Insights from QED simulations

Outflow properties and Metal Transport

Thinkshop: 13-18 July

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with Mark Krumholz, Ben Wibking

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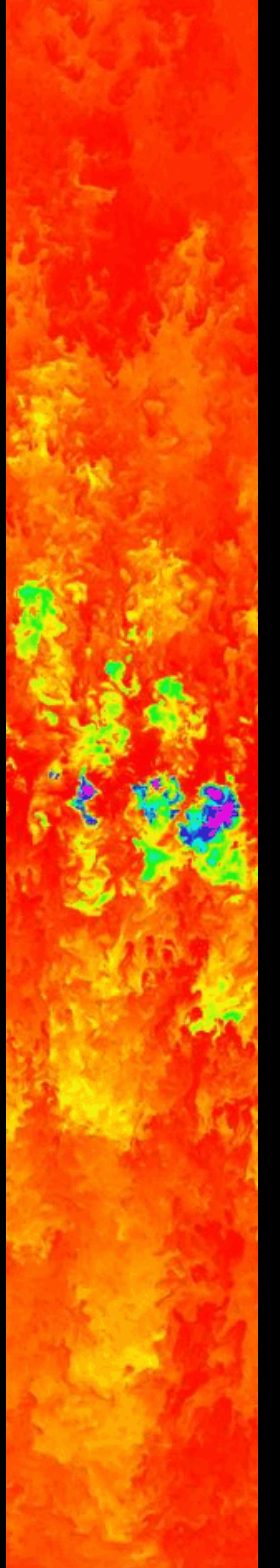
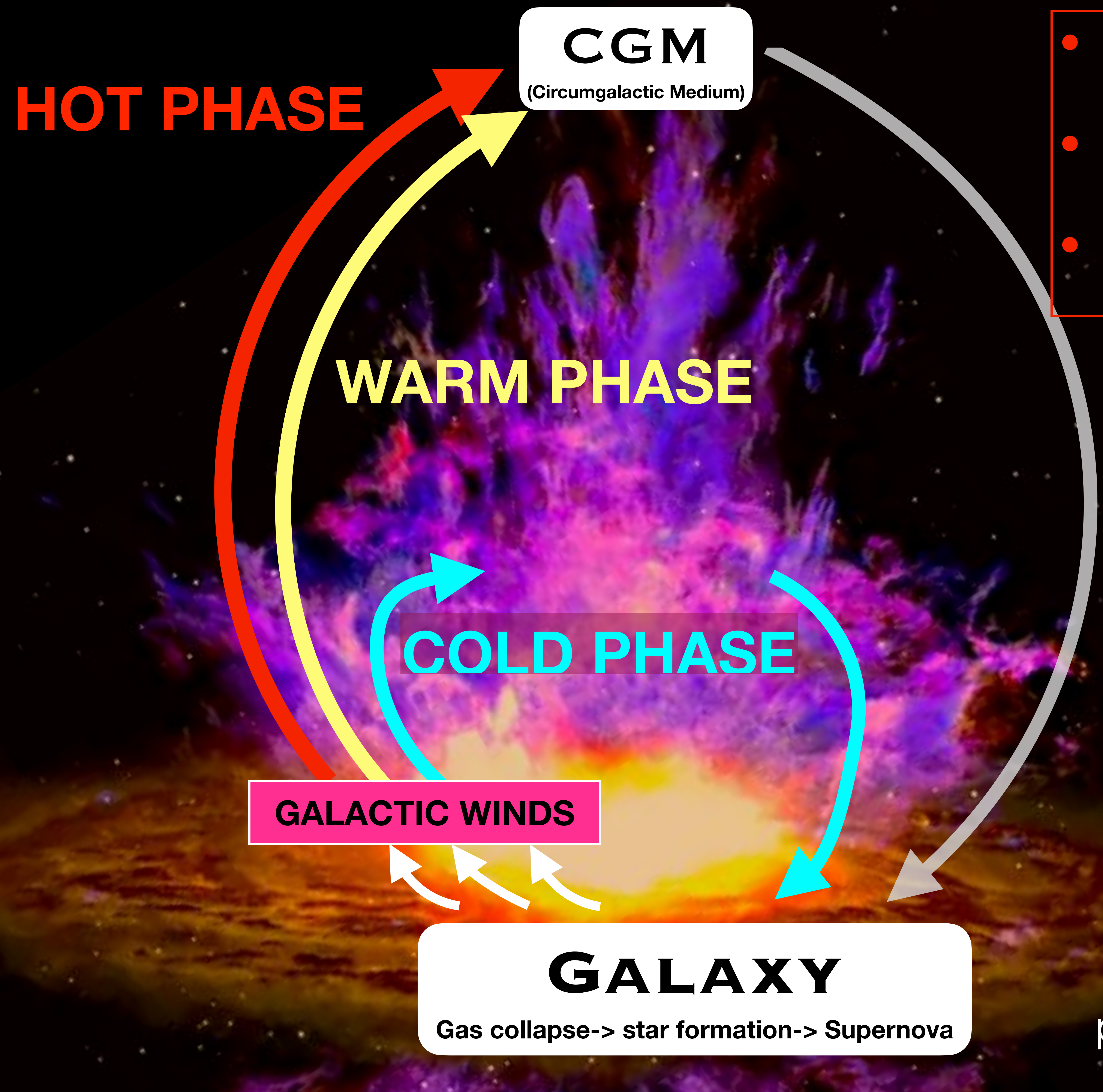


Multiphase Galactic Winds/Outflows



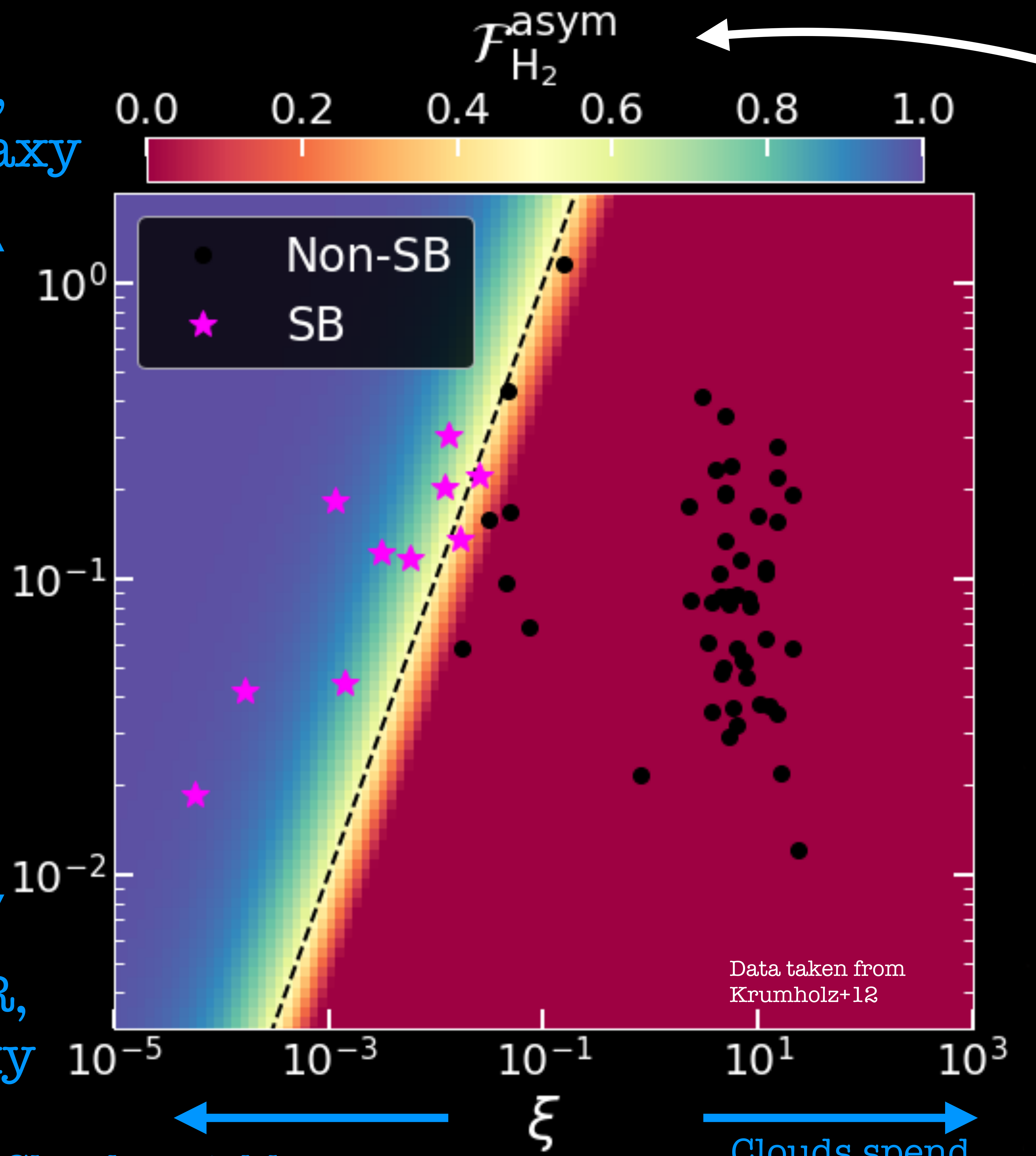
- "Momentum" or flux carrying phase – loaded with metals
- Lx linked to stellar mass, SFR (e.g.– Zhang+24, Wang+16, Li&Wang2013)
- Metal gradients in outflows (e.g.–Lopez+20, Porraz Barrera+24, Lopez+23)

- Ionised gas, UV emission/absorption
- Metal enrichment of outflows (Chisholm+17, Hamel–Bravo+24), outflow speed correlated with (s)SFR (Reichardt Chu+22), comprehensive reviews (Veilleux+05)

- Cool atomic molecular gas
- Few detections of the molecular phase (Martini+18, Leroy+15, Bolatto+13, Walter+17, Tchernyshyov2022, Di Teodoro +18,20), and Capucine's talk (Barferty+25)

plus all the info in Thorsten's and Matthew's review

Larger SFR,
smaller galaxy



Fractional Flux of
molecular gas

Smaller SFR,
larger galaxy

Clouds quickly escape
photon field

Clouds spend
longer in photon
field

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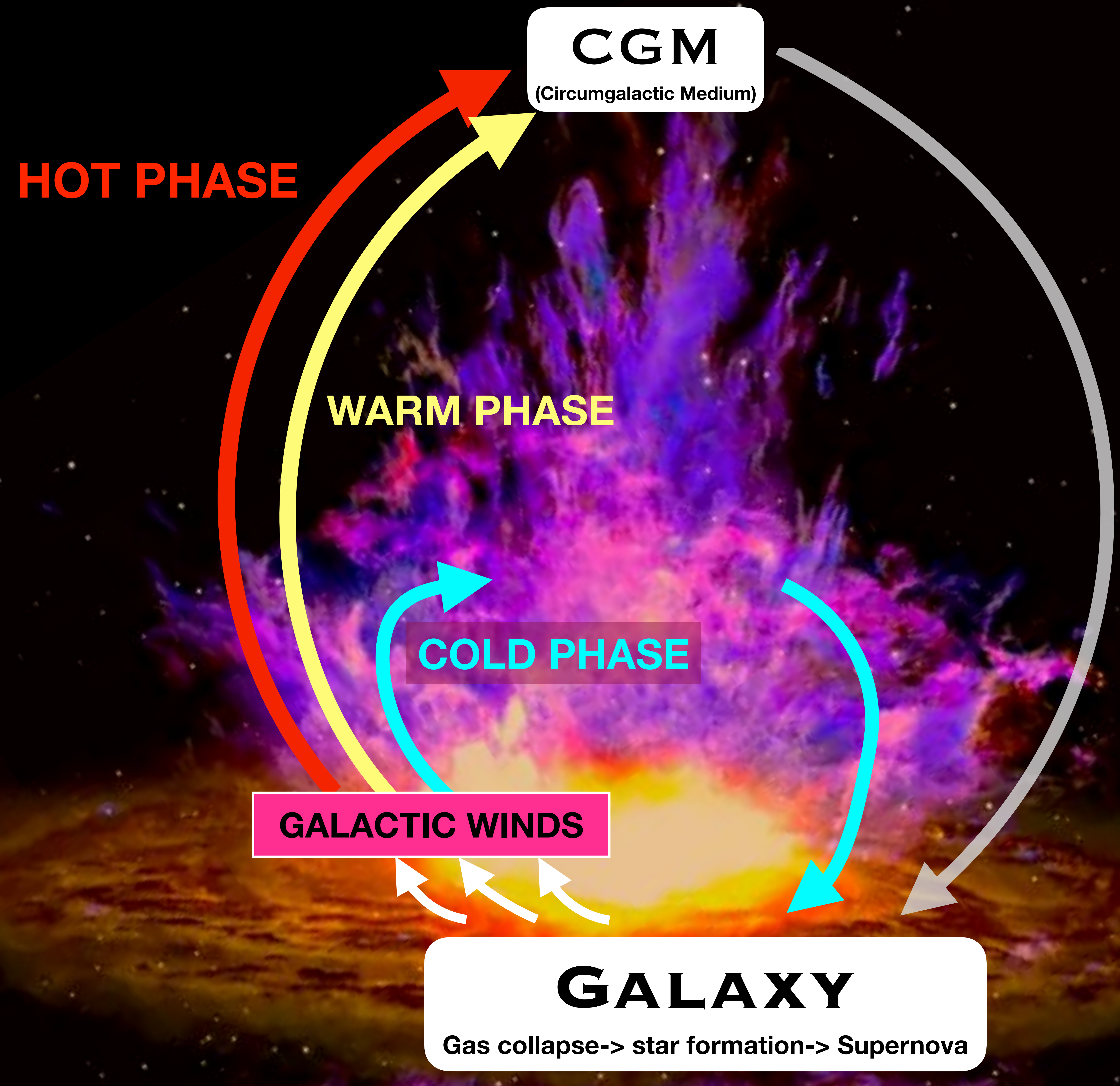
Loading factors of outflows



$$\eta = \frac{\text{Outflow rate}}{\text{Injection Rate}}$$

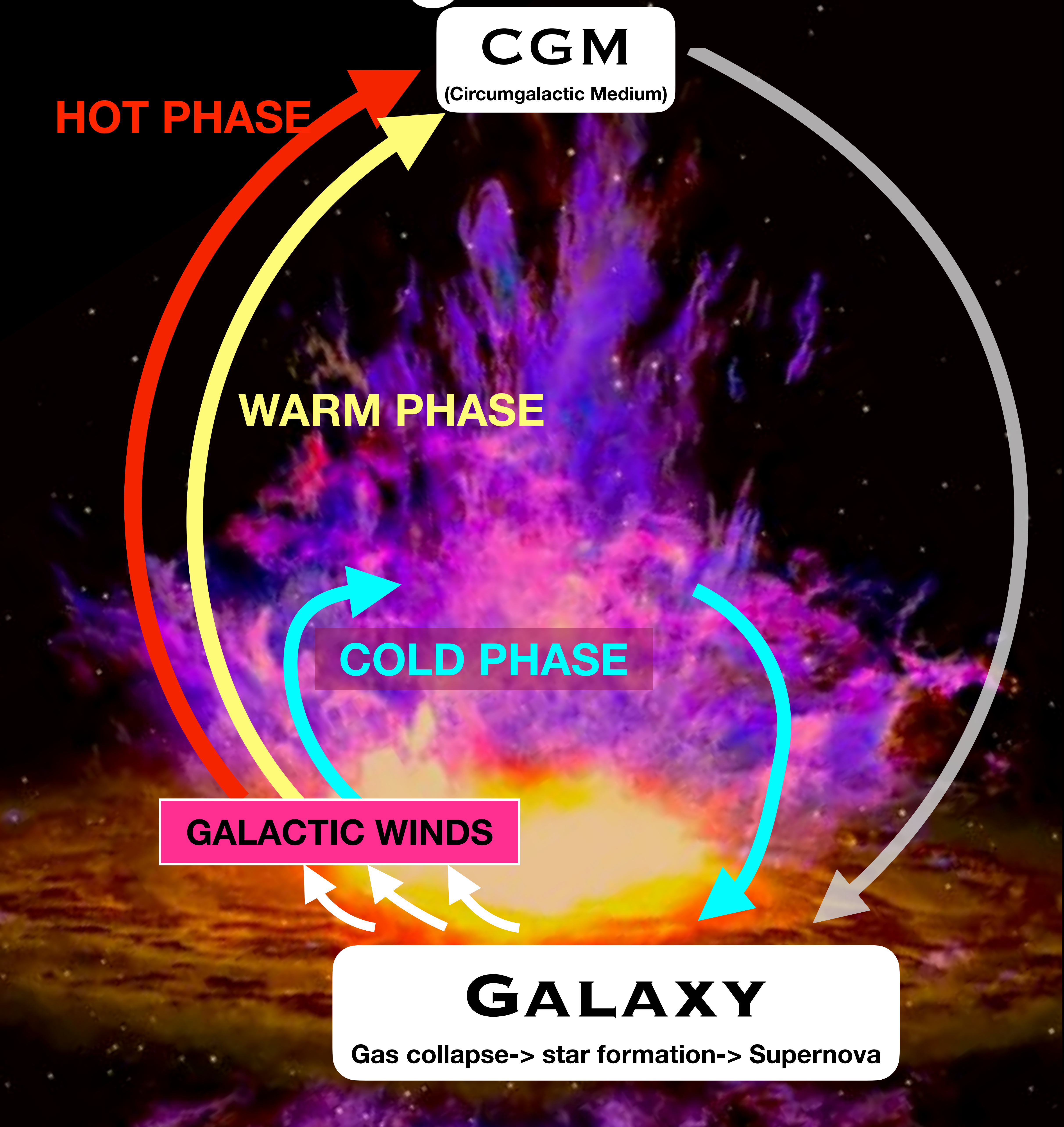
η_M — Stellar mass–halo mass relation, cosmic star formation history (Lilly+2013, Dekel&Mandelkar2014)

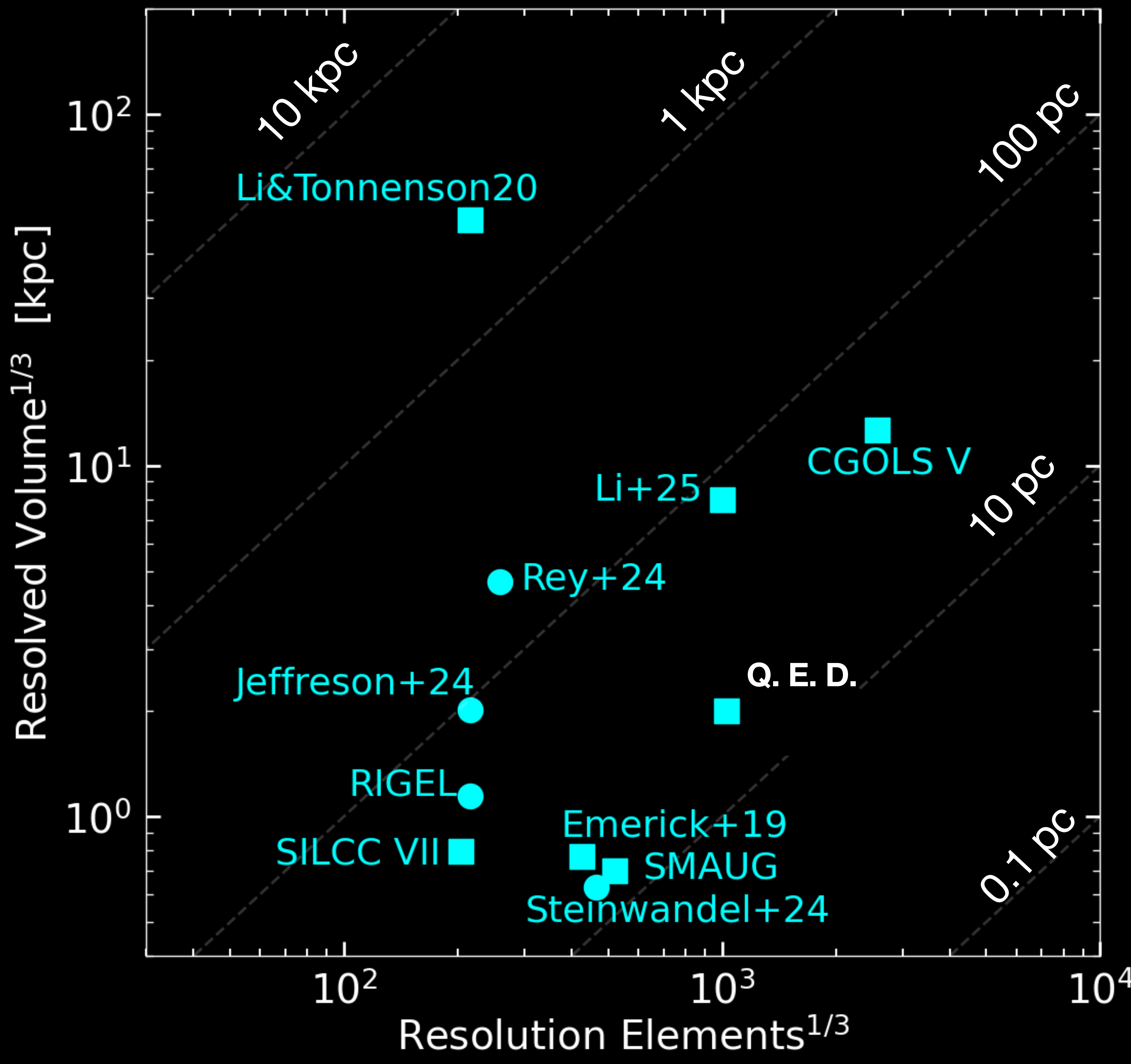
η_E — Energy balance of the CGM (Suresh+2015, Li&Tonneson2020)

η_Z, ϕ — MMR and metal gradient in galaxies (Peeples&Shankar2011, Forbes+2019, Sharda+2021a,b)

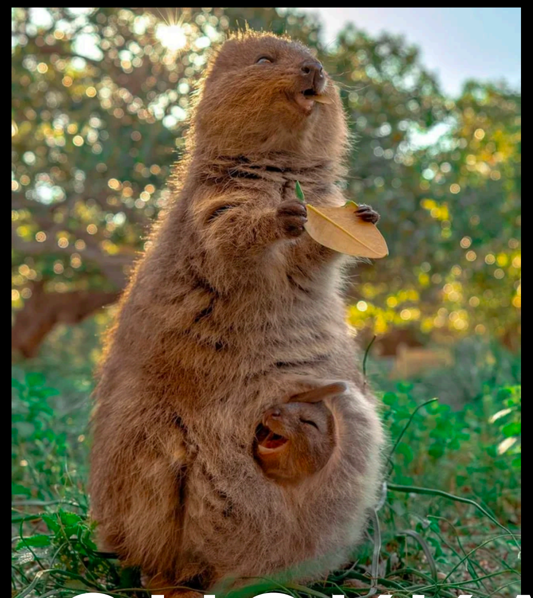
SILCC, TIGRESS/SMAUG, CGOLS, Rey+24, Steinwandel+24…

Loading factors of outflows





Q. E. D. Suite of simulations



- GPU-accelerated code QUOKKA
- 10 tall-box HD simulations
- Uniform resolution, $2\ \mathrm{pc}$
- Milky Way mass galaxy
- Three different environments:
  1. Solar neighbourhood (Σ_{gas})
  2. Inner galaxy ($\sim 4\ \Sigma_{\mathrm{gas}}$)
  3. Outer galaxy ($\sim 0.2\ \Sigma_{\mathrm{gas}}$)

Vijayan+24,25

Q. E. D. Suite of simulations

1. Initially smooth density/ temperature profiles.
2. $\Sigma_{gas} = 50,\ 13,\ 2.5\ M_{\odot}pc^{-2}$
3. $[x, y, z] = [1,1,8]$ kpc
4. Radiative Heating & Cooling through Grackle.
5. SN FB => 10^{51} erg of thermal energy.

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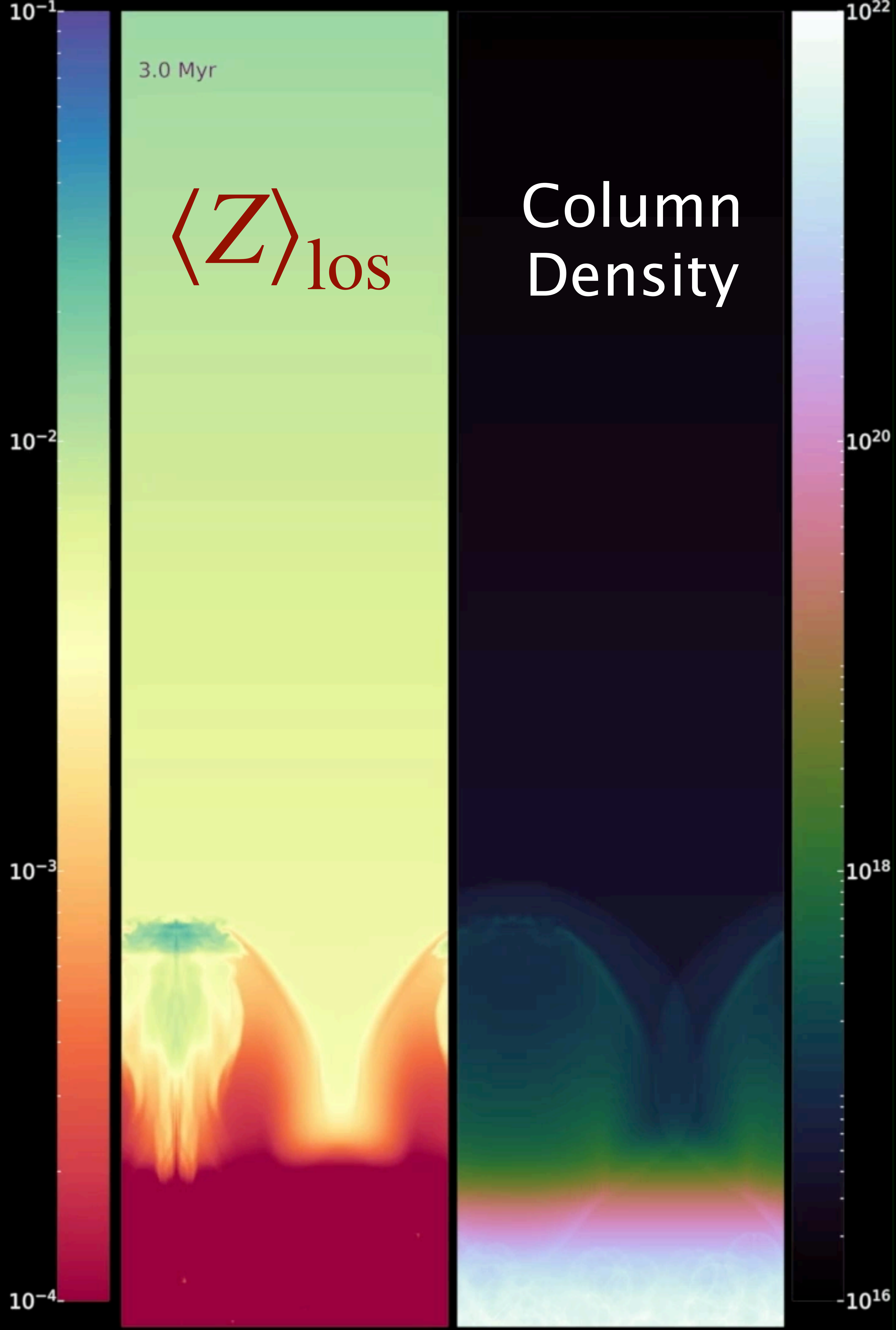

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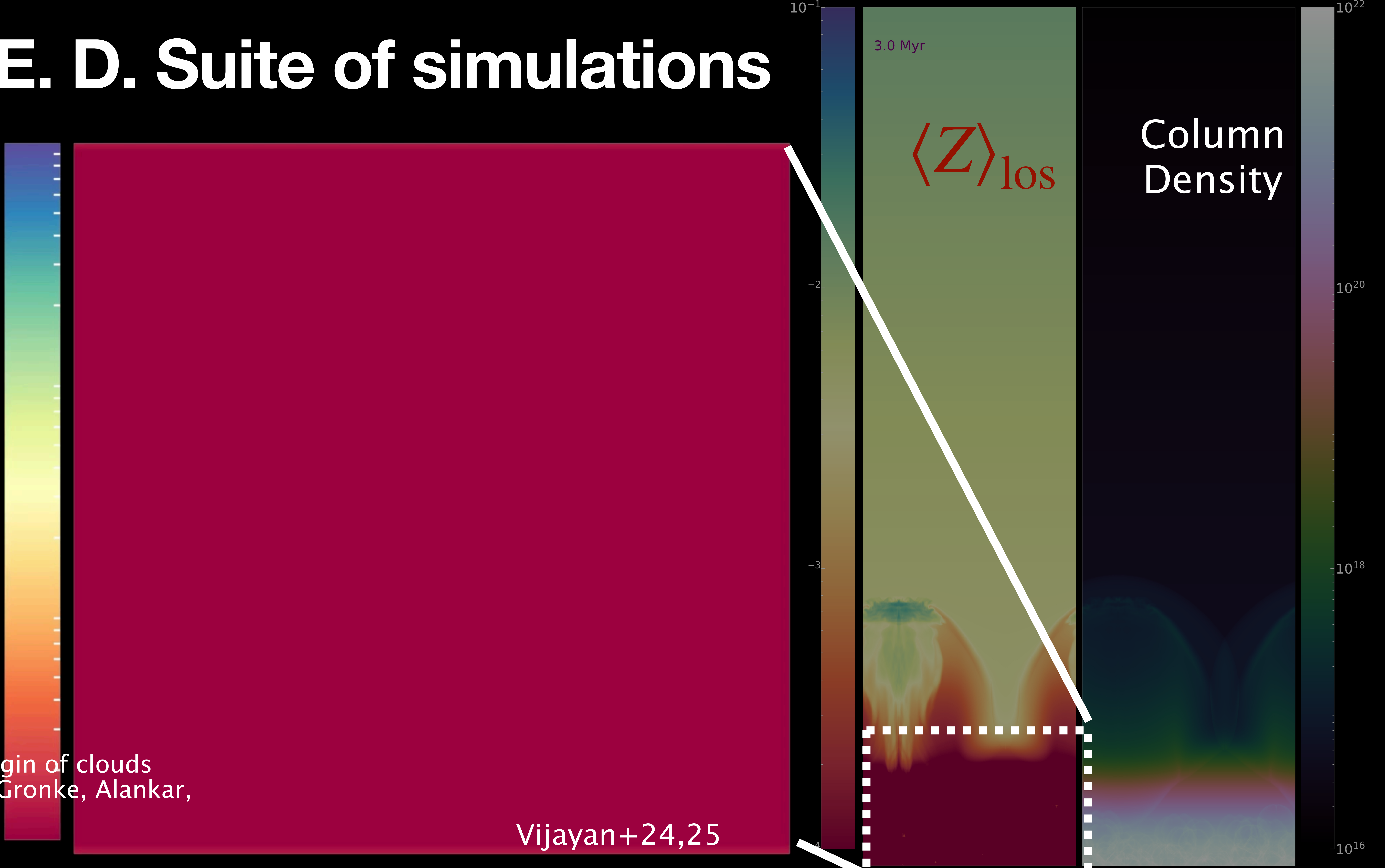

Possible origin of clouds studied by Gronke, Alankar, Ritali

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Insight 1: Loading factors respond to environment

Outflows

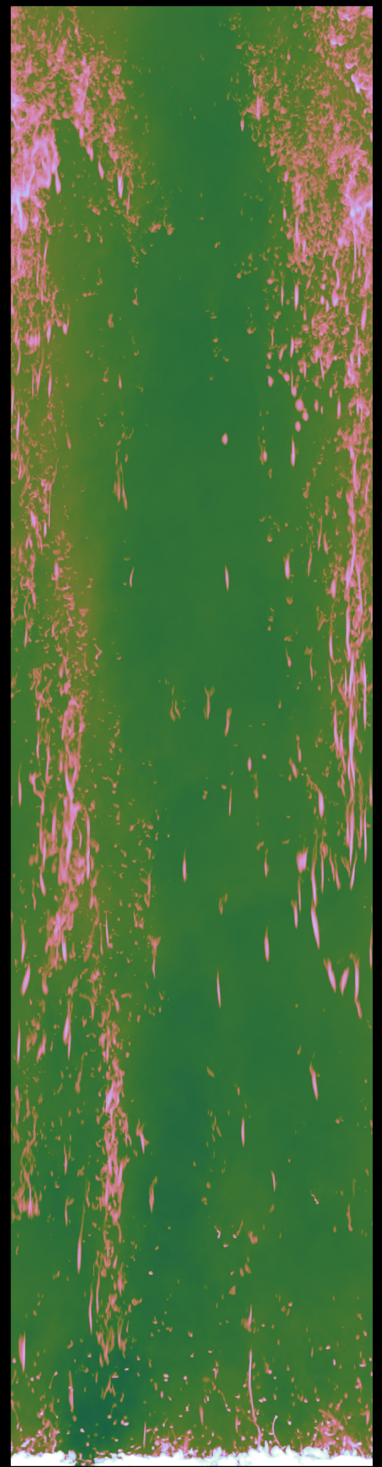
Stea
dy

Hot

- High SFR
- $\eta_M < 1$, not multiphase
- High metal loading
- Eg– Inner galaxy

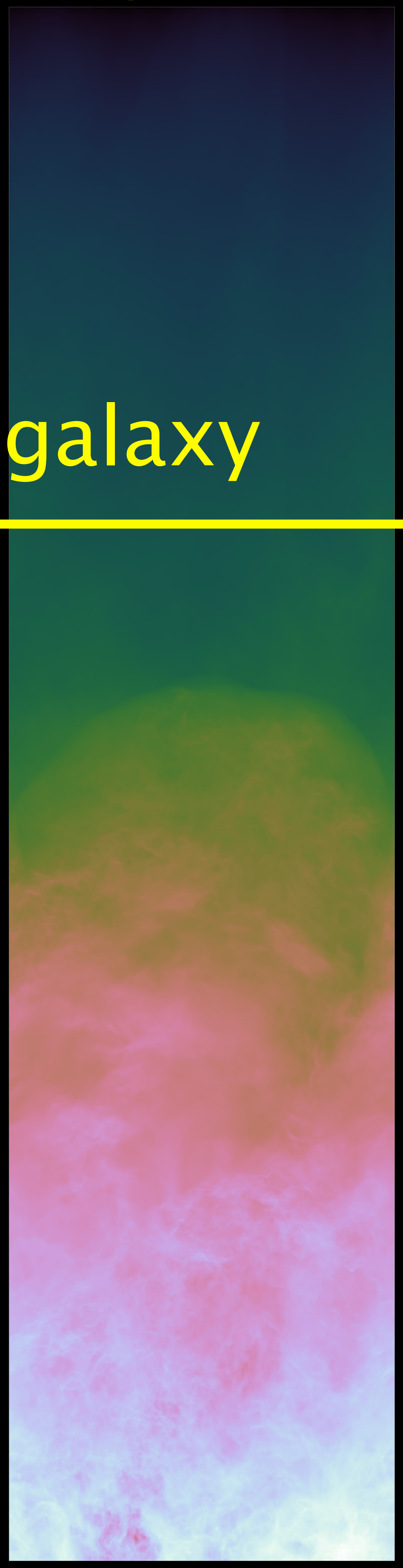
Multiphase

- $\eta_M \sim 1$
- High metal loading
- Eg – solar neighbourhood



Bursty

- Low SFR, low gas cooling
- $\eta_M < 1$
- $\eta_Z, \phi \approx 0$
- Eg – outer galaxy



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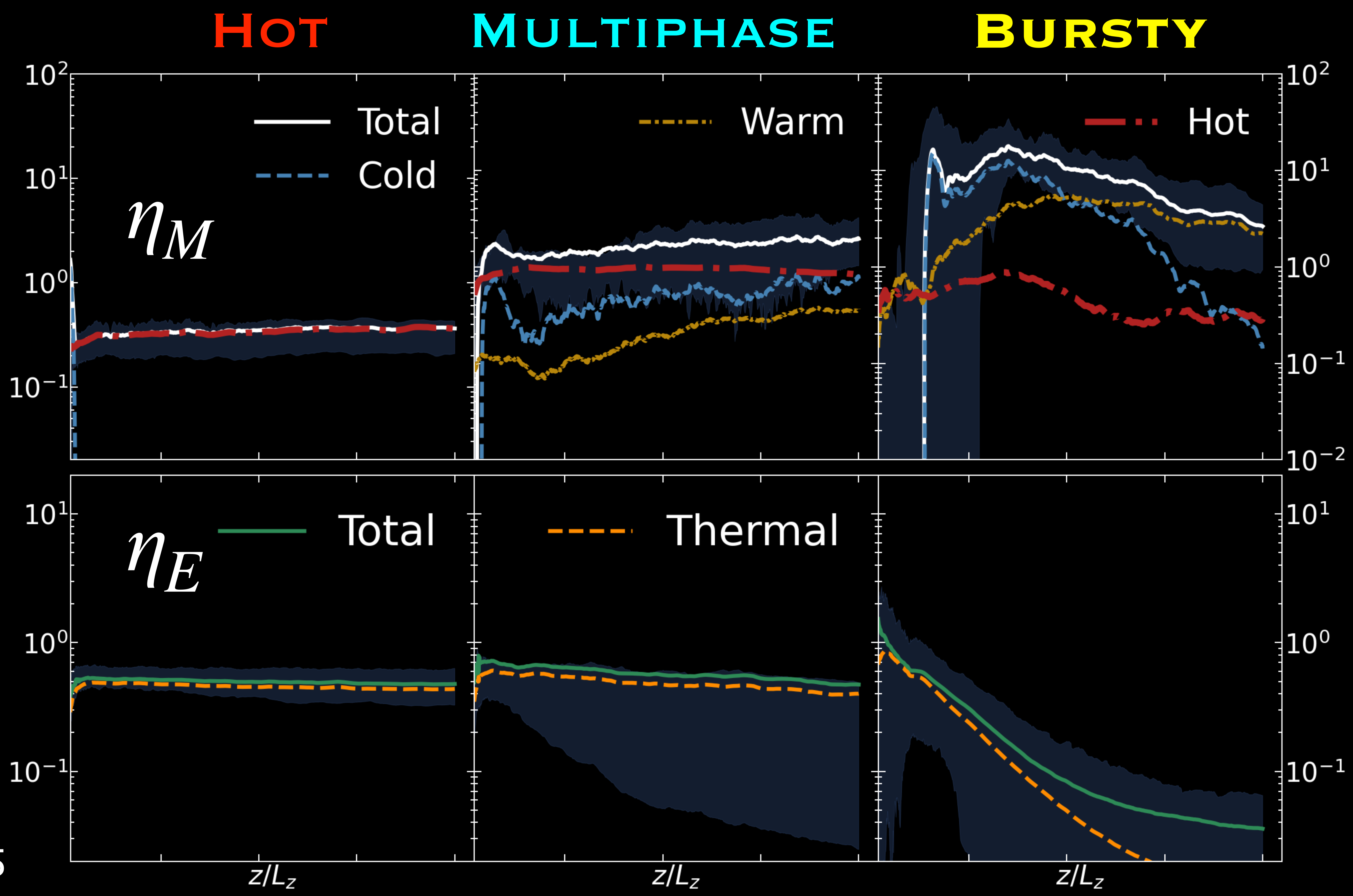
Insight 1: Loading factors respond to environment

- Different phase contribute differently
- Hot winds are hot, bursty winds are warm
- Hot/multiphase winds are thermal energy dominated



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Insight 2: Ratio of h_{gas} to h_{SN} drives the variety

HOT

■ $h_{\mathrm{gas}} < h_{\mathrm{SN}}$

SN go off in low density regions

MULTIPHASE

★ $h_{\mathrm{gas}} \sim h_{\mathrm{SN}}$

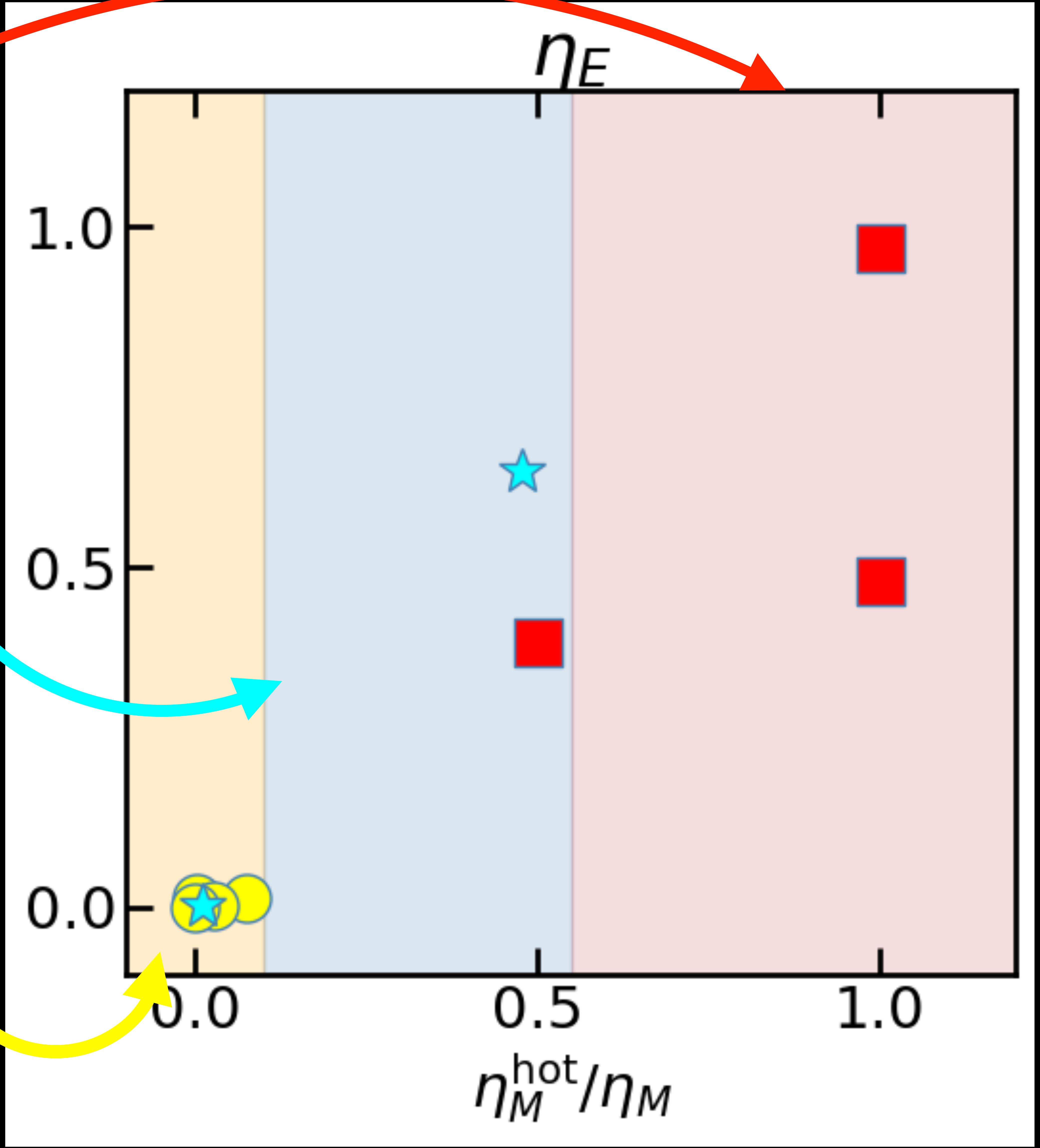
Outflows entrain ISM

BURSTY

● $h_{\mathrm{gas}} > h_{\mathrm{SN}}$

SN go off in dense regions

Vijayan+25



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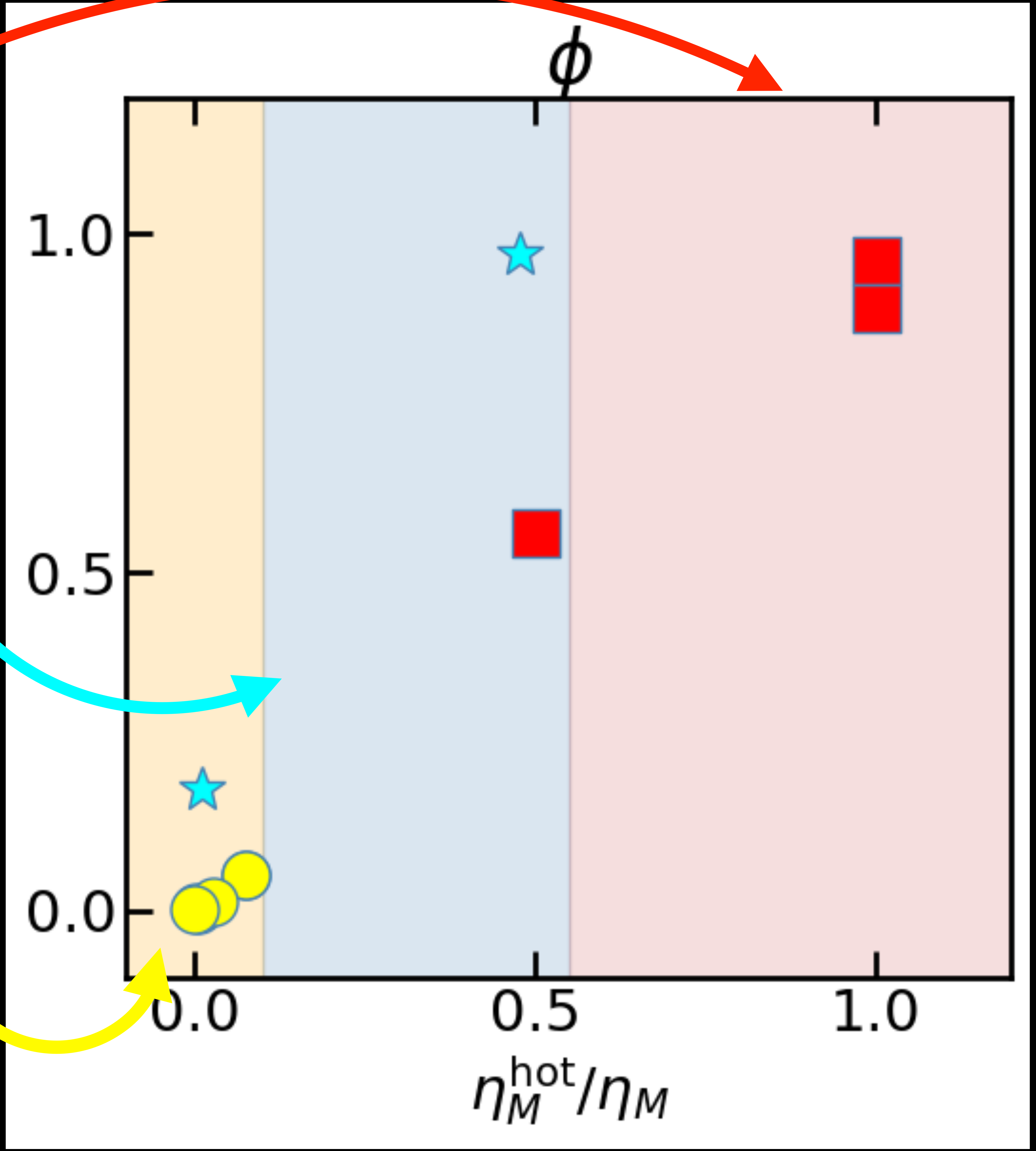
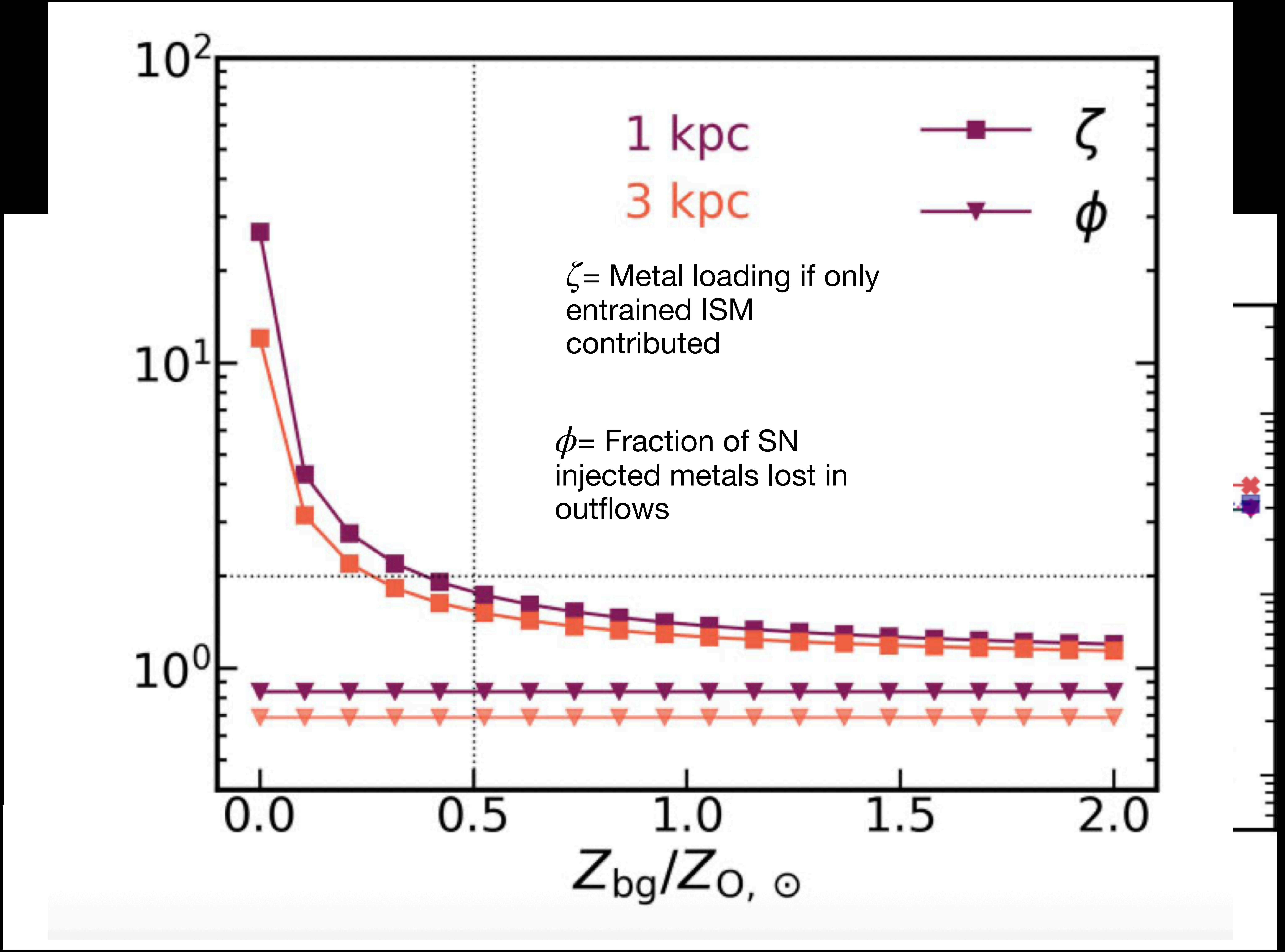


Insight 3: Metal loading varies with $Z_{\rm bg}$

- ★$\zeta > 1$ means that outflowing gas more metals than expected from purely entrained ISM.
- ★Entrained metals contribute more if $Z_{\rm bg} \gtrsim 0.2\ Z_\odot$
- ★ $\phi \simeq 0.8$ means most SN injected metals are lost to outflows



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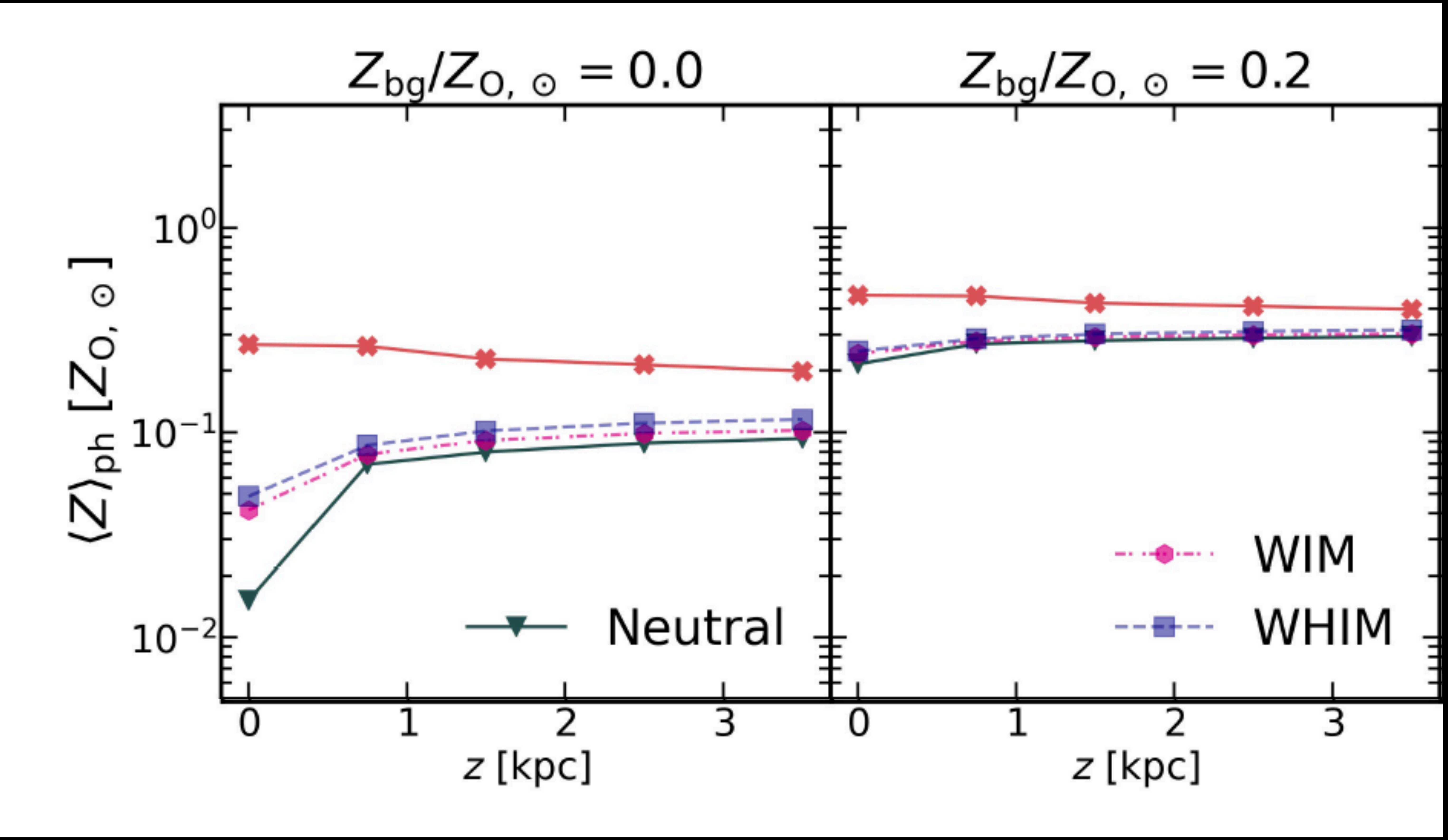
Insight 3: Metal loading varies with Z_{bg}

- ★Different phases are loaded differently with metals.
- ★Hot phase more metal enriched.
- ★Loses metals to warmer phases during its trajectory.
- ★Warm phase less enriched (eg in Ramona's talk)

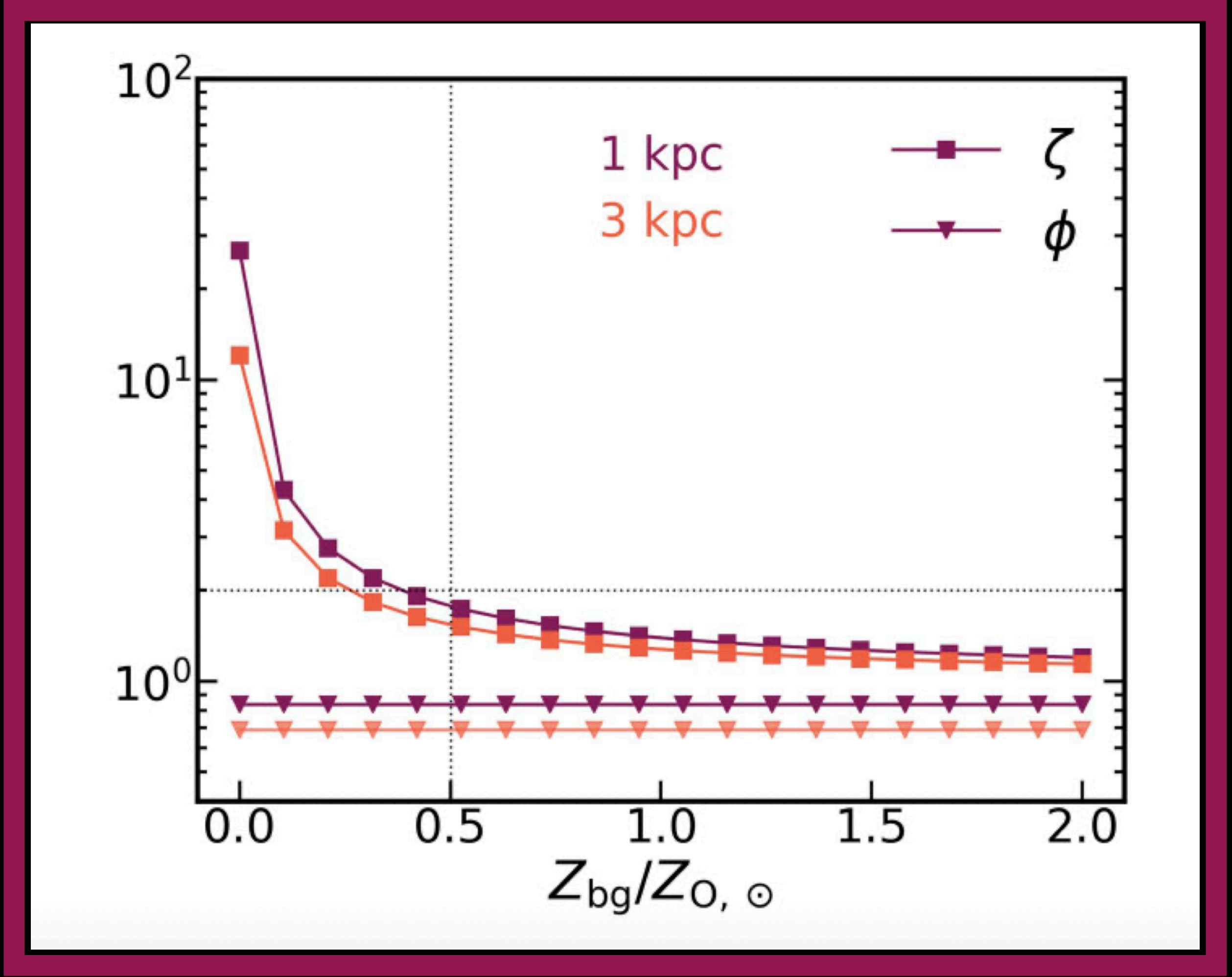
Vijayan+24

Metallicity in 1 kpc thick Sections vs Distance from Midplane



Quokka (-based QED simulations) say(s) what!

Insight 3: Metal loading varies with $Z_{\rm bg}$



Insight 1: Variety of Outflows

Insight 2: Ratio of $h_{\rm gas}$ to $h_{\rm SN}$ drives the variety