Supernova Remnants III, Chania, Crete, 13 June 2024

Supernova dust formation and destruction in the JWST era

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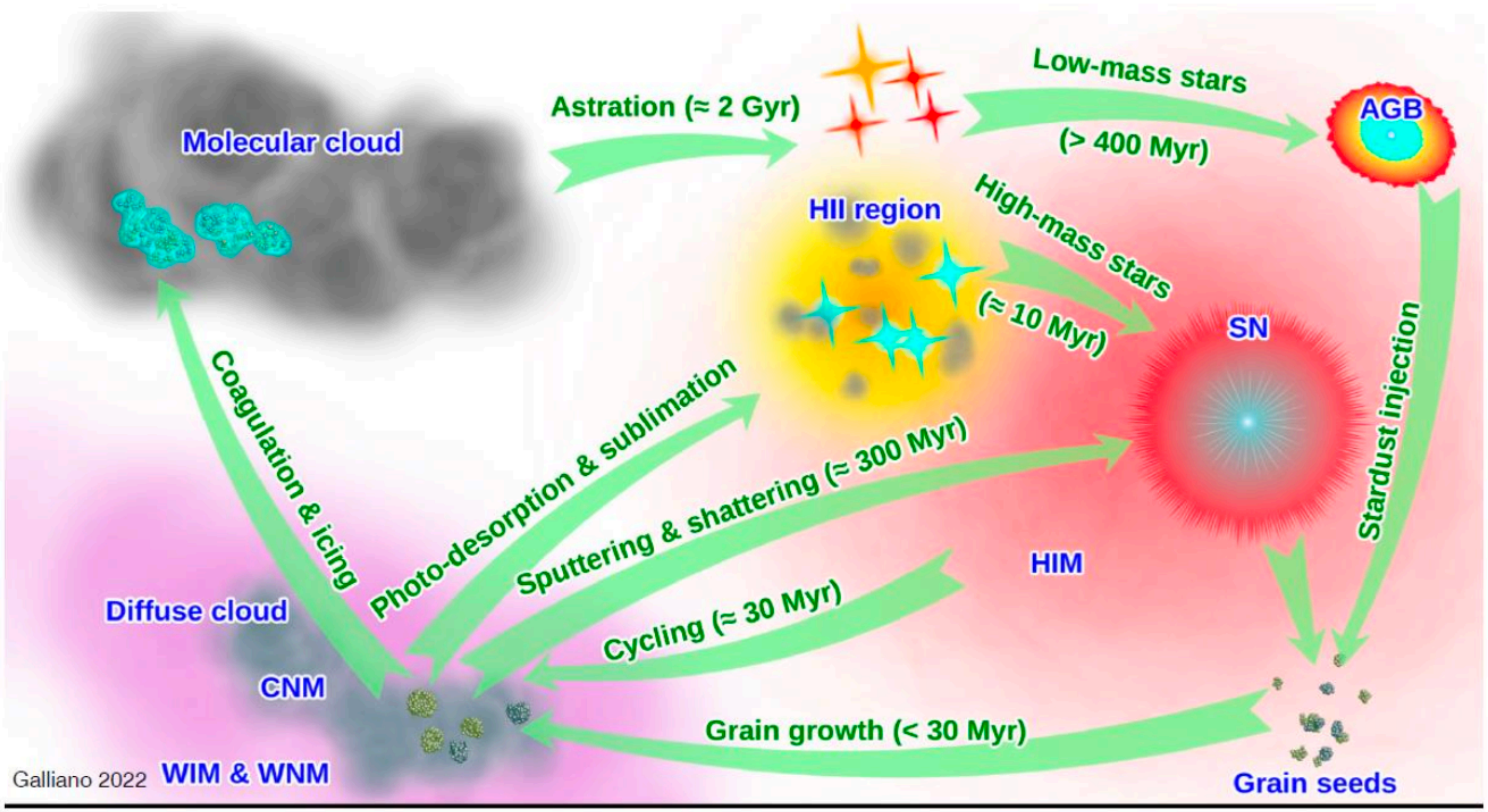
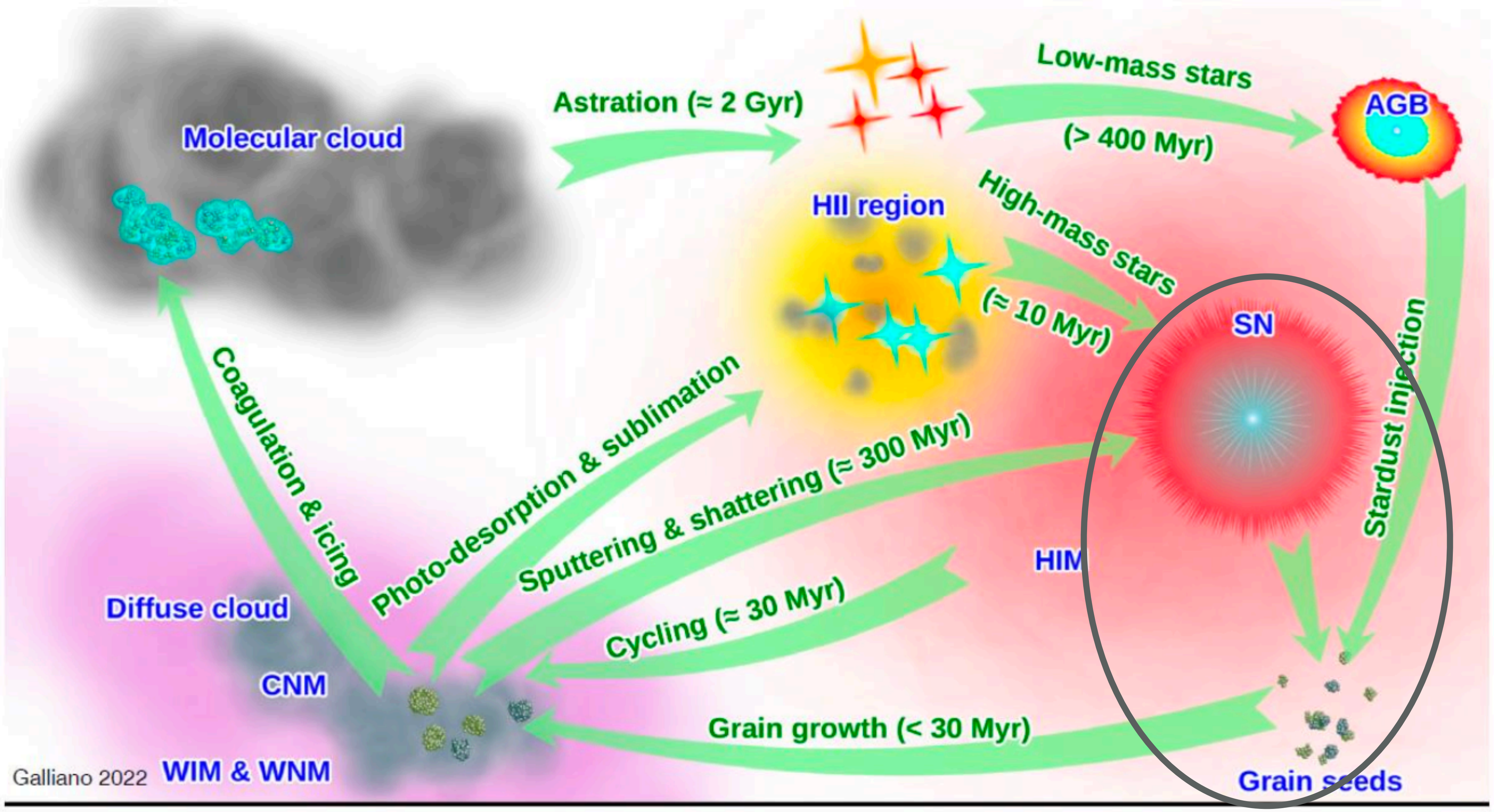
DustOrigin at UGent

Lifecycle of interstellar dust

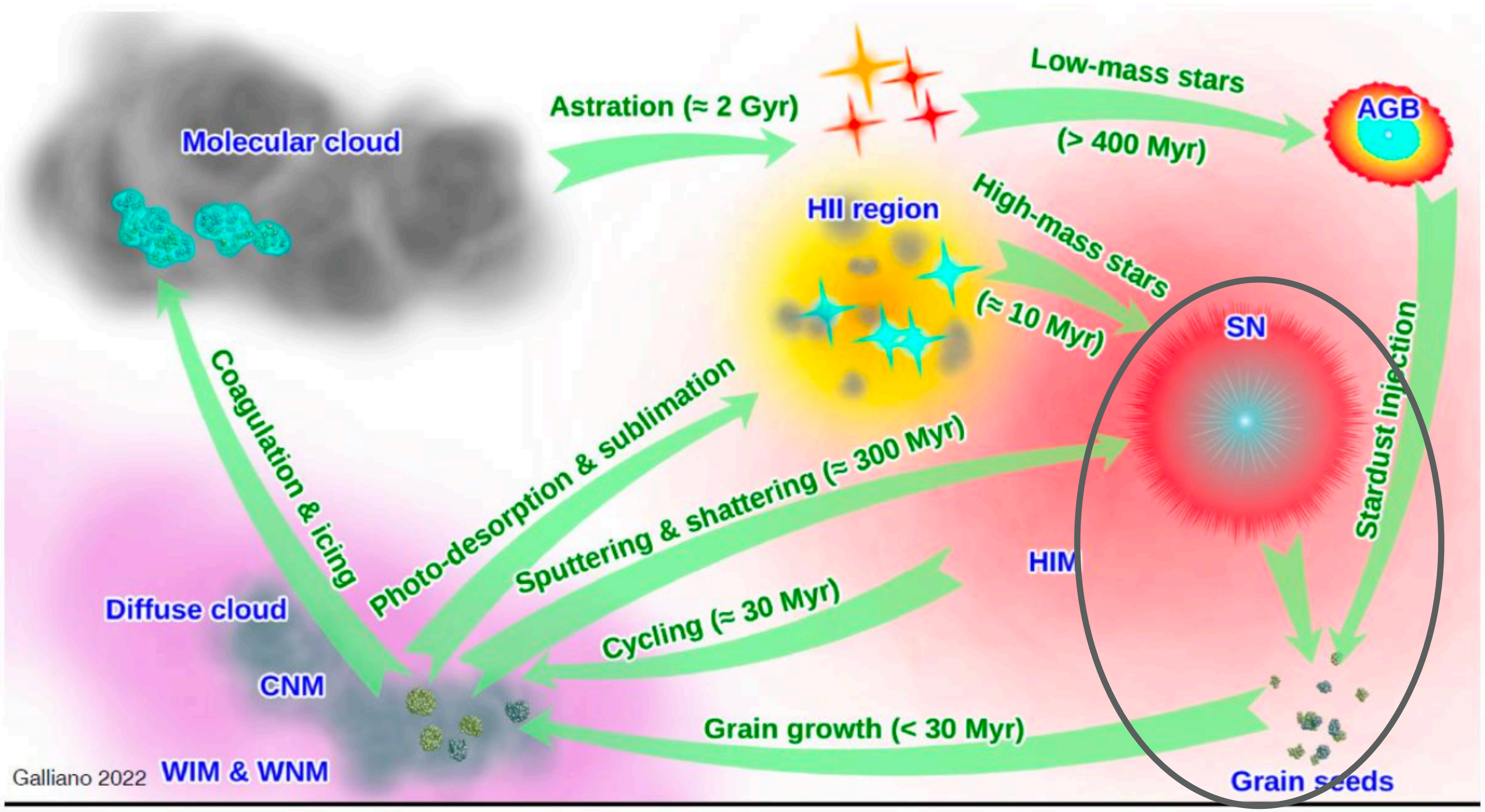


Lifecycle of interstellar dust



*** Dust forms in SNRs:**
up to 0.4-1.0 M_{sun}
from observations;
but theorie predicts
lower values

Lifecycle of interstellar dust



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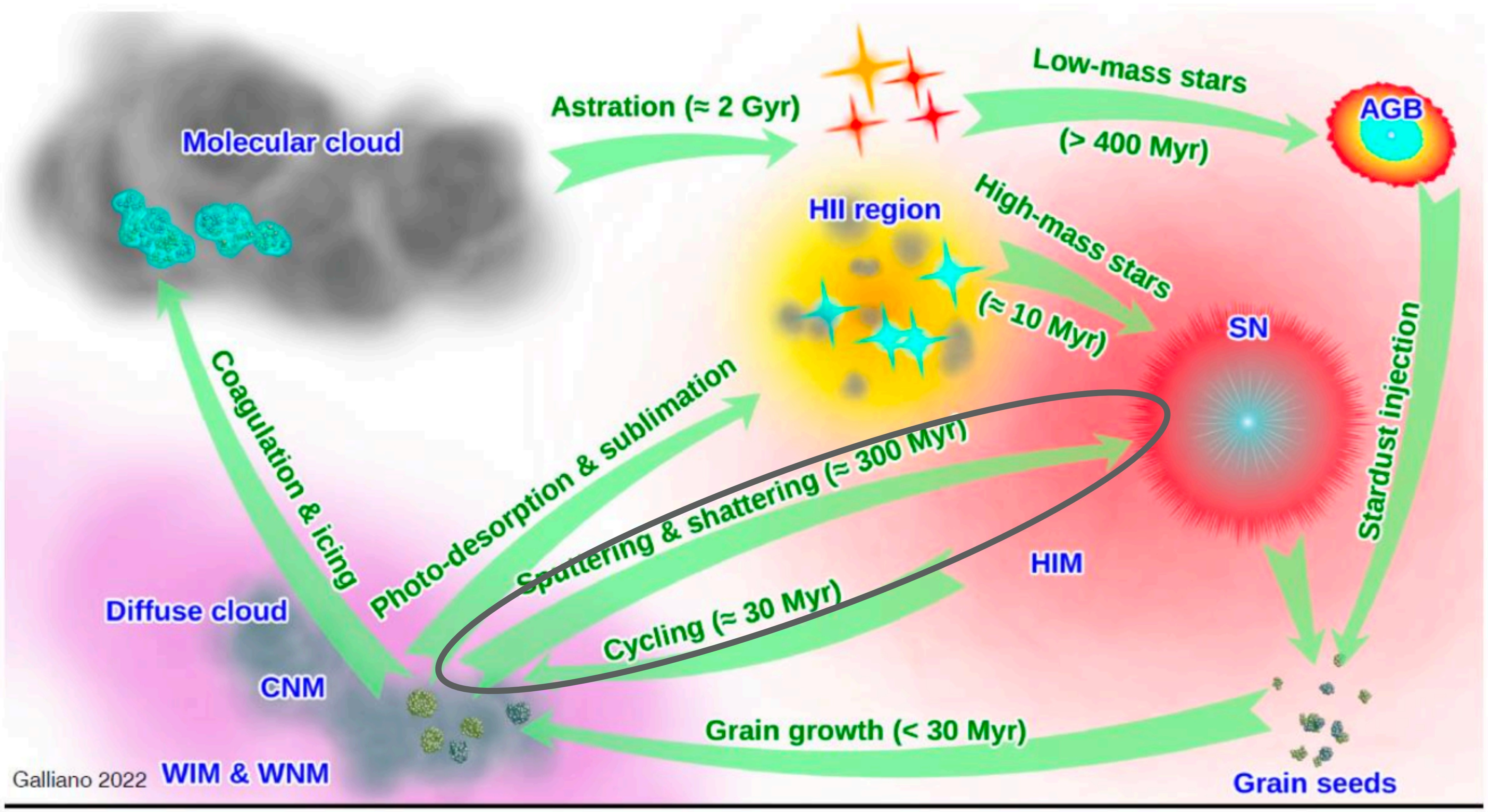
see Arka's talk

Lifecycle of interstellar dust



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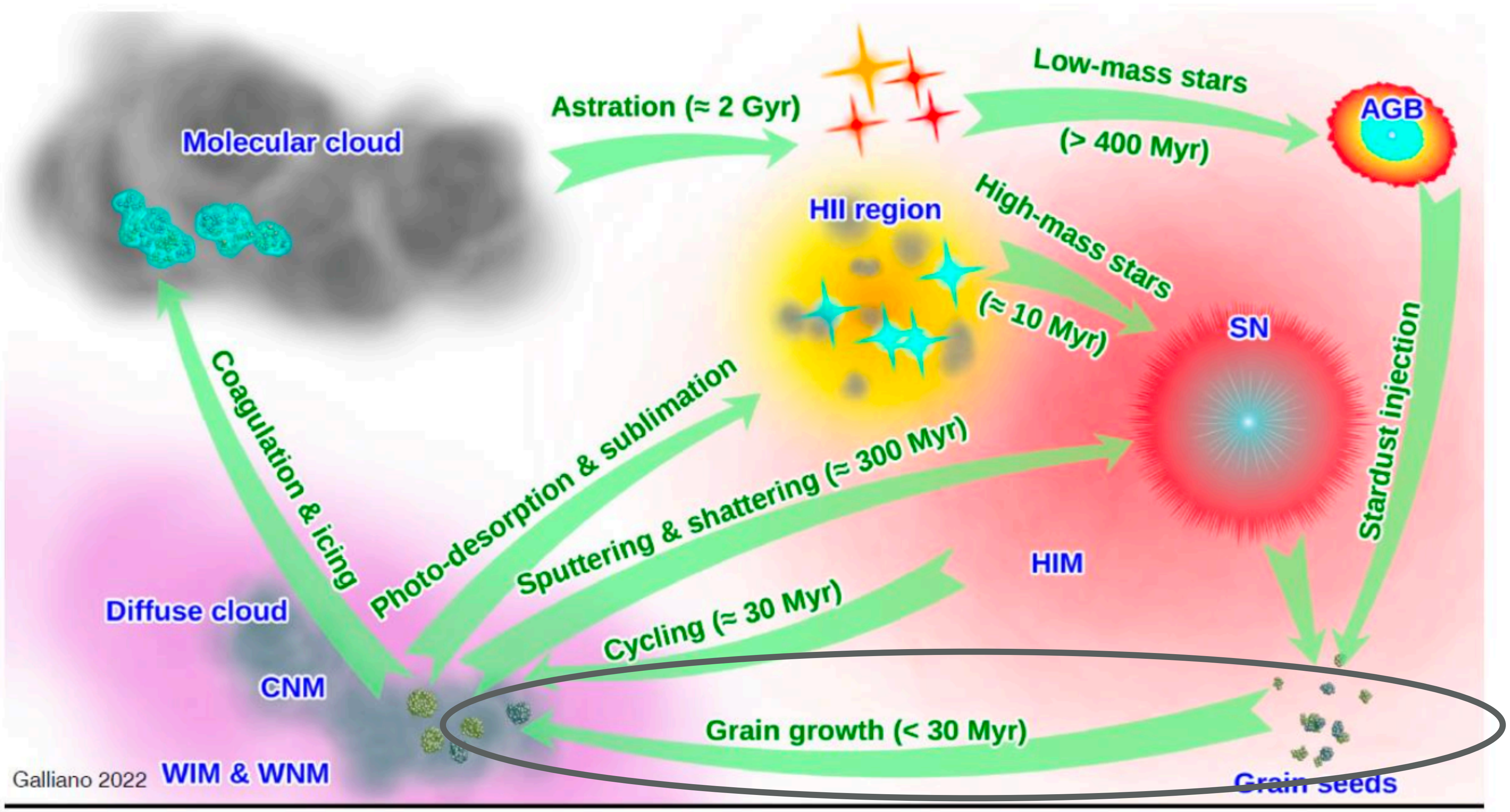
*** SN blast wave destroys lots of dust:**
each SN destroys
up to 70 M_{sun} !
(Slavin et al. 2015,
Kirchschlager et al. 2024)

Lifecycle of interstellar dust



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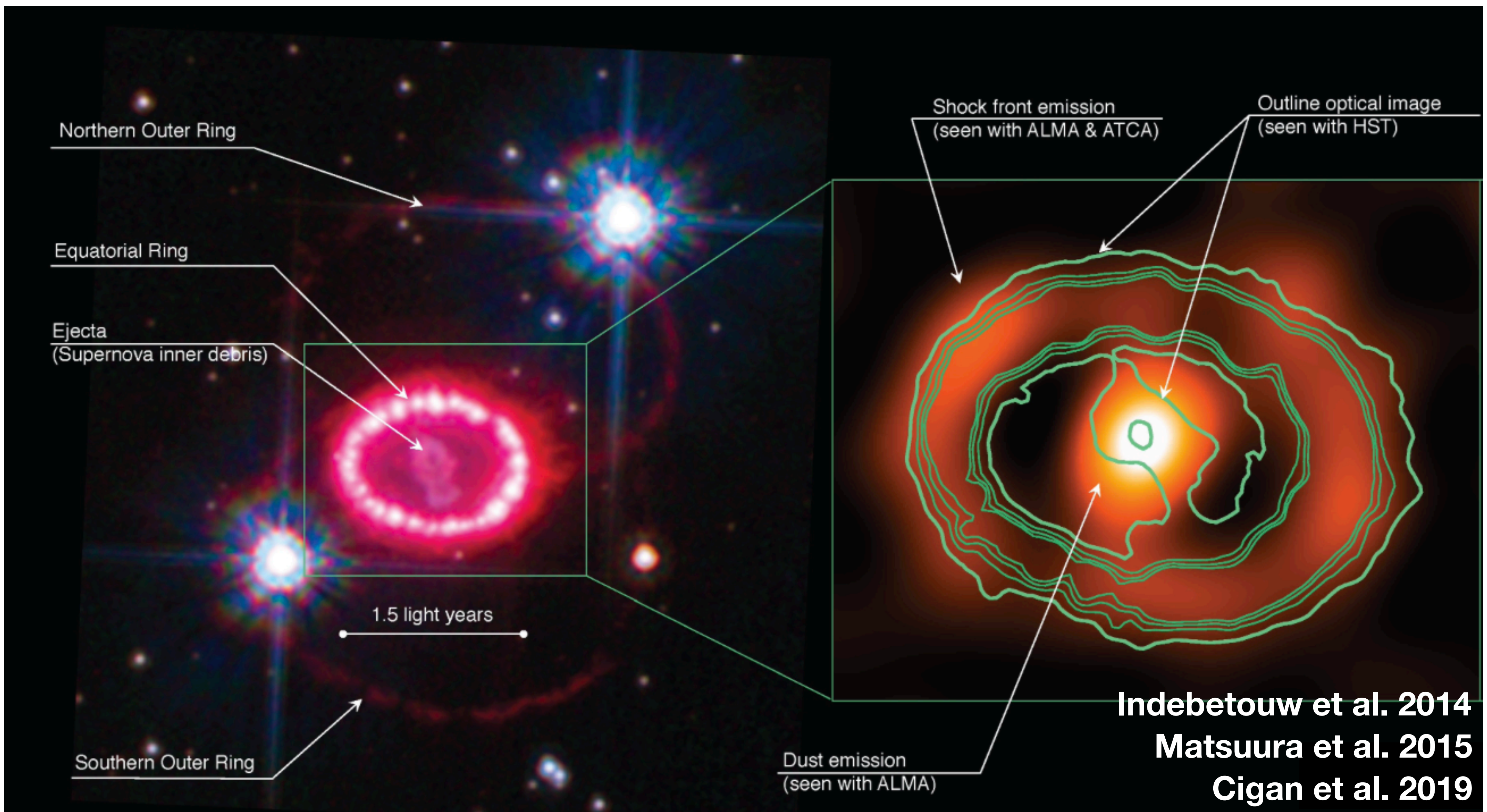
↓

SN are NET dust destroyers. We need another source of dust: grain growth?
This is a problem especially at high redshifts where galaxies only a few 100 Myrs after the Big Bang show large masses of dust!

Dust formation in SN(R)s

SN1987A was a game-changer: detection of large dust masses!

Large dust mass detection of 0.2-0.7 Msun only 30 years post-explosion

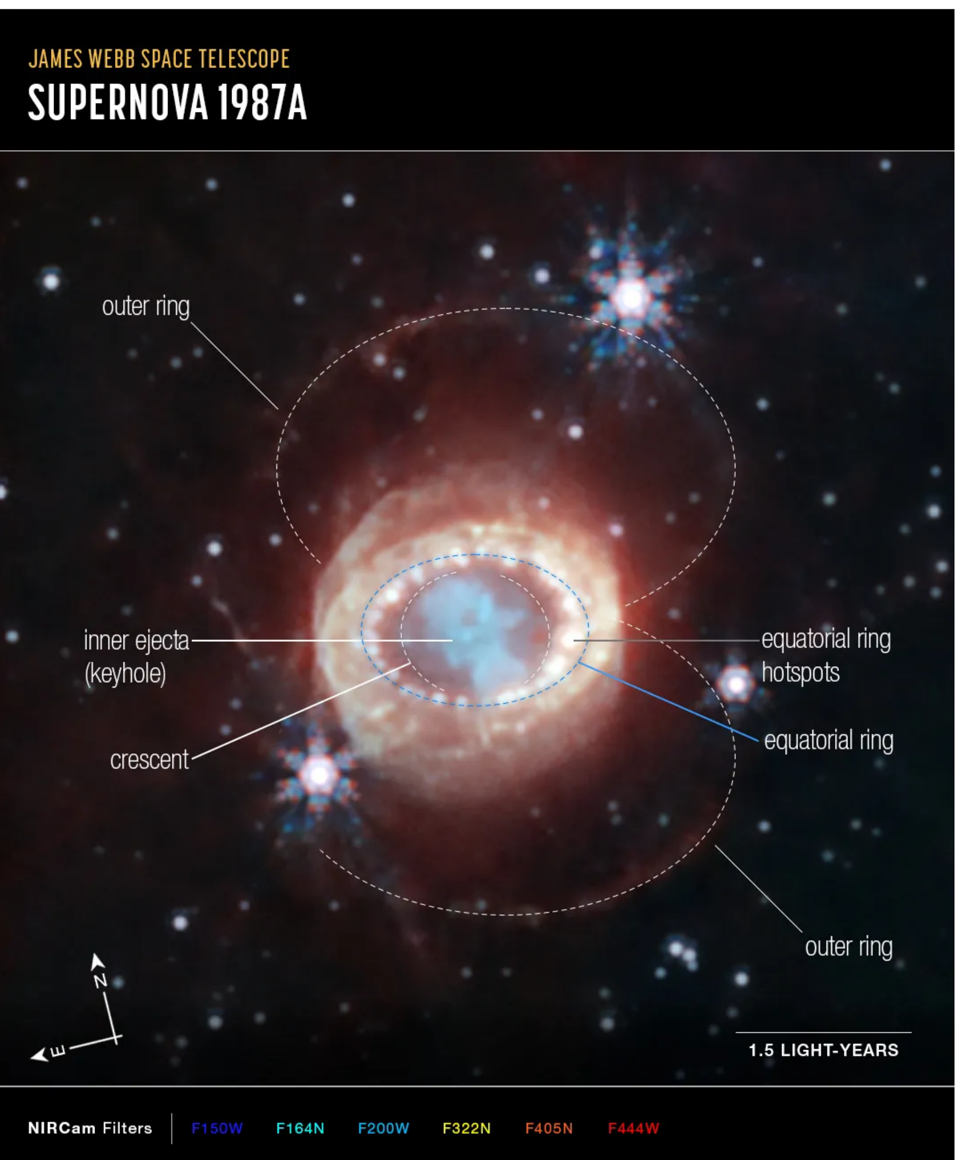


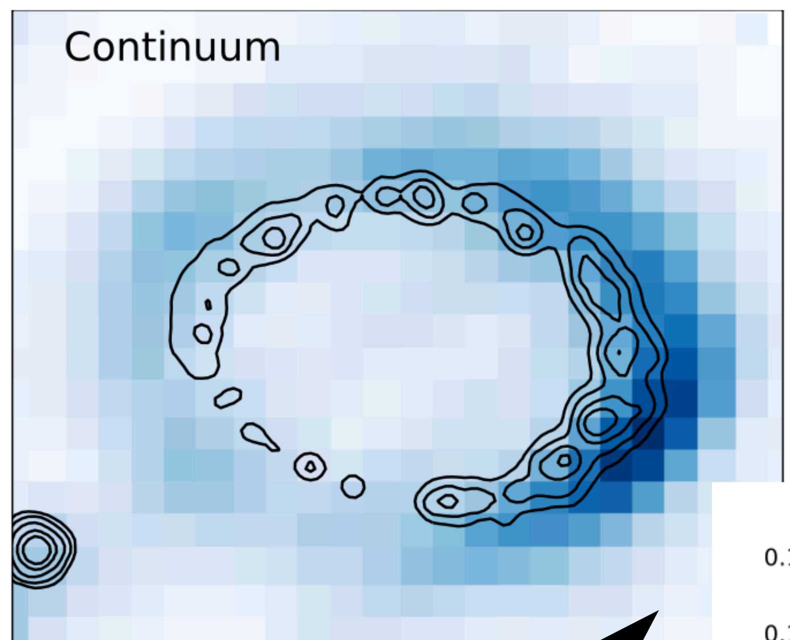
Indebetouw et al. 2014
Matsuura et al. 2015
Cigan et al. 2019

Dust formation in SN(R)s

SN1987A was a game-changer: detection of large dust masses!

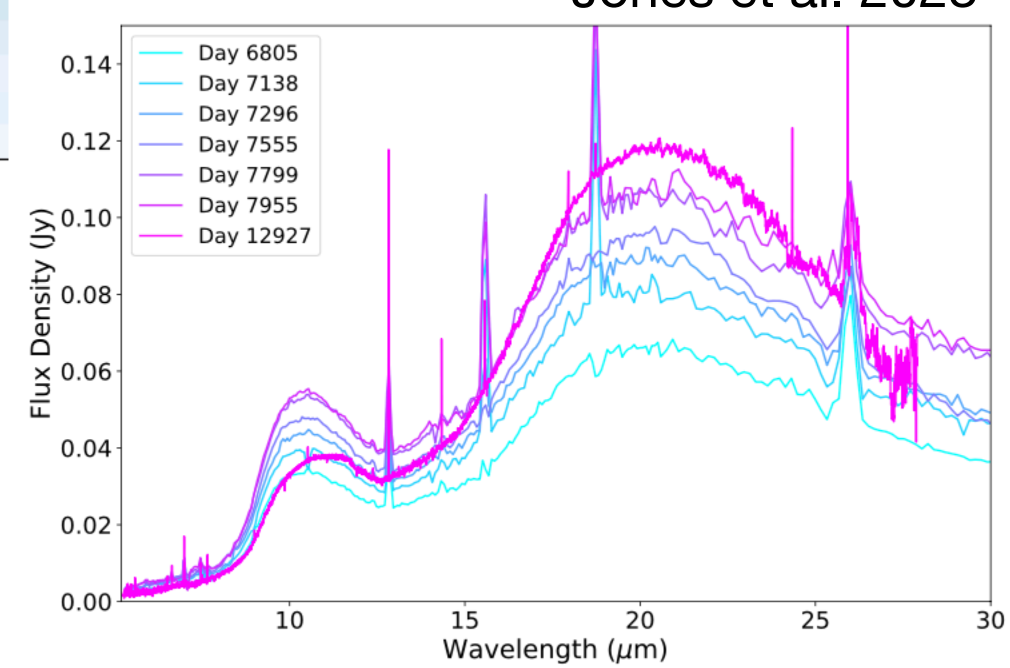
New JWST data will allow to study dust destruction in detail !





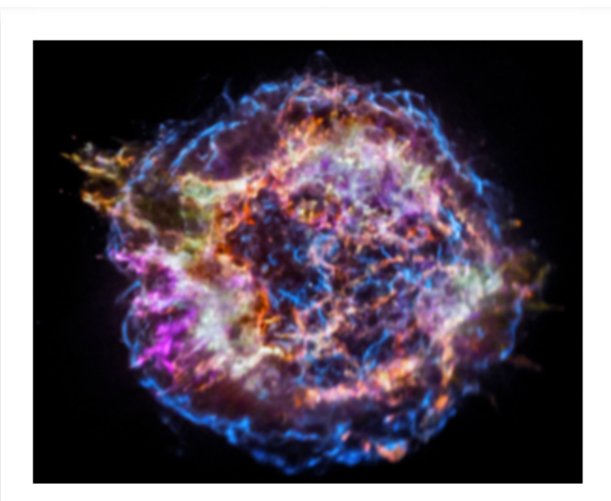
see Larsson's talk

Jones et al. 2023

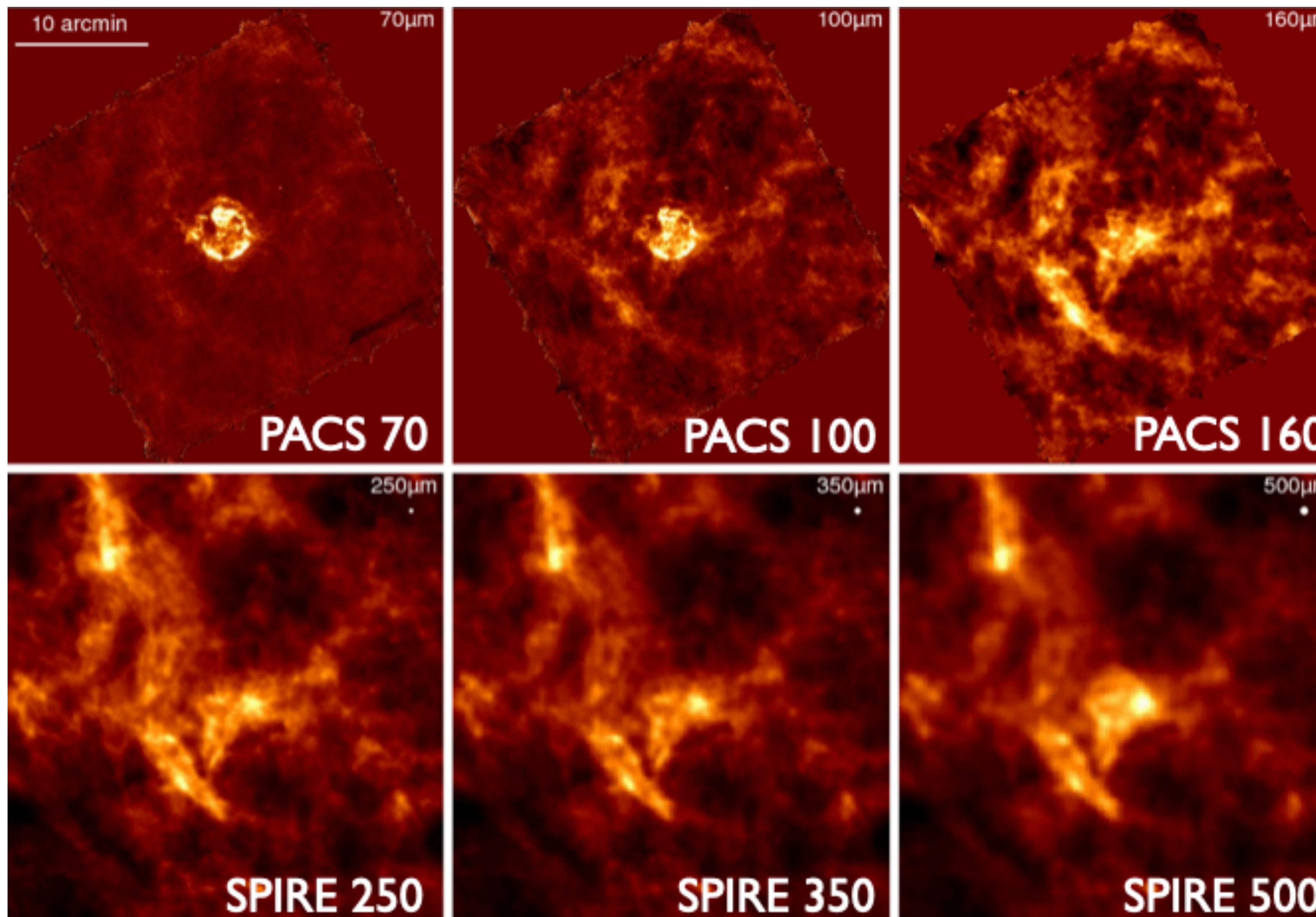


Dust formation in SN(R)s

Cas A: dust masses from infrared dust emission (Herschel)



Cassiopeia A
Type IIb

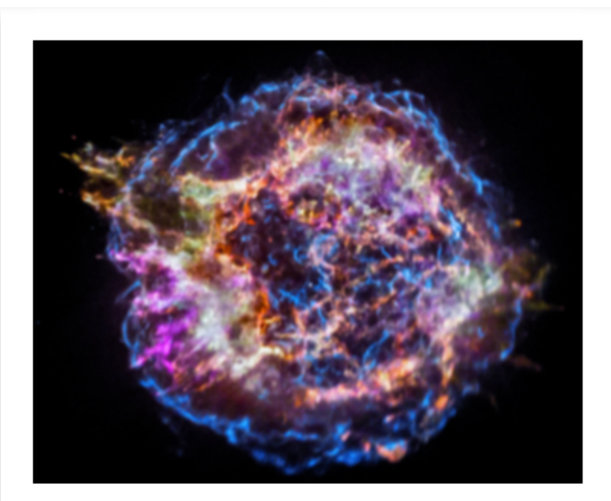


Barlow, et al. 2010

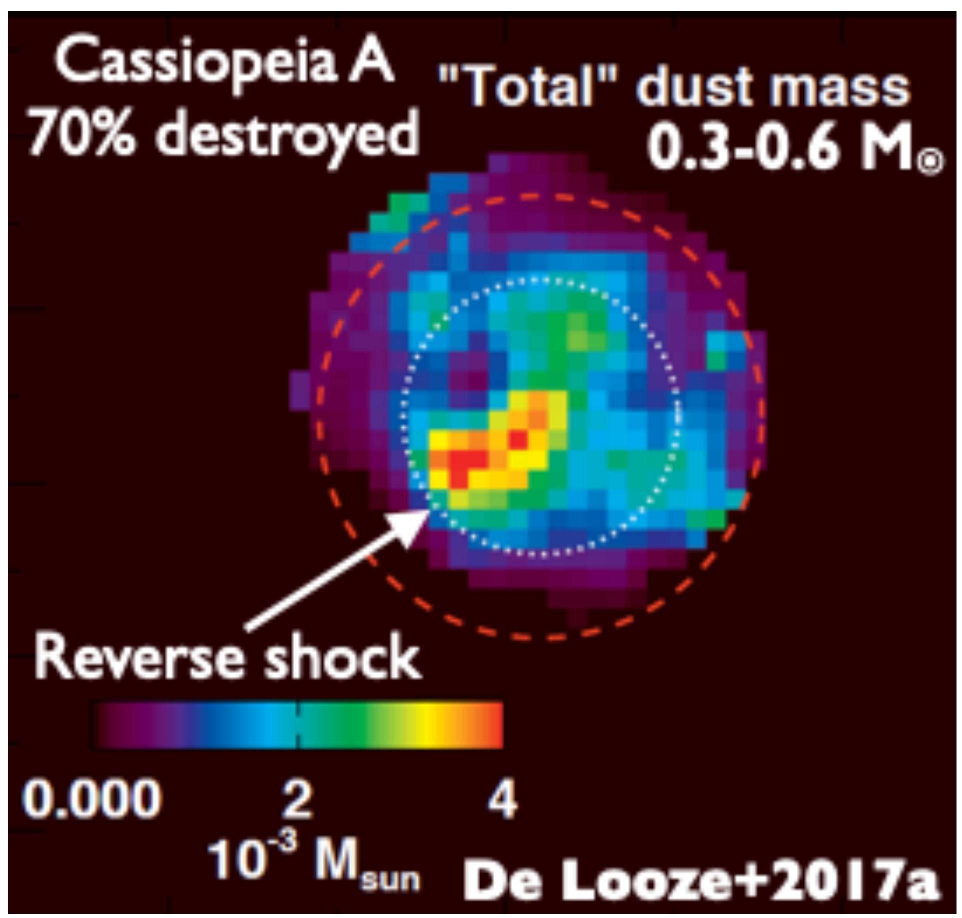
Dust formation in SN(R)s

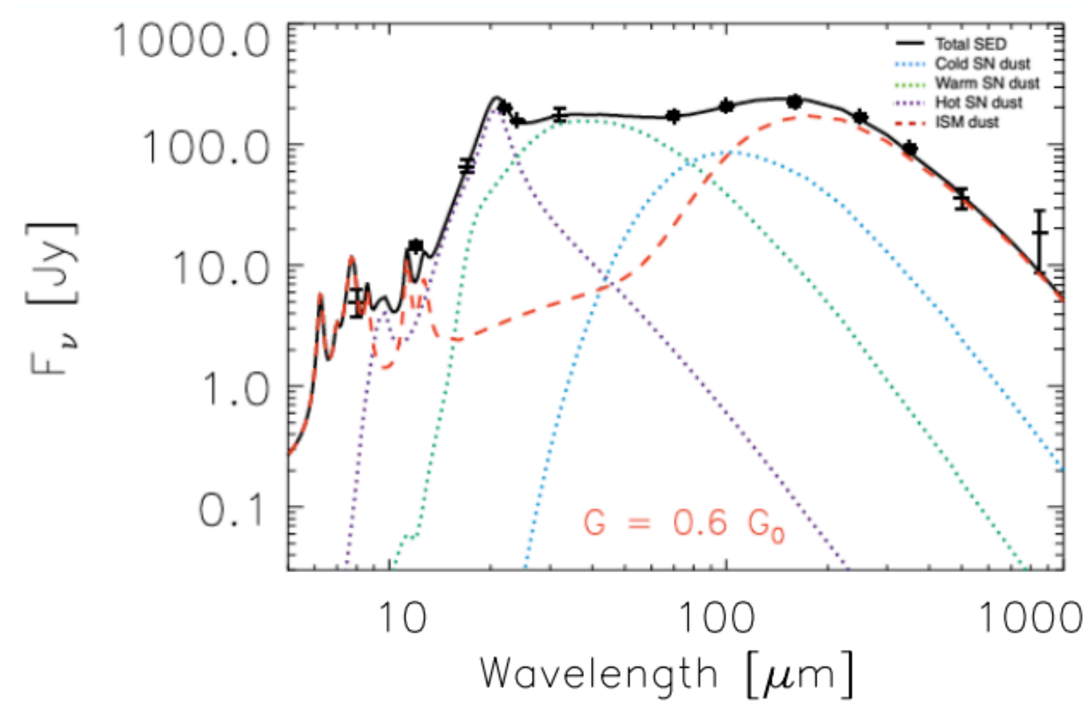
Cas A: dust masses from infrared dust emission (Herschel)

- **Main difficulty in disentangling all emission components.**
- **High mass 0.3-0.6 M_{sun} of dust.**
- **Most of the dust inside reverse shock.**



Cassiopeia A



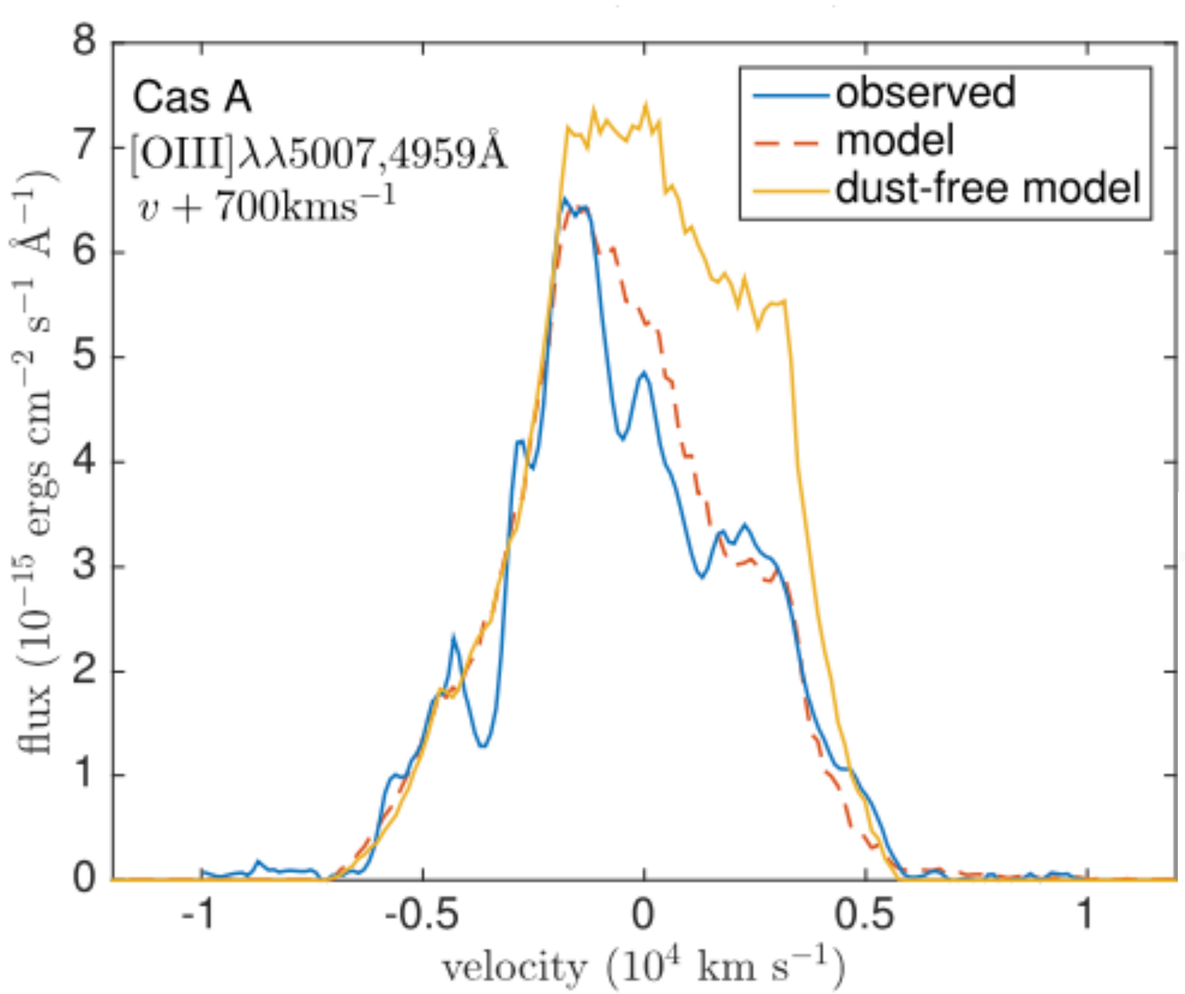


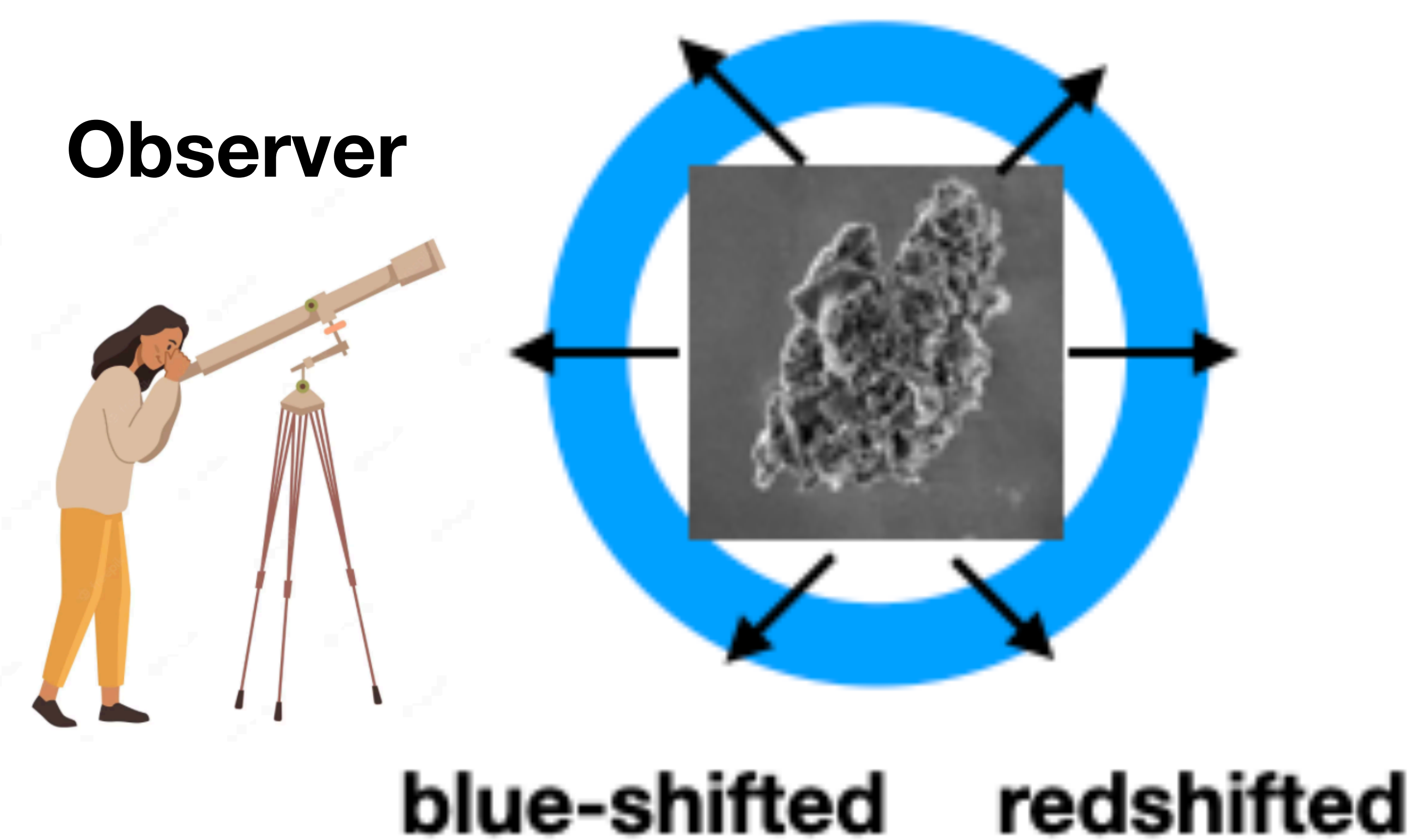
+ Independent dust mass estimates (0.5-1.0M_{sun}):
Niculescu-Duvaz et al. 2021, see also Priestley et al. 2019, 2022 and Bevan et al. 2017

De Looze, Barlow, et al. 2017

Dust formation in SN(R)s

Cas A: modelling optical line profile asymmetries

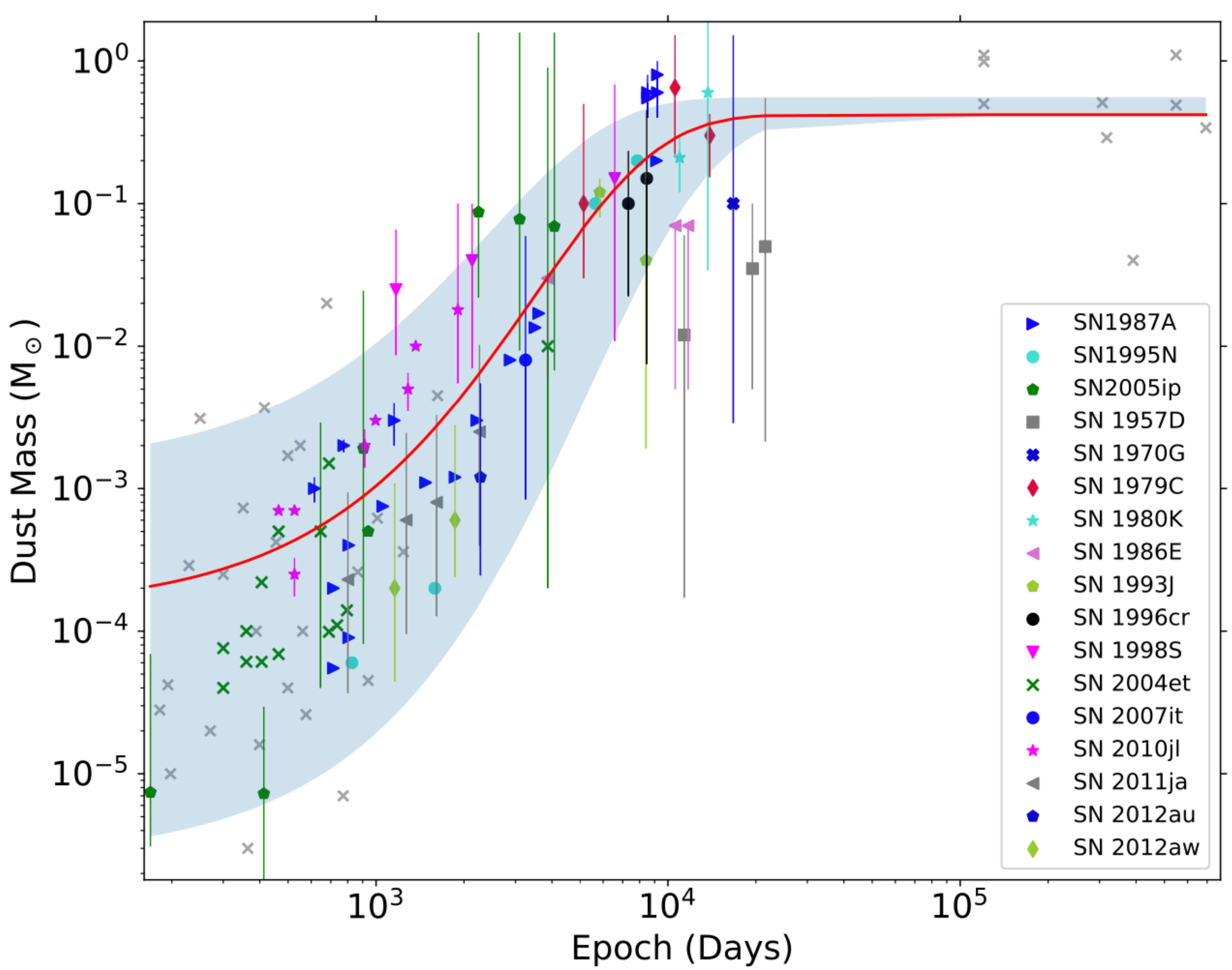




Bevan & Barlow 2016, Bevan, Barlow et al. 2017, 2019, Wesson et al. 2023

Dust formation in SN(R)s

Gradual growth in SN dust mass over (30 years) time

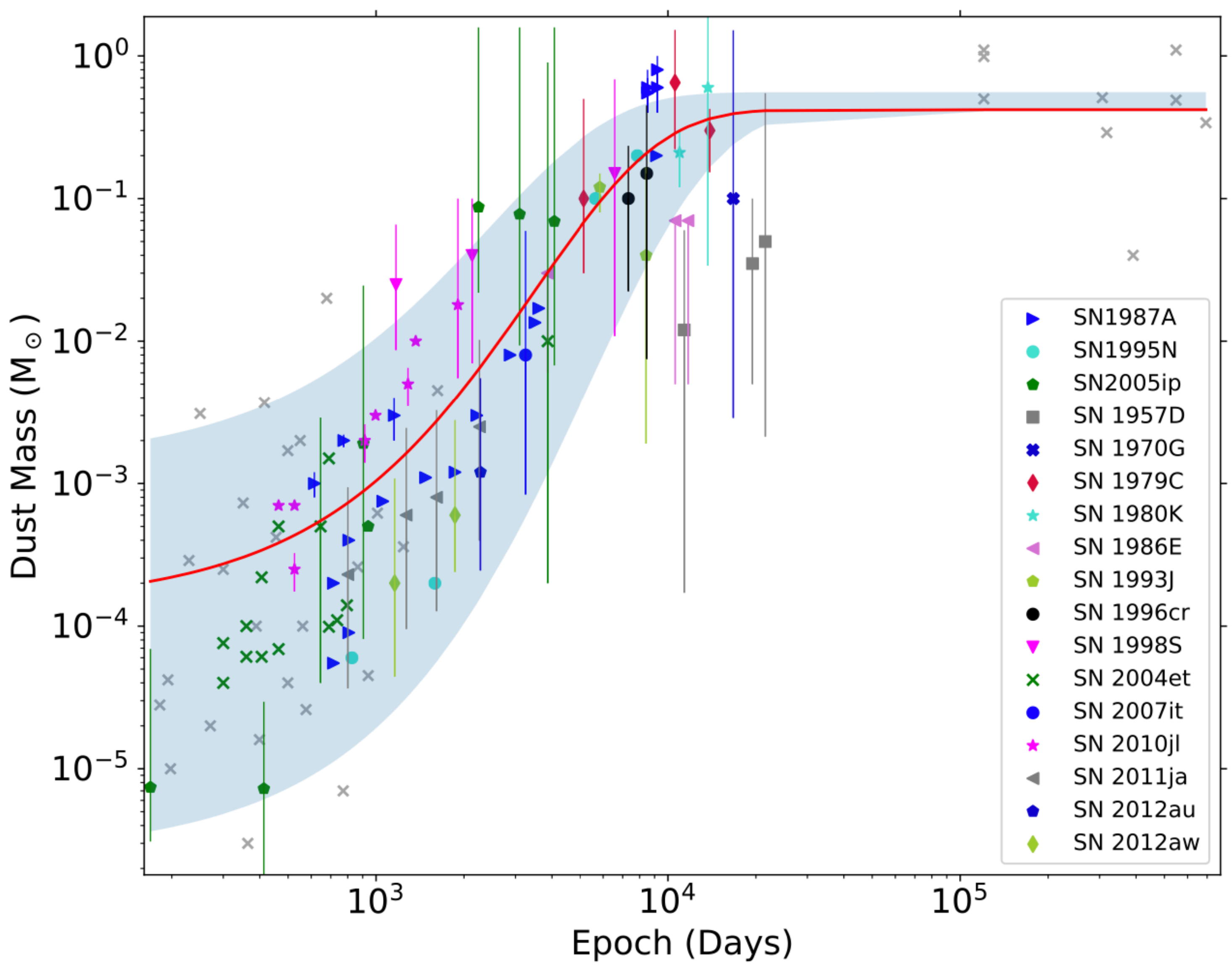


$0.42^{+0.09}_{-0.05}$ $M_\odot$

Niculescu-Duvaz, Barlow, et al. 2022

Dust formation in SN(R)s

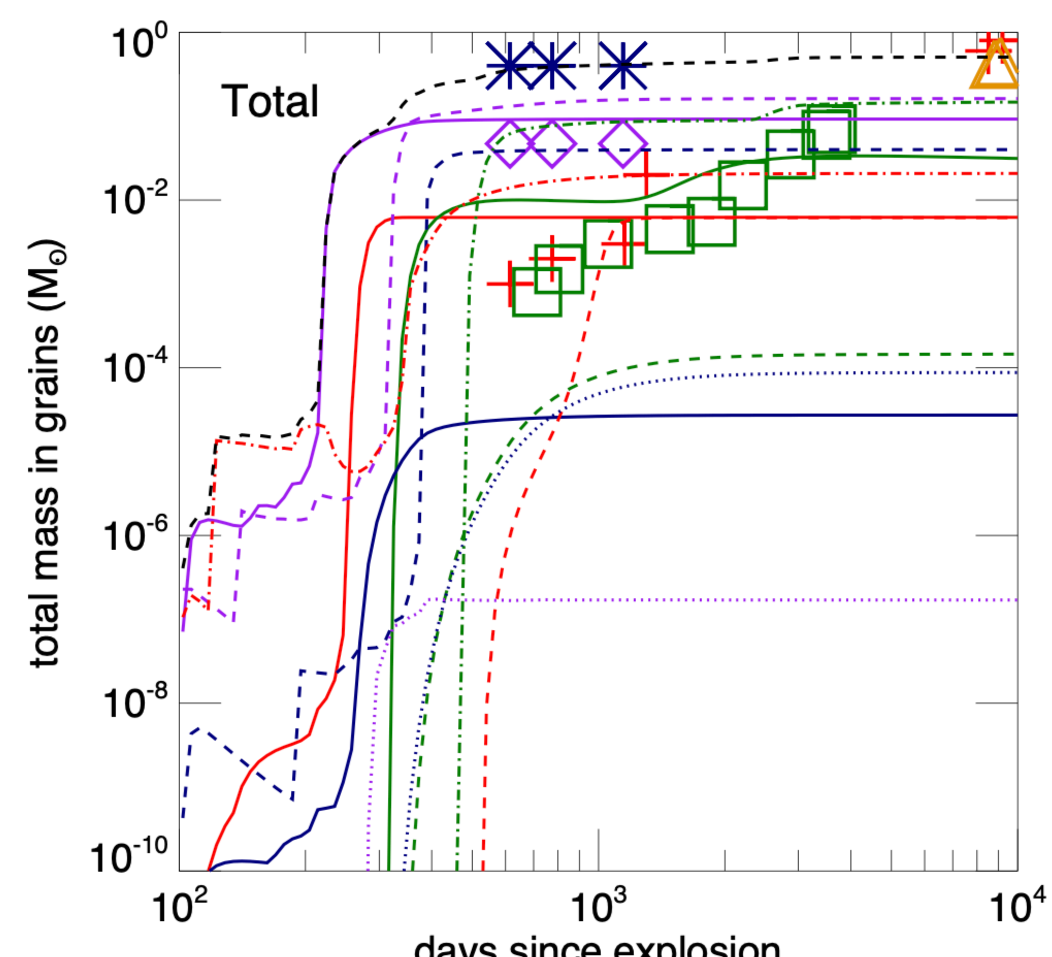
Gradual growth in SN dust mass over (30 years) time



Niculescu-Duvaz, Barlow, et al. 2022

However: SN dust formation modelling suggests all dust forms within first ~1000 days

Sluder et al. 2018



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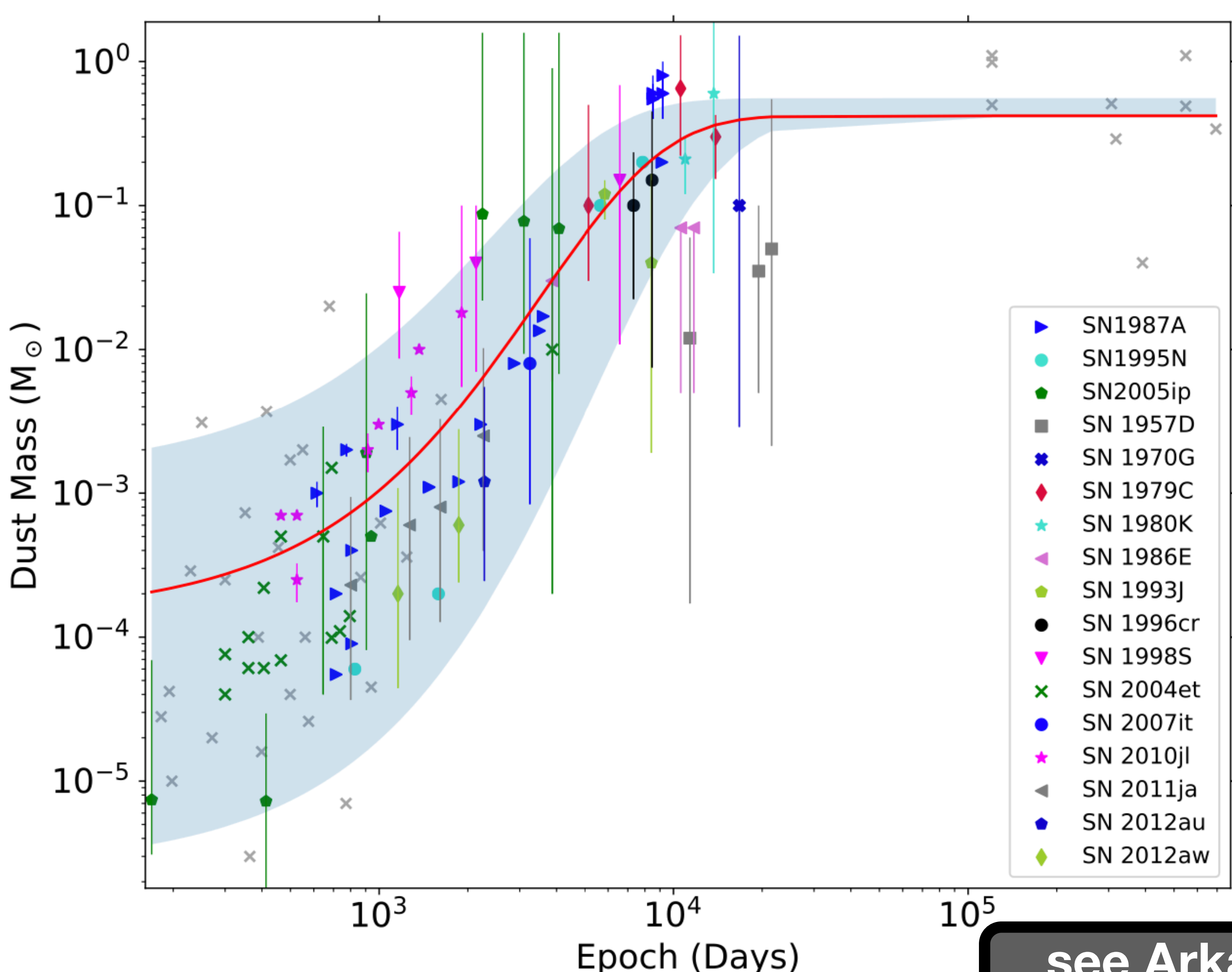

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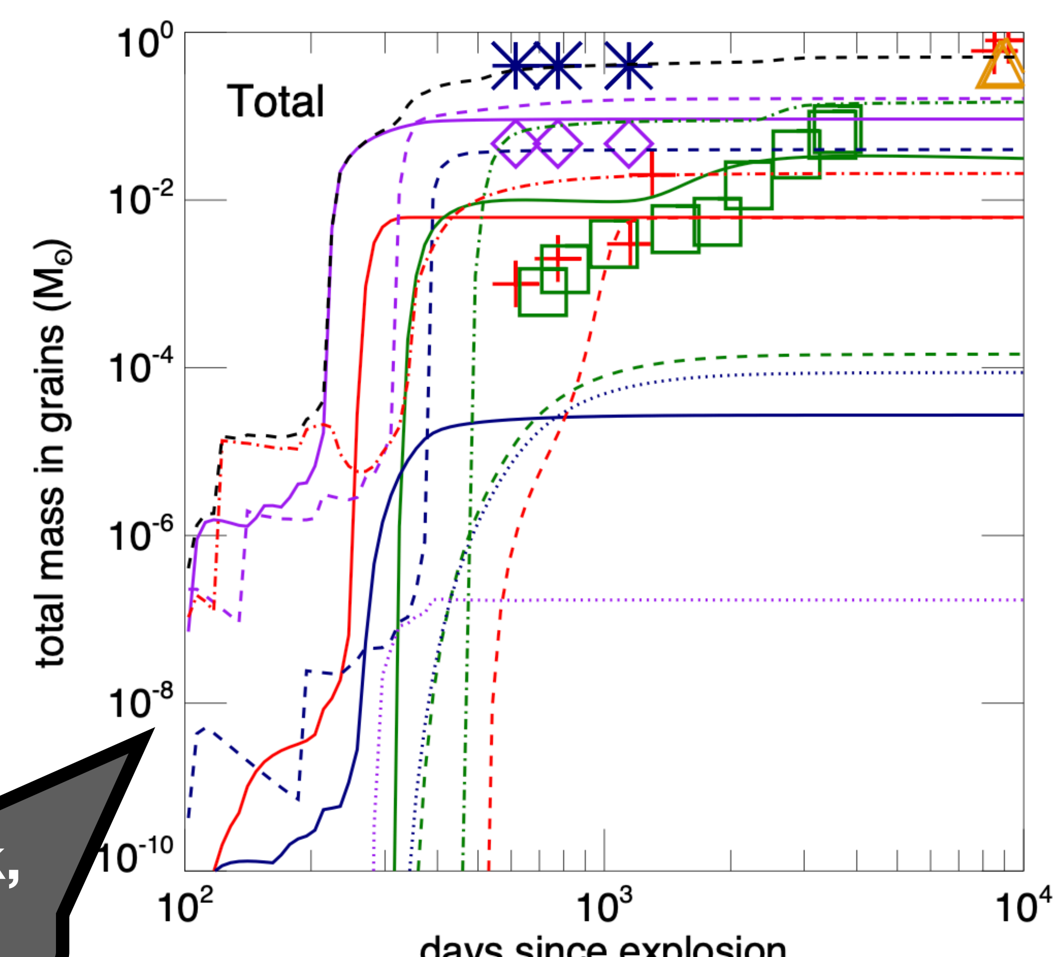
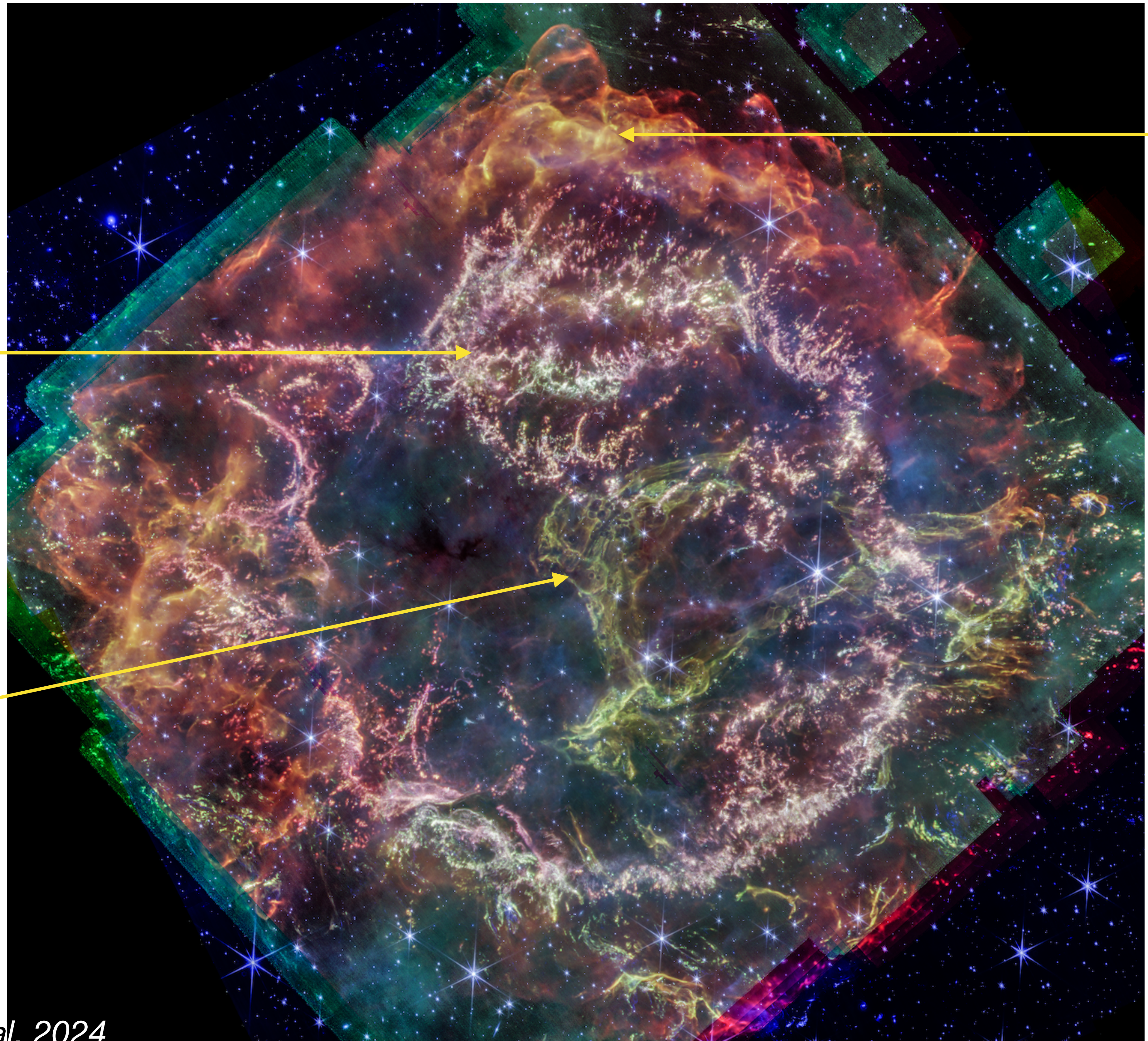


see Arka's talk, Poster S6.9

Cassiopeia A with JWST



Circumstellar material shocked by the SN blast wave

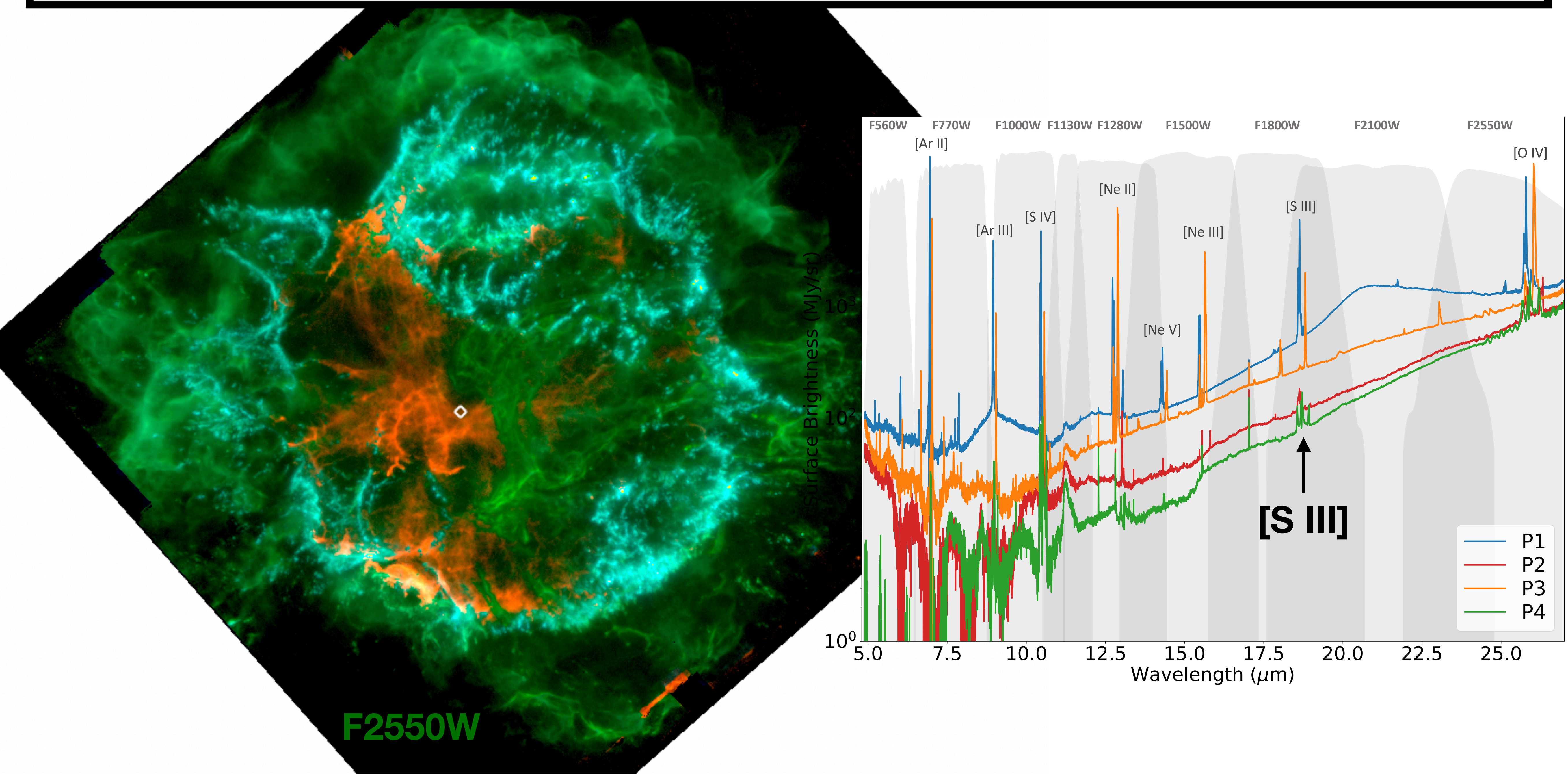
Processing of SN ejecta in the reverse shock

Newly identified “green monster” structure: unclear origin?

Milisavljevic et al. 2024

Cassiopeia A with JWST

Line-free emission at 21micron (cyan) + O-rich ejecta /cold dust (red)



Milisavljevic et al. 2024; Temim et al. in prep;

Cassiopeia A with JWST

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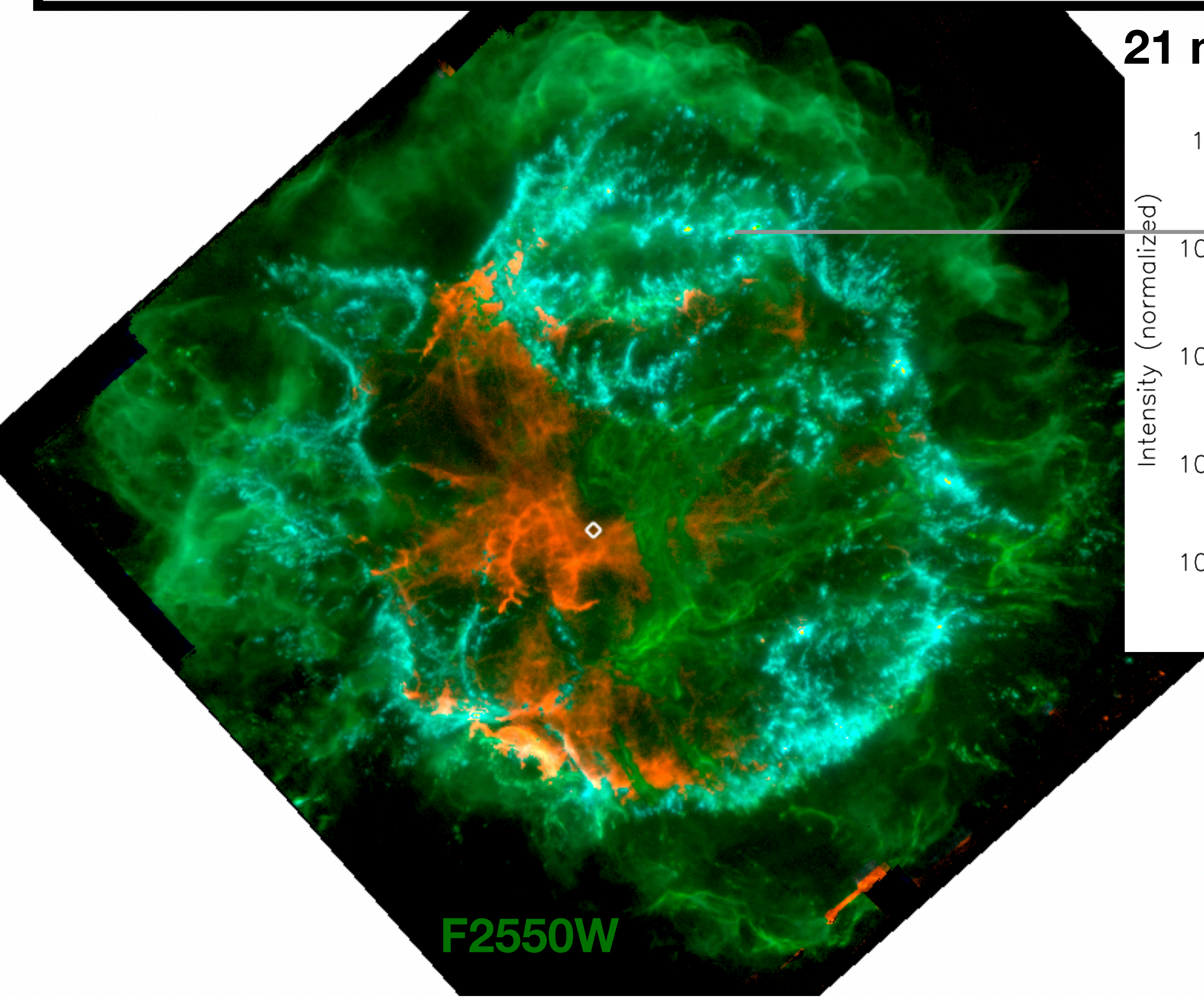
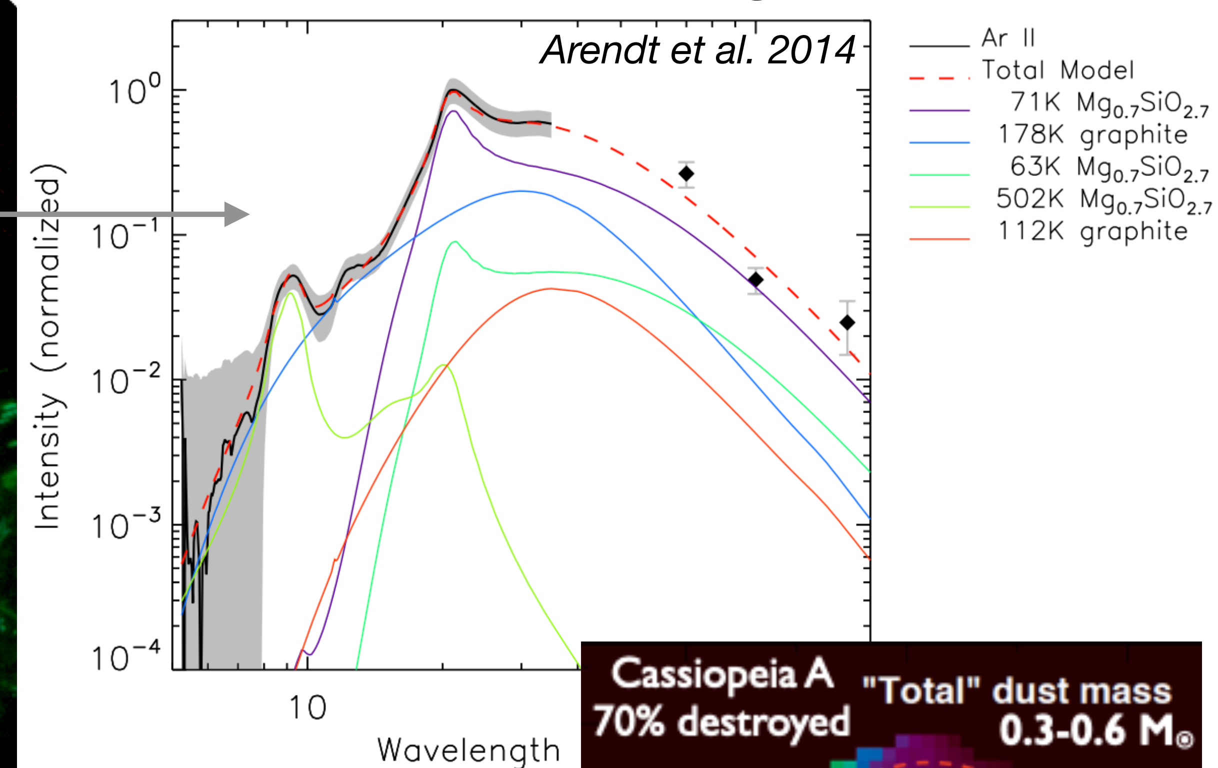
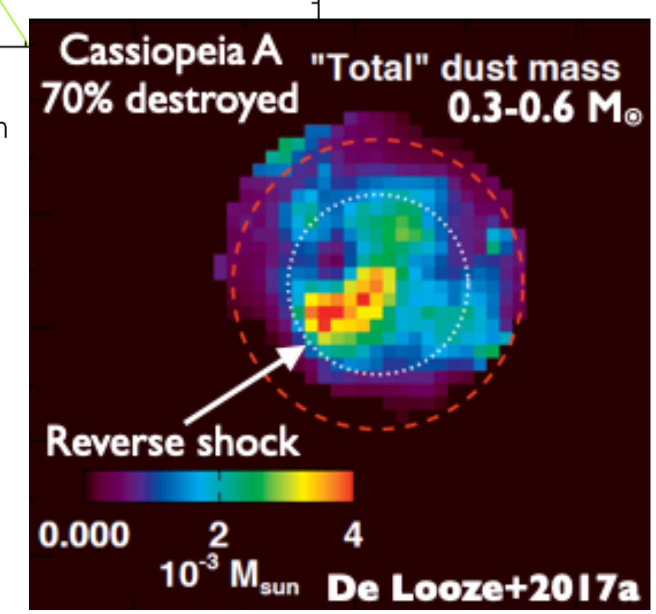


21 micron-peak dust ($Mg_{0.7}SiO_{2.7}$)





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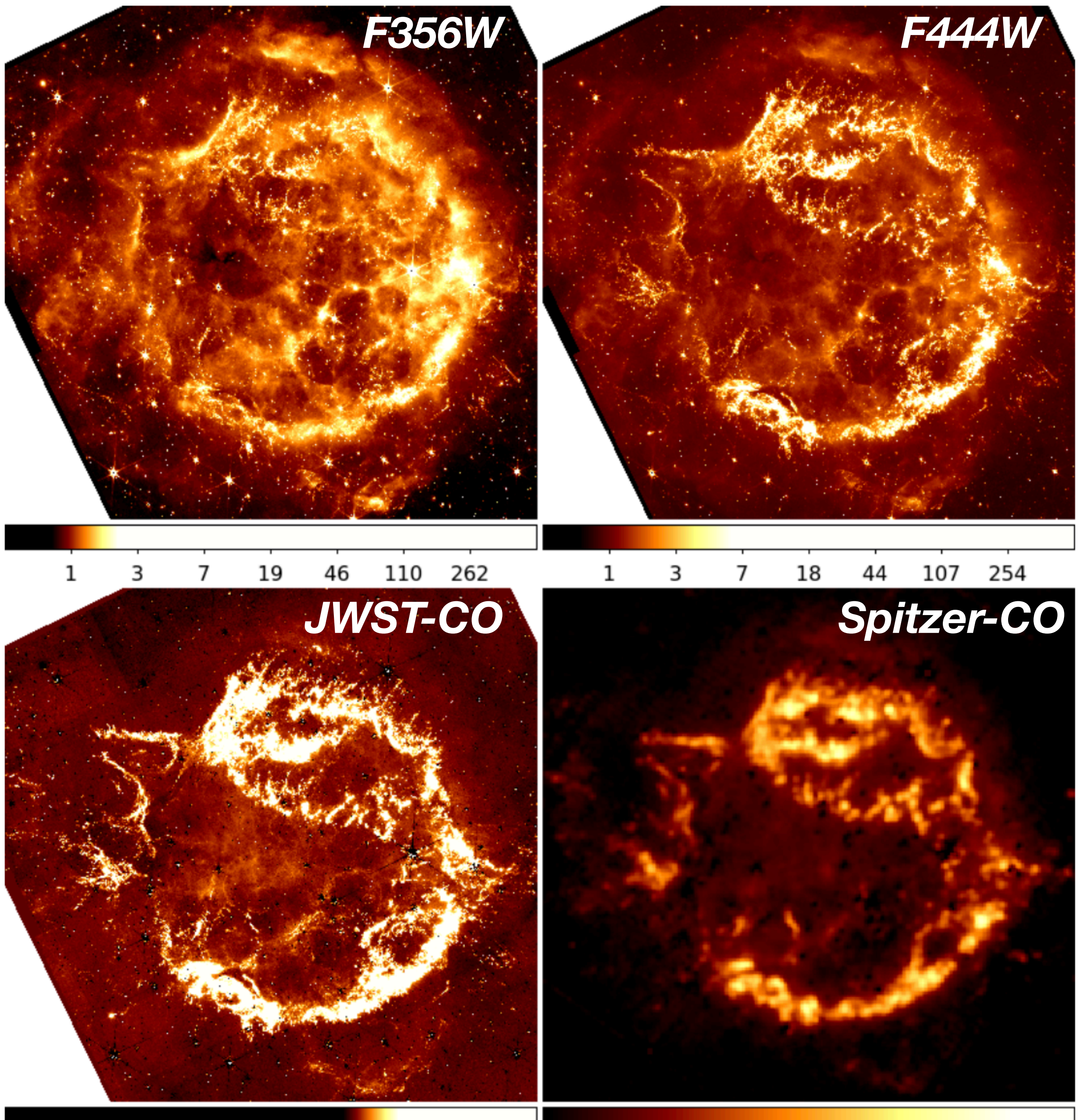
Cassiopeia A with JWST

CO 4.4 micron fundamental line: CO is reformed in post-shock gas



JWST-NIRCAM images

Rho et al. 2024

Cassiopeia A with JWST

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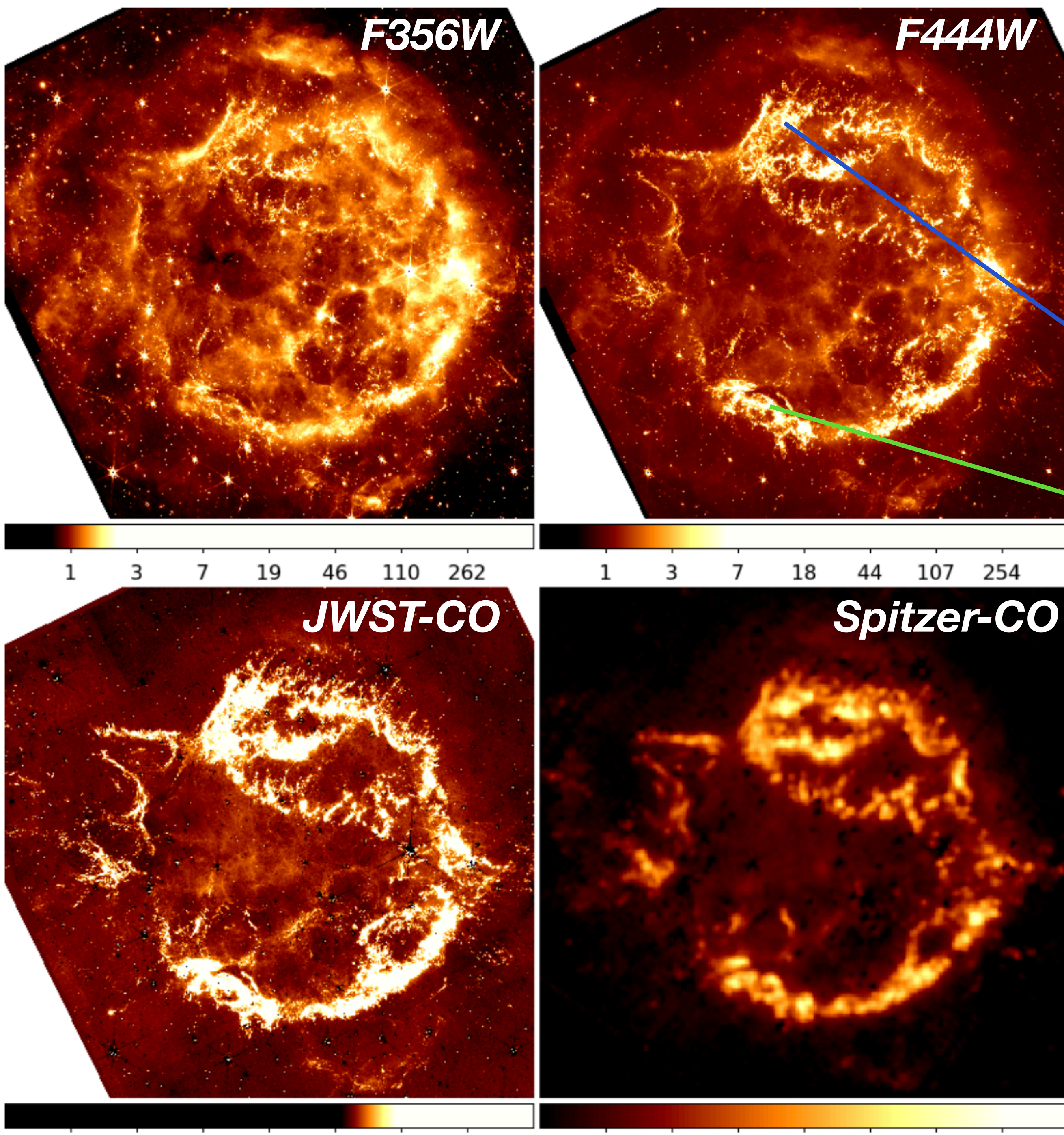

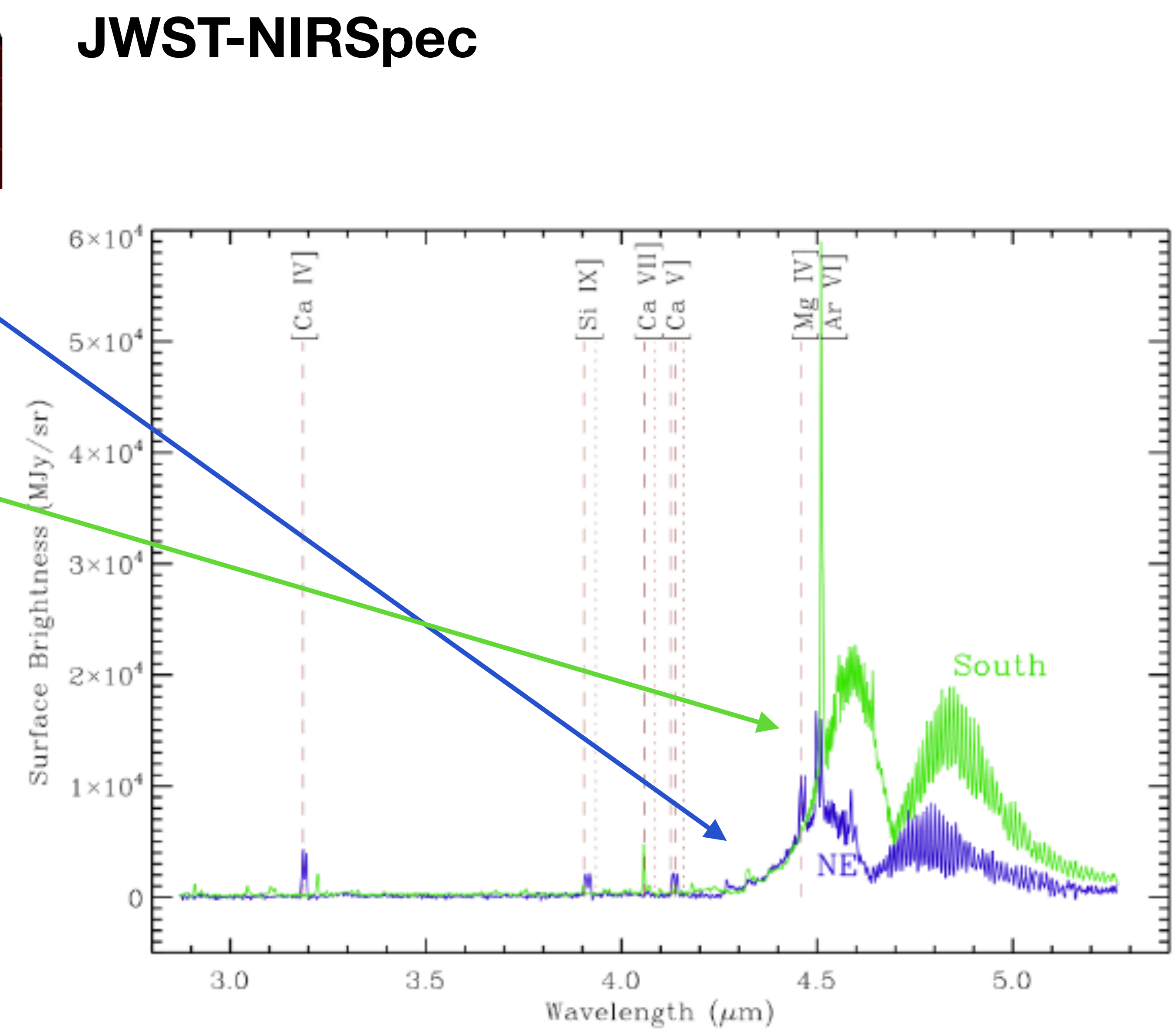

Rho et al. 2024

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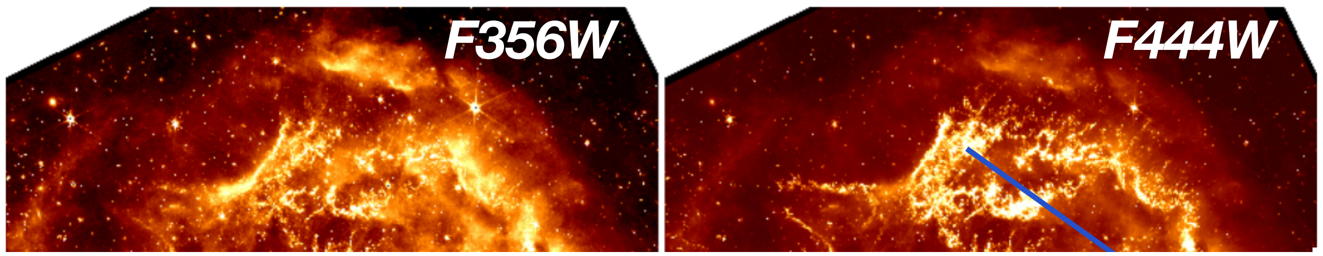
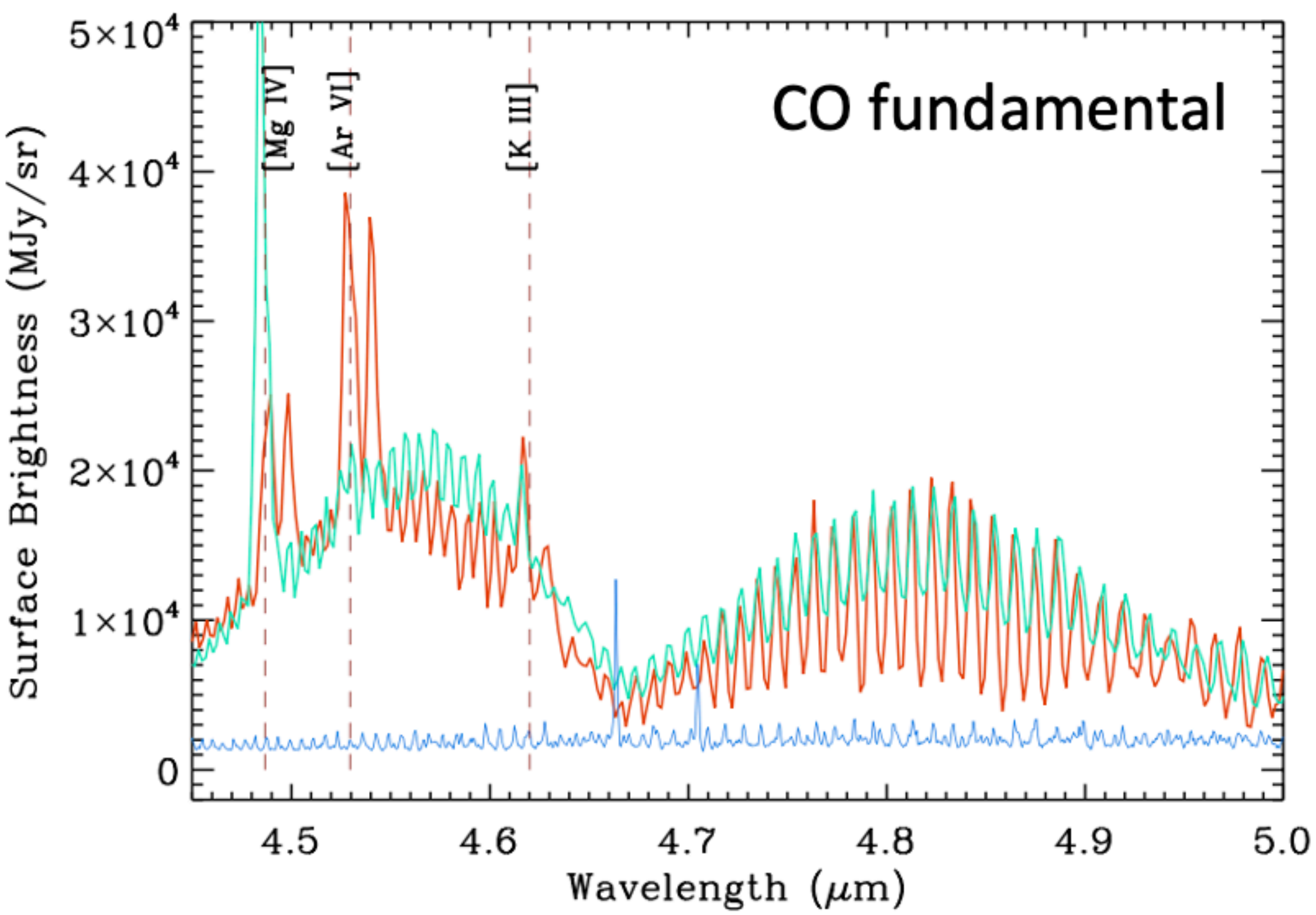
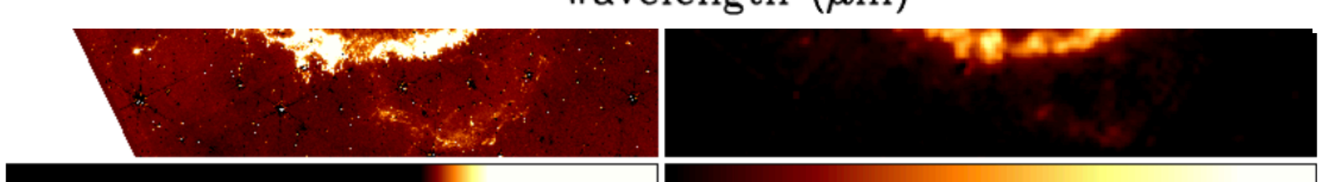
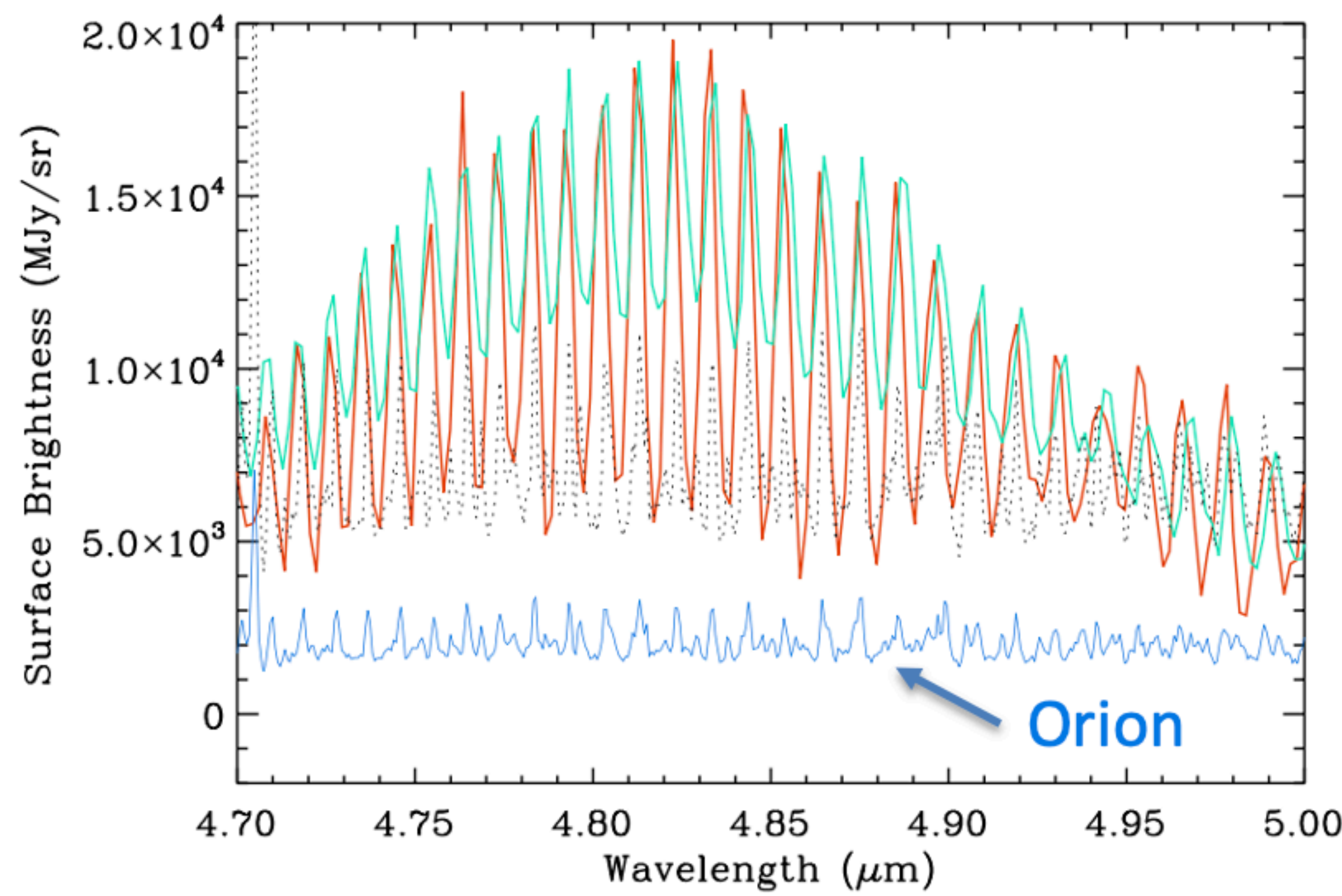


Line width suggests CO comes from post-shock gas







Rho et al. 2024

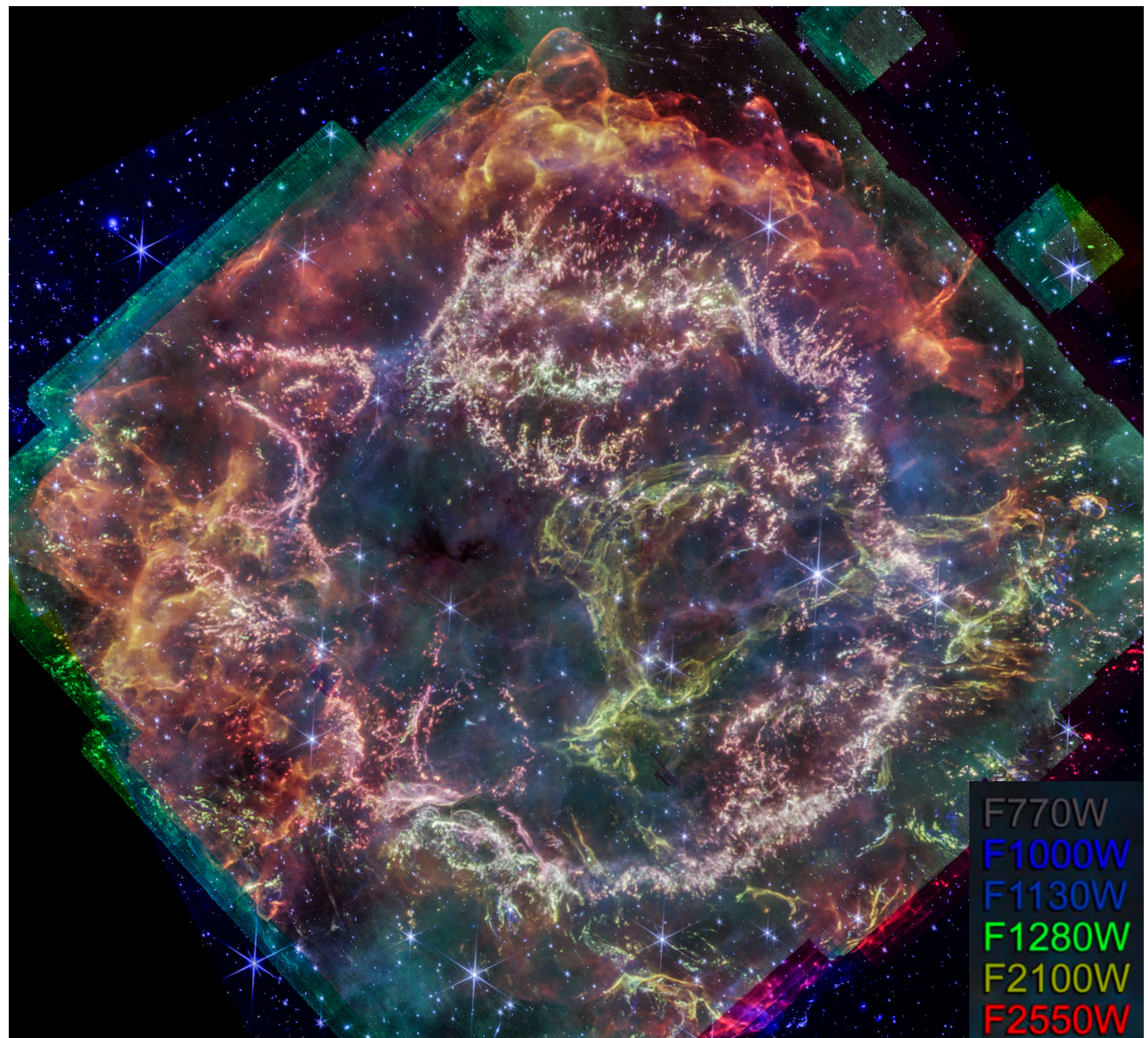
Cassiopeia A with JWST

Zooming in on the "green monster"

See also Milisavljevic's and Orlando's talks and poster 4.1

What is the nature of the Green Monster?

De Looze et al. in prep.



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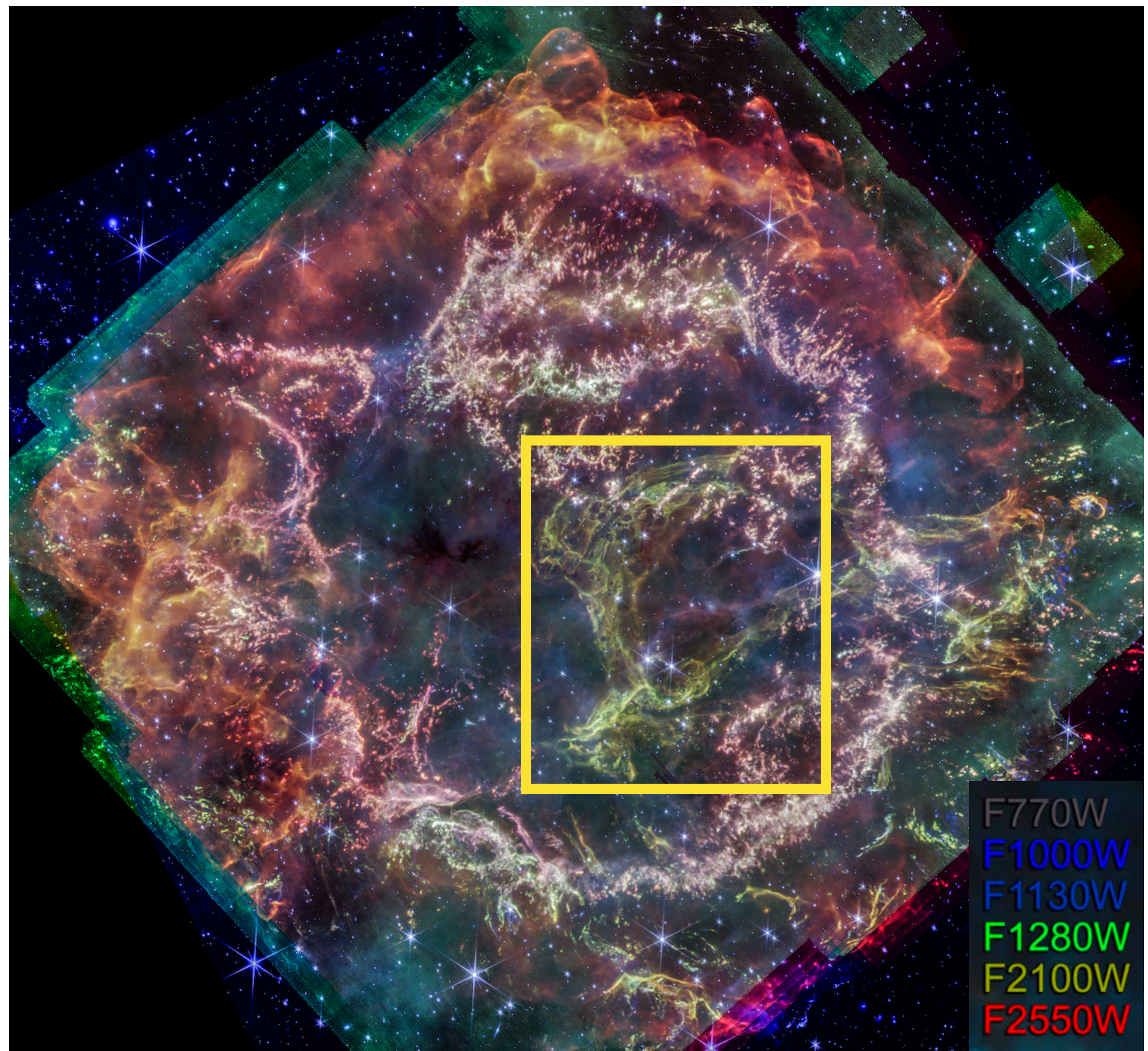
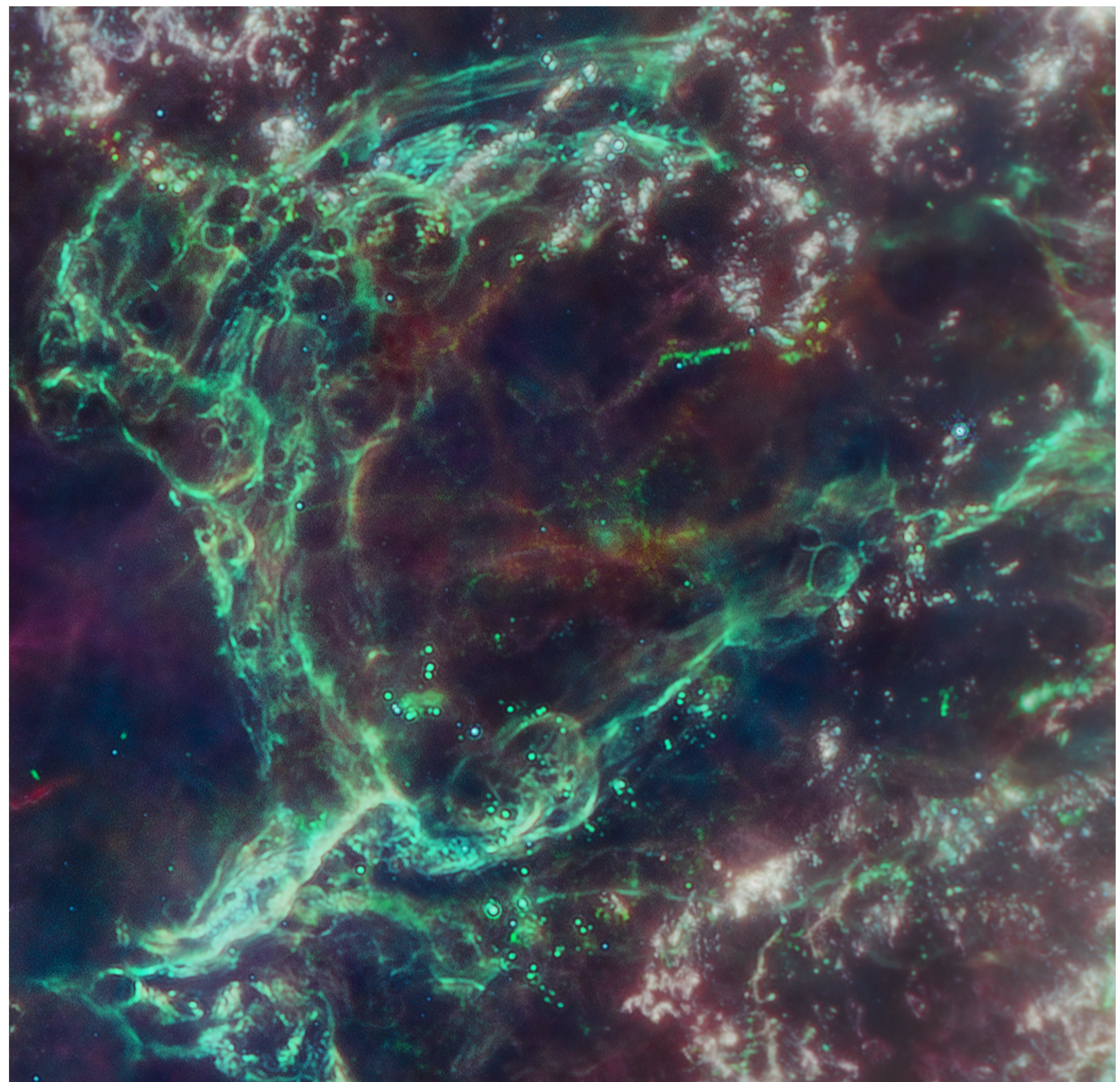


De Looze et al. in prep.

Cassiopeia A with JWST

The nature of the "green monster"



Look at all those holes with rings around!

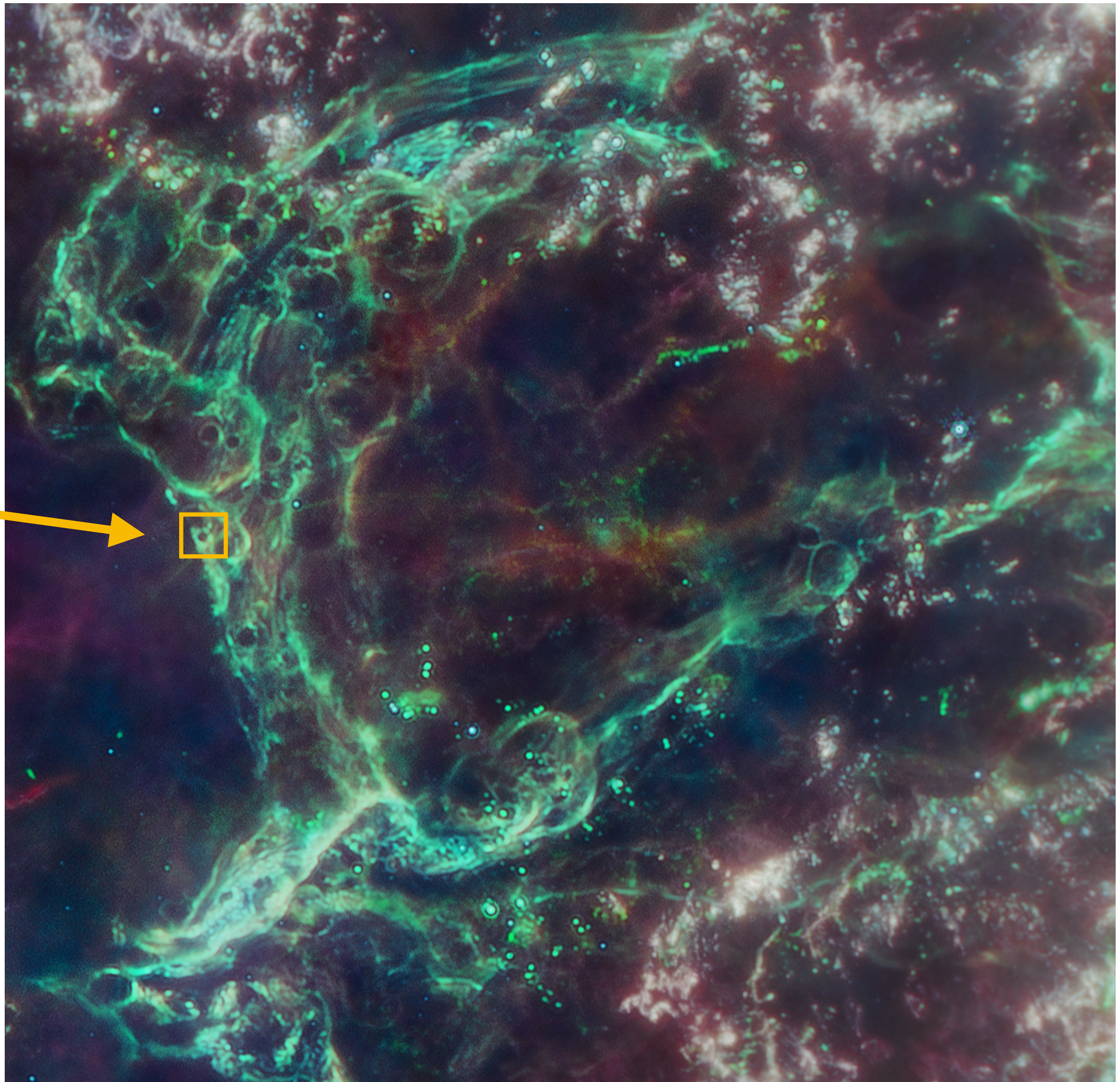
De Looze et al. in prep.

Cassiopeia A with JWST

The nature of the "green monster"

See also Orlando's talk and poster 4.1

Insights from MRS observations

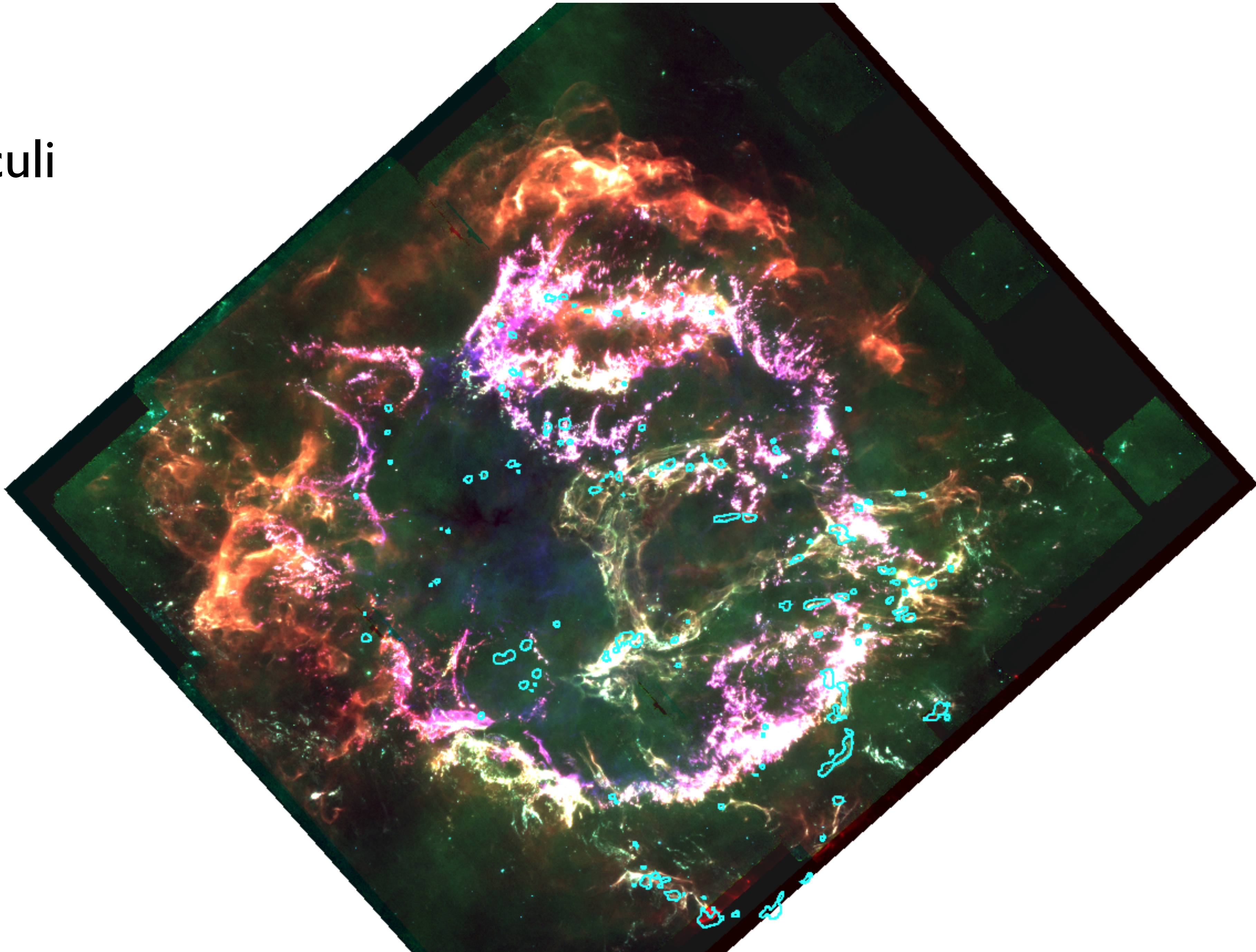


De Looze et al. in prep.

Cassiopeia A with JWST

The nature of the "green monster"

* Overlap with location of quasi-stationary flocculi (QSFs)

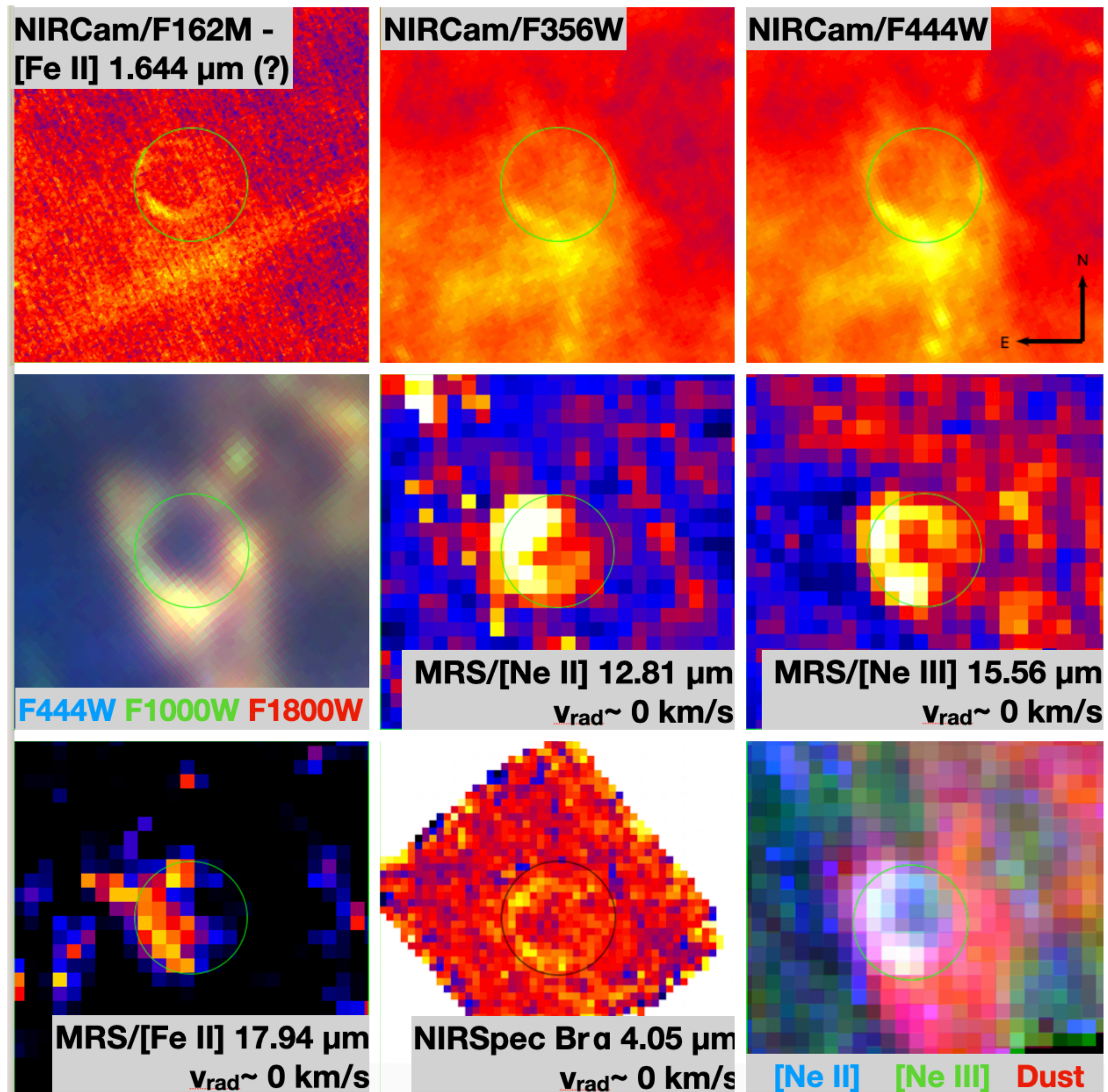


De Looze et al. in prep.

Cassiopeia A with JWST

The nature of the "green monster"

* Overlap with location of quasi-stationary flocculi (QSFs)
* Detection of Ne, Fe and H (Br α) emission



De Looze et al. in prep.

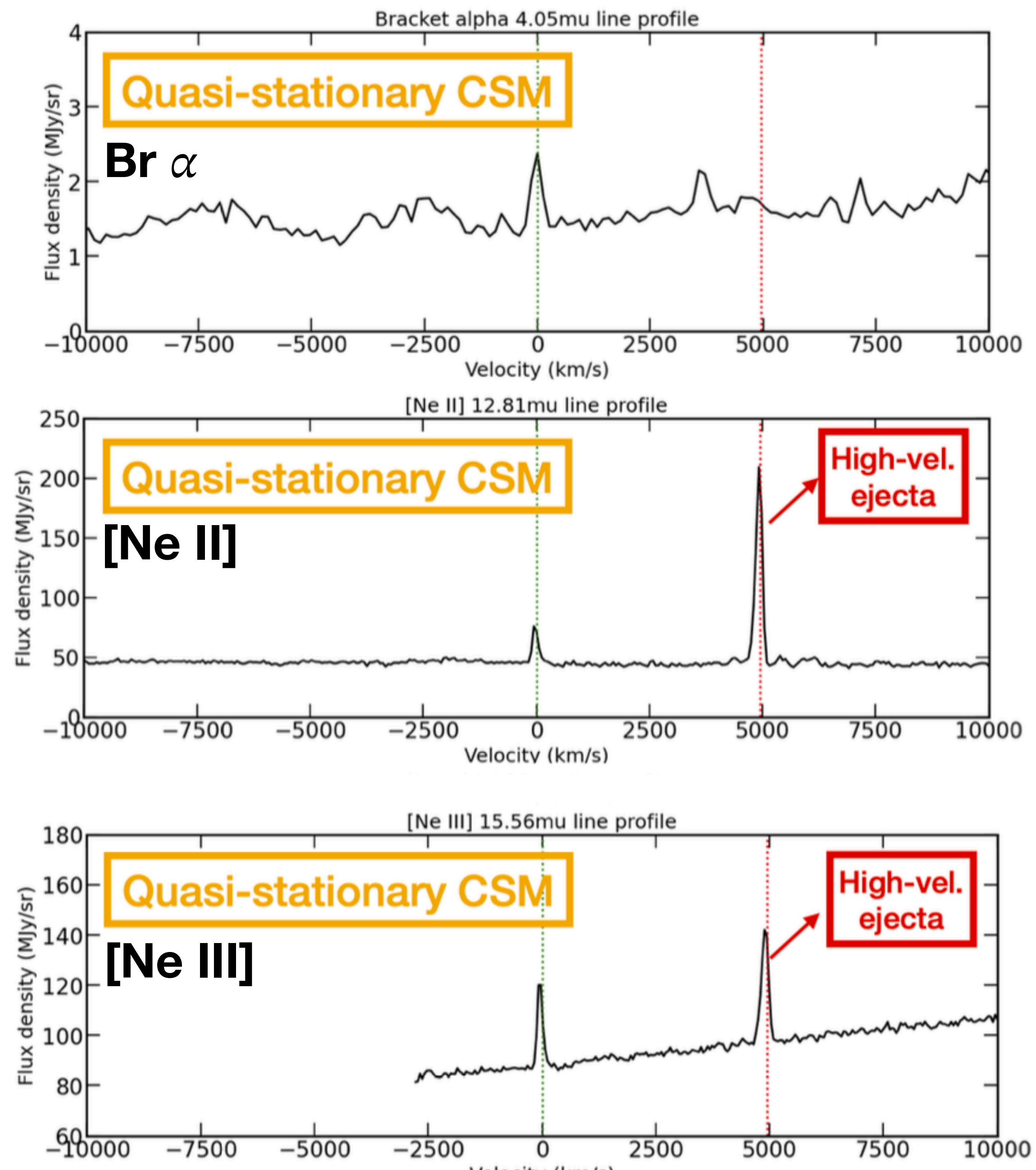
Cassiopeia A with JWST

The nature of the "green monster"

* Overlap with location of quasi-stationary flocculi (QSFs)

* Detection of Ne, Fe and H (Br α) emission

* Low velocities (v_{rad} ~ 0 km/s)



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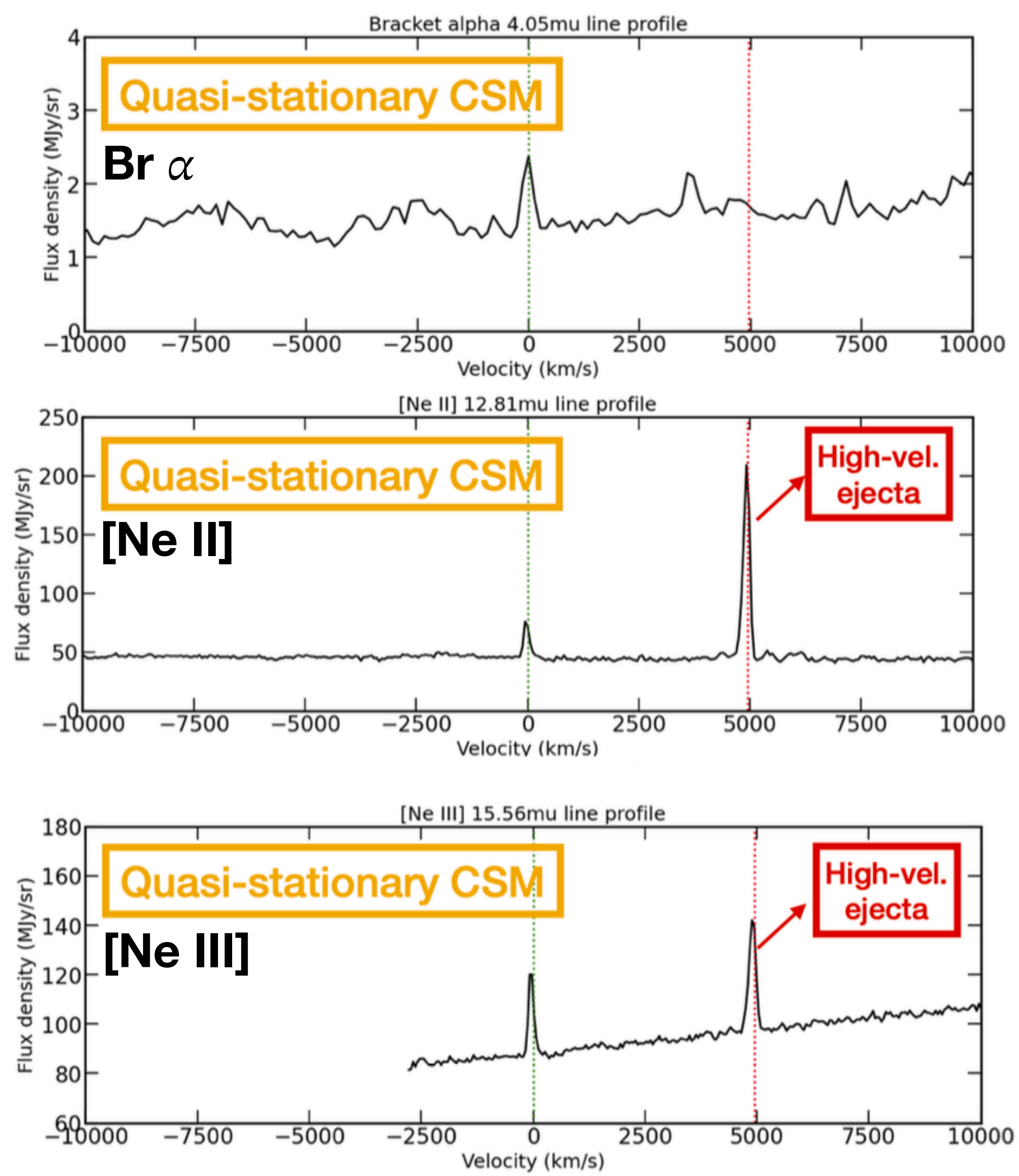
Cassiopeia A with JWST

The nature of the "green monster"

* Overlap with location of quasi-stationary flocculi (QSFs)
* Detection of Ne, Fe and H (Br α) emission
* Low velocities (v_{rad} ~ 0 km/s)

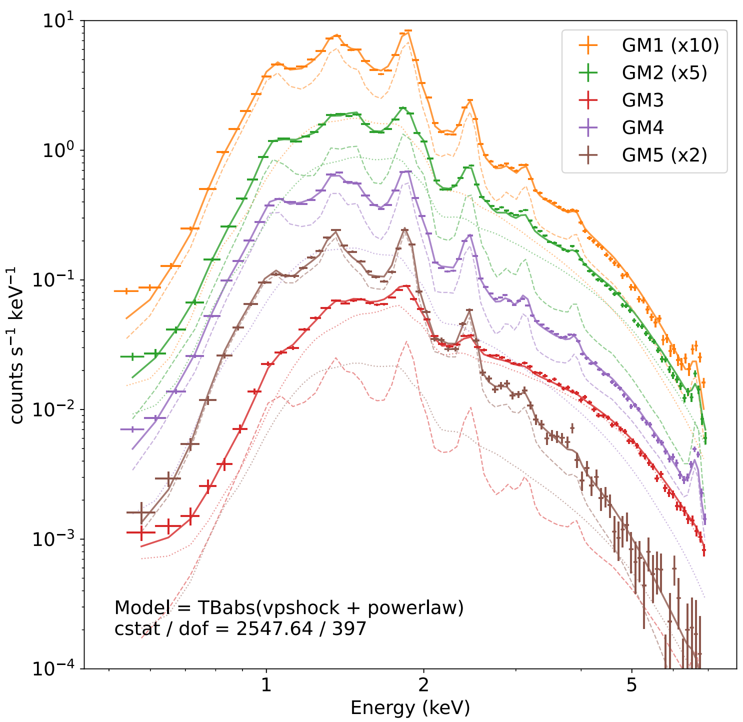
1. Green Monster is CSM
2. JWST = dominated by dust
3. Forward shock impact

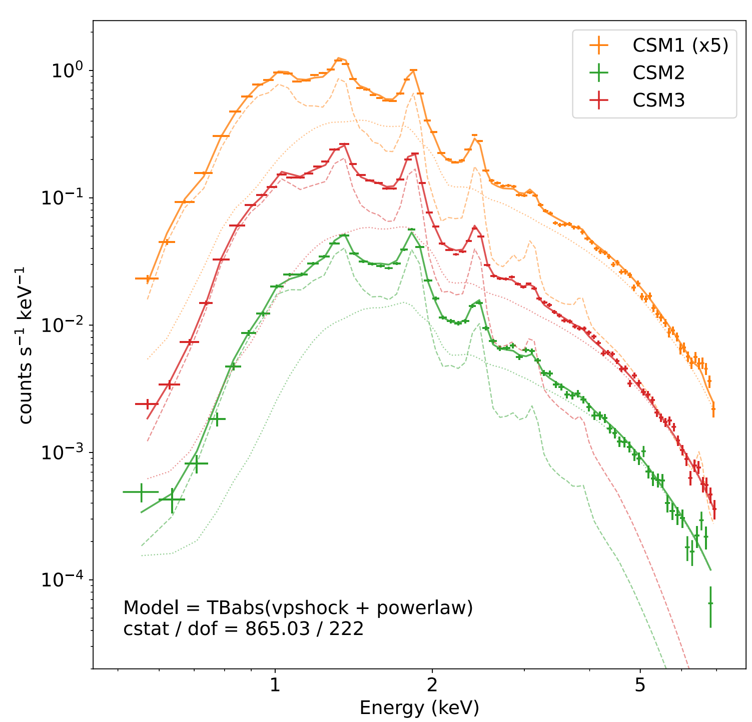


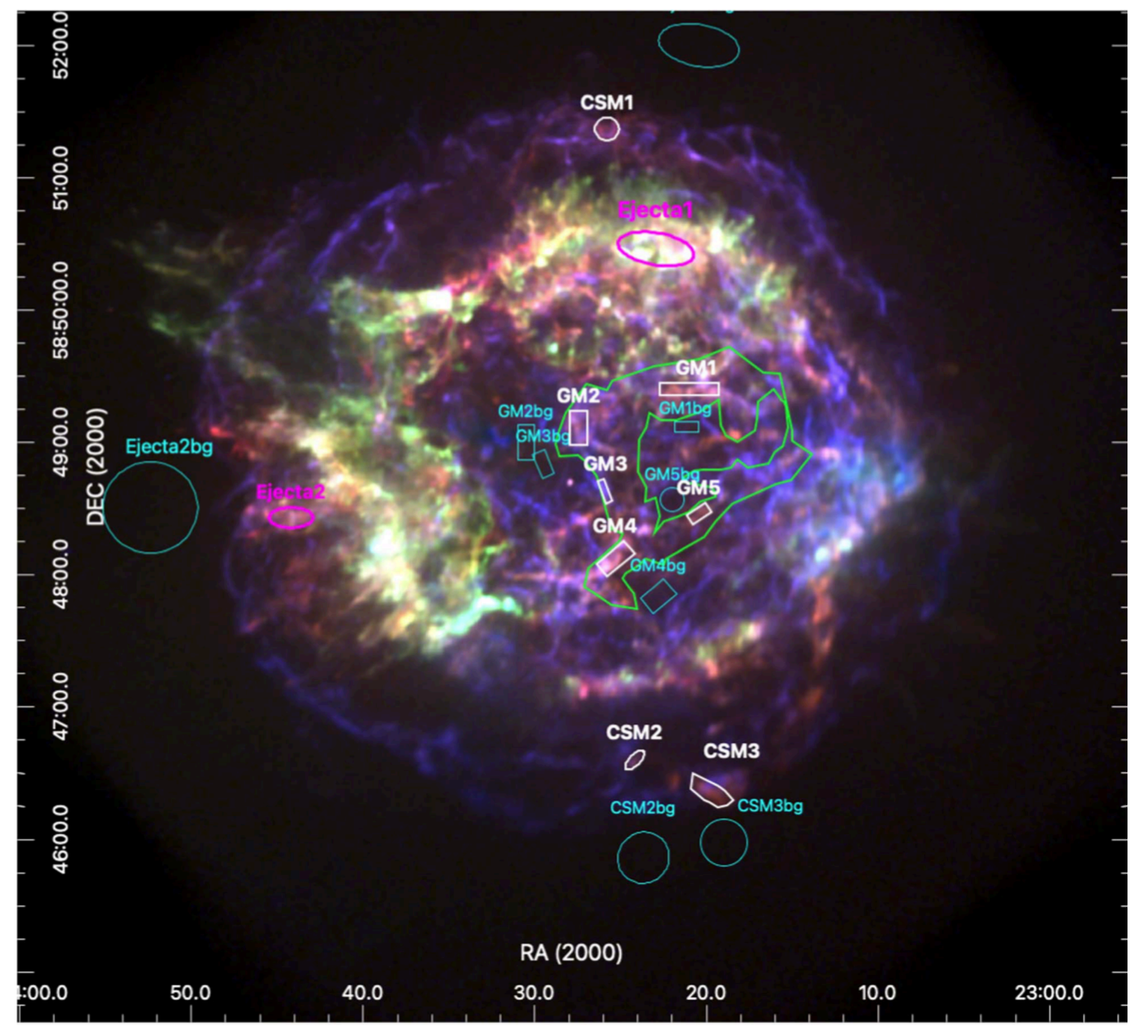
De Looze et al. in prep.

Cassiopeia A with JWST

Location of the "green monster" ?





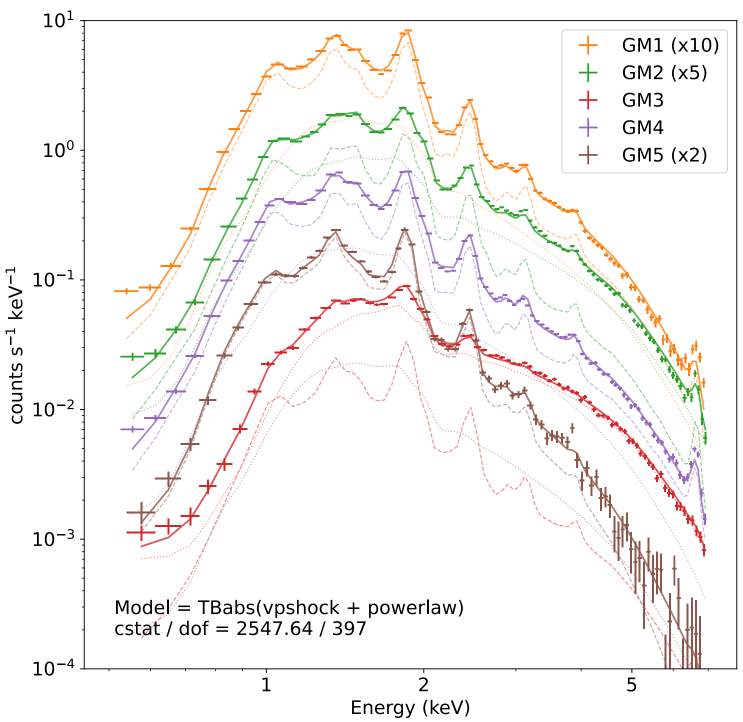


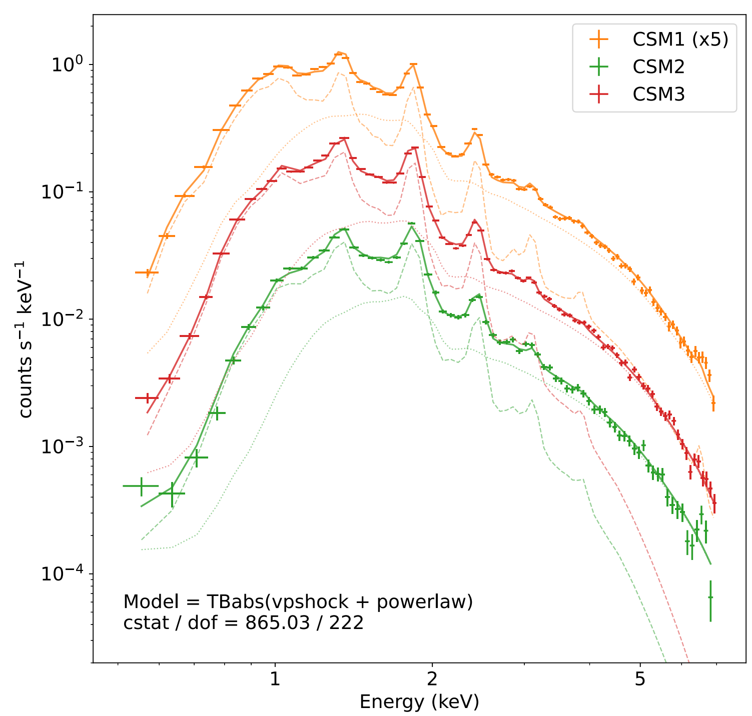
* X-ray emission is blue-shifted (-2300 km/s)
  ==> v_{shock} = 3500 km/s (relatively low)
  ==> GM in front of Cas A!
  ==> dense CSM (pre-shock n=12 cm^{-3})

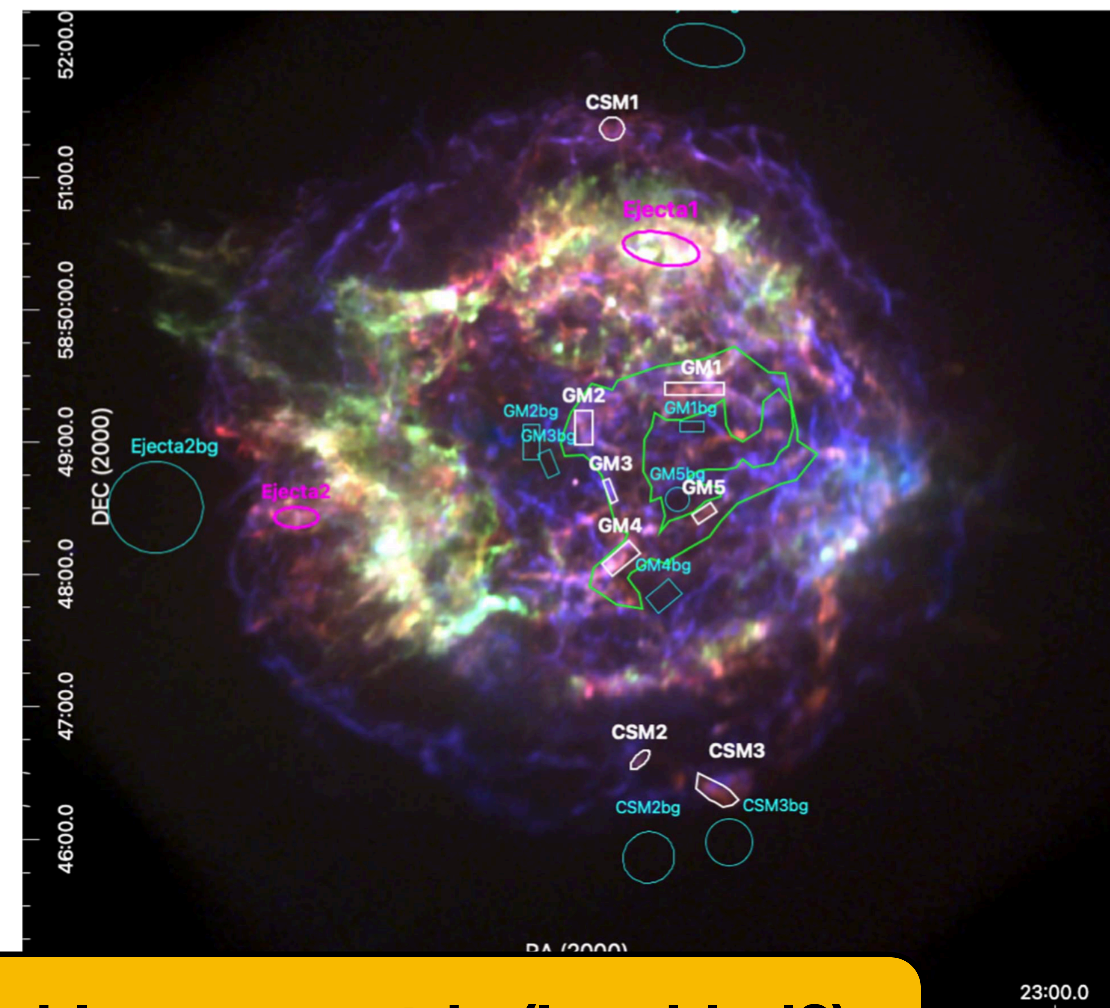
Vink et al. 2024

Cassiopeia A with JWST

Location of the “green monster” ?







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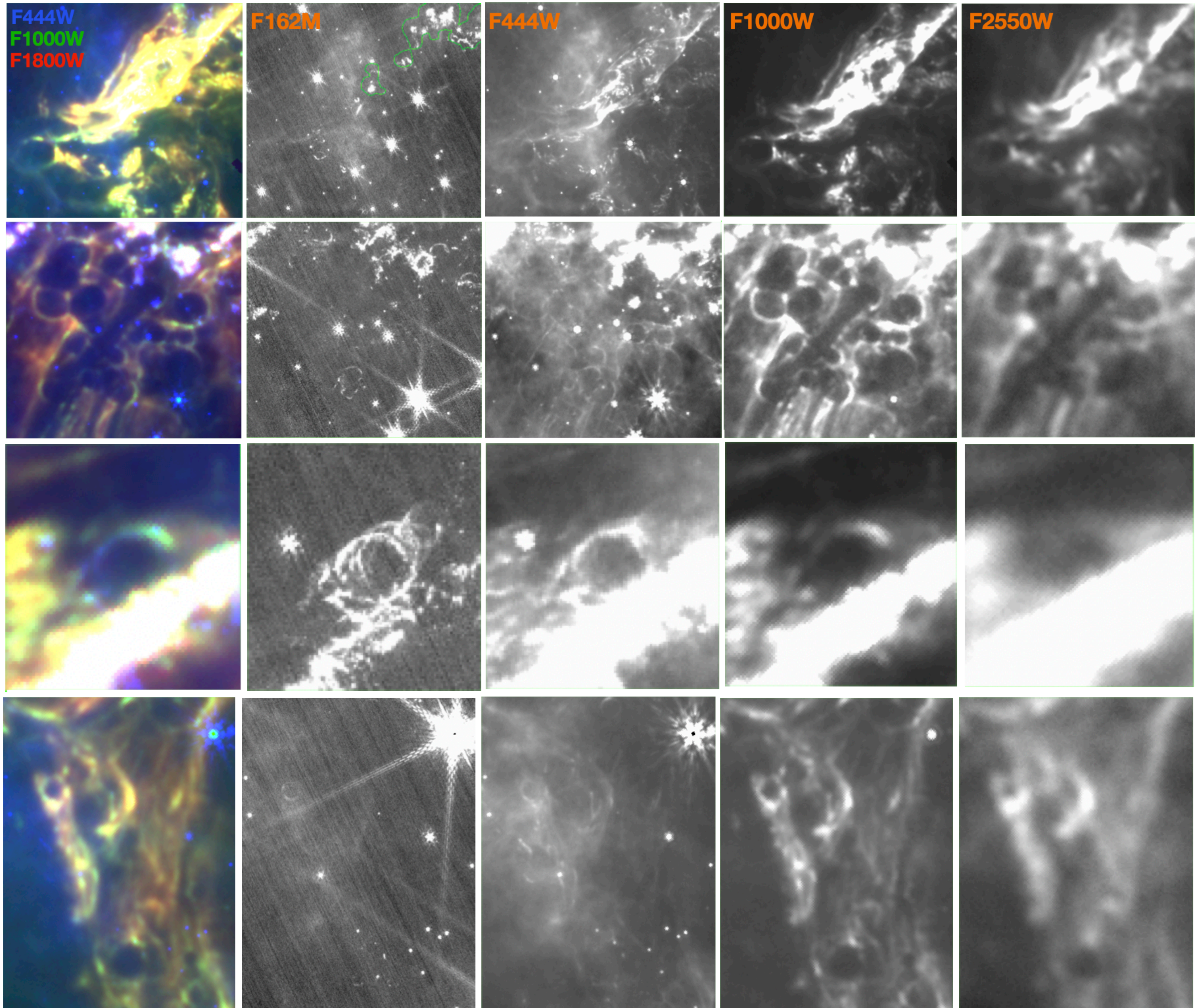
*** Highly asymmetric (lopsided?) dense mass loss phase**
*** Strong clue for binary scenario?**

Vink et al. 2024



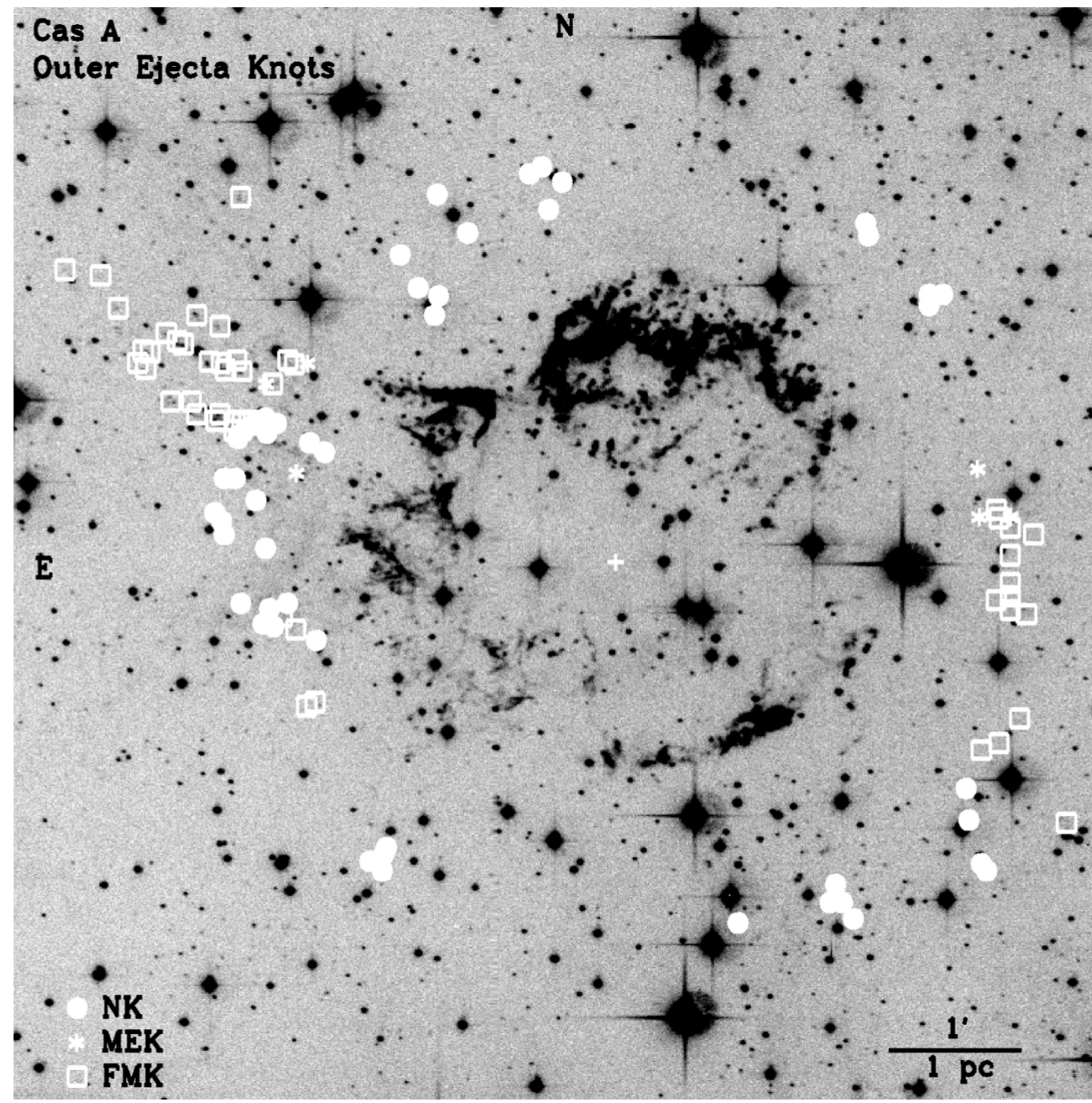
De Looze et al. in prep.

Cassiopeia A with JWST

How did holes in the Green Monster form?

Fesen et al. 2001

* Requires ejecta-CSM interaction!
* **<u>Option I.</u>** High-velocity ejecta knots (9000-10000 km/s) piercing holes through the GM (45-75 years ago)



De Looze et al. in prep.

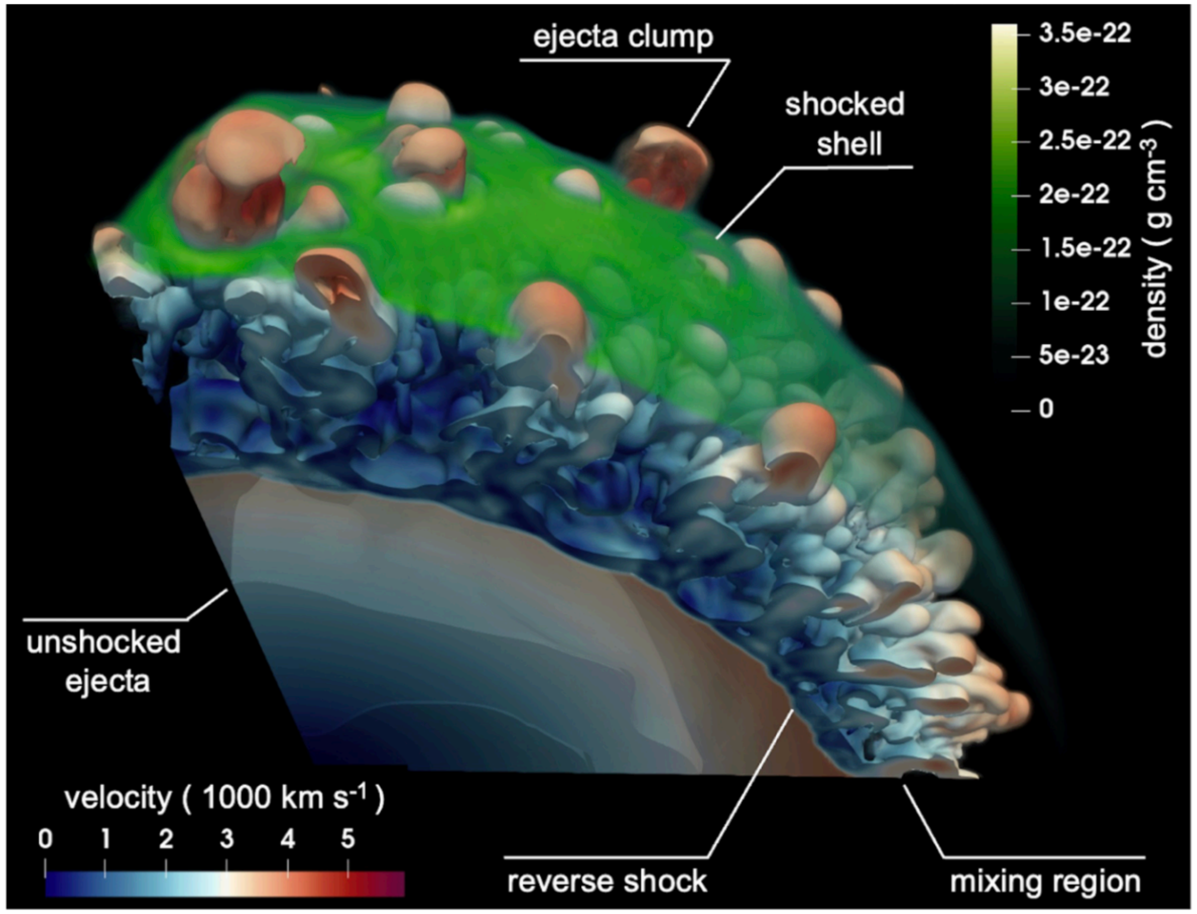
Cassiopeia A with JWST

How did holes in the Green Monster form?

* Requires ejecta-CSM interaction!
* **Option I.** High-velocity ejecta knots (9000-10000 km/s) piercing holes through the GM (45-75 years ago)
* **Option II.** After forward shock impact, hydrodynamic instabilities create fingers of ejecta material extending to the shocked dense shell of CSM (Orlando et al. 2022)

See Orlando's talk

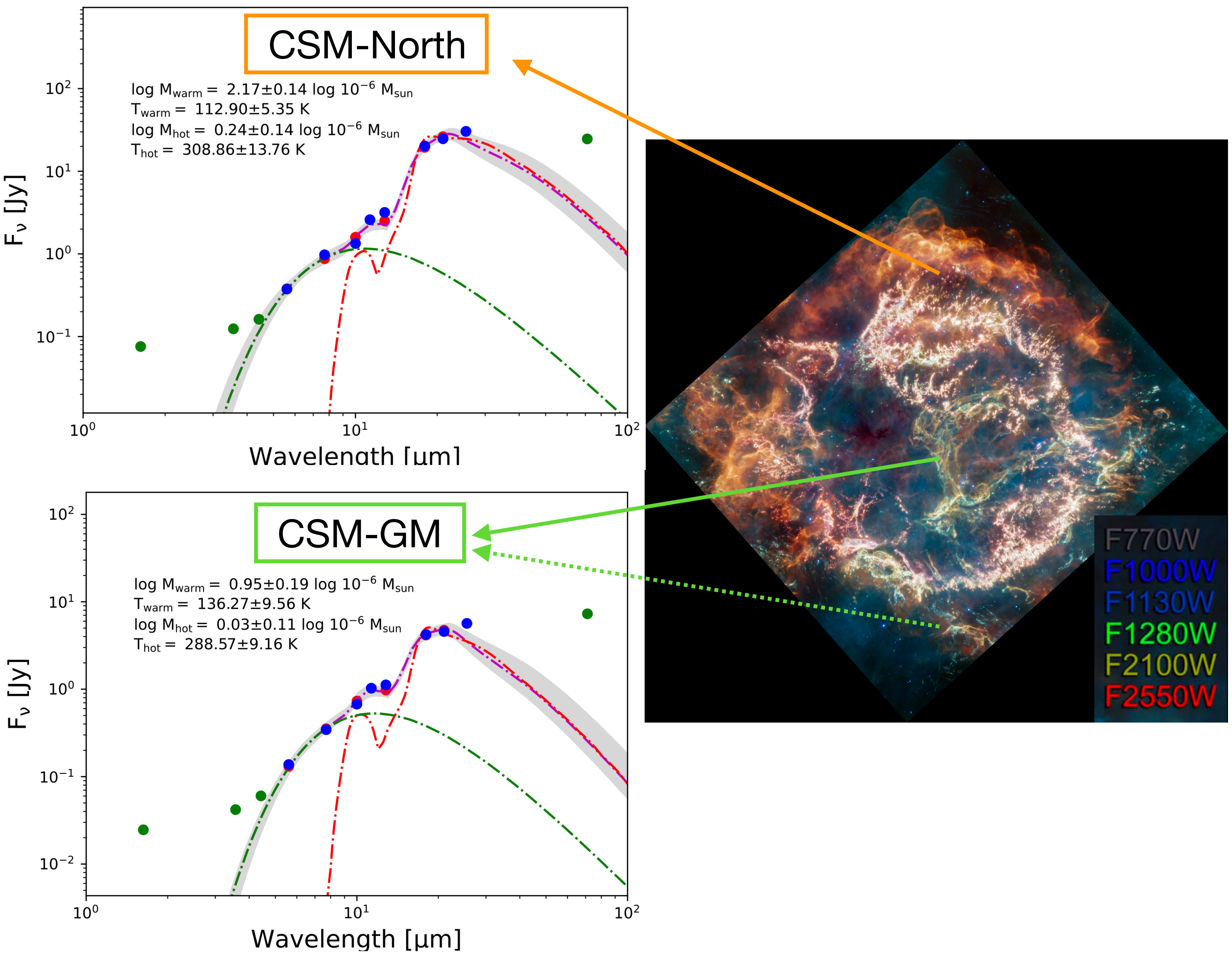
Orlando et al. 2022



De Looze et al. in prep.

Cassiopeia A with JWST

How does the Green Monster differ from other CSM phases?



- Both SEDs fitted well with silicate grains ($Mg_{2.4}SiO_{4.4}$, $MgFeSiO_4$)
- Differences due to grain sizes and/or heating mechanisms.
- If the GM consists of CNO processed material (like QSFs), then C/Sil formation should be inefficient.

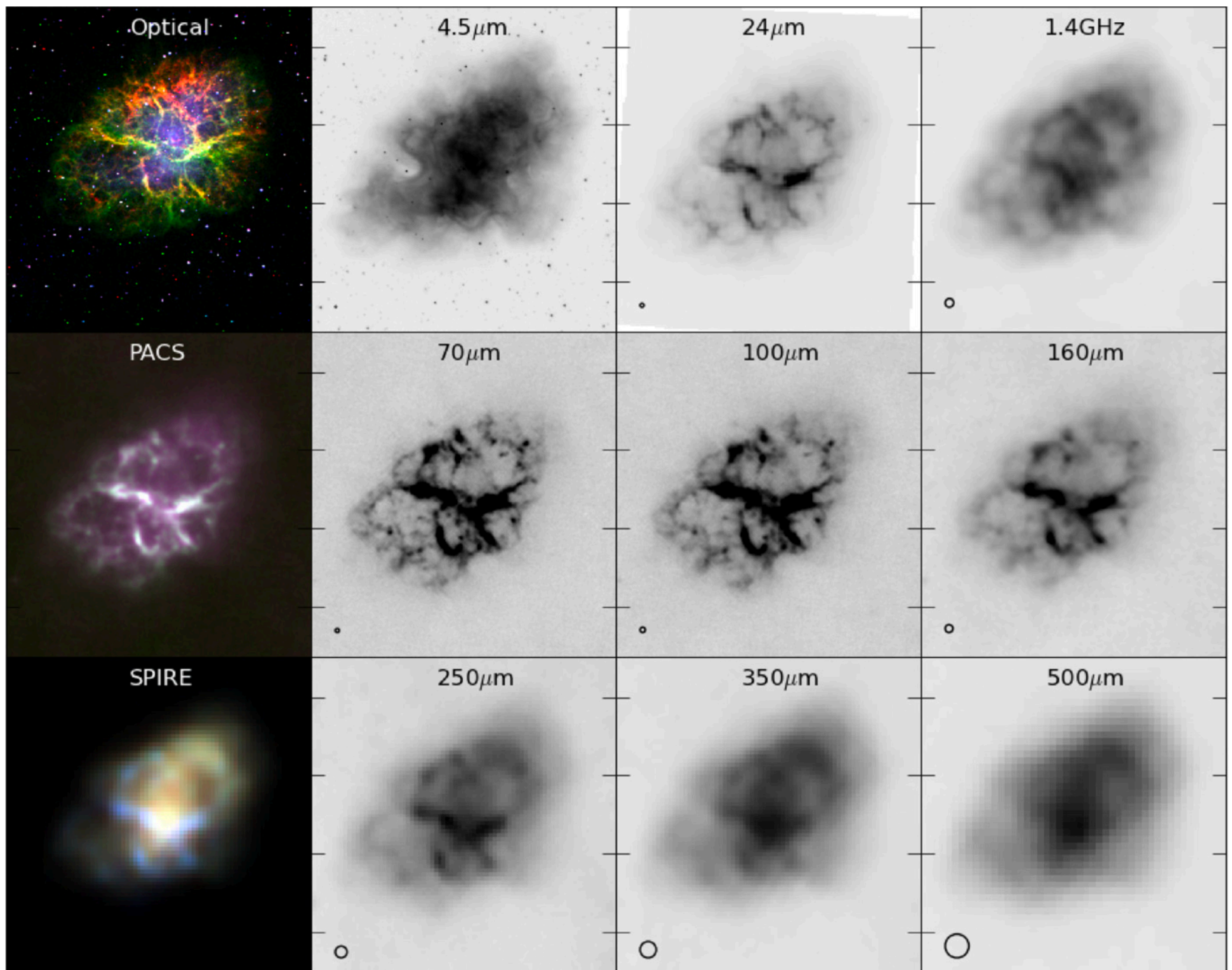
De Looze et al. in prep.

Dust formation in SN(R)s

Crab Nebula: dust masses from infrared dust emission (Herschel)

Crab Nebula = pulsar wind nebula

(electron capture SN?)

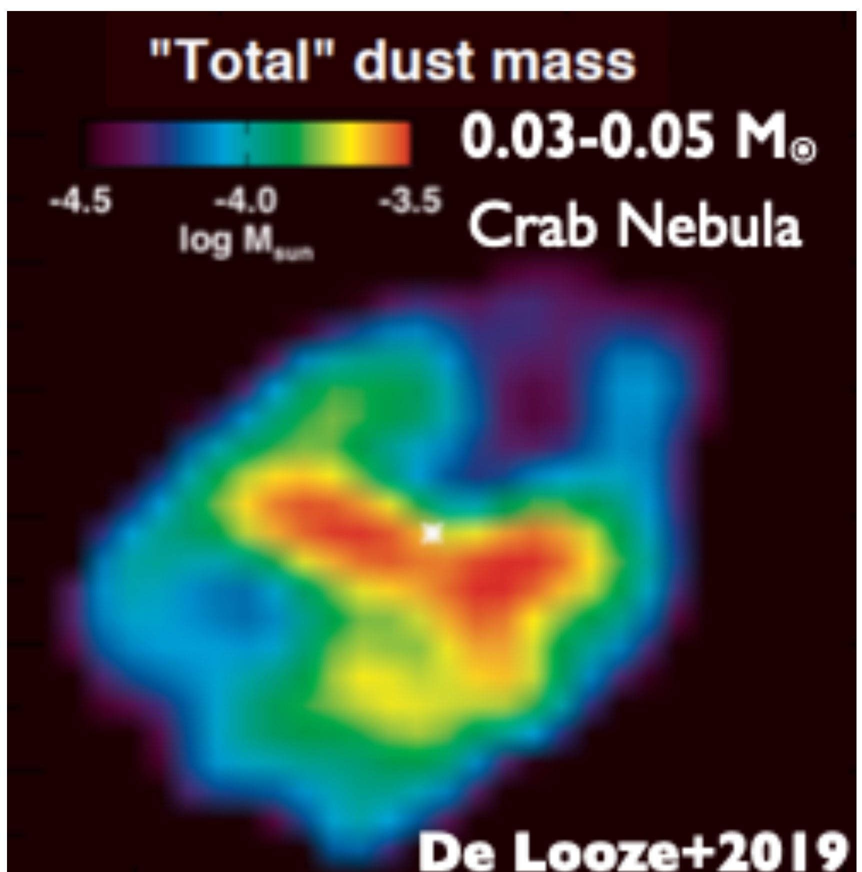


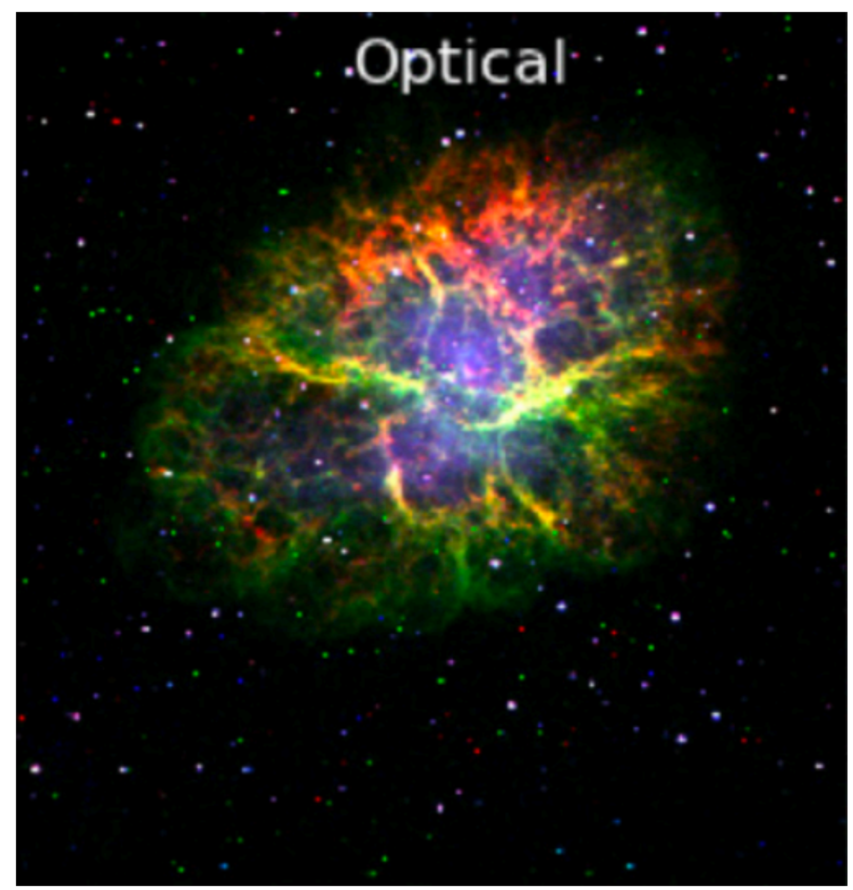
Dust formation in SN(R)s

Crab Nebula: dust masses from infrared dust emission (Herschel)

- **Dust mass in concentrated along dense filaments visible also in the optical**
- **Dust condensation efficiency of ~10% (similar to Cas A)**

Crab Nebula

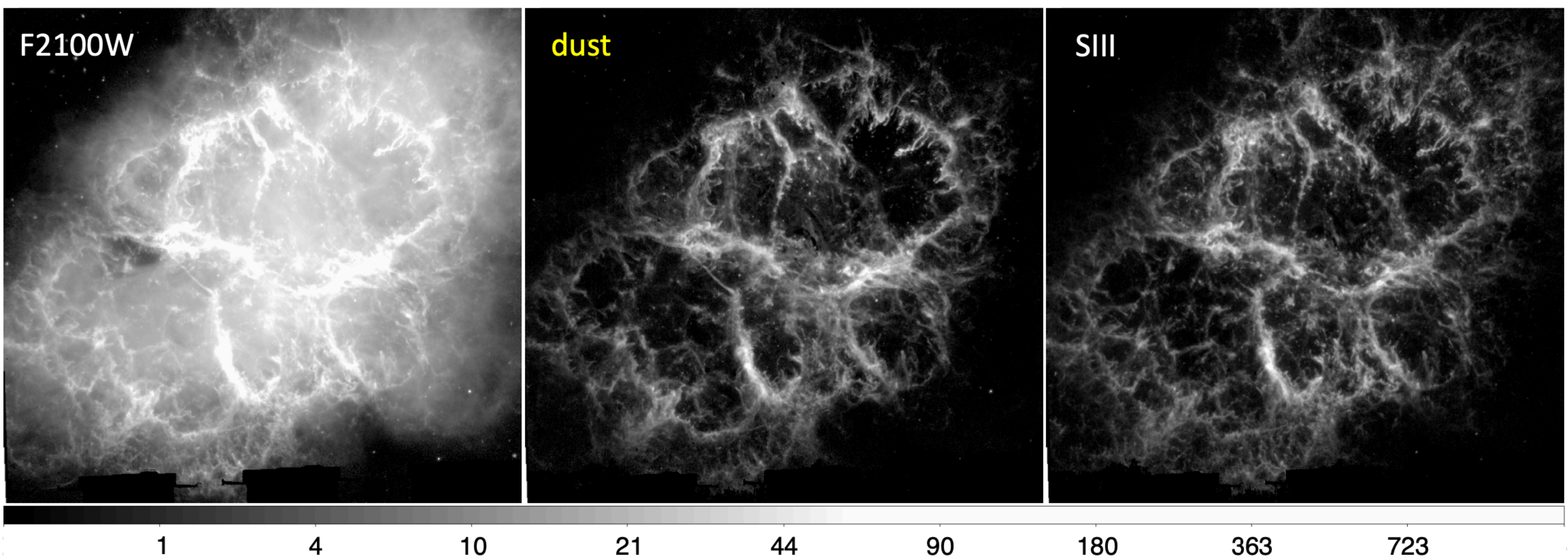




De Looze, Barlow, et al. 2019

Dust formation in SN(R)s

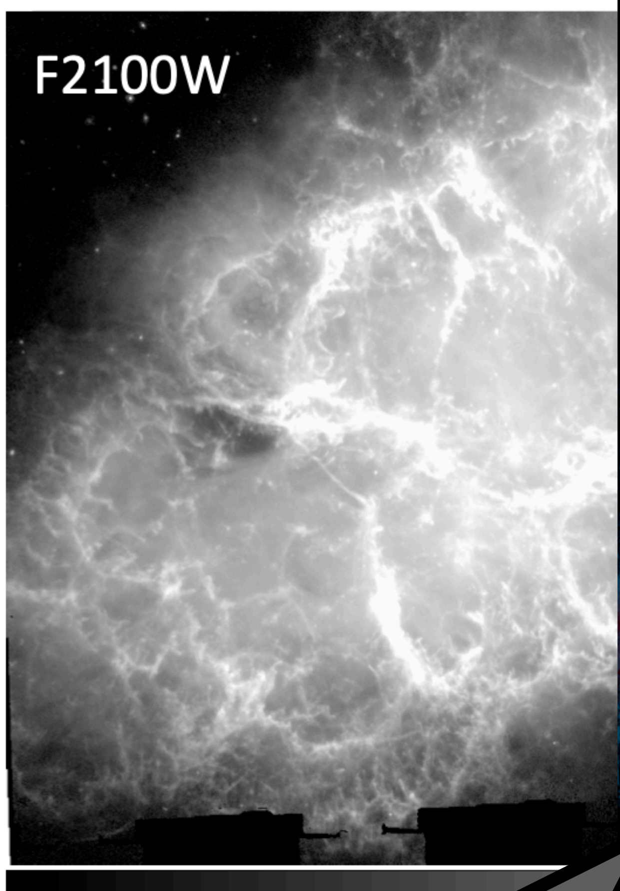
Crab Nebula with JWST

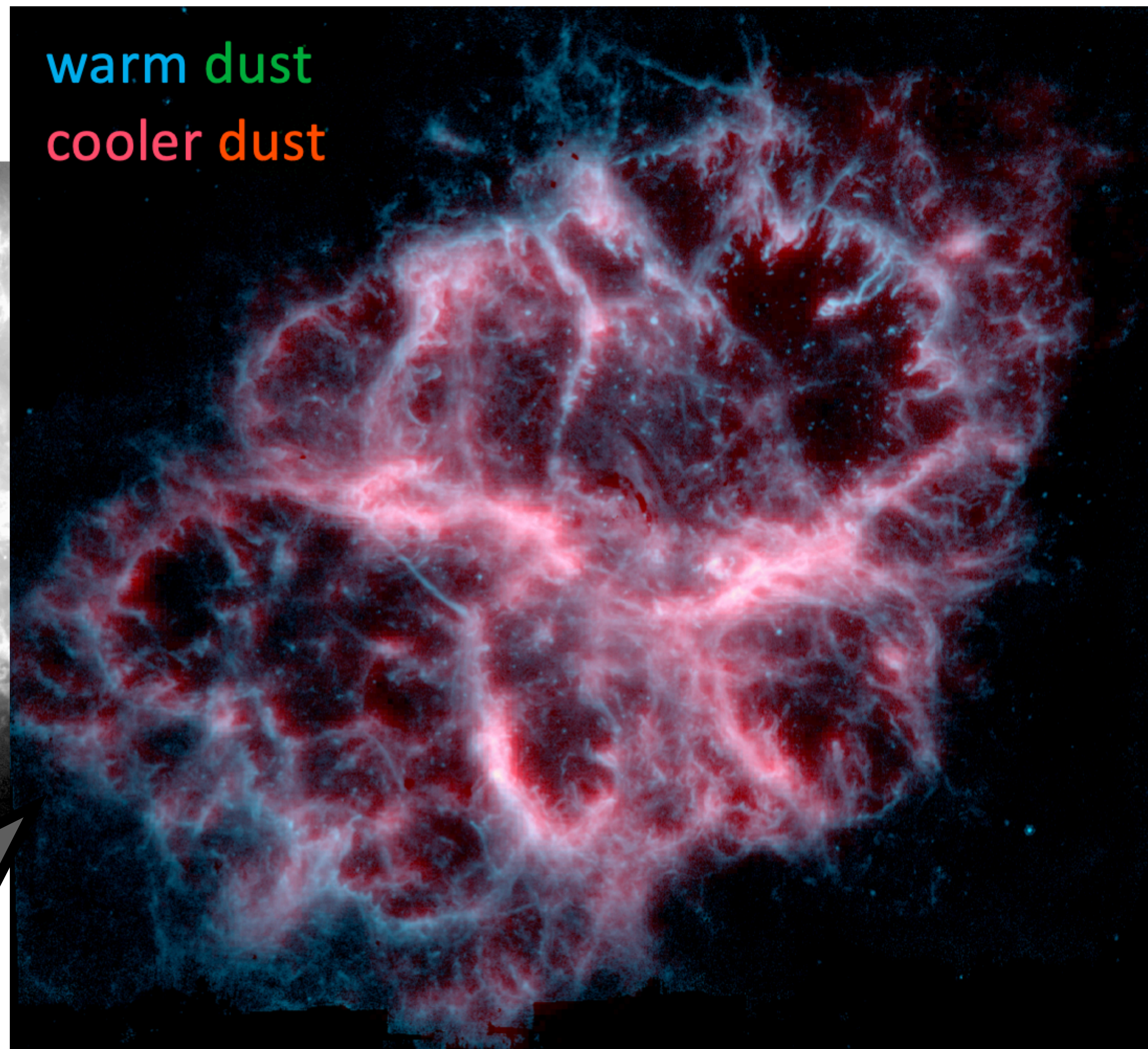


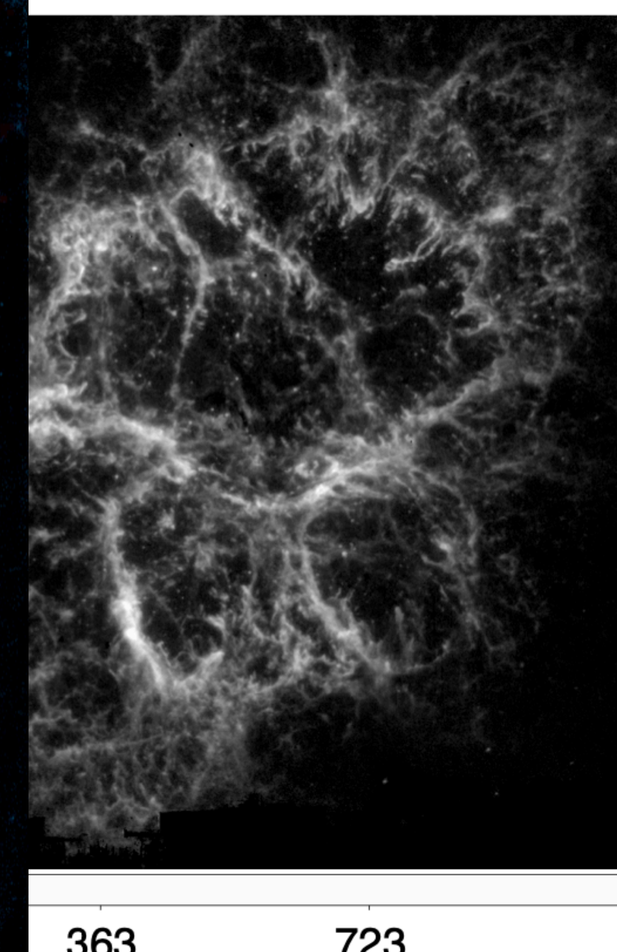
Temim et al. 2024

Dust formation in SN(R)s

Crab Nebula with JWST







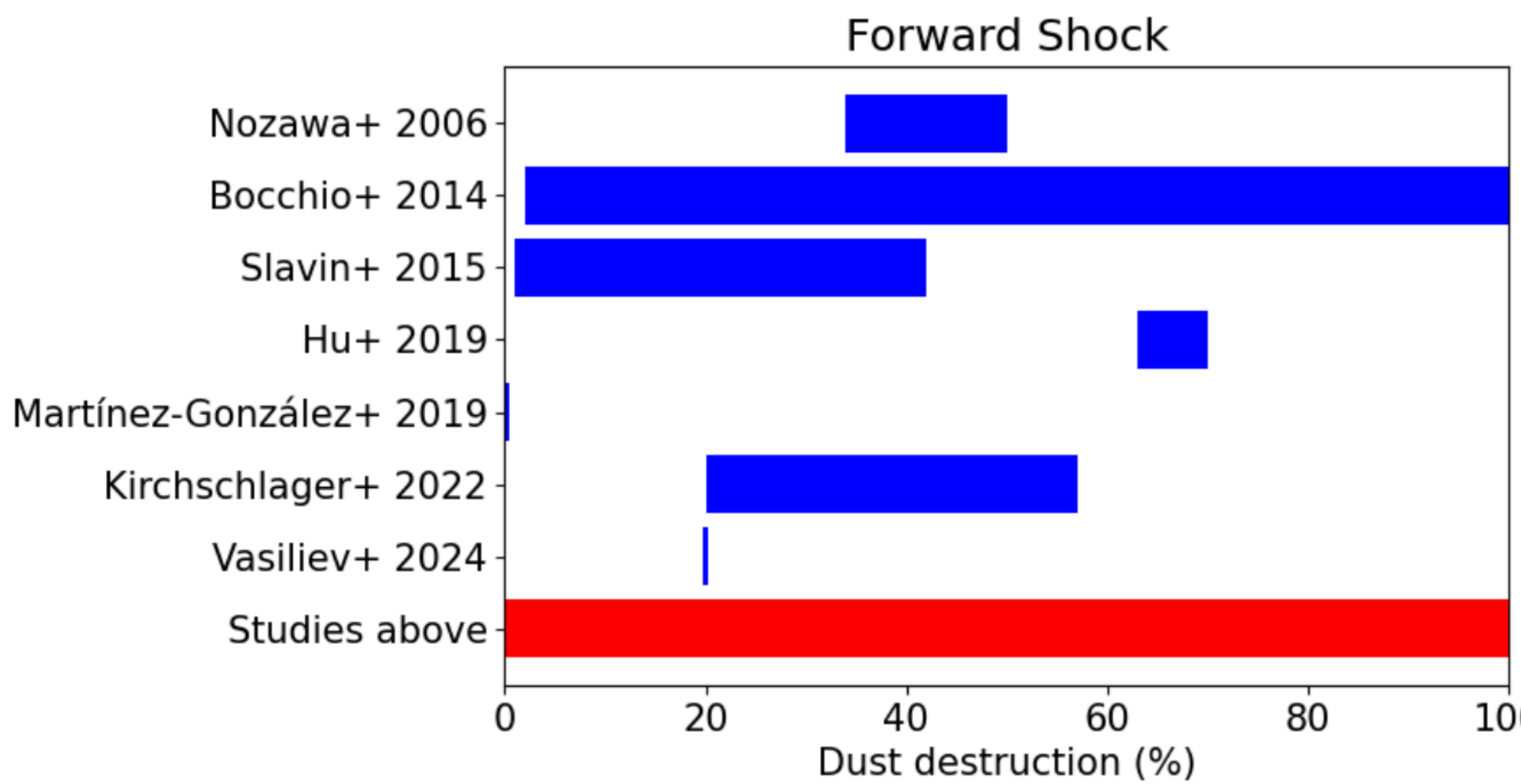
Talk by Tea

Temim et al. 2024

Dust destruction in SNR

How much dust will a single SN destroy through the blast wave*

- No consensus in the community!
- Step away from steady shock (Slavin et al. 2015)
- ISM is not homogeneous!



* the SN reverse shock can destroy the newly formed dust

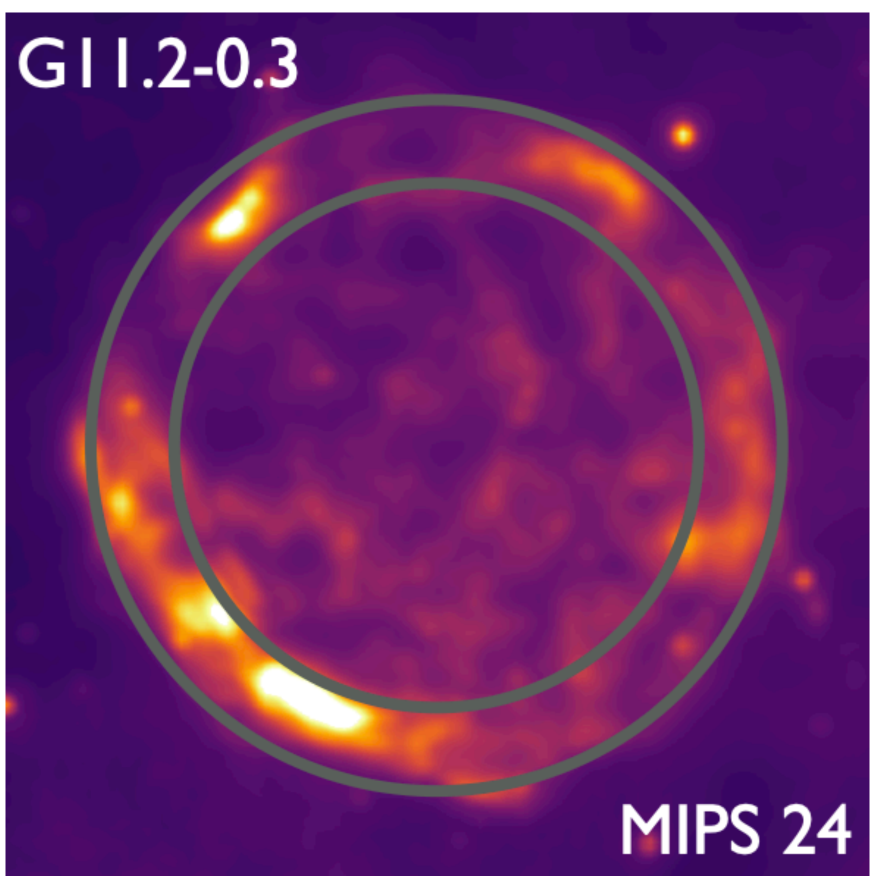
Talk by Florian Kirchschlager

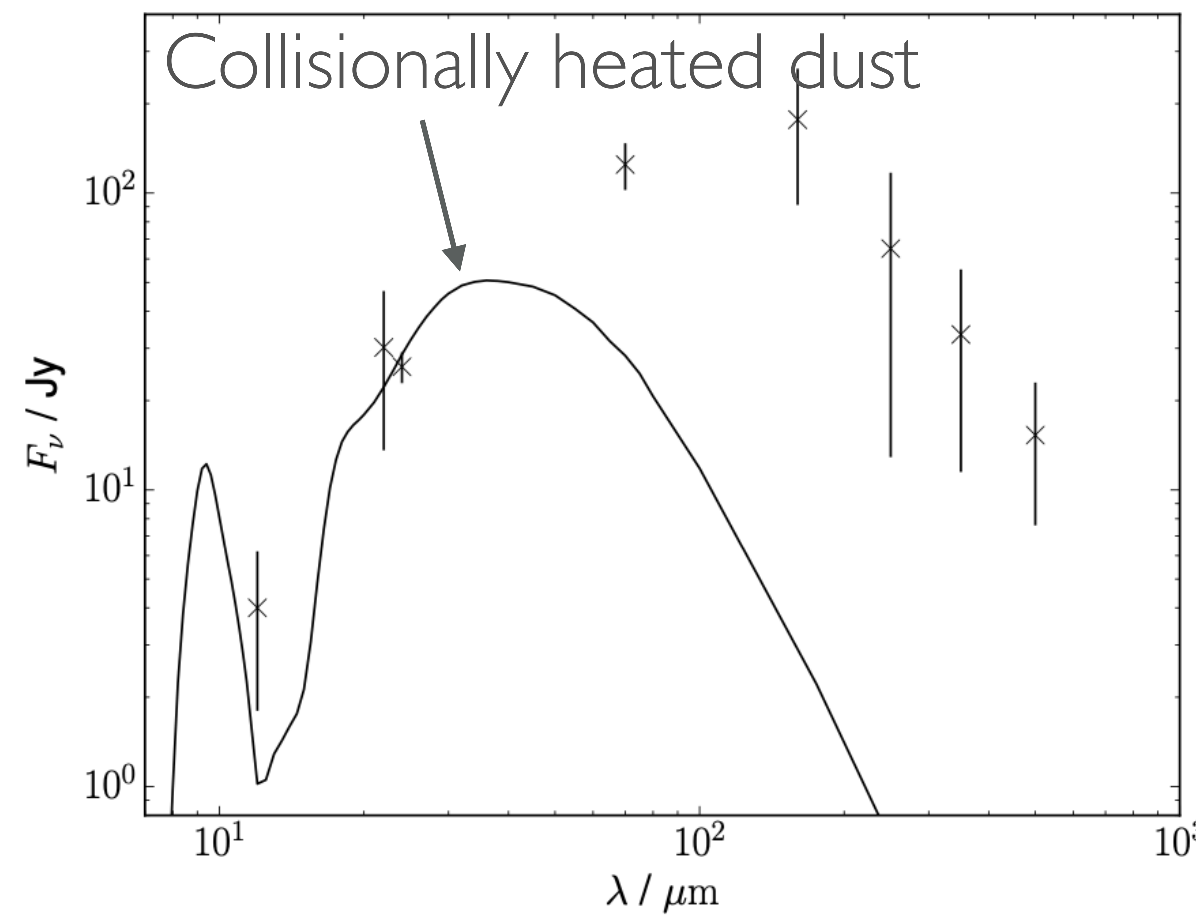
Credit Tassilo Scheffler

Dust destruction in SNR

Main problem: it is difficult to get observational constraints

Step 1: Extract multi-wavelength emission in an annulus around SNR
Step 2: Model X-ray properties to constrain electron T and density
Step 3: Model collisional dust heating



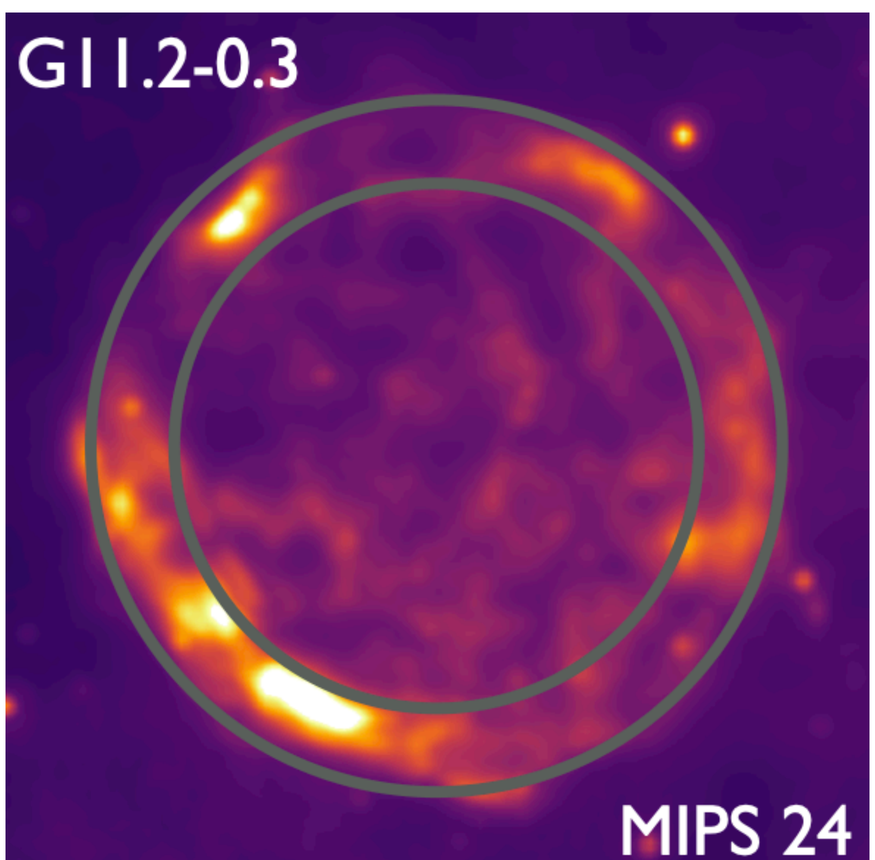


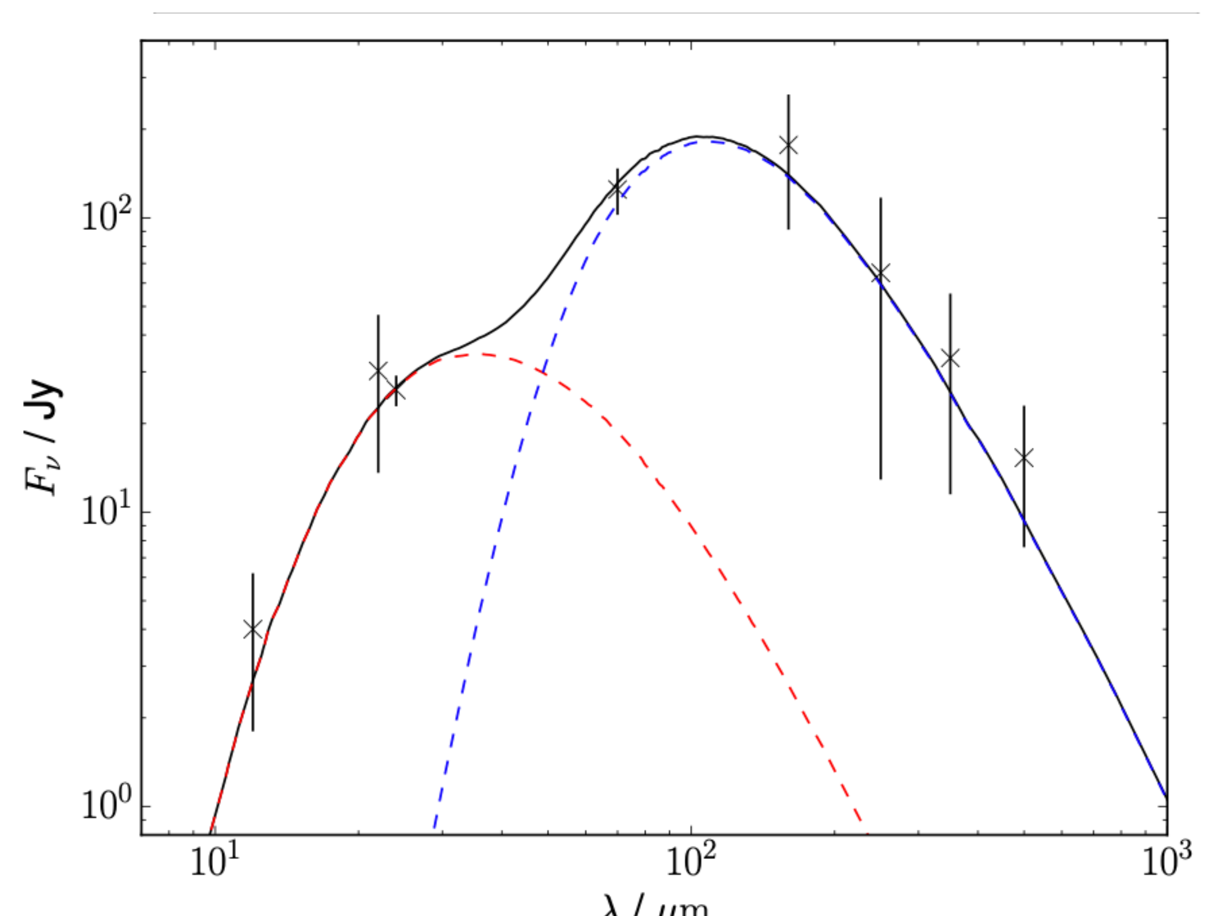
Priestley, Chawner, Matsuura, De Looze, Barlow 2022, see also Ferrara & Peroux 2021

Dust destruction in SNR

Main problem: it is difficult to get observational constraints

Observations suggest "cold" dust component that is able to shield from SN shocks
==> homogeneous models for dust destruction are not reliable



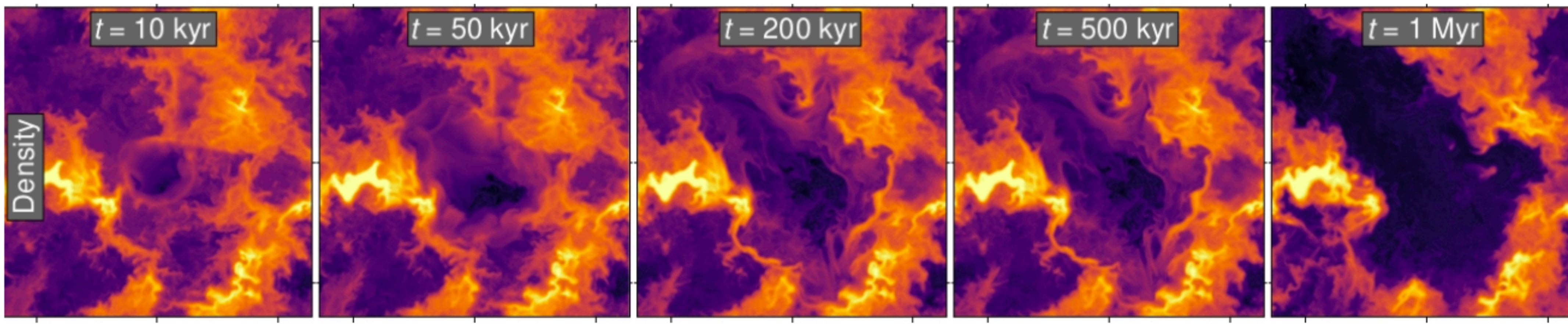


Priestley, Chawner, Matsuura, De Looze, Barlow 2022, see also Ferrara & Peroux 2021

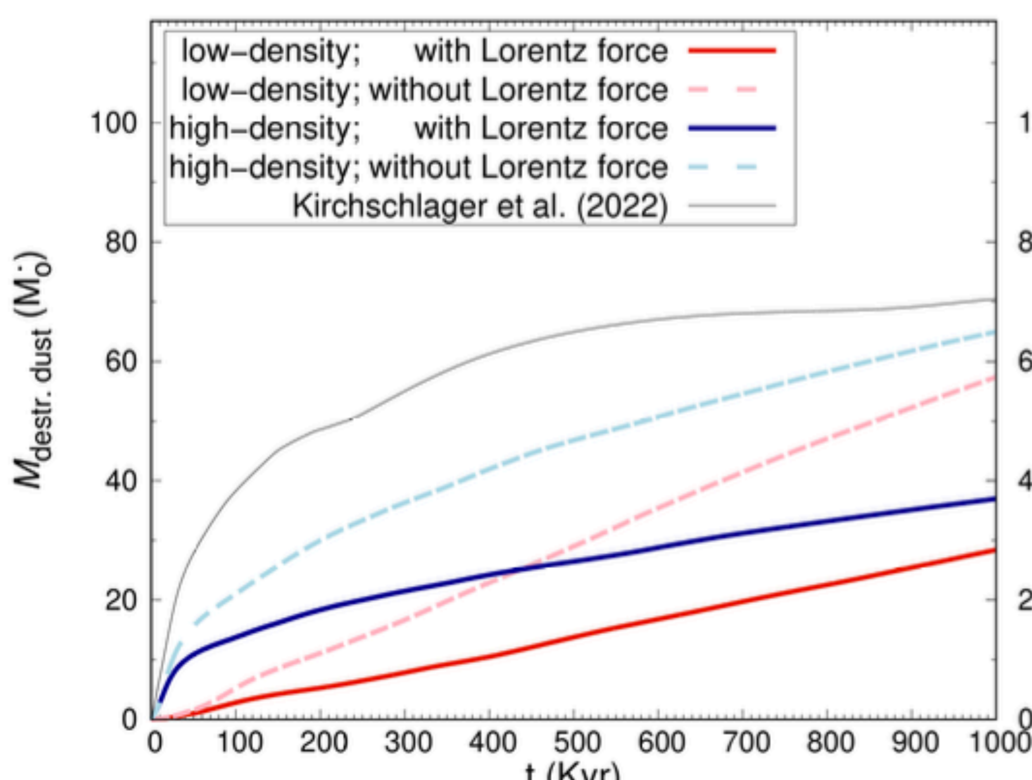
Dust destruction in SNR

Inhomogeneous ISM

Kirchschlager et al. 2024



Multiphase ISM as initial condition:
~40 SN explosions in the ISM (Gent et al. 2021)

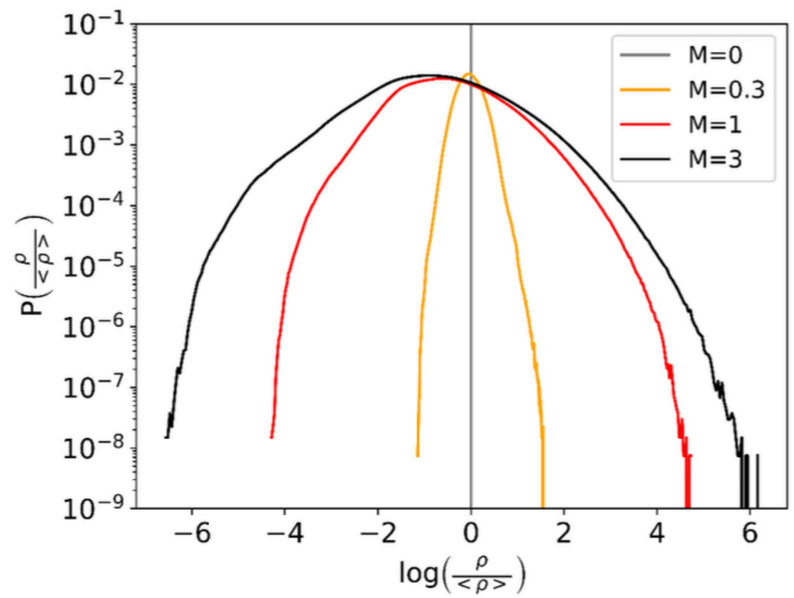


- ~70 solar masses (homogeneous ISM)
- ~60 solar masses (inhomogeneous ISM)
- 30 – 40 solar masses (inhomogeneous ISM plus magnetic field)

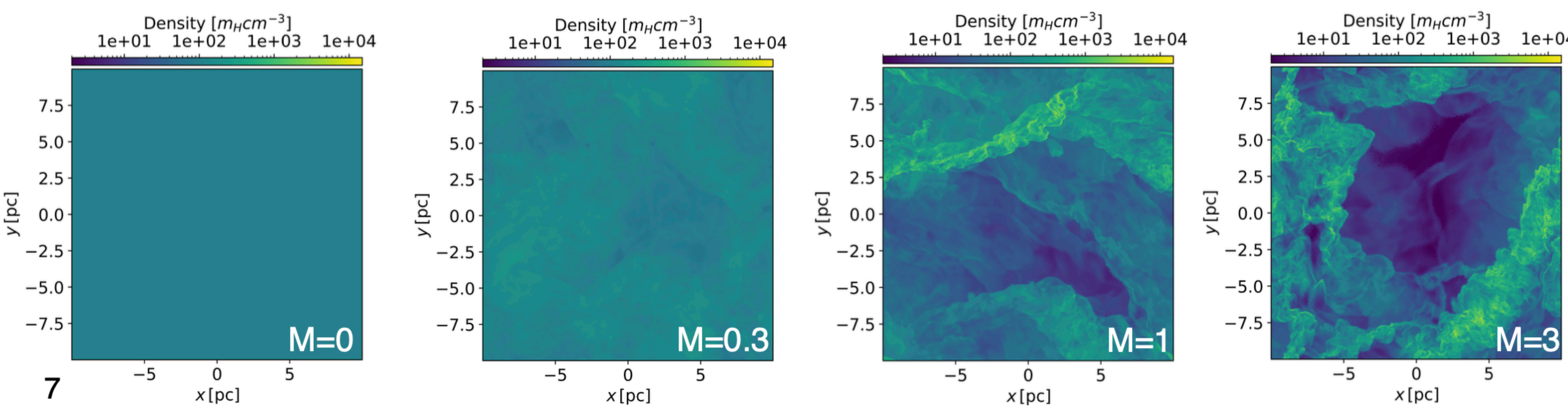
Dust destruction in SNR

New efforts underway, I: first SN going off in turbulent molecular cloud

* 3D MHD Arepo
* Turbulent ISM with n_H=100/cm^3
* Different density contrasts



homogeneous → strong turbulence

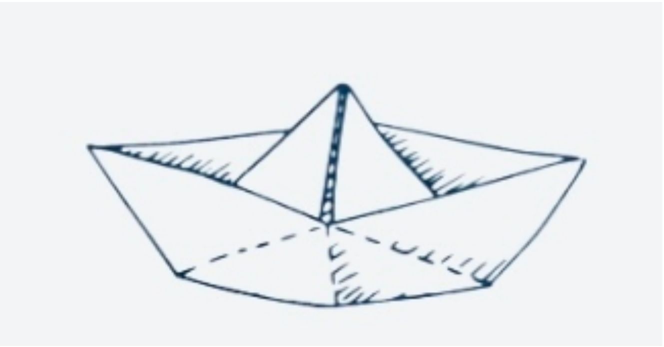


Scheffler, Sartorio, Kirchschlager, De Looze et al. prep

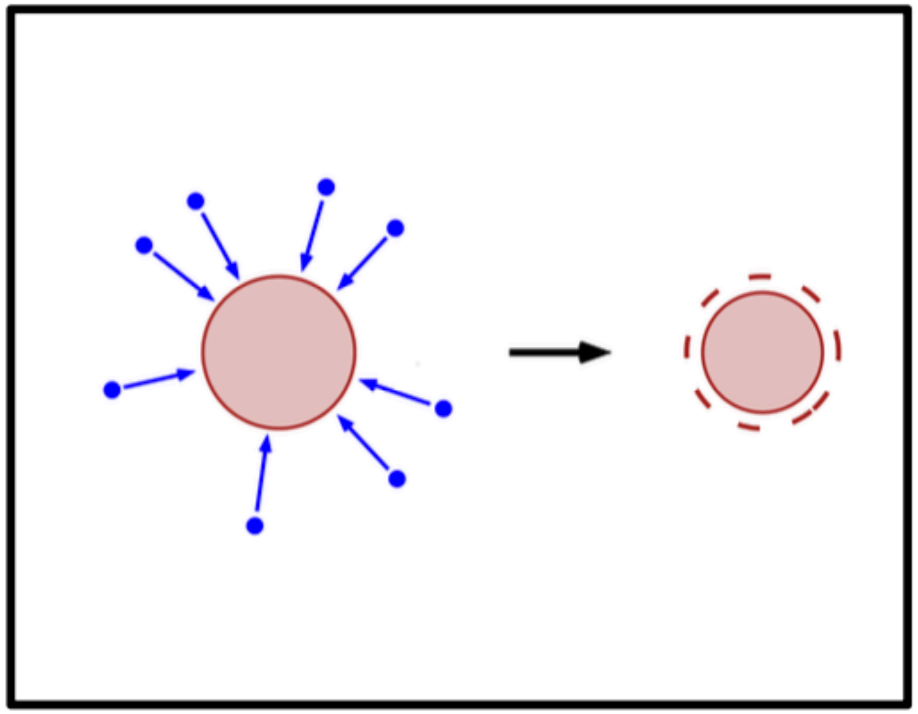
Dust destruction in SNR

Including the effects of dust in post-processing

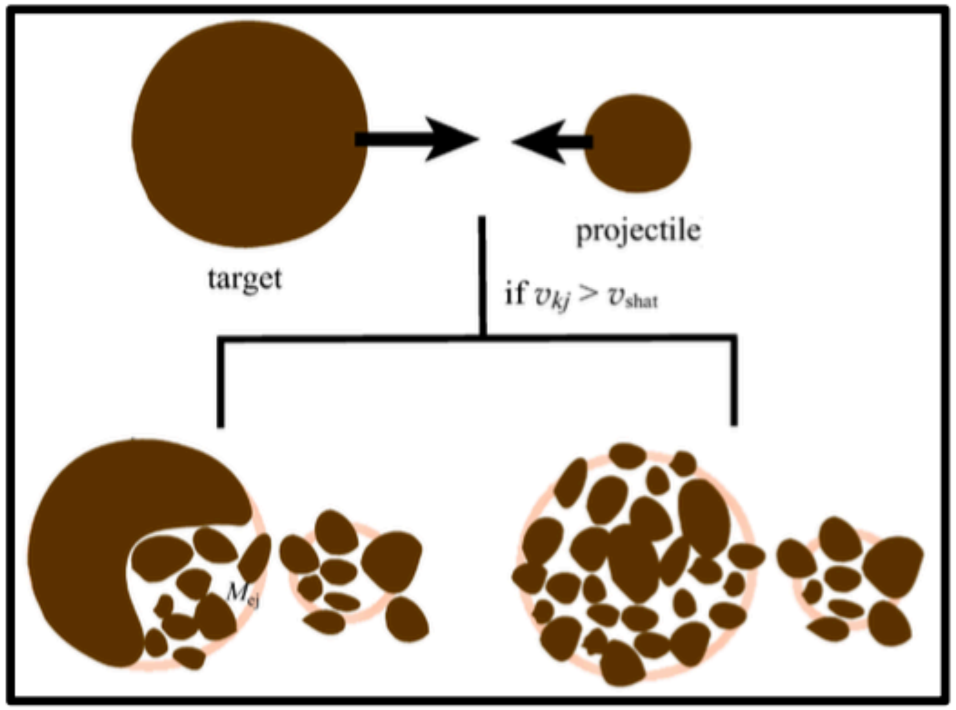
The **“Paperboats” code** (***Kirchschlager et al. 2019***) including
- transport of dust (gas and plasma drag)
- magnetic fields
- grain processing (sputtering, fragmentation, vaporisation and bouncing)



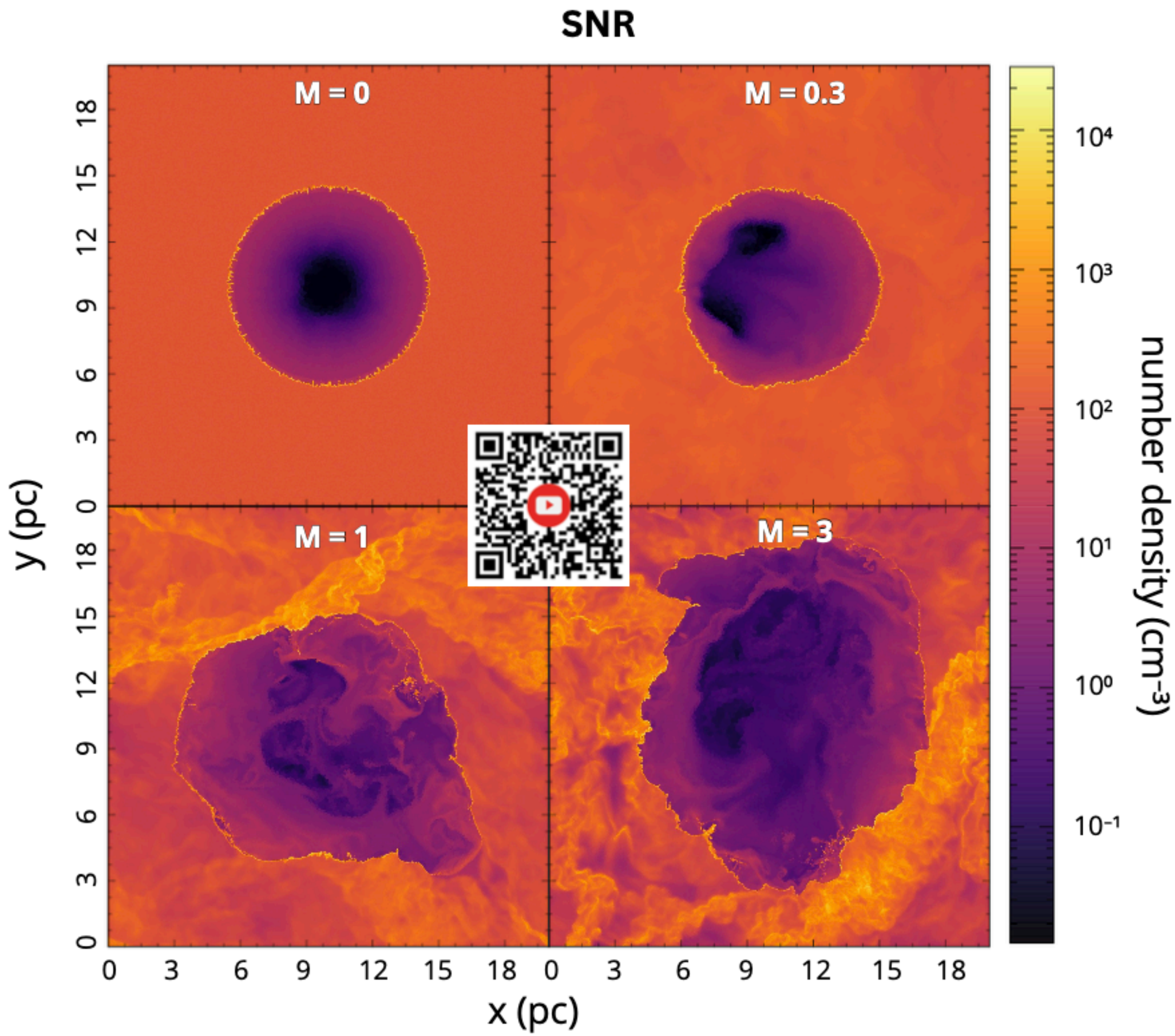
Sputtering



Grain-grain collisions



Results



Scheffler, Sartorio, Kirchschlager, De Looze et al. prep

Dust destruction in SNR

New efforts underway, I: first SN going off in turbulent molecular cloud

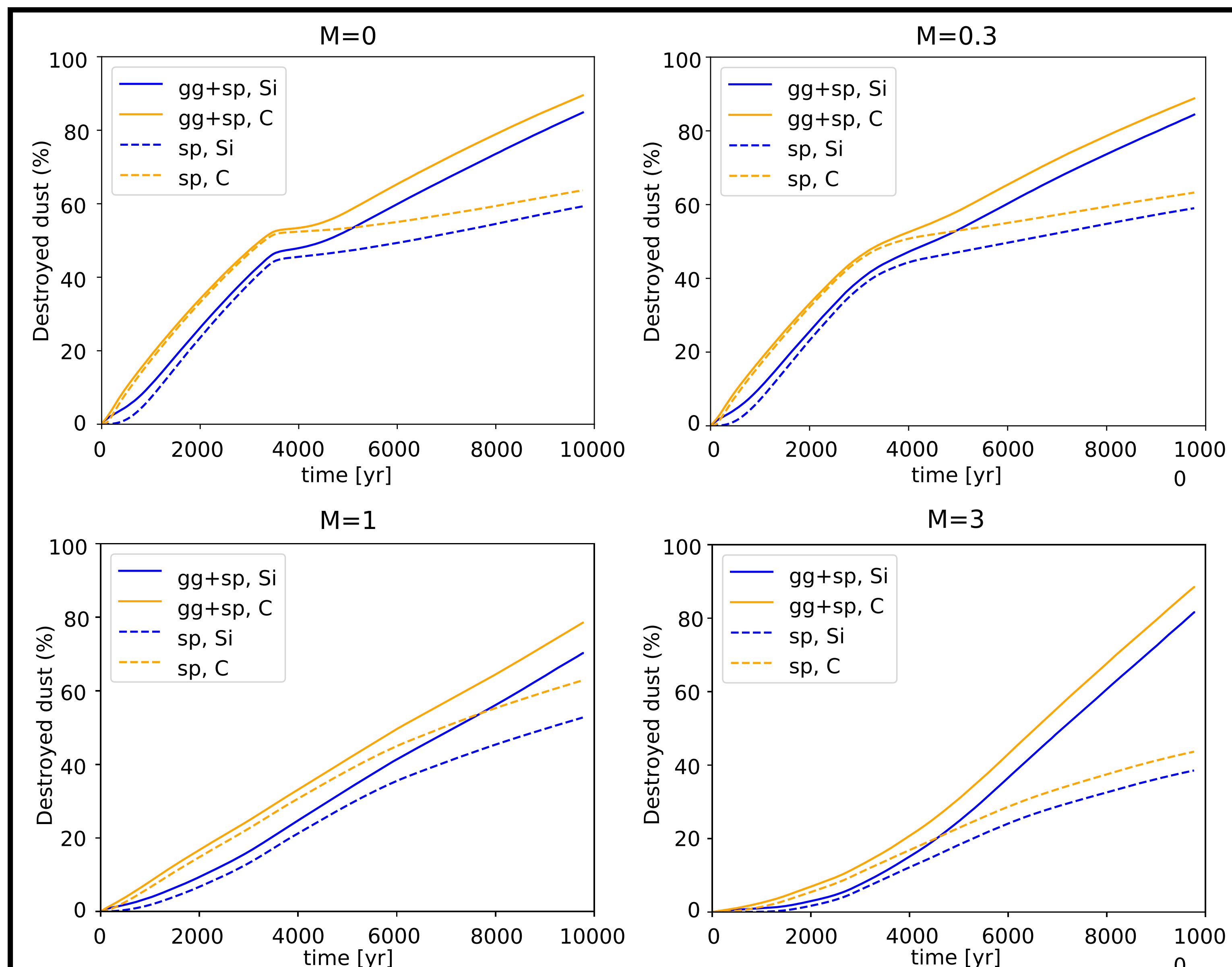
Main results:

* Efficient dust destruction (10 M_{sun}) at early SNR evolution (<10 kyr)
* Grain-grain collisions are important to destroy dust grains in dense environments

Future work:

* Less dense environments (1 and 10/cm^3) and longer timescales (1Myr)

Dust destruction



Scheffler, Sartorio, Kirchschlager, De Looze et al. prep

Dust destruction in SNR

New efforts underway, I: first SN going off in turbulent molecular cloud

Check out poster S6.5

Main results:

* Efficient dust destruction (10 M_{sun}) at early SNR evolution (<10 kyr)
* Grain-grain collisions are important to destroy dust grains in dense environments

Future work:

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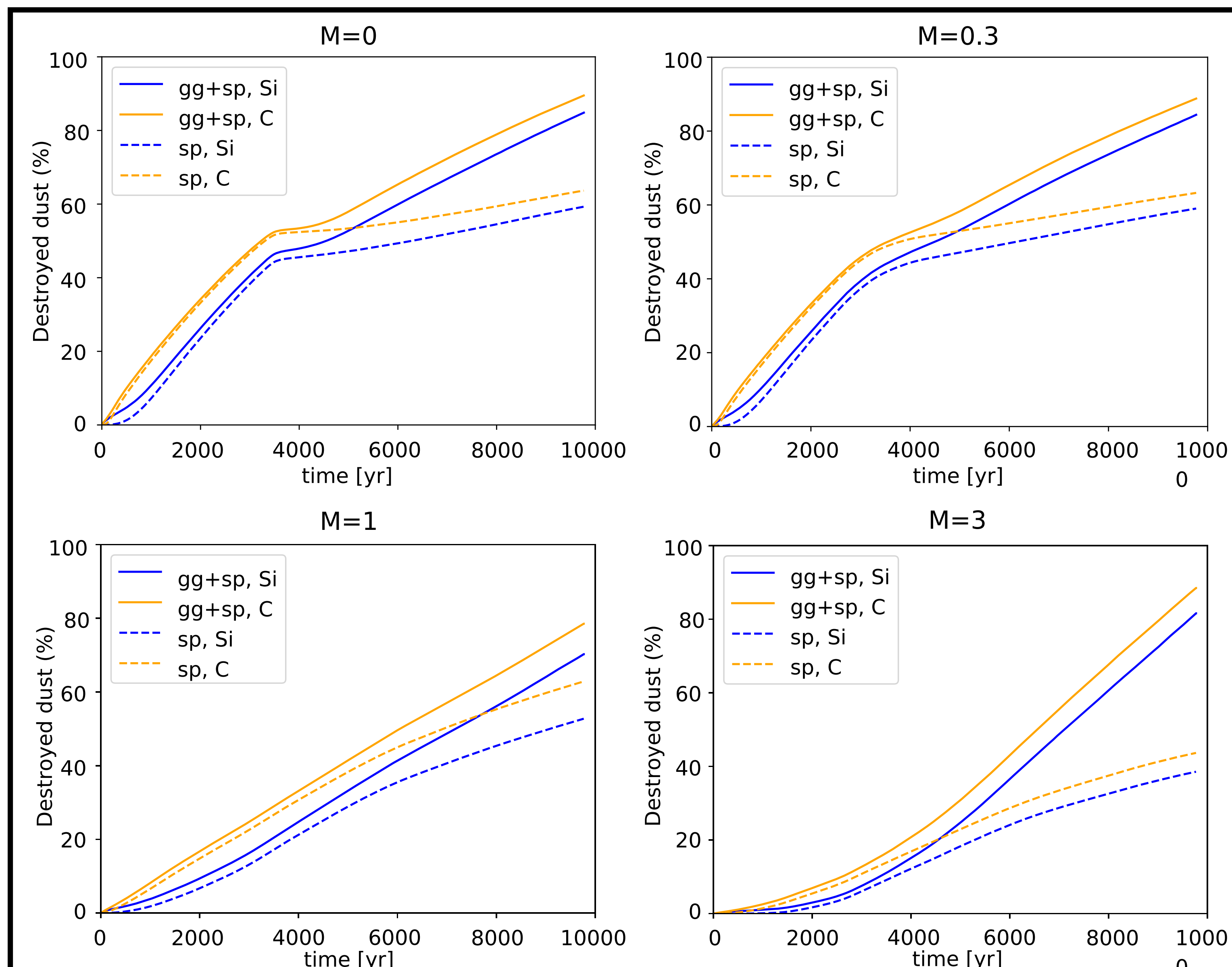
Dust destruction



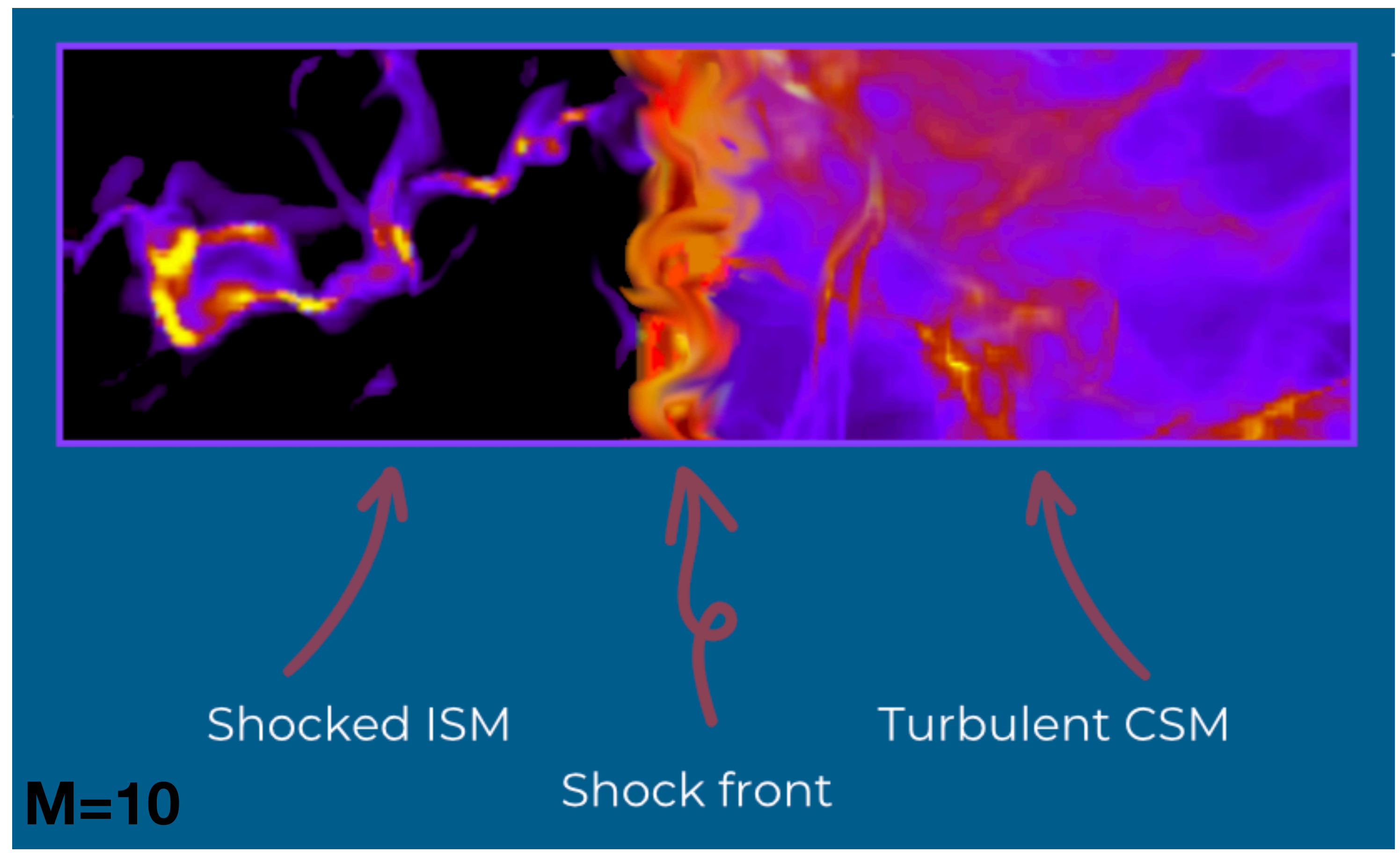
Scheffler, Sartorio, Kirchschlager, De Looze et al. prep

Dust destruction in SNR

New efforts underway, II: plane-parallel shock fronts @ ≠ velocities

<u>Set-up:</u>

* Plane parallel shock front at velocities v=1000 to 6000 km/s
* Turbulent CSM with n_H=6/cm^3



Sartorio, Kirchschlager, De Looze et al. prep

Dust destruction in SNR

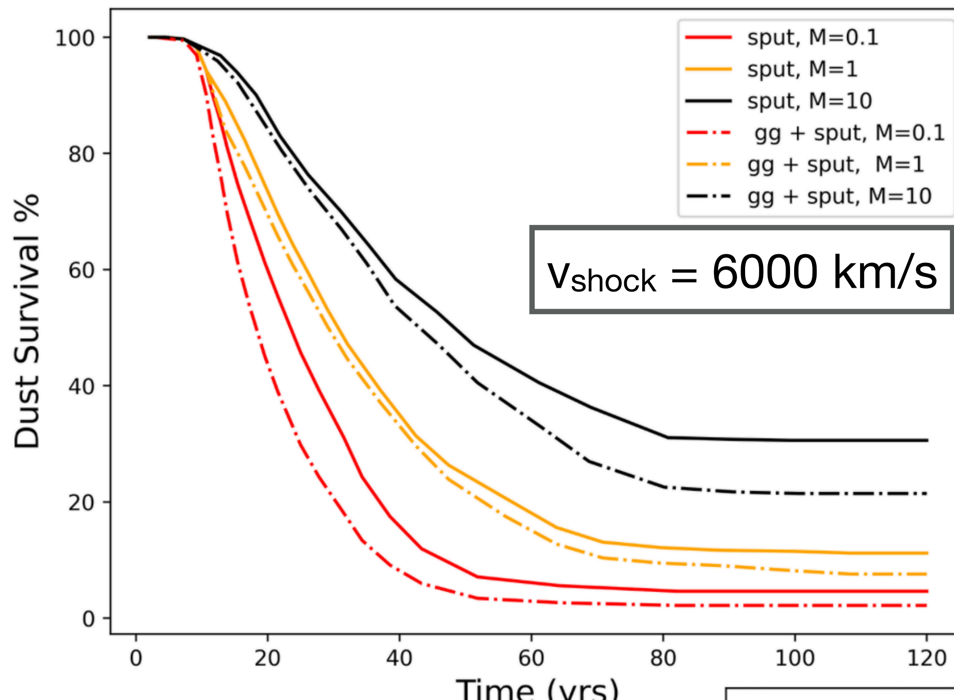
New efforts underway, II: plane-parallel shock fronts @ ≠ velocities

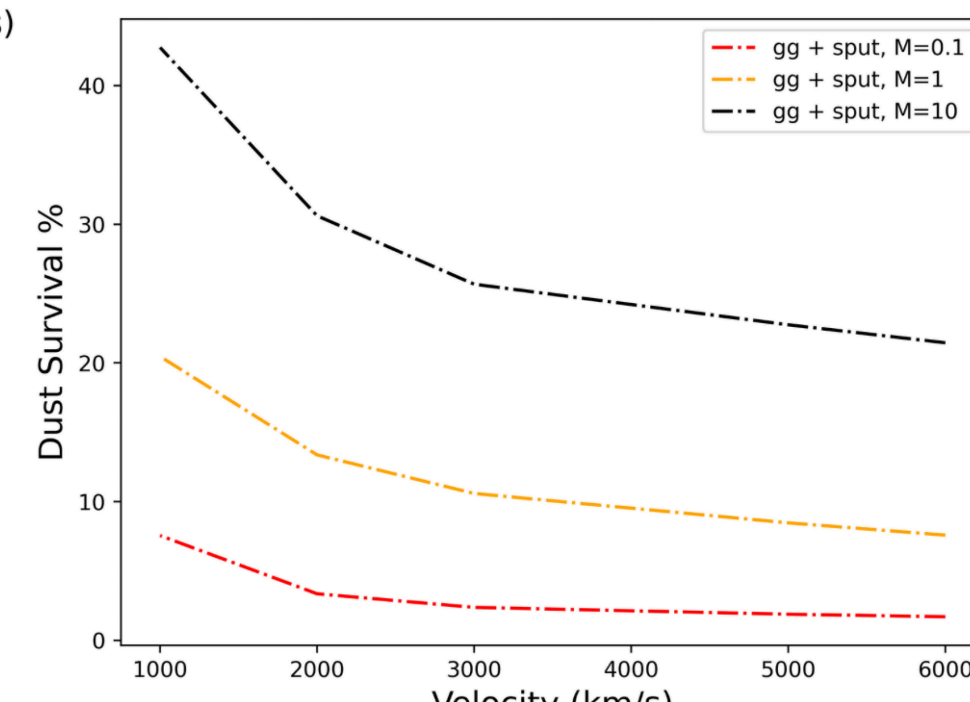
Set-up:

* Plane parallel shock front at velocities v=1000 to 6000 km/s
* Turbulent CSM with n_H=6/cm^3

Results:

* Dust in high-density filaments (high Mach numbers, M=10) is more resilient to SN shock
* Dust destruction is more efficient at high velocities
* Not all the filaments get destroyed





Sartorio, Kirchschlager, De Looze et al. prep

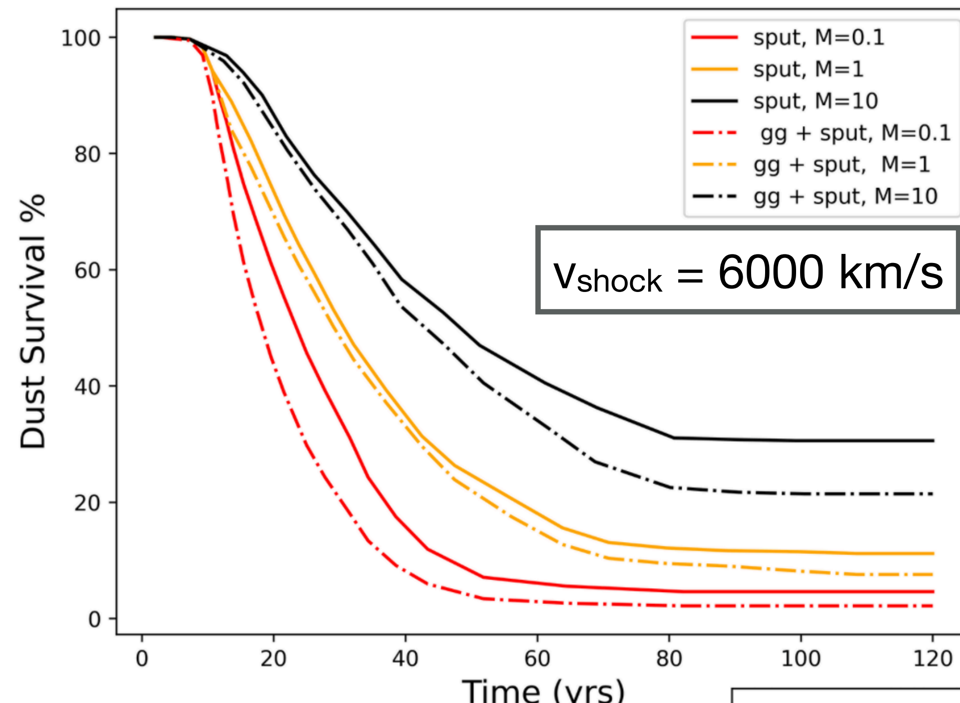
Dust destruction in SNR

New efforts underway, II: plane-parallel shock fronts @ ≠ velocities

Check out poster S6.3

Set-up:

- Plane parallel shock front at velocities v=1000 to 6000 km/s
- Turbulent CSM with n_H=6/cm^3



Results:

- Dust in high-density filaments (high Mach numbers, M=10) is more resilient to SN shock
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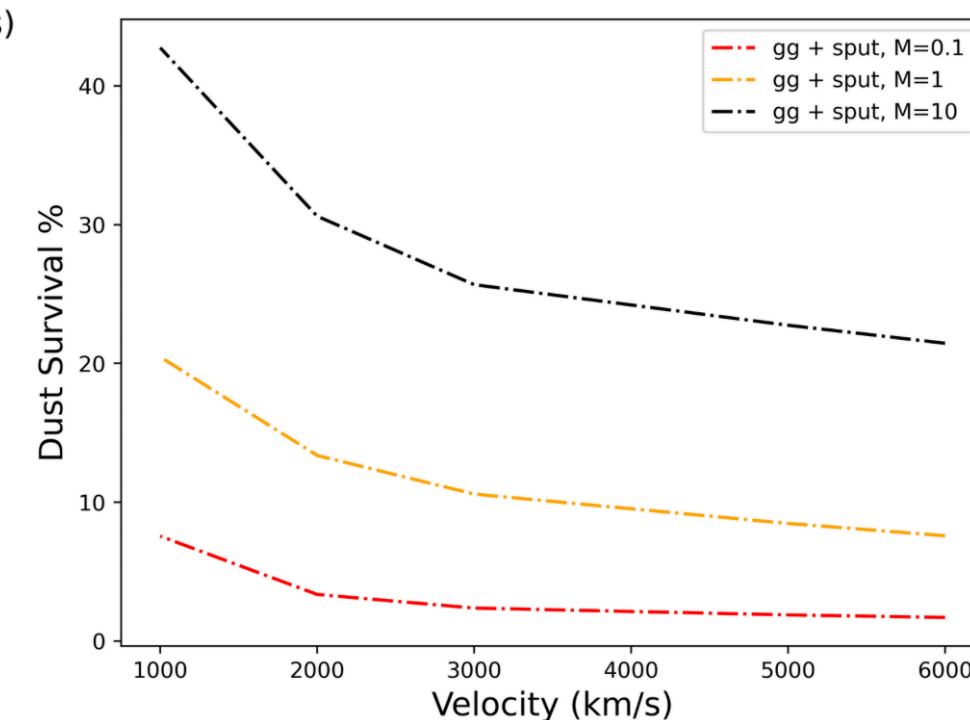


Sartorio, Kirchschlager, De Looze et al. prep

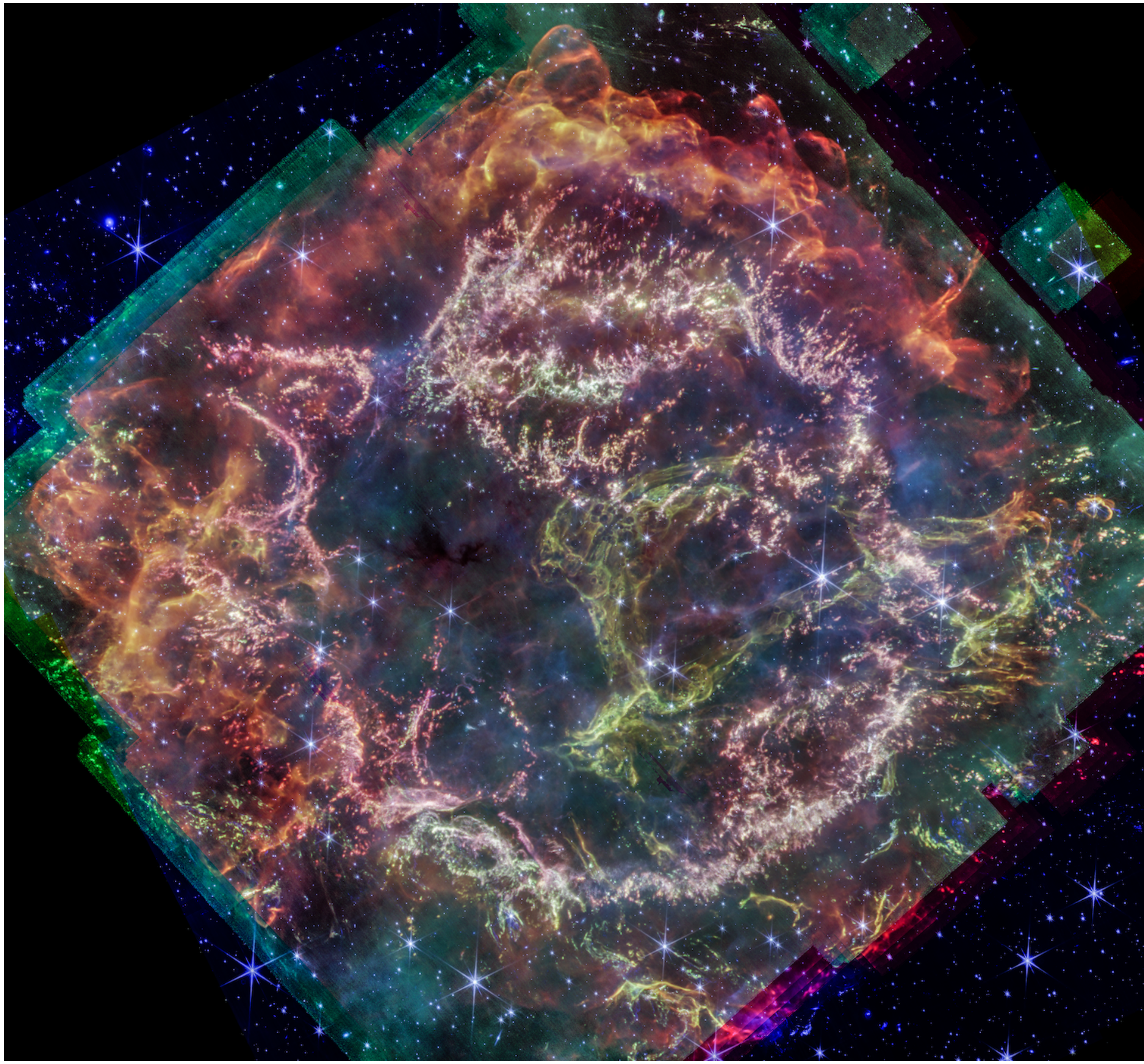
Conclusions

1. SNe efficiently produce dust
   (0.5-1 M_{sun})

2. SNe = NET dust destroyers

3. SN blastwave still efficiently destroys
   dust in turbulent media, but less
   efficiently (by a factor of ~2)
   for high-density contrasts

4. Green Monster dense CSM in front
   of Cassiopeia A
   ==> asymmetric mass loss
   ==> binary system

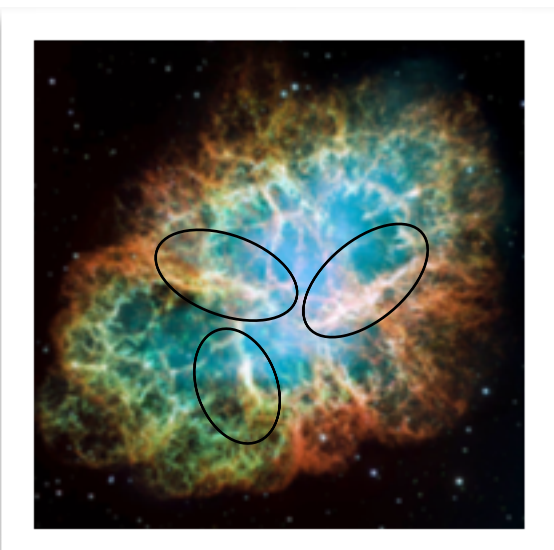


Extra

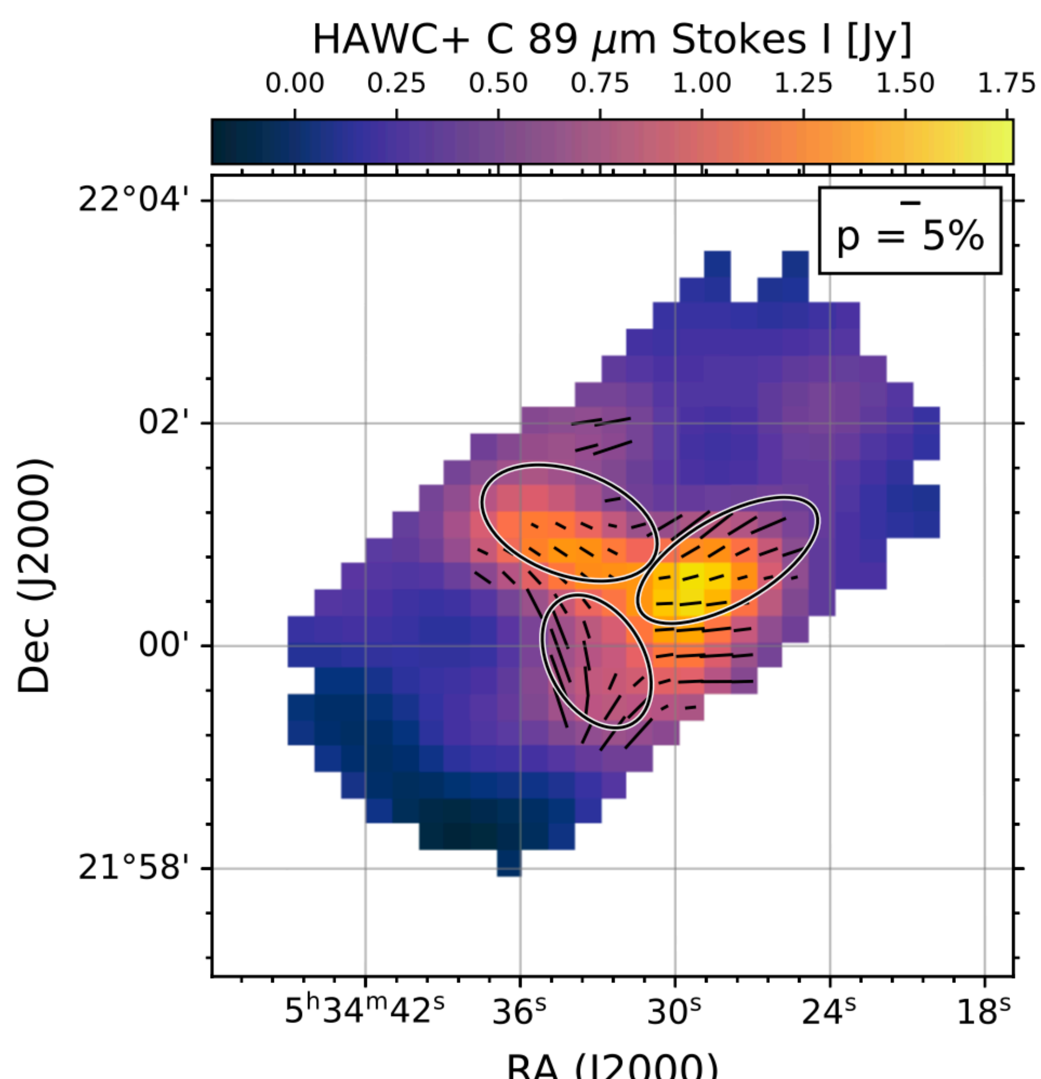
Dust formation in SN(R)s

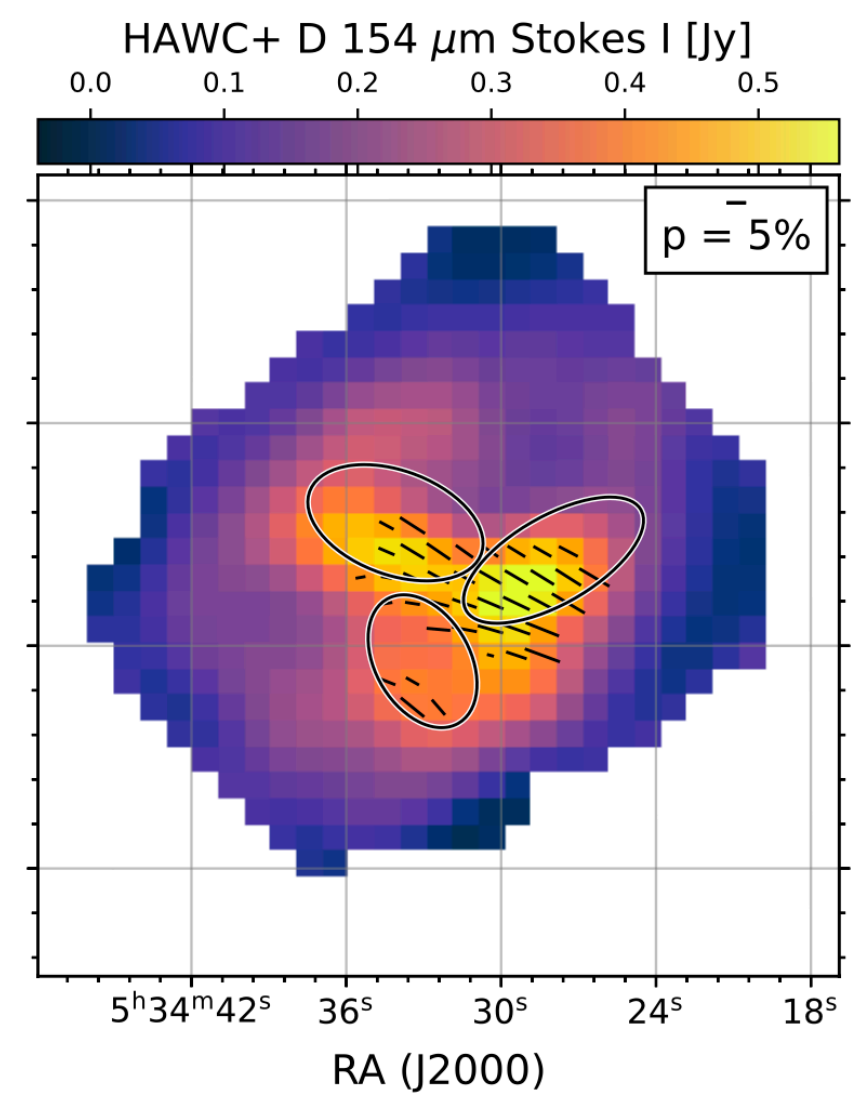
Crab Nebula: dust masses from dust polarisation emission

SOFIA polarisation fractions in two far-infrared wavebands
(after correcting for synchrotron polarisation)



Crab Nebula





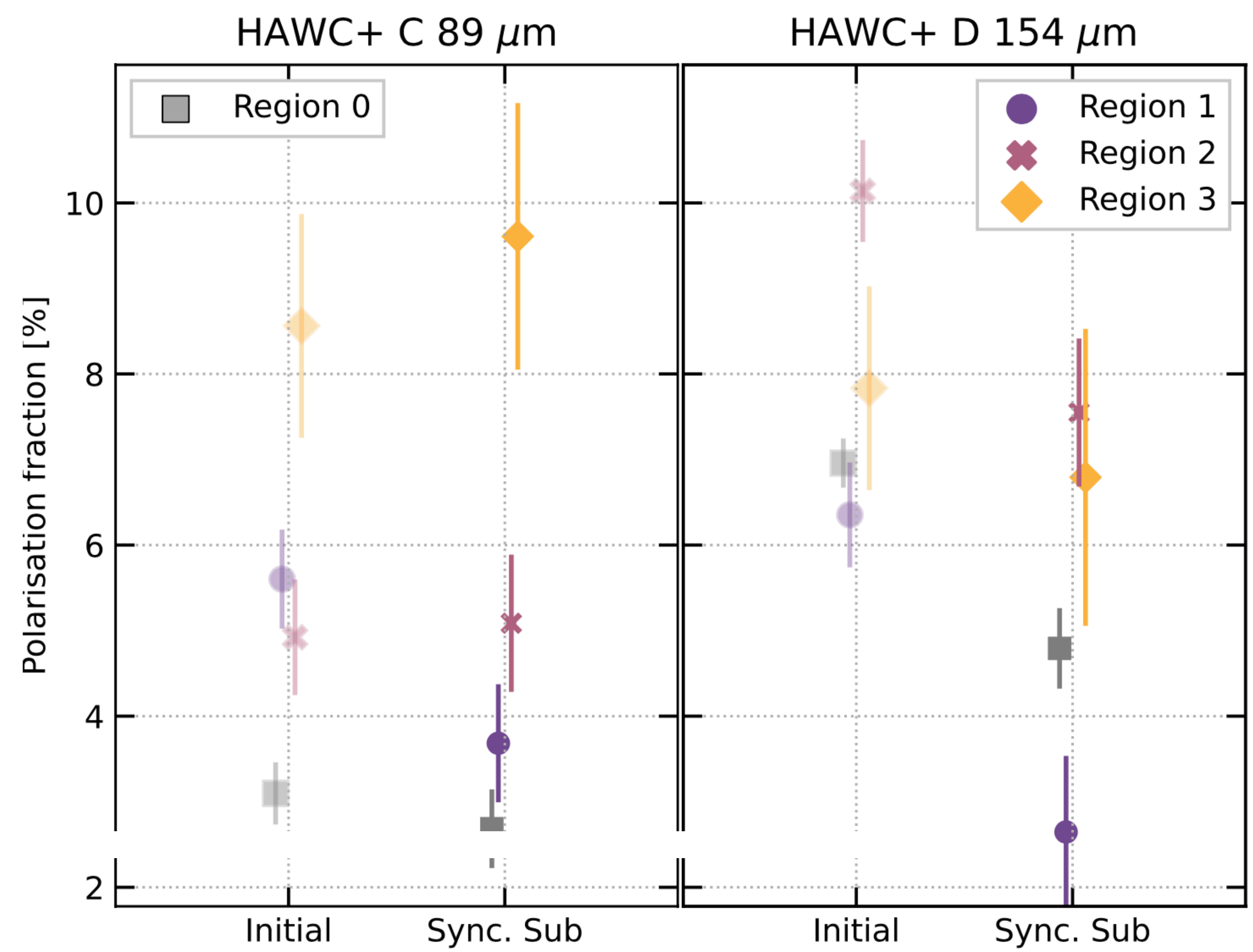
Chastenet, De Looze, et al. 2022

Dust formation in SN(R)s

Crab Nebula: dust masses from dust polarisation emission

Crab Nebula

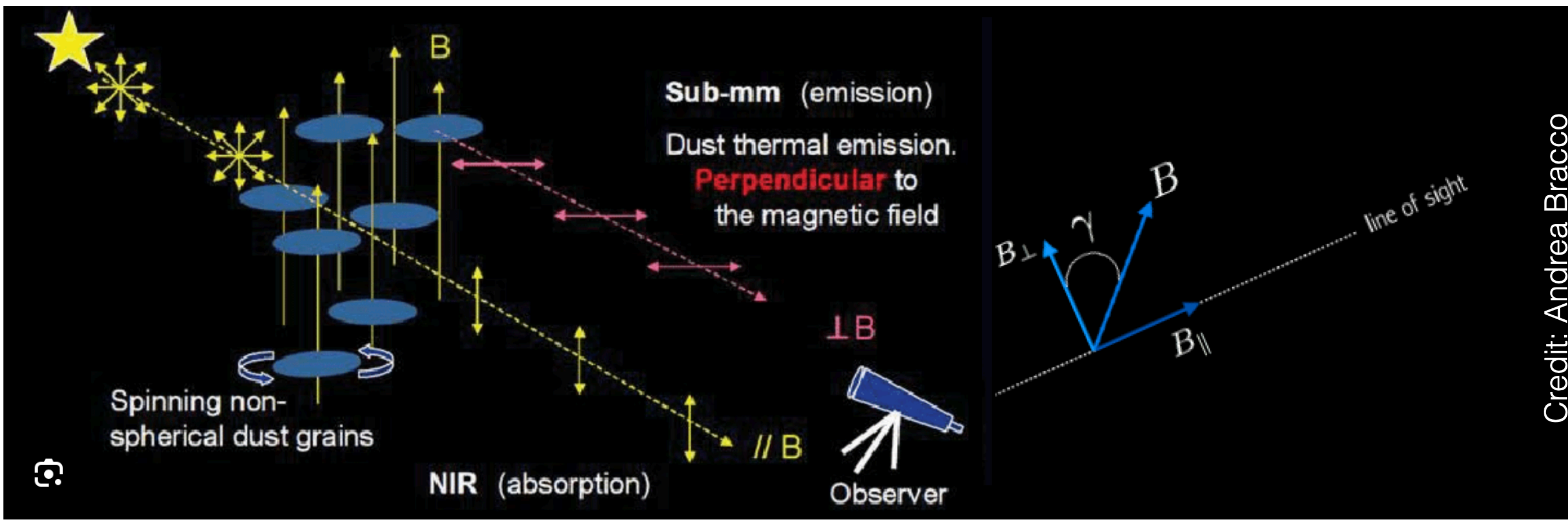
- Low dust polarisation fractions p < 10%
- Large grains (> 0.1 μm)
- Carbon mass fractions ~ 12-70%



Chastenet, De Looze, et al. 2022

I. Dust formation in SN(R)s

Method B+: dust masses from dust polarisation emission



Non-spherical grains align their axis of maximal inertia with the local magnetic field orientation.

Assumption: carbonaceous grains do not align, only silicate grains with sizes of 0.1 micron and larger

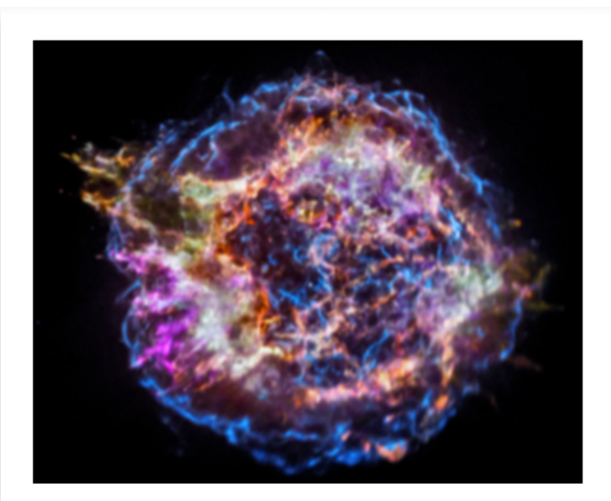
The polarisation fraction depends on the angle between the local magnetic field and the plane of the sky.

Chastenet, De Looze, et al. 2022

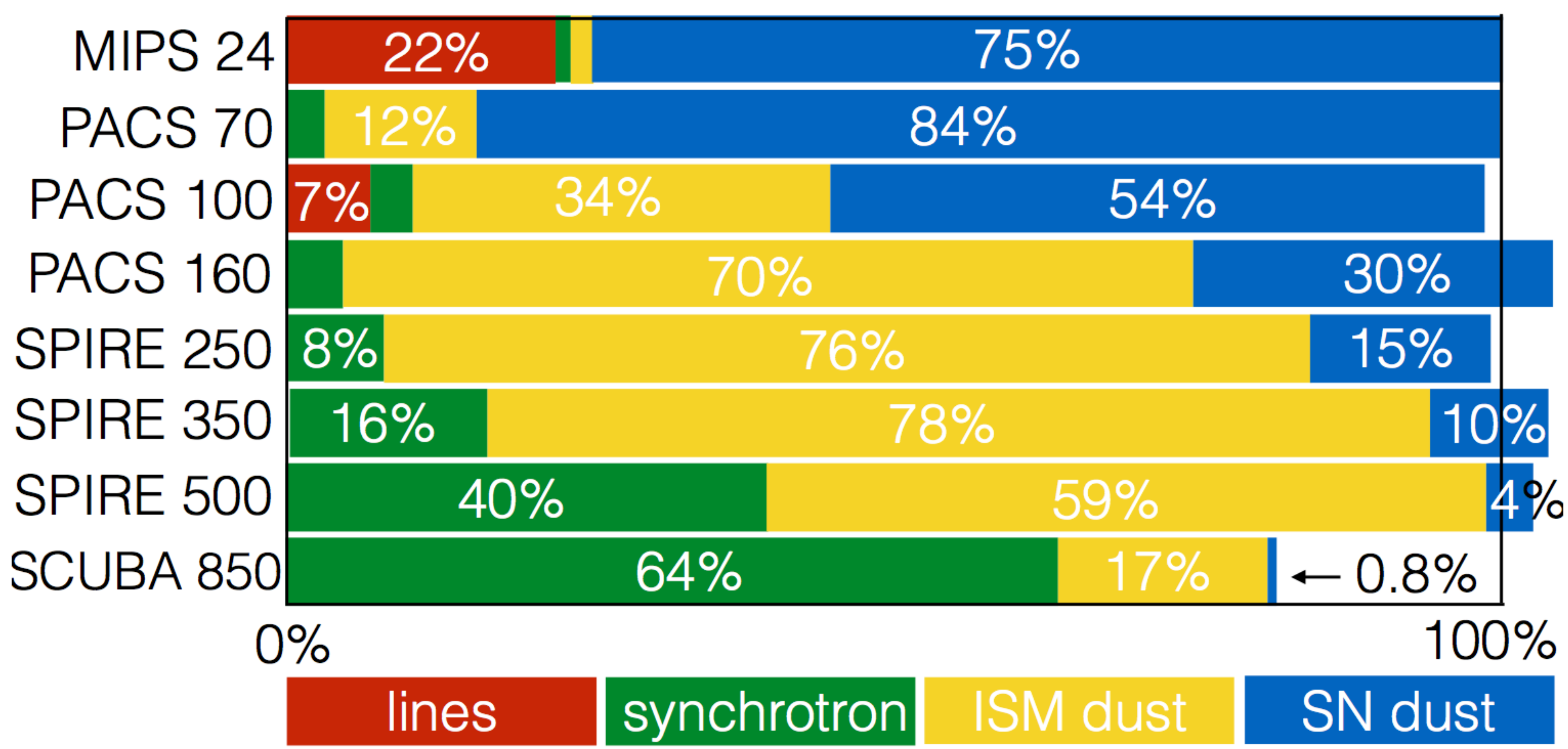
Dust formation in SN(R)s

Method B: dust masses from infrared dust emission (Herschel)

Main difficulty in constraining SN dust mass is contribution of various emission processes!



Cassiopeia A



De Looze, Barlow, et al. 2017

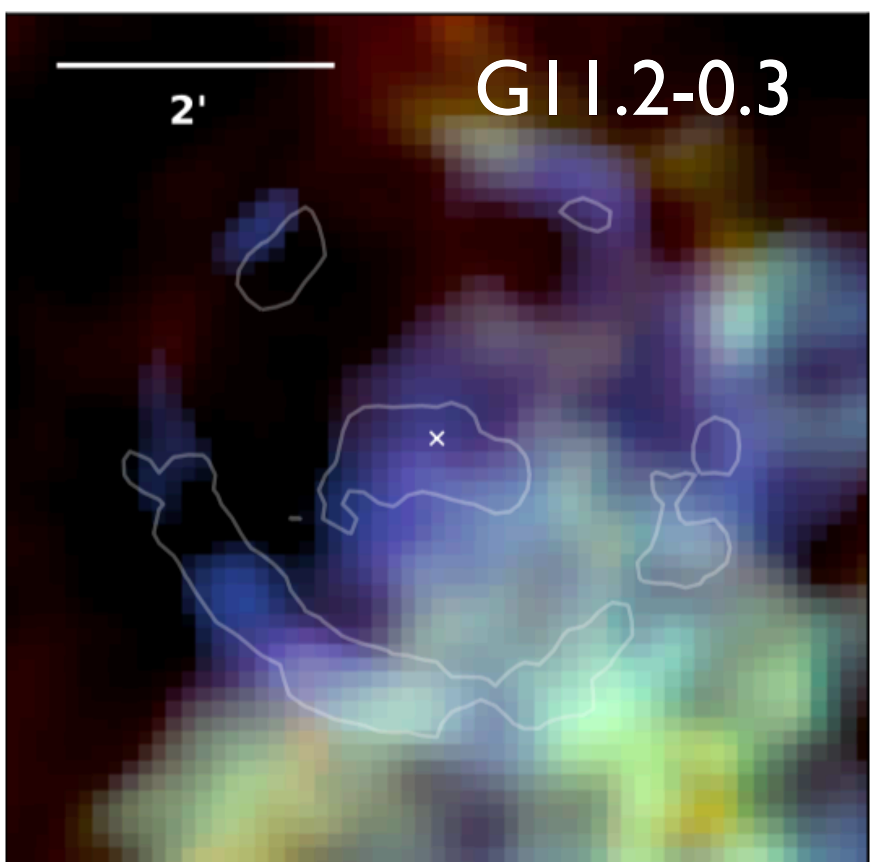
Dust formation in SN(R)s

Dust masses for other Galactic SNe (Herschel)

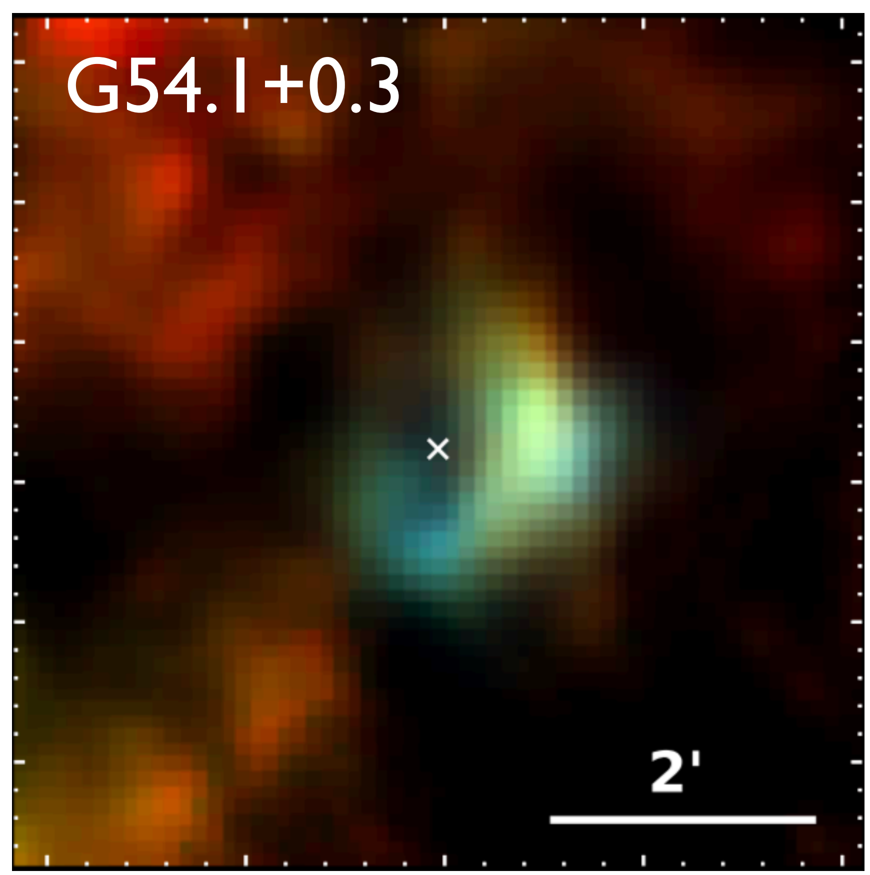
Study of the HiGAL dataset : 39/190 SNRs (~20%) SNRs have a FIR detection!

70 160 250

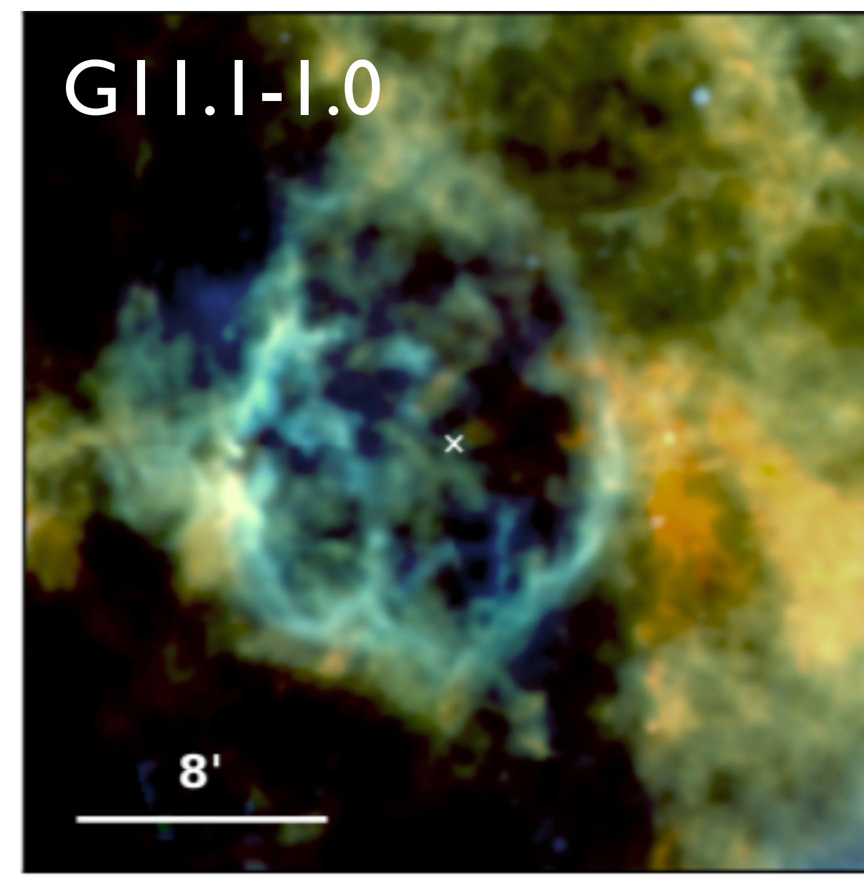
Chawner+2019, 2020



8/29: central dust detection



4/29: dust in pulsar wind nebulae



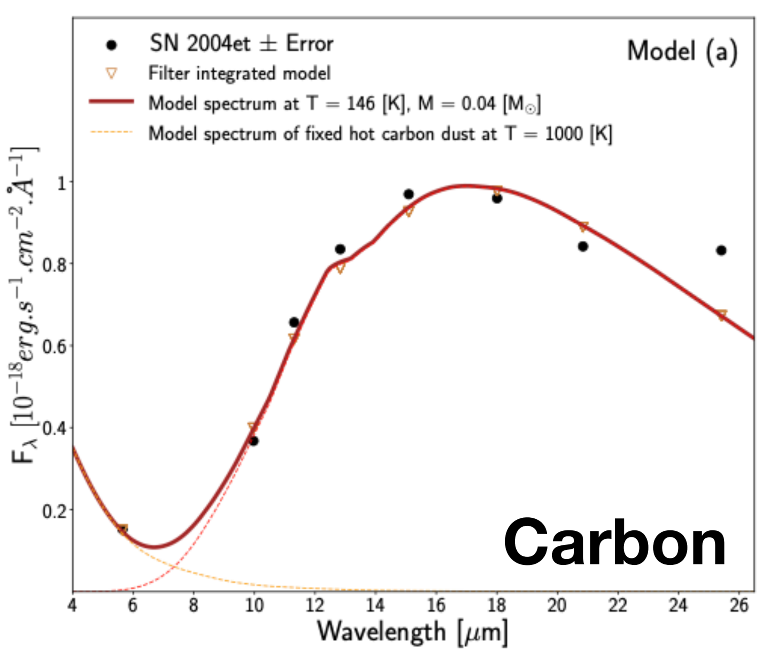
23/29: dust in outer shell: ejecta or swept up dust?

Extragalactic SNe with JWST

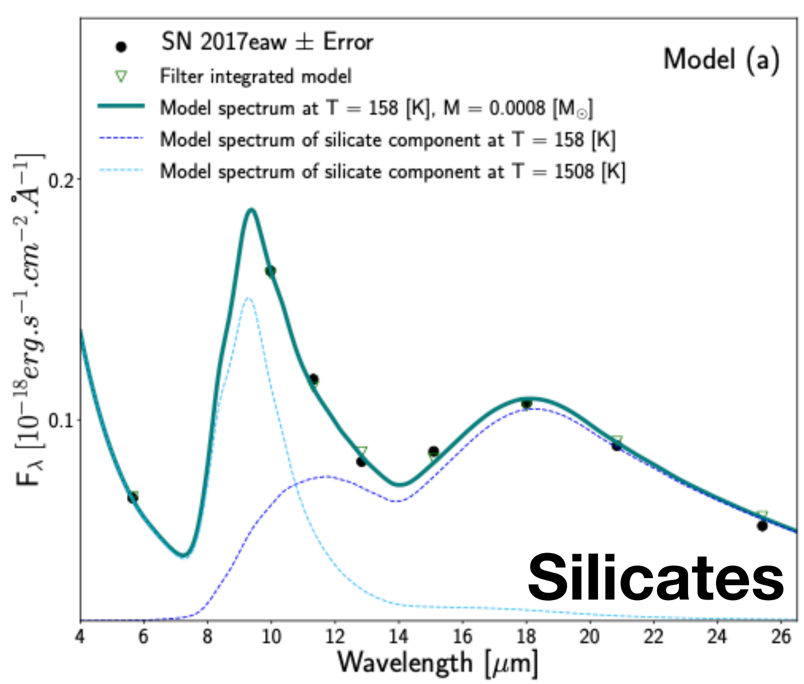
JWST has the sensitivity to pick up on warm SN dust in external SNe!

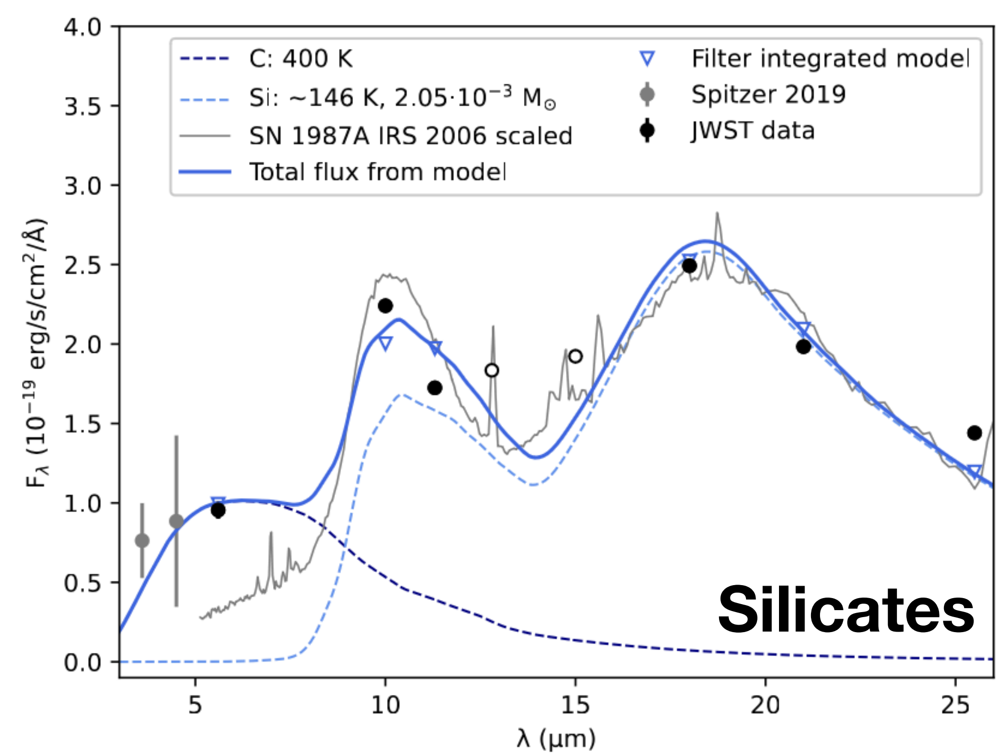
Type IIP SNe SN2004et and SN2017eaw host >0.014 M_{sun} and >0.0004 M_{sun} of dust

Type IIL SN SN1980K with 0.002 M_{sun} of dust: pre-existing or new dust?



Shahbandeh et al. 2024





Zsiros et al. 2024

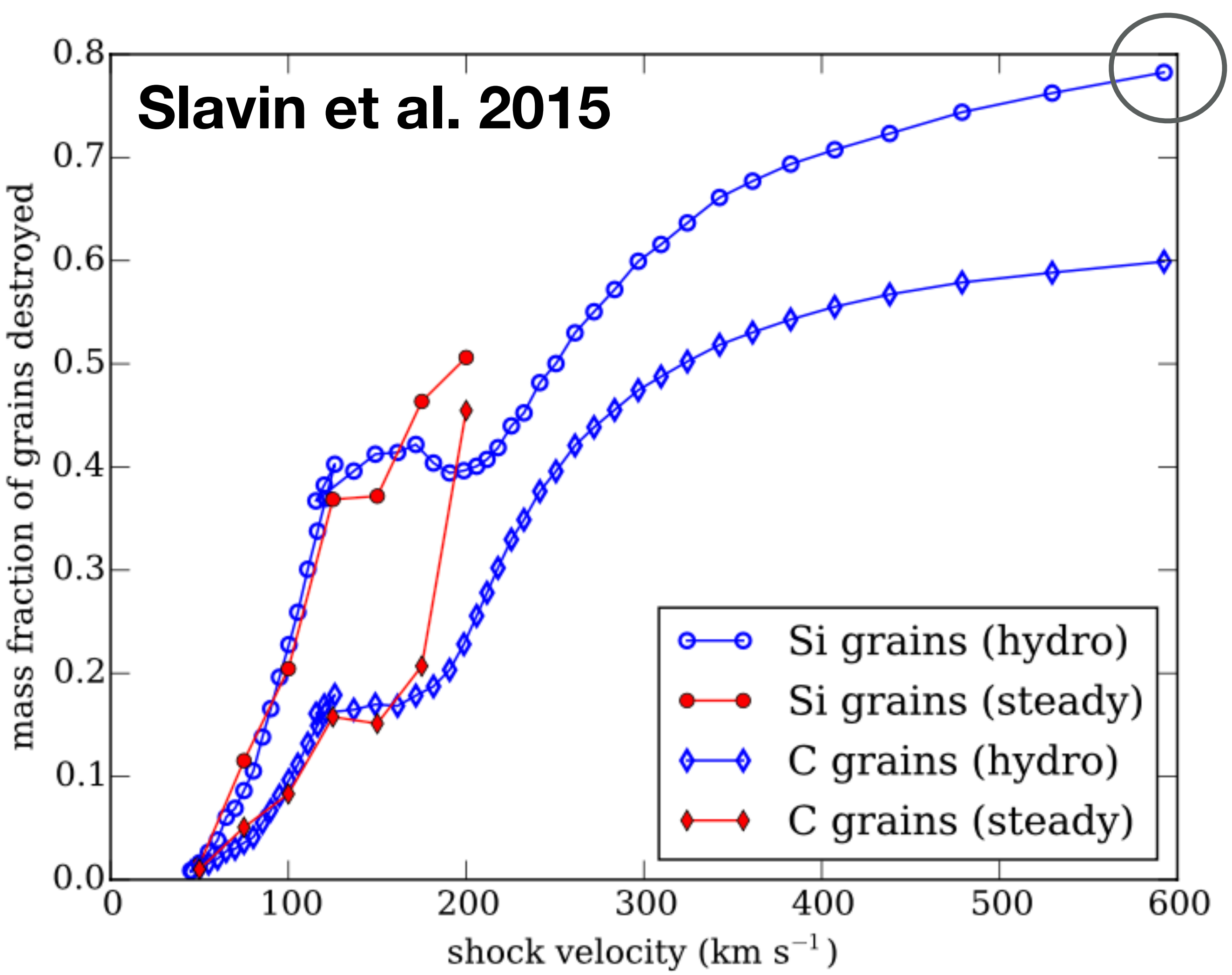
Talks by Shahbandeh and Ashall

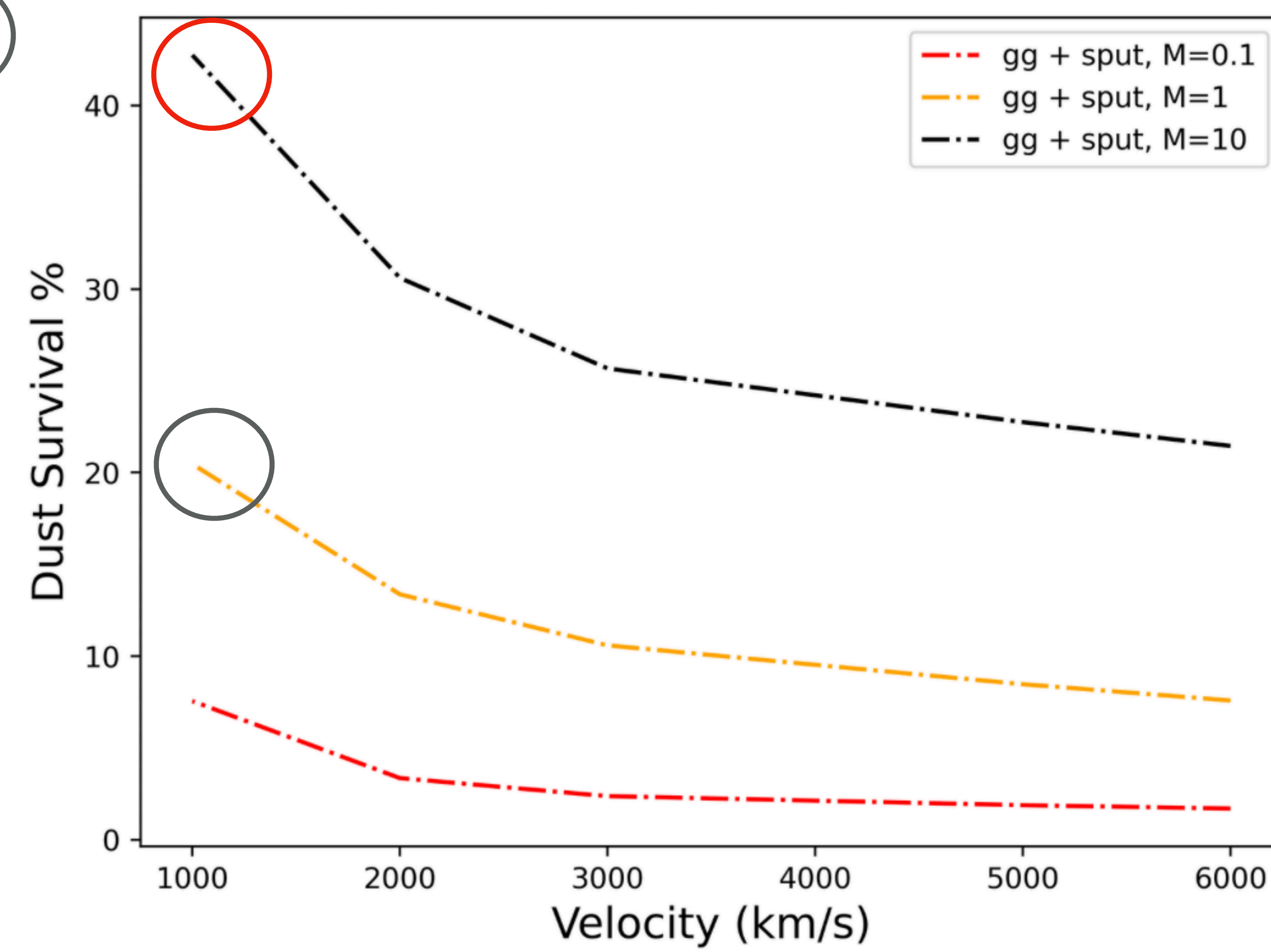
See Poster 6.13

Cycle 1 program ID2666 - PI: Ori Fox

Dust destruction in SNR

New efforts underway, II: plane-parallel shock fronts @ ≠ velocities





Sartorio, Kirchschlager, De Looze et al. prep