Interstellar dust -- near & far

T. Onaka
(Univ. of Tokyo)

Unsettled problems for interstellar dust

What kind of dust grains are present in the universe?
silicates (oxides) and carbonaceous, or anything else?
← elemental abundance from interstellar depletion:
reference abundance & depletion variation
Where is O (and Fe)?

Where is interstellar dust formed and destroyed?
Unbalance between stellar supply and destruction rates
Role of supernovae?
Evidence for dust formation & destruction in SNe & SNRs
Dust budget balance on a galactic scale (SMC & LMC)

Interstellar depletion

$$D(X) = \log[N(X)/N(H)] - \log[X/H]_{\rm ISM}$$

N(X): element X gas abundance
[X/H]: intrinsic ISM elemental abundance*

* solar abundance is the most accurately measured,
but old (4.56 Gyr) and may not represent present-day abundance
It might be more metal-rich than the ISM

HII region abundance should represent the ISM abundance,
but abundance determination is difficult and has a large uncertainty

B star abundance is relatively young (~10^7 yr) and the abundance analysis should be easier than HII regions,
but it shows so far a large scatter

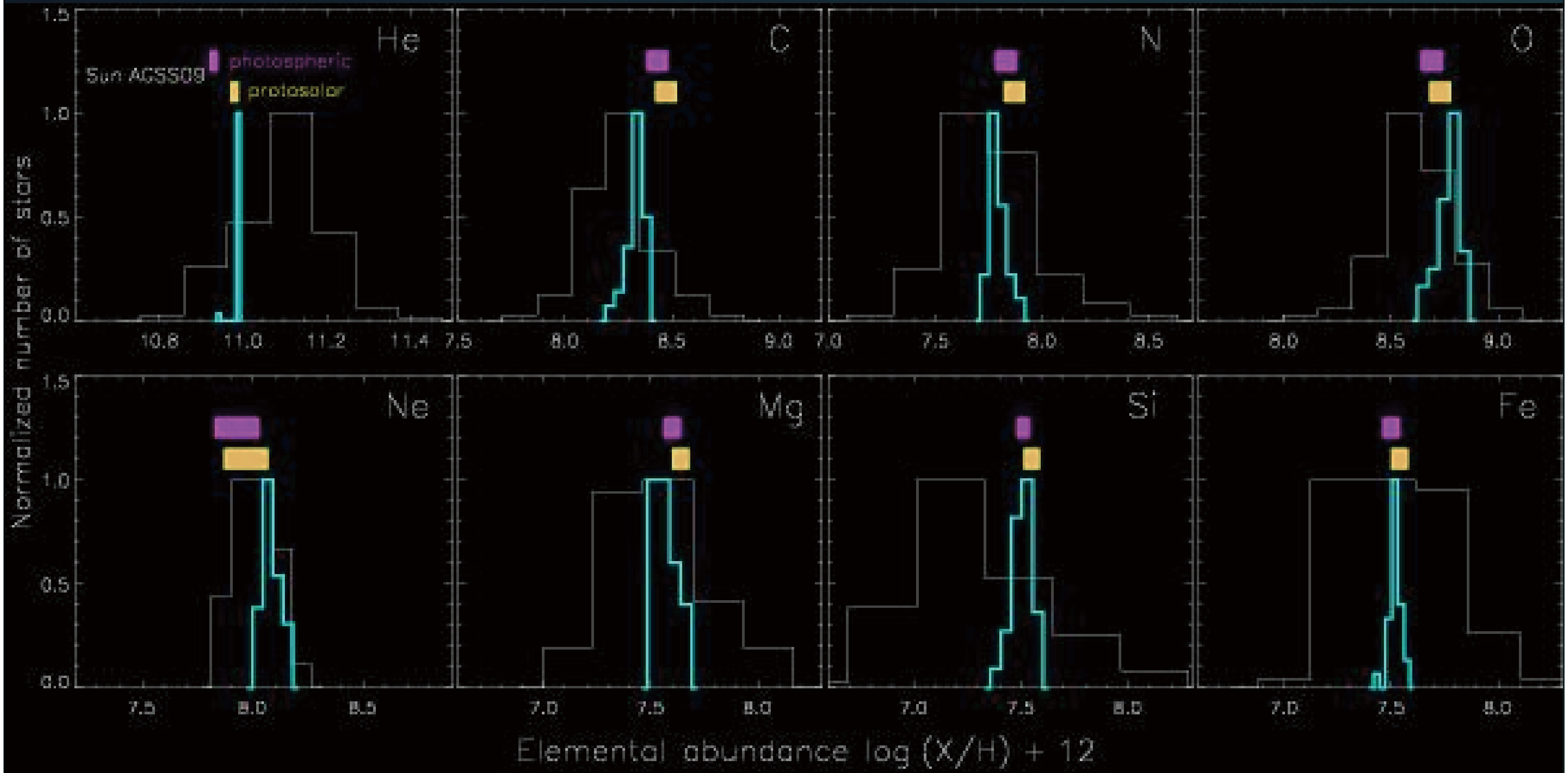
New abundance determination of B stars

Nieva & Przybilla 2012, A&A, 539, A143

Improved model atmosphere analysis (non-LTE...) of 29 B stars

Small scatter and consistent with solar values*

*Apslund et al. 2009 ARA&A, 47, 413 (AGSS09)



Comparison with other abundances

New B star abundance is not much different fromAGSS09

Carbon dust abundance in the Orion nebula will be ~0!

	Cosmic Standard		Orion nebula		Young	ISM		Sun		
Elem.	B stars		Gas	Dust	F&G stars	Gas	Dust	GS98	AGSS09	CLSFB10
He	10.99 ± 0.01	...	10.988 ± 0.003	...	...	...	...	10.93 ± 0.01		
C	8.33 ± 0.04	214 ± 20	8.37 ± 0.03	~0	8.55 ± 0.10	7.96 ± 0.03	123 ± 23	8.52 ± 0.06	8.43 ± 0.05	8.50 ± 0.06
N	7.79 ± 0.04	62 ± 6	7.73 ± 0.09	...	...	7.79 ± 0.03	0 ± 7	7.92 ± 0.06	7.83 ± 0.05	7.86 ± 0.12
O	8.76 ± 0.05	575 ± 66	8.65 ± 0.03	128 ± 73	8.65 ± 0.15	8.59 ± 0.01h	186 ± 67	8.83 ± 0.06	8.69 ± 0.05	8.76 ± 0.07
Ne	8.09 ± 0.05	123 ± 14	8.05 ± 0.03	...	...	...	...	8.08 ± 0.06	7.93 ± 0.10	...
Mg	7.56 ± 0.05	36.3 ± 4.2	6.50:	33.1 ± 4.2:	7.63 ± 0.17	6.17 ± 0.02	34.8 ± 4.2	7.58 ± 0.05	7.60 ± 0.04	...
Si	7.50 ± 0.05	31.6 ± 3.6	6.50 ± 0.25	28.4 ± 4.3	7.60 ± 0.14	6.35 ± 0.05	29.4 ± 3.6	7.55 ± 0.05	7.51 ± 0.03	...
Fe	7.52 ± 0.03	33.1 ± 2.3	6.0 ± 0.3	32.1 ± 2.5	7.45 ± 0.12	5.41 ± 0.04	32.9 ± 2.3	7.50 ± 0.05	7.50 ± 0.04	7.52 ± 0.06

C dust in the Orion nebula

Oxygen dust abundance is sufficient compared to model requirements (~140-150ppm; Draine 2003, ARA&A, 41, 241)

C dust abundance from the B-star abundance (123ppm) is not sufficient to match with model requirements (typically ~250ppm; >190 ppm; e.g., Zubko et al. 2004, ApJS, 152, 211)

C dust abundance of the Orion nebula is nearly 0

A possible interpretation is that the Orion nebula (or HII regions) has no graphite grains, which are supposed to be refractory, but has PAHs, which will be easily destroyed in ionized gas

There may be no graphite grains in the ISM

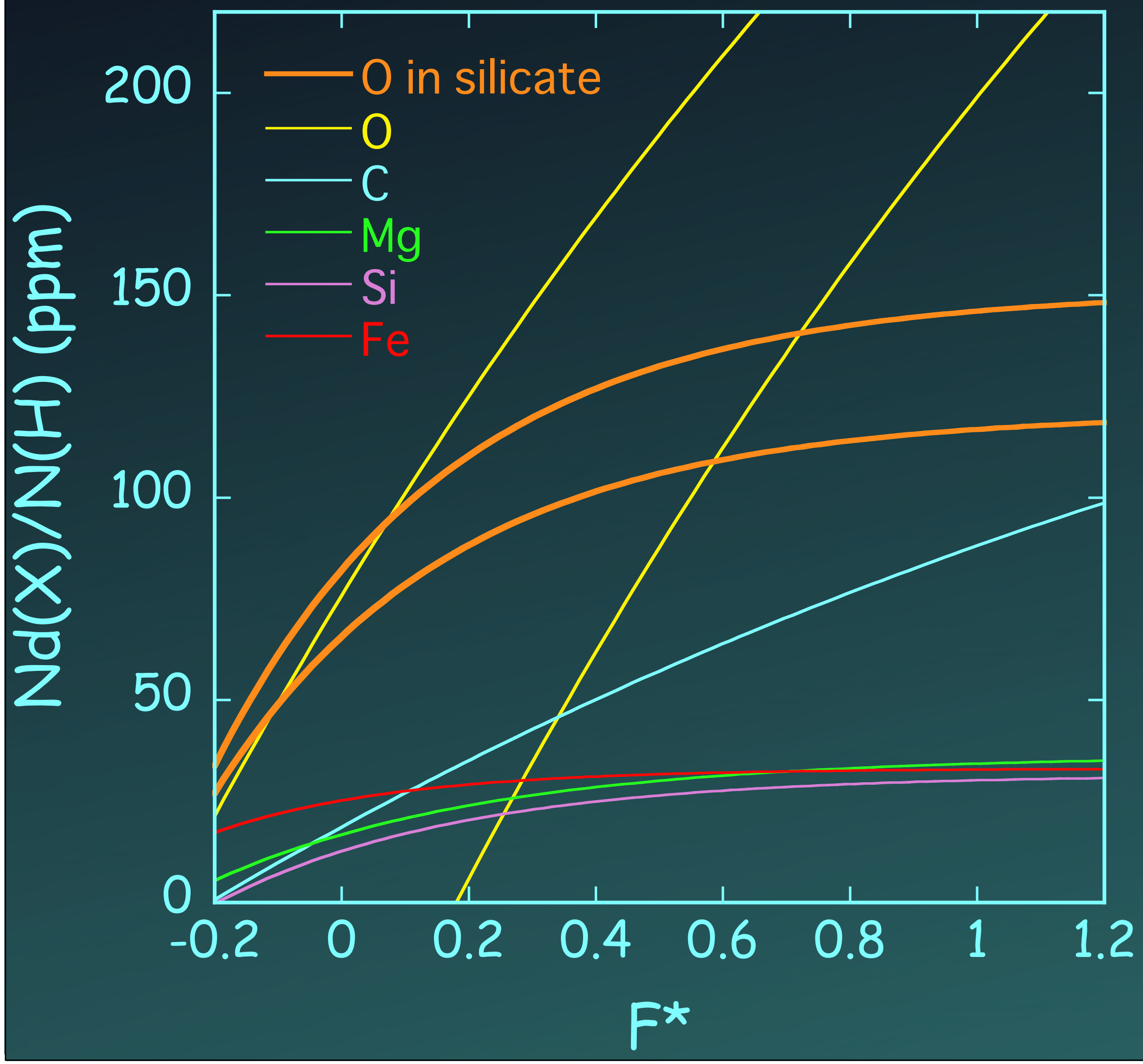
Nieva & Przybilla 2012, A&A, 539, A143

Correlation of elemental depletion

Based on UV absorption line observations, [Jenkins (2009) ApJ, 700, 1299]

$$D(X) = B_X + A_X(F_* - z_X)$$

F*: depletion factor; Ax, Bx: fit parameters

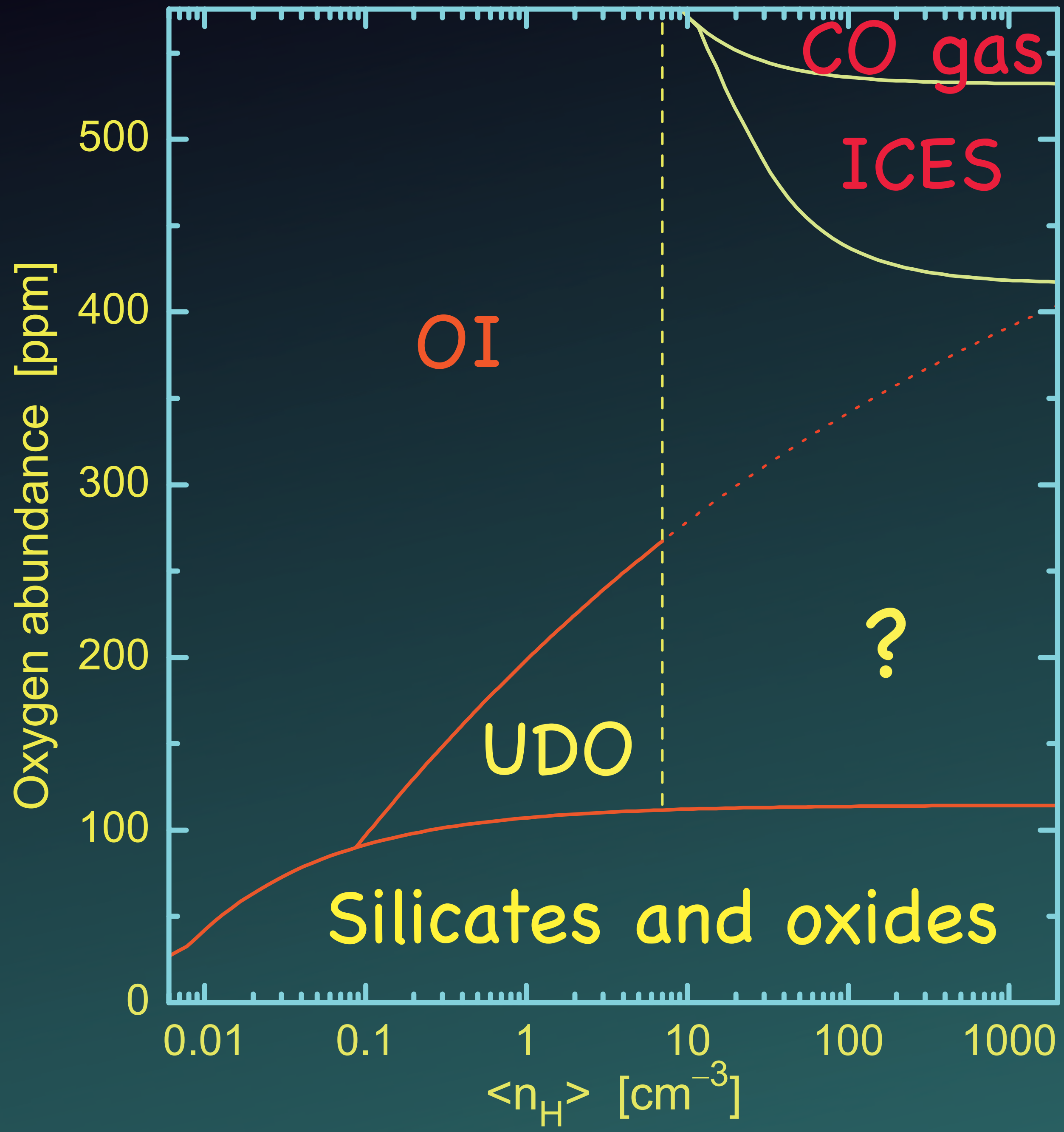


Fe persists in solid form separate population from silicates (oxides)?

If O/M=1.2~1.5 (brown lines) (cf., (Mg, Fe)$_2$SiO$_4$, FeO), there is unidentified depleted oxygen (UDO)

Whittet 2010 ApJ 710, 1009

Where has depleted oxygen gone?



Solid O2 is too volatile

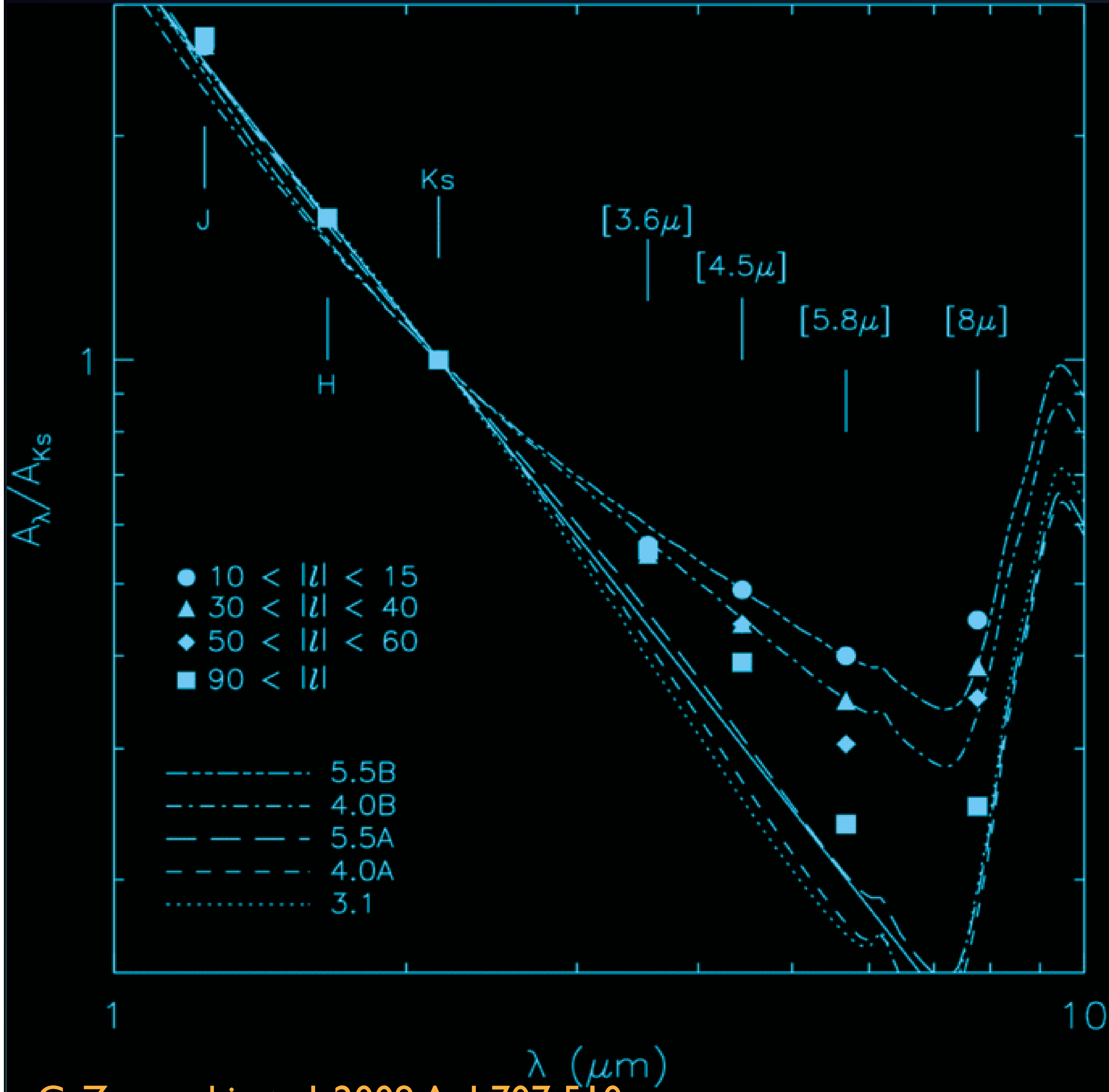
Remaining O may hide in C-bearing dust (`organic refractory')

But no spectroscopic evidence (e.g., C=O at 5.85μm) is seen

`dark dust'?

Whittet 2010 ApJ 710, 1009

Excess Extinction in 3--8μm



G. Zasowski et al. 2009 ApJ 707 510

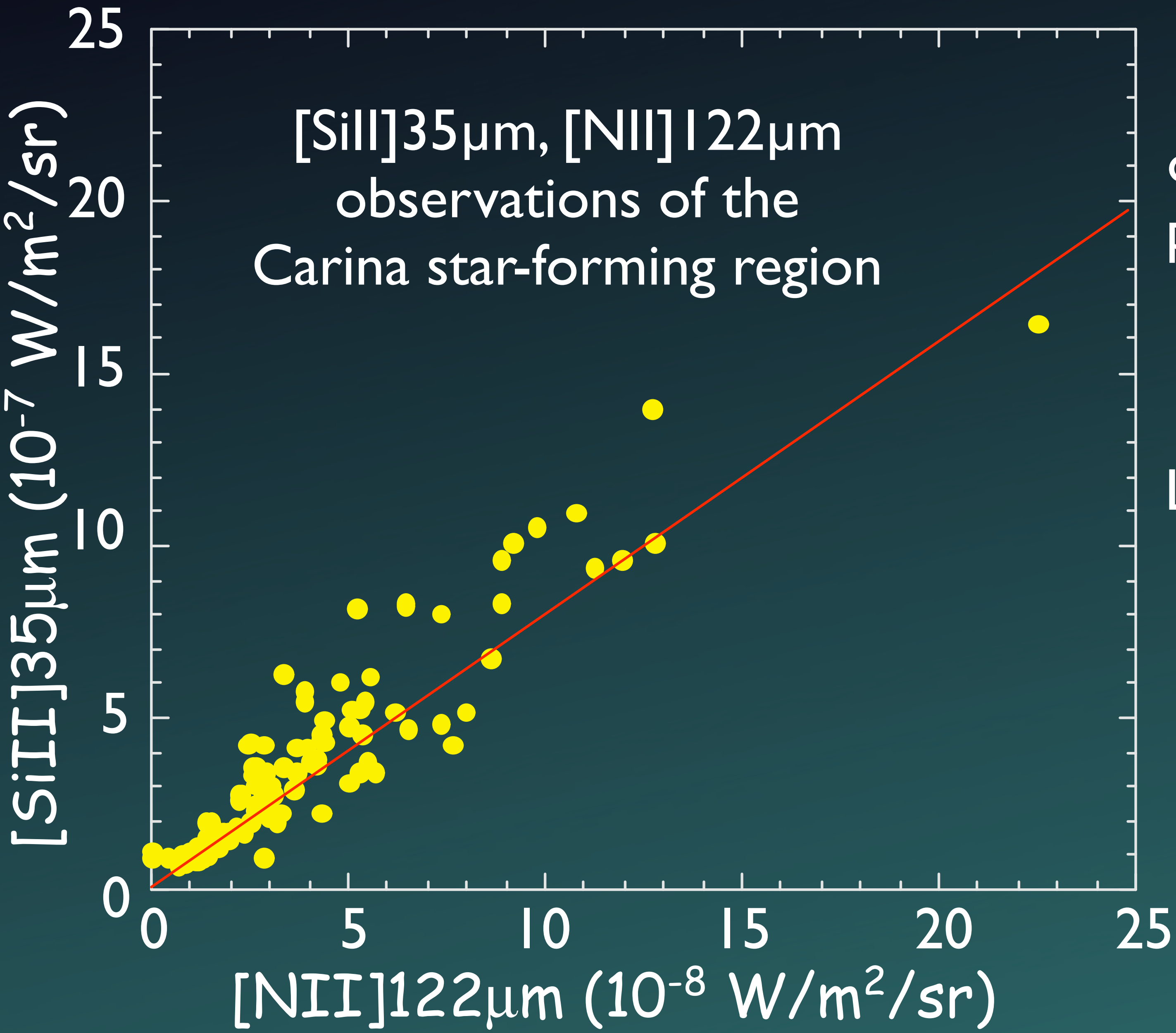
Excess extinction over standard dust models (Rv=3.1) in 3--8μm and it varies over the Galactic plane

Models with Rv=4--5 may account for the excess by contribution from carbonaceous dust

or

the excess is attributable to UDO?

Si gas abundance in star-forming regions based on IR forbidden line observations



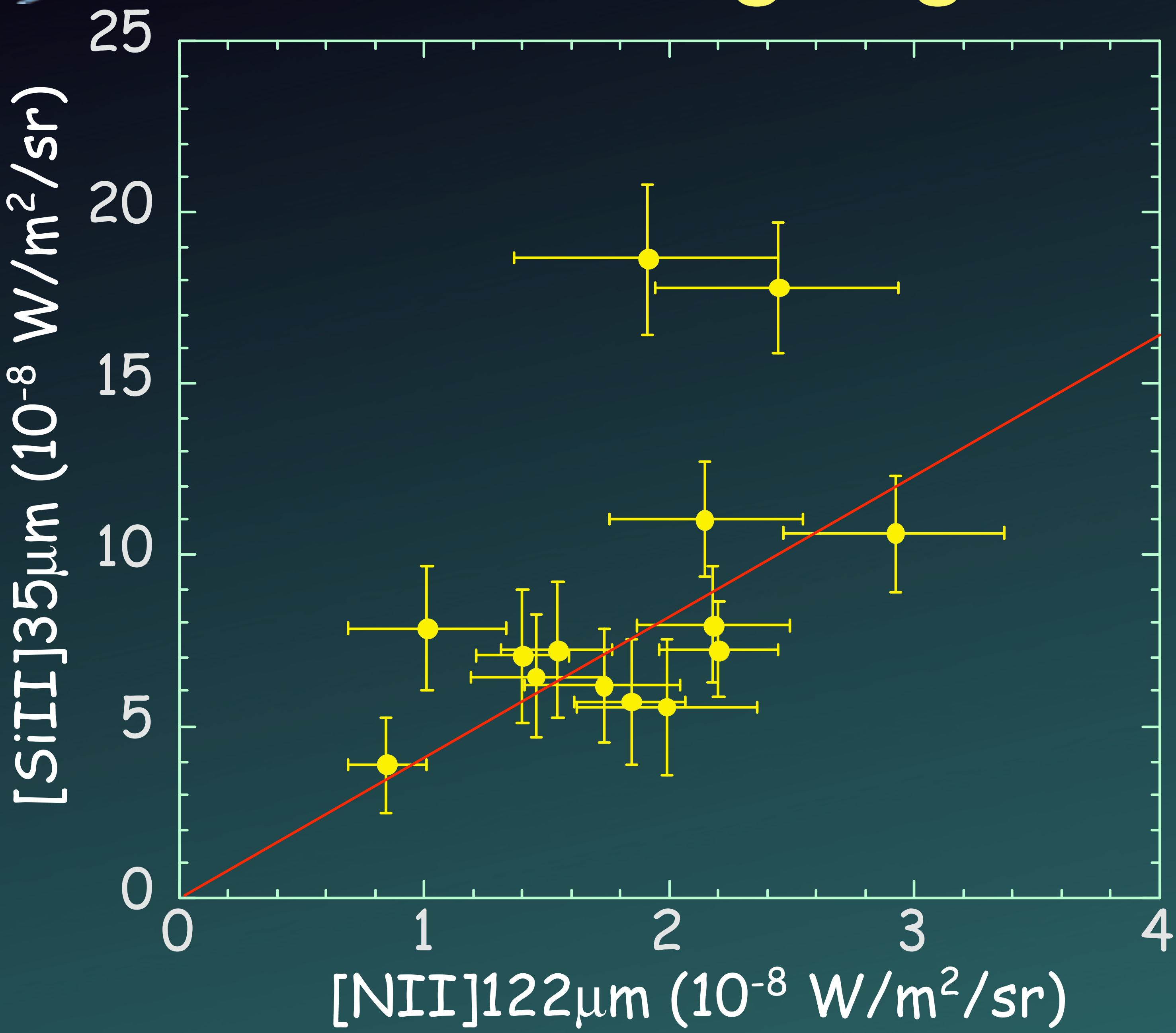
UV absorption observations cannot probe dense regions

Si/N ~ 70% solar

Large amount of Si-bearing dust is destroyed in SF regions

Mizutani et al. (2004) A&A, 423, 579

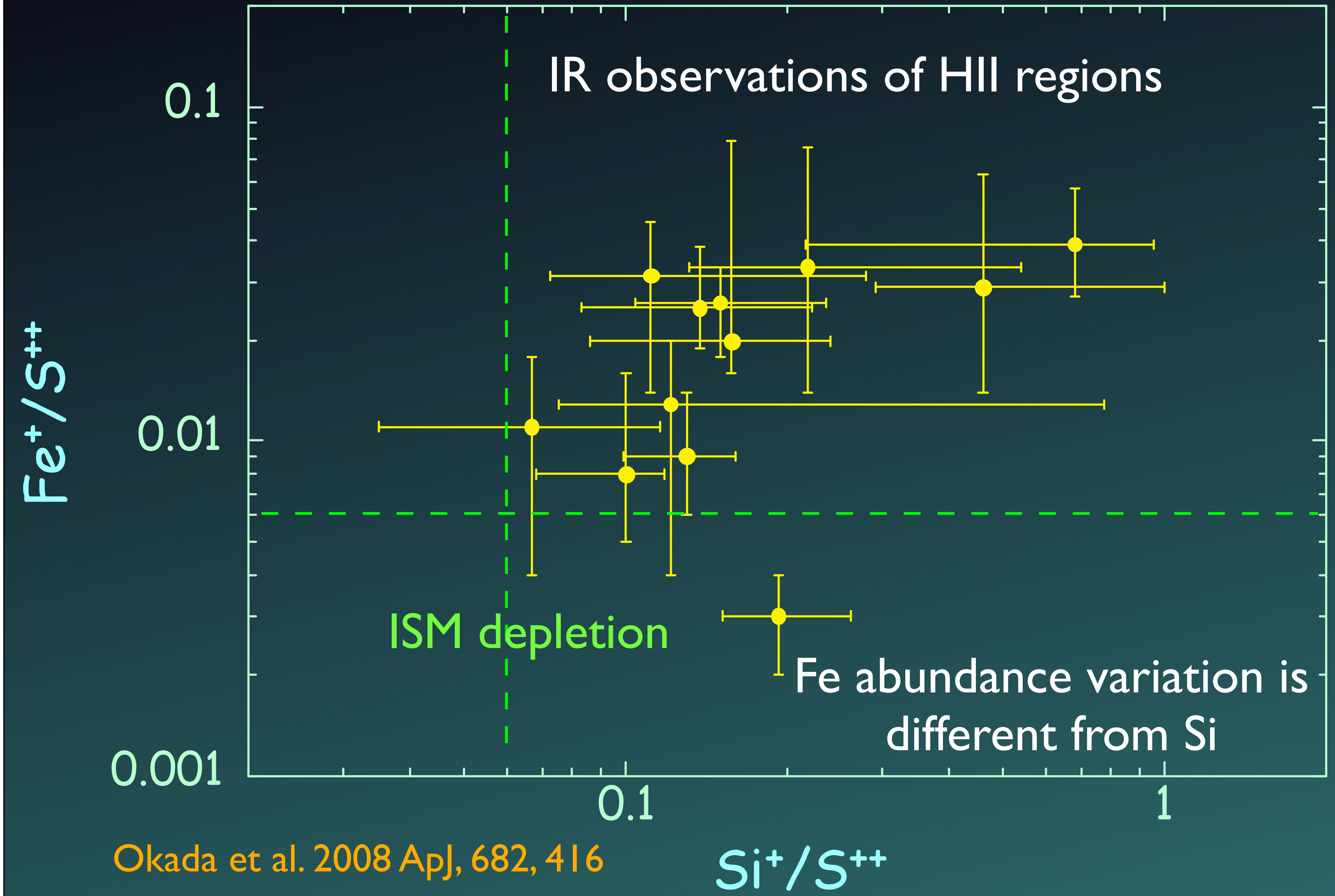
Star-Forming Region S171



Si/N
~ 40% Solar

Okada et al. (2003)
A&A, 412, 199

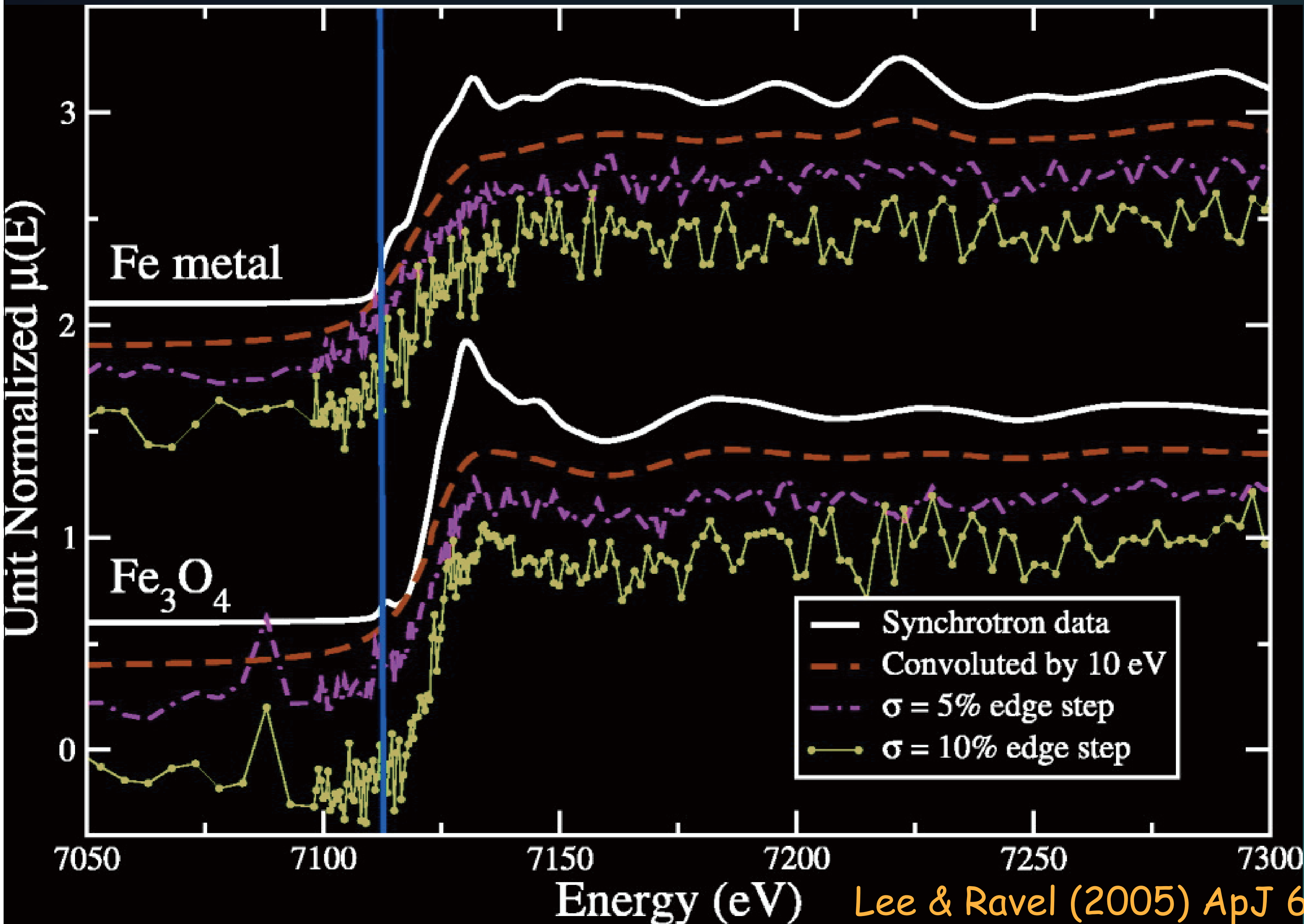
Fe gas abundance in star-forming regions



Okada et al. 2008 ApJ, 682, 416

Where is Fe in the ISM?

Metal or oxide can be investigated by X-ray spectroscopy
Metal Fe has a lower edge energy



Lee & Ravel (2005) ApJ 620, 970

L edge has complex structures
High energy-resolution is needed

Accurate laboratory data are also needed

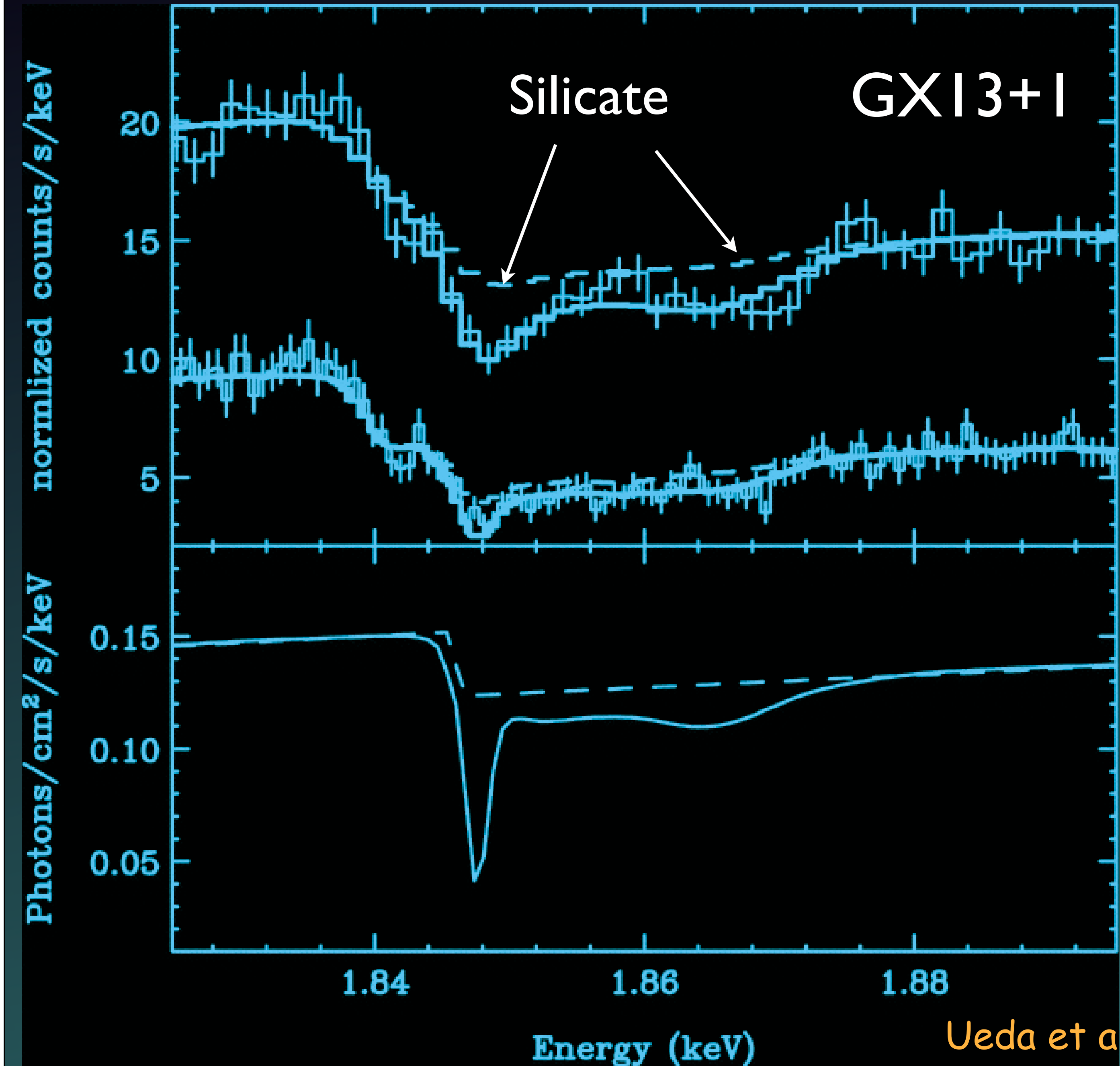
X-ray Absorption Fine Structure (XAFS)

X-ray Absorption Near-Edge Structures (XANES); ΔE ≤ 10-20 eV
-> local coordination geometry

Extended X-ray Absorption Fine Structures (EXAFS); ΔE ≥ 10-20 eV
-> bond length

Gas and dust abundance can be determined independently
Even chemical bonds of dust species can be investigated by XAFS

XAFS of Si

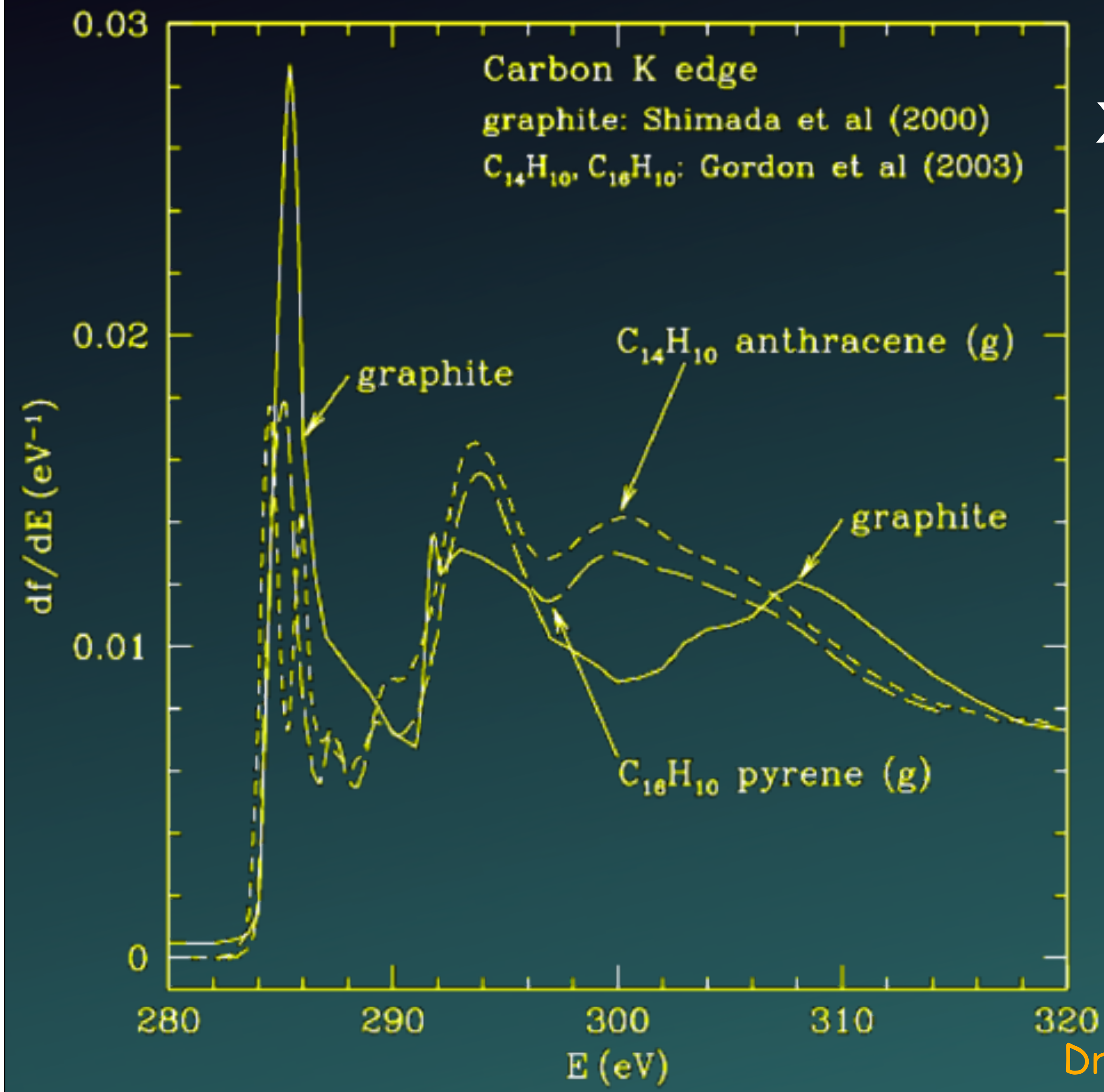


Signature of silicates is detected

But detailed compositions cannot be investigated from currently available spectra

Ueda et al. (2005) ApJ, 620, 274

XAFS of C



XAFS of C edge can tell us the structure of carbonaceous dust

Draine (2003) ApJ, 598, 1026

Balance sheet of interstellar dust budget

Stellar supply rate ~ (2-3) x10^9 yr

Destruction (by SN shock) rate ~ (2-6) x10^8 yr

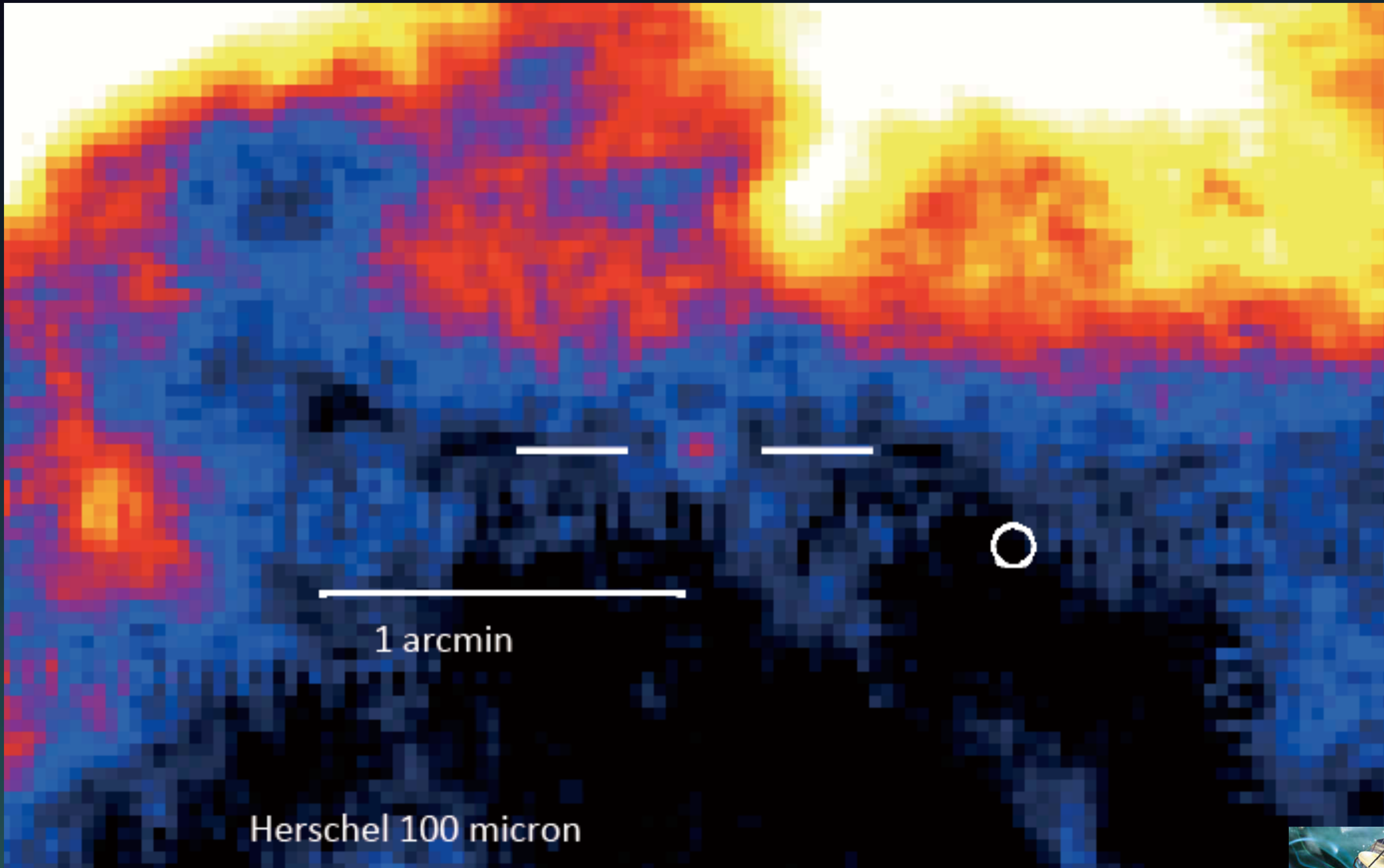
(silicates 4x10^8; a:C 6x10^8; a-C:H 2x10^8yr)

-> dust is being formed in dense clouds?

SNe are the largest supplier and destroyer of dust

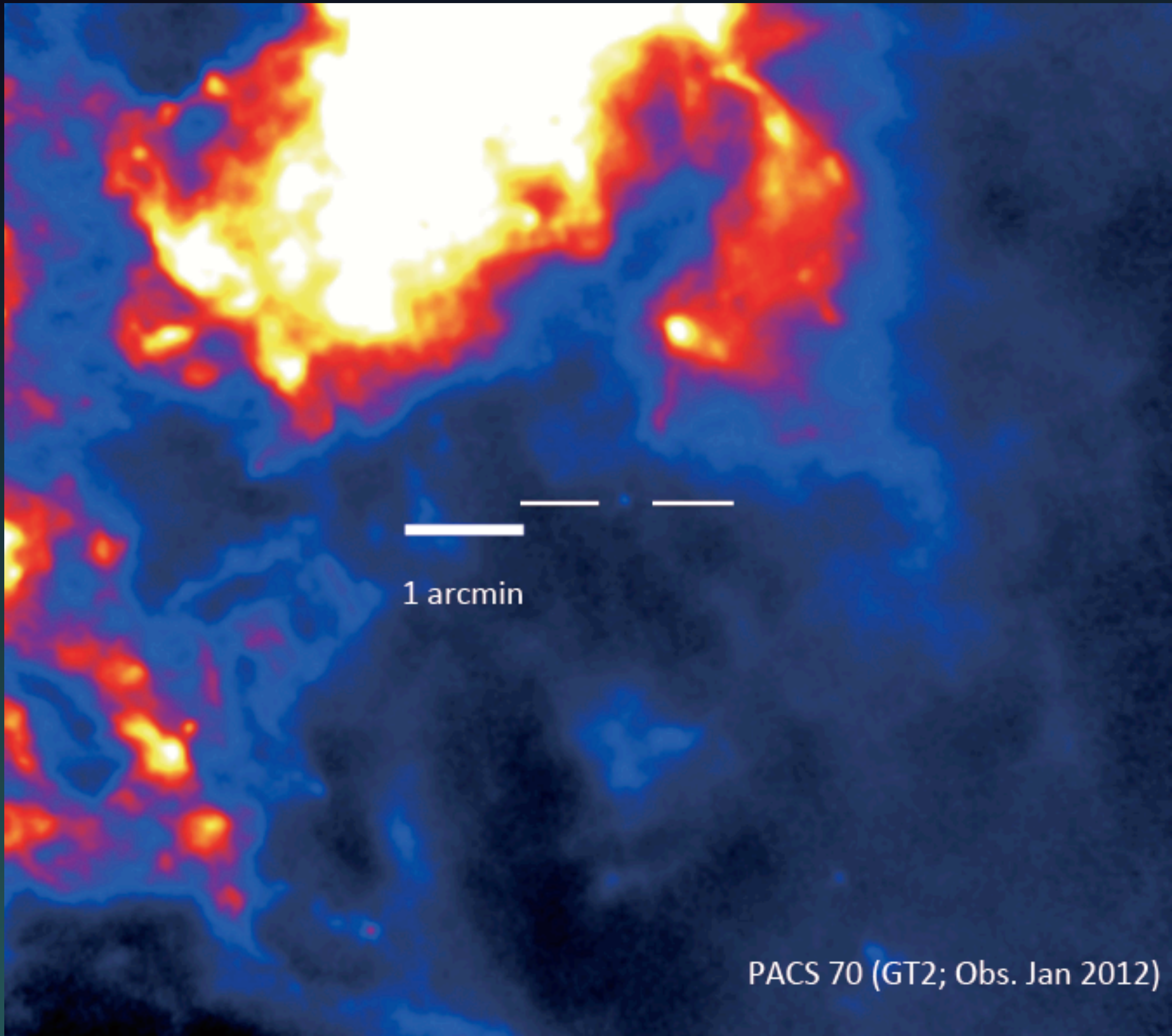
source	Carbon ($M_\odot$ kpc^{-2} Myr^{-1})	Silicate/Fe ($M_\odot$ kpc^{-2} Myr^{-1})
C star	3.0	
O-rich AGB		5.0
SN Ia*	<0.3	<2
SN II*	<2	<10
Novae	0.3	0.03
RSG		0.2
Wolf-Rayet	0.06	
SN Shock	40	80

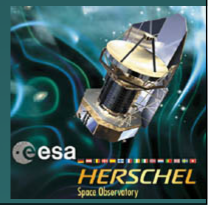
Detection of SN1987A with Herschel



Matsuura et al. (2011) Science, 333, 918

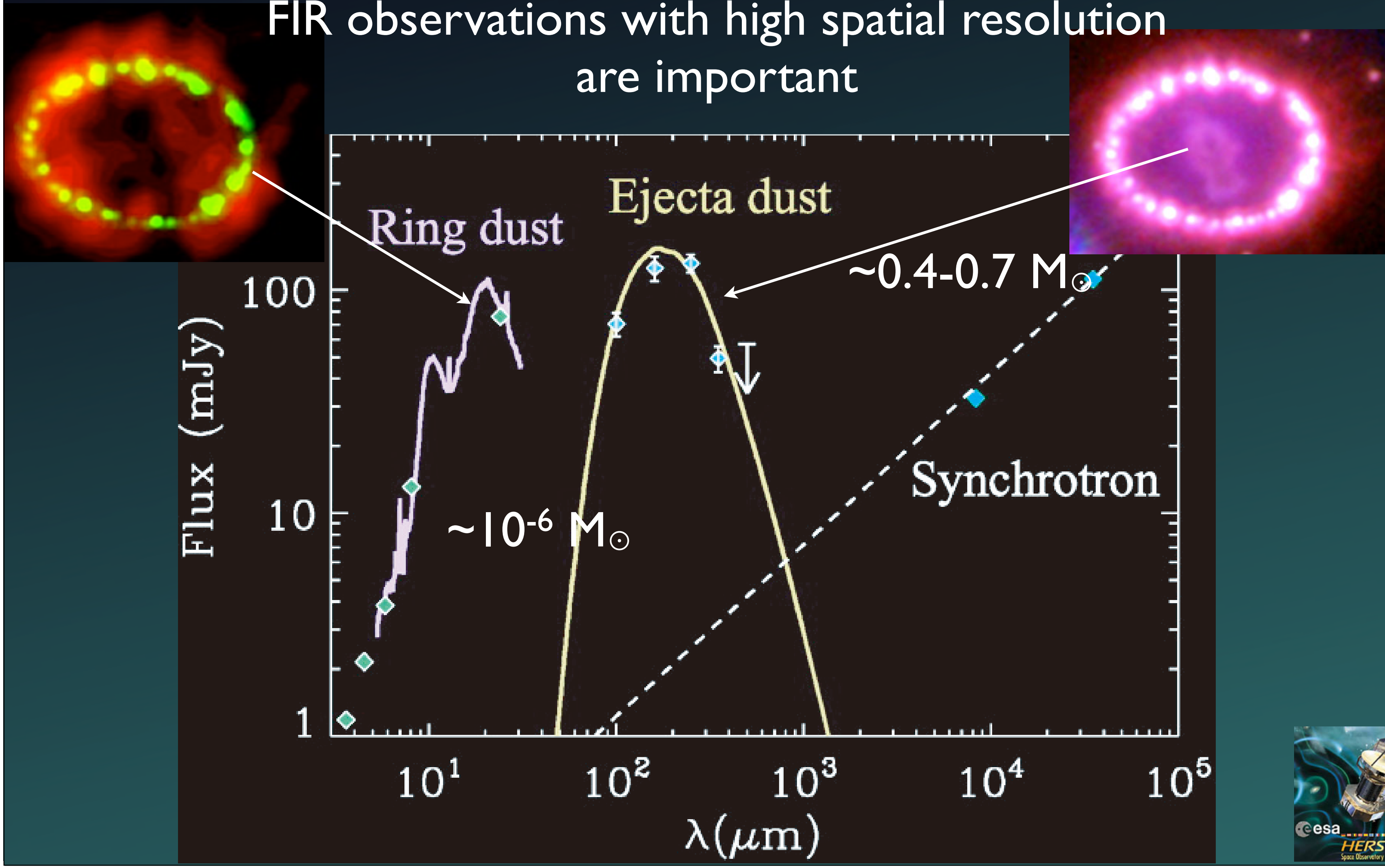
Confirmation of the detection at 70μm





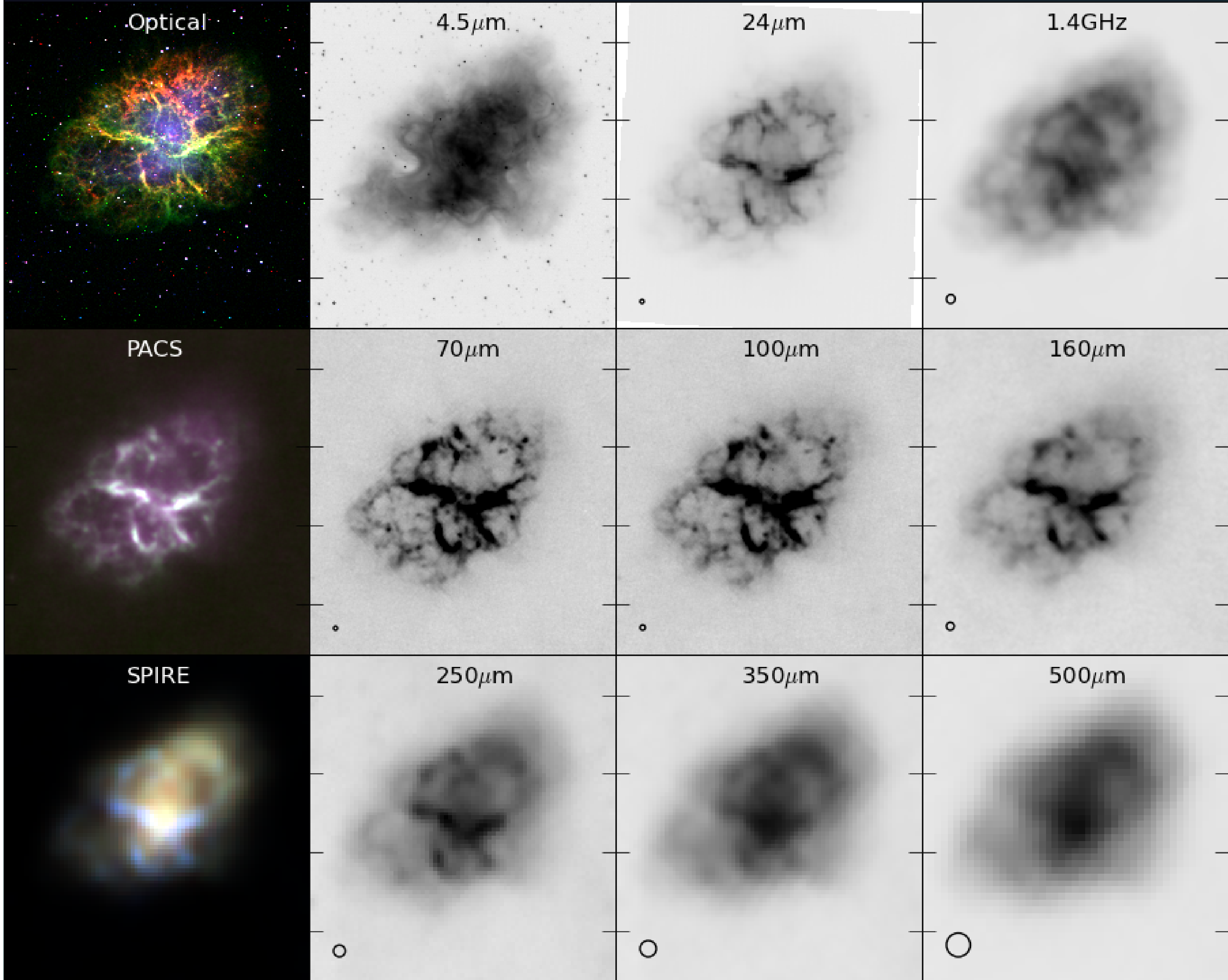
Appreciable amount of dust detected in ejecta of SN1987A (0.4-0.7M$_\odot$)

FIR observations with high spatial resolution are important



Dust in Crab

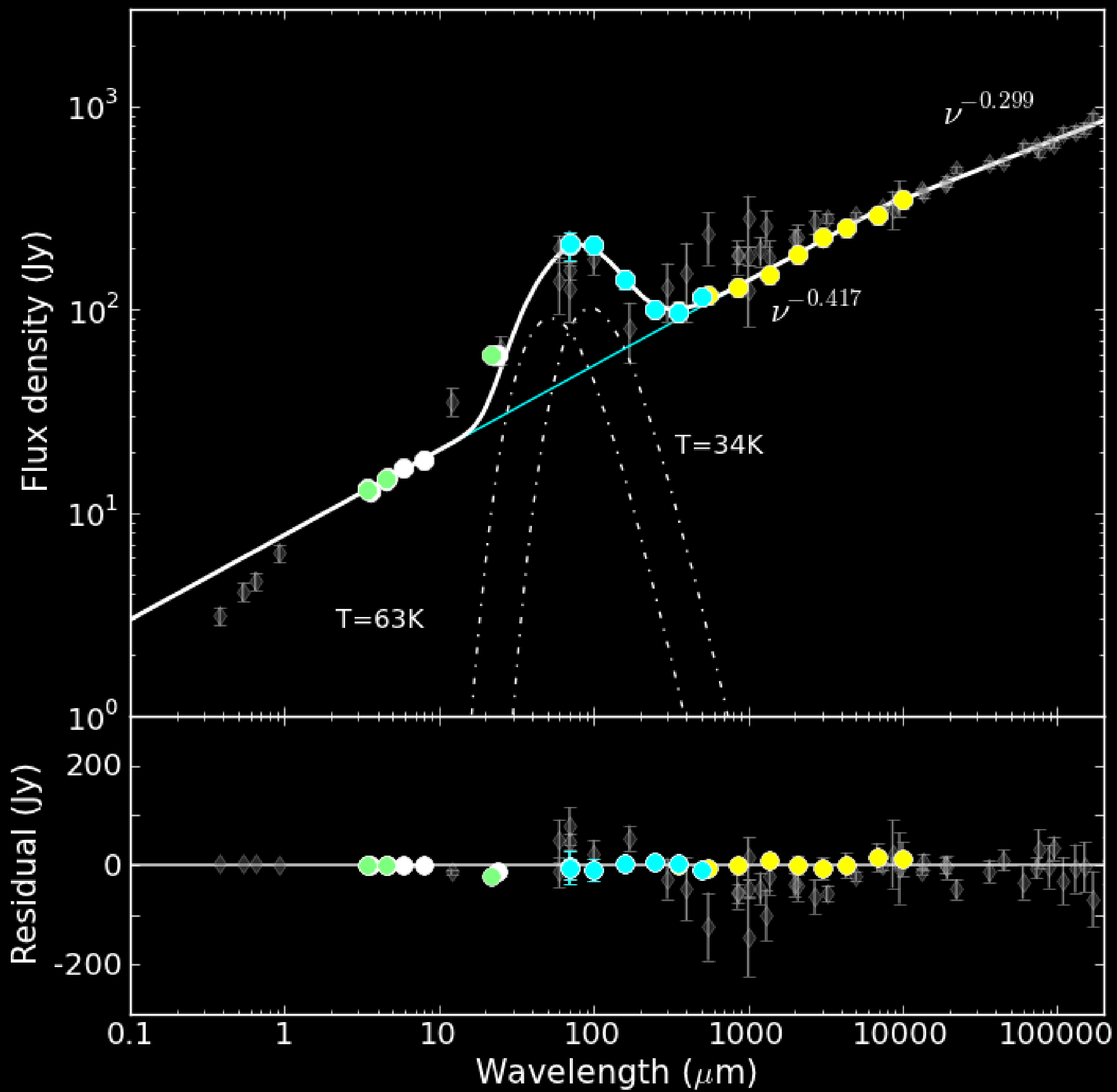
Gomez et al. (2012) ApJ 760, 96



ISO
Spitzer
Herschel
Planck
data

Synchrotron emission & line emission need to be subtracted

2 dust components

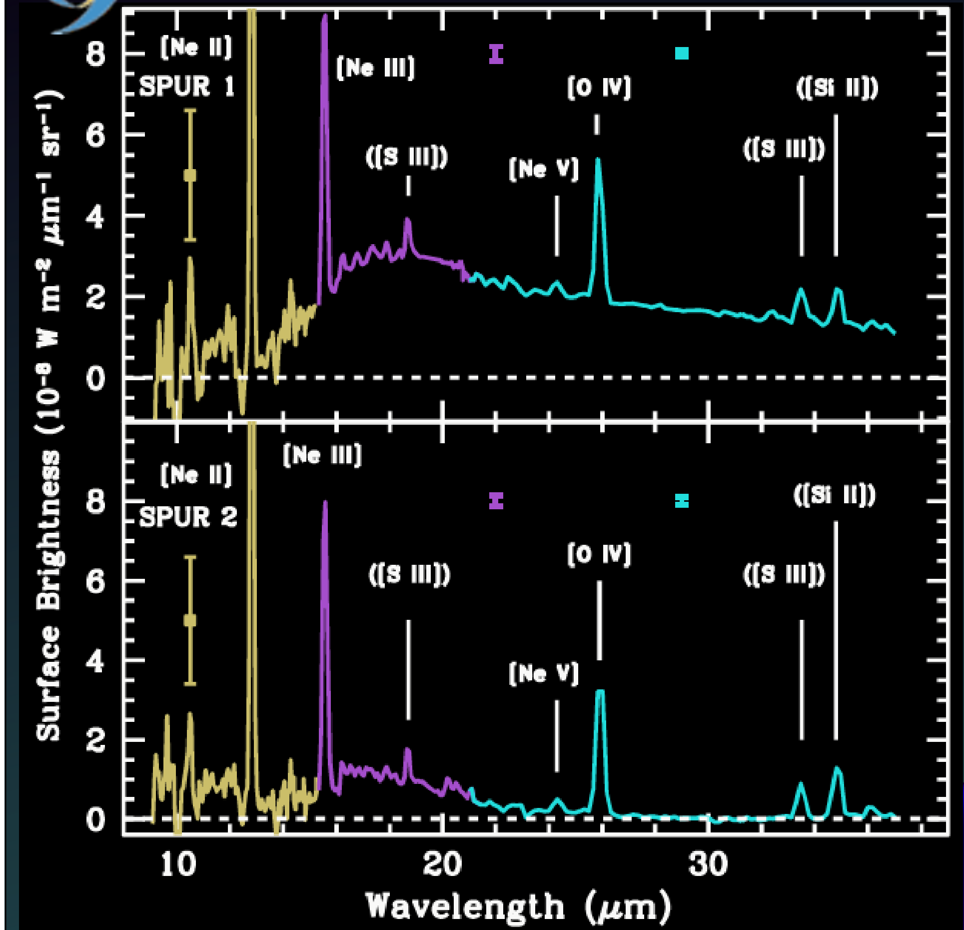


If silicates,
$M_d \sim 0.24\ M_\odot$ (T~28K)
+ $M_d \sim 0.008\ M_\odot$ (T~56K)

If amorphous carbon,
$M_d \sim 0.11\ M_\odot$ (T~34K)
+ $M_d \sim 0.006\ M_\odot$ (T~63K)

Ejected heavy elements
~ 0.2-0.5 $M_\odot$
Efficient dust formation

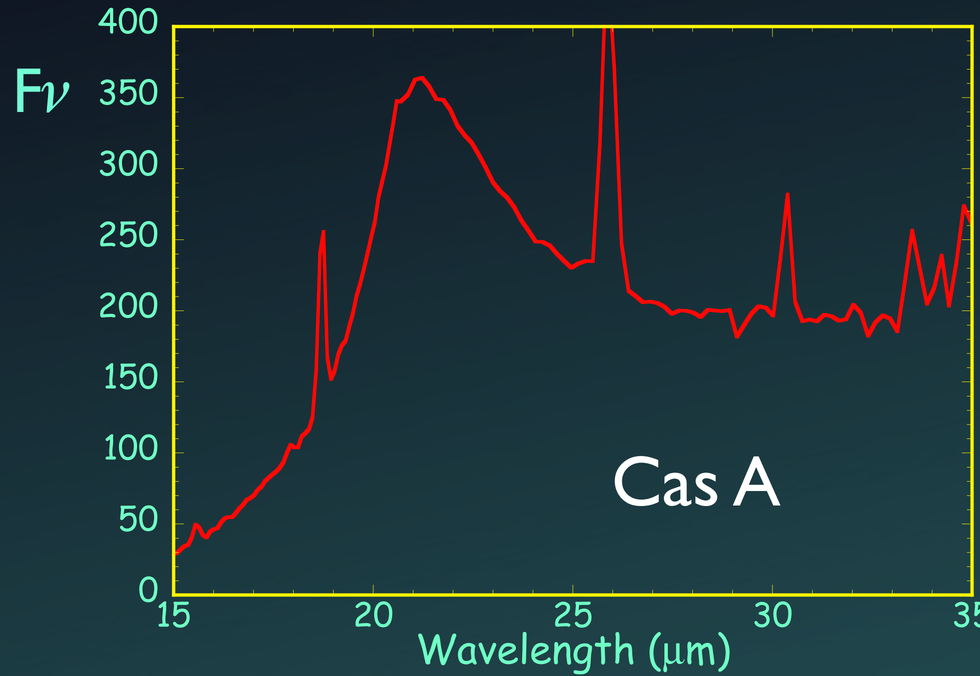
What kind of dust is formed in SNe?

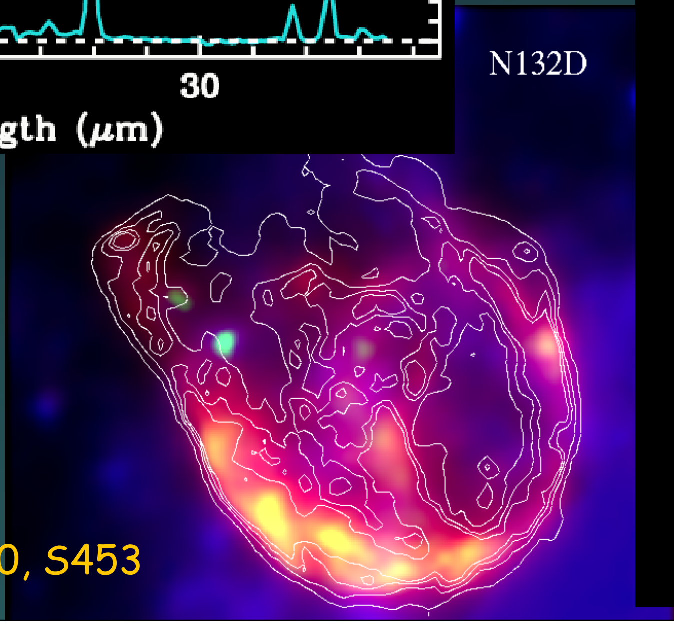


G292.0+1.8

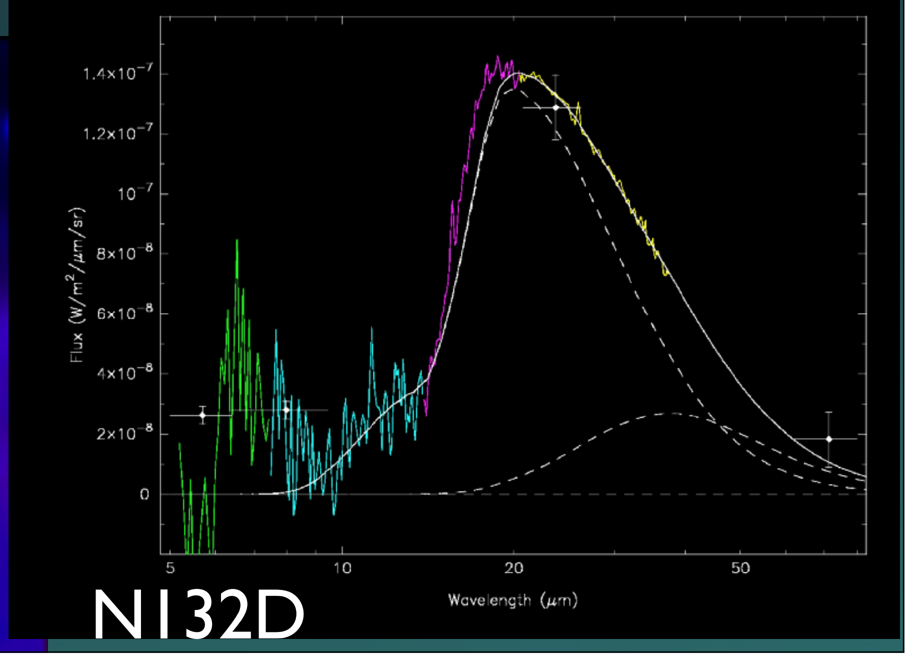
Ghavamian et al. 2009

Seok et al. 2008, PASJ, 60, S453

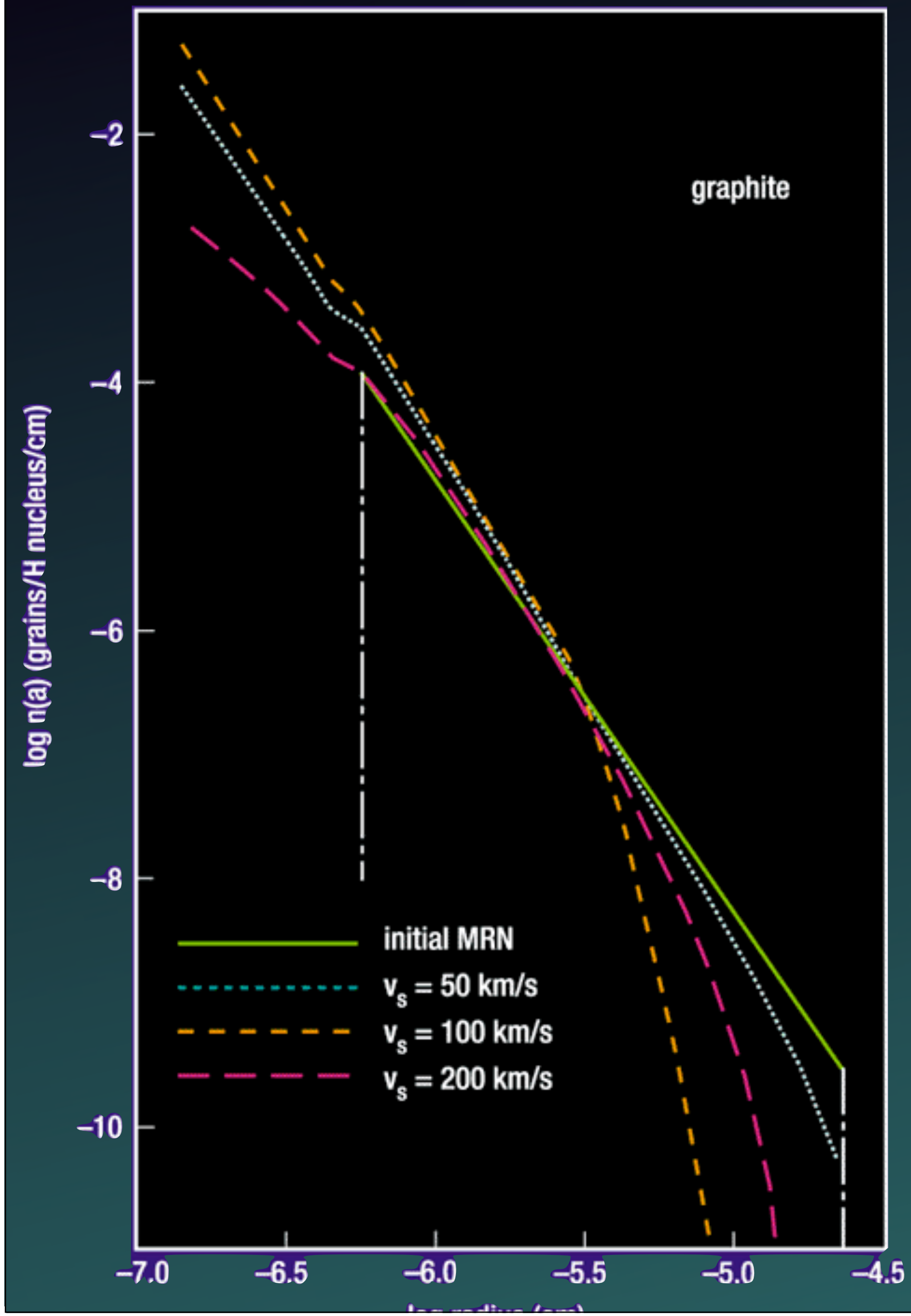




Tappe et al. 2006 ApJ 653, 267



Shock processing of dust: theory



In slow shocks ($\lesssim$ 100km/s)

shattering dominates and fragments larger grains into smaller grains

In fast shocks ($\gtrsim$100km/s)

sputtering dominates and depletes smaller grains efficiently

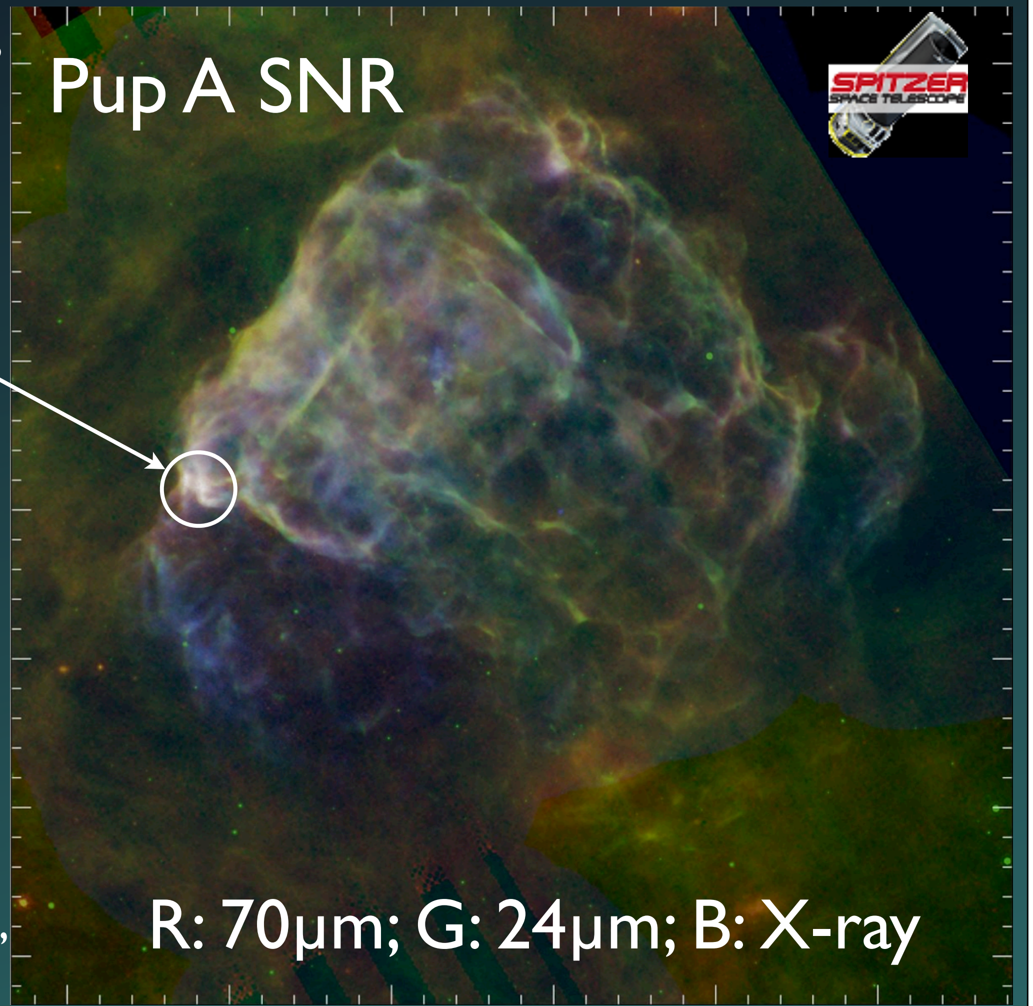
Williams 2003, N. Rev. As. &Geop. 44, 14
from Jones et al. 1996 ApJ, 469, 740;

Shock processing: observations of Pup A

Arendt et al. 2010, ApJ, 725, 585

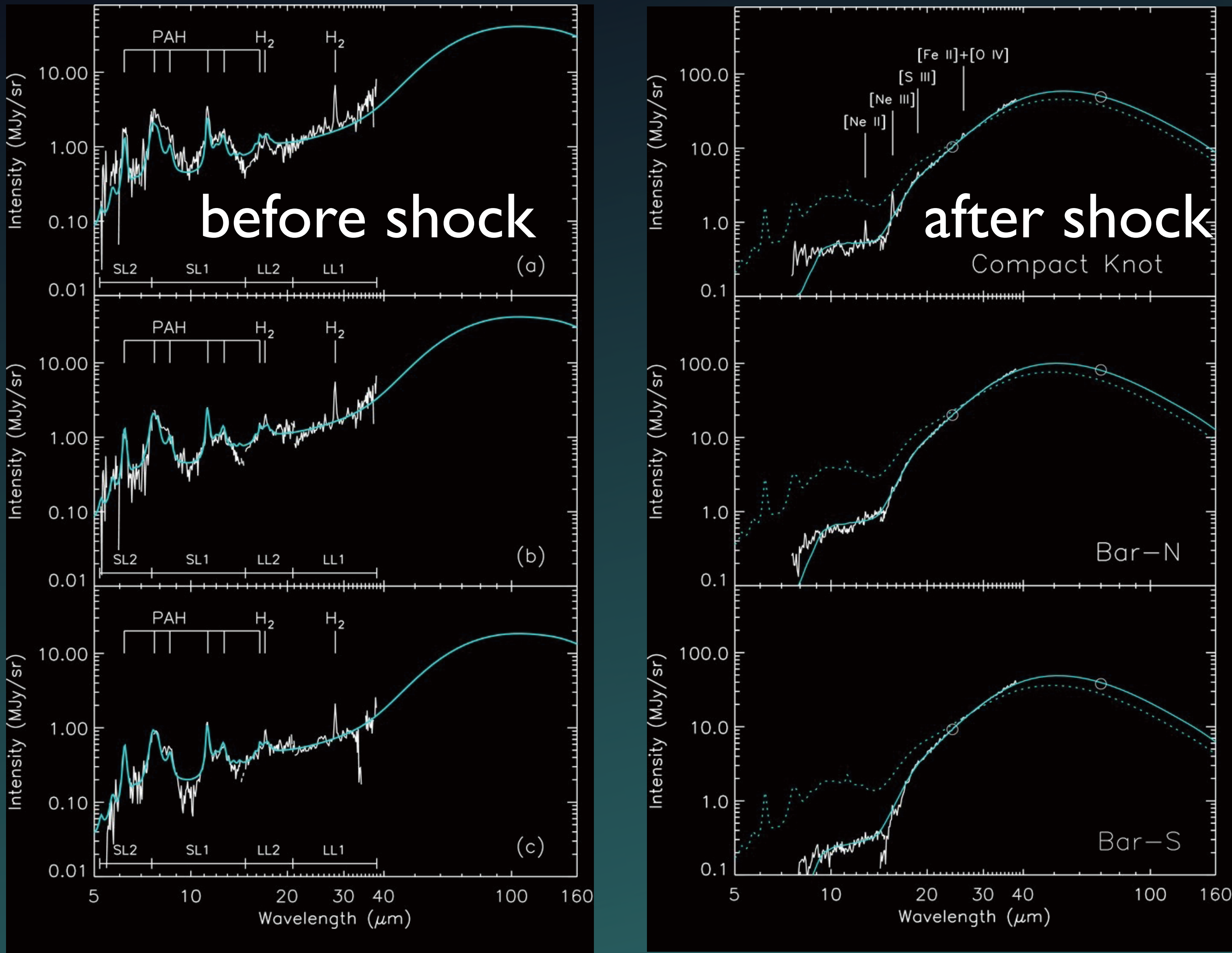
IRS spectroscopy of shocked region

and un-shocked region (east cloud)



Spectrum of before/after shock

Depletion of UIR bands in shocked regions

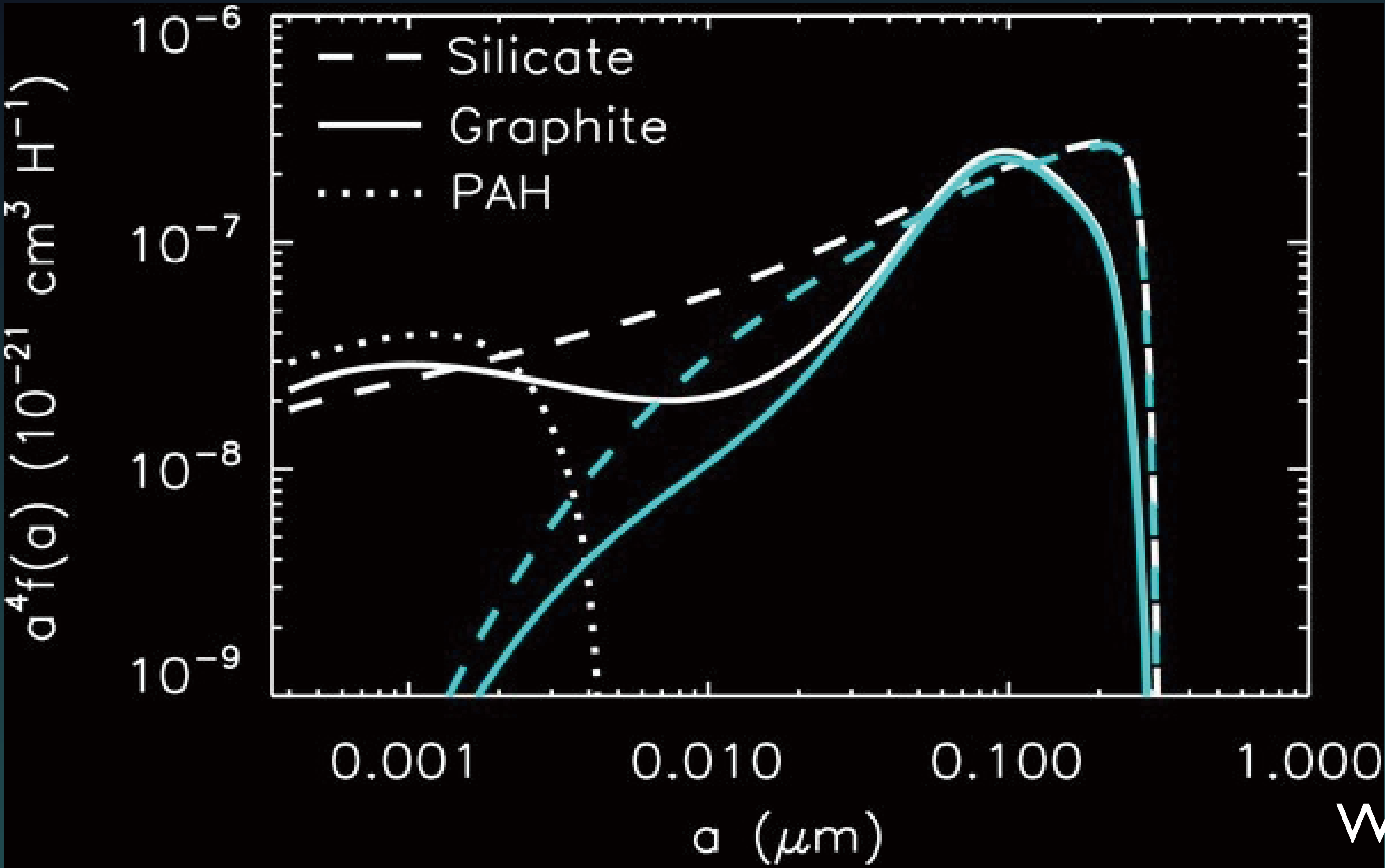


Arendt et al. 2010, ApJ, 725, 585

Change in the dust size distribution in Pup A

Complete destruction of PAHs

24% Silicate & 23% graphite grains are removed by sputtering



Arendt et al. 2010, ApJ, 725, 585

White: before shock
Blue: after shock

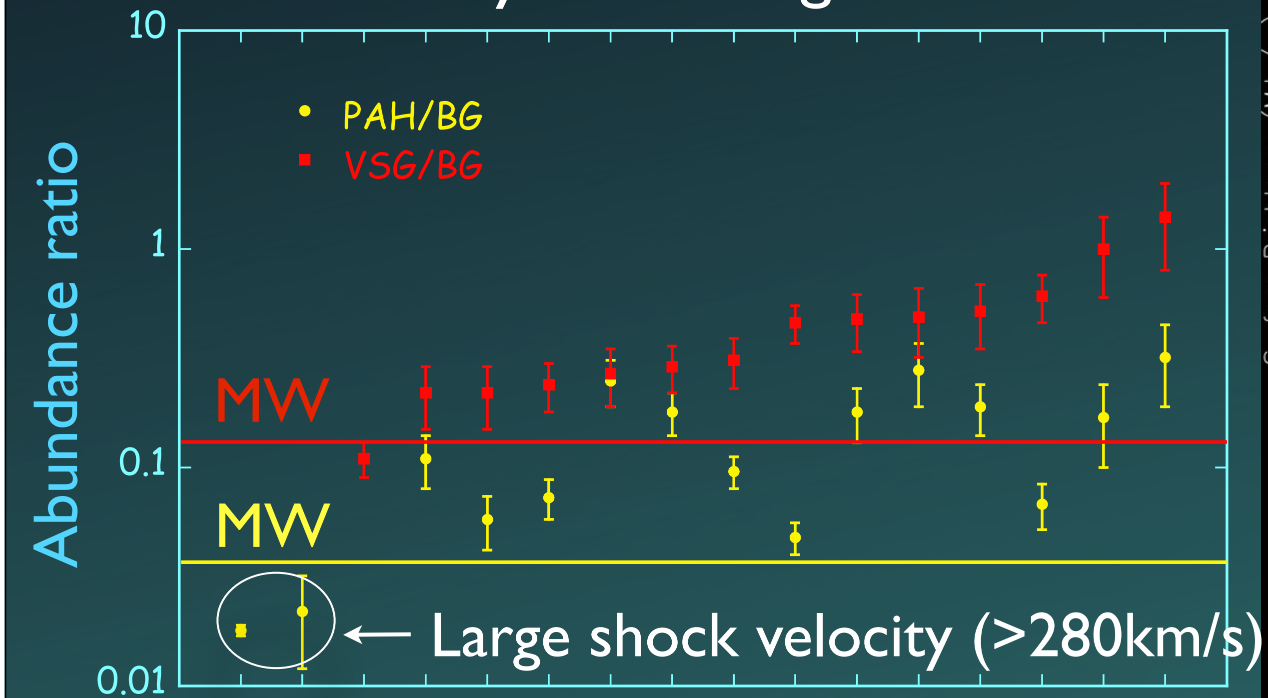
Dust processing in SNRs

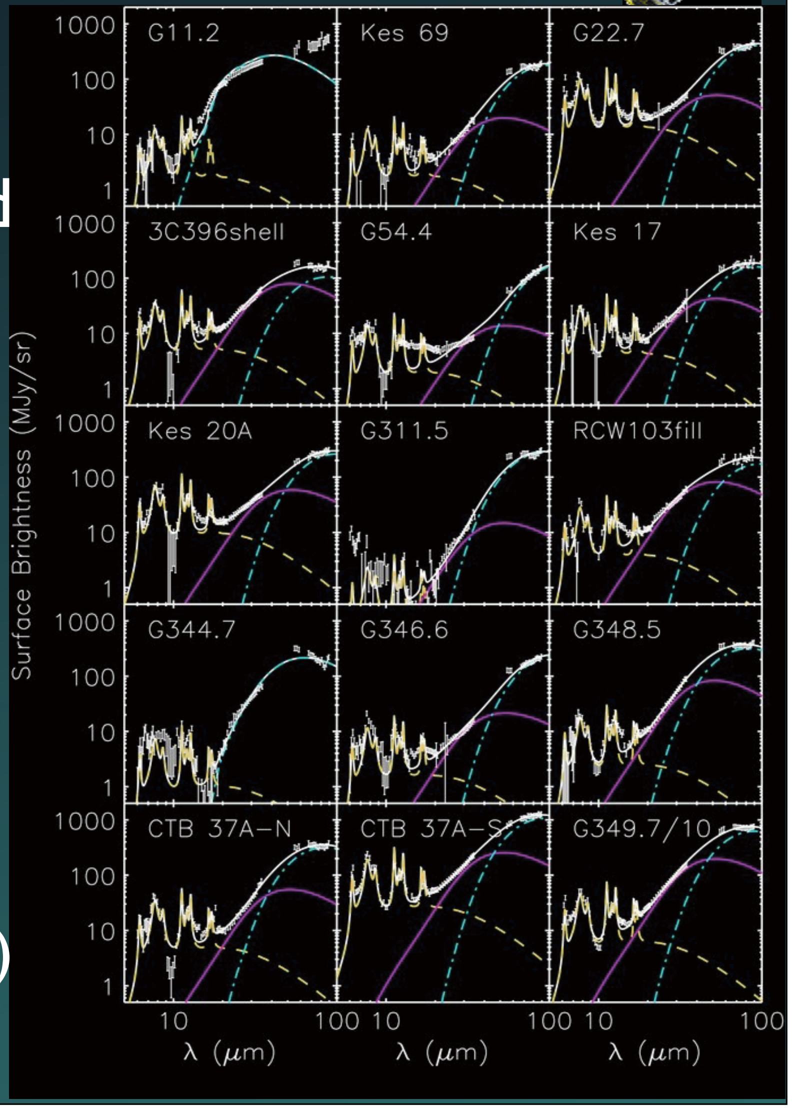
Andersen et al. 2011, ApJ, 742, 7

Observations of 14 Galactic SNRs with Spitzer/MIPS & IRS

SED model fit provides abundances of PAHs, Very Small Grains (VSGs), and Big Grains (BGs)

In most SNRs, PAH s & VSGs are enhanced by shattering



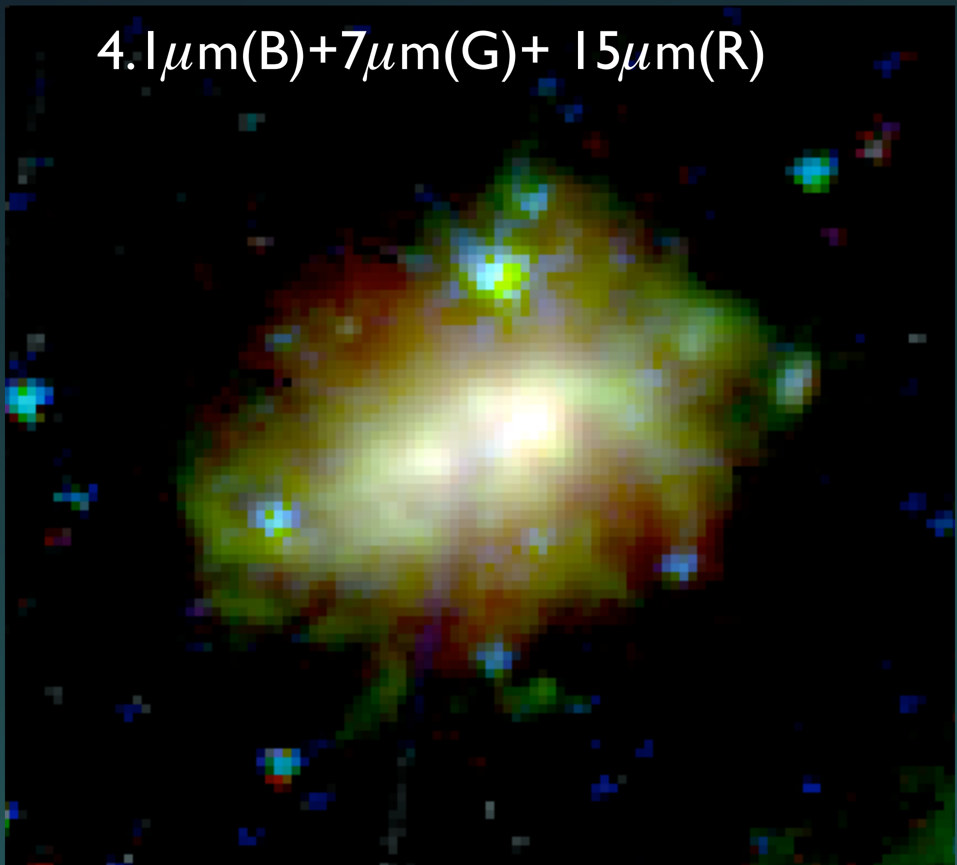


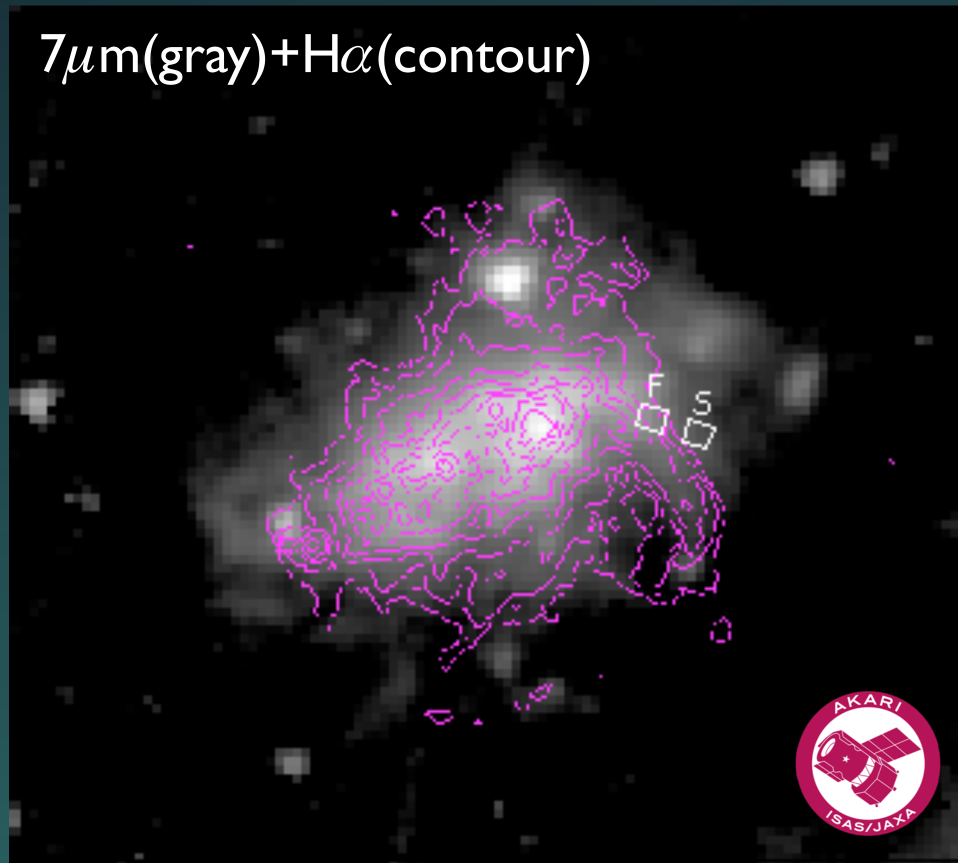
UIR bands in a Hα filament of NGC1569

T.O. et al. (2010) A&A 514, A15

NGC 1569: Nearby starburst dwarf (12+log(O/H) = 8.13) associated with several Hα filaments produced by galactic wind

7μm emission is well correlated with a Hα filament, which is created by galactic wind as indicated by X-ray emission

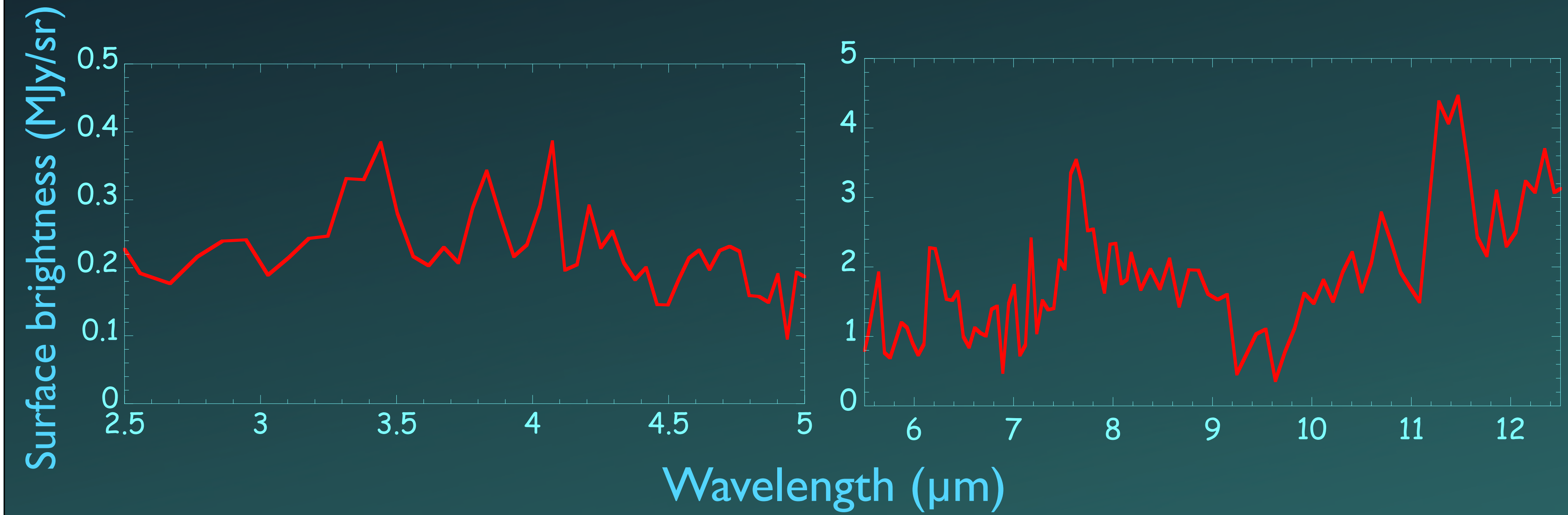




IRC spectrum of the filament

(3.3,) 6.2, 7.7, (8.6), 11.3μm emission detected in the filament

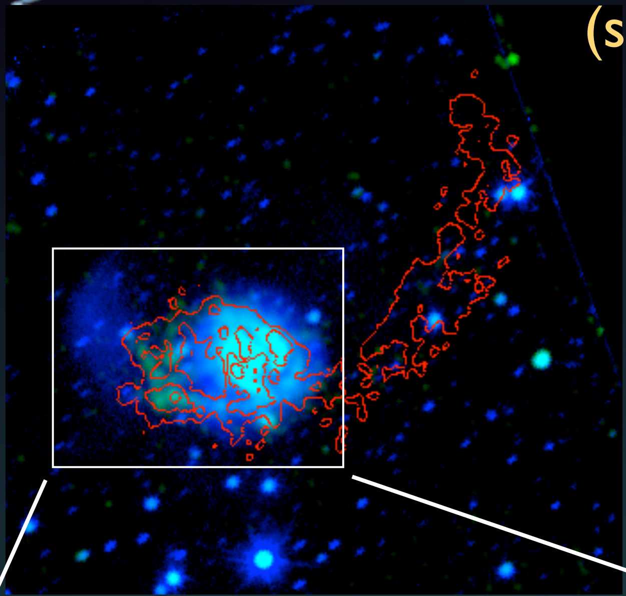
The filament age is ~ 1Myr
PAH destruction timescale < 1000yr
Weak 8.6μm & possible detection of the 3.3μm band
suggests dominance of small band carriers
Carriers are produced by shattering in shocks and may survive long



T.O. et al. (2010) A&A 514, A15

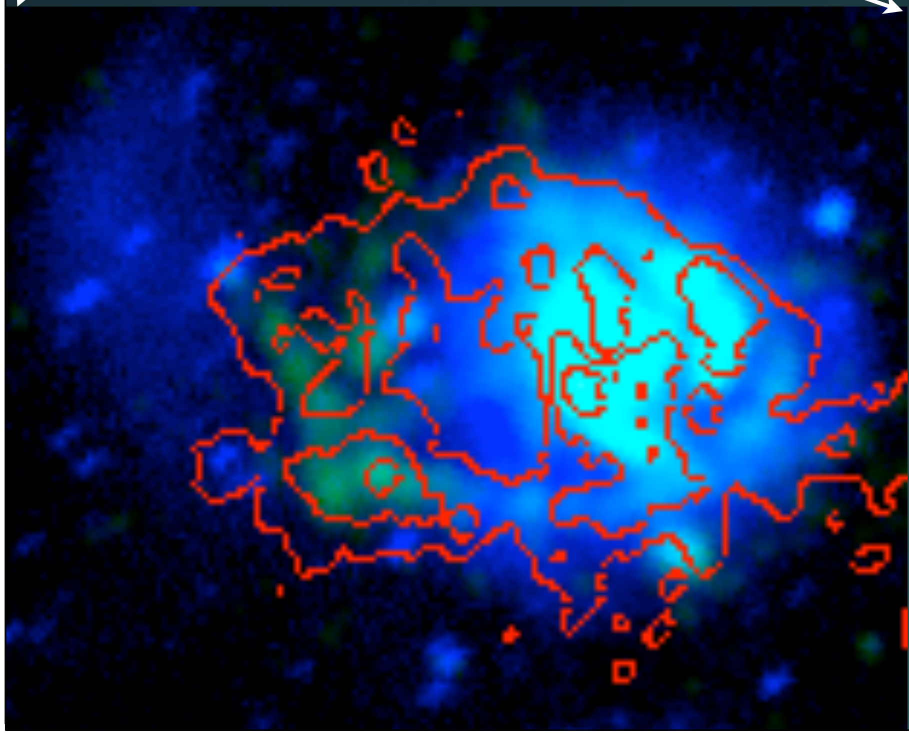
NGC2782

(see Nakamura's talk tomorrow)



Nearly head-on merger of 200Myr ago
A less massive galaxy collides from west

Filamentary structures at 7 and 11μm in the east side are well correlated with HI emission



HI and band carriers are stripped during merger and/or
band carriers are formed by shattering in cloud-cloud collisions

Then the carriers may survive for a long time

Revisit on dust lifetime

Jones & Nuth 2011 A&A, 530, A44

Stellar supply rate is more or less accurate
But dust species supplied from C-rich stars are not well understood
Mass-loss mechanism in O-rich stars is still uncertain
(e.g., Hofner 2008 A&A, 491, L1)

SN shock destroys dust as observed, but can also shatters
Sputtered atoms could recondense immediately

Estimate of dust lifetime is made in one-zone (e.g. McKee 1989)
and depends on a number of parameters (SN rate, locations, ..)
with a large uncertainty (> 50%)

Destruction time scale would be (0.3-10)x10^8yr for silicates
and (0.2-5.1)x10^8yr for a-C:H
being still short for a-C:H

Unless there is a significant error in the estimate of dust lifetime,
formation other than stellar sources seems necessary
to have high depletion of elements

Dust formation in dense clouds

Can silicates and carbonaceous grains form in dense clouds?
If they can, they may form as a mixture

Dust models may require independent silicate and carbon dust components, which may require chemistry controlled by C/O ratio

No relevant laboratory experiments are available for dust formation in dense clouds except for Nuth & Moore (1988, 1989), which suggests silicate formation at 10K,
but whose spectra do not match with observations

Observations of background stars in dense clouds at MIR may be useful for further understanding of dust formation in dense regions

Summary

B stars represent the present ISM abundance
ISM abundance has not changed in the last ~5Gyr

Interstellar depletion observations indicate missing O
and separate population of Fe-bearing dust

X-ray high-resolution spectroscopy is a promising means for the study of dust composition; accurate laboratory data are needed

Detection of SN ejecta dust requires high spatial resolution in FIR
SNe may form dust very efficiently

SN shocks sputter and shatter dust grains

Unless we underestimate the dust lifetime significantly,
dust must form in other than stellar sources efficiently
Dust may survive longer than prediction

Dust formation in dense clouds needs further investigation
Presently available laboratory data do not match with observations

The Life Cycle of Dust in the Universe: Observations, Theory, and Laboratory Experiments

Time: November 18-22, 2013

Place: Taipei, Taiwan

http://events.asiaa.sinica.edu.tw/meeting/20131118/index.php

Pre-registration is now open


Thank you for your attention