(Wind-blown) bubbles in the Galaxy

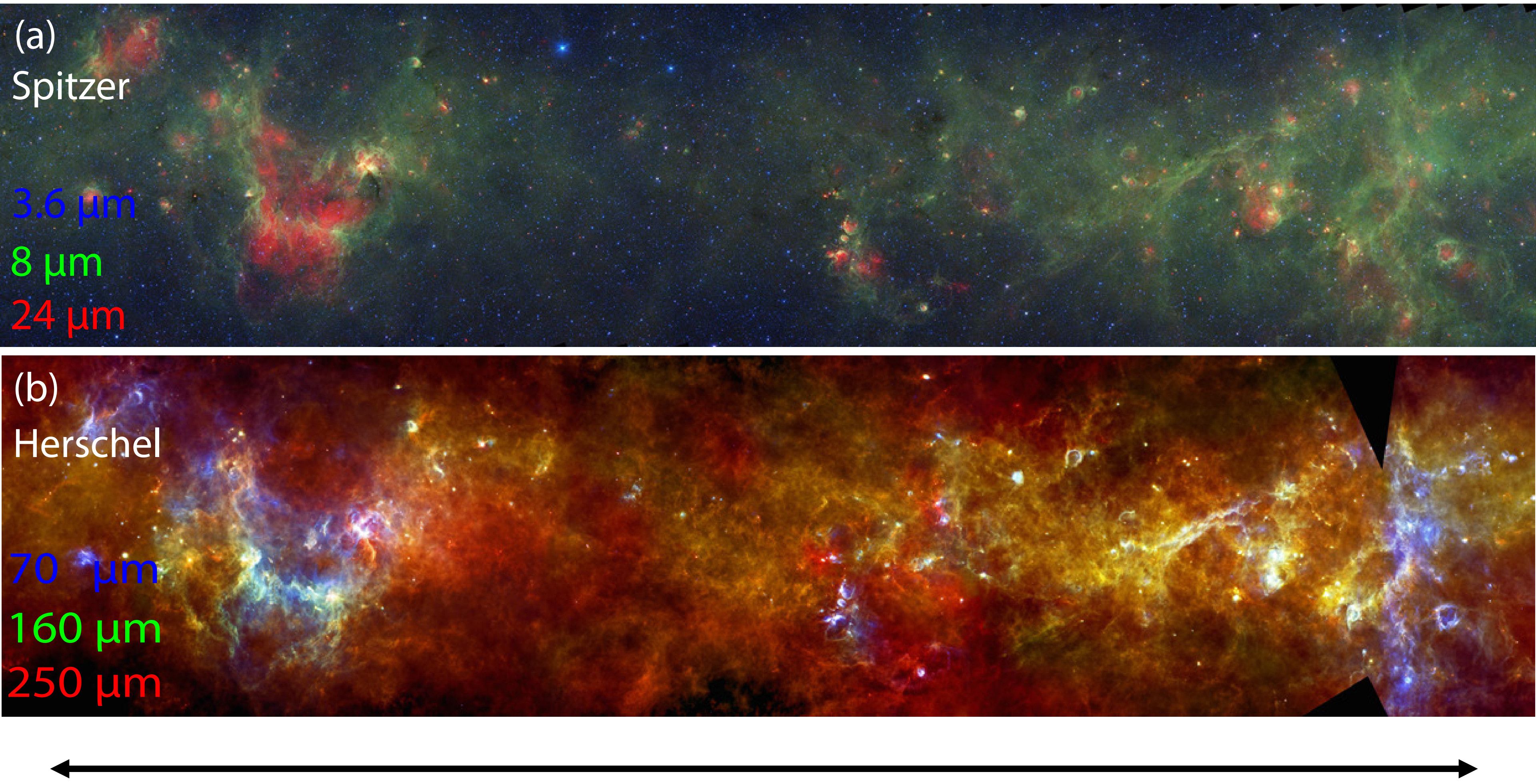
Bram Ochsendorf

Johns Hopkins University

Outline

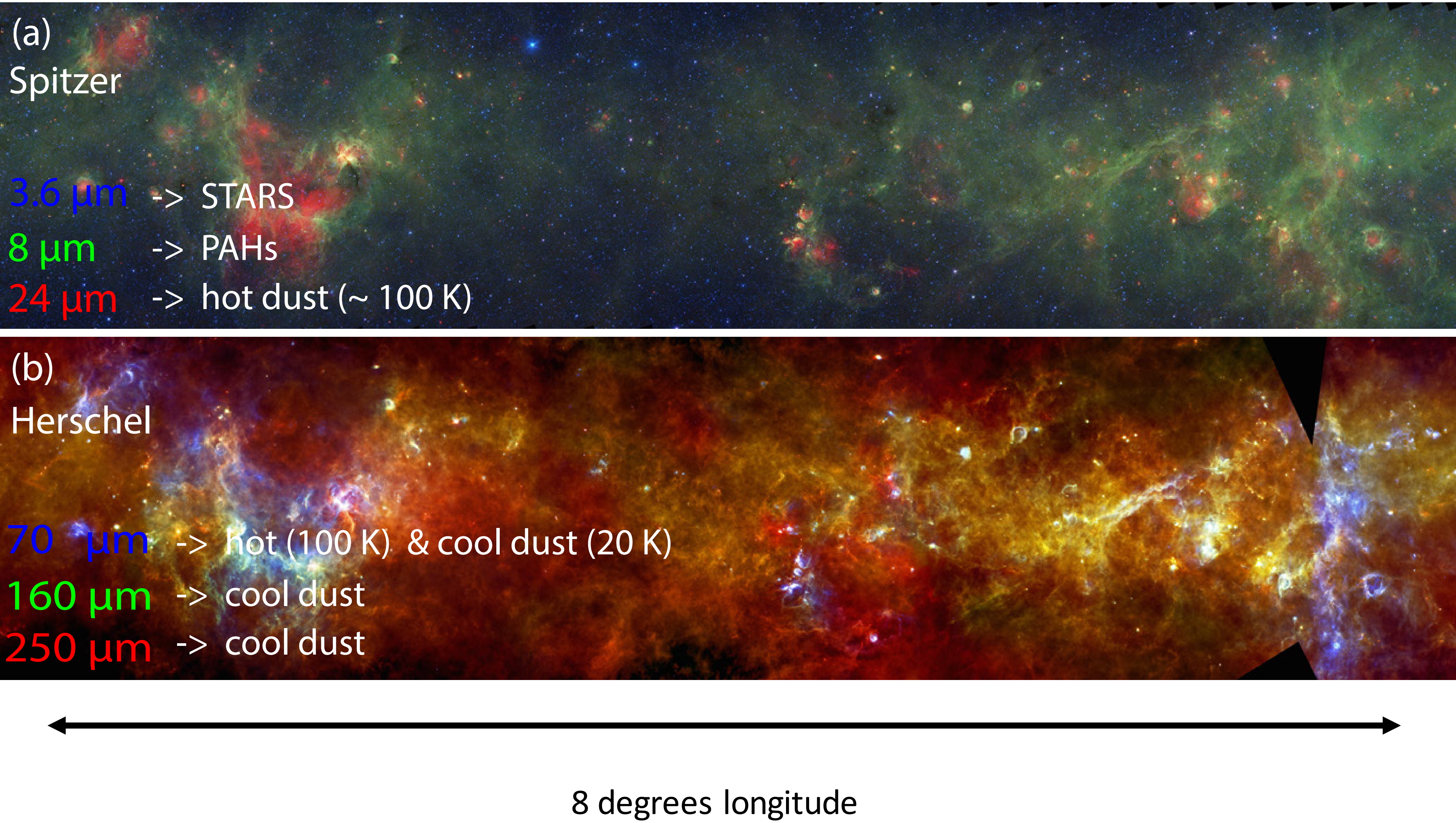
- Overview of bubbles in the Galaxy
    - Galactic surveys
    - Tracers and morphologies
- Driving mechanisms
    - stellar winds vs. ionization vs. supernovae
- Wind-blown bubbles: challenges
    - (missing) X-rays
    - Weak-wind problem
    - Dust inside bubbles
- Alternative to the wind-blown mechanism
    - Dust waves
- Bubbles around low-mass stars
- Summary

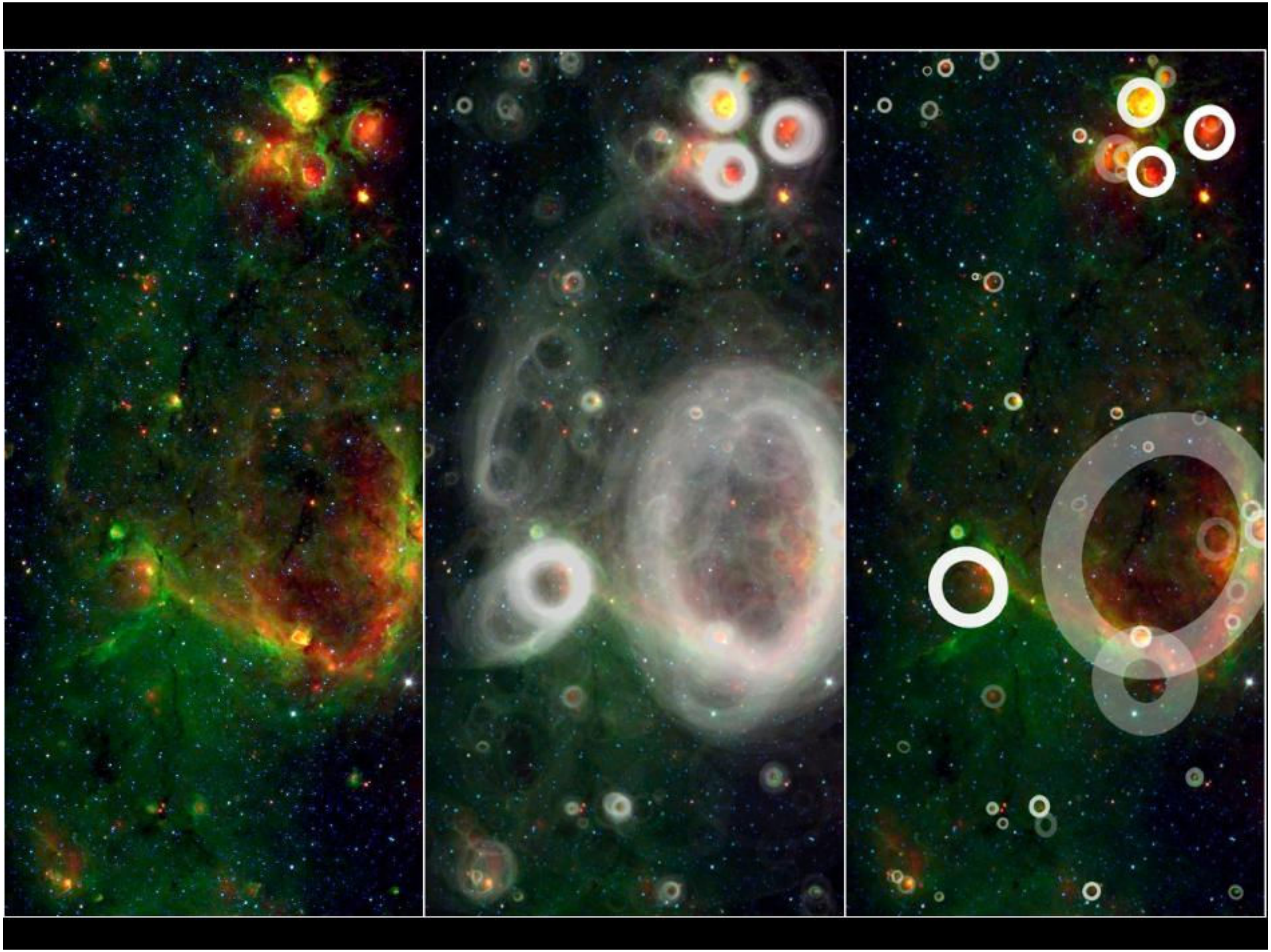
Opening up of the infrared sky



8 degrees longitude

Opening up of the infrared sky



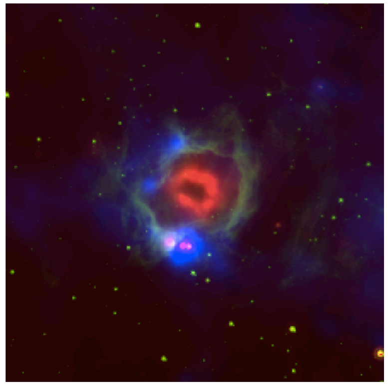


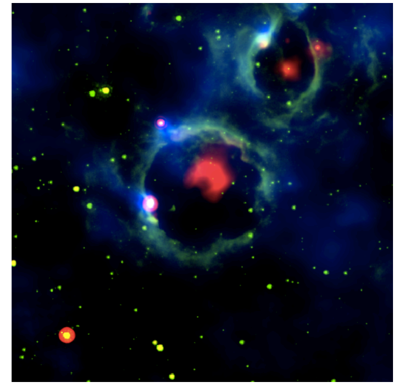
- The Milky Way project identified over 5000 bubbles (Simpson et al. 2012)

Bubble morphologies

Red: 24 μm
Green: 8 μm
Blue: 250 μm

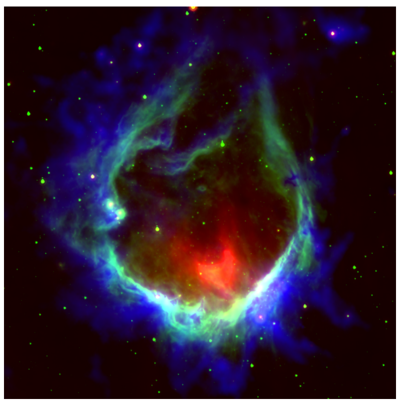
Closed bubbles

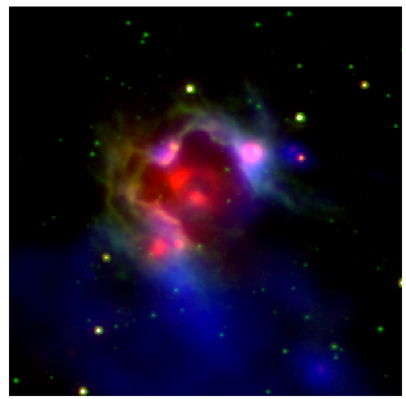


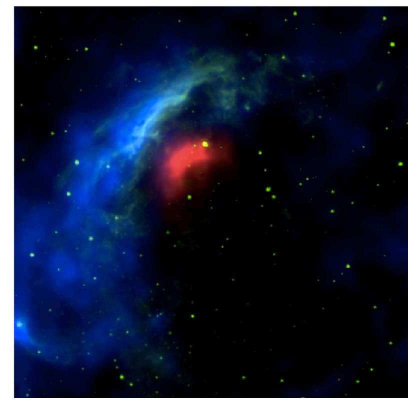


~1-10 pc
~ few Myr

Open bubbles

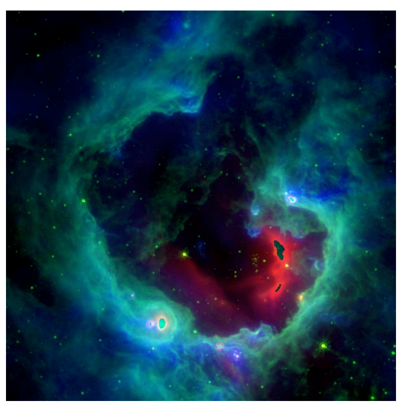


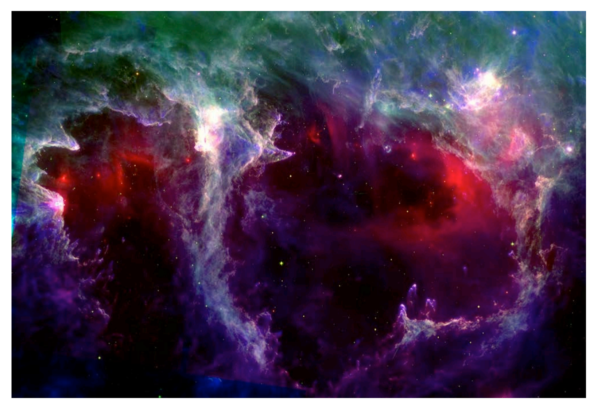




~1-10 pc
~ few Myr

'Large' bubbles

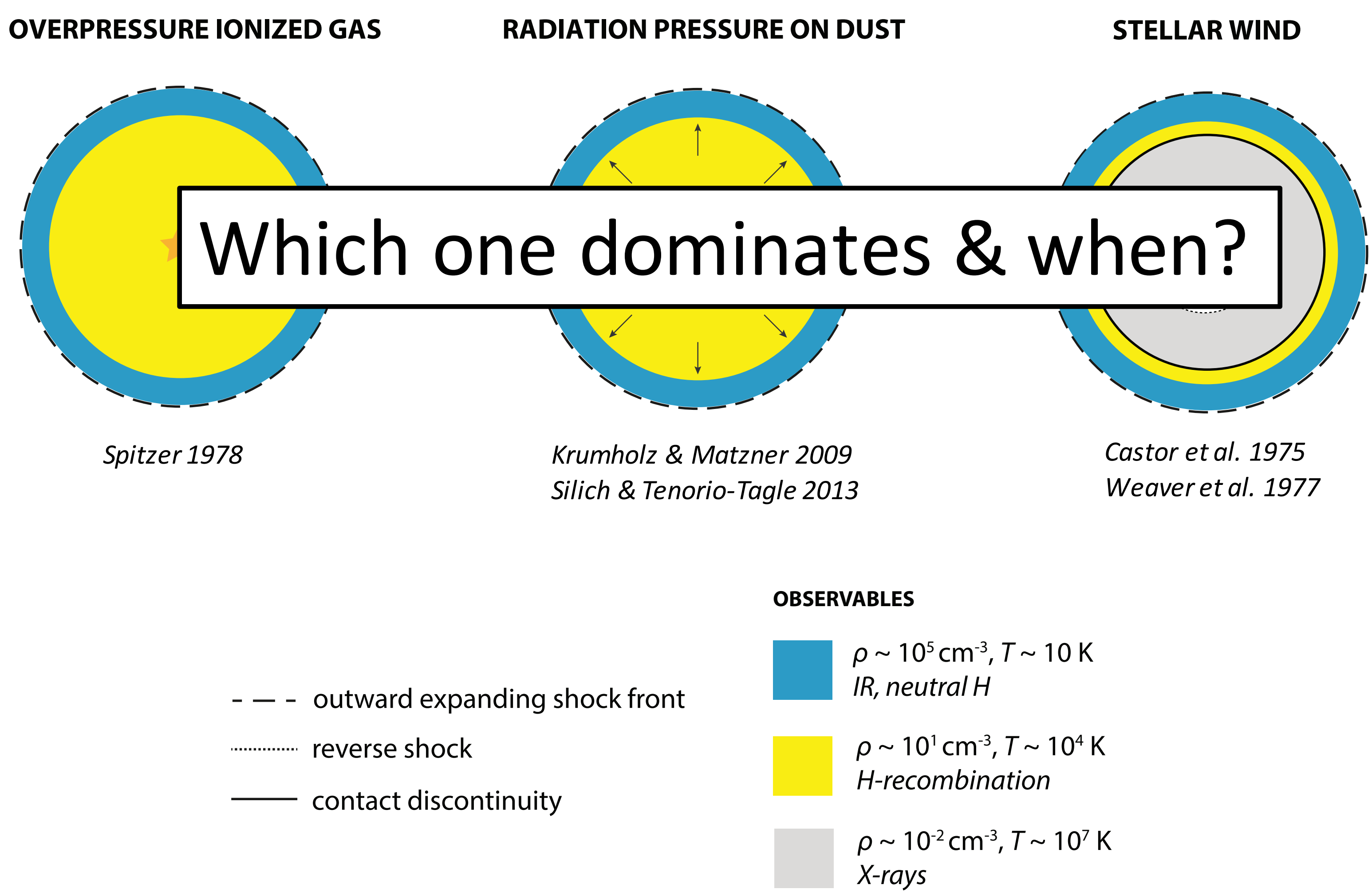




~10 - 100 pc
~ few Myr

What creates these bubbles?

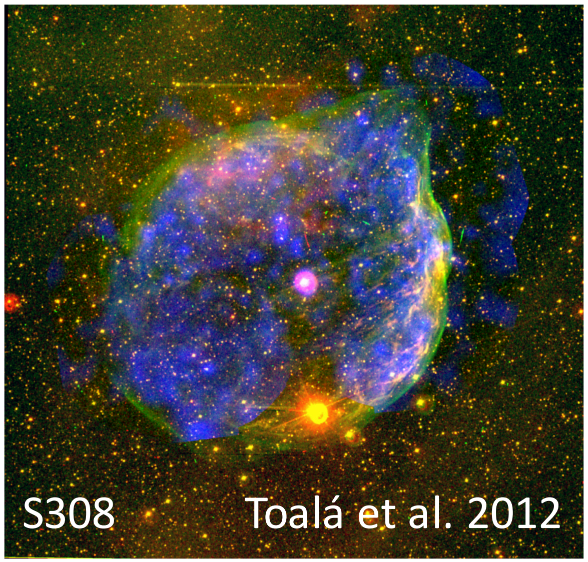
- No correlation with SNR (Deharveng et al. 2010)
- 80% has HII region → spectral type B2 or earlier



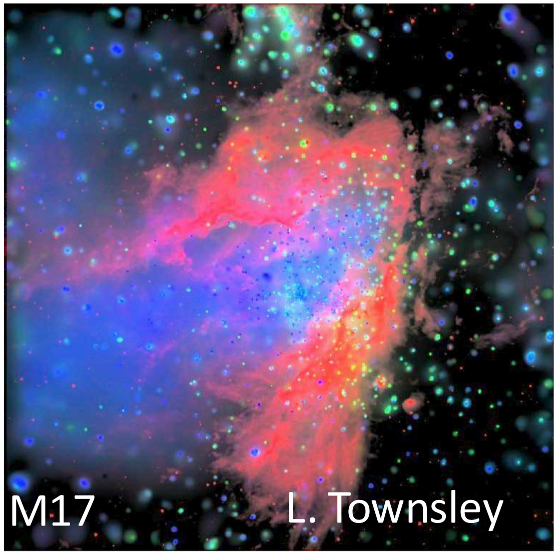
Wind-blown bubbles

-> Look for diffuse X-ray emission from hot plasma (10^6 -10^7 K)

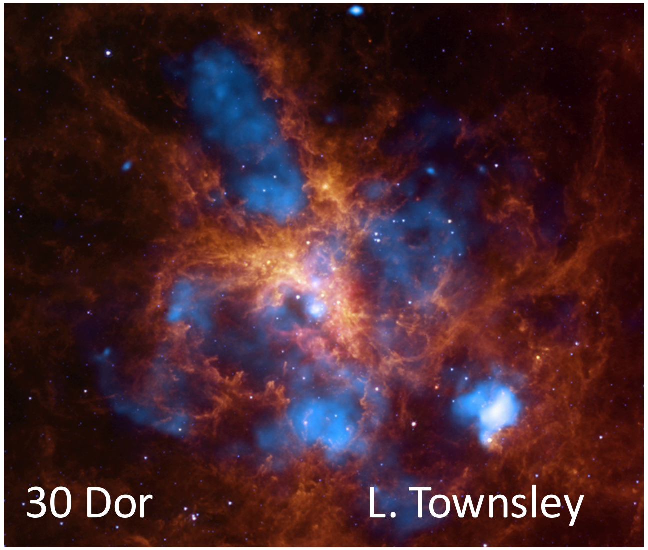
Wolf-Rayet stars



Clusters



Super star clusters



Blue = X-rays

Simulations from e.g.: Arthur et al. (2006, 2012), Verdolini et al., Van Marle et al. (2015)

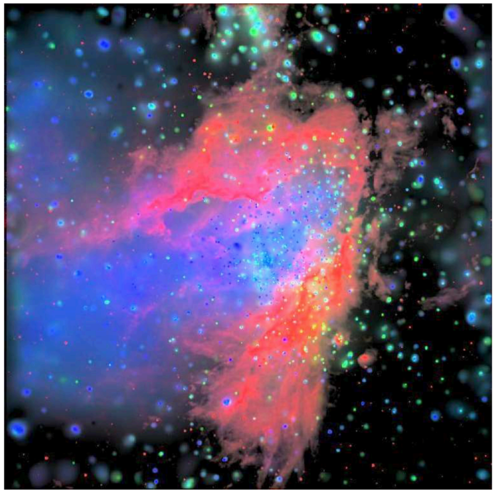
Wind-blown bubbles challenge #1: missing X-rays?

However…....
The vast majority of bubbles in the Galaxy do not show diffuse X-rays

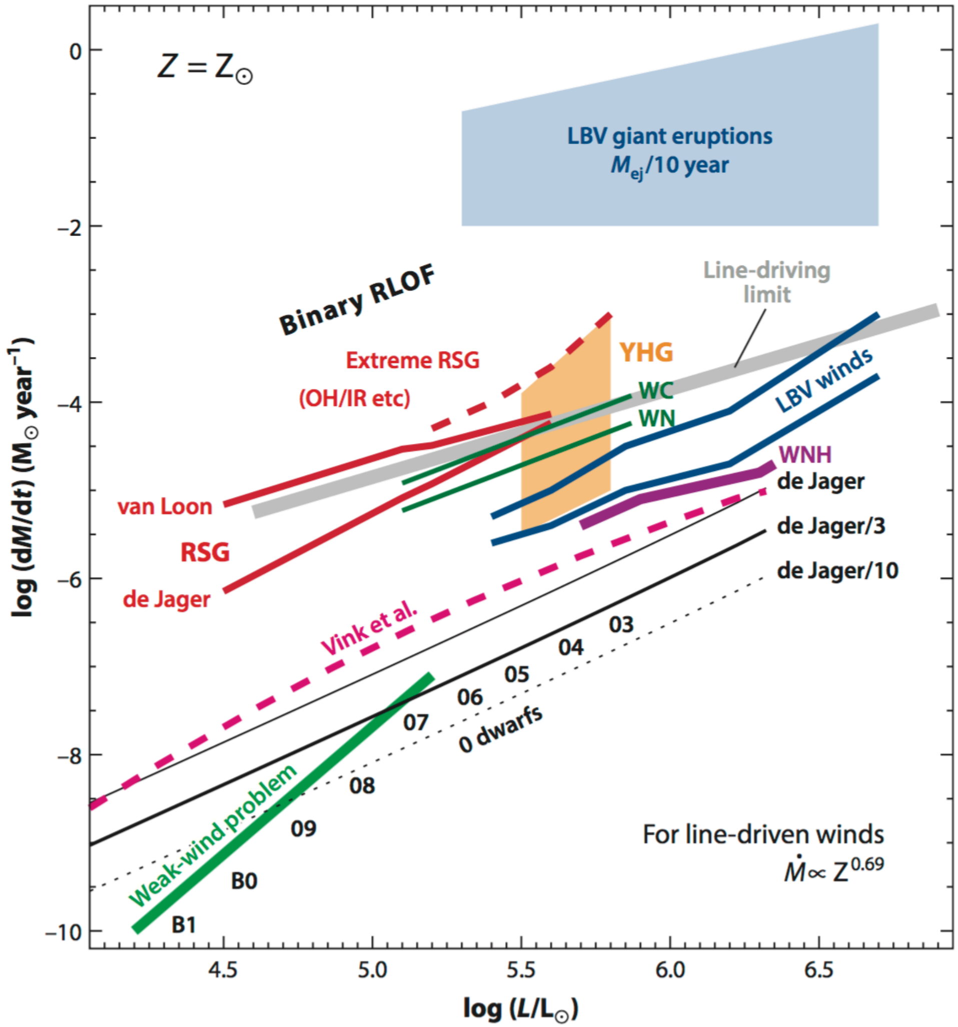
1) Extinction? → $\tau_x \sim 1$ @ 3.5×10^{20} cm^{-2}

2) Mass loading? → introduce mass in the bubble interior, lower *T*
(Hartquist et al. 1986)

3) Leakage?
(Harper-Clark & Murray 2009)



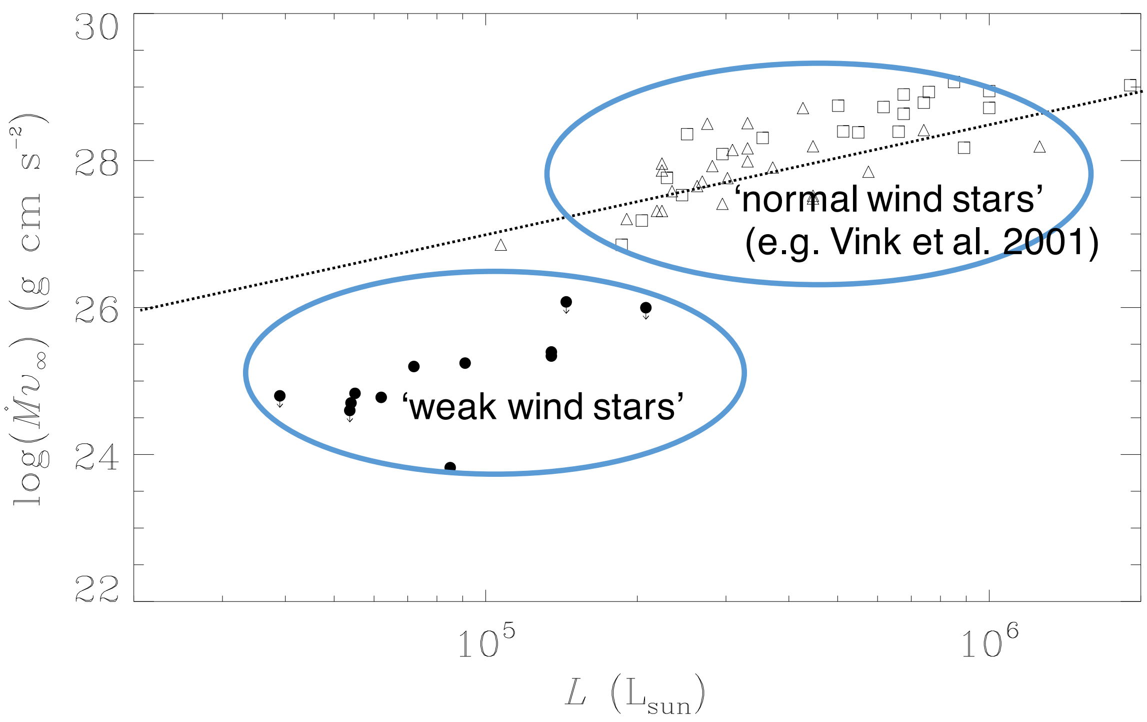
Wind-blown bubbles challenge #2: the weak-wind problem



Smith 2014, ARA&A

- Main sequence stars below Log L < 5.2 (spectral type O6V – O7V) appear to have weak winds!

Wind-blown bubbles challenge #2: the weak-wind problem



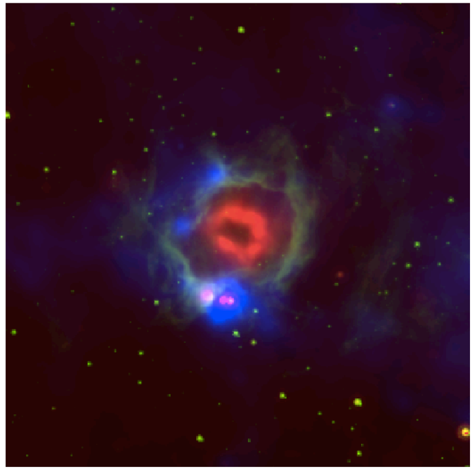
- Possible explanations:
    1. inefficient line driving in hot dwarfs *(Smith 2014, Oskinova 2016)*
    2. bulk of the wind may be in the hot phase *(Huenemoerder et al. 2012)*

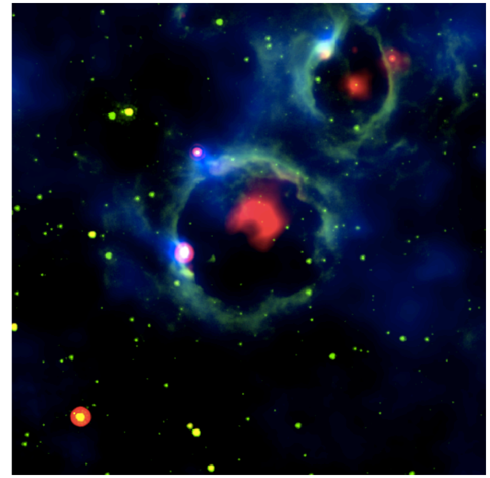
- Problem is that traditional mass-loss indicators (UV, Hα) become insensitive at low Mdot

- Bottom line: the discrepancy with Vink et al. 2001 is still debated

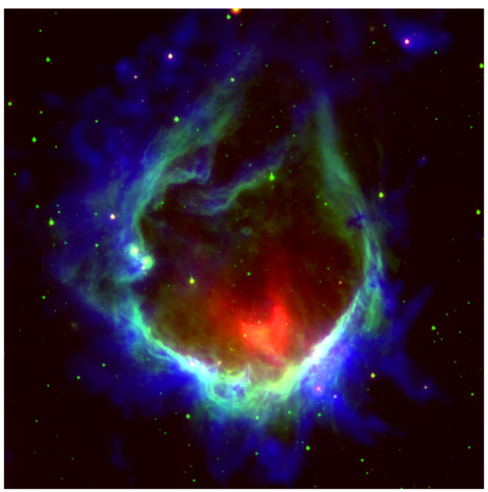
(e.g., Huenemoerder et al. 2012, Gvaradmadze et al. 2012, Ochsendorf et al. 2014)

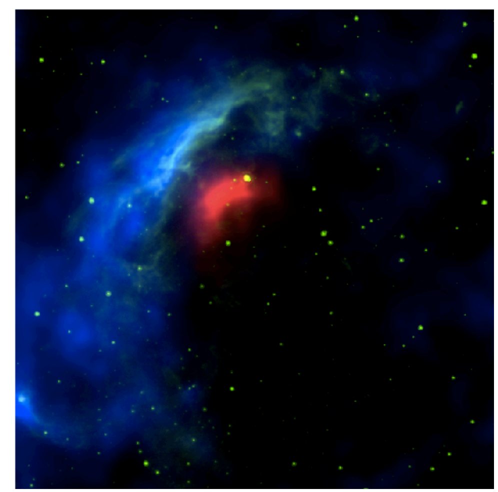
(Wind-blown) bubbles challenge #3: dust!





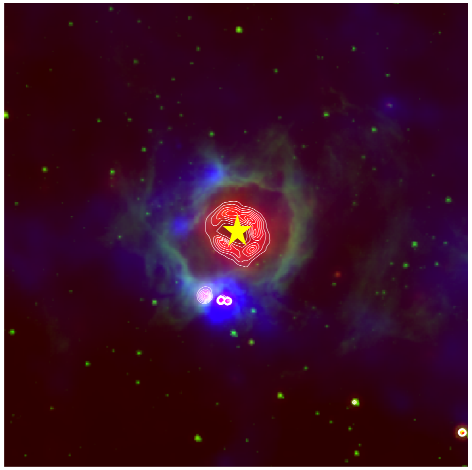
Red: 24 μm
Green: 8 μm
Blue: 250 μm

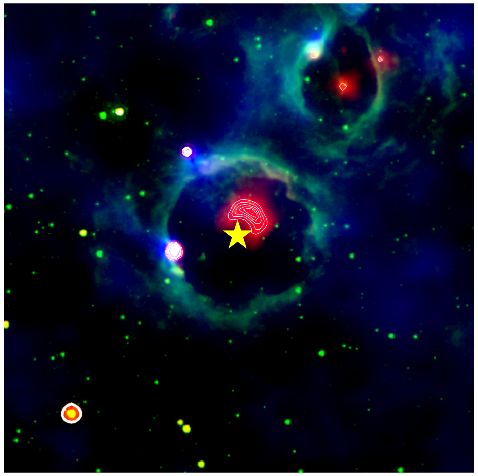




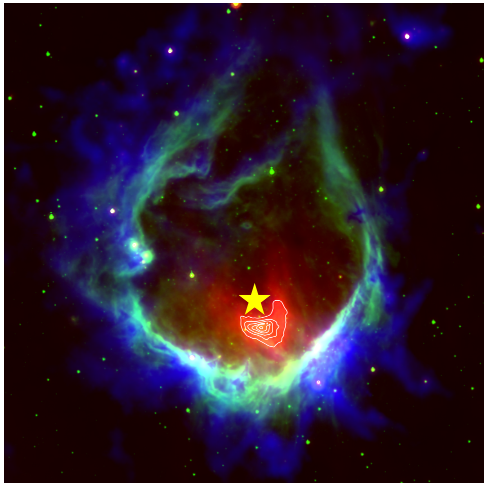
Dust grains should be cleared from wind-blown-bubbles within ~10^5 yr (Everett et al. 2010)

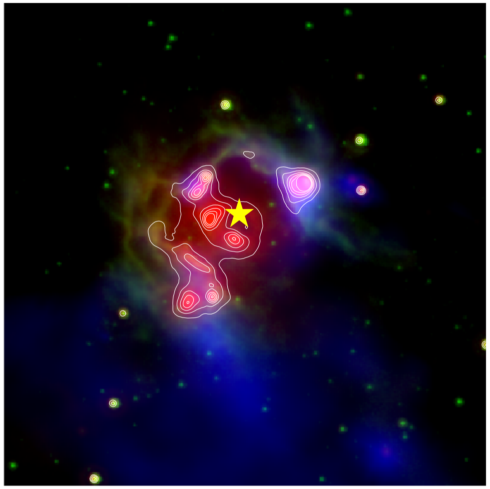
(Wind-blown) bubbles challenge #3 : dust!

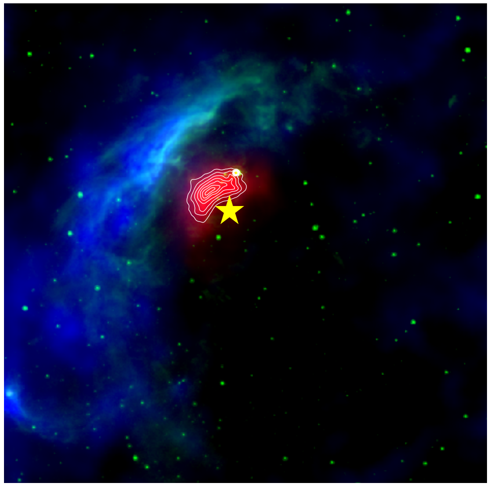




Red: 24 µm
Green: 8 µm
Blue: 250 µm



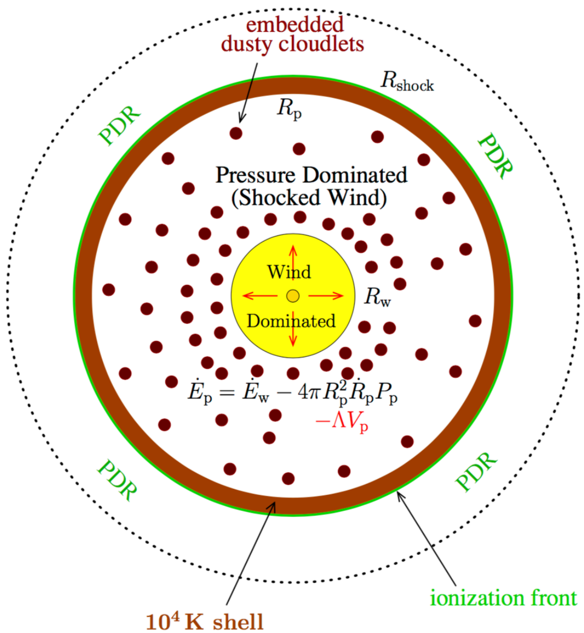




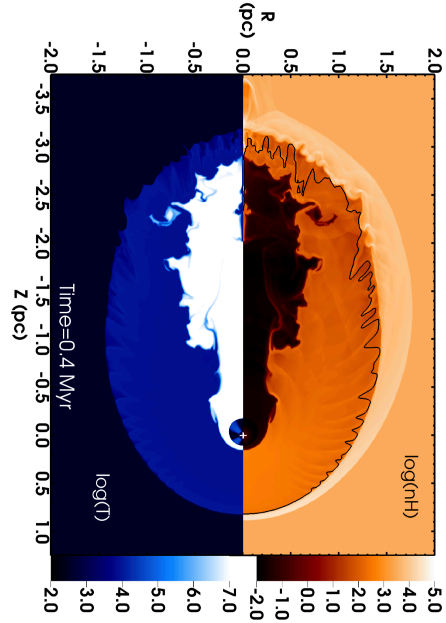
Dust grains should be cleared from wind-blown-bubbles within ~10^5 yr (Everett et al. 2010)

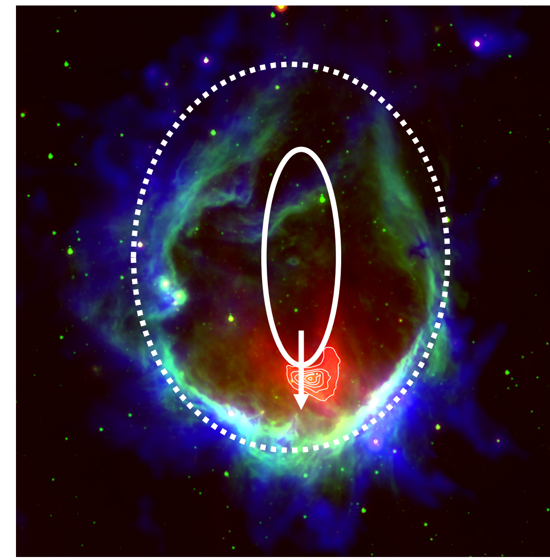
Wind-blown bubbles challenge #3: dust!

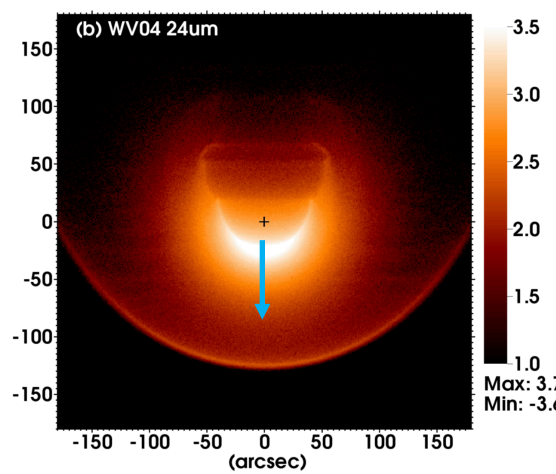
→ need a mechanism to constantly replenish WBB with dust.



(1) Evaporating cloudlets?
(Everett & Churchwell 2010)







⋯⋯ = ionization

—— = stellar wind

(2) Slow moving host star?
(Mackey et al. 2015)

Wind-blown bubbles: challenges

Summary:

1. **(Missing) X–rays**
   - extinction?
   - mass-loading?
   - leakage?

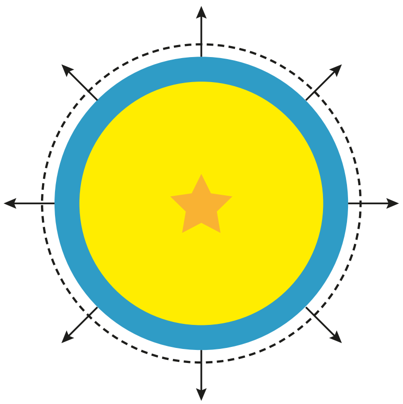
2. **Weak wind problem**
   - inefficient line driving?
   - wind in hot phase?

3. **Dust inside bubbles**
   - evaporating cloudlets?
   - slow moving stars?

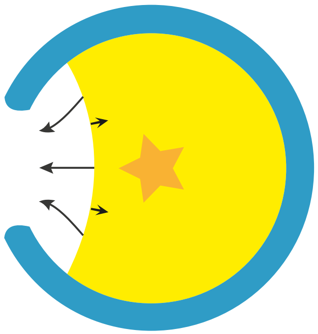
What if stellar winds for ~O6.5V stars and later are less important than previously thought?

Another train of thought…

Overpressure of ionized gas expands
(Spitzer 1978)

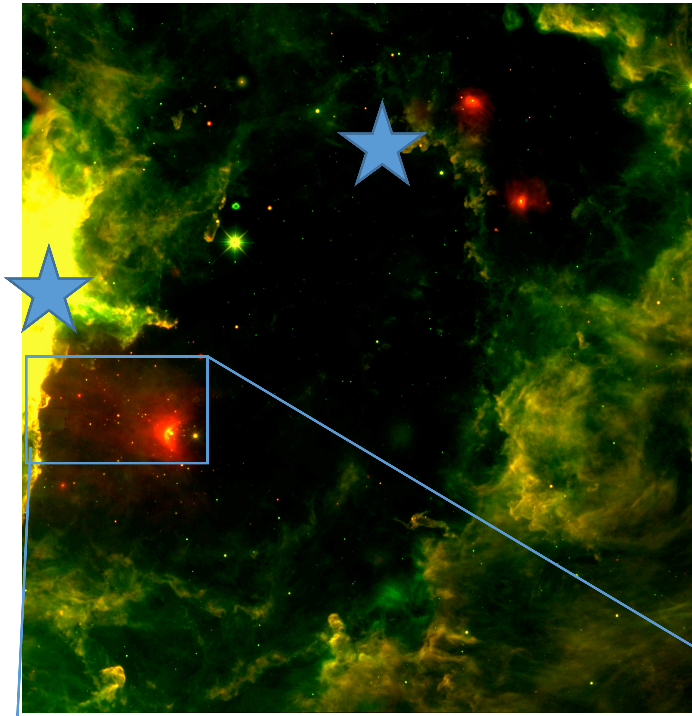


Density gradients/discontinuity lead to an ionized flow of gas
(Tenorio-Tagle 1979)



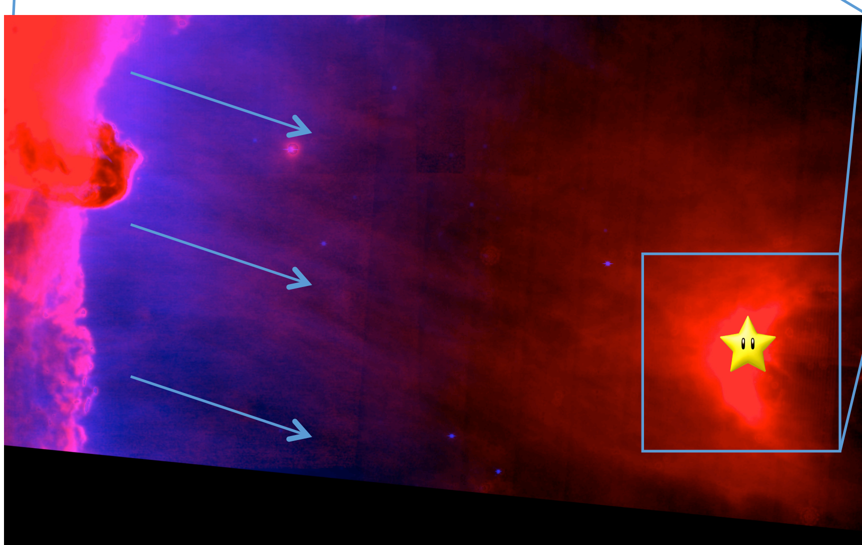
Dust contained in flow interacting with radiation pressure from the star leads to a **dust wave**
(Ochsendorf et al., 2014a,b)

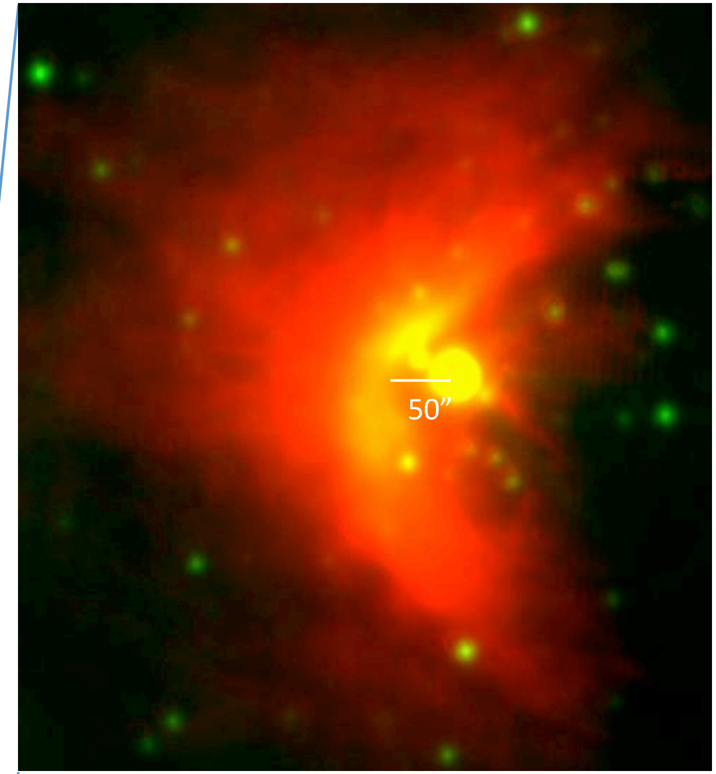
Dust waves



Red:
24 μm

Green:
12 μm





Red:
24 μm

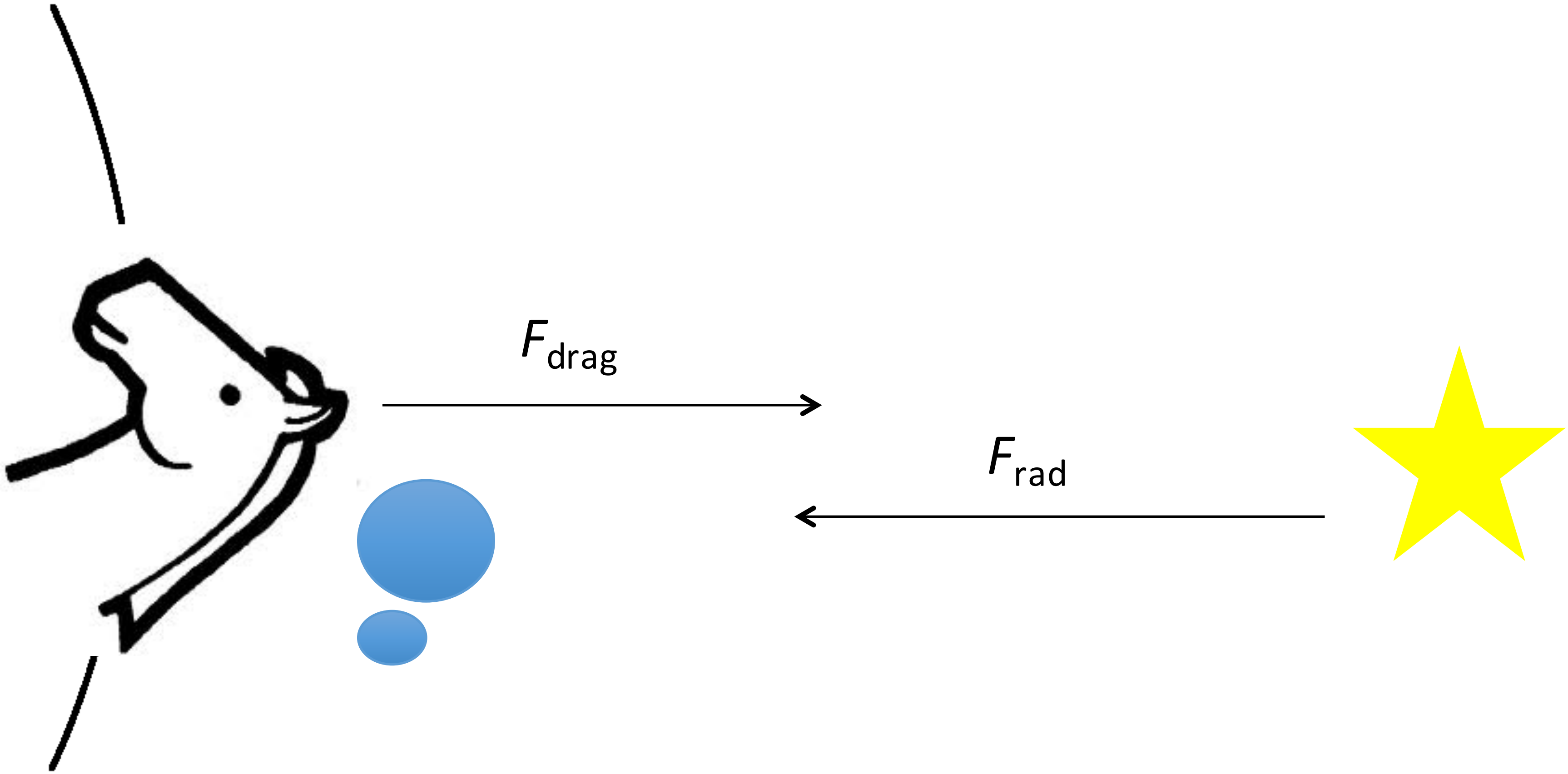
Blue:
Hα

Sigma Ori has a very weak wind!

$$\dot{M} = 2.0 \times 10^{-10}\, M_{\odot}\, yr^{-1}$$

Can not be stellar wind-driven
But what about radiation pressure?

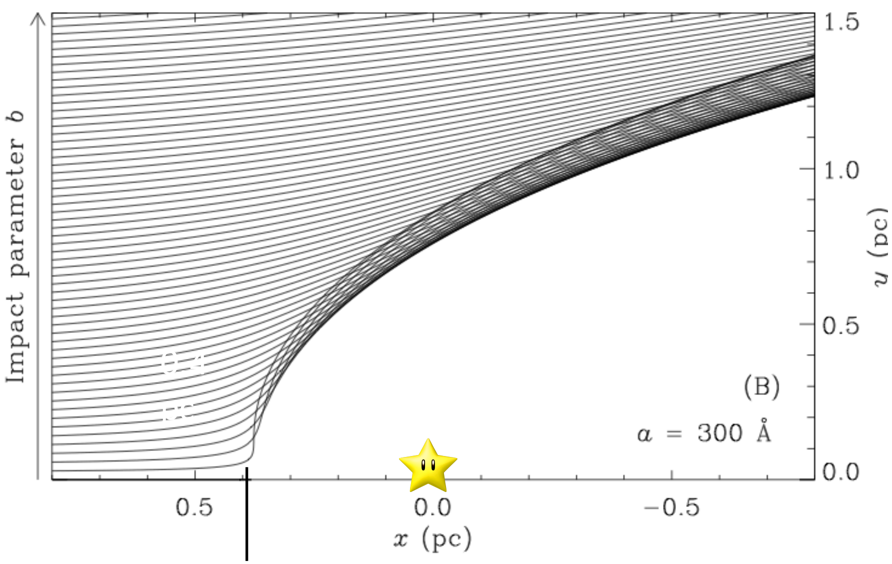
Dust waves: the basic idea



Dust waves

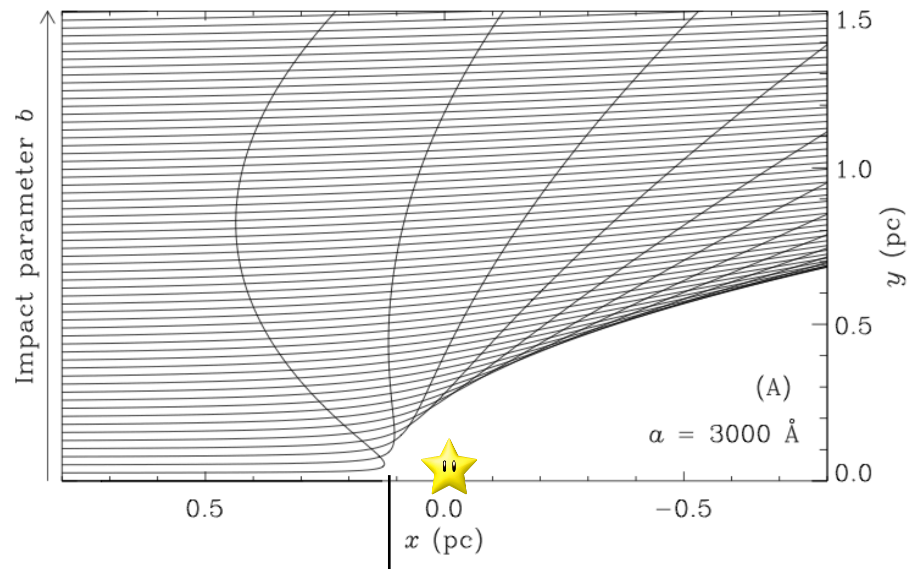
- Dust waves arise at the equilibrium point where radiation pressure force and drag force (gas-grain interactions) balance
- Stratify grains according to their radiation opacity

Ochsendorf et al. 2014



0.4 pc

Small dust grains



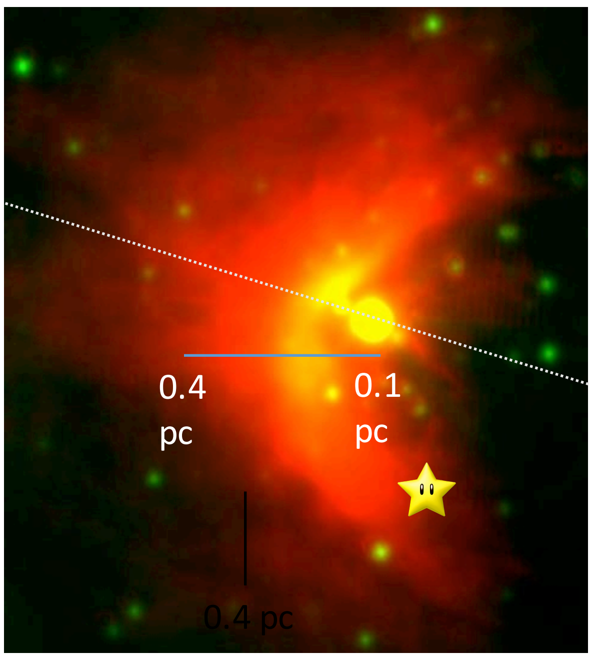
0.1 pc

Large dust grains

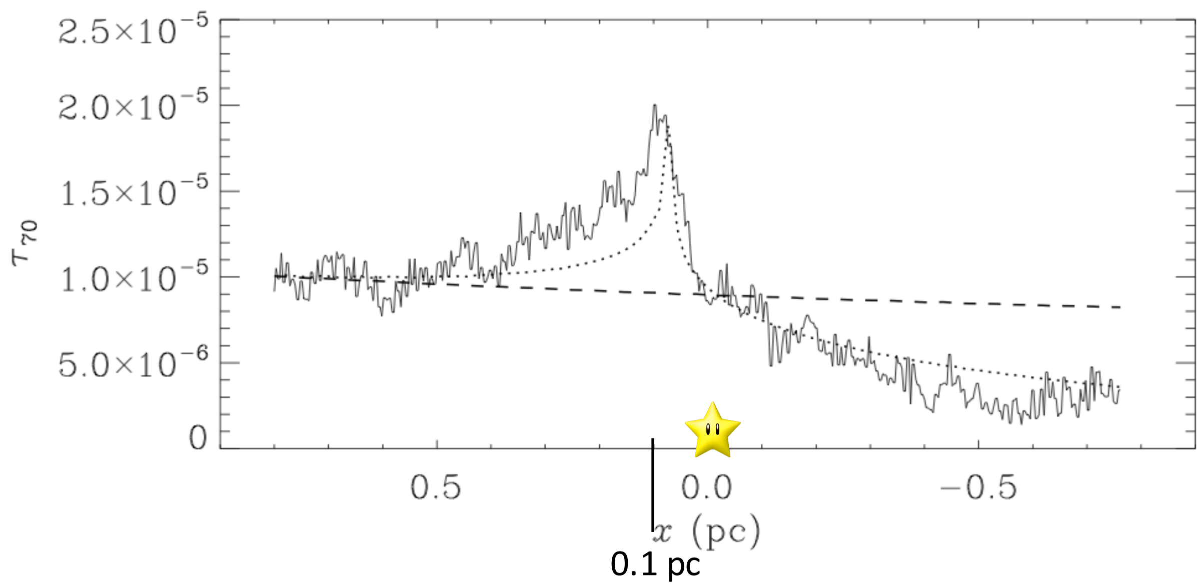
Dust waves

- Dust waves arise at the equilibrium point where radiation pressure force and drag force (gas-grain interactions) balance
- Stratify grains according to their radiation opacity

Ochsendorf et al. 2014



Small dust grains



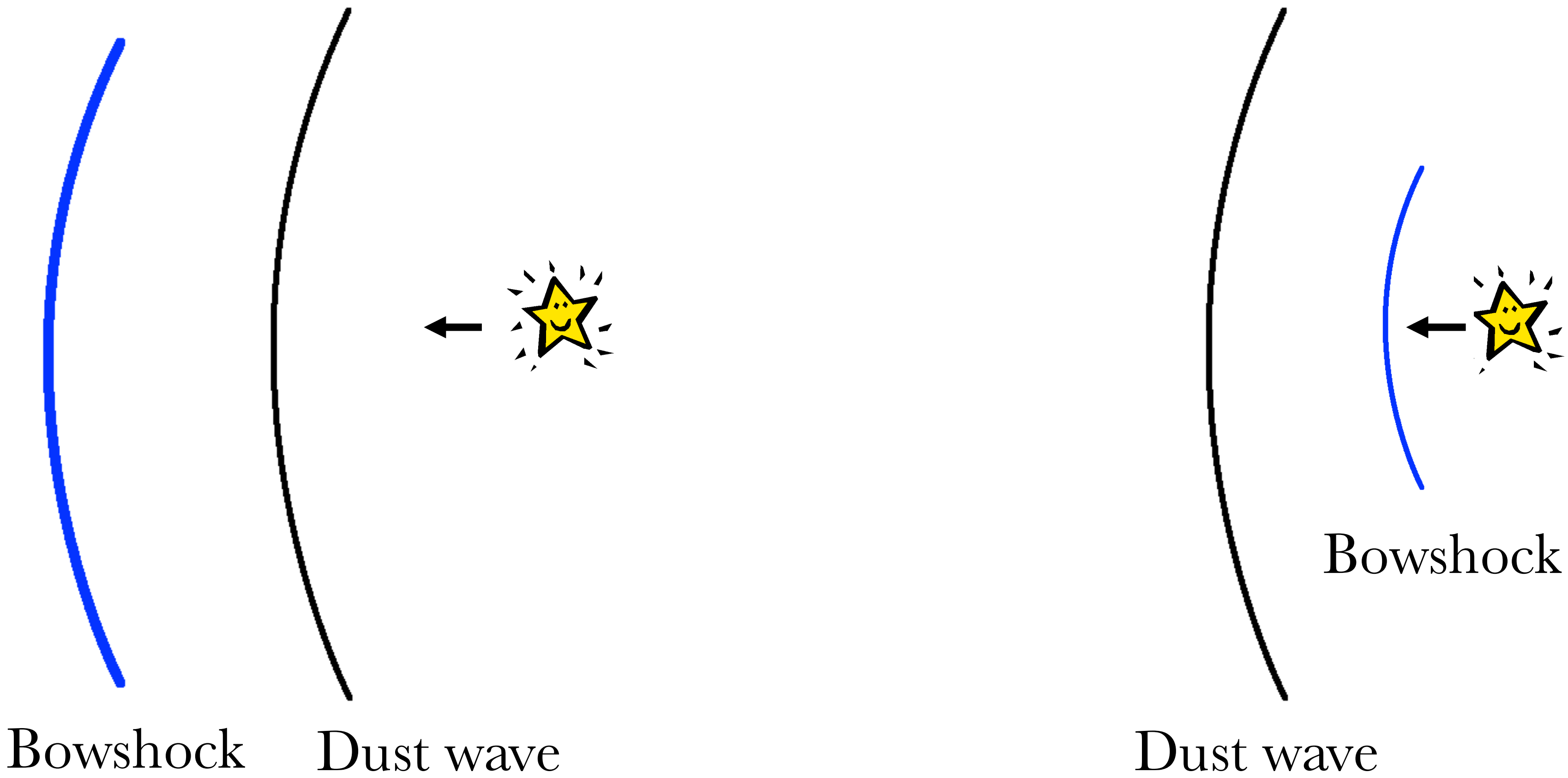
Large dust grains

Bow shocks vs. dust waves (stellar winds vs. radiation pressure)

Dust waves do not shock gas component

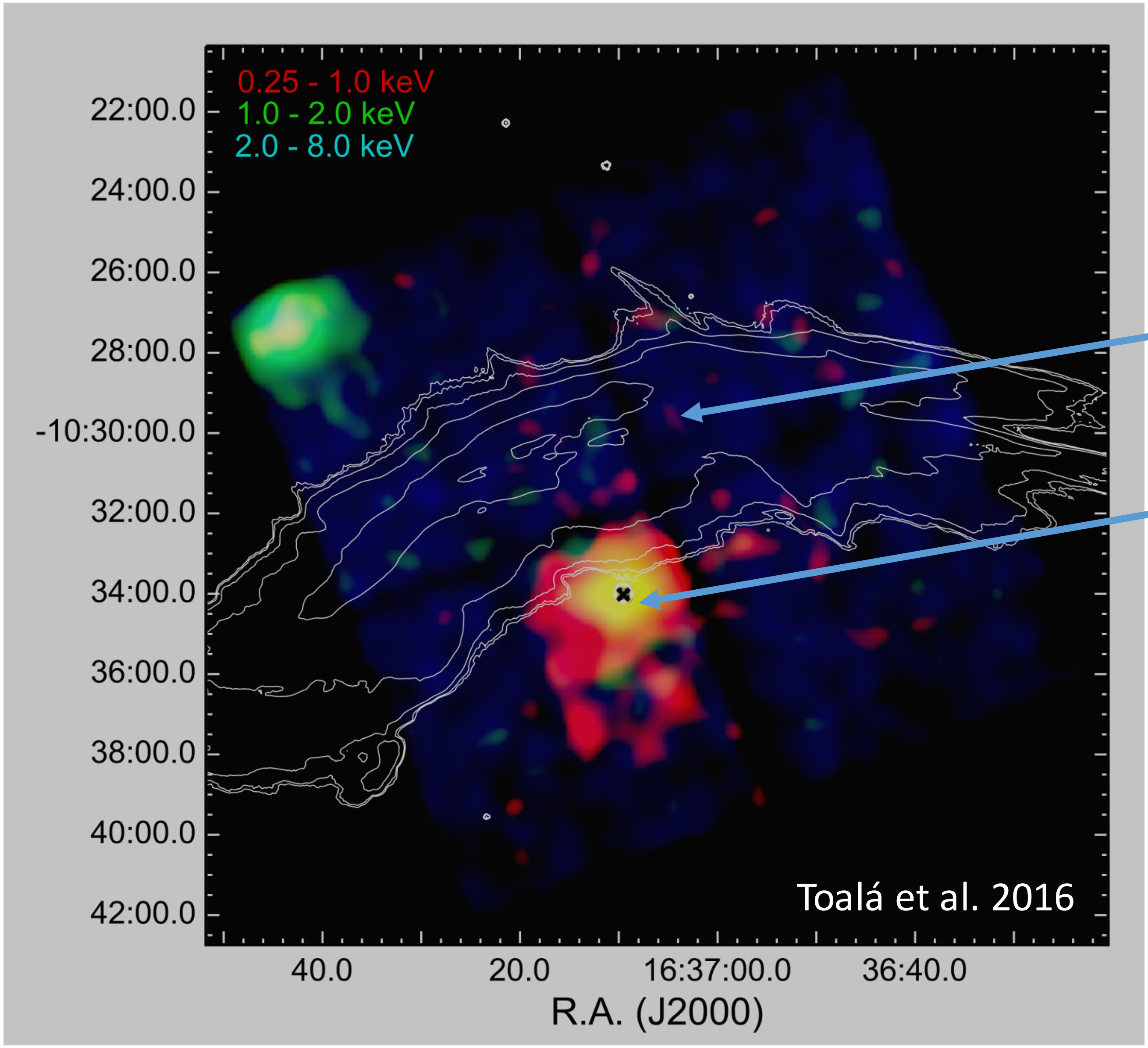
Stars with ‘normal’ winds create bow shocks

Stars with weak winds will create dust waves



Zeta oph: Weak wind star?

Runaway star
O9.5V



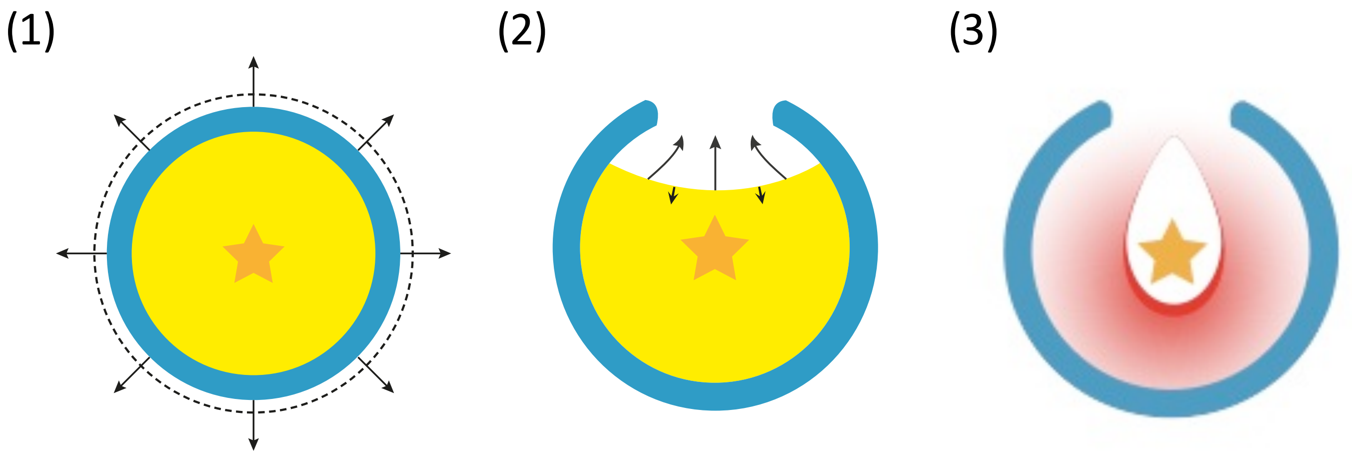
Dust wave?

Stellar wind zone

Recap

- Radiation pressure can perfectly explain the observed dust arcs around σ Ori AB, RCW120, etc.

→ *If the weak-wind problem is true*, IR arcs around O6.5V stars and later should be **radiation pressure-driven**
→ This constitutes over 50% of all known 'bow shocks' around runaway stars! (Peri et al. 2012, 2015)

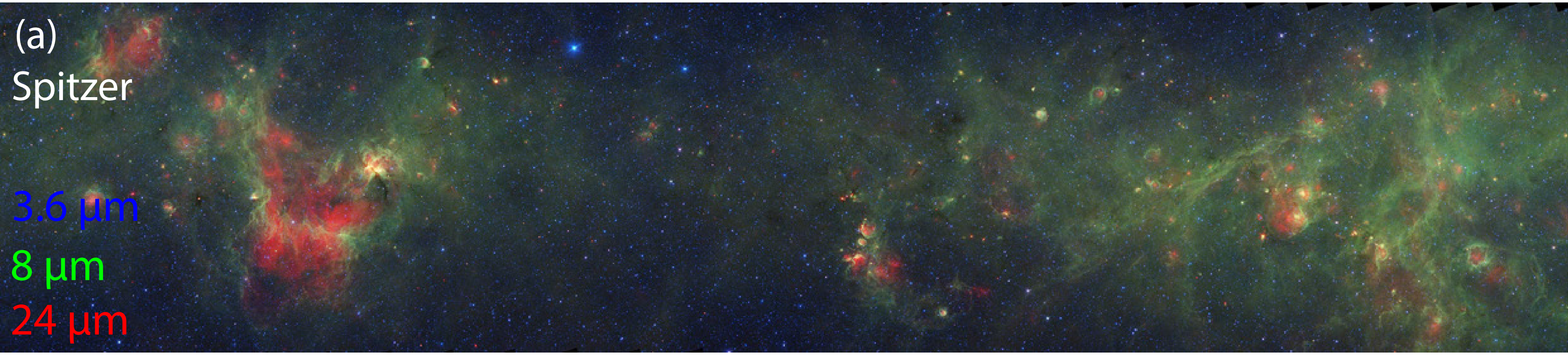


This scenario for HII region expansion and evolution accounts for

- Weak winds
- Missing X-rays
- Presence and morphology dust in HII regions

In addition: predicts that bubbles are relieving their pressure into the surrounding ISM → source of turbulence

Energy budget of the ISM



What are the important feedback mechanisms?

Energy budget of the ISM

Over a lifetime of a massive star:

Input (radiative)

Ionization: $E \sim 10^{53}$ erg

Radiation pressure on dust: $E \sim 10^{53}$ erg

ϵ = efficiency to couple to ISM

Input (mechanical)

Typical stellar wind: $E \sim 10^{48-50}$ erg (weak-normal wind)

SN explosion: $E \sim 10^{51}$ erg

+

The big question: what is ϵ???

Output (kinetic)

Expanding shells $\sim 10^{50}$ erg

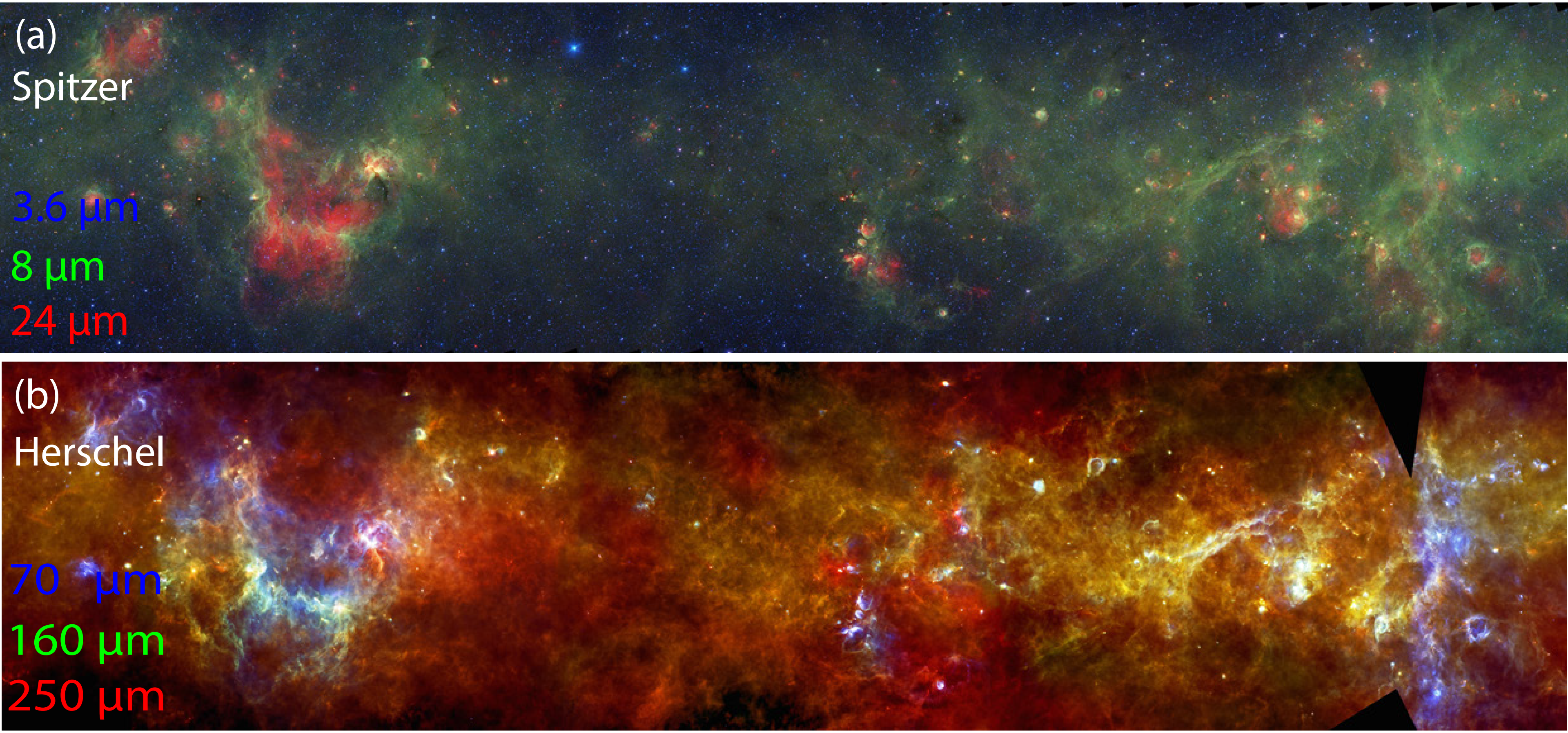
Ionized gas $\sim 10^{49-50}$ erg

Superbubbles (SNe) $\sim 10^{50-52}$ erg

Bottom line:

- Feedback imparted to the ISM during a massive stars lifetime is of order of that of an SN
- Efficiency ϵ on which scales the feedback processes act

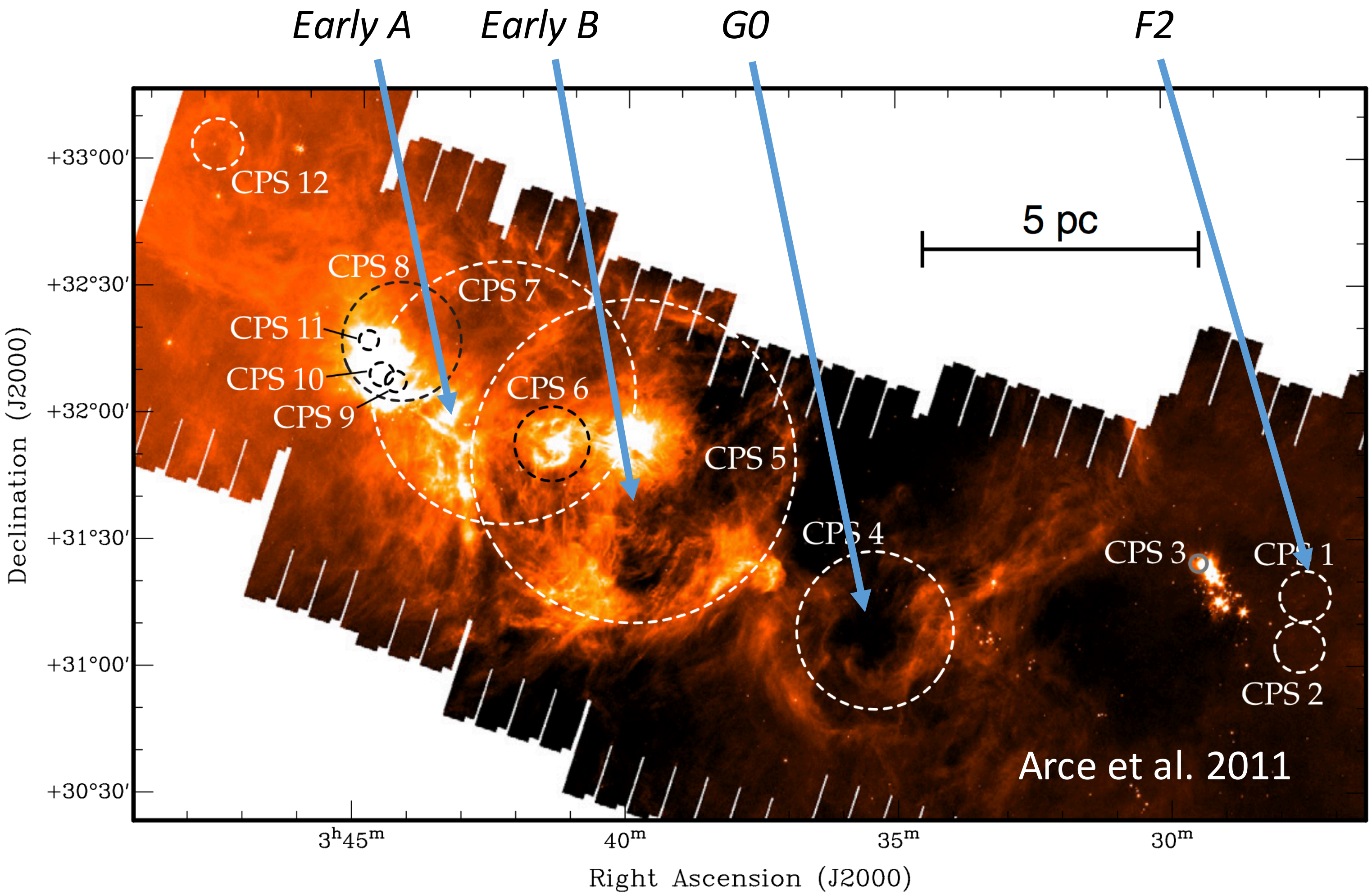
Energy budget of the ISM



Structure on 'large' scales (~100 pc): supernovae
(superbubbles)

Structure on 'small' scales (~<10 pc): Stellar winds, ionization, radiation pressure
(HII regions, WBBs, photo-evaporative flows) → **what is kinetic efficiency ϵ???**

Shells in Perseus: bubbles from 'low' mass stars



- No wind, no ionizing radiation. **What creates these bubbles?**

Bram Ochsendorf, Johns Hopkins U.

Summary

- The Galactic ISM is incredibly complex, bearing the imprints of multiple generations of massive stars.

- Stellar winds power bubbles around WR stars and high-mass clusters.

- However, the importance of stellar winds for stars > O7V is unclear (single/multiple)
    - *(Missing) X-rays, weak winds, dust inside bubbles*

- Bursting bubbles (created by ionization) as an alternative mechanism
    - *Consistent with recent observations*
    - *Provide natural explanation for presence and morphologies dust in bubbles*

- Infrared arcs around weak-wind stars must be dust waves instead of bow shocks

- Bubbles around low-mass stars (e.g., Perseus) are an open question

The way forward

- Observations of winds of stars with spectral type later than O7V (X-rays, L-band)
- Kinematics of ionized gas on a par with IR observations (SKA)