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Massive Stars with Infrared-Excess in the Young Supernova Remnant G54.1+0.3

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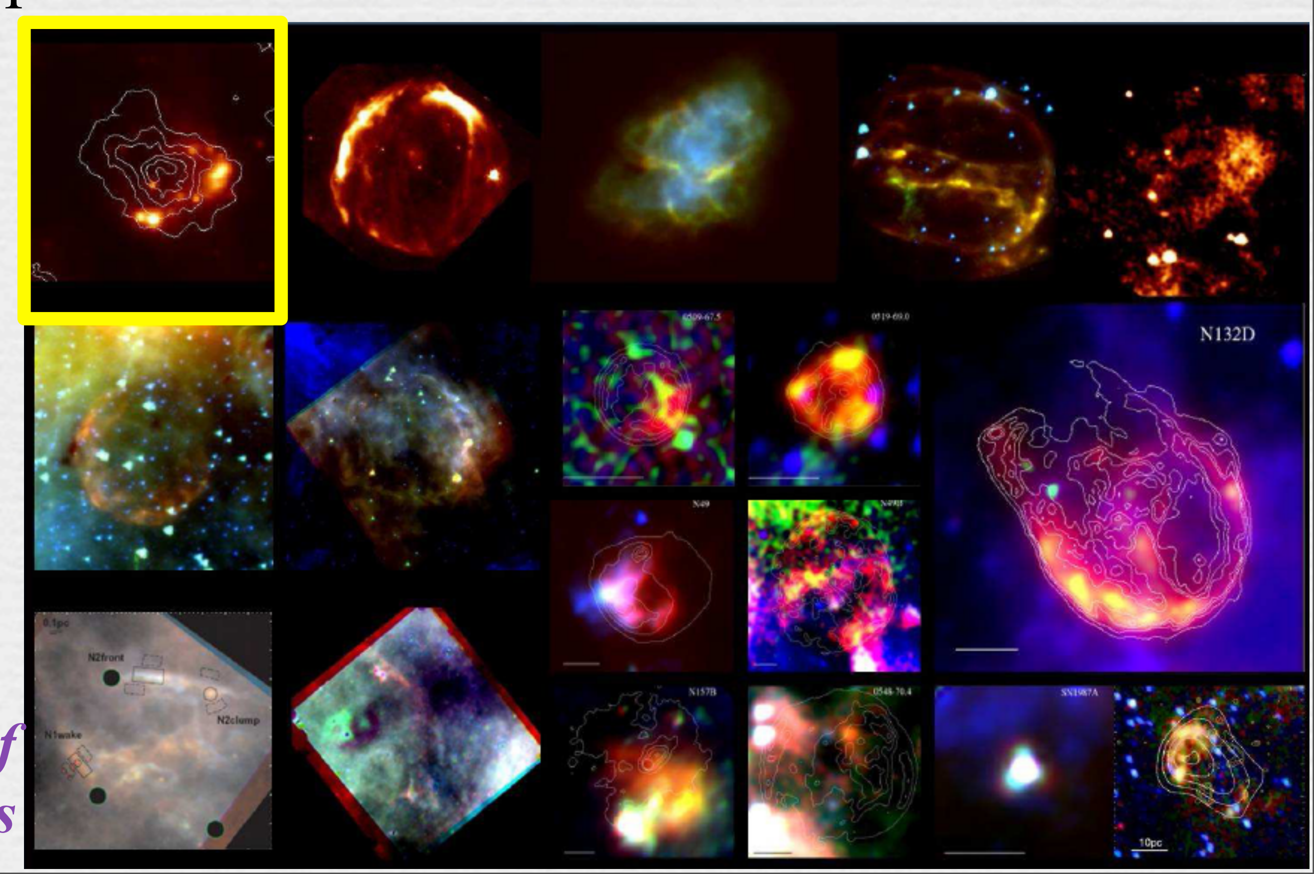
Massive Stars: Supernovae and Supernova Remnants

- **Supernova explosions** in galaxies
  - Sources of kinetic energy, heavy elements, and dust grains
  - Generate cosmic rays and hot gas phase, destroy dust grains, and trigger star formation.
  - Mostly **core-collapse SNe** with progenitor mass $\geq 8M_{\odot}$

- **Supernova Remnants** (in IR)
  - 20-30% of 274 Galactic SNRs in IR ***(Reach+2006; Goncalves+2011)***
  - MIR/FIR emission mainly from **thermal emission from dusts**
  - In Infrared, shock processing of dust grains, dust formation in SNe and in progenitors, the environment of SN explosion..

◆ **AKARI SNR Project (Koo et al.)**

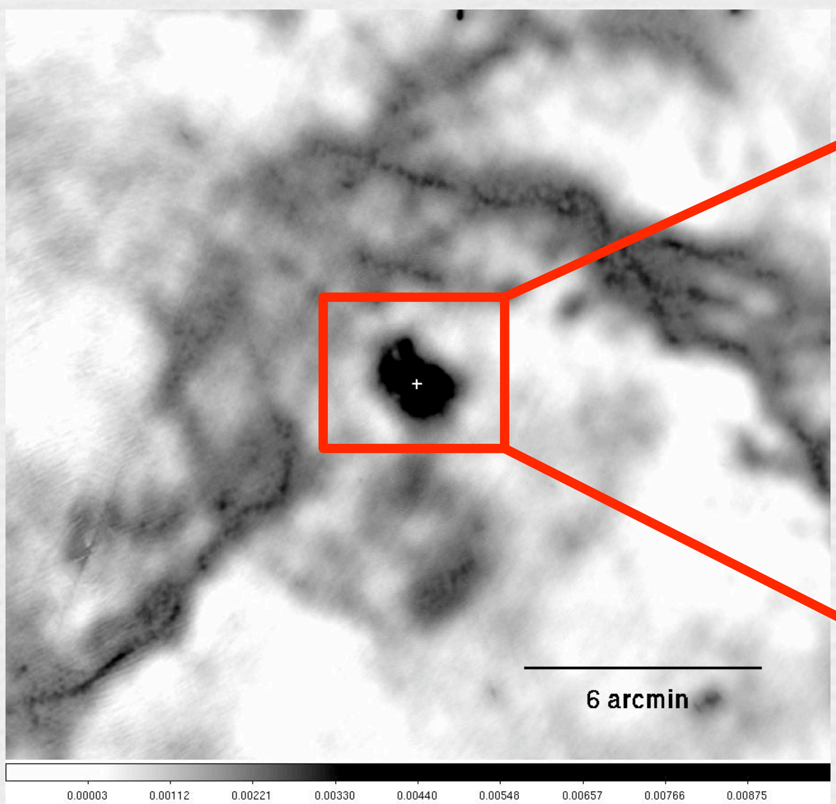


AKARI images of Galactic / LMC SNRs

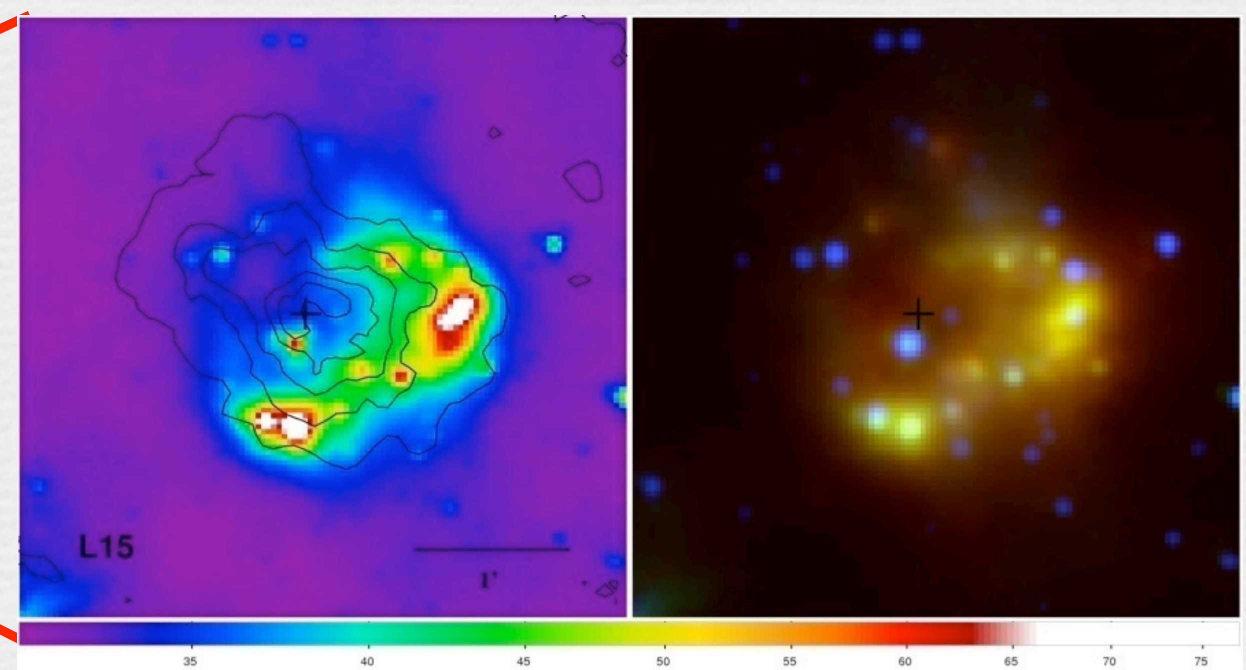
SNR G54.1+0.3

- **Young, composite SNR** @ 6-8 kpc
  - Crab-like SNR PWN (~ 3,000 yr)
  - SNR shell (Lang+2010; Bocchino+2010)
    cf. R_b=12. 6d_7 pc; n_0~0.1cm^{-3}, t=3,000 yr, M_{ej}=8

- AKARI observations (Koo+2008)
  - Bright, partially complete IR loop in the SNR
  - Point-like sources with strong MIR excess distributed along the IR loop
    - ➢ **IR-excess stellar objects**



VLA 20cm (Kurtz)

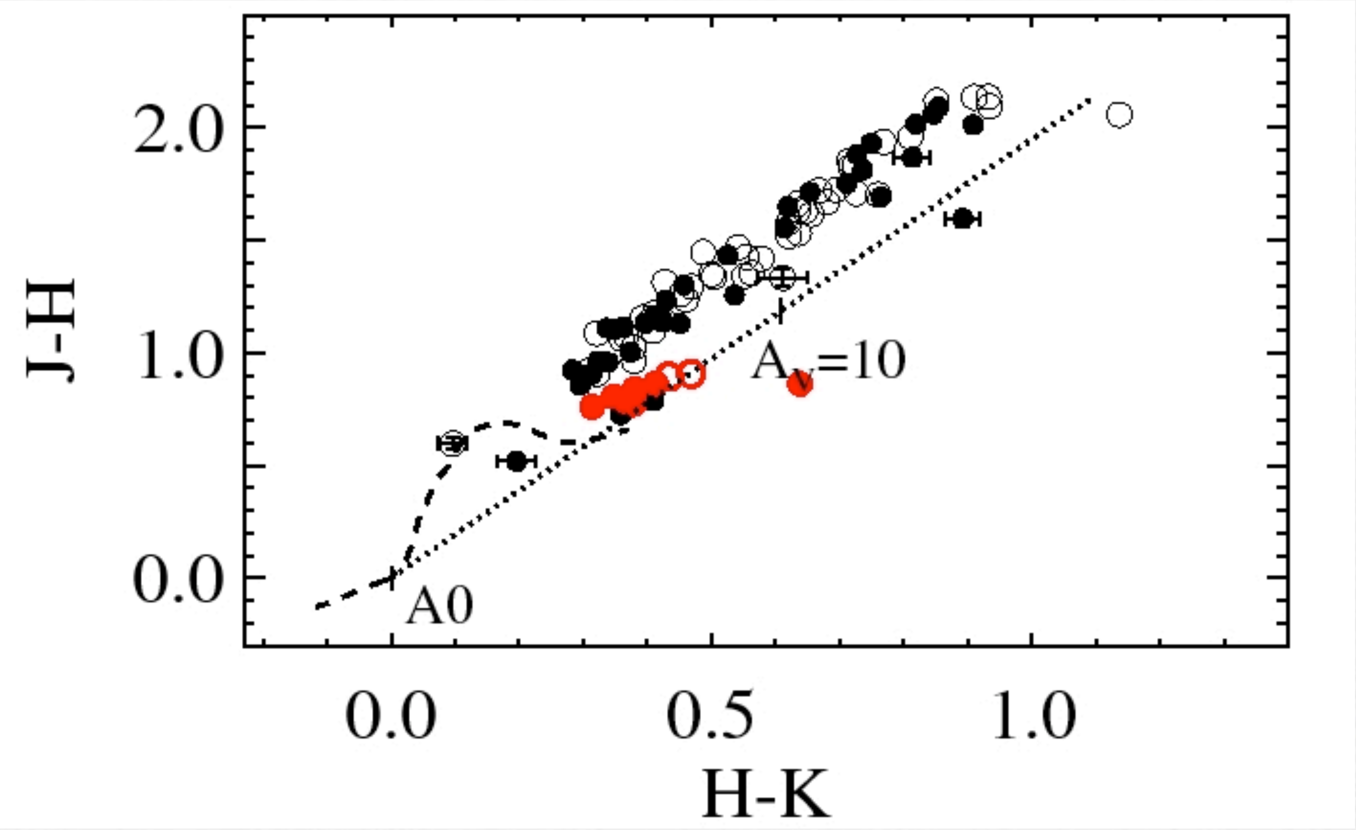


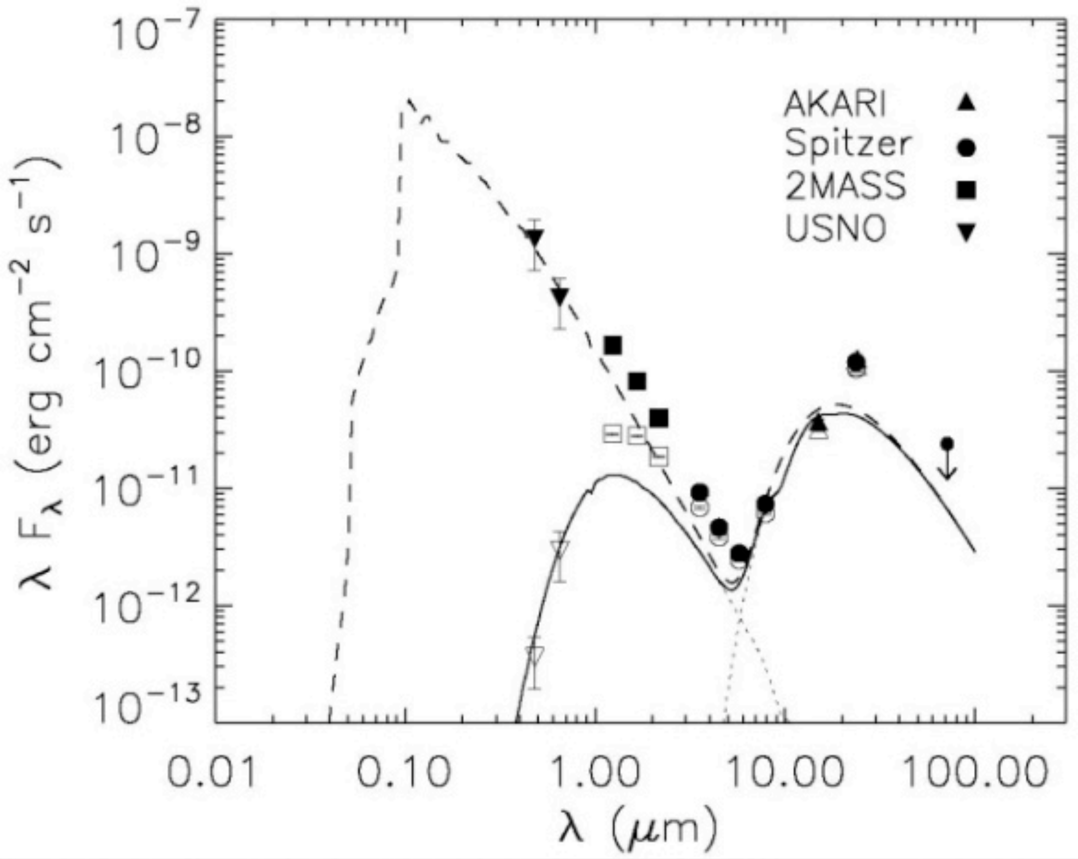
AKARI 15 μm(G)

Spitzer 5.8/24 μm(B/R) +AKARI 15 μm(G)

IR-excess Stellar Objects in G54.1+0.3

- JHK color-color diagram
  - clustered around **the positions of OB stars** with Av = 6.9-9.2 mag
  - not much near-IR excess
- Spectral energy distributions (SEDs)
  - **large mid-IR excess with a dip at 6-10µm**



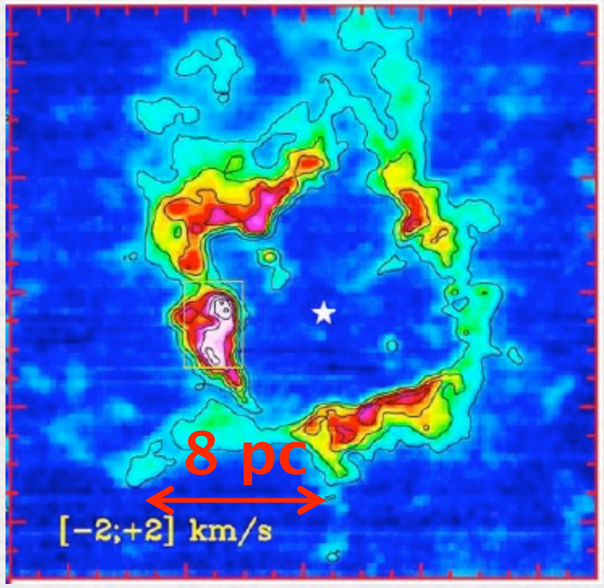


What is the origin of their IR-excess?

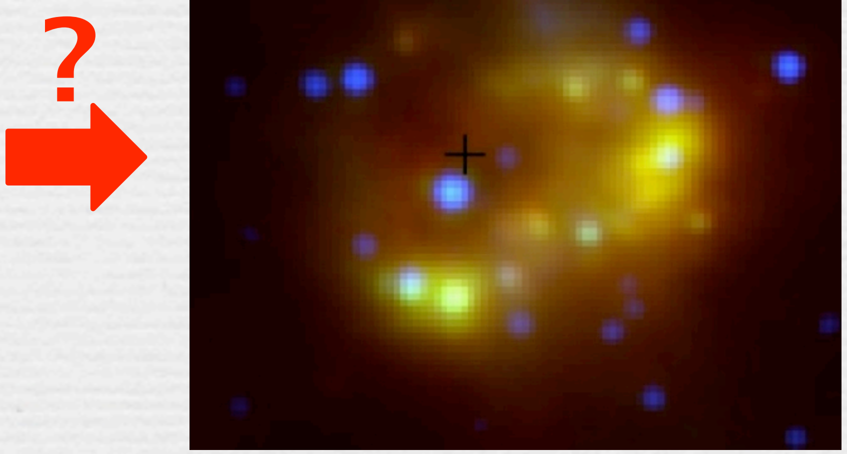
Origin of the IR-excess Stellar Objects (1)

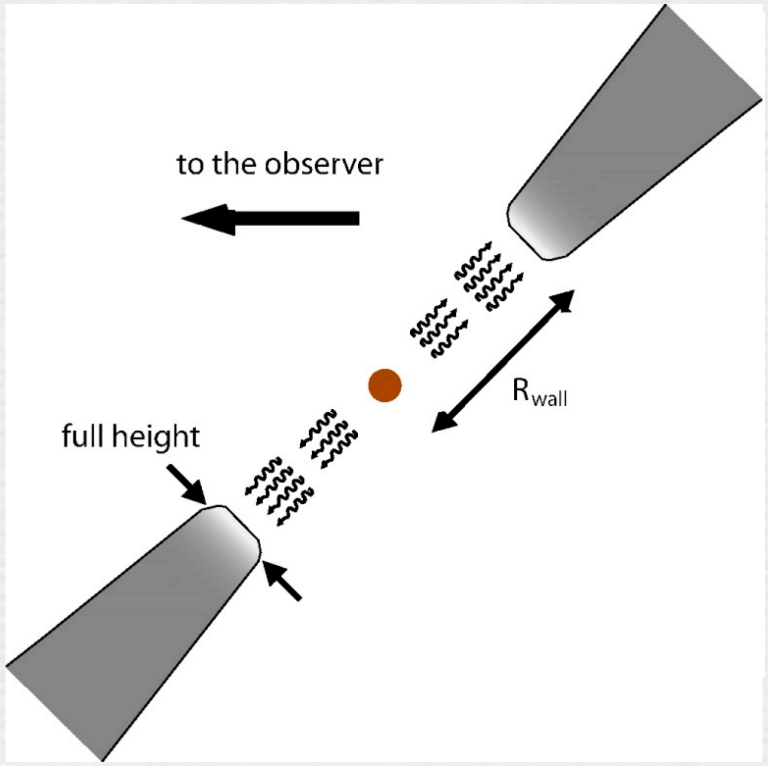
YSOs whose formation was triggered by the progenitor of G54.1+0.3
(Koo+2008)

- YSOs without much CSM (e.g. Herbig A/Be stars)
- IR emission originates **from remnants of massive star formation**.



Sh 104 (Deharveng et al. 2003)



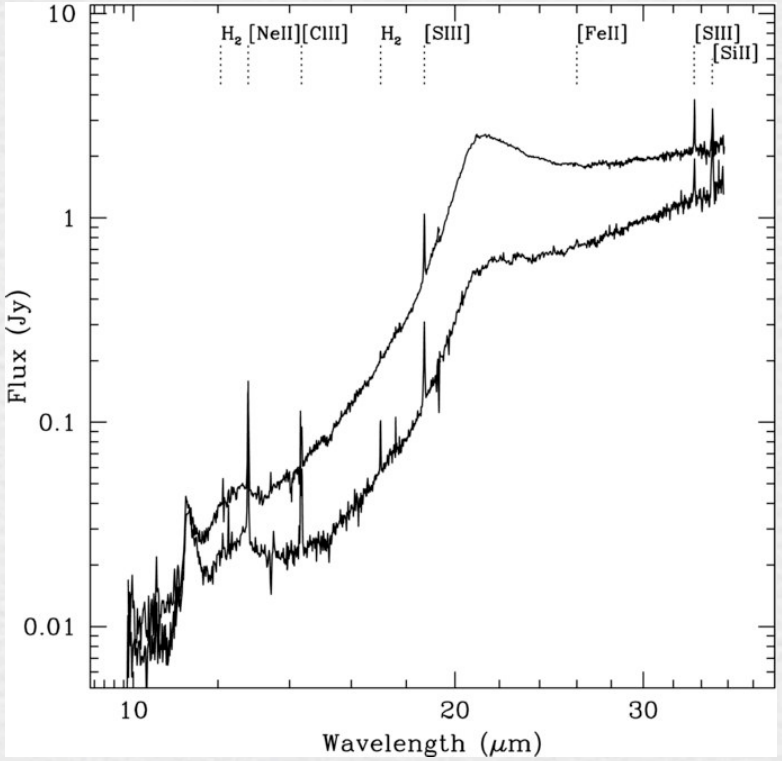


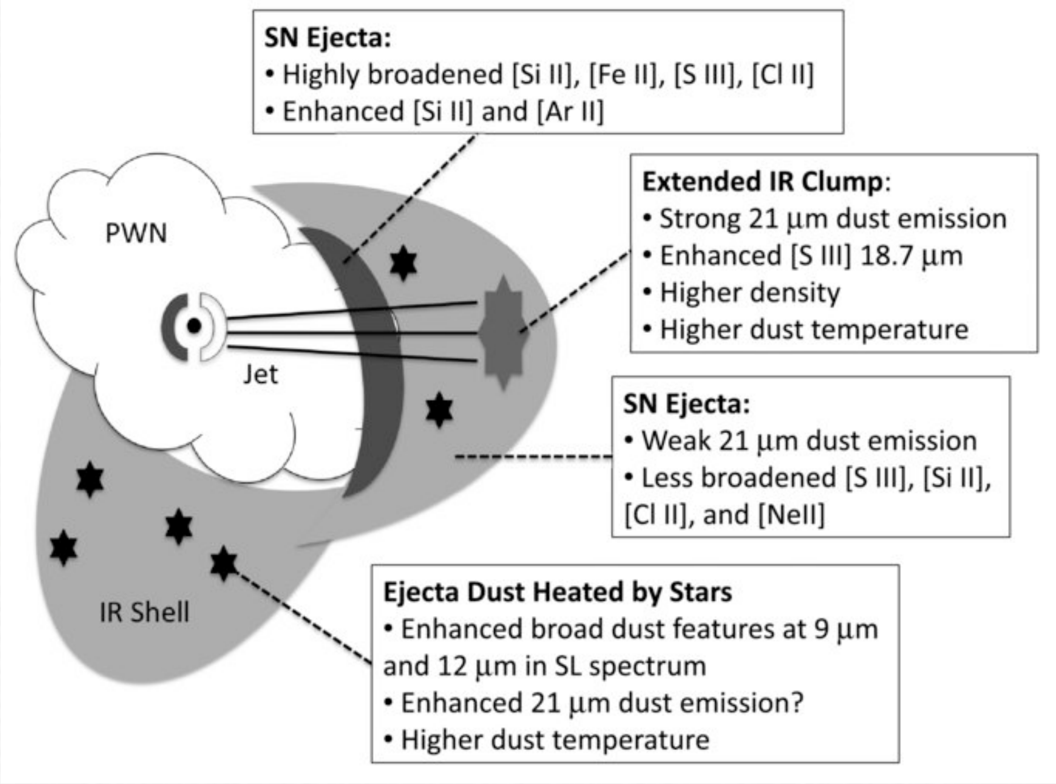
(D'Alessio et al. 2005)

Origin of the IR-excess Stellar Objects (2)

Early-type stars belonging to a cluster in which the SN exploded ***(Temim +2010)***

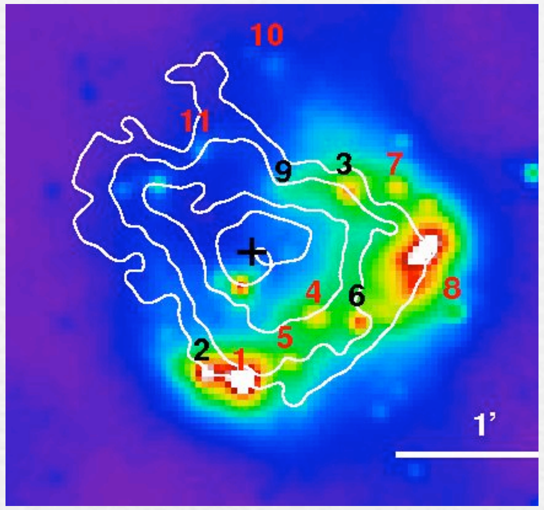
- Spitzer IRS spectrum of the IR loop similar to the spectrum of freshly-formed dust in Cas A
- IR emission originates **from the SN ejecta heated by the IR-excess stellar objects**

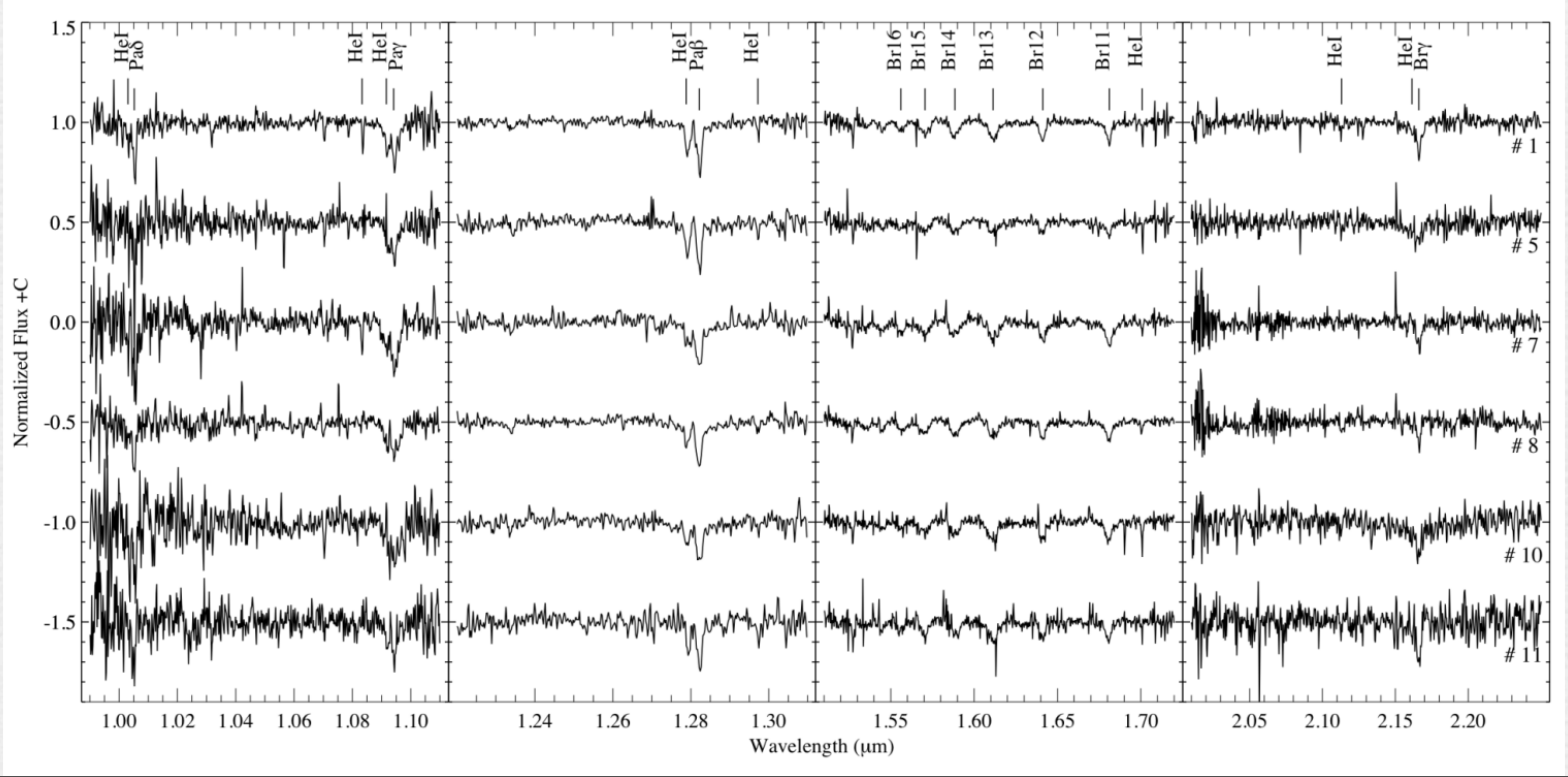




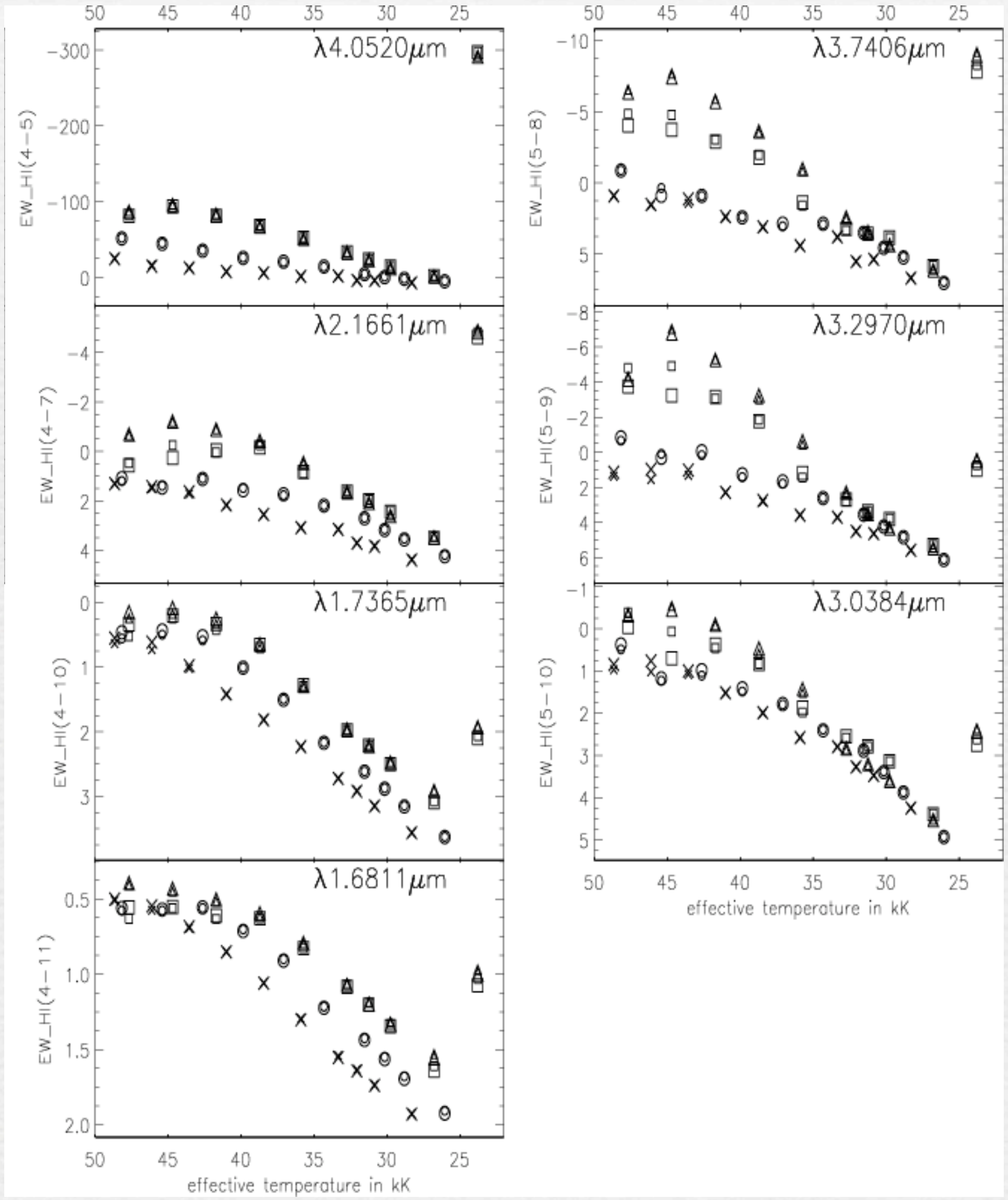
NIR Spectroscopy of the IR-excess Stellar Objects

- TripleSpec on Palomar Hale 5-m telescope (August 2008)
  - 1-2.4 μm (R ≈ 2500); 1″ x 30″ slit
  - 7 out of 11 objects; S/N = 5-30
- Moderately strong H lines, weak He I lines, no He II line
  - ➢ **Late O to early B stars (O8-B3)** *(Hanson+1996; 1998; 2005)*





Spectral Type Classification



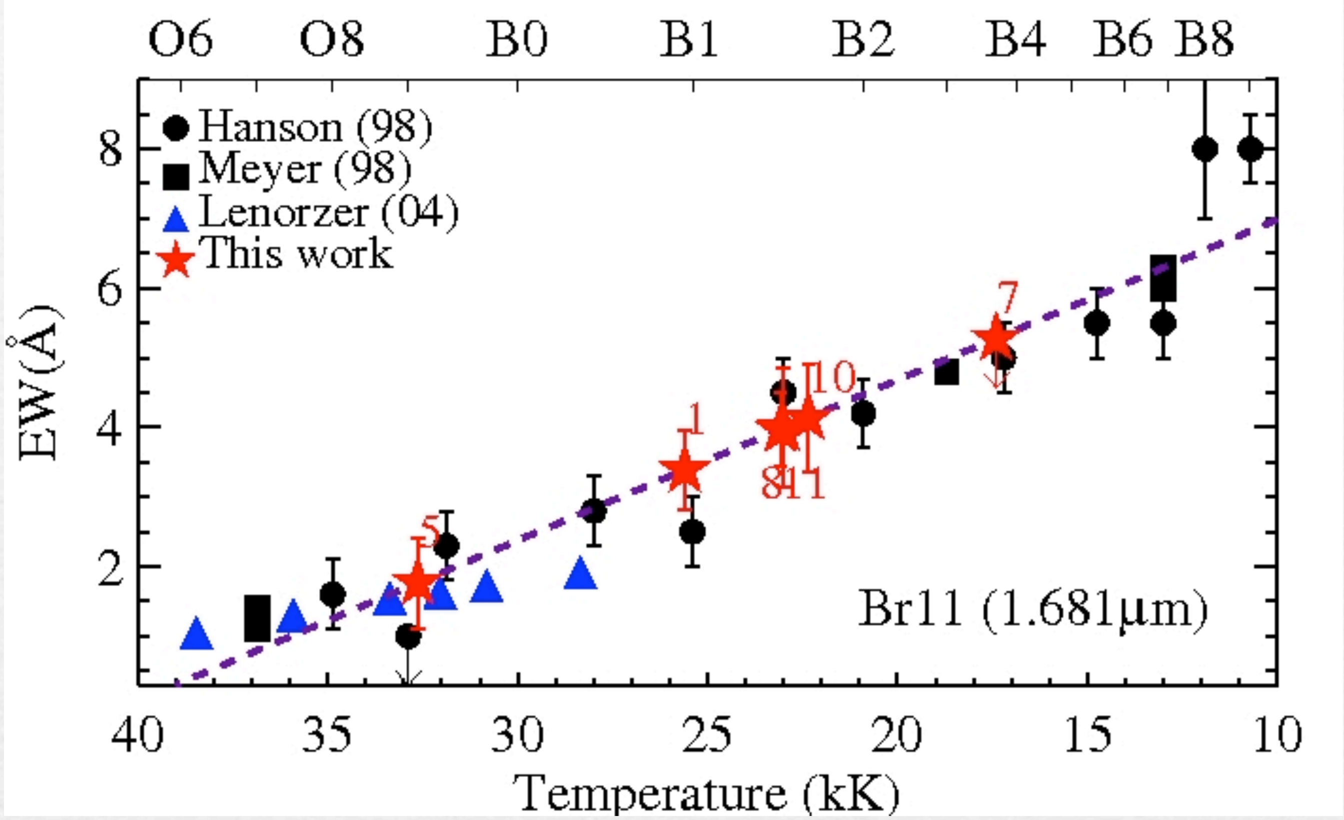
Lenorzer et al. (2004)

- Line ratio
- Direct comparison with spectral library
- Synthetic spectrum
- Theoretical NIR spectrum modeling

  → Temperature-sensitive Hydrogen lines.

➢ **Empirical relation bet. *EWs* and T_{eff}?**

Relation between *EW*s of hydrogen line & Temperature

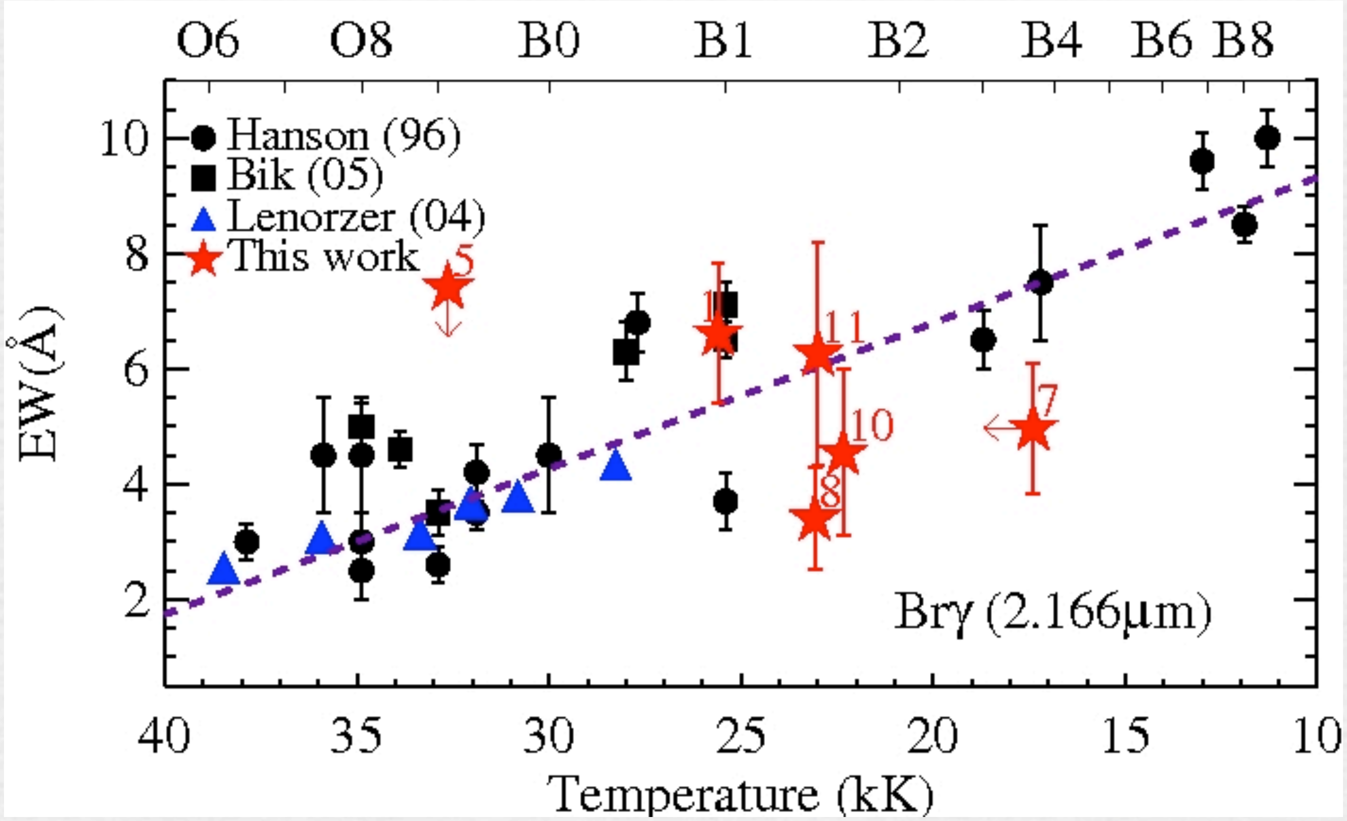


EW_{Br11}[Å] =

-0.23(±0.02) x (T_{eff} [kK]) + 9.29(±0.46)

$EW_{Br\gamma}$[Å] =

-0.25(±0.01) x (T_{eff} [kK]) + 11.84(±0.33)

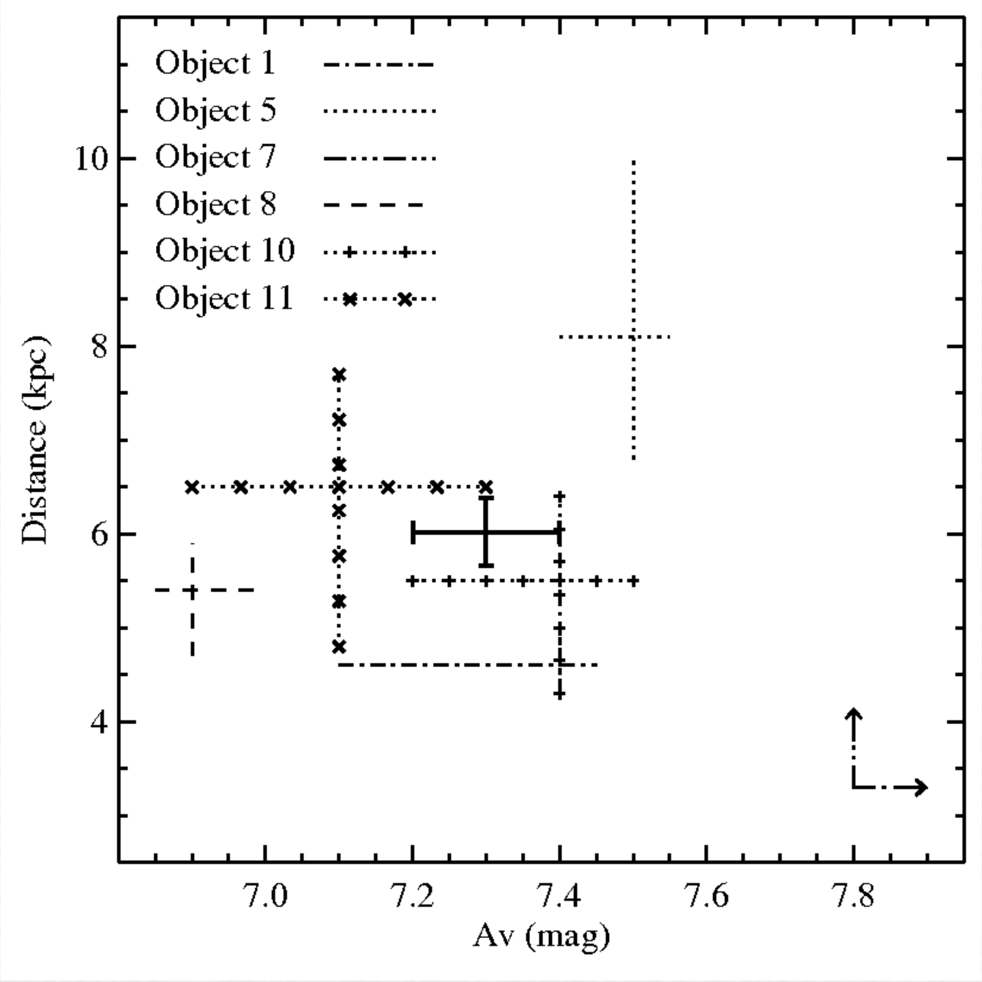


- **Sp. Type from EW_{BR11} – T_{eff} : O9-B2 (±0.5-1 subclass)**

Object	1	5	7	8	10	11
Sp. Type	B1	O9	< B3.5	B1.5	B1.5	B1.5
	(B0.5-B1.5)	(O7.5-B0)	-	(B1-B2)	(B1-B3)	(B1-B2.5)
Teff (kK)	26 ± 2	33 ± 3	> 17	23 ± 2	22 ± 3	23 ± 4

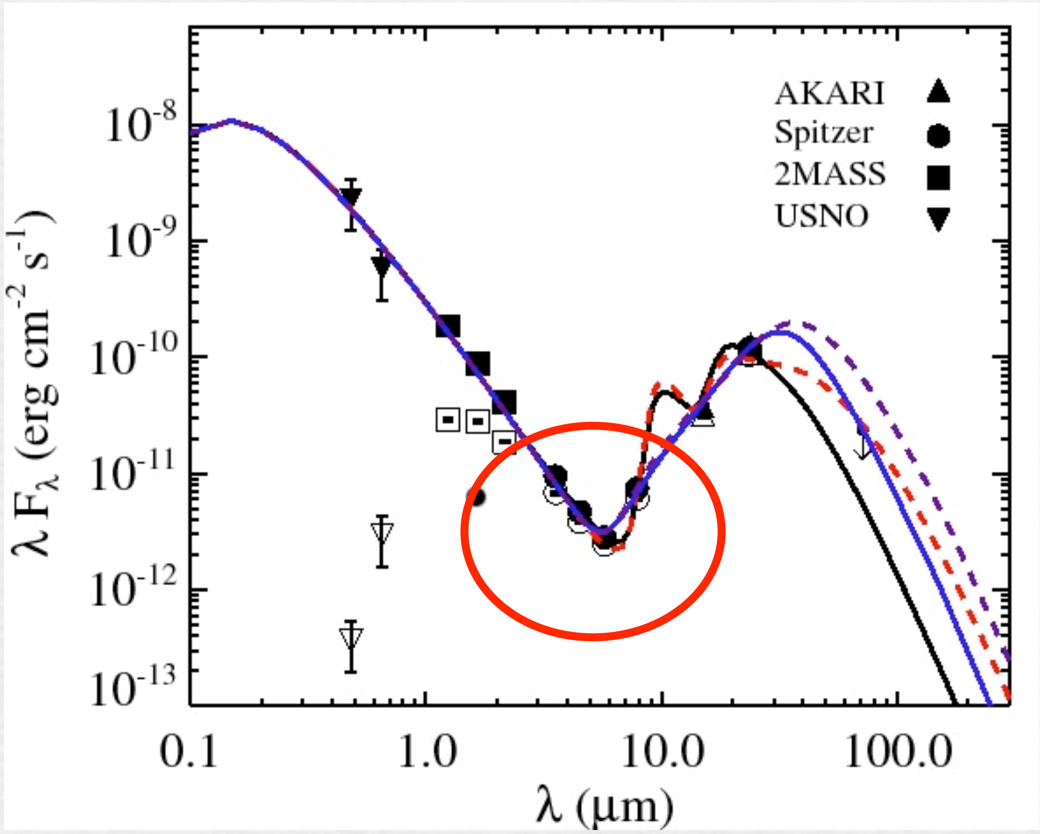
Distance to IR-excess Stellar Objects & G54.1+0.3

- Sp. Type + SED
  → d = 6.0 ± 0.4 kpc; Av = 7.3 ± 0.1 mag
- Av ≈ 8 mag from X-rays
- Other distance estimates
  - HI absorption
    : 5-10 kpc ($R_\odot$ = 8.5 kpc)
  - Pulsar DM
    : $9^{+1}_{-1.5}$ kpc
    (Camilo+2002; Cordes-Lazio NE2001)



Modeling of Spectral Energy Distribution

- From SED of the IR-excess stellar objects,
  → **circumstellar dusts located at a distance from the stars**
- Simple SED modeling of Object 1 (TRANSPHERE, Dullemond+2002)
  – blackbody of a B1V star (T=26,000 K; L=17,000$L_{\odot}$)
  – 1-d, spherically symmetric shell of a single dust (0.1 μm silicate; graphite)
  – power-law density distribution (p= 0; -1)



silicate (p=0); silicate (p=-1)
graphite(p=0); graphite(p=-1)

- Position and intensity of a dip ~ ***R_{in} & $\rho_{dust,Rin}$***
  – smaller R_{in}, / higher ρ, a dip at shorter λ
- Difference between different dusts

silicate	graphite
a sharp dip ~ 7μm	smooth around the dip
R_{in} = 50-530 AU, ~ density slope, p	R_{in} ~ 2000 of AU, similar in both slopes

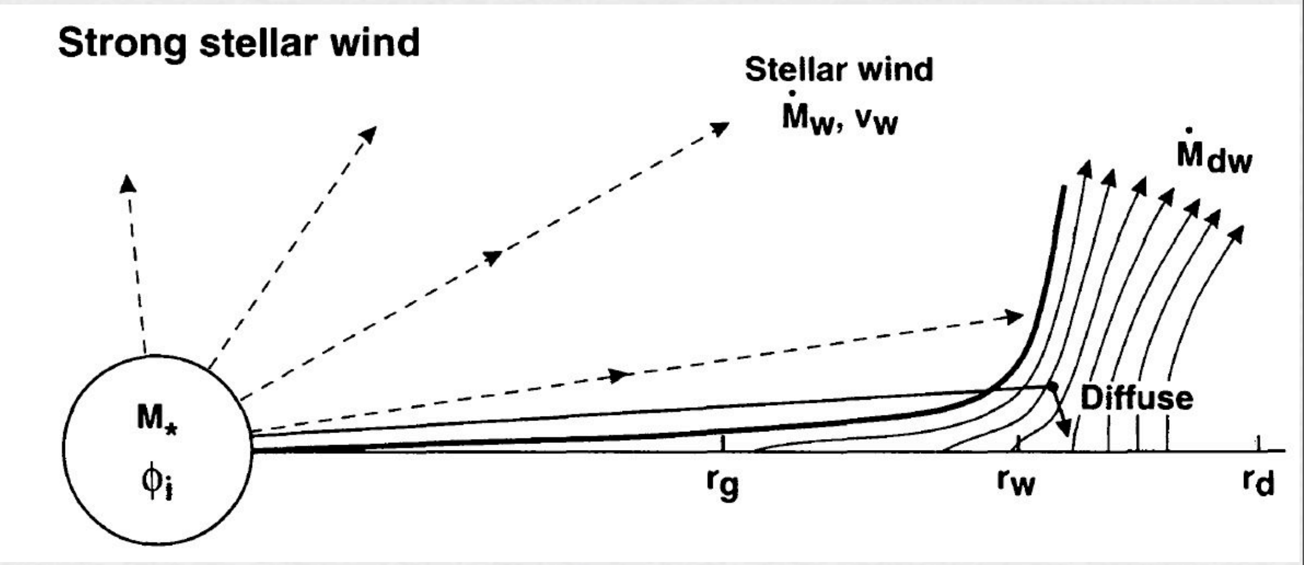
➢ **Models highly rely on dust properties (e.g. size, composition) and we need further observations in MIR (N-band).**

e.g. 0.5 μm silicate model (p=-1) : R_{in} = 75 AU

Implications on Origin of IR-excess Stellar Objects

1. YSOs triggered by the progenitor of the SN : IR emission from the remnant of circumstellar material

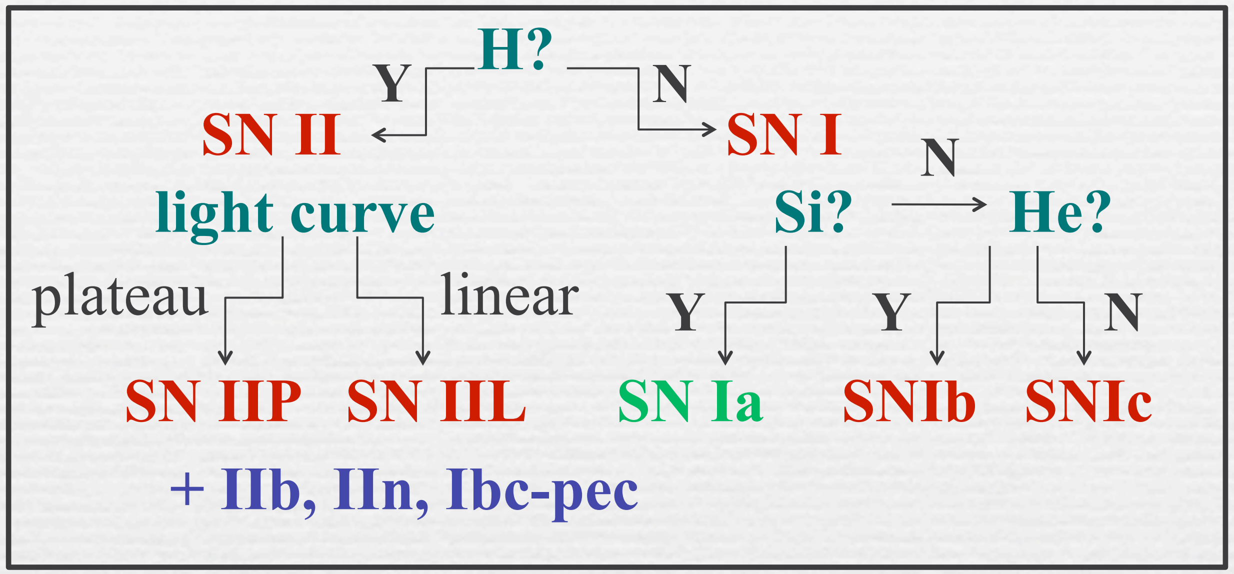
- Weaker MIR/lack of NIR excess than most of Herbig Ae/Be stars
  → large inner radius and large fraction of material already cleared out
    - R_{in} : < 50 (p=0); 530 (p=-1) AU for silicate; ~ 2000 AU for graphite
- Disk dispersion mechanism: **photoevaporation** ***(Hollenbach+1994;2000)***
  – rapid destruction of outer disk (> r_g)
  – destruction of inner disk by winds
  – late O-/early-B : **> 150 AU will be first destroyed** in 10^5-10^6 yrs (Bik+2006)



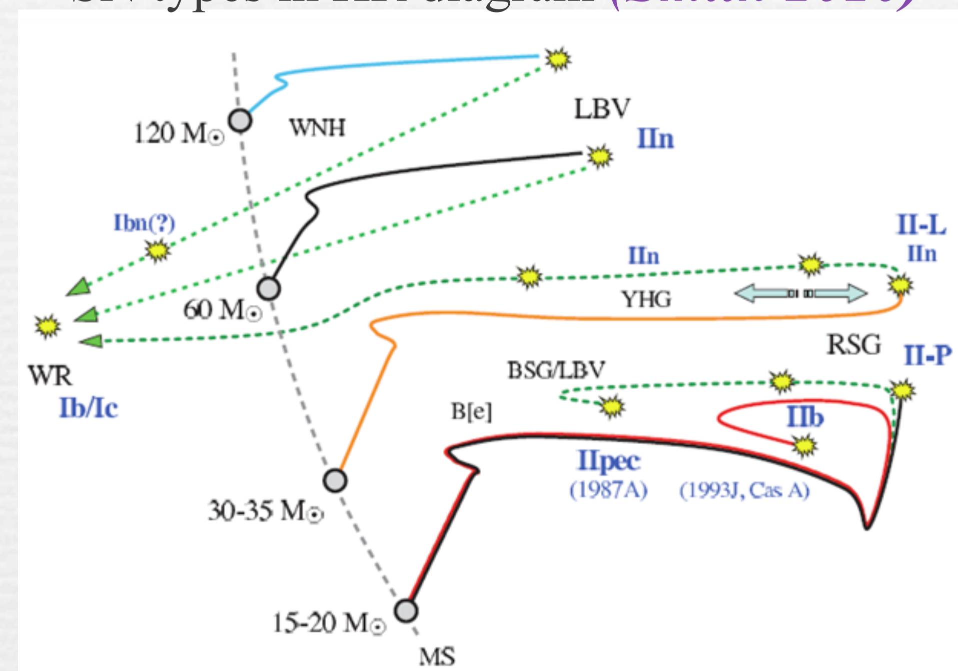
➢ **Rather uniformly distributed silicate or large dust grains?**

2. Stellar cluster where the SN exploded : IR emission from newly-formed SN ejecta

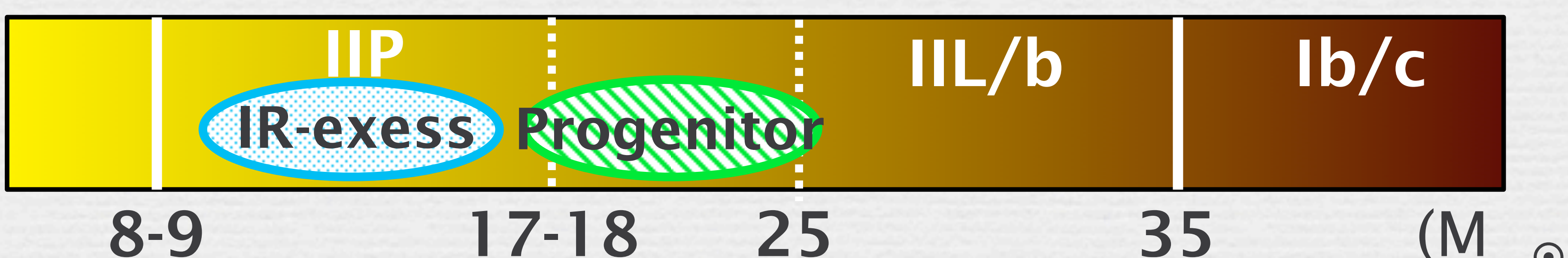
Mass of the progenitor of G54.1+0.3



SN types in HR diagram *(Smith 2010)*



- IR-excess stellar objects : **10-17 $M_\odot$** → **> 17 $M_\odot$**
  - Ib/c? – absence of 17-35$M_\odot$ stars
  - IIL/b? – lack of evidence showing circumstellar interactions (Chevalier 2005)

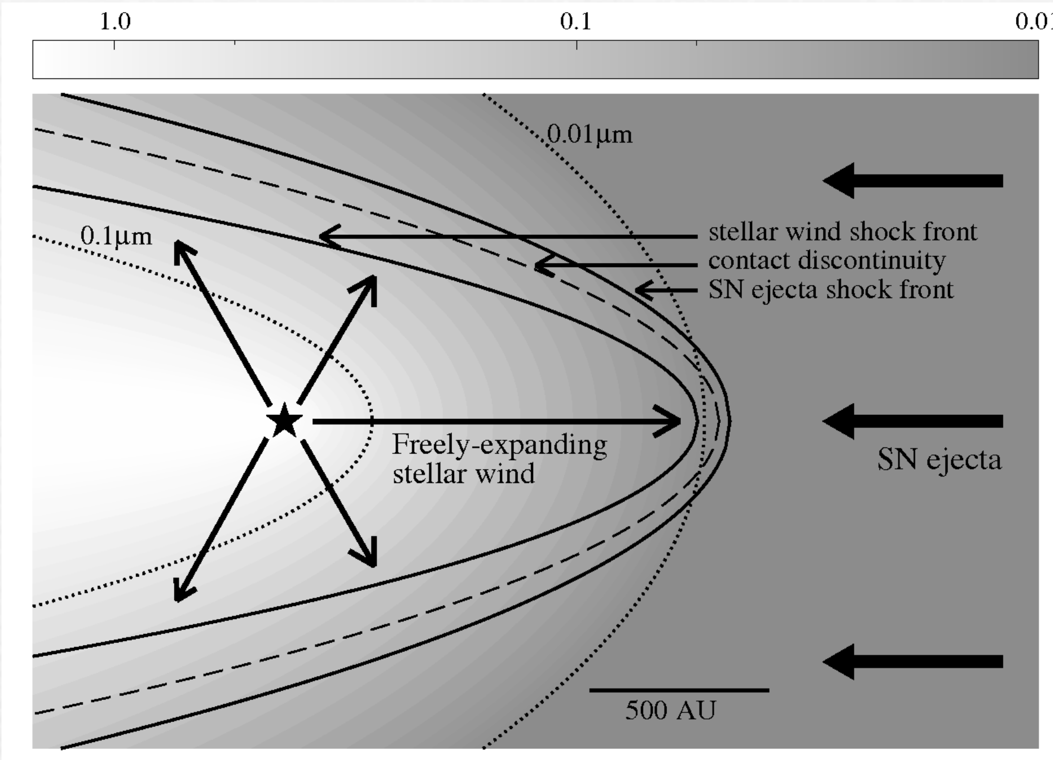


cf. **IIP vs. IIL/b** :
(Smith+11) ~ 18
(Heger+03) ~ 25

➢ **The progenitor mass : 18-25 $M_\odot$, at the high end of Type IIP**

➢ If a SN explodes in a cluster, we can use the cluster members to derive the progenitor mass.

Dust distribution around IR-excess stellar objects

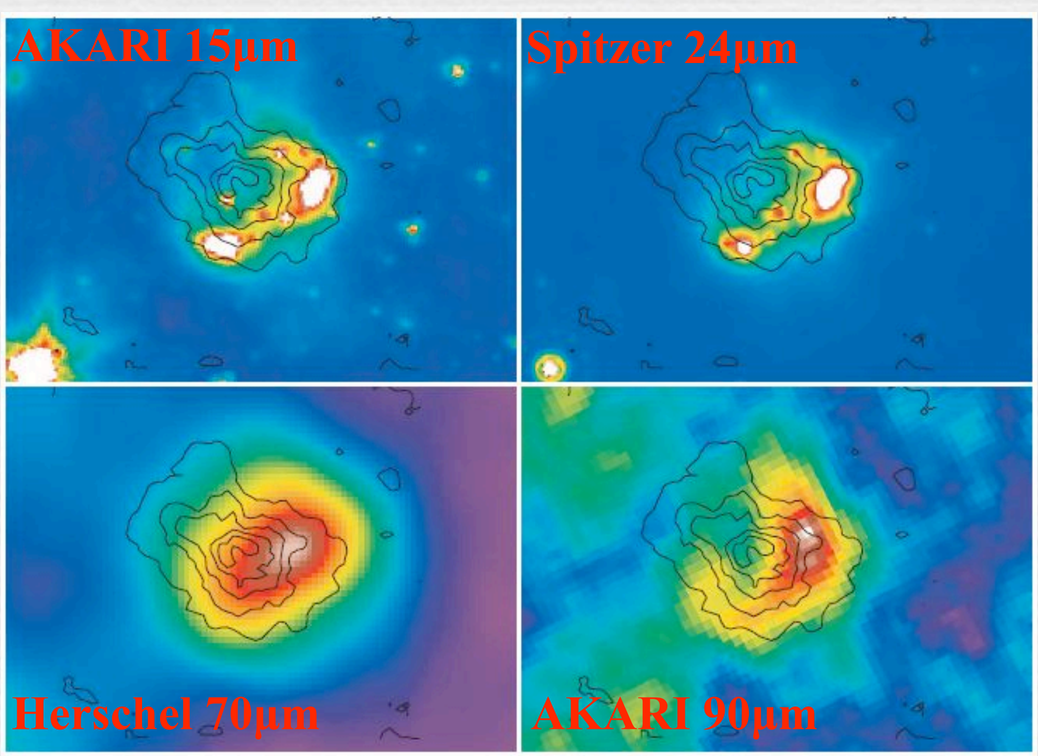


- Radiation pressure → **dust avoidance zone, r_{av}**
  (Artymowicz & Clampin 1997)
- Interaction between stellar winds and SN ejecta
  →bow-shock structure, r_{bs}

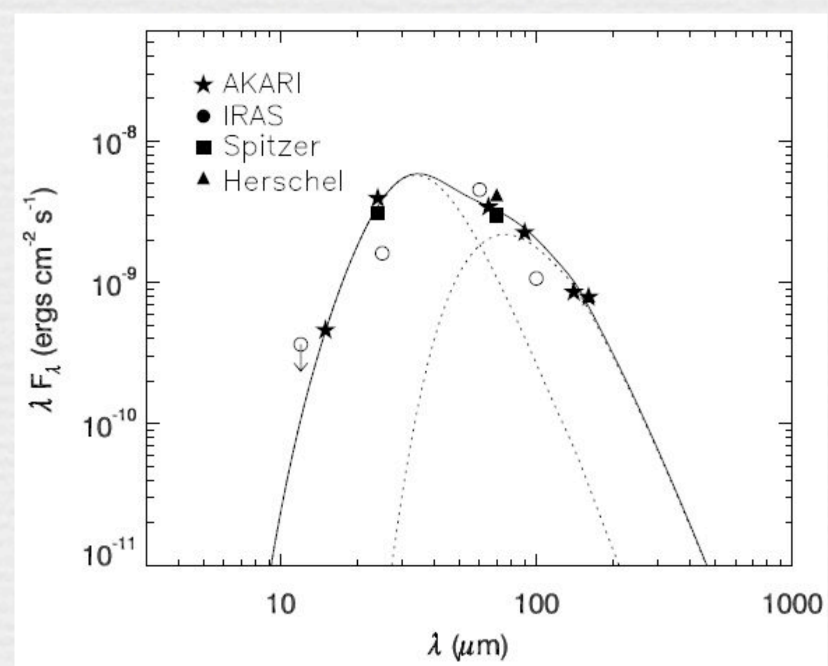
r_{bs} ~ 1,300 AU
silicate: r_{av}(0.1/0.01μm) ~ 170/600 AU
graphite: r_{av}(0.1/0.01μm) ~ 290/1,350 AU

➢ **Dependent on dust property; larger dusts tend to exist close to the stars**

Dust mass of the infrared loop from FIR (preliminary)



(Koo 2012)



silicate =
1.3 $M_\odot$@31K +
0.0016 $M_\odot$@96K

graphite =
0.54 $M_\odot$@31K +
0.0092 $M_\odot$@81K

Summary

- NIR spectroscopy of the IR-excess stellar objects embedded in the young, composite SNR G54.1+0.3 has shown that they are massive (O9-B2) stars.
  - d = 6.0±0.4 kpc; Av = 7.3±0.1 mag
- We have found a good correlation between observationally measured EWs of hydrogen lines and temperature in early-type stars. Confirmation using more lines and samples will be helpful in future study.
- Our NIR spectroscopy results and simple SED modeling give some implications on the two scenarios on the origin of the IR-excess stellar objects.

  i) YSOs triggered by the progenitor: if we adopt a current disk dispersion mechanism, rather large dust grains would be located near the central stars.

  ii) SN explosion in a stellar cluster: from the spectral types of the IR-excess stellar objects, the progenitor mass would be constrained as 18-25 $M_{\odot}$. Dusts distribution would be controlled by radiation pressure of the IR-excess stellar objects, and it also implies rather larger dust grains would be located close to the central stars.