Revisiting Stellar Winds: What do they do, and what does this mean for RAMSES simulations?

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Where I am so far:

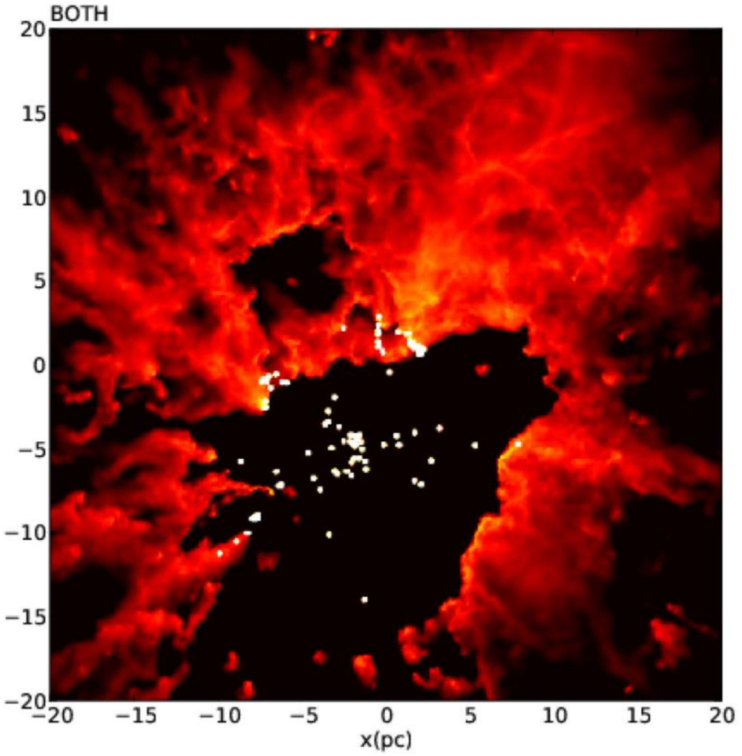
RUM 2018:

- Why **stellar winds are bad, they do nothing**
- Why **UV photoionisation is good**, the only feedback you need

RUM 2021:

- Why **stellar winds are good and important**
- Why **UV photoionisation is bad and wrong**
  (kinda, okay, not really, listen-)

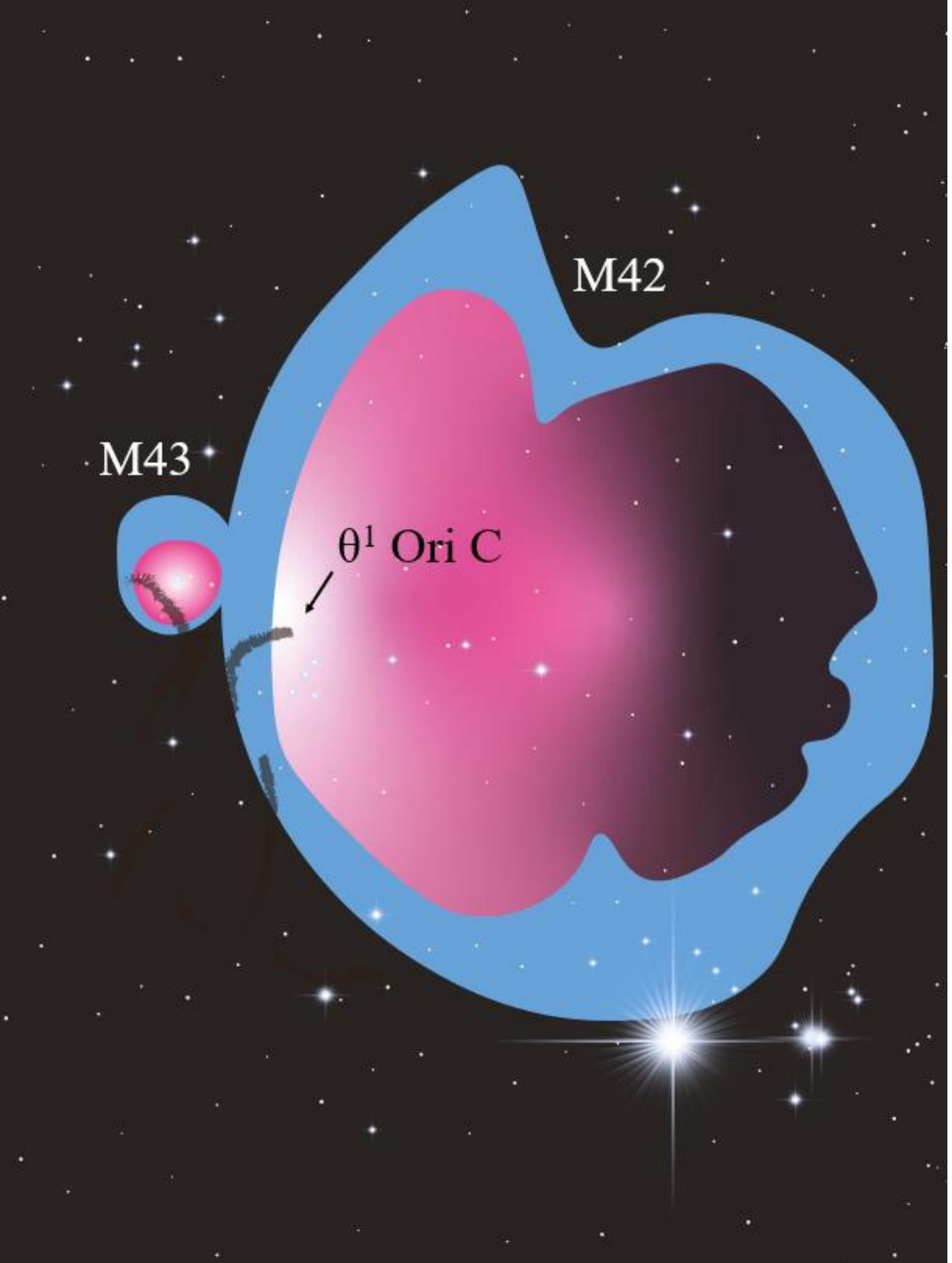
Simulations: Winds don't do much, they cool efficiently and photoionisation does all the work (e.g. Dale+ 2014, Geen+ 2021, Lancaster+ 2021ab)



BUT

Observations: photoionisation does nothing, winds don't cool efficiently, they drive nebulae (M42 in Orion, Pabst+ 2019,2020)

What's the deal with Orion?



I spent a whole day drawing this during lockdown

The Orion Nebula (M42):

- Driven by a 35 solar mass star
- **Filled with x-ray emitting gas** (Guedel+ 2008)
- Expanding away from the star, trapped by dense gas around it
- Diameter ~ 4 pc
- Expansion velocity ~ 13 km/s (Pabst+ 2019,2020)
    - (Measured using C^+ from the shell using SOFIA)
    - → has neutral gas around it
    - → so **NO champagne flow**!
- **No evidence of strong x-ray cooling**

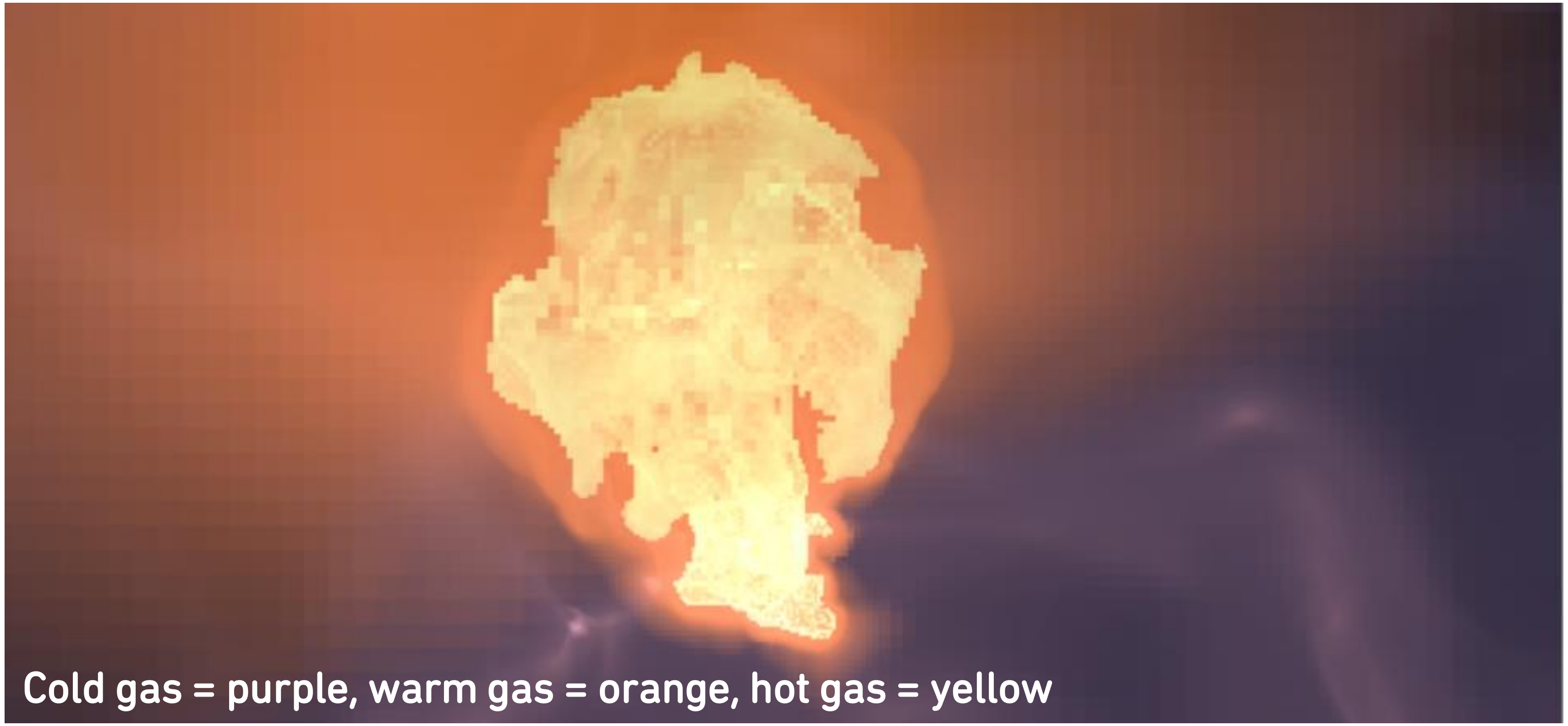
So, it seems like M42 in Orion is:

- **Driven by winds**
- **No evidence of strong photoionisation driving**

Why?

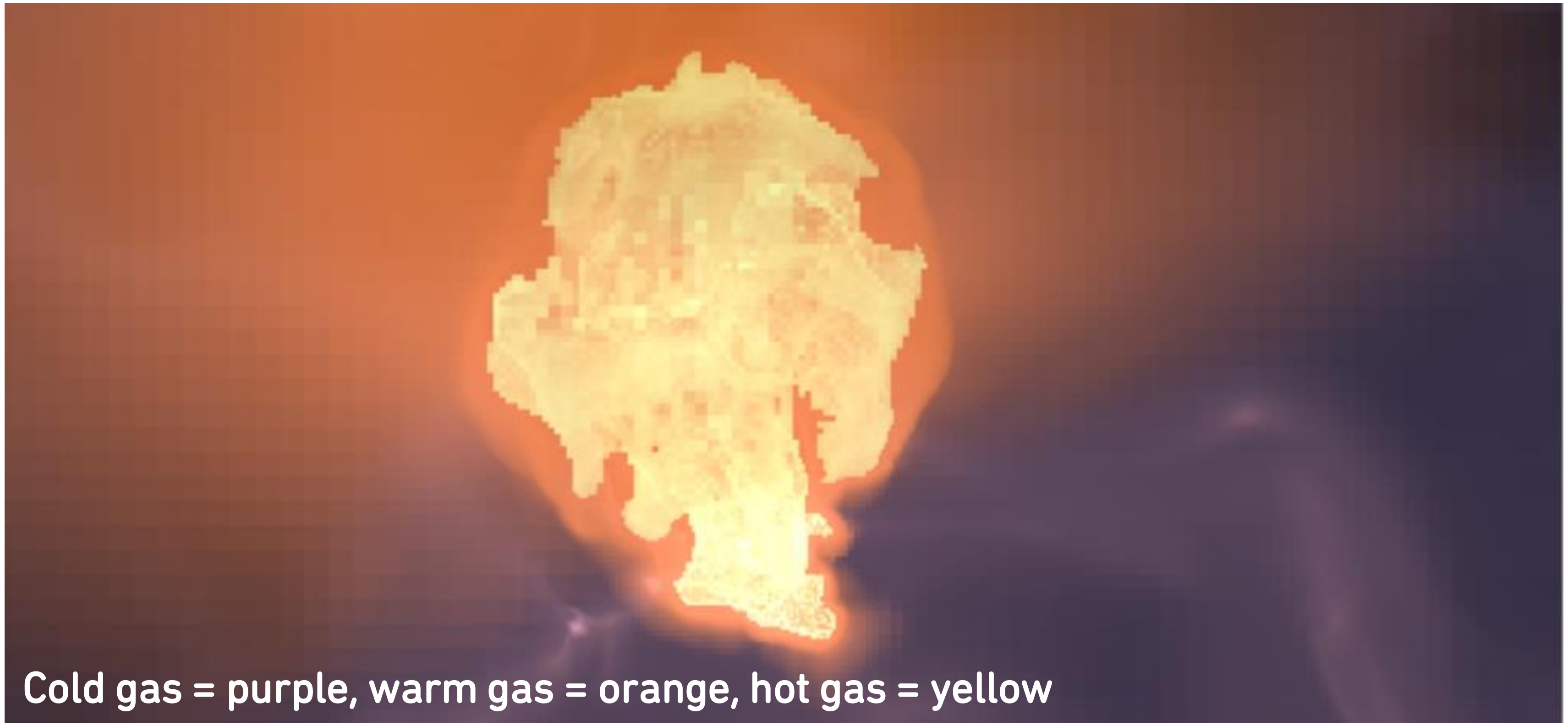
First try:

- See Geen+ (2021)
- Make a turbulent cloud (e.g. Iffrig+ 2014)
- Refine on Jeans criterion
- Form a star self-consistently when a sink accretes 120 Msun
- Pick the star's mass by hand (30,60,120 Msun)
- Emit winds as kinetic flows (Geneva model + correction for terminal velocity from Vink+ 2011)
- Emit FUV + EUV radiation
- Use radiation pressure (doesn't do much)
- Employ a general-purpose feedback module (merging TBD)



<u>First comparison to Orion:</u>

- **Pros:**
  - **Looks a bit like Orion** (flow in one direction)
  - **Expansion rate and radius are roughly similar** (although the expansion rate varies hugely since the bubble is so aspherical)
- Cons:
  - Wind bubble **cools very efficiently**
  - Ionising radiation has escaped in a "champagne flow" → **so no neutral shell as in Orion**



How can we do better?

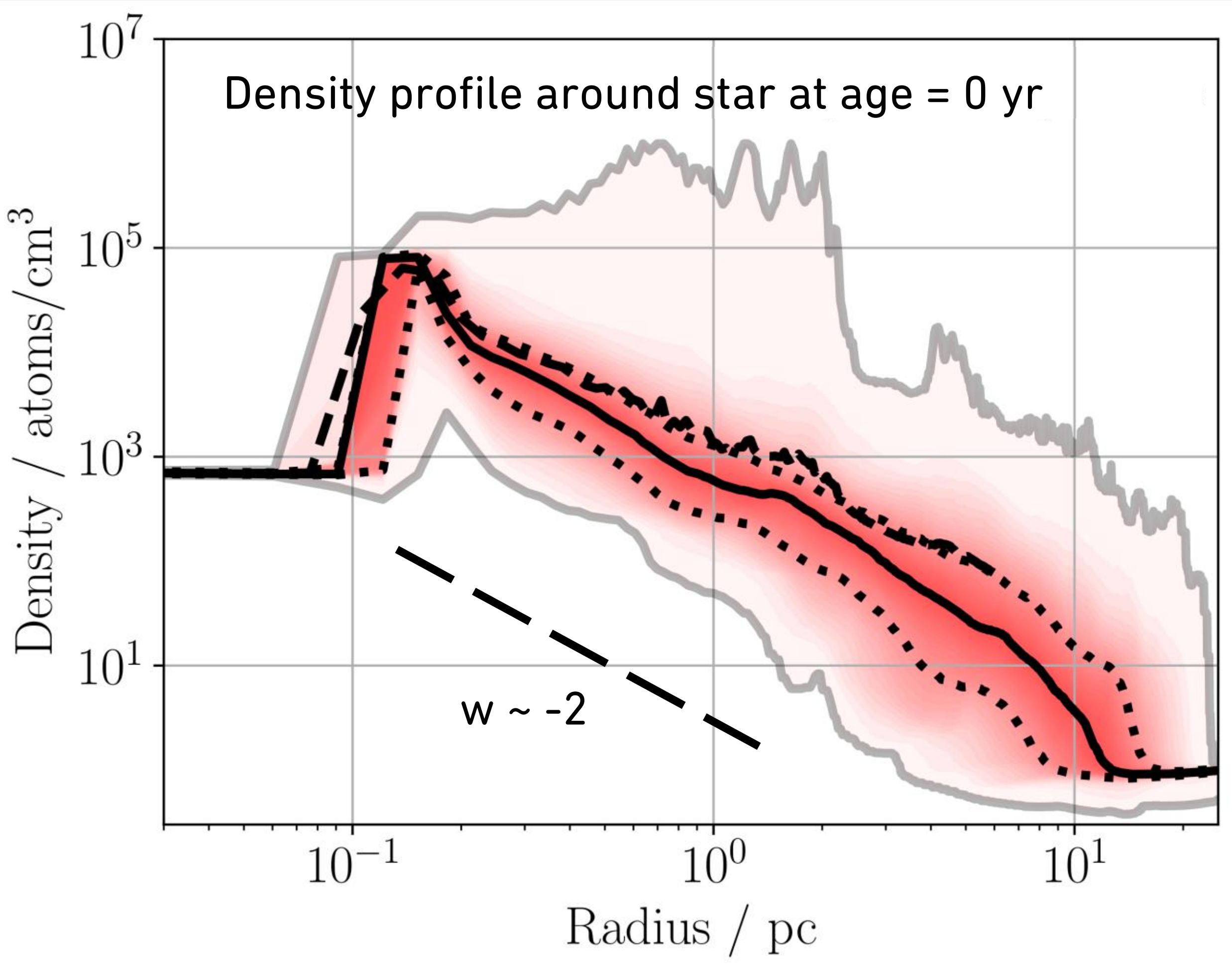
Rederiving Weaver+ 1977 winds

- Stars form in power law density fields
- Start from scratch with the Weaver & Spitzer solutions
- Re-derive Weaver+ 1977 (it's fun!)
- For a power law density field:

  $n(r) = n_0 \, (r/r_0)^{-w}$

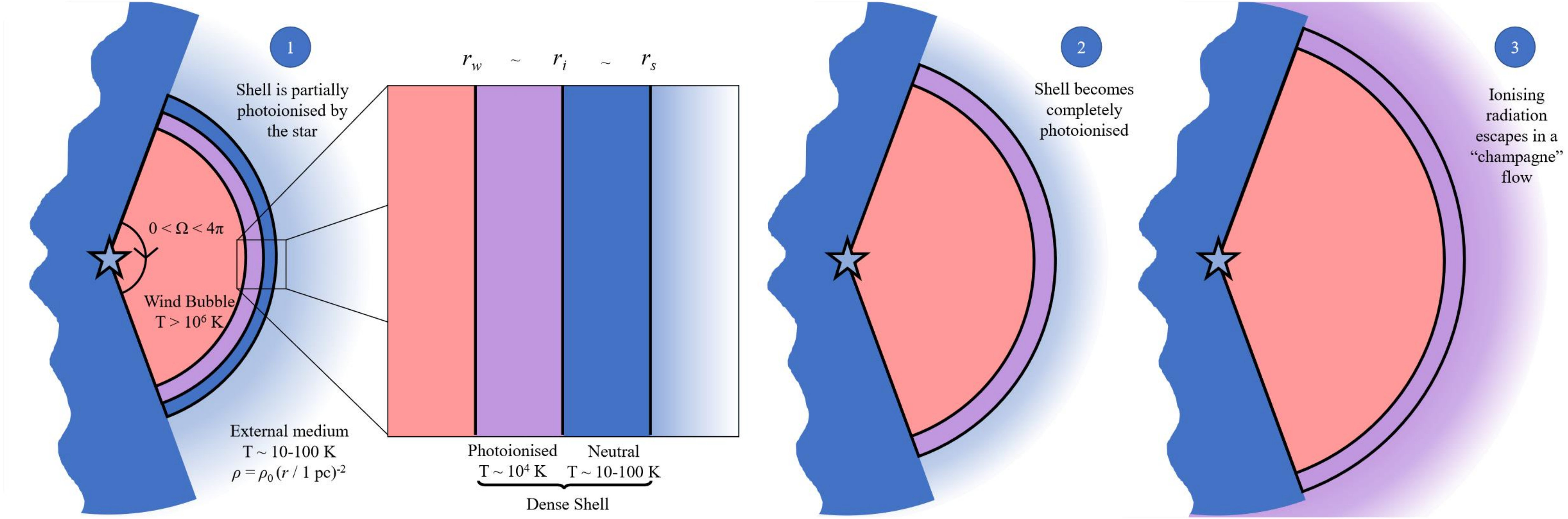
  we get:
- Stored energy = $(5-w)/(11-w) \, L_w \, t$
- Radial expansion:

  $r_w \propto \{L_w \, t^3 \, / \, (n_0 \, r_0^{\,w})\}^{1/(5-w)}$
- This means wind bubbles in isothermal profiles (w ~ 2) expand at a constant rate! (I told you this was fun)
- What does this mean for ionising radiation?



Bottling the Champagne

To make a champagne flow, UV radiation needs to "overflow" existing shells. For an Orion-like HII region:



Turns out, HII regions can last a long time in this state!

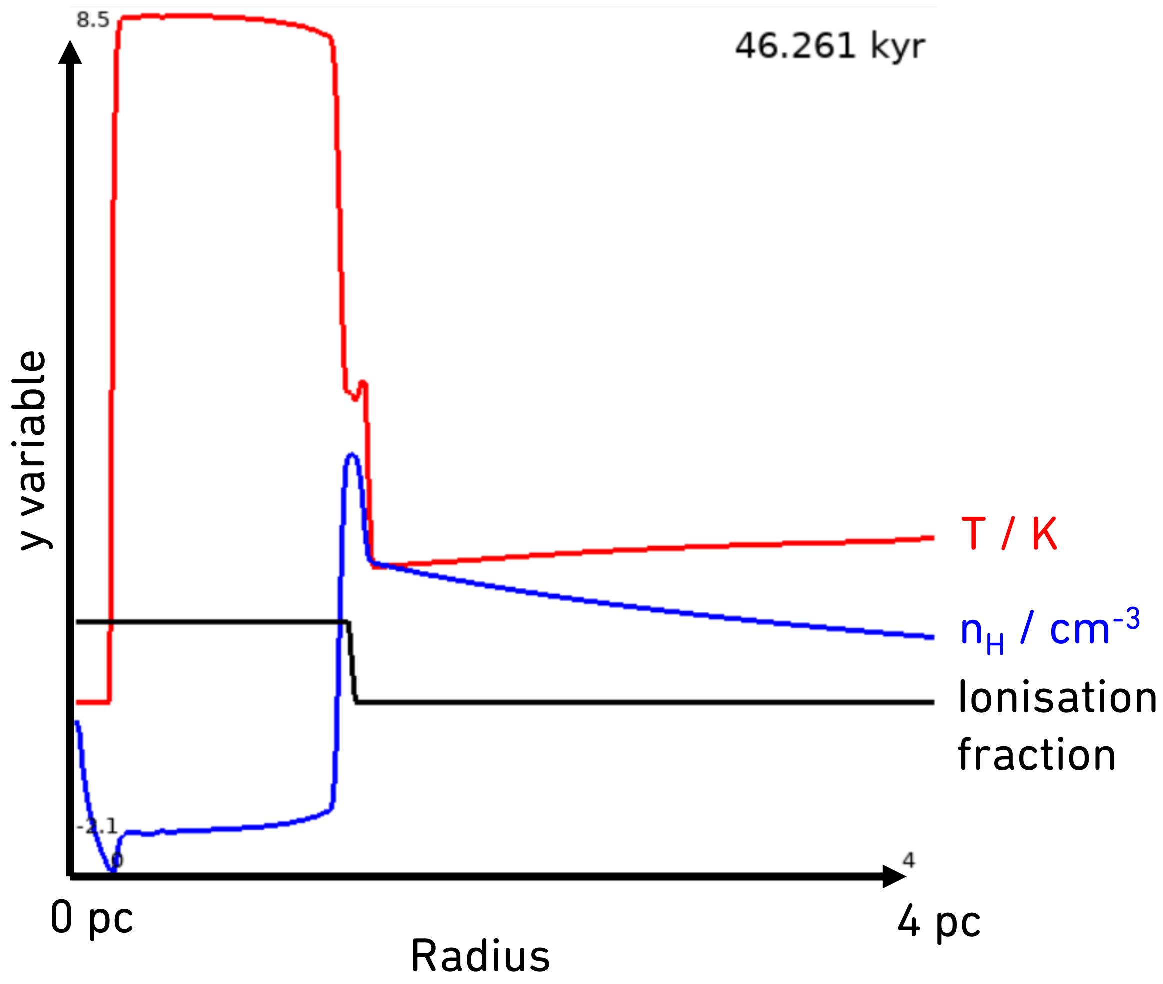
So regions like Orion can easily have neutral shells and block photoionised champagne flows

Verifying this with 1D simulations

- RAMSES doesn't have a 1D spherical coordinate system… so simple checks are hard
- So I made a code myself: WELTGEIST (https://github.com/samgeen/weltgeist)
  - Uses the simple hydro code VH-1
  - Implements other physics in a Python wrapper
  - Has a real-time visualisation option
  - Great for simple student projects and quick tests
  - Email me if you're interested
    – it requires some compilation

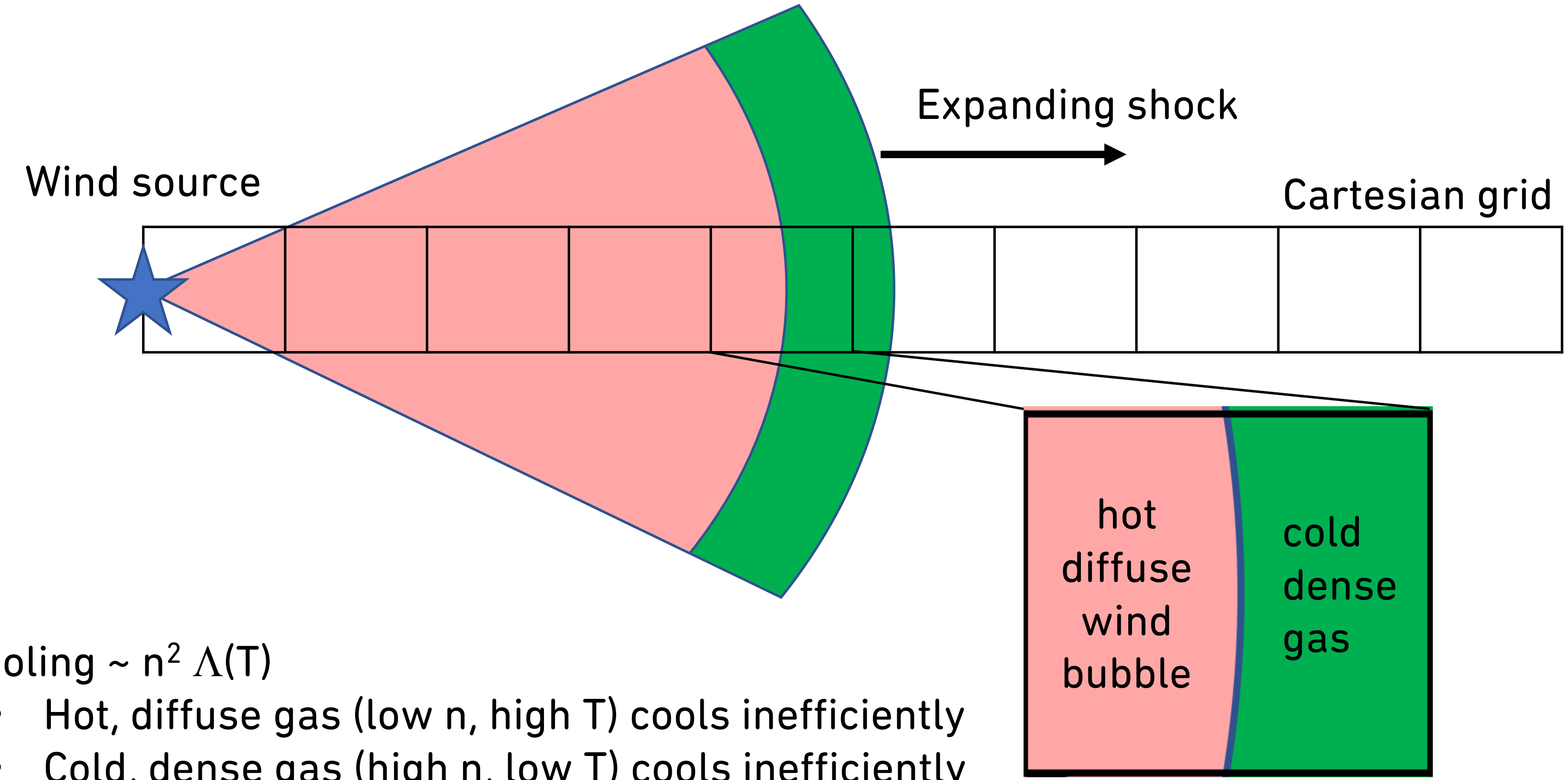
- Example run:
- Initial power law density field w=2, 1000 cm^{-3} at 1 pc
- 35 Msun star producing winds and UV radiation
- Uses Draine+ 2011 model for radiation pressure, dust
- Captures free-streaming wind sphere, hot wind bubble
- UV radiation trapped by dense shell around wind bubble

- OK so the UV trapping picture works in 1D… what about in 3D with RAMSES?



What new physics do we need?

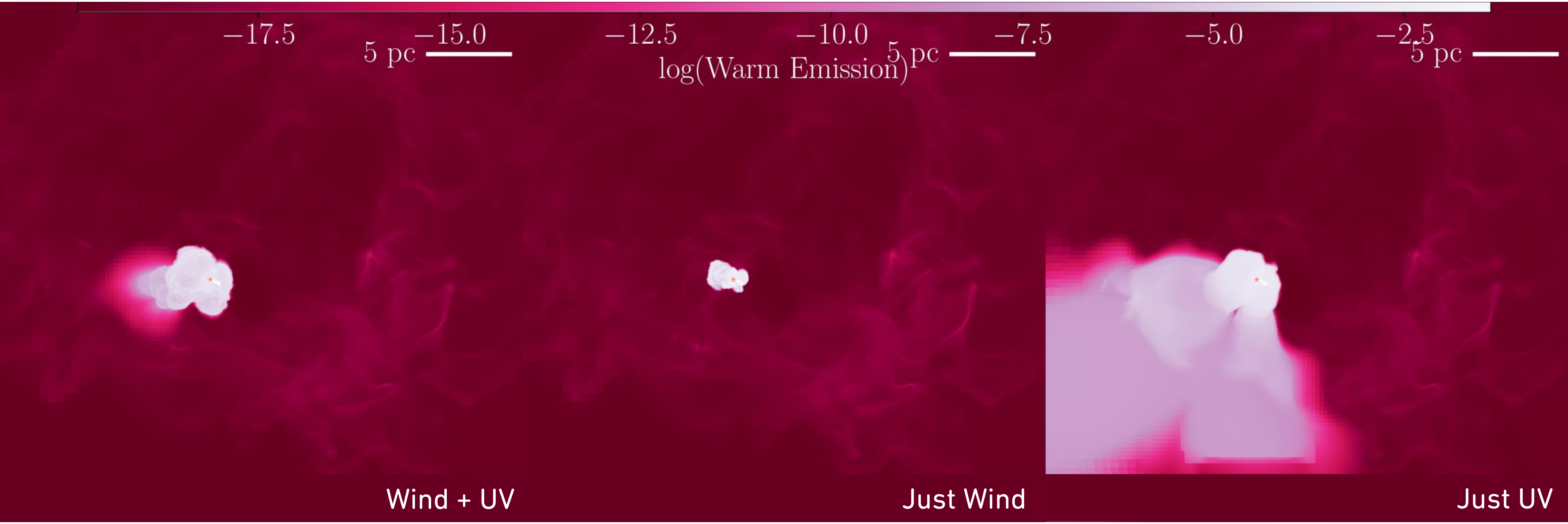
- Various guesses why the Geen+ 2021 simulations didn't reproduce the neutral Orion shell:
  - ✓ Maybe we need more refinement to resolve the shell – so **refine on pressure gradients**
  - ✓ Effects of **different magnetic fields**, **cosmic rays**? (simulations in progress…)
  - ✓ Suggestions that Eulerian grid codes overcool (e.g. Fierlinger+ 2016, Gentry+ 2017):



- Cooling ~ $n^2 \Lambda(T)$
  - Hot, diffuse gas (low n, high T) cools inefficiently
  - Cold, dense gas (high n, low T) cools inefficiently
  - **BUT mix them together in one cell and cooling is very efficient**
- Hack fix: **mask out the wind Contact Discontinuity** in the cooling module

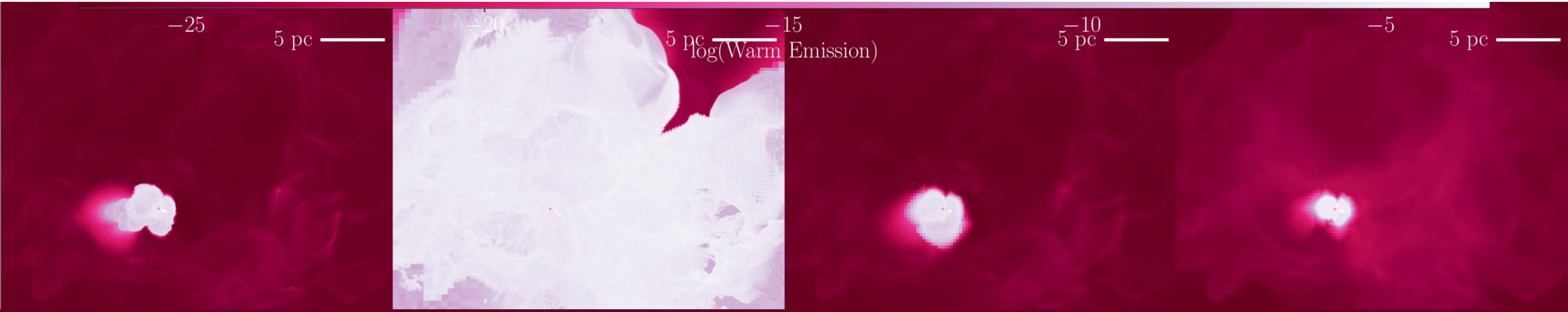
What happens when we simulate this in RAMSES?

Photoionised gas emission from HII region around a 35 Msun star (similar to Orion) at 200 kyr with the cooling mask fix:



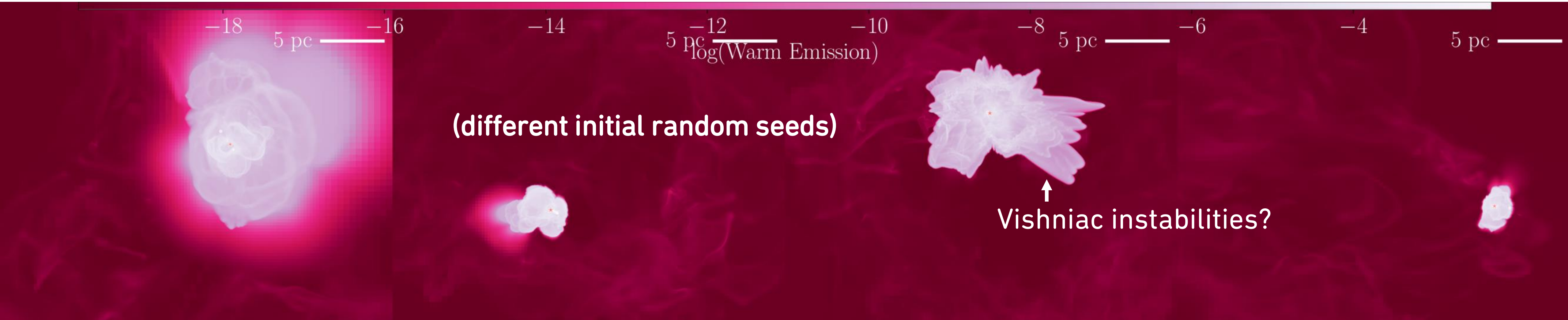
So efficient winds do trap UV radiation, even in 3D!

Couple more things:



Cooling Mask + Refinement | No Mask, Refinement | Mask, No Refinement | No Mask, No Refinement

1) Refinement is important, as is keeping the wind bubble pressurised with the cooling mask!



2) The initial turbulent seed still matters a huge amount even if the overall cloud density is the same

Where from here?

This might not happen in all regimes - there's a huge parameter space of clouds and stellar feedback behaviour to explore!

Watch out for PRALINES suite of cloud feedback runs – see previous talk by Taysun Kimm

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Conclusions

- Feedback is complicated
- The difference between "basically right" and "completely wrong" is quite small
- The big question is:
  Do wind bubbles cool efficiently?
- If they don't, winds can even reduce the impact of photoionisation by trapping UV

Take-home Message

- Let's do better than Spitzer & Weaver
- Combining simulations & new analytic models to answer specific observationally-motivated questions is the key