Lords of the IR Ring

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John Danziger (not shown)

SN1987A: Twenty five years of Pummeling the Ring

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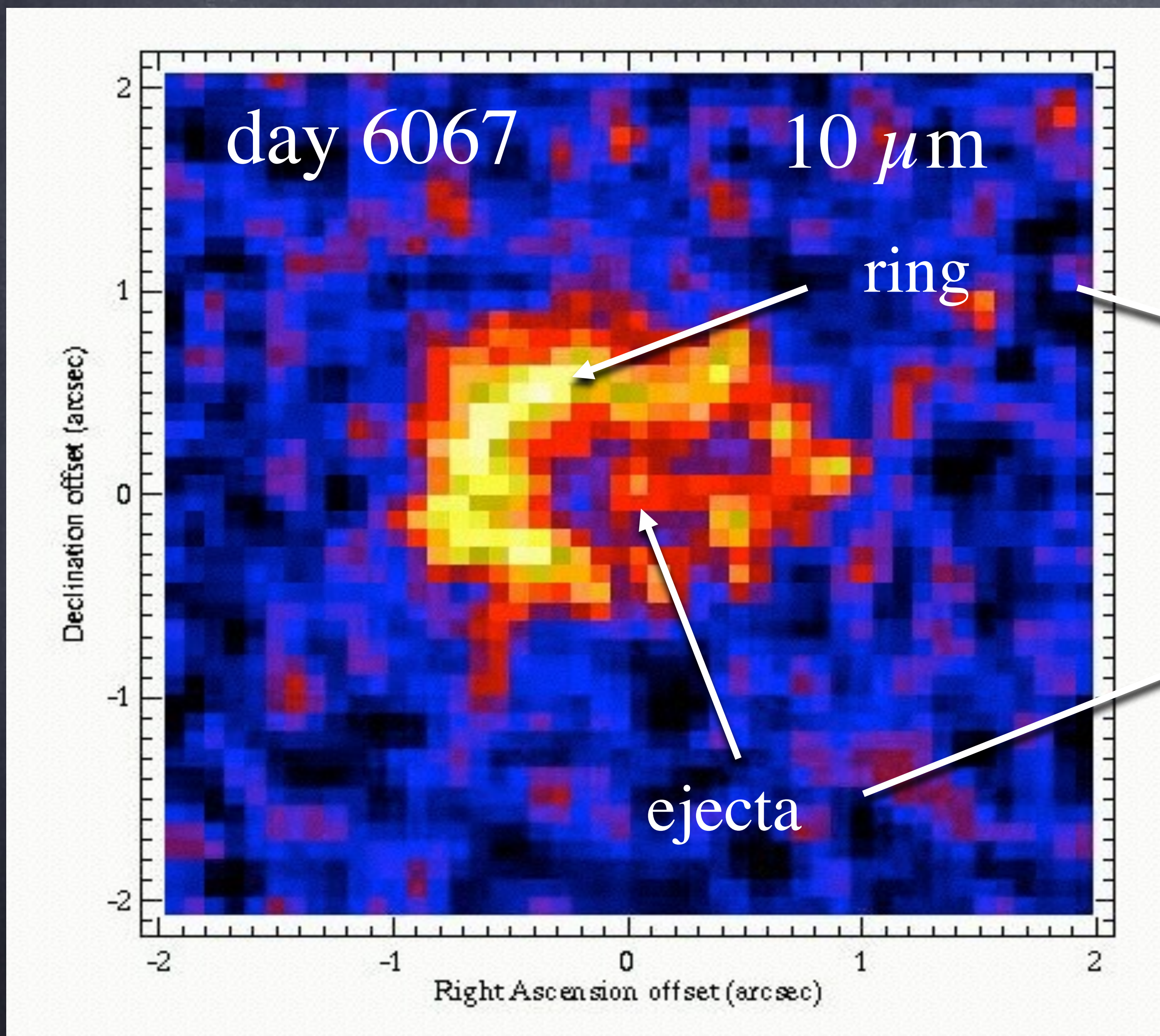
The circumstellar ring around SN1987A: A perfect environment for studying physical processes in a dusty plasma

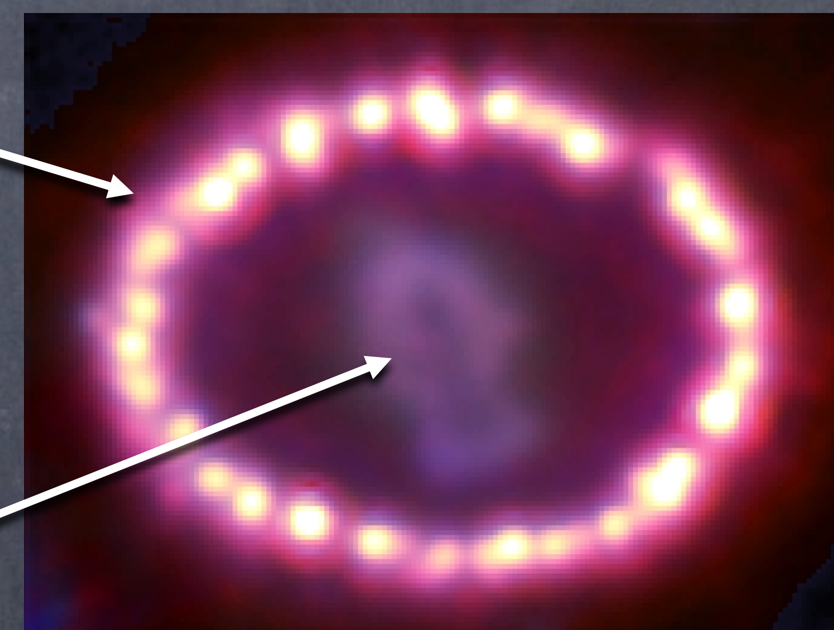
- Collisional heating of the dust (electron collision)
- IR cooling of the X-ray emitting gas, IRX
- Grain destruction by sputtering (heavy ions)
- Derivation of physical properties of the plasma (density, temperature) from IR emission

First detection of the ring at IR wavelengths

T-ReCS instrument on the Gemini South 8m telescope
(Bouchet et al. 2004)

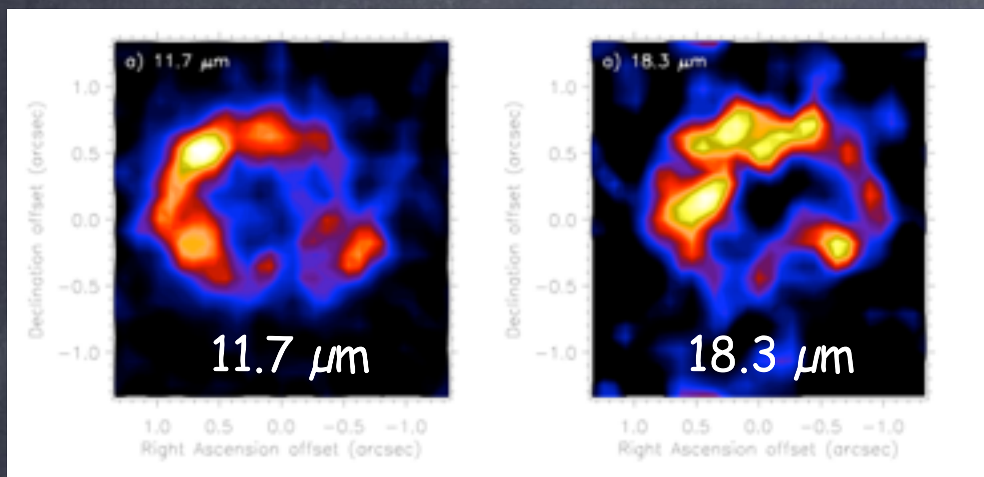


Hubble Space Telescope



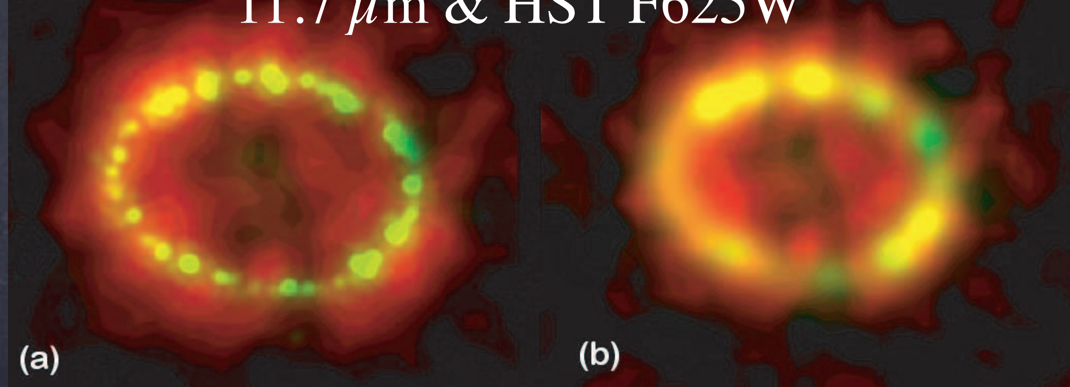
Shock-heated circumstellar dust

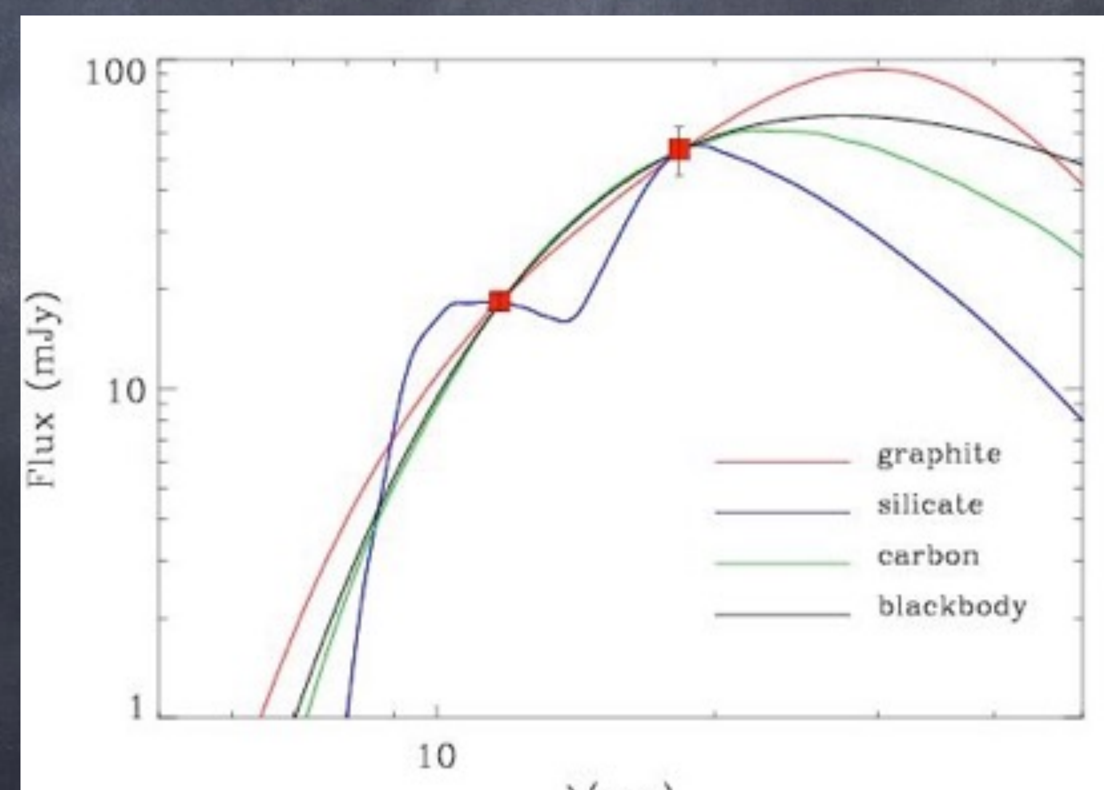
T-ReCS instrument on the Gemini South 8m telescope (Bouchet et al. 2004, 2006)



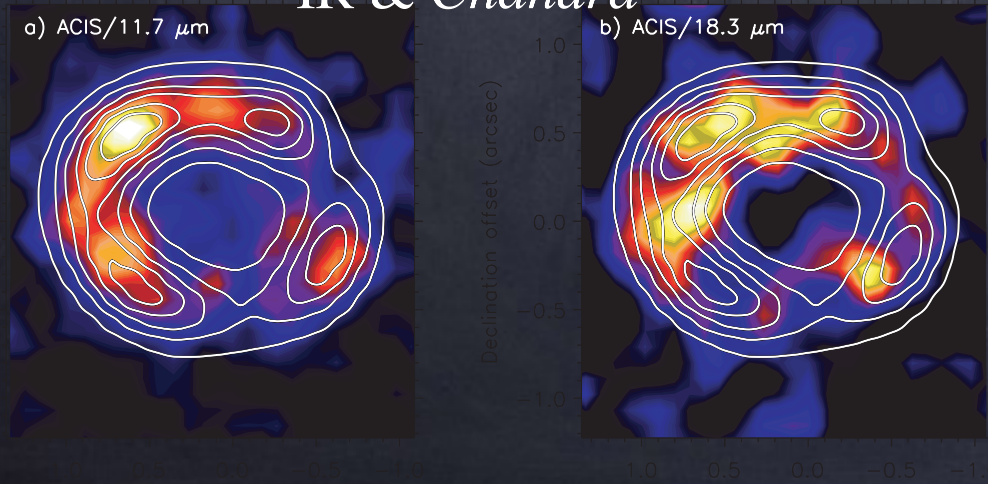
T-ReCS observations resolved the ring, but with only two wavelengths, it could not constraints the dust composition

11.7 μm & HST F625W





IR & *Chandra*



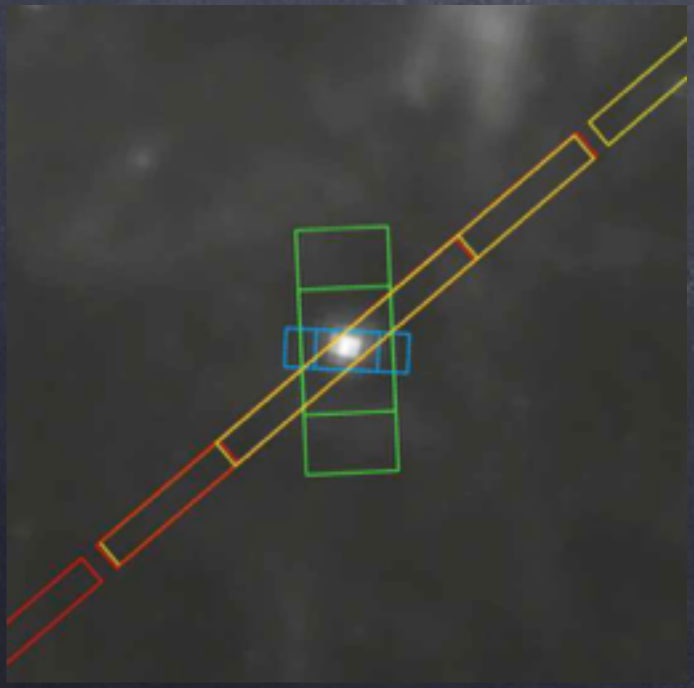
IR emission is generated by shock-heated circumstellar dust

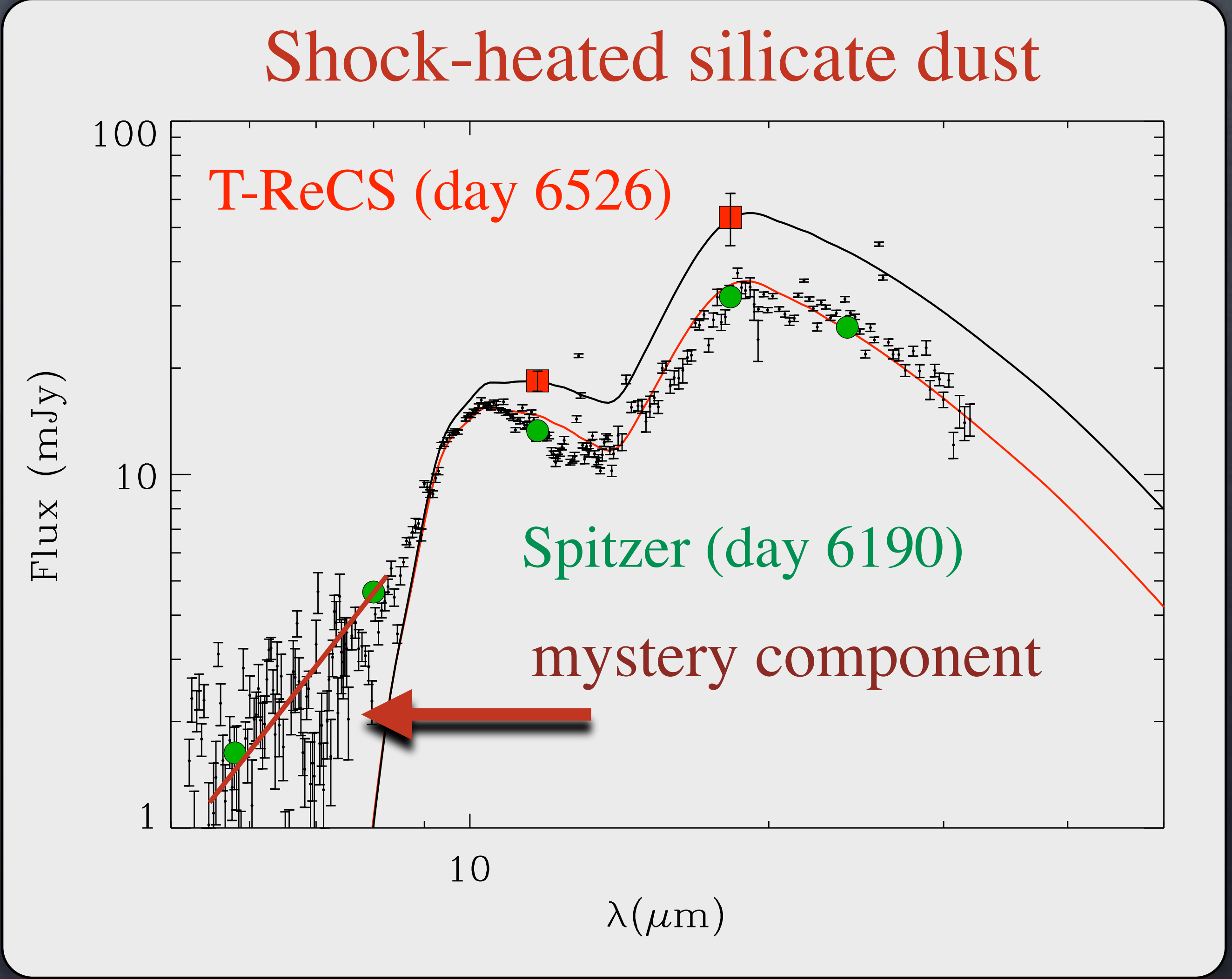
Spitzer – MIPS 24 μm (day 6184)
IRAC 3.6–8 μm (day 6130)
IRS 12–37 μm (day 6190)

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

Plasma: $T_e \approx 4 \times 10^6\ K$
$n_e \approx (0.3 - 1) \times 10^4\ \mathrm{cm}^{-3}$

Spitzer observations
day 6190
(Gehrz, Polomski)





Collisional Heating of Dust

$$\mathcal{H} = \pi a^2 n < v > E_{dep}$$

$$\langle v \rangle \propto T_g^{1/2}$$

electrons stopped

$$E_{dep} \propto T_g$$

$$\mathcal{H} \sim a^2 \, n \, T_g^{3/2}$$

electrons whiz through

$$dE/dx \sim E^{-1/2}$$
$$E_{dep} \sim a T_g^{-1/2}$$

$$\mathcal{H} \sim a^3 n$$

In equilibrium

$$\mathcal{L} = \mathcal{H}$$

$$\mathcal{L} = \pi a^2 \, \sigma T_d^4 \; < Q >$$

dust luminosity is proportional to the dust mass

$$\mathcal{L} \sim a^3 \, T_d^{4+\beta}$$

electrons stopped

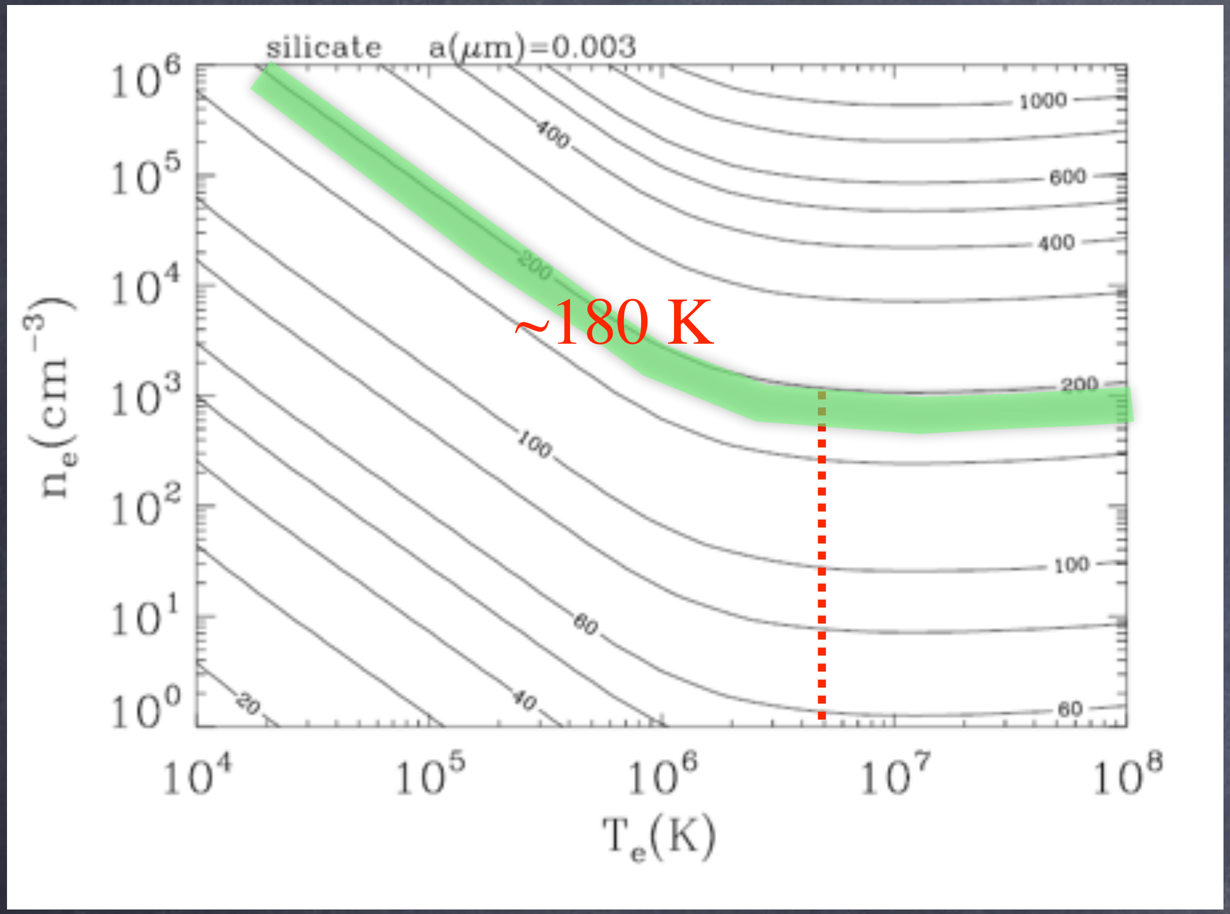
$$T_d \sim \frac{n}{a} \, T_g^{\gamma}$$

dust temperature is determined by gas density

$$T_d \sim n^{1/4+\beta}$$

There is a degeneracy between grain radii & plasma densities required to heat the dust to 180 K with electrons

$$T_{\rm gas} = 5 \times 10^6\,{\rm K}$$

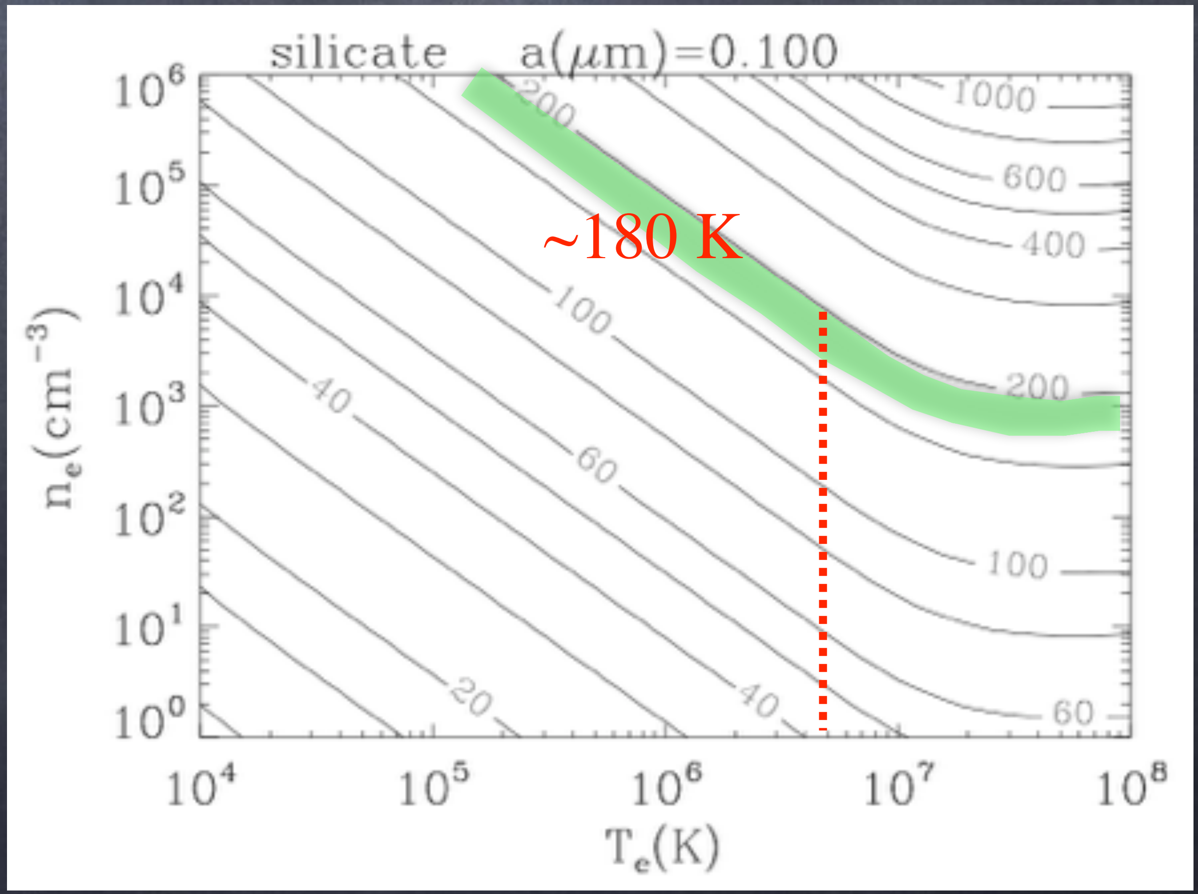


dust grains are transparent to electrons

$n_e \approx 10^3\,{\rm cm}^{-3}$

electrons are stopped in the grains

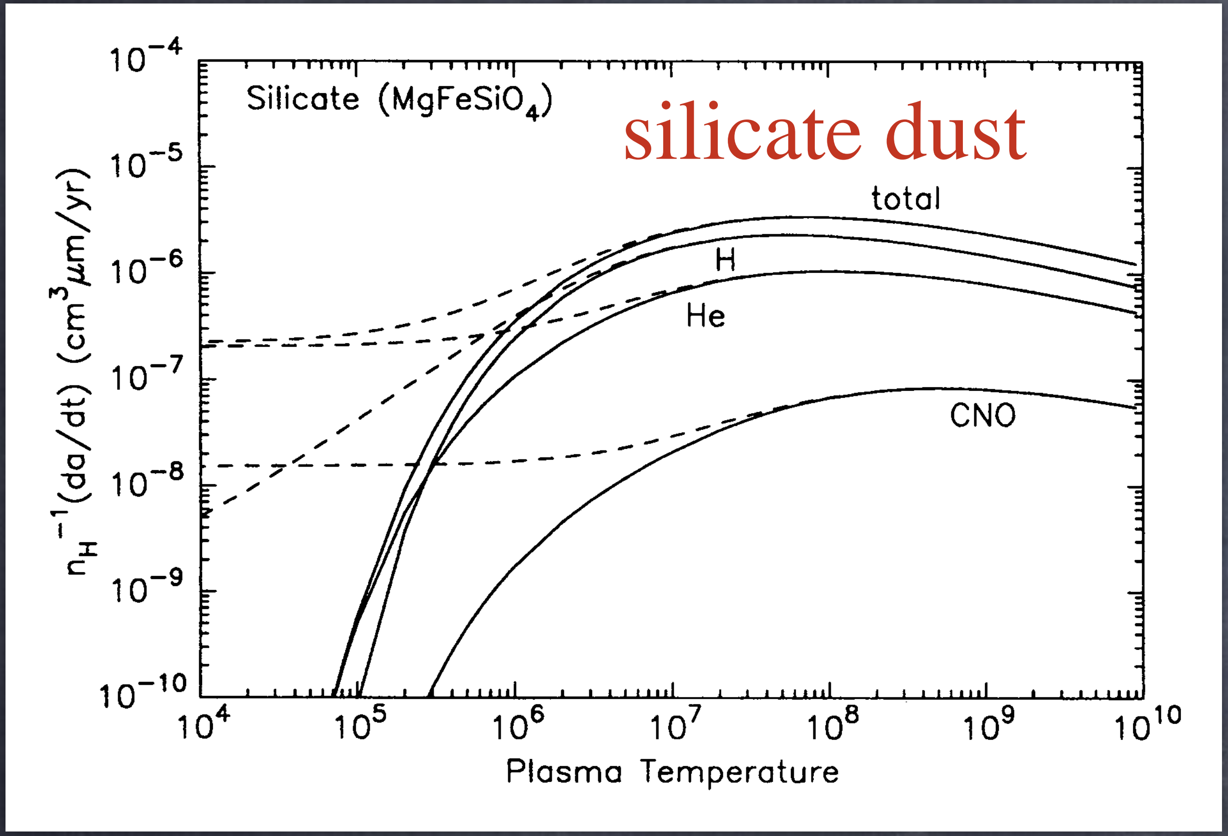
$n_e \approx 10^4\,{\rm cm}^{-3}$

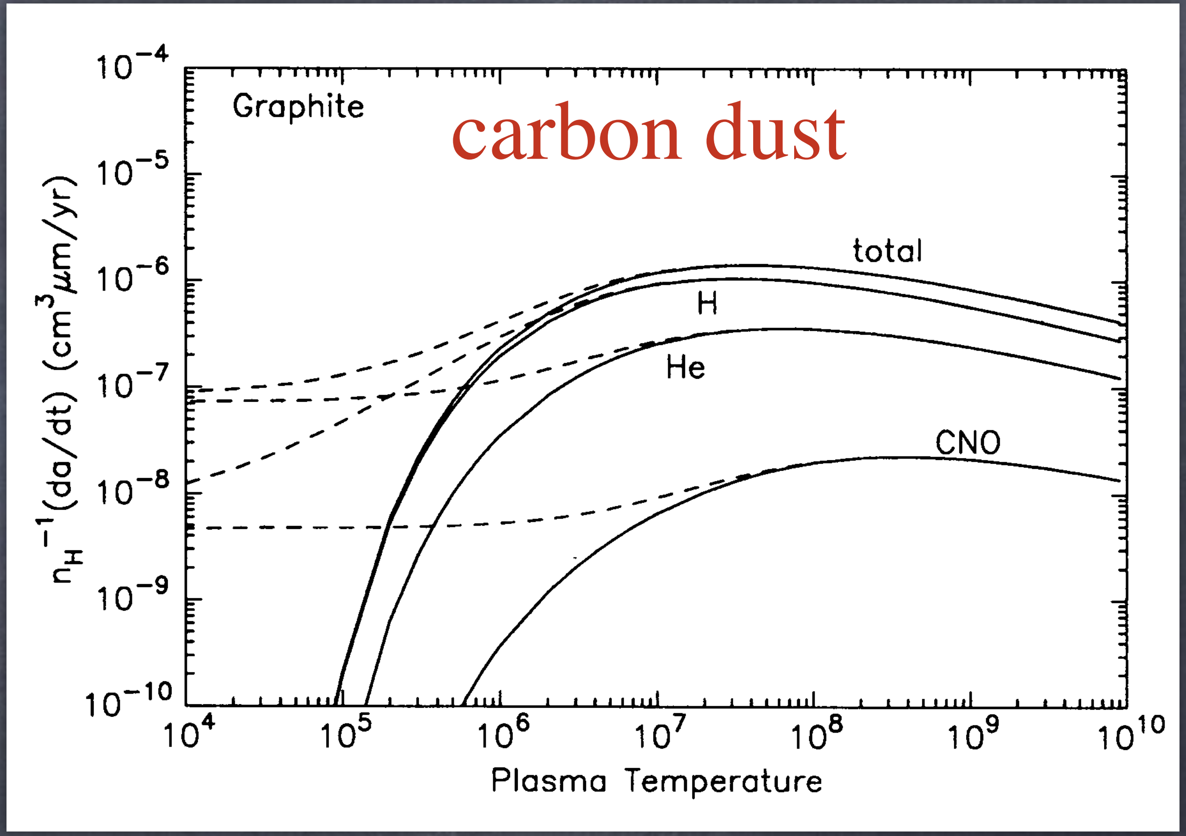


Grain destruction by thermo-kinetic sputtering

$$\tau_{\rm sput} \approx 3 \times 10^5 \, \frac{a(\mu{\rm m})}{n({\rm cm}^{-3})}$$

$$\tau_{\rm sput} \approx 10^6 \, \frac{a(\mu{\rm m})}{n({\rm cm}^{-3})}$$





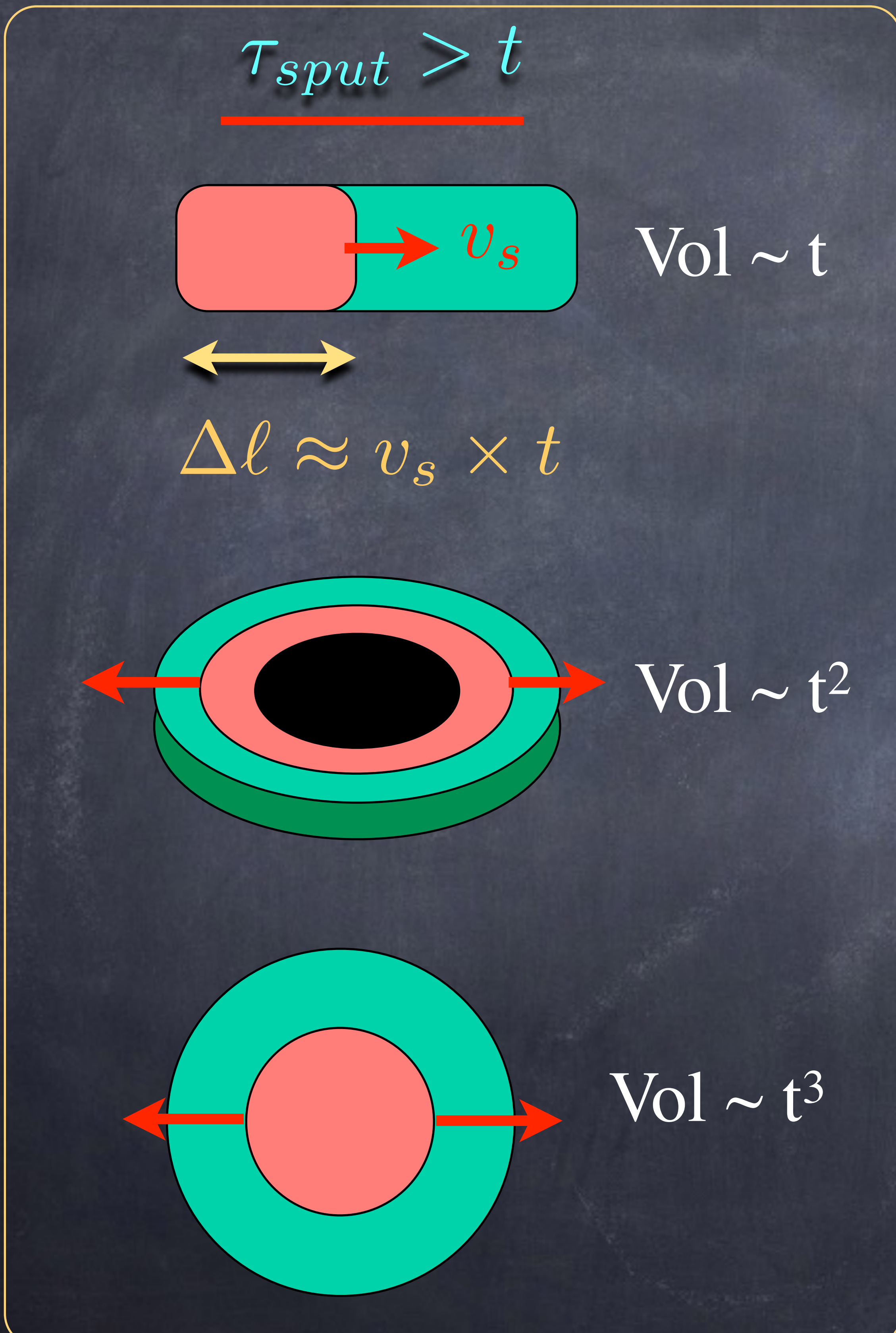
For $n_e \approx 10^4$ cm^{-3} and
$T_{gas} \approx 10^6$ K

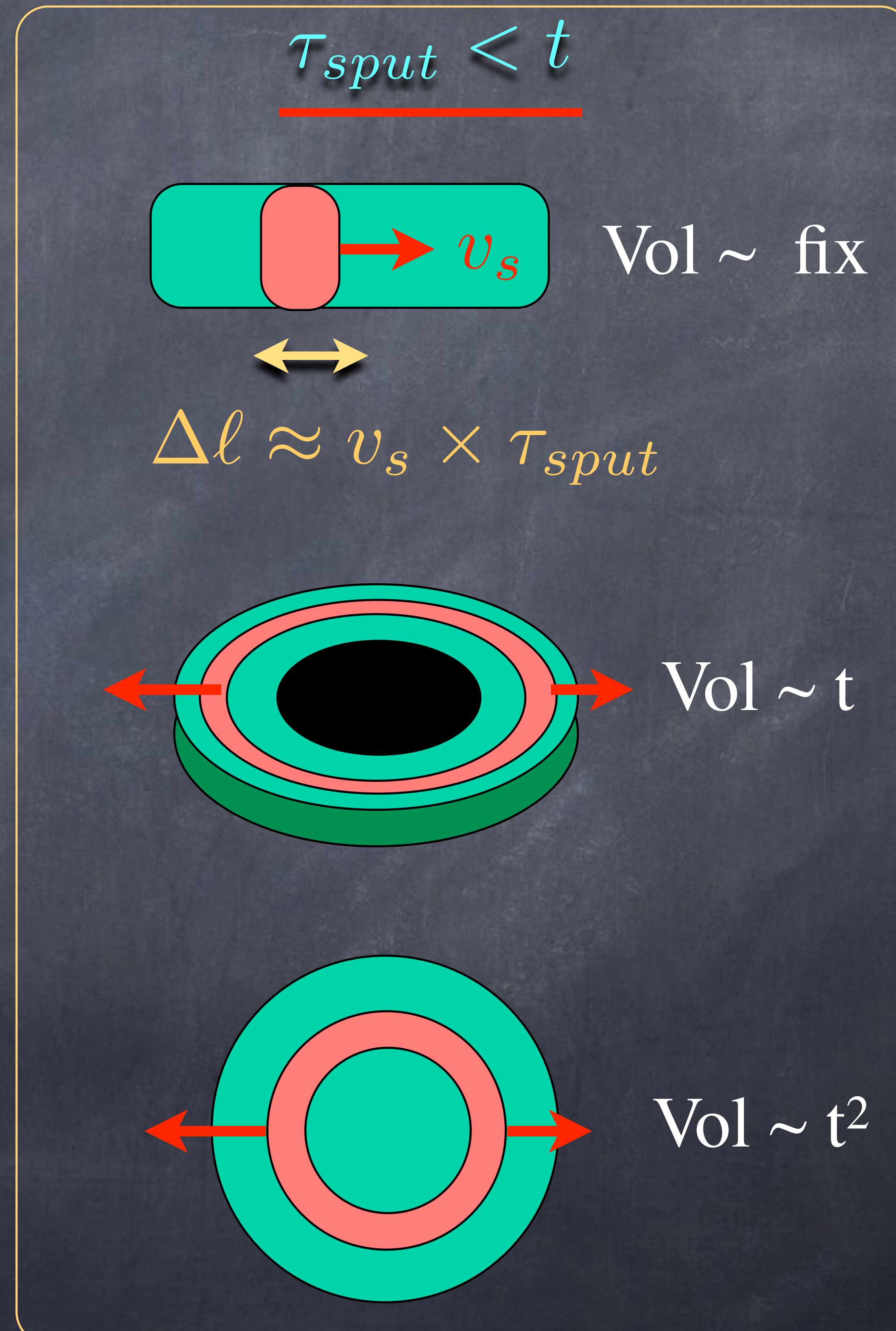
$\tau_{\rm sput} \approx 1 - 15$ yr

Depending on grain size and composition:
dust is destroyed on a dynamical timescale!

The Evolution of the IR Emission since the time since the first shock-ER encounter

More mathematical treatment in Dwek + 2008





What do observations tell us?

Three observing periods

- days 6800 – 7950 : Photometry at 3.6 – 24 μm and 5 – 30 μm spectroscopy
- day ~ 8000: Photometry at 3.6 – 24 μm
- days 8600 – 10,400 : 3.6 and 4.5 μm photometry

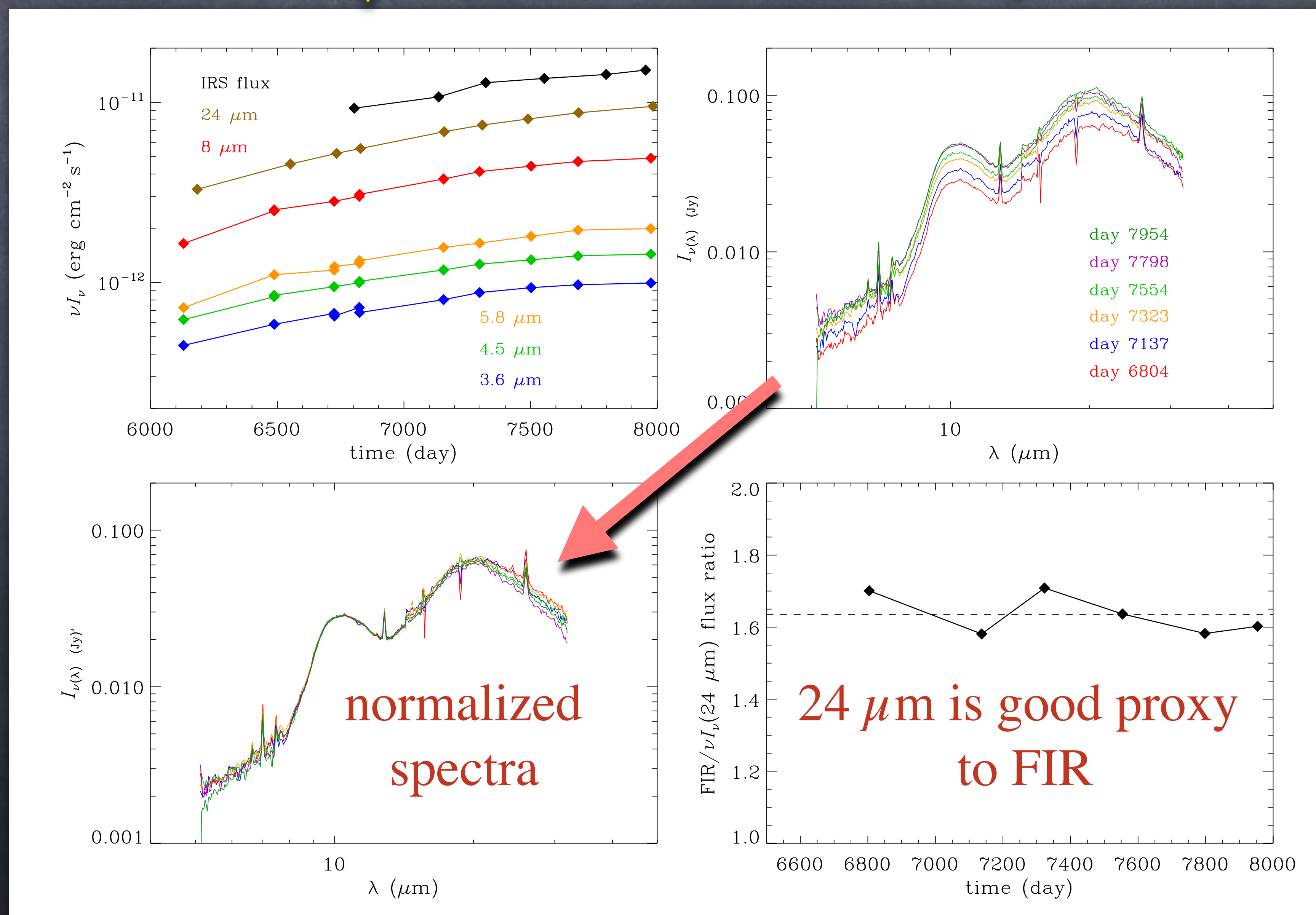
Days 6800 – 8000

fluxes are increasing

spectral shape unchanged

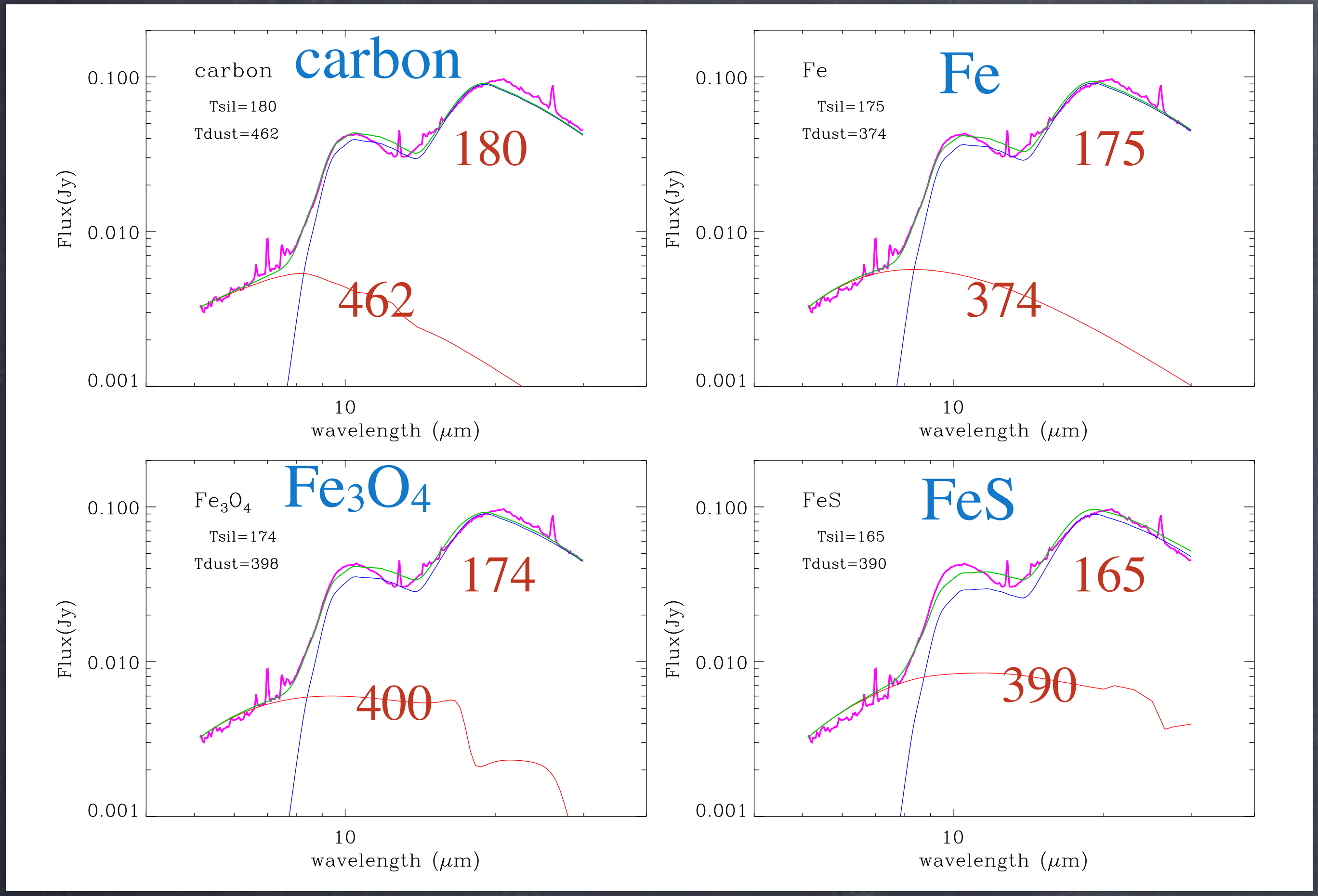
$\tau_{sput} > t$

plasma conditions fixed



The mysterious dust component

Candidates for component X



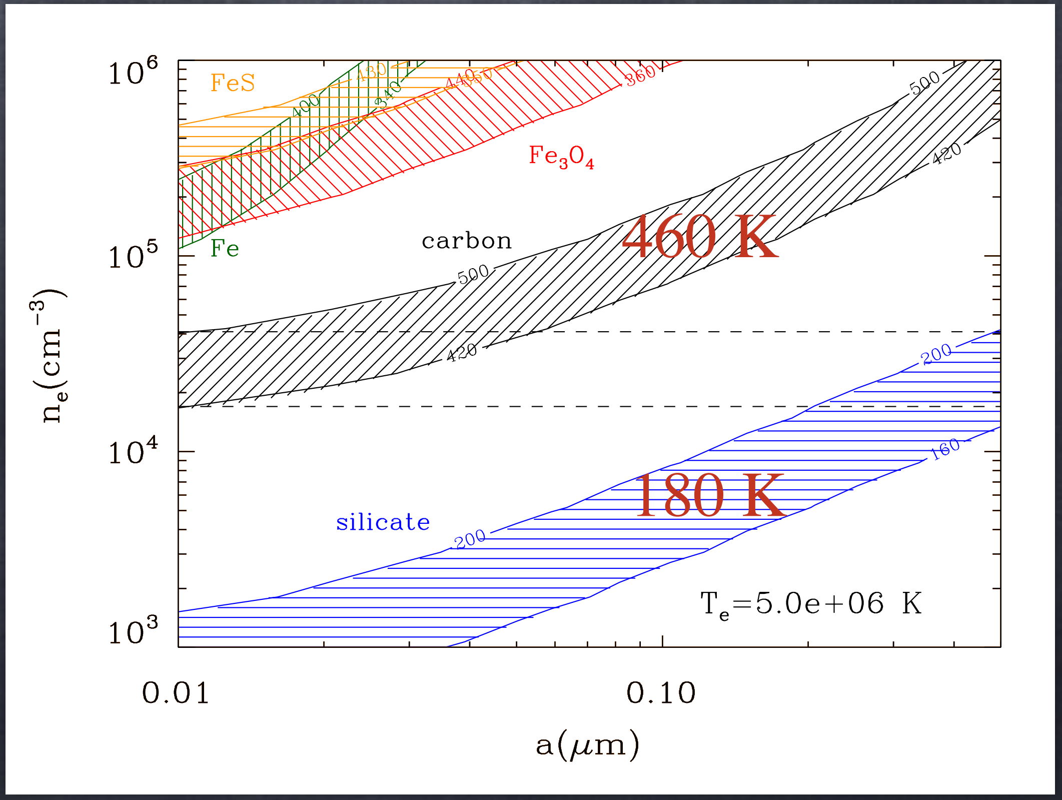
Conditions for both components to reside in the same plasma

carbon 0.01–0.05 μm

$t_{sput} \approx 2$ yr

silicate 0.2–0.5 μm

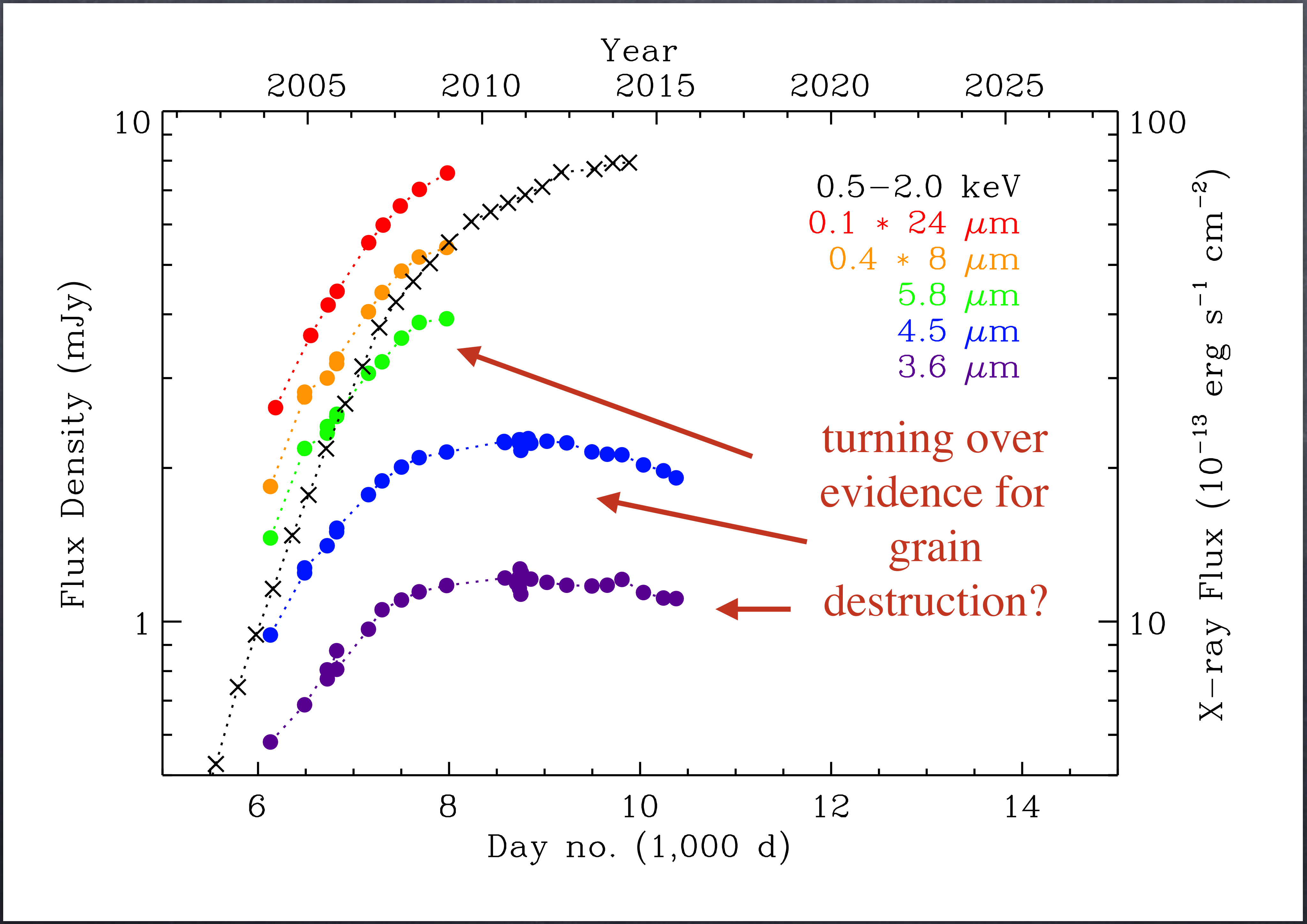
$t_{sput} \approx 7$ yr



Comparison of IR with soft X-ray fluxes

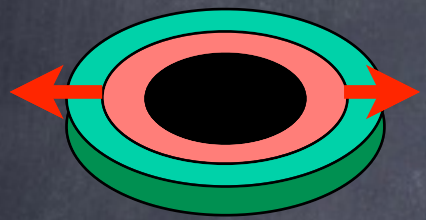
Arendt et al. 2016, AJ, 151, 62

Frank et al. 2016, preprint

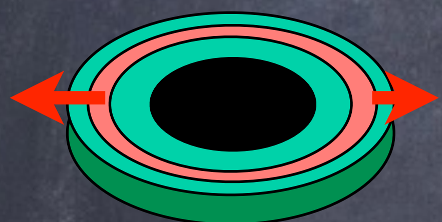


Evolution of IRX $\equiv \dfrac{n_{\rm dust}\,\Lambda_{\rm dust}(T_{\rm gas})}{n_{\rm gas}\,n_H\,\Lambda_{\rm gas}(T_{\rm gas})}$

X-ray cummulative
$F_X \sim t^2$

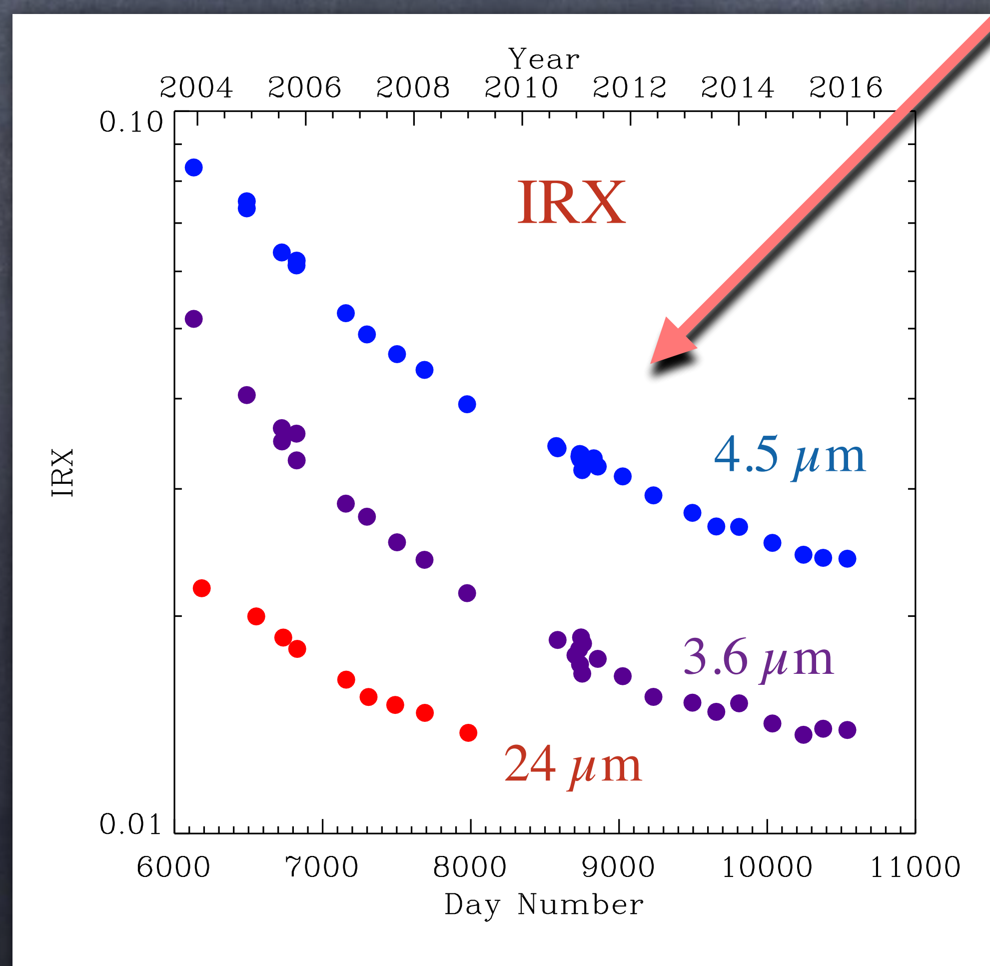


dust is destroyed
$F_{IR} \sim t$



$$\boxed{IRX = \frac{F(IR)}{F(X)} \sim \frac{1}{(t - t_0)}}$$

$t_0 \approx 5500$ days
= epoch of
shock-ring
encounter



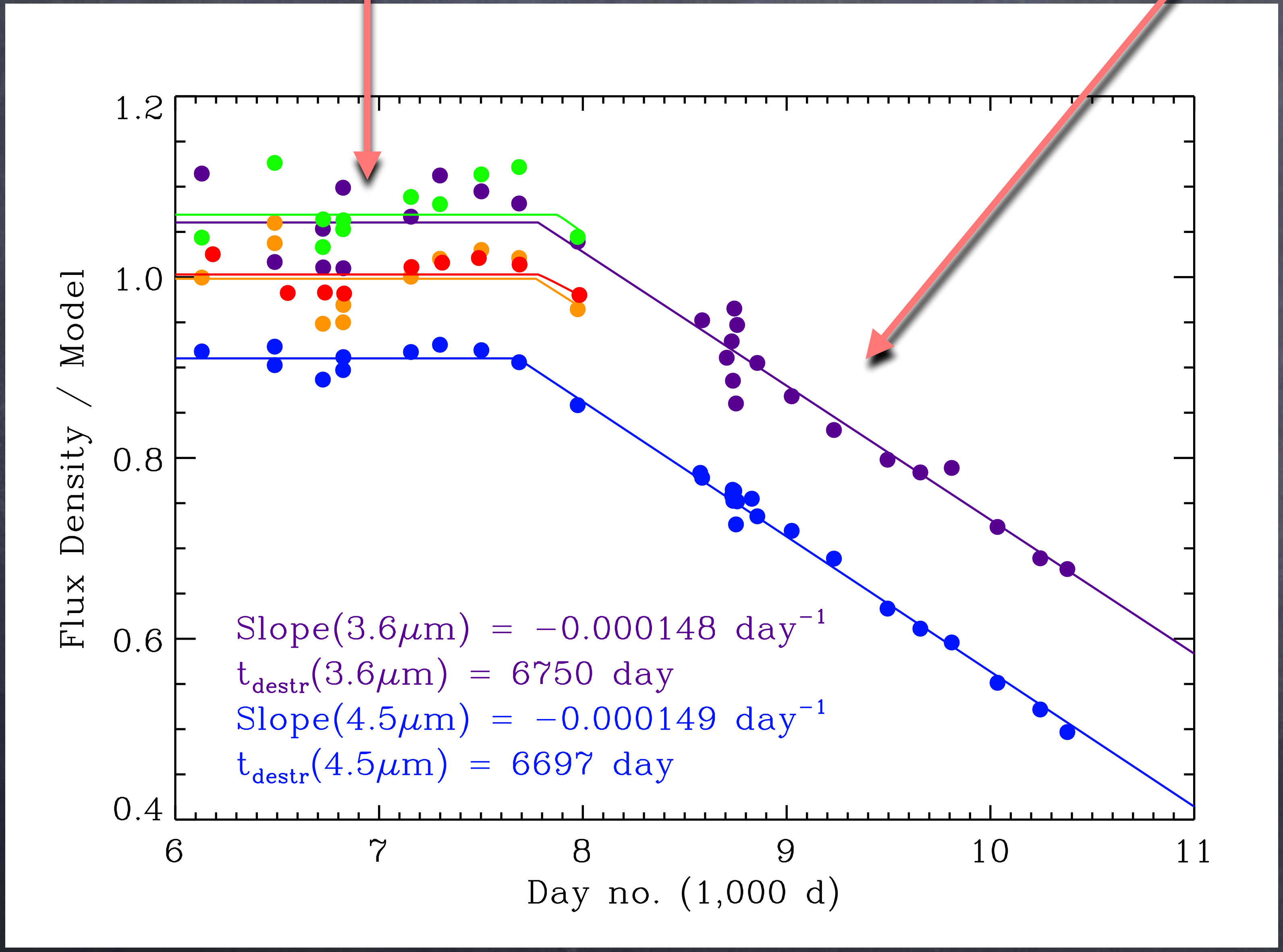
Both, X-ray and IR fluxes
increase with time, but
IR emission rises
less rapidly
than the X-ray
emission

Dust lifetime

Arendt et al. 2016

$$F(\lambda) \sim (t - t_0)$$

$$F(\lambda) \sim \frac{(t - t_0)}{[1 - (t - \tau)]}$$



Grain destruction time

$\tau \approx 6700\, d$

Theoretically it should be

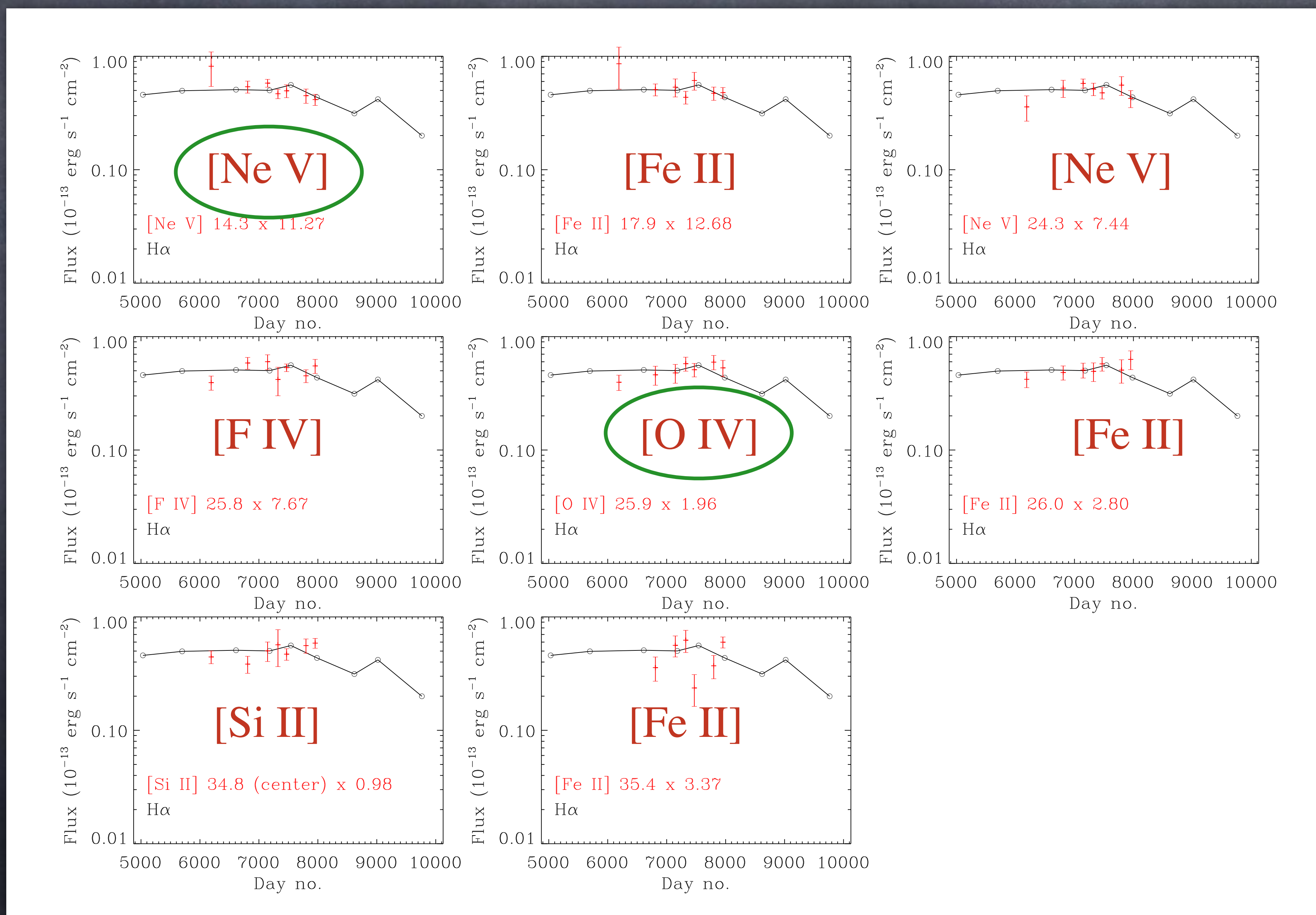
≈ 1200 d

Evolution of the line emission

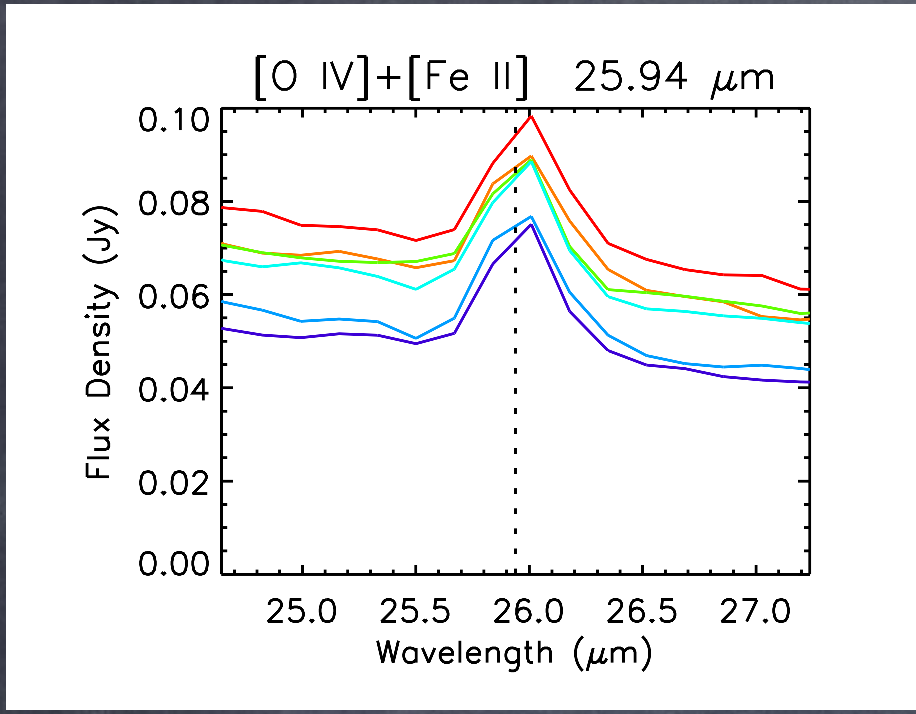
Arendt et al. 2016

see Fransson et al. 2015 for optical lines

Correlated with Ha from unshocked gas

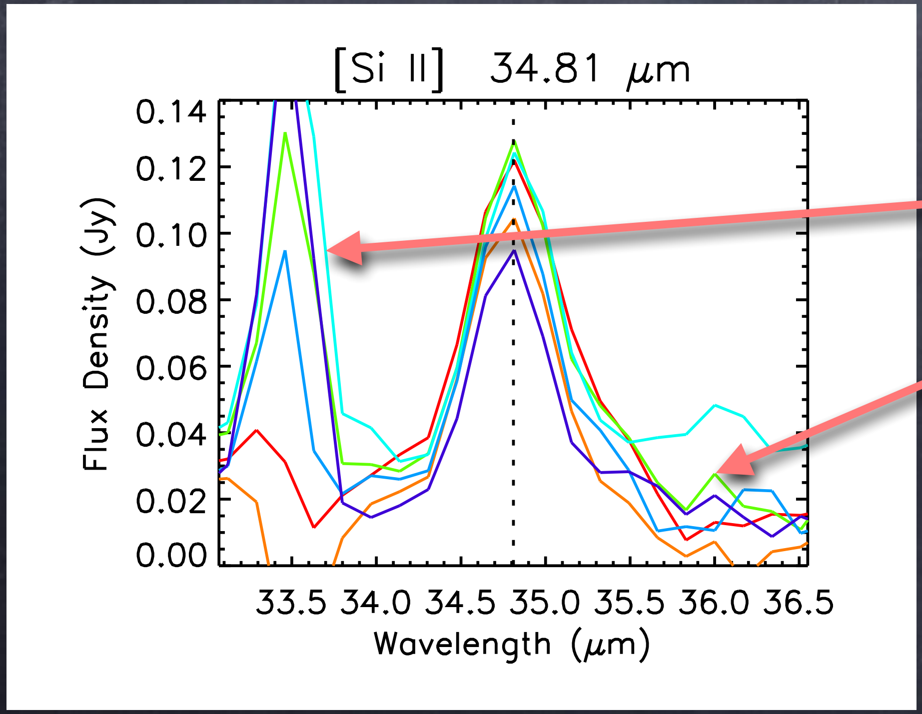


Infrared [Fe II] & [Si II] line emission
(Spitzer IRS)



High velocities
Suggesting shocked material
Sputtered from dust?
Ionization disequilibrium?

$\Delta\lambda = [-15,000, +15,000]$ km s^{-1}



High velocity wings
(not present for Fe)

Line diagnostic of the gas

Ha lines arise from the shocked gas

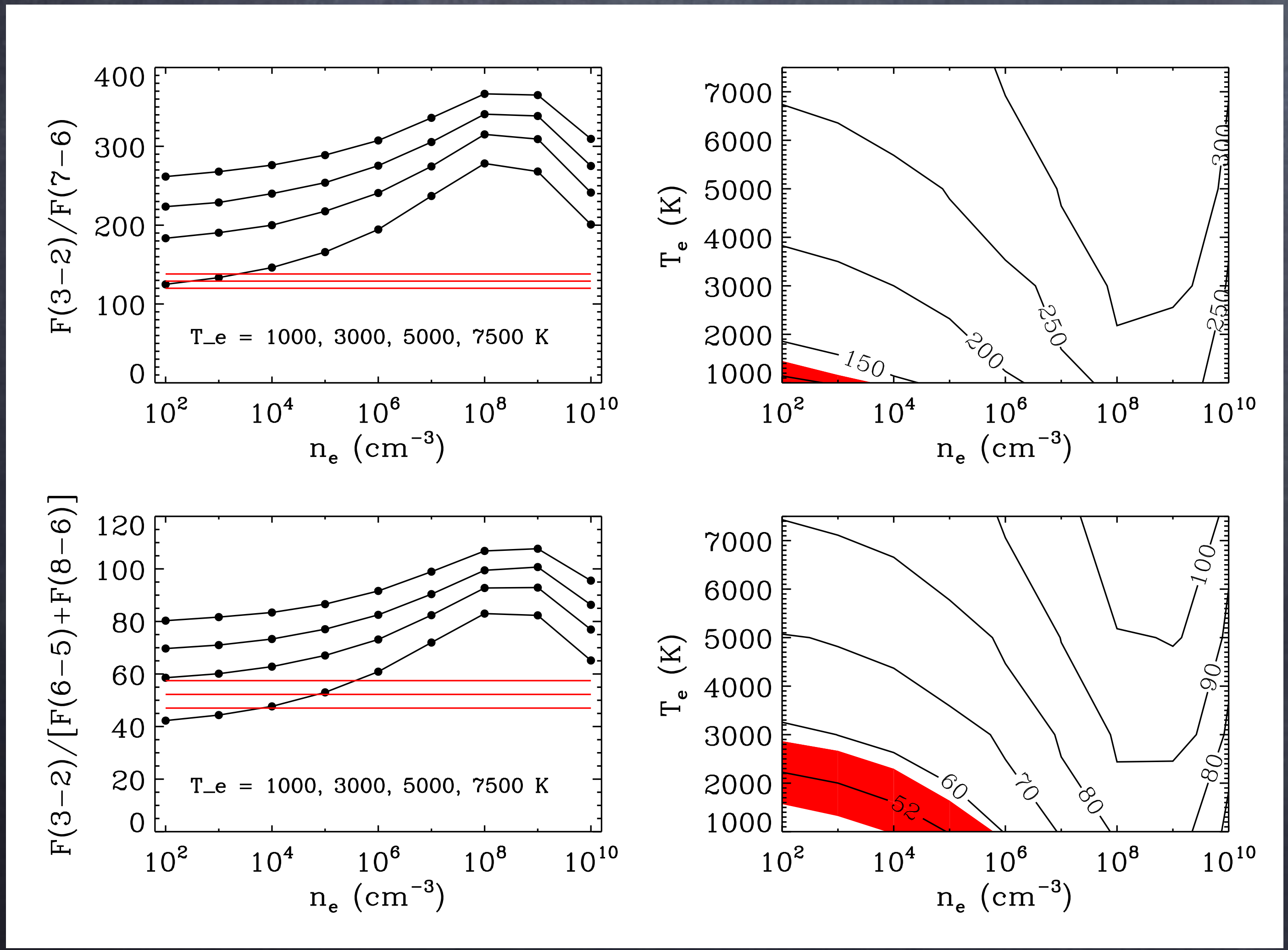
Fransson et al. 2015

$n_e \approx 10^3 - 10^5$ cm^{-3}

$T_{gas} \approx 1000 - 3000$ K

HI (7-6) @ 12.37 μm

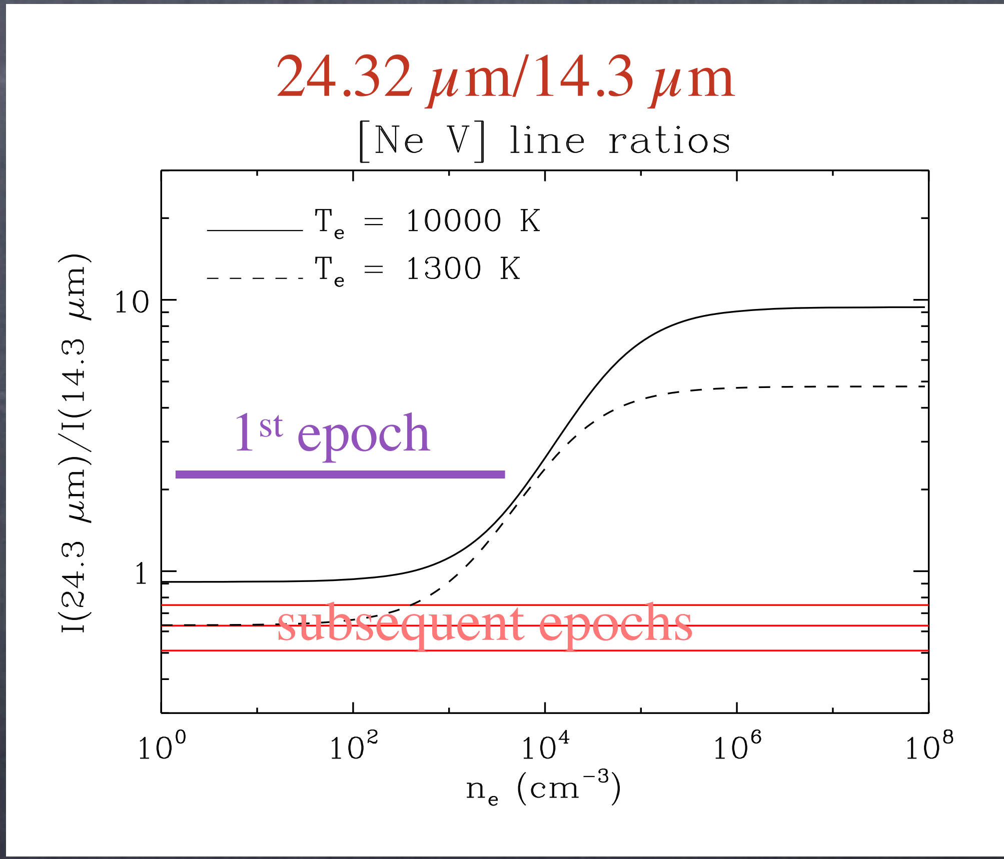
Ha (3-2) @ 0.656 μm

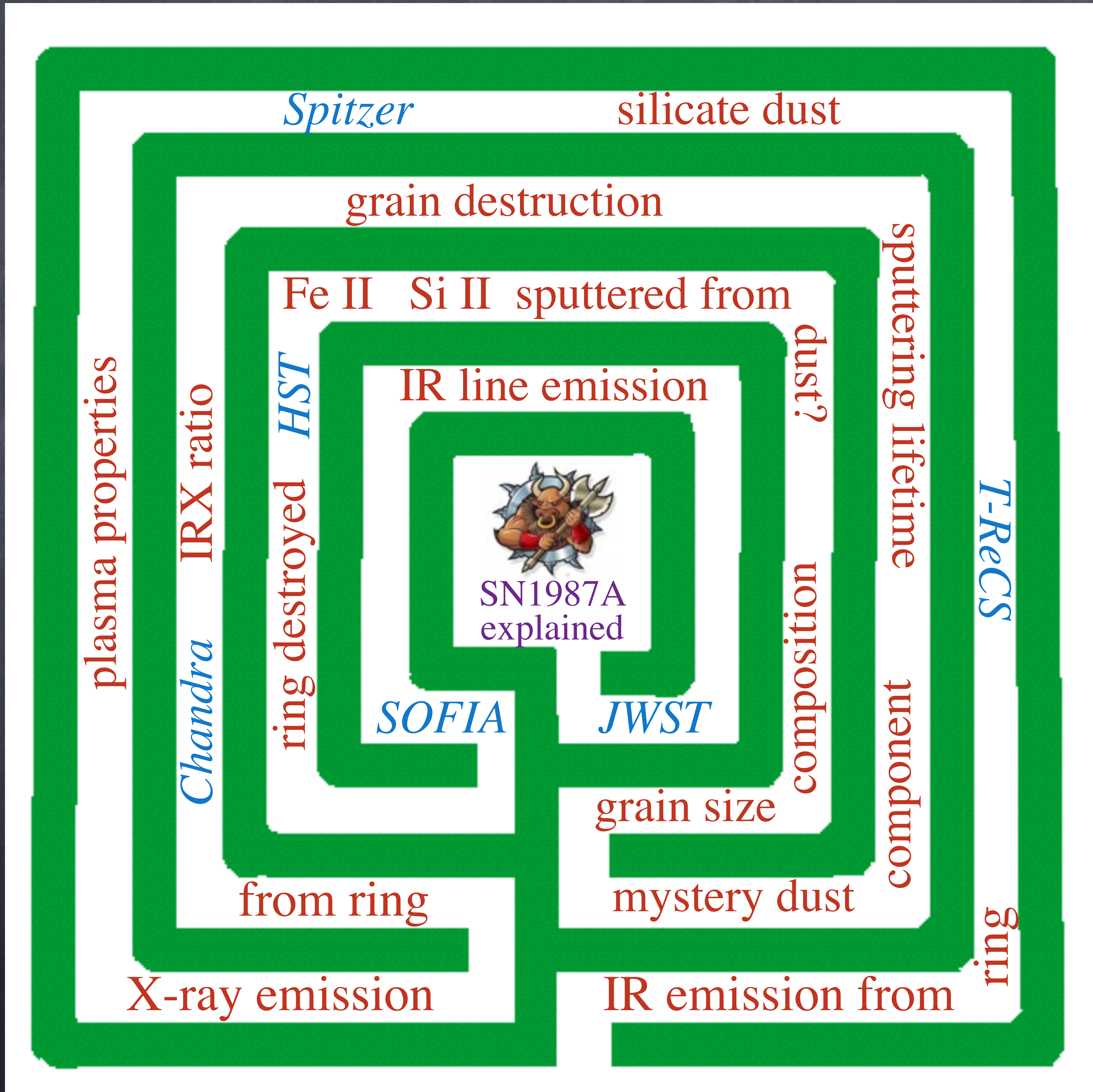


$n_e < 10^3$ cm^{-3}

$T_{gas} \lesssim 2500$ K

Low compared to e.g. Pun et al. 2002




Spitzer
silicate dust
grain destruction
Fe II
Si II
sputtered from
dust?
sputtering lifetime
IR line emission
HST
IRX ratio
plasma properties
ring destroyed
Chandra
T-ReCS
SN1987A
explained
SOFIA
JWST
composition
grain size
component
mystery dust
from ring
X-ray emission
IR emission from
ring