Star Formation, Feedback and the Interstellar Medium

Eve Ostriker

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Physical processes & numerical methods

- Magnetohydrodynamics
  - Finite volume methods (Athena*)
- Self-Gravity
  - FFT; multigrid Poisson solvers
  - Sink particles for unresolved collapse; PM gravity
- Radiation from massive stars
  - Adaptive ray tracing; moment method+M1+RSL
- Photochemistry
  - ODEs for key species (sub-stepped explicit; semi-implicit)
- Heating and cooling
  - CIE at higher T; rates based on species abundance at lower T
- Supernovae + stellar winds
  - Energy/momentum deposition depending on resolution of R_{cool}
- Cosmic rays
  - Moment method+RSL, scattering from self-confinement model

+ *Boundary conditions*

Method papers

The Astrophysical Journal Supplement Series, 204:8 (14pp), 2013 January doi:10.1088/0067-0049/204/1/8

IMPLEMENTATION OF SINK PARTICLES IN THE *ATHENA* CODE

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The Astrophysical Journal Supplement Series, 206:21 (29pp), 2013 June doi:10.1088/0067-0049/206/2/21

A TWO-MOMENT RADIATION HYDRODYNAMICS MODULE IN *ATHENA* USING A TIME-EXPLICIT GODUNOV METHOD

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The Astrophysical Journal, 843:38 (35pp), 2017 July 1 https://doi.org/10.3847/1538-4357/aa7561

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A Simple and Accurate Network for Hydrogen and Carbon Chemistry in the Interstellar Medium

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Method papers

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Three-phase Interstellar Medium in Galaxies Resolving Evolution with Star Formation and Supernova Feedback (TIGRESS): Algorithms, Fiducial Model, and Convergence

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Modeling UV Radiation Feedback from Massive Stars. I. Implementation of Adaptive Ray-tracing Method and Tests

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Photochemistry and Heating/Cooling of the Multiphase Interstellar Medium with UV Radiative Transfer for Magnetohydrodynamic Simulations

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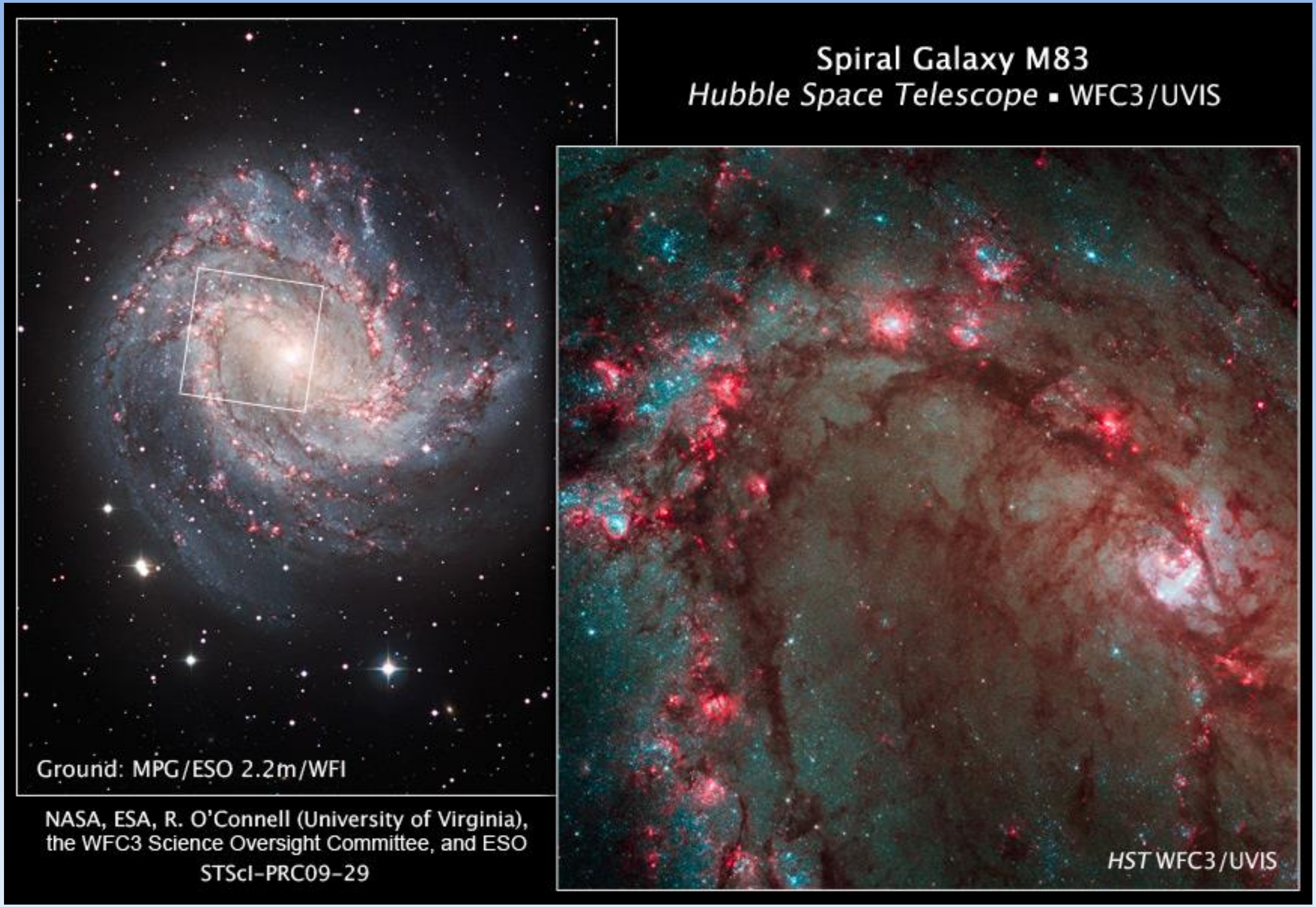
Galaxies, the ISM, and star formation



Interstellar medium

Milky Way has more than 10^{10} $M_\odot$ of ISM gas, mostly H & He

- Atomic gas, referred to as HI
  - seen in 21 cm radio emission (spin flip transition of H)
  - two thermal equilibrium phases (similar pressure):

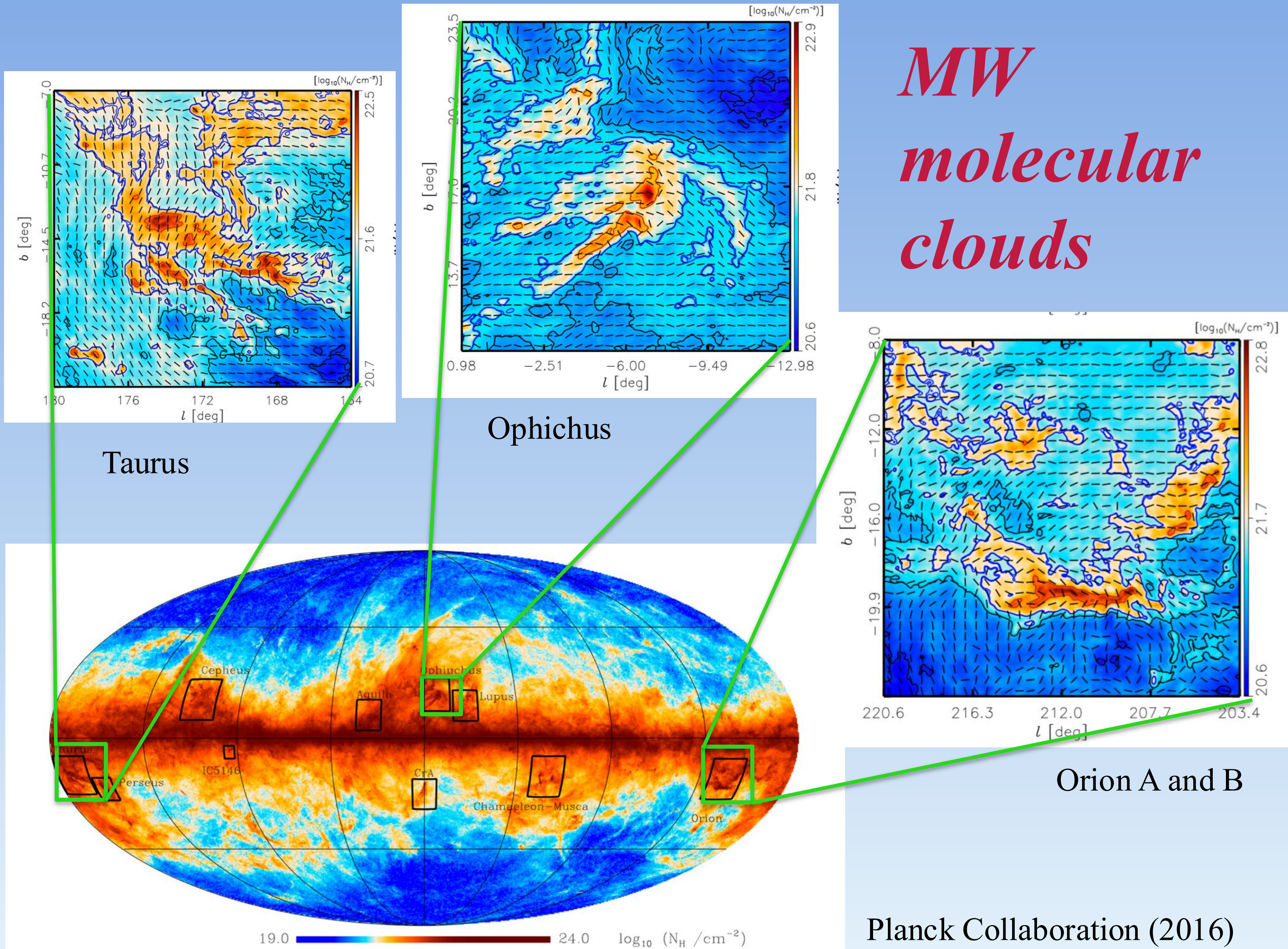
    warm (10^4 K) and low density (0.3 particle/cm^3) "diffuse" gas

    cold (100K) and high density (30 particles/cm^3) in clouds
- Molecular gas, referred to as H_2
  - Seen in mm-wave radio emission (rotational transitions of CO)
  - Extension of cold atomic gas to lower T (20K), higher n (>100 cm^{-3})
  - Organized into dense structures called Giant Molecular Clouds (GMCs). *All star formation is in molecular clouds*
- Warm ionized gas, referred to as HII
  - Photoionized by stars (HII regions + DIG); warm (T ~ 10^4 K)
- Hot ionized gas
  - Shock heated; very low density, very hot (>10^6K); emits X rays

Also contains: dust, ~ 1% of the mass of gas, in very small grains;

Cosmic rays, relativistic particles with power-law spectrum

MW molecular clouds



Planck Collaboration (2016)

ISM structure and evolution

- ISM is highly dynamic, with structures the gas continually forming and dispersing
- Driven by forces that compress and forces that disperse (by rarefaction, shear) gas:

$$\partial_t \rho = -\nabla \cdot (\rho \mathbf{v})$$

$$\partial_t (\rho \mathbf{v}) = -\rho \nabla \Phi - \nabla P_{\rm gas} - \nabla P_{\rm cr} + \rho \kappa \frac{\mathbf{F}_{\rm rad}}{c} - \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi}$$

  - Gravity, gas pressure, cosmic ray pressure, radiation pressure, Reynolds stresses (turbulent pressure), magnetic stresses
  - Some forces mostly one way (gravity); others are double-edged sword (+ or - divergence or shear in turbulent velocity field)

Star Formation

- Stars form by collecting material from the ISM
  - Mean local ISM density is $\rho = 2.4 \times 10^{-24}$ g/cm^3
  - Mean density in the Sun is 1.4 g/cm^3
  - Requires compression factor ~10^{24}!
- *Gravity* is considered prime motivator of SF, but measured SFR is factor ~100 lower than $M_{gas}/\ t_{ff}$

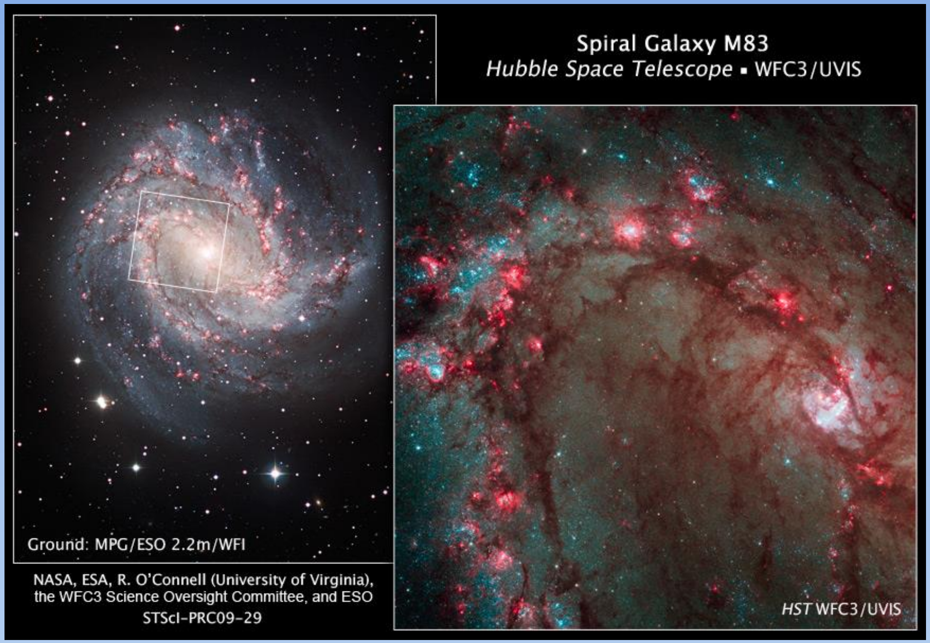
$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$ ~ 50 Myr at mean ISM density

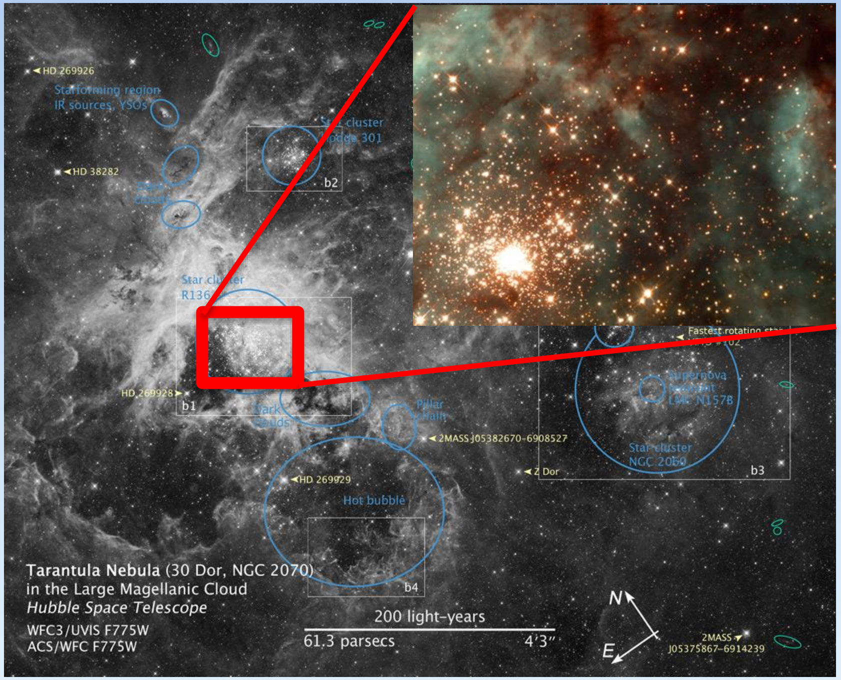
Actual SFR depends on:

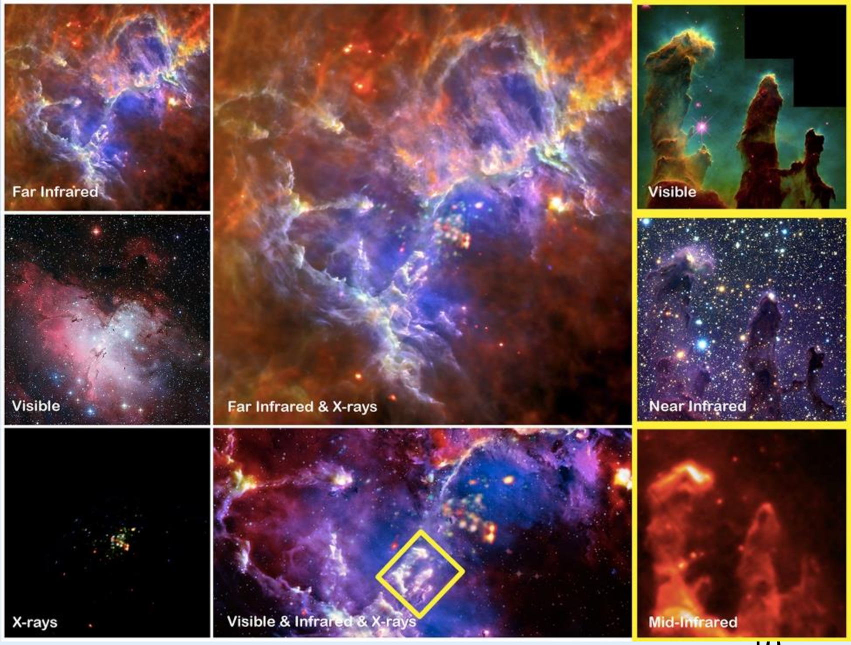
- *Competition* between compression and dispersal of gas
- Losses by dissipation, cooling reduce “support” forces
- *Sustaining the ISM (and SF) requires energy*
- *Most energy inputs are from stars themselves:* **feedback**

The need for SF feedback

- Without feedback, diffuse-ISM turbulence would dissipate, ISM would cool, and all ISM would collapse into dense clouds
- Without feedback, all the mass in dense clouds would collapse and end up in stars





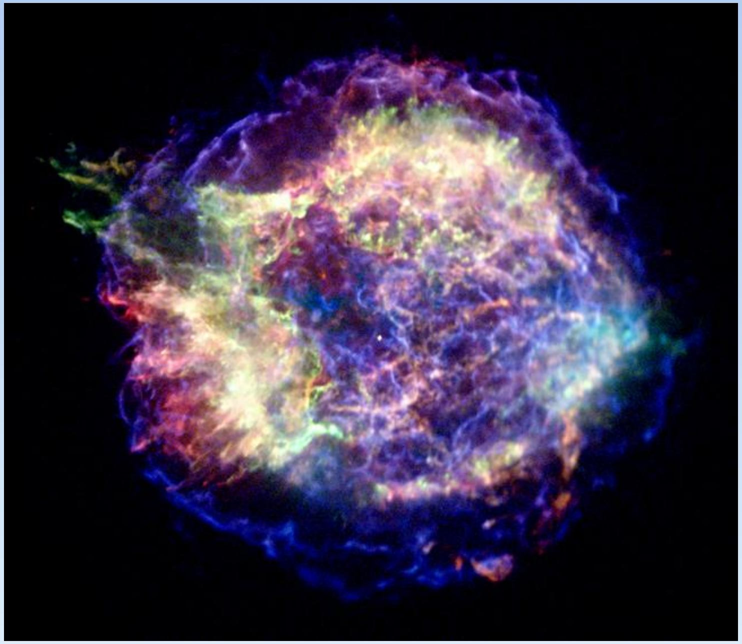


Eagle nebula/M16 cluster

Feedback mechanisms

- Dissipation, cooling, collapse are compensated by feedback from young (massive/luminous) stars:
  - Radiative heating
    - FUV → PE effect for diffuse ISM CNM, WNM
    - Dust heating → gas in dense regions
  - Photoionization/heating
    - Star-forming clouds → HII regions
    - Escaped radiation → DIG
  - Radiation force
    - Direct FUV on dust → gas, ionizing UV → gas
    - Reprocessed IR on dust → gas in opaque regions
  - Stellar winds
    - Line-driven winds (massive stars)
    - Magnetocentrifugal winds/jets (low-mass stars)
  - Supernova blasts
    - Individual: SNR; clustered: superbubble
    - Shock heating (HIM) and gas acceleration
  - Cosmic rays
    - Created in SNRs
    - Heat shielded gas; apply large-scale pressure

Herschel: Carina nebula



Cas A supernova remnant

Self-regulation concept

Cooling and turbulent dissipation times in the ISM are short

- leads to massive cloud formation on large scales
- leads to localized collapse within massive clouds

When some gas collapses to make new stars

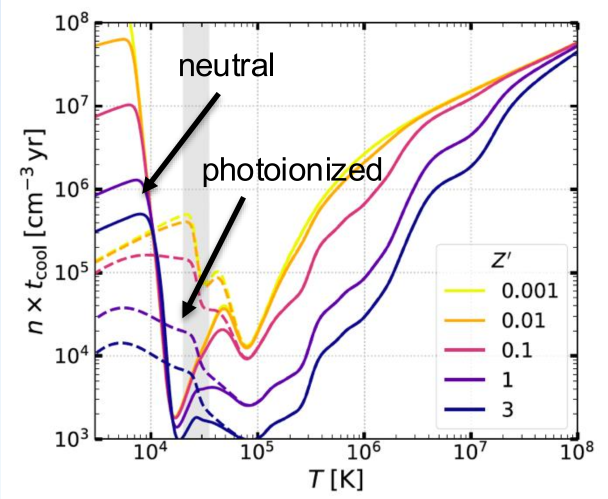
- massive stars inject energy, momentum to their surroundings
- short stellar lifetimes ⇒ feedback injection is rapid compared to system evolution

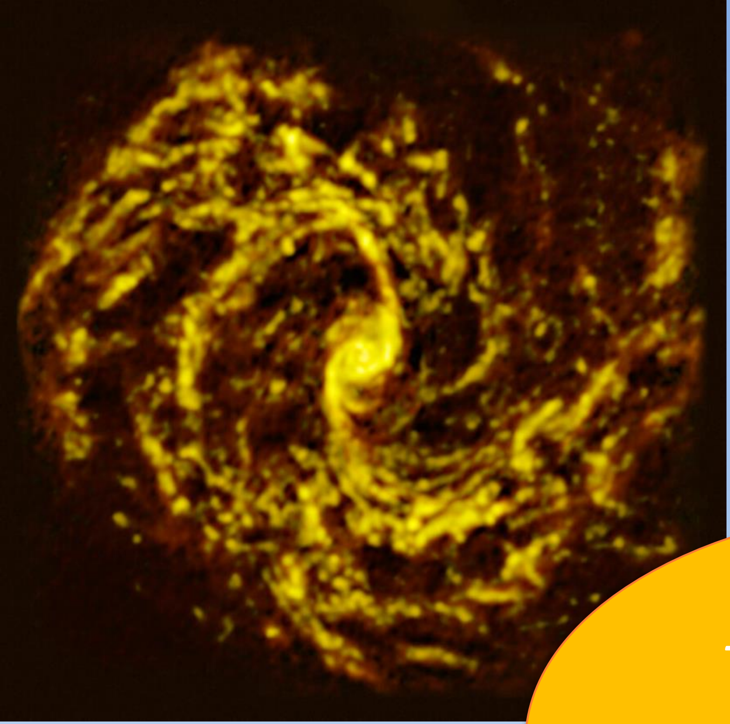
Energy injection by massive stars

- transforms thermal phase state of ISM gas (offsetting cooling)
- accelerates motions on a range of scales (offsetting dissipation)
- limits local collapse and may remove "fuel" from system

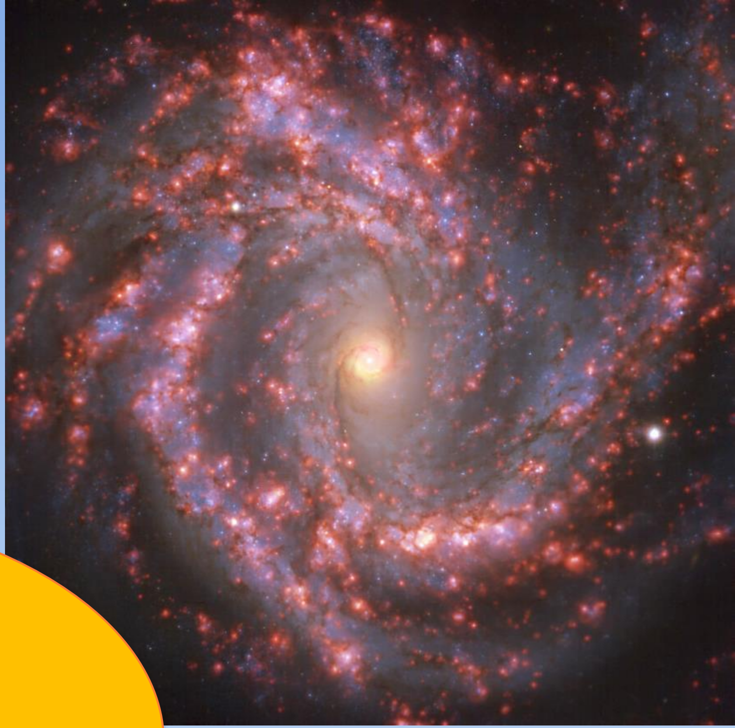
Star formation ***now*** *regulates*

- ***Near-future*** *state of ISM*
- ***Near-to-far future*** *star formation*





NGC 4303



ISM response

The star-forming ISM: a self-regulated ecosystem

ALMA CO (molec. gas)

MUSE gri + Hα
(stars + ionized gas)

collapse & SF

Young star feedback

MUSE gri (stars)

Credit:
MUSE(VLT-ESO)
ALMA(ESO/NAOJ/NRAO)
PHANGS

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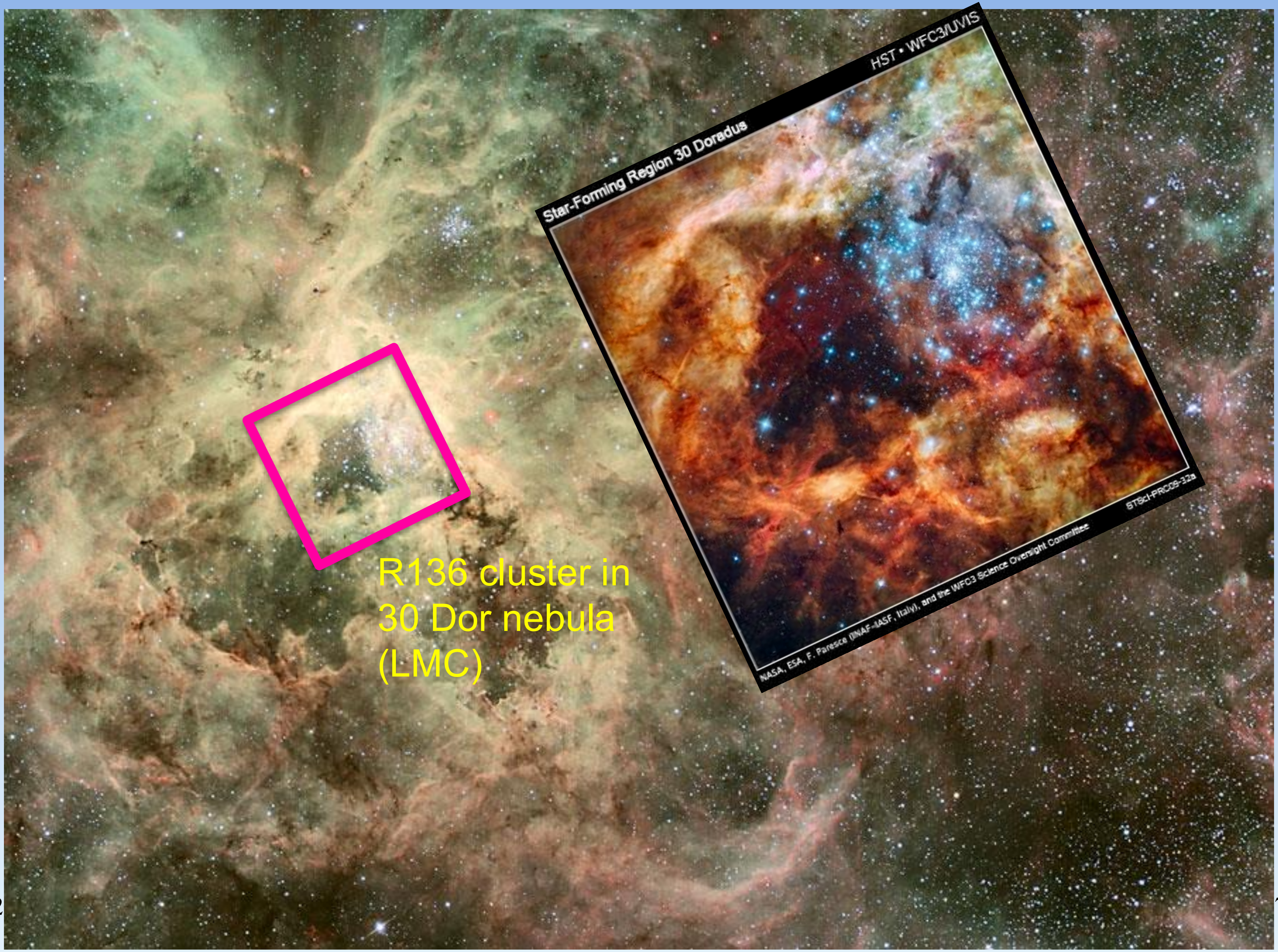
We use numerical radiation magnetohydrodynamic (RMHD) simulations to quantify these processes

Outline

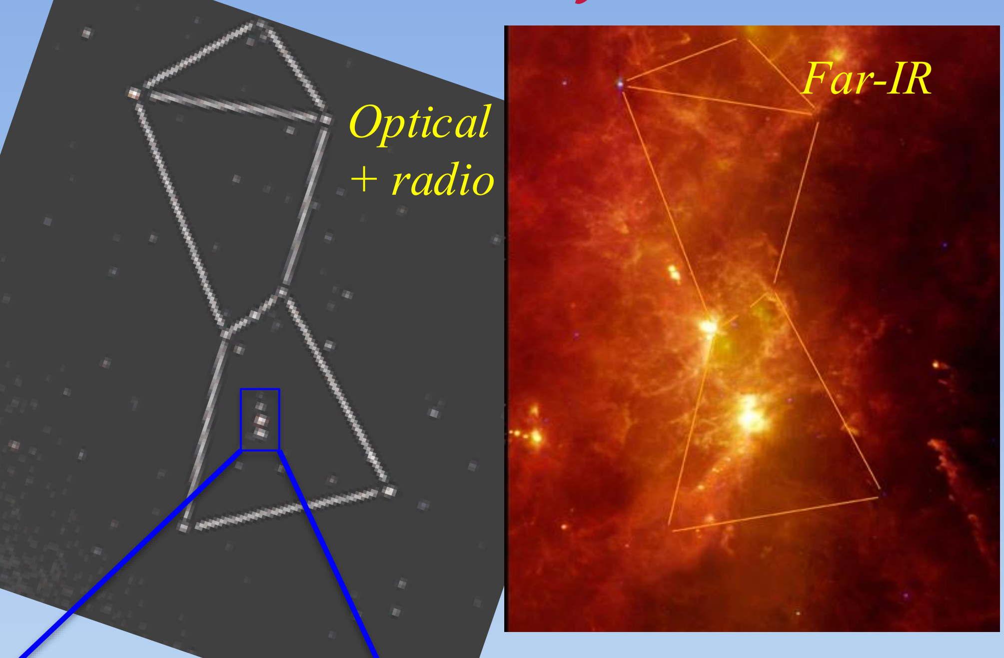
I. Introduction ✔
II. Quantifying stellar feedback
III. SFE in GMCs with feedback
IV. SFR regulation in the large-scale ISM with feedback

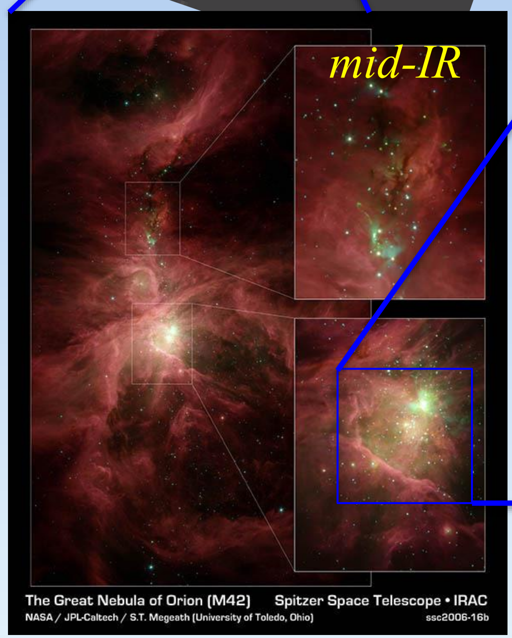
II.Quantifying feedback

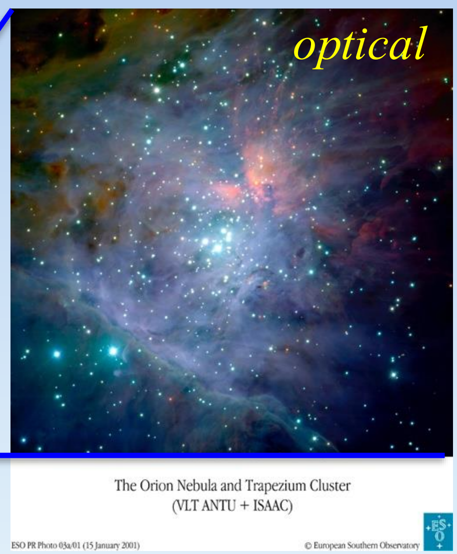
Feedback from massive stars/clusters



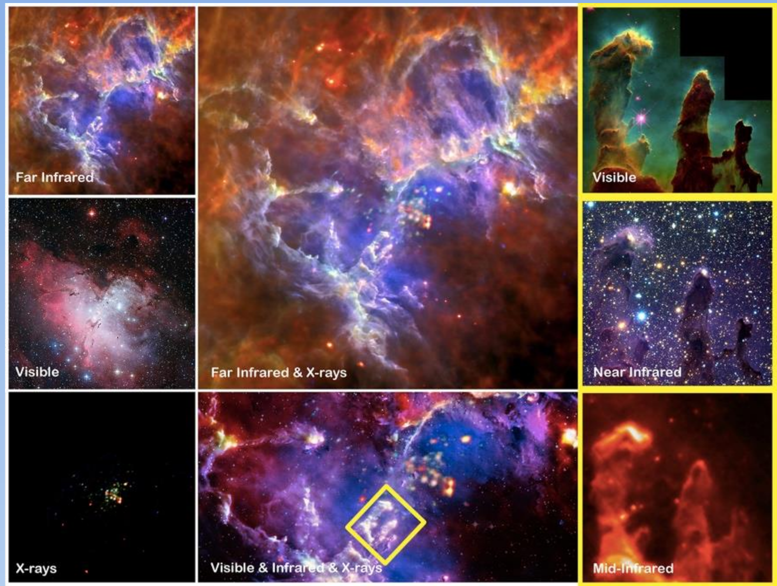
Feedback from massive stars/clusters







Orion GMC & Trapezium cluster

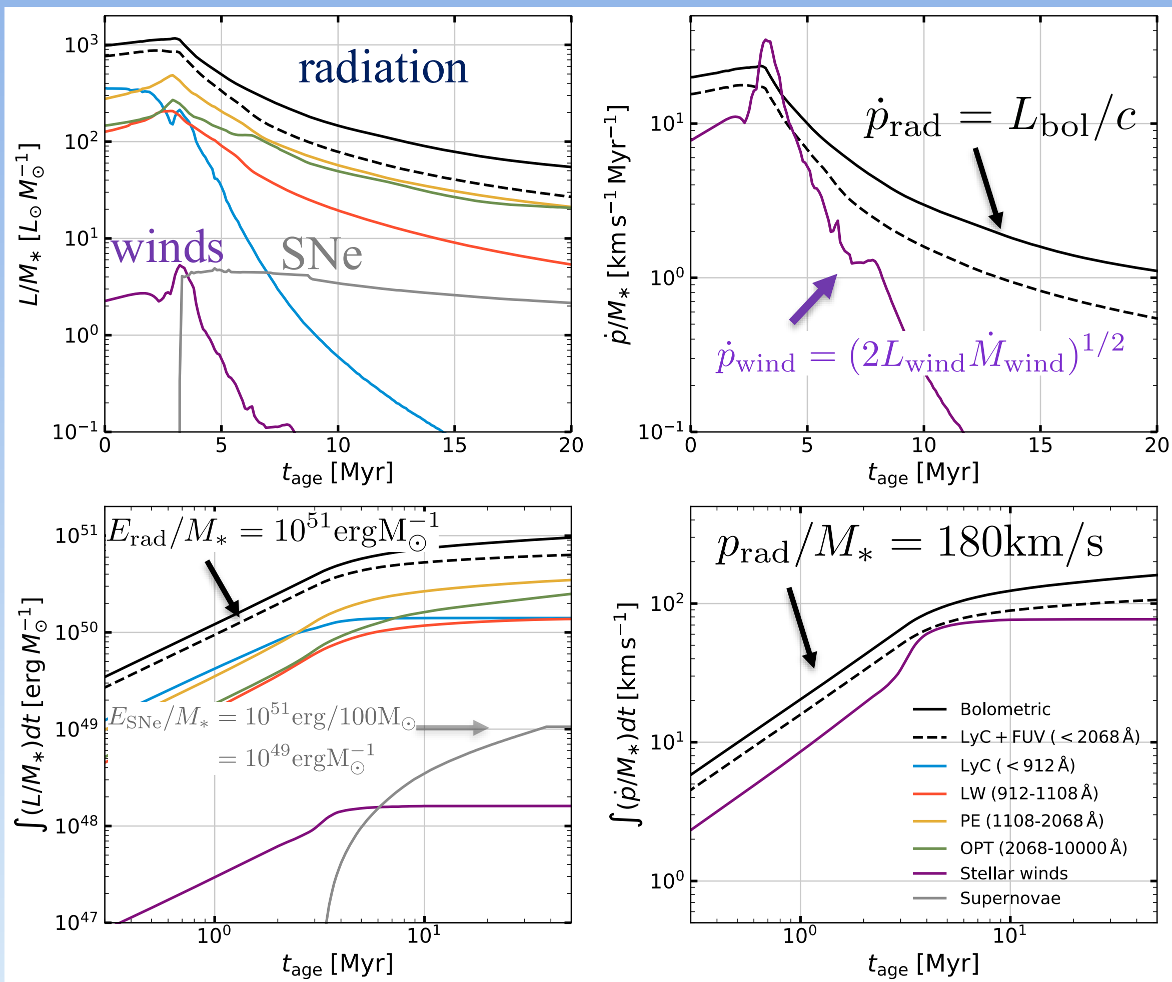


Eagle nebula/M16 cluster

Want to quantify theoretically the effects of massive stars:

- *thermal pressure from heating*
- *momentum injection*

Stellar E and p inputs



J.-G. Kim, M. Gong, C.-G. Kim, E. Ostriker (2023)

(from SB99 with fully-sampled Kroupa IMF and Geneva tracks)

LyC : $\lambda \leq 91.2{\rm nm}$

$13.6{\rm eV} \leq h\nu$

FUV

LW : $91.2{\rm nm} < \lambda \leq 110.8{\rm nm}$

$11.2{\rm eV} \leq h\nu < 13.6{\rm eV}$

PE : $110.8{\rm nm} < \lambda \leq 206.6{\rm nm}$

$6.0{\rm eV} \leq h\nu < 11.2{\rm eV}$

OPT : $206.6{\rm nm} < \lambda \leq 1000.0{\rm nm}$

$11.2{\rm eV} \leq h\nu < 1.2{\rm eV}$

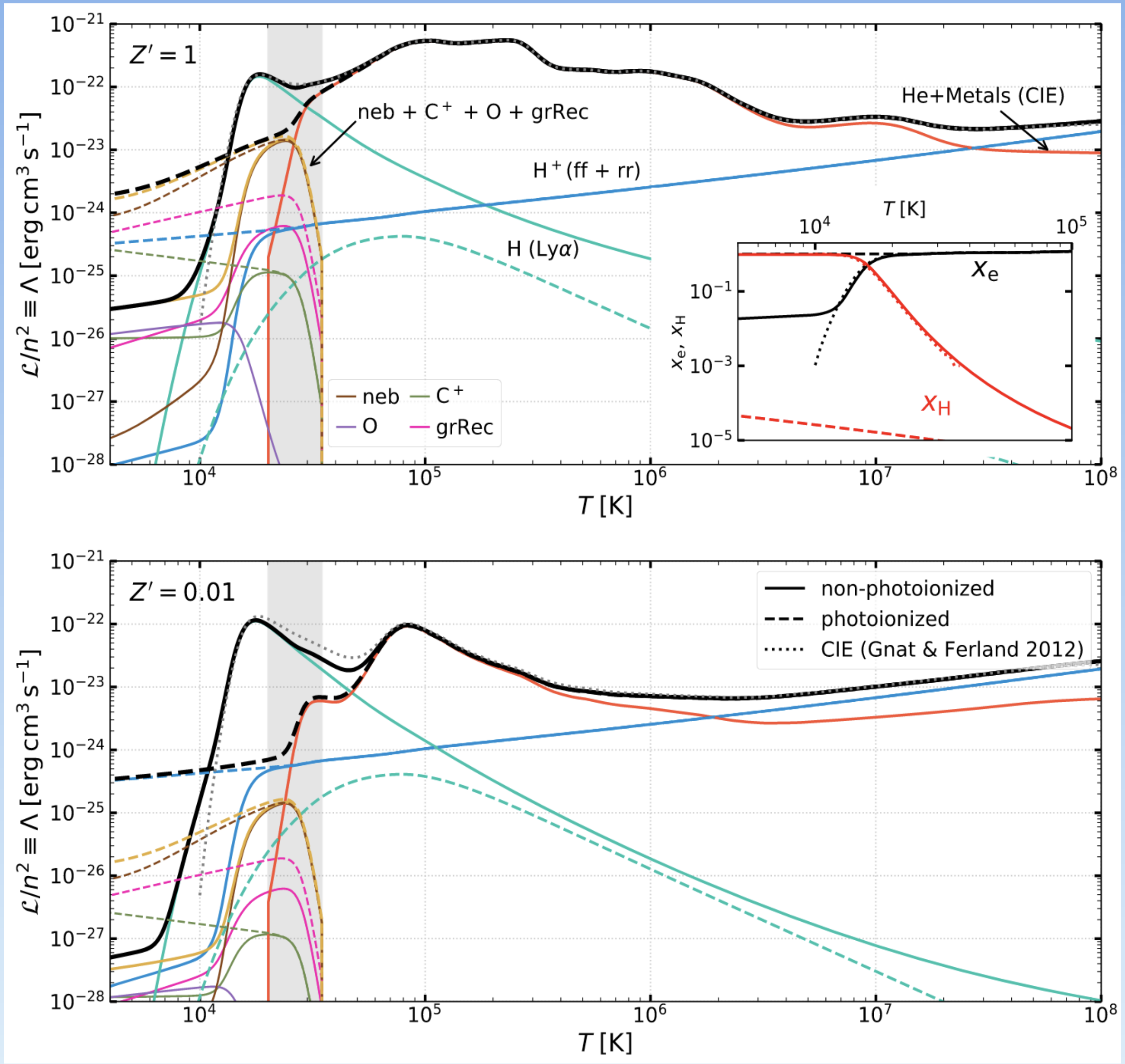
Radiation timescales:

	LyC	LW	PE	FUV	OPT	Bol
Timescales (Myr)						
(1) $\langle t \rangle$	1.9	6.6	11.9	10.4	20.7	12.9
(2) $t_{\rm cumul,50\%}$	1.7	3.4	4.3	4.0	7.8	4.1
(3) $t_{\rm cumul,90\%}$	3.7	14.9	34.3	28.6	63.4	40.8

Ionizing photon rate:

$$Q_{\rm ion} = 10^{44} s^{-1} \frac{M_*}{M_\odot} \times L_{\rm LyC}/M_*$$

Cooling function



JG Kim et al (2023)

FUV heating and thermal equilibrium

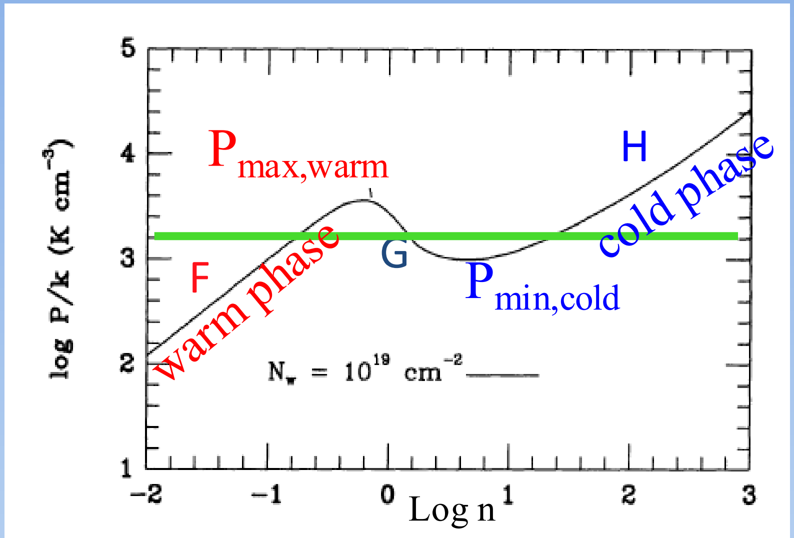
- FUV from OB stars incident to small grains produces the **photoelectric effect**
- PE dominates heating in neutral ISM for Z′=1

  (atomic and diffuse molec. gas)
- When $t_{cool}<t_{dyn}$ expect to reach thermal equilibrium $n\Lambda=\Gamma$
  - three equil. branches (Field, Goldsmith, Habing): warm (F), cold (H), unstable (G)
- In Solar neighborhood,

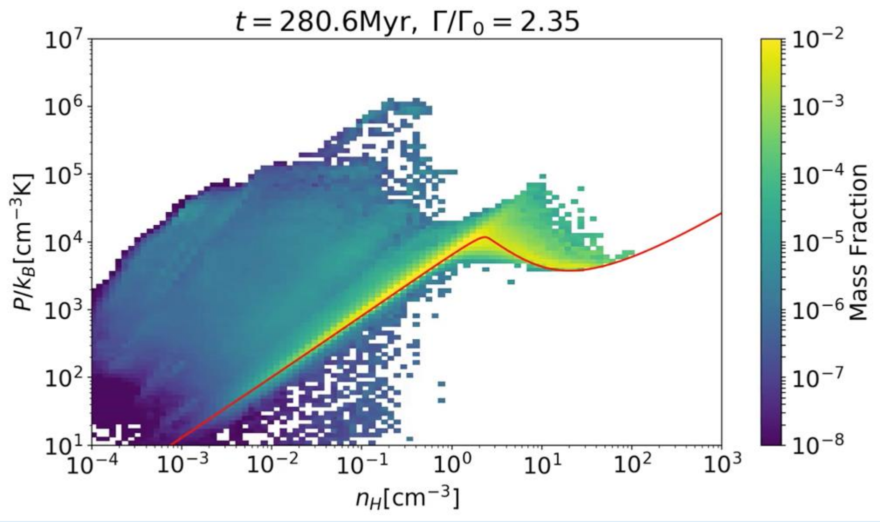
$$P_{th,0} \approx P_{two\text{-}phase} \equiv (P_{min,cold} P_{max,warm})^{1/2}$$

$$\approx 3000 \text{ k K cm}^{-3}$$

(Wolfire et al 2003)



Wolfire et al (1995)



Kim & Ostriker (2017)

FUV heating and thermal equilibrium

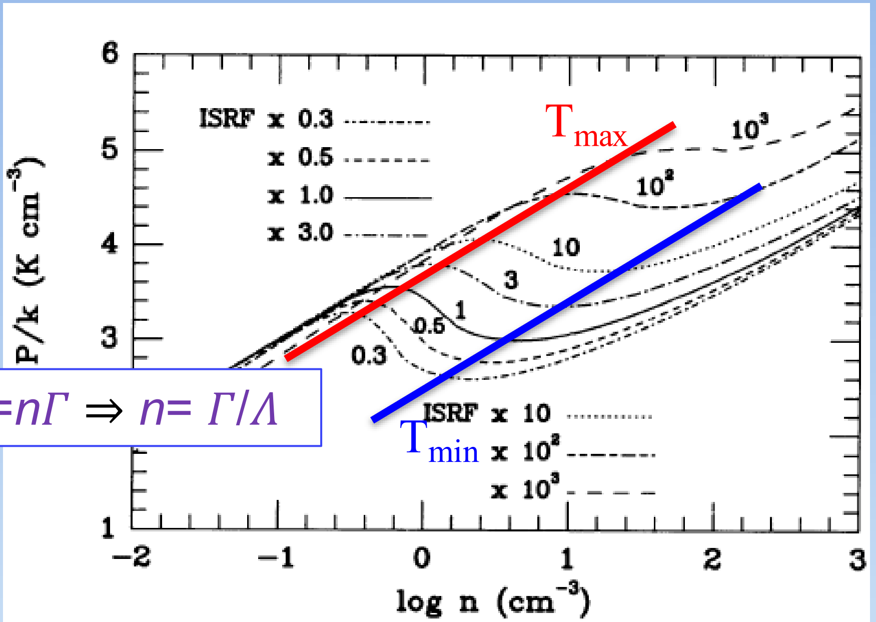
- Dependence of $P_{\text{two-phase}}$:

$$\frac{P_{\text{two-phase}}}{k} = \left[n_{\min} T_{\min} n_{\max} T_{\min} \right]^{1/2}$$

$$= \Gamma \left[\frac{T_{\min} T_{\max}}{\Lambda(T_{\min}) \Lambda(T_{\max})} \right]^{1/2}$$

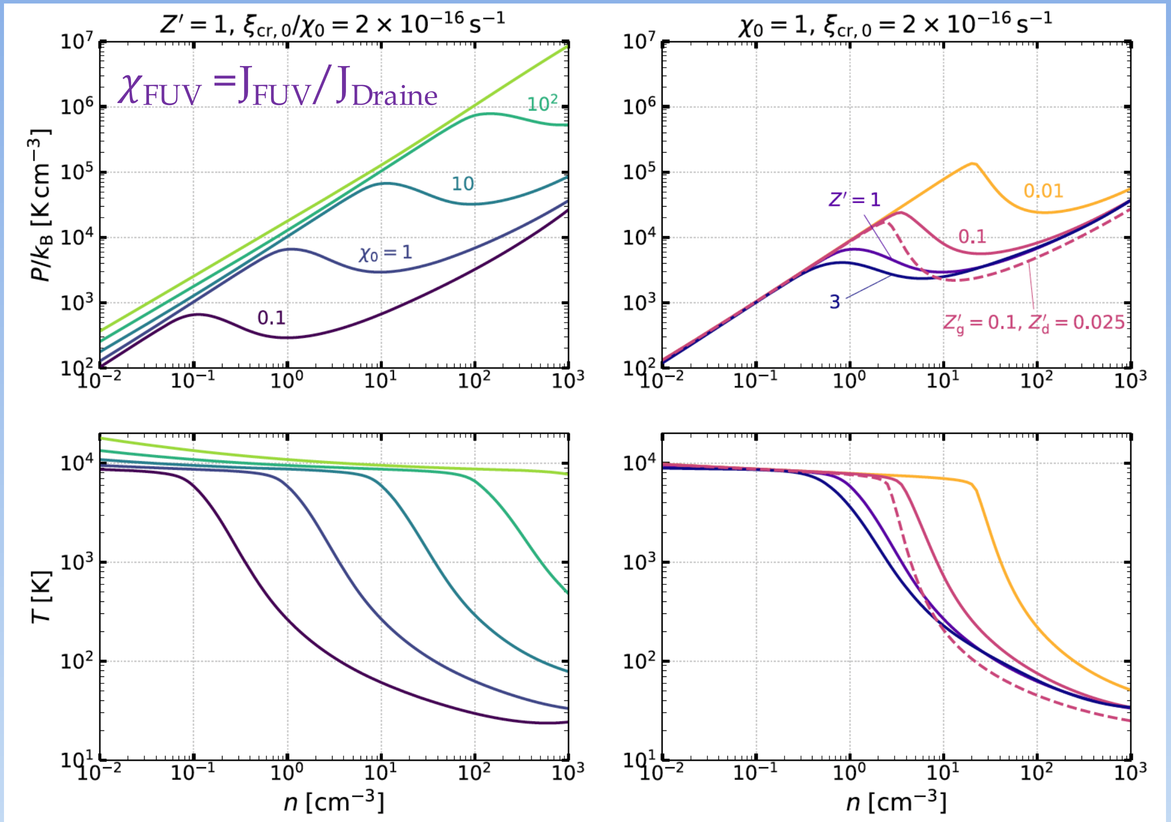
$n^2 \Lambda = n\Gamma \Rightarrow n = \Gamma / \Lambda$

- $T_{\min}$, $T_{\max}$ ~ const.;
- $\Gamma_{PE} \propto \epsilon_{PE} Z_d J_{FUV}$, $\Lambda \propto Z_g \Rightarrow$
- $P_{\text{two-phase}} \propto \epsilon_{PE} J_{FUV} Z_d / Z_g$
- J_{FUV} depends on local SFR



Wolfire et al (1995)

Thermal pressure from FUV + CRs



J.-G. Kim et al (2023)

- "Two-phase" thermal pressure $P_{\text{two-phase}} \propto \Gamma_{PE} + \Gamma_{CR}$
- $\Gamma_{PE} \propto \chi_{FUV} \propto J_{FUV} \propto \Sigma_{FUV} \propto \Sigma_{SFR}$, with dust attenuation factor
- $\Gamma_{CR} \propto \xi_{CR} \propto \Sigma_{SFR}$, with modest shielding at high column
- At low metallicity & dust abundance, ϵ_{PE} increases and CR heating begins to dominate $\Rightarrow P_{\text{two-phase}}$ increases for fixed χ_{FUV}

Photoionization by EUV

- Individual O star or cluster (mass M_*) photoionizes nearby gas
- Photon energy> 13.6 eV in electrons is shared with gas to maintain T~10^4K
- Ionizing photon rate (fully sampled IMF)

$$Q_i = \Xi M_* \text{ for } \Xi = 3 \times 10^{13} \text{photon s}^{-1}\text{ g}^{-1}$$

- Ionization is balanced by recombination in HII region
- Ideal Stromgren sphere:

$$(4\pi/3)R_s^3 \, \alpha_B \, n_e n_i = Q_i(1 - f_{dust} - f_{esc}) = Q_i f_{ion}$$

Photoionized bubble expansion

- Ionization=recombination in interior maintained by photoevaporation ⇒

$$n_{int} = \left[3Q_i/(4\pi r_{IF}^3 \alpha_B)\right]^{1/2} \;\Rightarrow\; M_i \propto (Q_i r_{IF}^3)^{1/2}$$

- Force on ionized/neutral interface from ionized gas pressure:

$$F_i = (2n_{int}kT)4\pi r_{IF}^2 \sim kT(Q_i r_{IF}/\alpha_B)^{1/2}$$

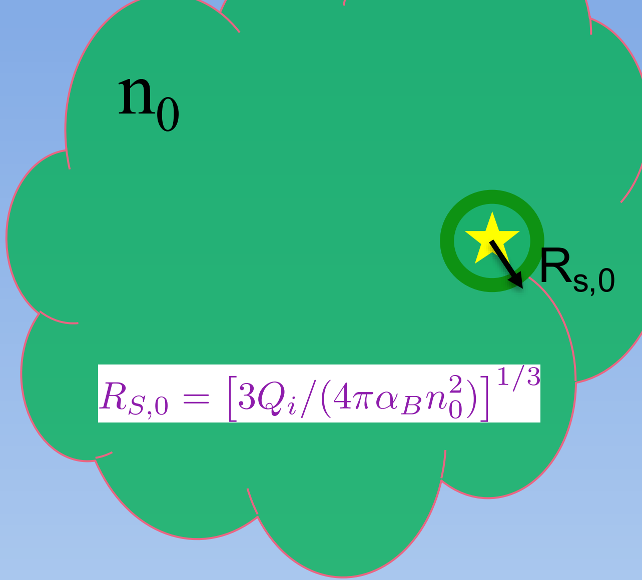
- Spitzer sol'n: $\frac{d(M_{sh}\dot{r}_{IF})}{dt} = F_i \quad \Rightarrow$

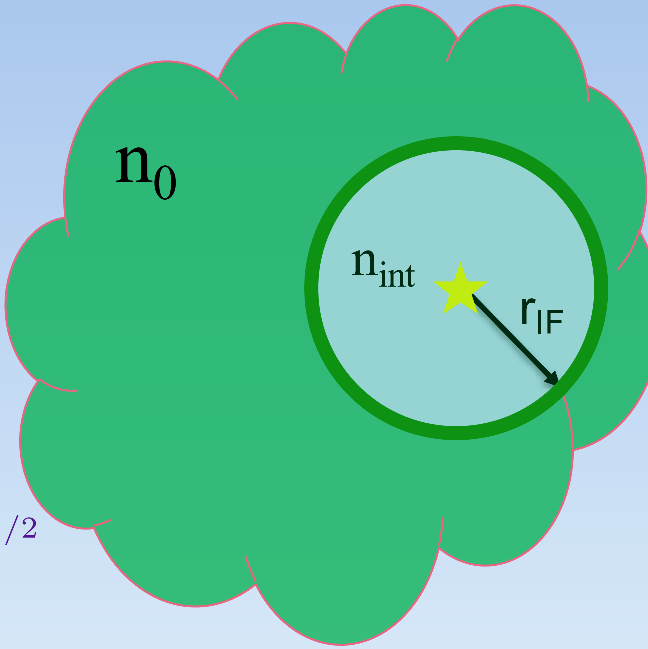
$$r_{IF} \sim R_{S,0}^{3/7}(c_i t)^{4/7} \sim \left(\frac{Q_i}{\alpha_B n_0^2}\right)^{1/7} (c_i t)^{4/7}$$

- Momentum injection rate from photoionized HII region to ISM:

$$\frac{\dot{p}_{\rm ion,th}}{M_*} = 190\frac{km\ s^{-1}}{Myr}\left(\frac{f_{\rm ion}\Xi}{2.5\times10^{13}}\right)^{1/2} \times \left(\frac{M_*}{10^3\,M_\odot}\right)^{-1/2}\left(\frac{r}{10\,pc}\right)^{1/2}$$

- Ideally, over $t_* \sim$ 5Myr could inject momentum/mass ~ 100-1000 km/s





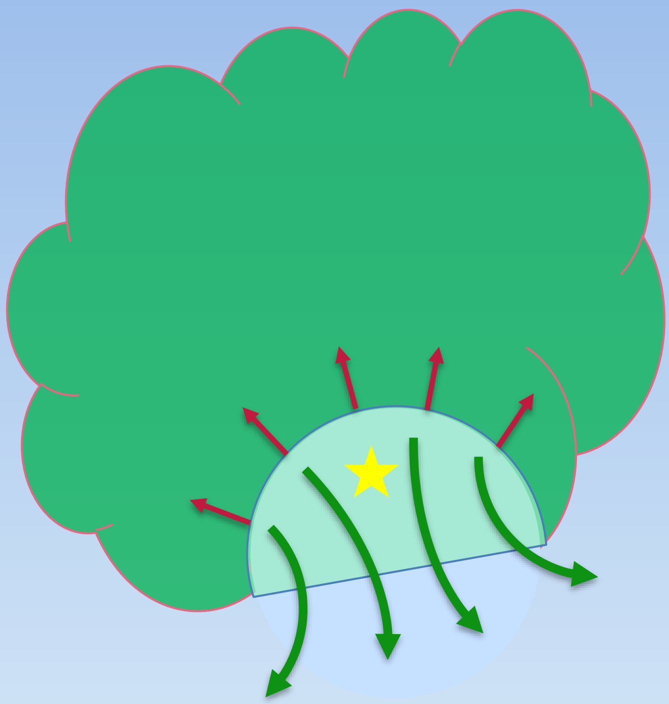
Photoevaporation: blister HII region

Whitworth (1979), Tenorio-Tagle (1979), Bertoldi & McKee (1990), Matzner (2002), Kim et al (2018)

- Radiation incident on ionization front photoevaporates gas
- Gas streams away at ~ $c_I=(kT/m_p)^{1/2}$
- Photoevap. rate~ $n_i\, c_I A \sim n_i\, c_I R^2$
- Ionization-recombination must be maintained in ionized region:

$$n_i \sim \left(\frac{Q}{\alpha_B R^3}\right)^{1/2}$$

⇒ photoevaporation rate $\sim c_I \left(\frac{QR}{\alpha_B}\right)^{1/2}$

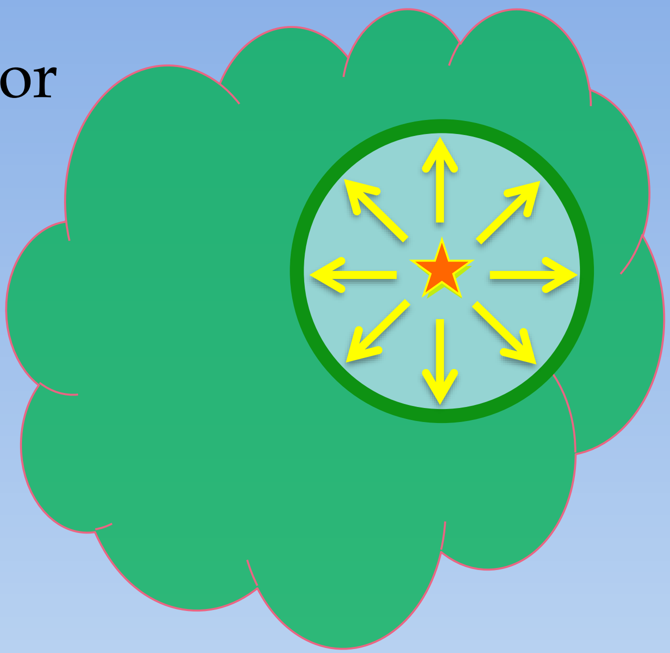


- Back-reaction force on ionized/neutral interface:

$$\sim c_I^2 m_p n_i A \sim c_I^2 m_p \left(\frac{QR}{\alpha_B}\right)^{1/2} = kT \left(\frac{\Xi \varepsilon M_{cloud} R}{\alpha_B}\right)^{1/2}$$

(comparable to gas pressure force on shell surrounding *embedded* HII region)

Direct radiation pressure force



- Photons (UV+Opt) directly absorbed or scattered by gas or dust transfer momentum $p = h\nu/c$
- Luminosity(fully sampled IMF)

  $L = \Psi M_*$ for Ψ=1800 erg s^{-1} g^{-1}
- Total radiation pressure force:

  $L/c = \Psi M_*/c$

$$\frac{\dot{p}_{rad}}{M_*} = \frac{L}{cM_*} = 19\,\mathrm{km\ s^{-1}\ Myr^{-1}}\,\frac{\Psi}{1800\,\mathrm{erg\,s^{-1}\,g^{-1}}}$$

- Exceeds gas pressure force for very luminous source (large M_*) or small HII region (small r_{IF}): $r/\mathrm{pc} \lesssim M_*/10^4\,M_\odot$
- Ideally, over t_*~ 10Myr could inject momentum/mass ~ 200 km/s

Reprocessed radiation force

- Stellar radiation absorbed by dust is reemitted in IR
- IR photons may be multiply absorbed/scattered.
- Radiation force on shell of optical depth $\tau_{shell} = \kappa_{IR} M_{shell}/(4\pi R^2) = \kappa_{IR} \Sigma_{shell}$:
  $F_{rad,IR} = L_* \tau_{shell}/c = \Psi M_* \kappa_{IR} \Sigma_{shell}/c$
- Can compare to gravitational force of star cluster:

$$F_{grav,*} = GM_* M_{shell}/R^2 = GM_* \Sigma_{shell} 4\pi$$

- Eddington ratio:

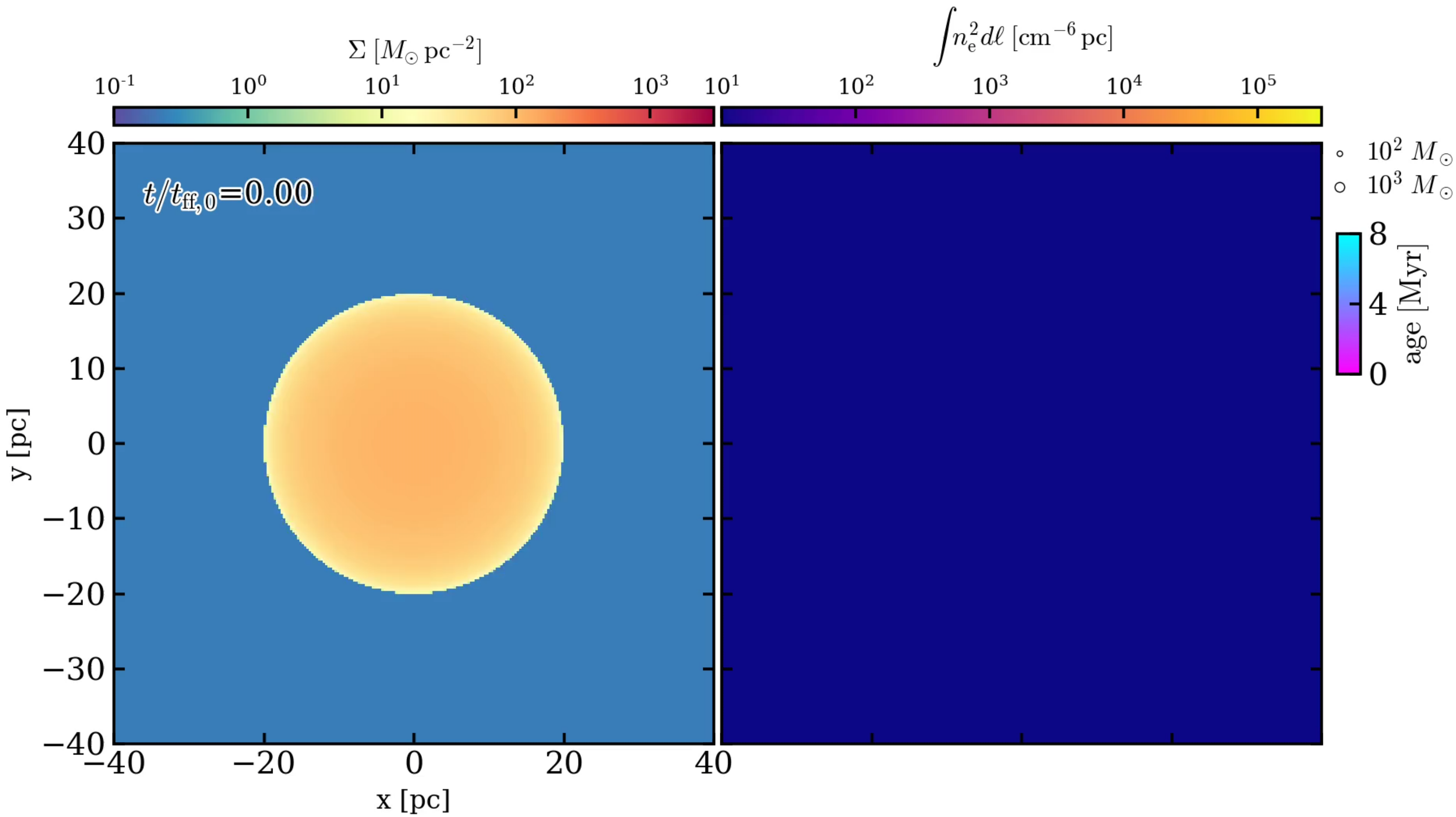
$$f_{Edd,IR} = F_{rad,IR}/F_{grav} = \Psi \kappa_{IR}/(4\pi\, Gc)$$
$$= 0.7\, (\kappa_{IR}/10\ \mathrm{cm^2/g})(\Psi/1800\ \mathrm{erg/s/g})$$

Because $\kappa_{IR} \lesssim 7$ for normal ISM dust, would need dust enhancement or top-heavy IMF (larger Ψ) for reprocessed radiation to have dynamical consequences

Simulations: turbulent cloud evolution with radiation feedback

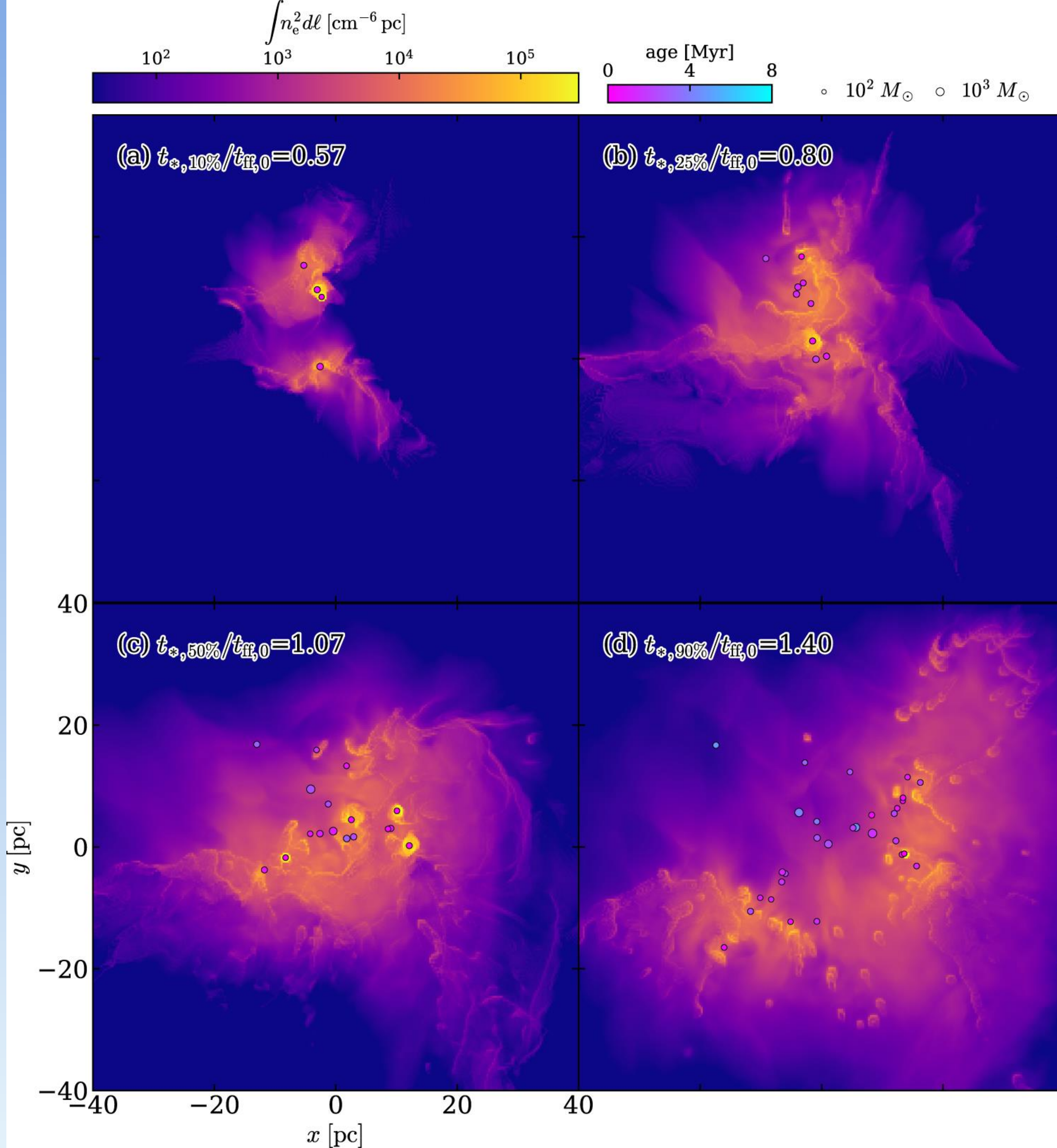
- In realistic clouds, structure is highly inhomogeneous
  - Radiation may escape through "holes"; ionized gas also escapes
  - Large variance in surface and volume density
- We follow gas + radiation interaction using *radiation hydrodynamics* (RHD) numerical simulations with *Athena*
  - Collapsing gas is replaced by "star particles" (representing clusters) with total luminosity $L_* = \Psi M_*$, ionizing photon rate $Q = \Xi M_*$
  - Accurate RT method is crucial because of high opacity to EUV in neutral gas and highly inhomogeneous cloud structure
  - J.G. Kim et al (2017) method uses adaptive ray tracing to compute $F_{\rm rad}$ and $\mathcal{E}_{\rm rad}$ for FUV (non-ionizing) and EUV (ionizing)
    - Start at HEALPix level 4 with 3072 rays from each source
    - Split rays when there are fewer than 4 per grid cell from each source
    - Practical use requires efficient parallelization to optimize load-balancing and reduce communication

Ionizing + non-ionizing radiation simulations with ART



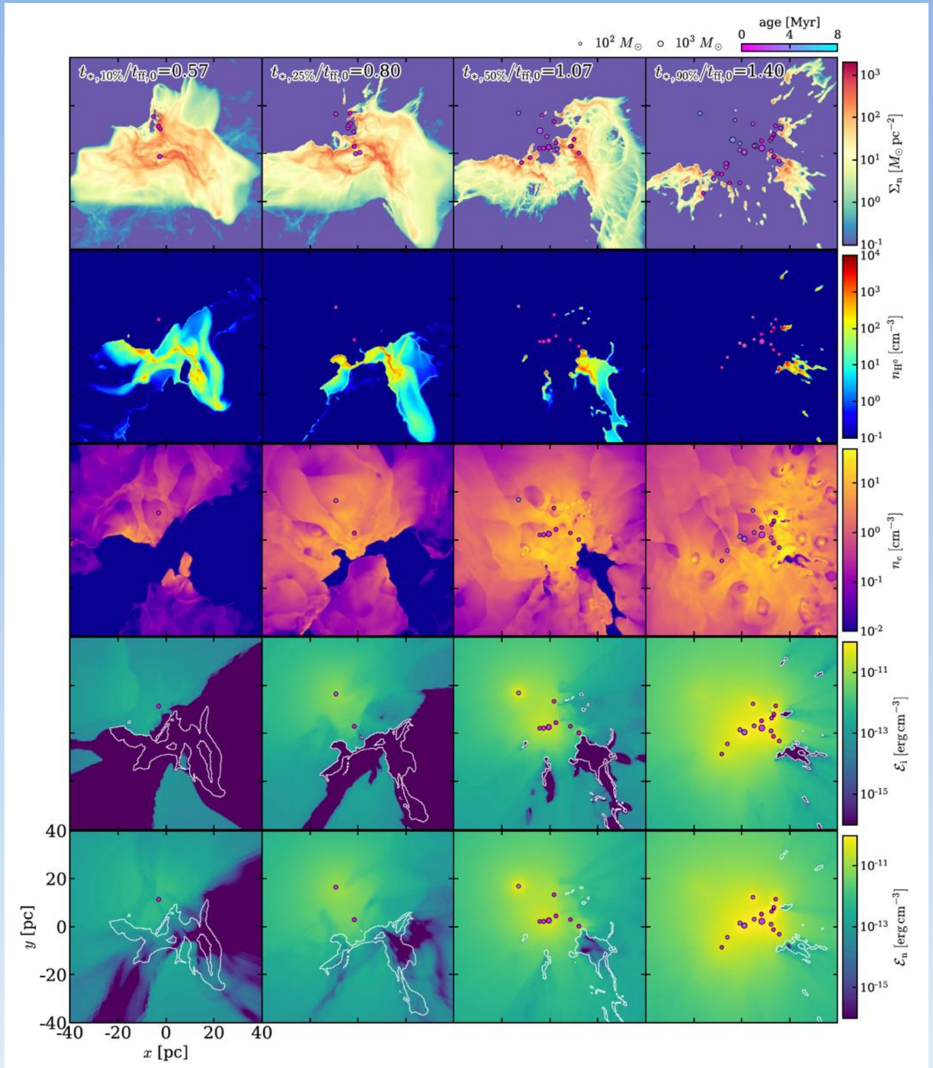
J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

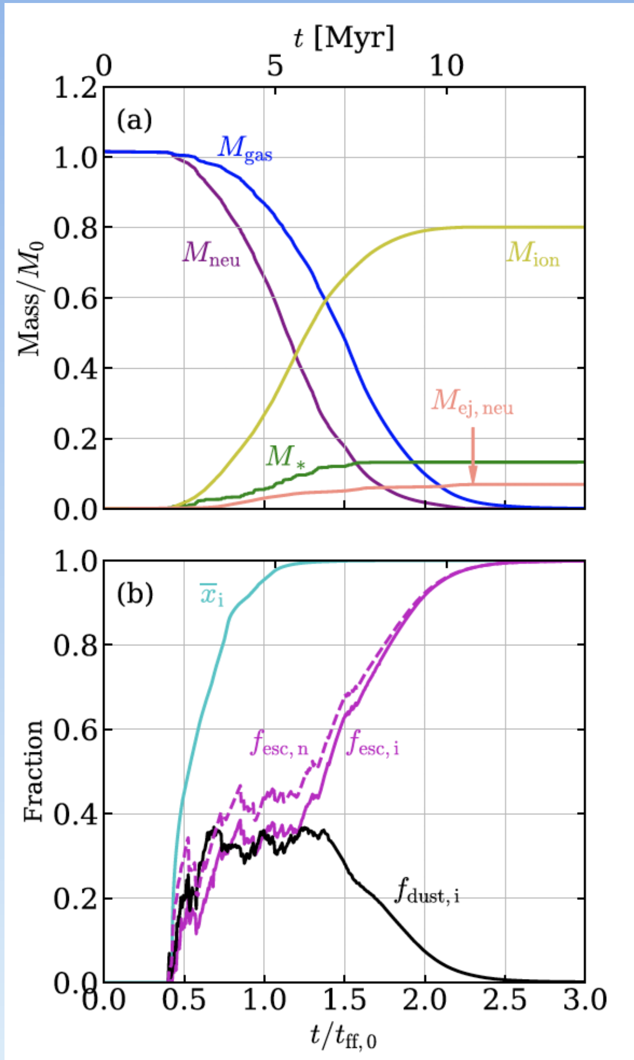
ART=Adaptive Ray Tracing; see J.-G. Kim, W.-T. Kim, E.C. Ostriker (2017) for *Athena* implementation



J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

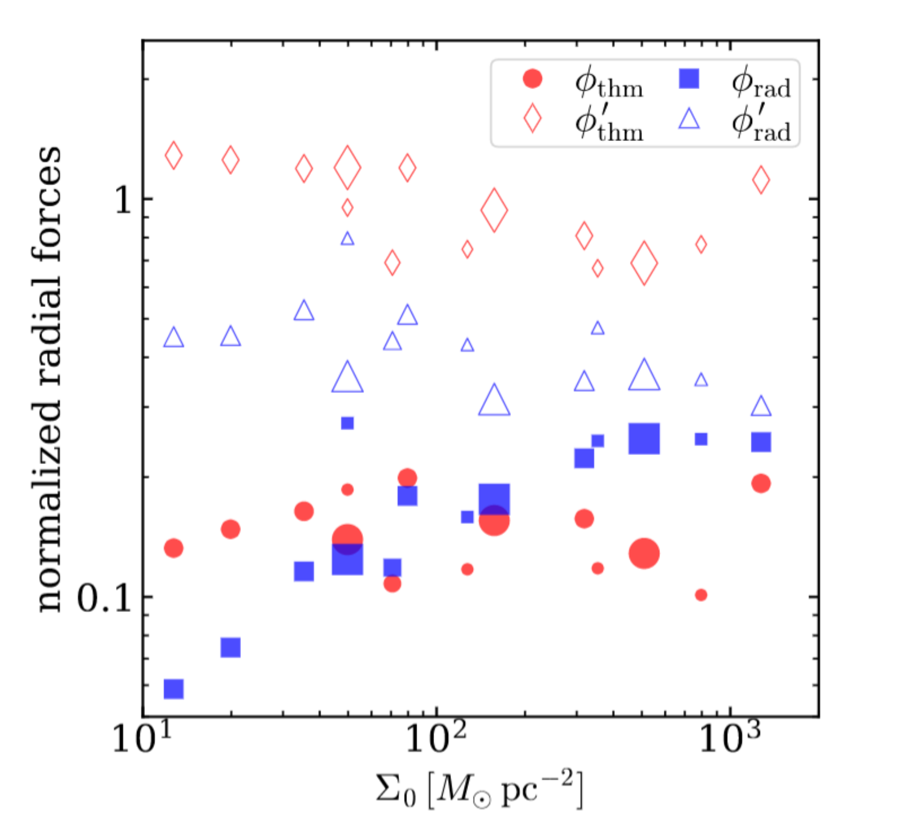
Ionizing + non-ionizing radiation simulations with ART





J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

Net forces in cloud: numerical vs. analytic



$$\phi_{\rm rad} \equiv \frac{\int_{t_{\rm i}}^{t_{\rm f}} \int \boldsymbol{f}_{\rm rad} \cdot \hat{\boldsymbol{r}}\, dVdt}{\int_{t_{\rm i}}^{t_{\rm f}} L/c\, dt},$$

$$\phi'_{\rm rad} \equiv \frac{\int_{t_{\rm i}}^{t_{\rm f}} \int \boldsymbol{f}_{\rm rad} \cdot \hat{\boldsymbol{r}}\, dVdt}{\int_{t_{\rm i}}^{t_{\rm f}} (1 - f_{\rm esc}) L/c\, dt},$$

$$\phi_{\rm thm} \equiv \frac{\int_{t_{\rm i}}^{t_{\rm f}} \int \boldsymbol{f}_{\rm thm} \cdot \hat{\boldsymbol{r}}\, dVdt}{\int_{t_{\rm i}}^{t_{\rm f}} \mu_{\rm H} c_{\rm i}^2 (12\pi Q_{\rm i} R_0/\alpha_{\rm B})^{1/2}\, dt},$$

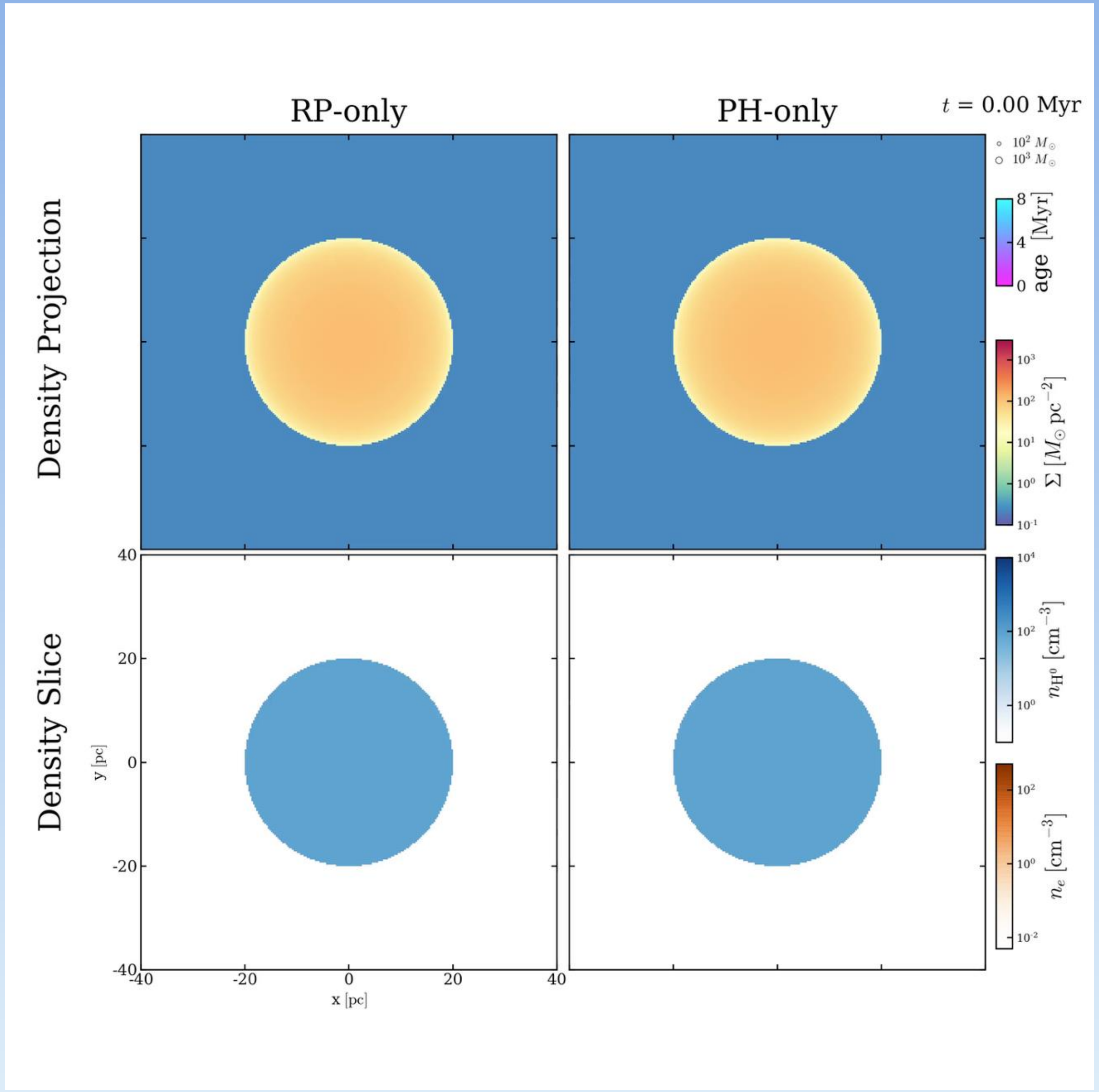
$$\phi'_{\rm thm} \equiv \frac{\int_{t_{\rm i}}^{t_{\rm f}} \int \boldsymbol{f}_{\rm thm} \cdot \hat{\boldsymbol{r}}\, dVdt}{\int_{t_{\rm i}}^{t_{\rm f}} \dot{M}_{\rm ion} c_{\rm i}\, dt},$$

J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

Turbulence-induced structure:

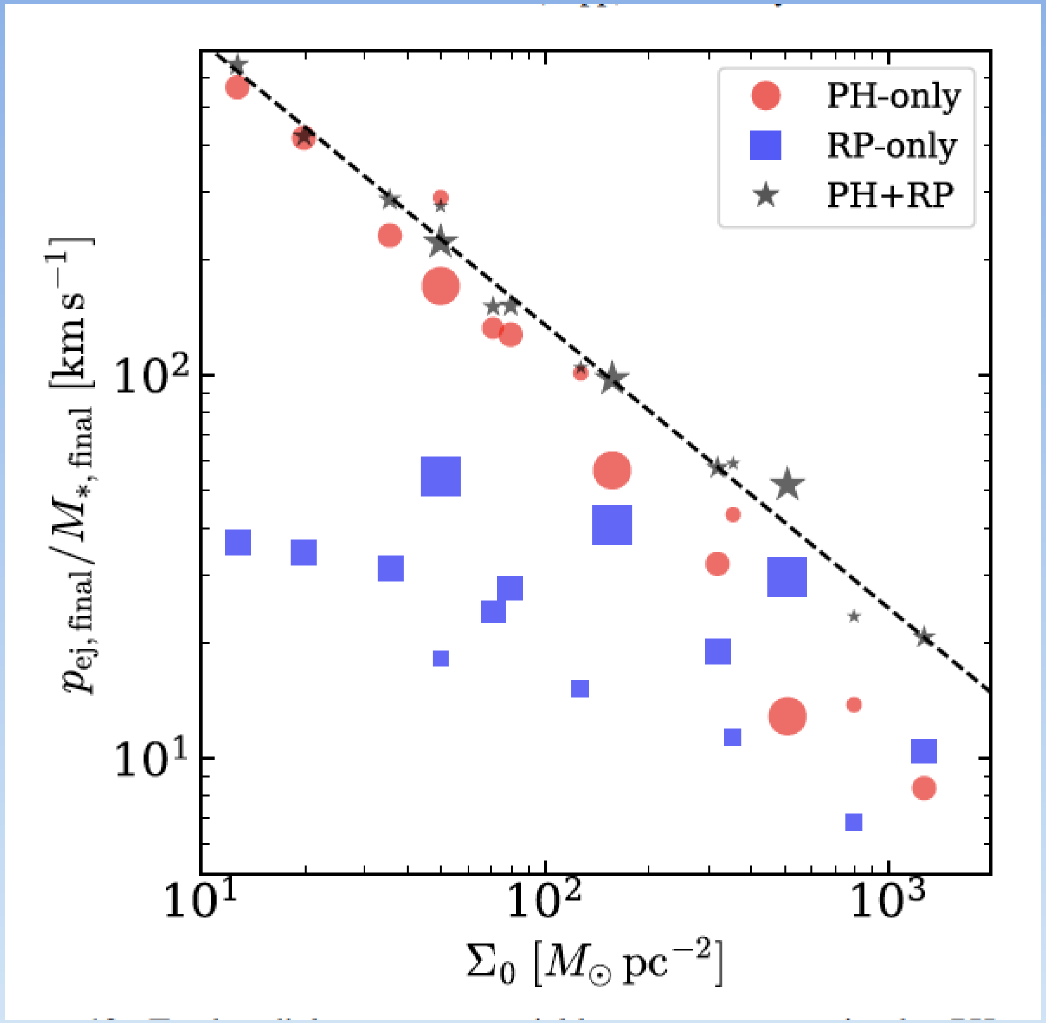
- Reduces radiation pressure force because gas is clumpy (radiation escapes) and sources are distributed (forces cancel)
- Reduces pressure force from ionized gas because neutrals compressed, photoevaporation area reduced ***Factor 5-10 reduction in force!***

non-ionizing-only vs. ionizing-only



J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

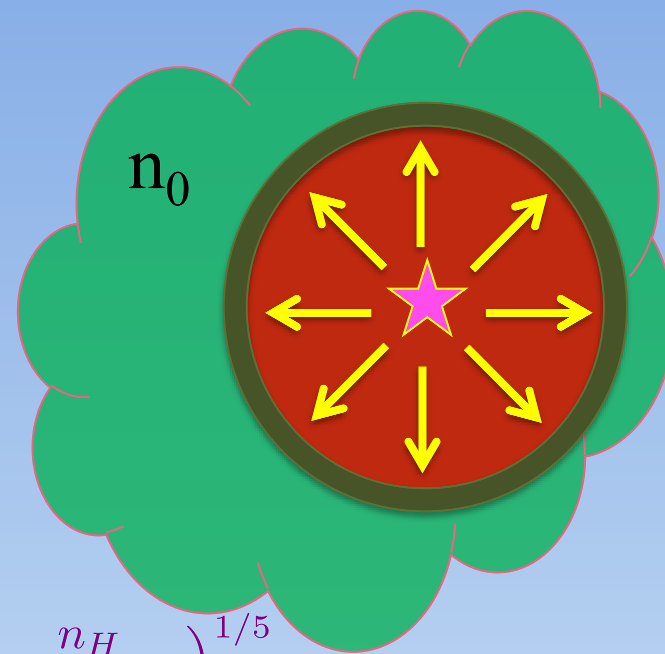
Momentum yield from radiation feedback



J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

- Photoionization more important than radiation pressure up to $\boldsymbol{\Sigma}_{\rm cloud} \sim 10^3 M_\odot/{\rm pc}^2$
- Factor 5-10 lower injection than idealized estimates
- p/M_* ~100 km/s for Orion-like system from radiation effects ("early feedback")

Stellar wind bubble



- O stars have very fast winds which shock to create a high T (~ 10^6 K) bubble
- Energy injection rate (fully sampled IMF):

$\dot{E}_{W,\,in}/M_* = (1/2)\dot{M}V_w^2/M_* = 5$ erg/s/g

- Classical solution by Weaver et al (1977) has $R \sim (\dot{E}\, t^3/\rho)^{1/5}$, which would imply

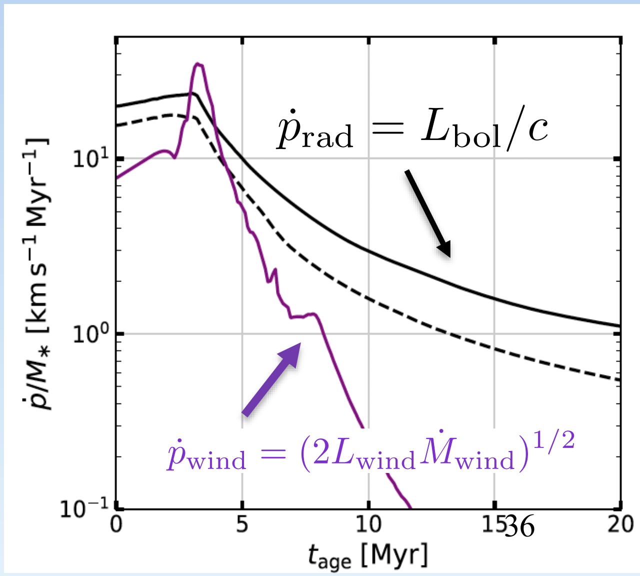
$$\frac{\dot{p}_{wind}}{M_*} = 880\,\mathrm{km\ s^{-1}\ Myr^{-1}} \left(\frac{t}{\mathrm{Myr}}\right)^{2/5} \left(\frac{M_*}{10^3\,M_\odot}\right)^{-1/5} \left(\frac{n_H}{10^2\mathrm{cm^{-3}}}\right)^{1/5}$$

- Realistically, **90-99% of energy is lost to cooling** in turbulent interface so that $R \sim (\dot{M}\, V_w\, t^2/\rho)^{1/4}$

Lancaster, Ostriker, Kim, & Kim (2021a)

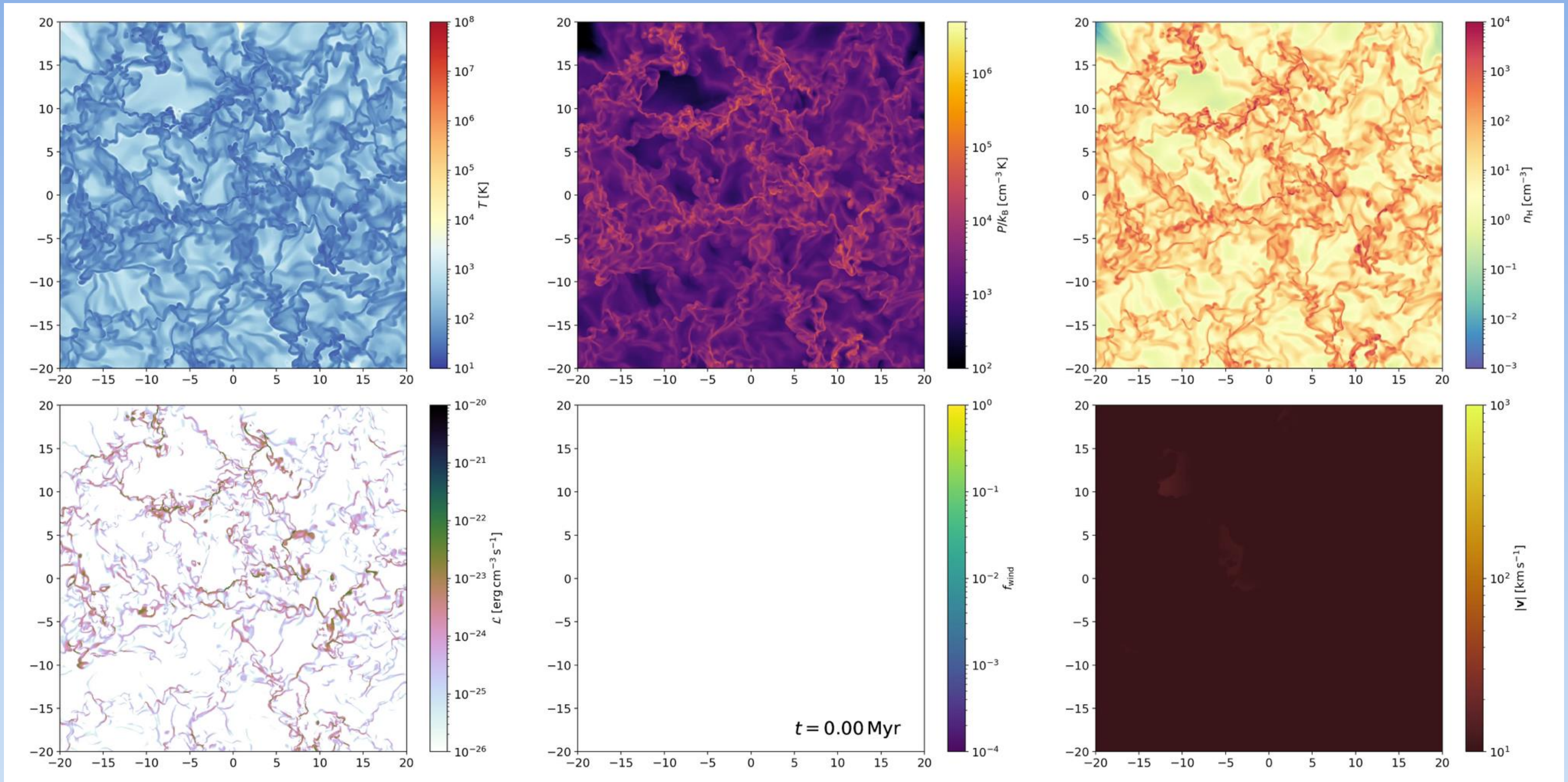
- In this case, momentum injection rate from wind is much lower, $\dot{p}_{wind}/M_* \sim (1-4)\dot{p}_{in}/M_*$
- With $\dot{p}_{in}/M_* = \dot{M}V_w/M_* = 9$ km/s/Myr

wind force ~ radiation pressure force



Stellar wind bubble in turbulent cloud

Lancaster, Ostriker, Kim, & Kim (2021b)



- *Hot gas mixes with ambient gas at turbulent interface, leading to radiative cooling*

$M_{cloud}=10^5 M_\odot$, $M_* = 10^3 M_\odot$

Supernovae

- Stars of mass > 8 $M_\odot$ have SNe at the end of their lives.
- Explosion drives blast wave into surroundings
- Shock compresses & accelerates ambient gas in shell
- Momentum of shell

  $p(t) \sim [0.6\, E_{SN}\, M_{shell}(t)]^{1/2} = M_{shell}(t)\, v_{sh}(t)$
- Shell cools when $v_{sh} \sim 200$ km/s
- Subsequent 50% increase in momentum during pressure-driven snowplow
- Momentum injection to ISM insensitive to background n_0
- ***Final momentum 10 ×greater than in initial ejecta***

Shell formation:

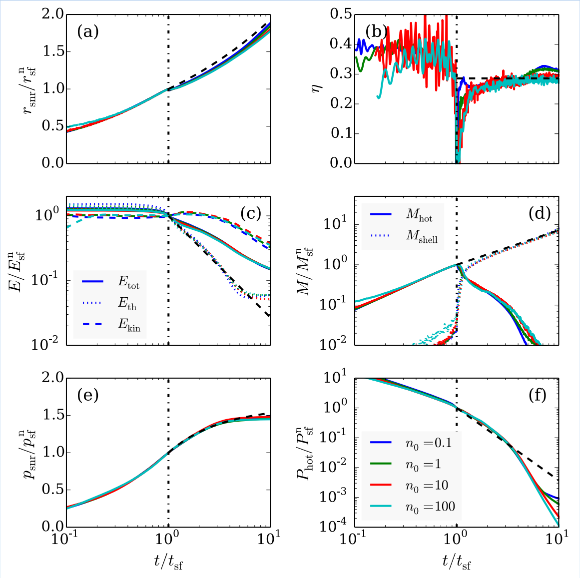
$$t_{sf} = 40\,\mathrm{kyr}\, n_0^{-0.6}$$

$$r_{sf} = 22\,\mathrm{pc}\, n_0^{-0.4}$$

$$v_{sf} = 210\mathrm{km/s}\, n_0^{0.1}$$

$$M_{sf} = 1550\mathrm{M}_\odot\, n_0^{-0.3}$$

$$p_{sf} = 2 \times 10^5\, \mathrm{M}_\odot\, \mathrm{km/s}\, n_0^{-0.15}$$



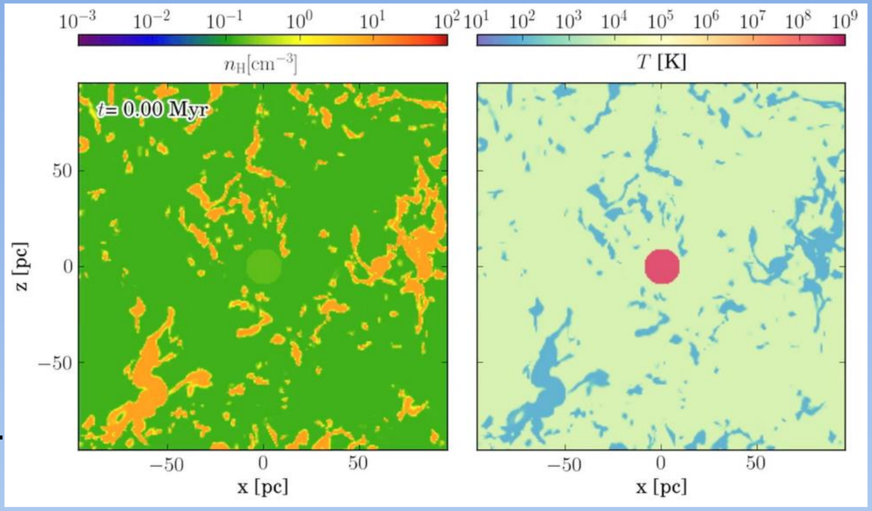
SNR evolution for varying ISM density (C.-G. Kim & Ostriker 2015)

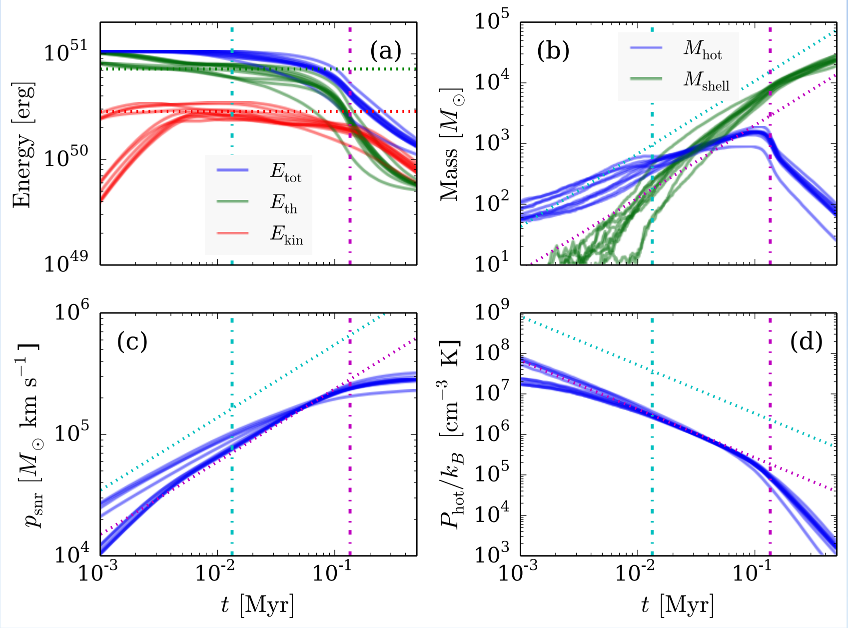
Supernovae

- Cloudy ISM
  - Shell formation time set by volume-filling low density medium
  - Comparable $M_{hot,max}$ to single-phase
  - Both warm, cold gas is accelerated
  - Comparable momentum injection to single-phase case using average ambient density:

Iffrig & Hennebelle (2015), C.-G. Kim & Ostriker (2015), Martizzi et al (2015), Walch & Naab (2015)

$$p_{final} = 2.8\times10^5\ M_\odot km/s\ \langle n_0\rangle^{-0.17}$$

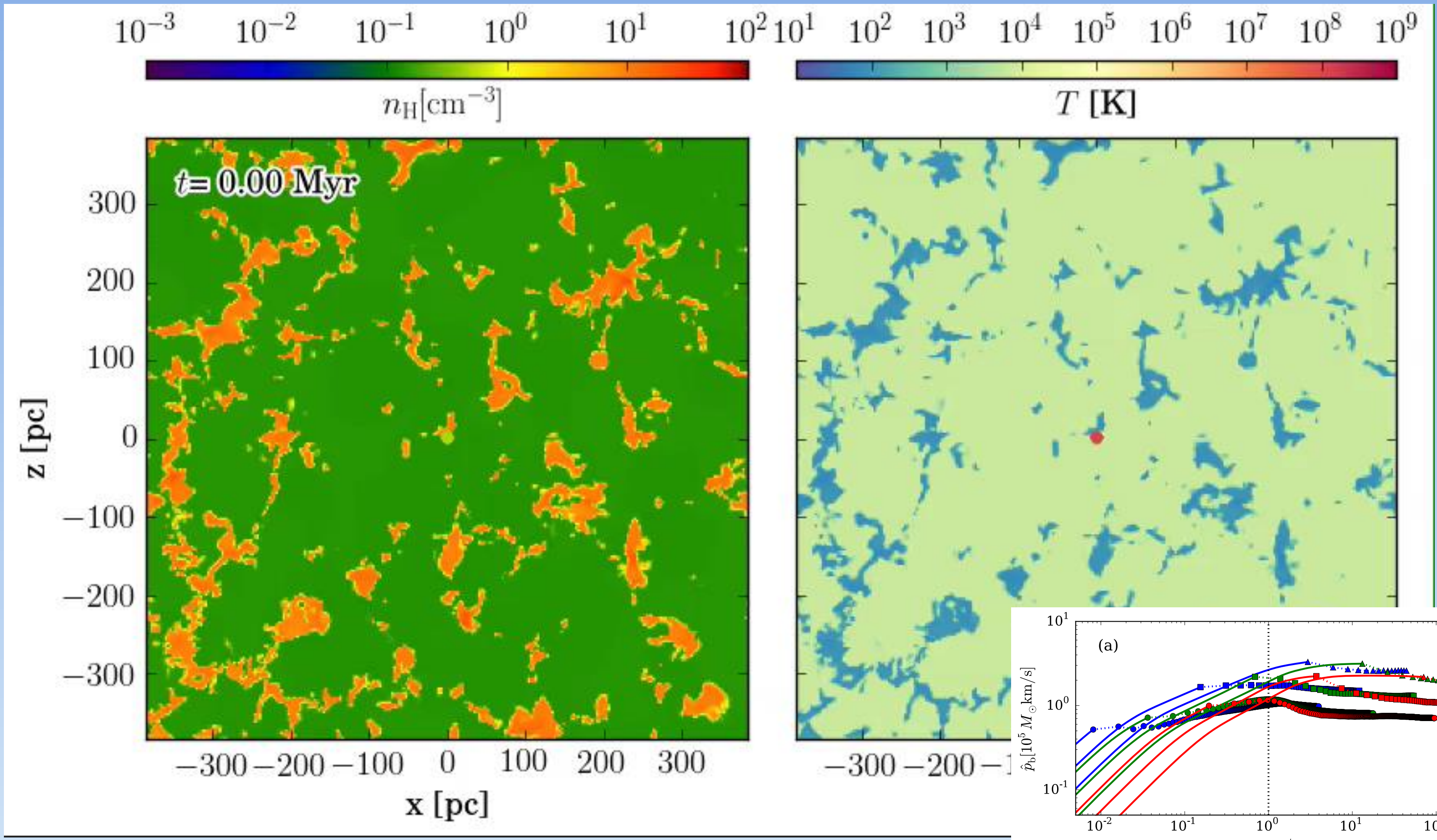


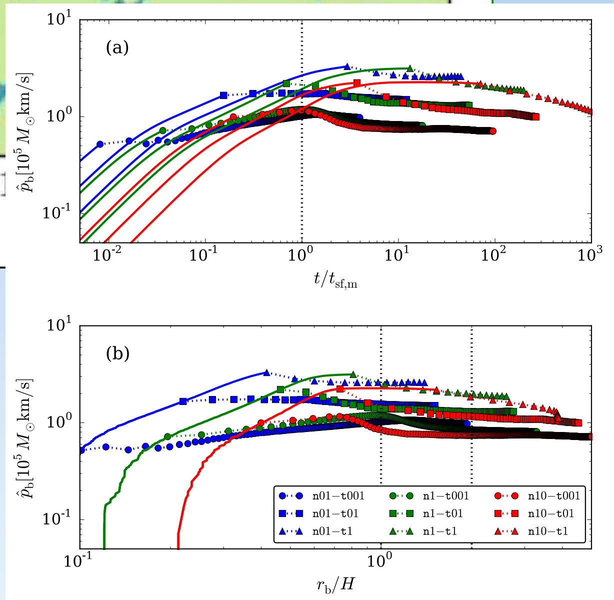


Cloudy-ISM simulations (C.-G. Kim & Ostriker 2015)

Cloudy ISM & multiple SNe

C.-G. Kim, Ostriker, & Raileanu (2017)

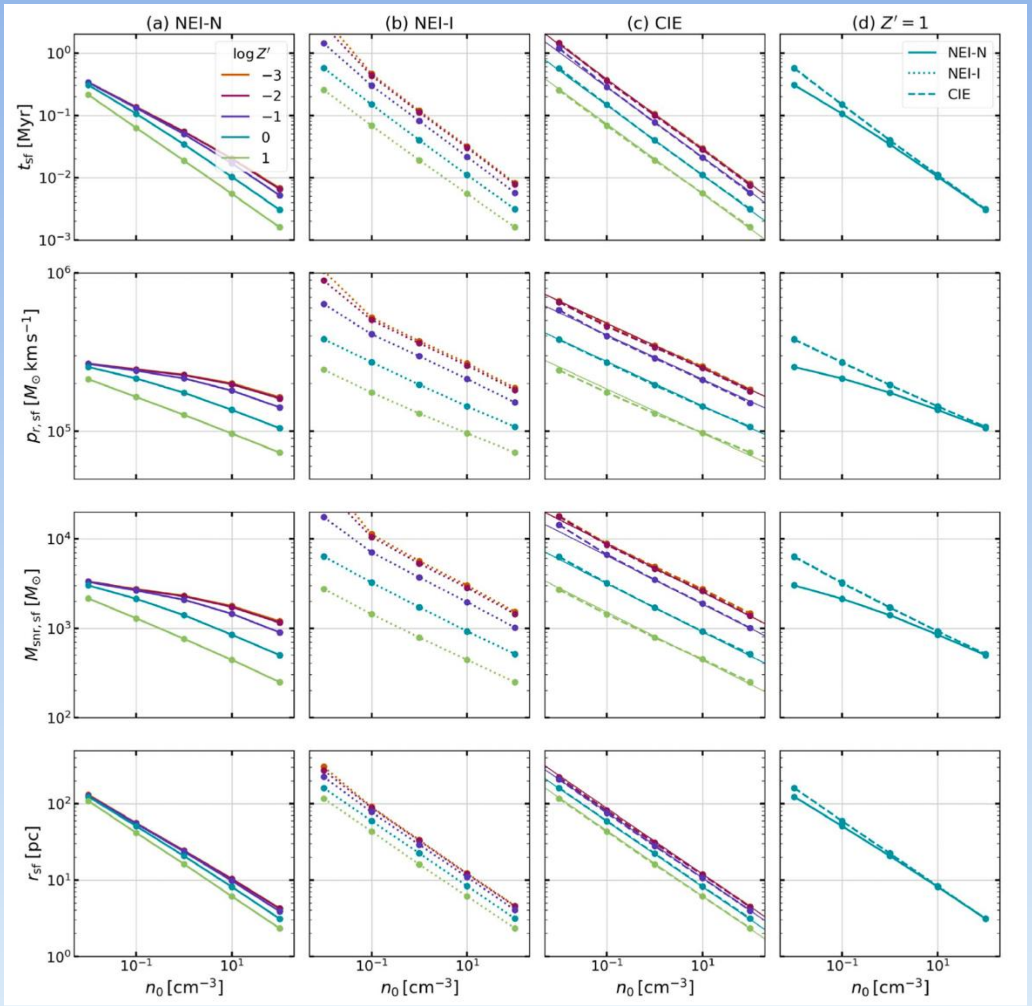




- Stars are clustered ⇒ SNe are correlated
- Superbubble and individual SN have ~ same p_*/event
- Momentum injection insensitive to ISM structure
- Averaged over IMF, p_*/m_* from SNe is 10x higher than from early feedback

SNe in ISM with varying *n*, *Z*

J.-G. Kim, M. Gong, C.-G. Kim, & E. C. Ostriker (2023)



With collisional & ionization equilibrium:

$$t_{\rm sf} = 40\ {\rm kyr} \times (n_0/\ {\rm cm^{-3}})^{-0.56}(Z'^2 + Z_0'^2)^{-0.15},$$

$$p_{\rm r,sf} = 2 \times 10^5\ M_\odot\ {\rm km\ s^{-1}} \times (n_0/{\rm cm^{-3}})^{-0.14}(Z'^2 + Z_0'^2)^{-0.087},$$

$$M_{\rm snr,sf} = 1.7 \times 10^3\ M_\odot \times (n_0/{\rm cm^{-3}})^{-0.27}(Z'^2 + Z_0'^2)^{-0.16},$$

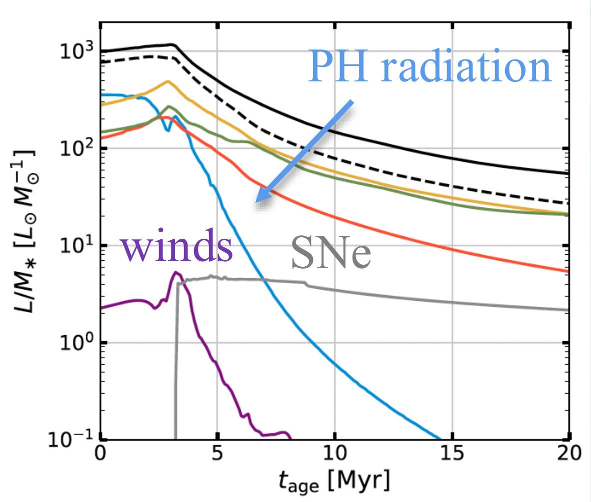
$$r_{\rm sf} = 22\ {\rm pc} \times (n_0/{\rm cm^{-3}})^{-0.43}(Z'^2 + Z_0'^2)^{-0.061},$$

Momentum injection is ***insensitive*** *to density & metallicity*

Momentum injection: conclusions

- Over 5-10 Myr lifetime of star-forming cloud, largest effect is from photoionization
  - *leads to the destruction/dispersal of GMCs*
- Over ~40Myr lifetime of *all* massive stars, largest effect is from SNe
  - *most SN momentum goes into the diffuse ISM*
- Momentum/cluster mass from radiative SNe:

  $p_* / m_* \sim 2000$ km/s



J.-G. Kim et al (2023)

III. SFE in GMCs with feedback

Radiation pressure and SFE: scalings

- Radiation pressure force:

  $L/c = \Psi M_*/c = \varepsilon M_{\rm cloud} \Psi / c$

- Gravitational force on ejected gas:

  $G M_{\rm ej} M_{\rm cloud}/R^2 = (1-\varepsilon) G (M_{\rm cloud}/R^2)$

- *Radiation force exceeds gravity provided*

$$\frac{\varepsilon}{1-\varepsilon} > \frac{cG}{\Psi}\frac{M_{\rm cloud}}{R^2} \sim \frac{cG}{\Psi}\Sigma_{\rm cloud}$$

Suggests higher SFE ε when Σ_{cloud} is higher

Ionized gas pressure and SFE: scalings

- Ionized gas force for spherical HII region:

$$4\pi R^2 nkT = kT\left(\frac{12\pi Q R}{\alpha_B}\right)^{1/2} = kT\left(\frac{12\pi \Xi \varepsilon M_{cloud} R}{\alpha_B}\right)^{1/2}$$

- Gravitational force on ejected gas:

$$GM_{ej}M_{cloud}/R^2 = (1-\boldsymbol{\varepsilon})G(M_{cloud}/R)^2$$

- *Gas pressure force exceeds gravity provided*

$$\frac{\varepsilon}{(1-\varepsilon)^2} \sim \frac{G^2\alpha_B}{m_p^2 c_I^2 \Xi}\Sigma_{\rm cloud}^{5/2} M_{\rm cloud}^{1/2}$$

Suggests higher SFE when Σ_{cloud}, M_{cloud} higher

Photoevaporation and SFE: scalings

- Photoevaporation rate:

$$\dot{N} = c_I A n \sim c_I \left(\frac{QR}{\alpha_B}\right)^{1/2} \sim c_I \left(\frac{\Xi}{\alpha_B}\right)^{1/2} \left(\frac{\varepsilon M_{\rm cloud} R_{\rm cloud}}{\alpha_B}\right)^{1/2}$$

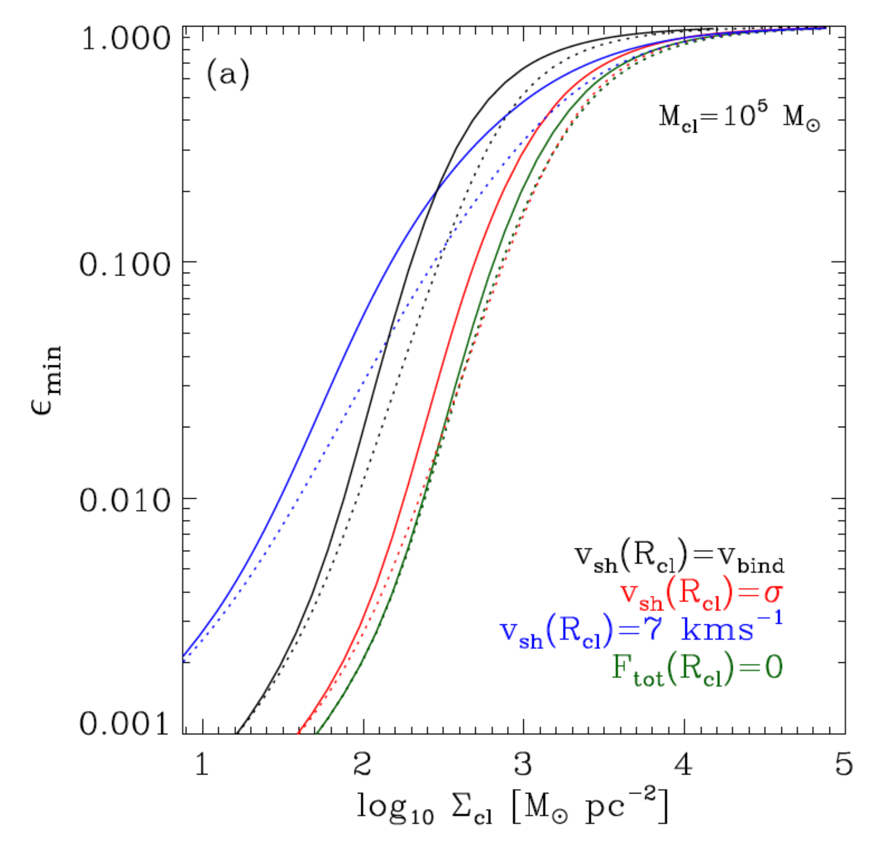
- Can lose $\sim(1-\varepsilon)M_{\rm cloud}$ within $\sim t_{\rm ff} \sim (R^3_{\rm cloud}/GM_{\rm cloud})^{1/2}$ provided:

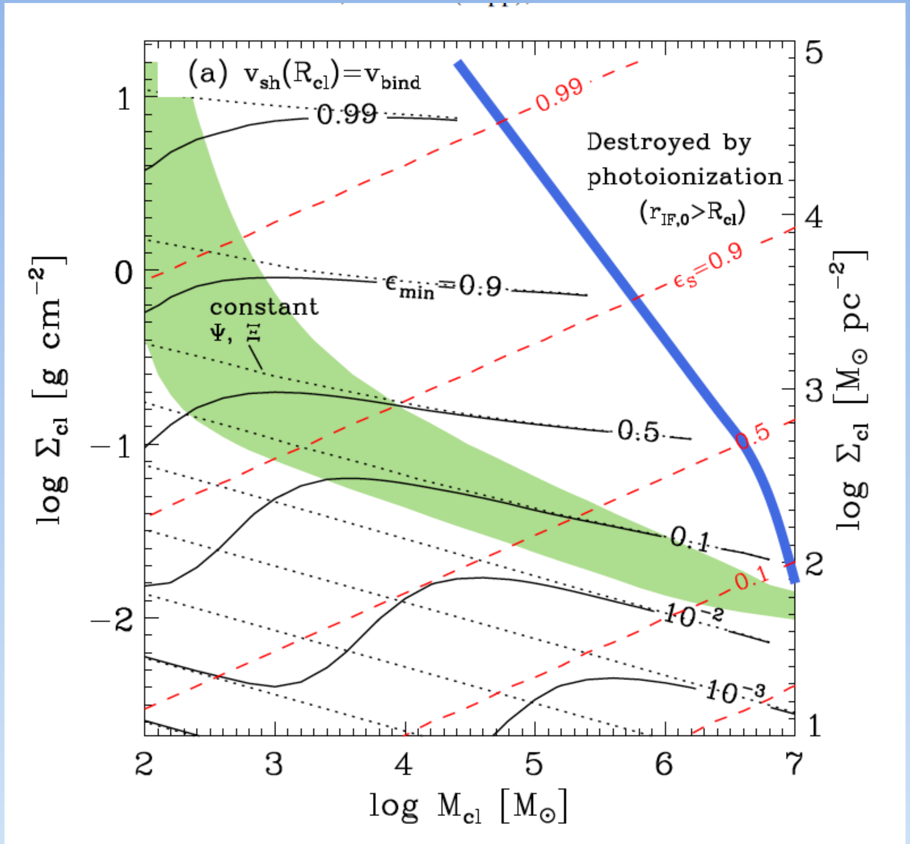
$$\frac{\varepsilon}{(1-\varepsilon)^2} \sim \frac{G\alpha_B}{m_p^2 c_I^2 \Xi}\Sigma^2_{\rm cloud} \sim \left(\frac{\Sigma_{\rm cloud}}{500 M_\odot {\rm pc}^{-2}}\right)^2$$

- Alternatively, using sol'n for expanding blister HII region to reach $R_{\rm cloud}$ (Matzner 2002): $\boldsymbol{\varepsilon} \propto \boldsymbol{\Sigma}^{3/2} M^{-1/2}$

Suggests higher SFE when Σ_{cloud} is higher

Spherical cloud: SFE from dynamical disruption



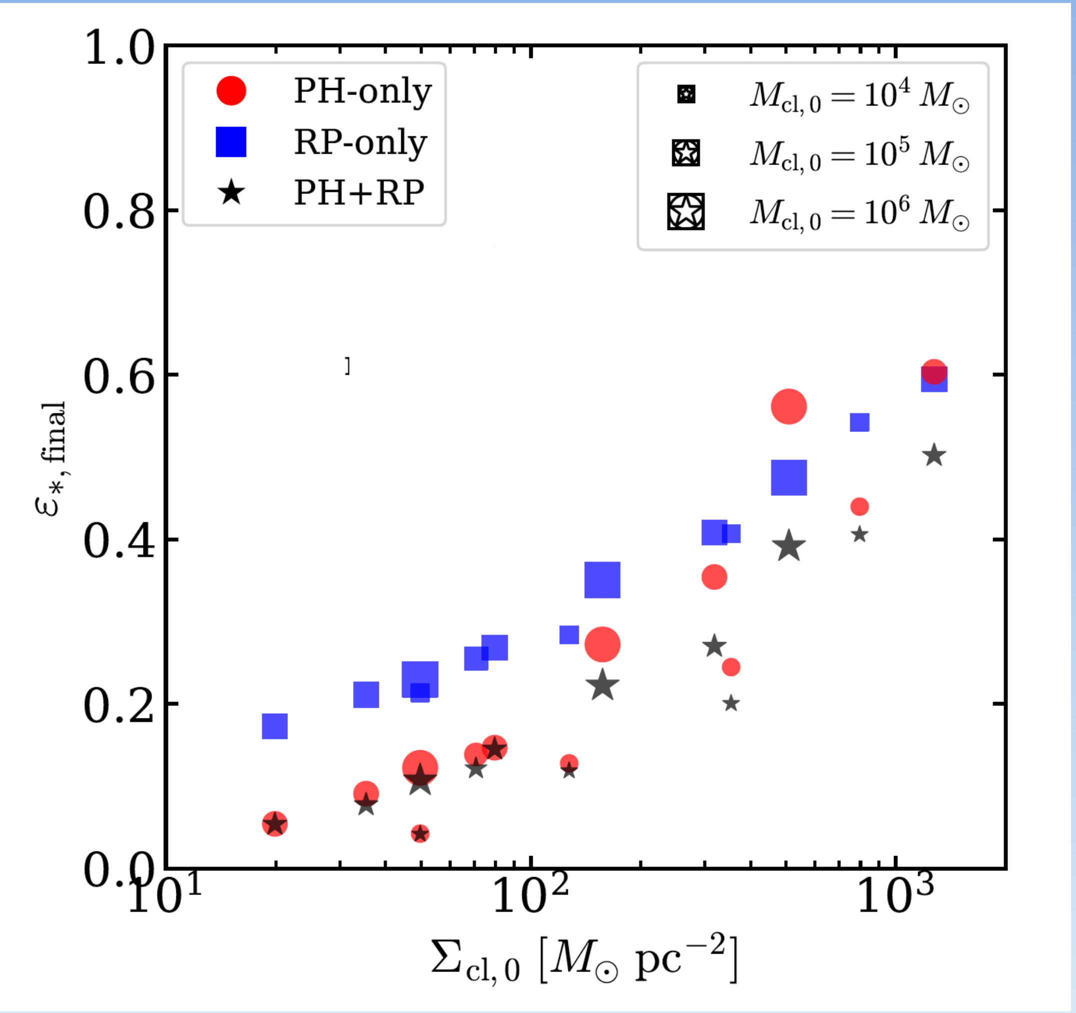


J.-G. Kim, W.-T. Kim, & Ostriker (2016)

*Predicted SFE for **spherical** model **ε** ~ 0.01 -0.1 for typical MW GMC properties*

See also: Fall et al (2010), Murray et al (2010), Rahner et al (2019)

SFE with ionizing and/or non-ionizing radiation



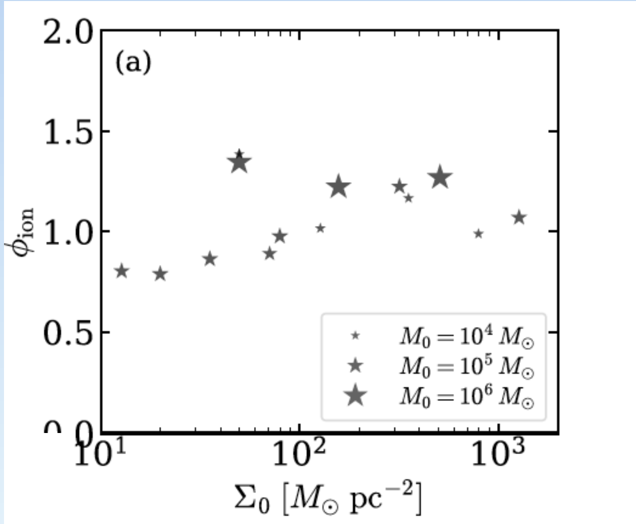
J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

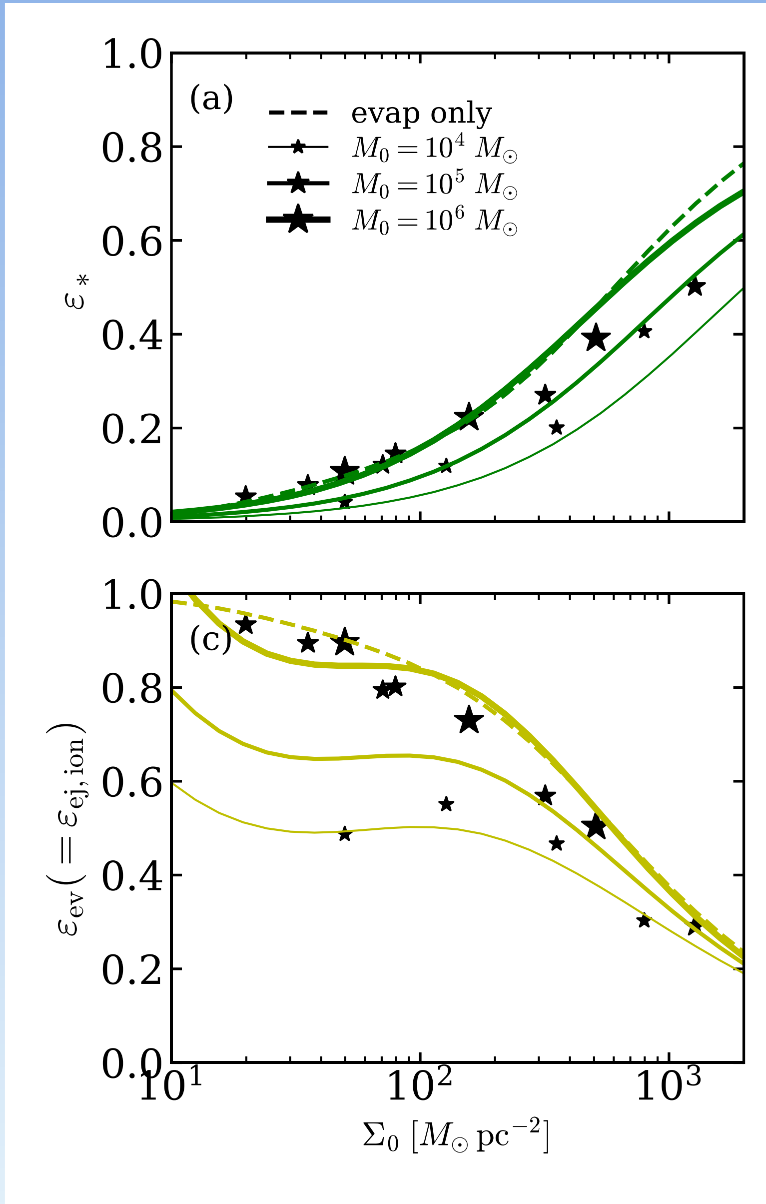
Ionizing radiation is more important than non-ionizing in clouds at moderate $\boldsymbol{\Sigma}_{\rm cloud}$

Photoevaporation model for SFE

$$Q_{i,eff} = (1 - f_{esc} - f_{dust})Q_i$$
$$= \int I dV$$
$$\approx \int \mathcal{R} dV \equiv \alpha_B n_i^2 A_i H_i$$

$$\dot{N}_e \equiv n_i c_i A_i$$
$$\approx \frac{c_i}{\alpha_B^{1/2}} \left(\frac{Q_{i,eff} A_i}{H_i} \right)^{1/2}$$
$$\rightarrow \phi_{ion} \frac{c_i}{\alpha_B^{1/2}} (Q_{i,max} R_0)^{1/2}$$

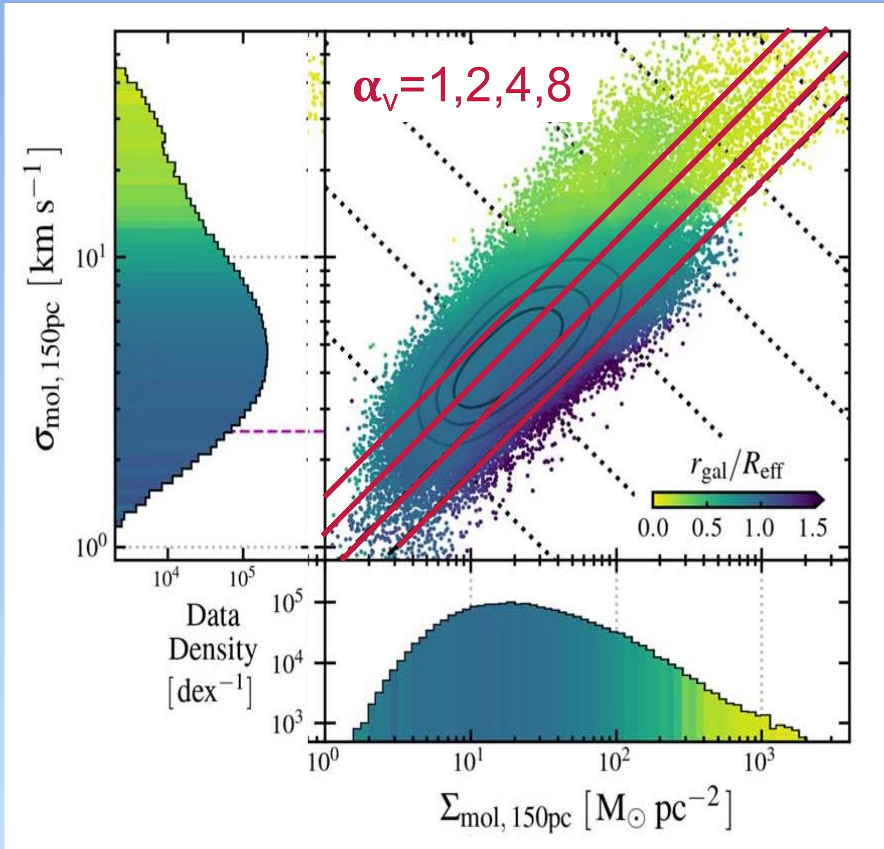




J.-G. Kim, W.-T. Kim, & E.C. Ostriker (2018)

Virial parameter in GMCs

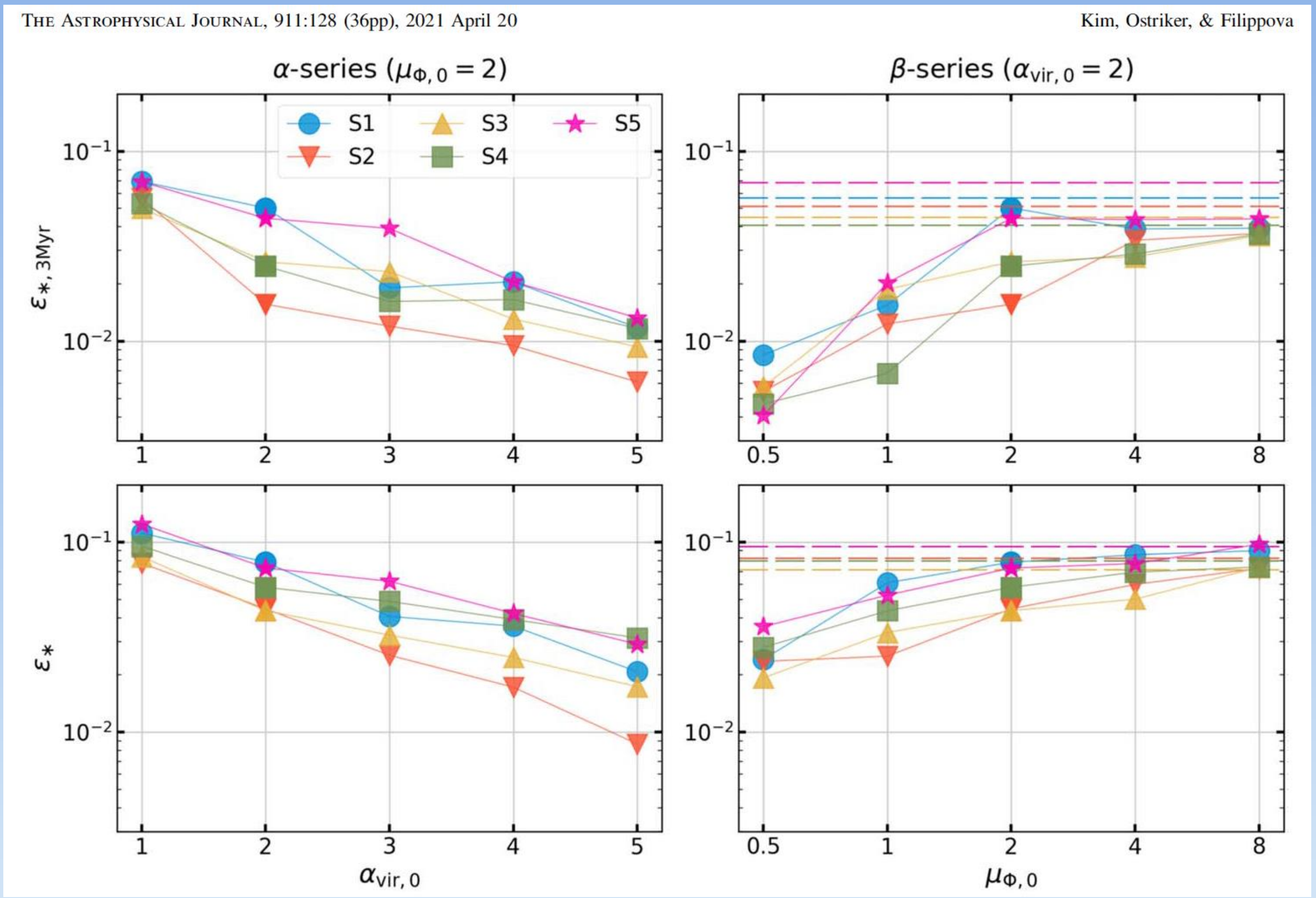
- Traditional virial parameter defined as $\alpha_v = 2E_k/E_g$
- For isolated spherical cloud with uniform density:
  $\alpha_v = 5\,\sigma_{los}^2\,R/(GM)$
- At fixed R (fixed beam),
  $\sigma_{los}^2 = \alpha_v\,G\,\boldsymbol{\Sigma}\pi R/5 \propto \alpha_v \boldsymbol{\Sigma}$
- *Observations suggest that most of molecular gas in galaxies is only lightly bound at ~100pc scale,* $\alpha_v \sim 4$



Sun et al (2020) (PHANGS)

- Note: traditional estimate also neglects tidal effects, internal substructure, stratification for E_g

Turbulence and magnetization effects



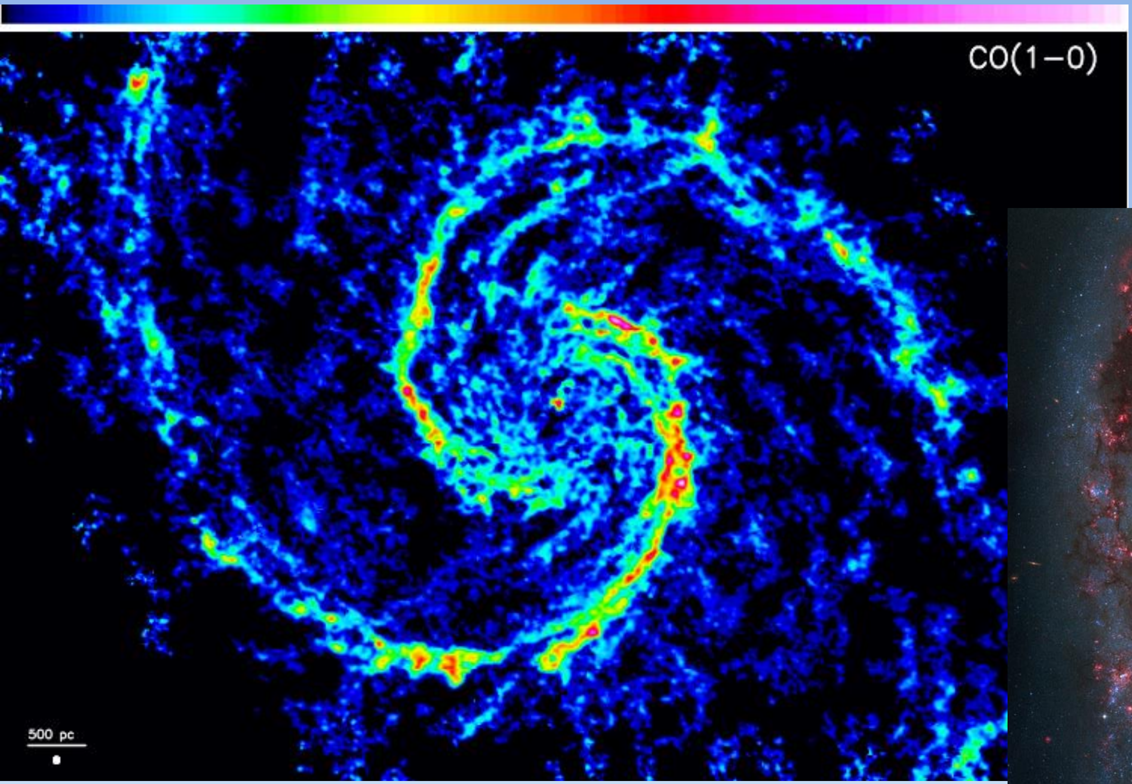
J.-G. Kim, Ostriker, Filippova (2021)

SFE in RMHD simulations for varying

- initial $\boldsymbol{\alpha}_{v}$
- μ=mass-to-magnetic flux ratio

IV. SFR regulation in the large-scale ISM with feedback

star formation regulation

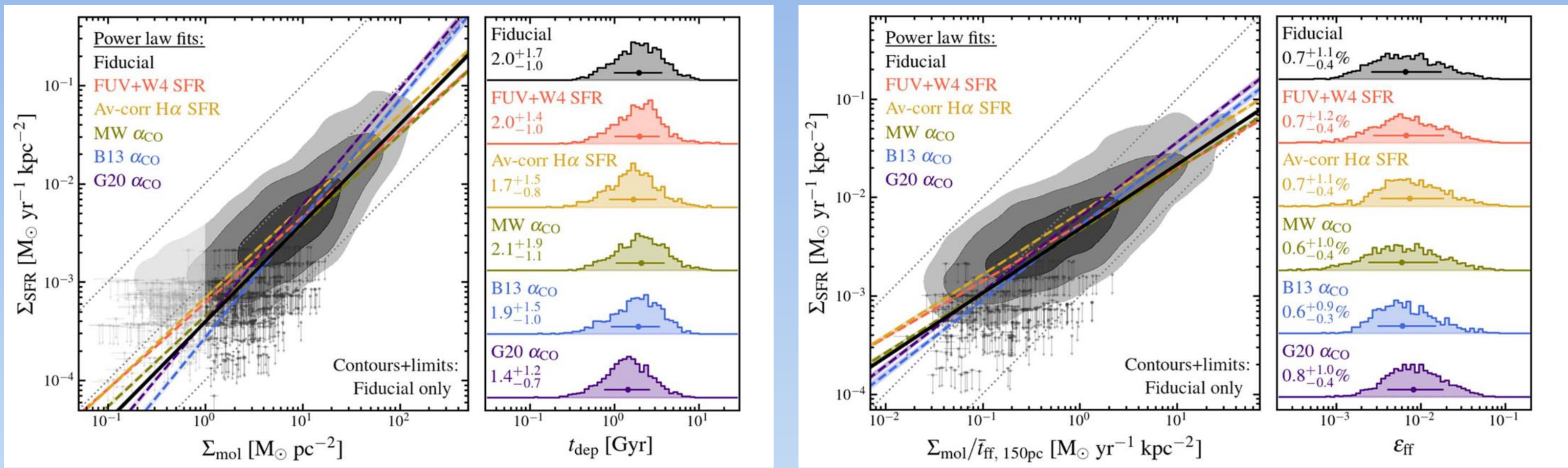


M51: PAWS (Schinnerer et al 2013)

M51: Hubble Heritage

How does feedback regulate SFRs of galaxies?

Large-scale "gas consumption" in galaxies

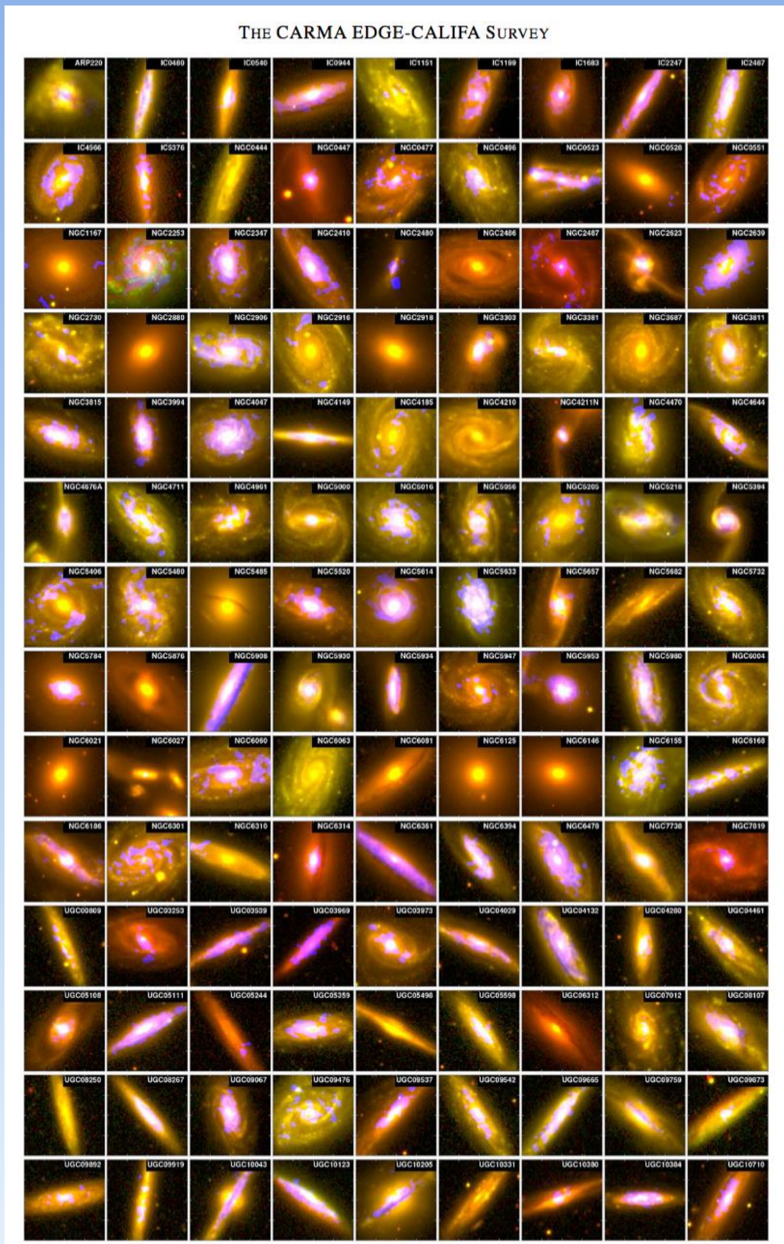


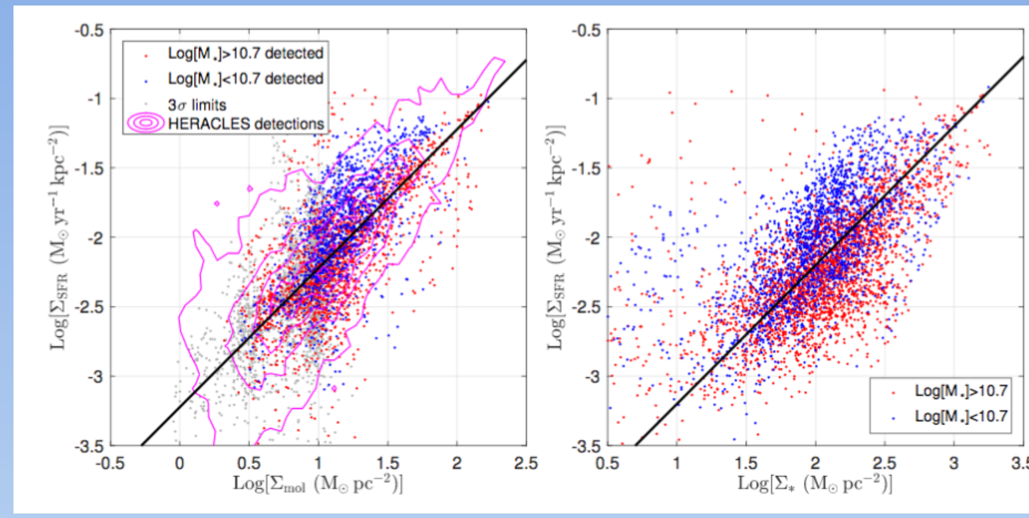
Sun et al (2023): PHANGS survey of 80 nearby galaxies

Conclusion: large-scale galactic $t_{dep} = \mathbf{\Sigma}_{gas} / \mathbf{\Sigma}_{SFR} \sim$ Gyr

This is much longer than t_{ff} in ambient gas (50Myr) or clouds (5Myr)

SFR/stellar correlation





EDGE survey: Bolatto et al (2017)

- Σ_{SFR} increases with Σ_{mol}
- Σ_{SFR} increases with Σ_*

⇒ gas "fuel" *and* galactic environment *equally important*

> Σ_* *important because it sets vertical gravity* g_z *in disk*

Self-regulation concept

Cooling and turbulent dissipation times in the ISM are short

- leads to massive cloud formation on large scales
- leads to localized collapse within massive clouds

When some gas collapses to make new stars

- massive stars inject energy, momentum to their surroundings
- short stellar lifetimes ⇒ feedback injection is rapid compared to system evolution

Energy injection by massive stars

- transforms thermal phase state of ISM gas (offsetting cooling)
- accelerates motions on a range of scales (offsetting dissipation)
- limits local collapse and may remove "fuel" from system

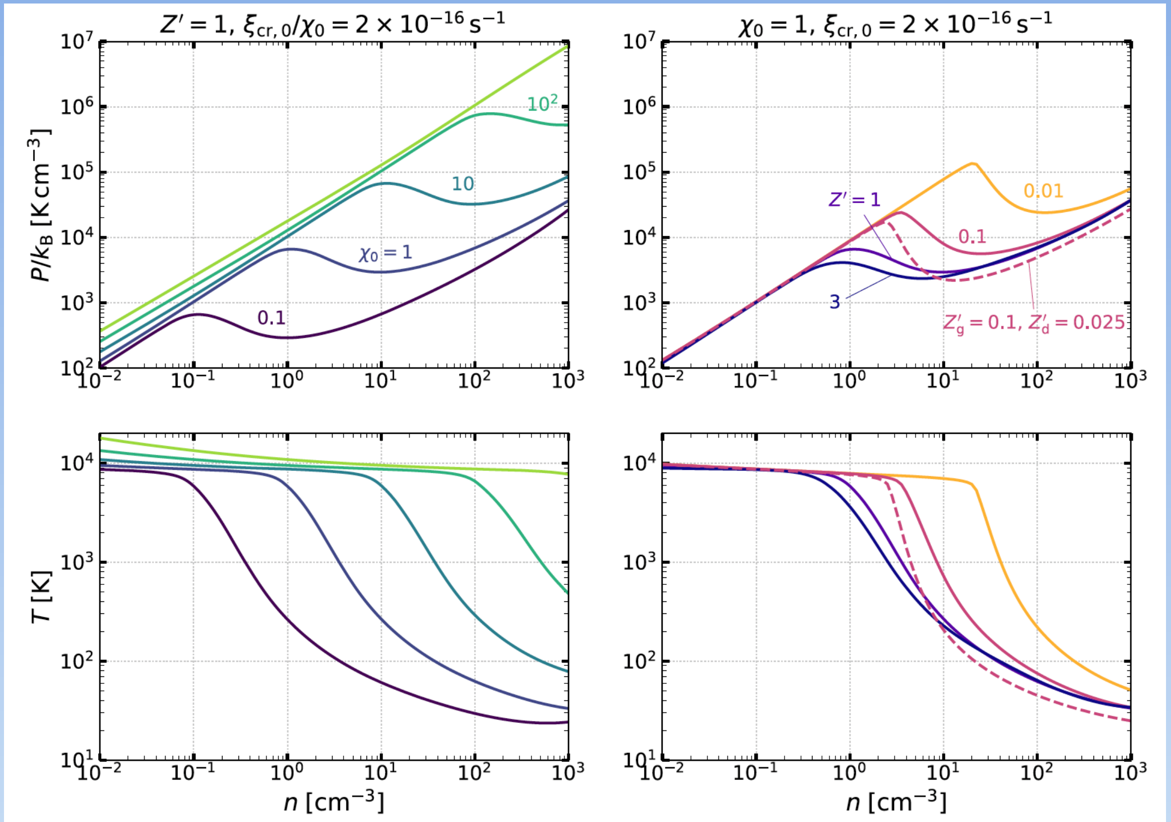
Star formation ***now*** *regulates*

- ***Near-future*** *state of the ISM*
- ***Near-to-far future*** *star formation*

On galactic scales, feedback requirements ***to maintain ISM equilibrium*** *can be used to predict star formation rate*

HST/JWST: NGC 628 (PHANGS team)

Thermal pressure from FUV + CRs



J.-G. Kim et al (2023)

- "Two-phase" thermal pressure $P_{\text{two-phase}} \propto \chi_{\text{FUV}} = J_{\text{FUV}}/J_{\text{Draine}}$
- $\chi_{\text{FUV}} \propto J_{\text{FUV}} \propto \Sigma_{\text{FUV}} \propto \Sigma_{\text{SFR}}$, with dust attenuation factor:

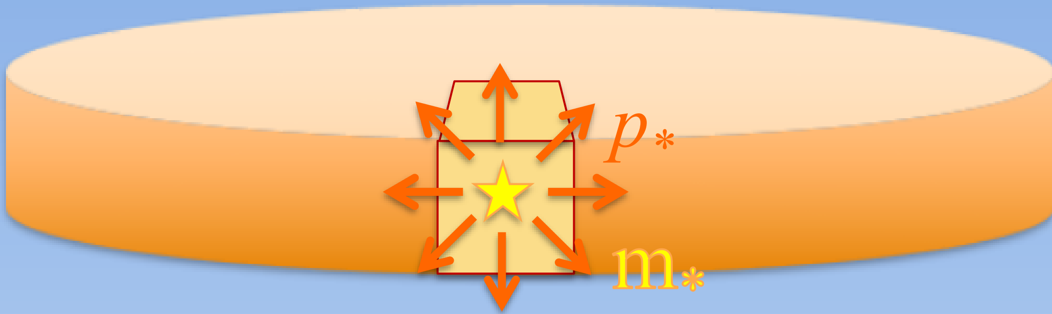
$$J_{\text{FUV}} \equiv \mathcal{J}\Sigma_{\text{FUV}}/(4\pi); \quad \mathcal{J} \approx \frac{1}{\tau_\perp}\left[1 - \frac{1}{2\tau_\perp} + \frac{E_3(\tau_\perp)}{\tau_\perp}\right]$$

$P_{\text{th}} = \Upsilon_{\text{th}}\, \Sigma_{\text{SFR}}$ for FUV thermal heating

$\Upsilon_{\text{th}} \sim 250$ km/s is "yield" in solar neighborhood; higher when τ_{dust} lower

Turbulent pressure from SNe

Momentum injection sets the turbulent pressure



- Driving and dissipation: $\dot{\mathcal{E}}_{in} \sim \dot{p}\sigma \sim \frac{p_*}{m_*}\Sigma_{SFR}H^2\sigma$

$$\dot{\mathcal{E}}_{out} \sim (\rho H^3)\sigma^2\frac{\sigma}{H} \sim \rho\sigma^3 H^2$$

- Balancing:

$$\dot{\mathcal{E}}_{in} = \dot{\mathcal{E}}_{out} \Rightarrow P_{\rm turb} = \rho\sigma^2 \sim \frac{p_*}{m_*}\Sigma_{SFR}$$

- Alternatively, vertical momentum flux/area:

$$P_{\rm turb} \sim \frac{p_{+,z}}{m_*}\Sigma_{SFR} = \frac{1}{4}\frac{p_*}{m_*}\Sigma_{SFR}$$

$P_{\rm turb}=\Upsilon_{\rm turb}\,\Sigma_{\rm SFR}$ for turb. "yield" $\Upsilon_{\rm turb} = p_*/(4\,m_*)\sim 500$ km/s

Feedback yield in the ISM

- Thermal pressure in w+c ISM, from FUV PE + CR heating:

  $n\Lambda(T) = \Gamma \propto J_{FUV}, \xi_{CR} \Rightarrow P_{th}\, \Lambda(T)/T \propto \Sigma_{SFR} \Rightarrow P_{th} = \Upsilon_{th}\, \Sigma_{SFR}$

- Turbulent pressure, largely from SN momentum injection:

  $P_{turb} \sim (1/4) p_* \Sigma_{SFR}/m_* \quad \Rightarrow P_{turb} = \Upsilon_{turb} \Sigma_{SFR}$

- Magnetic pressure, driven by turbulence (+sheared rotation):

  $P_{\delta B} \sim 0.4\, P_{turb} \quad \Rightarrow P_{\delta B} = \Upsilon_{\delta B} \Sigma_{SFR}$

Total ISM pressure $P_{tot} = P_{th} + P_{turb} + P_B = \Upsilon_{tot} \Sigma_{SFR}$

Total expected yield $\Upsilon_{tot} \sim 1000$ km/s for Z'=1

see Ostriker & Kim (2022), & references therein

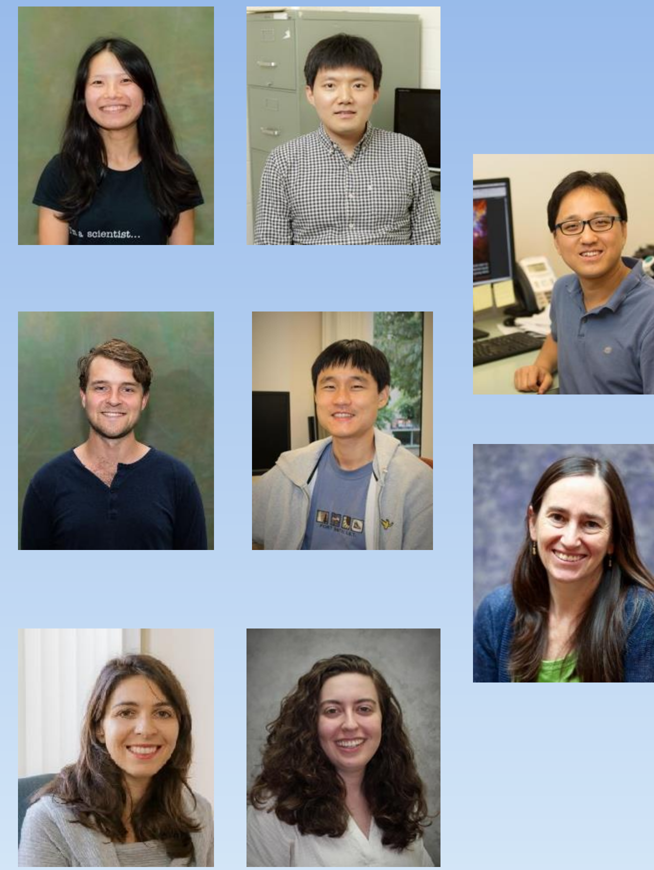
SF-ISM with TIGRESS*/TIGRESS-NCR/TIGRESS++

Key physics elements for studying the star-forming ISM, from GMC scales to kpc-patch scales:

- –hydrodynamics/MHD
- –gravity
- –star formation/sink particles
- –stellar feedback
  - supernovae
  - radiation *(adaptive ray tracing)*
  - winds
  - cosmic rays
- –photochemistry *(non-equilibrium)*
- –multiphase gas cooling and heating

Implementated in Athena/Athena++

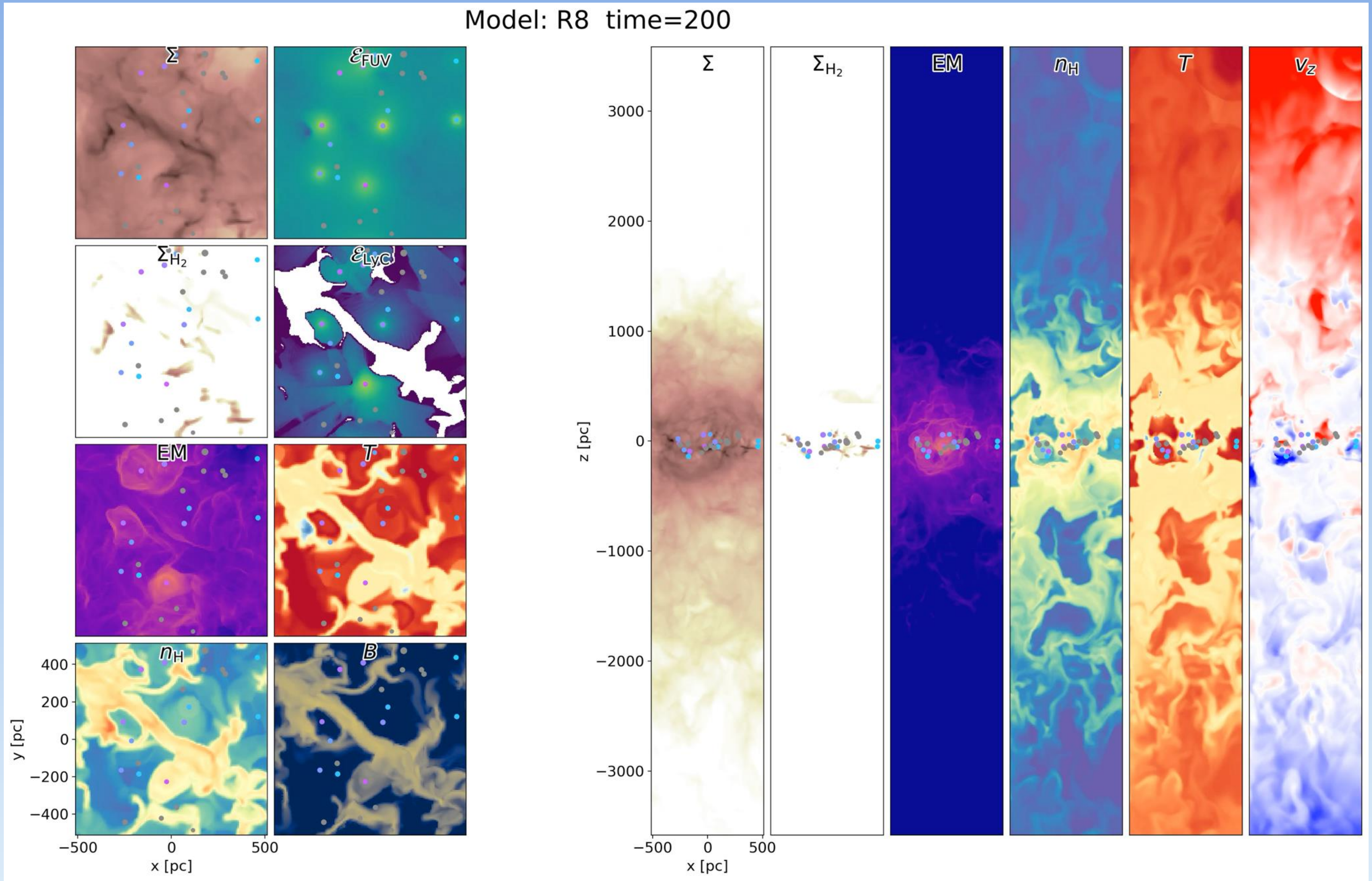
Team TIGRESS:



M. Gong, J.-G. Kim, C.-G. Kim, L. Lancaster, S. Moon, E. Ostriker, L. Armillotta, N. Linzer

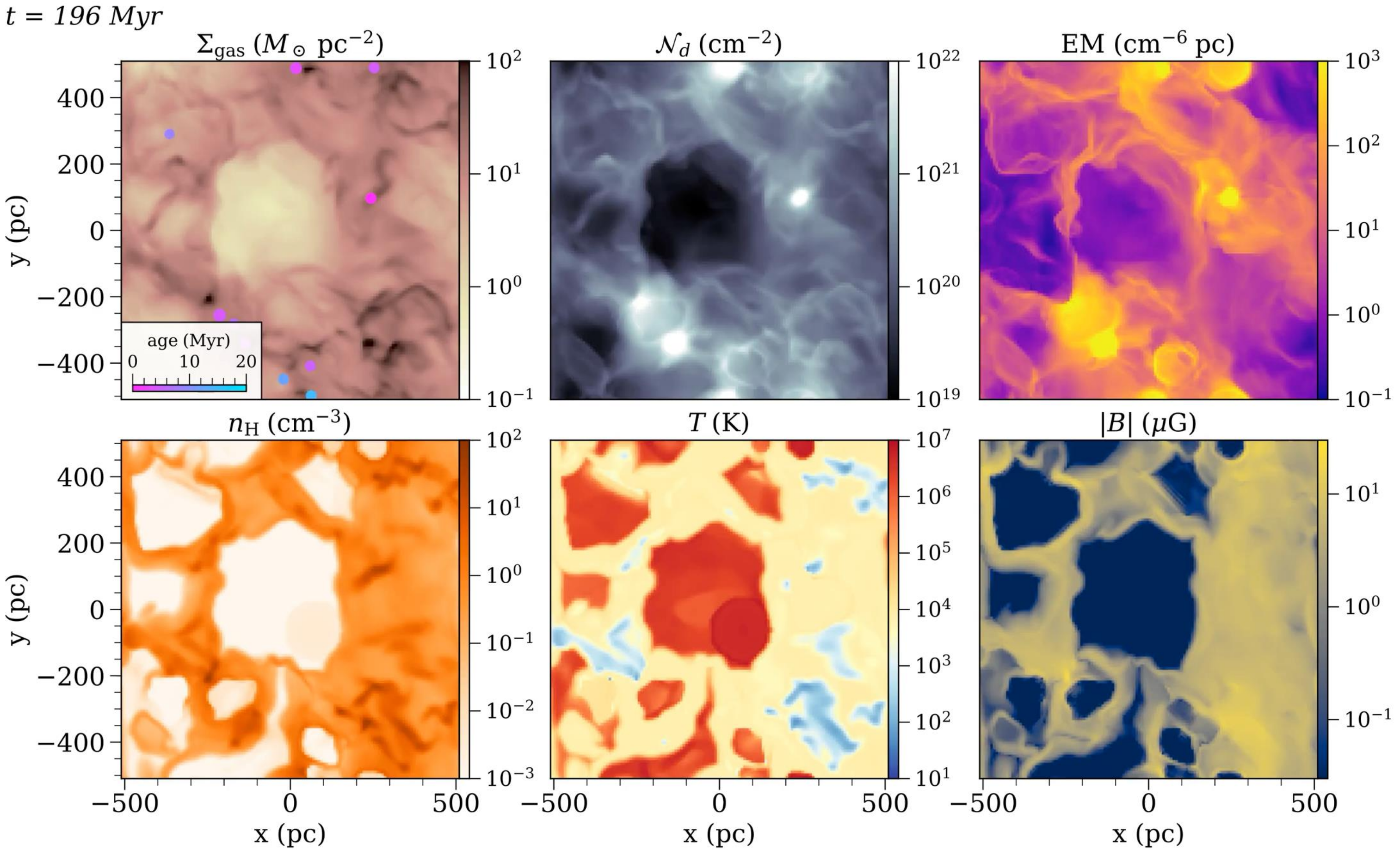
* *T*hree-phase *I*SM in *G*alaxies *R*esolving *E*volution with *S*tar formation and *S*tellar feedback

Star-forming ISM with TIGRESS*/TIGRESS-NCR/TIGRESS++



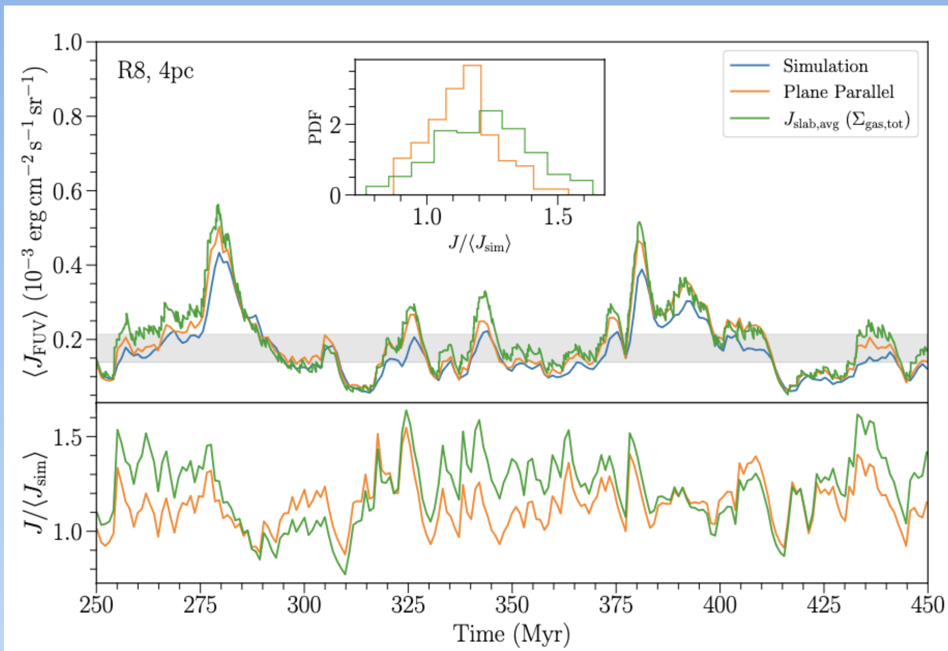
* *T*hree-phase *I*SM in *G*alaxies *R*esolving *E*volution with *S*tar formation and *S*tellar feedback

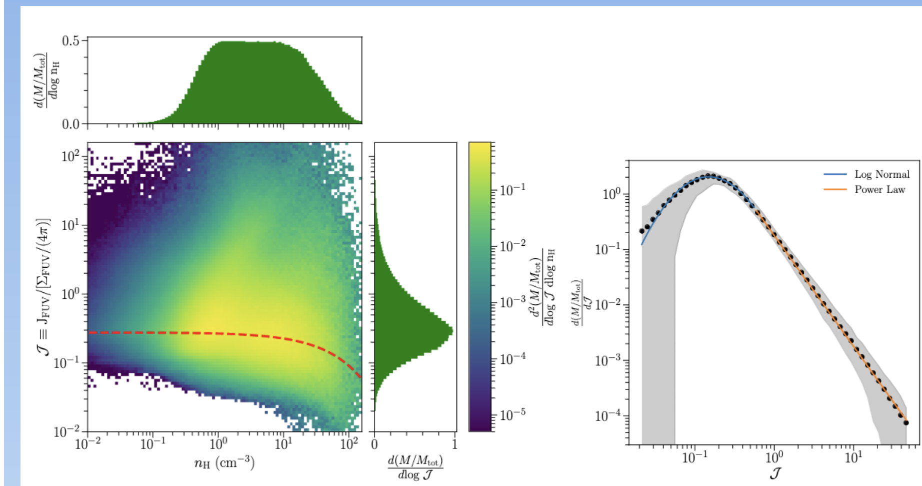
Radiation and heating in TIGRESS-NCR



Linzer et al (2024)

Radiation and heating in TIGRESS-NCR





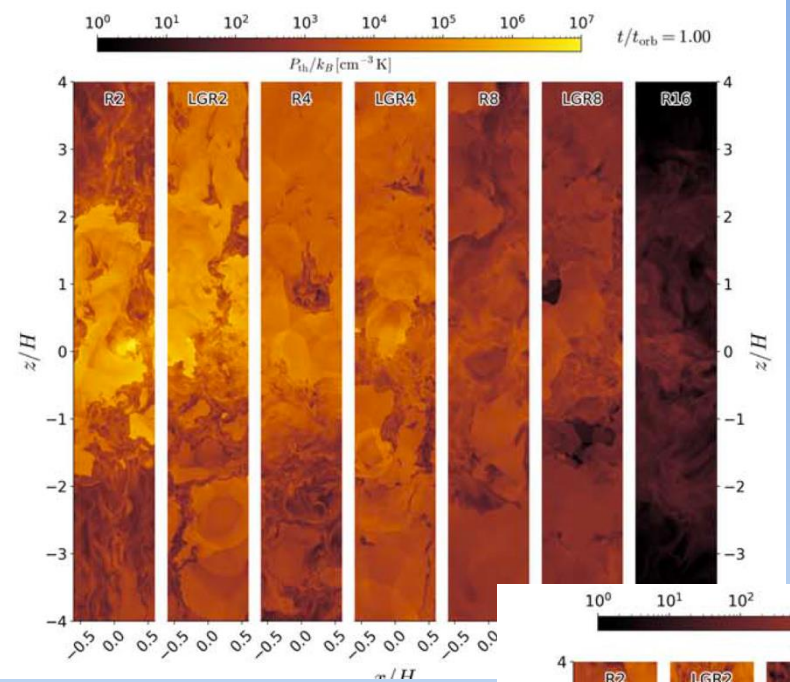
Linzer et al (2024)

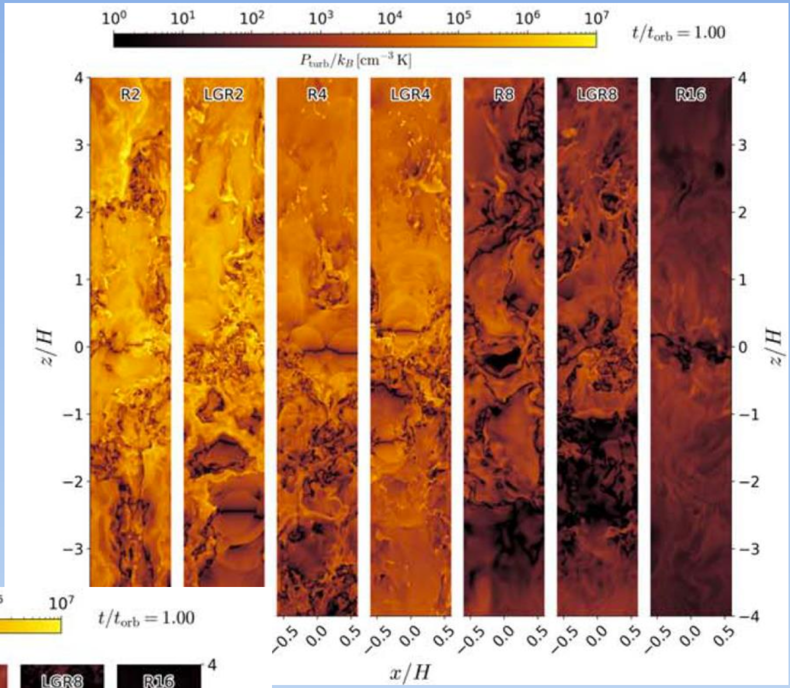
$$J_{\rm FUV} \equiv \mathcal{J}\Sigma_{\rm FUV}/(4\pi); \quad \mathcal{J}_{\rm slab,ave} = \frac{1}{\tau_\perp}\left[1 - \frac{1}{2\tau_\perp} + \frac{E_3(\tau_\perp)}{\tau_\perp}\right]$$

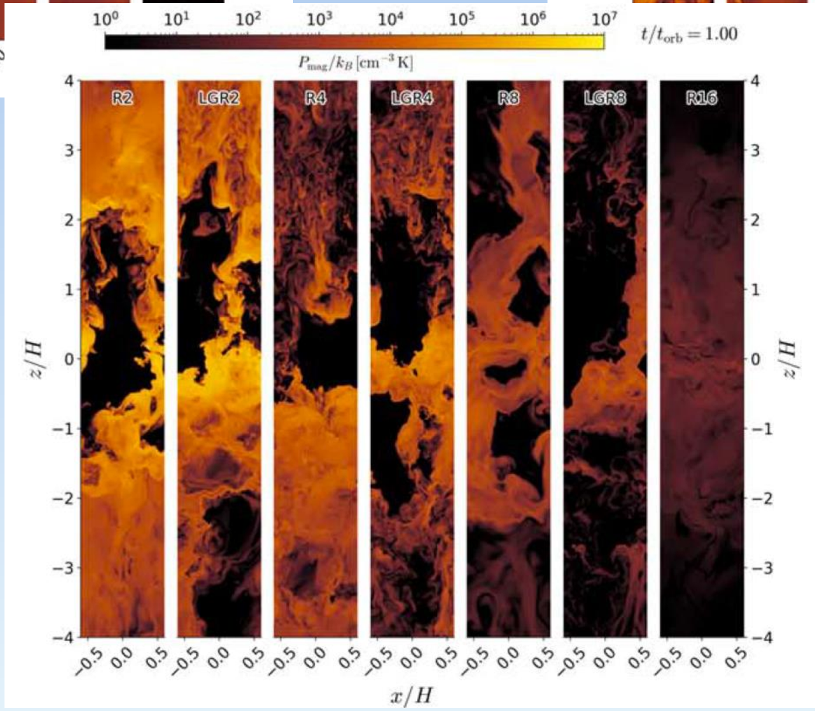
Radiation field in good agreement with analytic estimate

Pressure components in TIGRESS

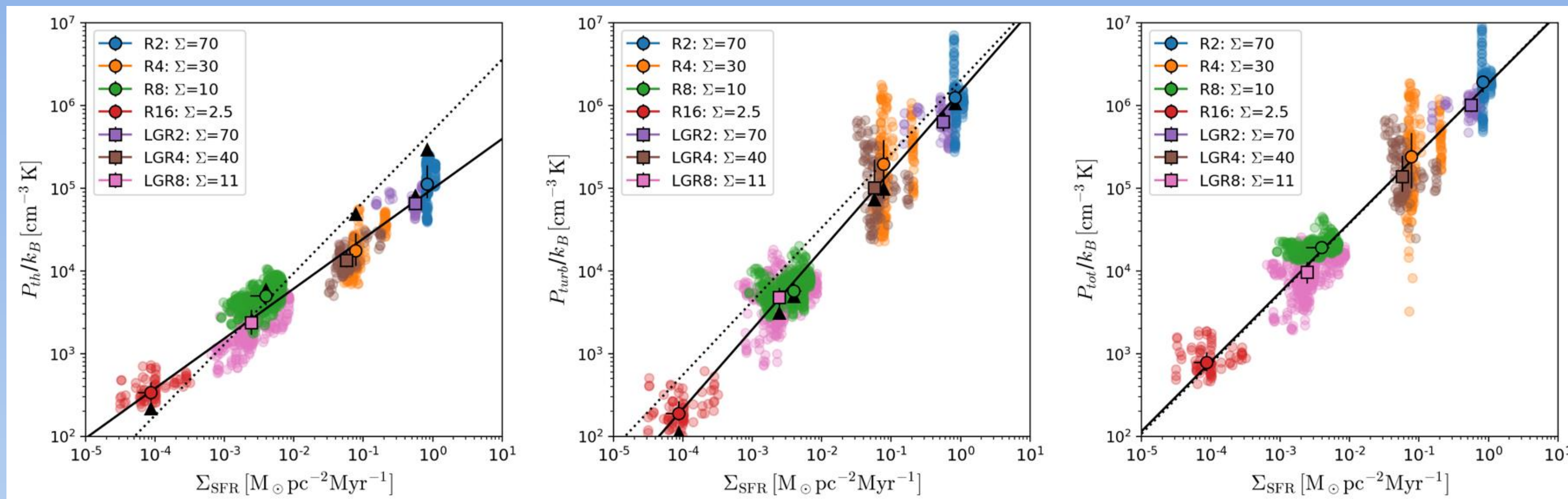
Ostriker & C.-G. Kim (2022)



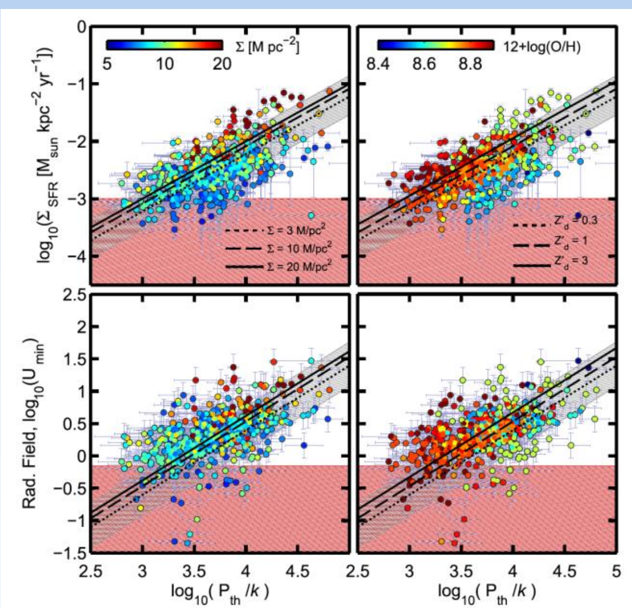




P_{th}, P_{turb}, P_{tot} in simulations



Ostriker & Kim (2022), from TIGRESS "classic" simulation suite (C.-G. Kim et al 2020)



See also empirical P_{turb} vs. Σ_{SFR} from PHANGS-ALMA (Sun et al 2020)

Empirical P_{th} vs. Σ_{SFR} from Herschel/KINGFISH (Herrera-Camus et al 2017)

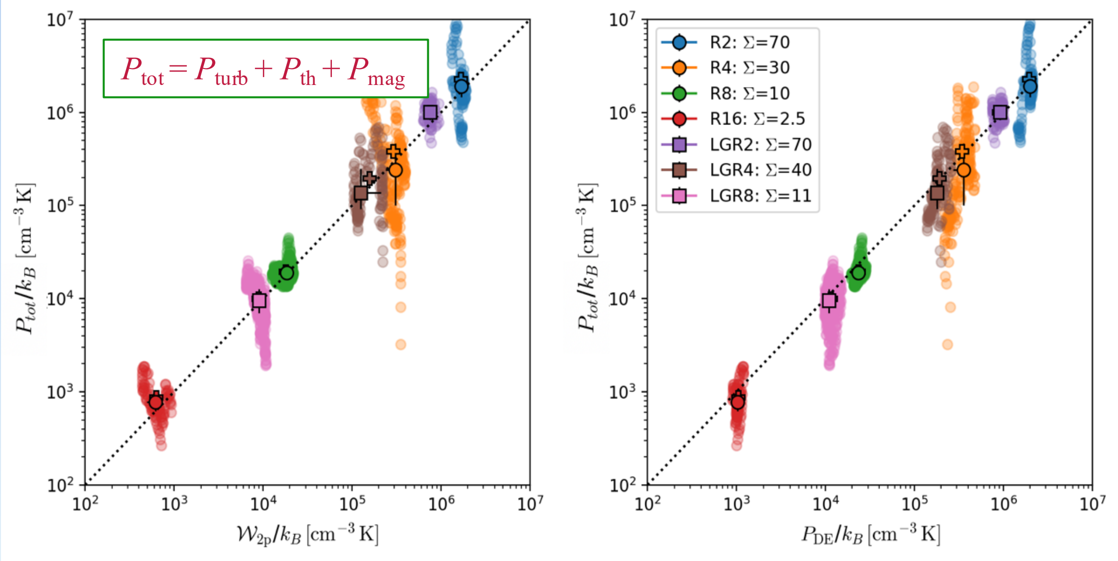
Vertical dynamical equilibrium

- Disk system:
- $\mathcal{W} = \int_0^{zmax} dz\rho g_z = \Sigma_{\rm gas}\langle g_z\rangle/2$

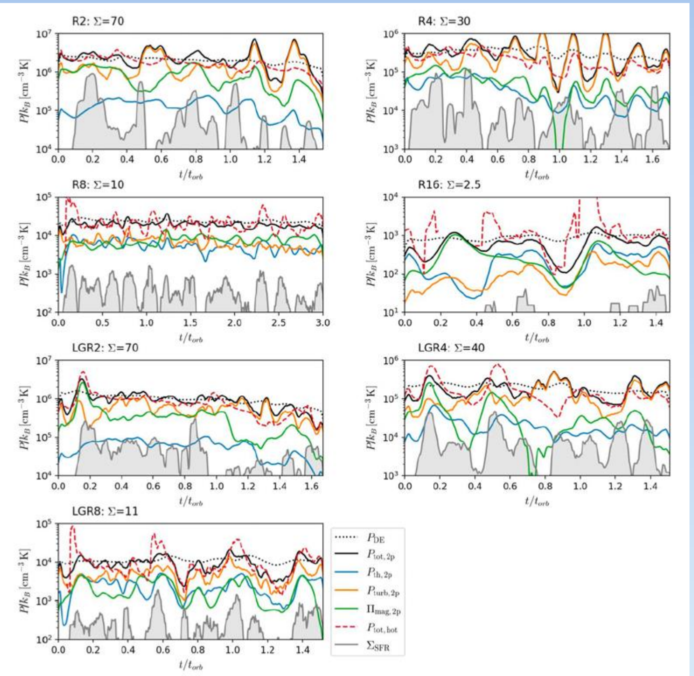
  $\approx \pi G\Sigma_{\rm gas}^2/2 + \pi G\Sigma_{\rm gas}\,\Sigma_* H_g/(H_g + H_*) + (1/3)\,\Sigma_{\rm gas}\,\Omega_{\rm dm}^2 H_g$

  $\approx \pi G\Sigma_{\rm gas}^2/2 + \Sigma_{\rm gas}\sqrt{2G\rho_*}\sigma_{\rm eff,z} \equiv P_{\rm DE}$
- To maintain vertical equilibrium, sum of turbulent, thermal, magnetic, cosmic ray, radiation terms must balance ISM weight:

  $$\Delta P_{turb} + \Delta P_{th} + \Delta\Pi_{mag} + \Delta P_{CR} + \Delta P_{rad} = \mathcal{W}$$
- The most important terms are turbulent, thermal, and magnetic



Ostriker & C.-G. Kim (2022)



Dynamical equilibrium in TIGRESS simulations

Global equilibrium

- Since P_{DE} depends on large-scale galaxy properties (Σ_{gas}, Σ_*, Ω_{dm}) that are insensitive to SF, system must adjust P_{turb}, P_{th}, etc. to reach balance
- Achieved by varying Σ_{SFR} with $P_i = \Upsilon_i \Sigma_{SFR}$

*Global equilibrium **demands** a certain level of SF feedback*

*Requirement to **maintain ISM equilibrium via feedback** can be used to predict star formation rate!*

*P*ressure-*R*egulated, *F*eedback-*M*odulated star formation

- Pressure responds to feedback:

  $P_{tot} = \Upsilon_{tot}\, \boldsymbol{\Sigma}_{SFR}$

- Pressure balances ISM weight:

  $\mathcal{W} = \boldsymbol{\Sigma}_{gas} \langle g_z/2 \rangle \approx P_{DE}$

- Equating, $\boldsymbol{\Sigma}_{SFR} = \mathcal{W}/\Upsilon_{tot} \approx P_{DE}\,/\,\Upsilon_{tot}$

  $\Upsilon_{tot} \sim 1000\ \mathrm{km/s}\ (P/k/10^4)^{-0.2}$ for $Z'=1$

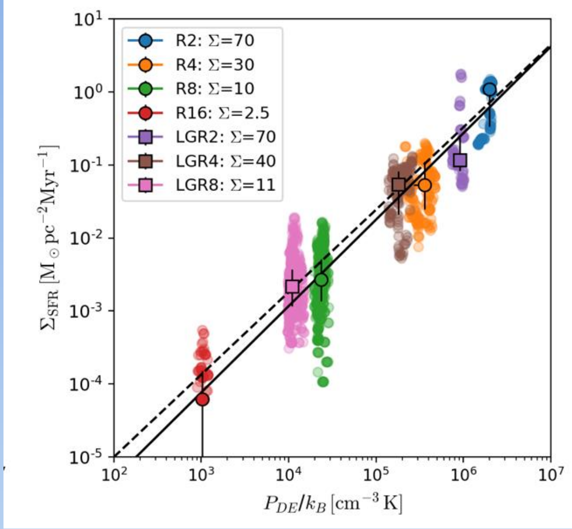
- Predicted *gas depletion time*:

$t_{dyn} = 2H_g/\sigma_{eff}$

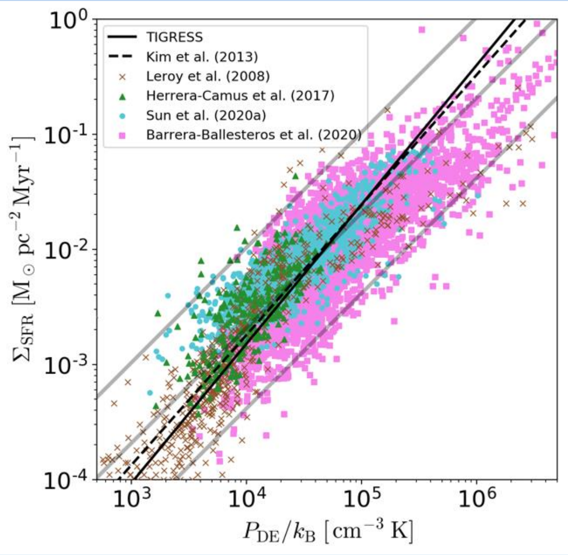
$$t_{dep} = \frac{m_g}{\dot{m}_*} = \frac{\Sigma_g}{\Sigma_{SFR}} = \Upsilon_{tot}\frac{\Sigma_g}{P_{tot}} = \Upsilon_{tot}\frac{2H_g\rho_g}{\sigma_{eff}^2\rho_g} = \frac{\Upsilon_{tot}}{\sigma_{eff}} t_{dyn}$$

$$= \frac{2\Upsilon_{tot}}{\langle g_z \rangle} \sim \begin{cases} \frac{2\Upsilon_{tot}}{\pi G(\Sigma_g + \Sigma_*)} & for\ H_g = H_* \\ \frac{2\Upsilon_{tot}}{\pi G \Sigma_g + \sqrt{2G\rho_*}\,\sigma_{eff}} & for\ H_g \ll H_* \end{cases}$$

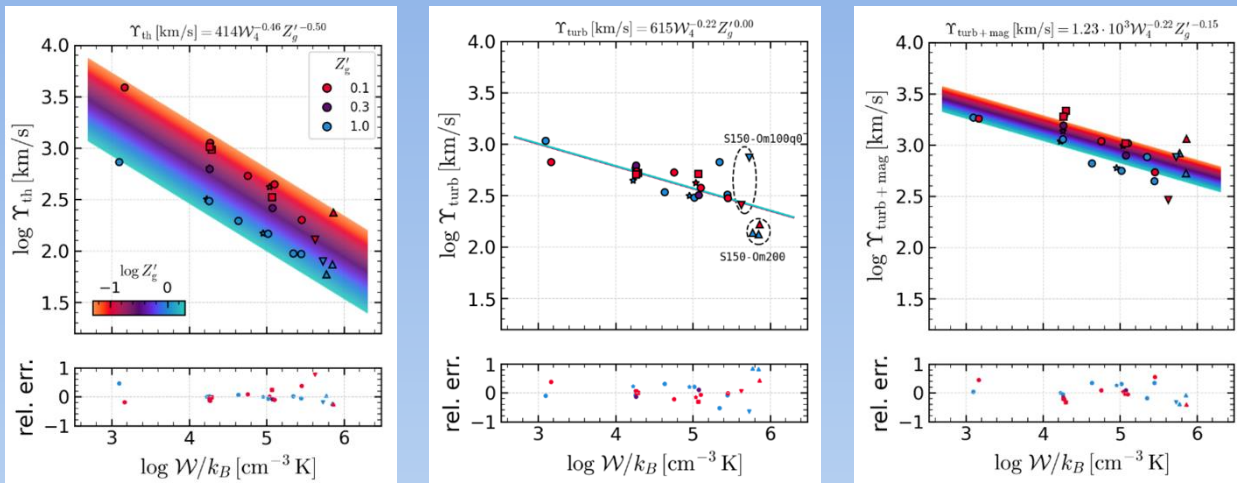
- With $\Upsilon_{tot}/\sigma_{eff} \sim 100$ for $Z'=1$, $t_{dep} \sim 100 t_{dyn}$
- t_{dep} increases for larger Υ_{tot} and decreases for larger g_z



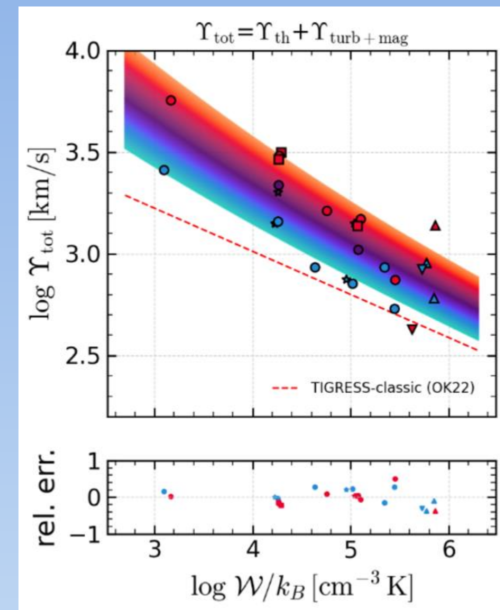
Ostriker & Kim (2022): TIGRESS "Classic"



Z-dependent feedback yield $\Upsilon = P/\Sigma_{SFR}$



C.-G. Kim et al (2024), from TIGRESS-NCR extended-Z′ suite



- Thermal yield increases at low Z (red) because radiation propagates further
- Turbulent yield varies less with Z because momentum injection from SNe is insensitive to Z
- Larger Υ_{tot} at low Z⇒ longer depletion time predicted compared to TIGRESS-classic:

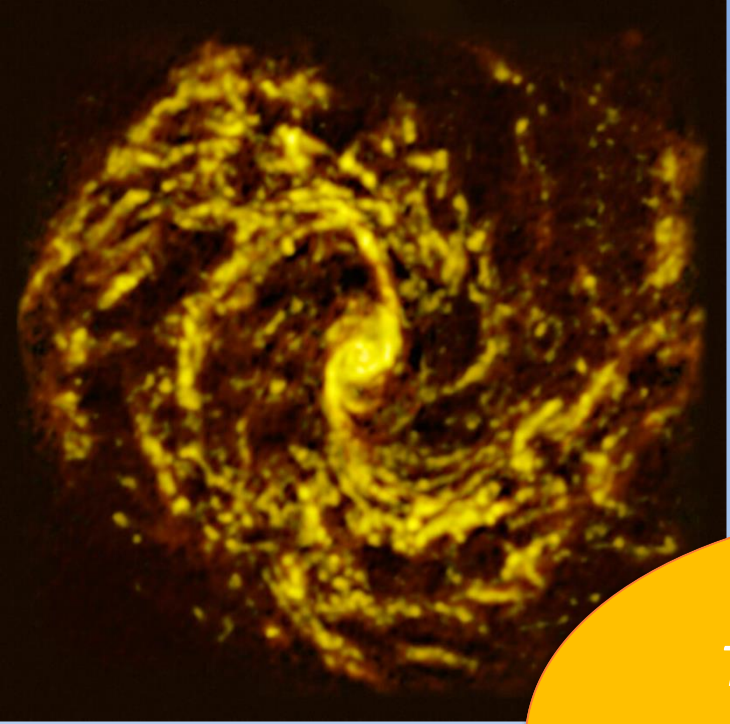
$$t_{dep} = \frac{\Upsilon_{tot}}{\sigma_{eff}} t_{dyn} \sim \frac{2\Upsilon_{tot}}{\pi G(\Sigma_g + \Sigma_*)}$$

Large-scale regulation: thermal & dynamical equilibrium via feedback

ISM conditions and SFR must be self-consistent

- For equilibrium, energy losses must be replenished:
  - Heating (from feedback) balances cooling
  - Turbulent driving (from feedback) balances dissipation
- For equilibrium, midplane pressure must balance vertical gravitational force
  - weight depends on gravity of gas, stars, dark matter
  - pressure terms $\propto$ energy density terms
- Combining energy, momentum balance equations yields $\mathbf{\Sigma}_{SFR}$ as function of $\mathbf{\Sigma}_{gas}$, g_*
- ***High efficiency*** *of energy & momentum* ***production*** *by feedback allows* ***low efficiency*** *of gas* ***consumption***

NGC 4303



ALMA CO (molec. gas)

ISM response

The star-forming ISM: a self-regulated ecosystem

collapse & SF

MUSE gri + Hα (stars + ionized gas)

Young star feedback

MUSE gri (stars)

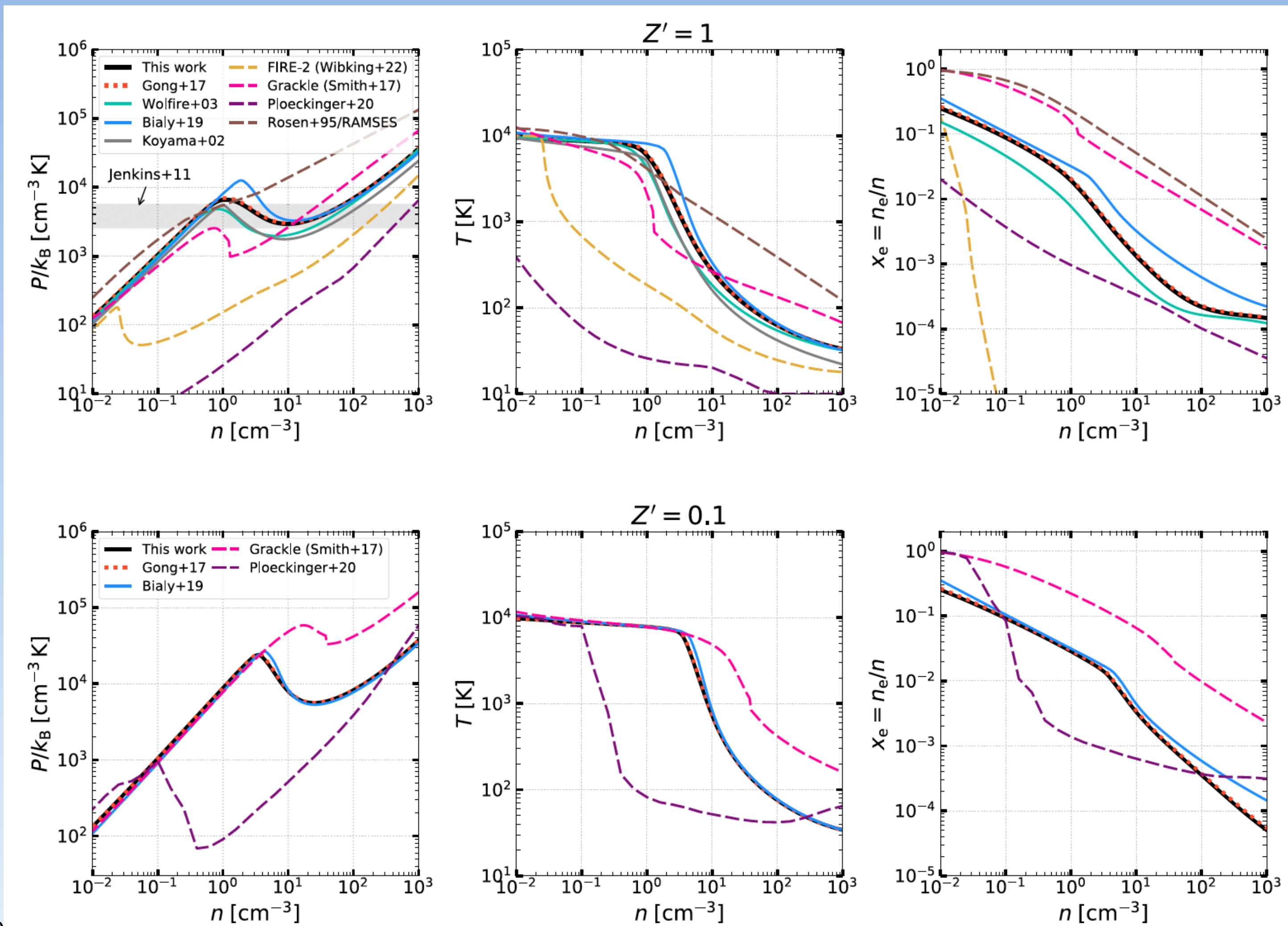
Credit:
MUSE(VLT-ESO)
ALMA(ESO/NAOJ/NRAO)
PHANGS

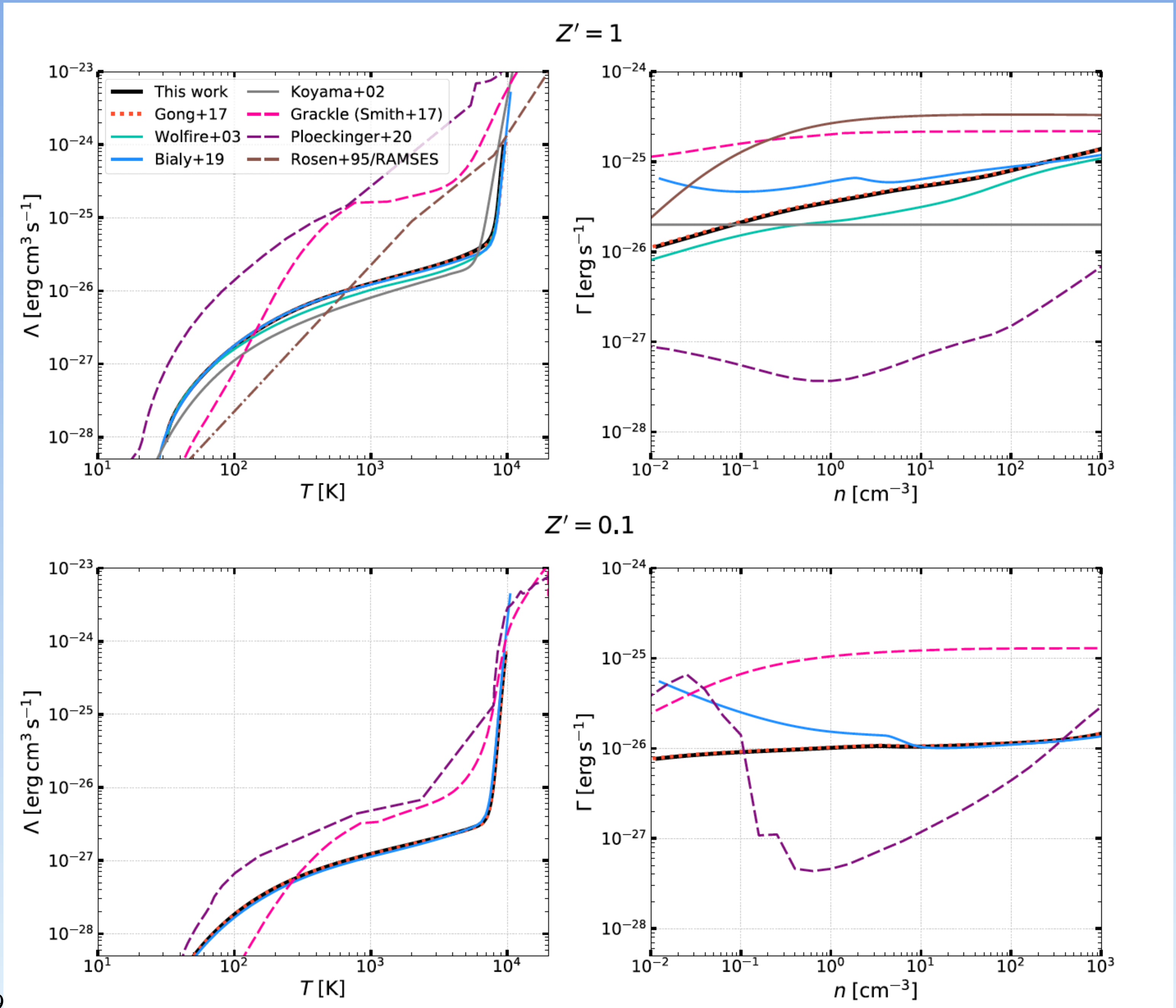
Large-scale regulation: thermal & dynamical equilibrium via feedback

- P_{th}, P_{turb}, P_{mag} are comparable; obtaining realistic values in numerical simulations depends on accurately modeling feedback processes
  - Heating rates depend on radiation field
  - Heating and cooling rates depend on species abundances, including trace ionization
  - Turbulence level depends on realistic space-time correlation of SN feedback energy inputs with gas structure
  - Magnetic energy depends on sheared rotation and turbulent driving
- Since SFR ∝ feedback rate ∝ $P \sim W$, realistic SFR depends on accurate modeling of feedback

Photochemistry and Heating/Cooling of the Multiphase Interstellar Medium with UV Radiative Transfer for Magnetohydrodynamic Simulations

Jeong-Gyu Kim[1,2,3], Munan Gong[4], Chang-Goo Kim[1], and Eve C. Ostriker[1]





$Z' = 1$
This work
Gong+17
Wolfire+03
Bialy+19
Koyama+02
Grackle (Smith+17)
Ploeckinger+20
Rosen+95/RAMSES
Λ [erg cm^3 s^{-1}]
T [K]
Γ [erg s^{-1}]
n [cm^{-3}]
$Z' = 0.1$
Λ [erg cm^3 s^{-1}]
T [K]
Γ [erg s^{-1}]
n [cm^{-3}]