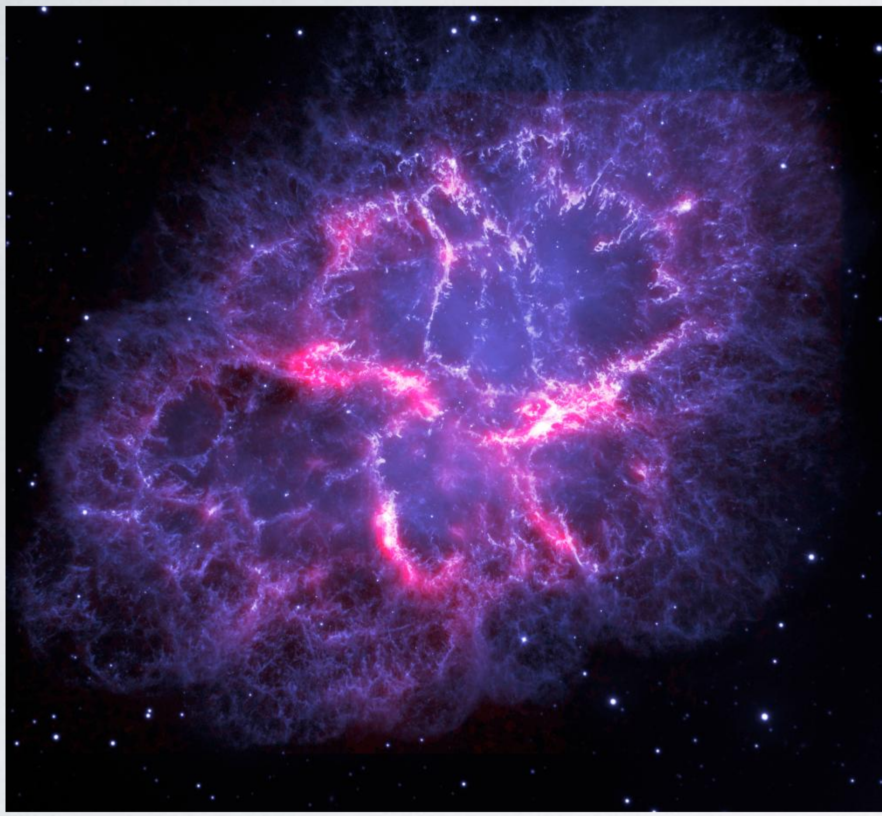
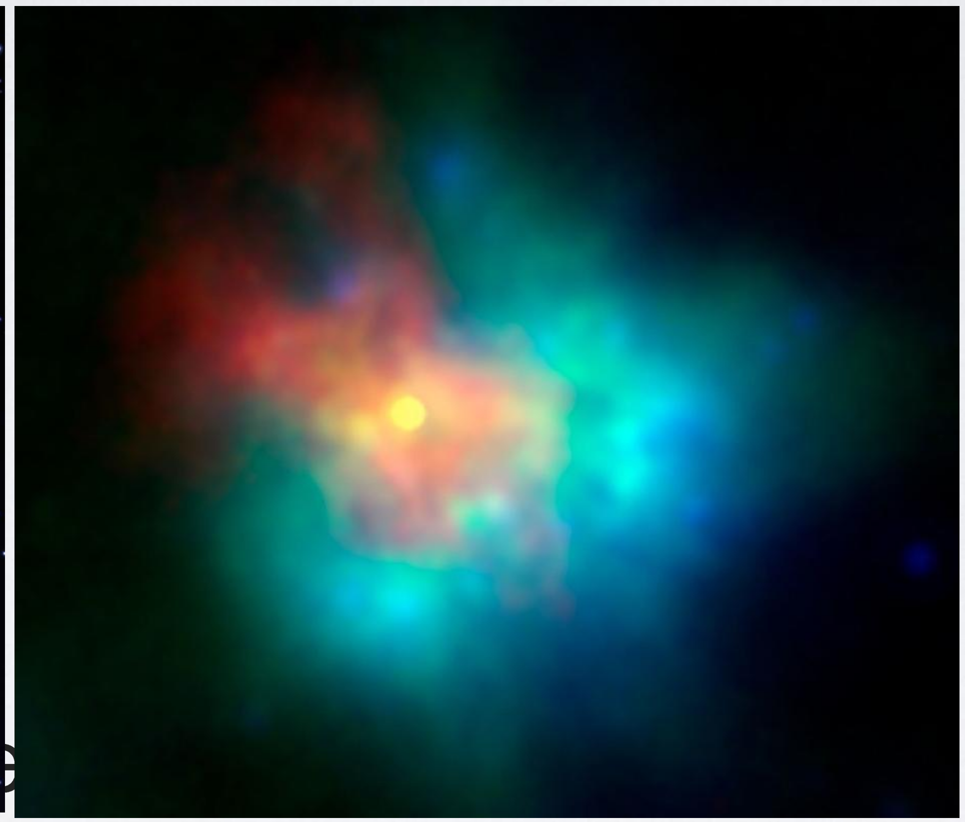
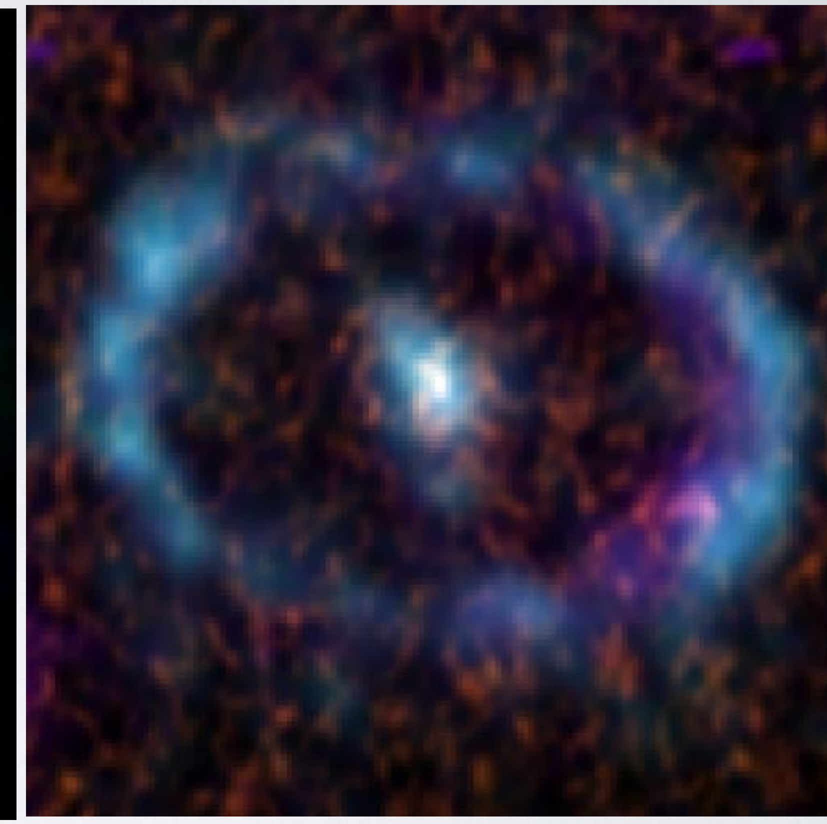
SUPERNOVA DUST FACTORIES

Haley Gomez and Mike Barlow

with Mikako Matsuura, Phil Cigan, Hannah Chawner, Jeonghee Rho, Ilse De Looze, Matt Smith, Loretta Dunne

European Research Council
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CARDIFF UNIVERSITY
PRIFYSGOL CAERDYD
COSMIC DUST
SNDUST

THE DUSTY UNIVERSE

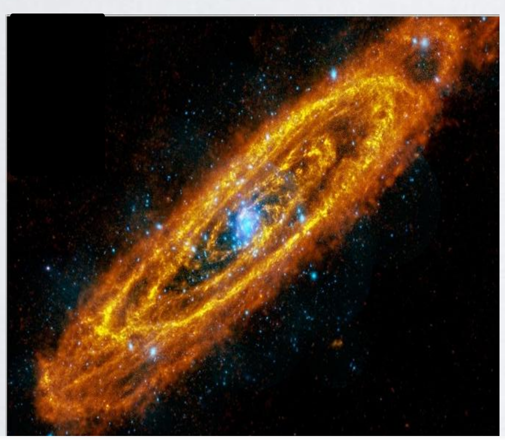
Galaxies at z>4 very dusty

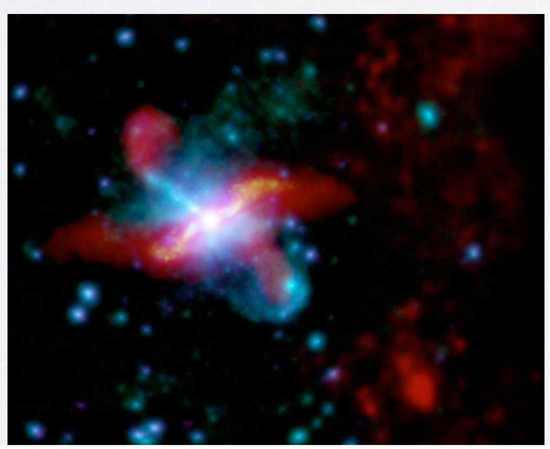
Morgan & Edmunds 2003
Hirashita+ 2014, Gall+ 2011, Dwek+2007, Valiante+2011, Asano+ 2013, Venemans+ 2017a,b, Marrone+ 2017

Also z = 6.4-8.6 @ ~300Myrs

Dwek+ 2007, Watson+ 2015, Laporte+ 2017

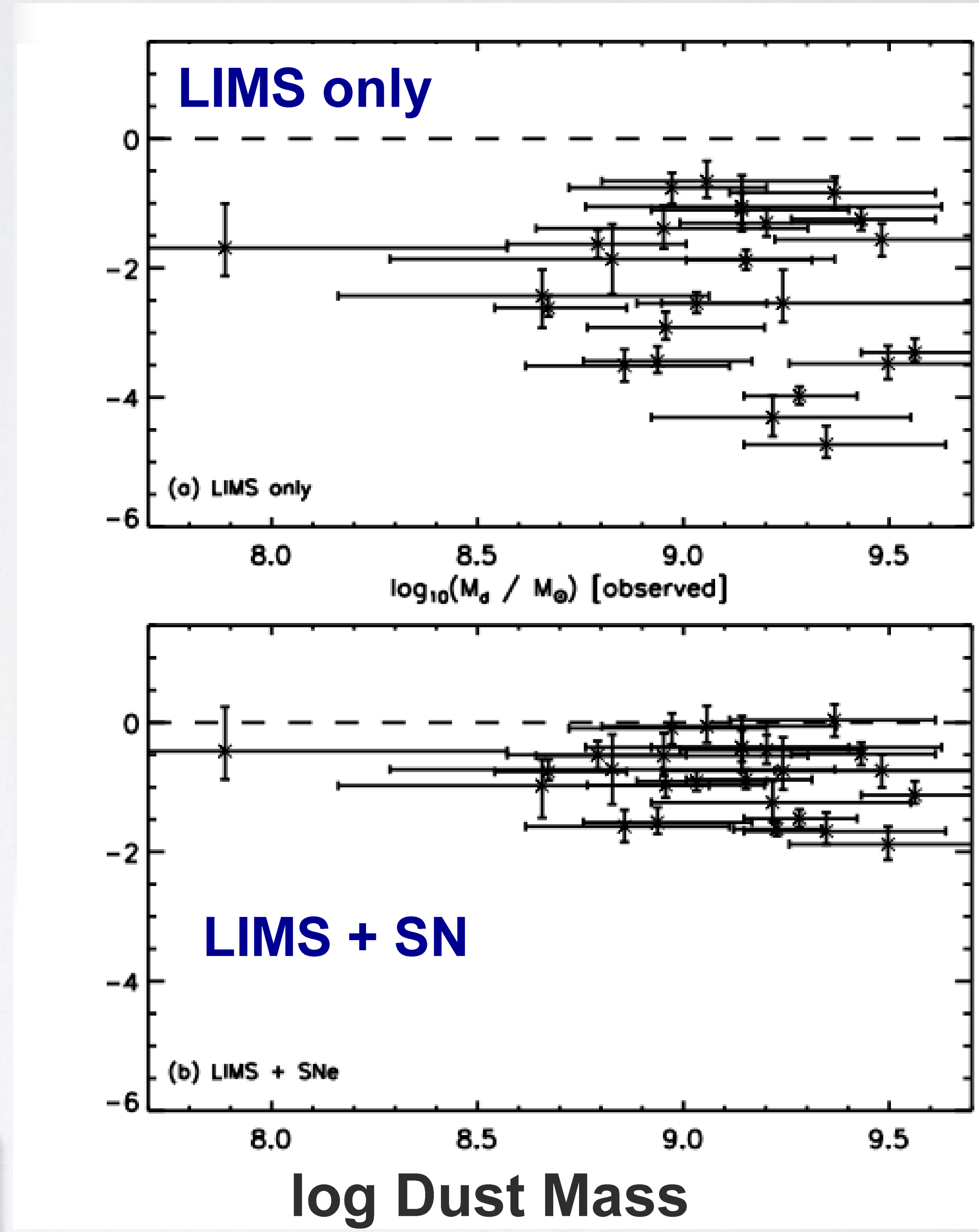
Same for local galaxies





need 0.1-1Msun of dust per SN

Temim+2015



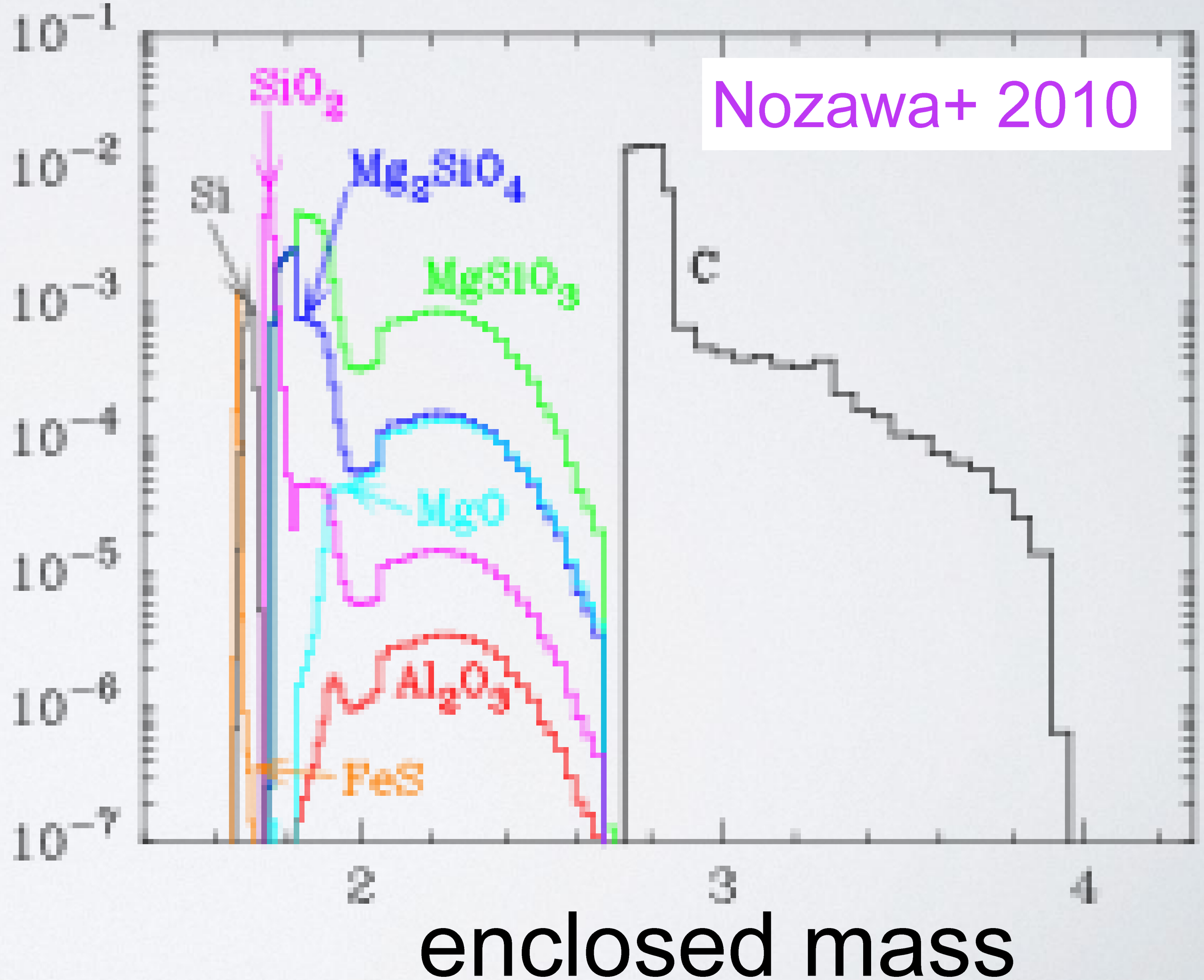
Rowlands,Gomez+ 2014

DUST FORMATION THEORY:

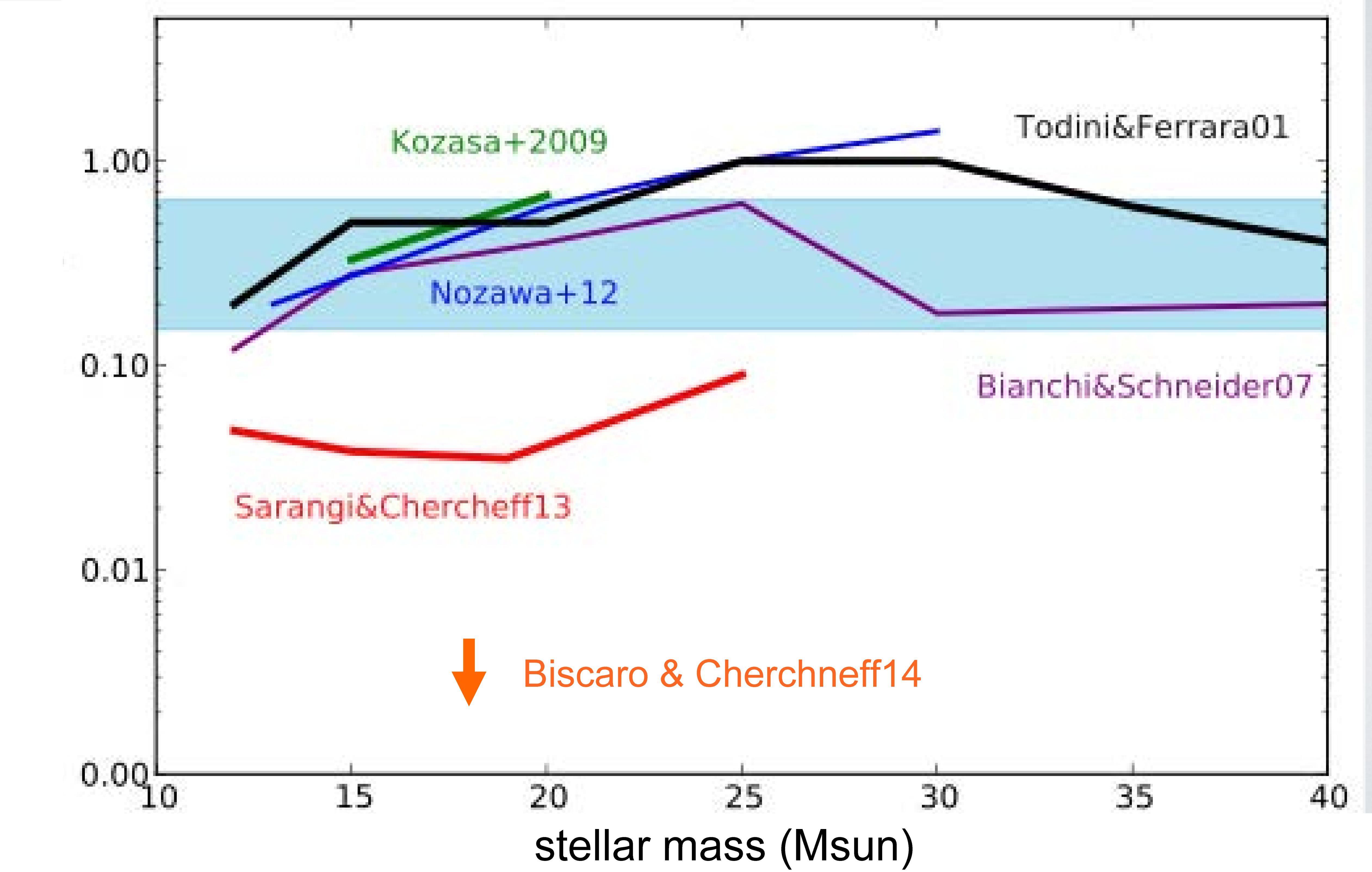
CHEMICAL KINETICS: CHERCHNEFF & DWEK 2009; SARANGI & CHERCHNEFF 2013, CLAYTON 1999, 2001, NOZAWA & KOZASA 2013

CLASSICAL NUCLEATION

KOZASA+. 1989, TODINI & FERRARA 2001, NOZAWA ET AL. 2003, 2007, 2010, 2012



PREDICTED YIELDS FROM DIFFERENT MODELS



HOW DO WE OBSERVE DUST IN SUPERNOVAE?

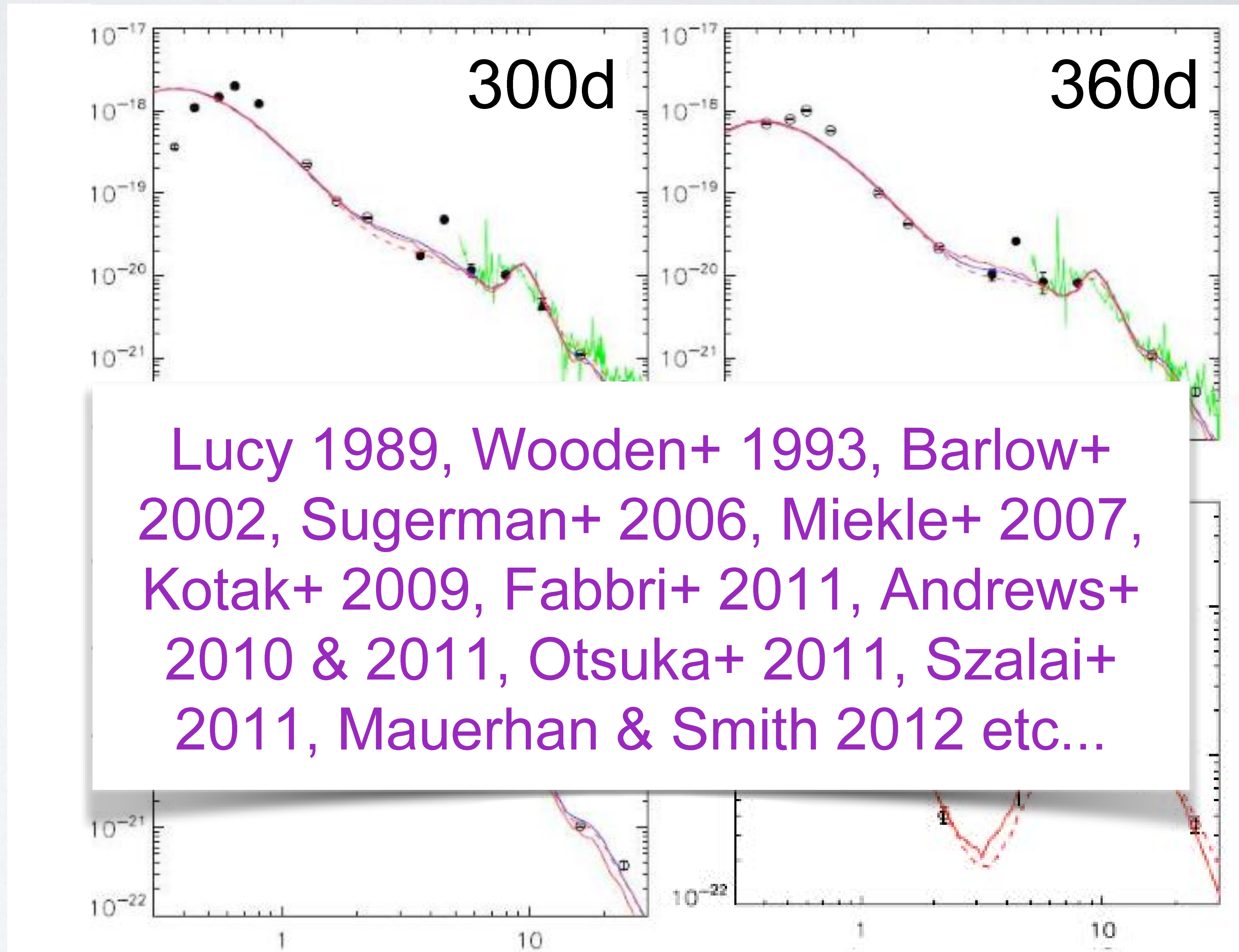
i) onset of dust formation in mid IR

ii) dip in light curve

iii) red-blue asymmetry in optical line profiles

iv) thermal FIR emission

SN2004et - Fabbri et al 2011

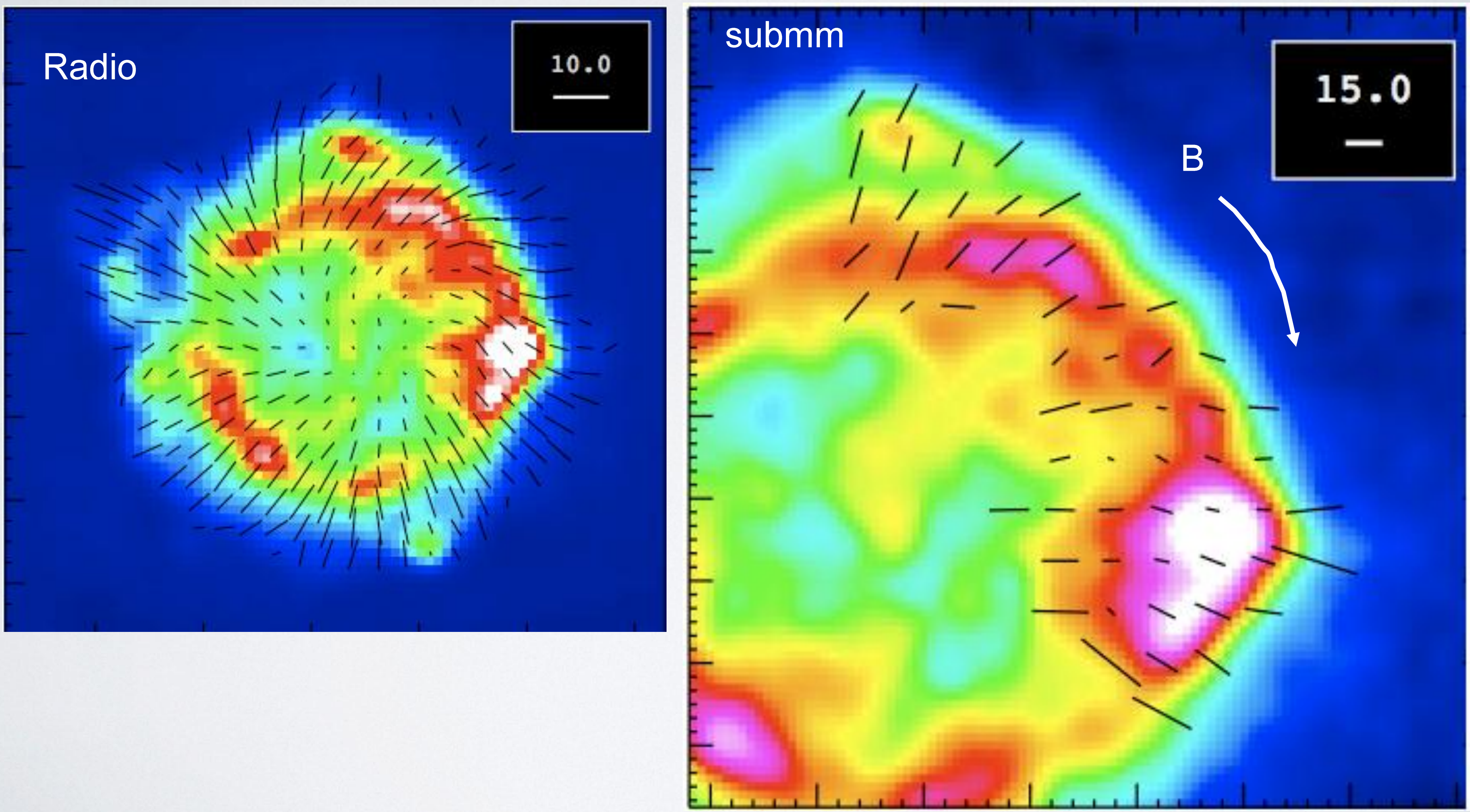


Lucy 1989, Wooden+ 1993, Barlow+ 2002, Sugerman+ 2006, Miekle+ 2007, Kotak+ 2009, Fabbri+ 2011, Andrews+ 2010 & 2011, Otsuka+ 2011, Szalai+ 2011, Mauerhan & Smith 2012 etc...

wavelength (micron)

THE SPITZER, HERSCHEL AND ALMA ERA

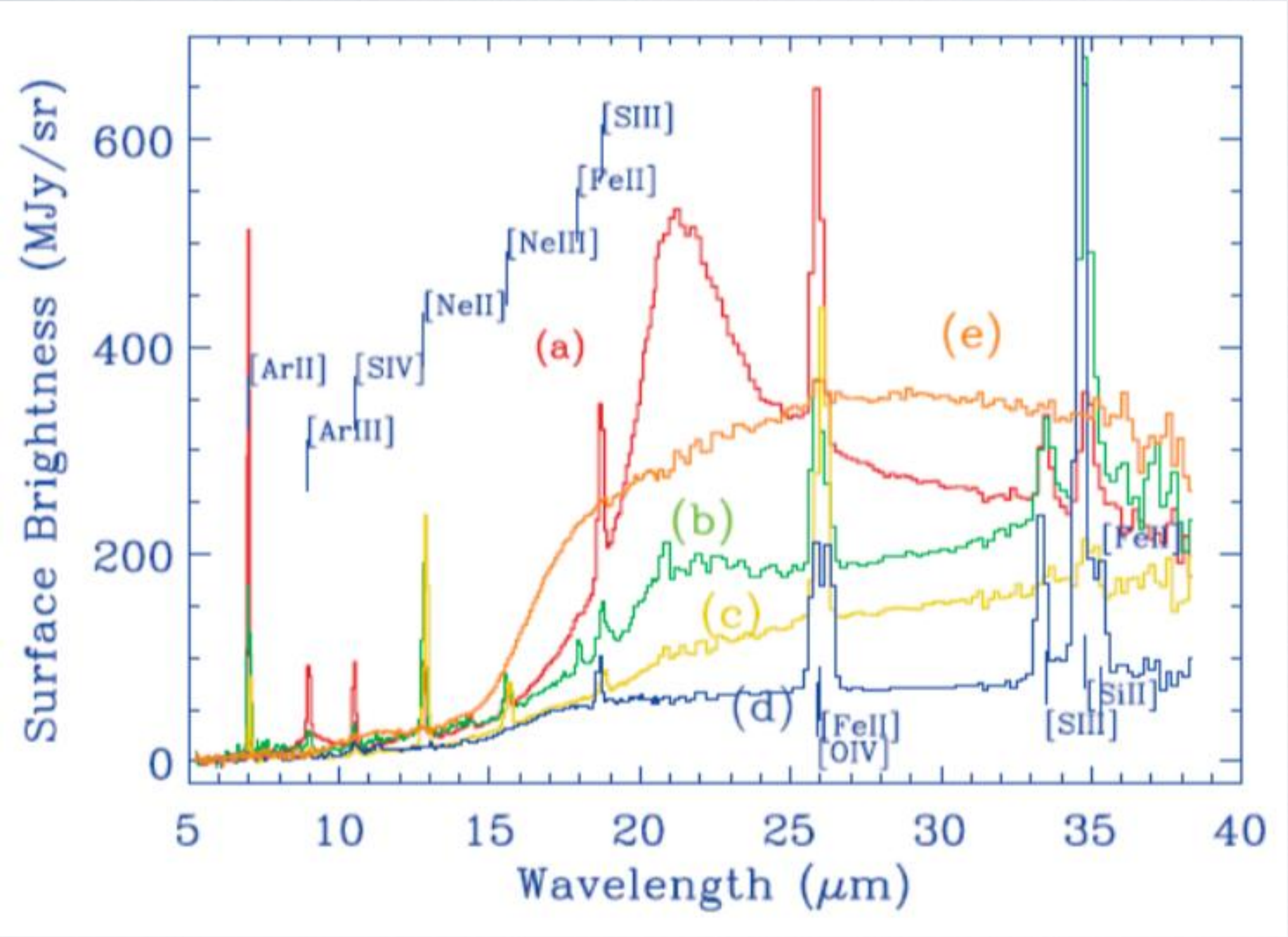
SCUBA: A COLD DUST FACTORY

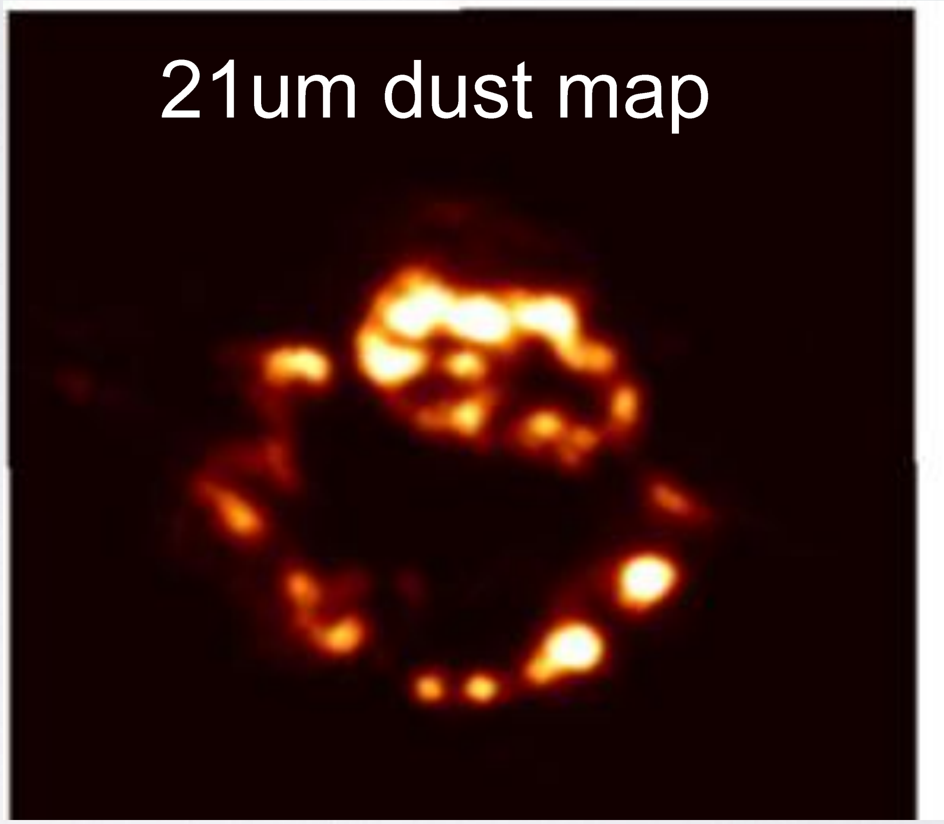


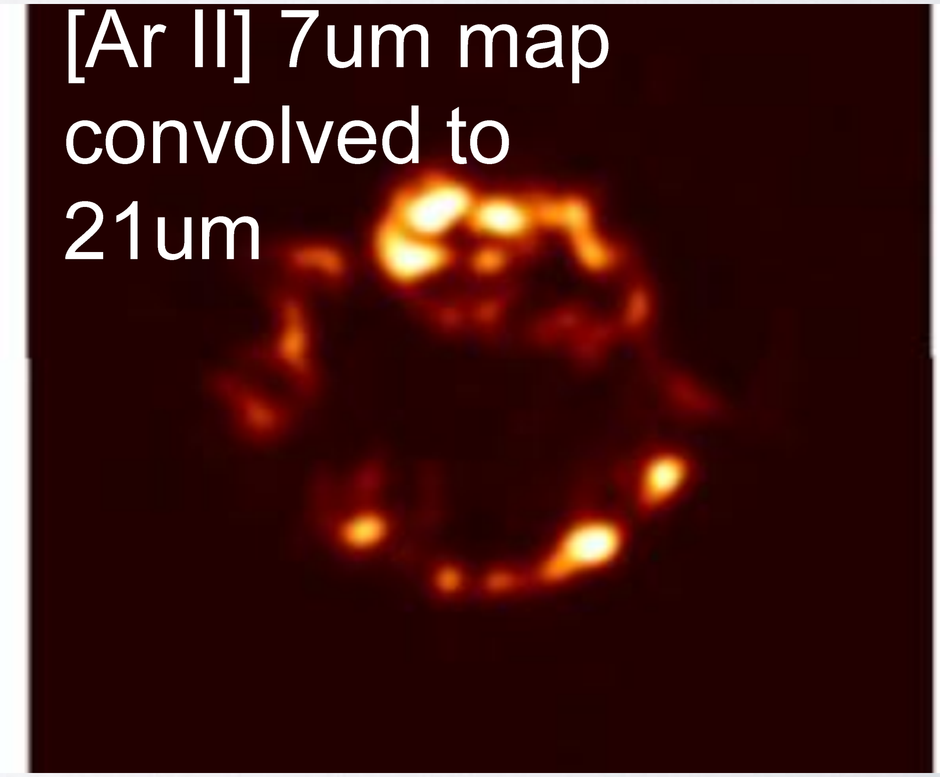
1 Msun of dust @ 20K

Dunne+ 2003, Dunne+ 2009

SPITZER: DUST IN SHOCKED EJECTA

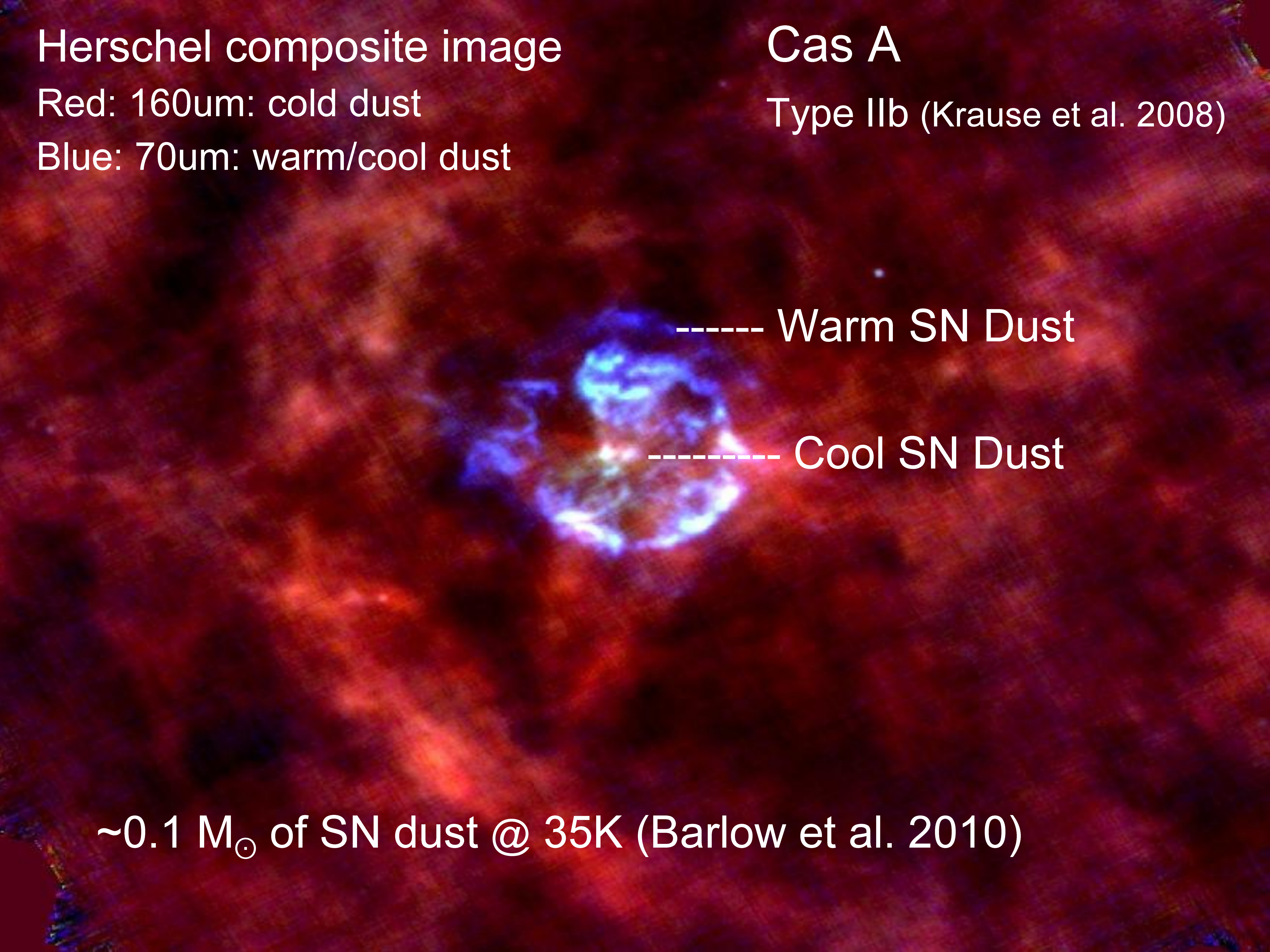




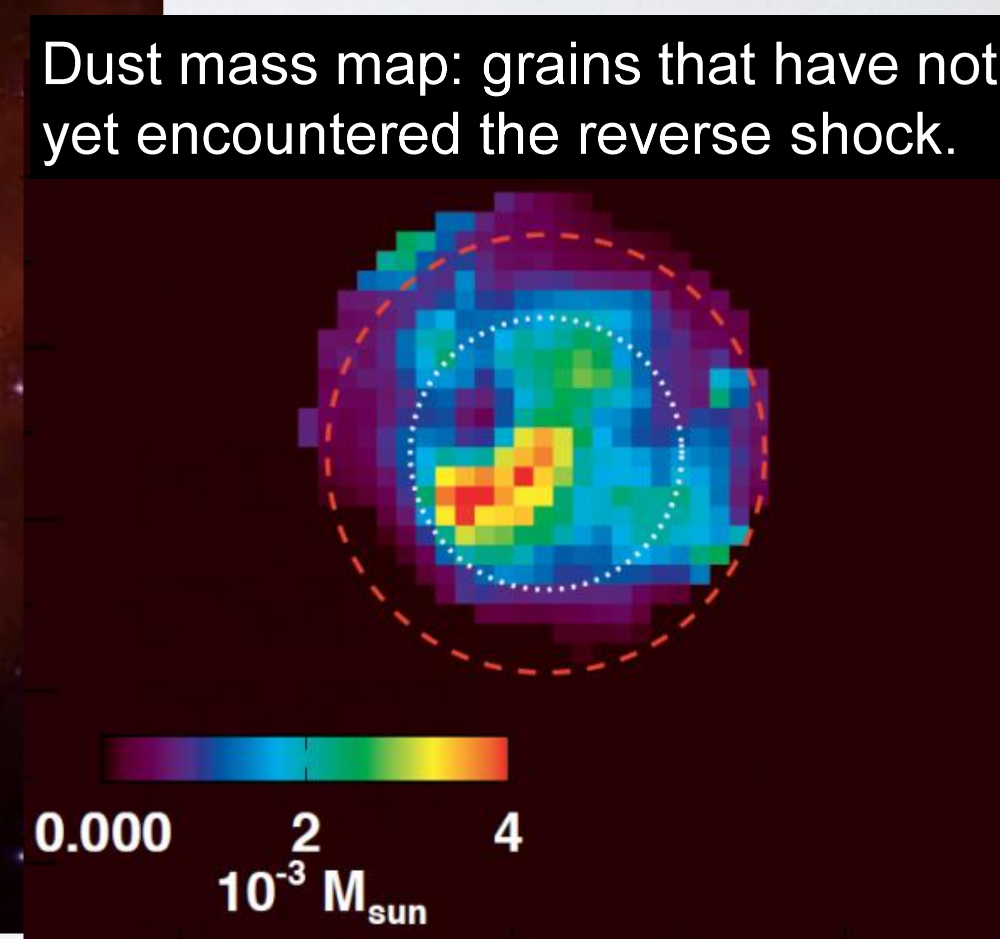


0.02 – 0.054 Msun of dust @ ~50K

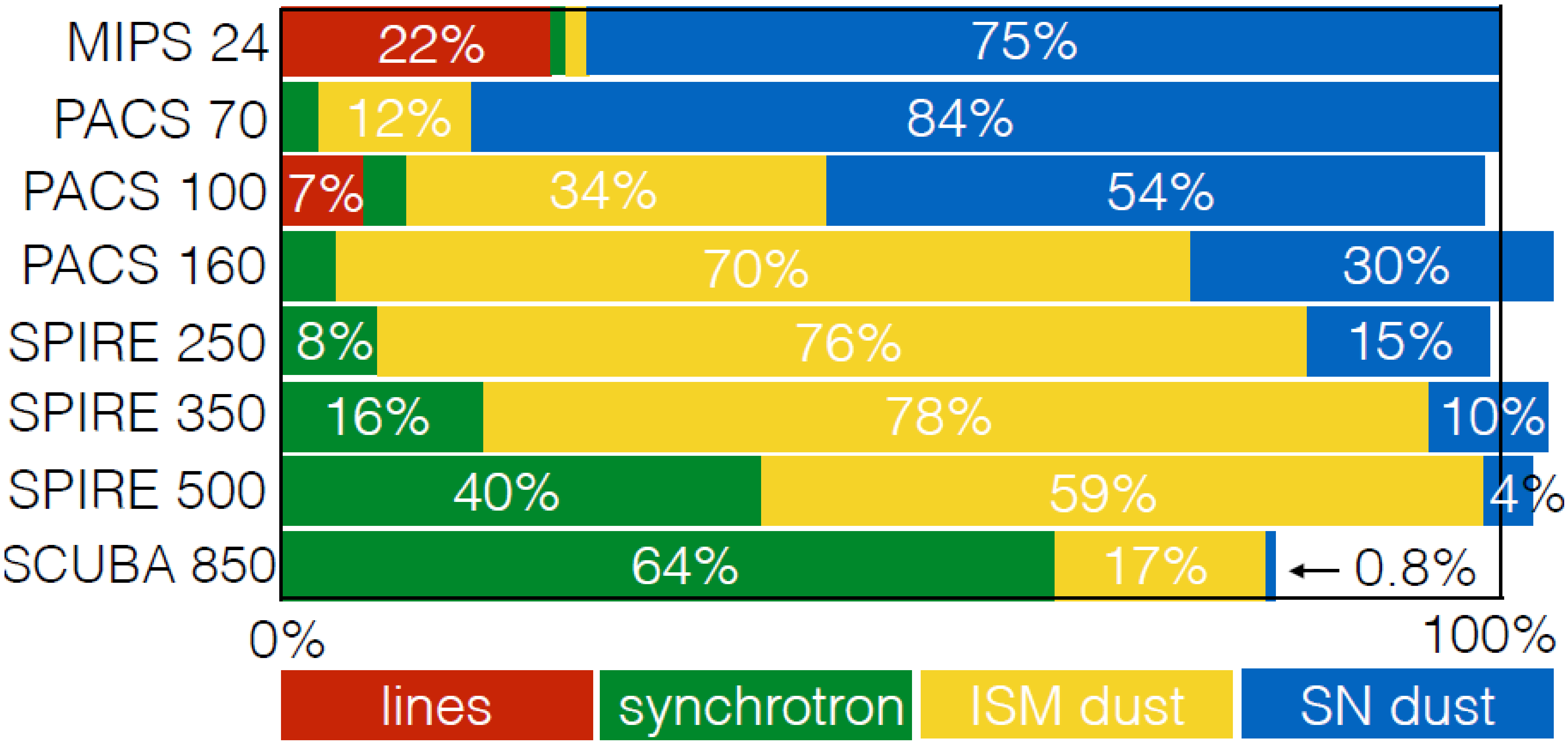
Rho et al 2008


Herschel composite image
Red: 160um: cold dust
Blue: 70um: warm/cool dust
Cas A
Type IIb (Krause et al. 2008)
------- Warm SN Dust
---------- Cool SN Dust
~0.1 $M_{\odot}$ of SN dust @ 35K (Barlow et al. 2010)

A REVISED DUST MASS FROM MODELLING THE FOREGROUND AND BACKGROUND ISM DUST EMISSION

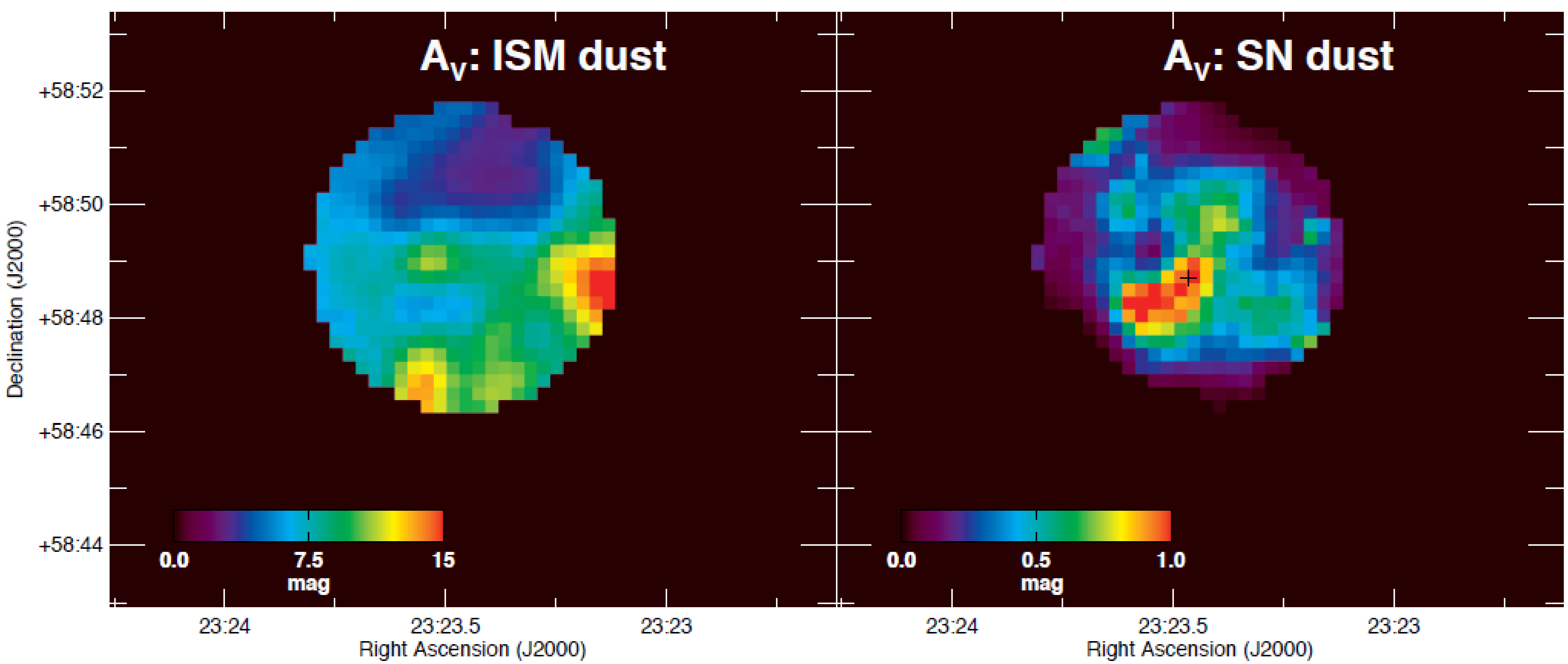


De Looze+ 2017



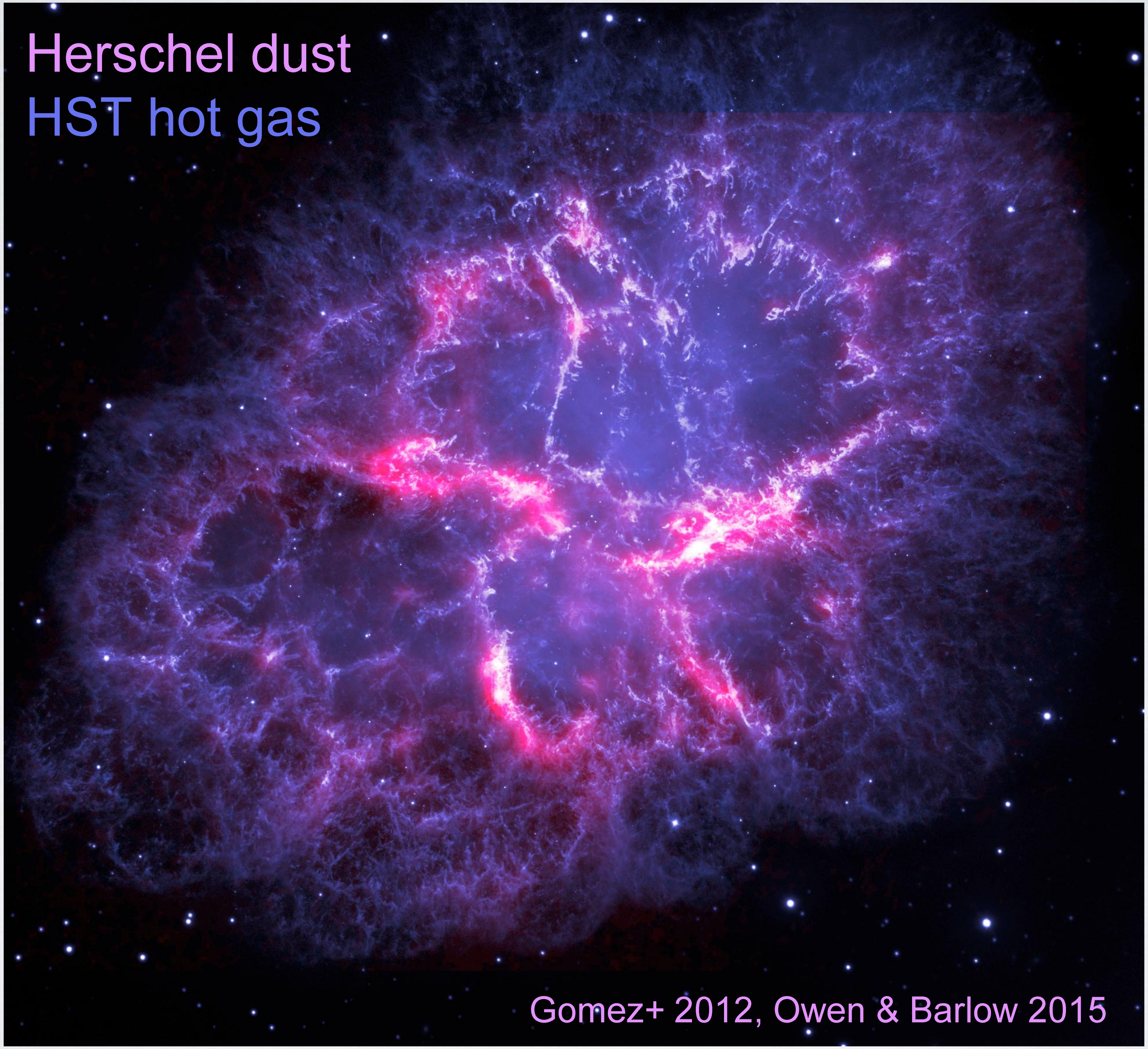
Cas A

De Looze et al. 2017



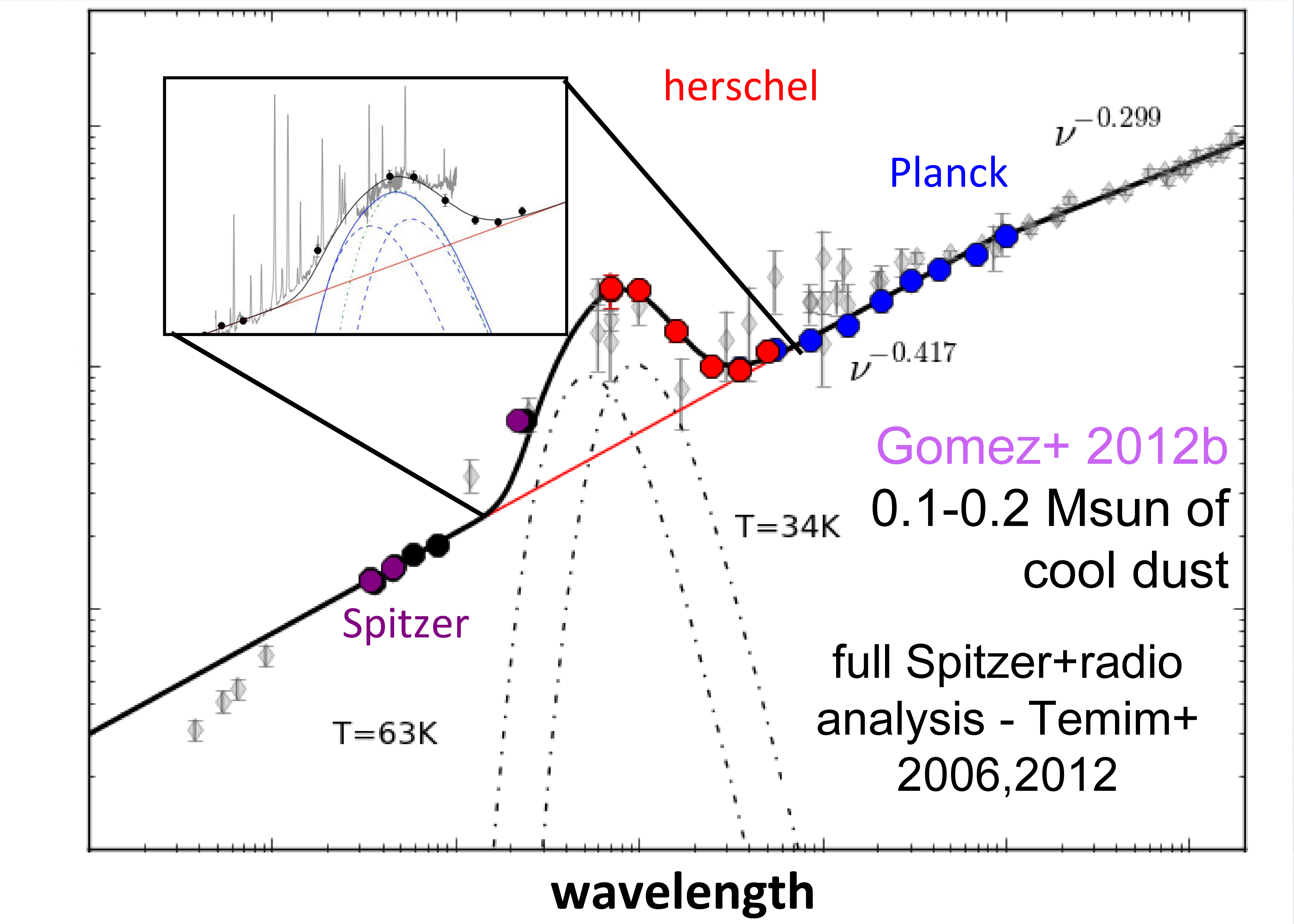
Total Cas A dust mass = 0.3-0.5 Msun (silicates)

WANT SOME DUST WITH YOUR CRAB?



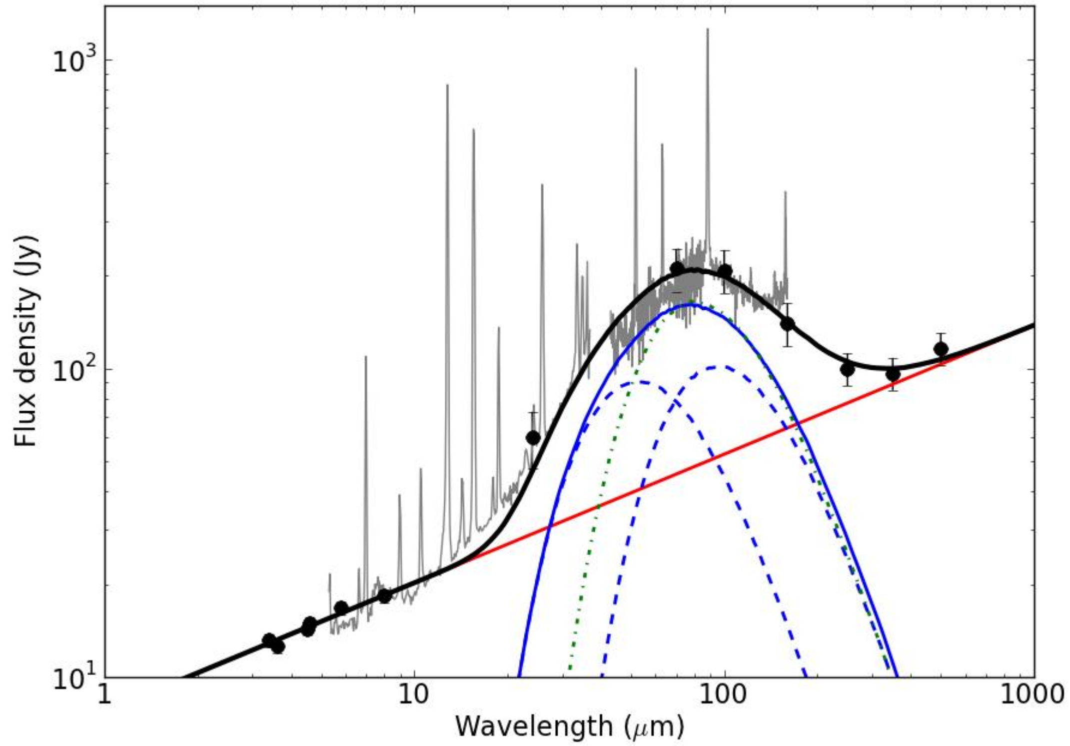
Type IIn-P Smith 2013

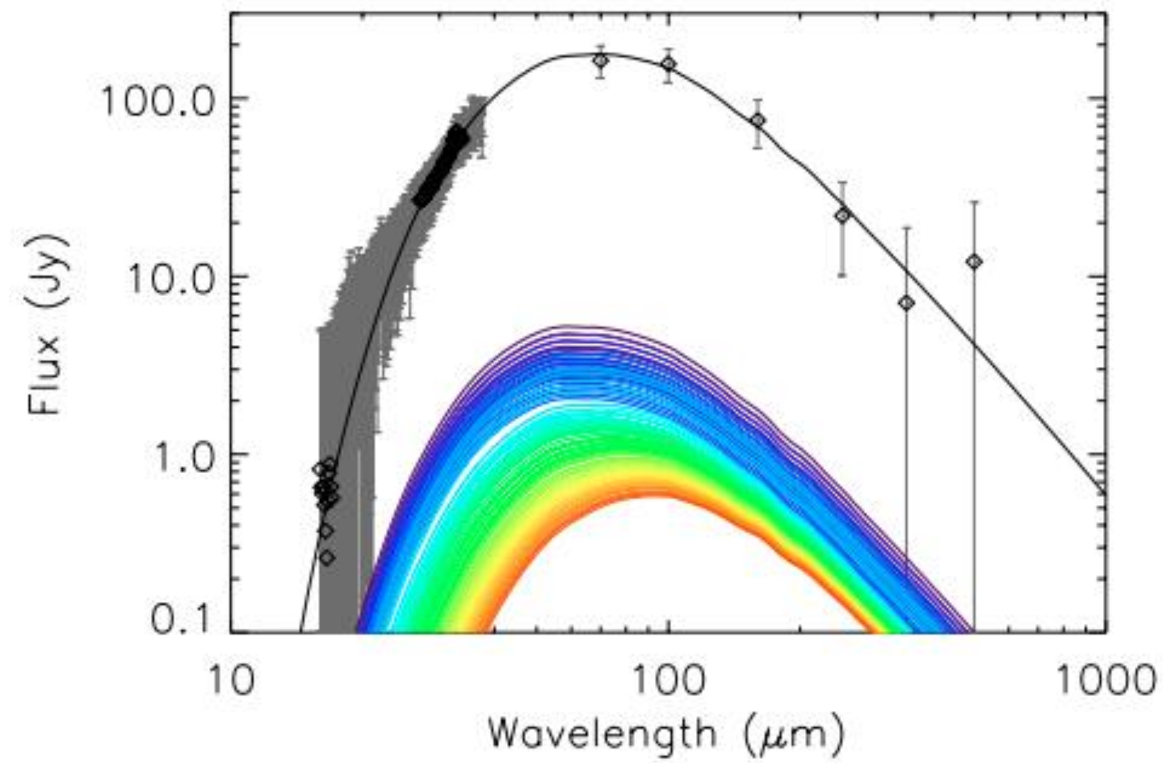
DISENTANGLING THE COMPONENTS



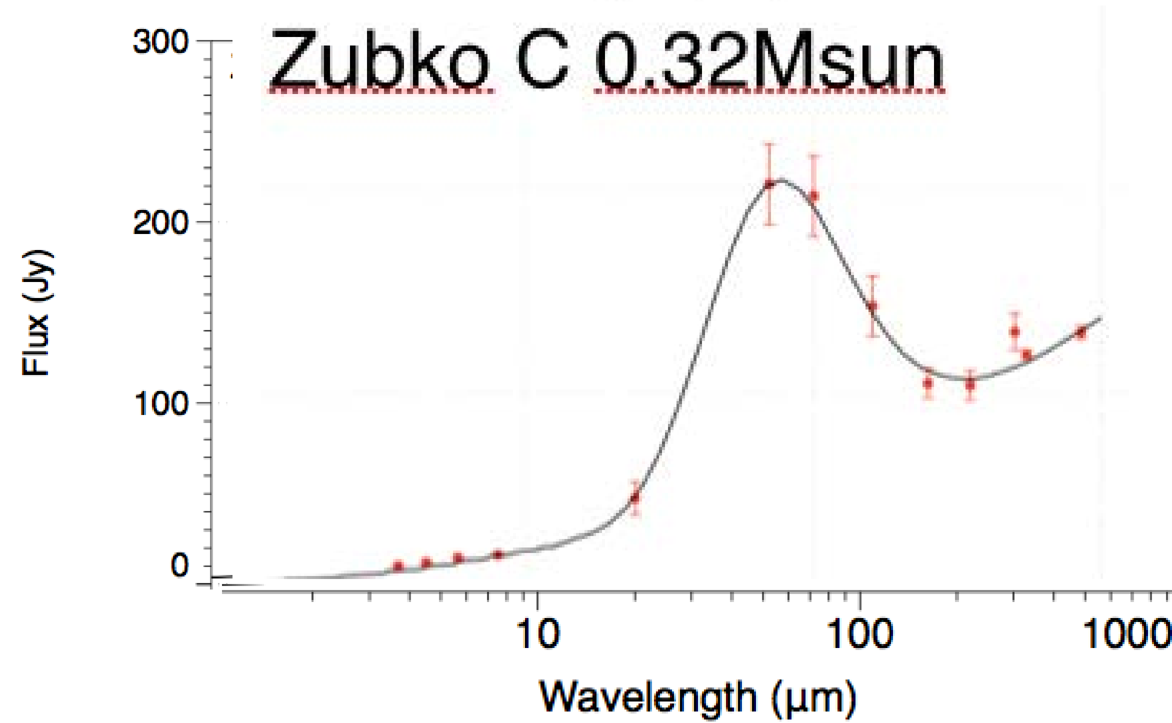
HOW UNCERTAIN IS THE DUST MASS?

Gomez et al. 2012: 0.11-0.24 Msun of dust vs. Temim & Dwek 2013: 0.019 – 0.13 Msun of dust





see also Mattsson, HLG+ MNRAS 2015

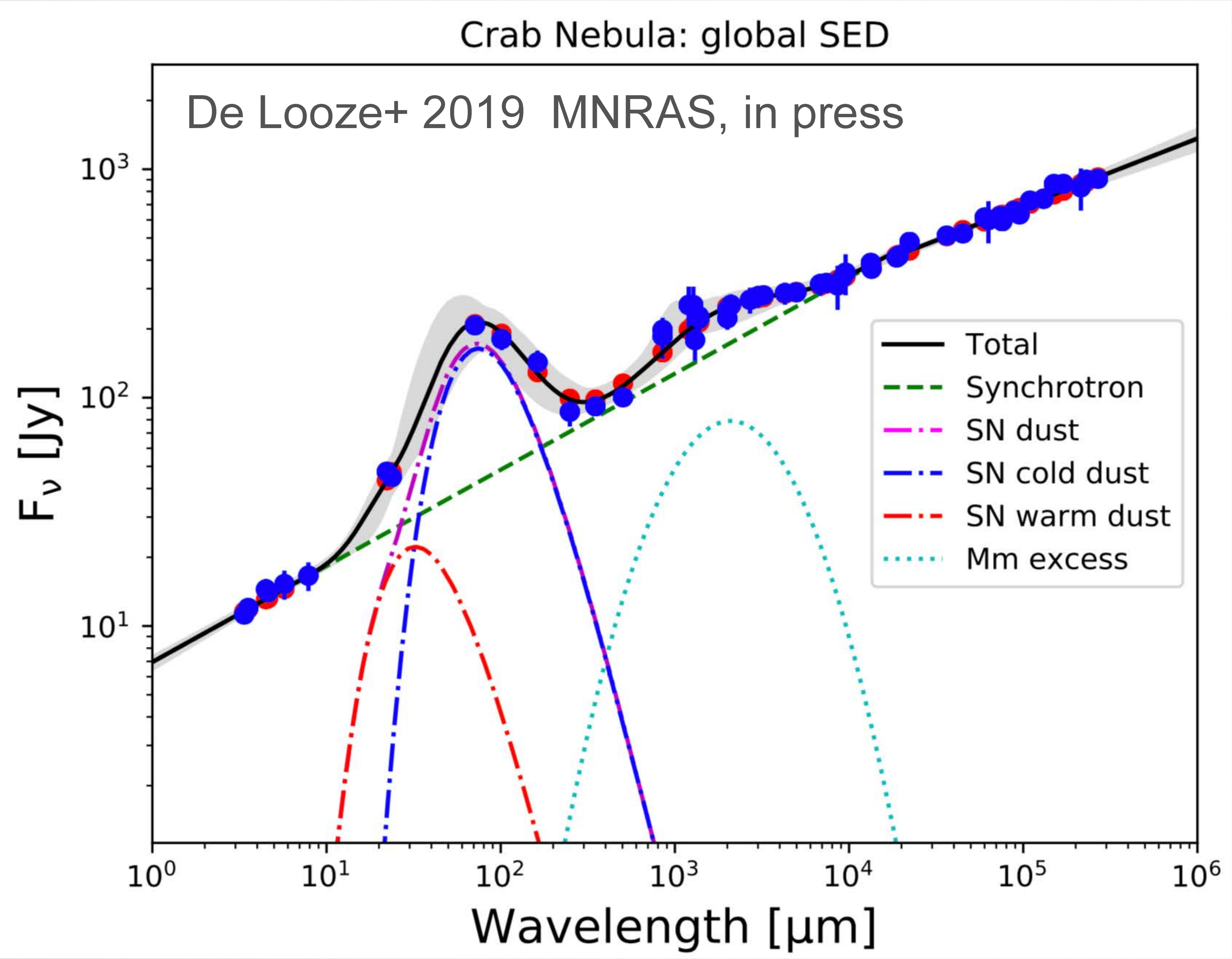


RT models by Owen & Barlow 2015 needed 0.18-0.5 M_{sun}

De Looze+ MNRAS, in press and Poster S5.8

THE CRAB REVISITED

Bayesian MCMC spatially resolved modelling includes:



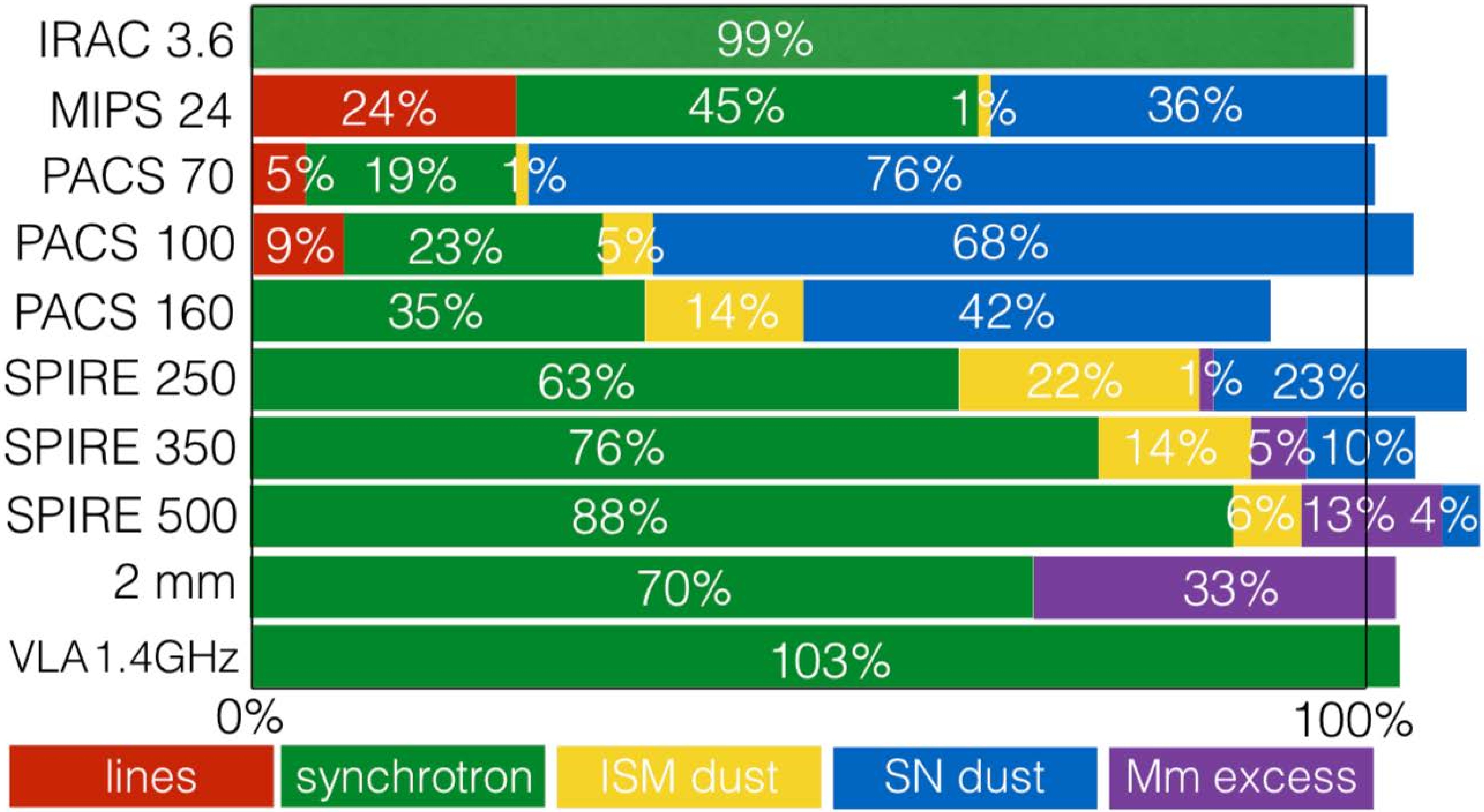
- synchrotron power law with spectral break
- warm+cold SN dust SED
- mm xs. emission (log-normal)

↓

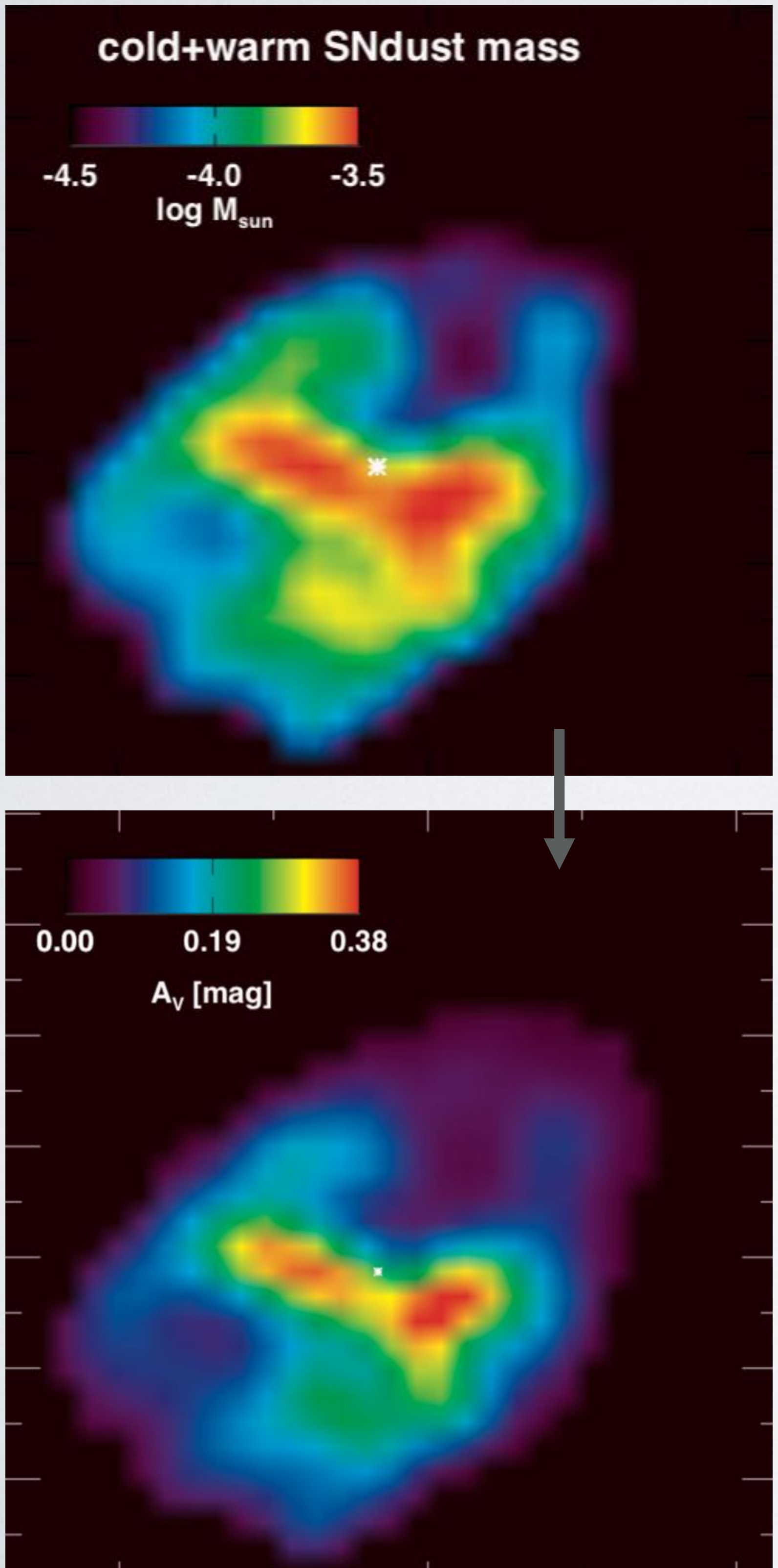
11 free parameters

CRAB: SPLITTING INTO ITS COMPONENTS

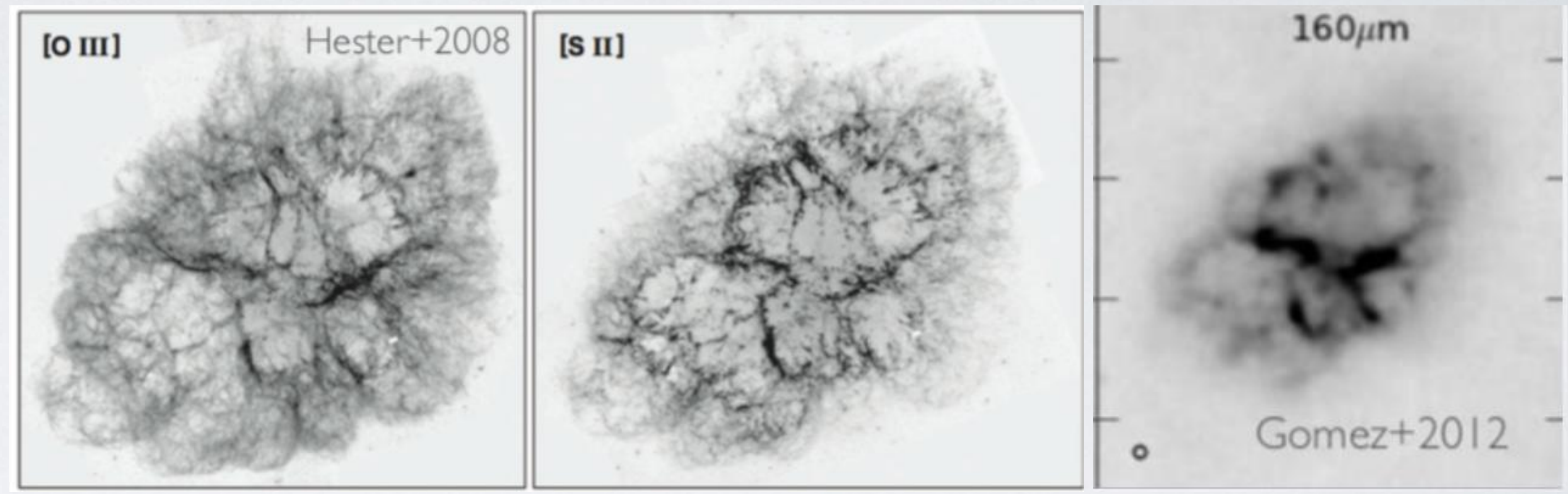
De Looze+ MN, and Poster S5.8



A NEW CRAB DUST MASS



1. Dust production = elevated in dense filaments



2. Total dust mass (a-C grains, Jones+2012a,b,c): **0.032-0.049 M_{sun},** lower than most previous estimates due to: * lower SPIRE 500 flux
   * interstellar dust corrections (up to 20%)
   * higher average T_{dust} (41±3K)
3. A_V (between 0.20 and 0.38) = consistent with optical globules (Grenman+2017)
4. Dust condensation efficiency ~ 8-12%

Independent analysis: 0.056+-0.037 M_{sun} at T=42.1+-1.1K (Nehme+ arXiv:1903.03389)

CRAB: MM EXCESS?

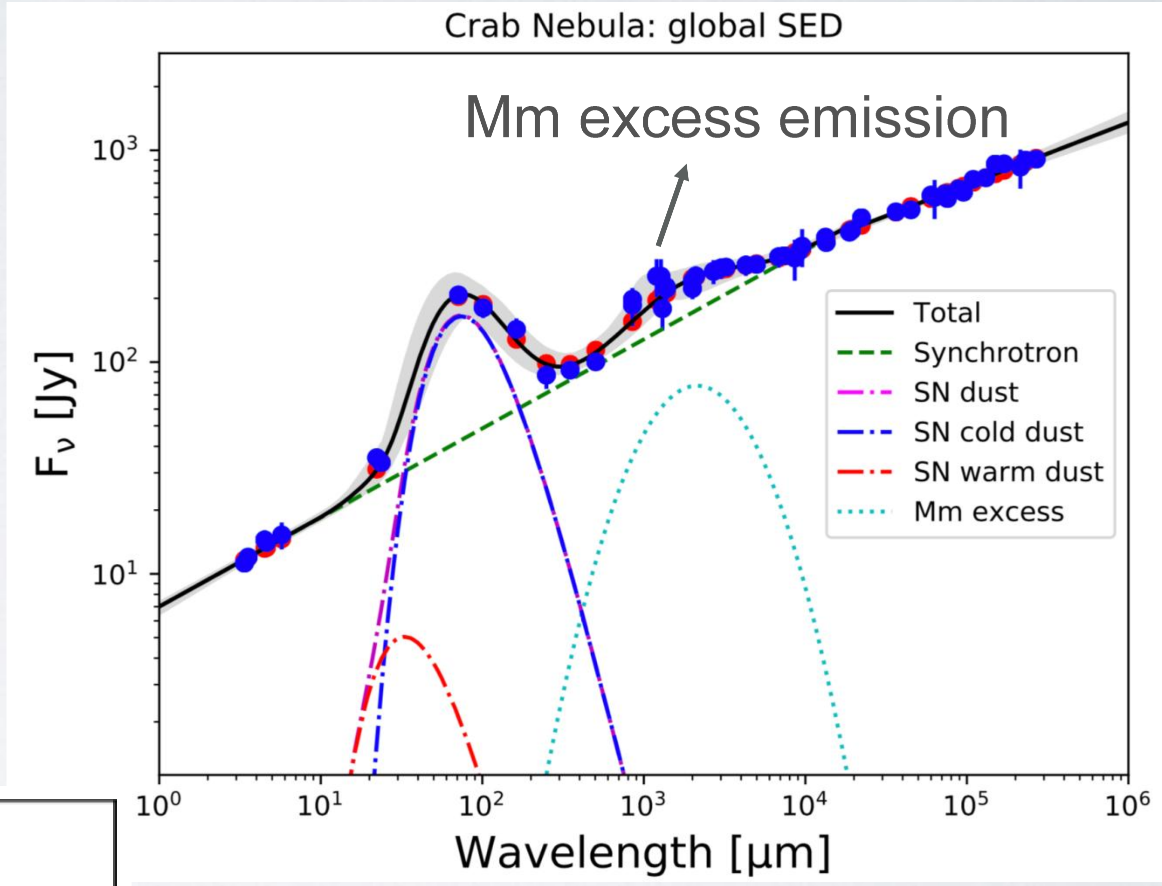
Possible explanations:

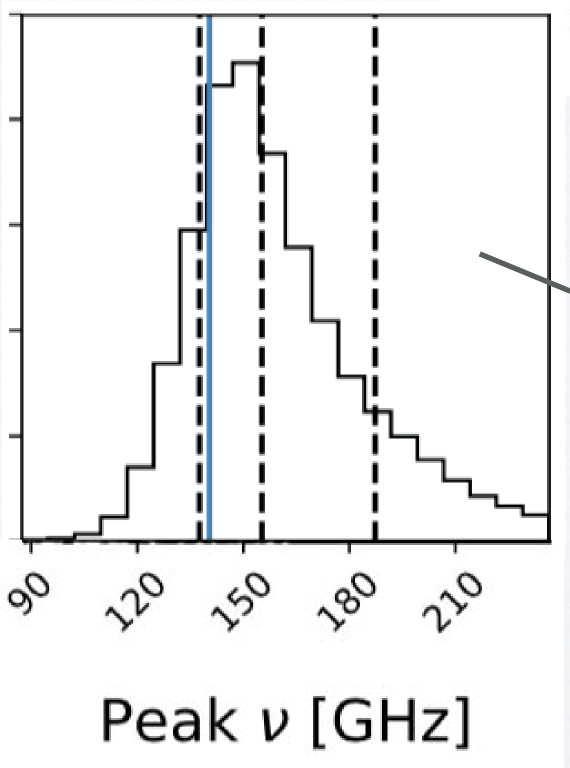
1. Secondary synchrotron component and/or multi-break spectrum

2. Free-free emission from hot plasma

3. Spinning dust grains

4. Magnetic (Fe-bearing grains)

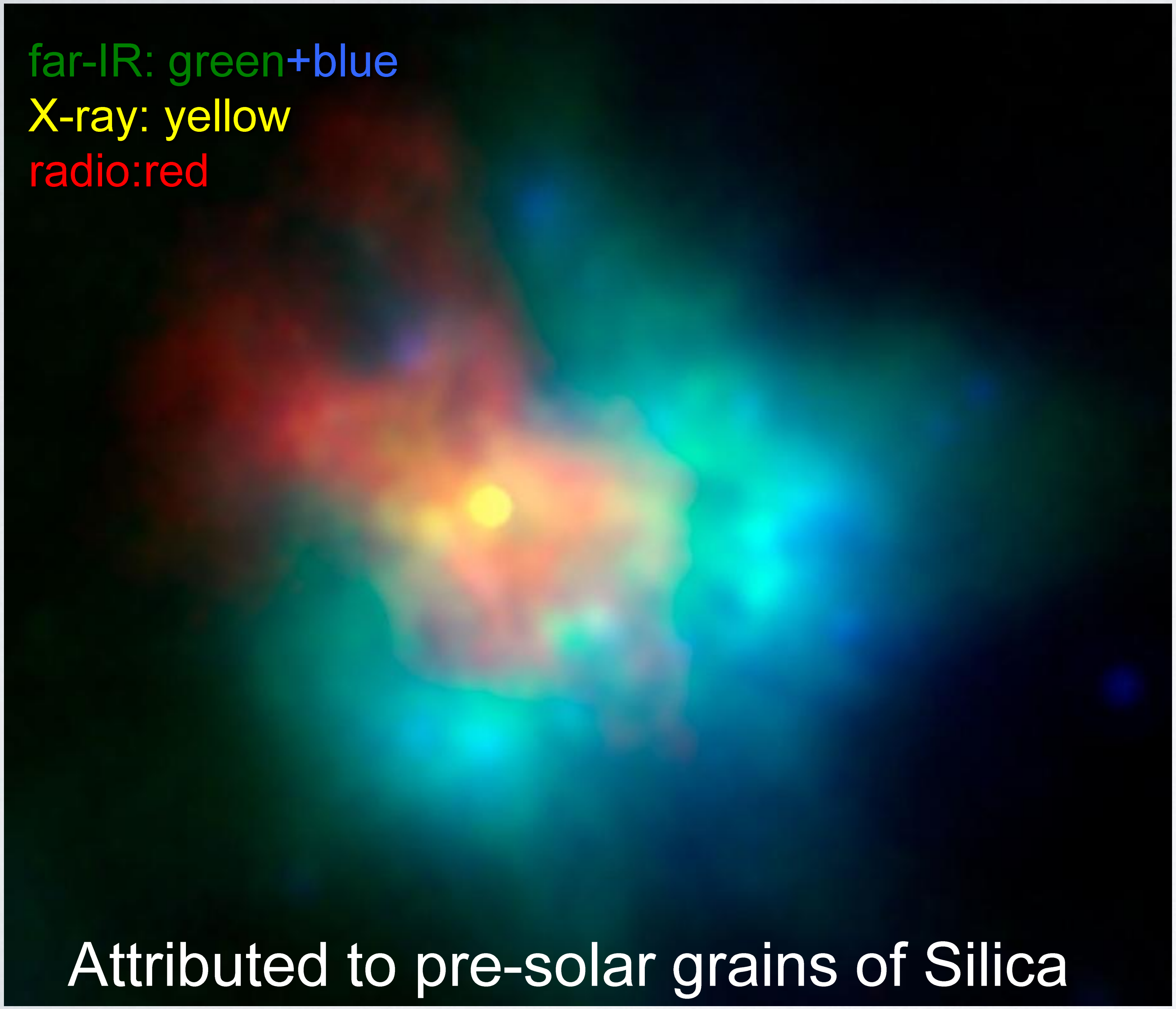




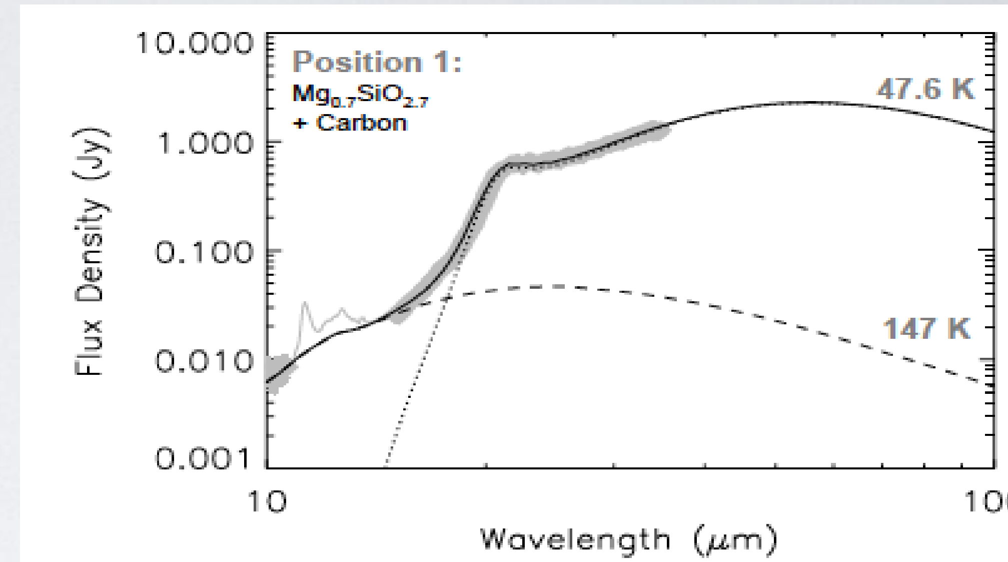
Excess peaks at 140-150 GHz (or around 2mm)

G54.1+0.3 - A DUST TWIN OF CAS A

contains a pulsar wind nebula

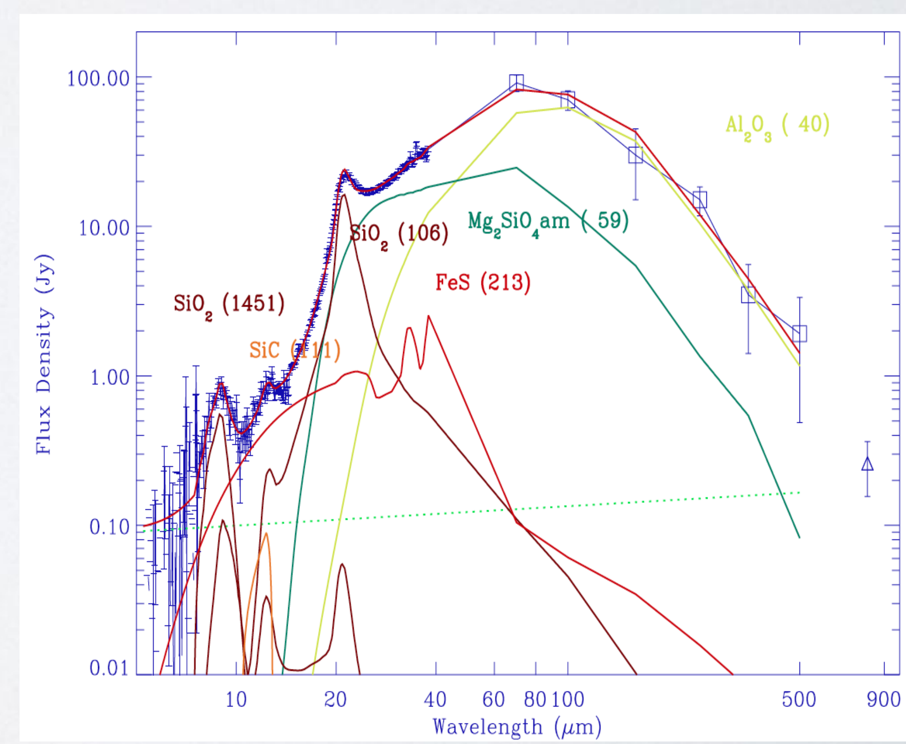


Rho+ 2018



Md ~1.1 $M_\odot$ Temim+ 2017

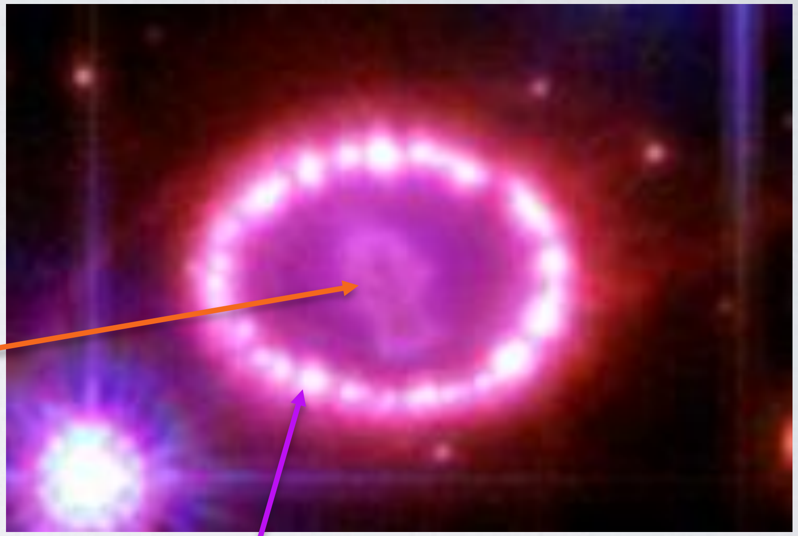
Md ~0.1-0.9 $M_\odot$ Rho+ 2018



DUST EMISSION IN SN 1987A

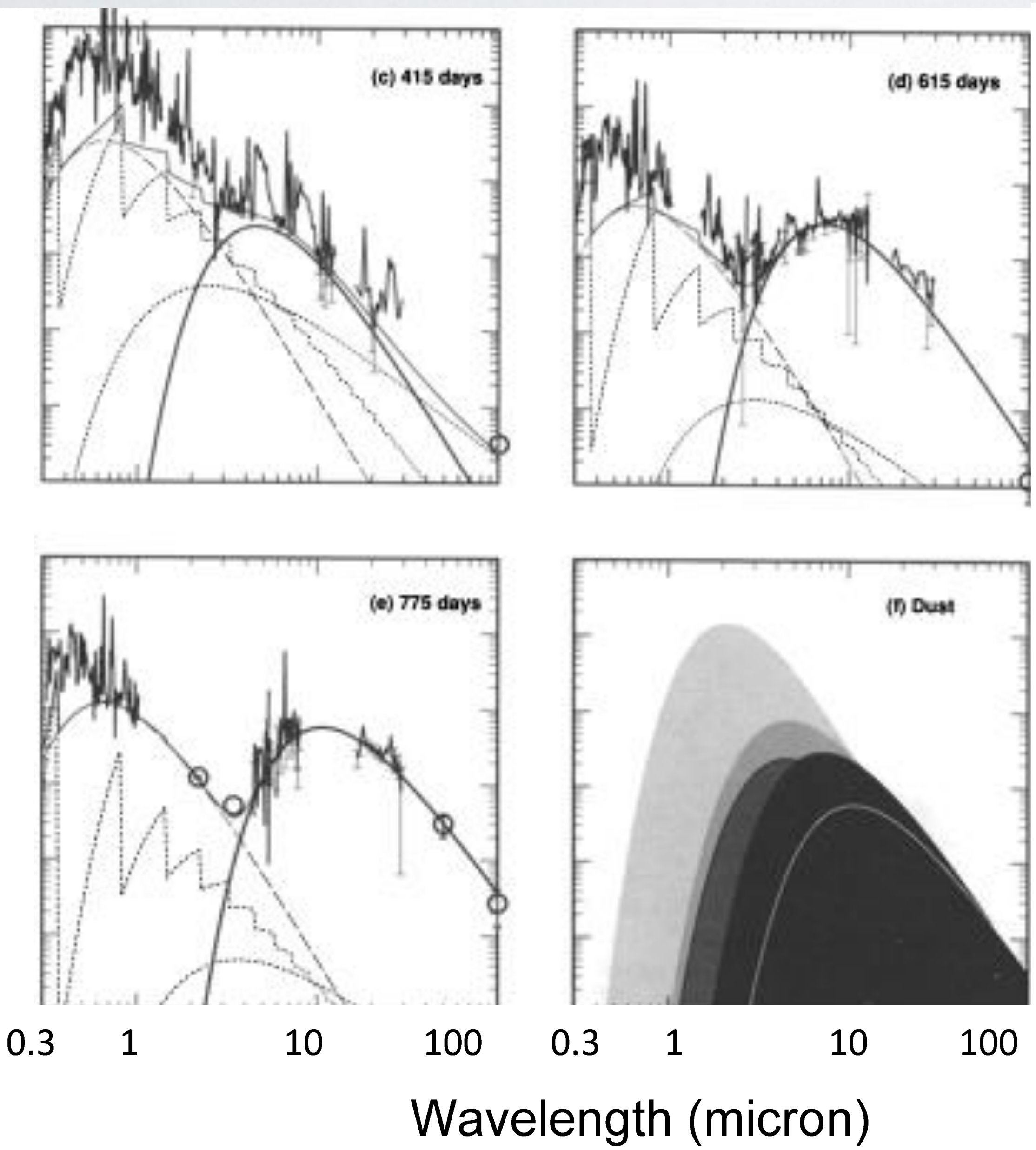
- 450-777 days
- $<10^{-3}$ M_{sun} dust

Lucy+ 1989; Wooden+ 1993, Bouchet+ 1991

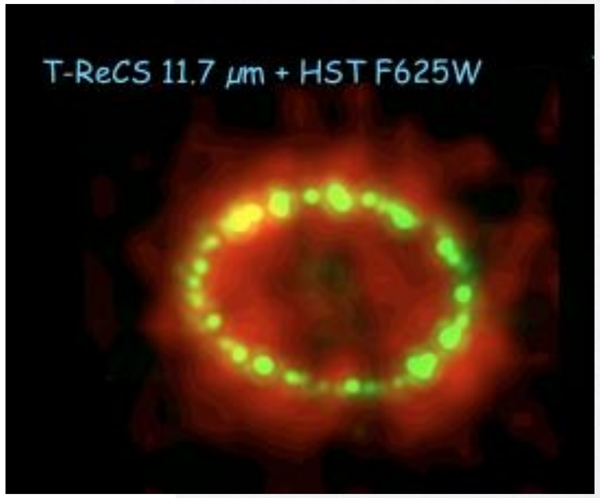


ejecta

ring: progenitor



Bouchet+ 2006



Day 1731,
MIR observations see ring $\sim 10^{-6}$ M_{sun}

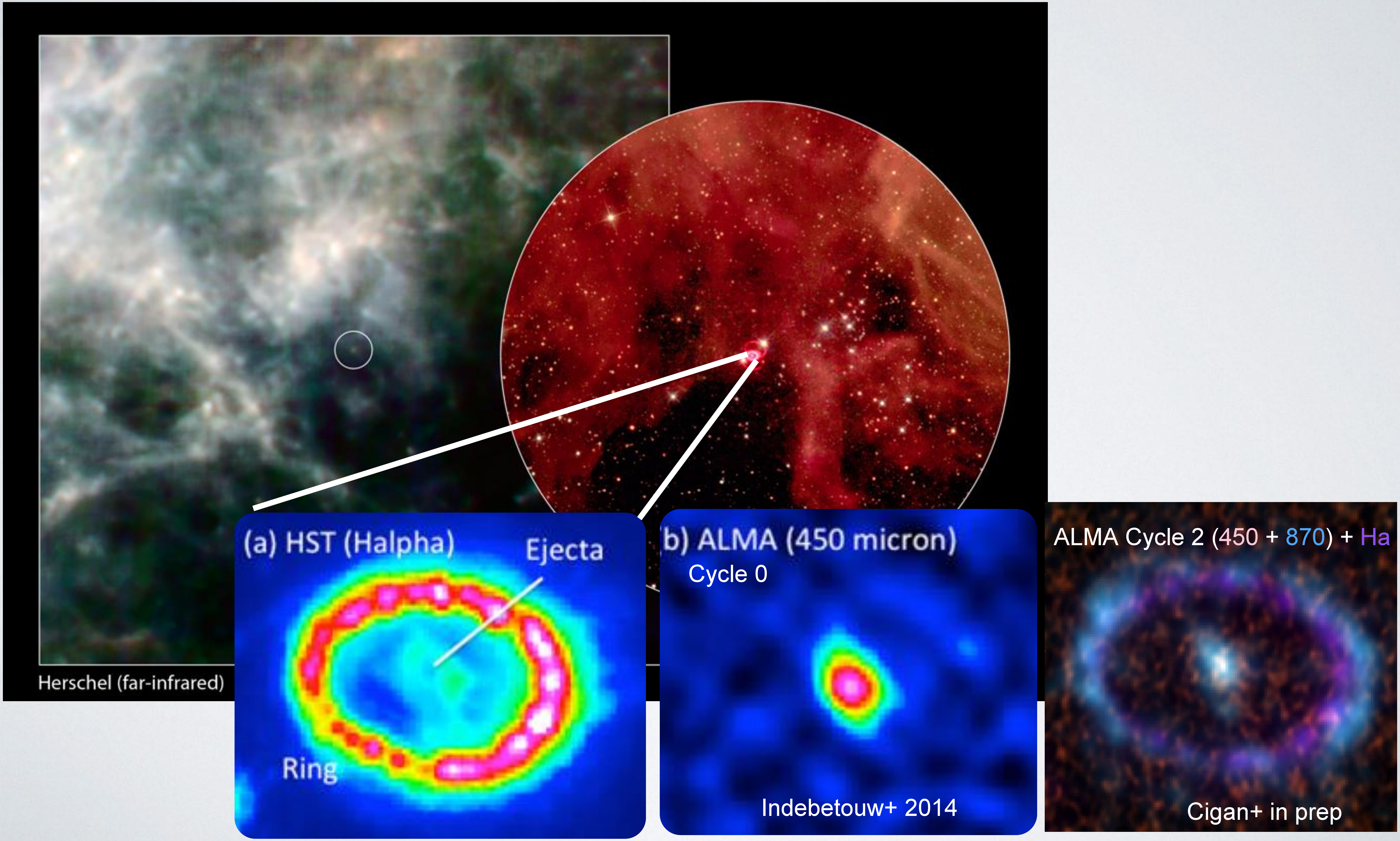
The Herschel Space Observatory reveals cold dust

Herschel 250 micron days 8467 & 8564
Spitzer 8 micron + 24 micron

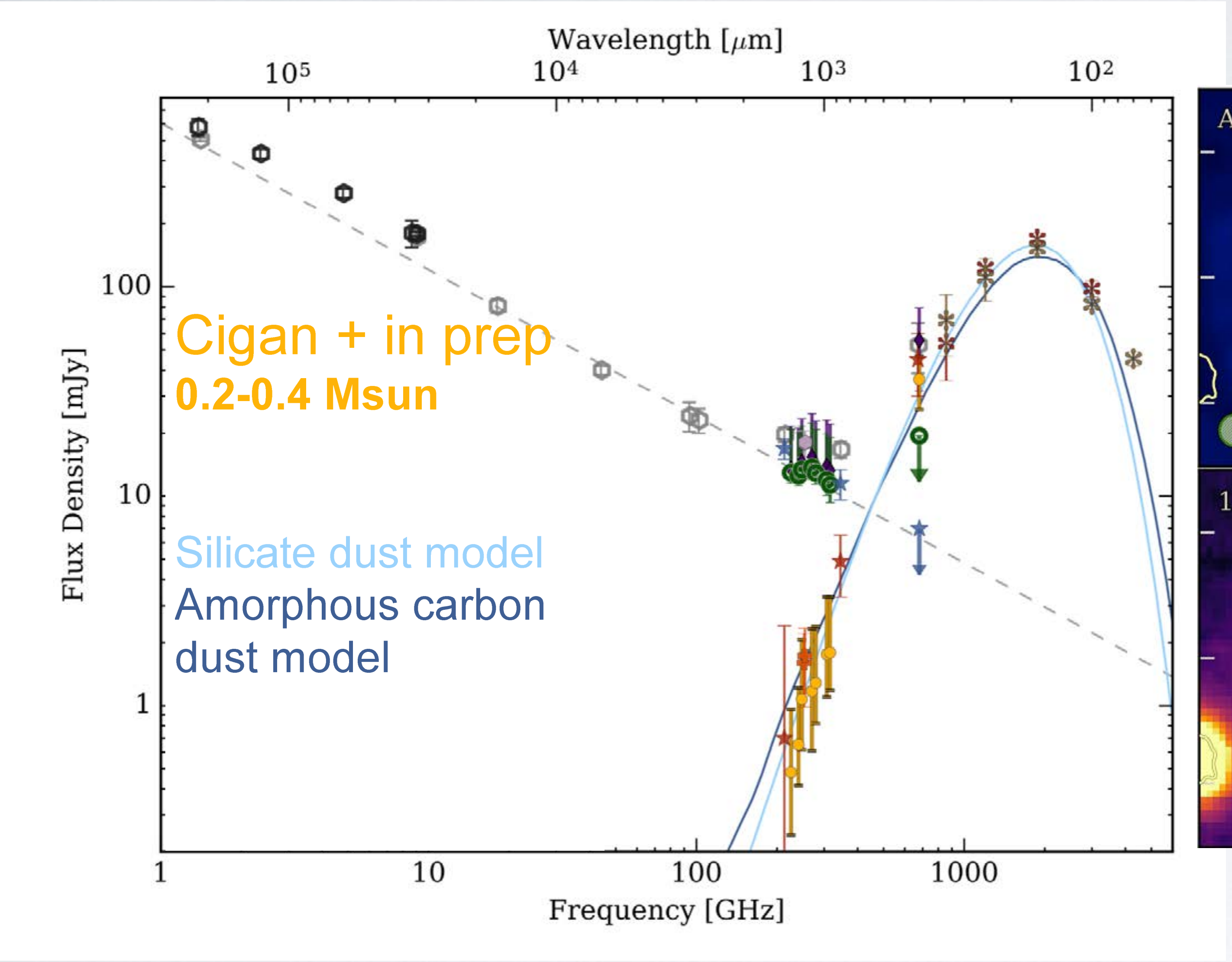
Matsuura + 2011, Science

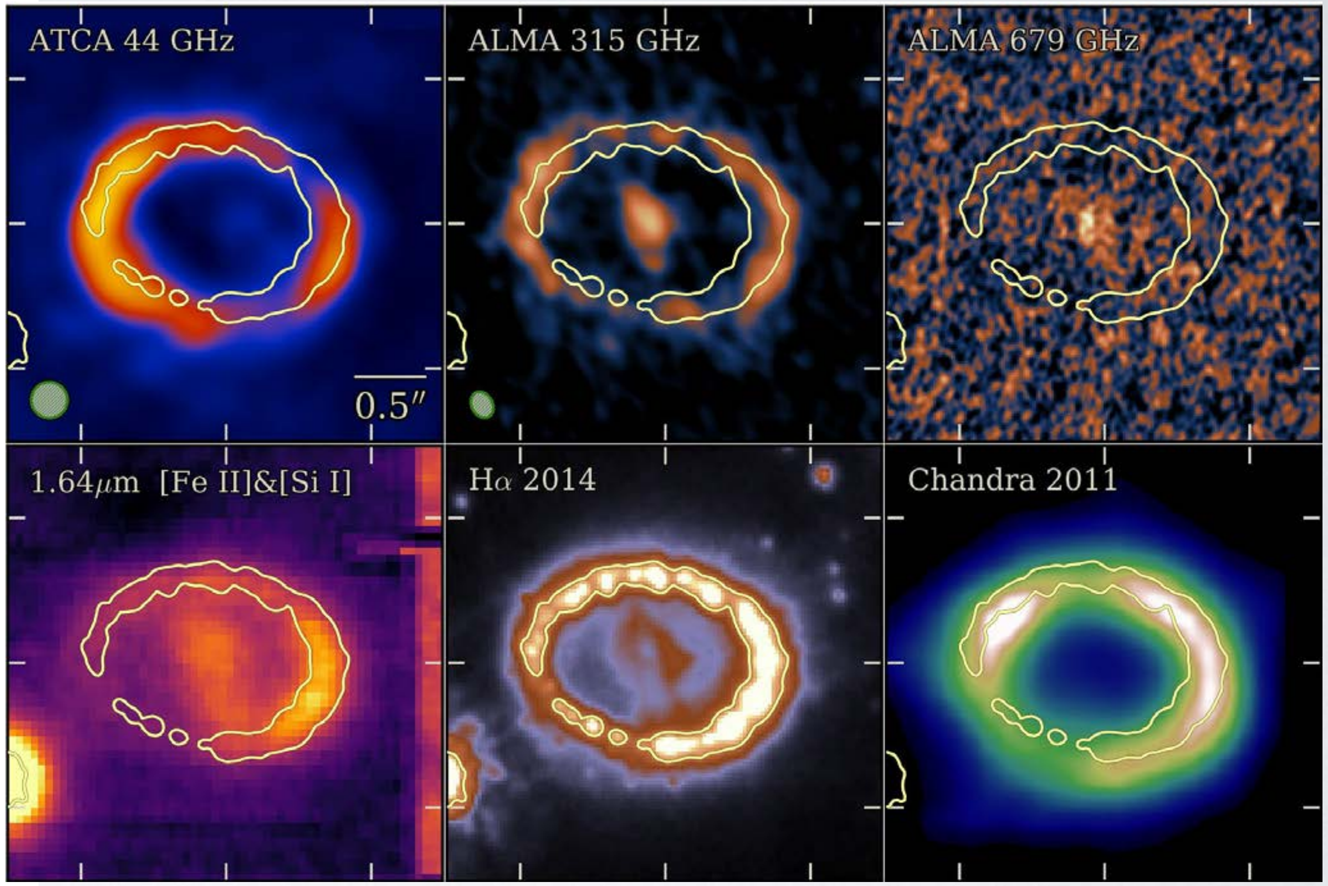
See talk by Mikako Matsuura

ALMA RESOLVES THE DUST LOCATION



CYCLE 2 ALMA RESULTS





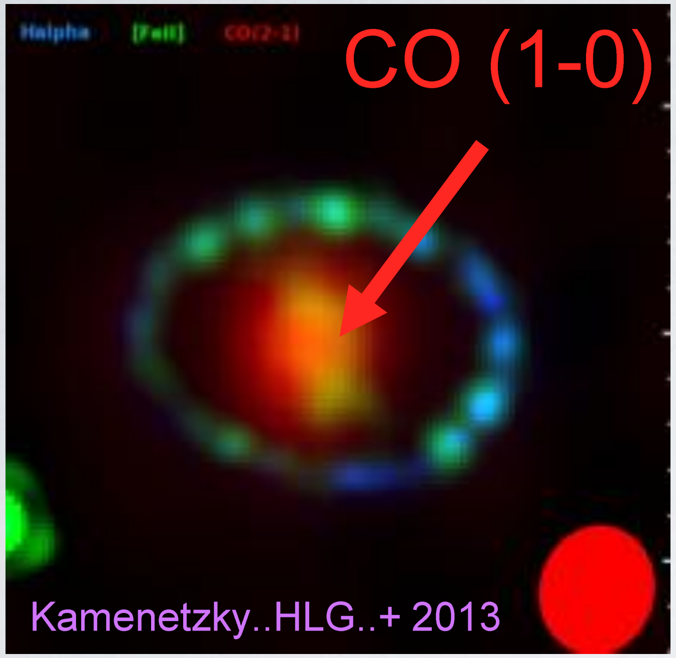
- Dust in the ejecta is asymmetric and clumpy with some features resolved to 63×81 mas scales

- Fills in gap in Halpha - “key in the keyhole”

see Matsuura+ 2015, Indebetouw+ 2014, Lakicevic+ 2012, Zanardo+2014, Callingham+ 2016

See talk by Mikako Matsuura

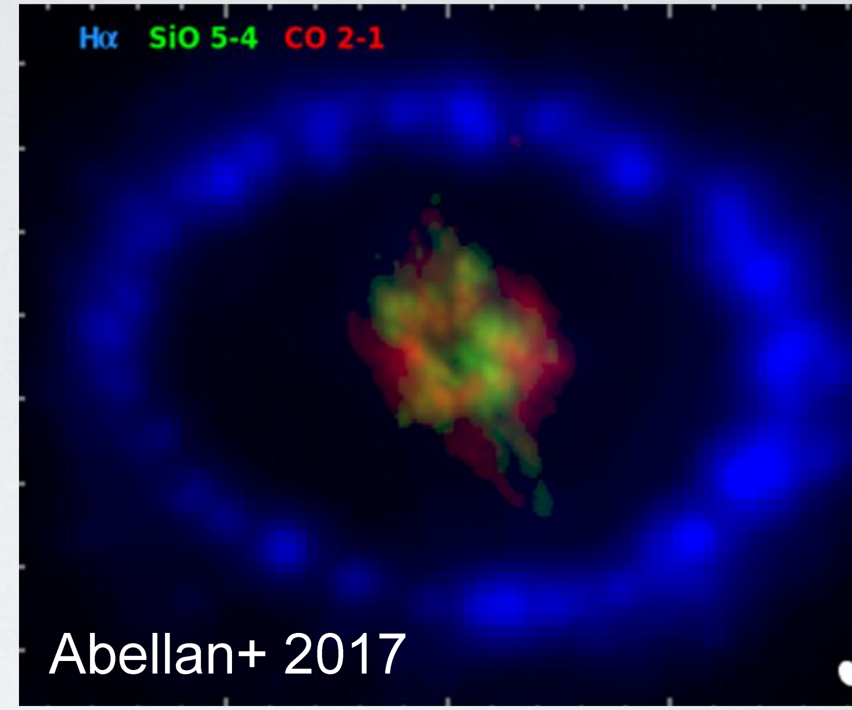
SNE AS MOLECULAR FACTORIES



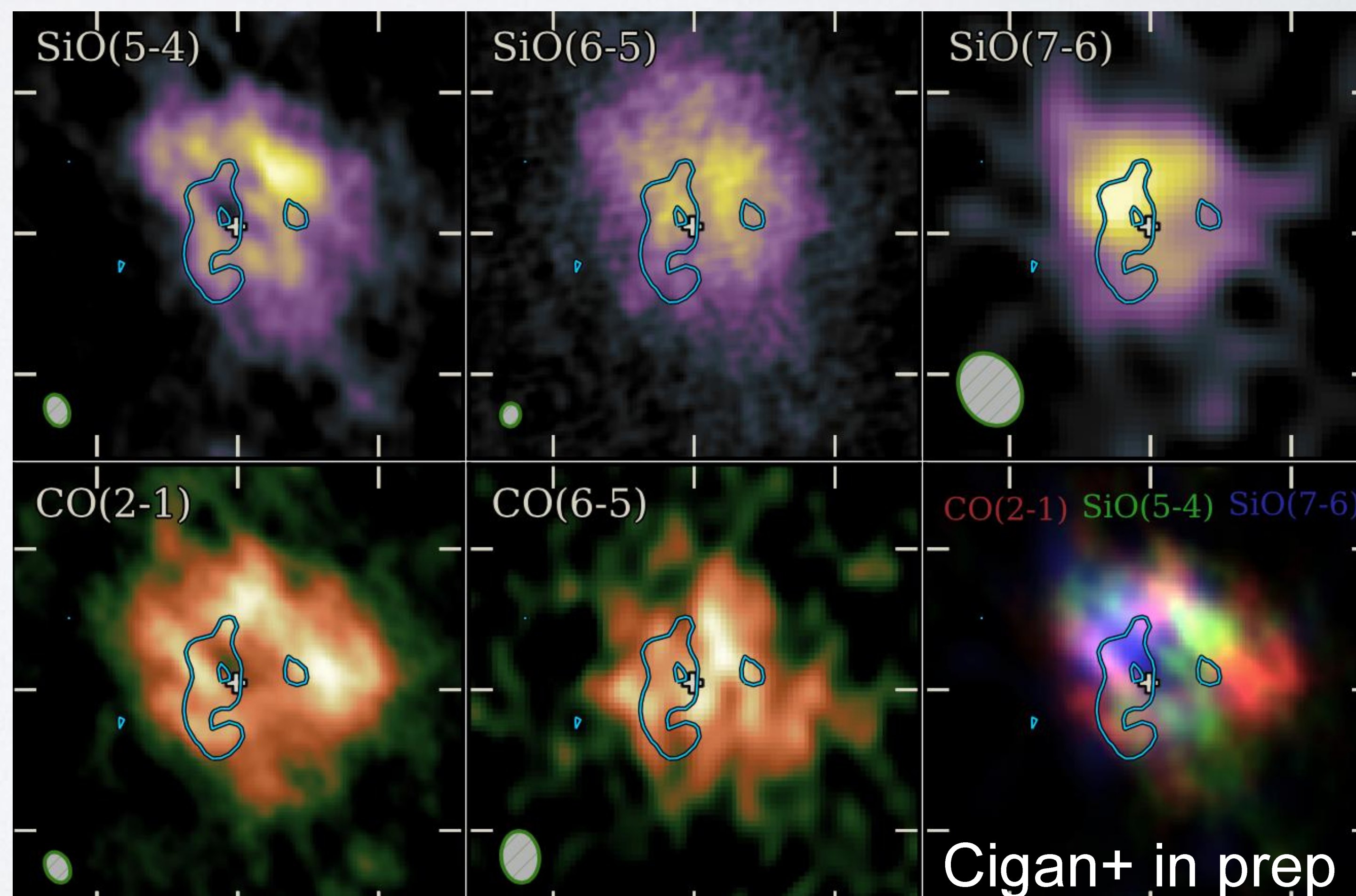
ALMA Cycle 0 and Herschel data revealed >0.01Msun of CO

ALMA Cycle 2: Matsuura+ 2017 detect SiO, HCO+, CO

ALMA Cycle 2; Abellan + 2017 revealed molecular 'holes' and compared with explosion models



- dust clumps generally fill space where CO J=6→5 is fainter, indicating dust and CO are locationally and chemically linked.
- Cycle 2 reveala a dust peak coincident with the hole seen in CO J=2→1 and SiO J=5→4. Properties suggest the dust and gas at higher temperatures than the surroundings



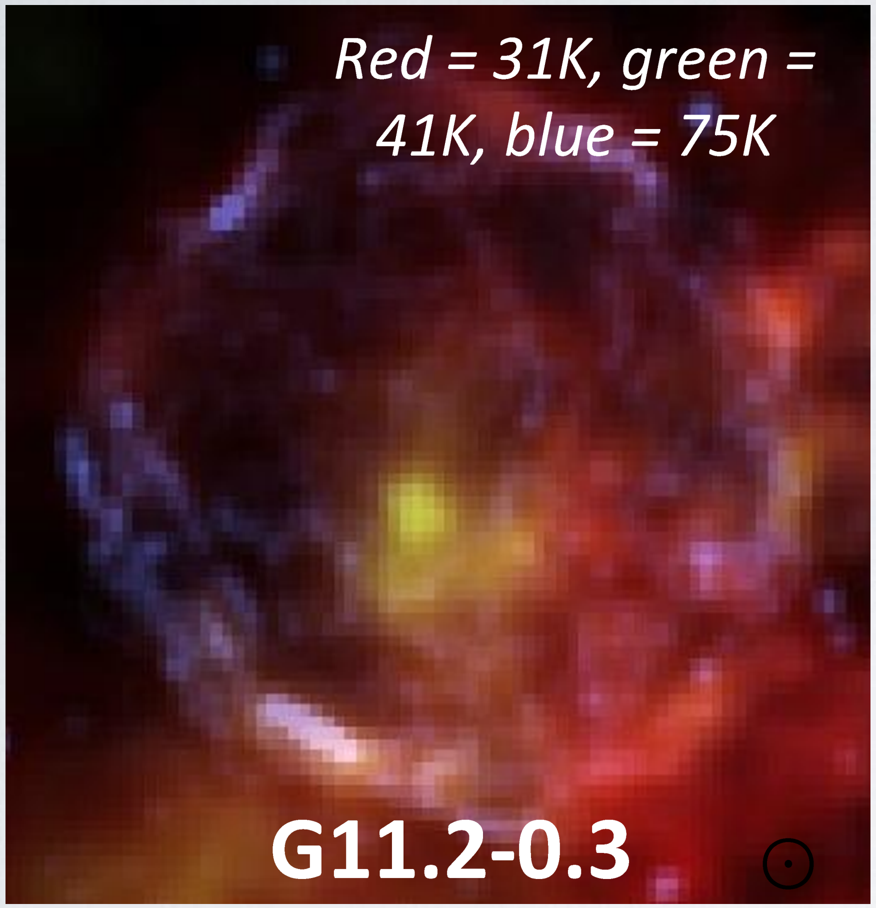
A “COMPLETE” HERSCHEL SURVEY OF MILKY WAY SNRS

Talk by Hannah Chawner

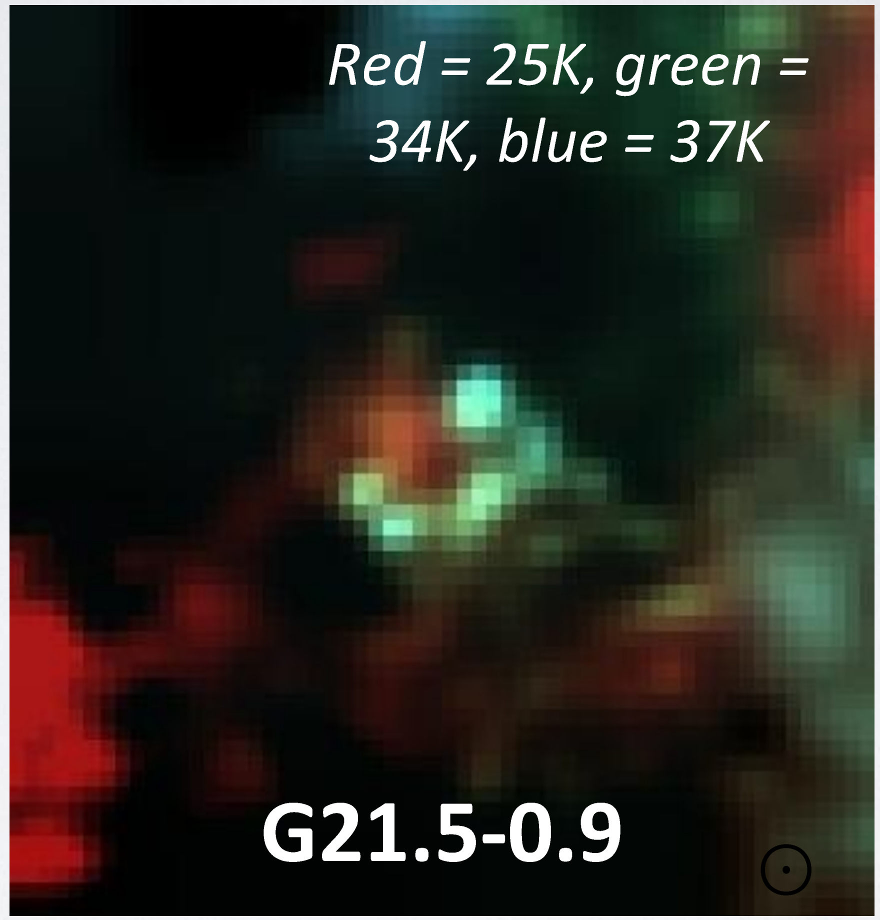
Chawner et al 2019a, Chawner et al 2019b in review MNRAS

See also Temim+ 2015, Seok+ 2013 for LMC and MW Spitzer SNR catalogues: Reach+ 2006, Pinheiro Goncalves+ 201

DUST EMISSION FROM PULSAR WIND NEBULAE



$M_d = 0.34 \pm 0.14\ M_\odot$



$M_d = 0.29 \pm 0.08\ M_\odot$

$M_d = 0.51 \pm 0.13\ M_\odot$

Chawner+ 2019a

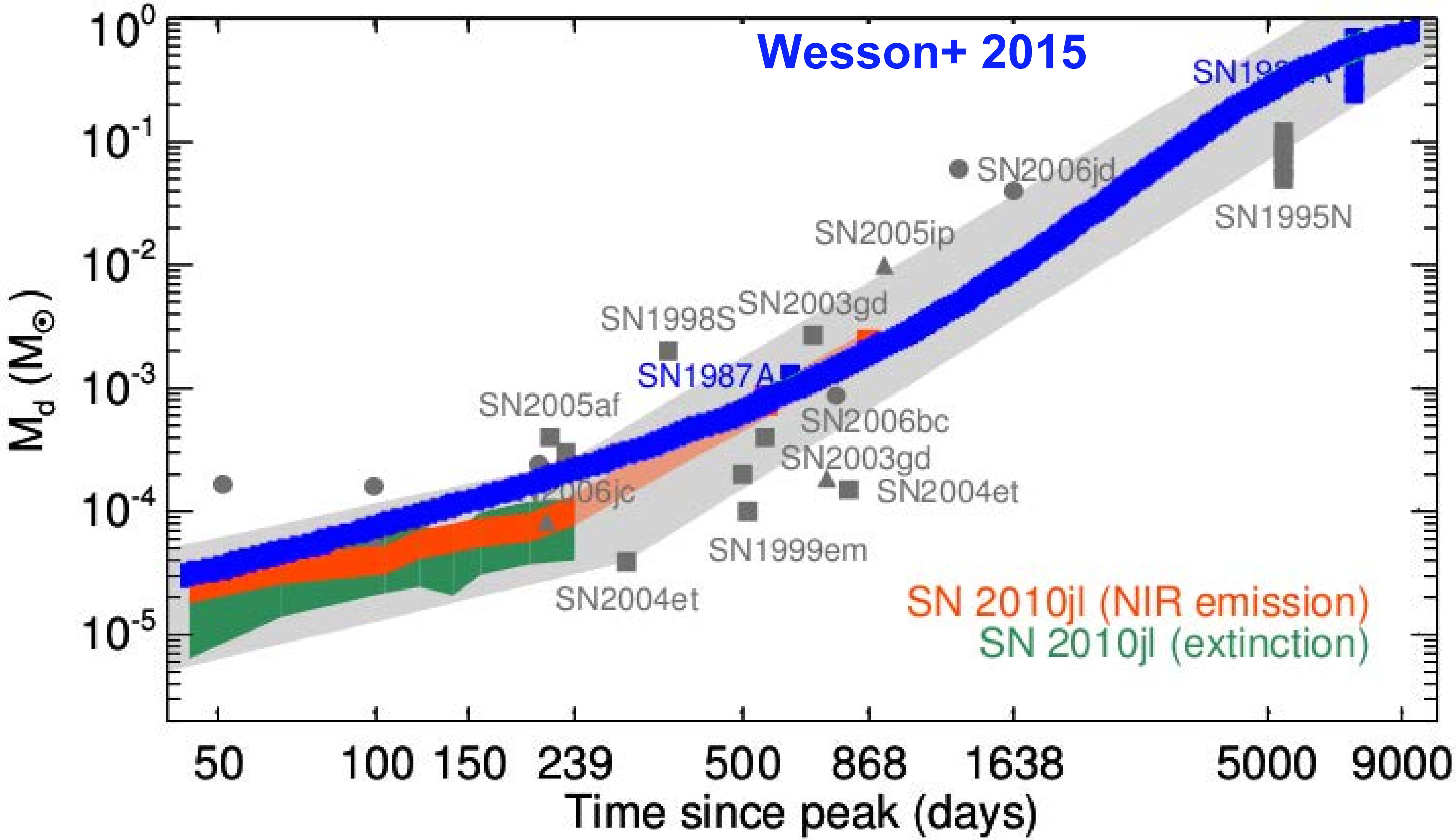
Hannah Chawner's talk
Tea Temim's talk
Priestley+ poster S5.9

Omand+ 2019 suggest that PWNe could accelerate dust formation if B fields high

$M_d < 0.04 M_\odot$ → $< 0.15 M_\odot$

Temim+ submitted, arXiv:1905.02849

THE LINK BETWEEN SNRS AND SNE?

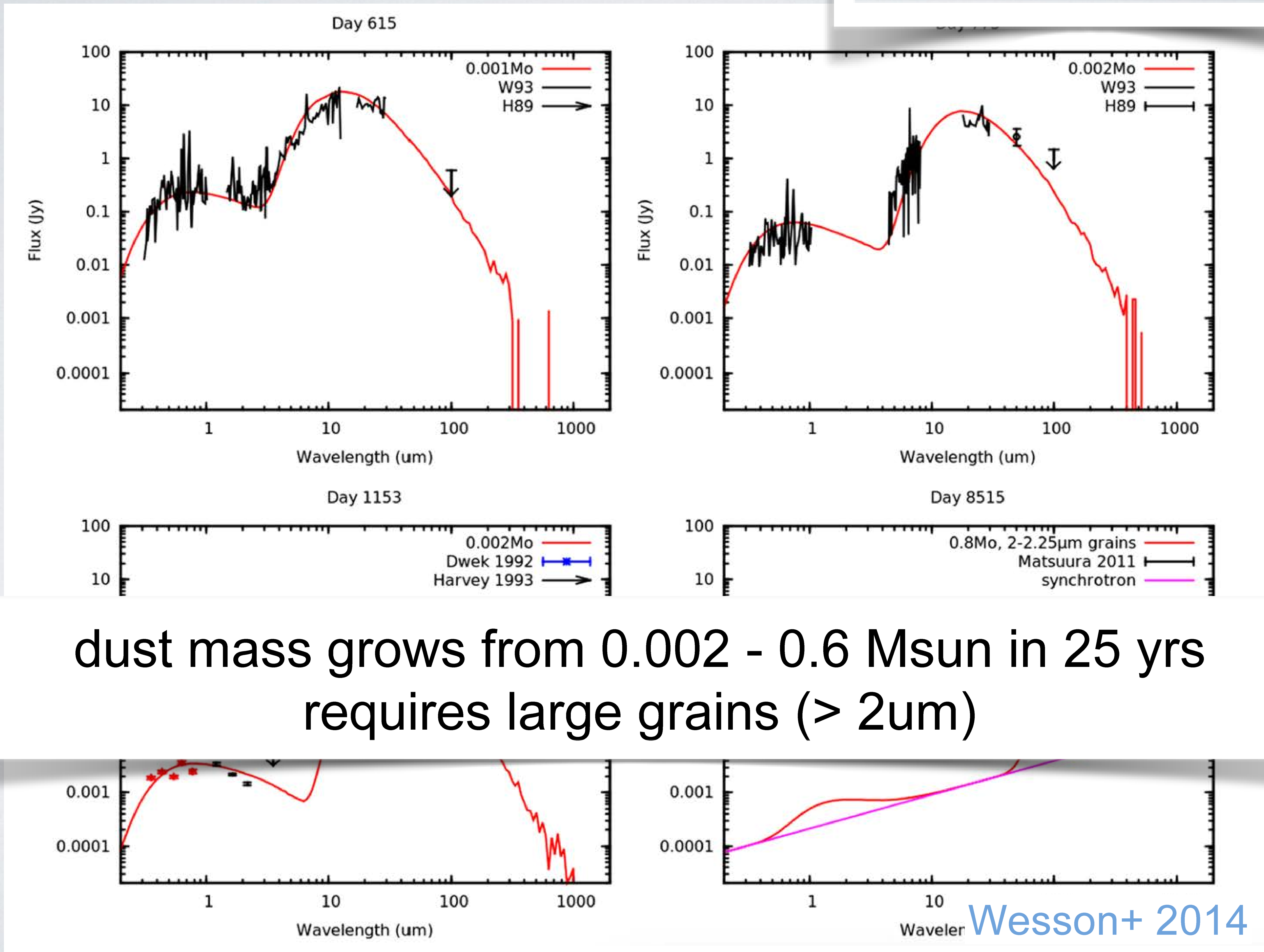


Gall+ 2014, Nature

Gomez N&V 2014

DUST EVOLUTION IN

see also SN1995N
Poster S5.12 by Wesson+



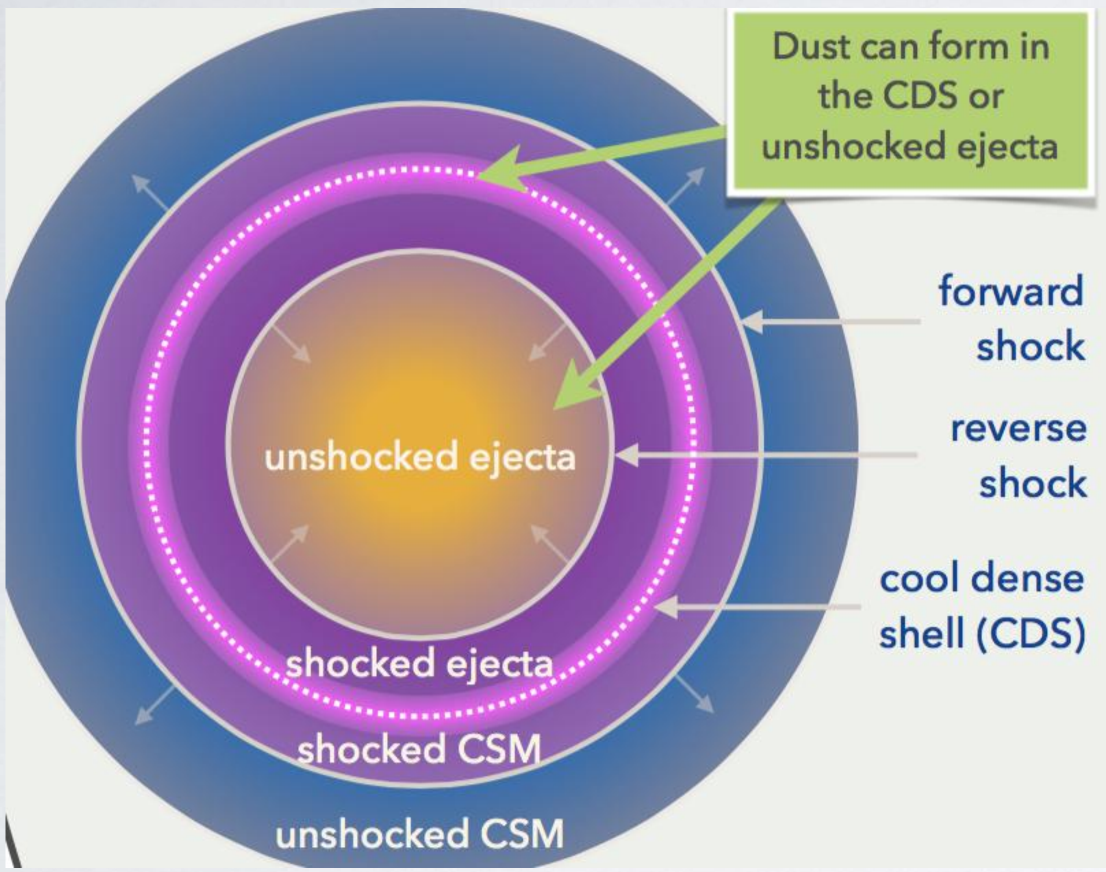
dust mass grows from 0.002 - 0.6 Msun in 25 yrs
requires large grains (> 2um)

Wesson+ 2014

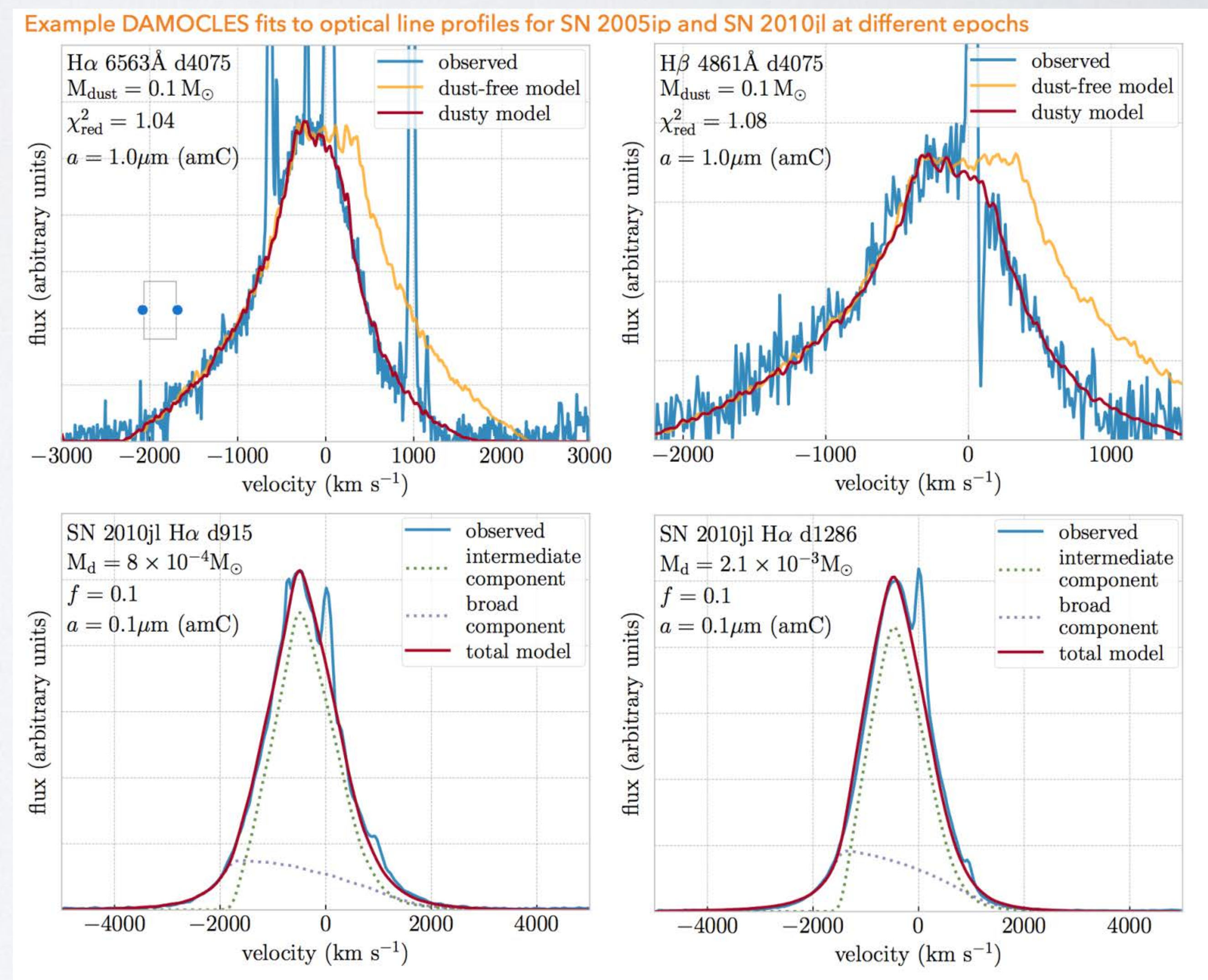
data from Wooden 1993, Harvey+ 1989, Bouchet+ 1993, Dwek+ 1992, Matsuura+ 2011

A DIFFERENT VIEW OF THE DUST MASS

Poster S5.2 by Bevan et al



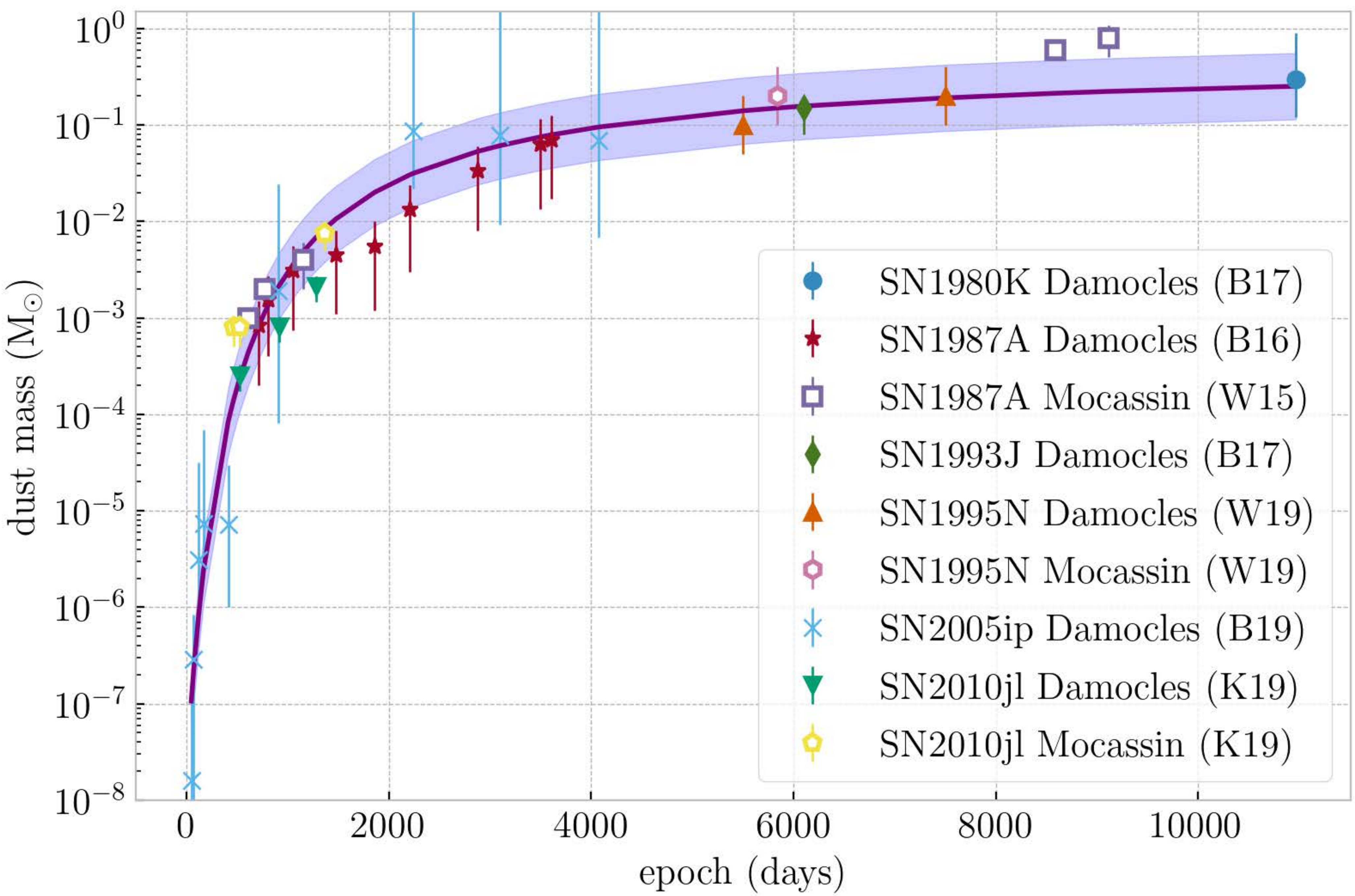
Dust formed in CCSN ejecta can induce asymmetries in optical and NIR line profiles (redshifted emission from the far side undergoes more dust extinction) – using a method pioneered by Lucy et al. 1989, this can used to **measure** dust masses



DAMOCLES (Dust Affected Models Of Characteristic Line Emission in Supernovae) - a Monte Carlo radiative transfer code that models CCSN line profiles

Bevan+ 2016, 2017, 2018

Poster S5.2 by Antonia Bevan et al.



The inferred growth of ejecta dust masses well beyond day 1500 seriously disagrees with the predictions of dust condensation models, all of which predict an end to dust mass growth by then.

Dwek & Arendt 2015 and Dwek, Sarangi & Arendt 2019 have argued that this dichotomy can be resolved if ejecta dust masses actually grow to their final values (~0.5 Msun) well before day 1000, with most of that dust being effectively hidden in highly optically thick regions that are only unveiled later in the IR SED by the continued expansion of the ejecta.

Wesson et al. 2015's numerical modelling of the optical-IR SED of SN 1987A at multiple epochs found a dust mass of 0.003 Msun on day 1153, with dust masses significantly larger than this at that epoch `firmly ruled out by the observations'. From optical line profile modelling, Bevan & Barlow 2016 ruled out SN 1987A dust masses larger than 0.003 Msun on day 714 for most grain types apart from silicates, for which an upper limit of 0.07 Msun was found.

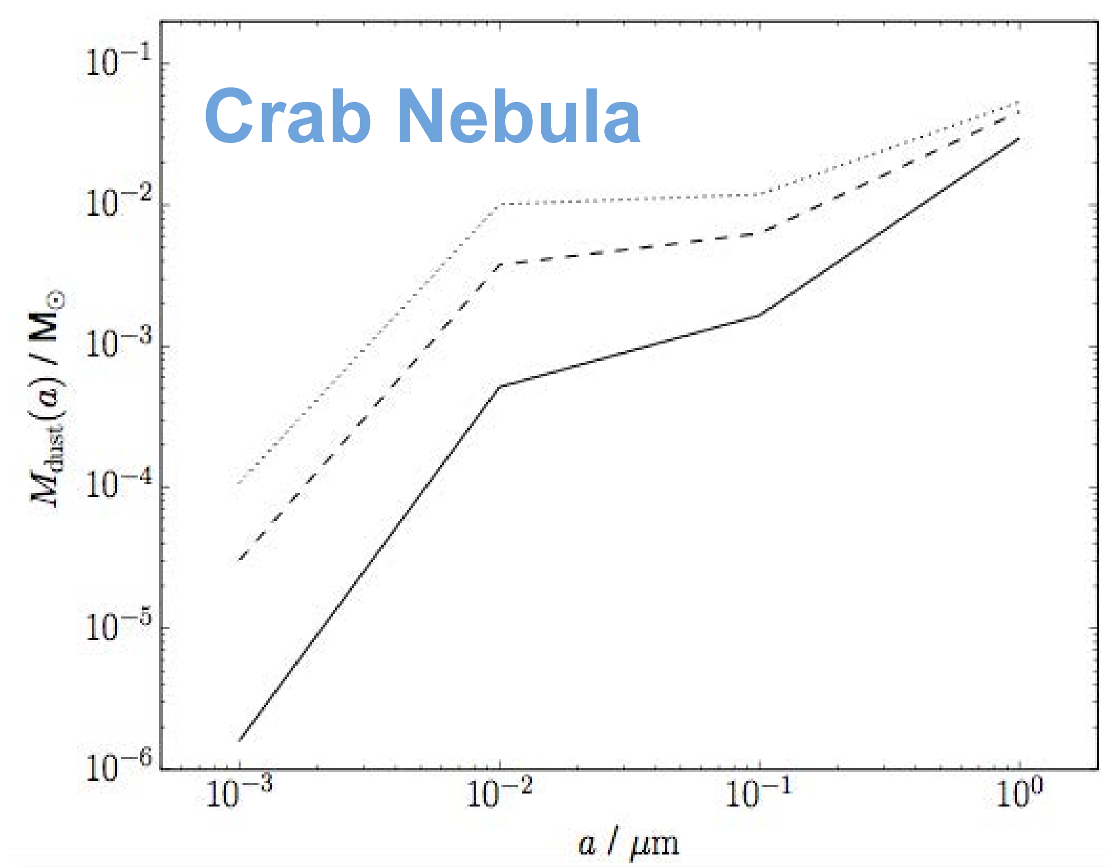
This issue is currently unresolved.

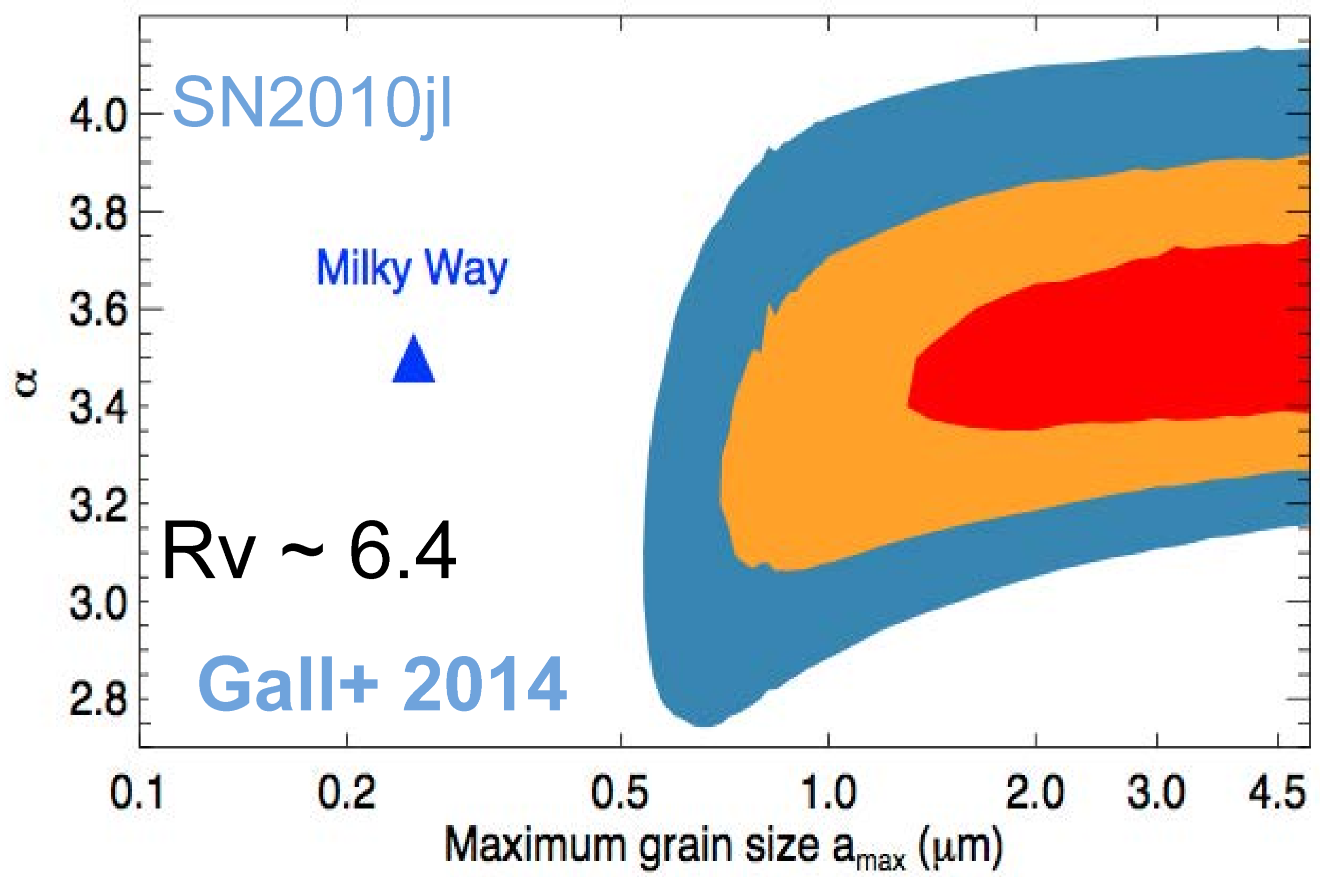
NO DOUBT DUST IS FORMED, HOW MUCH SURVIVES?

Destroyers of dust?

Observations: Borkowski+2006, William+2006,Raymond+2013, Williams+2013,Sankrit+2010

Reverse shock destruction models: Bocchio+2016, Micelotta+2016, Slavin+ poster S5.10, Kirschlager+ poster S5.5



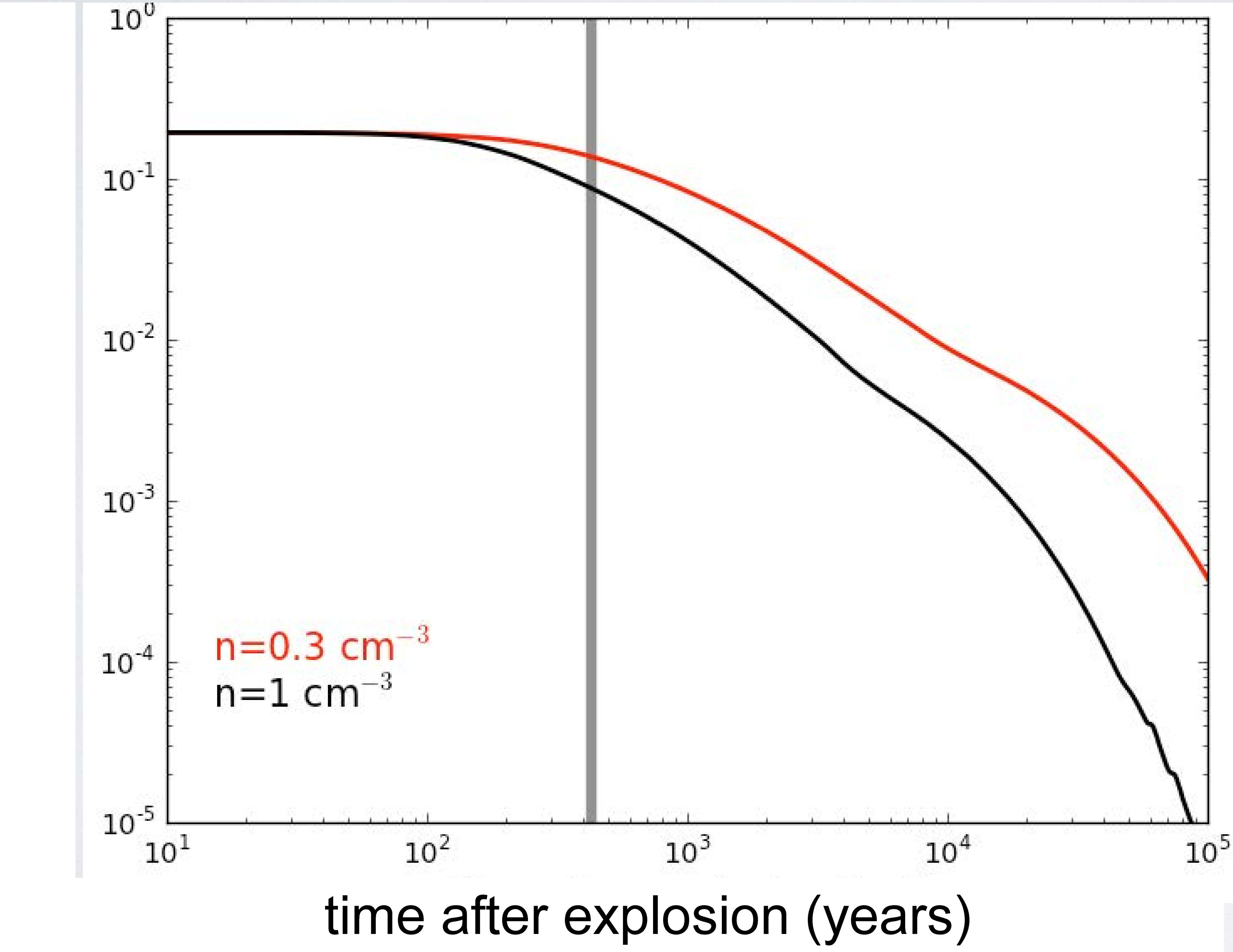


Priestley+ Poster S5.9

Evidence for micron size grains which can better withstand sputtering

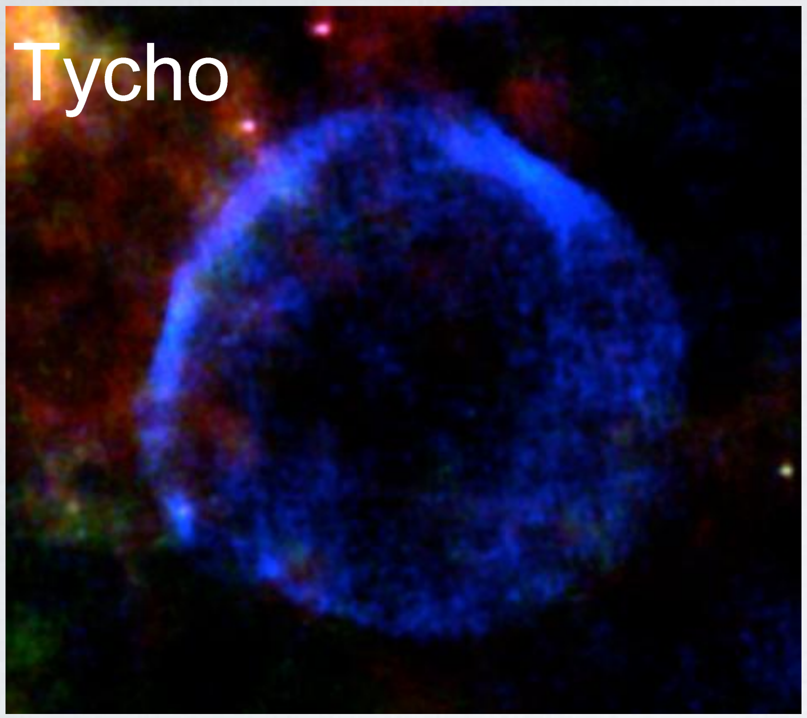
A TYPE IA DEFLAGRATION MODEL

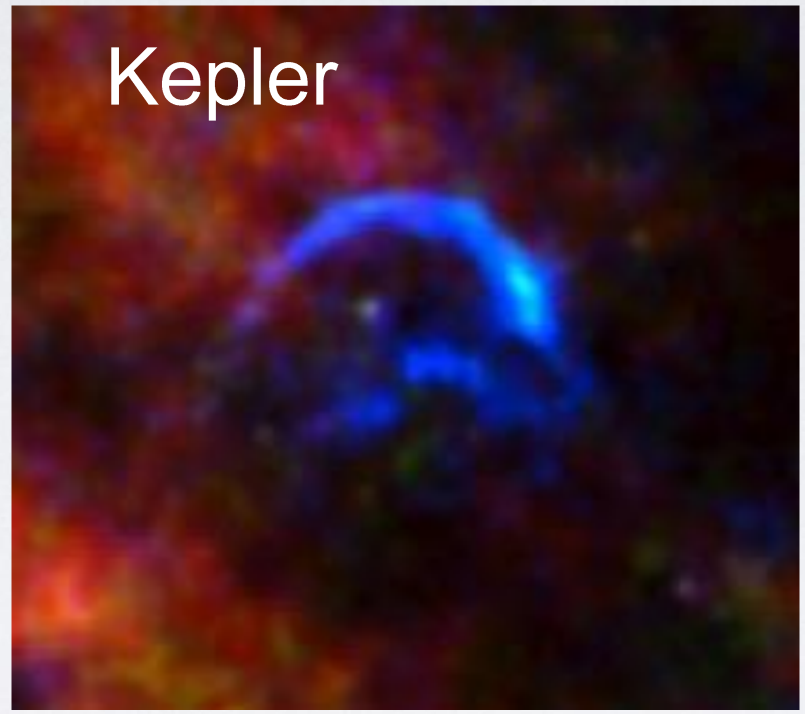
W7 model from Nozawa+ 2011



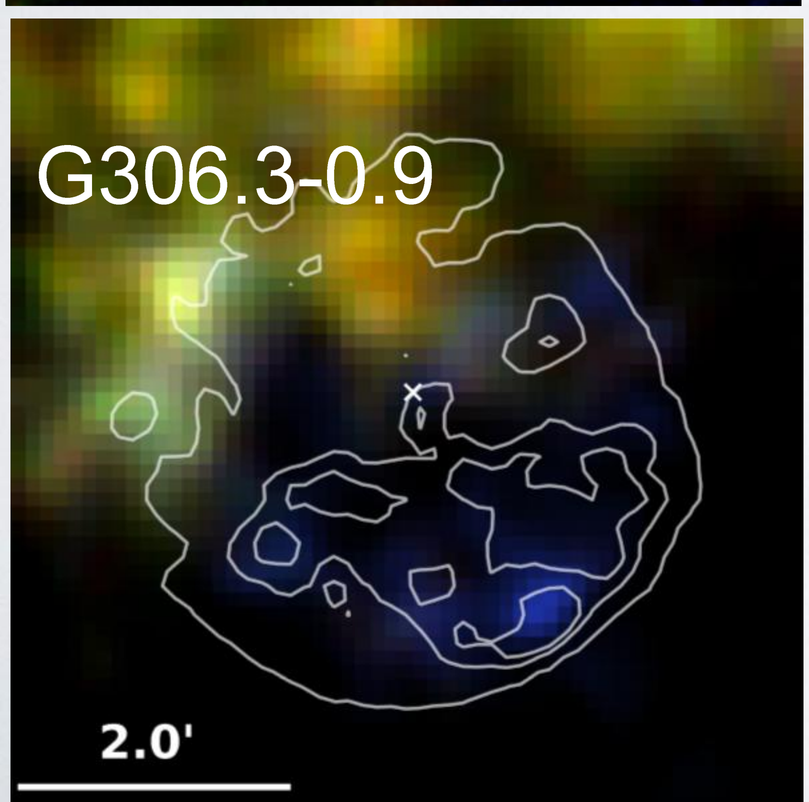
Model for Type Ia expanding into ISM, with reverse shock dust destruction

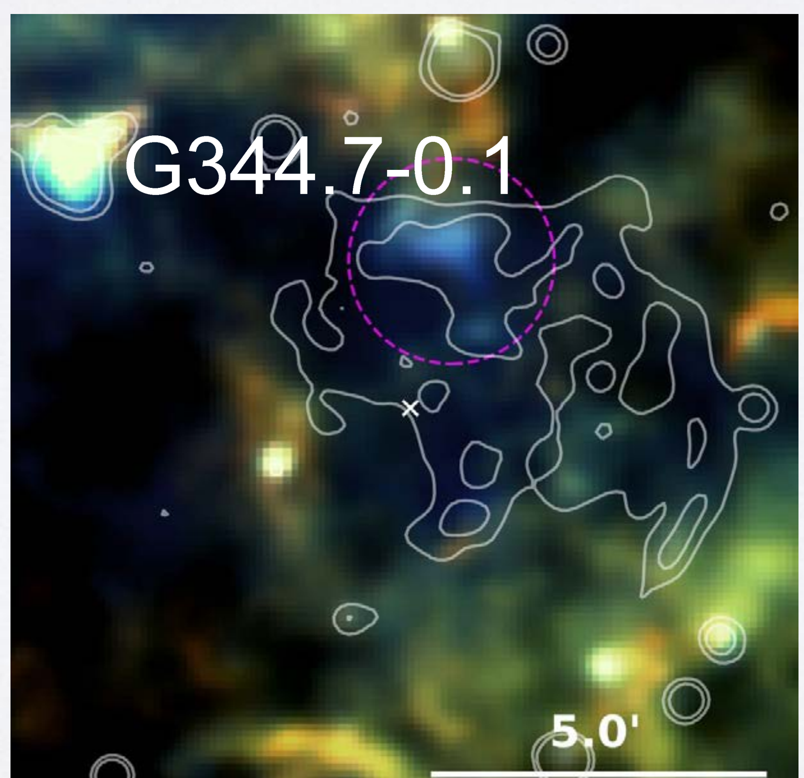
ANY EVIDENCE FOR SN DUST IN TYPE IA'S?





Gomez+ 2012a

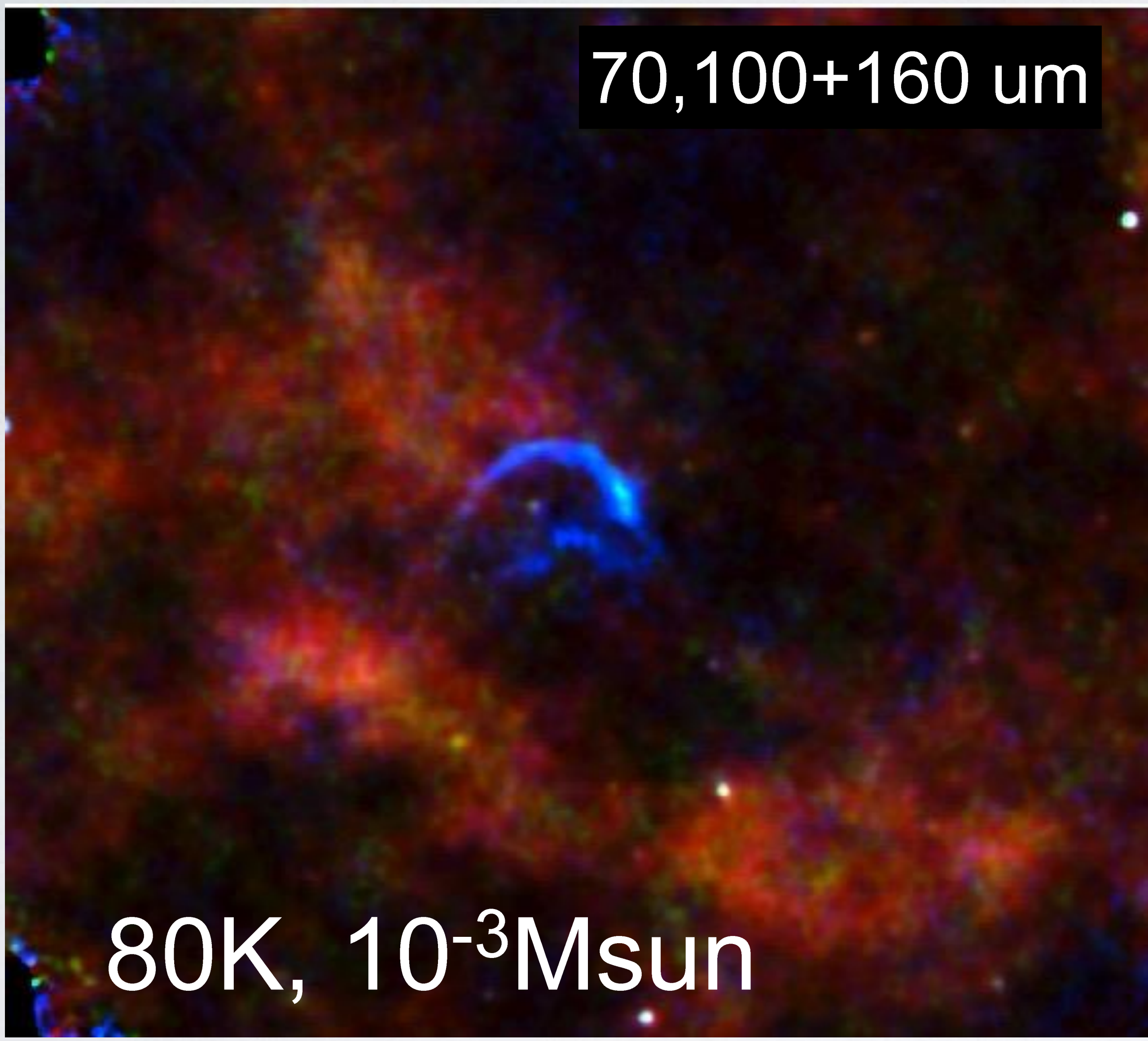


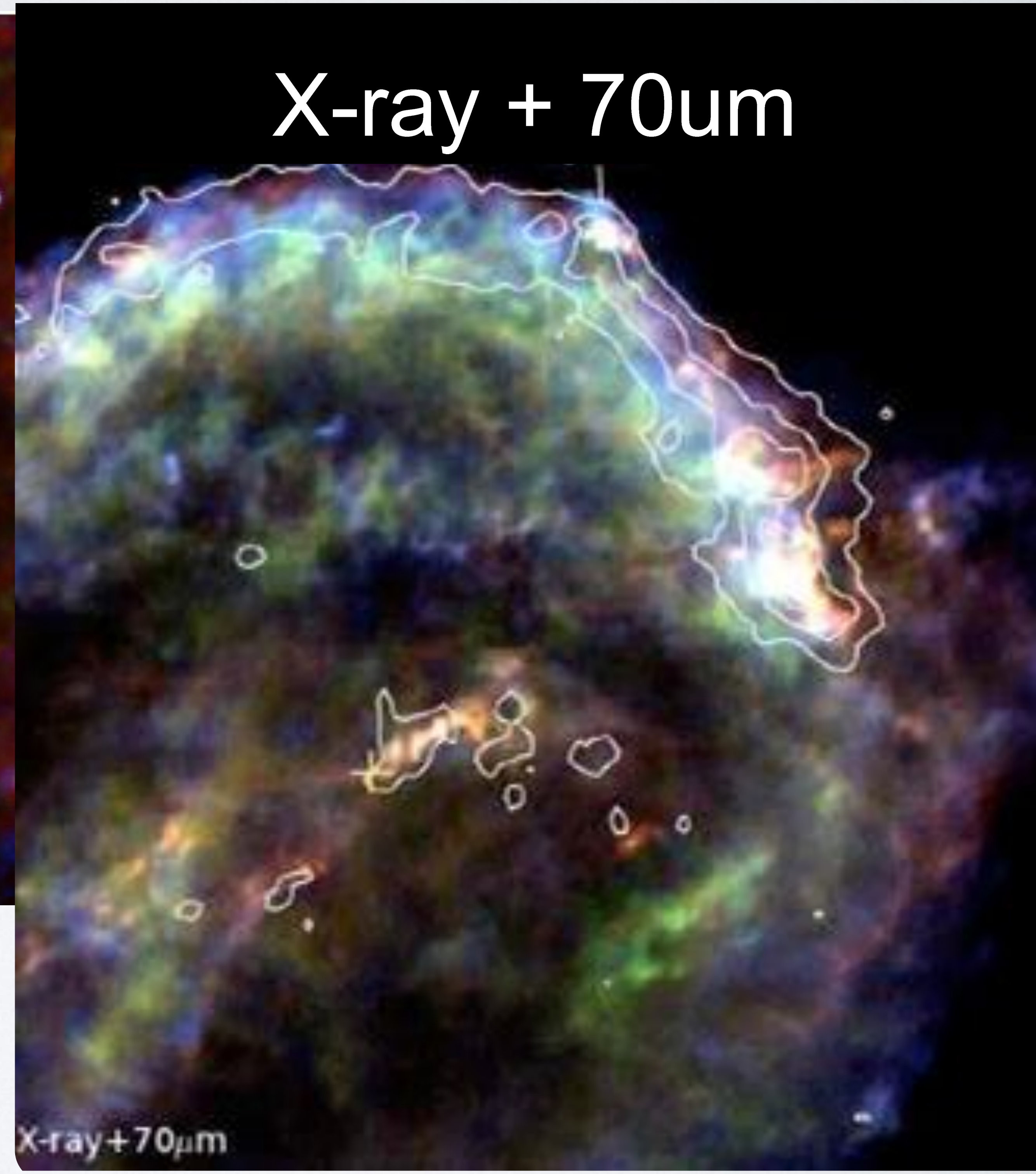


Chawner+ 2019a
Chawner+ 2019b in review

Reynolds+ 2016, Combi+ 2016, Reach+ 2006,
Giacani+2011,Andersen+ 2011

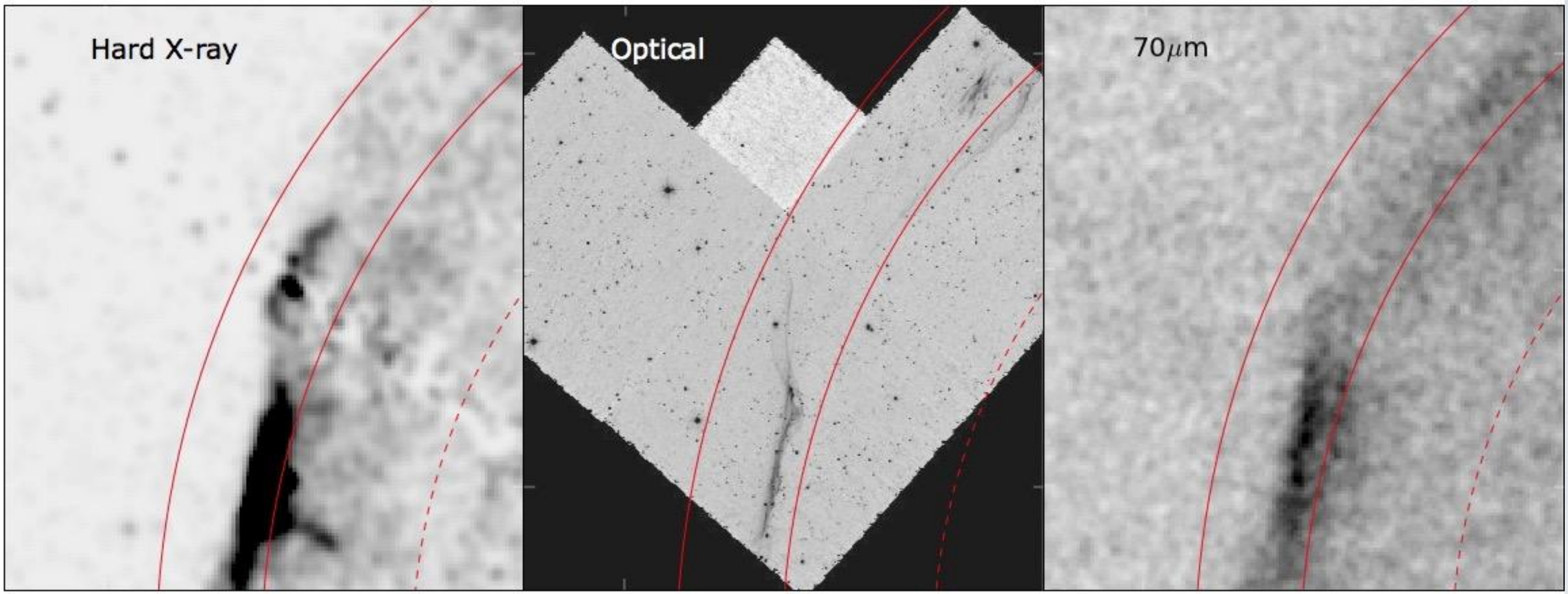
KEPLER'S SUPERNOVA REMNANT





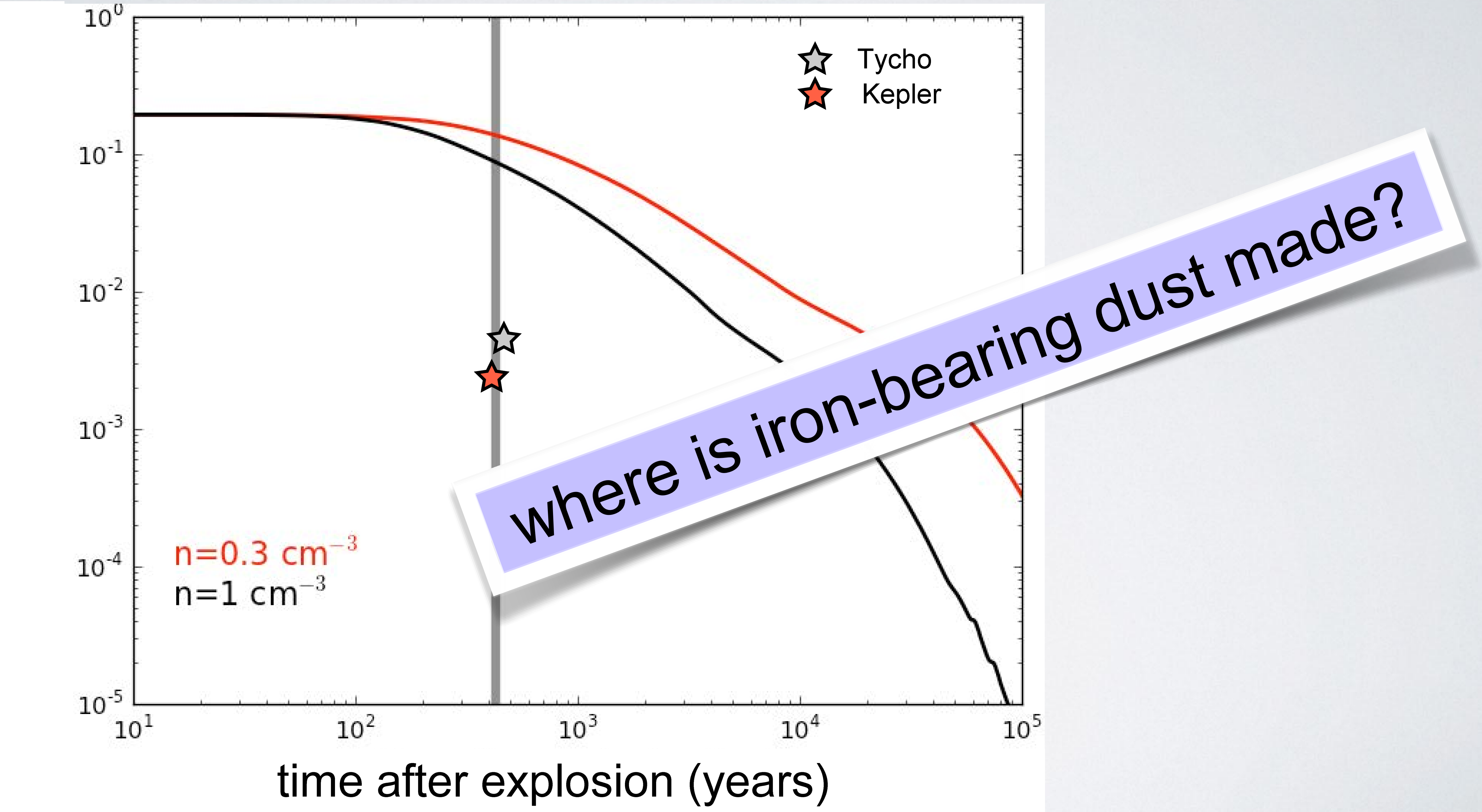
warm dust only where shock front meets surrounding gas - in this case swept up CSM

TYCHO: WARM DUST COINCIDENT WITH SWEPT UP ISM



We see warm dust only where shock front meets surrounding gas in all four SNRs i.e. no clear evidence of dust in the ejecta of Ia's
- in this case swept-up ISM

A TYPE IA DEFLAGRATION MODEL



see also Borkowski 2006, Gerardy+ 2007, Williams+ 2012, 2013, Ishihara+ 2012, Winkler+ 2013, Johannsson+ 2013

WHERE DO WE STAND?

- **Consensus**

=> Dust and molecules in remnants of core collapse SNe
=> Significant quantities found in PWNe
=> Each CC SN produces ~ 0.1-1.0 Msun dust
=> Grains need to be large (> um size)
=> Mass grows up to at least 1500 days

- **Conflicts/Issues**

=> Largest dust masses found at even later times; continued dust mass growth not predicted by current models
=> How much dust survives?
=> For SNR IR SEDs, dust size/composition and unrelated dust emission along l.o.s. produce largest uncertainties on mass