## Sweating the Small Stuff:

# Stellar Feedback in Massive Star Clusters

Anna Rosen | San Diego State University

**TOSCA**: Topical Overview of Star Cluster Astrophysics

# Key Scientific Challenges for the Next Decade

*Understanding Massive Star Formation and Stellar Feedback is crucial to address these goals*

**Cosmic Ecosystems**

*Priority Area: Unveiling the Drivers of Galaxy Growth*

Astro Decadal Survey (Astro2020)

“Research in the coming decade will *revolutionize our understanding* of the origins and evolution of galaxies, from the cosmic webs of gas that feed them to *the formation of stars*.”

# Key Scientific Challenges for the Next Decade

*Understanding Massive Star Formation and Stellar Feedback is crucial to address these goals*

**Cosmic Ecosystems**

Spitzer (Infrared)
Hubble (Optical)
Chandra (X-ray)

*Priority Area: Unveiling the Drivers of Galaxy Growth*

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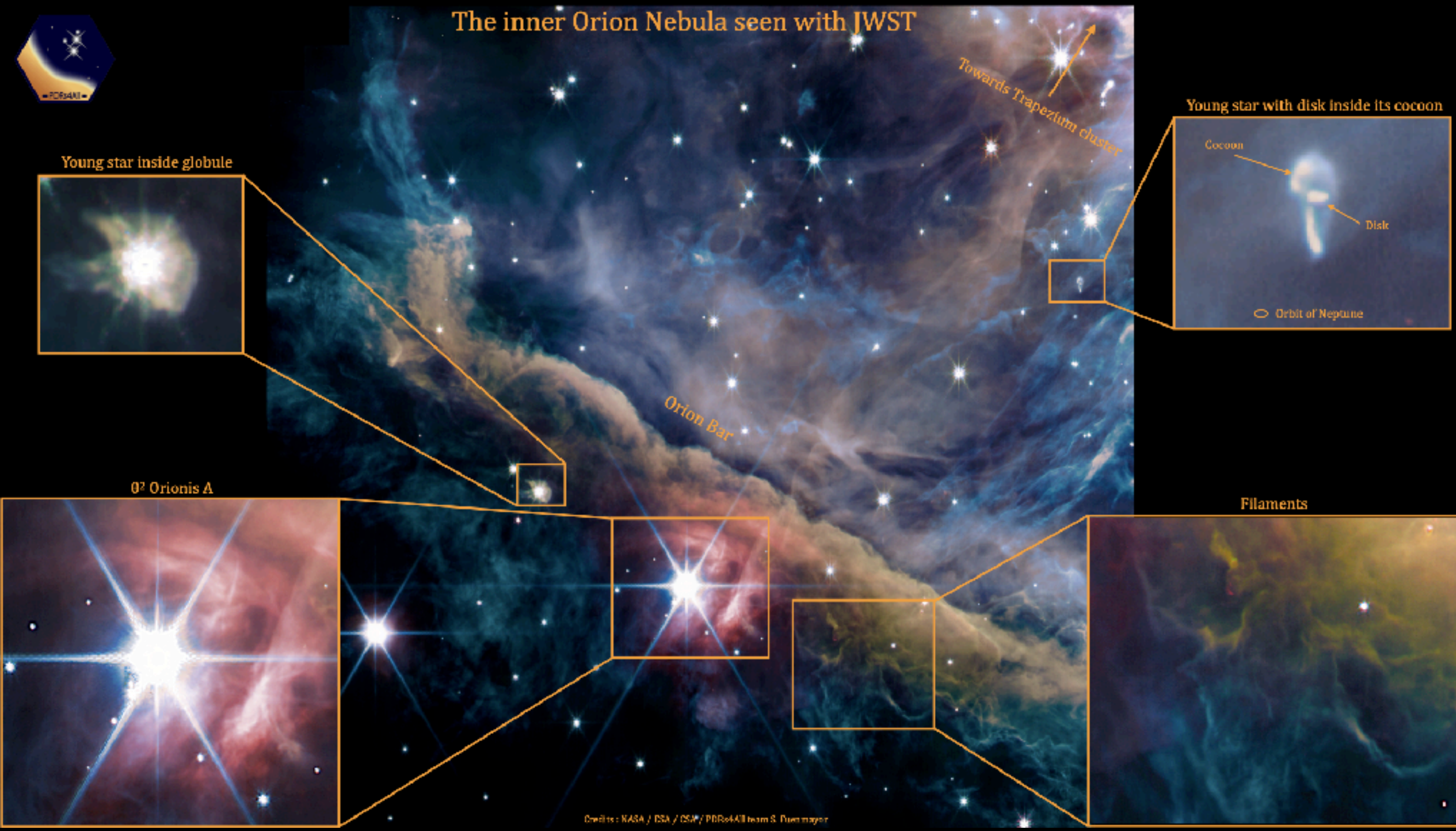
"Research in the coming decade will *revolutionize our understanding* of the origins and evolution of galaxies, from the cosmic webs of gas that feed them to *the formation of stars*."

# Stars form via the hierarchical collapse of gas in GMCs. Stars inject mass, energy, and momentum into the ISM

(i.e., they ***feedback*** on their natal environment)



Credits: NASA / ESA / CSA / PDRs4All team S. Fuenmayor

See Review by **Rosen**+2020

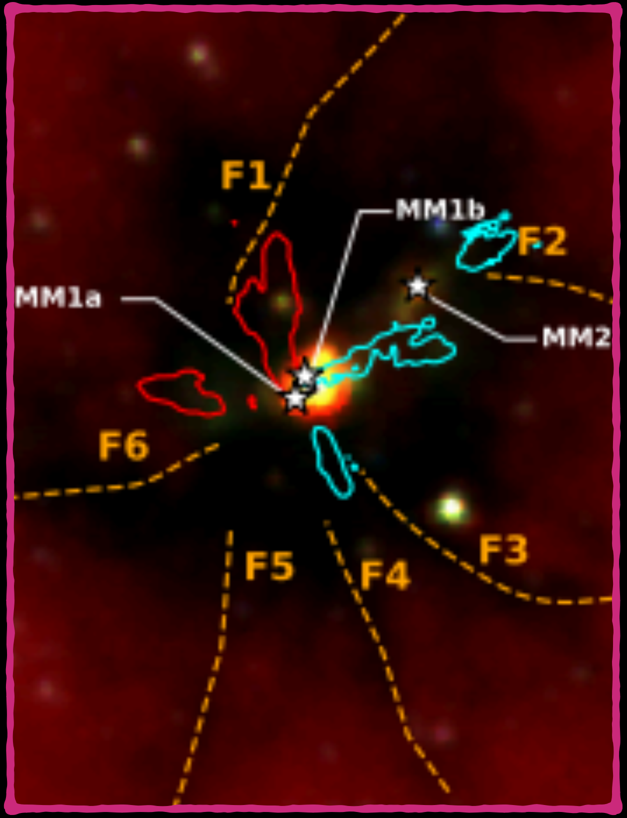
# Stellar Feedback on Small Scales

## (e.g., stars)

**Radiation**

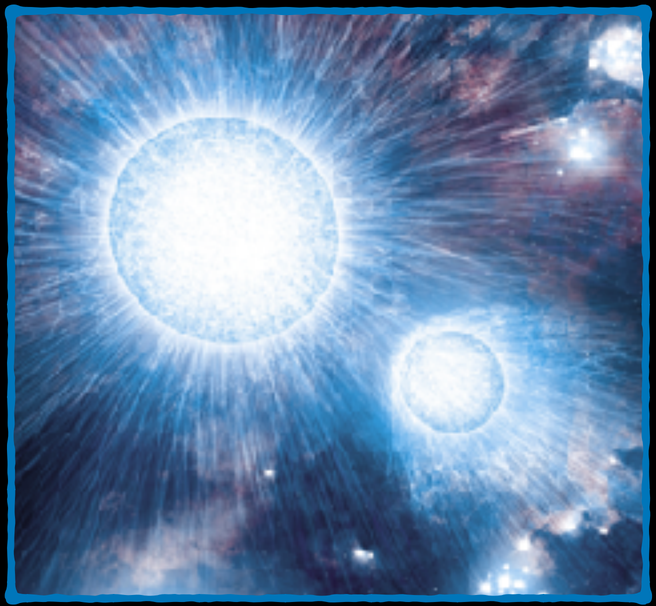
R136 in the LMC (*JWST*)

**Protostellar Outflows**



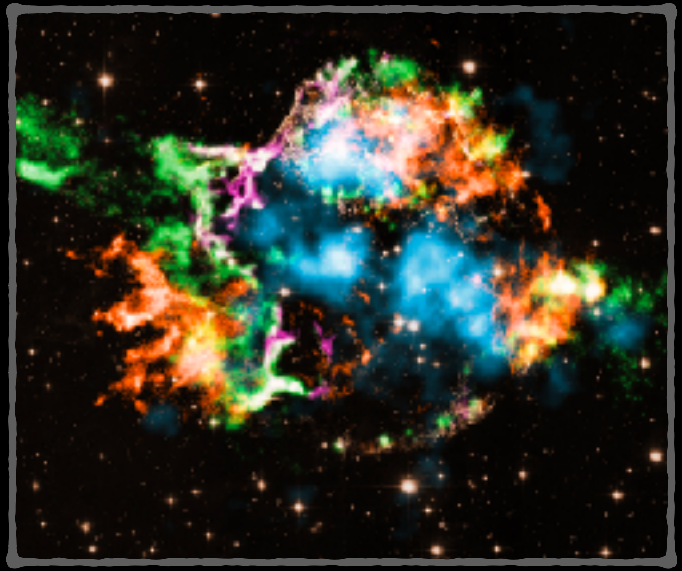
Avison+(incl. **Rosen**) 2021

**Stellar winds**



NASA (Artist rendition)

**Supernovae**

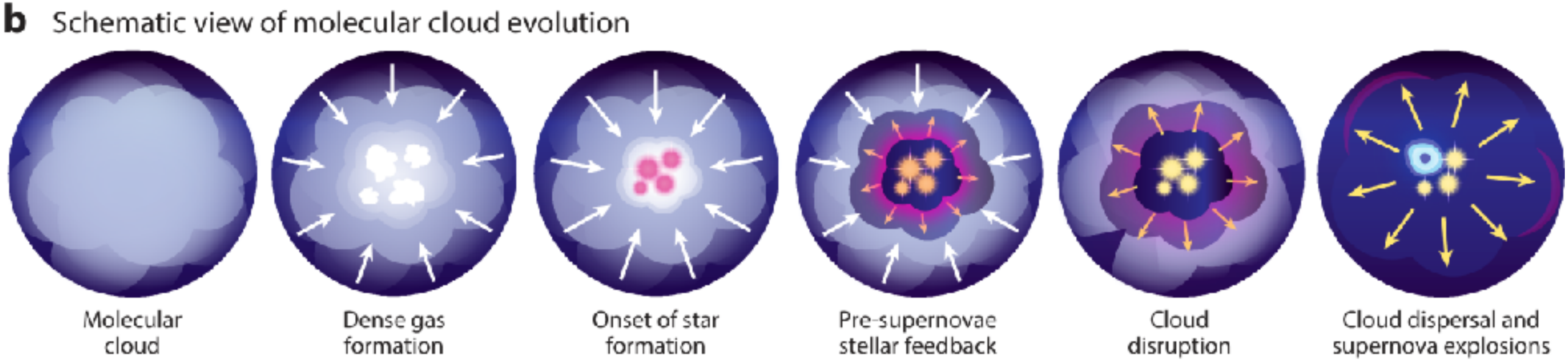


Cassiopeia A (*HST/Chandra*)

Massive stars ($\gtrsim 8M_\odot$) are rare (~1% by number), but dominate the energetics of massive star forming regions & star-forming galaxies

Stellar feedback can halt stellar accretion → leads to inefficient star formation in GMCs and galaxies → launches galactic outflows.

# The Chaotic Lives of Star-forming GMCs



Schinnerer E, Leroy AK. 2024
*Annu. Rev. Astron. Astrophys.* 62:369–436

Both observations & simulations confirm that pre-supernovae feedback (*early feedback* — radiation & winds) disrupts star-forming clouds quickly.
(e.g., see Grudic+2022, Chevance+2022, 2023, Jeffreson+2024)

# The Chaotic Lives of Star-forming Galaxies

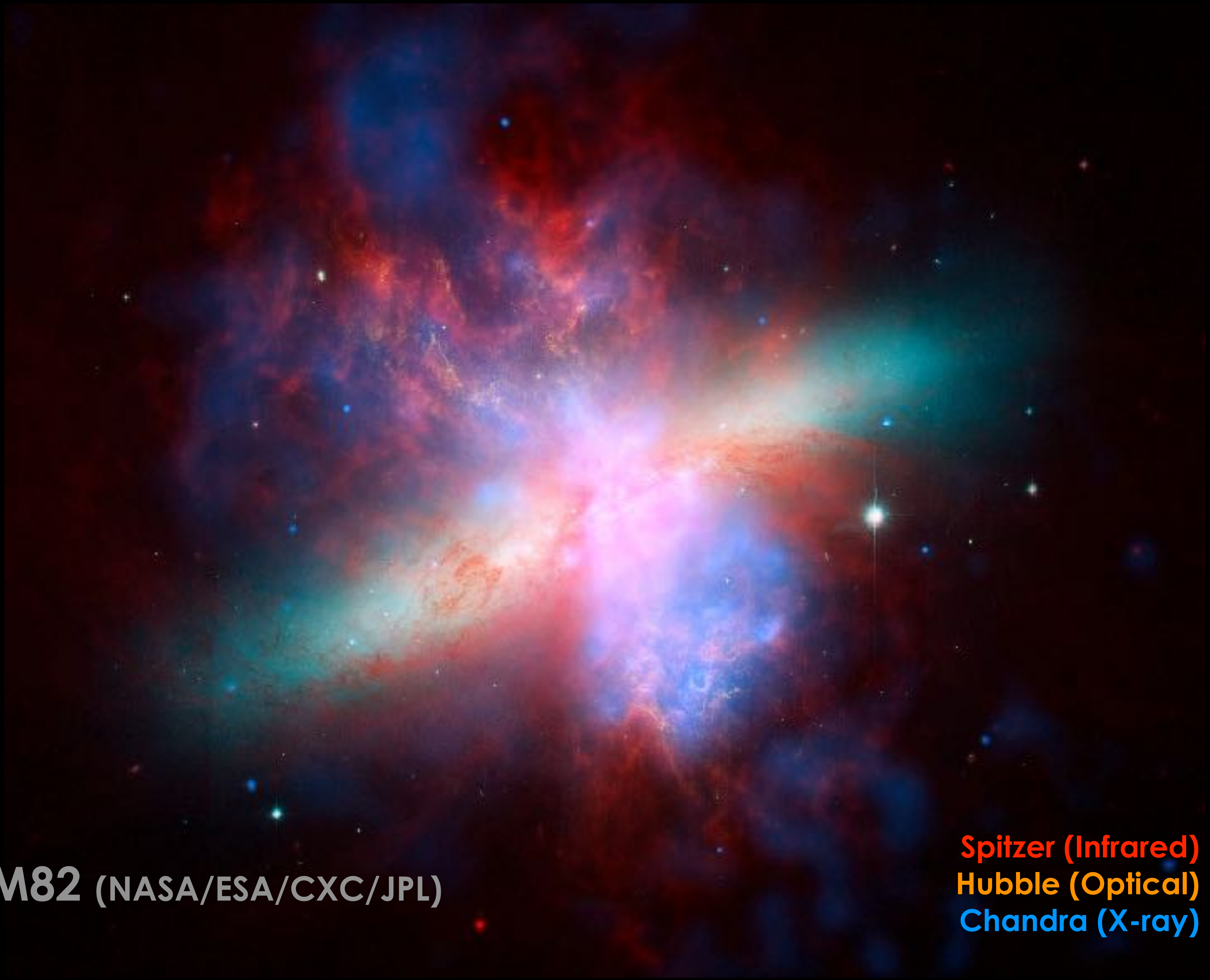
**PHANGS-JWST: NGC 628 aka "Phantom Galaxy"**

**MIRI: F770W/F1000W/F1130W/F2100W**

(e.g., Barnes, PHANGS-JWST+2023; Watkins, PHANGS-JWST+2023)

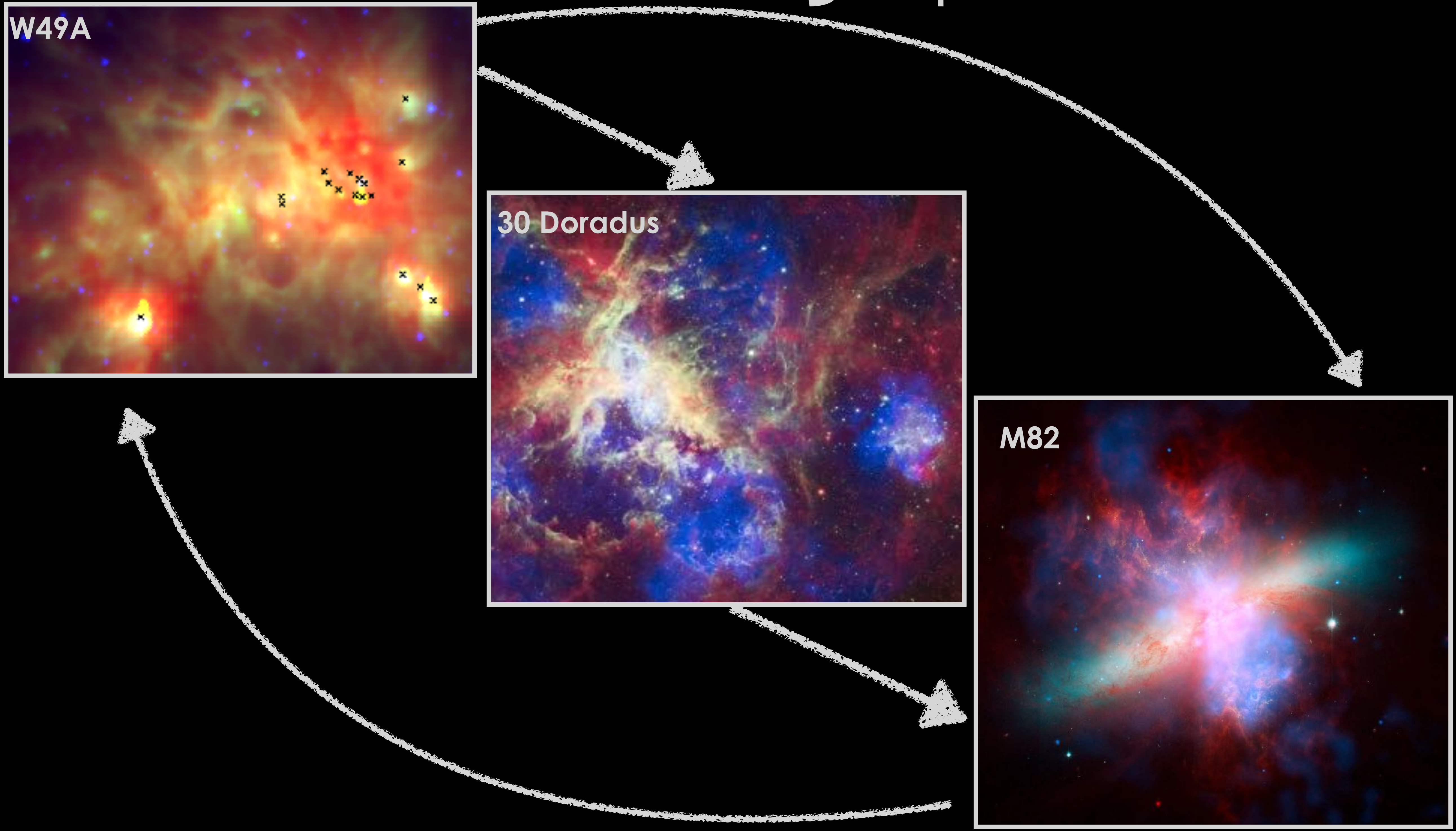
Credit: https://sites.google.com/view/phangs/home

# Stellar feedback disrupts GMCs → Creates galactic super-bubbles → Launches galactic outflows



(e.g., Bolatto+2013, Hopkins+2014, Thompson & Krumholz 2016, Lopez+2018, Lopez+2022)

# Stellar feedback is a **multi-scale**, **multi-physics**, & **multi-wavelength** problem



**…and remains as one of the *largest uncertainties* in star and galaxy formation**

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(e.g., stars)

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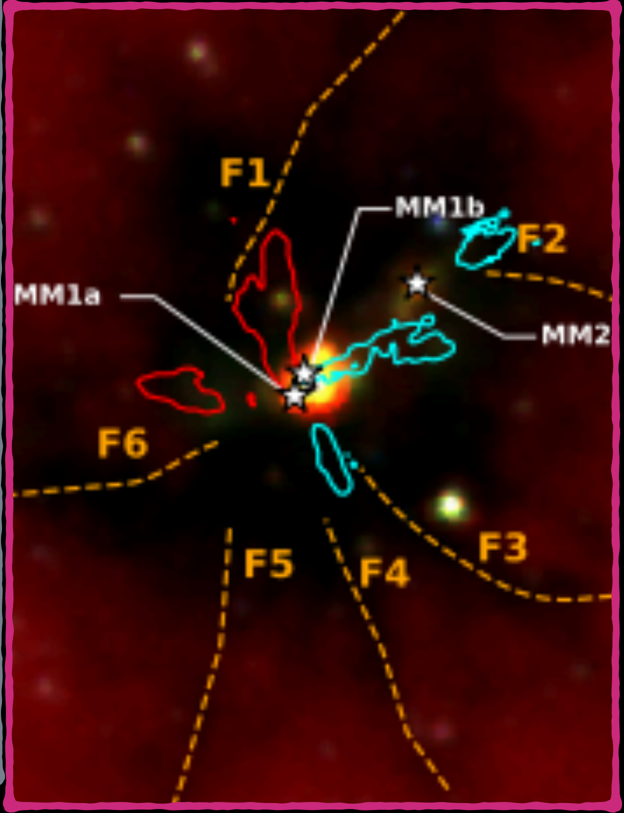
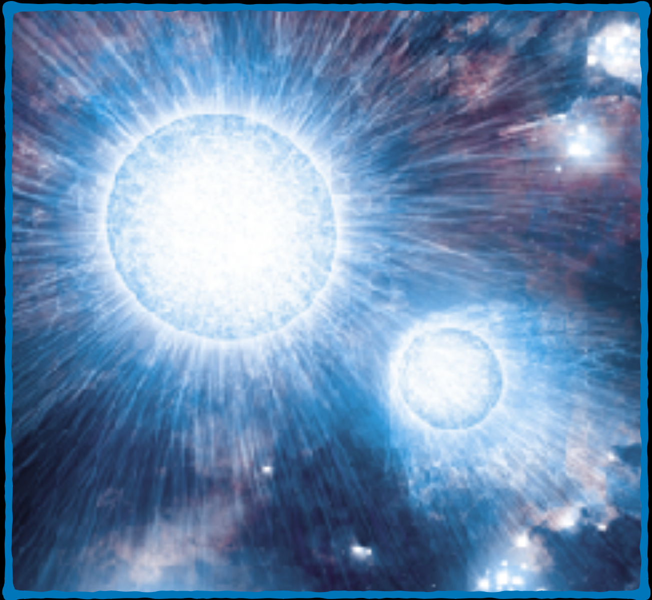


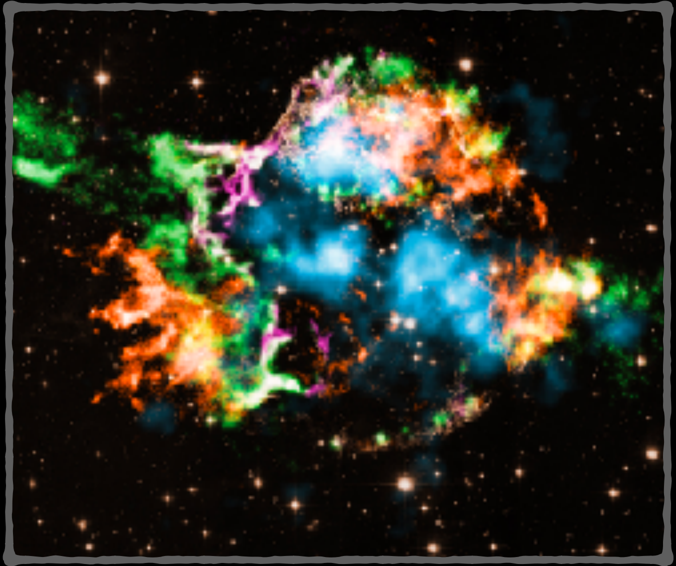
Avison+(incl. **Rosen**) 2021

**Stellar winds**



NASA (Artist rendition)

**Supernovae**



Cassiopeia A (*HST/Chandra*)

# Stellar Radiation: **Radiation Pressure** & Photoionization

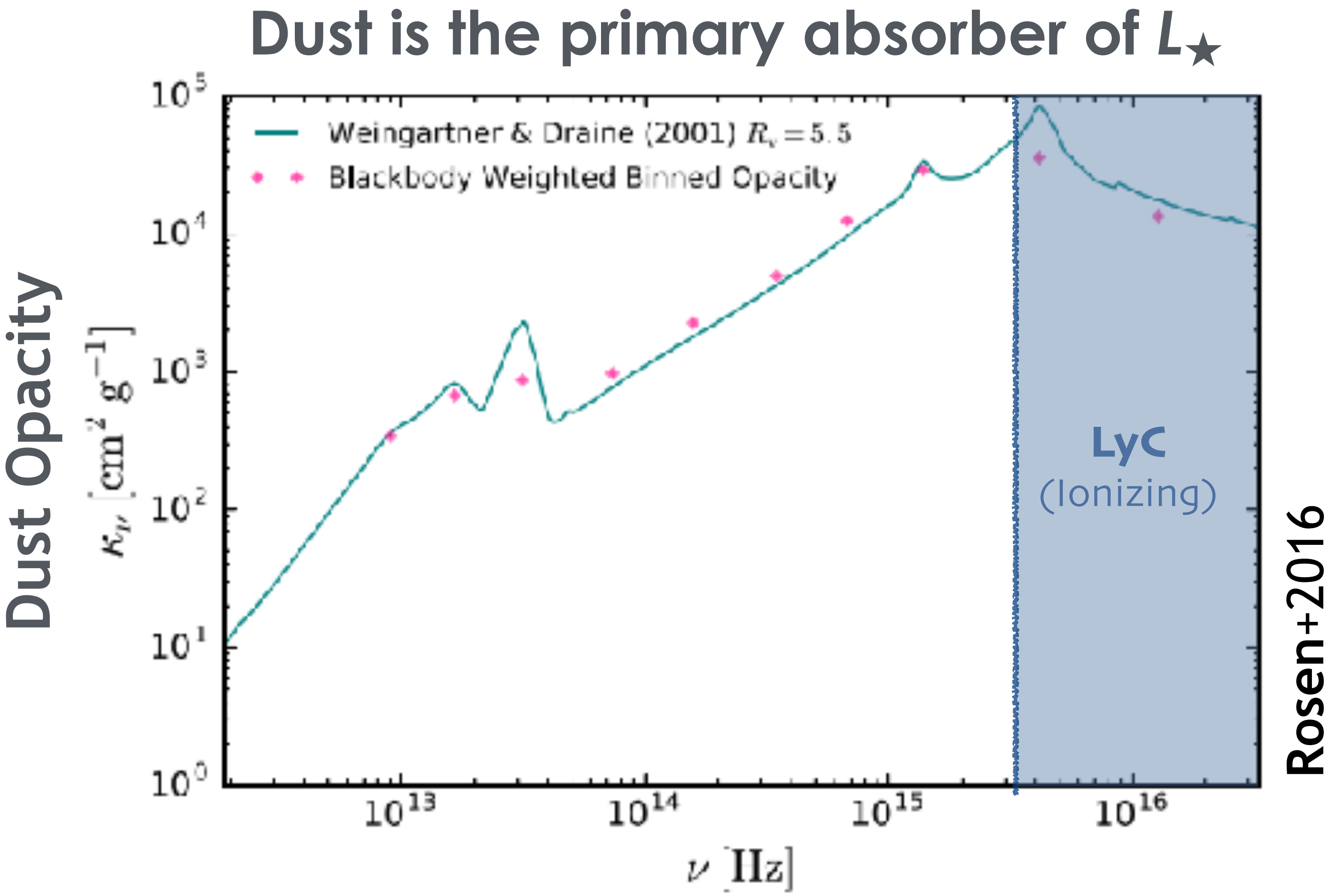
**Gravitational Collapse**
**→ Stellar Accretion:**

$$P_{\rm grav} = \frac{GM\Sigma}{r^2}$$

**Radiation Pressure:**
Direct (Stellar) + Dust-Reprocessed

$$P_{\rm rad} = \frac{L_\star}{4\pi r^2}\left(1 + f_{\rm trap}\right)$$

$L_\star \propto M_\star^3$ (for $M_\star \lesssim 50\ {\rm M}_\odot$)



**Dust is the primary absorber of $L_\star$**

Rosen+2016

**P<sub></sub>**

## P$_{\rm rad}$ Barrier: $P_{\rm grav} = P_{\rm rad}$

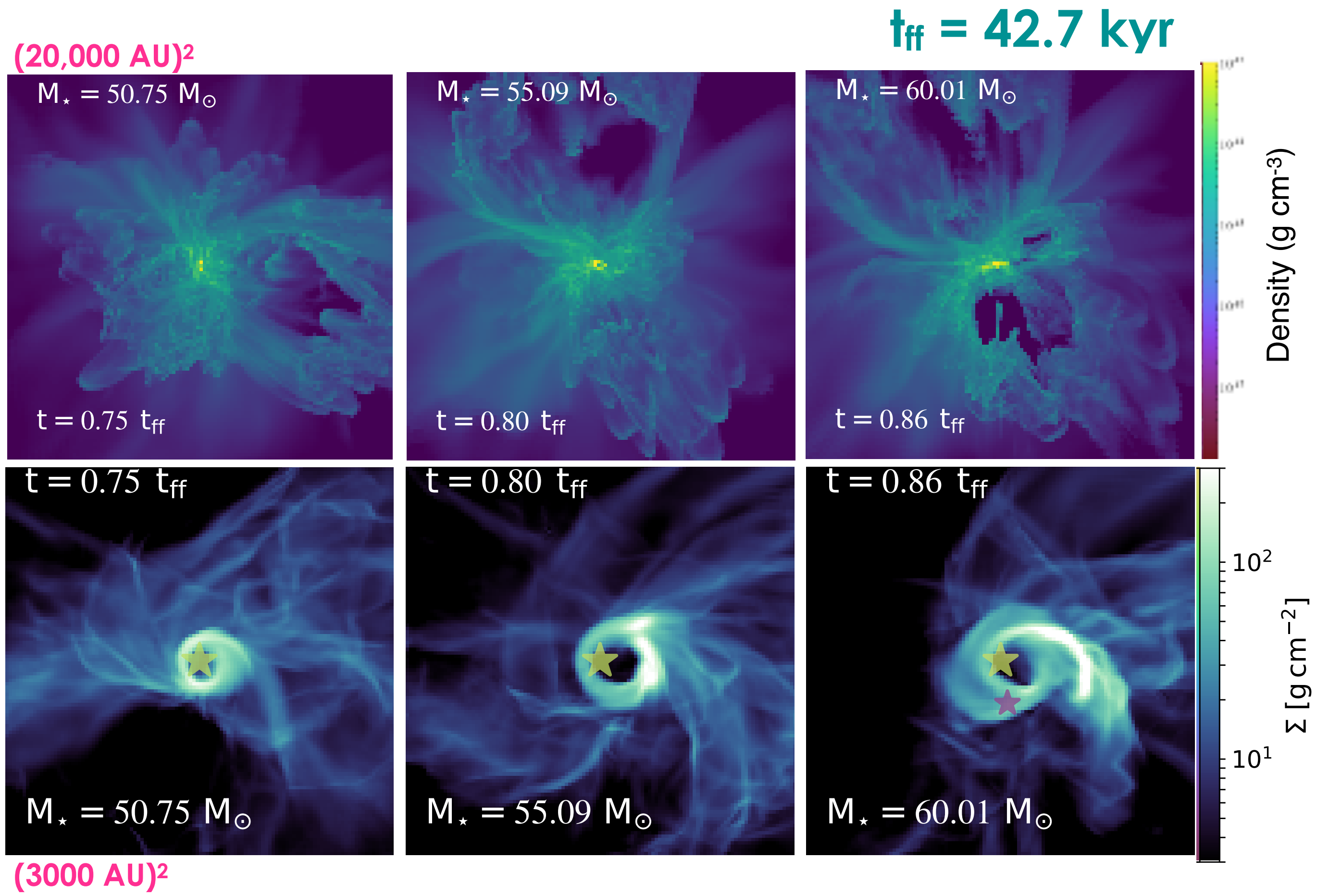
*(Assuming Isotropic accretion)*

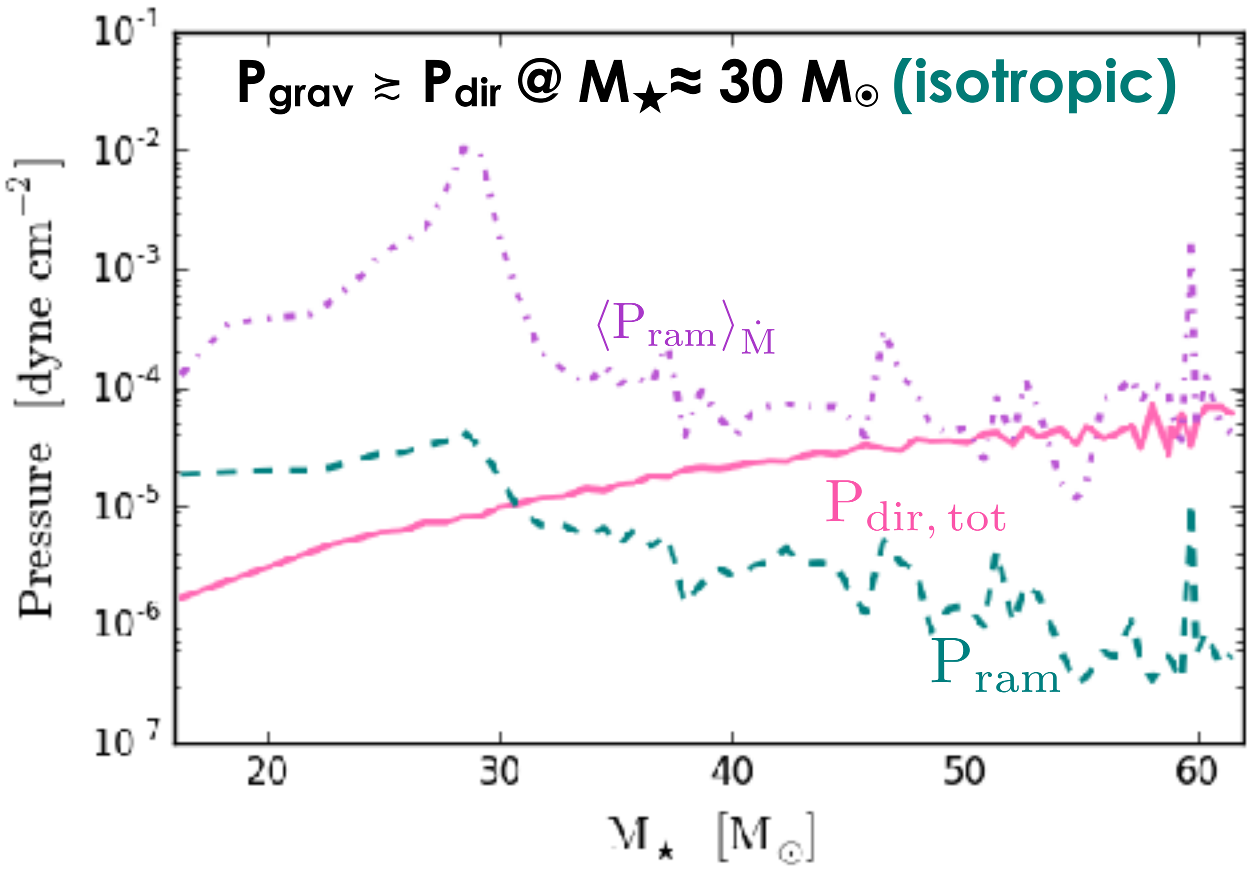
$$f_{\rm Edd} \approx 10^{-4}\left(1 + f_{\rm trap}\right)\left(\frac{L_\star}{M_\star}\right)\left(\frac{\Sigma}{1\ {\rm g\ cm^{-2}}}\right)^{-1}$$

(e.g., Larson & Starrfield 1971, Kahn 1974, Yorke 1979, Yorke+1995, Wolfire & Cassinelli 1986, 1987)

# Averting the Radiation Pressure Barrier in MSF

## (via anisotropic accretion)




$P_{grav} \gtrsim P_{dir}$ @ $M_\star \approx 30\ M_\odot$ (isotropic)

Mass delivered to massive protostar via anisotropic accretion flows (e.g., infalling dense filaments, disk accretion, & radiative RT instabilities

→ $P_{\rm rad}$ likely unable to eject gas from birth sites during main accretion phase

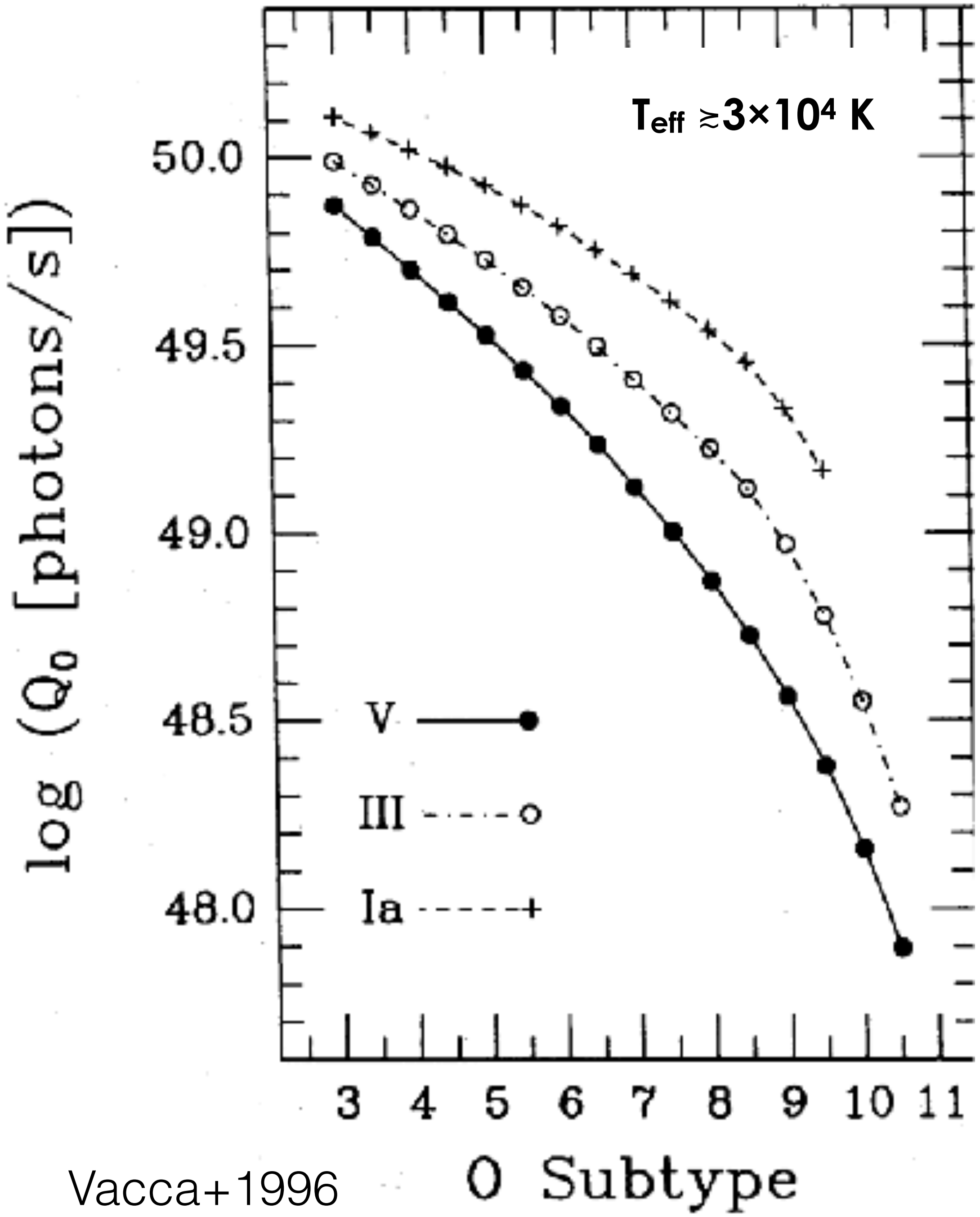
**Rosen**+2016, 2019 ($P_{\rm rad} = P_{\rm dir} + P_{\rm IR}$ modeled via **HARM²** Hybrid RT method from **Rosen**+2017)

**See also:** Yorke & Bodenheimer 1999, Krumholz+2009, Kuiper+2010, 2011, 2013; Commerçon+2010, 2011; Klassen+2016 Mignon-Risse+ 2020, 2021

# Stellar Radiation: Radiation Pressure & **Photoionization**

## **Photoionization:** Warm Gas Pressure ($P_{\rm HII}$)→ Thermal Expansion

Lyman Continuum (**LyC;** $E_\nu \geq 13.6$ eV = $\epsilon_0$) photons ionize HI → HII ($T_{\rm HII} \approx 10^4$ K)



Vacca+1996

$$P_{\rm HII} = \rho_{\rm HII} c_s^2 \quad \rightarrow P_{\rm HII} \propto Q_0 T_{\rm HII} r^{-3/2}$$

where the Ionizing (LyC) photon rate is

$$Q_0 = \int_{R_\infty c}^{\infty} \left(\frac{L_{\star,\nu}}{h\nu}\right) d\nu$$

For O main-sequence stars
~10-50% $L_\star$ in LyC
O9.5 10% $L_\star$ → O3 50% $L_\star$

# Stellar Radiation: **Radiation Pressure** & **Photoionization**

## HII Regions driven by $P_{\rm rad}$ + $P_{\rm HII}$

**HII Region Shell Momentum:**

$$p_{\rm sh} = M_{\rm sh}\dot{r}_{\rm sh}$$

$$\frac{d}{dt}\left(M_{\rm sh}\dot{r}_{\rm sh}\right) = 4\pi r_{\rm sh}^2\left(P_{\rm rad} + P_{\rm HII}\right)$$

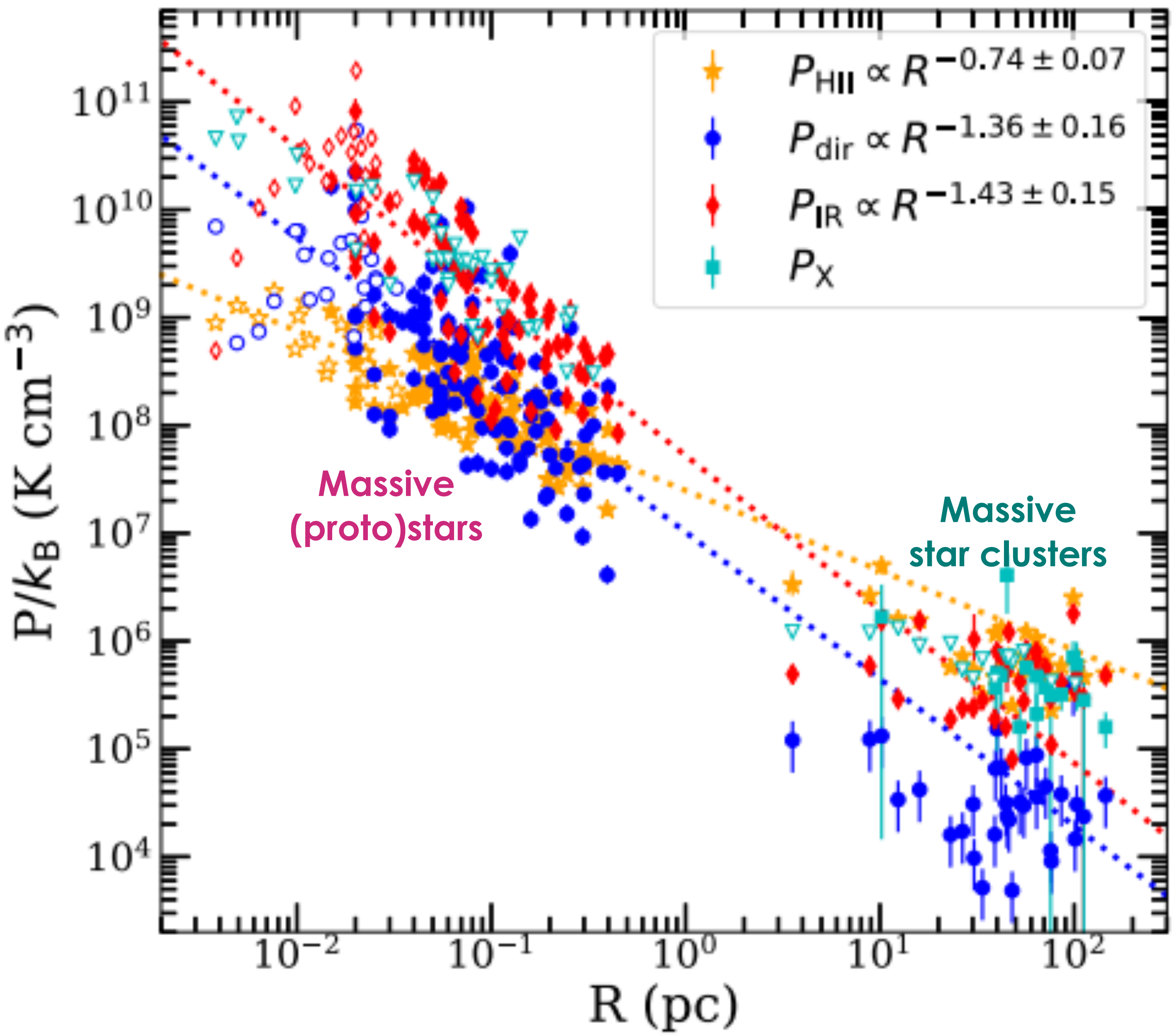
$$P_{\rm rad} \propto L_\star\left(1 + f_{\rm trap}\right) r^{-2}$$

$$P_{\rm HII} \propto Q_0 T_{\rm HII} r^{-3/2}$$

Radius at which HII region dynamics *switches* from $P_{\rm rad}$→ $P_{\rm HII}$-dominated

$$r_{\rm ch} = 0.018\left(1 + f_{\rm trap}\right)^2\left(\frac{Q_0}{10^{49}\,{\rm s}^{-1}}\right)\ {\rm pc}$$

Krumholz & Matzner 2009



Lopez+2011, 2014; Olivier, Lopez, **Rosen**+2021

Dynamics of compact HII regions ($R_{\rm sh}$ < 0.5 pc) switch from $P_{\rm IR}$**-dominated**→$P_{\rm HII}$**-dominated** for giant (extended) HII regions

Krumholz & Matzner 2009; Lopez+2011, 2014; Olivier, Lopez, **Rosen**+2021

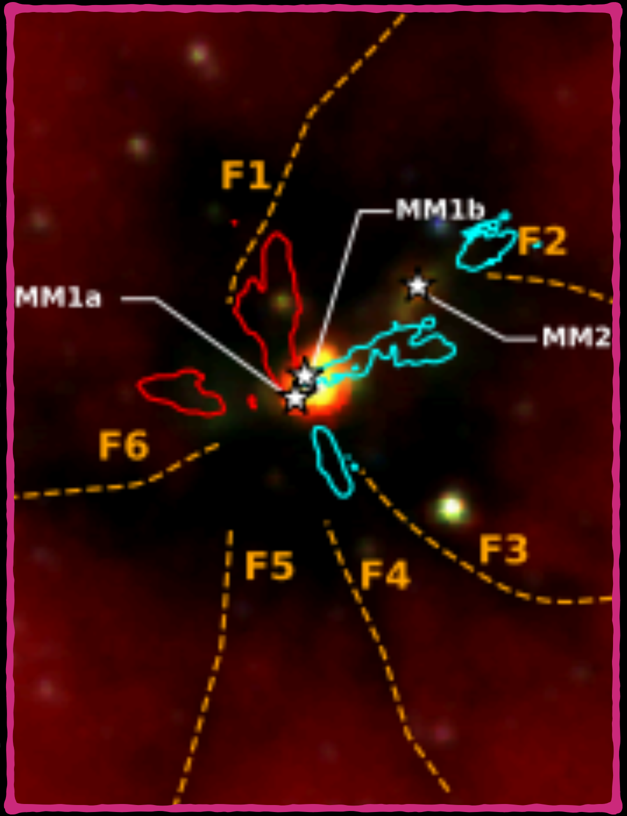
# Stellar Feedback on Small Scales

## (e.g., stars)

### Radiation

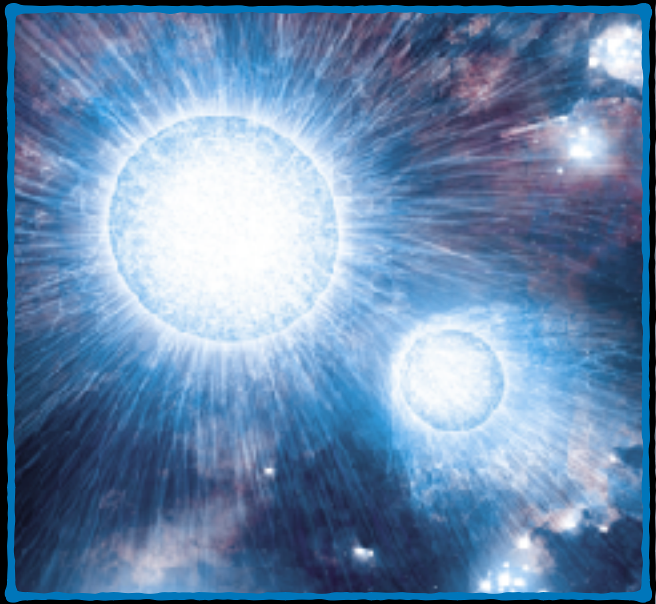
R136 in the LMC (*JWST*)

### Protostellar Outflows



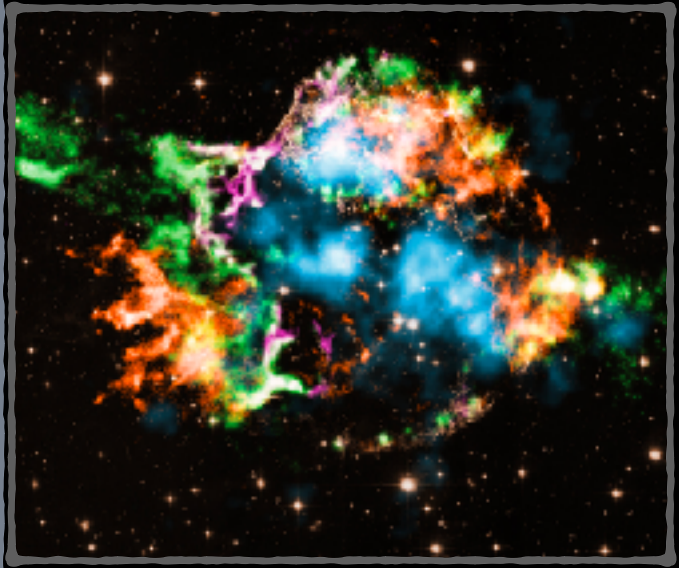
Avison+(incl. **Rosen**) 2021

### Stellar winds



NASA (Artist rendition)

### Supernovae



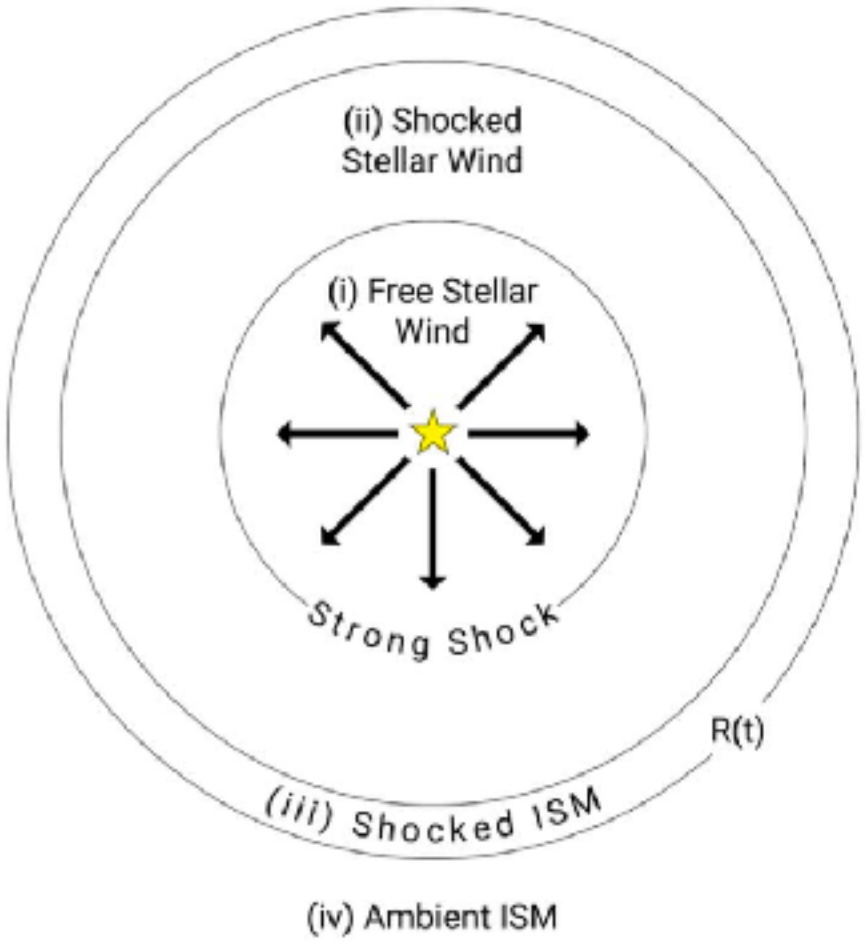
Cassiopeia A (*HST/Chandra*)

# Energy-driven vs. Momentum-driven Stellar Feedback

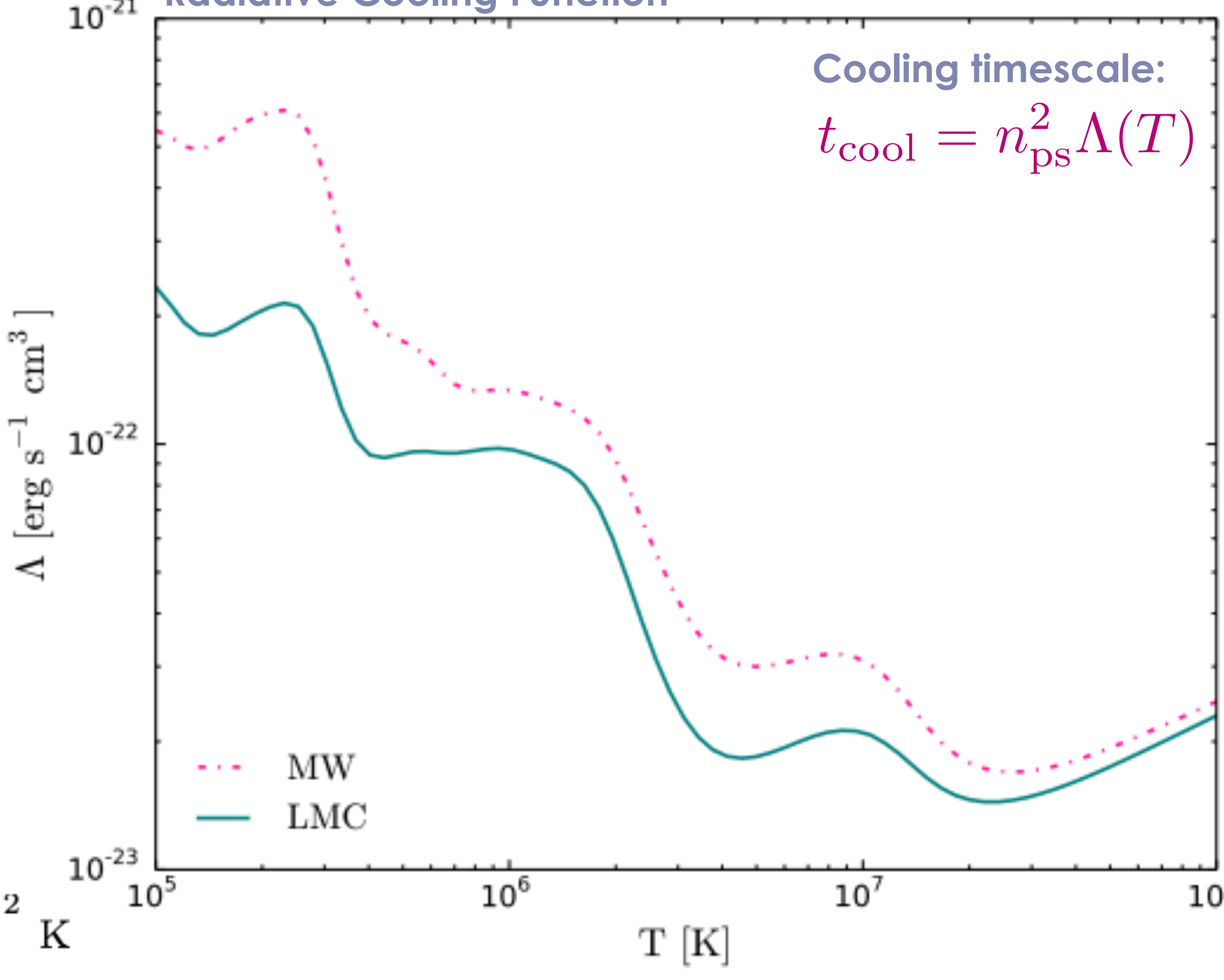
## “fast winds” vs. “slow winds” (Koo & McKee 1992)

Collimated outflows (i.e., jets) and stellar winds are characterized by a mass-loss rate $\dot{M}_w$ and a (supersonic) launching velocity $v_w$.

**Wind Bubble Structure for Isotropic Wind**



**Radiative Cooling Function**



**Cooling timescale:**

$$t_{\rm cool} = n_{\rm ps}^2 \Lambda(T)$$

Rosen+2014

**Post-shock Wind Temperature ($E_{KE} \Rightarrow E_{Th}$)**

$$T_{\rm ps} = \frac{\mu m_{\rm H} v_{\rm w}^2}{3k_{\rm B}} \sim 2\times 10^7 \left(\frac{v_w}{1000\ {\rm km\ s^{-1}}}\right)^2\ {\rm K}$$

e.g., Castor+1975, Weaver+1977, Koo & McKee 1992, **Rosen**+2014, Lancaster+2021, **Rosen** 2022, **Rosen**+ (in prep)

# Energy-driven vs. Momentum-driven Stellar Feedback

## "fast winds" vs. "slow winds" (Koo & McKee 1992)

**Injected Momentum & Kinetic Energy**

$$\dot{p}_w = \dot{M}_w v_w$$

$$\dot{E}_w = \frac{1}{2}\dot{M}_w v_w^2$$

**Shell Momentum & Kinetic Energy**

$$p_{\rm sh} = M_{\rm sh} v_{\rm sh}$$

$$E_{\rm sh} = \frac{1}{2} M_{\rm sh} v_{\rm sh}^2$$

**Momentum Conserving**
**(*significant* radiative losses)**

$$p_{\rm sh,p} = \dot{p}_w t$$

$$E_{\rm sh,p} = \frac{1}{2} v_{\rm sh,p} \dot{p}_w t$$

**Energy Conserving**
**(*negligible* radiative losses)**

$$p_{\rm sh,E} = \frac{2\dot{E}_w t}{v_{\rm sh,E}}$$

$$E_{\rm sh,E} = \dot{E}_w t$$

$E_{\rm sh}$ ($v_{\rm sh}$) ⇒ maximized for energy-driven feedback
⇒ minimized for momentum-driven feedback

$$\frac{E_{\rm sh,E}}{E_{\rm sh,p}} = \frac{v_w}{v_{sh,p}}$$

e.g., Castor+1975; Weaver+1977; Koo & McKee 1992; **Rosen**+2014, 2022; Lancaster+2021, 2024

# Energy-driven vs. Momentum-driven Stellar Feedback

## “fast winds” vs. “slow winds” (Koo & McKee 1992)

Momentum conserving vs. energy conserving feedback depends on how efficiently the shock heated gas can cool. $(t_{\rm cool} = n_{\rm ps}^2 \Lambda(T))$

| **Collimated Outflows:** | **Stellar Winds:** |
|---|---|
| $v_w \sim 300\ \mathrm{km\,s^{-1}}$ | $v_w \sim 1000\ \mathrm{km\,s^{-1}}$ |

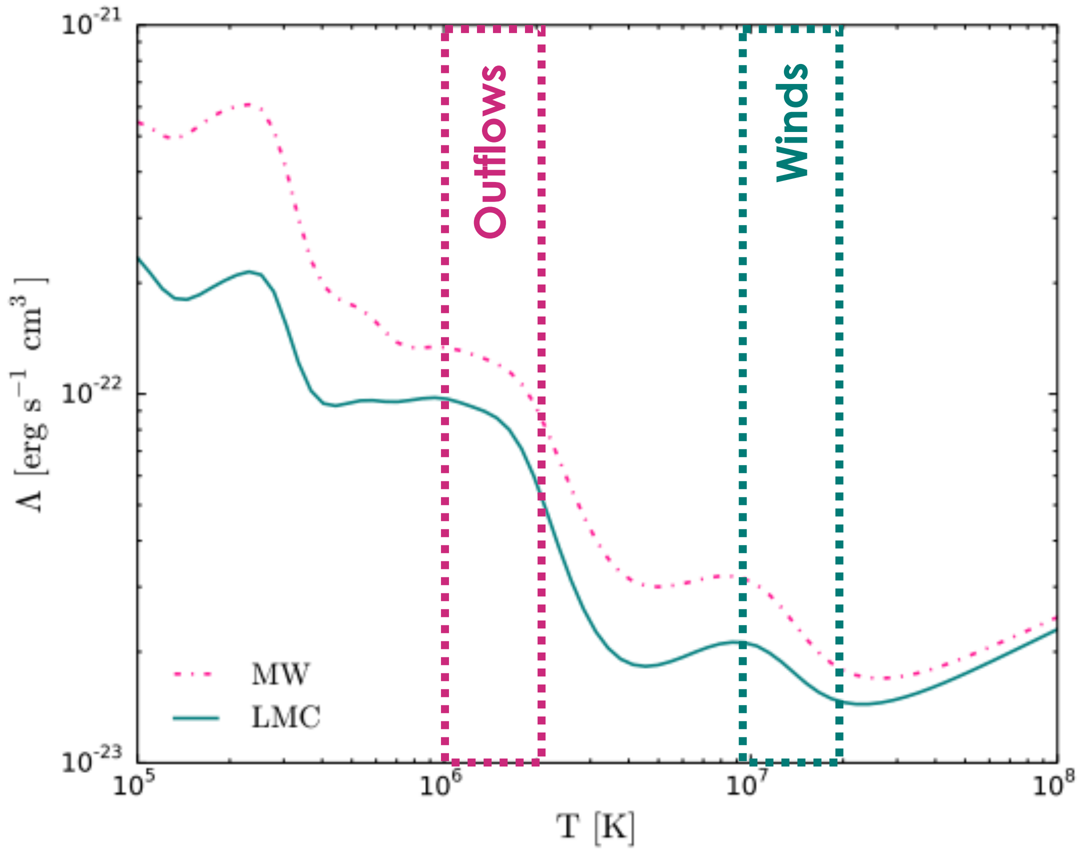
$v_{\rm cr}$ = **critical velocity** where $t_{\rm cool} \approx t_{\rm expand}$

If $v_w \ll v_{cr}$ (slow winds) $t_{\rm cool} \gg t_{\rm expand}$

⇒ significant radiative losses

If $v_w \gg v_{cr}$ (fast winds) $t_{\rm cool} \ll t_{\rm expand}$

$$v_{\rm cr} \sim 430 \left(\frac{\dot{M}_{\rm w}}{10^{-6}\ \mathrm{M_\odot\ yr^{-1}}}\right)^{1/9} \left(\frac{n_0}{10^5\ \mathrm{cm^{-3}}}\right)^{1/9}\ \mathrm{km\ s^{-1}}$$



**Rosen**+2014

$$T_{\rm ps} \sim 2 \times 10^7 \left(\frac{v_w}{1000\ \mathrm{km\ s^{-1}}}\right)^2\ \mathrm{K}$$

Collimated outflows ⇒ momentum-driven feedback (slow winds)

Stellar winds ⇒ energy-driven (fast winds) feedback

e.g., Castor+1975; Weaver+1977; Koo & McKee 1992; **Rosen**+2014, 2022; Lancaster+2021, 2024

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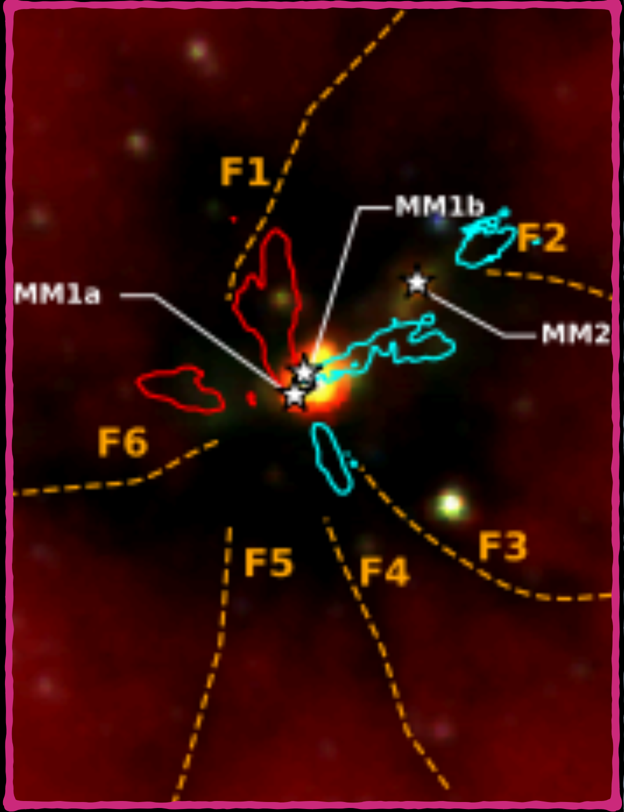
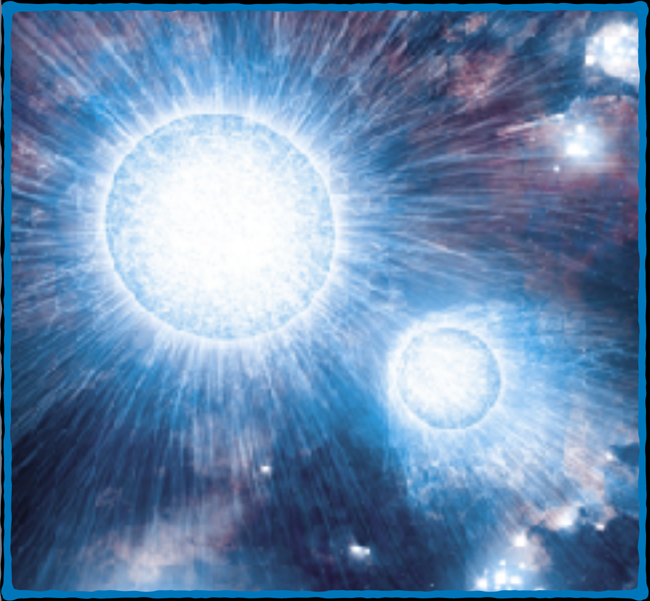


Avison+(incl. **Rosen**) 2021

### Stellar winds



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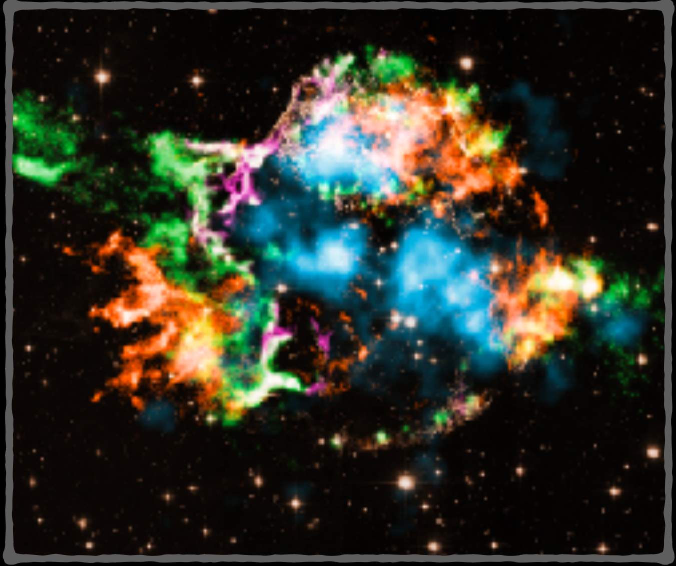
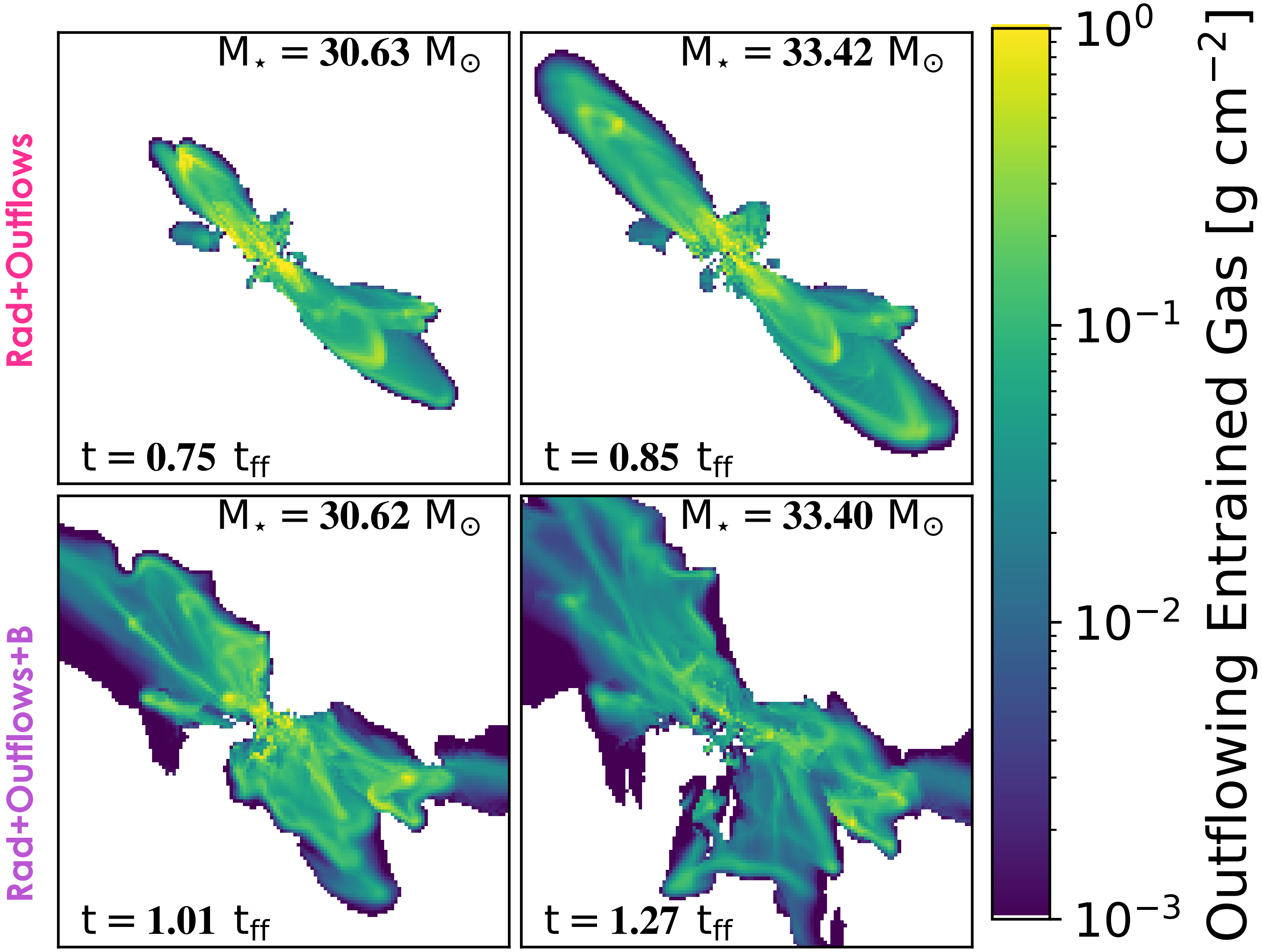
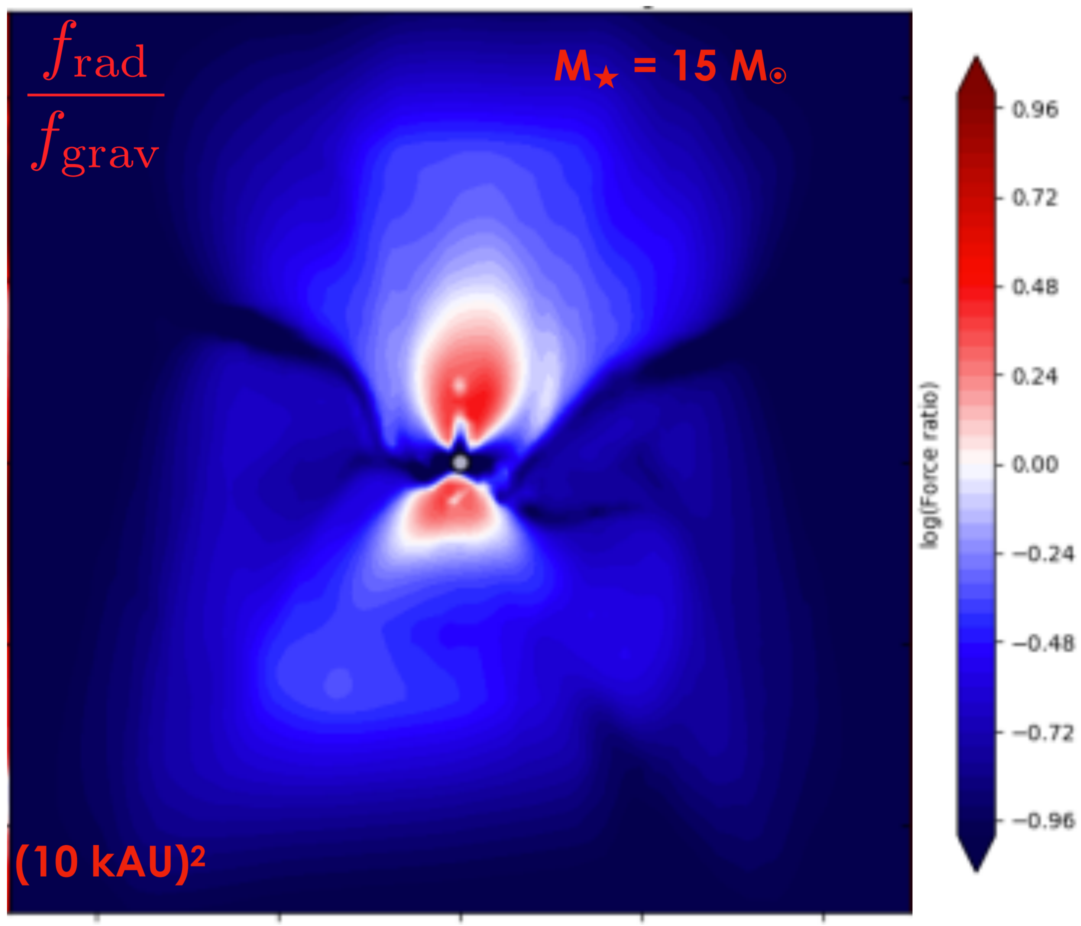


Cassiopeia A (*HST/Chandra*)

# Stellar Feedback on Small Scales:

## Collimated Protostellar Outflows





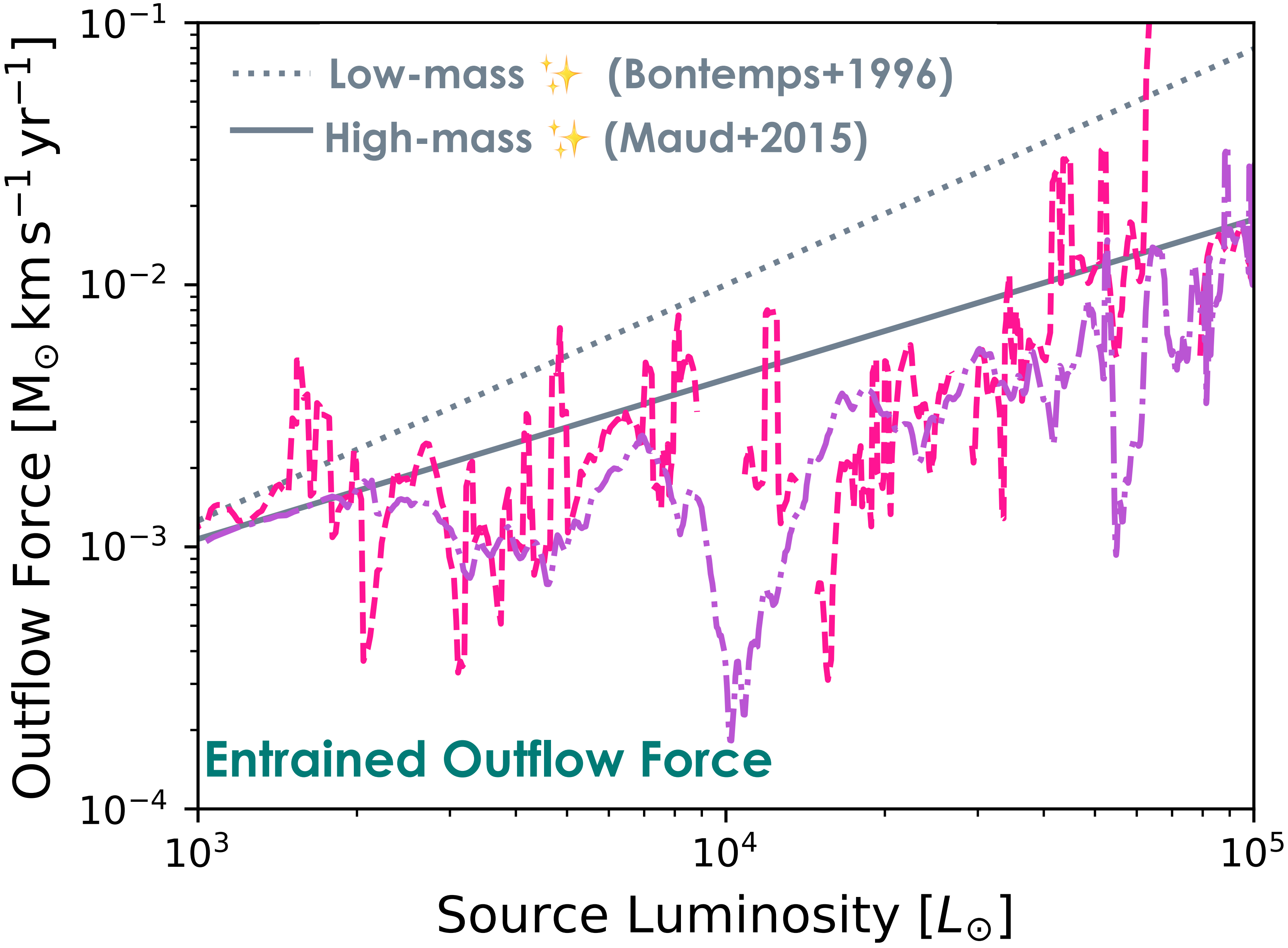
Commerçon+2022

Radiation vents through swept-up outflow cavities → radiation pressure becomes less important

**See also:** Krumholz+2005; Cunningham+2011, Kuiper+2015, 2016; Kolligan & Kuiper 2018; Mignon-Risse+2021

# Stellar Feedback on Small Scales:

## Collimated Protostellar Outflows



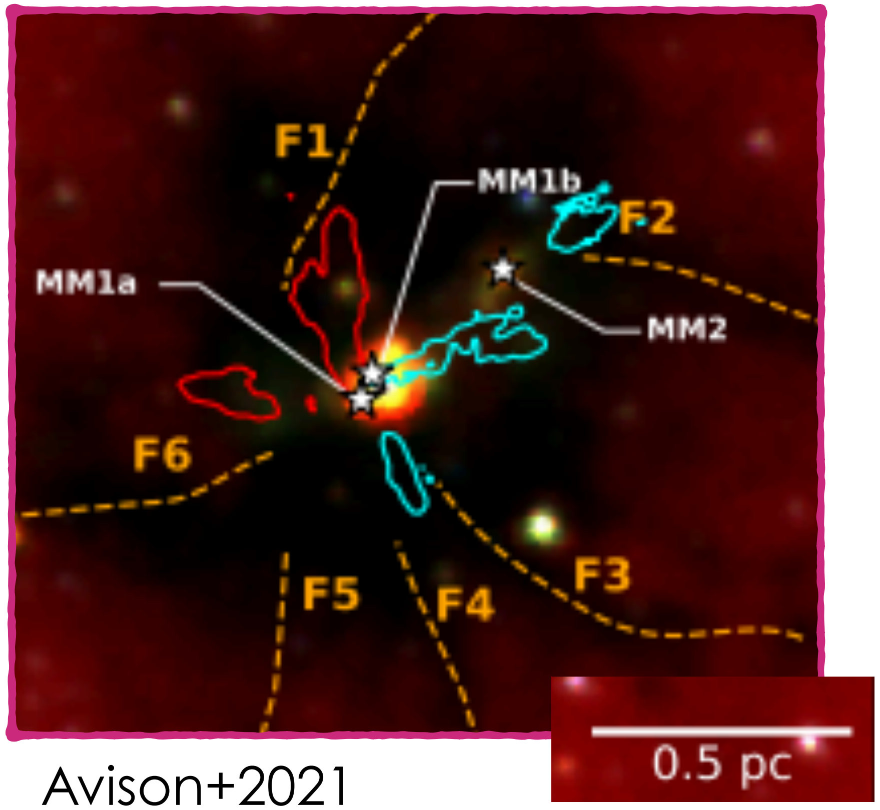
**Rosen** & Krumholz 2020

### Energetics & Mass-loading

$$p_{\mathrm{OF,\,ent}} \approx 25\,\%\,p_{\mathrm{OF,\,inj}}$$

$\Rightarrow$ *slow winds*

$$M_{\mathrm{OF,\,ent}} \approx 3 \times M_{\mathrm{OF,\,inj}}$$



Avison+2021

Outflows remove significant material from the birth sites of stars.

**See also:** Krumholz+2005; Cunningham+2011, Kuiper+2015, 2016; Kolligan & Kuiper 2018; Mignon-Risse+2021

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(e.g., stars)

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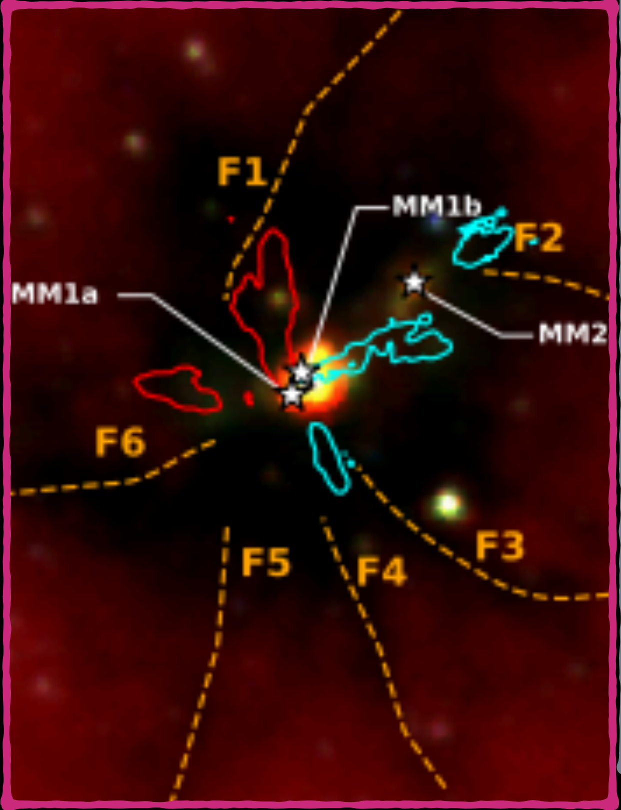
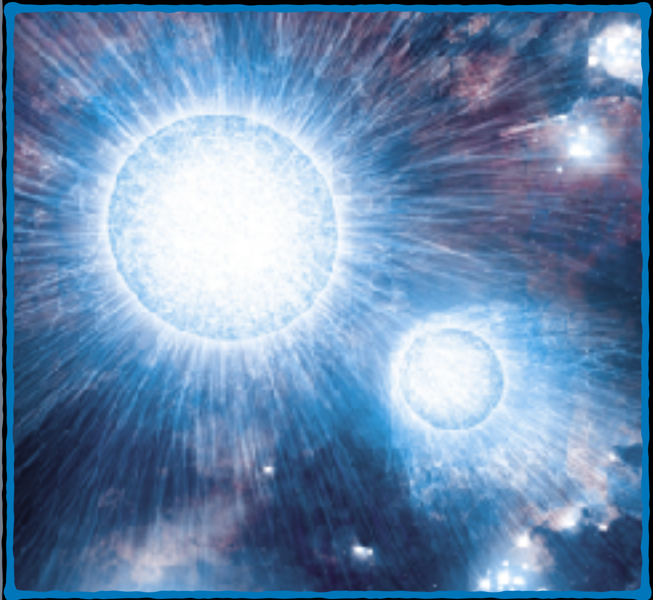


Avison+(incl. **Rosen**) 2021

## Stellar winds



NASA (Artist rendition)

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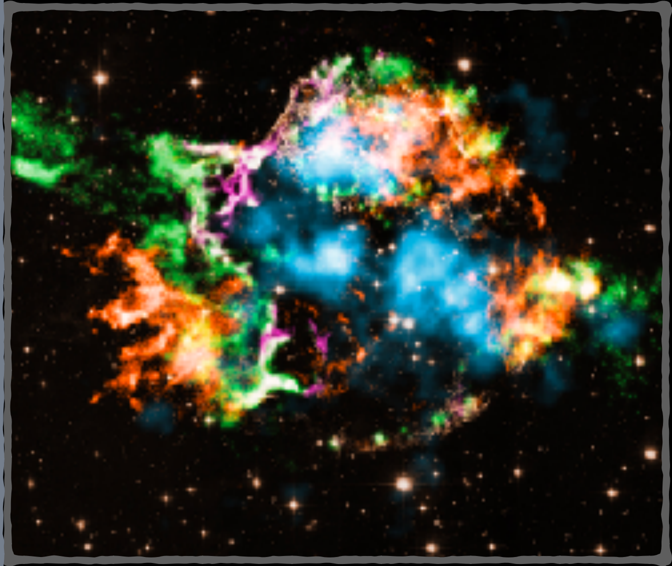
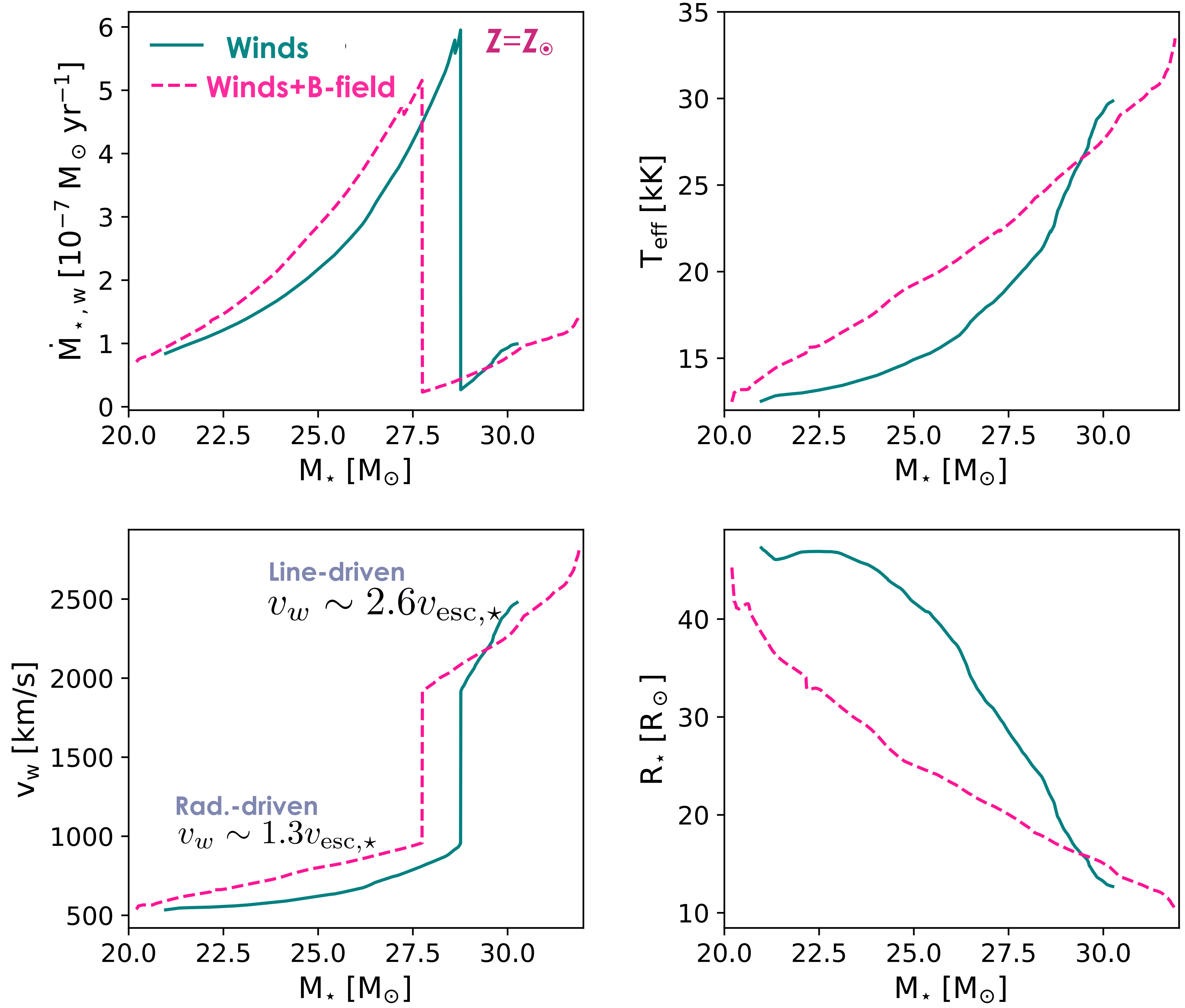


Cassiopeia A (*HST/Chandra*)

# Massive protostars *should* launch line-driven isotropic winds as they contract to the main-sequence



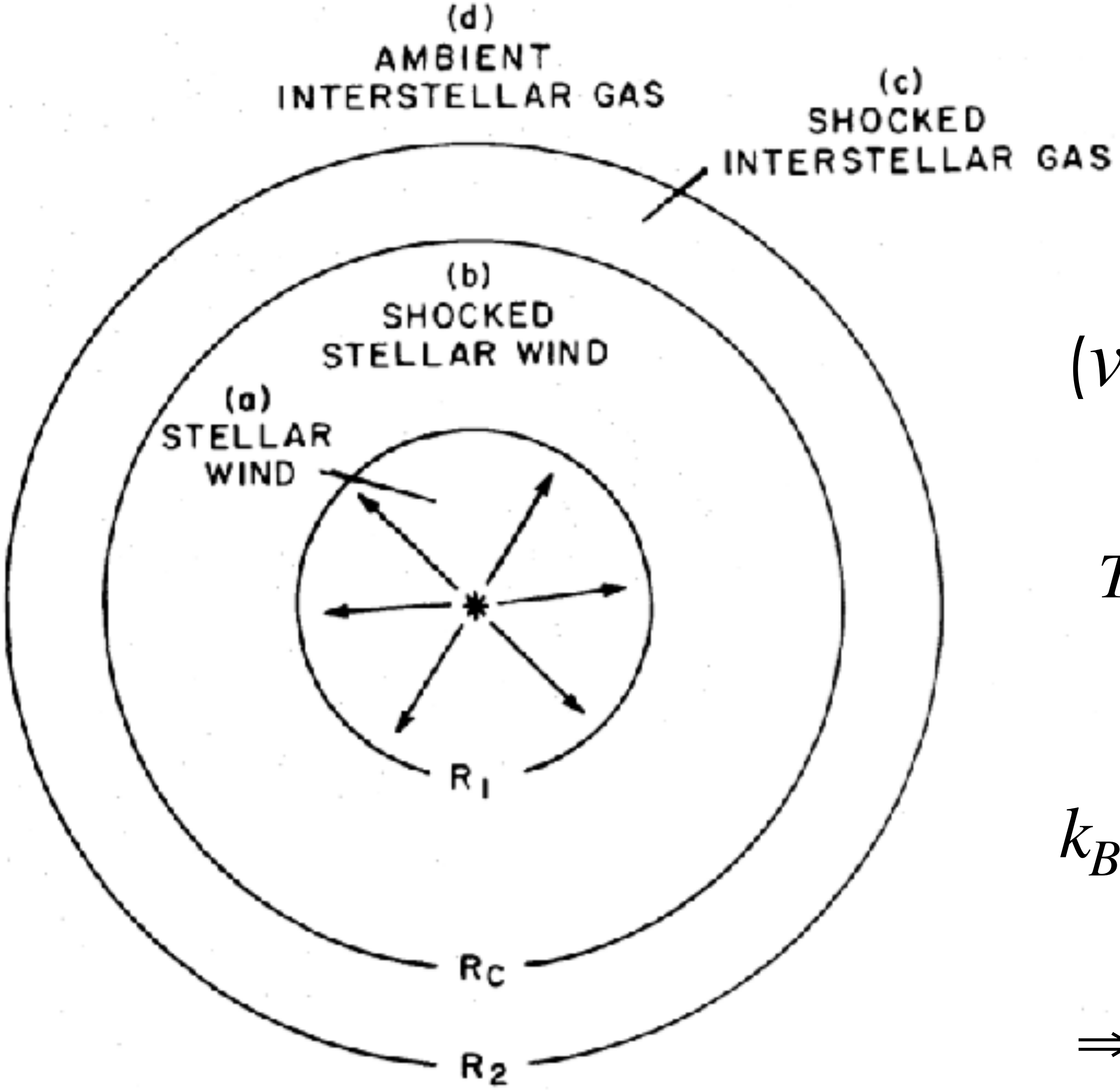
**Rosen** 2022

Jumps in $\dot{M}_w$ and $v_w$ occur when wind launching switches from radiatively-driven (scattering dominates) → line-driven (metal-ion absorption dominates)

(aka *bi-stability jump*: Vink+2001; see review talks by Jon Sundqvist & Andreas Sander)

# Fast stellar winds collides with the ISM → Produces hot shock heated gas that cools primarily via adiabatic expansion

(Remember wind feedback *should be* in the "fast winds" regime)



Assuming $\dot{E}_{w,\,\mathrm{KE}} = \frac{1}{2}\dot{M}_w v_w^2$

($v_w > v_{\mathrm{esc}}$) is fully thermalized:

$$T_{\mathrm{ps}} \sim 2 \times 10^7 \left(\frac{v_w}{10^3\ \mathrm{km\ s^{-1}}}\right)^2 \mathrm{K}$$

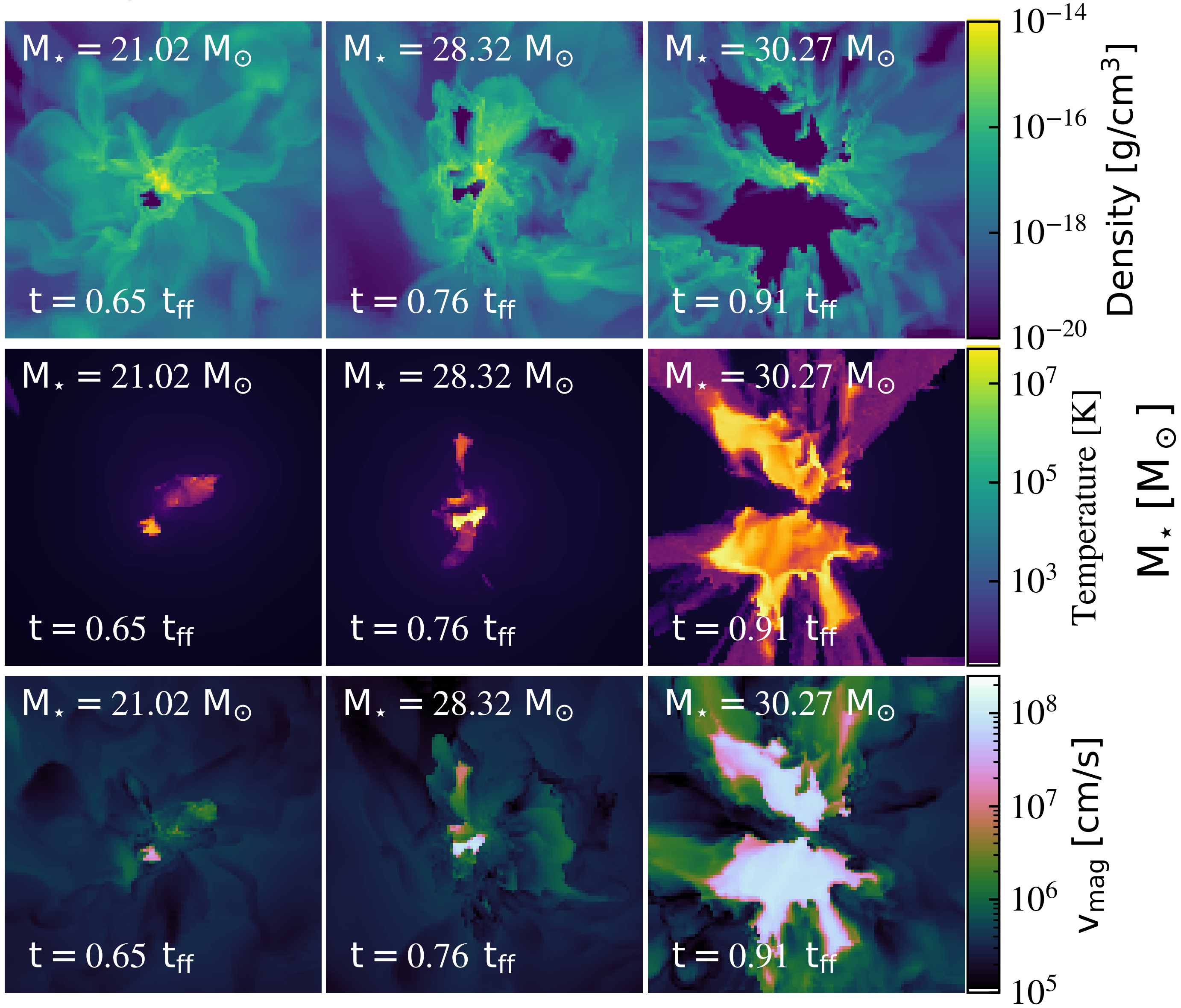
$$k_B T_{\mathrm{ps}} \sim 2 \left(\frac{v_w}{10^3\ \mathrm{km\ s^{-1}}}\right)^2 \mathrm{keV}$$

⇒ Hot gas thermally emits X-rays

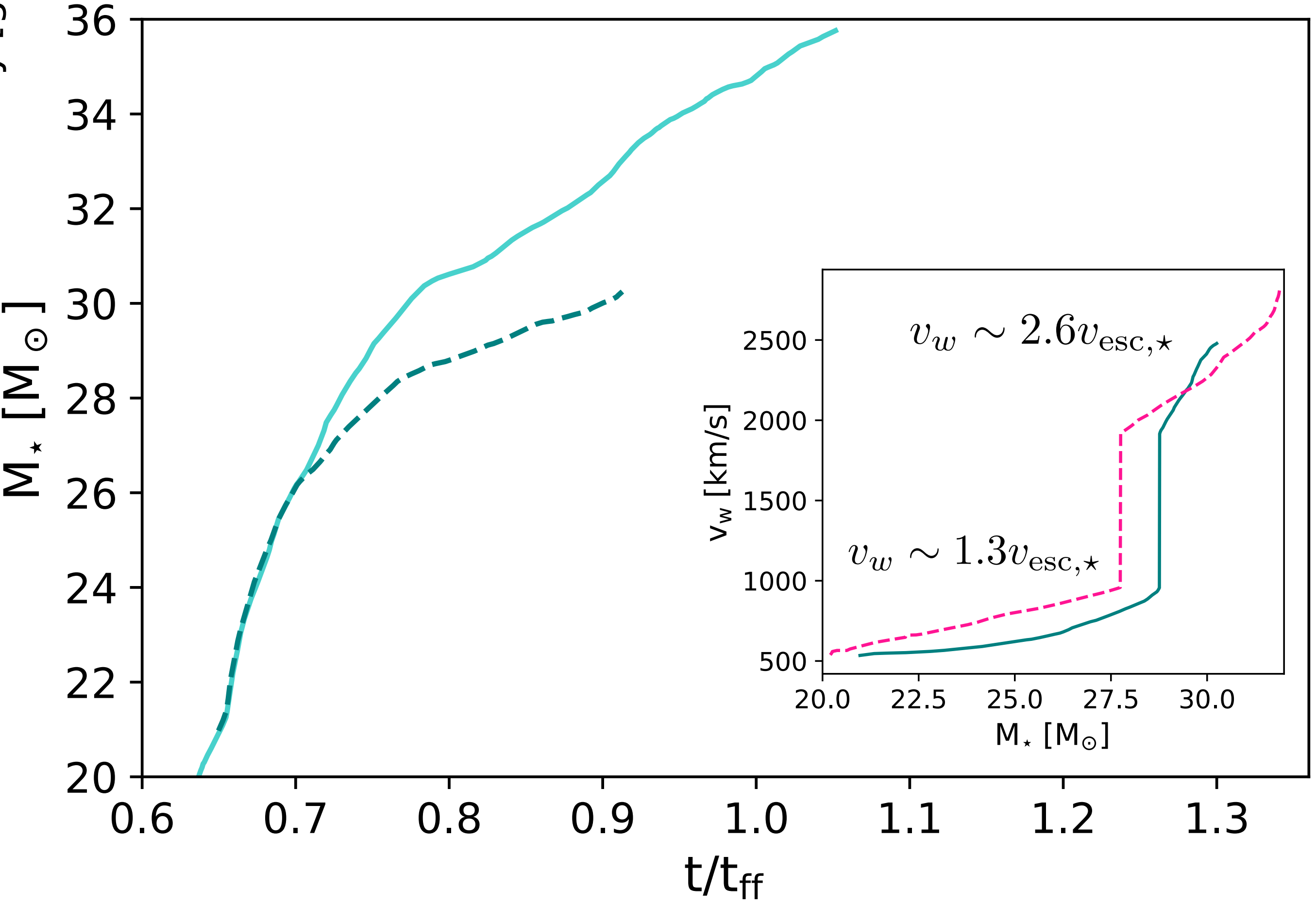
(e.g., Castor+1975, Weaver+1977; Koo & McKee 1992; Harper-Clark & Murray 2009; **Rosen**+2014; Lancaster+2021, 2024; **Rosen** 2022)

# **Importance of Wind Feedback during MSF:**
## Shock-heated gas eventually *quenches* accretion

**Rad+Outflows+Winds**



***(0.1 pc)²***



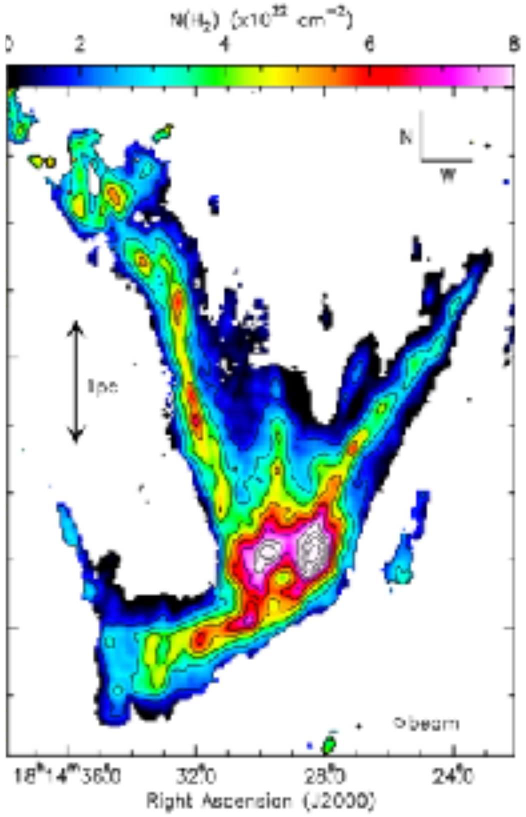
Wind feedback may be responsible for halting accretion on (sub-pc) core scales for stars with $M_\star \gtrsim 30\ \mathrm{M}_\odot$

**Rosen** 2022

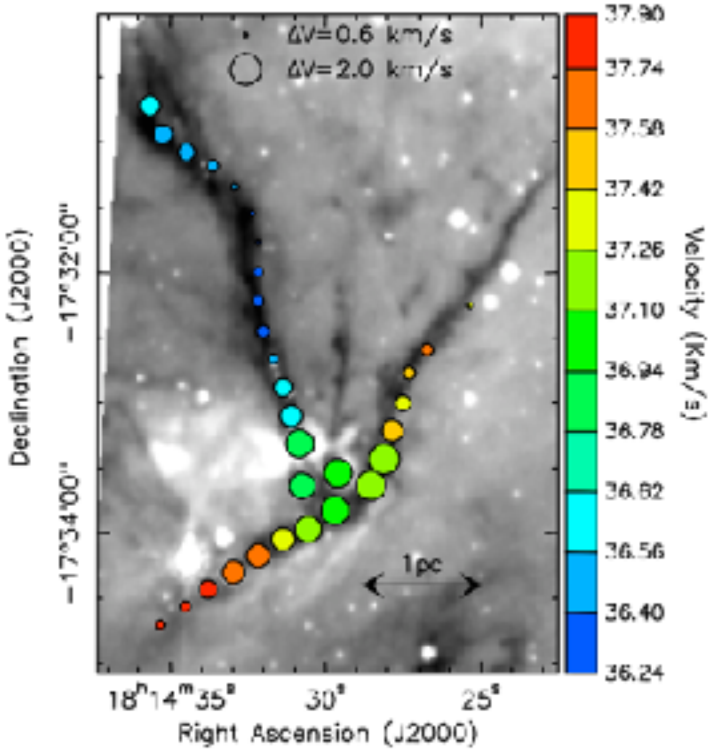
# **How to make stars $\gtrsim 30\ M_\odot$?** Observations & simulations show that massive star formation is a highly dynamical process

## **Hub-filament Systems:** Sites of Galactic Massive Star Formation

### Massive Star forming Region SDC13

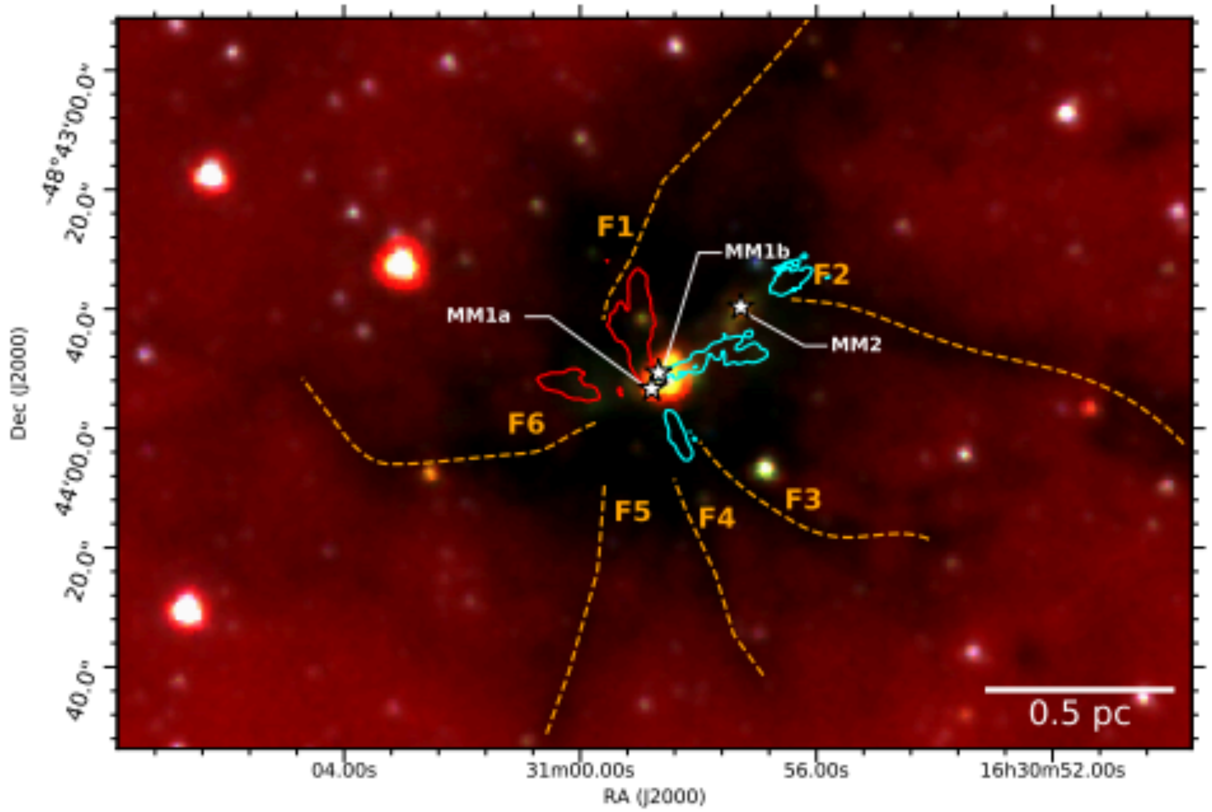


Williams+2018



Peretto+2014

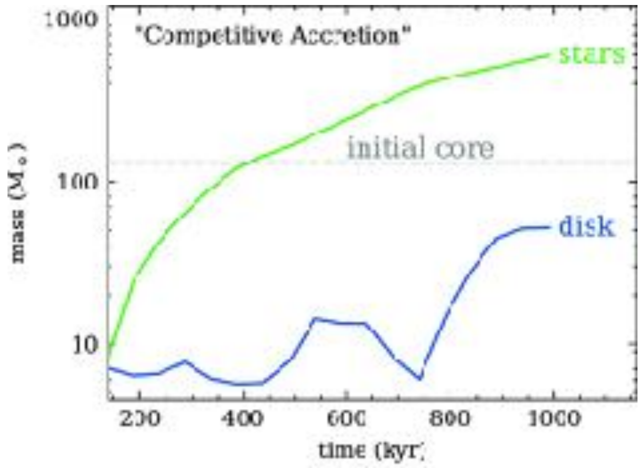
### Massive Star Forming Clump SDC335

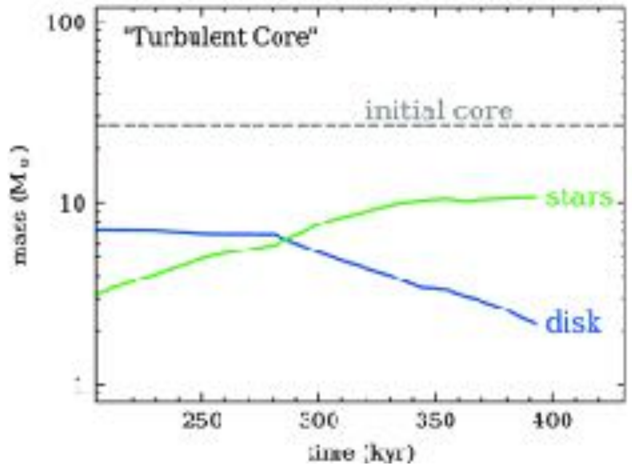


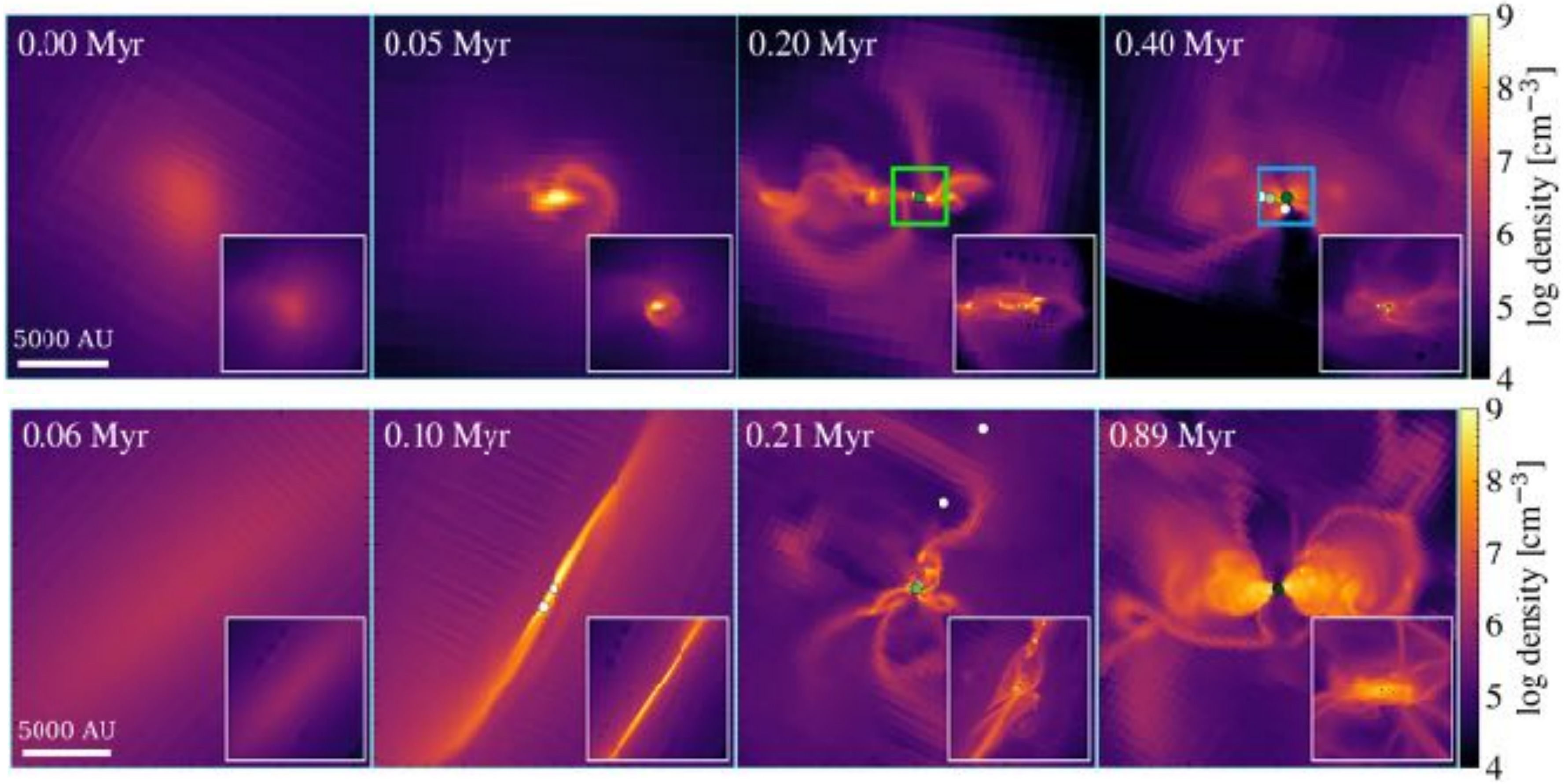
Avison (incl. **Rosen**)+ 2021

High ram-pressure inflows in GMCs (& galaxies) is likely capable of circumventing stellar feedback.

**How to make stars ≳30 M⊙?** Observations & simulations show that massive star formation is a highly dynamical process







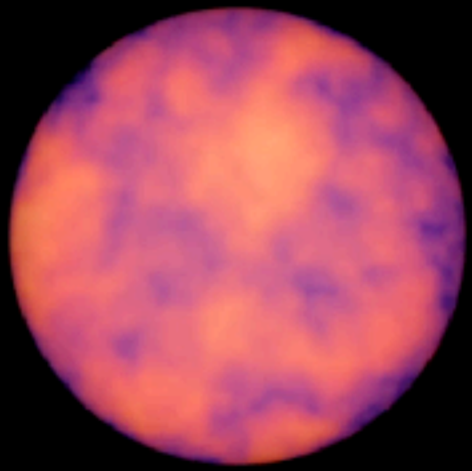
He & Ricotti 2023

High ram-pressure inflows in GMCs (& galaxies) is likely capable of circumventing stellar feedback.

# **STAR FOR**mation in **G**aseous **E**nvironments (STARFORGE)

**Initial Conditions:** $M_{GMC} = 2\times10^4\ M_\odot$, $R_{GMC} = 10$ pc, $\Sigma_{GMC} = 0.01$ g cm$^{-2}$

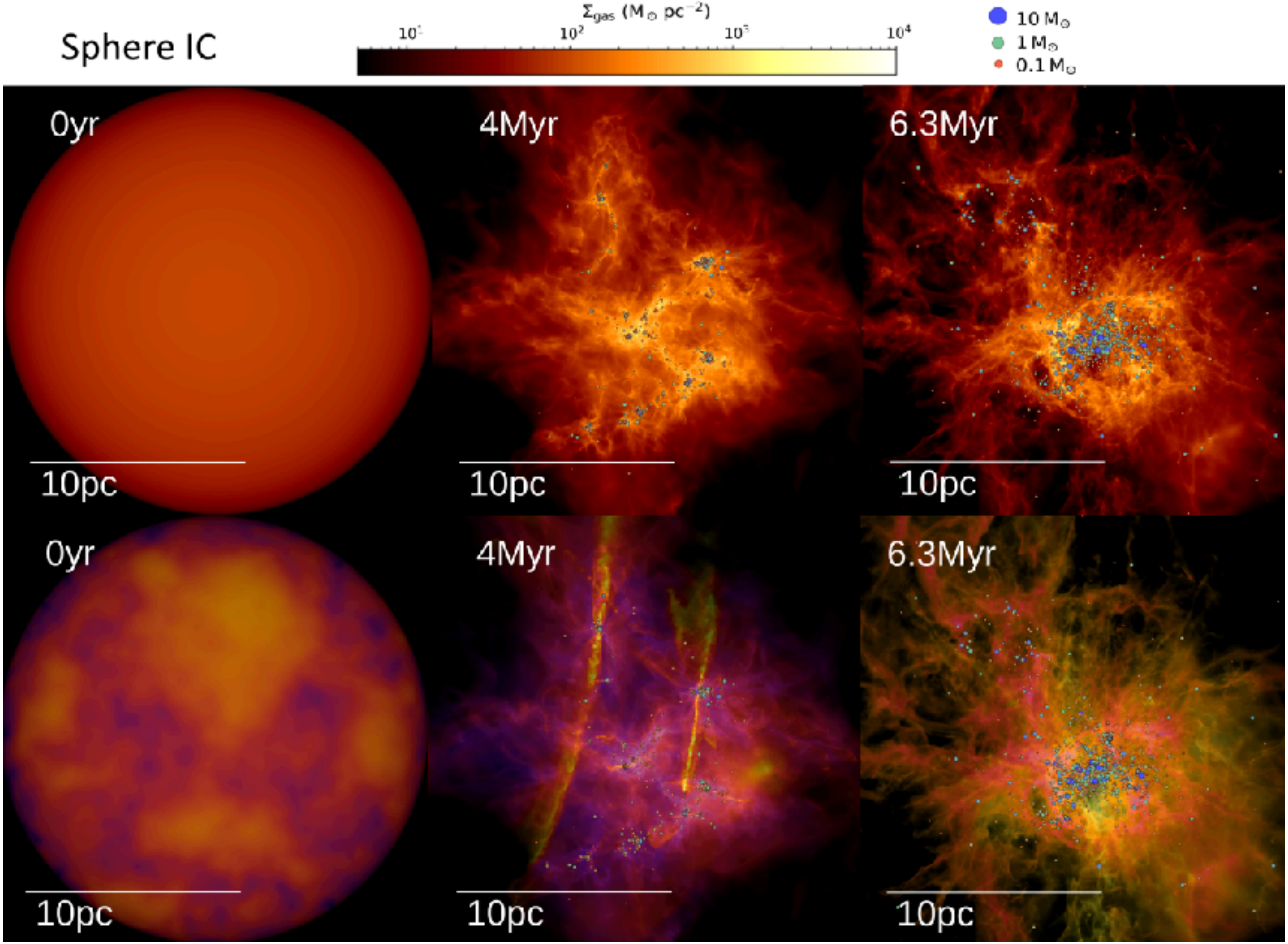
Stellar Initial Mass Function (IMF) completeness limit: 0.1 $M_\odot$



Grudić (incl. **Rosen**)+ 2022

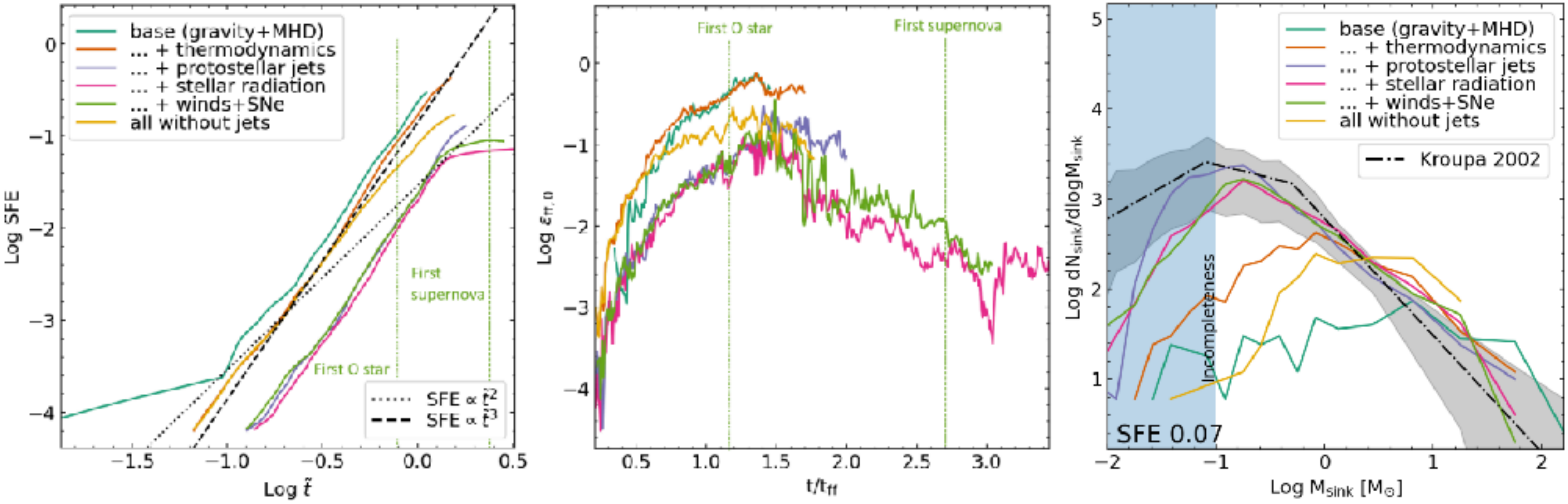
Guszejnov (incl. **Rosen**)+, 2022a,b, 2023

# **STARFORGE:** Radiation & stellar winds from massive stars ("early feedback") disrupts GMC before SNe occur



Grudic+(incl. **Rosen**) 2022, Guszejnov+(incl. **Rosen**) 2022a,b, 2023

# Feedback sets the stellar IMF & is responsible for low SFEs (SFE = $M_\star/M_{GMC}$)



$\tilde{t}(t) \equiv (t - t_{\mathrm{SF\,starts}})/t_{\mathrm{ff}}$

Guszejnov+(incl. **Rosen**) 2022b

Protostellar jets → large-scale mass-loaded entrained outflows & sets the low-mass IMF peak.

Radiation & stellar winds* control the high-mass slope of the IMF & quenches star formation.

***Caveat:** Winds are **only launched** for **Main-Sequence massive stars & Wolf-Rayet stars**
**Rosen** 2022 found that **massive protostars launch winds** → **wind feedback** reduces accretion onto massive protostars

# $P_{rad}$ vs. $P_{HII}$-Dominated HII Regions Powered by Young Star Clusters

(t$\lesssim$ few Myr)

## Massive Star Clusters (MSCs)

$M_{MSC} \approx$ **few** $\times 10^2$ **- few** $\times 10^3\ M_\odot$

$R_{MSC} \approx$ **10s - 100s pc**

$L_{MSC} \approx 10^4 - 10^6\ L_\odot$

$Q_{O,\,MSC} \approx 10^{48} - 10^{50}\ s^{-1}$

MSCs form in **quiescent** environments (e.g., galactic disks)

**High** $L_{SSC}$**, extended** $R_{SSC}$ **→** $P_{HII}$**-dom**

## Super Star Clusters (SSCs)

$M_{SSC} \approx$ **few** $\times 10^3$ **- few** $\times 10^6\ M_\odot$

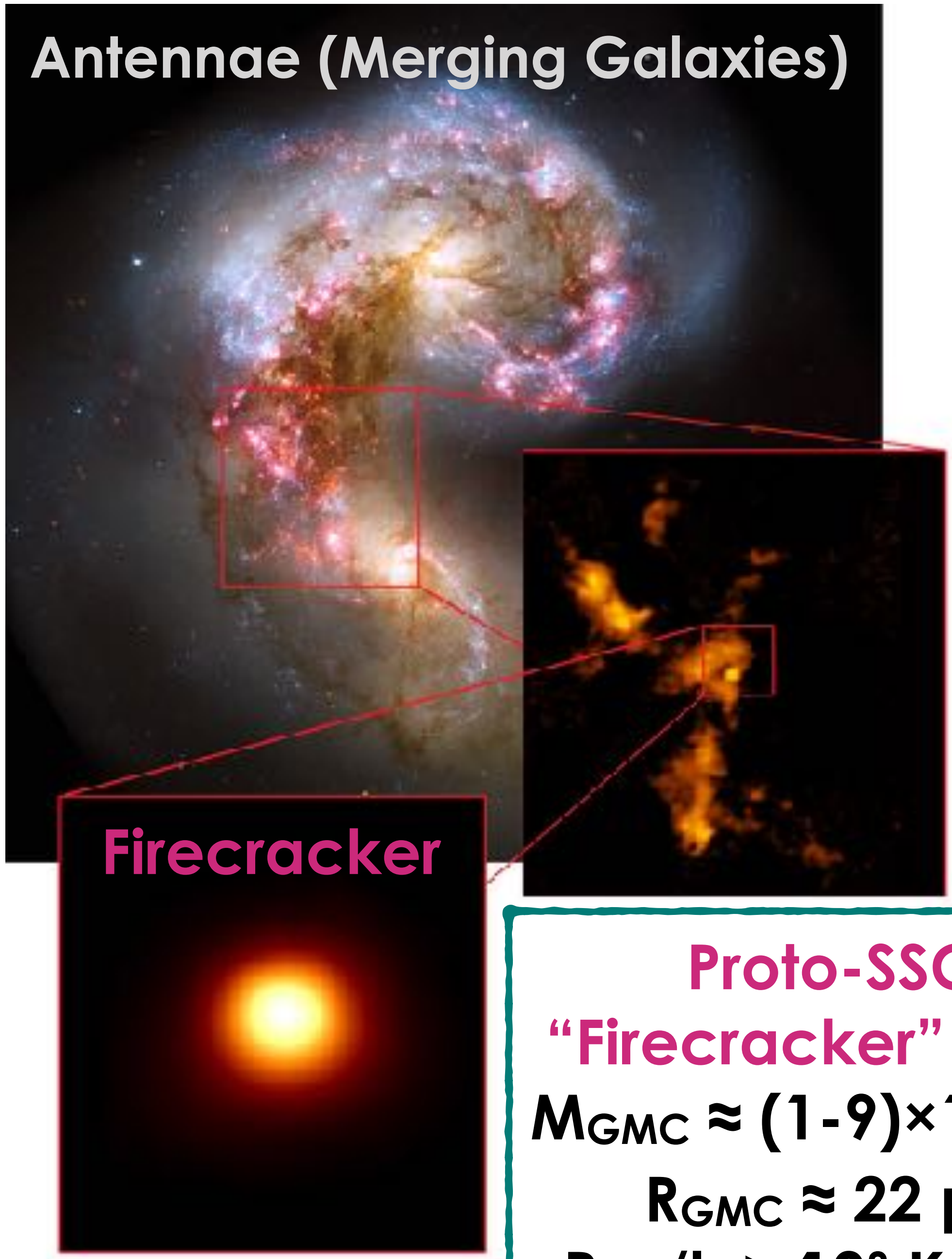
$R_{SSC} \lesssim$ **few pc**

$L_{SSC} \approx 10^6 - 10^8\ L_\odot$

$Q_{O,\,SSC} \approx 10^{50} - 10^{52}\ s^{-1}$

SSCs form in **extreme** environments (e.g., starburst galaxies, mergers)

**High** $L_{SSC}$**, compact** $R_{SSC}$ **→** $P_{rad}$**-dom.**



Finn+2019

**Proto-SSC**
**"Firecracker" GMC**

$M_{GMC} \approx (1\text{-}9) \times 10^6\ M_\odot$

$R_{GMC} \approx 22$ **pc**

$P_{ext}/k > 10^8\ K\ cm^{-3}$

**...but what about stellar winds?**

# A **key signature** of **stellar wind feedback** is the **soft, diffuse X-ray emission** observed within **giant HII Regions** powered by **MSCs**

**Super Star Cluster R136 in the heart of 30 Doradus**

**JWST NIRCam and MIRI composite mosaic**

**Chandra X-ray: T-ReX Survey 2 Ms/23 day survey (PI: L. Townsley)**

(e.g., Krumholz & Matzner 2009, Lopez+2011, 2014, Rosen+2014, Townsley+2024)

**Image credit: IR: NASA/ESA/CSA/STScI/JWST ERO Production Team; X-ray: NASA/CXC/Penn State Univ./L. Townsley et al.**

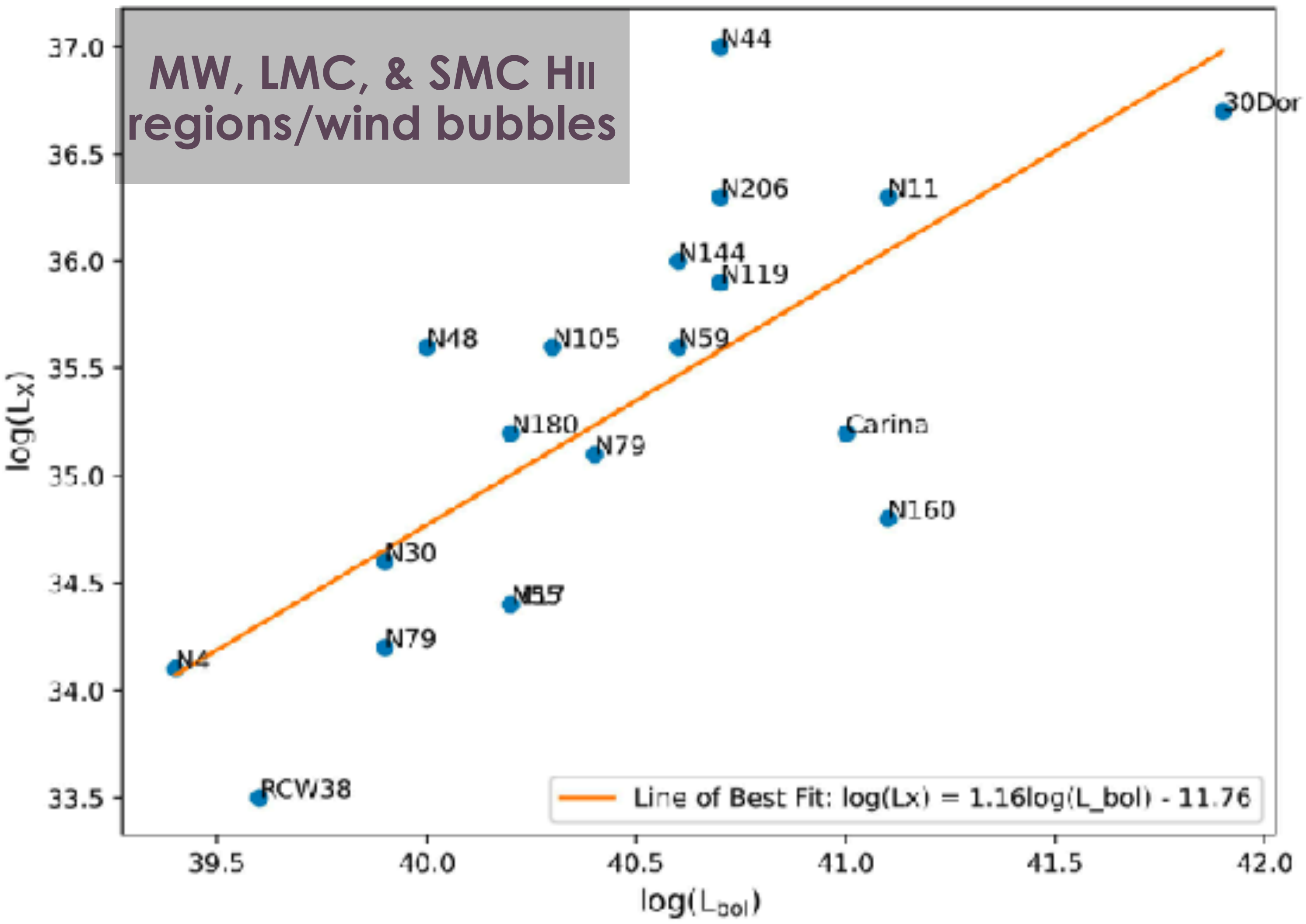
# X-ray emission from HII Regions is weaker than expected:

## Are stellar winds *dynamically important* or does the wind energy "leak" out?

(e.g., Dunne+03, Harper-Clark & Murray+09, Lopez+11, Rosen+2014, Ramachandran+2018,Lancaster+2021, 2024)

Giant HII Region 30 Doradus
(NASA; Townsley+2024)

$$\frac{L_{\mathrm{W}} t_{\mathrm{cl}}}{V} \gg \frac{3}{2} n k_{\mathrm{B}} T_{\mathrm{X}}$$



**MW, LMC, & SMC HII regions/wind bubbles**

**Data:** Townsley+2011; Rosen+2014; Lopez+2014;
Webb, Rodriguez+(incl. **Rosen**; subm. to ApJ) , Pandey+(incl. **Rosen**) 2024; Rodriguez+(incl. Rosen) in prep

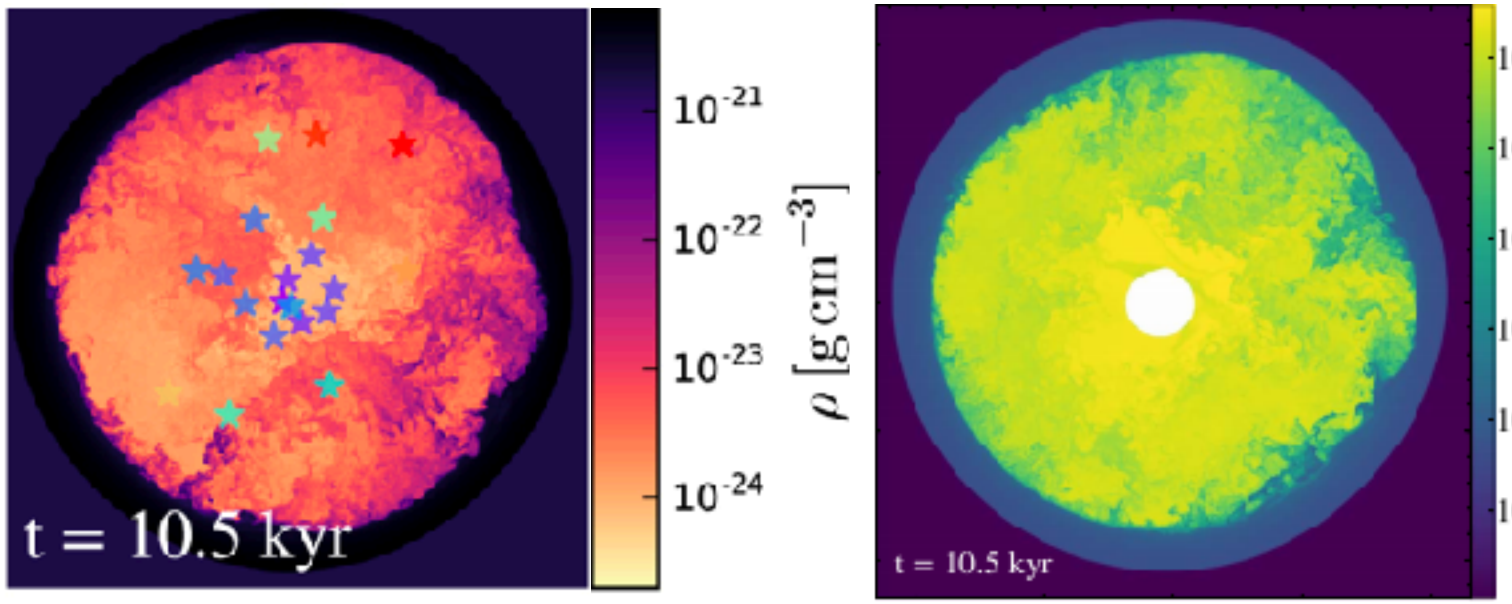
*Figure from Jennifer Rodriguez (PhD student at OSU)*

***Note:*** *Supernova remnants can contaminate $L_X$ (i.e., yields higher $L_X$)*

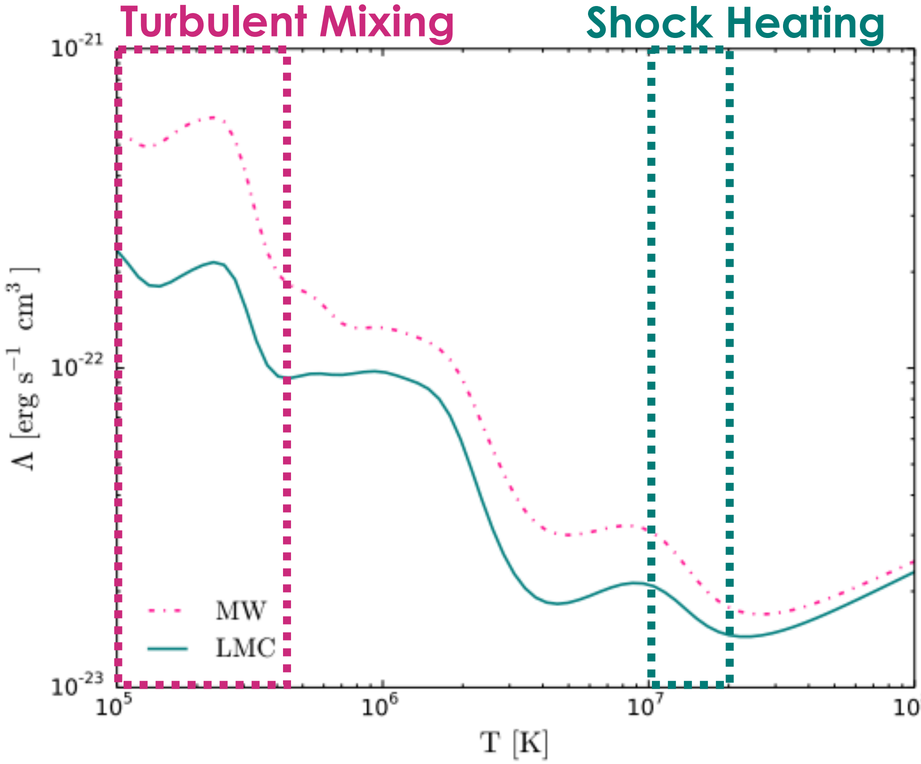
# **Wind Feedback Drives Turbulence in Star Clusters:**

## Wind Energy can be lost via turbulent mixing

**Turbulent Mixing → Efficient Cooling**

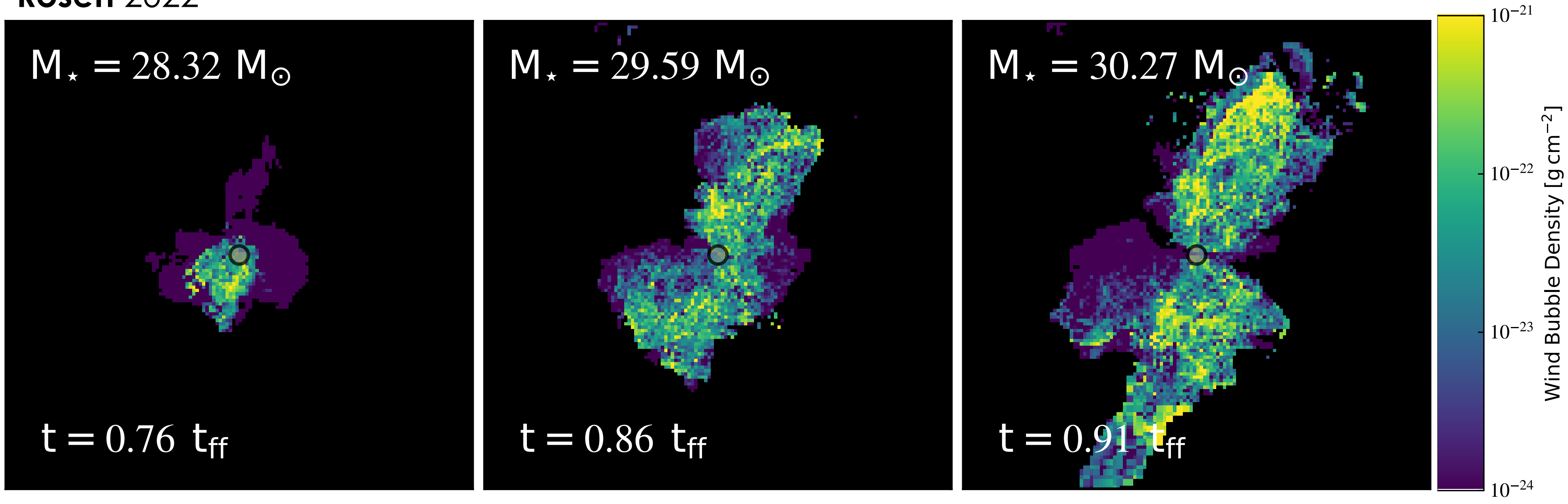


Gallegos-Garcia, Burkhart, **Rosen**+(2020)



**Rosen**+2014, Lancaster+2021a,b

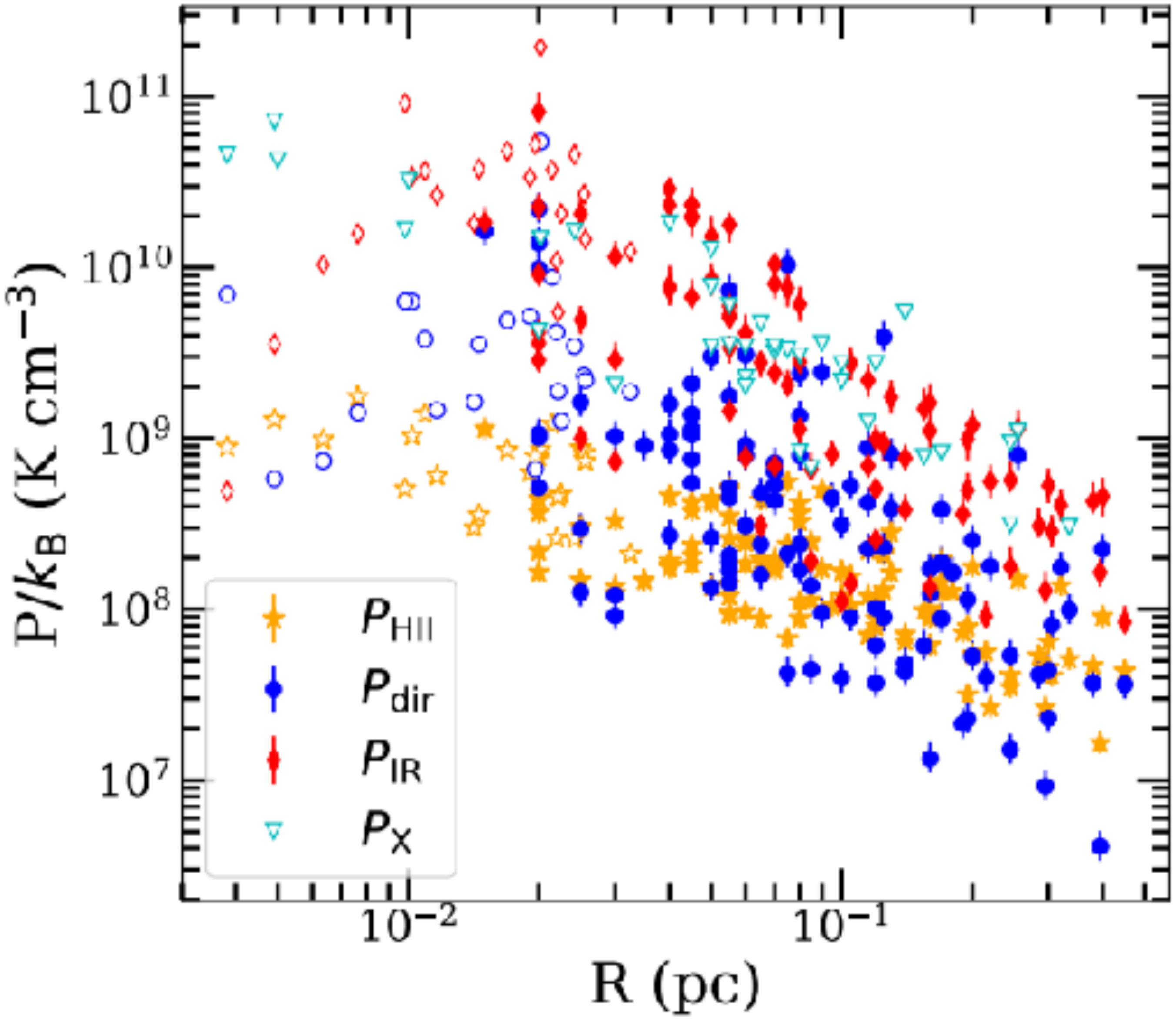
**Rosen** 2022



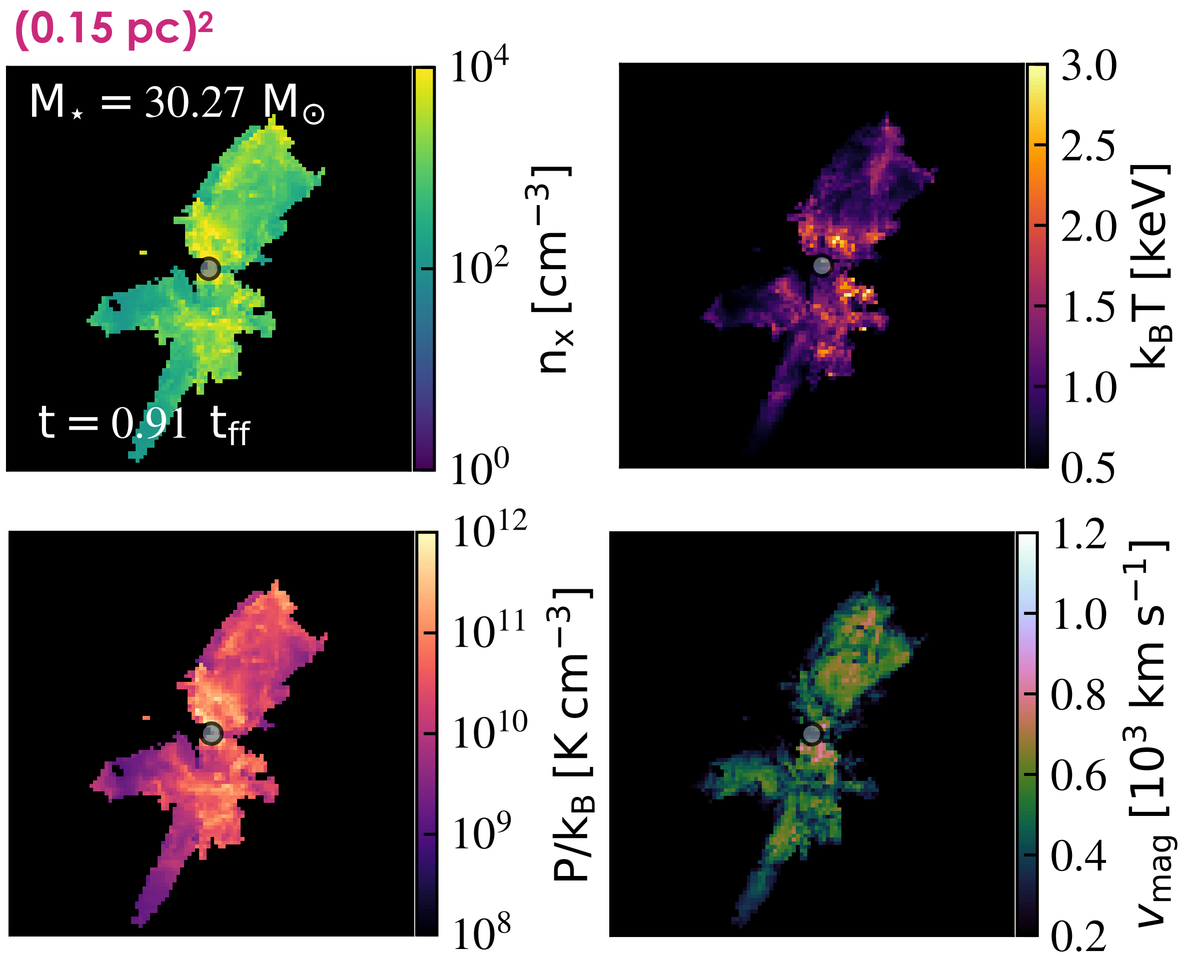
Compact wind bubbles undergo efficient mixing at bubble edges.

**Turbulent mixing occurs early!**

# **On Small Scales:** Diffuse X-ray emission expected from wind bubbles in embedded, compact HII regions is challenging to observe



Olivier, Lopez, **Rosen**+2021



**$P_X$ upper limits (X-ray non-detections) likely due to high attenuating $N_H$ & wind bubble confinement**

**Wind-driven Bubble Properties**

| | |
|---|---|
| $n_X$ [cm$^{-3}$]$^a$ | $1.16 \times 10^3$ |
| $T_X$ [keV]$^a$ | 1.19 |
| $P_X/k$ [K cm$^{-3}$]$^a$ | $4.48 \times 10^9$ |
| $N_H$ [cm$^{-2}$]$^d$ | $1.0 \times 10^{24}$ |
| $(0.5-3)$ keV CPS [s$^{-1}$]$^f$ | $1.083 \times 10^{-8}$ |
| $(3-7)$ keV CPS [s$^{-1}$]$^f$ | $4.099 \times 10^{-5}$ |

**Rosen** 2022

# Wind energy can also be lost via **physical leakage:**

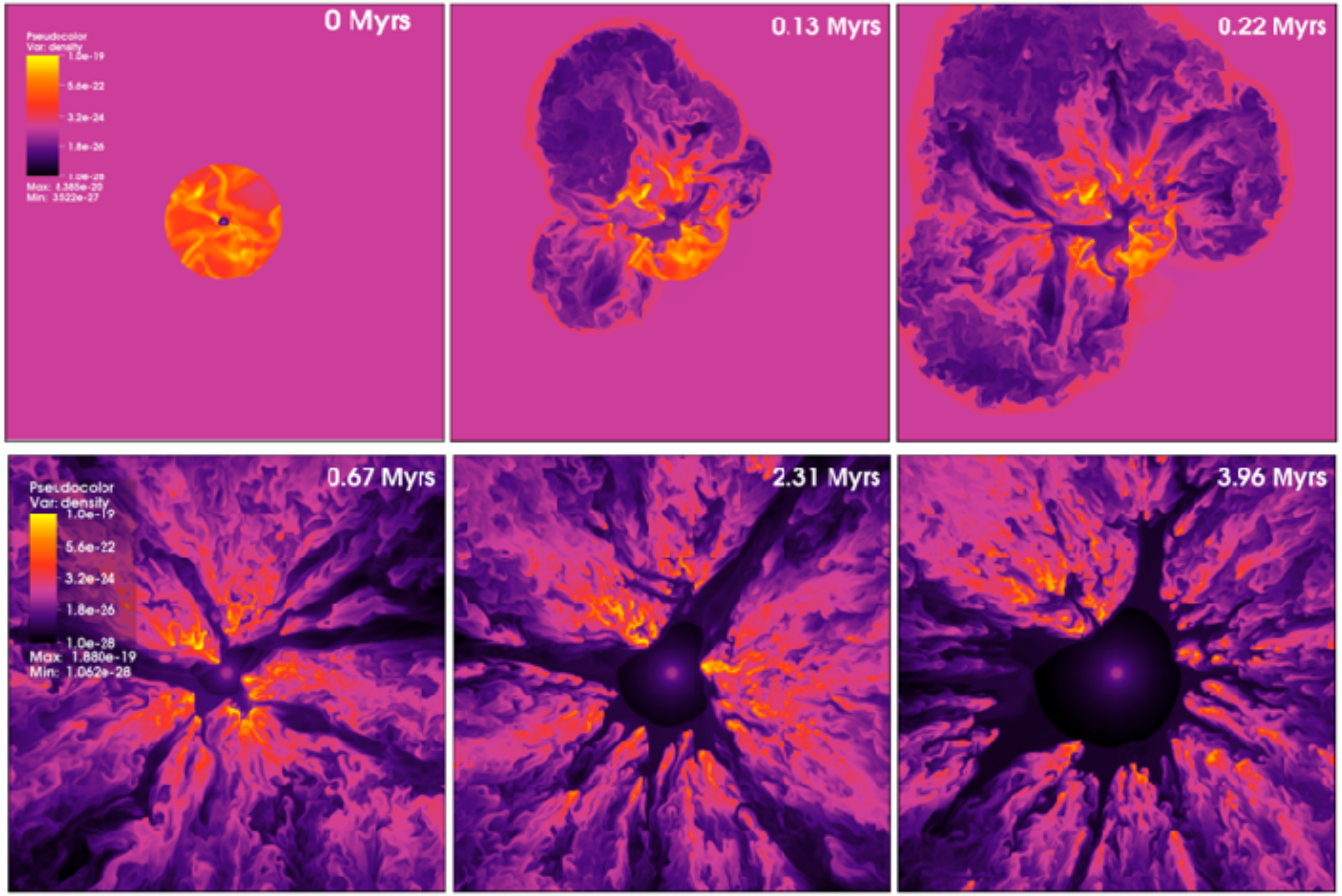
(e.g., Harper-Clark & Murray 2009, Lopez+2011, Rogers & Pittard 2013, **Rosen**+2014)

**Warm Photoionized Gas:**

$c_{\mathrm{s,\ HII}} \approx 10\ \mathrm{km\ s^{-1}} \approx v_{\mathrm{sh}}$

**Hot Shock-heated Gas:**

$c_{\mathrm{s,\ X}} \approx 10\ c_{\mathrm{s,\ HII}}$

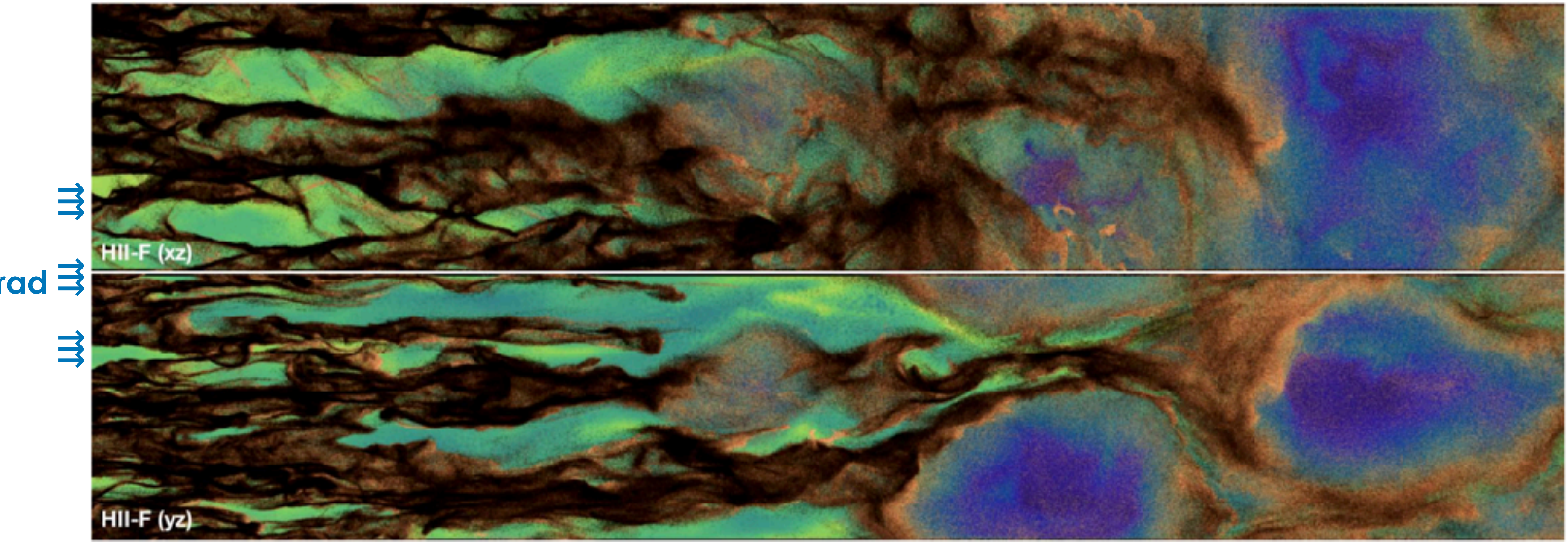


Rogers & Pittard 2013

# **Stellar wind energy** can also be lost via Dust Heating via Collisions

e.g., Draine 1979, **Rosen**+2014; Rodriguez (incl. **Rosen**)+(in prep)

## Dust clumping & turbulence in HII Regions



Resonant Drag Instabilities (RDIs; due to dust grains streaming in fluids) & $P_{\rm rad}$ cause dust clumping of larger grains near HII region shell.

(Squire & Hopkins 2018; Hopkins, **Rosen**+2022)

### Hot Gas-Dust Cooling Rate:

$$\Lambda_{\rm gd} = n_{\rm X} n_{\rm d} \sigma_{\rm d} \left(\frac{8k_{\rm B}T}{\pi m_{\rm e}}\right)^{1/2} \bar{\alpha}_{\rm T} \left(2k_{\rm B}T_{\rm d} - 2k_{\rm B}T\right)$$

**Hot gas sputters dust →**
**Dust must be replenished**

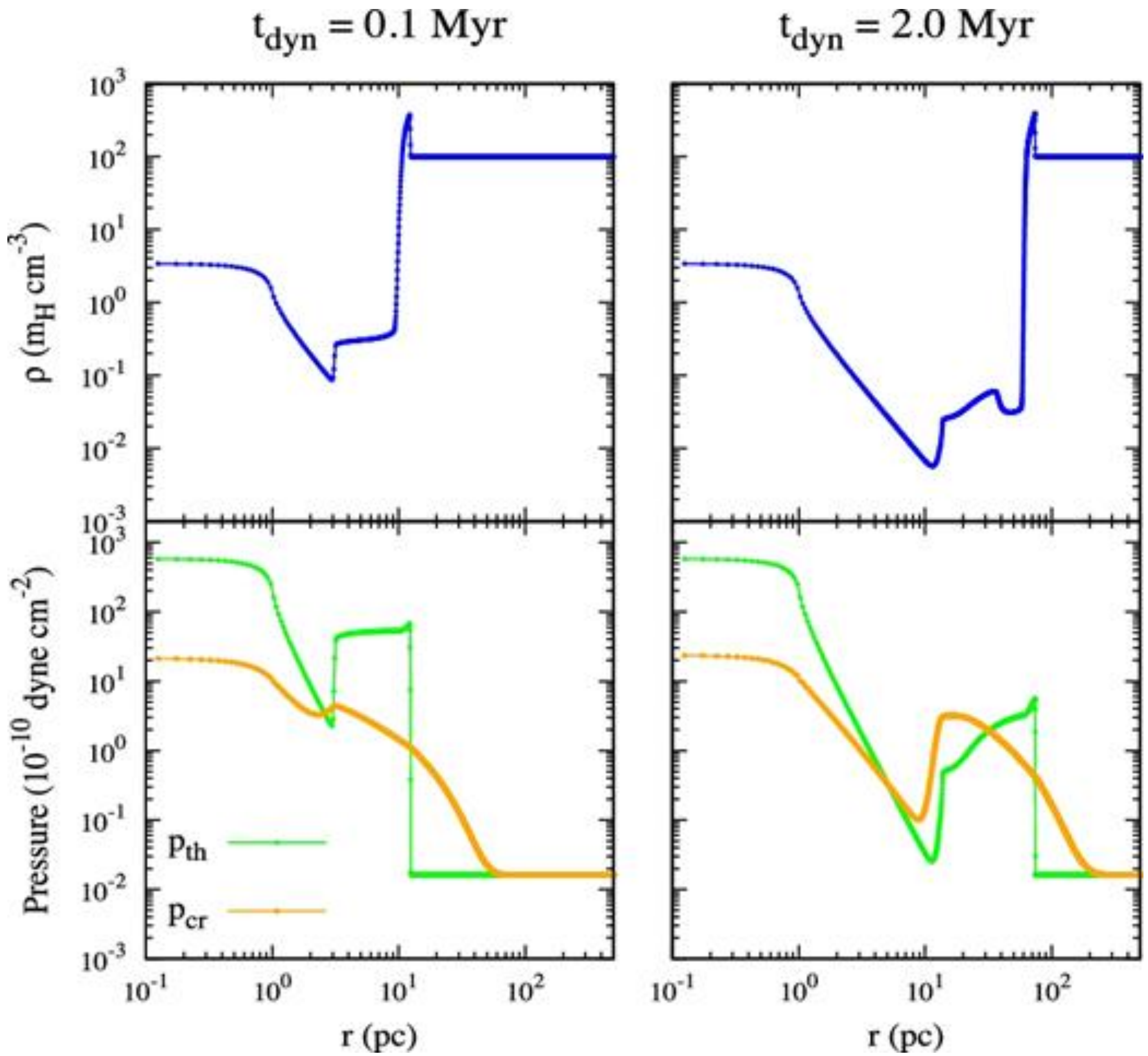
**Potential Dust Injection Sources:**

**Winds from evolved massive stars**
(**Red Super Giants**, **Wolf Rayet stars**)

**Turbulent Mixing**
(mix gas + dust at HII region interface)

# **Stellar wind energy** can also be lost via Cosmic Ray Acceleration in MSCs

(e.g., Gupta+2018a,b)



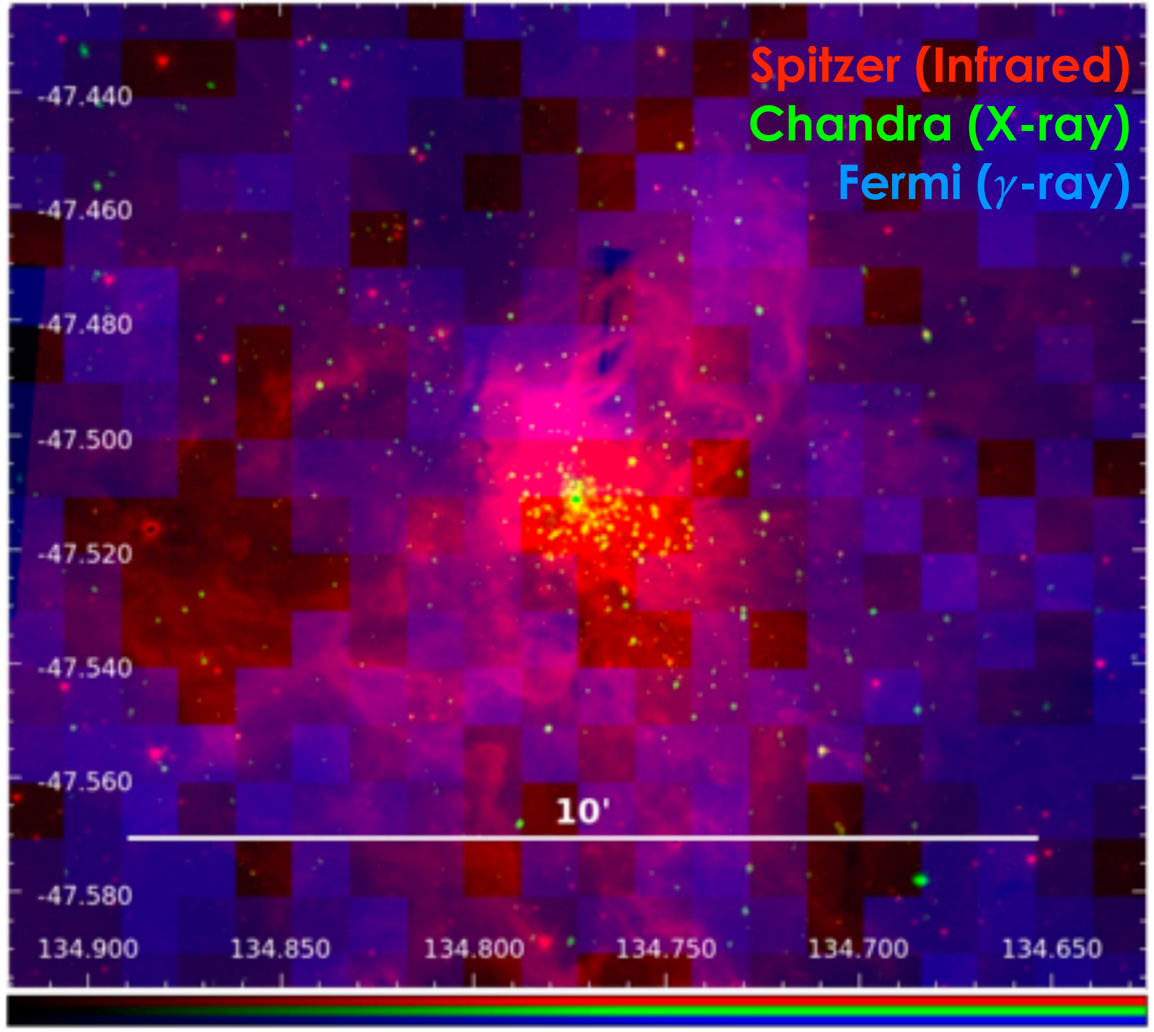
Energy exchange between hot shock-heated gas & CRs at the reverse shock leads to cooler wind bubbles.

Gupta+2018a,b

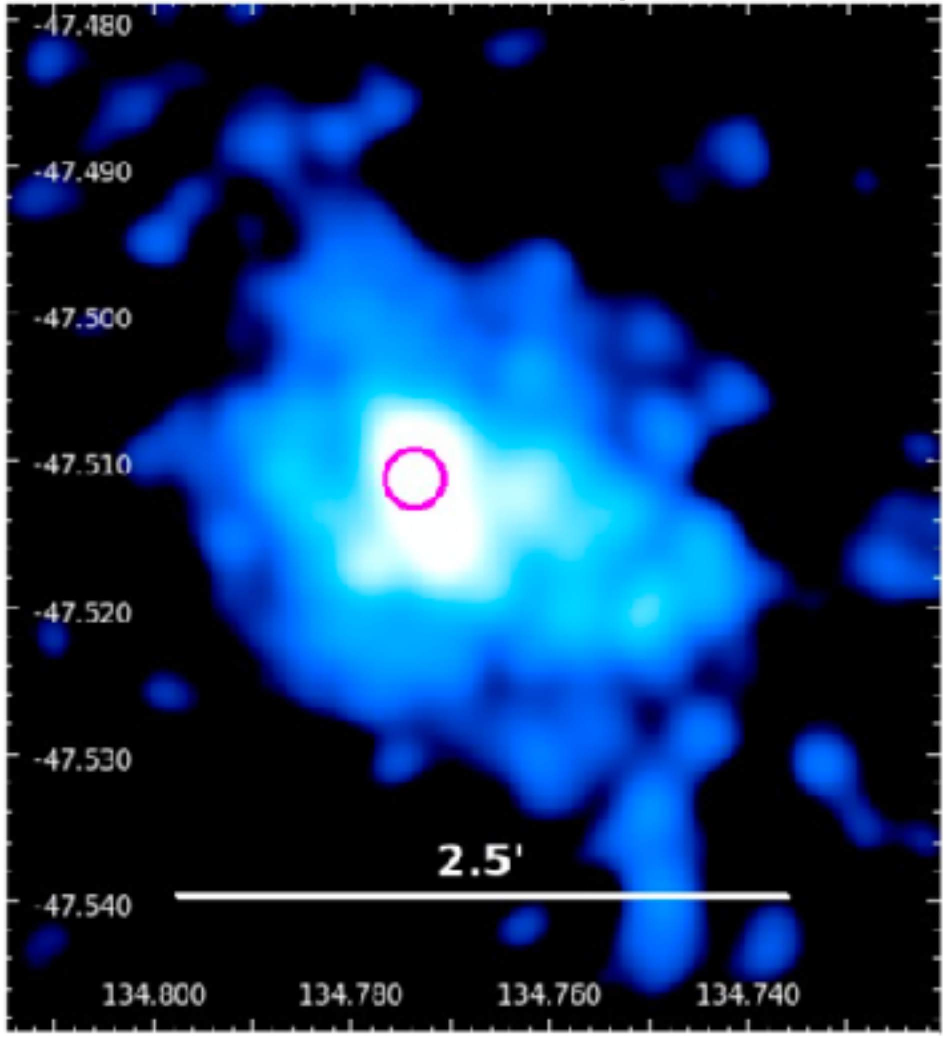
# Young MSCs $(t \lesssim 3\ \mathrm{Myr})$ are $\gamma$-ray bright, confirming Stellar Wind Collisions are CR accelerators

(e.g., Pandey+2024, Peron+2024, etc.)

RCW 38 $(t \sim 0.5\ \mathrm{Myr})$



2-7 keV Diffuse X-ray Emission



Diffuse X-ray emission is primarily due to **colliding winds** from the massive IRS 2 binary star system.

**Energetics:** $P_X \gg P_{CR}$

See poster by **Paarmita Pandey**

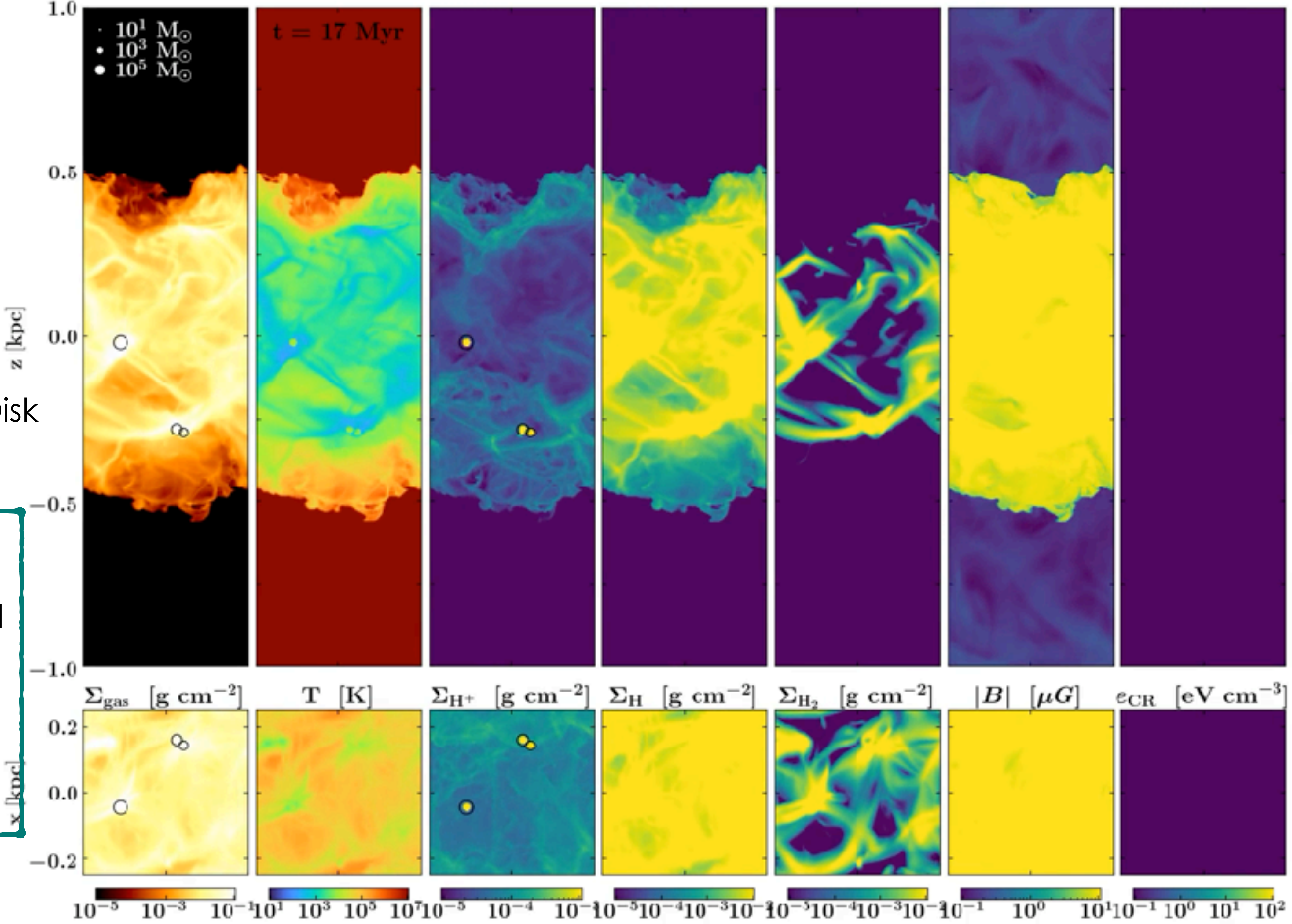
# CR Pressure efficiently launches galactic outflows & alters the CGM structure

Rathjen+2022

**SILCC:**
Simulating the Life-Cycle of molecular Clouds

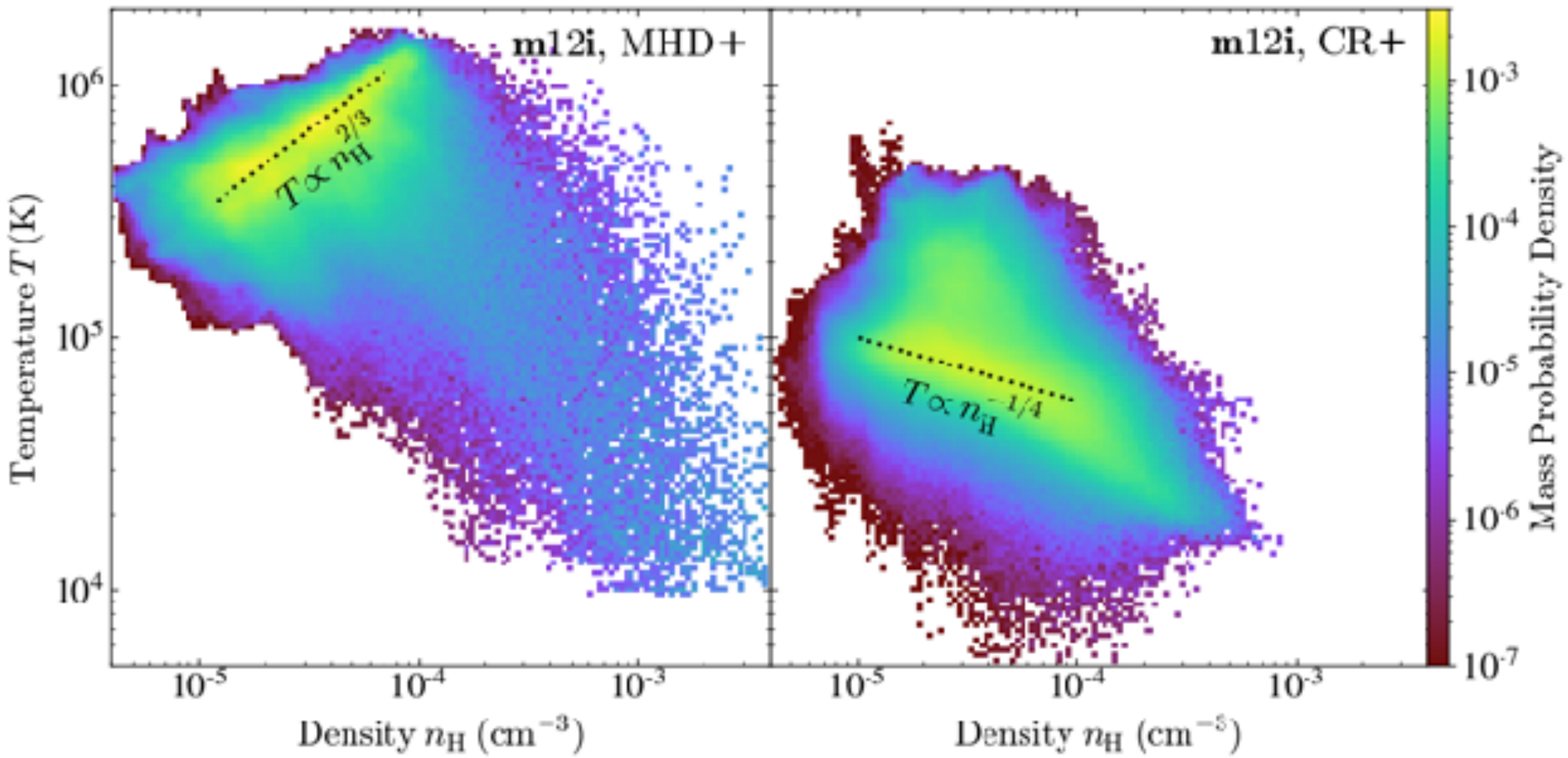
MHD stratified Gas Disk
$\Sigma_{\rm gas} = 100\,{\rm M_\odot}\ {\rm pc}^2$

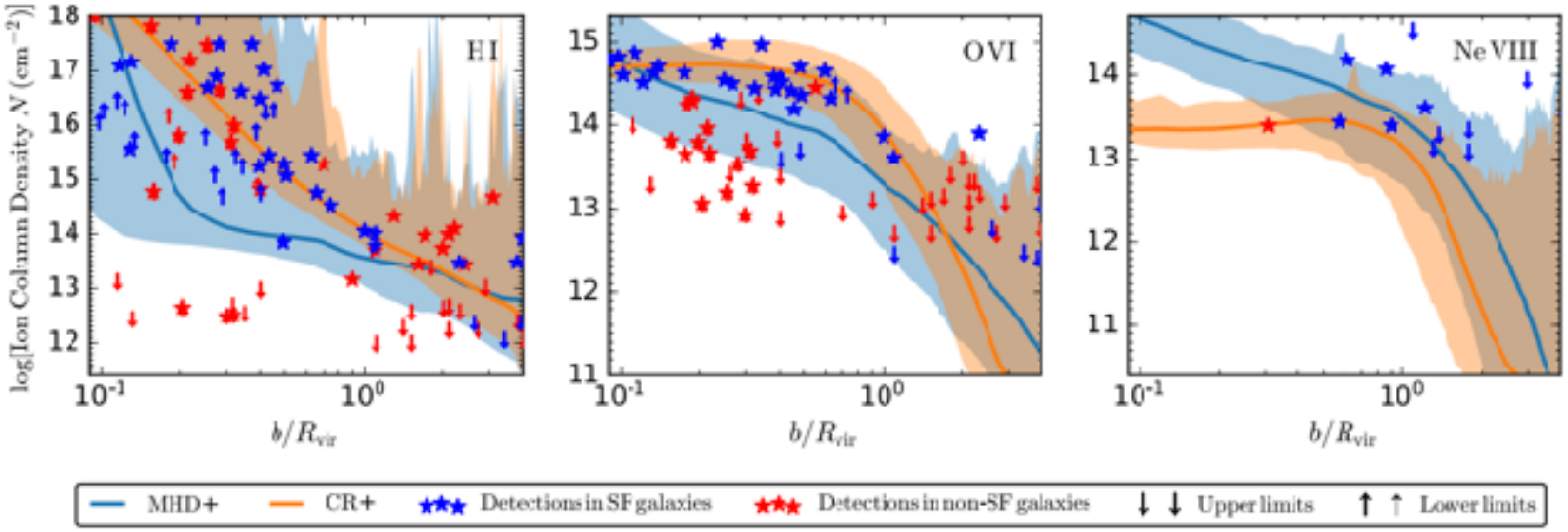
**CR Injection:**
~few-10% of the wind & SNe kinetic energy accelerates CRs
Outflow mass-loading factor ~ 1



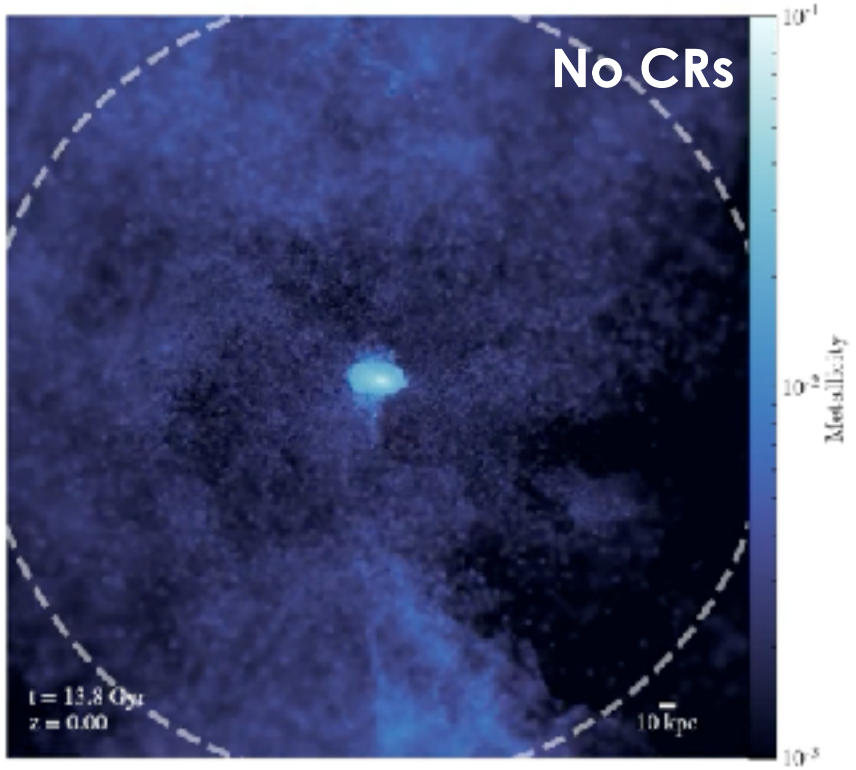
**Hot Gas** (T> 3×10⁵ K) produced by **SNe feedback drives galactic outflows** → **CRs** **alters the outflow phase structure** → 3 phases (cold, warm, & hot) **within 1 kpc** of galactic disk

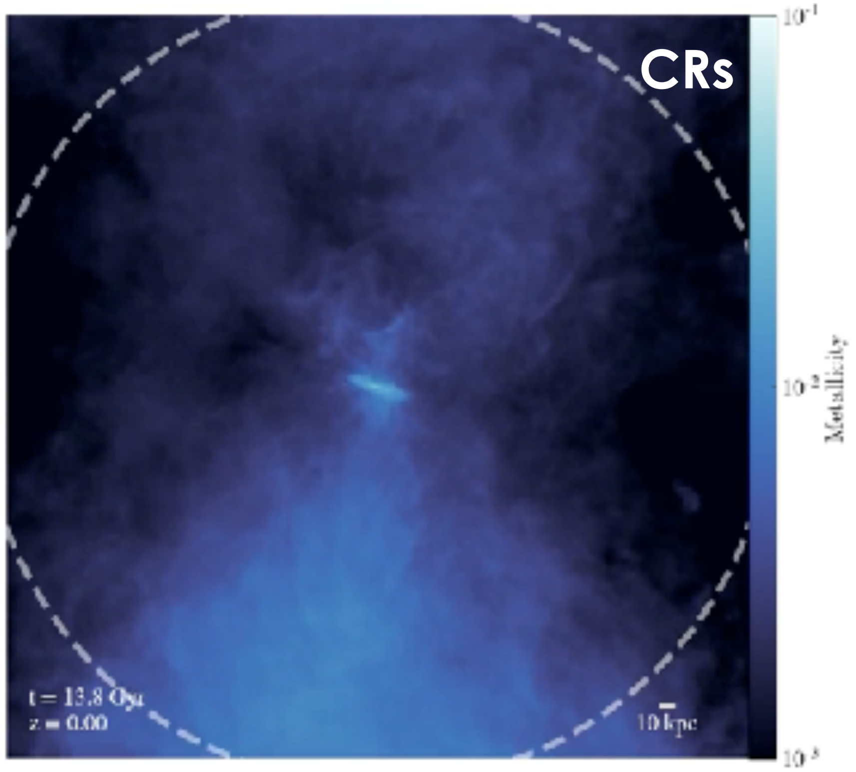
# CRs provide pressure support to the CGM → Results in lower $T_{CGM}$ and alters the density gas distribution (and metals/ions)





Ji+2020; FIRE Collab





CR feedback produces **lower CGM gas temperatures**,
**alters** the gas density distribution → **CR support** produces **smoother CGM**

# Summary:

- Massive stars **dominant** the galactic stellar feedback budget. Stars feedback on their environment via radiation, protostellar outflows, stellar winds, & SNe.
- **Stellar winds** from massive protostars, are able to **quench** stellar accretion.
- Diffuse, soft X-ray emission traces the hot shock-heated gas produced by stellar wind feedback.
- In MSCs wind feedback is dynamically unimportant because wind energy is lost.
    - **Potential Loss mechanisms:** hot gas physical leakage, multi-phase turbulent mixing, dust grain collisional heating, CR acceleration (?)
- **CR feedback** may be dynamically unimportant in MSCs but is a *crucial* component for shaping the CGM
- CRs add additional pressure support in the HII Regions & the CGM

# FIN.