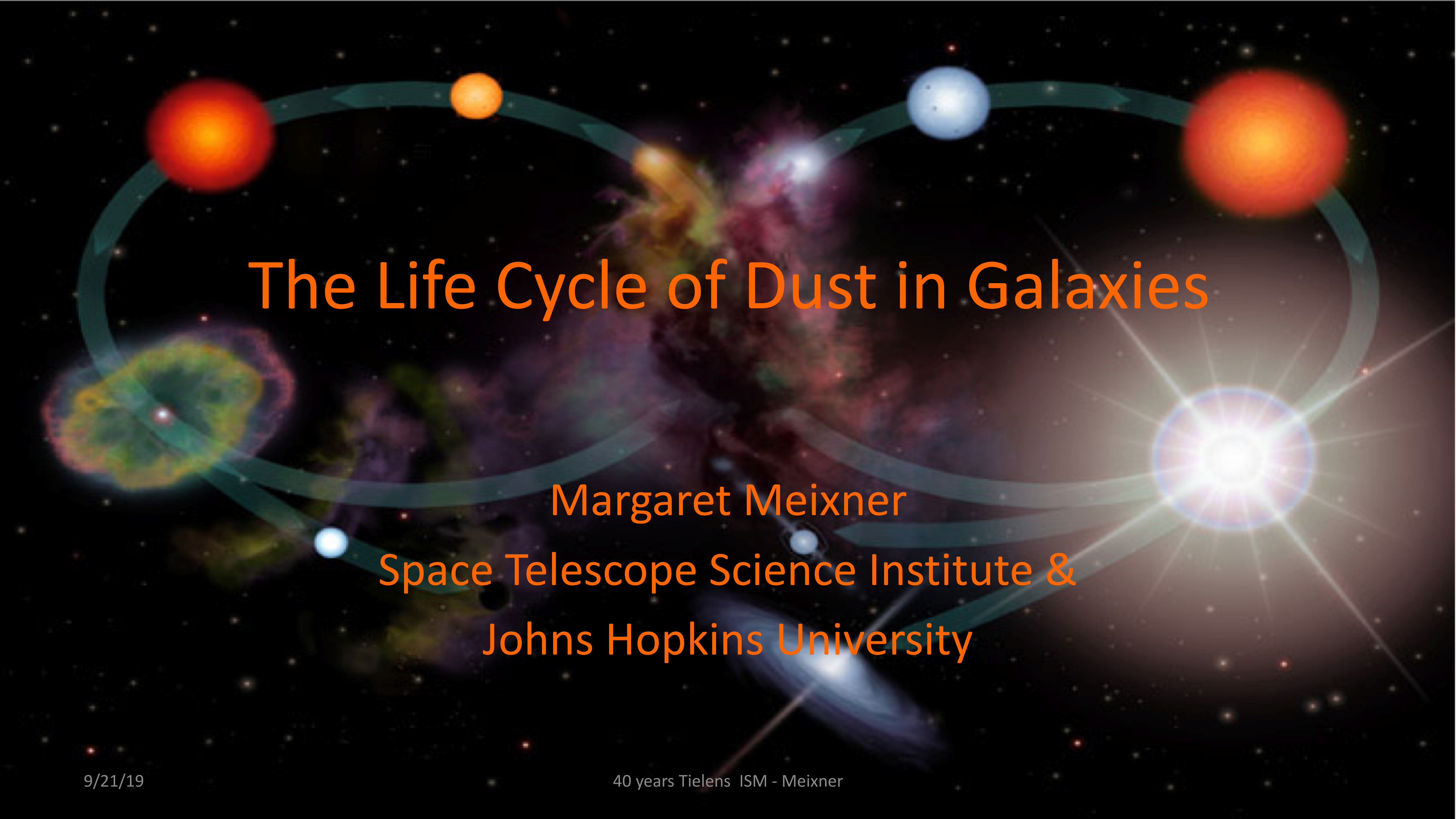


The Life Cycle of Dust in Galaxies

Margaret Meixner
Space Telescope Science Institute &
Johns Hopkins University

Thanks to the Mega-SAGE Team:

September 2015

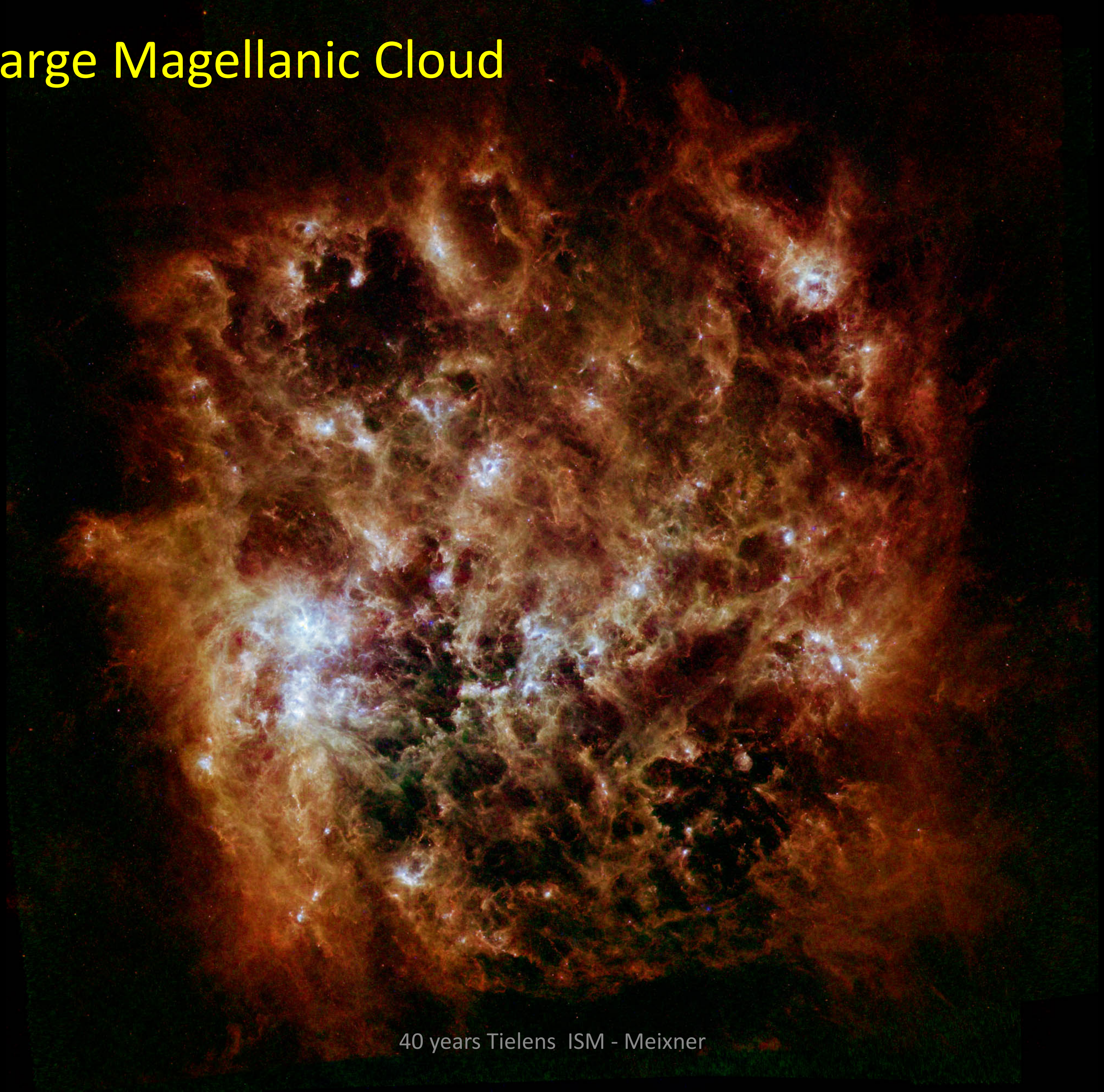
http://sage.stsci.edu/

Thanks to the Mega-SAGE Team:

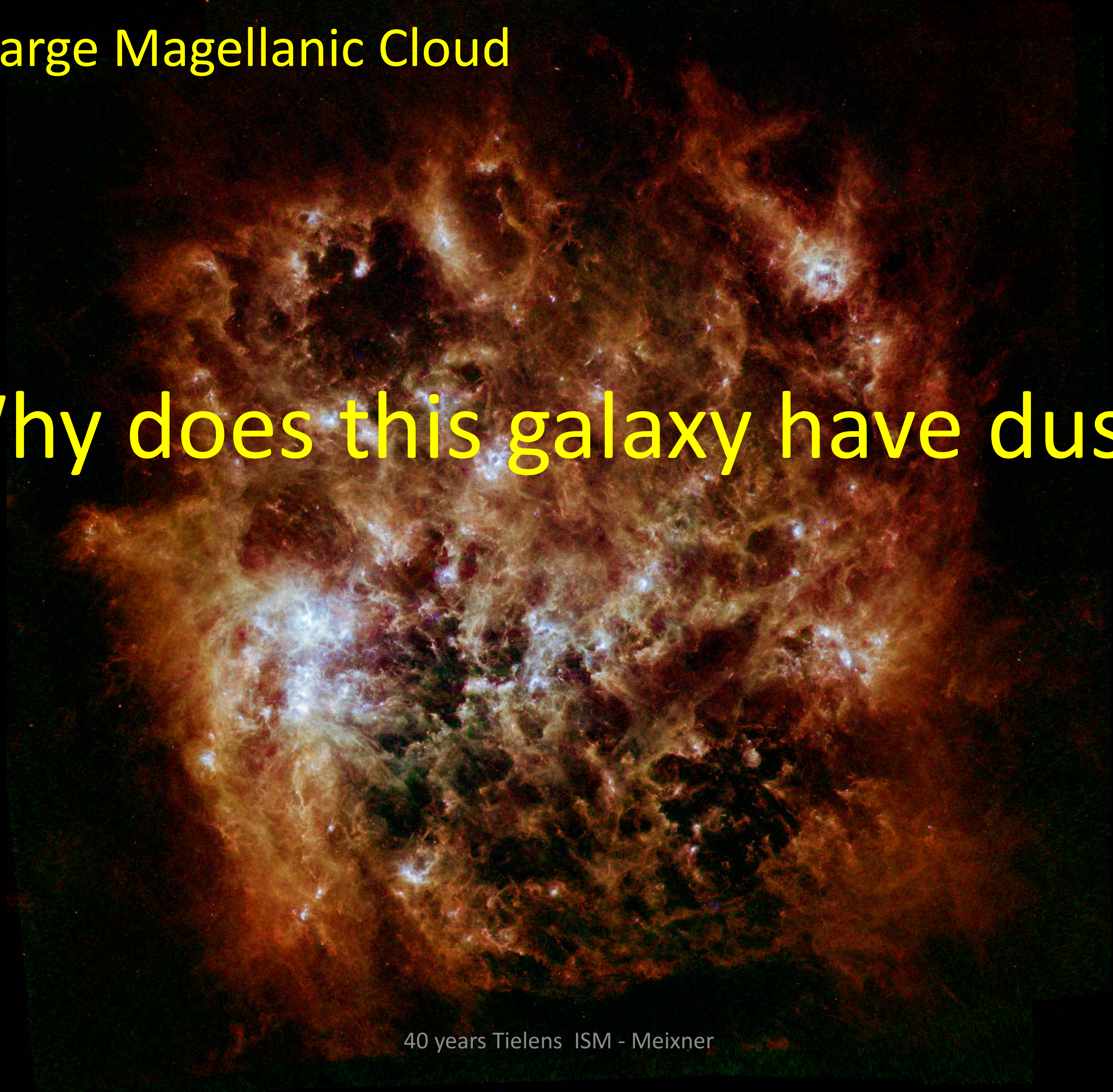
September 2015

http://sage.stsci.edu/

The Large Magellanic Cloud

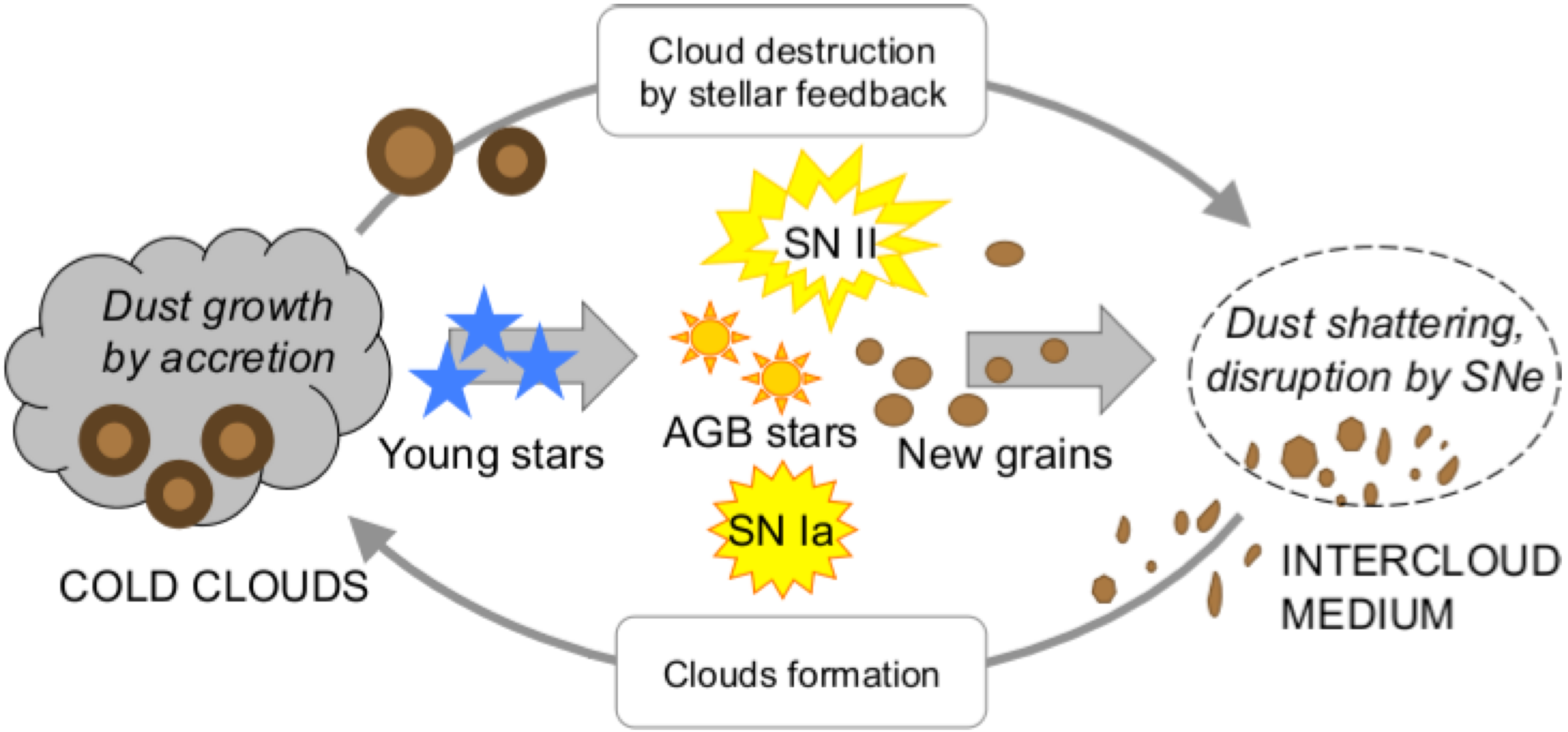


The Large Magellanic Cloud



Why does this galaxy have dust?

Life Cycle of Dust in Galaxies

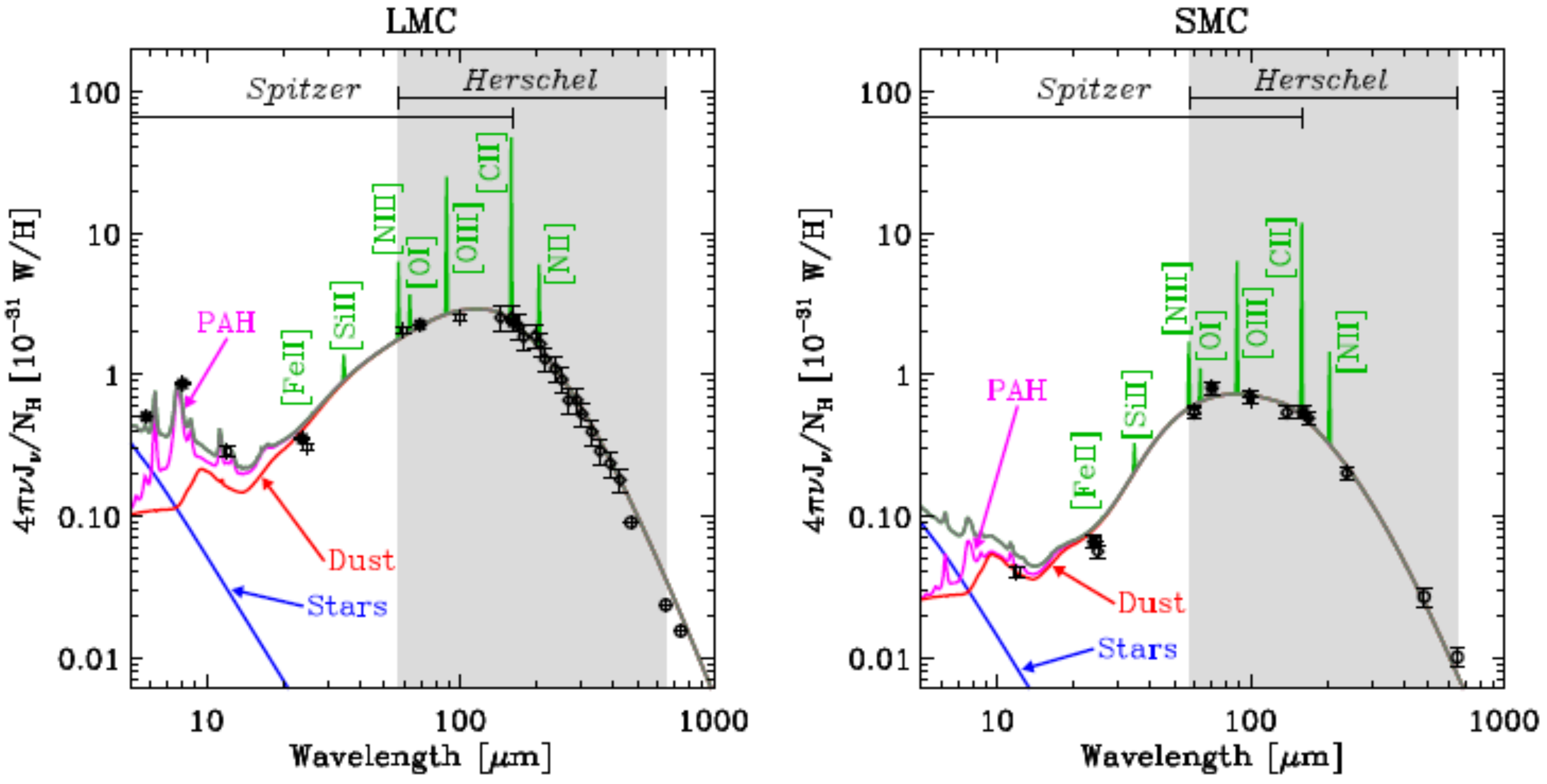


Dwek, Zhkovska

Magellanic Clouds

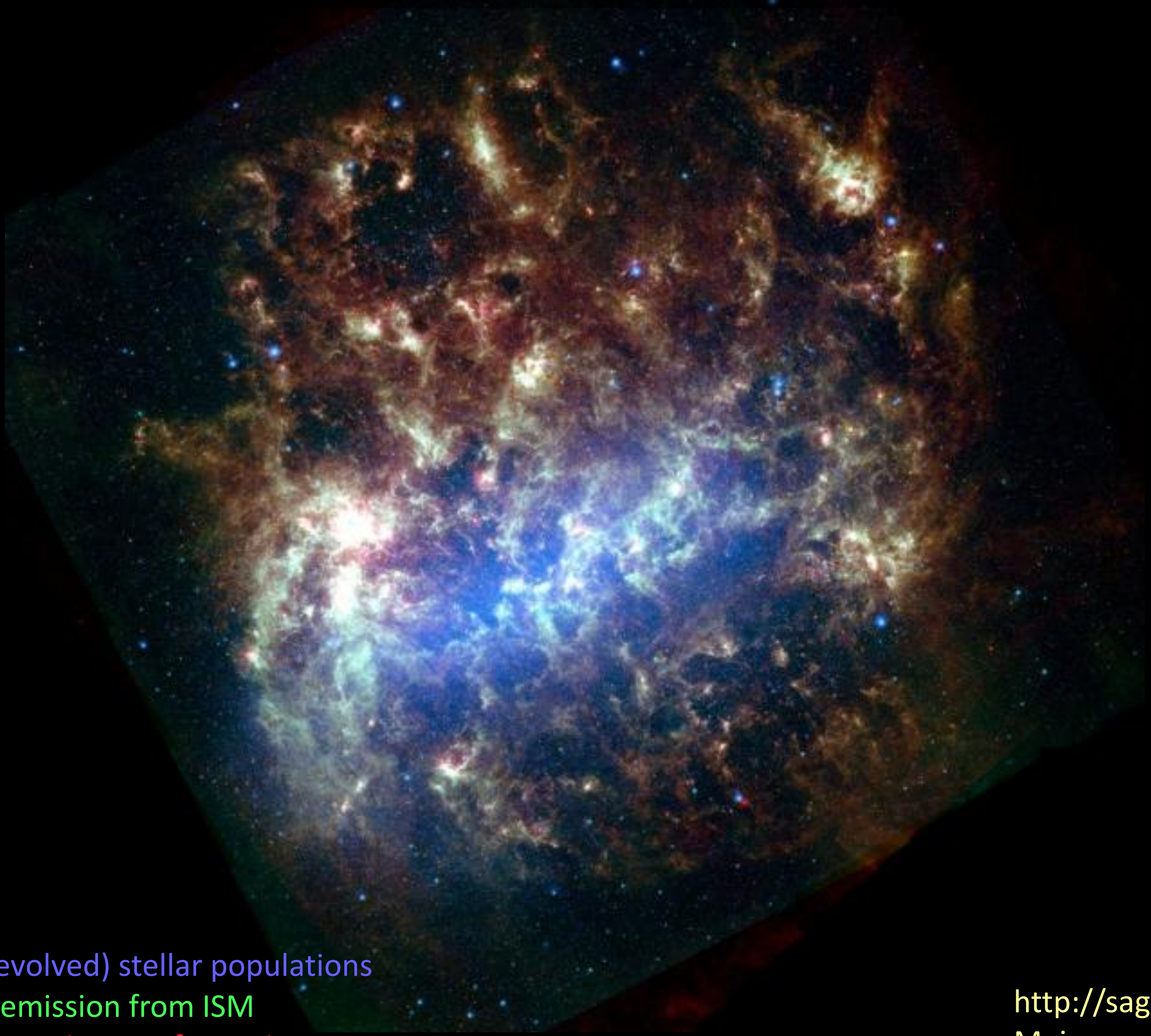
- Proximity:
  ~50 kpc Large Magellanic Cloud (LMC) (Schaefer 2008)
  ~60 kpc Small Magellanic Cloud (SMC) (Szewczyk et al. 2009)
- Inclination of LMC ~23° −37° (Subramanain & Subramanain)
- Stepping stone between galactic and extragalactic studies.
- Mean metallicity: (Russel & Dopita 1992; Asplund et al. 2004)
  - LMC: Z~0.5 x $Z_\odot$
  - SMC: Z~0.2 x $Z_\odot$
  - ISM during Universe's peak star formation epoch (z~1.5 Pei et al 1999)
  - Dust content (dust-to-gas ratio) lower: LMC~0.5xMW, SMC~0.1xMW
- Known tidal interactions between LMC and SMC, possibly the Milky Way.
- Long History of Studies & used as a proving ground:
  - Ideal Case study for a galaxy evolution (Bekki & Chiba 2005)

Spitzer Surveying the Agents of Galaxy Evolution (SAGE) & HERschel Inventory of The Agents of Galaxy Evolution (HERITAGE)



Galliano 2008

LMC: Spitzer SAGE

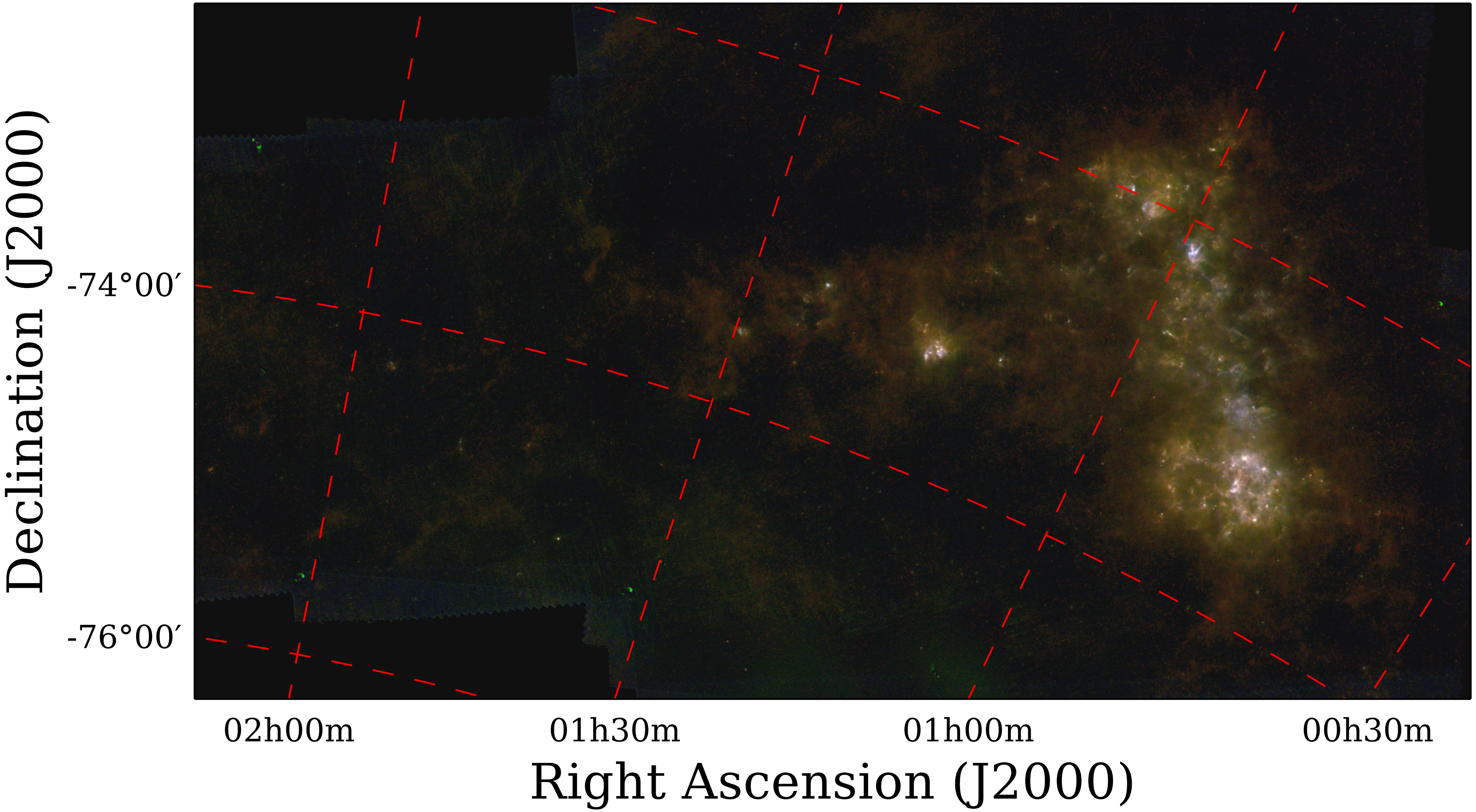


IRAC 3.6 μm: old (evolved) stellar populations
IRAC 8.0 μm: dust emission from ISM
MIPS 24 μm: new massive star formation

http://sage.stsci.edu/
Meixner et al. 2006

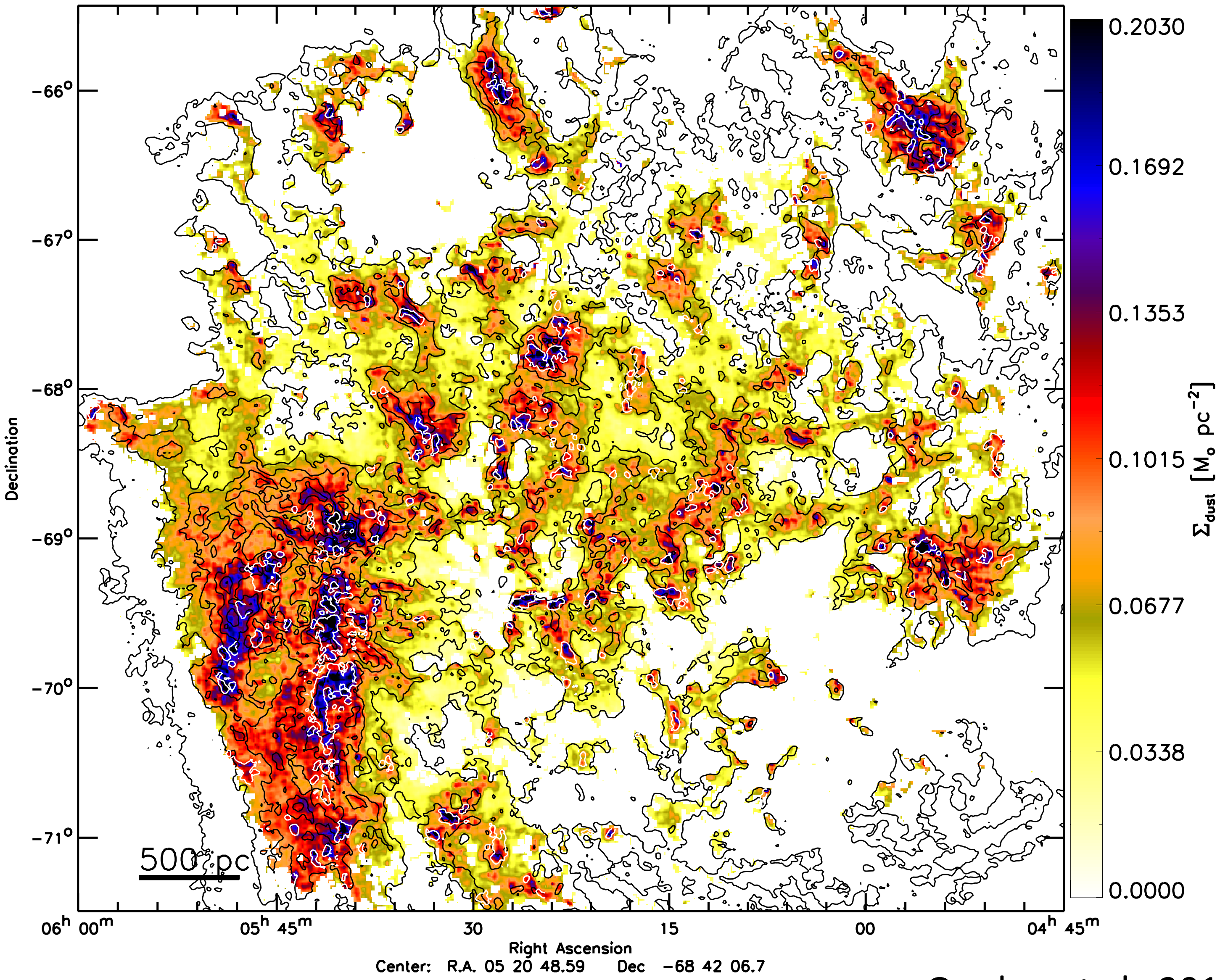
SMC: Herschel HERITAGE

SPIRE 250 μm PACS 160 μm PACS 100 μm



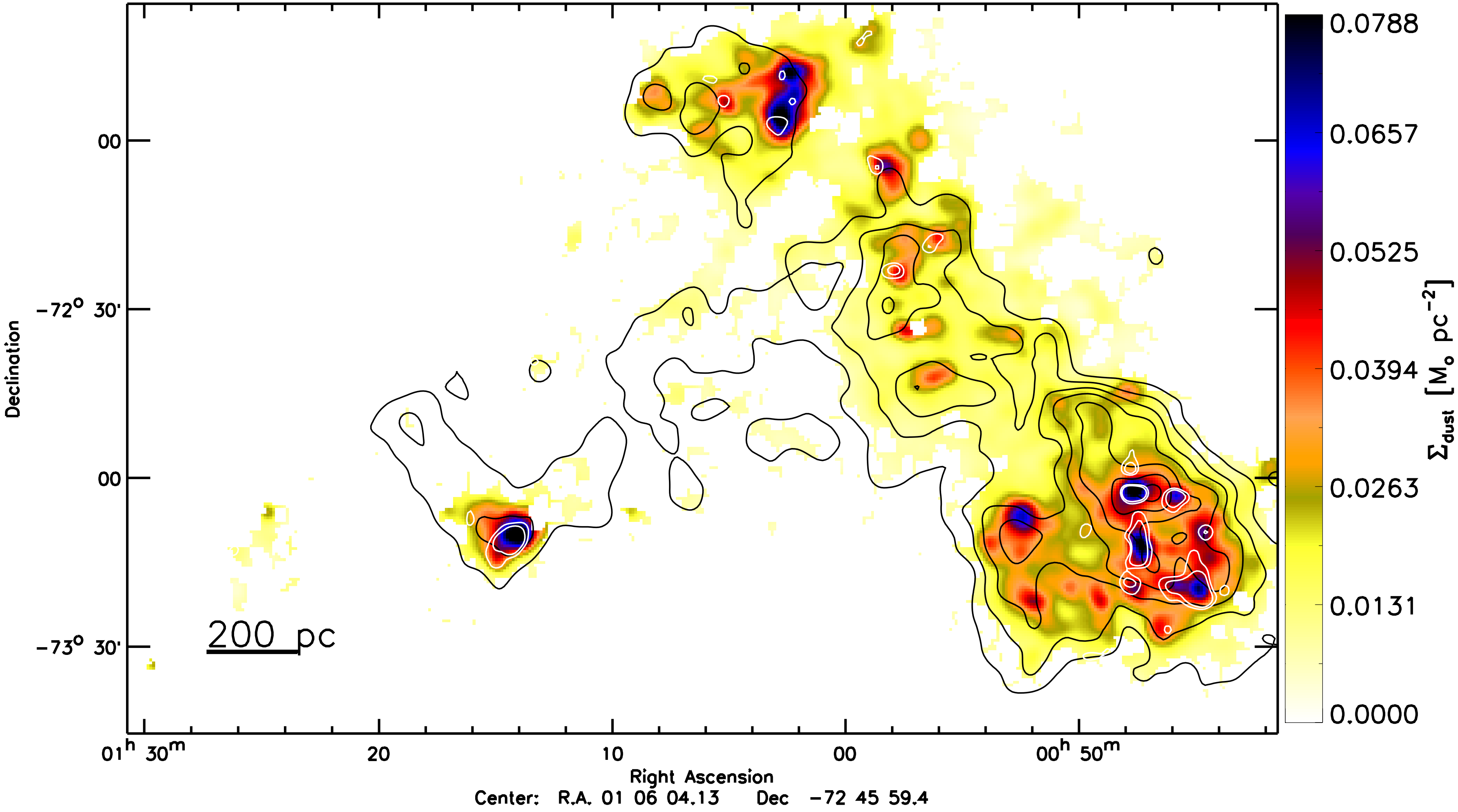
Meixner et al 2013

LMC Dust Mass: $7.3 \pm 1.0 \times 10^5\ M_\odot$



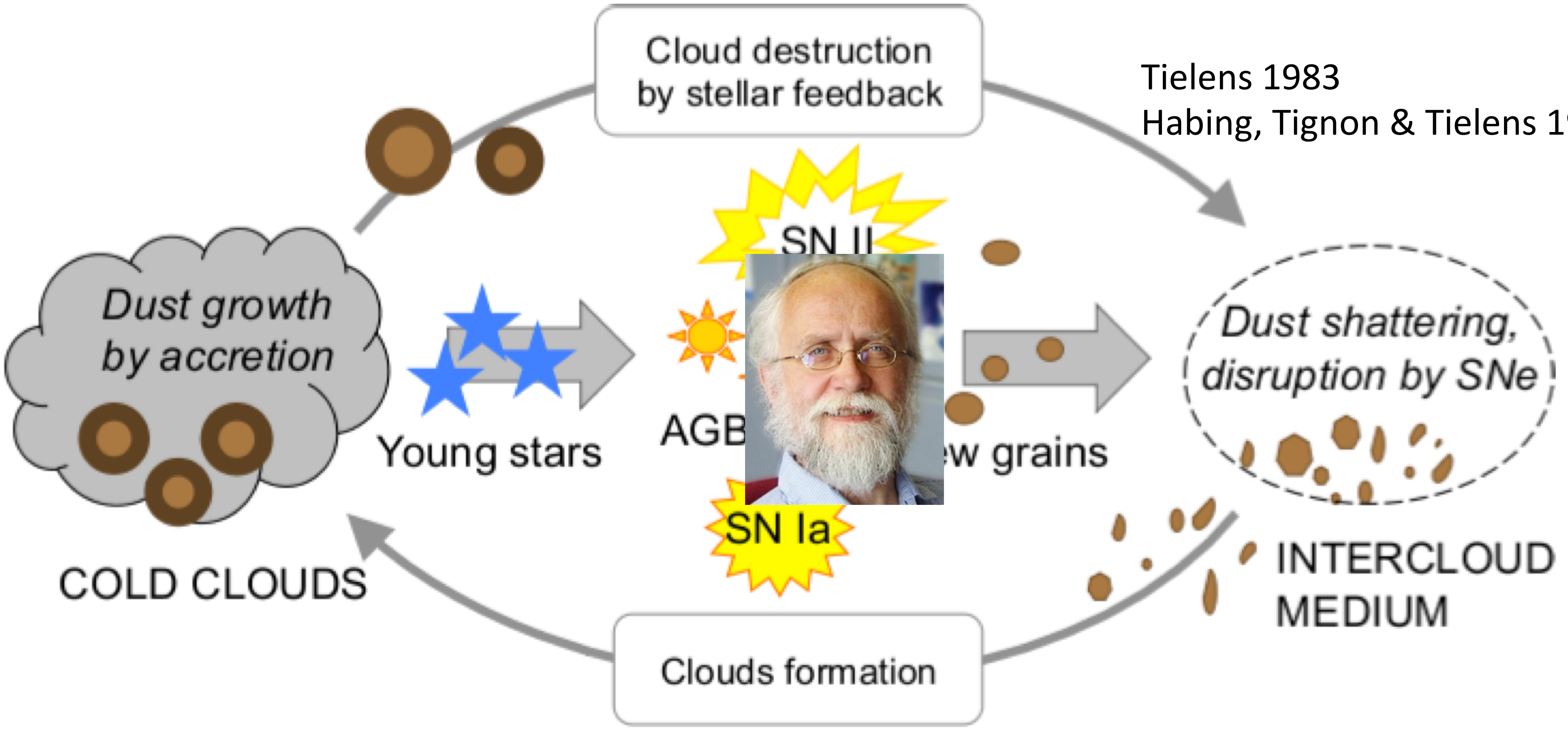
Gordon et al. 2014
Roman-Duval et al. 2014

SMC Dust Mass: $8.3 \pm 1.0 \times 10^4\ M_\odot$



Gordon et al. 2014
Roman-Duval et al. 2014

Life Cycle of Dust in Galaxies

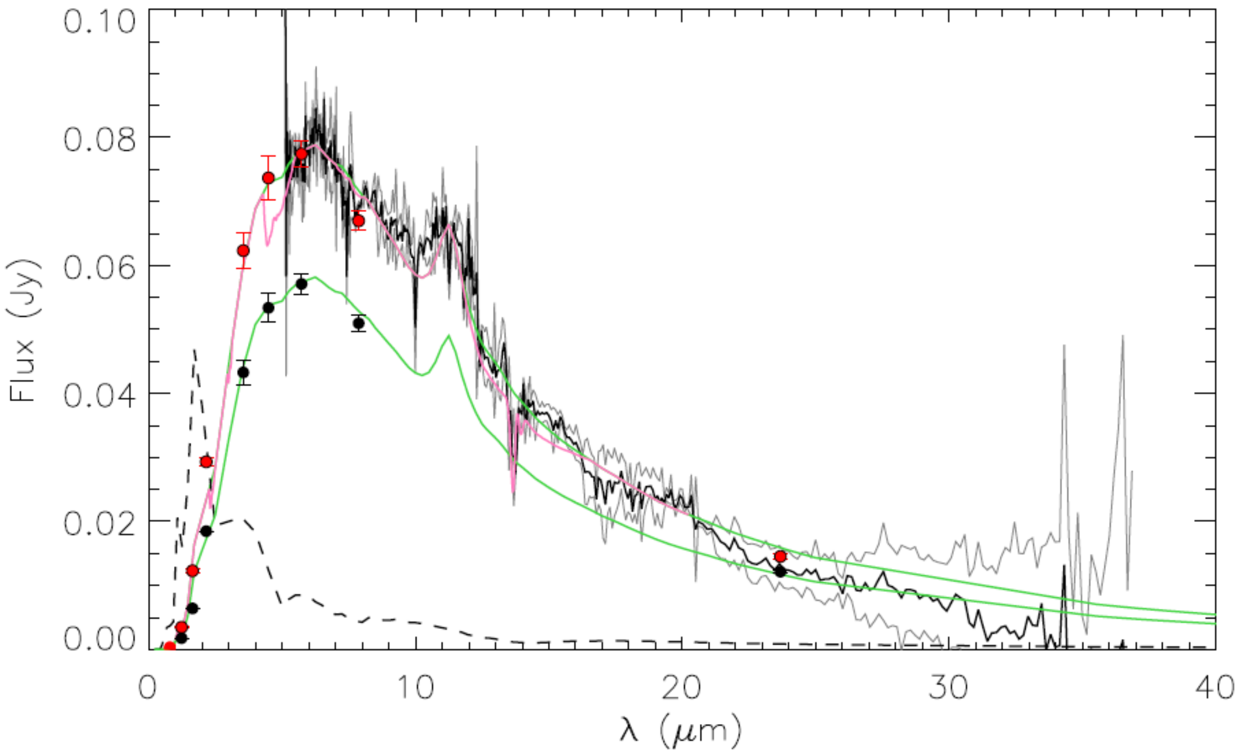


Tielens 1983
Habing, Tignon & Tielens 1994

Dwek, Zhkovska

GRAMS:

Grid of Red supergiant and Asymptotic giant branch star ModelS:



Carbon Rich Dust:

Amorphous Carbon
SiC

Size distribution:
KMH, 0.01-1μm

Star:
5670 $L_\odot$
2.6×10^{-9} $M_\odot$ yr^{-1}

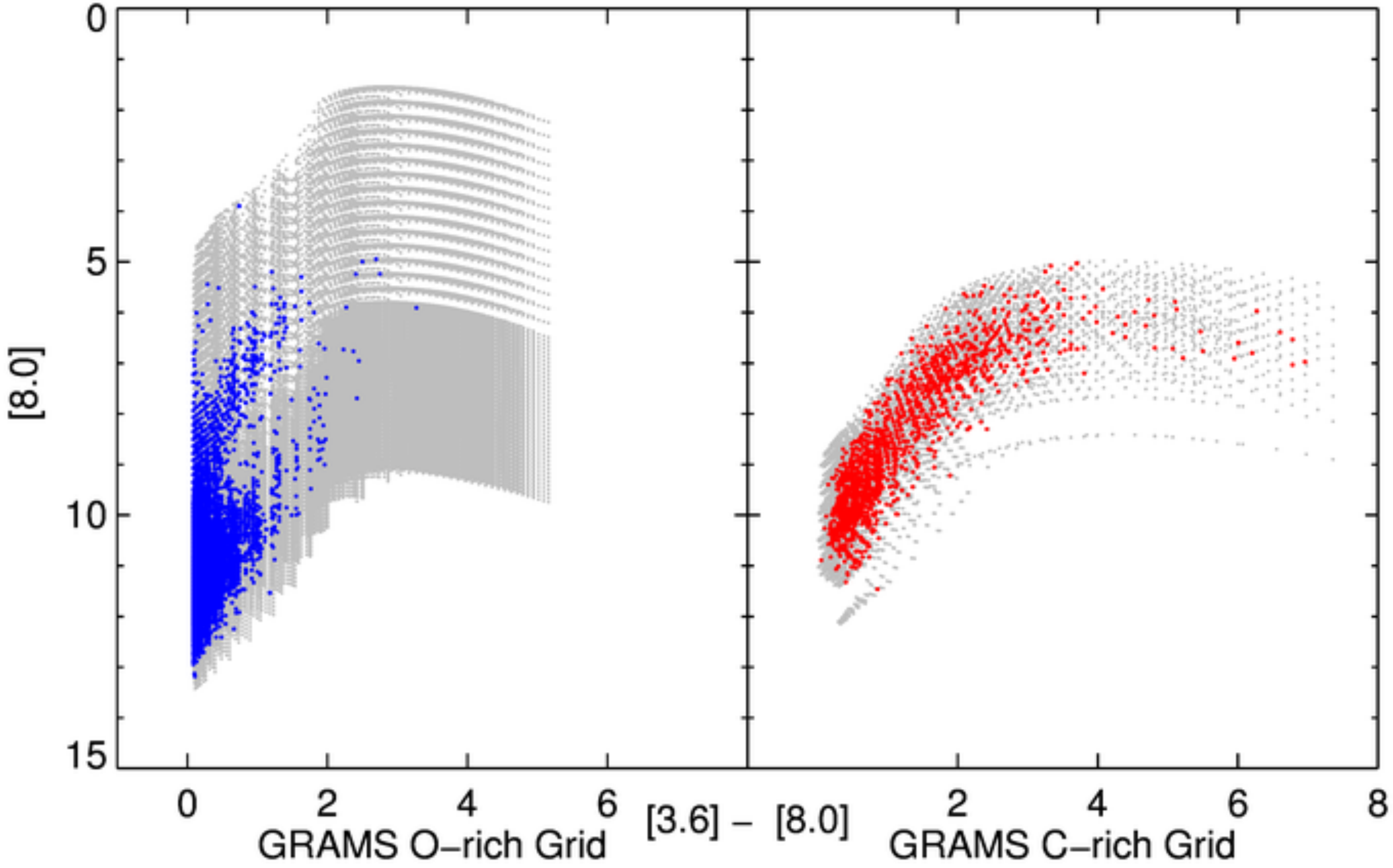
Srinivasan et al. 2010

GRAMS:

Grid of Red supergiant and Asymptotic giant branch star ModelS:

~68,000 O-rich models: AGB & RSGs

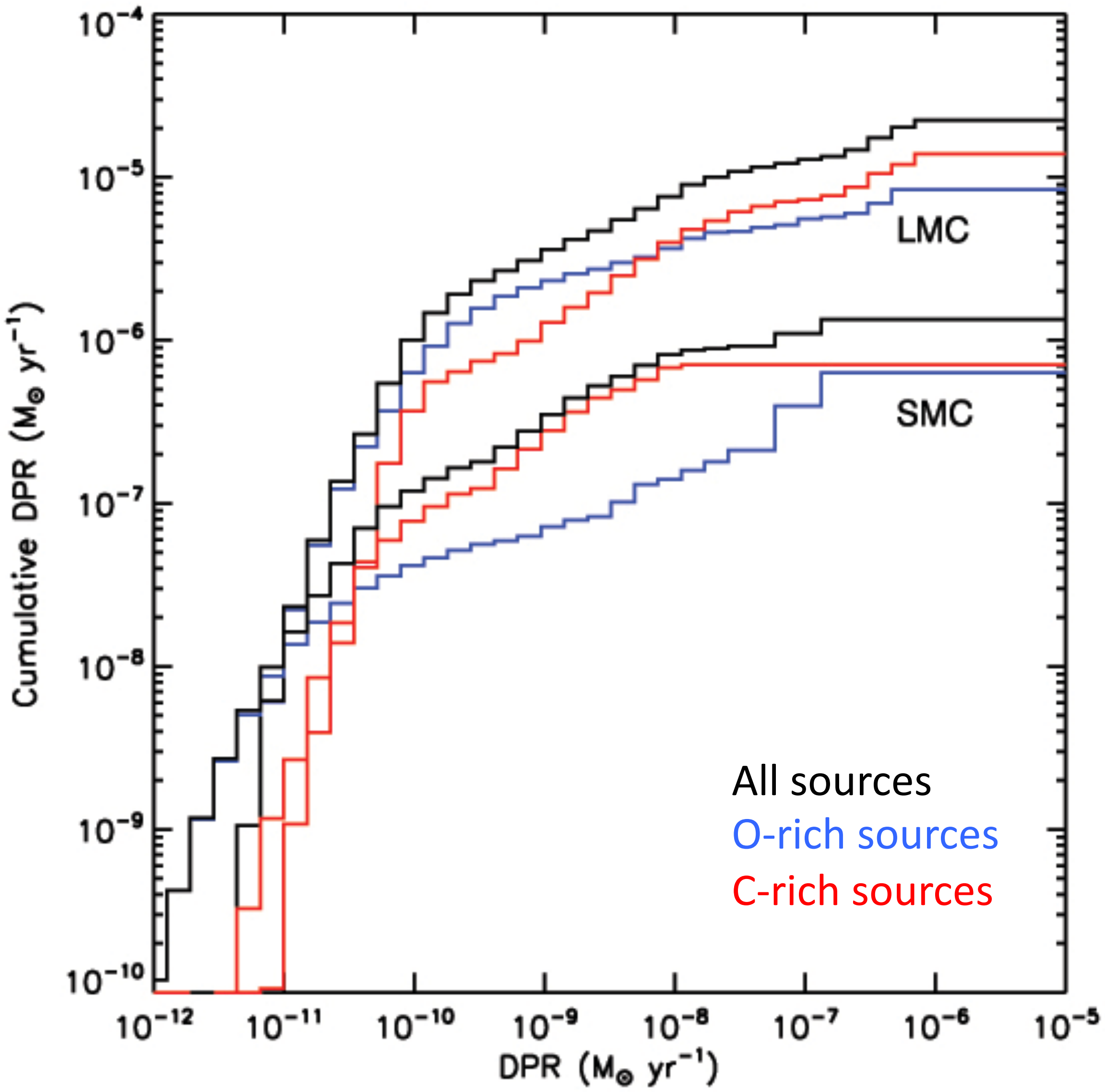
~12,000 C-rich models: AGB only



Sargent, Srinivasan, Meixner 2011

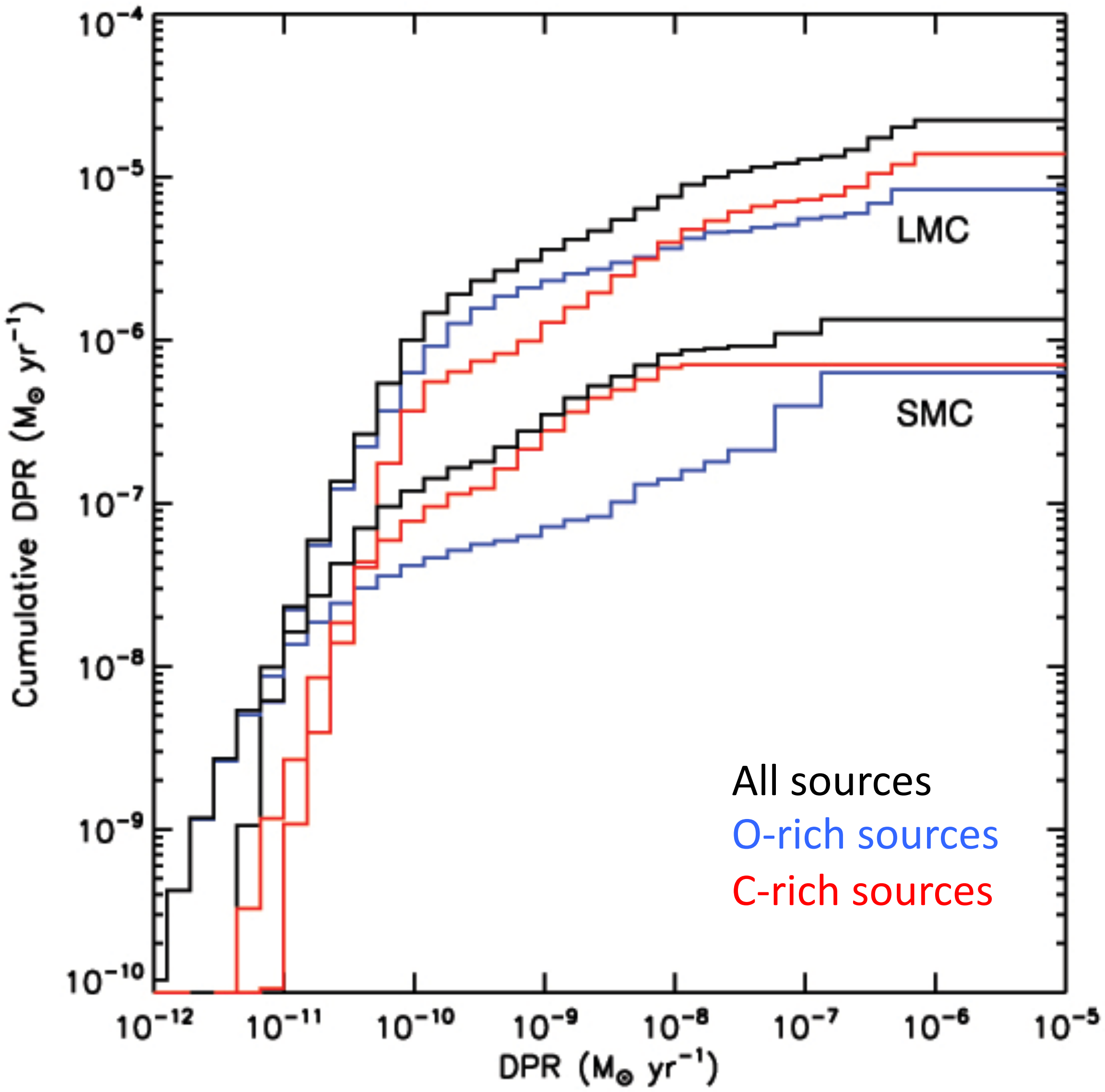
Srinivasan, Sargent, Meixner 2011

GRAMS applied to LMC & SMC



Srinivasan et al. 2016,
Riebel et al. 2012

GRAMS applied to LMC & SMC

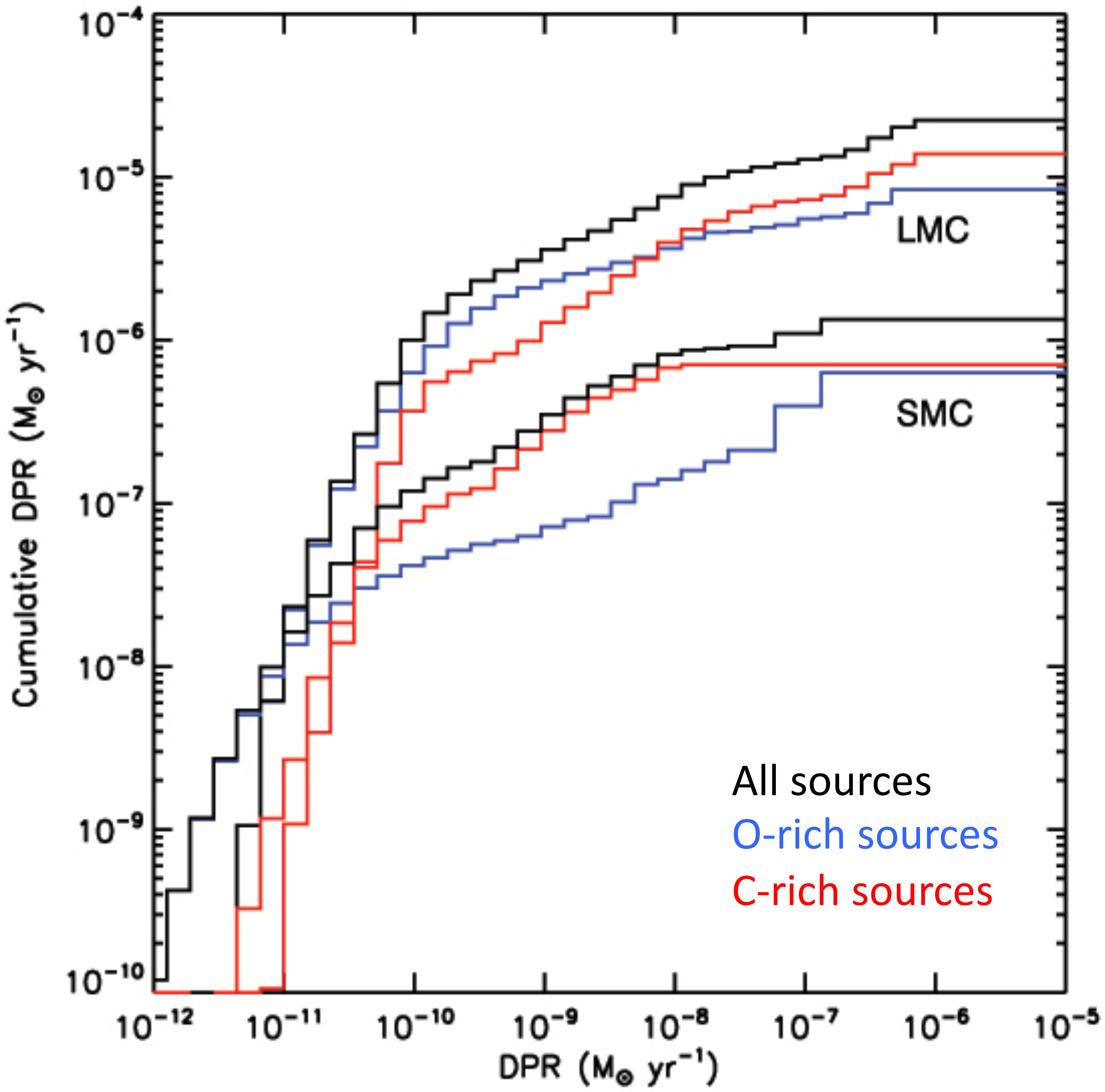


LMC: Riebel et al. 2012
Total = 2.1 (±0.1) ×10^{-5} $M_\odot yr^{-1}$

SMC: Srinivasan et al. 2016
Total = 8.9 (±0.1) ×10^{-7} $M_\odot yr^{-1}$

Srinivasan et al. 2016,
Riebel et al. 2012

GRAMS applied to LMC & SMC



LMC: Riebel et al. 2012

Total = 2.1 (±0.1) ×10^{-5} $M_\odot yr^{-1}$

65% is C-rich

35% is O-rich

SMC: Srinivasan et al. 2016

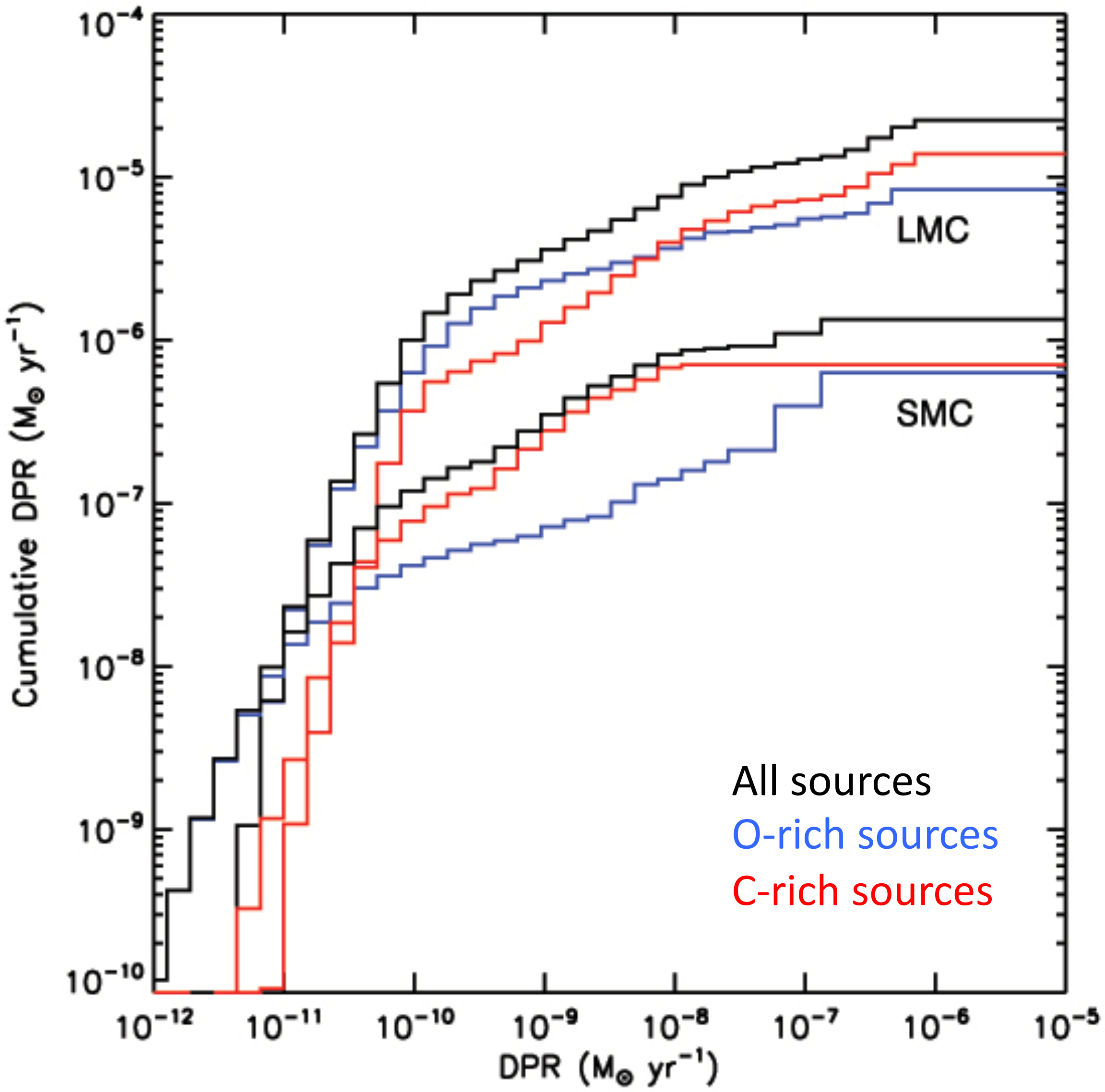
Total = 8.9 (±0.1) ×10^{-7} $M_\odot yr^{-1}$

50% is C-rich

50% is O-rich

Srinivasan et al. 2016,
Riebel et al. 2012

GRAMS applied to LMC & SMC



LMC: Riebel et al. 2012

Total = 2.1 (±0.1) ×10^{-5} $M_\odot yr^{-1}$

65% is C-rich

35% is O-rich

9% RSG

26% AGB

SMC: Srinivasan et al. 2016

Total = 8.9 (±0.1) ×10^{-7} $M_\odot yr^{-1}$

50% is C-rich

50% is O-rich

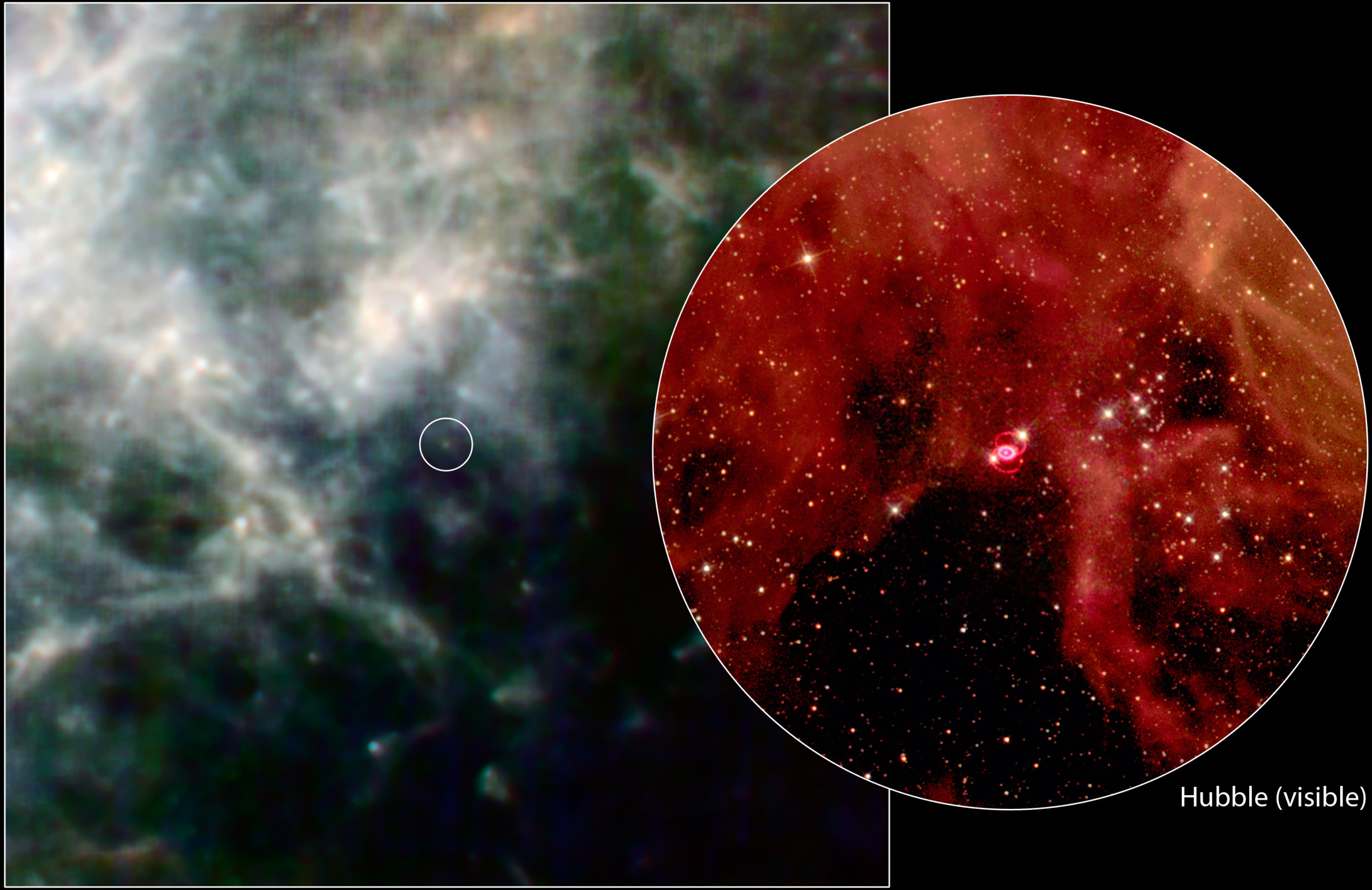
25% RSG

25% AGB

Srinivasan et al. 2016, Riebel et al. 2012

Supernova 1987A (SN 1987A)

HST: Challis, Krishner



Hubble (visible)

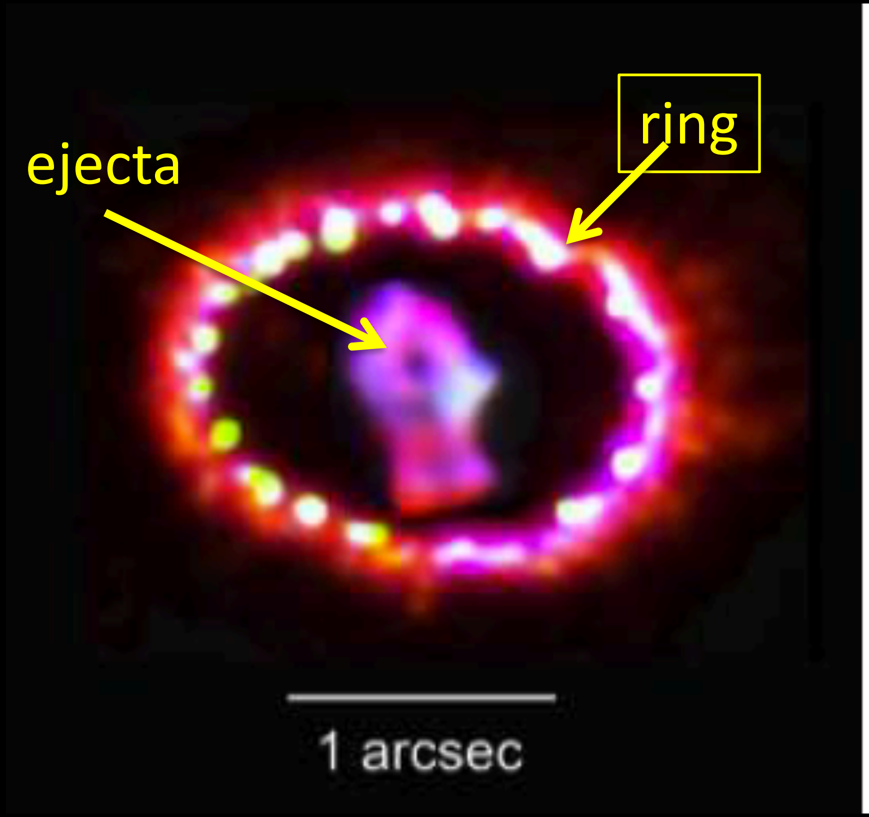
Herschel (far-infrared)

Herschel Finds Enormous Stores of Dust in Supernova 1987A

ESA/NASA-JPL/Caltech/UCL/STScI

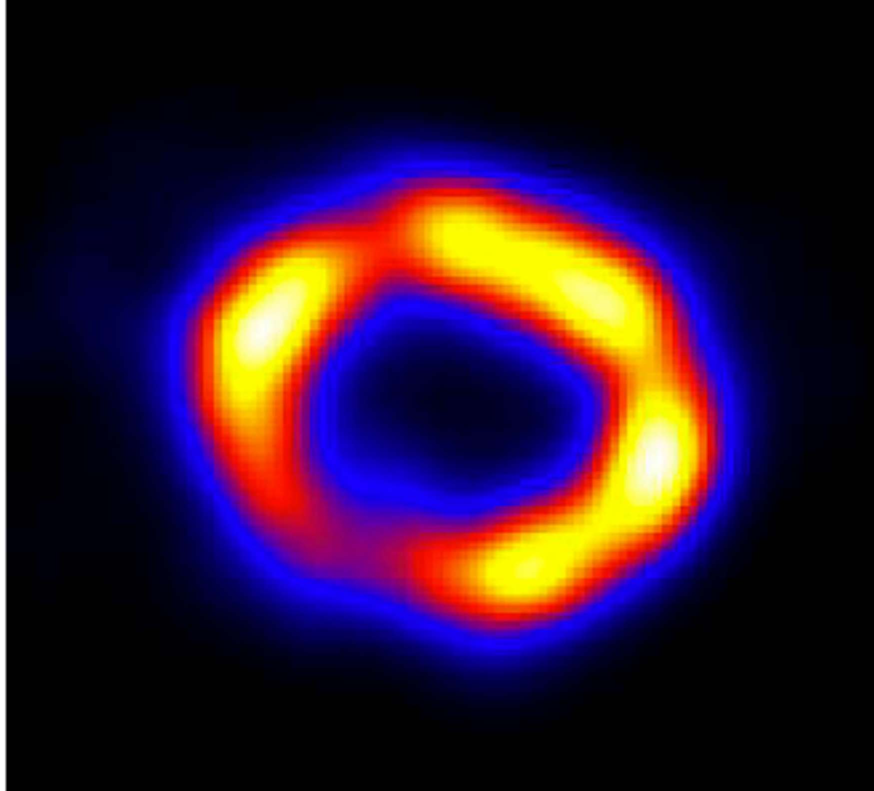
Images of SN1987A

HST



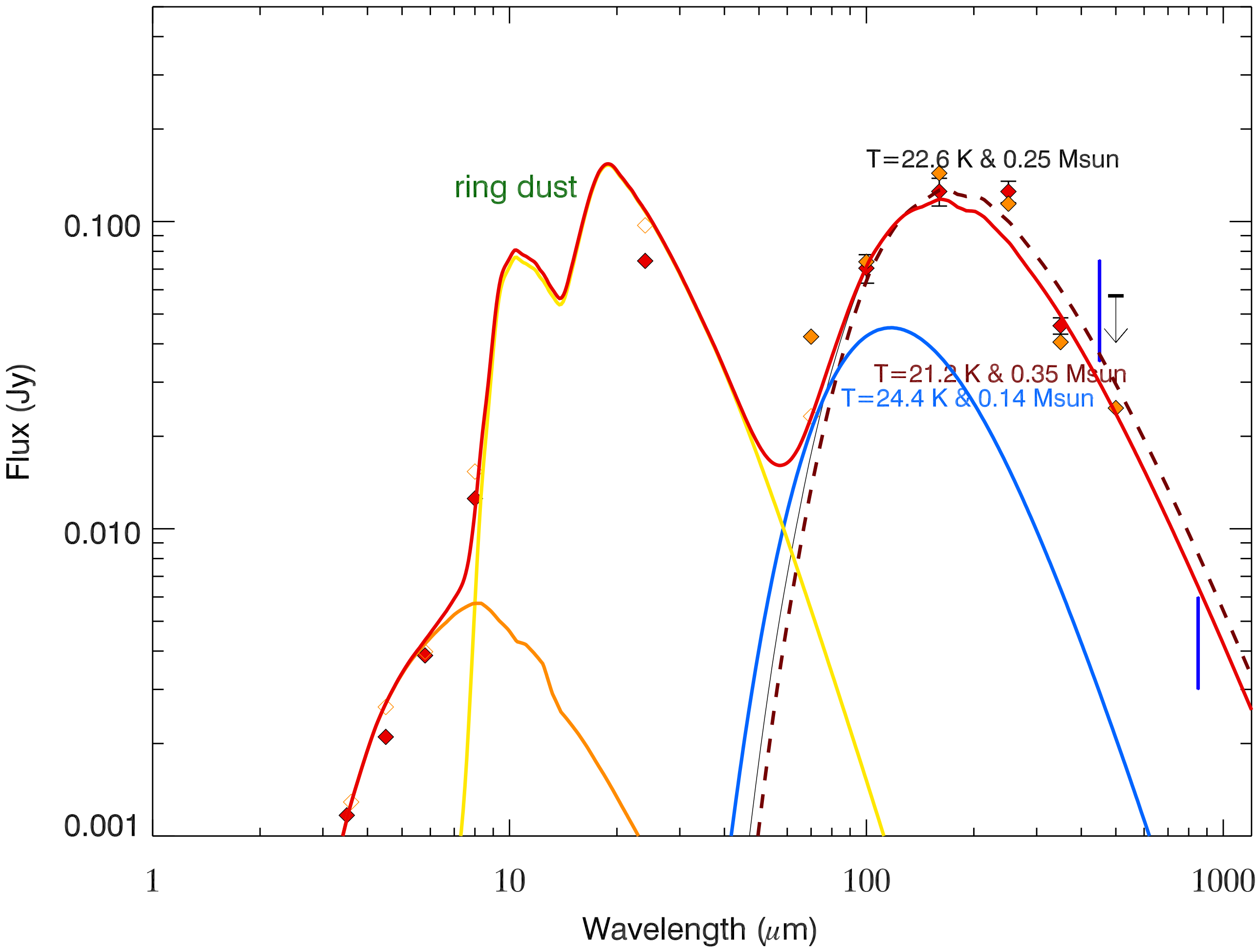
Challis, Kirshner

Chandra



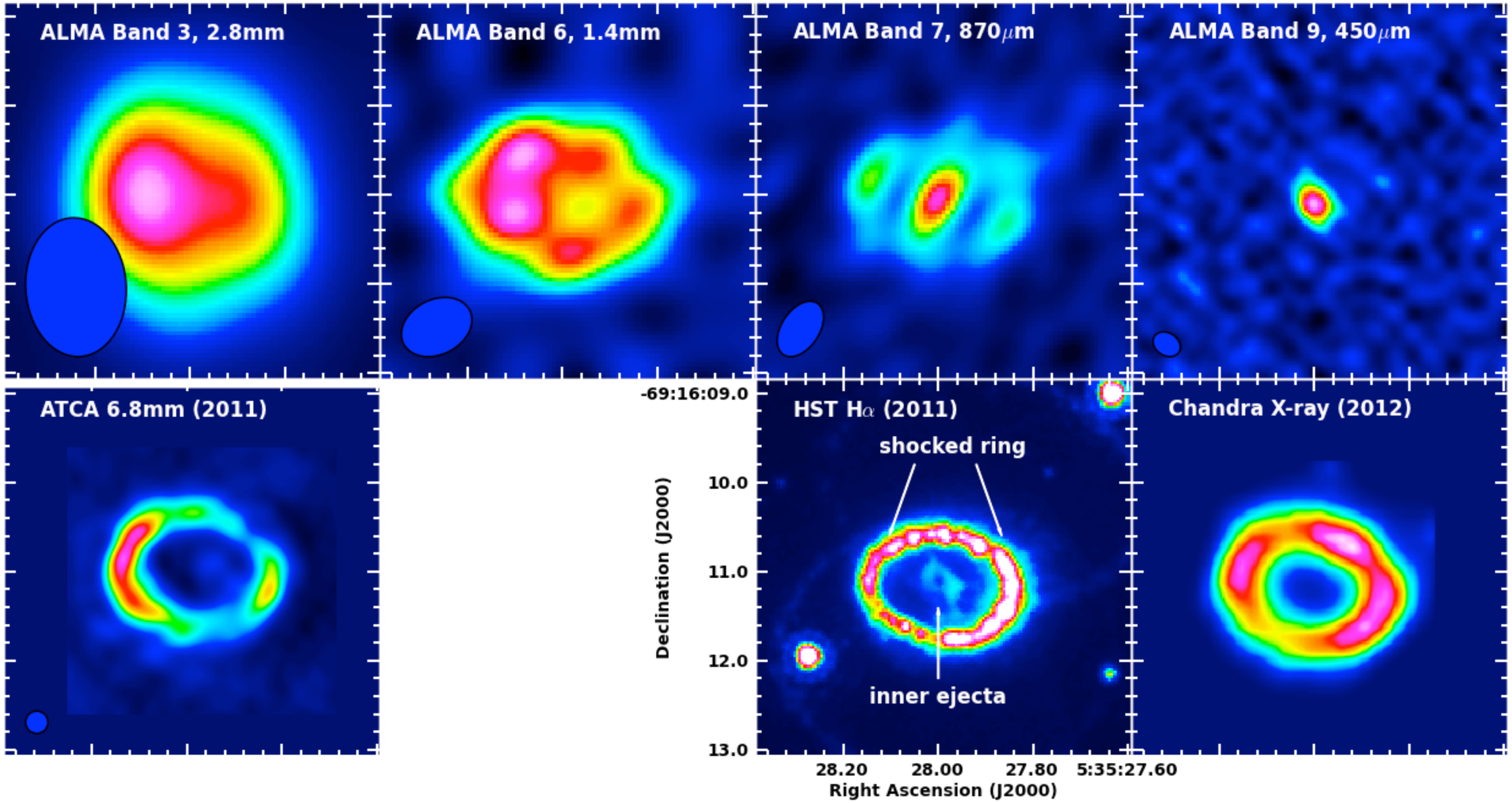
Burrows et al. 2000

First Far-IR detection of SN 1987A: ~0.4-0.7 $M_\odot$



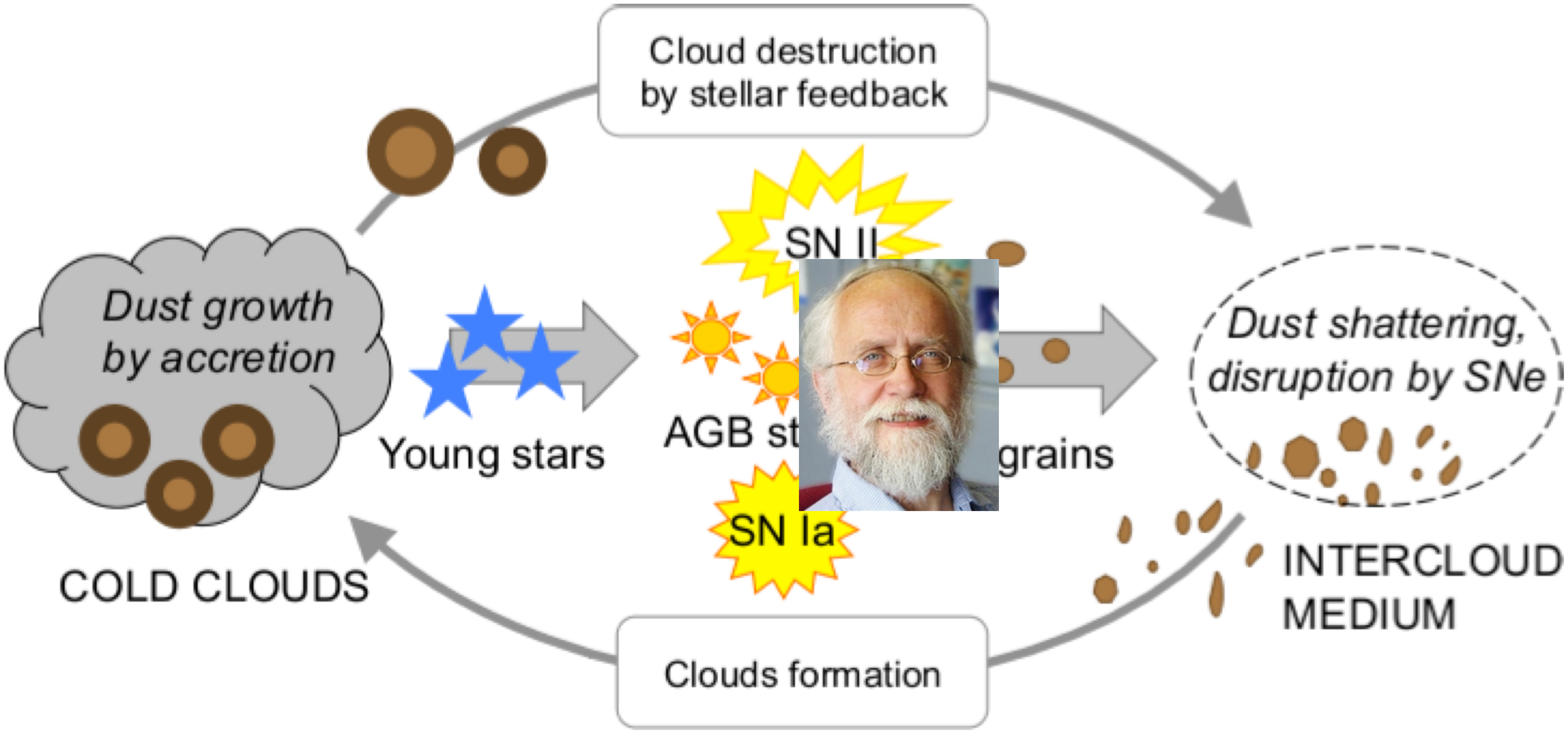
Matsuura, Dwek & Meixner et al. 2011; Matsuura et al. 2015

Confirmed by ALMA



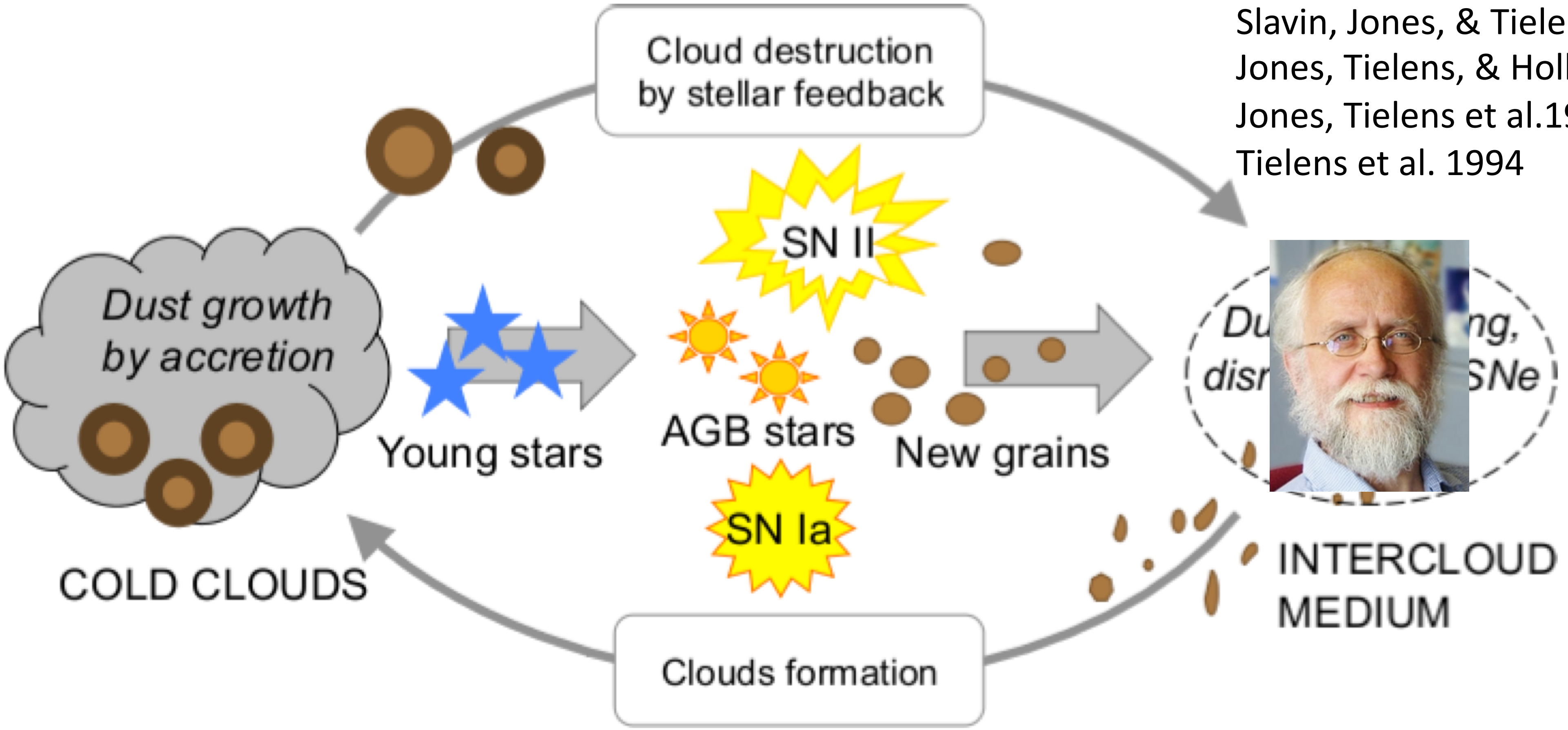
Indebetouw et al. (2014)

Life Cycle of Dust in Galaxies



Dwek, Zhkovska

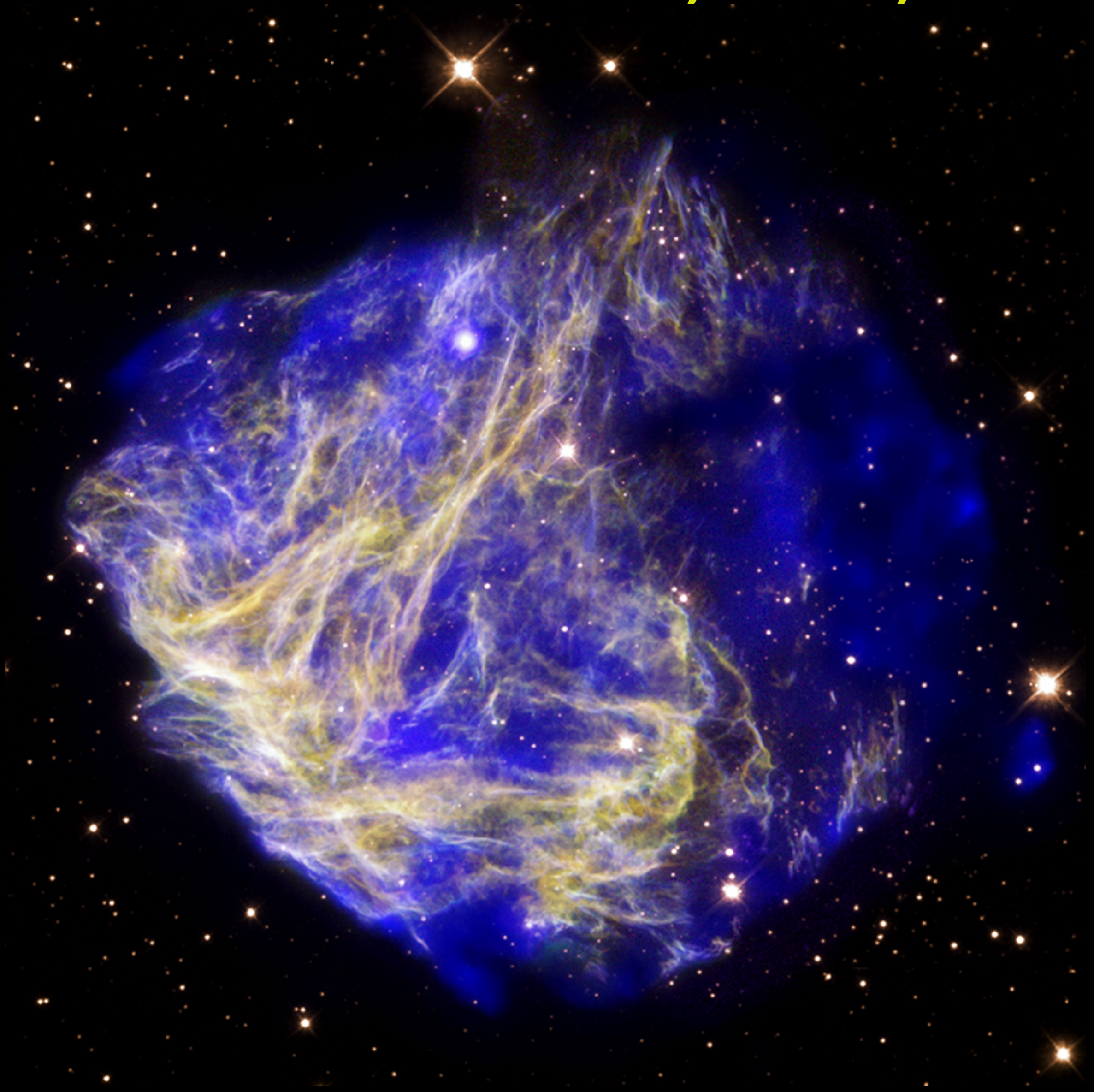
Life Cycle of Dust in Galaxies



Slavin, Jones, & Tielens 2004
Jones, Tielens, & Hollenbach 1996
Jones, Tielens et al.1994
Tielens et al. 1994

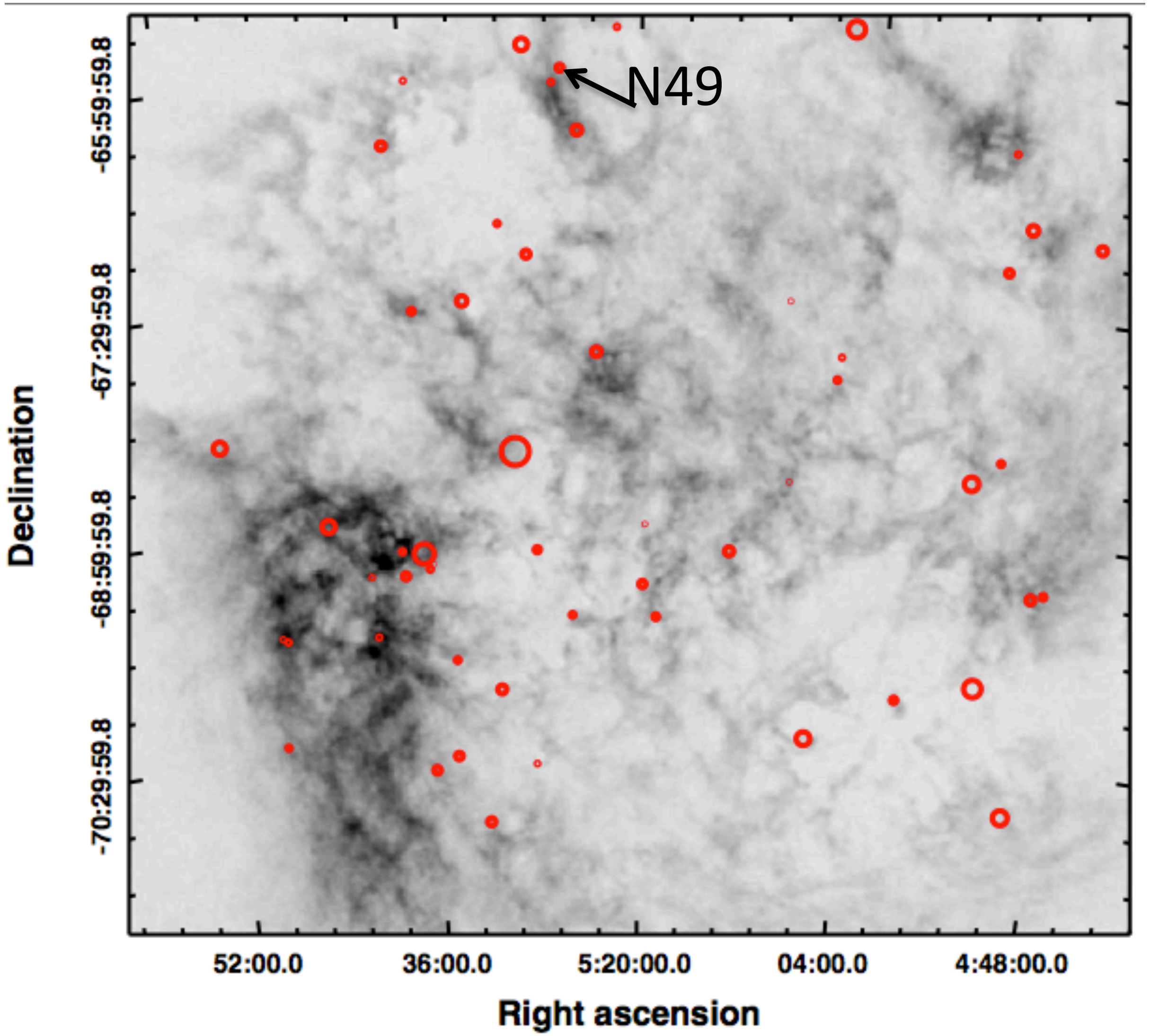
Dwek, Zhkovska

Supernova Remnant, N49, in LMC



HST: [SII], [OIII], Hα (Chu & Williams)
Chandra, Xray (S. Park et al.)

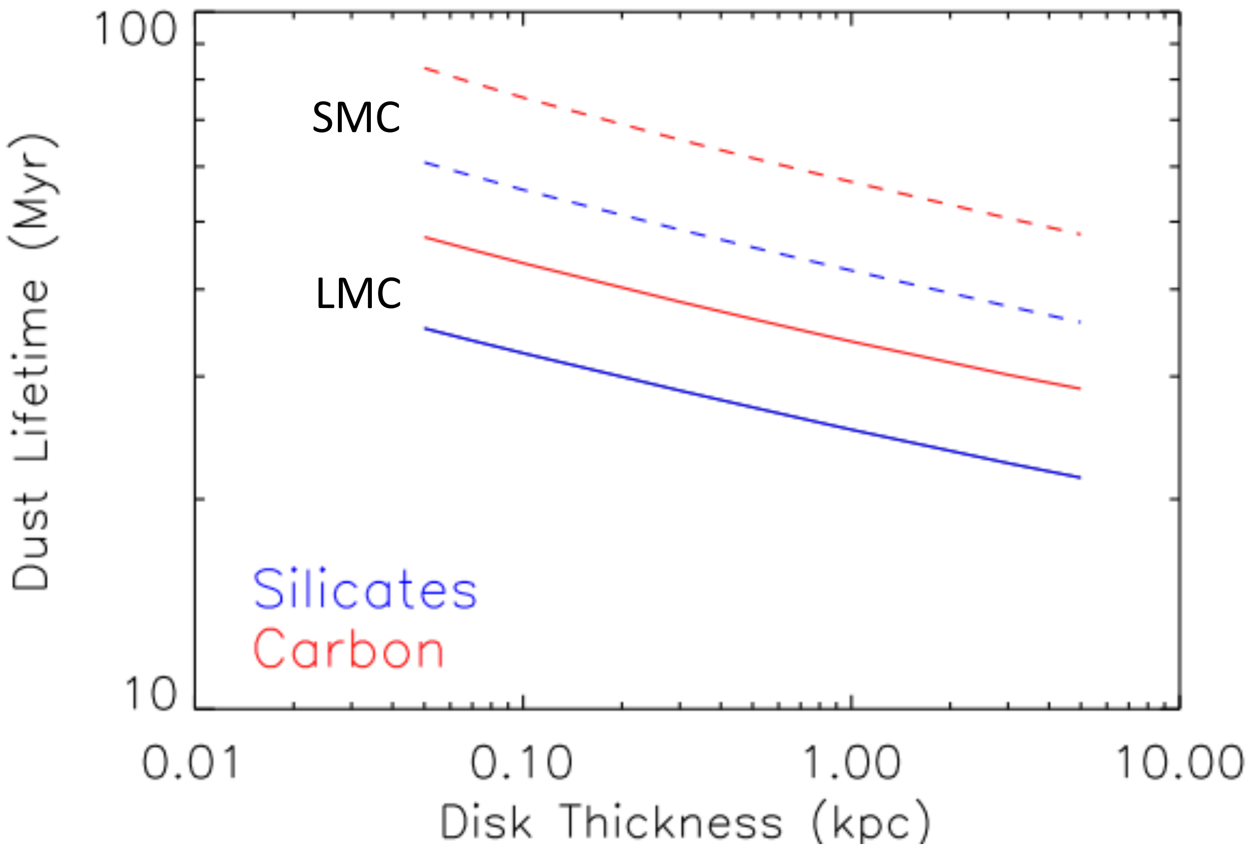
Supernova Remnants (SNRs) in LMC destroy dust



Badenes, Maoz, & Draine (2010), Temim et al.(2015)

Average lifetime of a dust grain in ISM

$$\tau_d = \frac{M_d(LMC)}{< m_{dest} > R_{SN}}$$



LMC:

silicates:

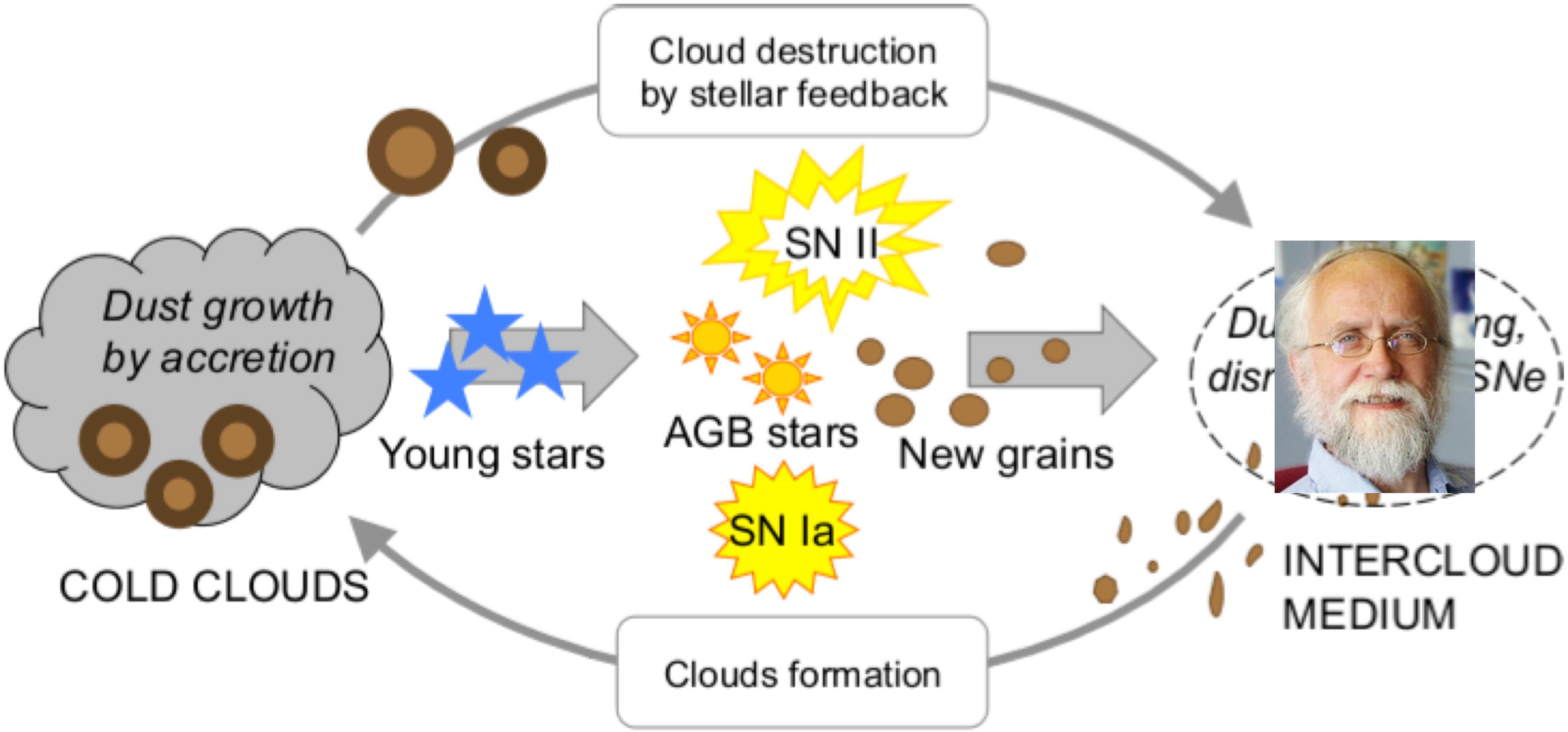
26 – 42 Myr

carbon:

34 – 57 Myr

Temim et al. 2015

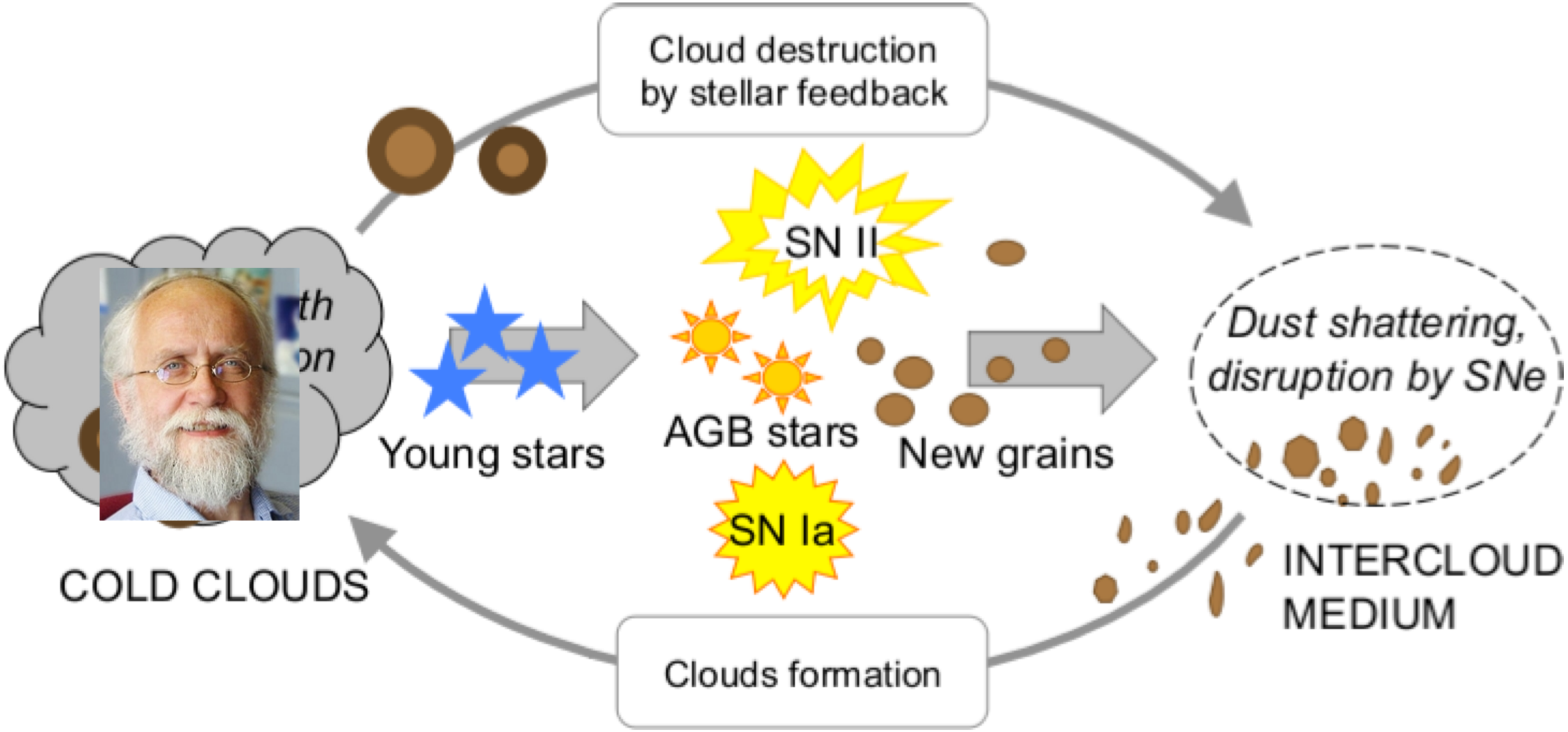
Life Cycle of Dust in Galaxies



Dwek, Zhkovska

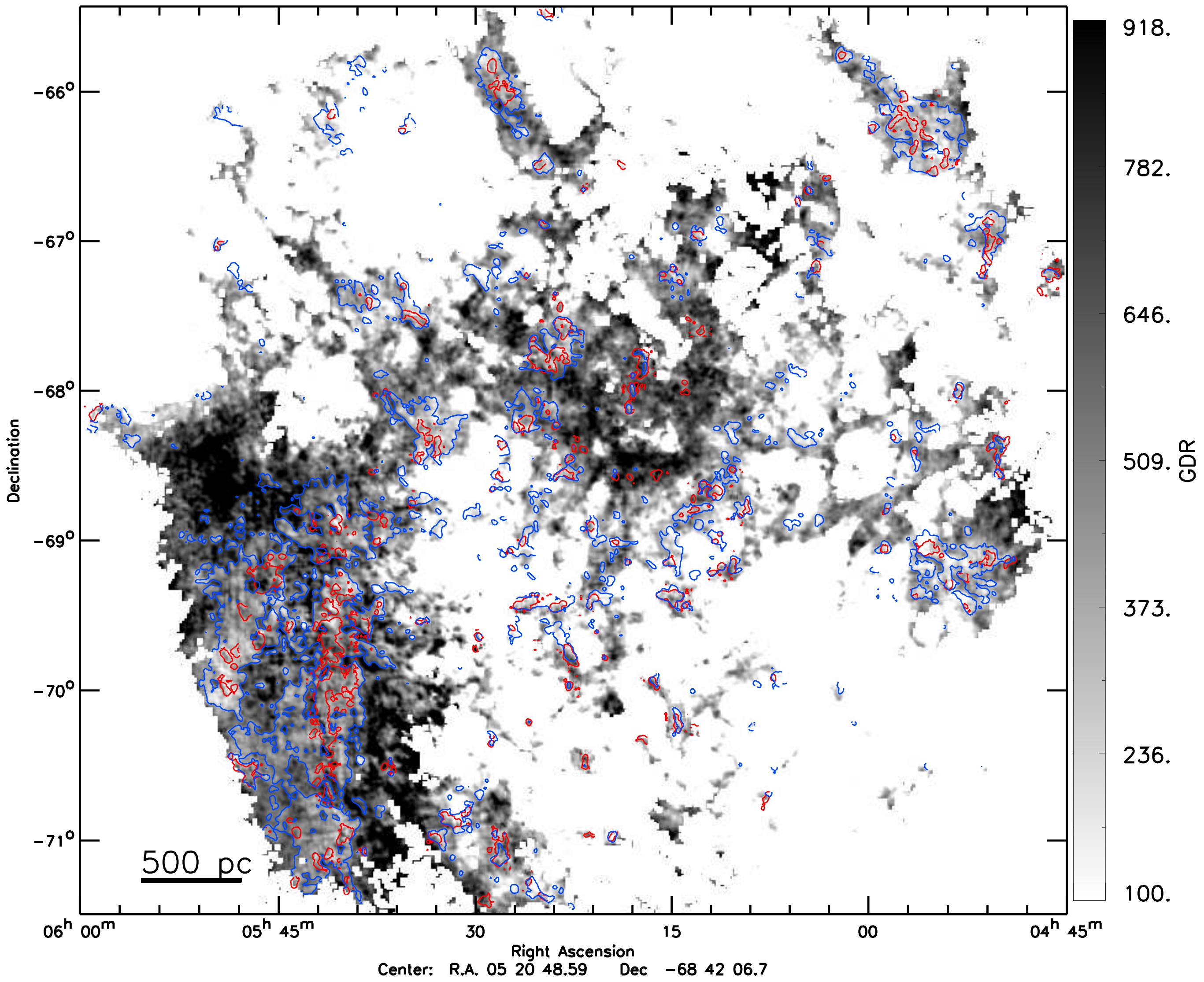
Life Cycle of Dust in Galaxies

Tielens 1998



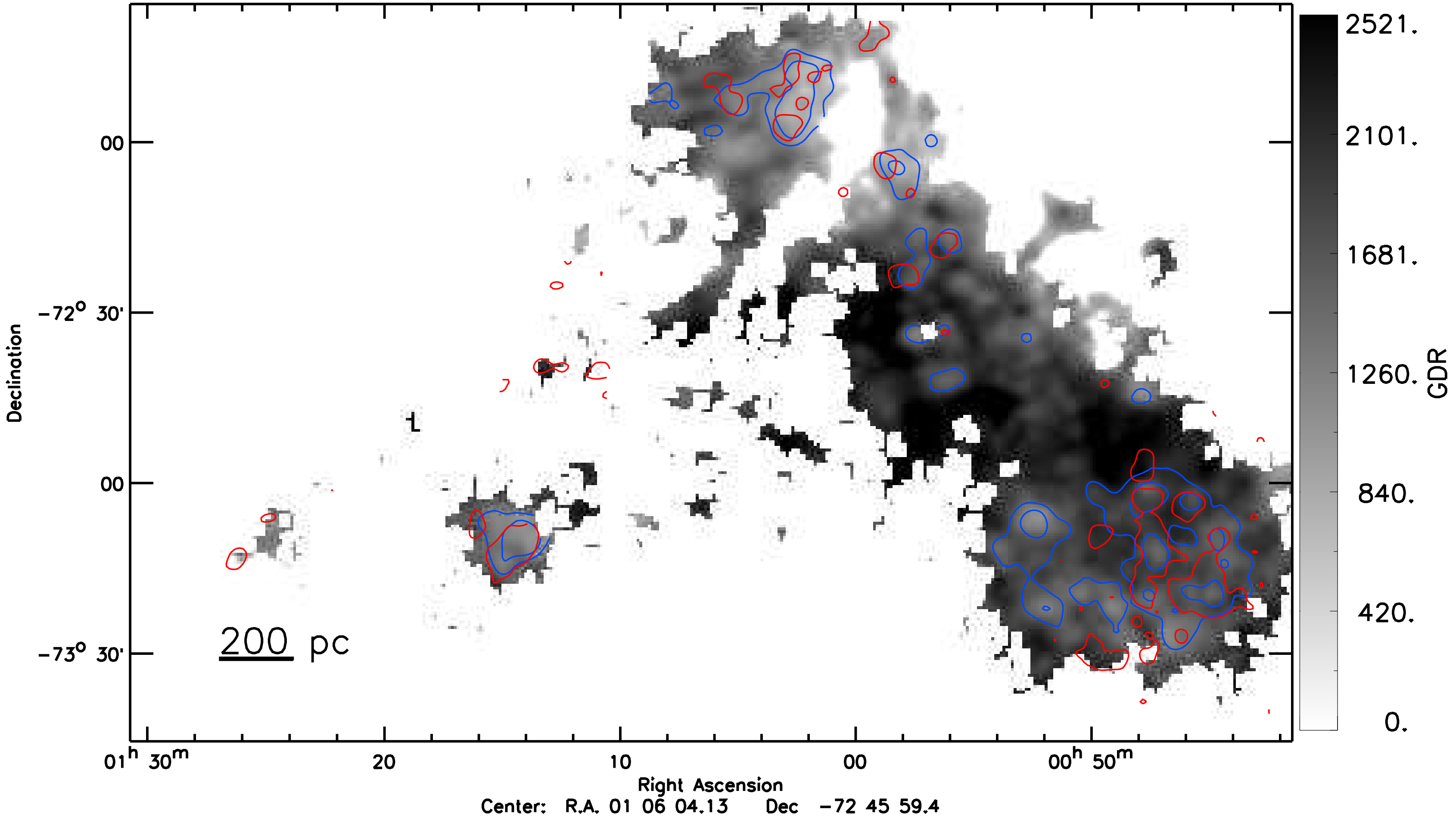
Dwek, Zhkovska

LMC Gas-to-Dust Ratio (GDR)



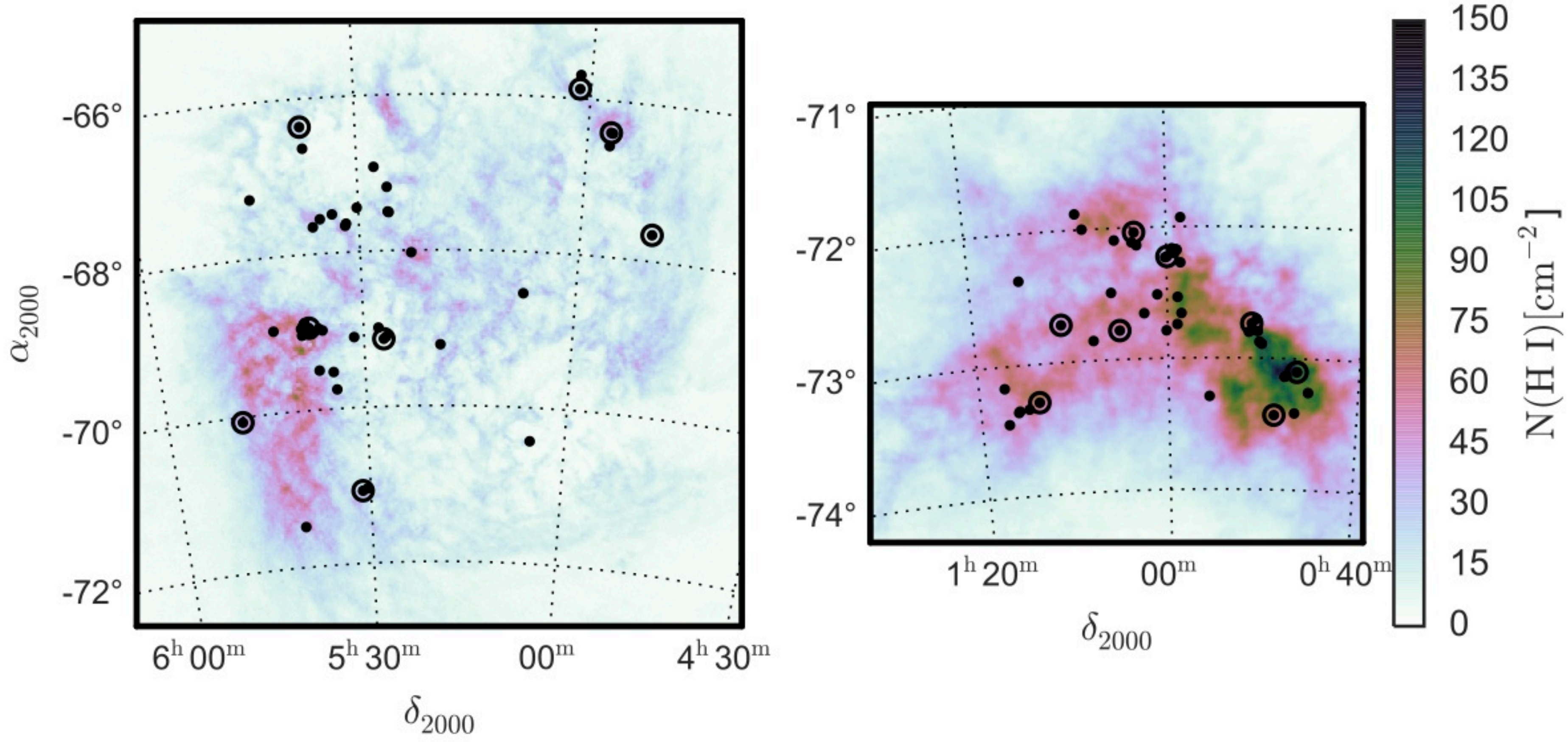
Roman-Duval et al. 2014

SMC Gas-to-Dust Ratio (GDR)



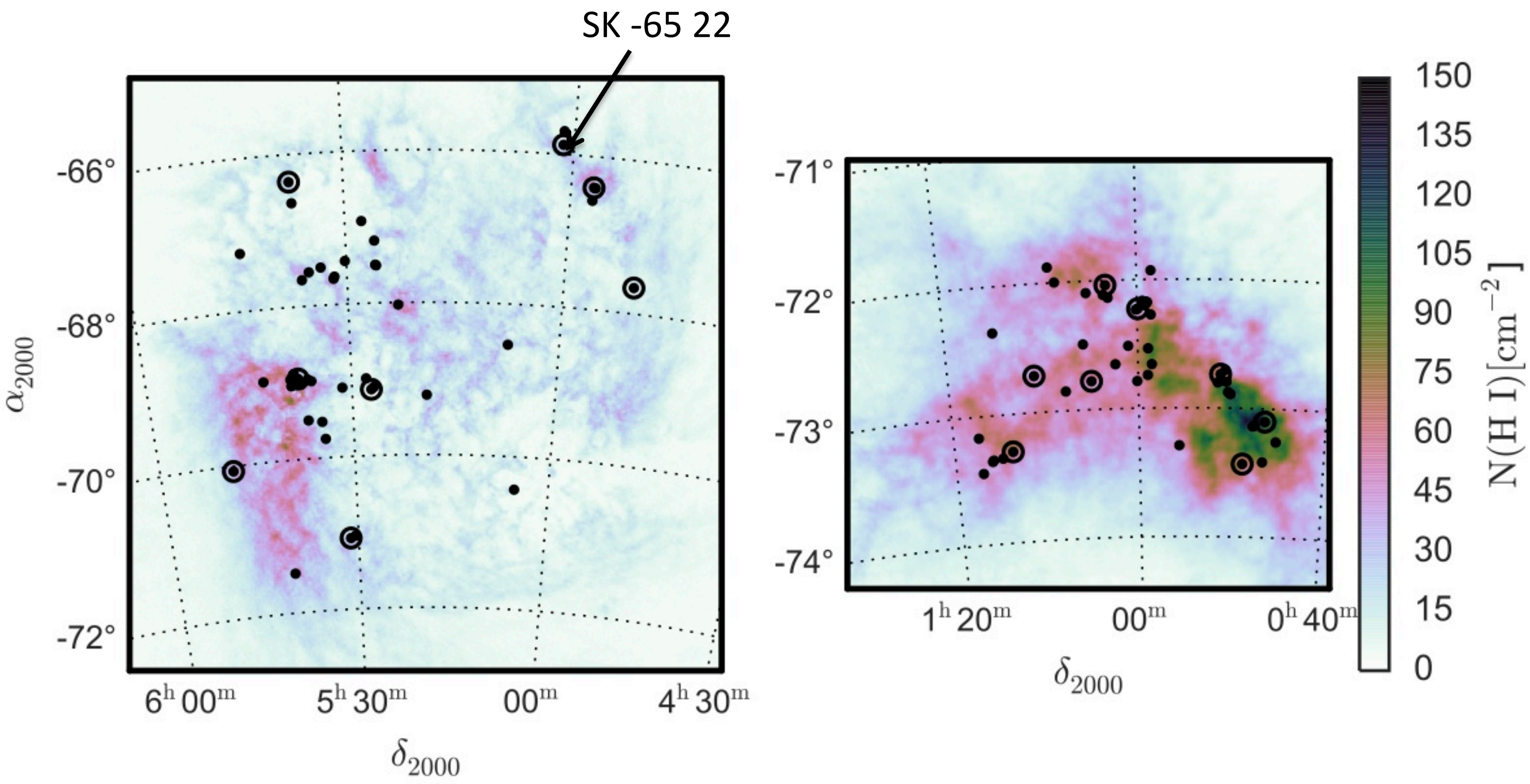
Roman-Duval et al. 2014

Metal Depletion onto Dust

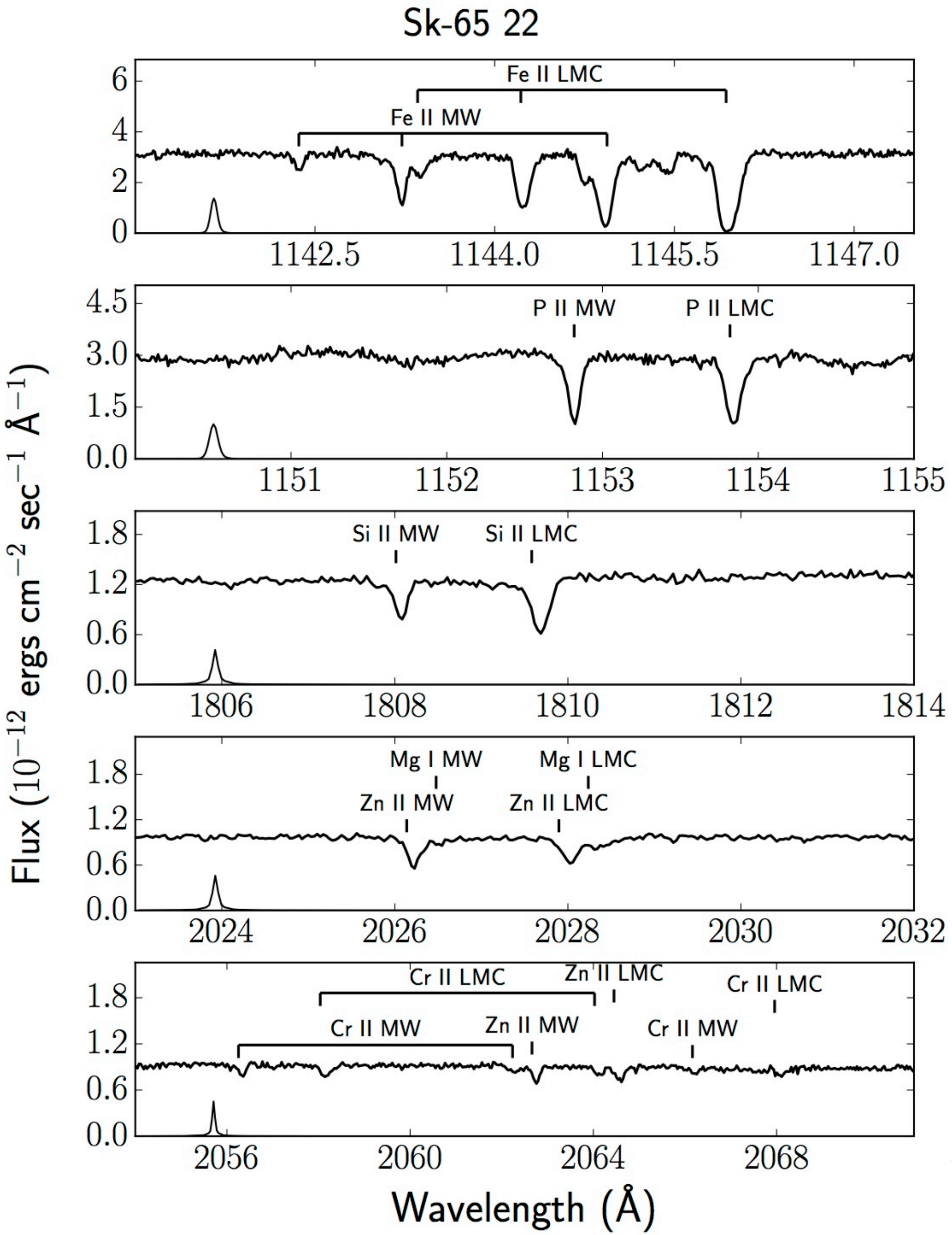


Tchernyshyov et al. 2015

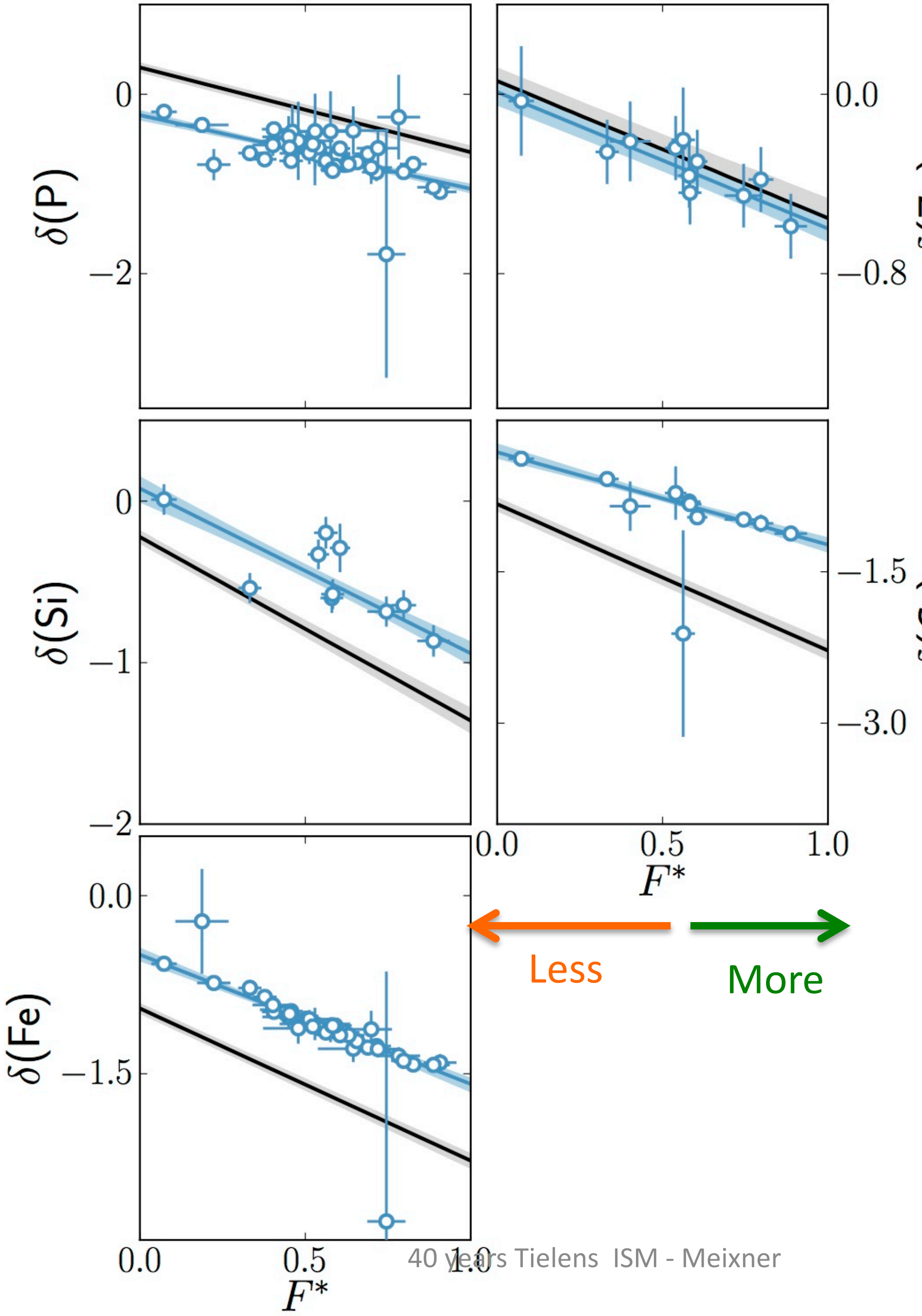
Metal Depletion onto Dust



Tchernyshyov et al. 2015



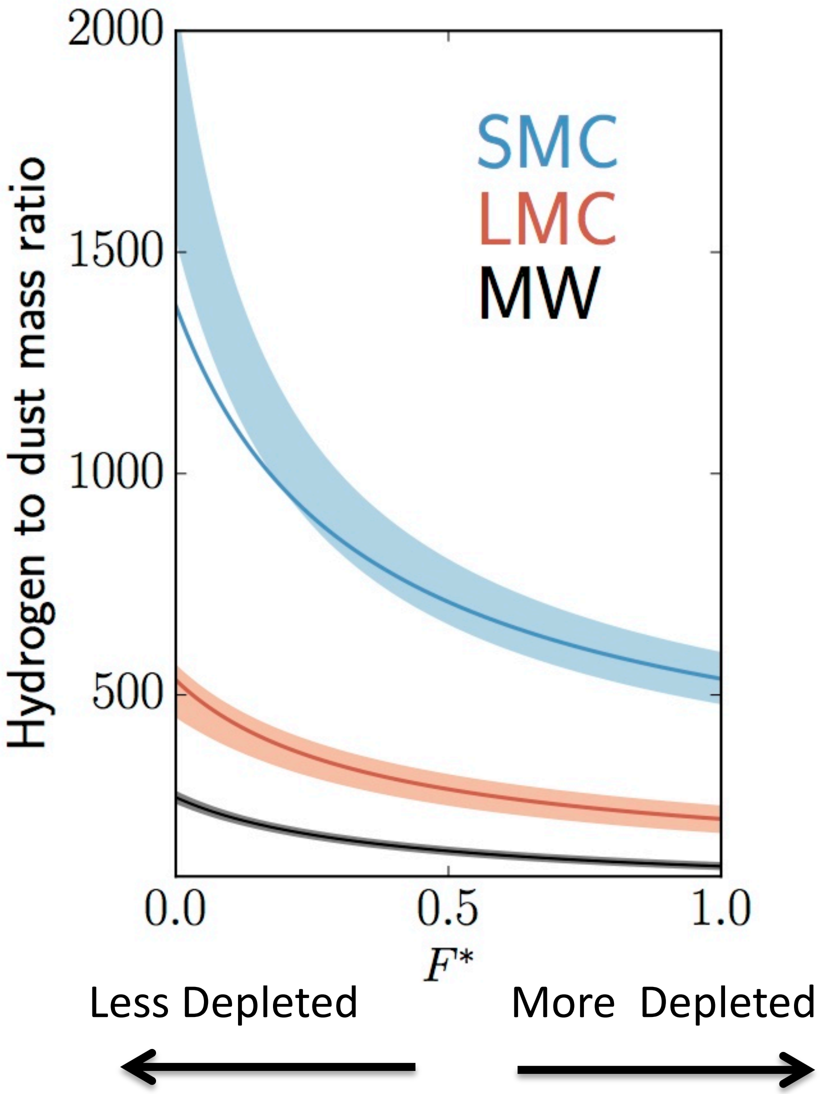
Tchernyshyov et al. 2015



SMC

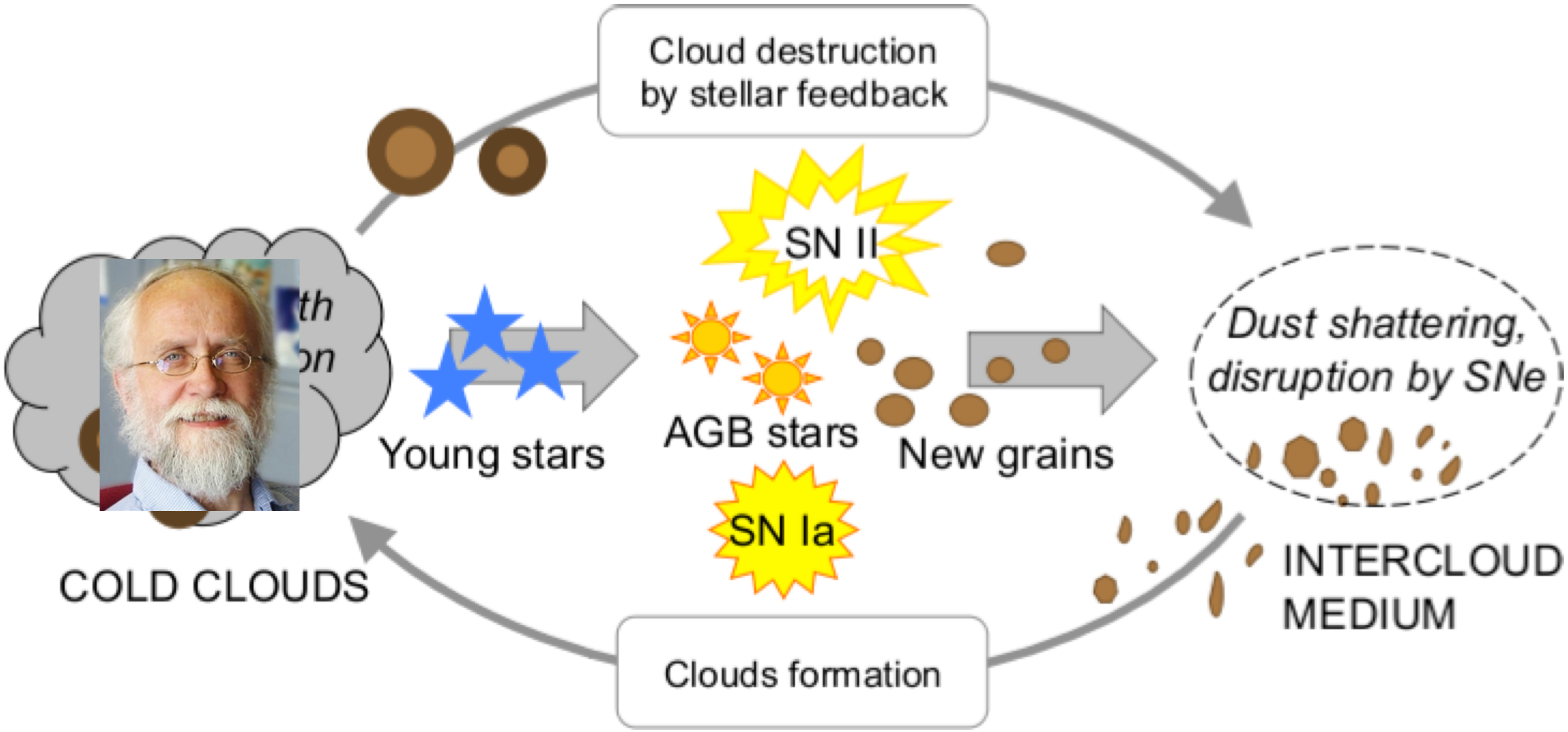
Tchernyshyov et al. 2015

Metal Depletion onto Dust



Tchernyshyov et al. 2015

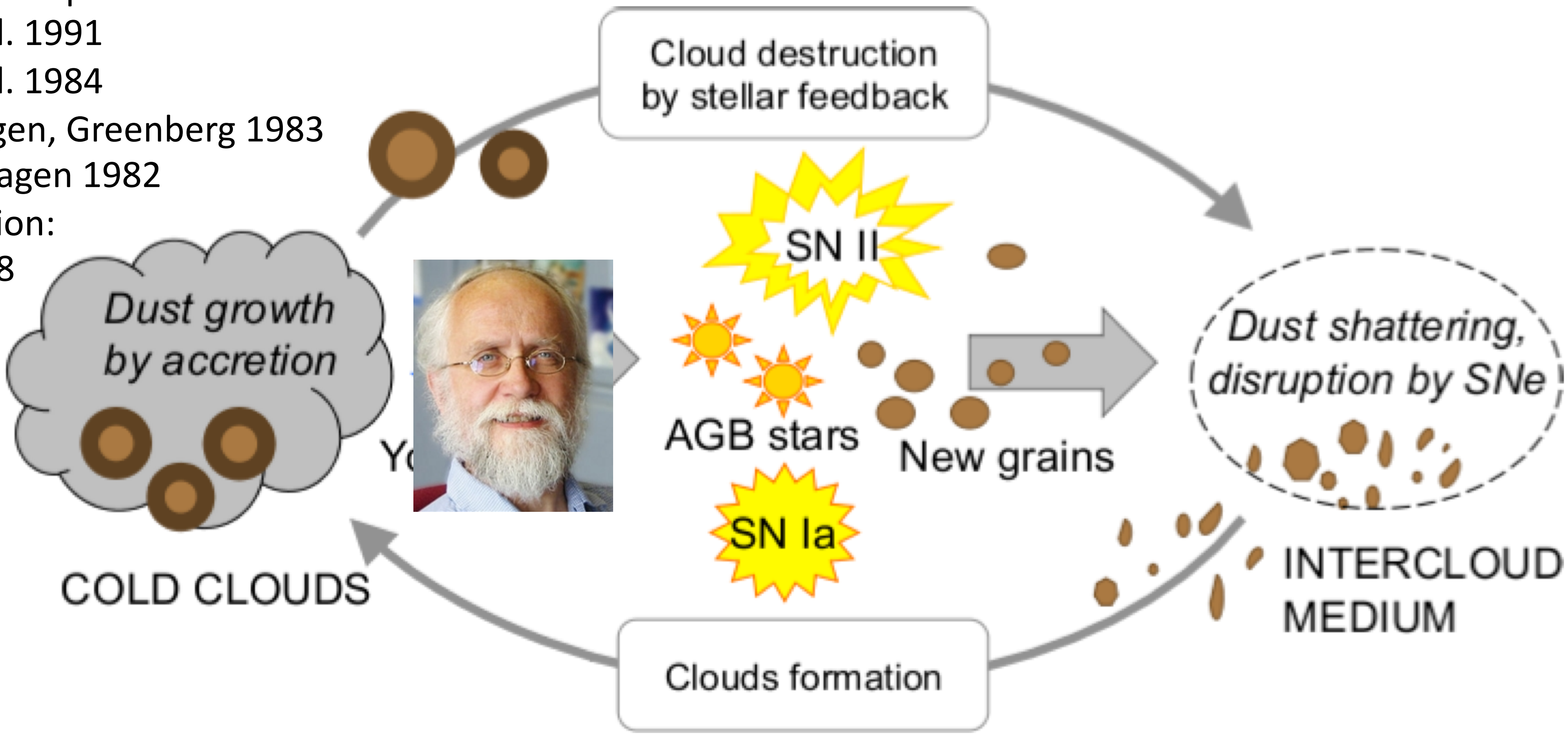
Life Cycle of Dust in Galaxies



Dwek, Zhkovska

Life Cycle of Dust in Galaxies

YSO & Ice absorption features:
Tielens et al. 1991
Tielens et al. 1984
Tielens, Hagen, Greenberg 1983
Tielens & Hagen 1982
Star formation:
Tielens 1988

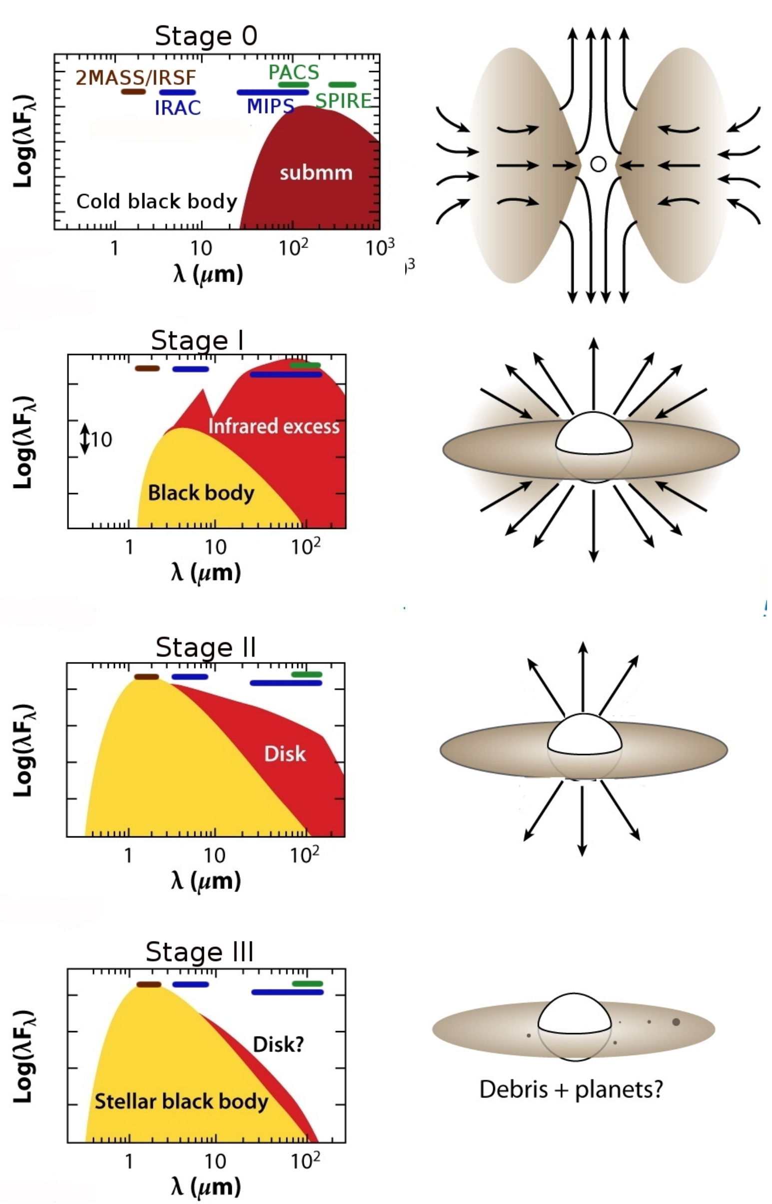


Dwek, Zhkovska

Young Stellar Object (YSO)

HST, S106;
Hubble Heritage

YSO Evolutionary Stages



~10^4 Stage 0 — Young Protostar: Main Accretion Phase

~10^5 Stage I — Evolved Accreting Protostar

~10^6 Stage II — Thick disk, accreting, Herbig Ae/Be

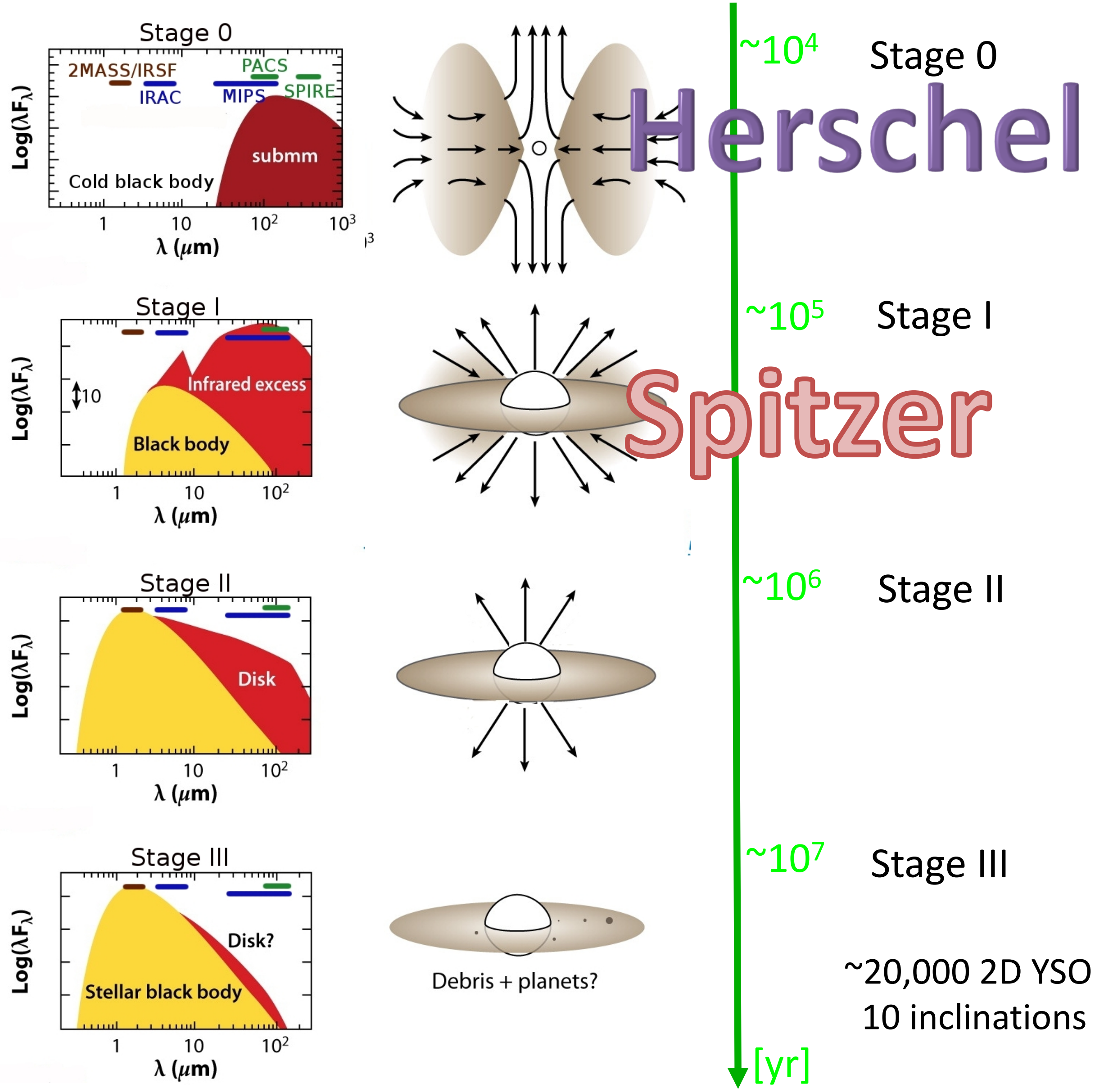
~10^7 Stage III — Thin disk, T-Tauri

[yr]

~20,000 2D YSO radiative transfer models at 10 inclinations each

Robitaille et al. (2006)

YSO Evolutionary Stages



Young Protostar:
Main Accretion Phase

Evolved Accreting Protostar

Thick disk, accreting,
Herbig Ae/Be

Thin disk,
T-Tauri

~20,000 2D YSO radiative transfer models at 10 inclinations each

Robitaille et al. (2006)

SMC: YSO Candidates

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area occupied
by galaxies

evolved

young

models

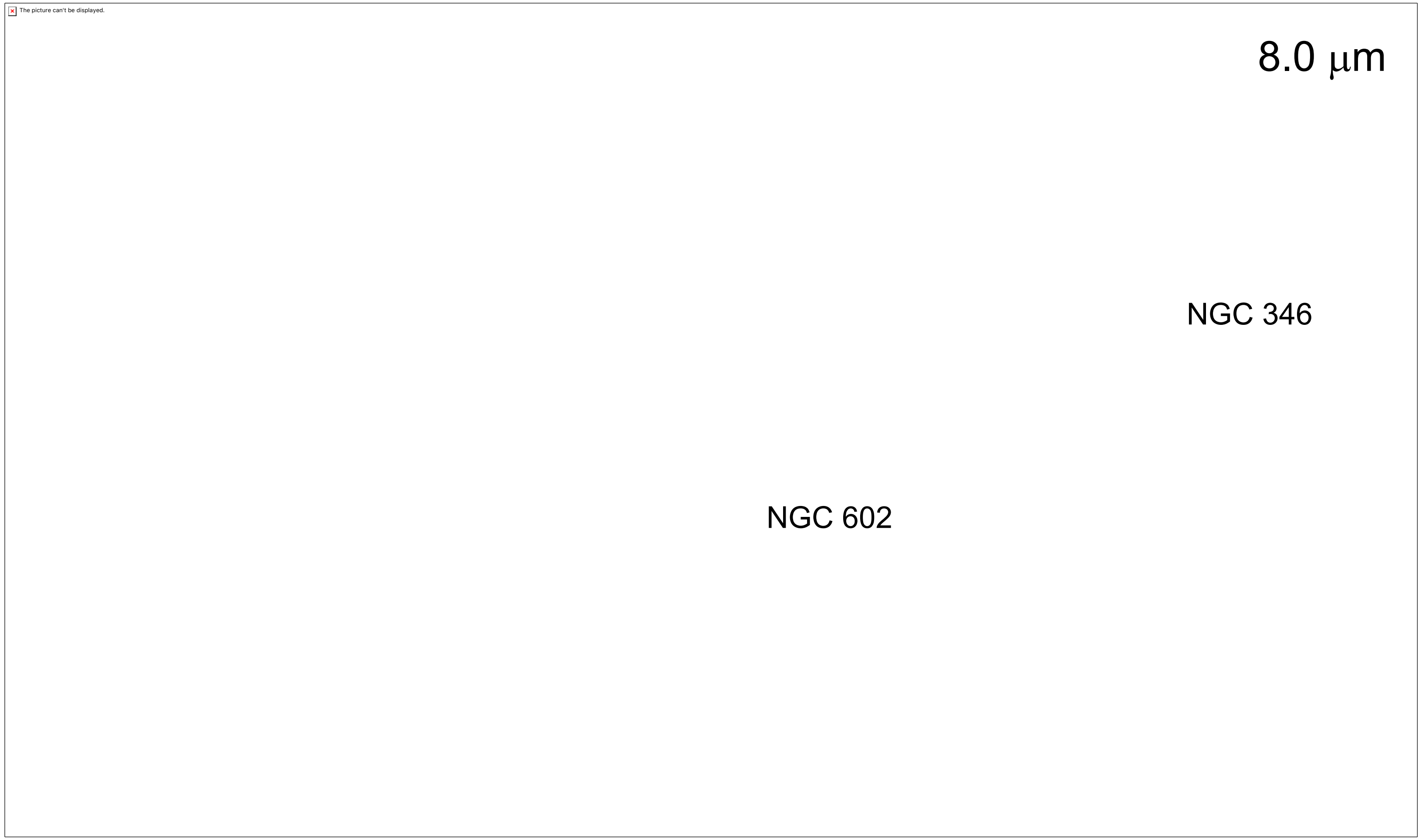
Boyer et al. (2011)
Bonanos et al. (2010)

Bolatto et al. (2007)
Simon et al. (2007)
Carlson et al. (2011)

Robitaille et al. (2006)

Sewilo et al. (2013)

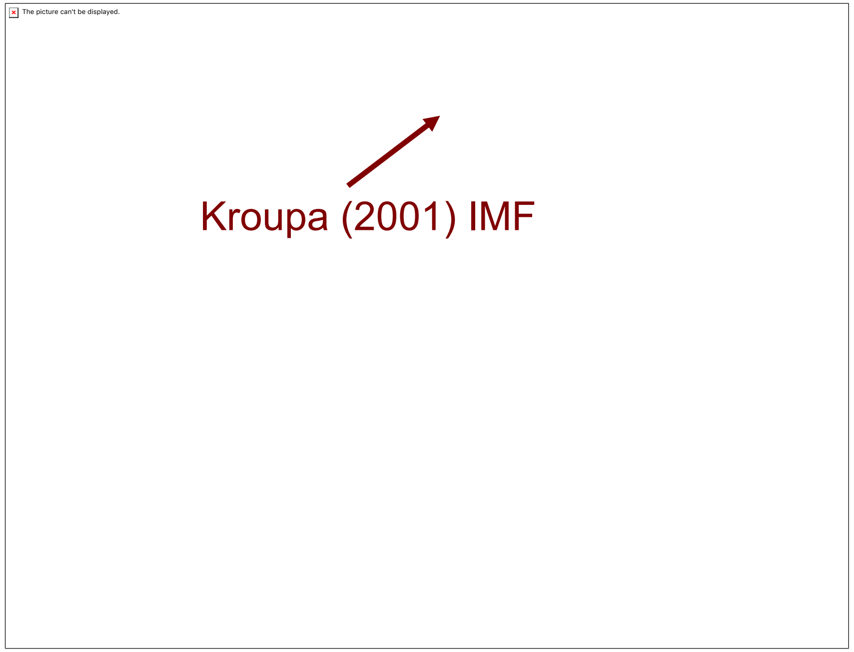
SMC: ~1100 YSO Candidates



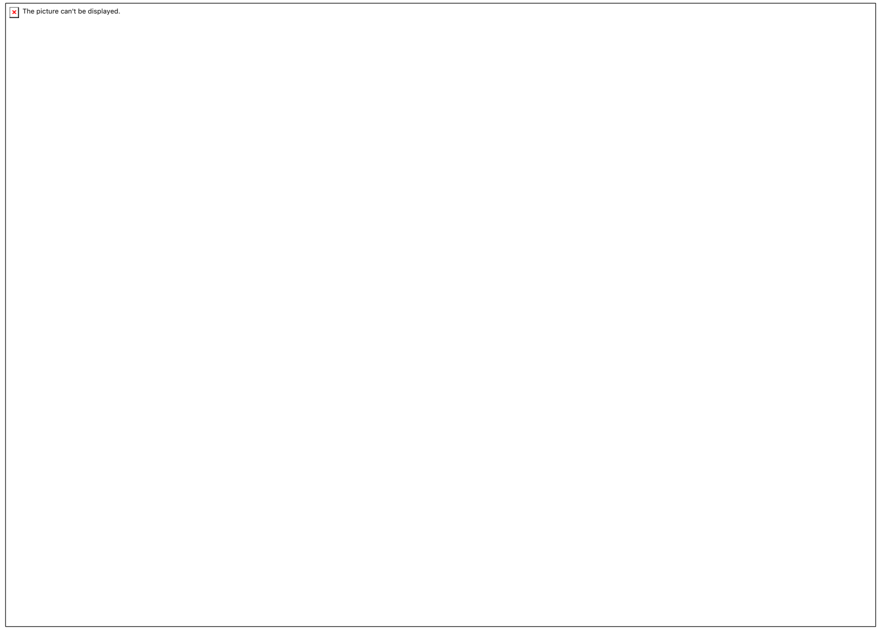
Sewilo et al. 2013

SMC: YSO properties
Star Formation Rate (SFR)

Histogram of Stellar Mass



Luminosity Histogram



SFR ~ 0.06 M_{sun} / year

Sewilo et al. (2013)

Stage 0 YSO & Dust Clumps

HST, Carinae
Smith et al.

SMC: YSOs and Dust Clumps

~7500

~660 ~110 ~5100

Seale et al. 2014

MCs inventory of dust

Item	LMC Value	SMC Value
ISM Dust mass	$7.3 \times 10^5\ M_\odot$	$8.3 \times 10^4\ M_\odot$
RSG & AGB & LBV Mass Loss return	$2.5 \times 10^{-5}\ M_\odot\ yr^{-1}$	$4.2 \times 10^{-6}\ M_\odot\ yr^{-1}$
Supernovae Dust production	$\sim 2 \times 10^{-3}\ M_\odot\ yr^{-1}$	$\sim 1 \times 10^{-3}\ M_\odot\ yr^{-1}$
Dust destruction by SNe	$\sim 2 \times 10^{-2}\ M_\odot\ yr^{-1}$	$\sim 1 \times 10^{-2}\ M_\odot\ yr^{-1}$
Star formation rate -stellar astration of dust	$\sim 0.1\ M_\odot\ yr^{-1}$ $\sim 2 \times 10^{-4}\ M_\odot\ yr^{-1}$	$\sim 0.06\ M_\odot\ yr^{-1}$ $\sim 5 \times 10^{-5}\ M_\odot\ yr^{-1}$
Net Loss of Dust Dust growth rate in ISM?	$\sim 1.8 \times 10^{-2}\ M_\odot\ yr^{-1}$	$\sim 9.0 \times 10^{-3}\ M_\odot\ yr^{-1}$

I would love some one to model the MCs inventory of dust

Item	LMC Value	SMC Value
ISM Dust mass	$7.3x\ 10^5\ M_\odot$	$8.3x\ 10^4\ M_\odot$
RSG & AGB & LBV Mass Loss return	$2.5 \times 10^{-5}\ M_\odot\ yr^{-1}$	$4.2 \times 10^{-6}\ M_\odot\ yr^{-1}$
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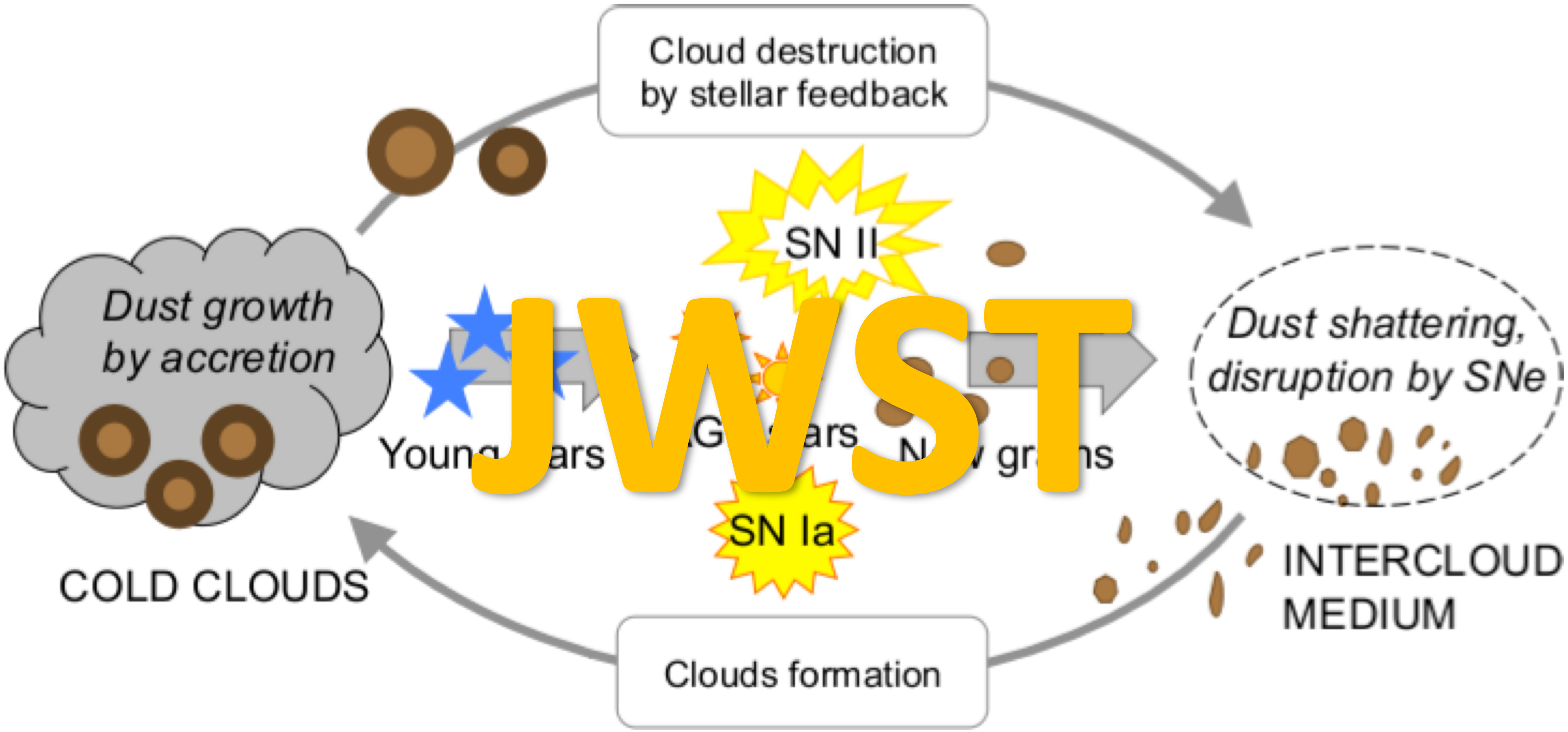
Net Loss of Dust Dust growth rate in ISM?	$\sim 1.8 \times 10^{-2}\ M_\odot\ yr^{-1}$	$\sim 9.0 \times 10^{-3}\ M_\odot\ yr^{-1}$

Life Cycle of Dust in Galaxies



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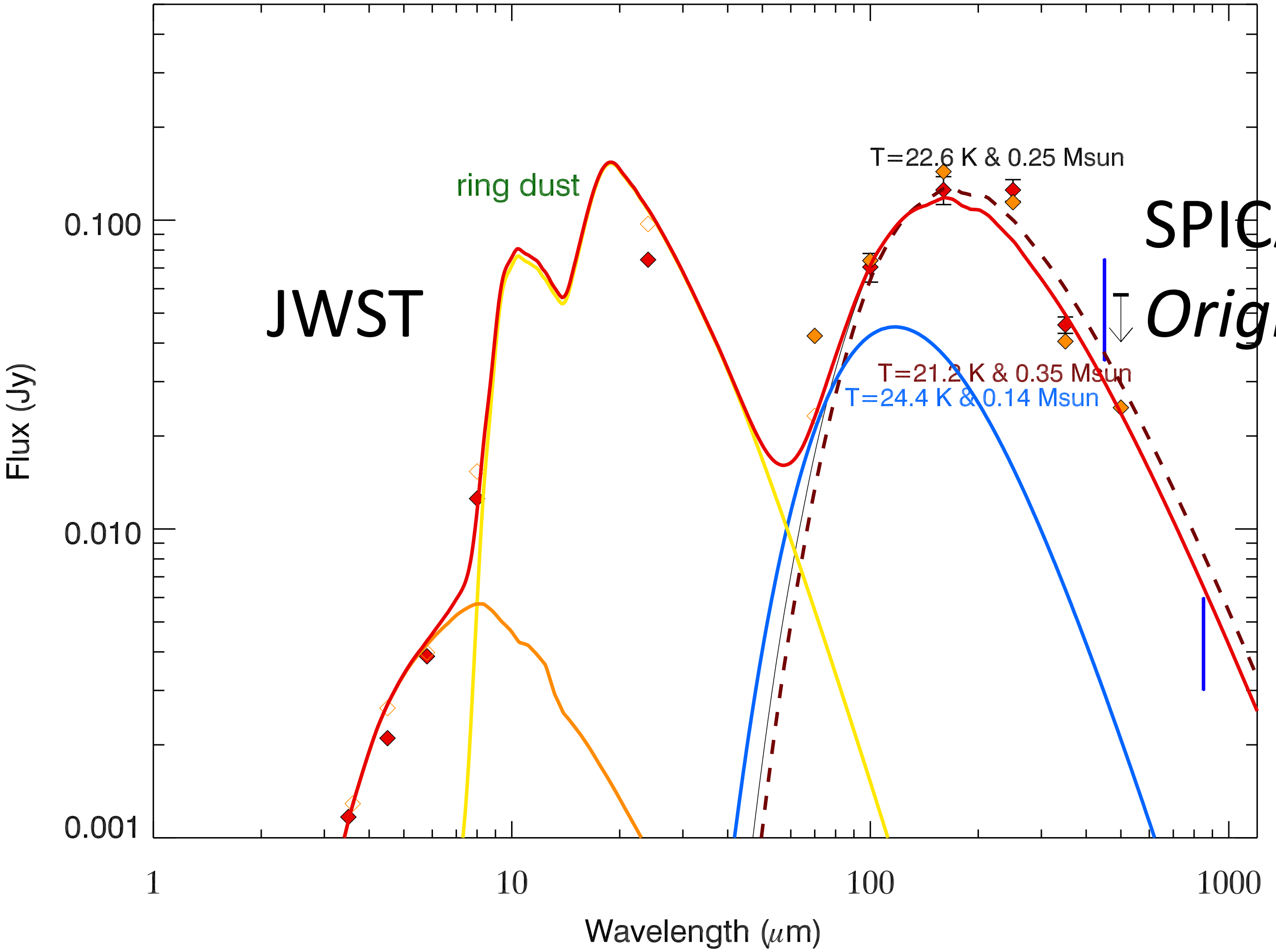
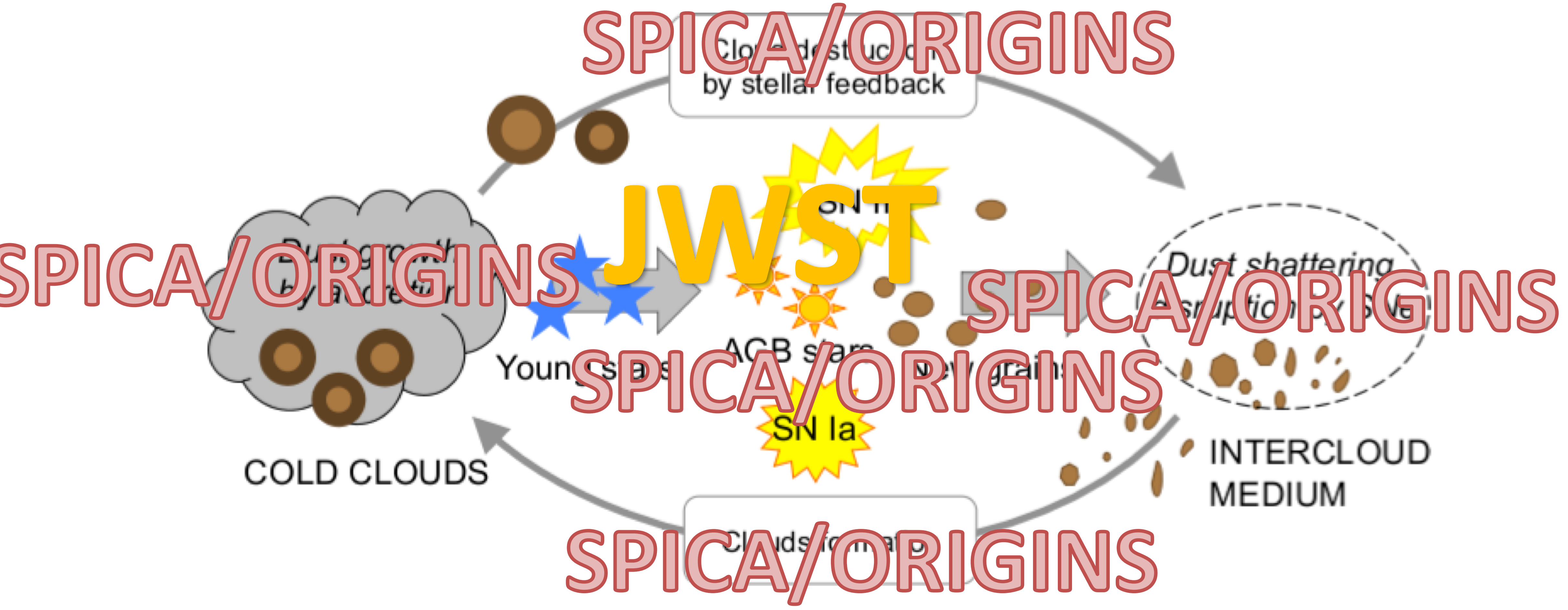
Far-IR detection of dust in SNe/SNR – will need *Origins* or SPICA



SPICA: SAFARI/B-BOP

Origins: OSS/B-BOP

Life Cycle of Dust in Galaxies



Dwek, Zhkovska

Large Mission Studies for Decadal

Origins Space Telescope
Margaret Meixner (STScI/JHU)
Asantha Cooray (UC Irvine)

Lynx
Feryal Özel (U. Arizona)
Alexey Vikhlinin (Harvard/CfA)

Habex
Sara Seager (MIT)
Scott Gaudi (OSU)

LUVOIR
Debra Fischer (Yale)
Brad Peterson (OSU)

The picture can't be displayed.

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Origins: Spitzer-like minimal deployable design

wavelength coverage: 2.8-588 μm

Telescope:

- diameter: 5.9 m
- area: 25 m^2 (=JWST area)
- diffraction-limit: 30 μm
- temperature: 4.5 K

Cooling: long life cryro-coolers

Agile Observatory for surveys: 60” per second

Launch Vehicle:

Large, SLS Block 1, Space-X BFR

Mission: 10 year propellant, serviceable

Orbit: Sun-Earth L2

Three Instruments

OSS: Origins Survey Spectrometer

-25-588 μm R~300, survey mapping

-25-588 μm R~43,000, spectral surveys

-100-200 μm R~325,000, kinematics

FIP: Far-infrared Imager Polarimeter

- 50 or 250 μm, Large area survey mapping

- 50 or 250 μm, polarimetry

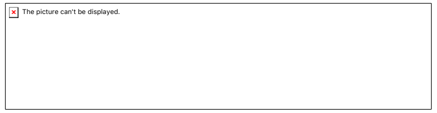
MISC-T: Mid-Infrared Spectrometer Camera Transit

-Ultra-Stable Transit Spectroscopy

-2.8-20 μm R~50-295

Mission Parameters & Programmatics

Parameter	***Origins***	**SPICA**
Scope	NASA Large Mission Study	ESA: M5 + JAXA:Strategic L
Wavelength Coverage	2.8 – 588 µm	12 – 350 µm
Telescope aperture, undeployed	5.9 m	2.5 m
Diffraction limit	30 µm	20 µm
Telescope/instrument temp With cyrocoolers	4.5 K / 50 mK	<8 K / 50 mK
Orbit	Sun-Earth L2	
Mapping Speed	60“ per second	20“-60” per second
Life time	5 yrs req., 10 yr goal	3 yrs req., 5 yr goal
Decision date	Late 2020/ early 2021	June 2021
Launch date	>2035	2032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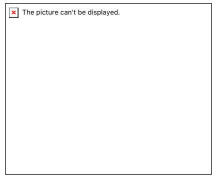
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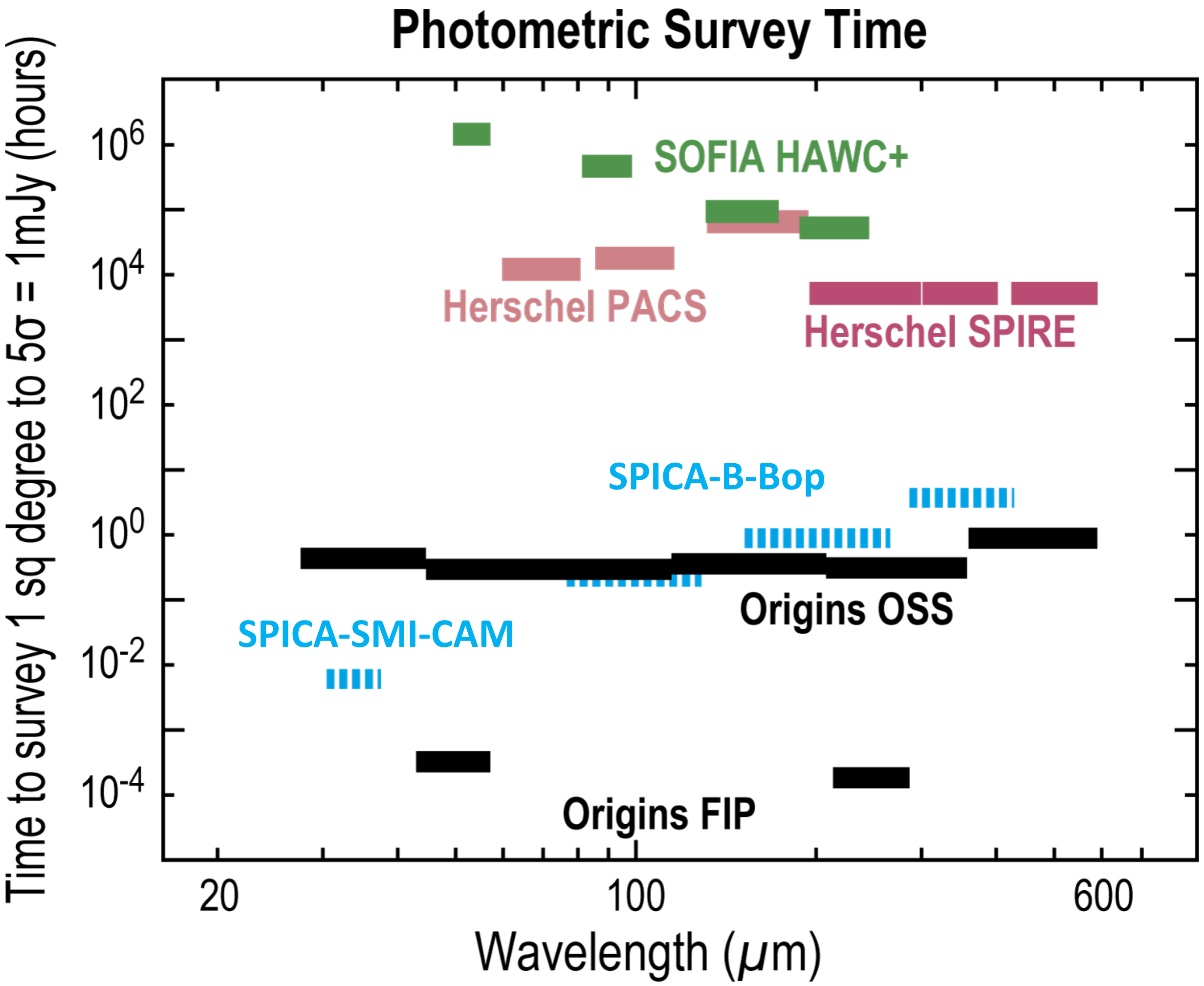
SPICA SAFARI


Photometric Survey Time
Time to survey 1 sq degree to 5σ = 1mJy (hours)
10^6
10^4
10^2
10^0
10^-2
10^-4
SOFIA HAWC+
Herschel PACS
Herschel SPIRE
SPICA-B-Bop
Origins OSS
SPICA-SMI-CAM
Origins FIP
20
100
600
Wavelength (μm)

Summary

- With SAGE and HERITAGE, we have an inventory of dust production, desctruction, ISM growth and star formation in the Magellanic Clouds
- A comprehensive dust evolution model of the Magellanic Clouds would be timely
- Dust evolution in galaxies is popular and being adopted in local galaxy models as well as cosmological simulations
- Future is bright with observational opportunities with JWST and hopefully *Origins* or SPICA.