The Importance and Challenges of Assessing Stellar Feedback

THE OHIO STATE UNIVERSITY
DEPARTMENT OF ASTRONOMY

CCAPP

Laura A. Lopez
(The) Ohio State University
Twitter: @ohdearz

Group & Collaborators





Katie Auchettl	Tyler Holland-Ashford	Grace Olivier	Ness Mayker	Sebastian Lopez
Prof @ UMelbourne	OSU PhD Student	OSU PhD Student	OSU PhD Student	OSU PhD Student

Other collaborator folks: Anna Rosen (Harvard), Isha Nayak (STScI), Megan Reiter (UK ATC), Dustin Nguyen (OSU), Tim Linden (Stockholm), Todd Thompson (OSU), Adam Leroy (OSU), Mark Krumholz (ANU), Alberto Bolatto (Maryland), Enrico Ramirez-Ruiz (UCSC)

Conclusions

Stellar feedback, the injection of energy and momentum by stars, is important on small (~1 pc) and large (>10 kpc) scales

There are many challenges to assessing feedback: 1) dynamic range; 2) need observational constraints; 3) where is the energy/momentum deposited?; 4) there are many mechanisms that vary with time & conditions

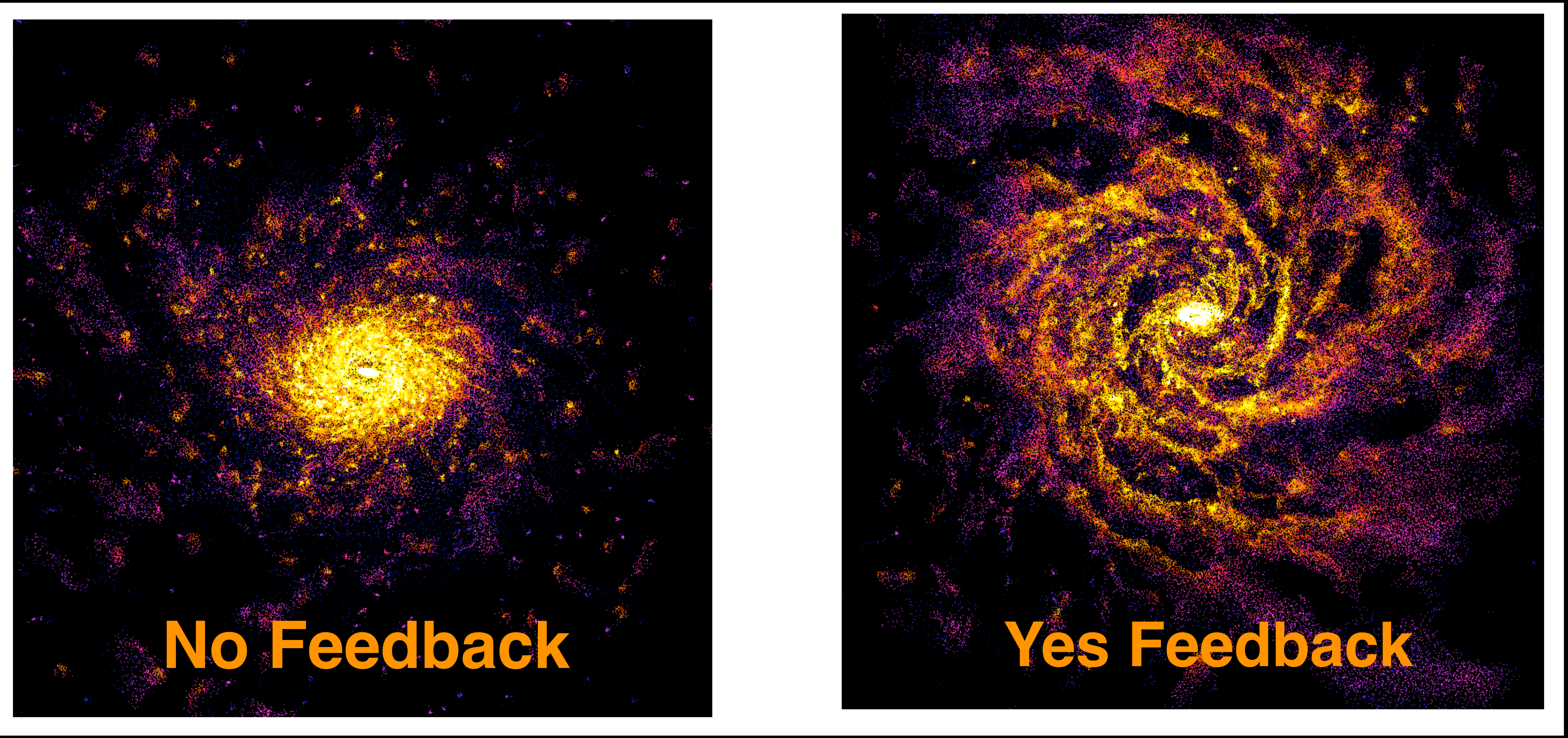
There are observational and theoretical solutions to each problem, and a lot of progress in the last 5 years assessing dynamical role of feedback on small & large scales

Multiwavelength approach enables evaluation of comparative role of feedback modes versus e.g., stellar age, conditions

X-ray and gamma-ray observations constrain presence / properties of galactic outflows from star-forming galaxies.

Importance of Feedback

Identified in the late 1970s that stellar feedback is necessary to form realistic disk galaxies (White & Rees 1978)



Guedes et al. 2011

Stellar and Bulge mass 10x too big (Keres al. 2009)

Importance of Feedback

Large Scale (>kpc)

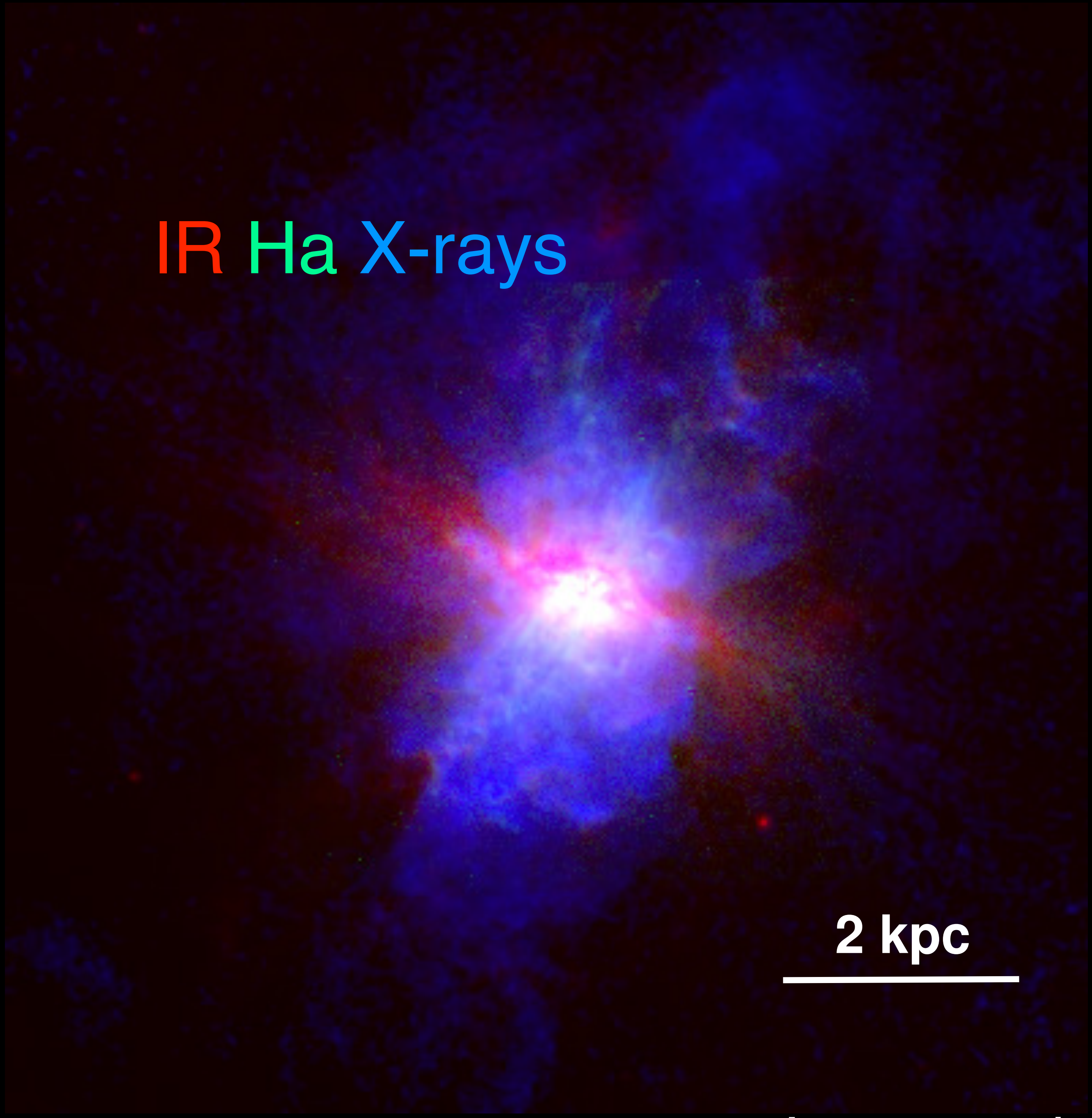
Realistic stellar masses and bulges in galaxies (e.g., White & Rees78; Keres+09)

Formation of bulgeless dwarf galaxies (e.g., Mashchenko+08; Governato+10)

Galaxy luminosity function and the mass-metallicity relation (e.g., Kauffman+94; Cole+1994; Somerville & Primack99)

Star formation efficiency on galactic scales (e.g., Kennicutt98)

Kpc-scale galactic winds (e.g., Veilleux+05)



Lopez+20b

Importance of Feedback

Large Scale (>kpc)

Realistic stellar masses and bulges in galaxies (e.g., White & Rees78; Keres+09)

Formation of bulgeless dwarf galaxies (e.g., Mashchenko+08; Governato+10)

Galaxy luminosity function and the mass-metallicity relation (e.g., Kauffman+94; Cole+1994; Somerville & Primack99)

Star formation efficiency on galactic scales (e.g., Kennicutt98)

Kpc-scale galactic winds (e.g., Veilleux+05)

Small Scale (<100 pc)

Creates ISM phase structure (e.g., McKee & Ostriker77)

Low star formation efficiency in giant molecular clouds (e.g., Zuckerman & Evans74; Krumholz & Tan07)

Disruption & destruction of GMCs (e.g., Matzner02; Krumholz+06)

Drives turbulence (e.g., Mac Low & Klessen04; Offner & Liu16)

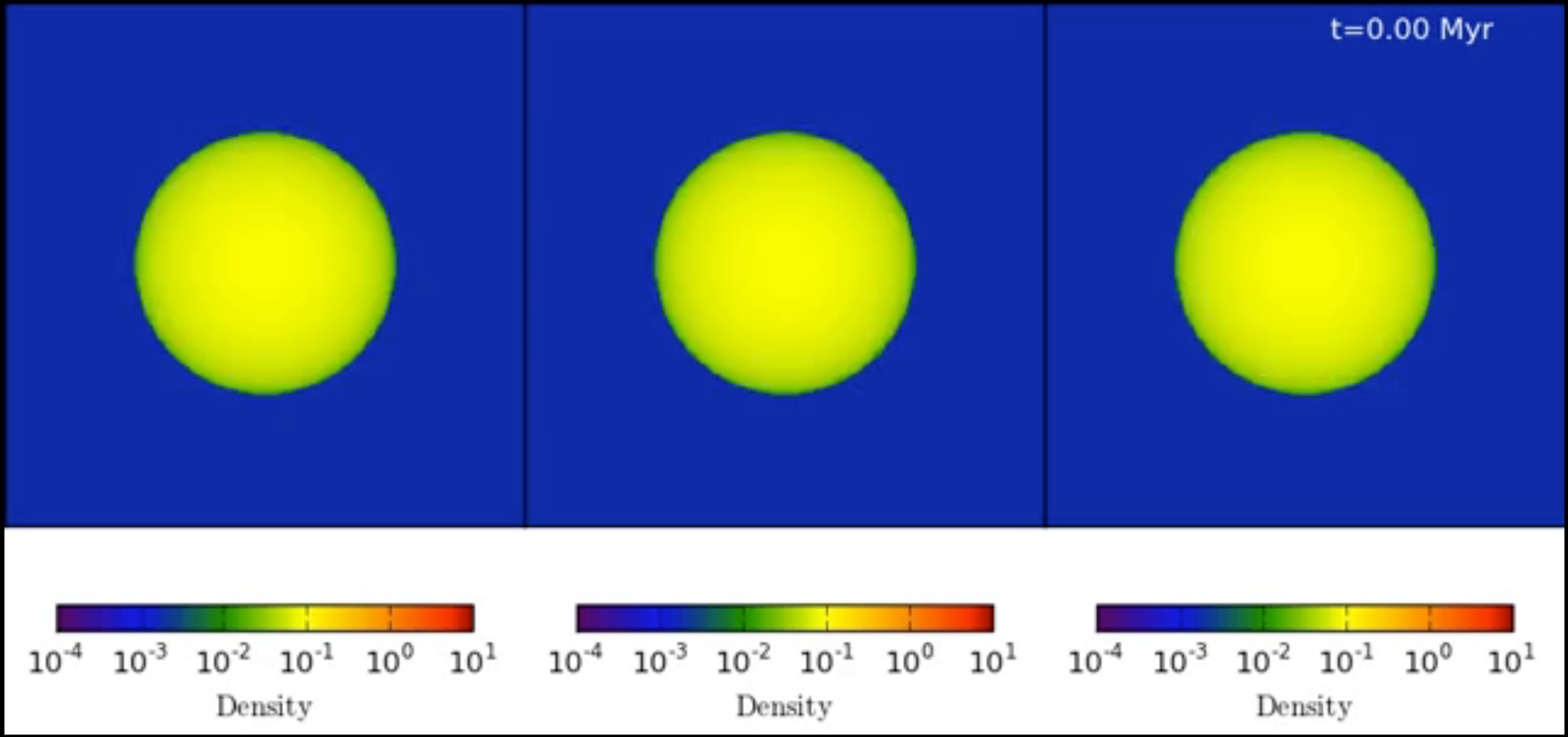
Triggers star formation (e.g., Elmegreen98; Deharveng+05)

In the Feedback Loop - Small Scales

Stellar feedback: the injection of energy & momentum by stars

Protostellar Jets

Quillen+05, Cunningham+06, Matzner07, Nakamura+08, Cunningham+09, Wang+10, Krumholz+12, Offner+14, Li+15, Matzner+15, Bally16, Offner+17, Murray+18



Offner & Arce 2014

In the Feedback Loop - Small Scales

Stellar feedback: the injection of energy & momentum by stars

Protostellar Jets

Quillen+05, Cunningham+06, Matzner07, Nakamura+08, Cunningham+09, Wang+10, Krumholz+12, Offner+14, Li+15, Matzner+15, Bally16, Offner+17, Murray+18

Radiation Pressure (direct and dust-processed)

Jijina+96, Krumholz&Matzner09, Fall+10, Krumholz+10, Draine+11, Murray+11, Skinner+15, Gupta+16, Kim+16, Raskutti+16, Rodriguez-Ramirez+16, Raskutti+17, Ali+18, Kim+18, Krumholz18, Tsang+18

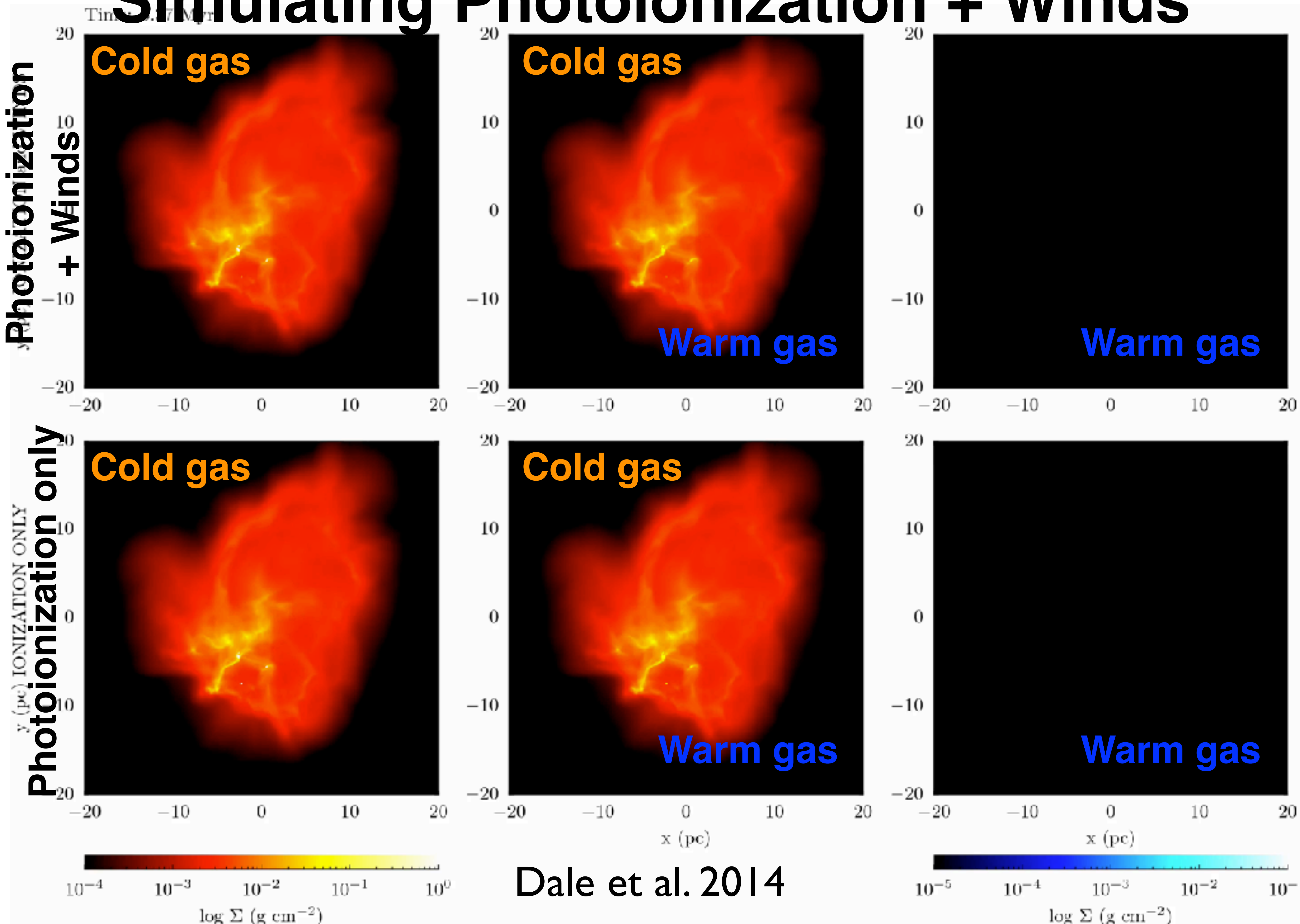
Photoionization Heating

Whitworth79, Dale+05, Dale+14, Geen+16, Gavagnin+17, Ali+18, Haid+18, Kim+18, Kuiper+18, Shima+18

Stellar Winds

Yorke+89, Harper-Clark+09, Rogers+13, Dale+14, Goldsmith+17, Rahner+17, Haid+18, Naiman+18, Wareing+18

Simulating Photoionization + Winds



Dale et al. 2014

In the Feedback Loop - Small Scales

Stellar feedback: the injection of energy & momentum by stars

Protostellar Jets

Quillen+05, Cunningham+06, Matzner07, Nakamura+08, Cunningham+09, Wang+10, Krumholz+12, Offner+14, Li+15, Matzner+15, Bally16, Offner+17, Murray+18

Radiation Pressure (direct and dust-processed)

Jijina+96, Krumholz&Matzner09, Fall+10, Krumholz+10, Draine+11, Murray+11, Skinner+15, Gupta+16, Kim+16, Raskutti+16, Rodriguez-Ramirez+16, Raskutti+17, Ali+18, Kim+18, Krumholz18, Tsang+18

Photoionization Heating

Whitworth79, Dale+05, Dale+14, Geen+16, Gavagnin+17, Ali+18, Haid+18, Kim+18, Kuiper+18, Shima+18

Stellar Winds

Yorke+89, Harper-Clark+09, Rogers+13, Dale+14, Goldsmith+17, Rahner+17, Haid+18, Naiman+18, Wareing+18

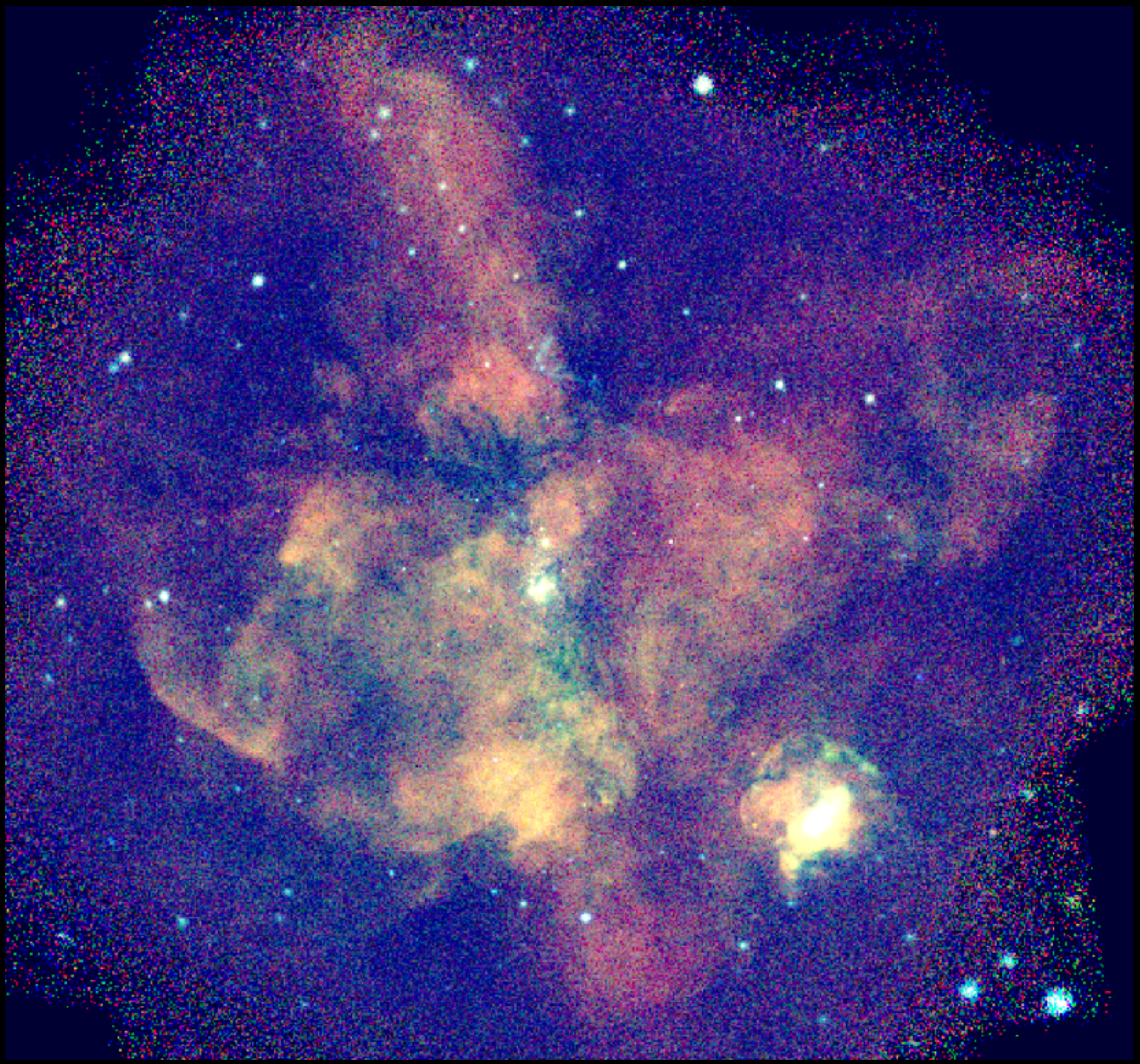
Supernovae

Rogers+13, Kim & Ostriker15, Martizzi+15, Walch+15, Geen+16, Haid+16, Kortgen+16, Gentry+17, 18, Zhang+18

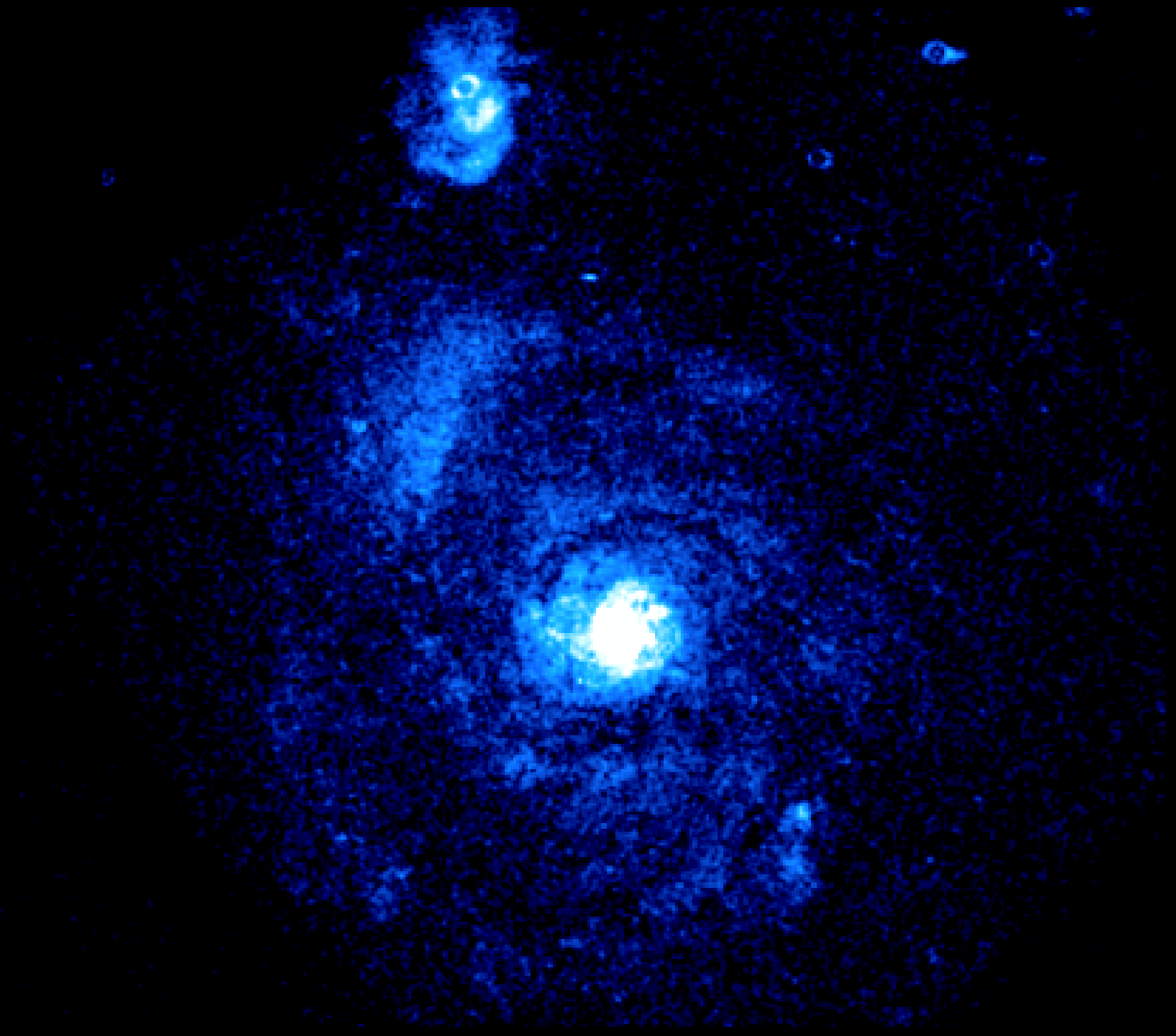
Cosmic Rays

Shock-Heated Gas - Observable in X-rays

Stellar winds and supernovae shock-heat gas to 10^7 K temperatures and are observable in X-rays



30 Doradus
2 Ms *Chandra*



M51
750 ks *Chandra*

Cosmic-Ray Feedback

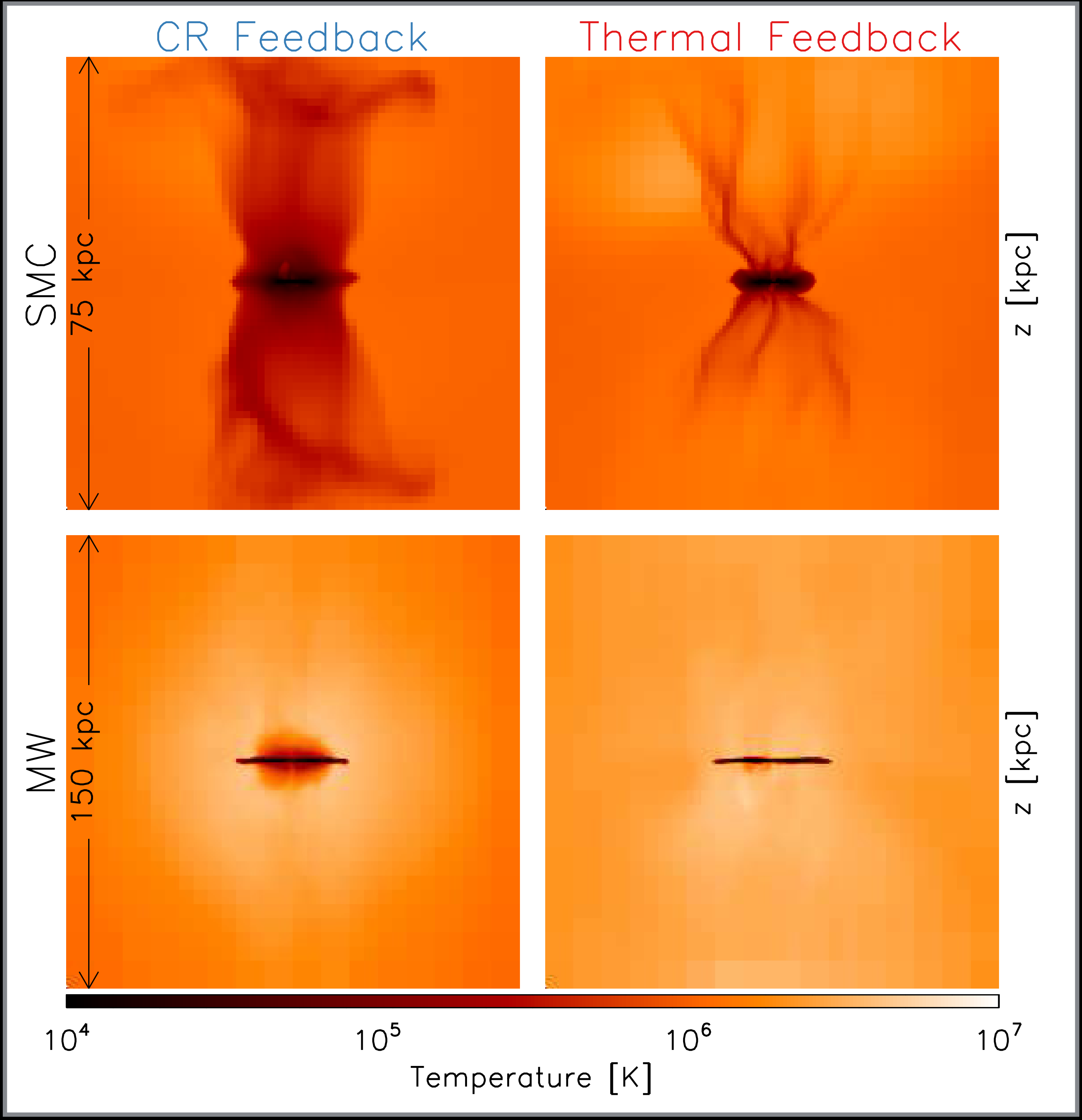
~10% of E_{SN} goes into accelerating particles up to TeV energies at the forward shock (cosmic rays)

1. CRs can drive galactic winds

2. CRs can suppress star formation

3. CRs can affect wind properties: CR winds are cooler, multiphase, accelerated more gently

4. CRs can affect CGM properties: CGM is cooler and metal-enriched



Booth et al. 2013

Cosmic-Ray Feedback

References: Ipavich75, Breitschwerdt+91, Zirakashvili+96, Ptuskin+97, Everett+08, Jubelgas+08, Socrates+08, Everett+10, Samui+10, Wadepuhl+11, Dorfi+12, Uhlig+12, Booth+13, Hanasz+13, Salem+14, Girichidis+16, Liang+16, Pakmor+16, Ruszkowski+16, Simpson+16, Pfrommer+17a,b, Recchia+17, Ruszkowski+17, Wiener+17, Butsky+18, Chan+18, Farber+18, Girichidis+18, Heintz+18, Holguin+18, Jacob+18, Mao+18, Samui+18, Butsky+18, Chan+19, Hopkins+19, Brüggen+20, Buck+20, Bustard+20, Butsky+20, Dashyan+19, Hopkins20abcd, Jana+20, Ji+20….

Feedback Uncertainties

Feedback is one of the biggest uncertainties in star and galaxy formation models today

Feedback Challenge #1: Dynamic Range

~ 1 pc
1 AU ~ 5e-6 pc

~100 pc

~10 kpc

Solutions:

Observations: Study MW and nearby galaxies where all scales are observable

Theory: Zoom-in simulations give pc resolution

Feedback Challenge #2:
Need Observational Constraints

Radiation Pressure (direct and dust-processed)

Optical/UV/IR

Photoionization Heating

Optical/Radio

Stellar Winds

X-rays

Supernovae

X-rays/Radio

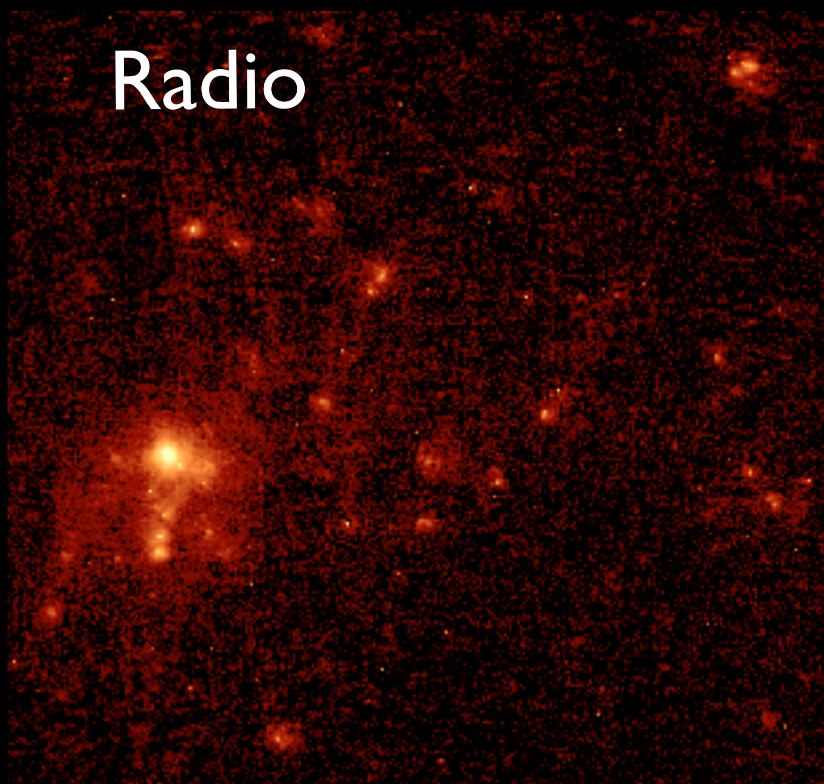
Protostellar Jets

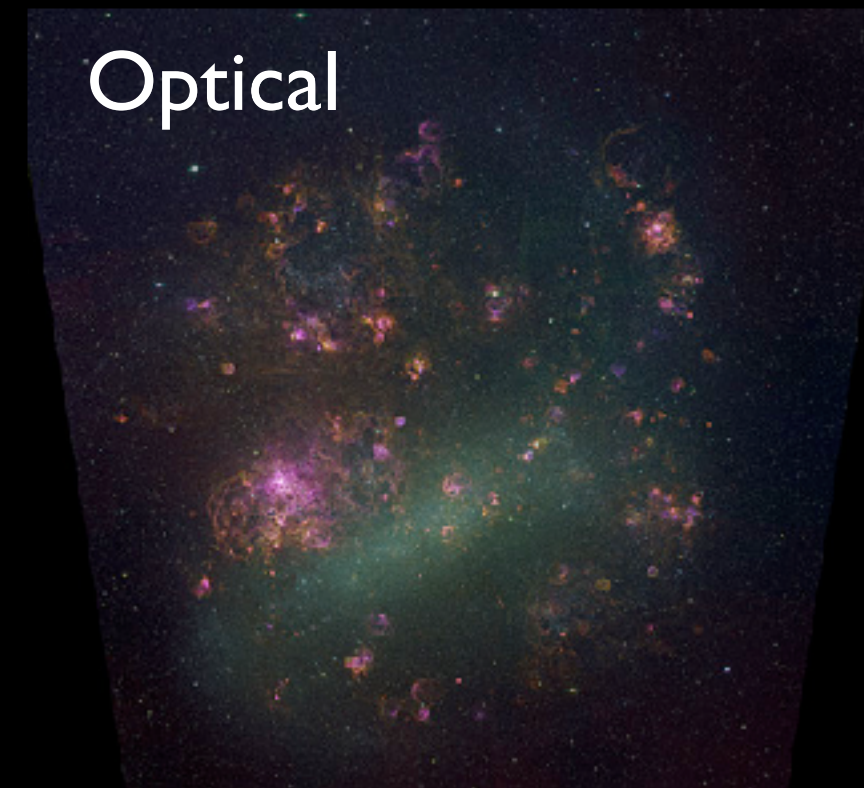
Optical/IR/mm

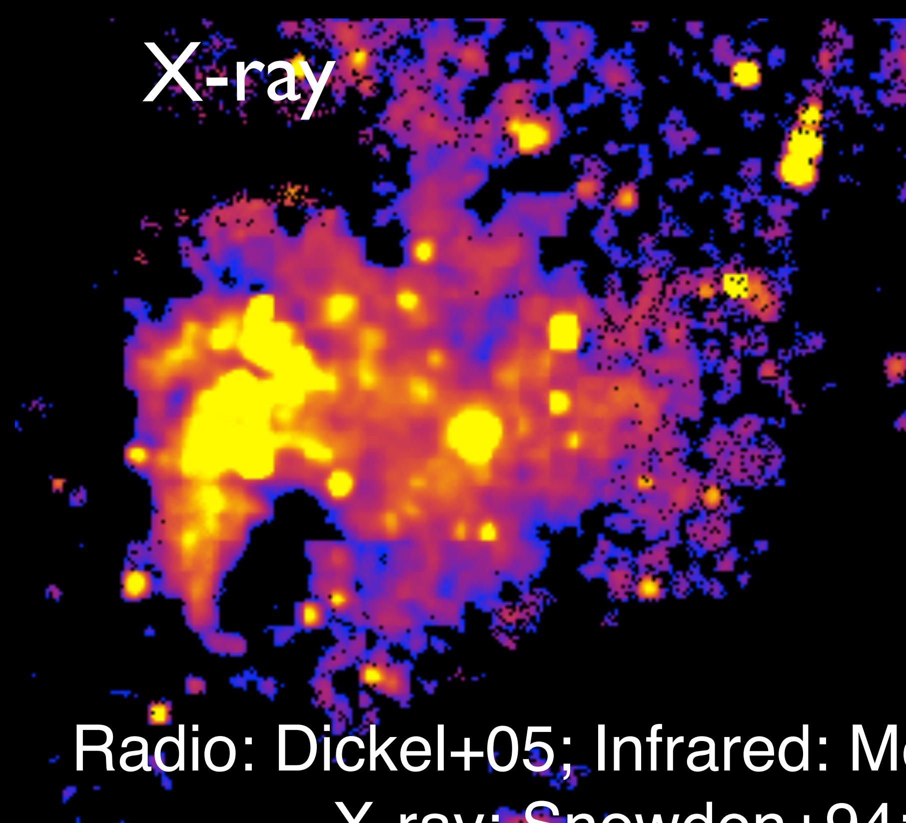
Cosmic rays

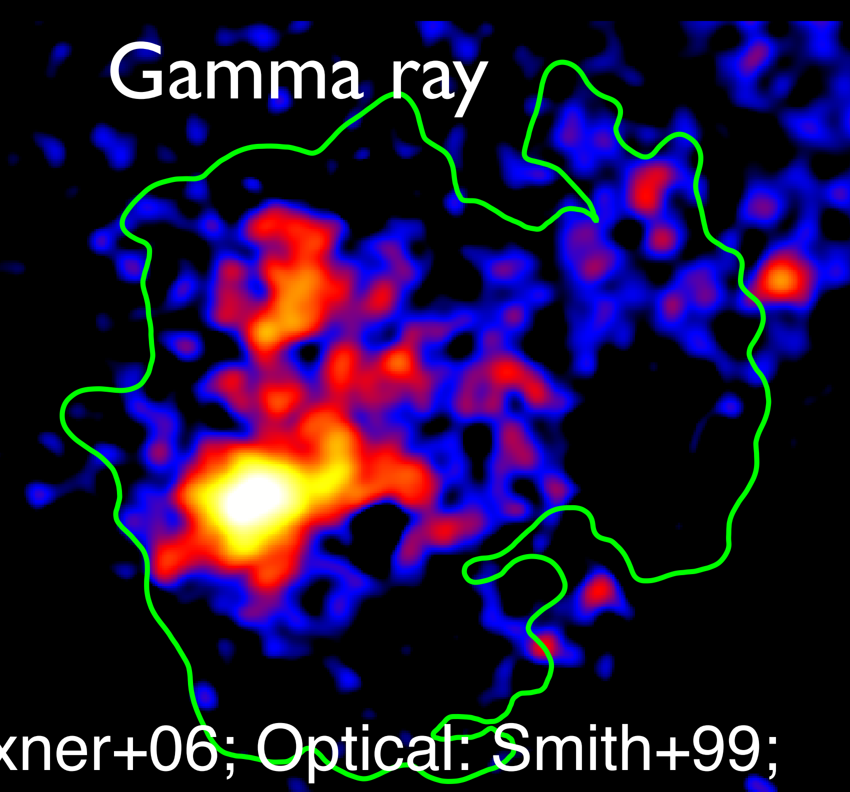
Gamma-rays/Radio

Feedback Challenge #2:
Need Observational Constraints - Solutions







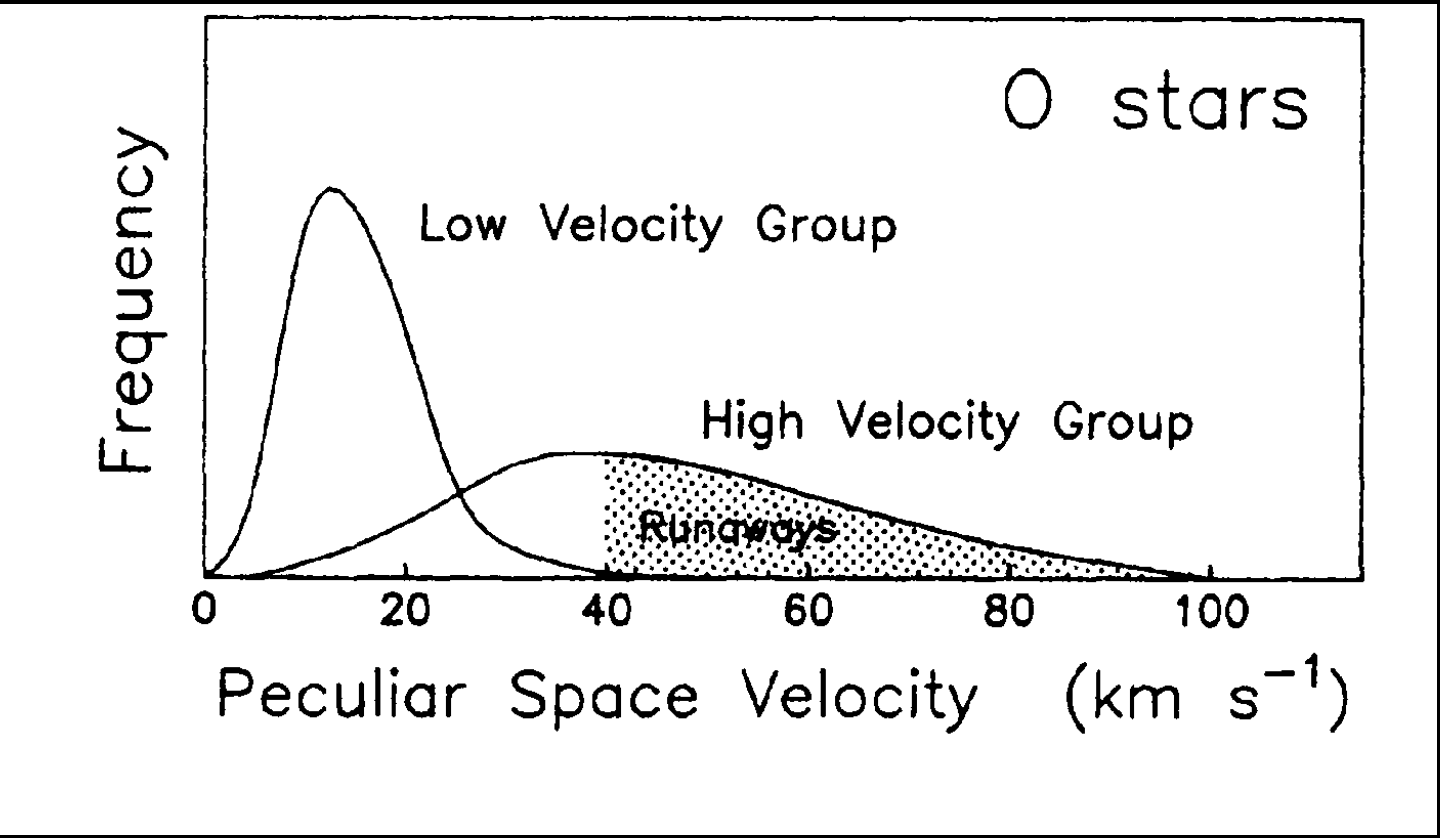


Radio: Dickel+05; Infrared: Meixner+06; Optical: Smith+99;
X-ray: Snowden+94; Gamma ray: LL+21

Feedback Challenge #3:
Where is Energy/Momentum Deposited?

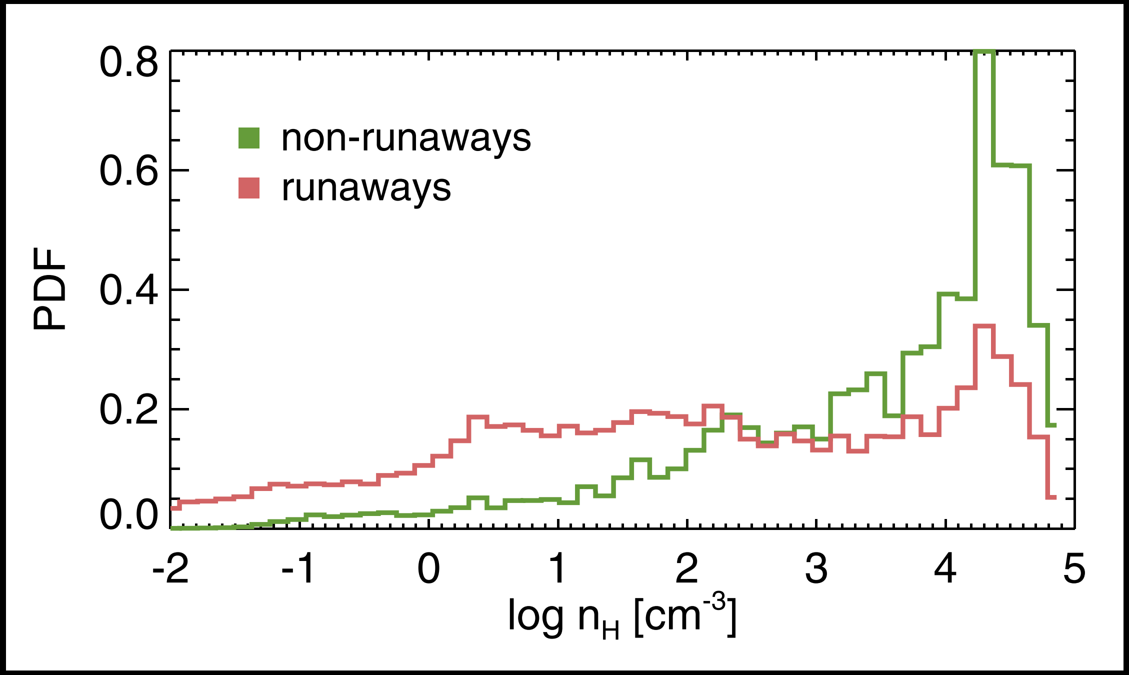
Stars move.

Stone91



46% of O stars and 10% of B stars are "runaway" (with v > 30 km s^{-1})

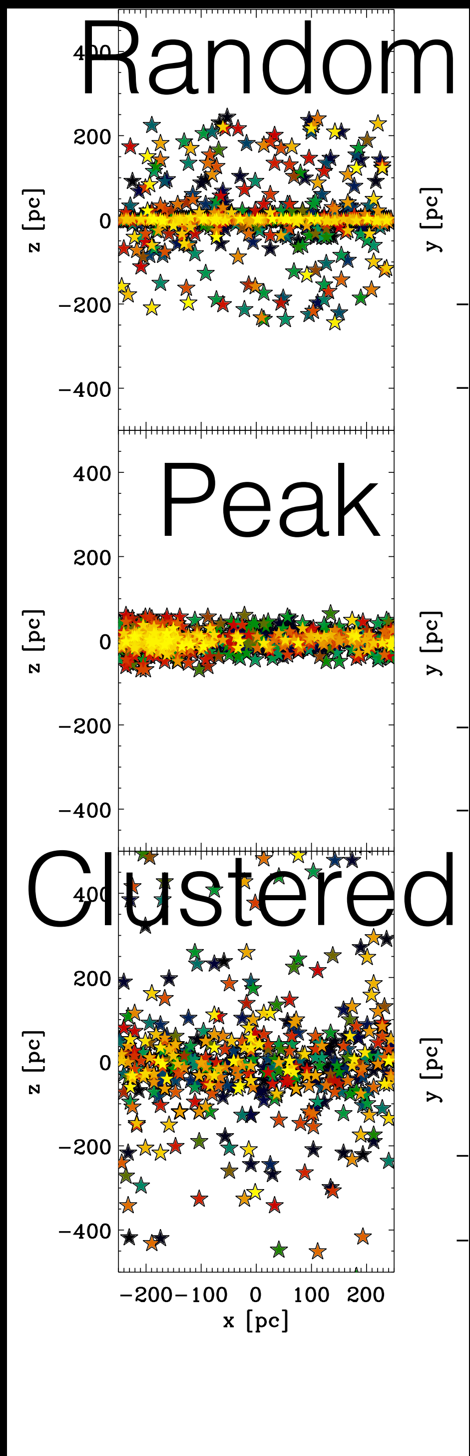
OB stars travel 50-500 pc before exploding as SNe



Runaway stars are located in much less dense regions - leads to higher escape fractions

Kimm & Cen14

Feedback Challenge #3: Where is Energy/Momentum Deposited?

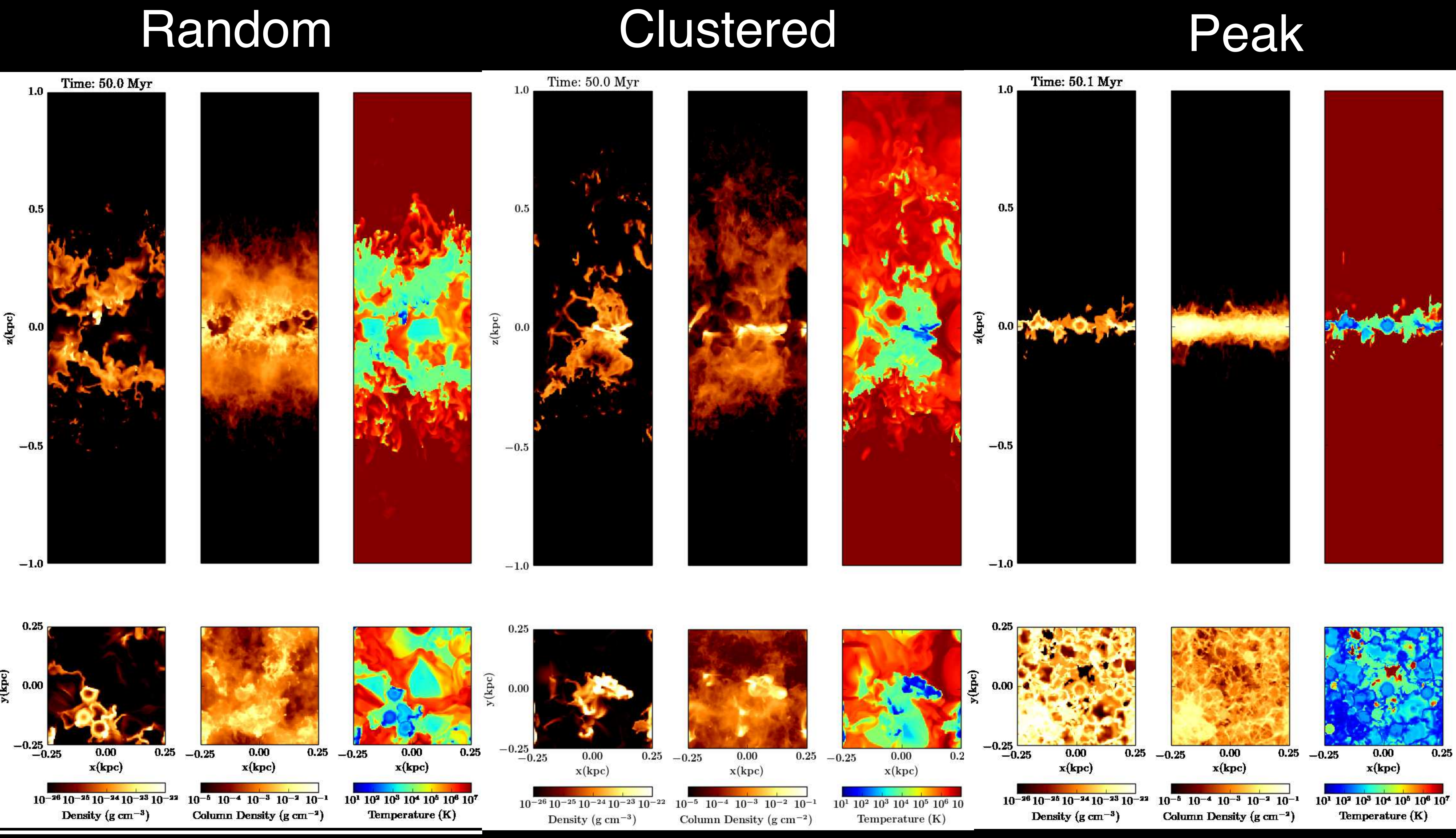


Walch+15

Solutions

Theory: Test different placement of SNe and compare simulation results to observables.

Feedback Challenge #3:
Where is Energy/Momentum Deposited?



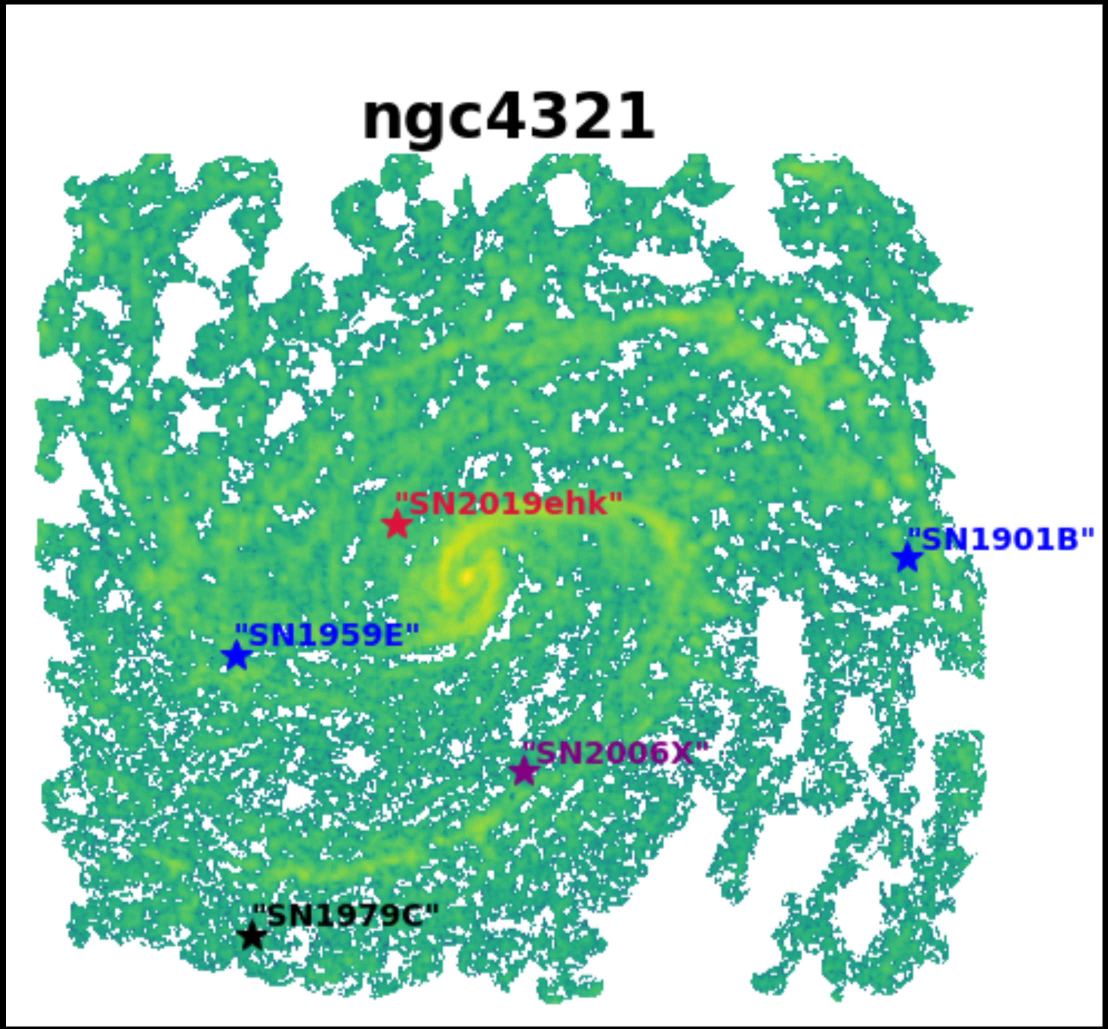
Walch+15

Feedback Challenge #3:
Where is Energy/Momentum Deposited?

Solutions

Observations:

Use Atacama Large Millimeter/submillimeter Array (ALMA) data to show how close SNe are to molecular clouds (Mayker, Leroy, LL+ in prep)

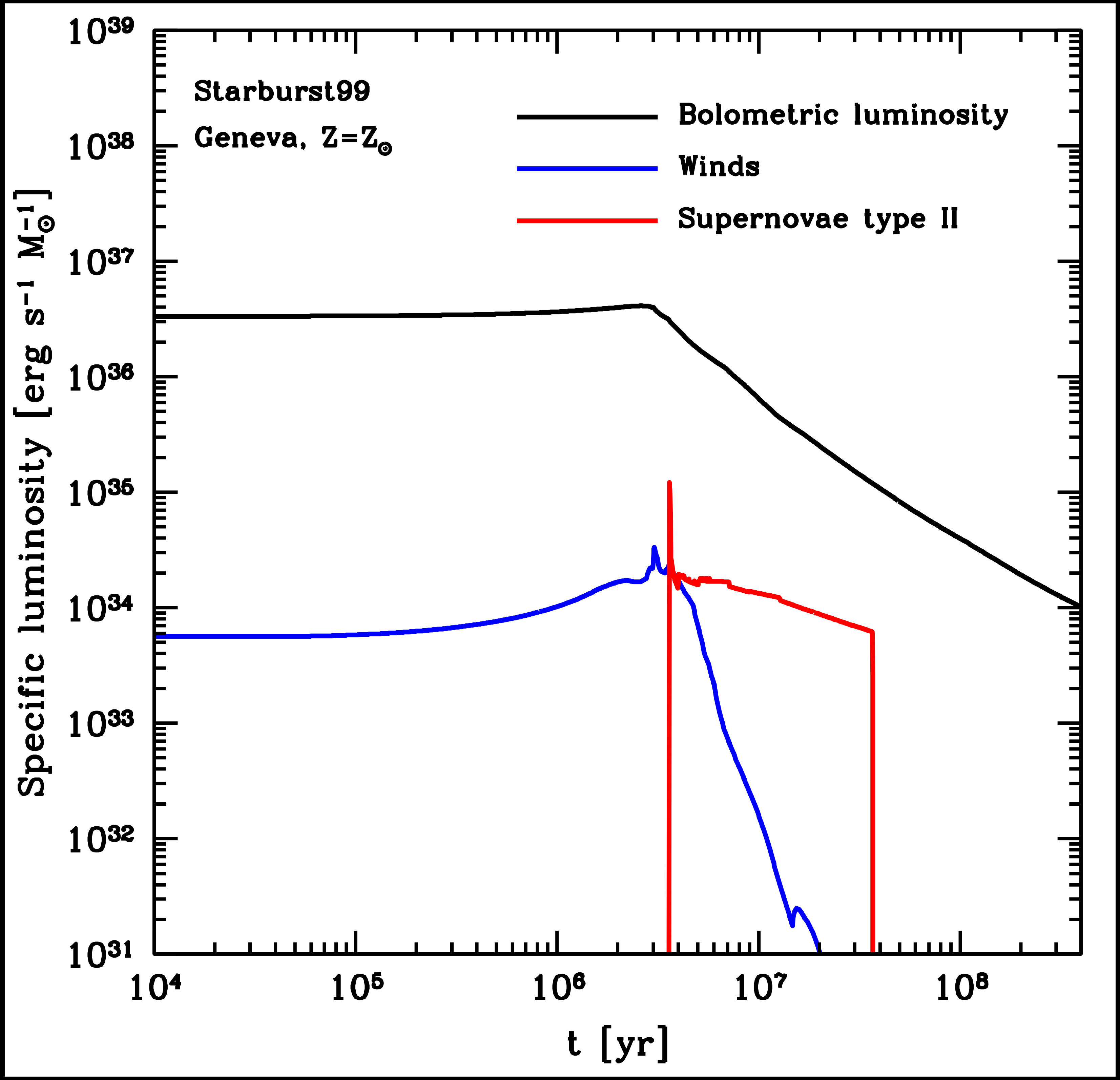


Type Ia SNe preferentially occur in lower surface density locations far from molecular gas

Core-collapse SNe occur in higher surface density in/near molecular gas

Feedback Challenge #4: Many Mechanisms

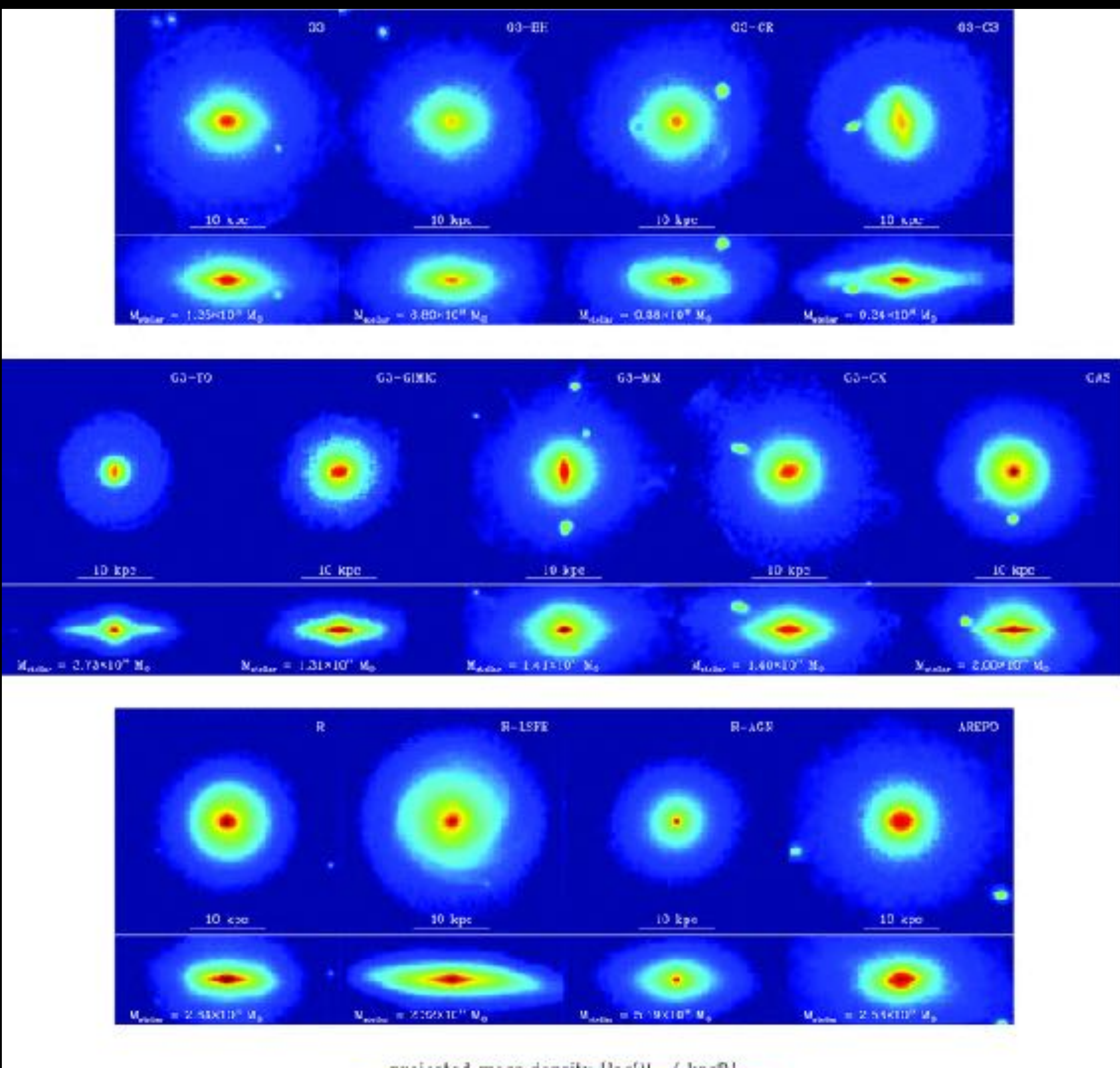
Dominant feedback mode changes with time



Agertz et al. 2013

Feedback Challenge #4: Many Mechanisms

In simulations, different mechanisms produce vastly different galaxies at z~0 (Aquila Comparison Project: Scannapieco et al. 2011)



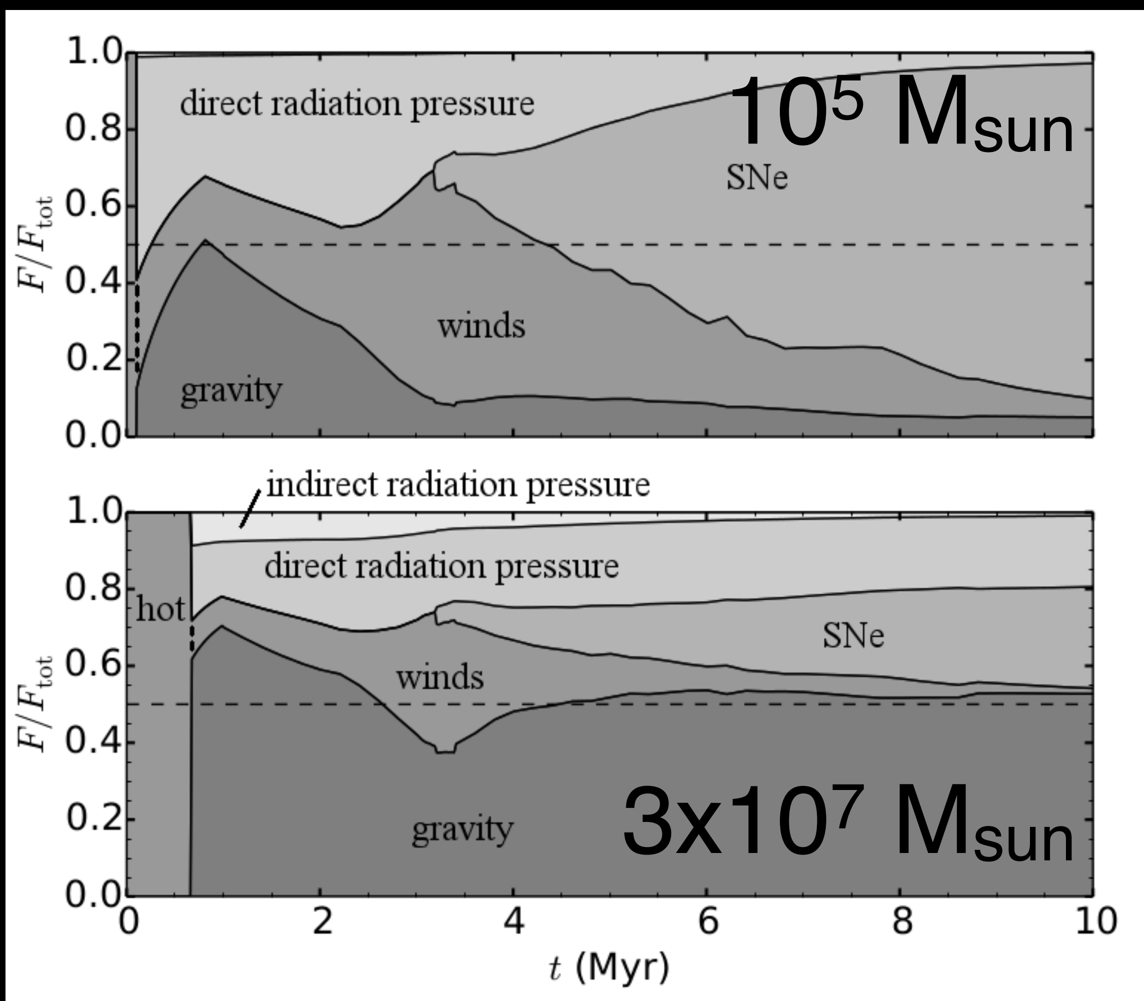
Major differences in:
Morphology
Radius
Gas Fraction
Stellar Masses
Star Formation Histories

$M_{stars} \sim 4x10^{10}$ - $3x10^{11}$ M_{sun}
SFR ~ 0.1-10 M_{sun}/yr

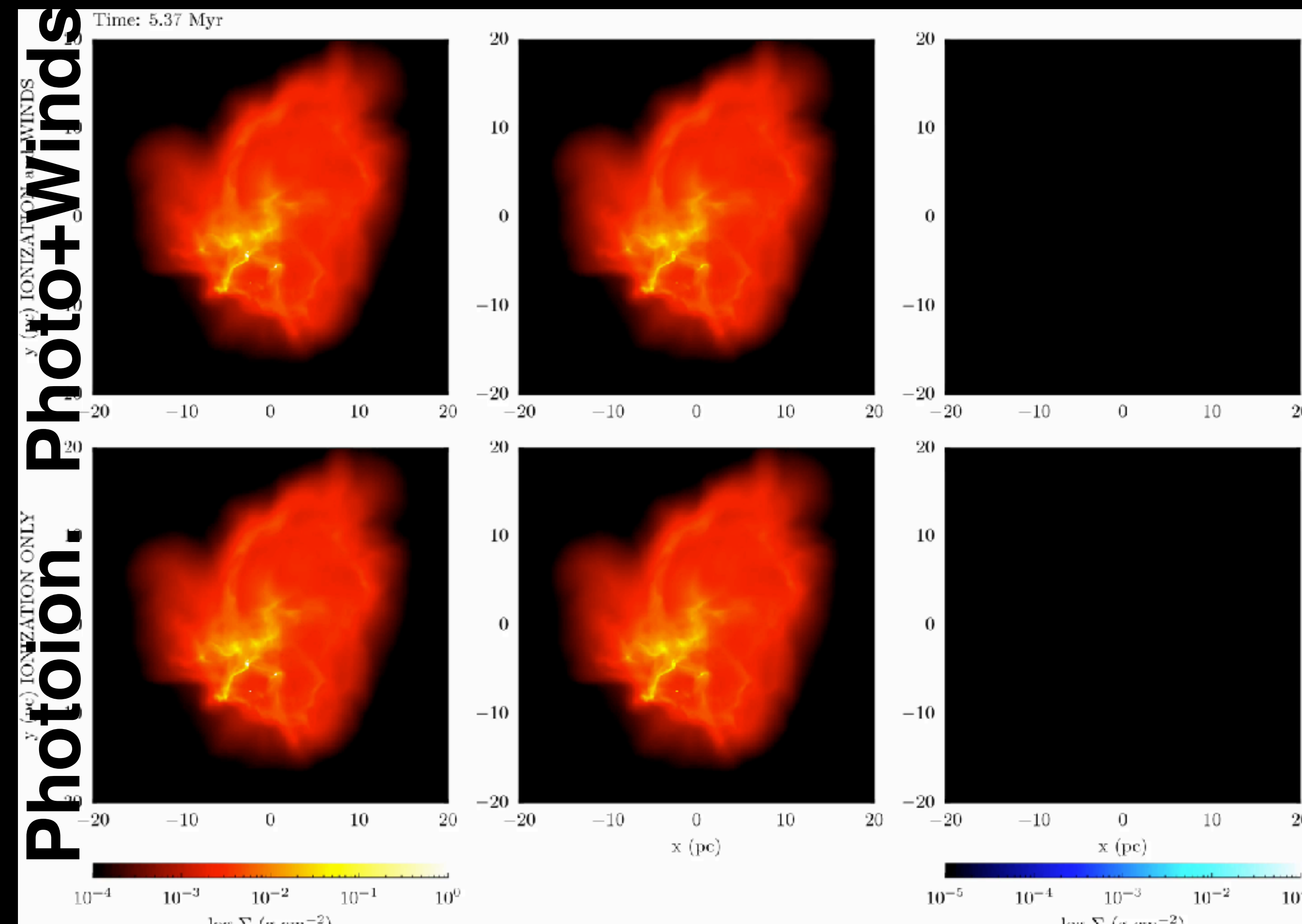
Feedback Challenge #4: Many Mechanisms

Solutions:

Theory: Incorporate many mechanisms; compare relative role of those mechanisms with e.g., age, mass, conditions



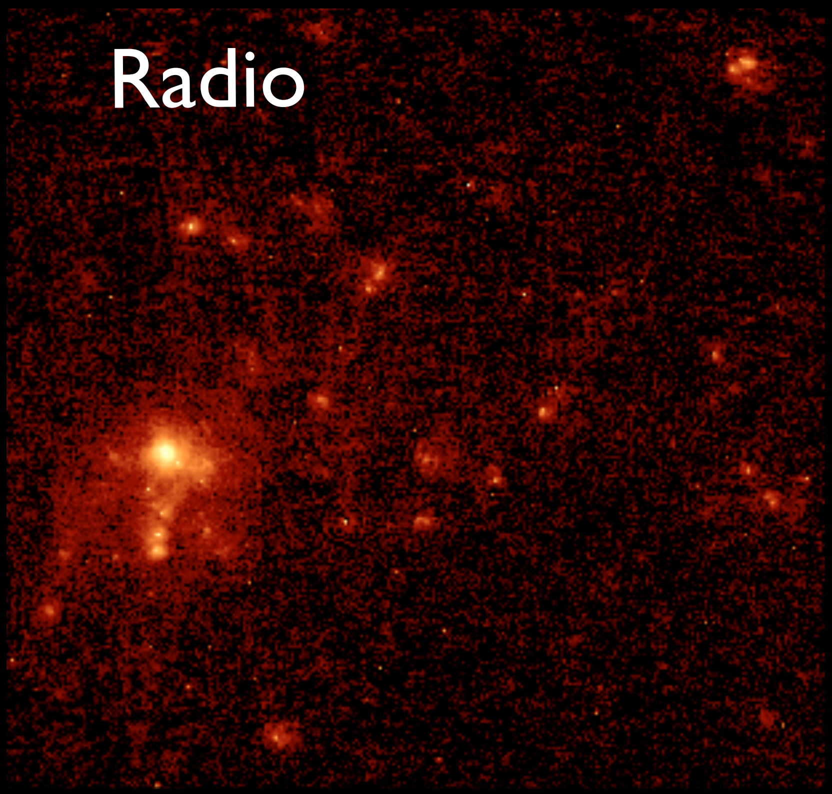
Rahner+17

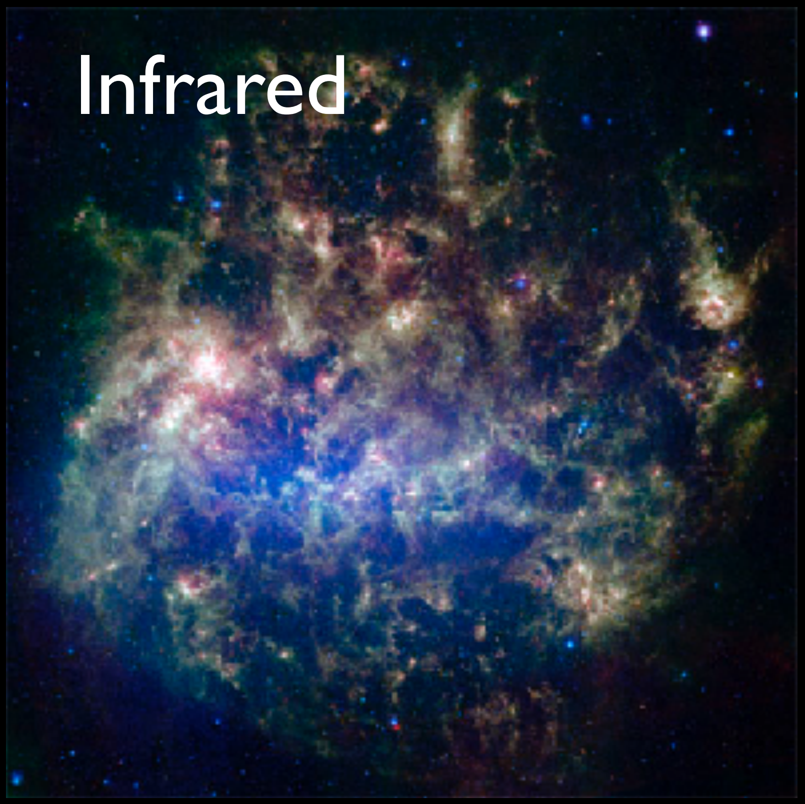


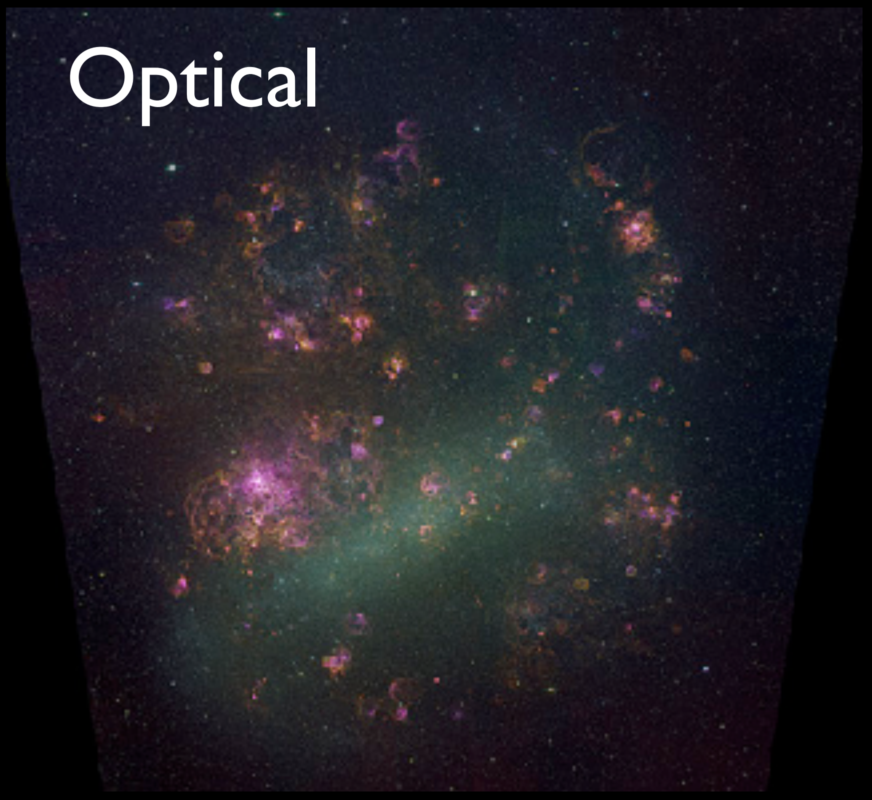
Dale+14

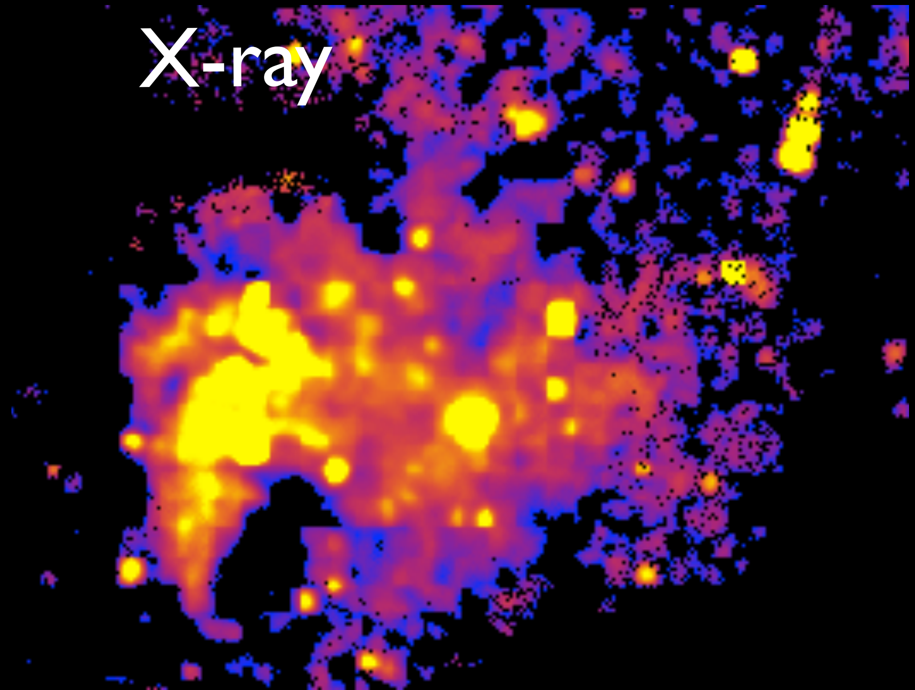
Feedback Challenge #4: Many Mechanisms

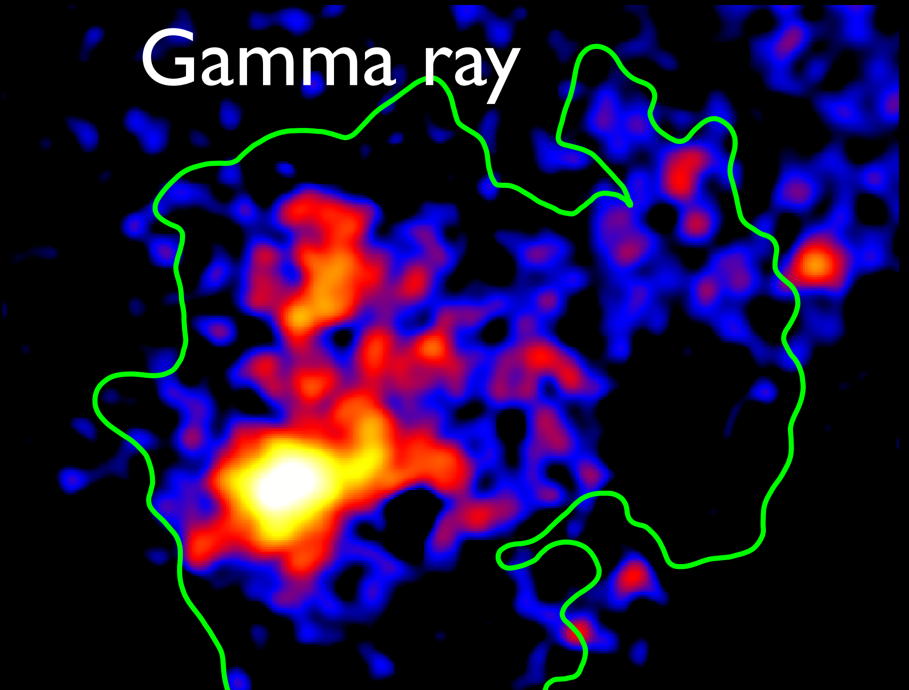
Observations: Exploit multiwavelength data; study many sources at different ages / conditions - my group's approach











Putting it All Together: Measuring Feedback Observationally

Measuring pressures associated with each mechanism

Pressure Source	Direct Radiation from stars
Relation	$P_{dir} = u_{\nu} = \frac{3L_{bol}}{4\pi r^2 c}$
Methods	UBV photometry or radio free-free emission $\rightarrow L_{bol}$
Data	Optical or Radio

LL+11, LL+14, Olivier+20

Putting it All Together: Measuring Feedback Observationally

Measuring pressures associated with each mechanism

Pressure Source	Direct Radiation from stars	Dust-Processed Radiation
Relation	$P_{dir} = u_\nu = \frac{3L_{bol}}{4\pi r^2 c}$	$P_{IR} = \frac{1}{3} u_\nu$
Methods	UBV photometry or radio free-free emission $\rightarrow L_{bol}$	IR SED modeling (e.g., Draine & Li 2007) $\rightarrow u_\nu$
Data	Optical or Radio	Infrared

LL+11, LL+14, Olivier+20

Putting it All Together: Measuring Feedback Observationally

Measuring pressures associated with each mechanism

Pressure Source	Direct Radiation from stars	Dust-Processed Radiation	Photoionization (Warm HII Gas)
Relation	$P_{dir} = u_\nu = \frac{3L_{bol}}{4\pi r^2 c}$	$P_{IR} = \frac{1}{3} u_\nu$	$P_{HII} = n_{HII} k T_{HII}$
Methods	UBV photometry or radio free-free emission $\rightarrow L_{bol}$	IR SED modeling (e.g., Draine & Li 2007) $\rightarrow u_\nu$	Obtain n_{HII} using flux density of free-free emission
Data	Optical or Radio	Infrared	Radio

LL+11, LL+14, Olivier+20

Putting it All Together: Measuring Feedback Observationally

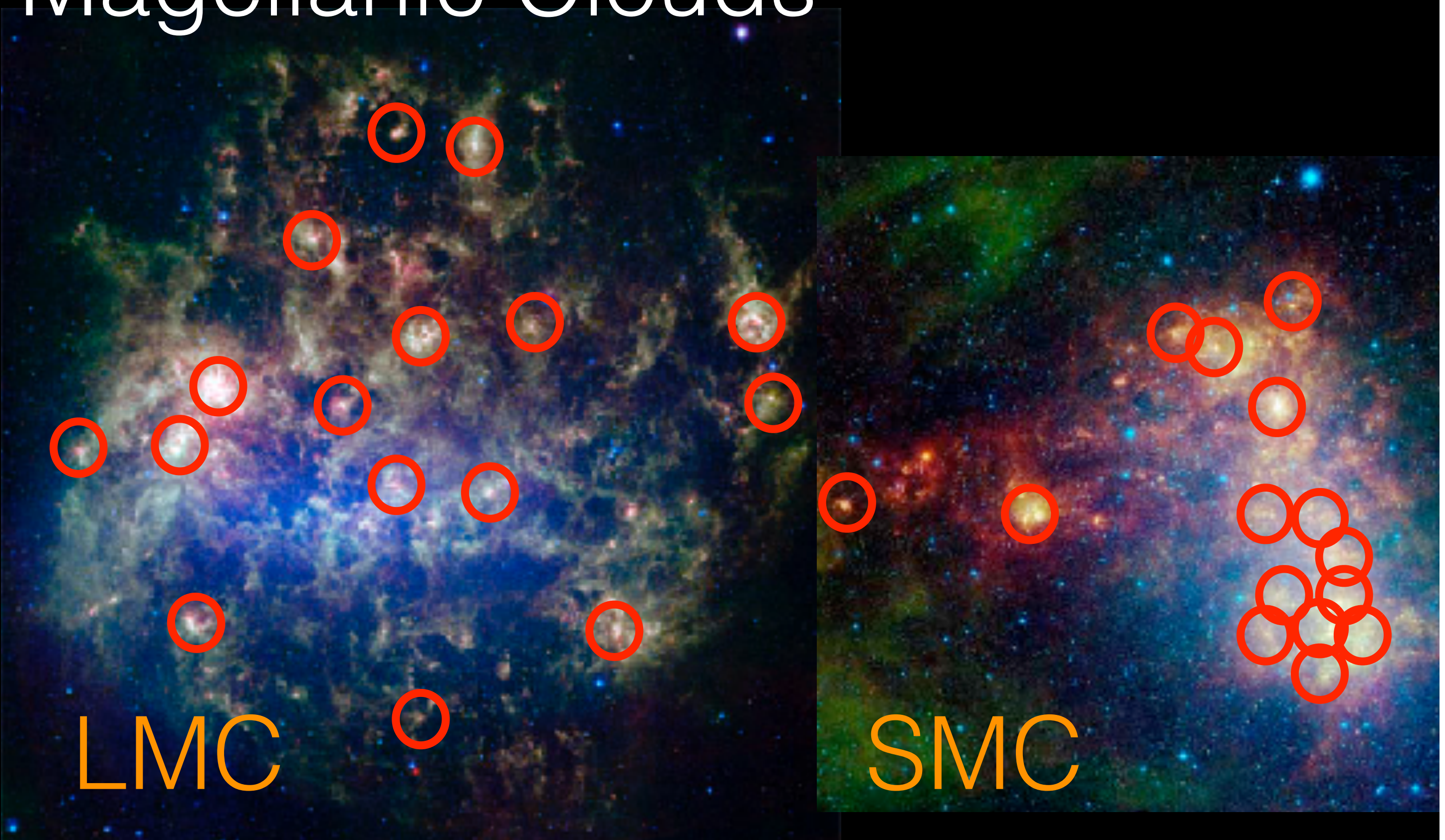
Measuring pressures associated with each mechanism

Pressure Source	Direct Radiation from stars	Dust-Processed Radiation	Photoionization (Warm HII Gas)	Stellar Winds/ SNe (Hot Gas)
Relation	$P_{dir} = u_\nu = \frac{3L_{bol}}{4\pi r^2 c}$	$P_{IR} = \frac{1}{3} u_\nu$	$P_{HII} = n_{HII} k T_{HII}$	$P_x = 2\, n_x k T_x$
Methods	UBV photometry or radio free-free emission $\rightarrow L_{bol}$	IR SED modeling (e.g., Draine & Li 2007) $\rightarrow u_\nu$	Obtain n_{HII} using flux density of free-free emission	X-ray spectral modeling of bremsstrahlung
Data	Optical or Radio	Infrared	Radio	X-ray

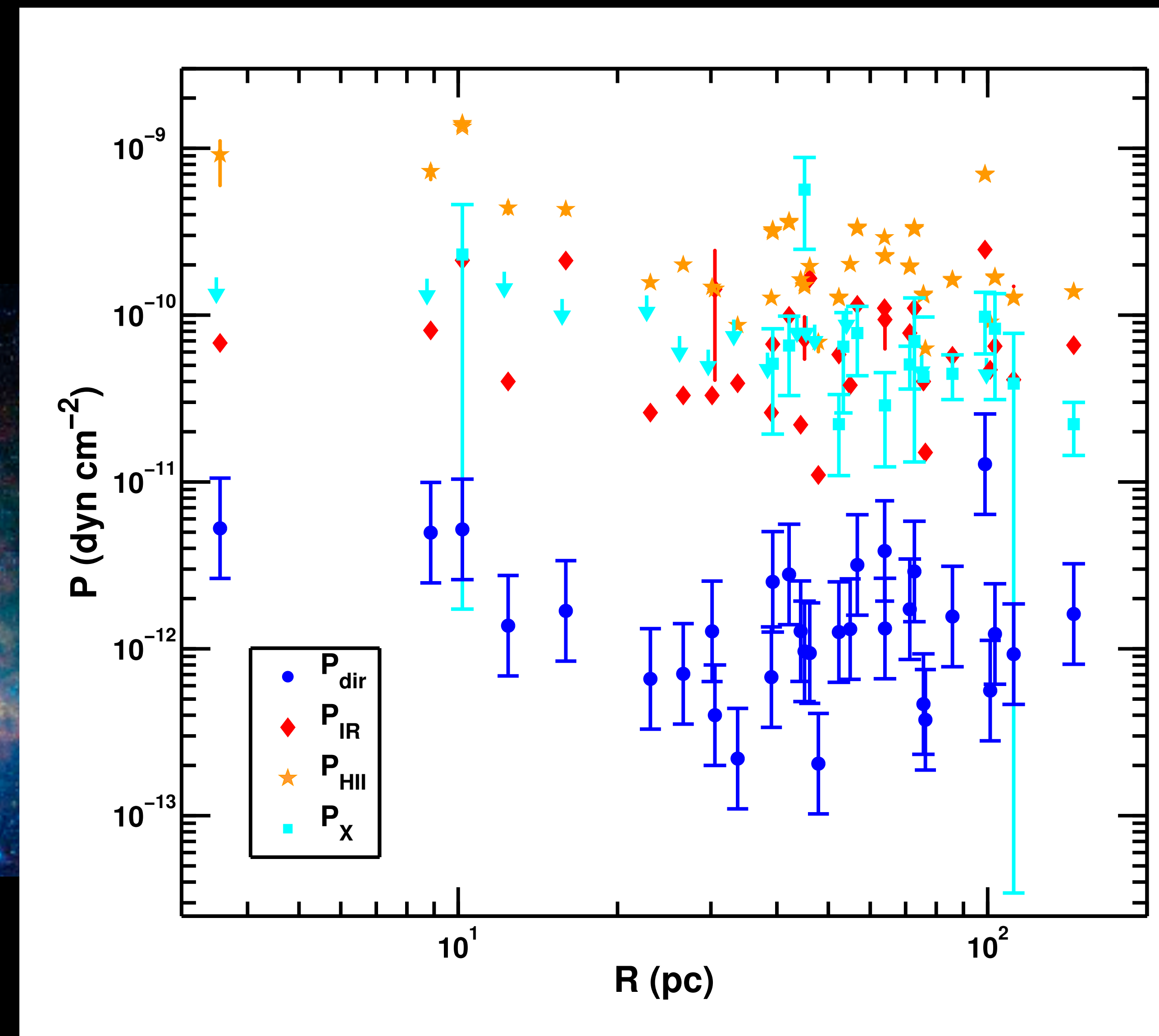
LL+11, LL+14, Olivier+20

Putting it All Together: Measuring Feedback Observationally

HII Regions in the Magellanic Clouds



Spitzer SAGE, SAGE-SMC Teams



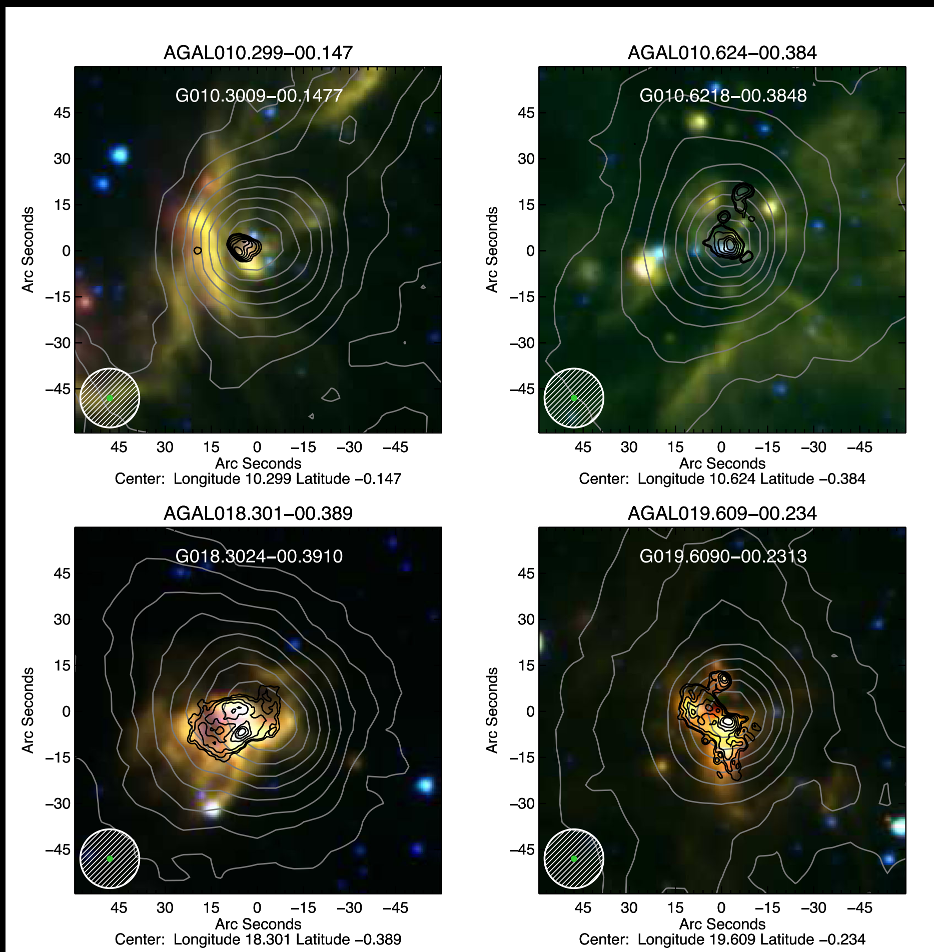
LL+14

R ~ 3-200 pc
n ~ 1 cm^{-3}

Photoionization > Dust-Processed Radiation > Winds/SNe > Direct Radiation

Putting it All Together: Measuring Feedback Observationally

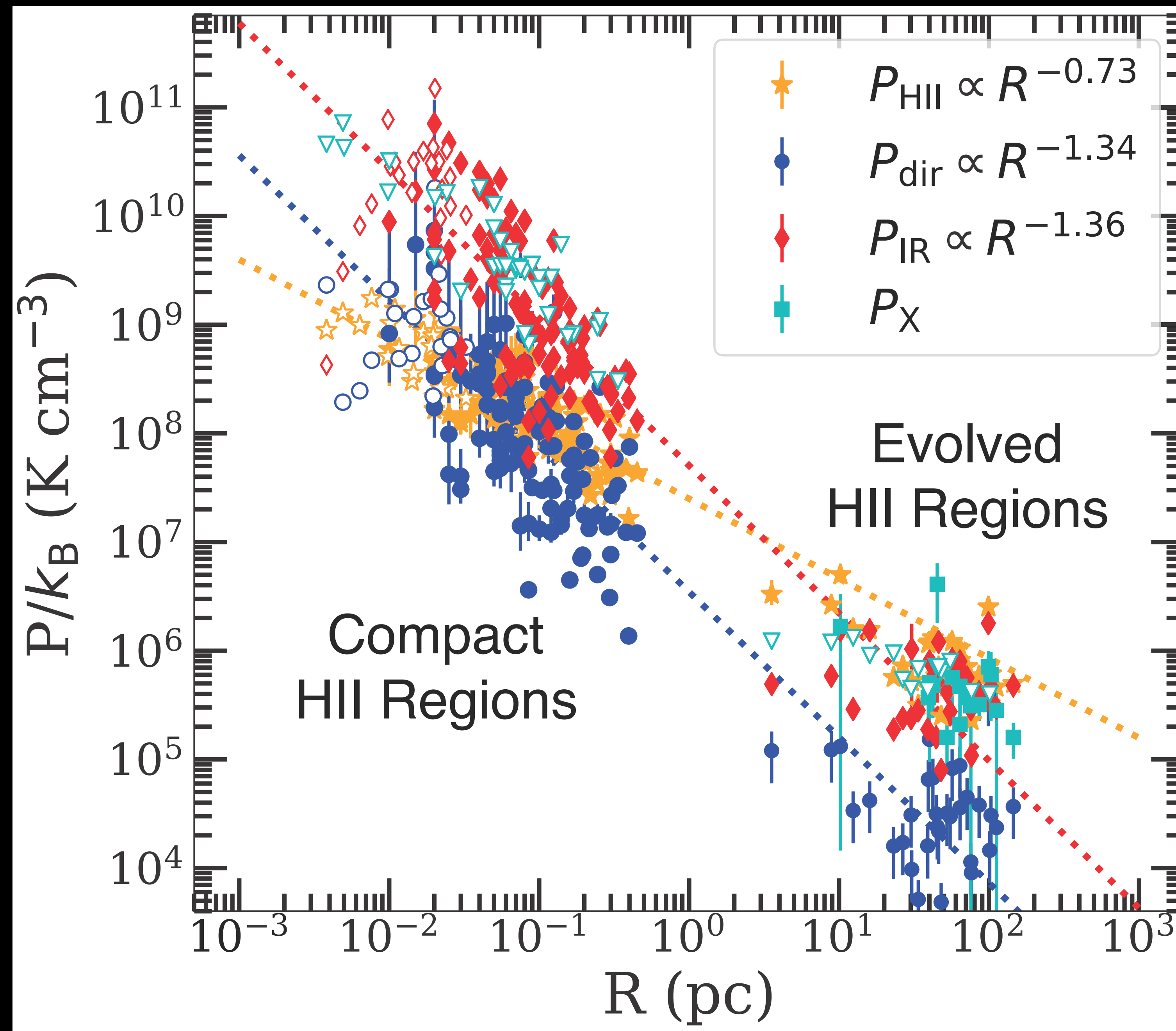
Compact HII Regions



Urquhart+13

$n > 10^4$ cm^{-3}

R < 0.1 pc



Olivier, LL+20, arXiv:2009.10079

Dust-Processed Radiation > Photoionization ~ Direct Radiation (Winds ?)

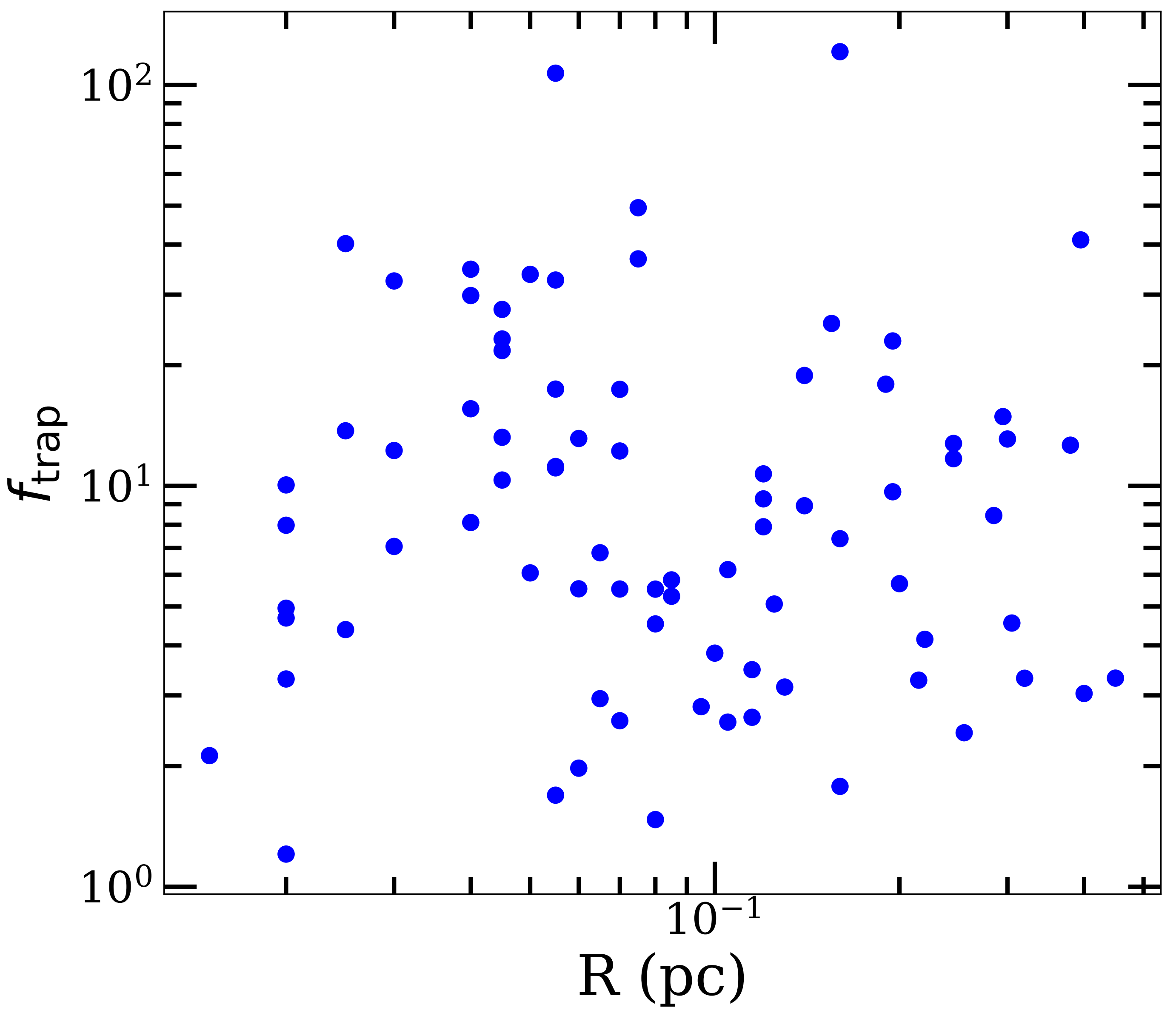
Putting it All Together: Measuring Feedback Observationally

$f_{trap} = 1 + P_{IR}/P_{dir}$ has a median of ~8

No trend in f_{trap} with HII region radius < 0.5 pc

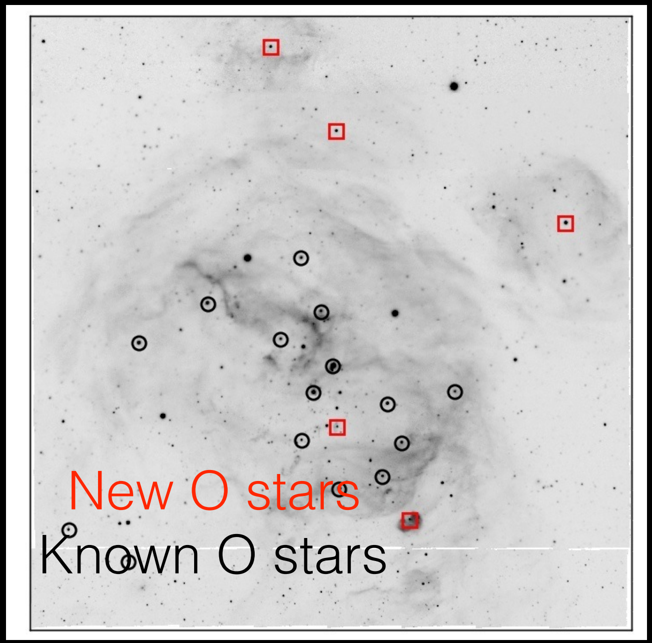
$$\dot{E}_{\rm rad} = f_{\rm trap} L_{\rm bol}$$

$$\dot{p}_{\rm rad} = \frac{\dot{E}_{\rm rad}}{c}$$



Olivier, LL+20, arXiv:2009.10079

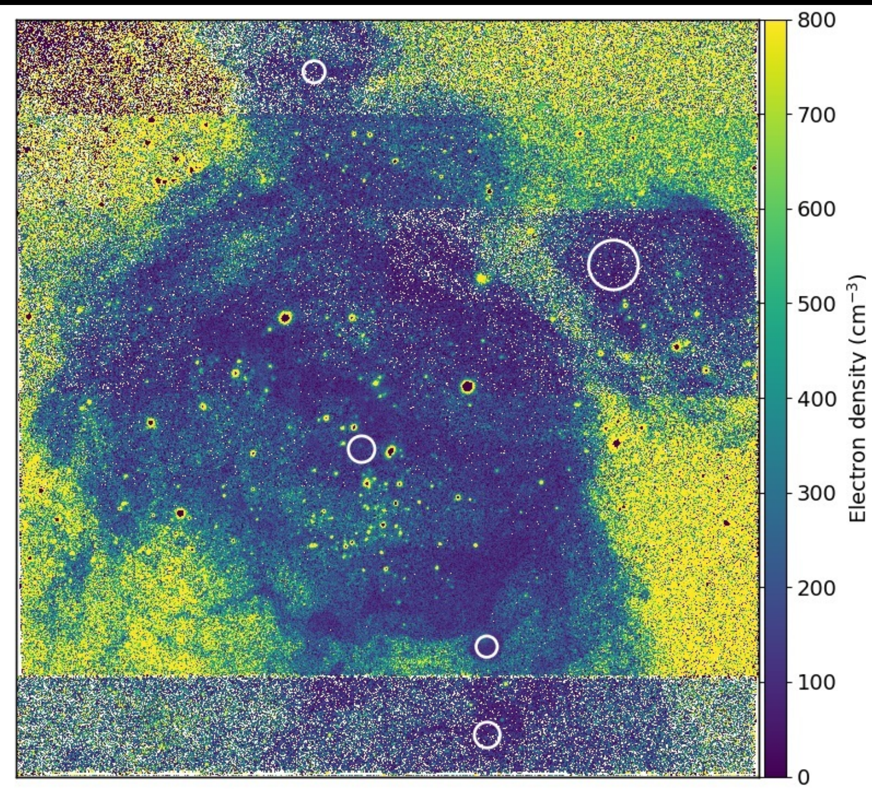
Putting it All Together: Measuring Feedback Observationally



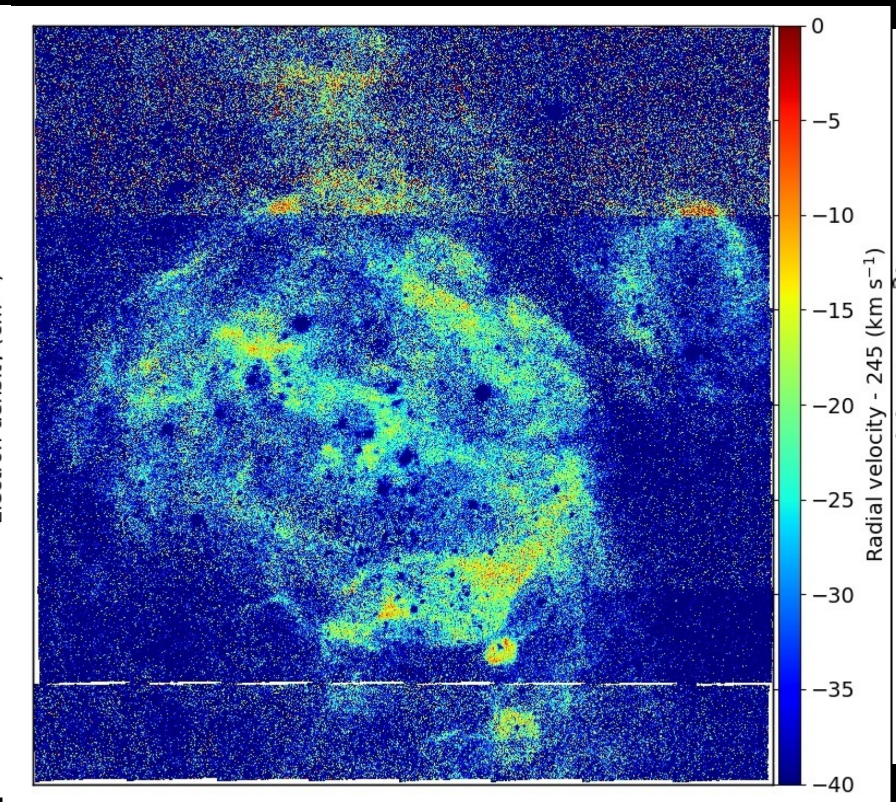
Integral field spectroscopy enables characterization of the stellar content powering HII regions as well as measurement of their gas properties (e.g., density, kinematics)

McLeod+19

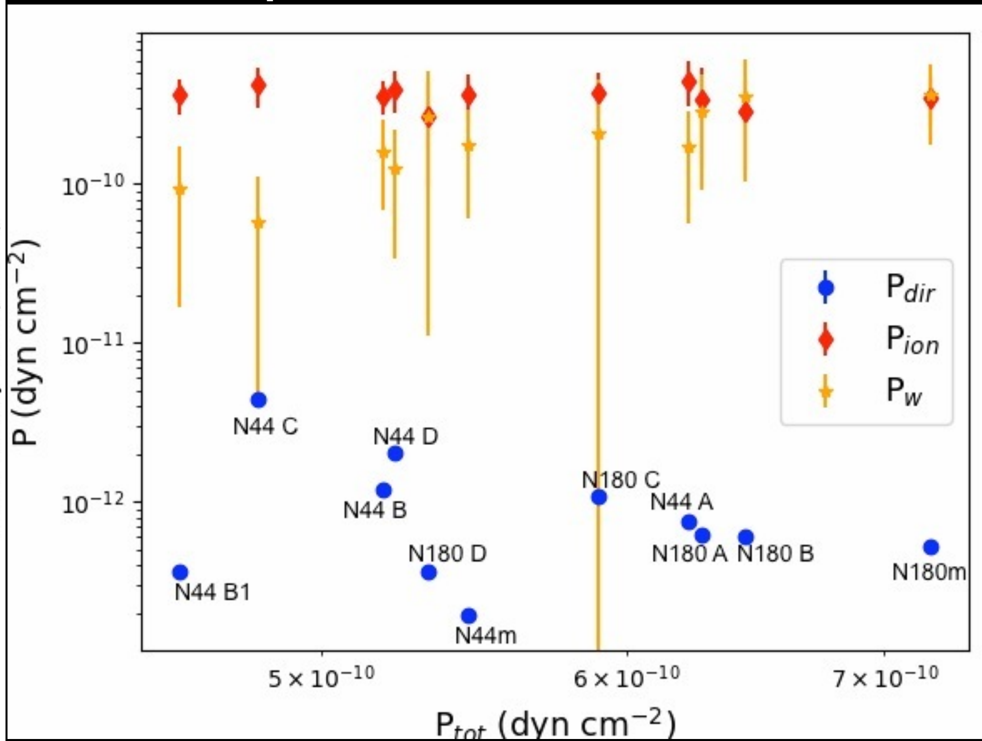
Density structure



Velocity structure

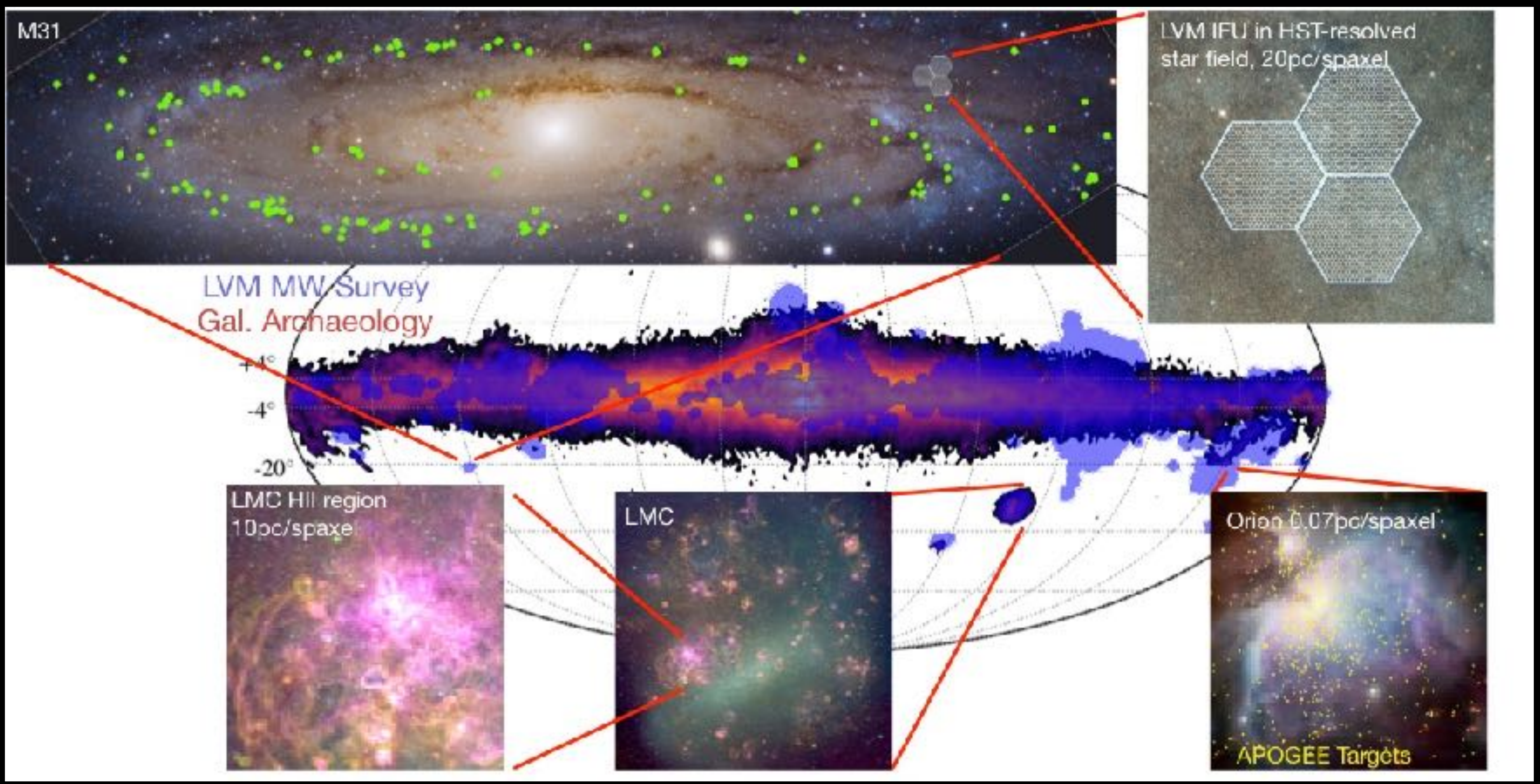


Feedback pressures



Future: Measuring Feedback Observationally with SDSS-V

SDSS-V Local Volume Mapper (LVM) will survey the Milky Way, SMC, LMC, M31, and other Local galaxies doing IFS. It will connect small (tens of pc) to large (kpc) scales.

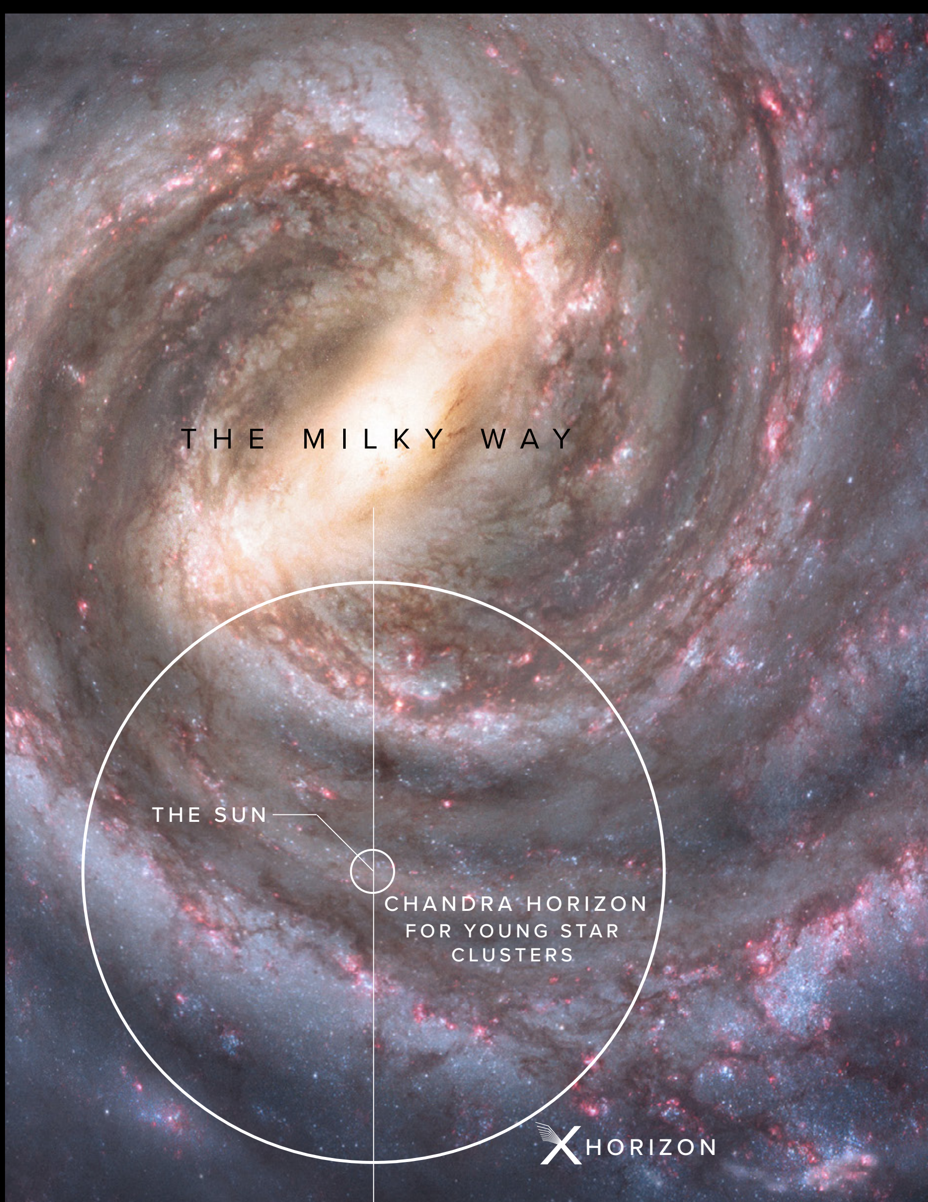


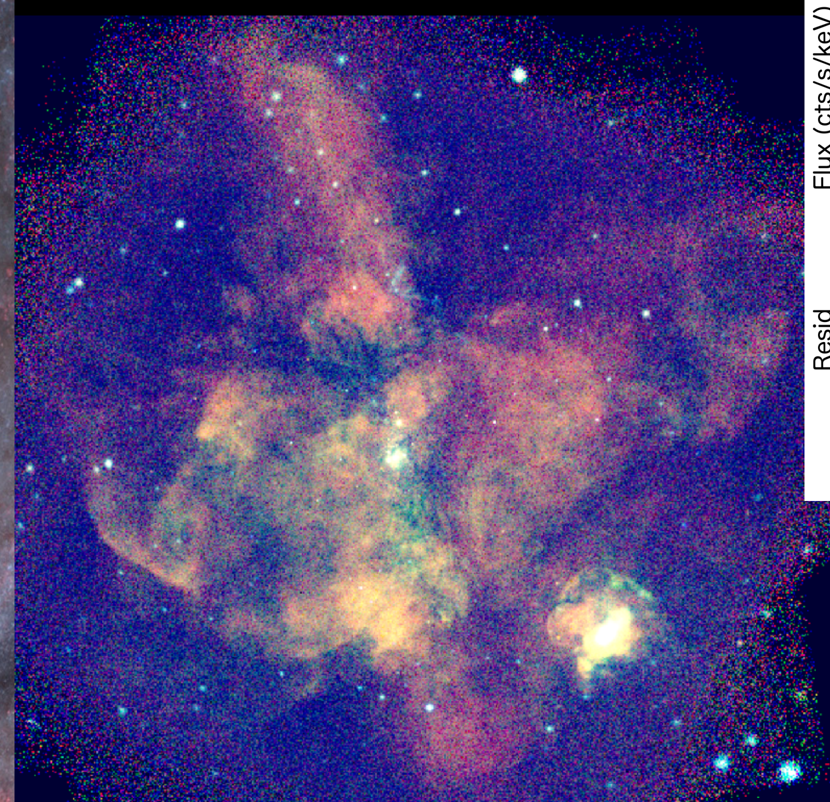
Kollmeier+17 https://www.sdss.org/future/lvm/

Future: Measuring Feedback Observationally with Lynx

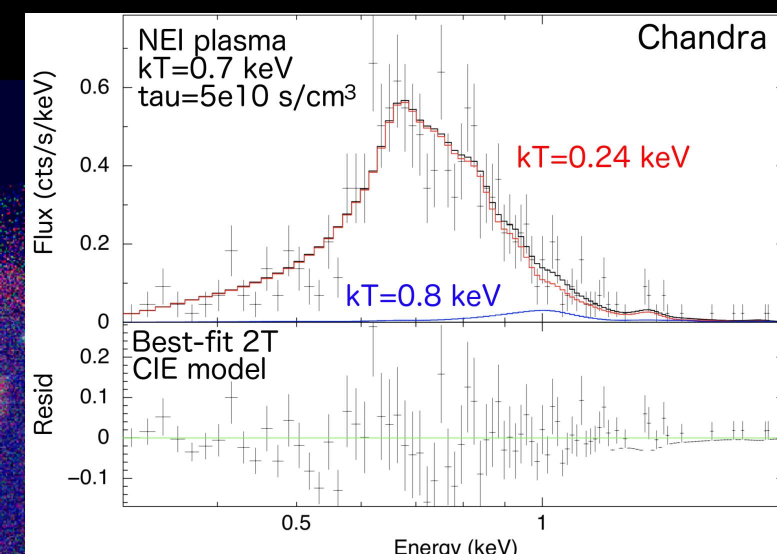
Lynx (successor to *Chandra*) will enable inventories of star clusters and hot gas from feedback

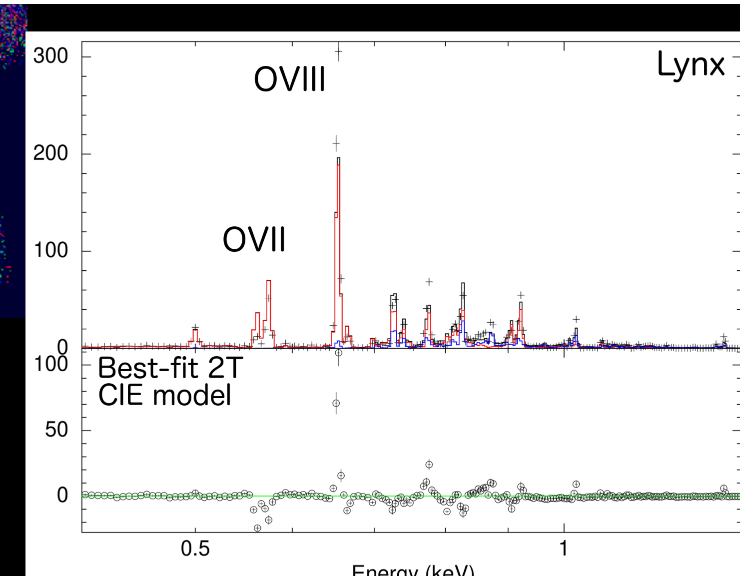
Detect X-rays from all stars (brown dwarfs up to O/WR stars) out to d ~ 5 kpc through column densities of $N_H \sim 10^{23}$ cm^{-2}





2 Ms *Chandra*
~10 ks *Lynx*





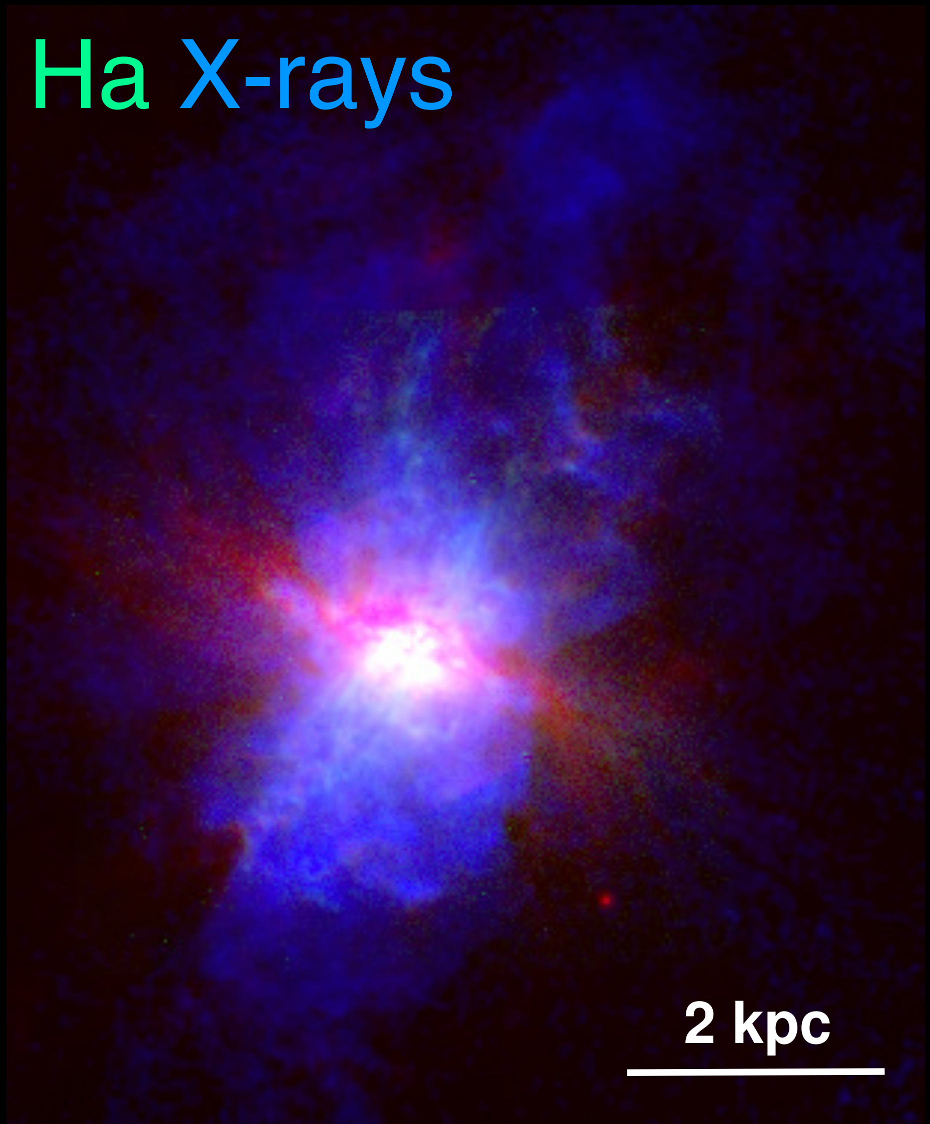
Hodges-Kluck, LL+19
arXiv: 1903.09692

Larger Scales: Galactic Outflows

Galaxy-scale outflows driven by star formation are ubiquitous (Heckman+90, Veilleux+05, Rubin+14)

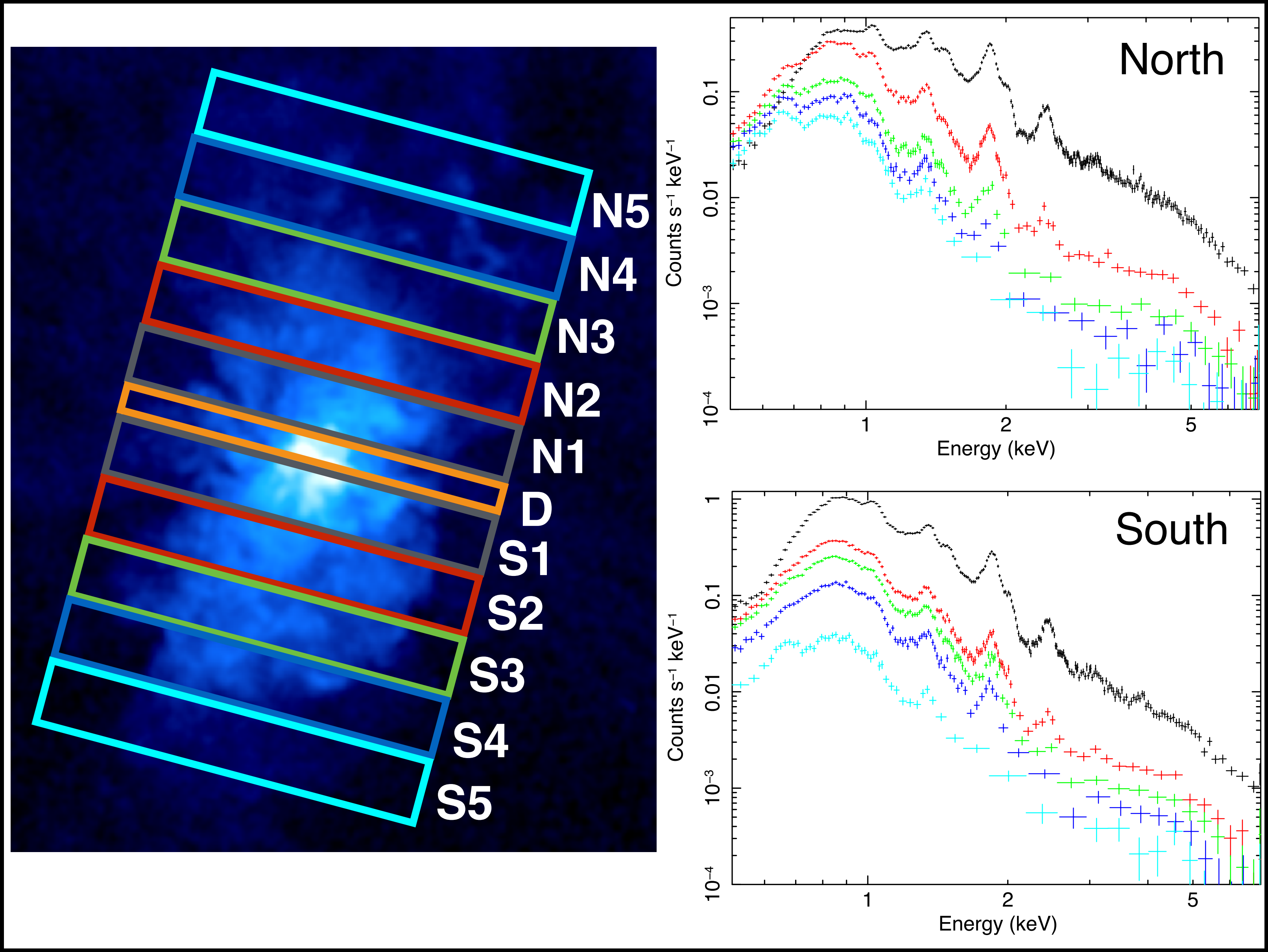
Prevailing picture is that outflows are driven by hot gas shock-heated by SNe that entrains dust, cold, and warm gases in the flow (e.g., Chevalier & Clegg 85)

Many open questions remain: how does the hot wind couple to the cooler clouds? How does the wind evolve, and how many metals does it carry?



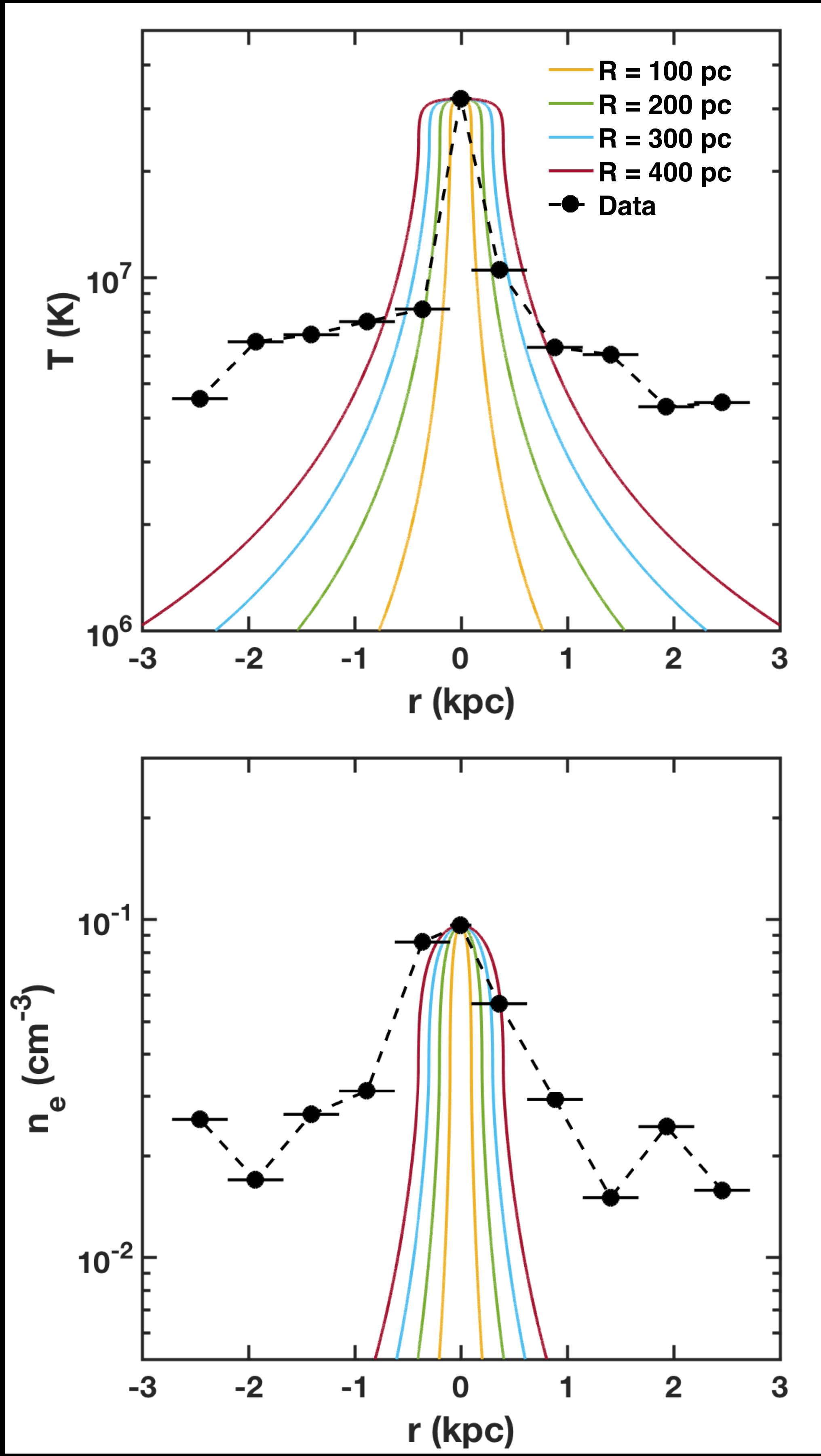
Lopez+20b

Galaxy-Scale Outflows

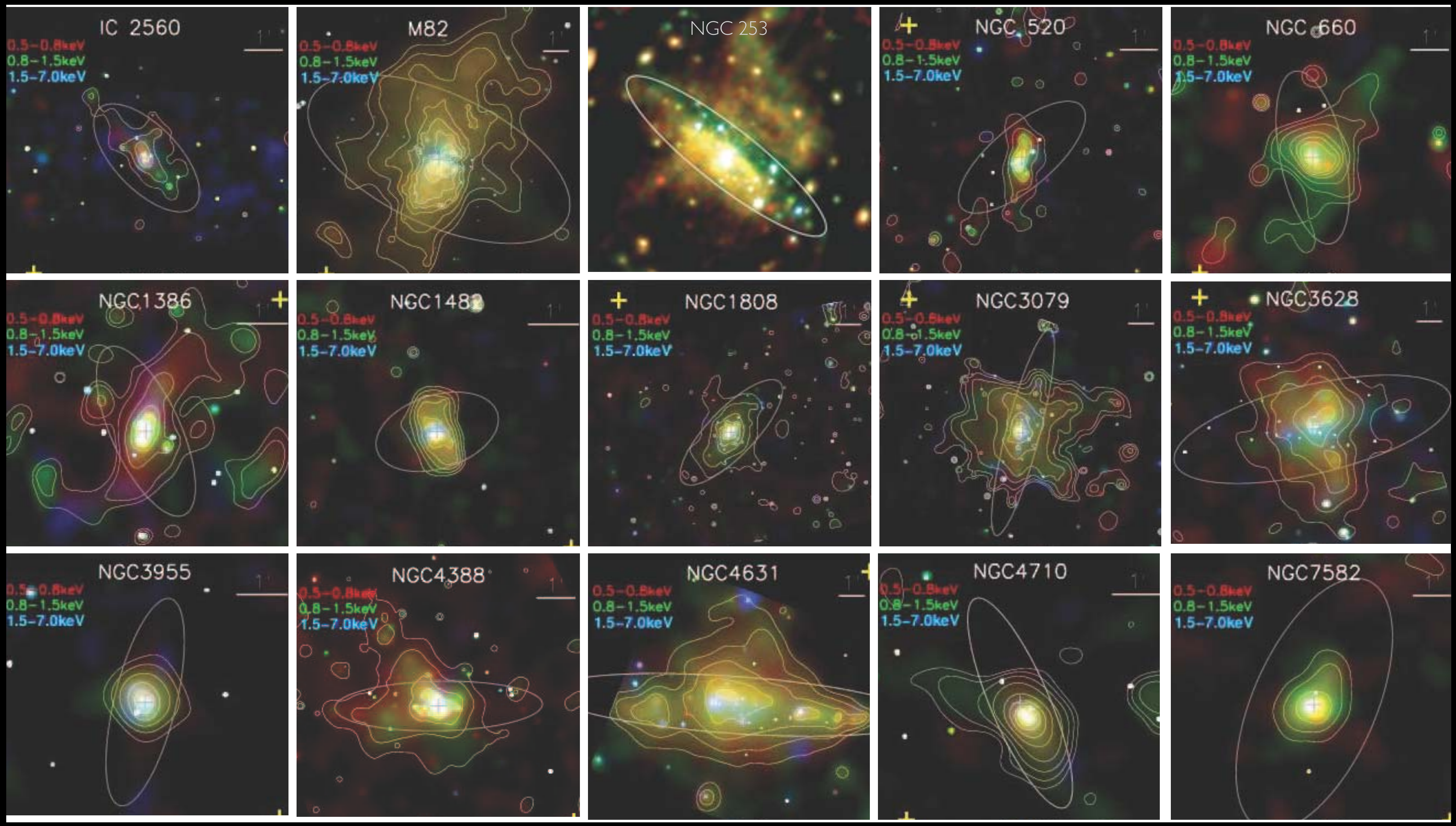


Lopez+20b, arXiV:2006.08623

Temperature and density profiles are broader than expected for adiabatic expansion, suggesting mass-loading / mixing with cooler phase.



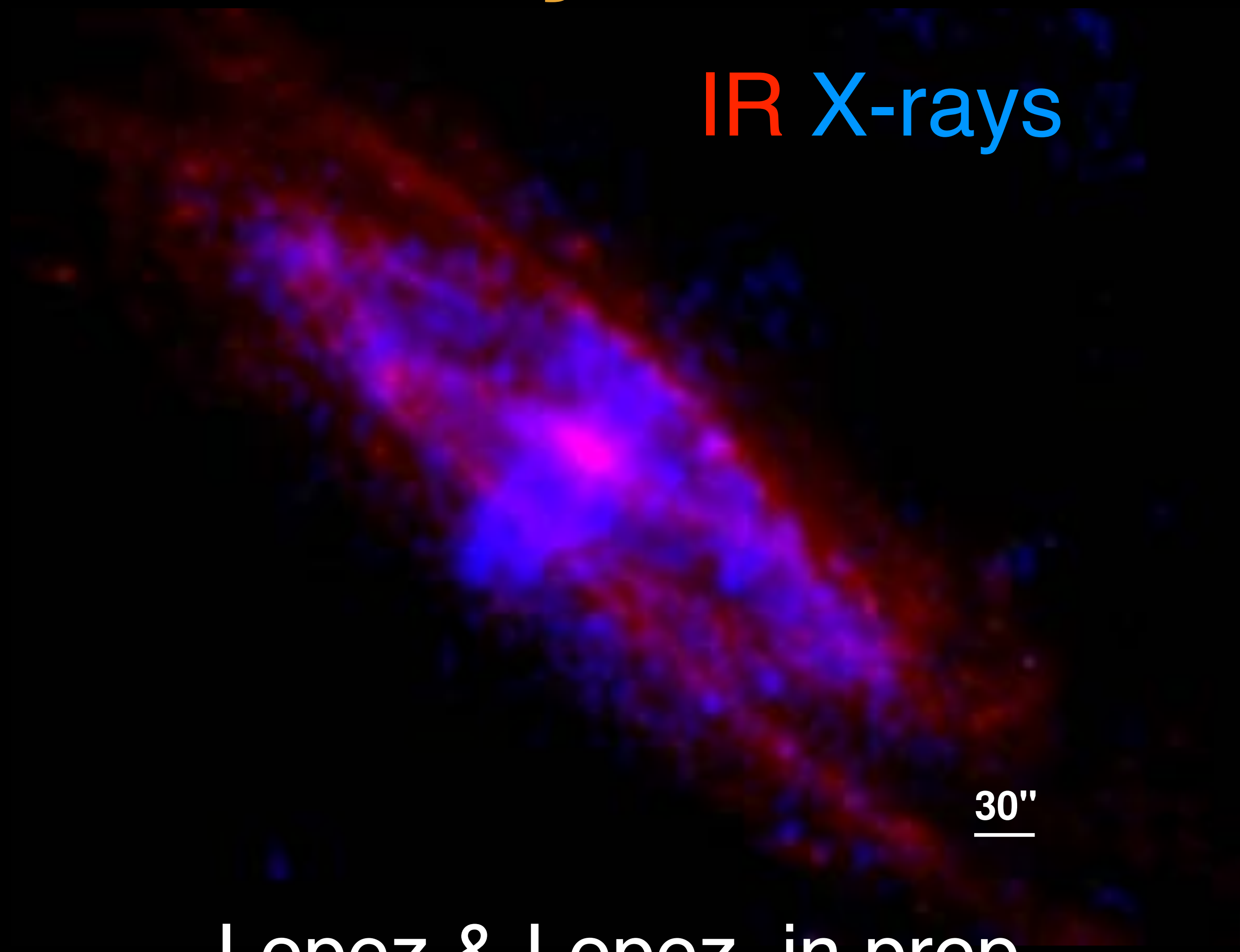
Future: Galaxy-Scale Outflows



Li & Wang13, Bauer+08

Conducting a similar analysis for the 15 nearby, edge-on starbursting galaxies.

Future: Galaxy-Scale Outflows



Lopez & Lopez, in prep.

We are turning next to NGC 253. We find that the diffuse X-rays trace the disk's spiral structure and doing a spatially-resolved analysis now to measure the gradients in temperature/density/metallicity of outflow.

Conclusions

Stellar feedback, the injection of energy and momentum by stars, is important on small (~1 pc) and large (>10 kpc) scales

There are many challenges to assessing feedback: 1) dynamic range; 2) need observational constraints; 3) where is the energy/momentum deposited?; 4) there are many mechanisms that vary with time & conditions

There are observational and theoretical solutions to each problem, and a lot of progress in the last 5 years assessing dynamical role of feedback on small & large scales

Multiwavelength approach enables evaluation of comparative role of feedback modes versus e.g., stellar age, conditions

X-ray and gamma-ray observations constrain presence / properties of galactic outflows from star-forming galaxies.