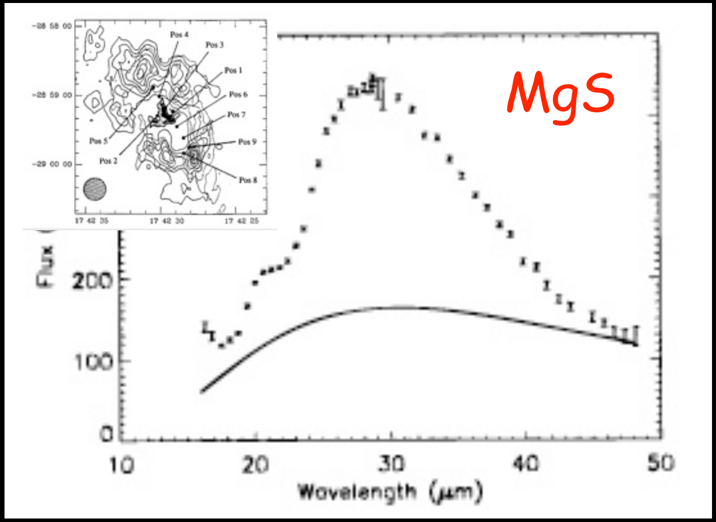



■ U.S. Primary Instrument
● U.S. Facility Instrument
♦ SOFIA German Instrument
♦ GREAT
■ CASIMIR
■ EXES
● FLITECAM
♦ FIFI LS
■ SAFIRE
■ HIPO
● FORCAST
● HAWC
Spectral Resolution
Wavelength [μm]
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
1
10
100
1000

Where in the ISM do grains get processed?

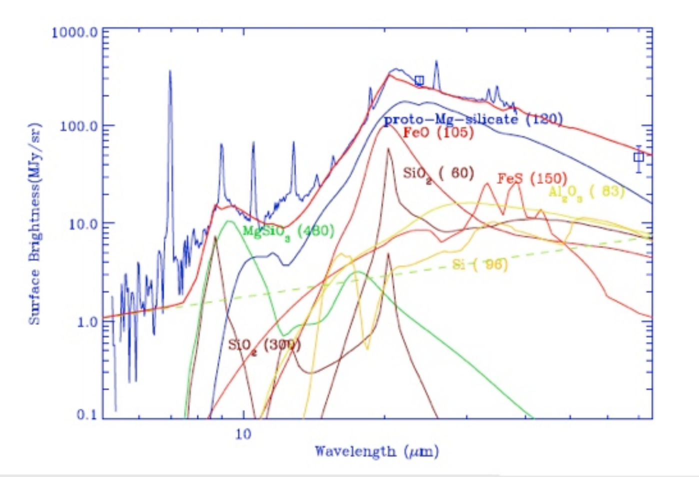
Circumnuclear ring

(Chan et al. 1997)



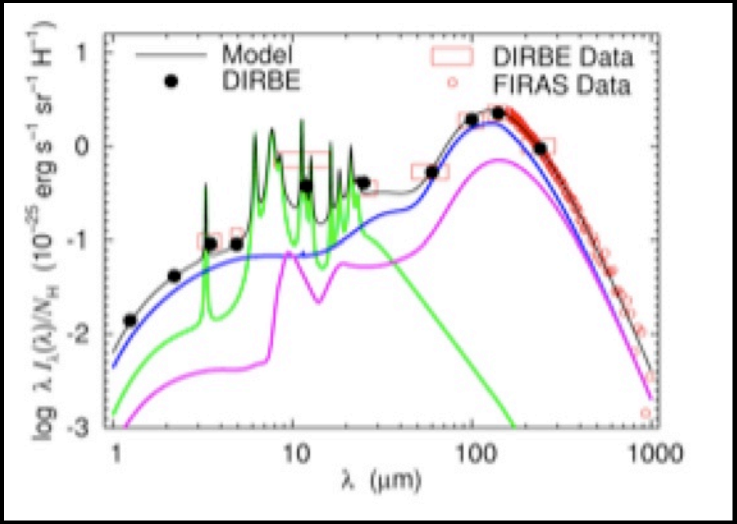
MgS

Cas A (Rho et al. 2007)



Diffuse ISM (Zubko et al. 2004)

silicates, graphite, PAHs

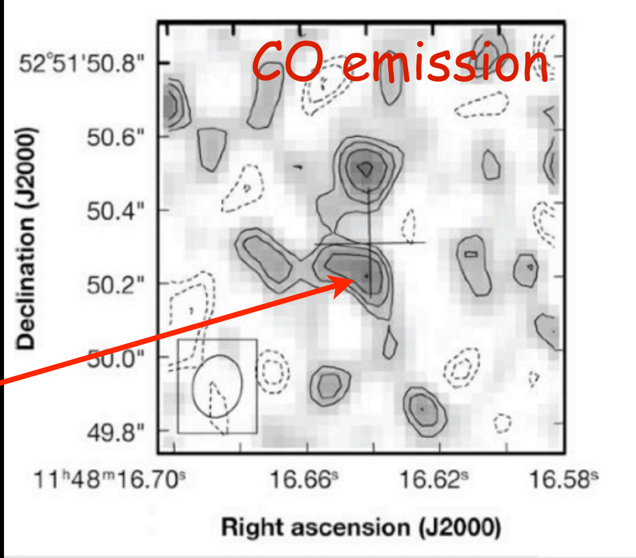


SN1987A and

- Shock-ER interaction
- Reverse shock-ejecta interaction

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}

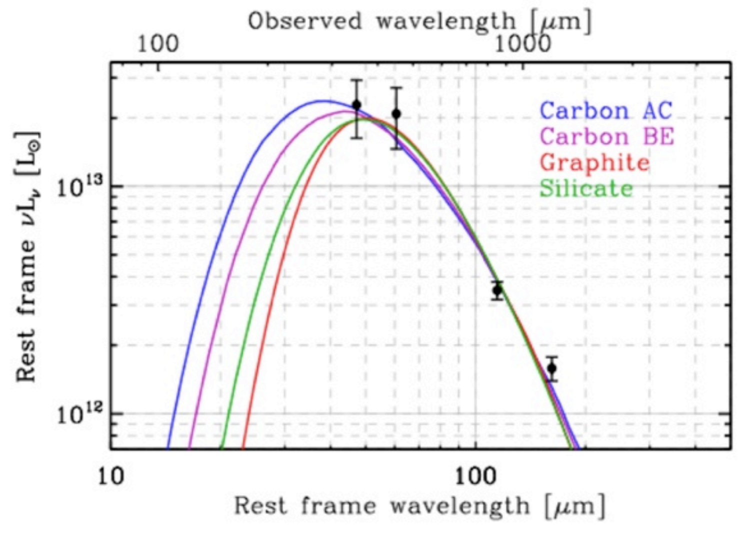
M_{dust} ≈ $(0.9 - 4)\times10^{8}$ M_{sun}

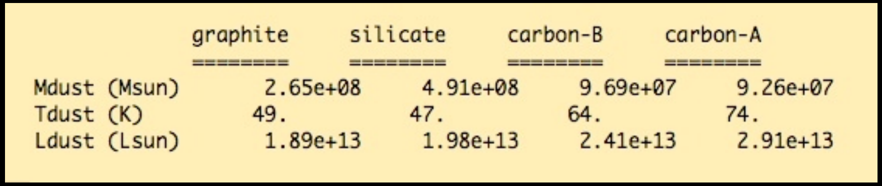
M_{gas} ≈ 2×10^{10} M_{sun}

M_{dyn} ≈ 5×10^{10} M_{sun}

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

SFR ≈ 4000 M_{sun}/yr

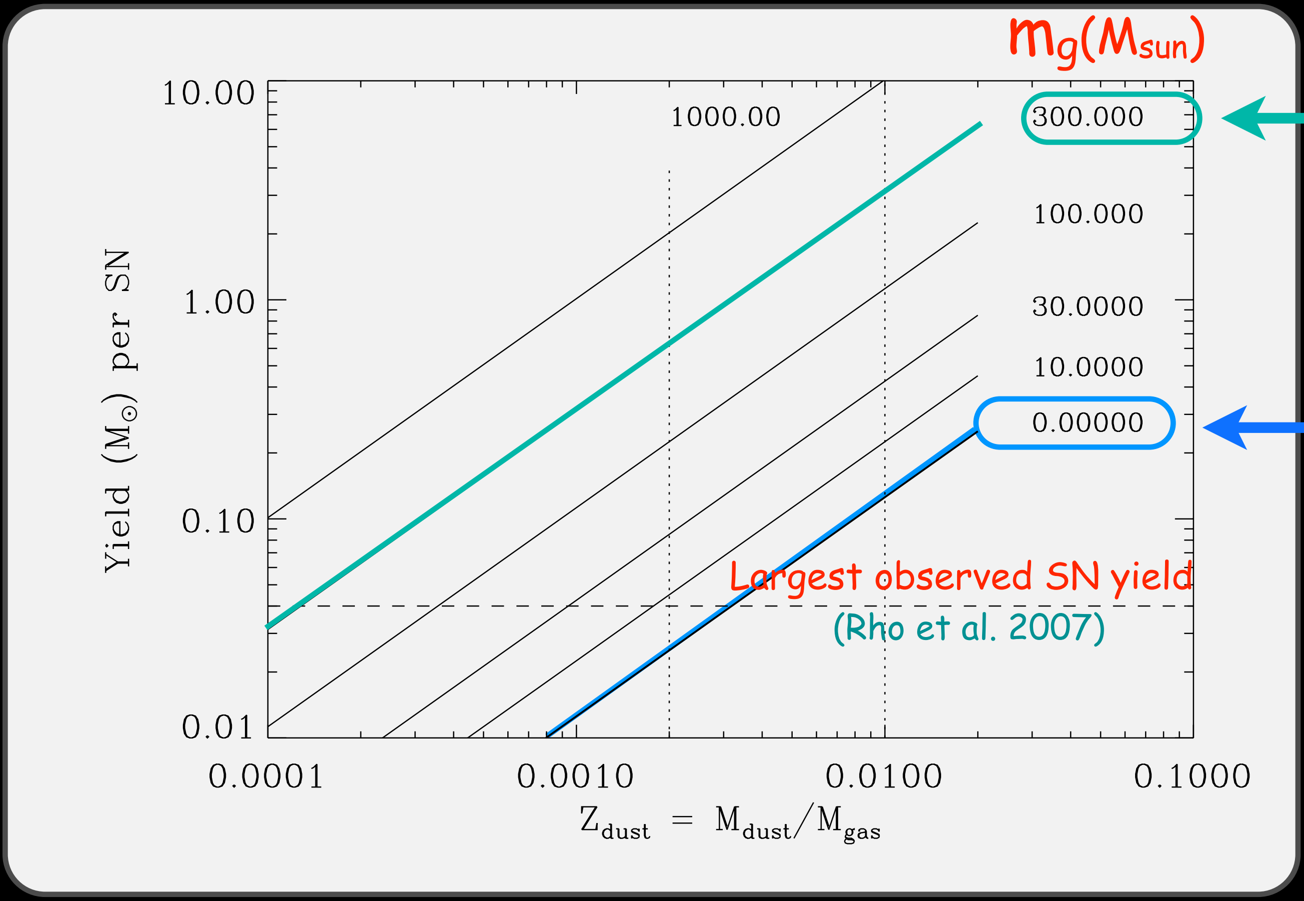




```
                  graphite      silicate      carbon-B      carbon-A
                  ========      ========      ========      ========
Mdust (Msun)        2.65e+08      4.91e+08      9.69e+07      9.26e+07
Tdust (K)         49.           47.           64.           74.
Ldust (Lsun)        1.89e+13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

SN Yield Required to Produce an Observed Z_d

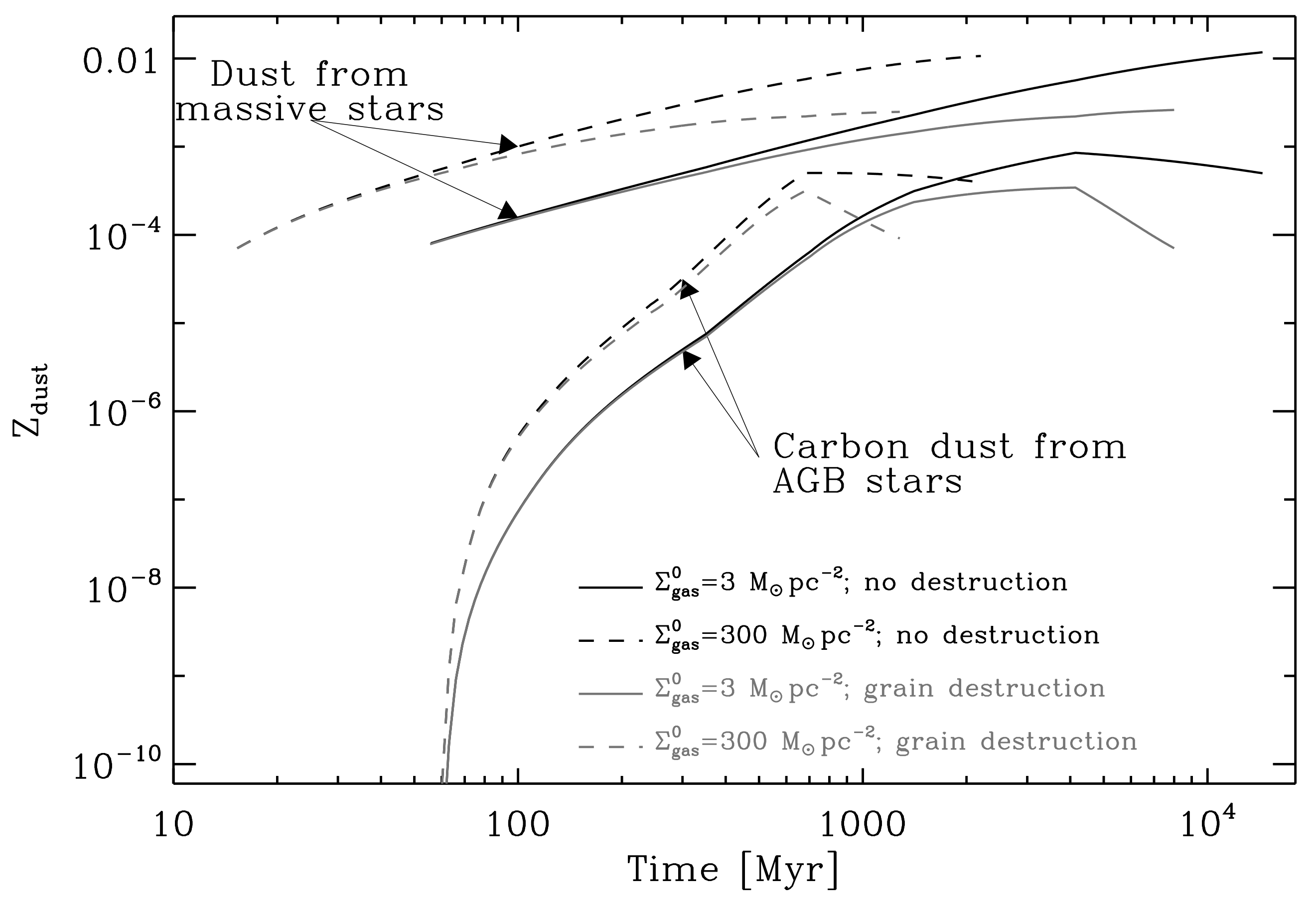
$$Y_d = Z_d(t)\left[\frac{m_g + \langle m_{SN}\rangle R}{1-\mu^{\nu}}\right]$$



Milky Way value

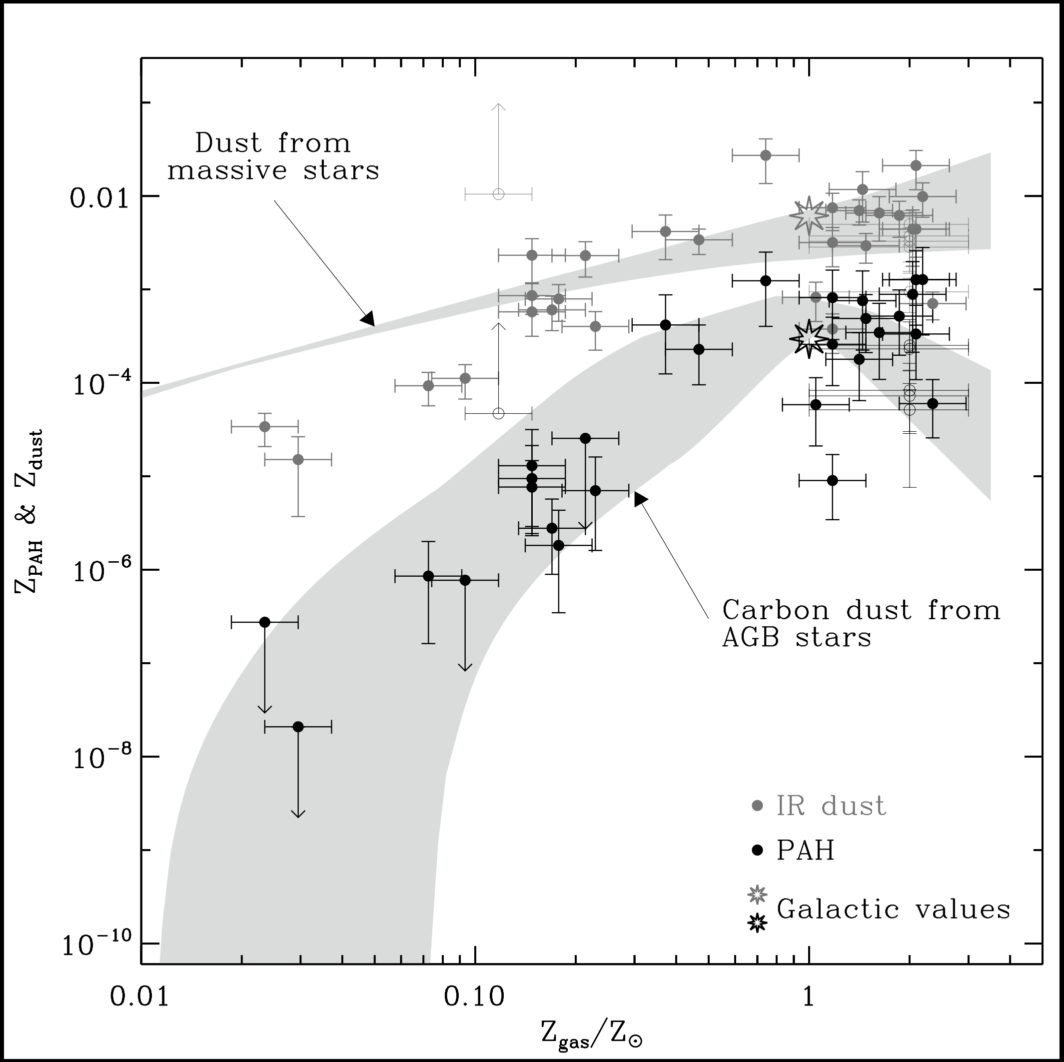
No grain destruction

The evolution of dust



The delayed injection of PAHs in galaxies

(Galliano, Dwek, & Chanial 2007, APJ, in press)



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

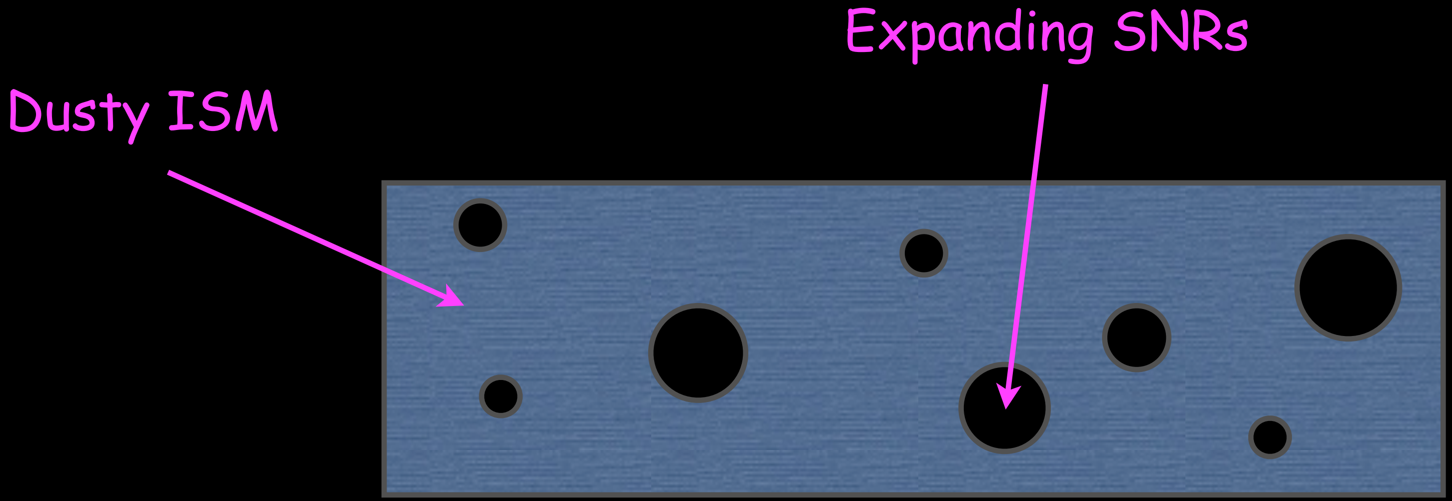
No problem:

- Dust could only have formed in core collapse SN
- SFR ≈ 4000 M_{sun}/yr → SN rate ≈ 30/yr (Salpeter IMF)In 400 Myr there were 10^{10} SNe To produce 2×10^8 Msun of dust, each SN must make only 0.02 M_{sun} of dust

But there is a problem:

- SN are also very efficient destroyers of interstellar dust If the lifetime of the dust is ≈ 4 Myr, then each SN must make ≈ 2 M_{sun} of dust

The lifetime of interstellar dust



Dust lifetime

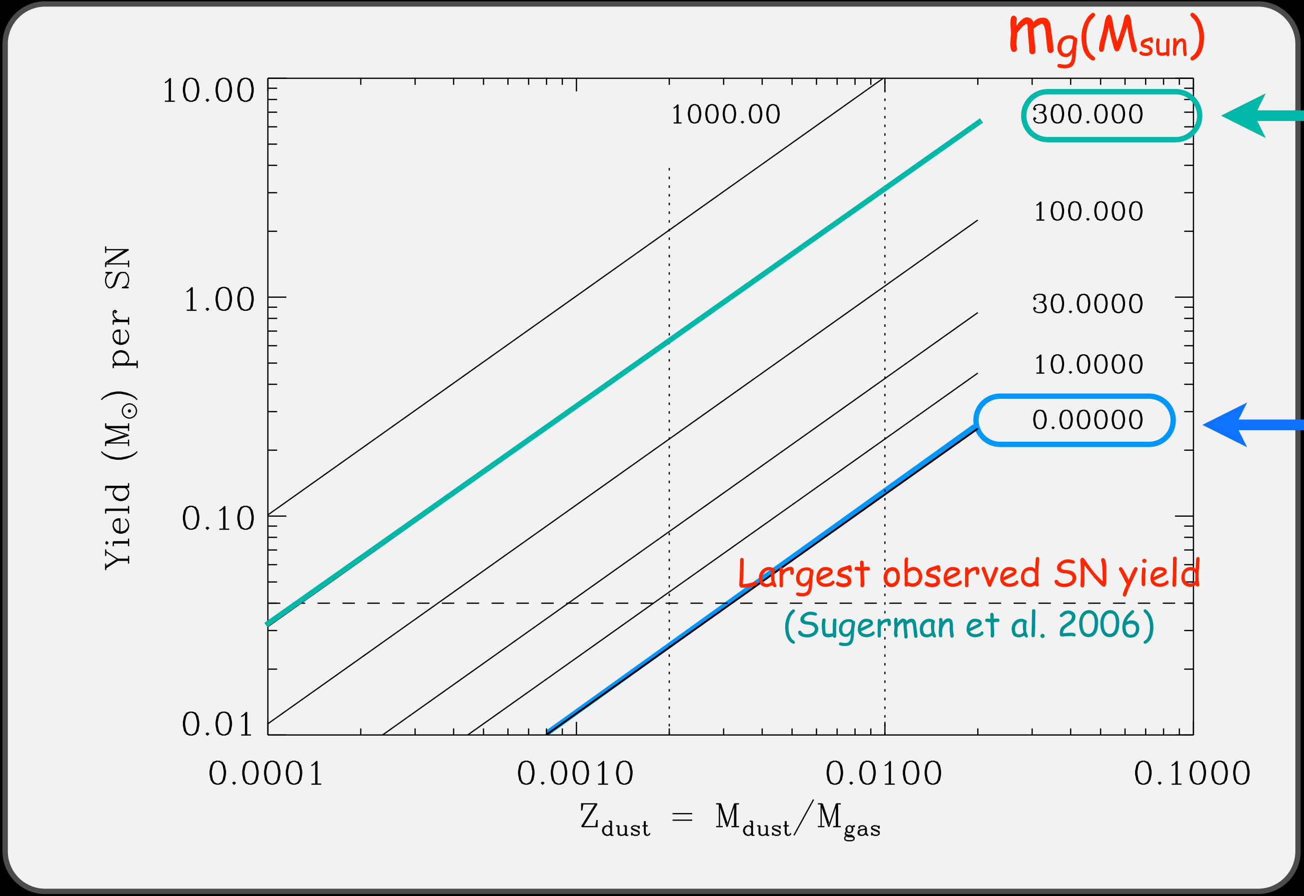
$$\tau_d(t) \equiv \frac{M_d}{m_d\, R_{SN}} = \frac{M_{gas}}{m_g\, R_{SN}}$$

m_g

The effective ISM mass that is cleared of dust by a single SNR

SN Yield Required to Produce an Observed Z_d

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



Largest observed SN yield
(Sugerman et al. 2006)

Milky Way value

No grain destruction