SOURCES OF DUST IN THE EARLY UNIVERSE

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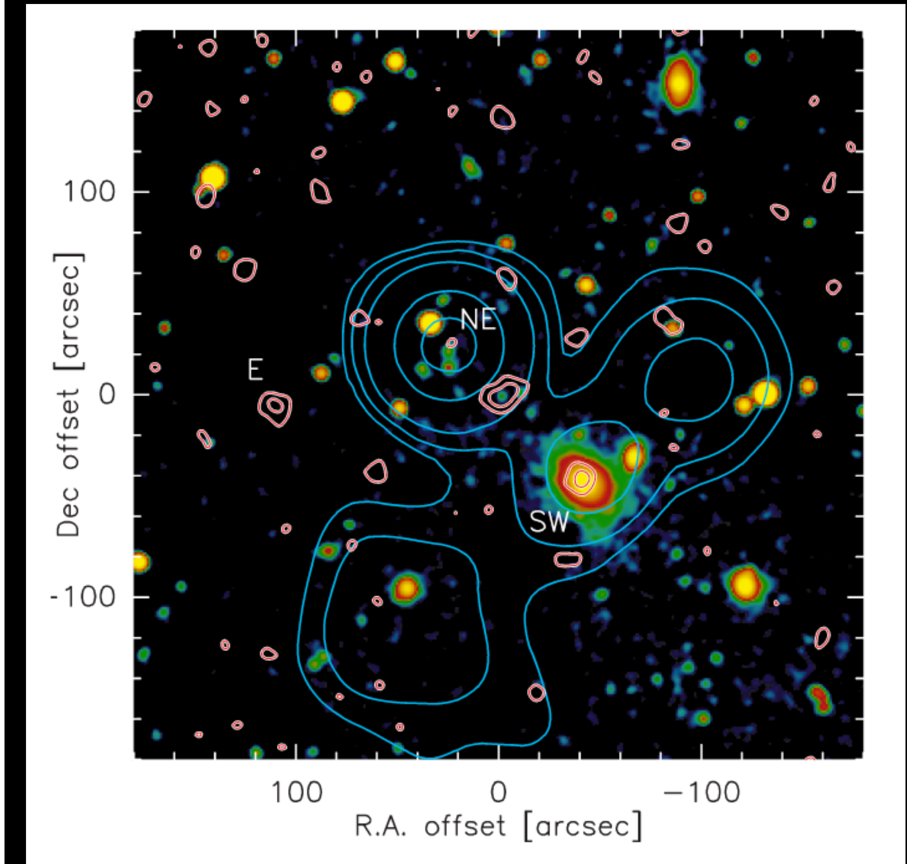
Dark Cosmology Centre

NASA

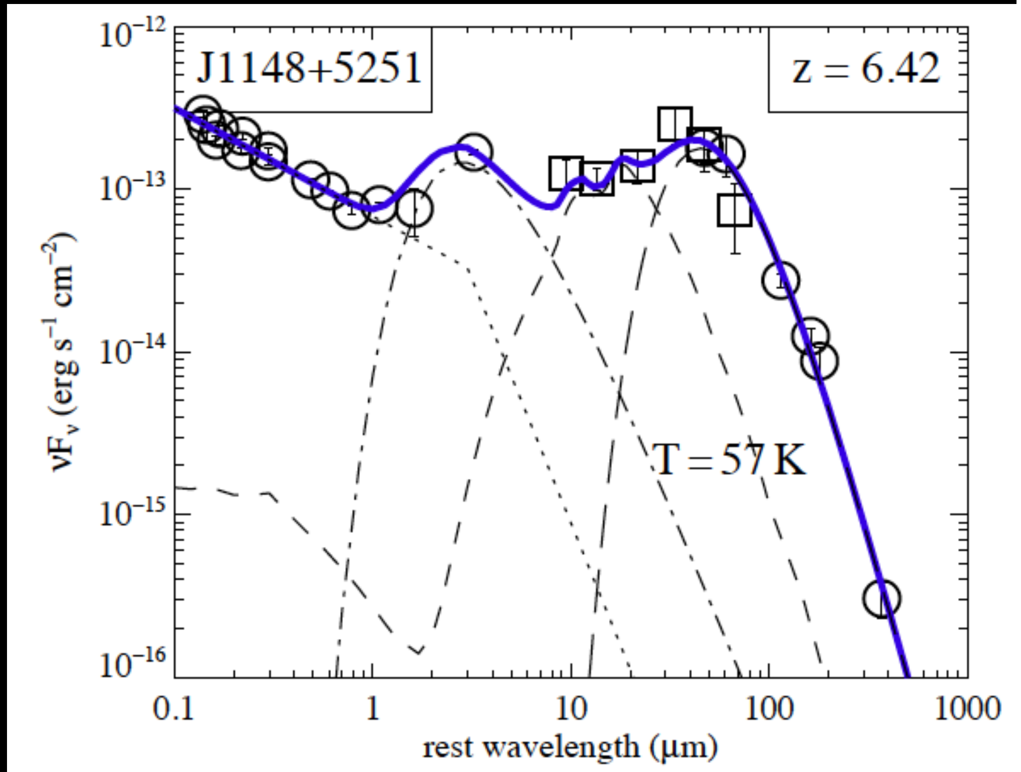
The Life Cycle of dust in the Universe
Taipei, Taiwan, November 18-22

DUST AT HIGH REDSHIFT

Dust at high redshift



Bertoldi et al. 2003

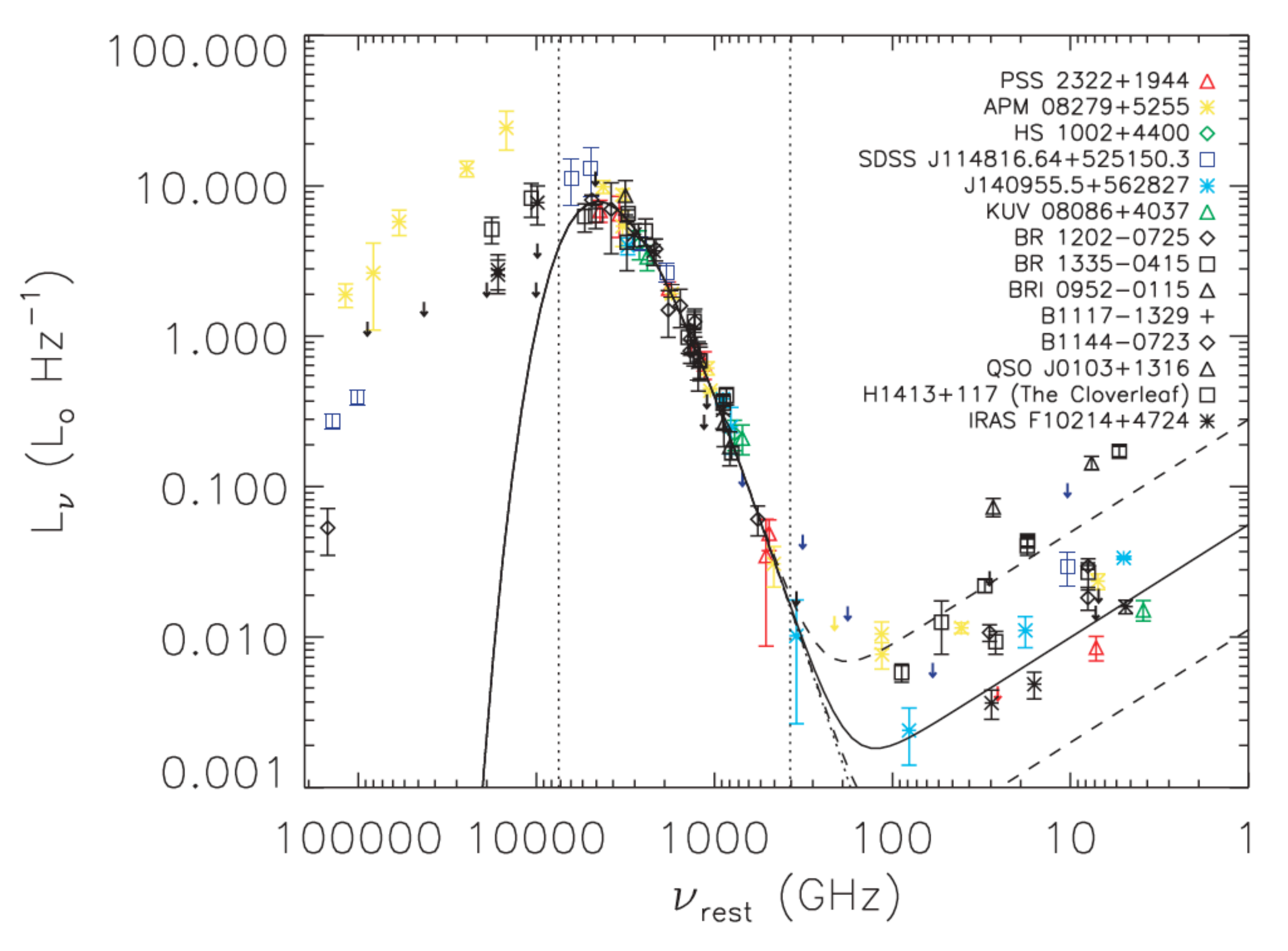


Leipski et al. 2013

$$M_{\rm d} = \frac{S(\nu_{\rm o})\,D_{\rm L}^2}{(1+z)\kappa_{\rm d}(\nu_{\rm r})\,B(\nu_{\rm r},\,T_{\rm d})}$$

$M_d \sim 2 - 8 \times 10^8\, M_\odot$

Dust at high redshift



$T_d \sim 47$ K

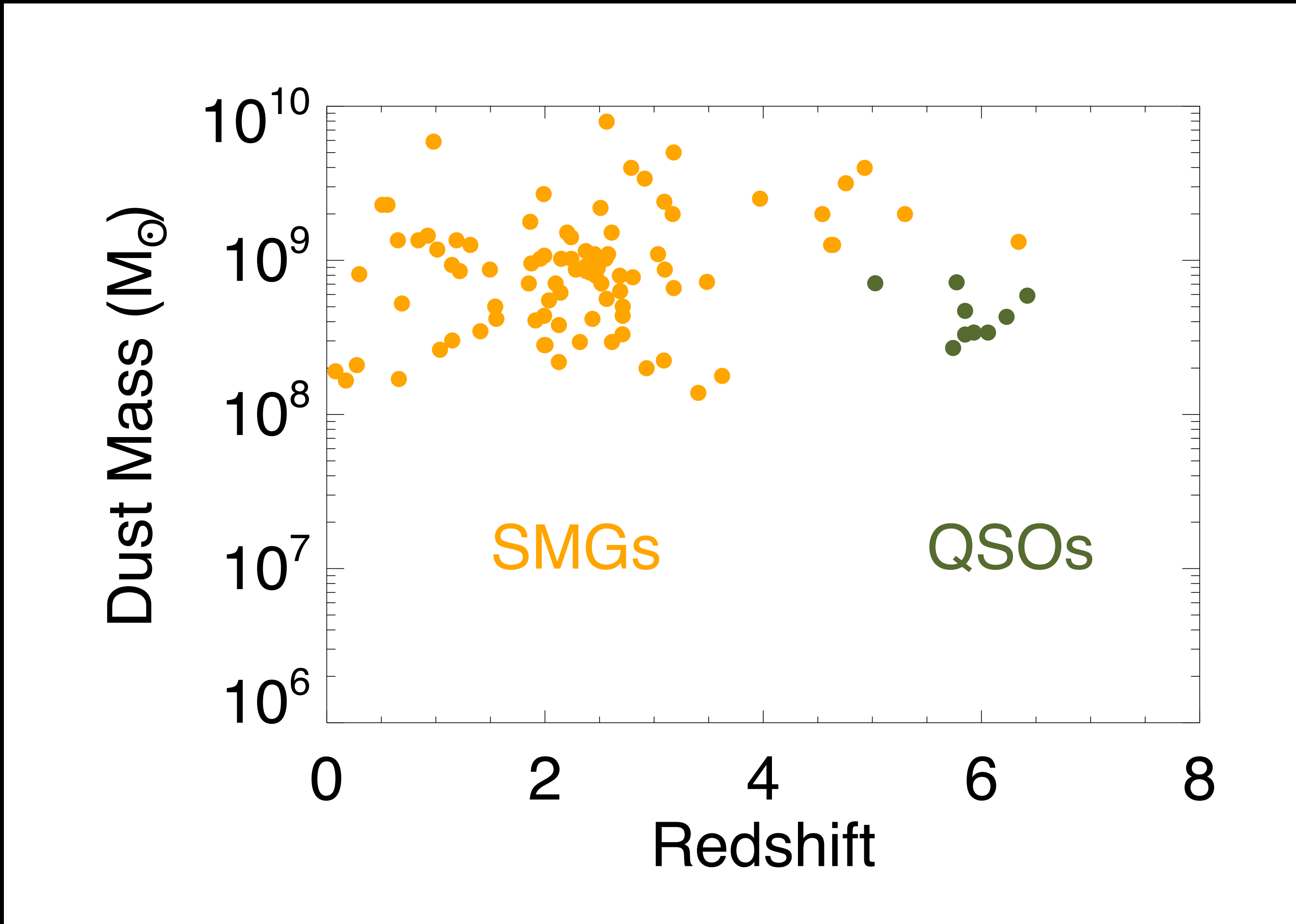
$\beta \sim 1.6$

Beelen et al. 2006

Emissivity:

$$\kappa_d(\nu_r) = \kappa_d(\nu_0)\left(\frac{\nu_r}{\nu_0}\right)^{\beta}$$

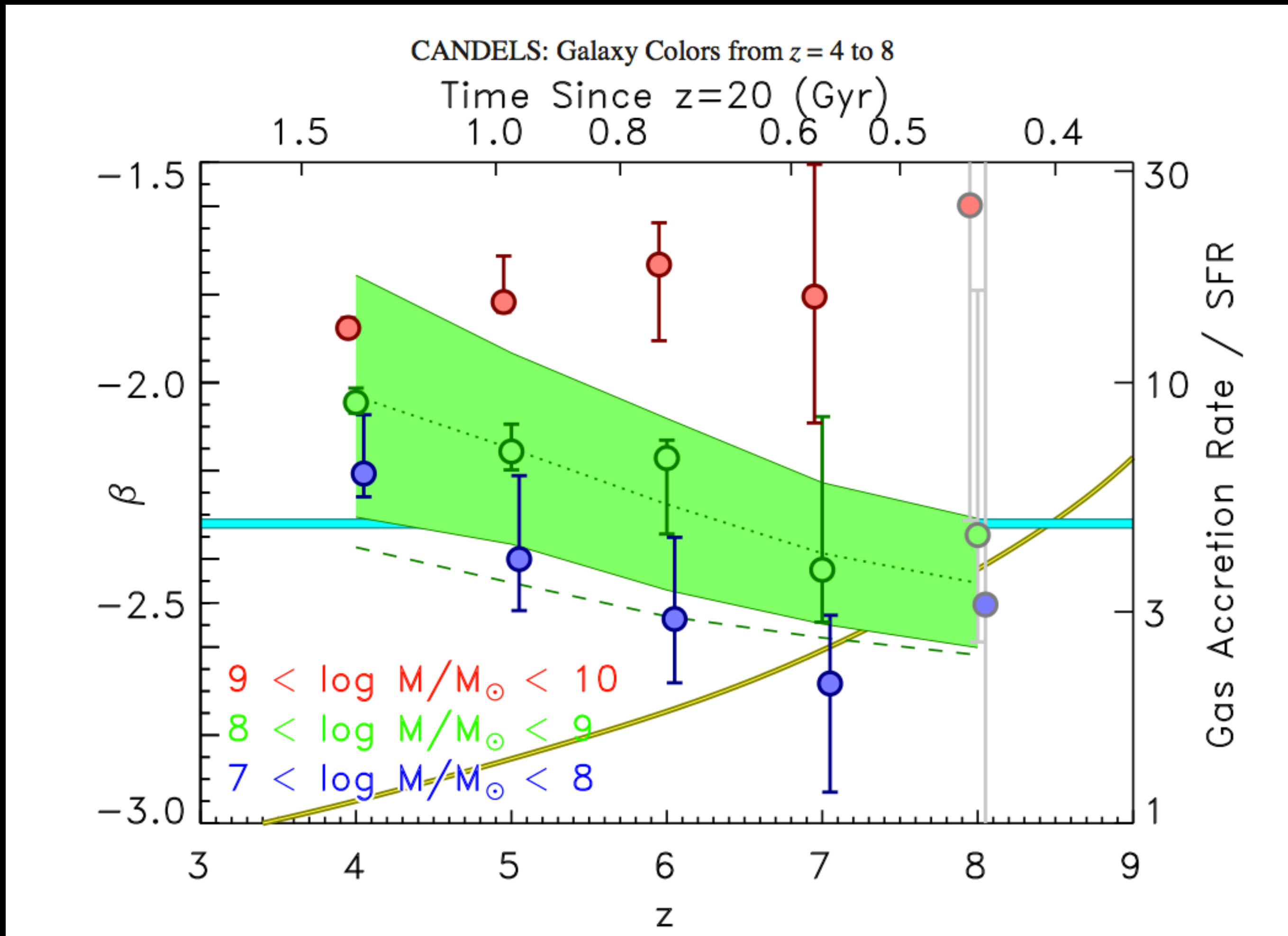
Dust at high redshift



e.g., Wang et al. 2010, Walter et al. 2004, Michalowski et al. 2010, Hjorth et al. 2013

Dust at high redshift

Galaxies at z = 4 - 8



Finkelstein et al. 2012

Dust at high redshift

- Large amounts of dust

Galaxy	SFR ($M_\odot$ /yr)	Dust mass ($M_\odot$)	Stellar mass ($M_\odot$)
SMGs	100–1000	$10^{8\text{-}9}$	10^{11}
QSOs	≥ 1000	$10^{8\text{-}9}$	10^{11}

Requirement for sources:

➩Fast

➩Efficient

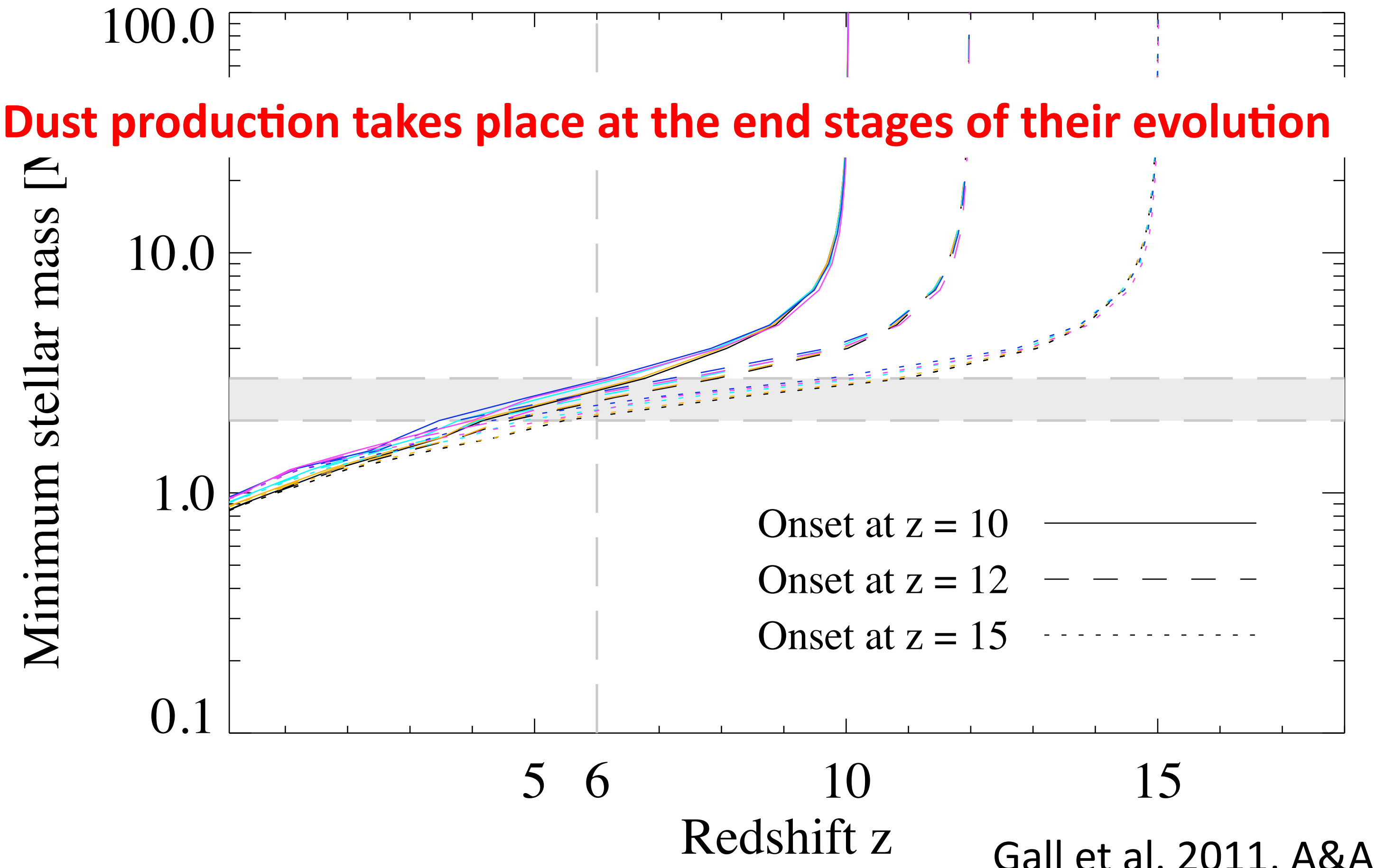
Dust Sources

- Stellar sources
  - AGB stars
  - Massive stars
  - Supernovae

- Non-stellar sources
  - Grain growth in molecular clouds
  - Dust formation in AGN outflows

Timeline

Late Stage of Stellar Evolution - Lifetimes



Dust production takes place at the end stages of their evolution

Gall et al. 2011, A&AR

Dust Sources

- Direct observations of dust sources, e.g. stellar sources at high redshift, are impossible

- Highest redshift detected core collapse SN is
  – at z = 2.37 (Rodney et al. 2014)

- Two options to study sources at high z
  ⇨ Look at sources in local Universe
  ⇨ Study galaxy evolution (models)

Standard picture in local Universe

dust ($M_\odot$/yr)	Stellar Source
0.002	Planetary Nebulae (~0.3/yr)
0.0025	Red Giant, Red Supergiant, C star winds
<0.0001?	OB, WR, other warm/hot star winds
0.0002?	SNe (1/100 yr, $\sim 10^{-2} M_\odot$ dust/SN?)
0.00001	Novae (100/yr, $10^{-7} M_\odot$ dust/nova?)
~0.005	**All stellar sources**

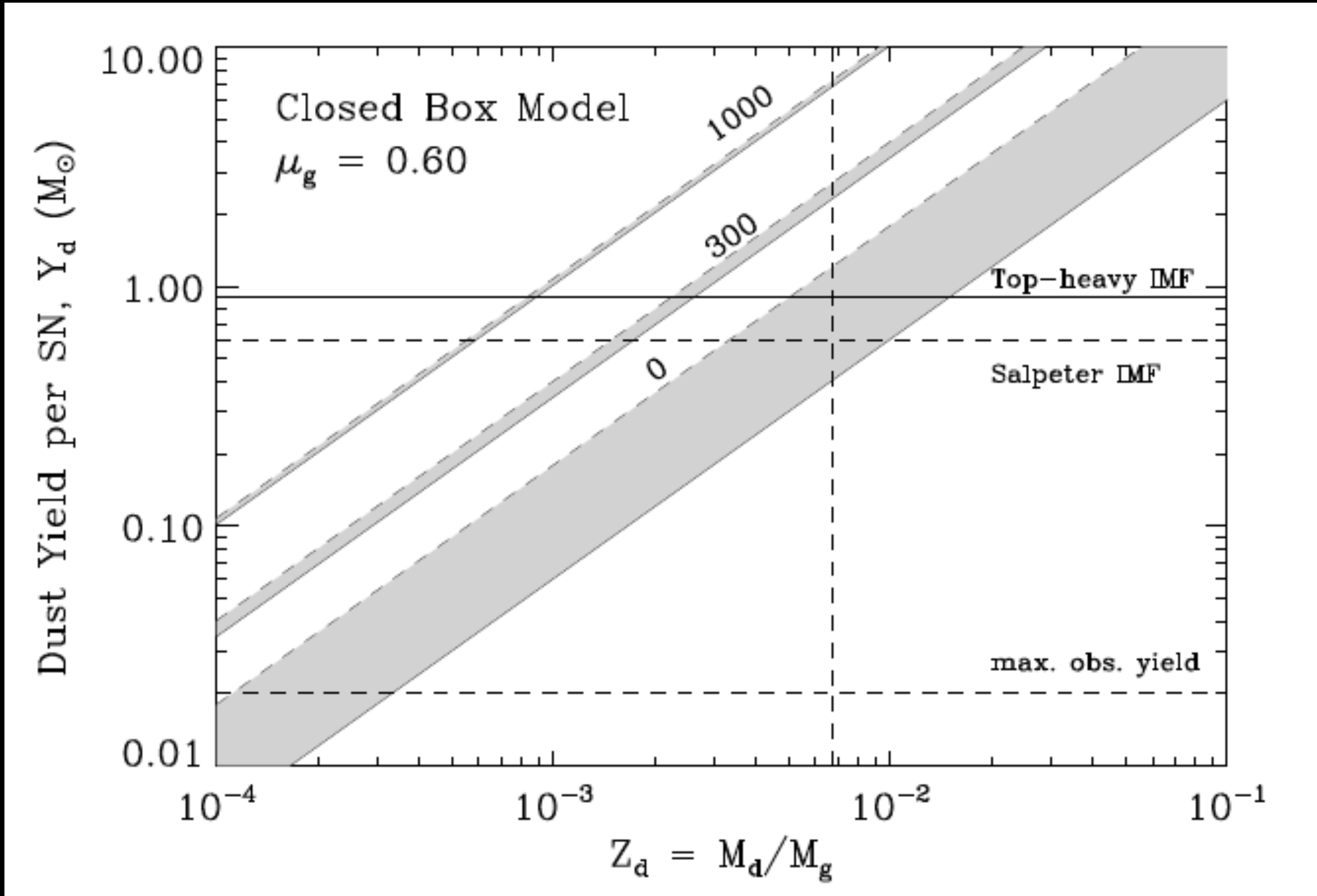
Draine 2009

Problem in MW, SMC, LMC: only 4-10% stellar dust

(e.g., Draine 2009, Matsuura et al. 2009, Boyer et al. 2012)

Efficiency

Quasar J1148+5251 (z = 6.4)



~ 1 $M_\odot$ per SN

Dwek et al. 2007

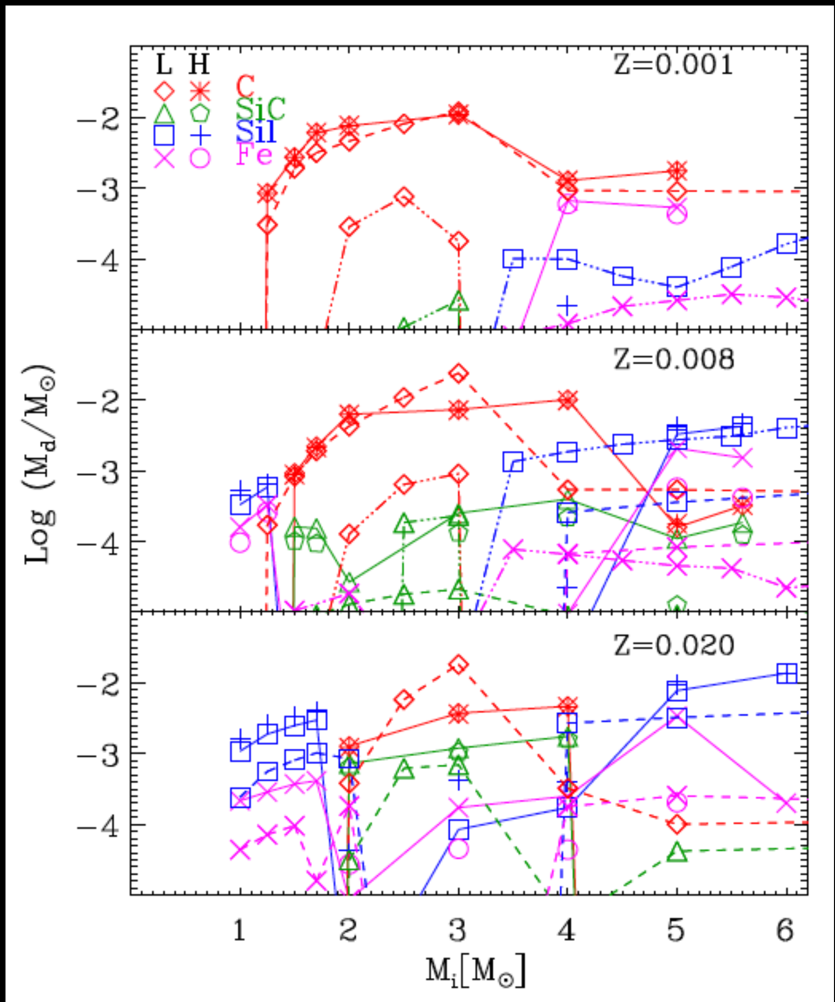
Potential sources

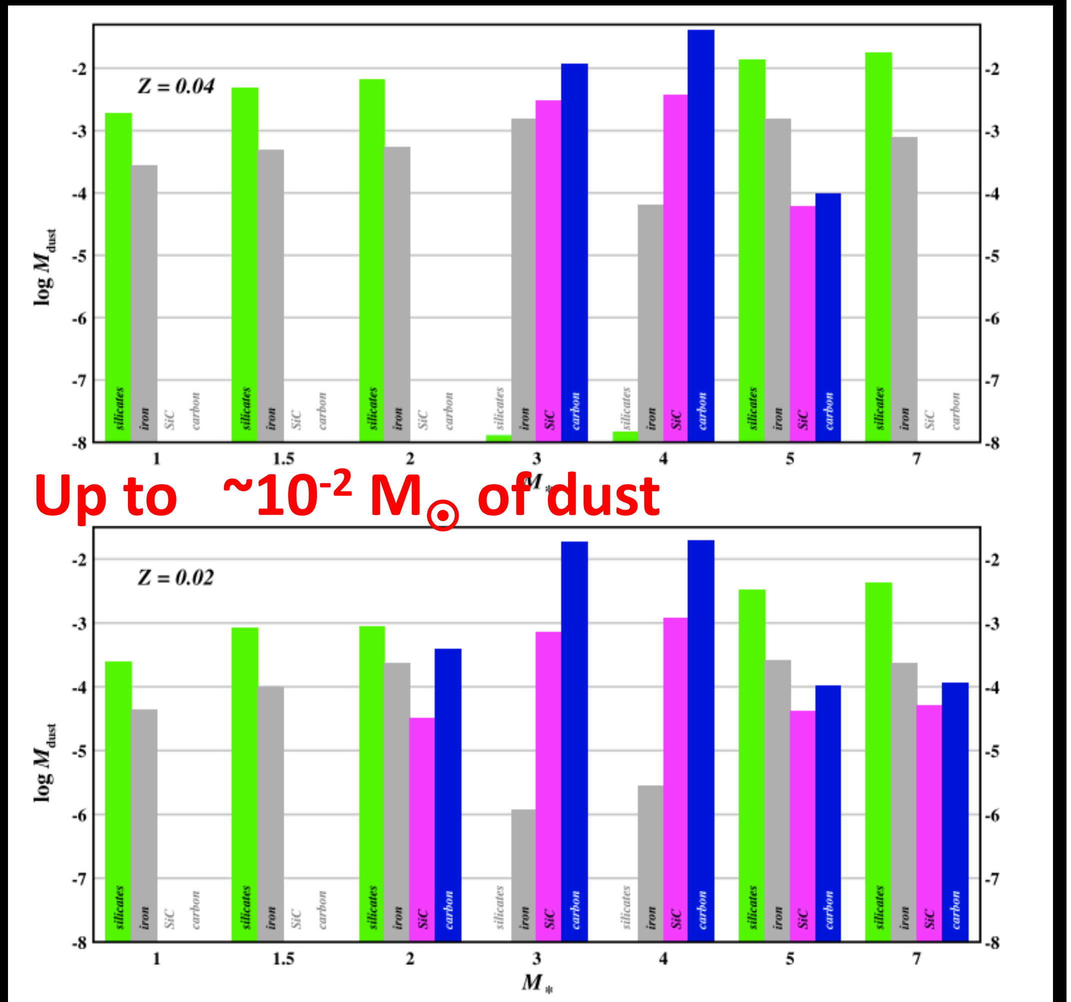
First Stars - Population III Stars

- Formed in dark-matter mini halos of ~10^{5-6} $M_\odot$ at redshift z ~ 10–50
  (Tegmark et al. 1997)
- Pair Instability Supernova (PISNE) ~140–260 $M_\odot$
- Dust:
  - 140 – 260 $M_\odot$ ~ 15–30% (Nozawa et al. 2003)
  - 170 $M_\odot$ ~ 5.6 – 25 $M_\odot$ (Cherchneff & Dwek 2009, 2010)
- Type Ic SN 2007bi has been reported as a PISN
  (Gal-Yam et al. 2009)
  - Core collapse SN (~100–280 $M_\odot$)
    (Moriya et al. 2010; Yoshida and Umeda 2011)
- Chemical signature not unambiguously detected yet
  (e.g.,Beers and Christlieb 2005)

AGB Stars

Theoretical dust yields for AGB stars



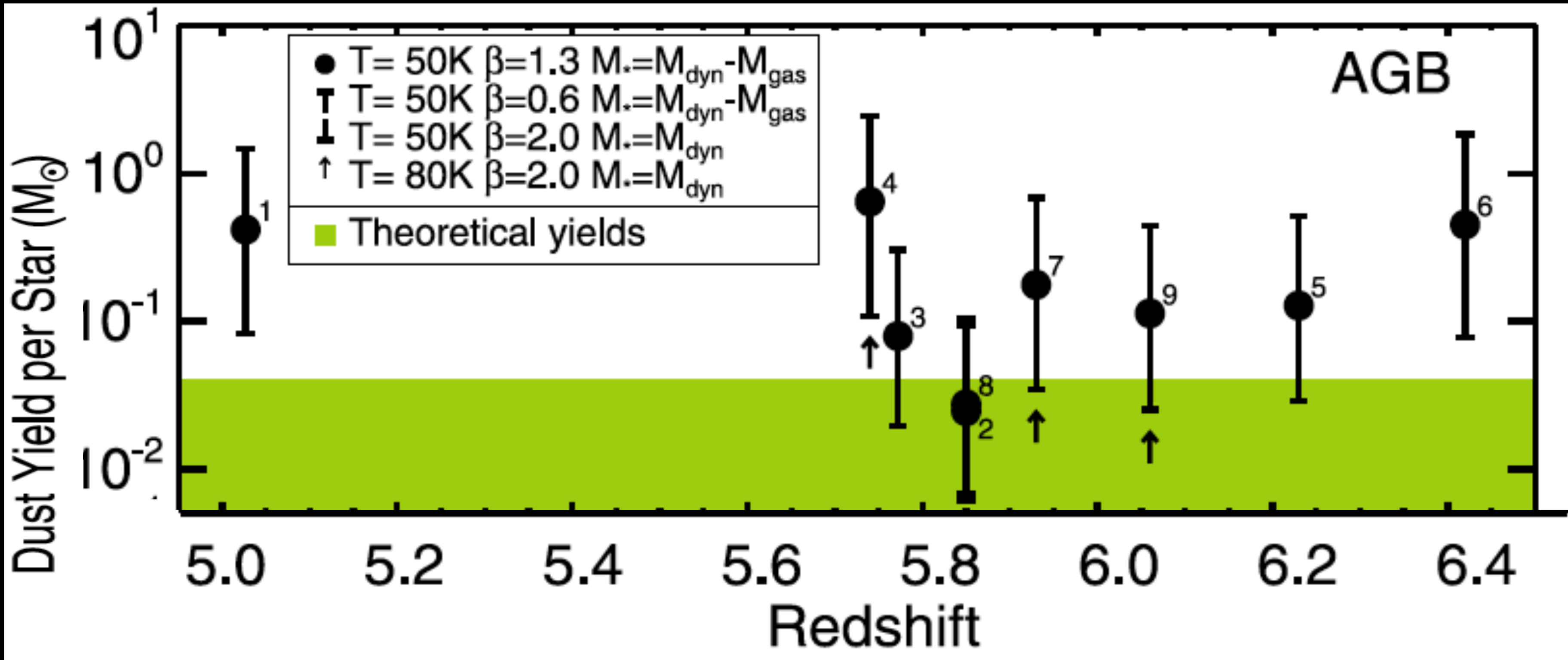


Up to ~10^{-2} $M_\odot$ of dust

Nanni et al. 2013

Ferrarotti and Gail 2006

AGB Stars



Michalowski et al. 2011

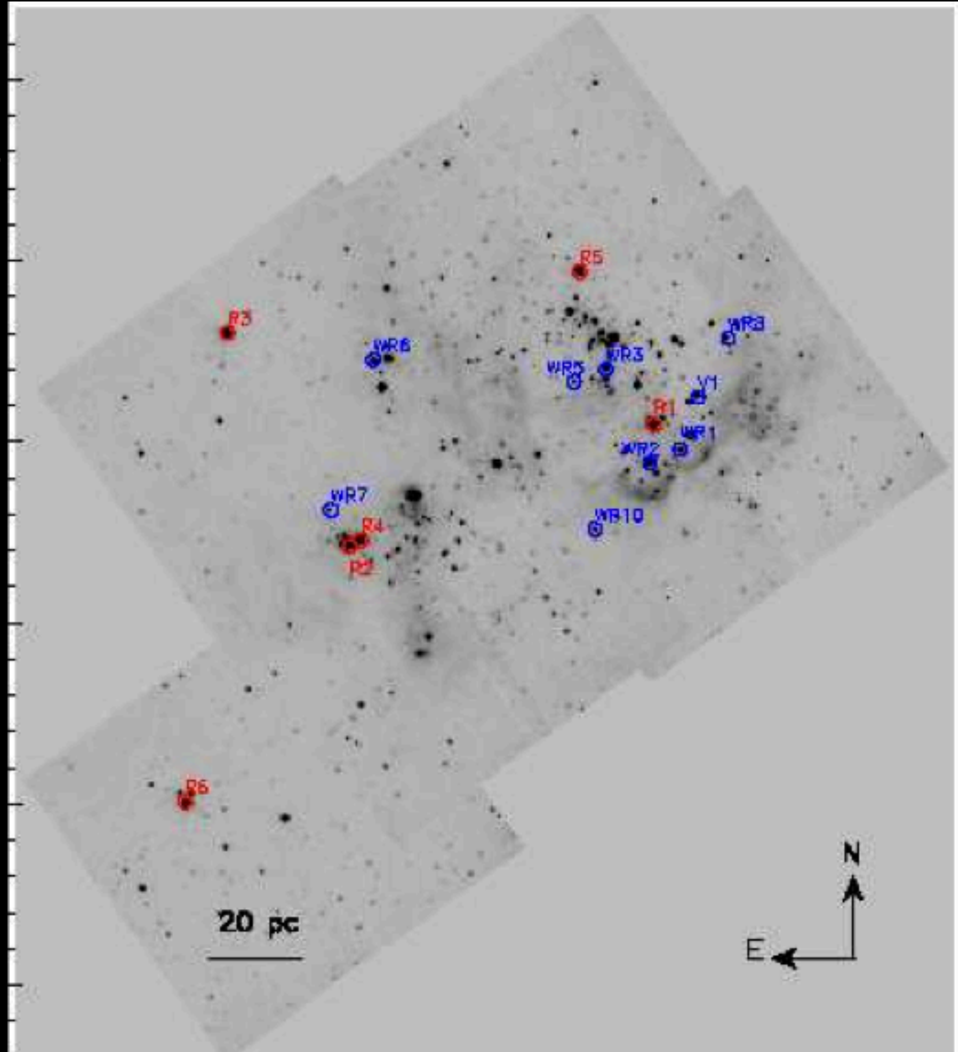
Massive Stars

- RSGs and WR stars in NGC 604,HII region in M33
  (Eldridge et al. 2006, Eldridge and Relaño 2011)

⇨WR stars appear less extinguished than RSGs

- Dust in colliding winds of binary systems: WR104, WR140 ,~8 x 10^{-7} $M_\odot$ yr^{-1}

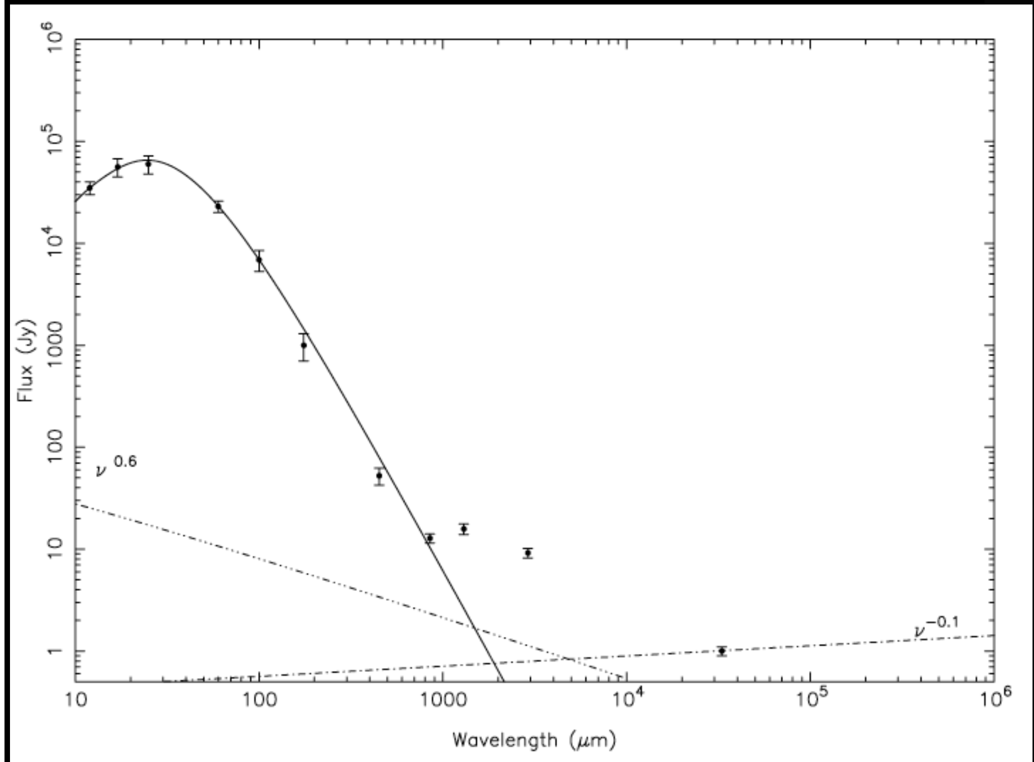
  (e.g., Crowther 1997, Williams et al. 1990, Harris et al. 2004)

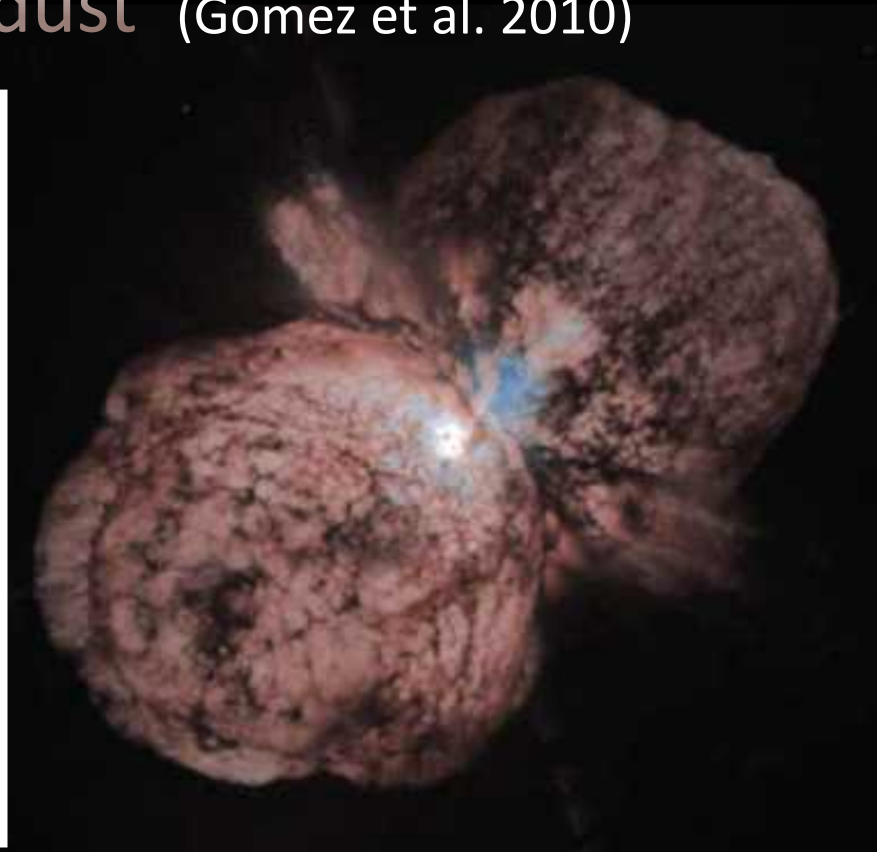


⇨ 3 × 10^{-8} $M_\odot$ yr^{-1} kpc^{-2} → ~ 1% of AGBs (Massey et al. 2005)

Massive Stars

- LBV stars, > 25 $M_\odot$
- e.g., η Car : ~ 0.4 $M_\odot$ of dust (Gomez et al. 2010)

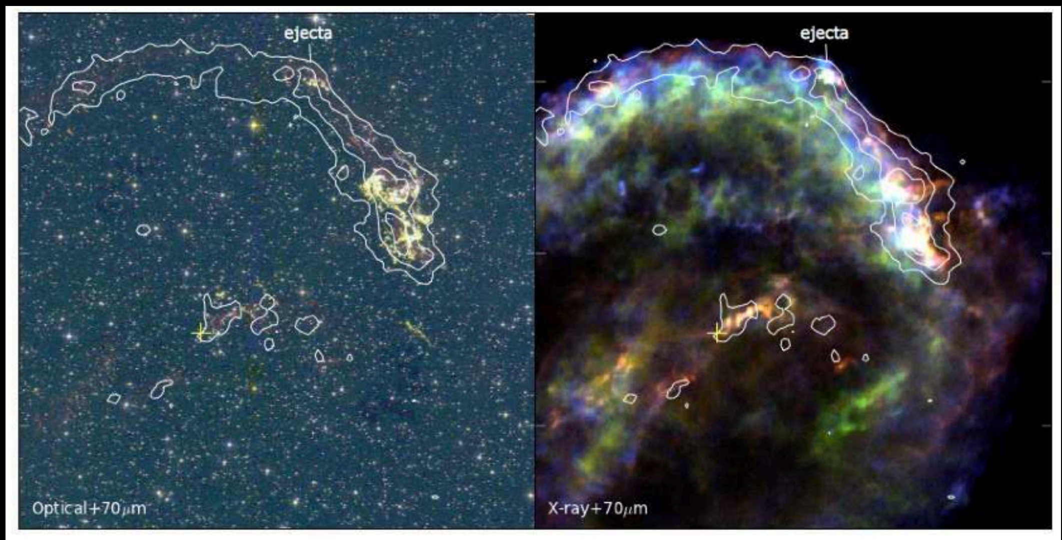


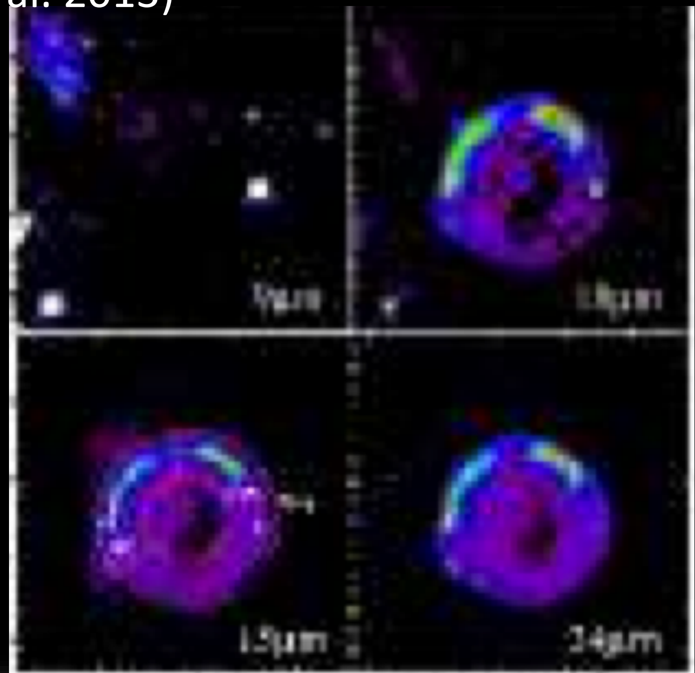


Supernovae – Type Ia

- Little to no dust in Ia SN (Nozawa et al. 2011)
- No observational evidence
- Dust is circumstellar or interstellar

(e.g.: Ishihara et al. 2010, Gomez et al. 2012, Phillips et al. 2013)



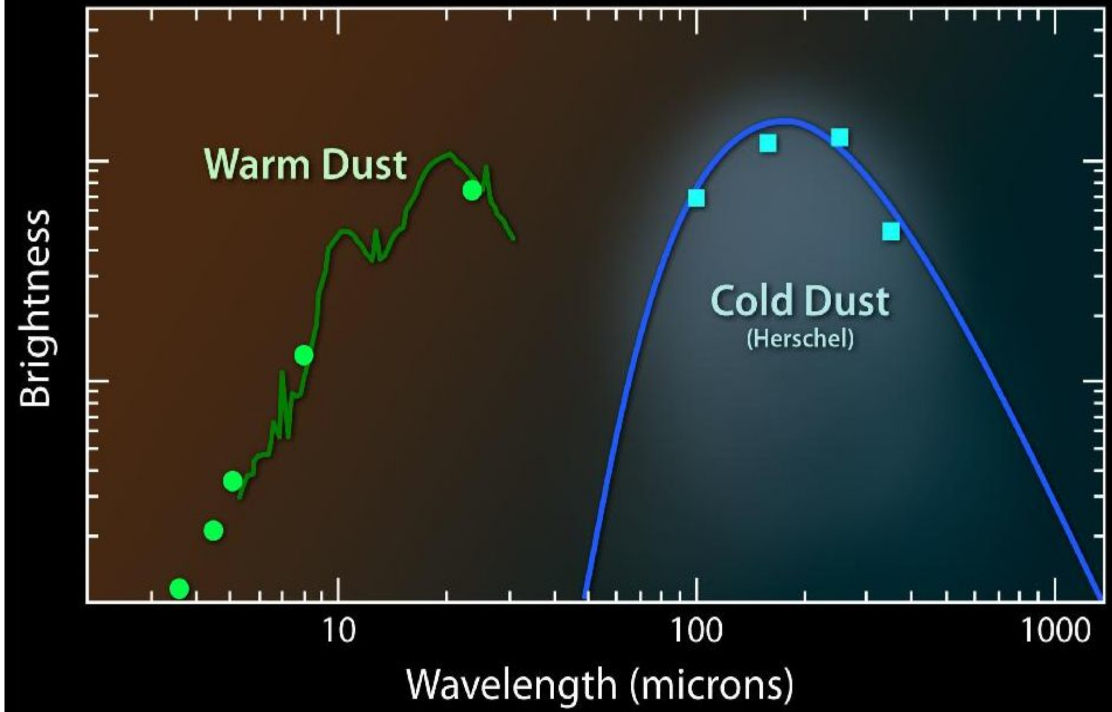


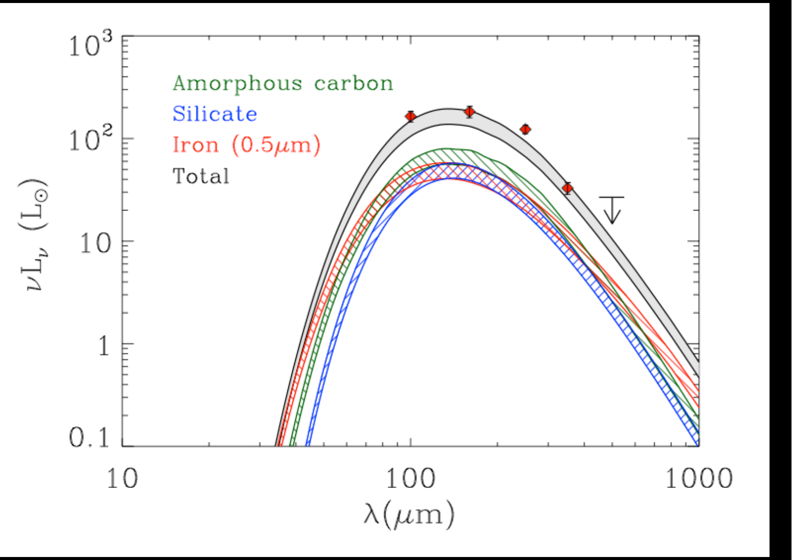
CORE COLLAPSE SUPERNOVAE KNOWN DUST PRODUCERS

Core Collapse Supernovae

Herschel Observations of SN 1987A

~ 20 K ~ 0.5-0.7 M_{sun}



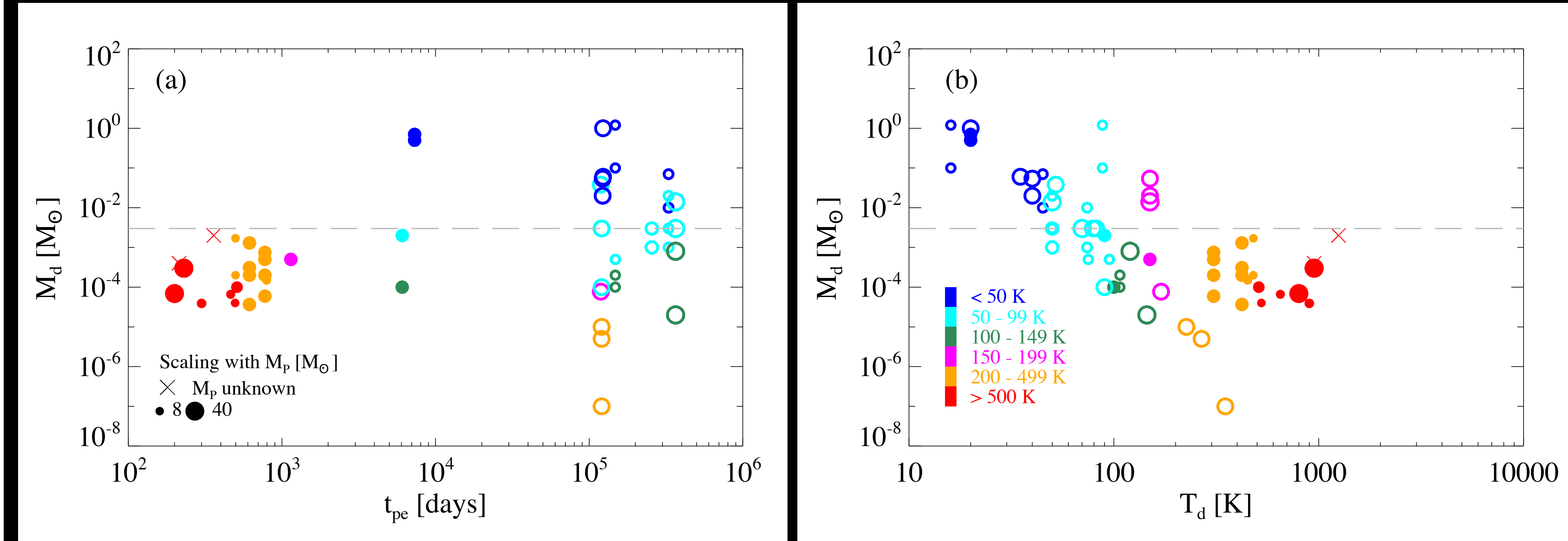


Matsuura et al. 2011

Lower dust masses suggested by Lakićević et al. 2012

Core Collapse Supernovae

Observational evidence of dust from supernovae

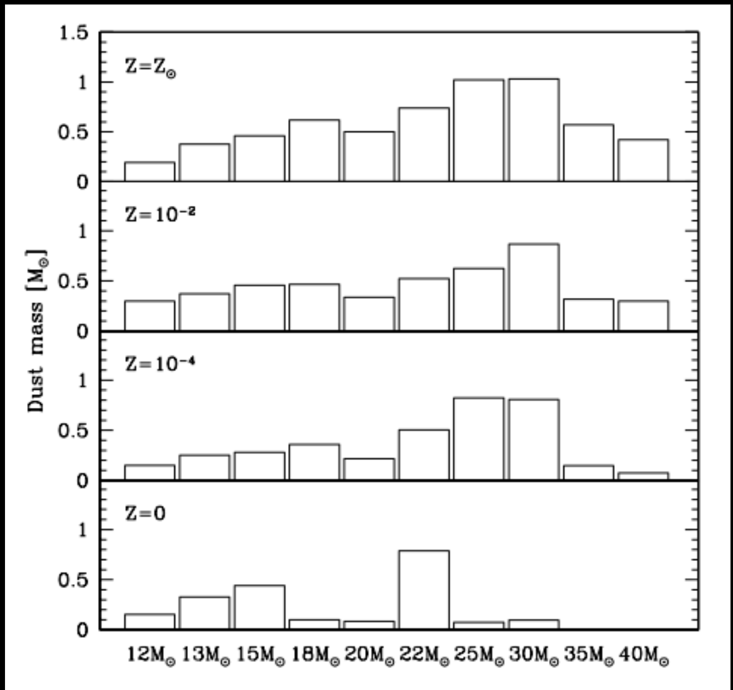


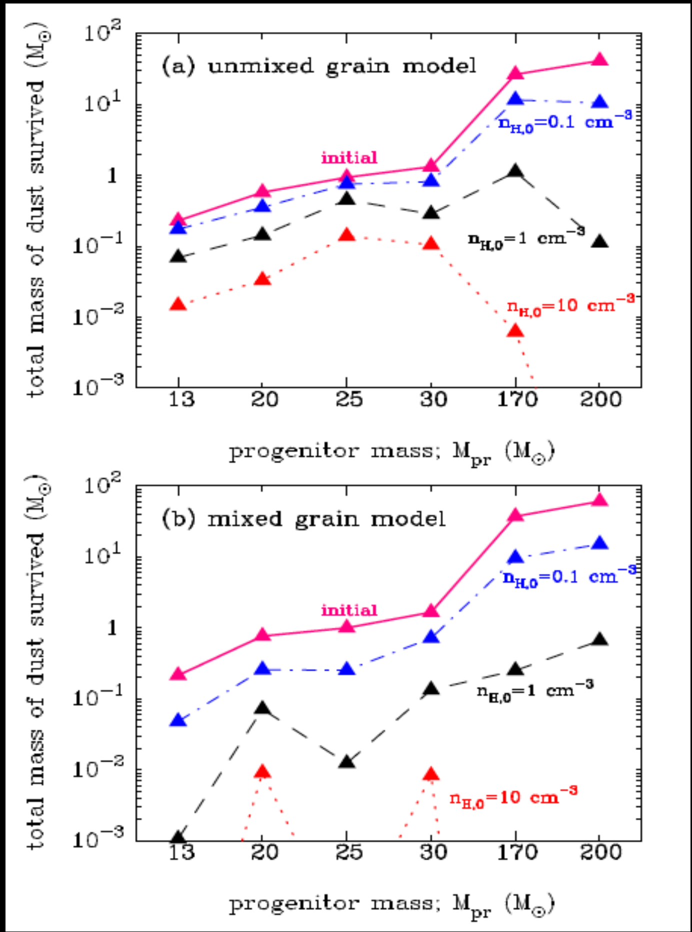
Gall et al. 2011, A&ARv

Core Collapse Supernovae

SNe (13–40 $M_\odot$) about 2–5%
(Nozawa et al. 2003)

SNe (20$M_\odot$) ~ 0.103 – 0.16$M_\odot$
(Cherchneff & Dwek 2009, 2010)





Todini & Ferrara 2001, Bianchi & Schneider 2007, Nozawa et al. 2007

Core Collapse Supernovae

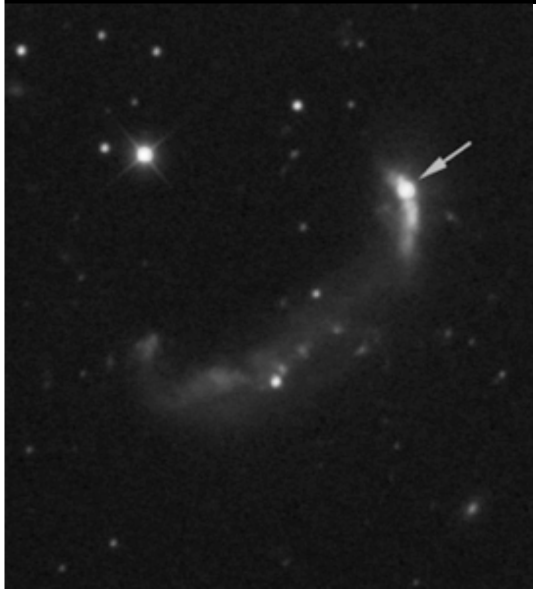
Different types of core collapse supernovae

SN Type	Characteristics	Progenitor $M_\odot$	Progenitor Type
II-P (plateau)	Hydrogen present	(7) 8 - 25	RSG
II-L (linear)	Blue	~ 15 – 25	YSG
IIn (narrow line)	Narrow emission lines, broad base	~ 8 – 10 > 25 – 30	SAGB LBV
IIb	Little hydrogen	> 25 - 30	WR, binary
Ib	Helium rich	> 25	WR
Ic	Helium deficient	> 25	WR, binary

No evidence of dust from Ic SNe!

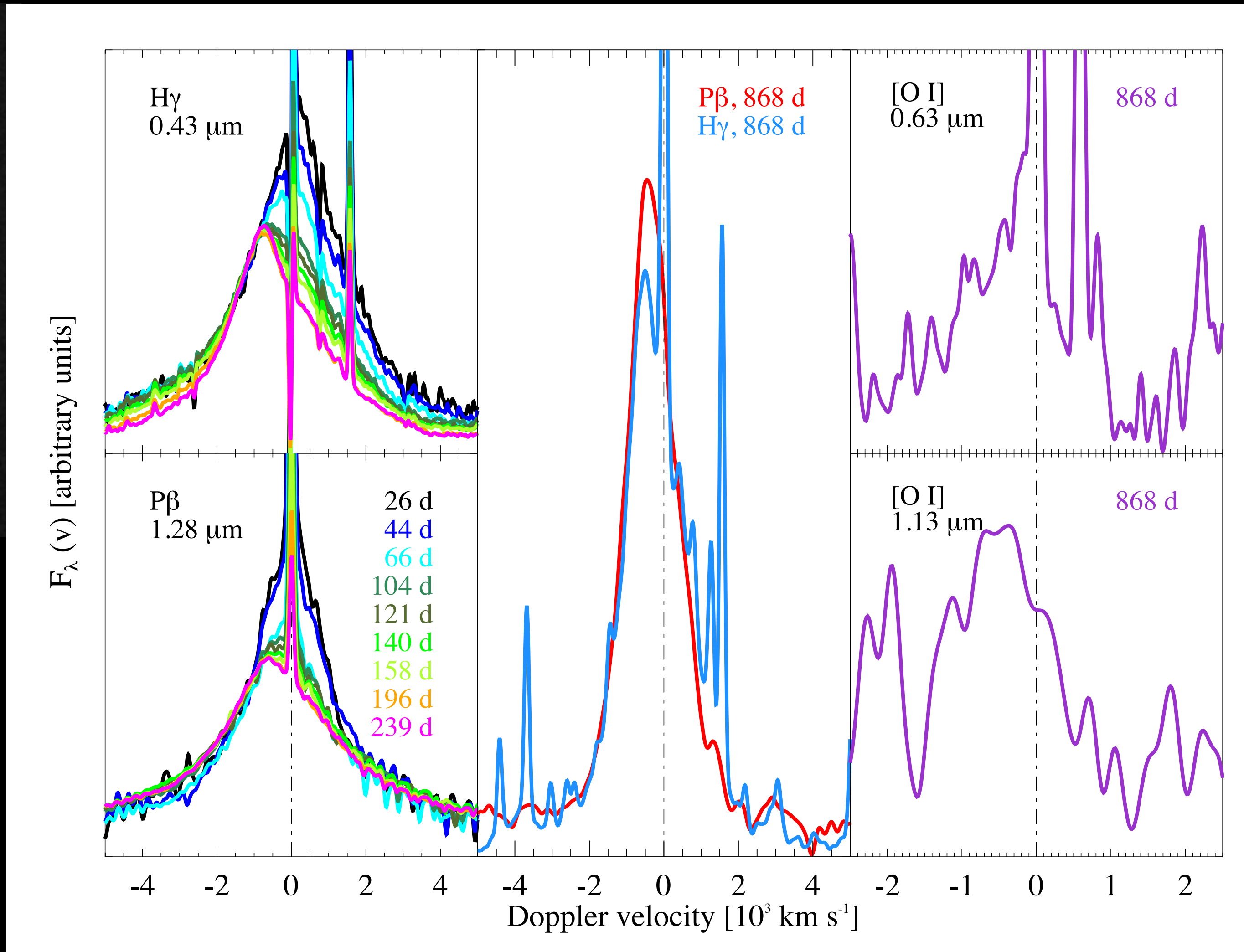
SUPERNOVAE WITH CIRCUMSTELLAR INTERACTION

Type IIn SN 2010jl, VLT/X-shooter



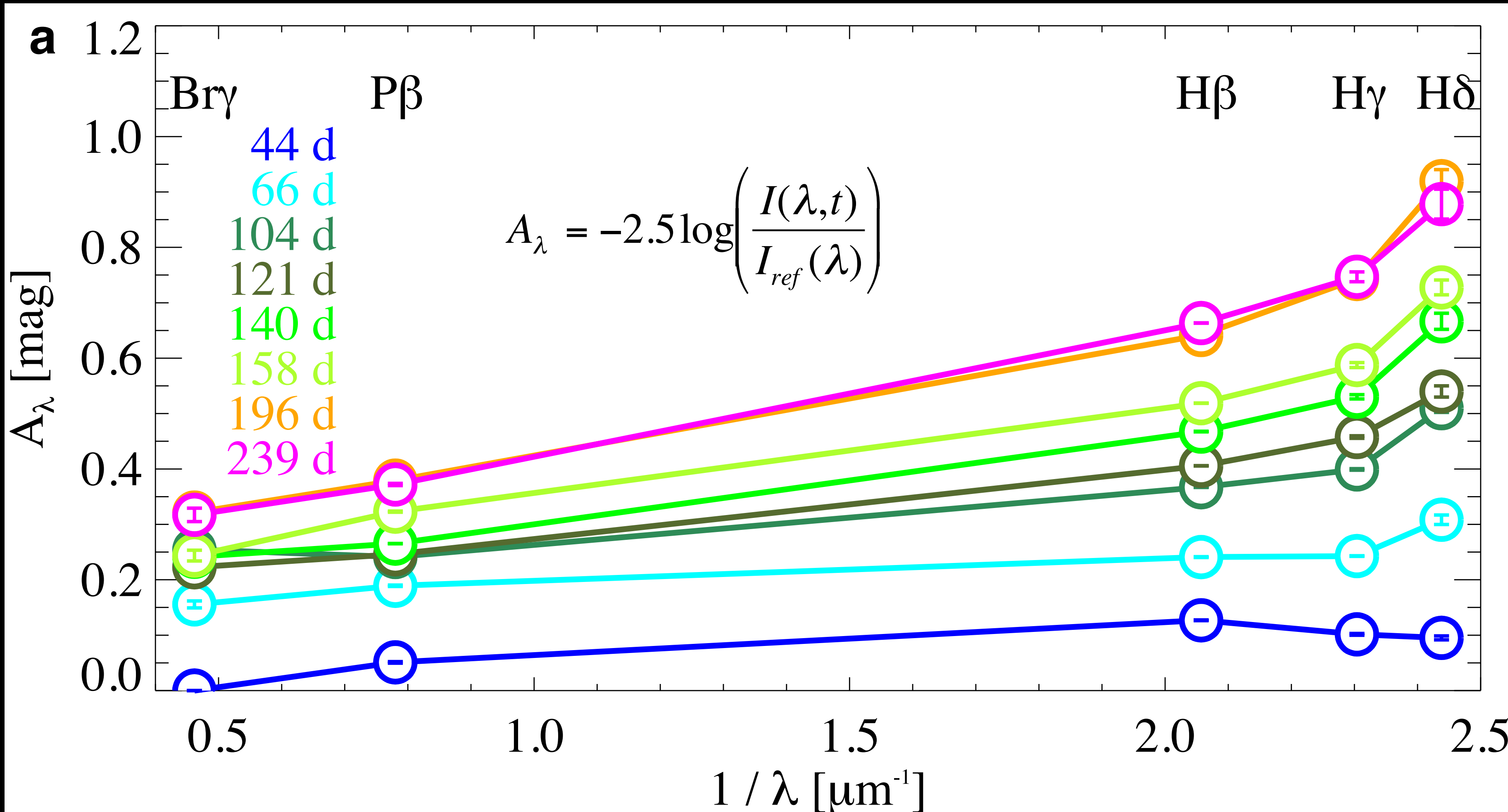
UGC 5189

Redshift of SN
z = 0.01058



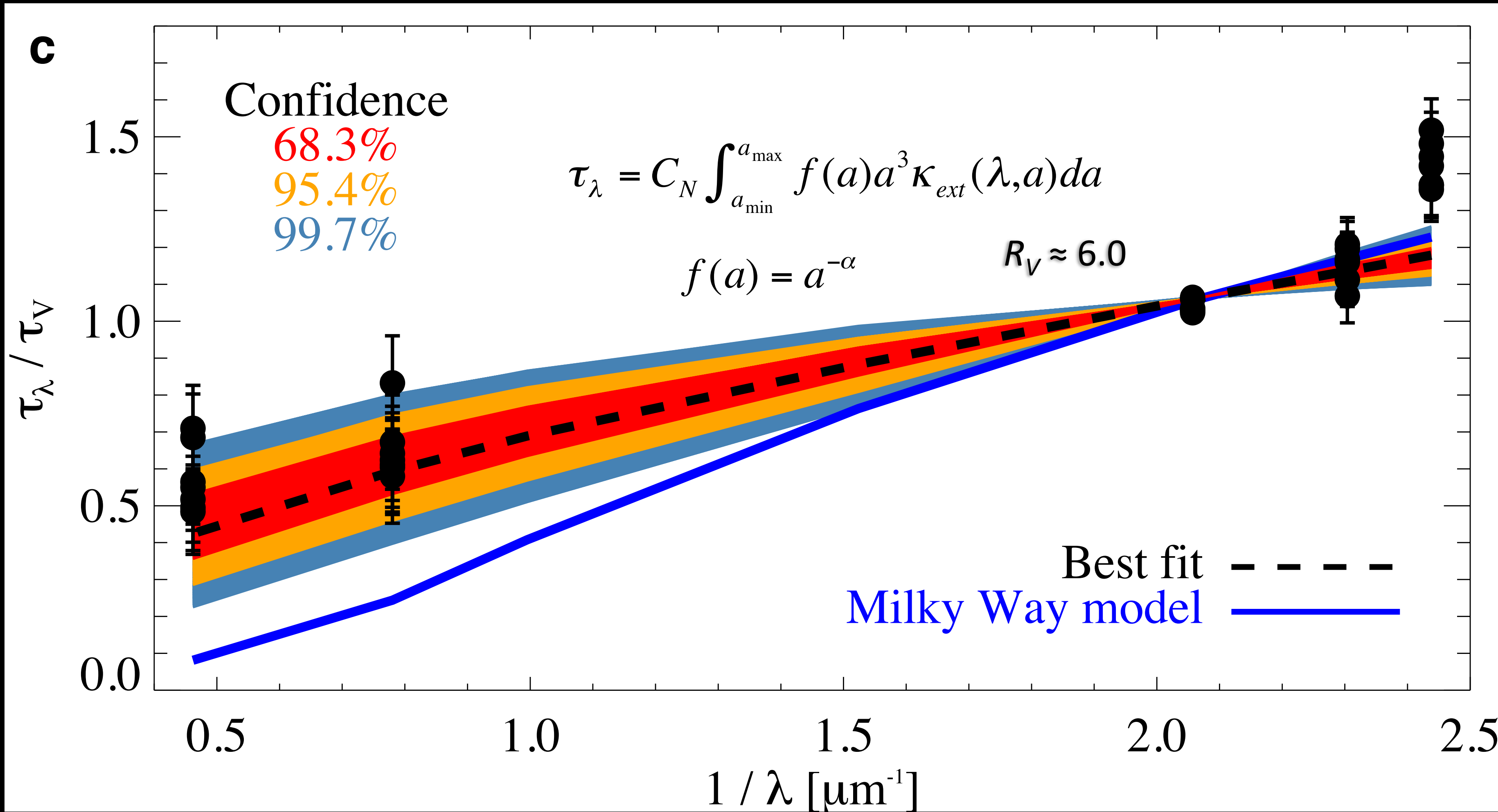
Gall et al. 2013, submitted

Supernova extinction curve



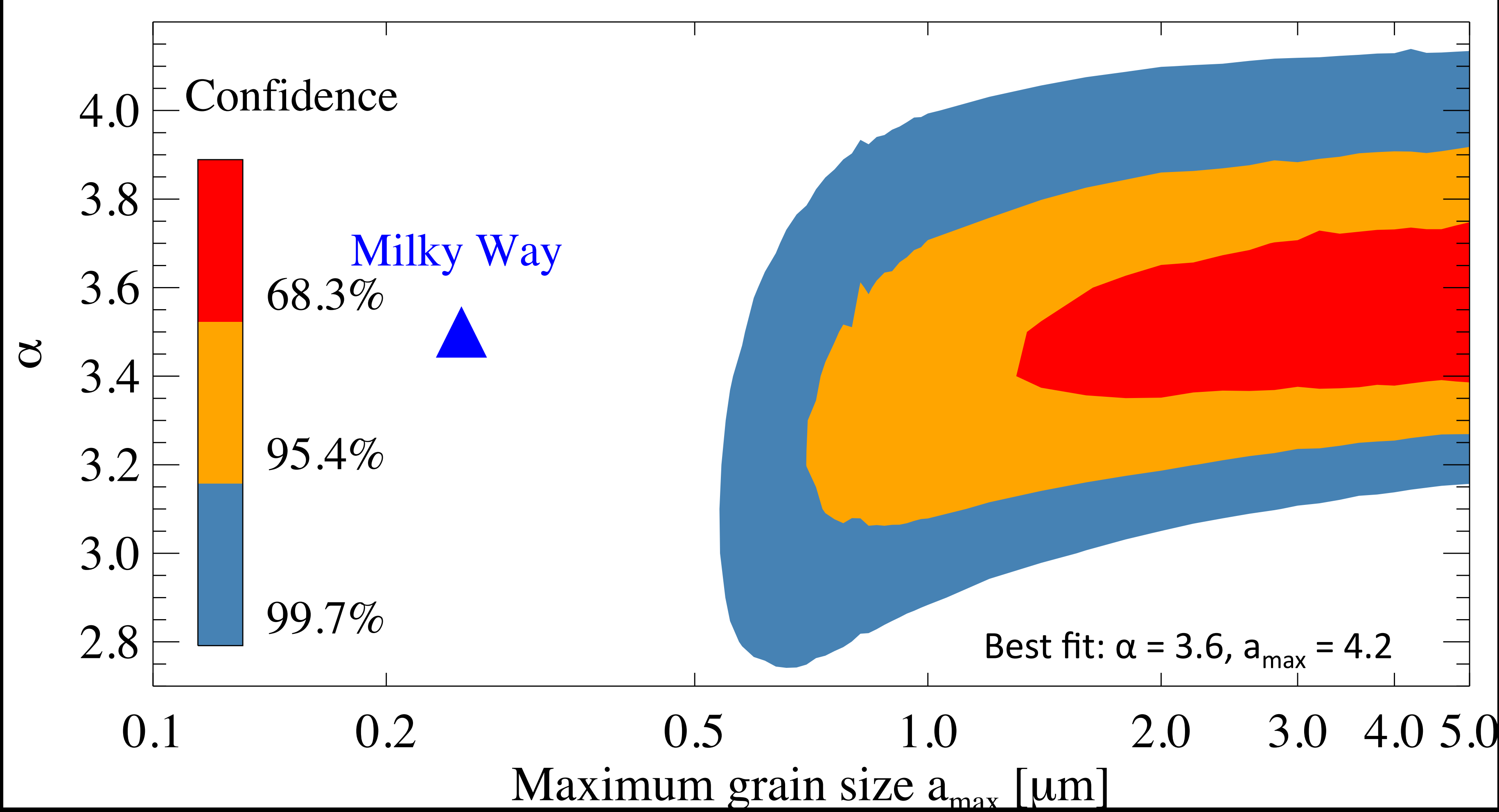
Gall et al. 2013, submitted

Supernova extinction curve



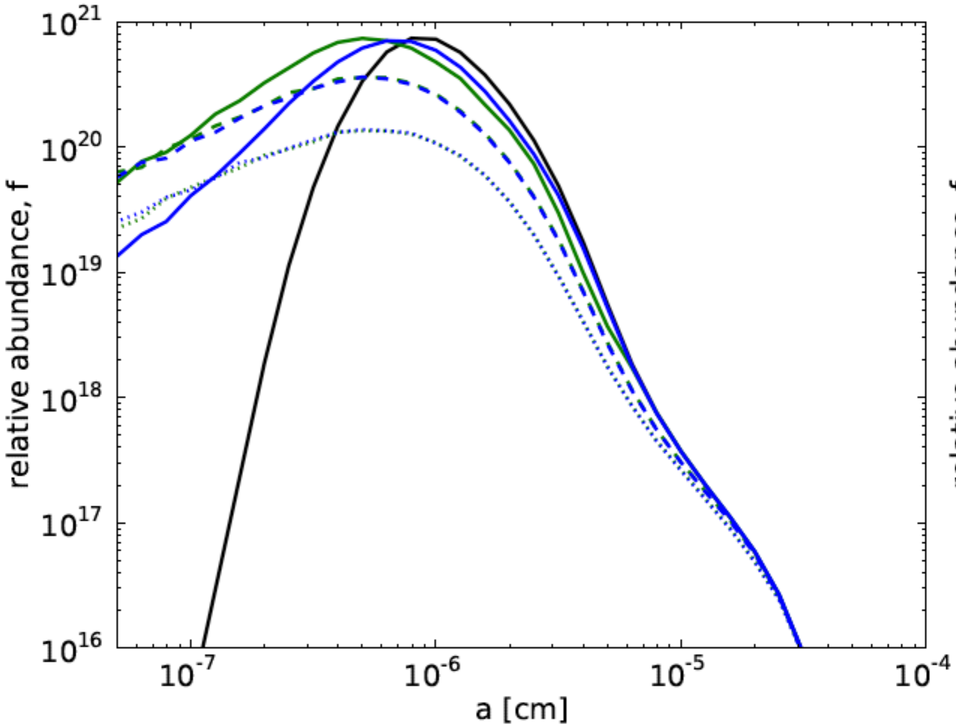
Gall et al. 2013, submitted

Large grains

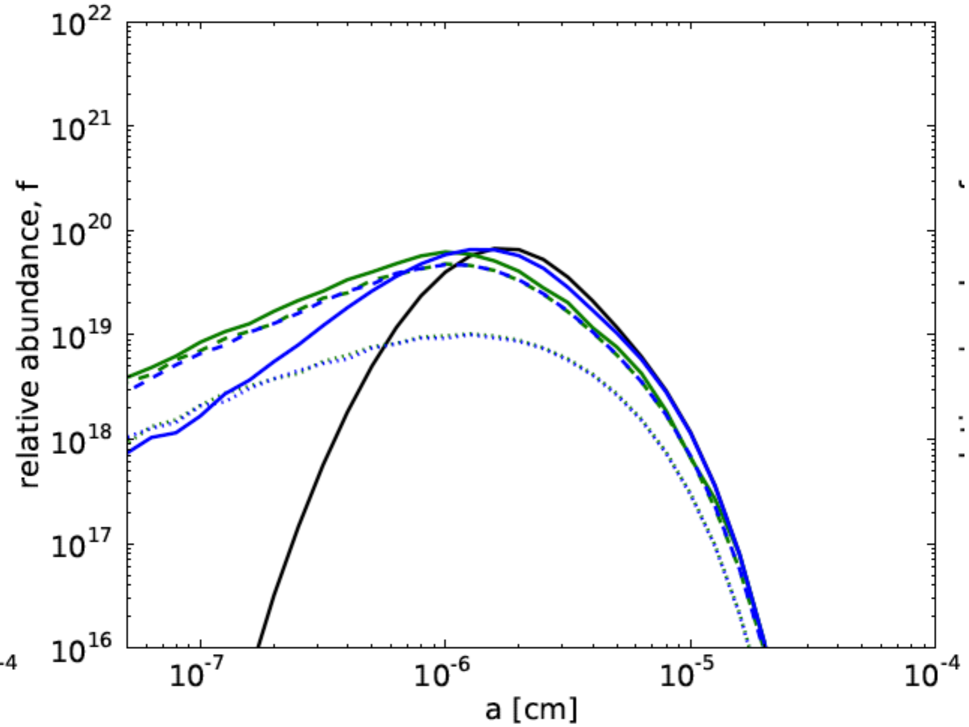


Gall et al. 2013, submitted

Large grains are robust against destruction



(a) C



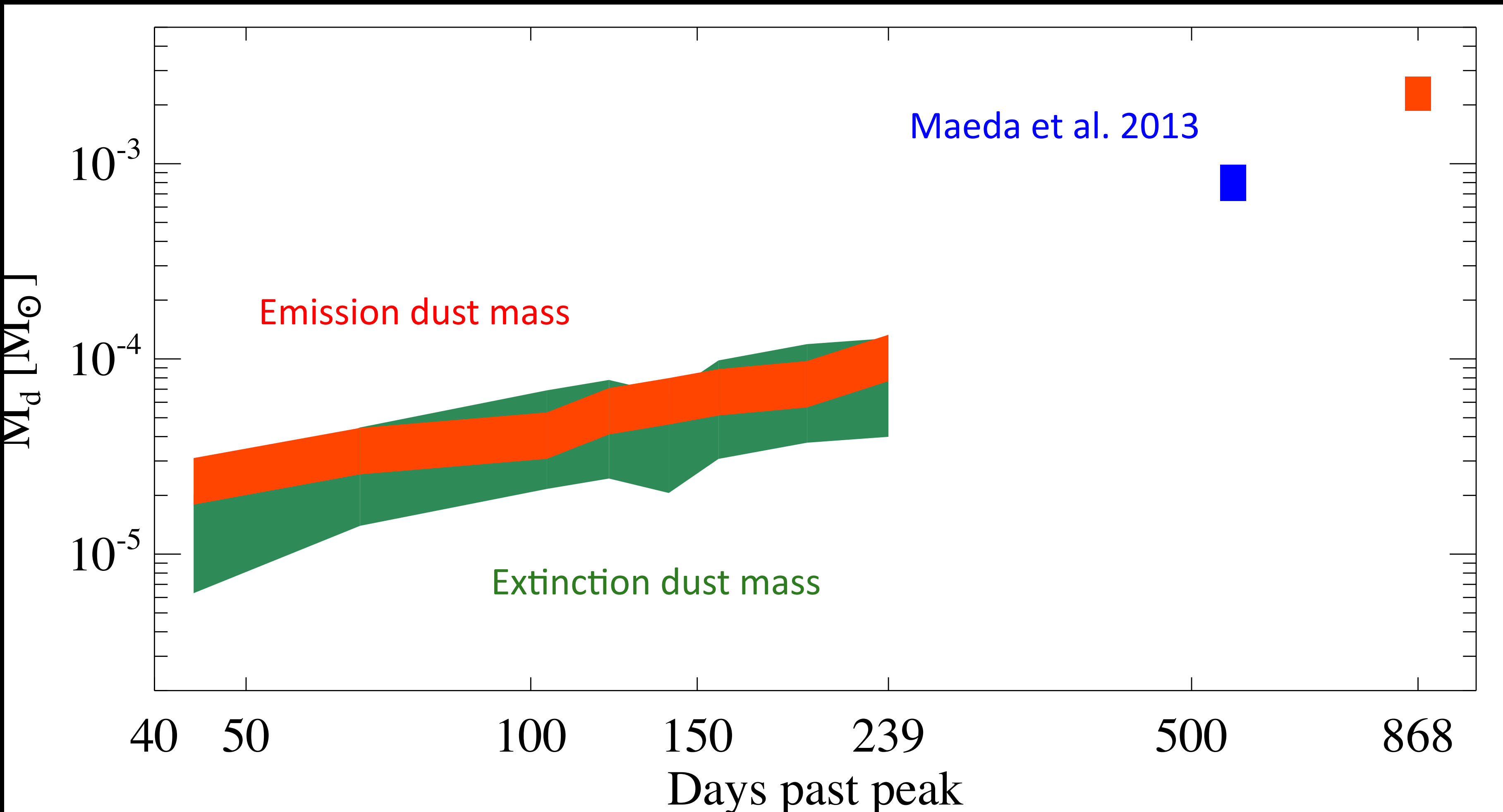
(b) Silicates

Silvia et al. 2010

Grains > 0.1 µm have highest survival rate

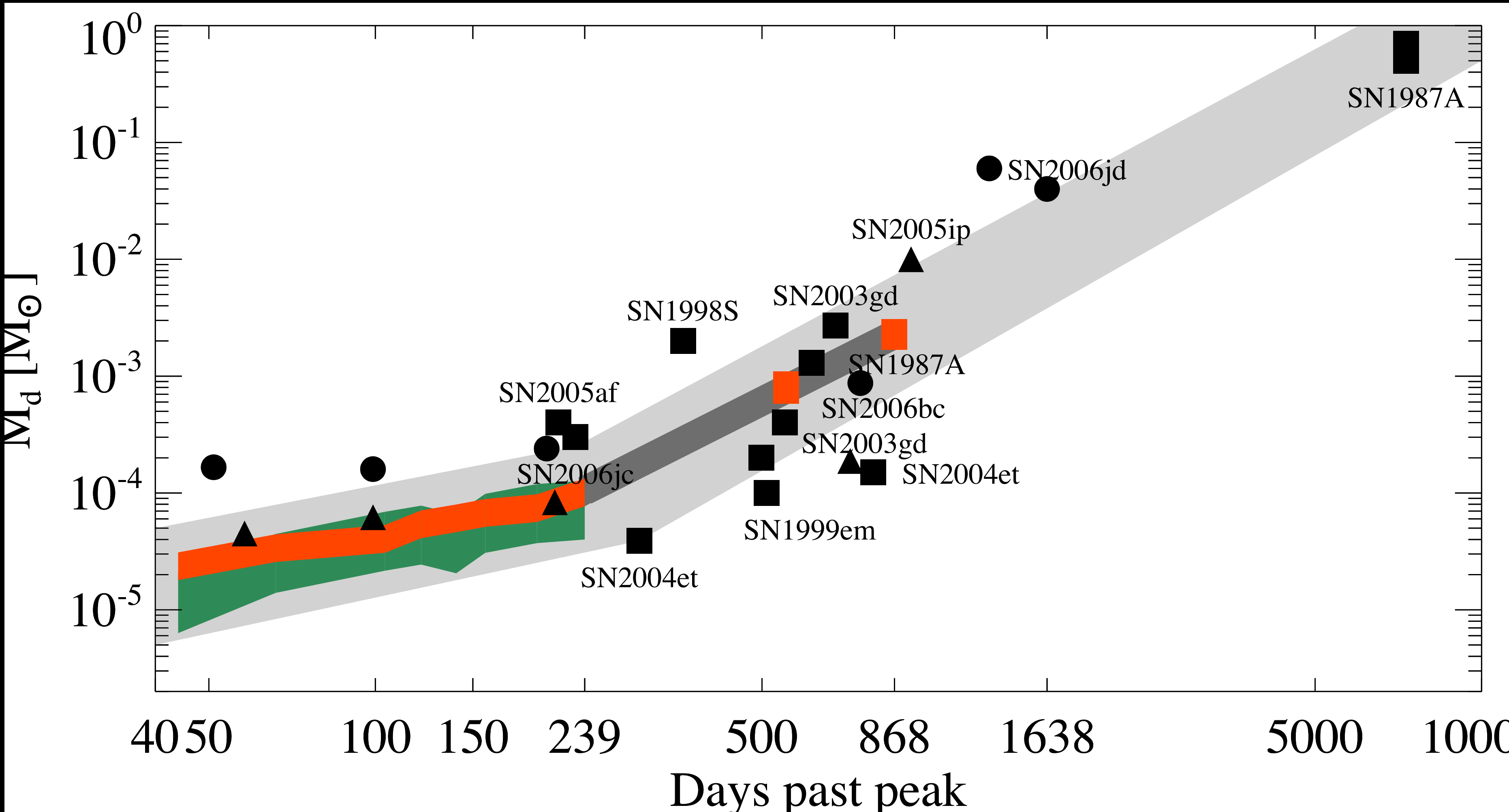
SN 2010jl: 80% of dust mass is in form of large grains !!

Dust mass estimates



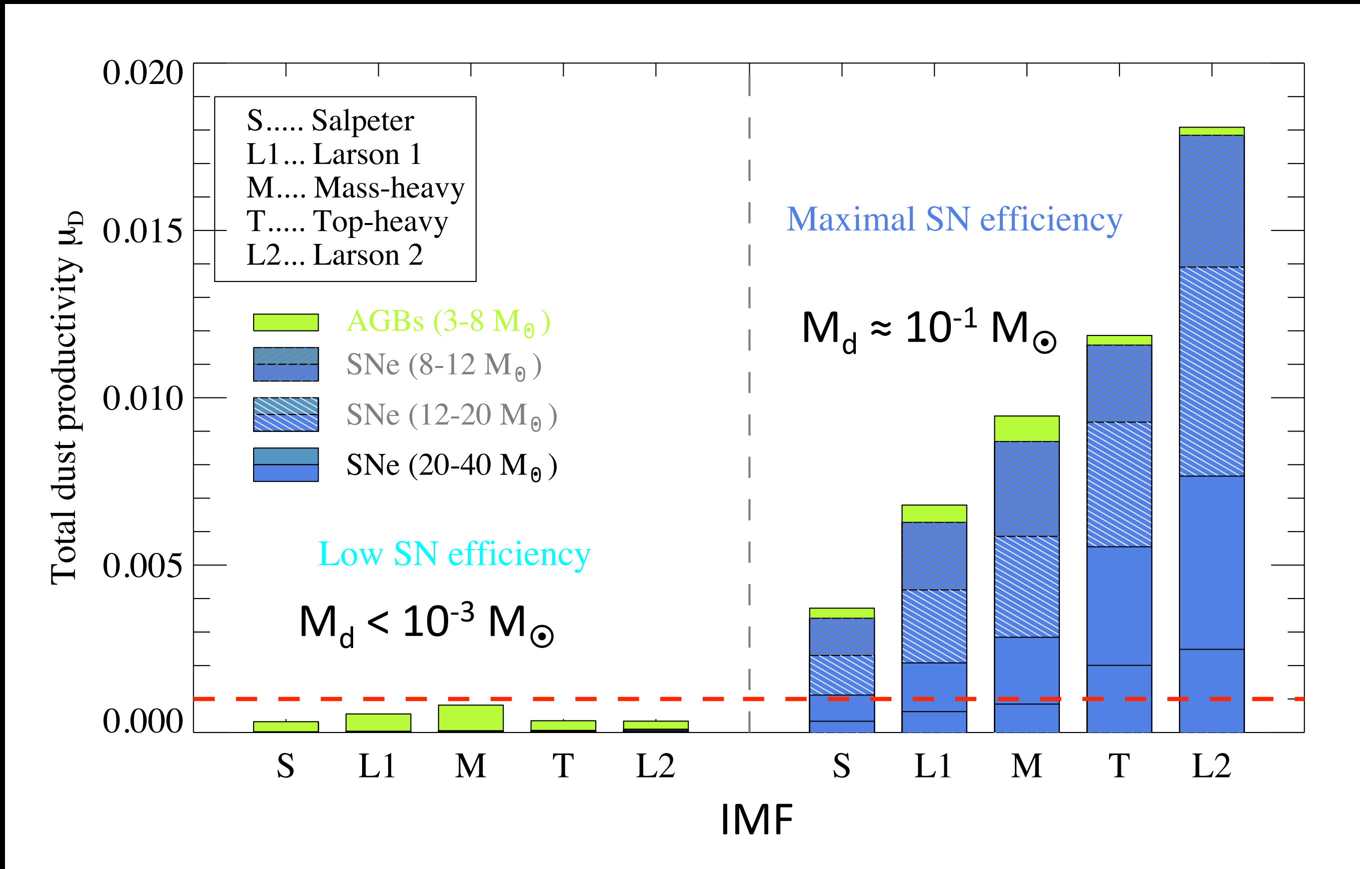
Gall et al. 2013, submitted

Linking early and late dust masses



Gall et al. 2013, submitted

Dust productivity



Gall et al. 2011, A&ARv

$$\mu_D = \int_{m_L}^{m_U} \phi(m) M_z(m) \varepsilon(m) dm$$

$$M_{dust} = \mu_D \times SFR \times \Delta t$$

ADDRESSING DUST IN GALAXIES

Modeling dust evolution

Different model predictions

e.g.:

Morgan & Edmunds et al. 2003

Dwek et al. 2007

Calura et al. 2008

Valiante et al. 2009, 2012 -> favour AGB stars, grain growth

Pipino et al. 2010

Dwek & Cherchneff 2010

Gall et al. 2011 A&A,525,13; 525,14 -> favour SNe !!

Mattsson 2011 -> favour grain growth

Asano et al. 2013

and many more ……..

Different assumptions!!!

Chemical Evolution models

Parameters	Value	Unit	Description
$M_{\rm ini}$	5×10^{10}, 1×10^{11}, 5×10^{11}, 1.3×10^{12}	$M_\odot$	Initial mass of the galaxy
$\psi_{\rm ini}$	1×10^{3}	$M_\odot\ {\rm yr}^{-1}$	Star formation rate
$Z_{\rm ini}$	10^{-6}	$Z_\odot$	Initial metallicity
k	1.5		Power for the relation $\psi(t) \propto M_{\rm ISM}(t)^k$
$M_{\rm cl}$	800, 100, 0	$M_\odot$	Swept-up ISM mass per SN
$M_{\rm core}^{\rm crit}$	15	$M_\odot$	Critical He core mass
$\xi_{\rm SN}$	0.93		SN dust destruction factor
$M_{\rm SMBH}$	3×10^{9}, 5×10^{9}	$M_\odot$	Mass of the SMBH
$t_{\rm SMBH}$	4×10^{8}	yr	Growth timscale for the SMBH
$t_{\rm max}$	10^{9}	yr	Maximum computed age of the galaxy
Parameters	**Switch**		**Description**
$Y_{\rm Z}$, $Y_{\rm E}$, $Y_{\rm Q}$ (for SN)	EIT08, WW95, N06, Georgy et al. (2009)		Possibilities for the SN yields
$Y_{\rm Z}$, $Y_{\rm E}$, $Y_{\rm Q}$ (for AGB)	van den Hoek & Groenewegen (1997)		Possibilities for the AGB yields
$\phi(m)$	Salpeter, mass-heavy, top-heavy, Larson 1, Larson 2		Initial mass function
SFR	evolving/constant		Additional switch for the SFR
$\epsilon_{\rm AGB}(m, Z)$	only one case considered		Dust formation efficiency, AGB
$\epsilon_{\rm SN}(m)$	max/low		SN dust formation efficiency
$\xi_{\rm SN}$	considered/not considered		SN dust destruction
BH/SN	SN when BH/no SN when BH		Possibility, if a SN occurs even a BH is formed or not
SMBH	considered/not considered		Growth of SMBH

Gall et al. 2011

Chemical Evolution models

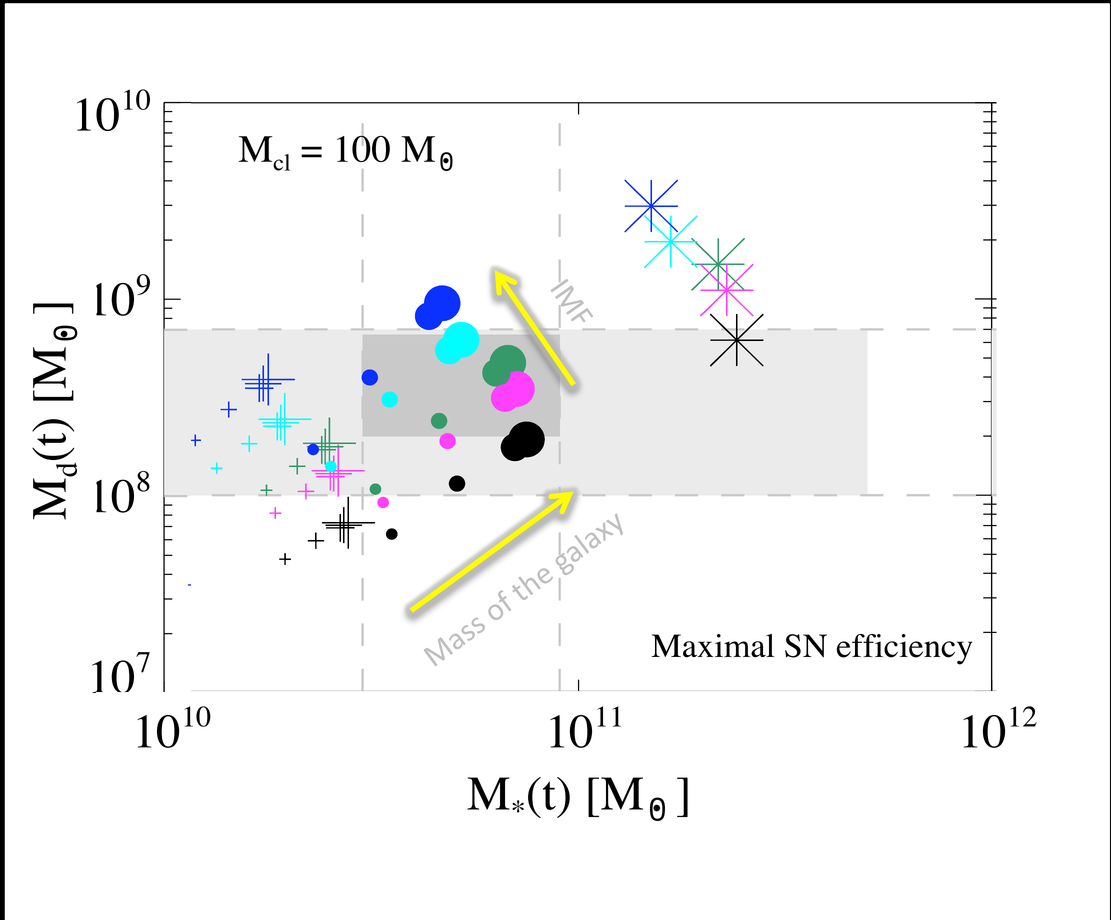
Tuning parameters

Most important:
SFR, IMF, Dust source, SN dust destruction

Good models:
Consistent with observational constraints

Chemical Evolution models

Modeling quasars at $z > 6$



Rapid evolution (30 Myr) with SN ~0.1-1 $M_\odot$

Gall et al. 2011A&A,525,13; 525,14

NON-STELLAR SOURCES

Grain growth in the ISM

- Accretion and coagulation in cold molecular clouds
- Various models: (e.g.: Dwek 1998; Hirashita 2000, Zhukovska, Gail, & Trieloff 2008; Draine 2009; Hirashita & Yan 2009; Pipino et al. 2011; Valiante et al. 2011; Inoue 2011; Asano et al. 2013)
- Growth timescales: ~ $10^{7\text{-}8}$ years
- Still need SNe to produce the metals and seeds
- Ejection of elements and dust into clouds ?
- Need to grow in a fairly high-density region, shielded from SN shocks, and need to grow a very large fraction of all metals ejected by SNe
- Fraction of cold molecular clouds ?
- Still subject to destruction

LAST WORDS

LAST WORDS

- Indication of fast and efficient process of dust formation
- Supernovae most promising sources
- Can account for dust in galaxies
- Challenges:
  - Destruction of SN dust by shock interactions
  - Destruction of all kinds of dust by SN shocks
- Importance of grain growth vs. direct formation
- Large grains?
- Can we trust observations, notably derived dust masses (kappa, …) and stellar masses

THANK YOU