How Supernovae-driven **Hot** Outflows Regulate Circum-galactic Medium?

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— CGM: galactic outflows interact with cosmic inflows

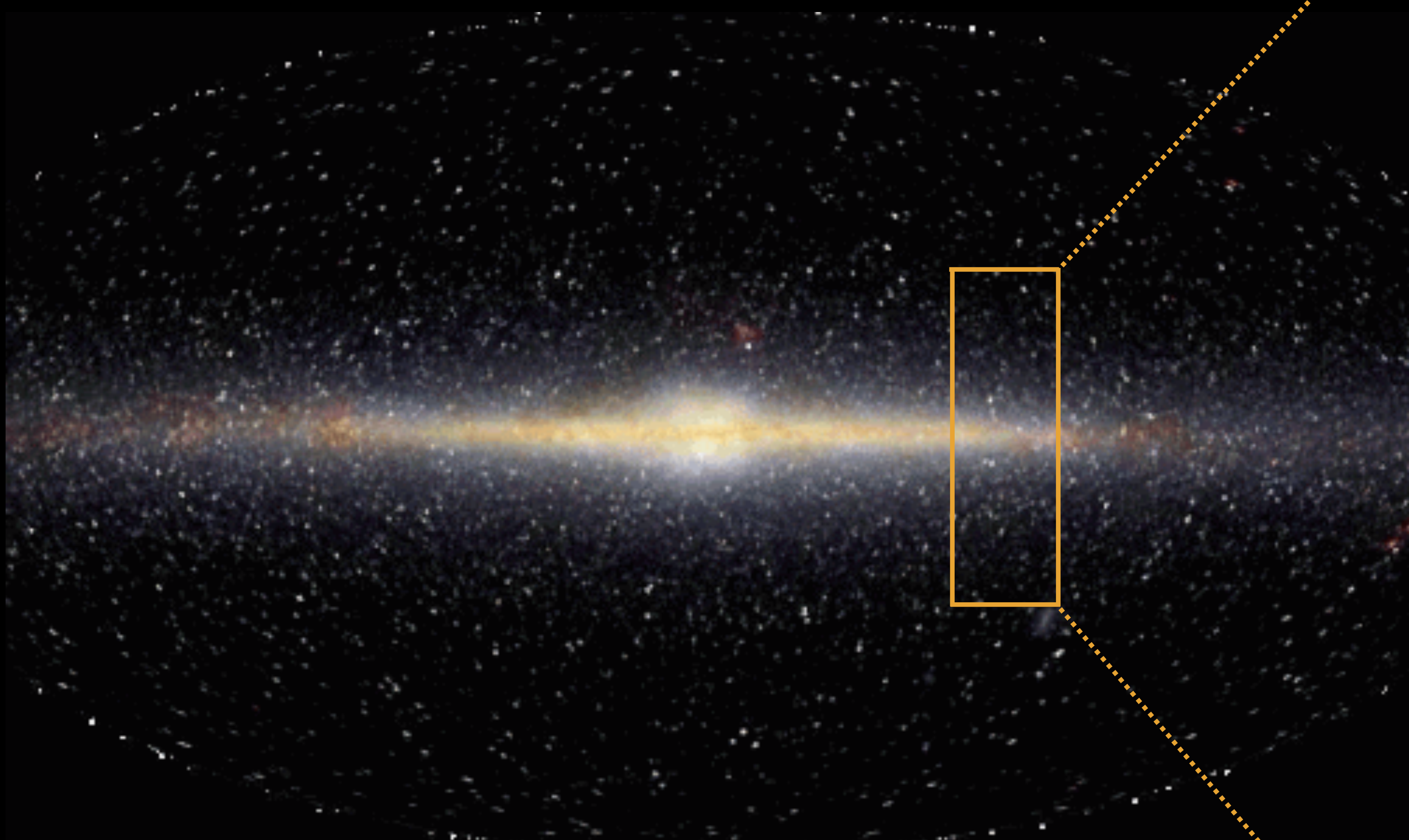
But most current feedback models rely on parameter-tuning
e.g. mass/energy/metal fluxes of outflows

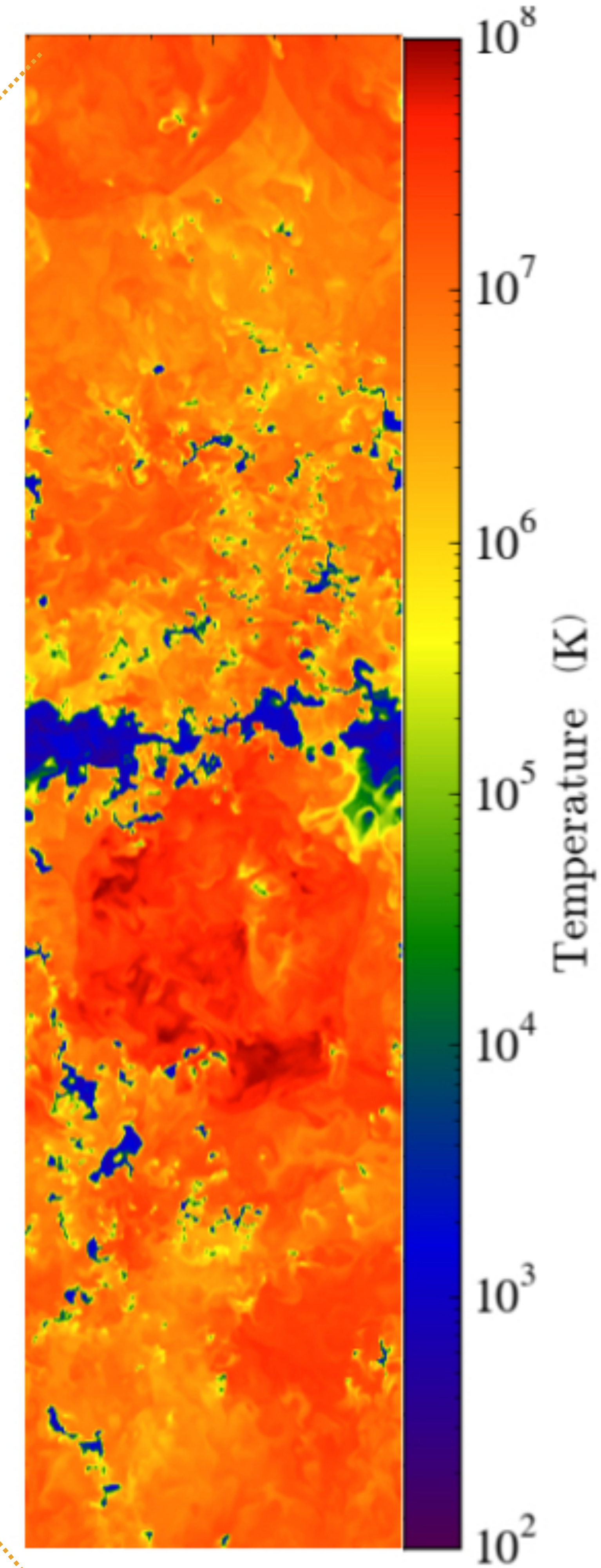
Our approach:

- *First, study SNe FB using high-resolution sims, and quantify parameters (Li+15, 17a,b)*

- *Then, use the results as sub-grid models in large-scale sims, and study its impact in galaxy formation (Li+ in prep)*

High-resolution simulations: A kpc-patch of galaxy disk





- Stratified medium, explode SNe near mid-plane
- (sub-)pc resolution, resolving multiphase ISM
- SNe self-consistently regulate ISM and launch outflows

Li+17a

image: scienceblog.com

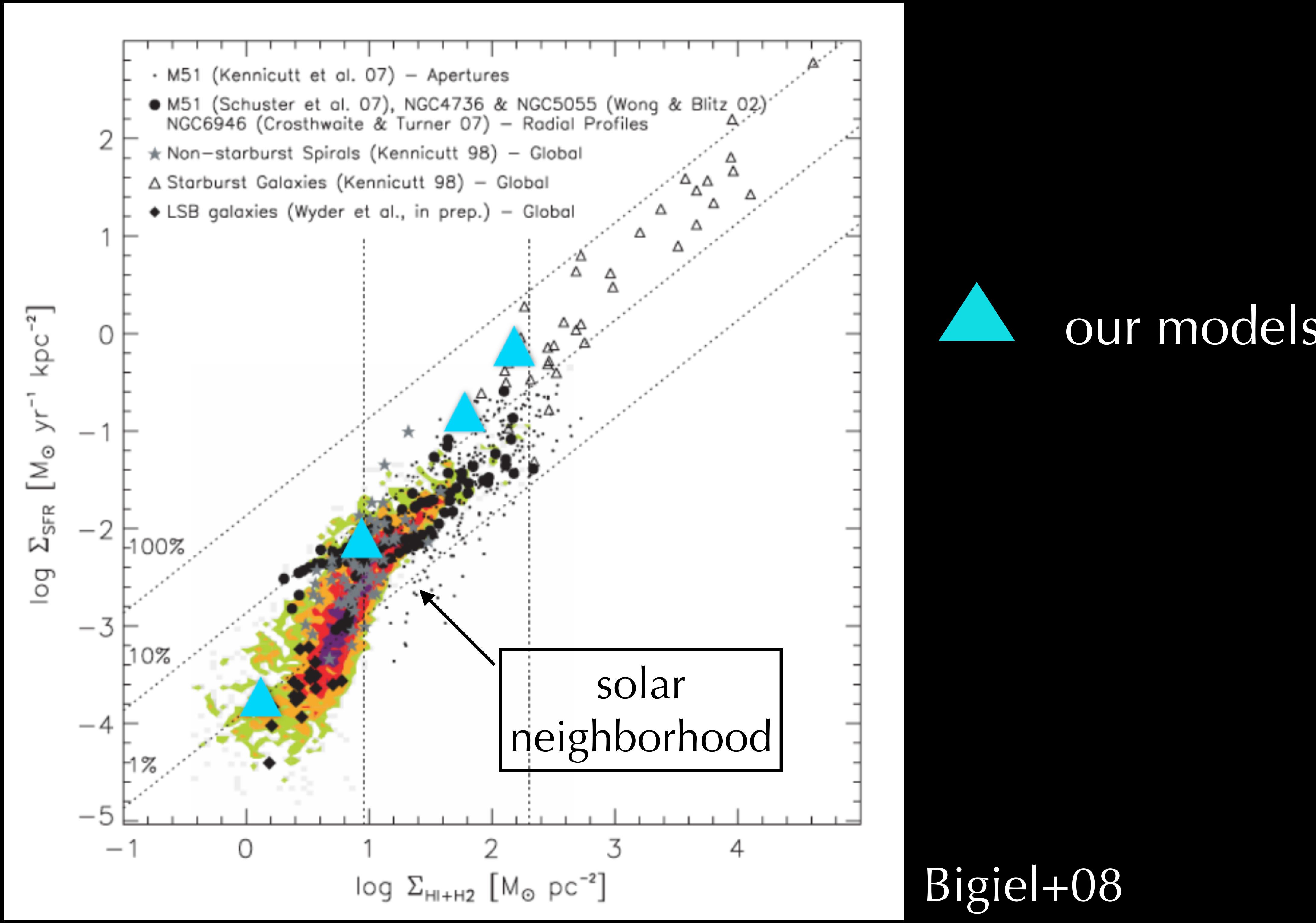
Quantify SN-driven outflows —

- Mass loading $\eta_m \equiv \dot{M}_{outflow} / \dot{M}_{SFR}$
- Energy loading $\eta_E \equiv \dot{E}_{outflow} / \dot{E}_{SN}$
- Metal loading $\eta_{metal} \equiv \dot{M}_{metal,out} / \dot{M}_{metal,\ SN}$

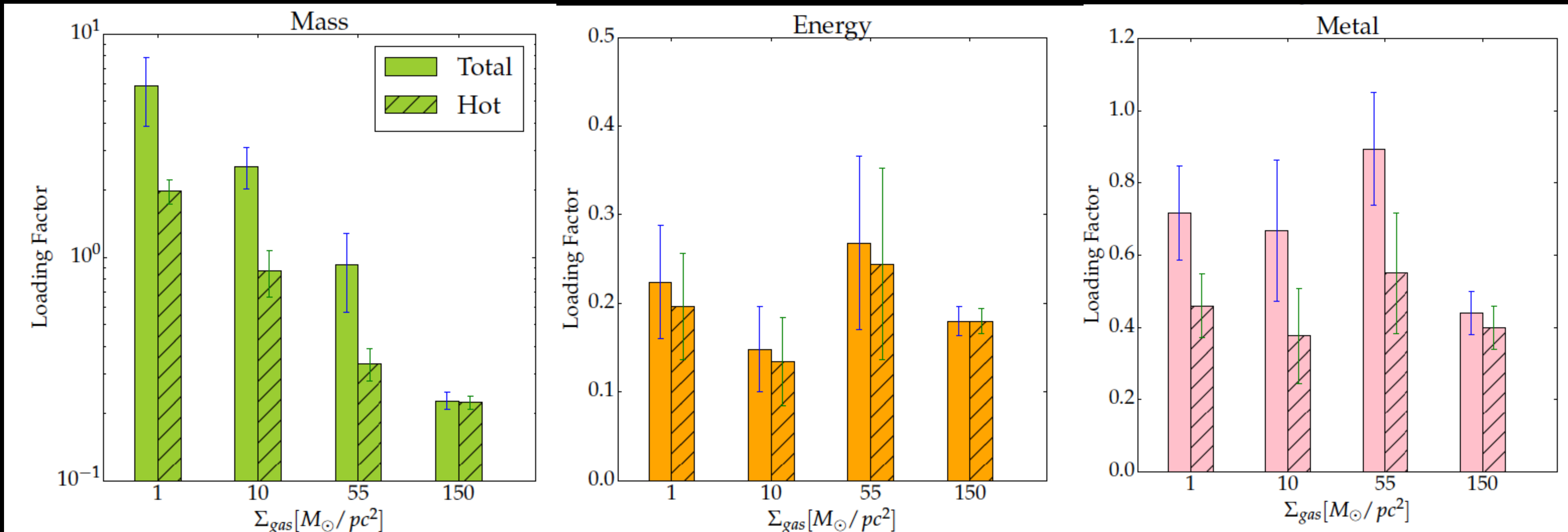
Loading factors measured at 1-2.5 kpc above the disk

input (Σgas, ΣSFR) along Kennicutt relation

ΣSFR= 150 Msun * ΣSN



Bigiel+08



$\eta_{m,h} \propto \Sigma_{SFR}$ ^-0.44

$\eta_{E,h} \sim 0.25 +/- 0.1$

$\eta_{metal,h} \sim 0.5 +/- 0.1$

- hot gas carries most energy flux

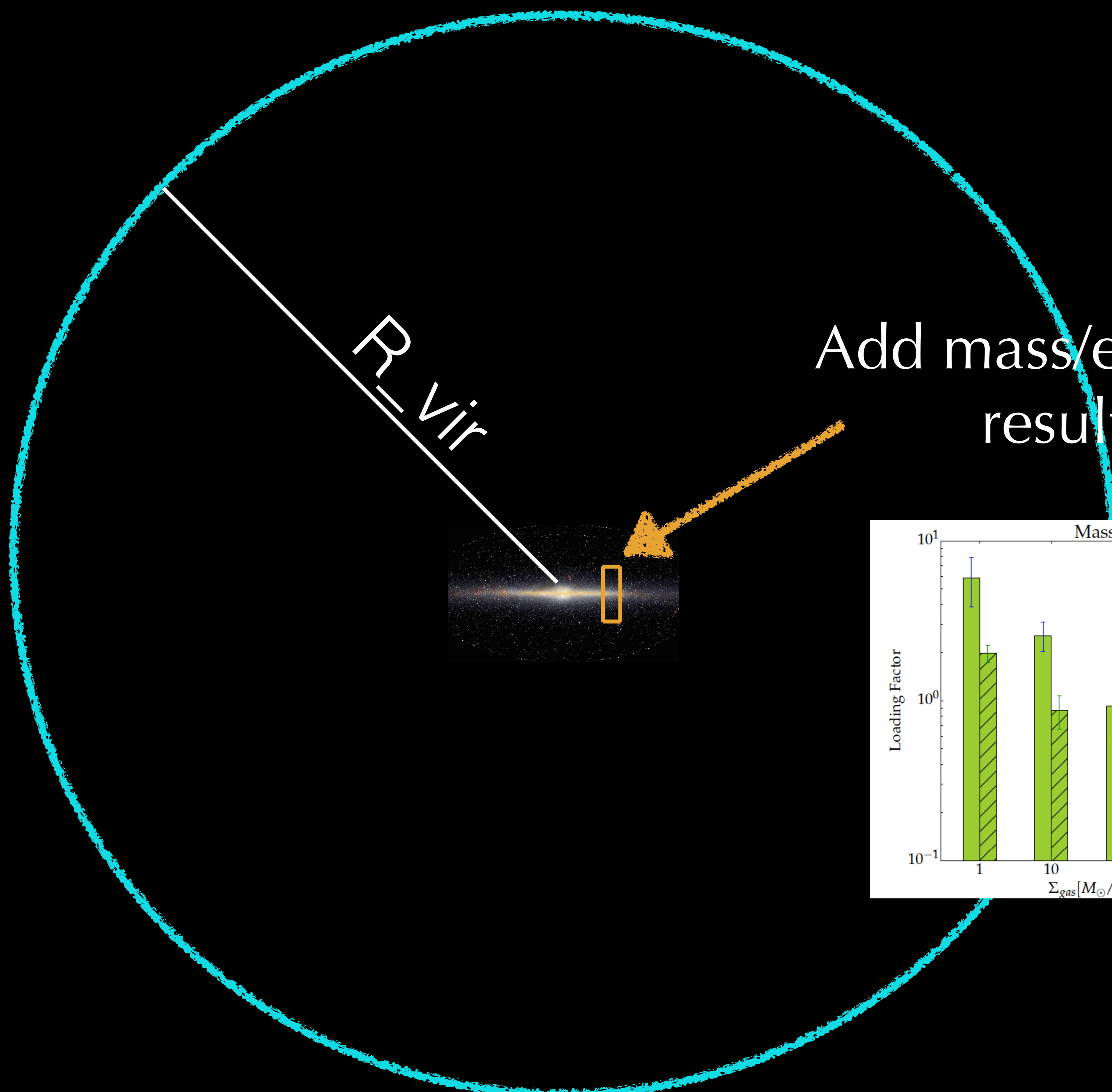
- hot gas carries most metal flux
- Metallicity: hot gas > ISM mean

Hot: T~ 10^6-7K;
the only phase that can travel far

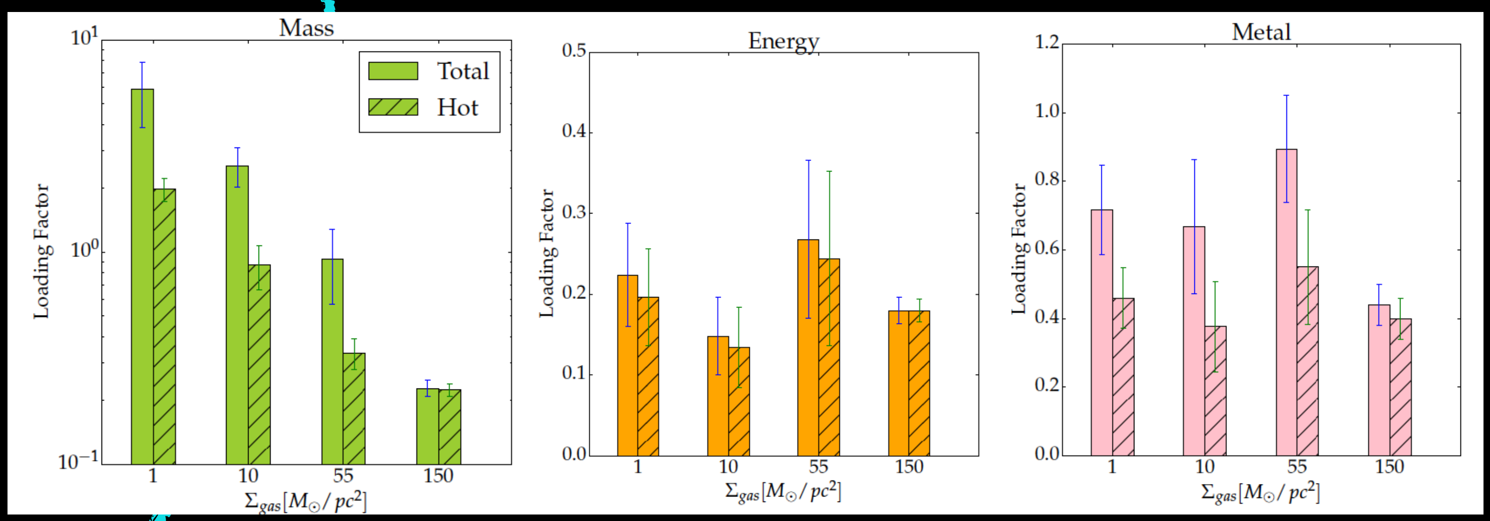
Li+17a

Galaxy-scale simulation

Larger box,
coarser resolution (0.5kpc)



Add mass/energy/metals fluxes according to results of small-box simulations



Add only hot outflows

image: scienceblog.com

Hot gas around MW-like galaxies: What are observed?

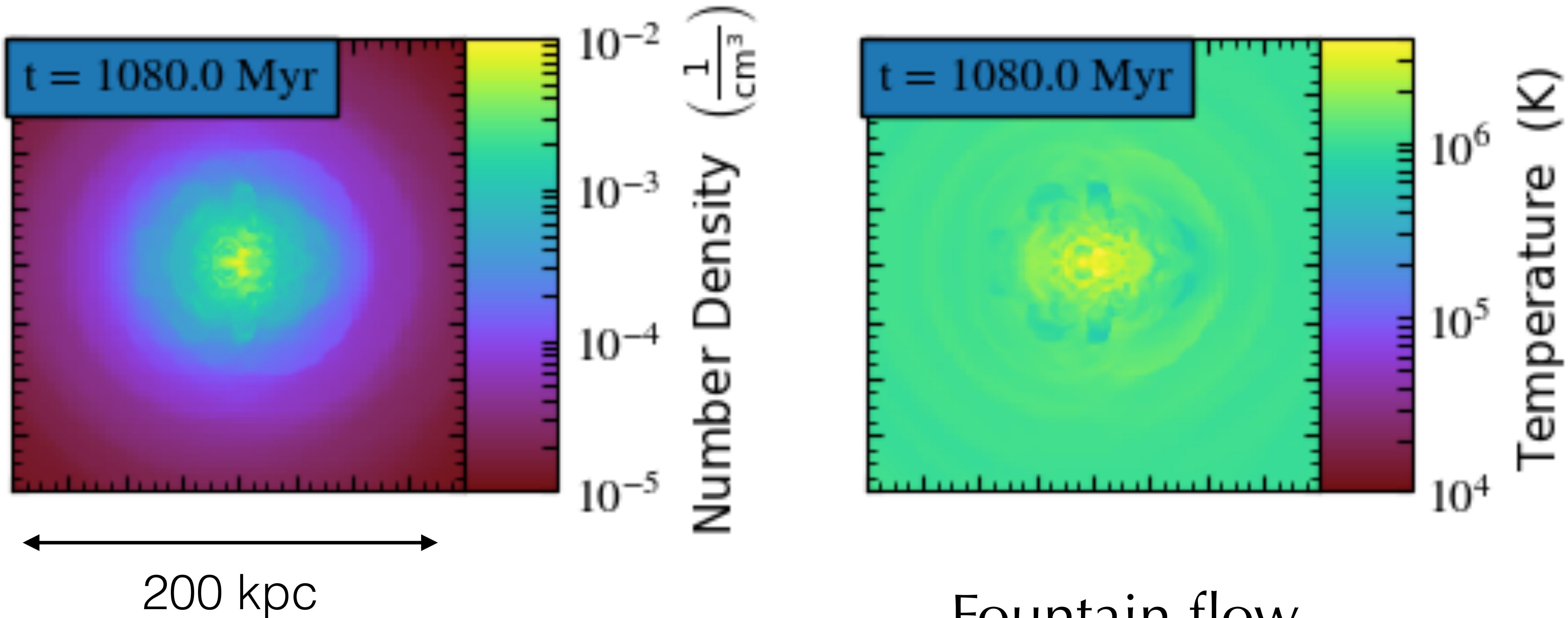
- Metals exist far away from MW-like galaxy: >~150 kpc (e.g. Tumlinson+11)
- Galaxy corona X-ray emission: a few percent of SN energy (e.g. Anderson+10, Mineo+12, Li & Wang13)
- MW: n(R~50 kpc) ~ 10^{-4} cm^{-3} (ram pressure stripping of LMC (Gatto+13, Salem+15)
- MW: N_O (OVII +O VIII) ~ 3e(16+/-0.5) cm^{-2} (Gupta+12, Fang+15)

- Using a physically-based outflow model, together with observational clues, what can we learn about the elusive WHIM around galaxies?

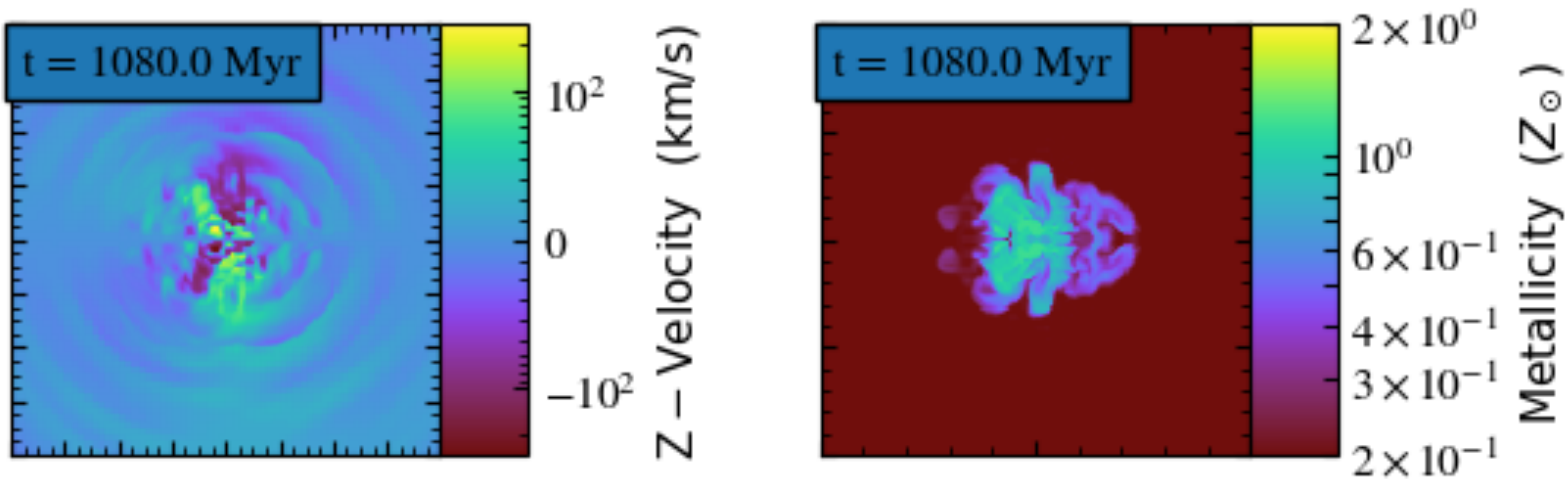
fiducial model:

- MW-like setup at z=0, isolated, box size: 800 kpc
  Gravitational potential: DM (Burkert) + stellar disk + bulge
  SFR : 1 Msun/yr
- Outflows added by hand, at 2-3 kpc above mid-plane
  $\eta_m = 1.0$; $\eta_E = 0.3$; $\eta_{metal} = 0.5$
- initial halo gas
  n_0 = 1e-5/cc [mean density of halo], $T_0=10^6$ K, no gaseous disk
- Enzo: Eulerian hydro code, same as small-box sims
- Resolution: 0.5kpc (inner 50 kpc of box); 1kpc (50- 100kpc); 2kpc (100-200 kpc), etc.

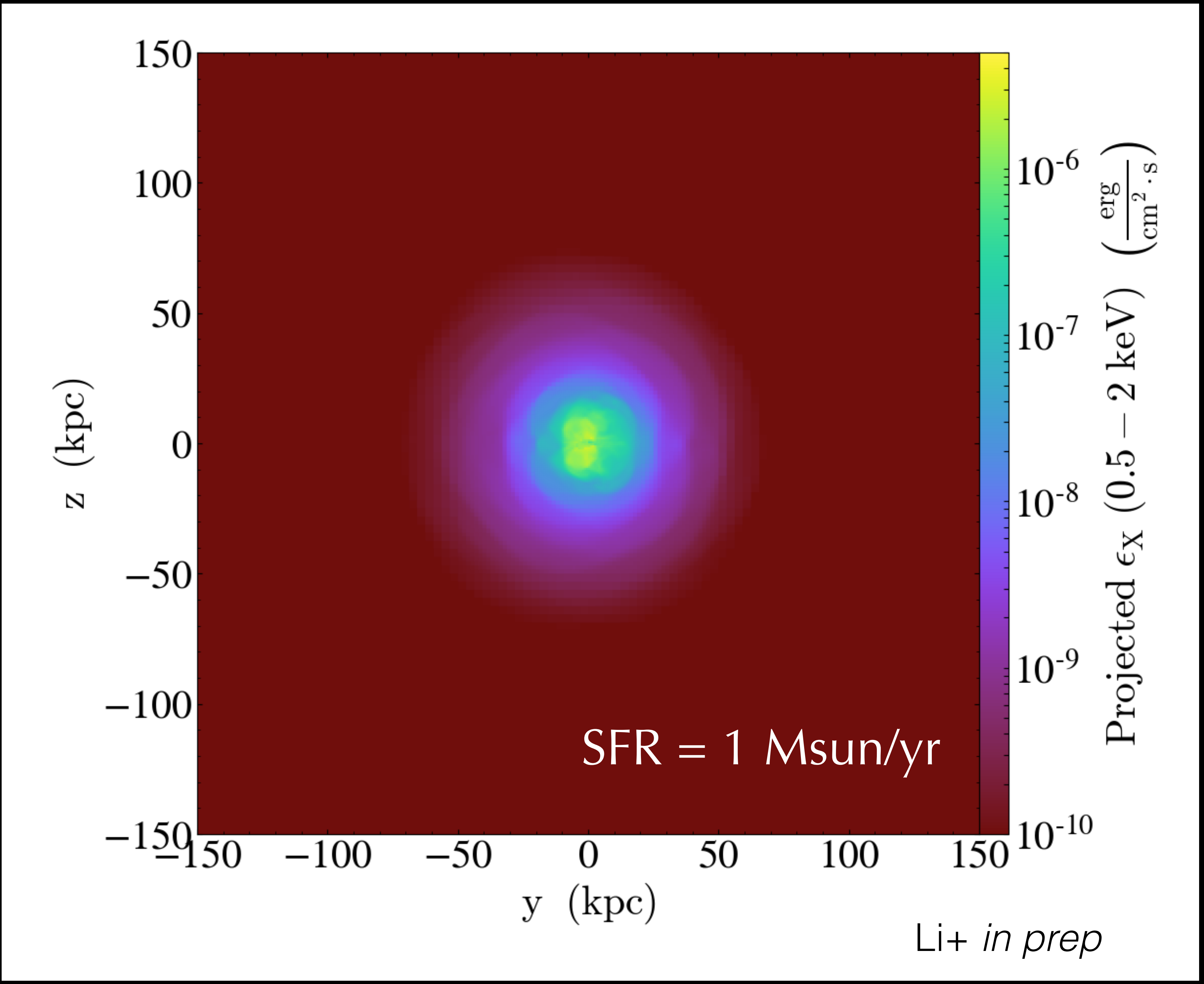
Free parameters: n_0



Fountain flow,
Metal goes to ~ 30-40kpc



X-ray emission map

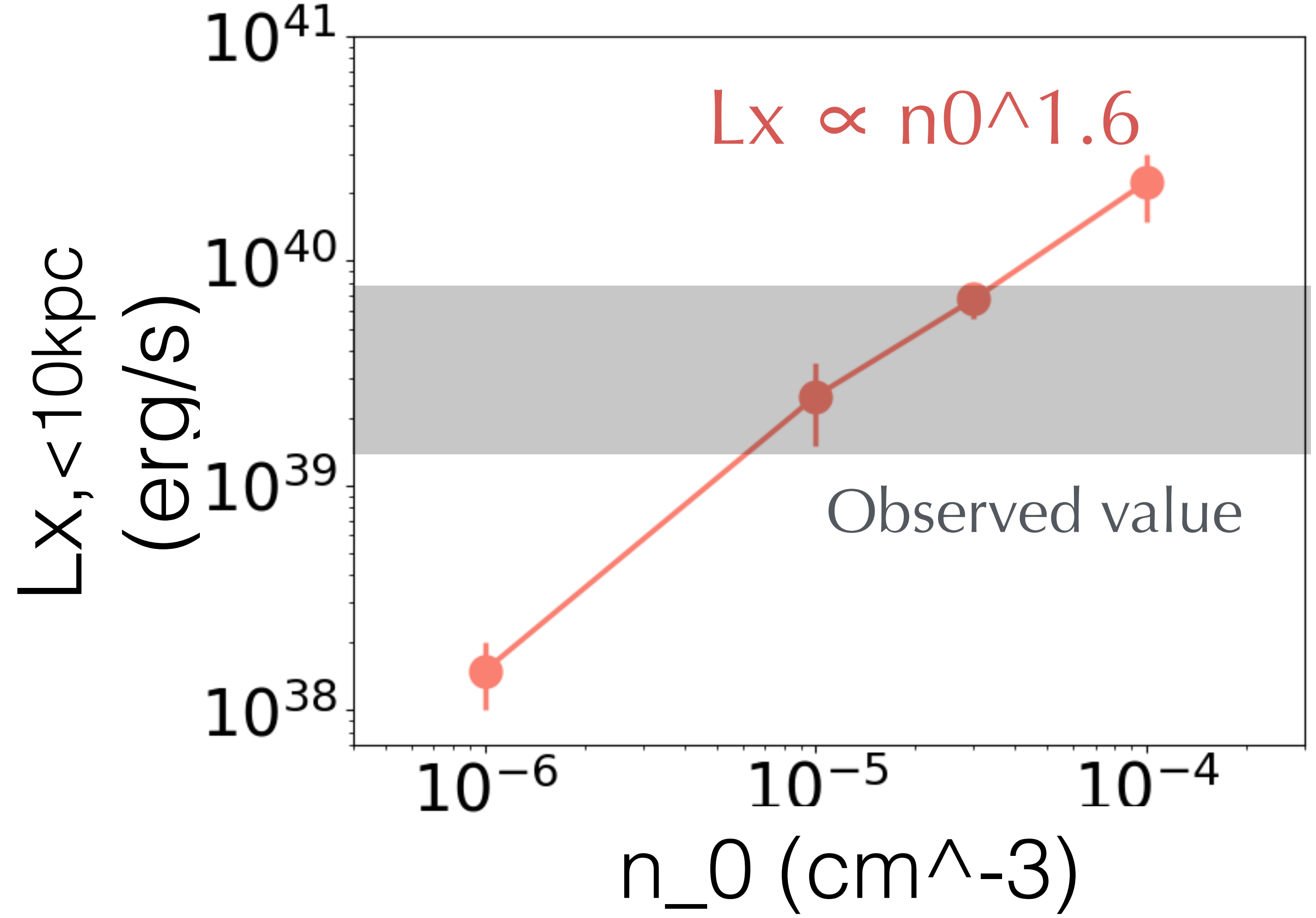


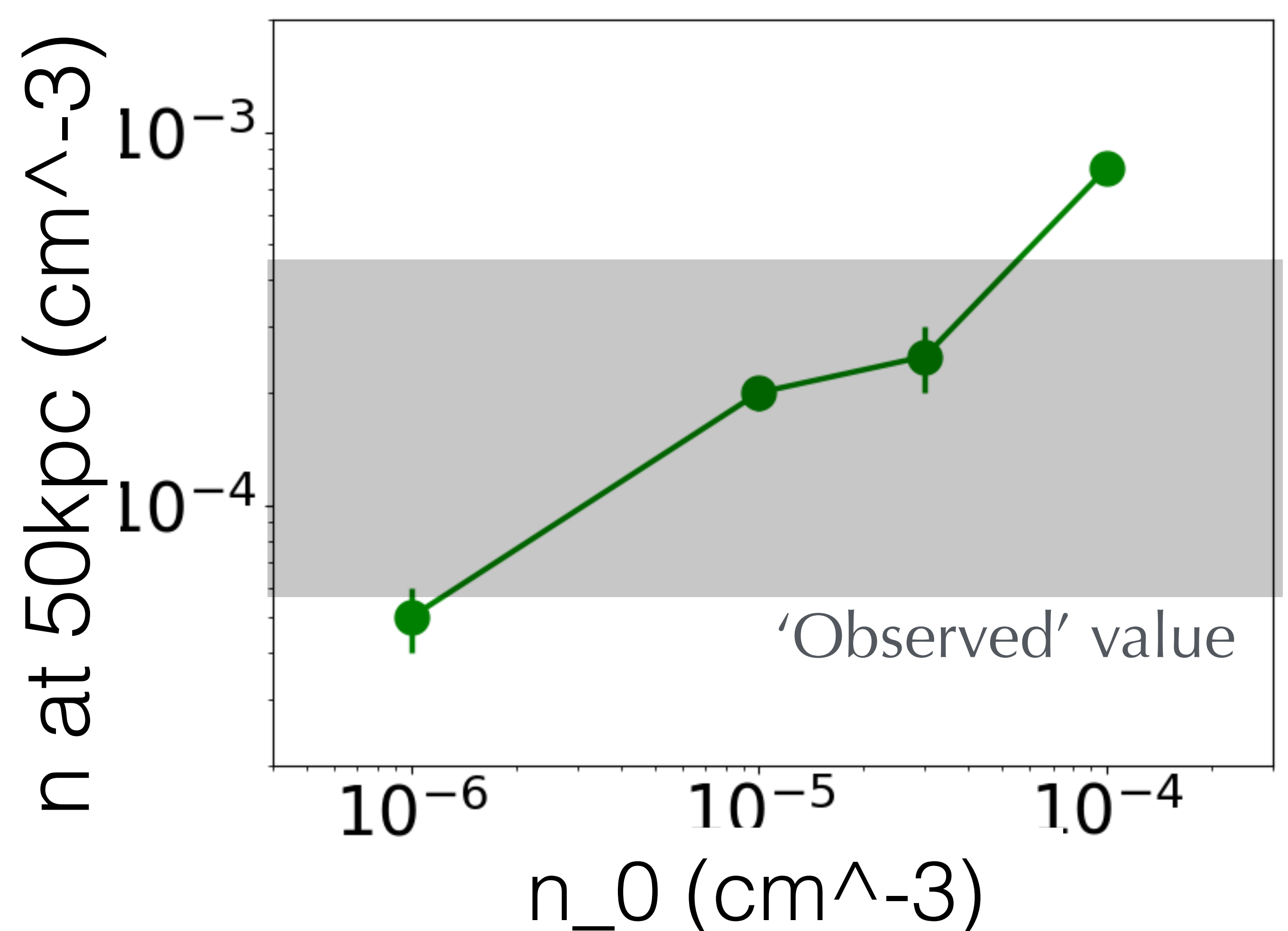
- most bright at R< 20 kpc
- **total L_X:** 2-8% SN energy

How do results depend on model parameters?

1. Changing n_0:

- Lx & n(50kpc) favor **n_0 ~ 1-3 x10^-5 cm^-3**





Li+ *in prep*

1. Changing n_0:

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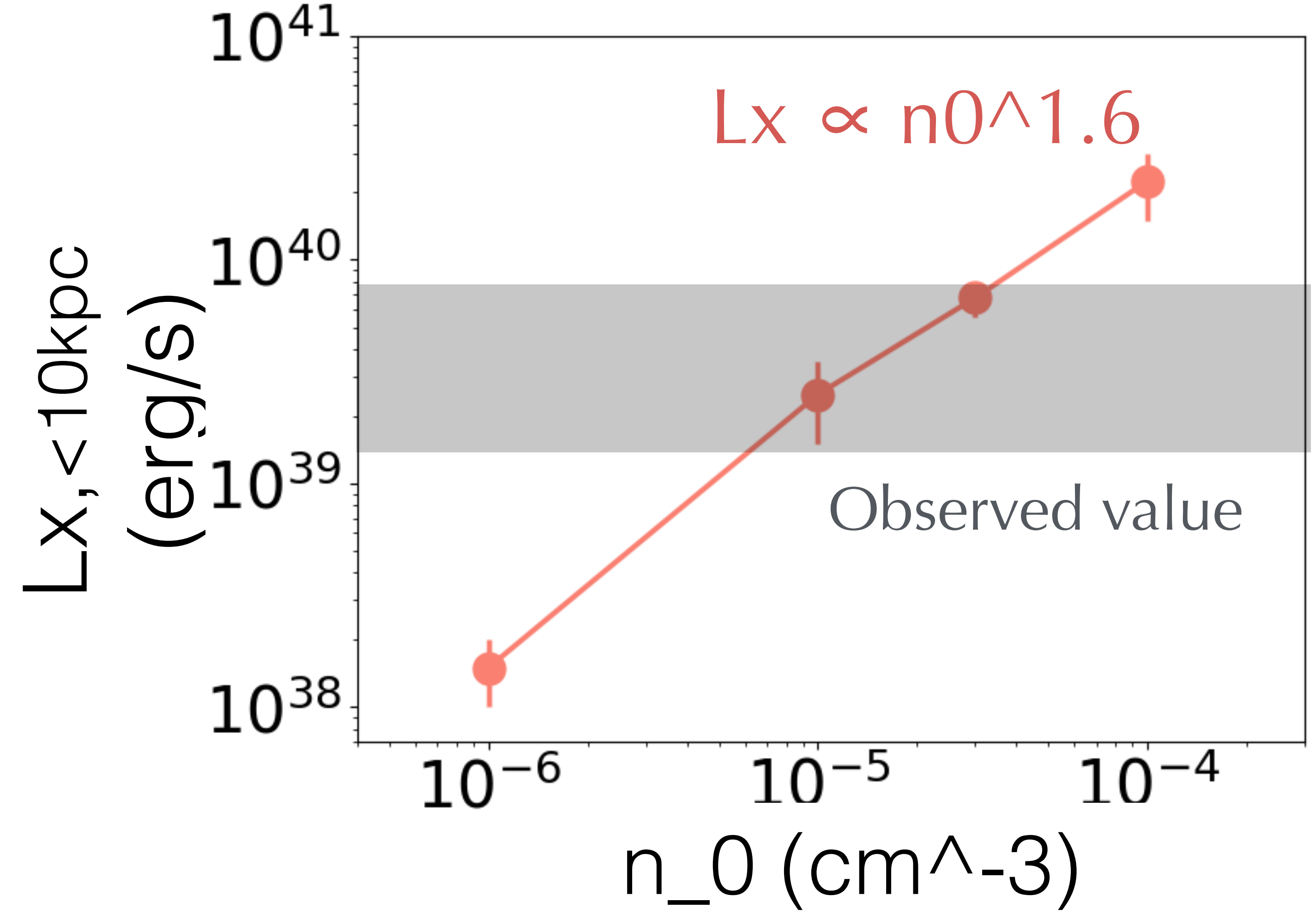
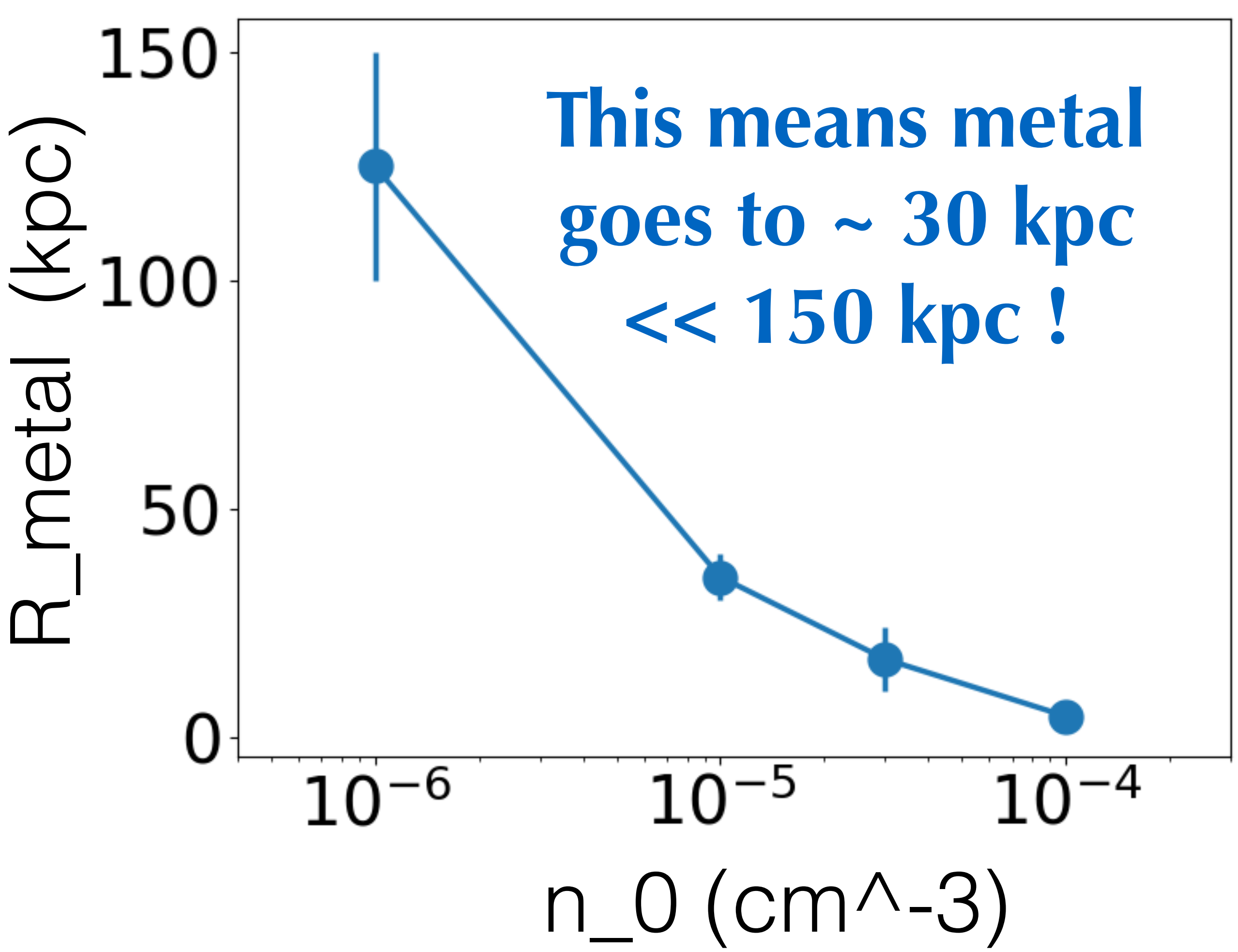
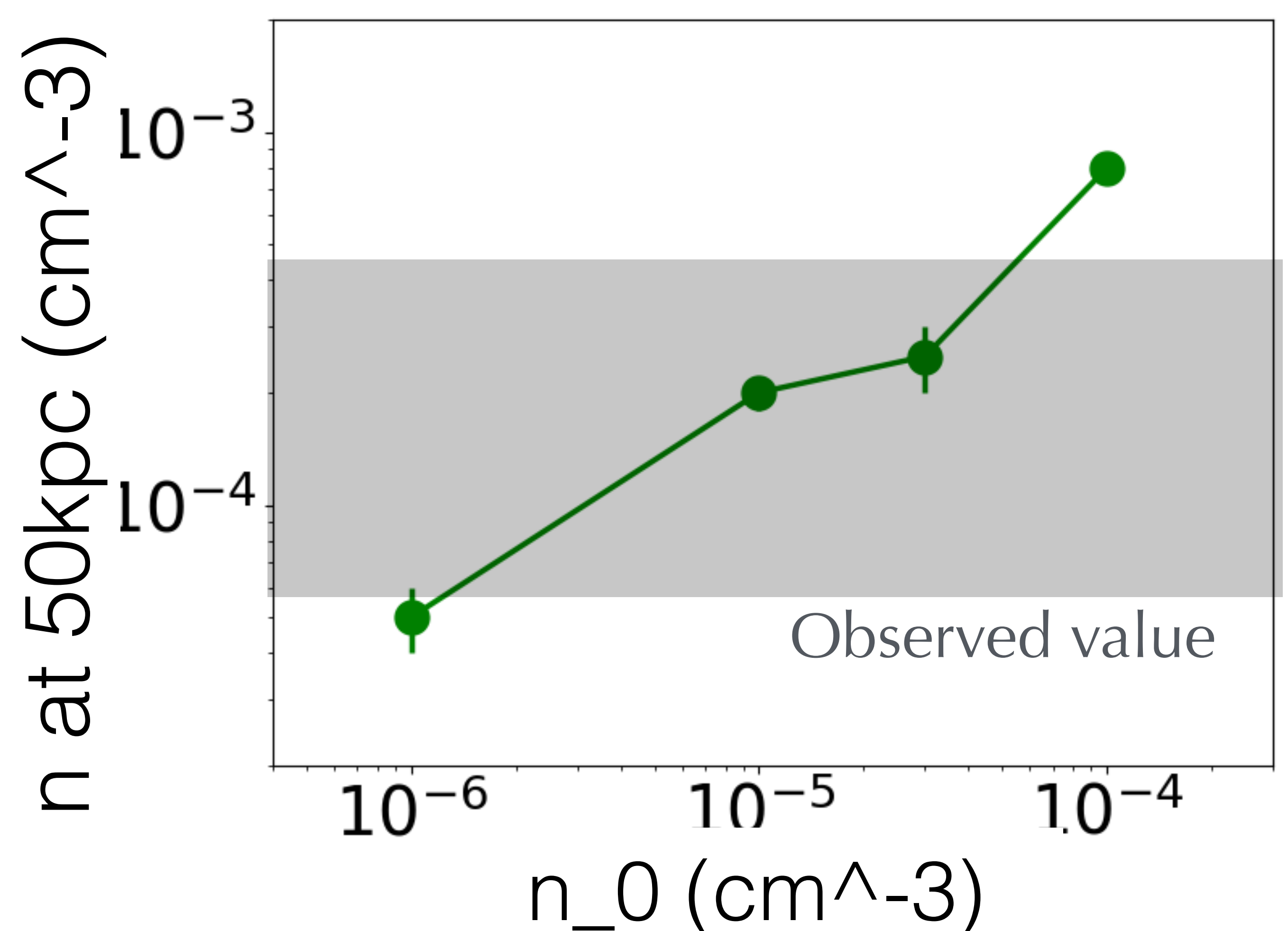
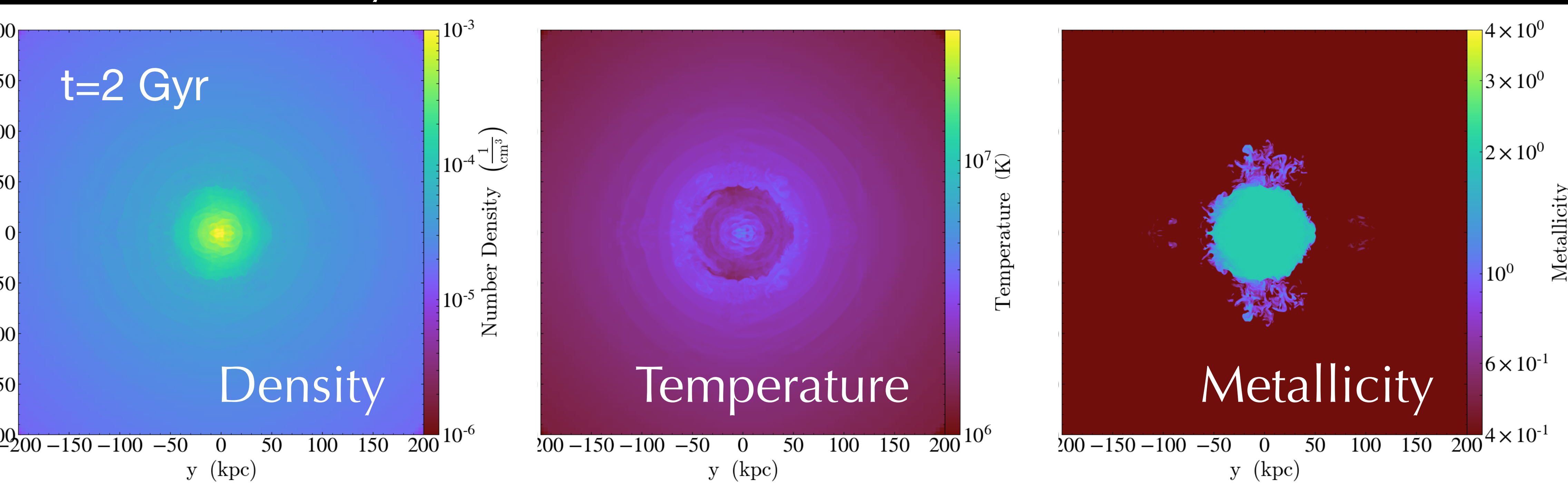






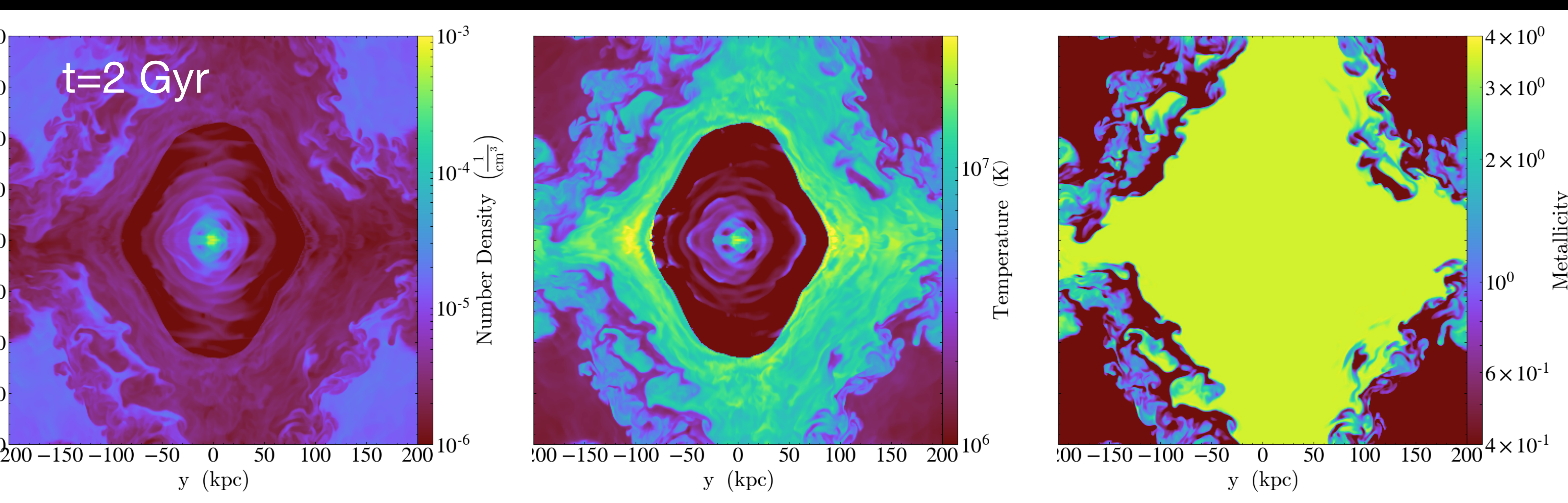
2. Changing SFR (keeping n_0 =1e-5/cc):

SFR = 1 Msun/yr, ηm =1, ηE=0.3, ηmetal=0.5 (fiducial)



Fountain

SFR = 10 Msun/yr, ηm =0.2, ηE =0.3, ηmetal=0.5 (2x mass flux, 10x energy flux)



Breakout!

Li+ *in prep*

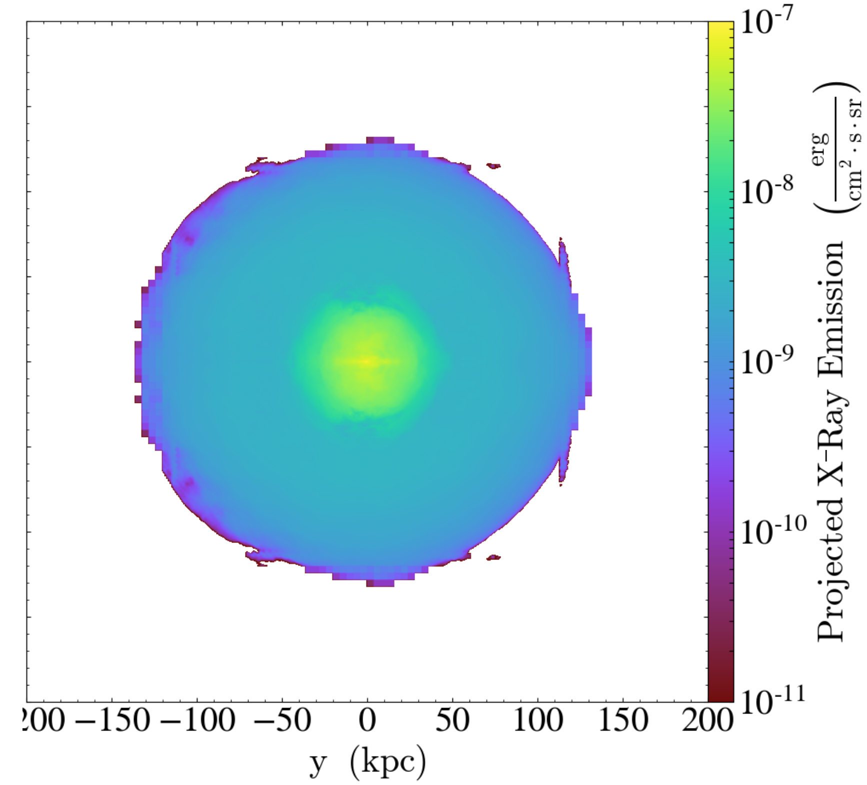
X-ray emission map:

(n_0= 10^-5 /cc)

(fiducial)

SFR = 1 Msun/yr

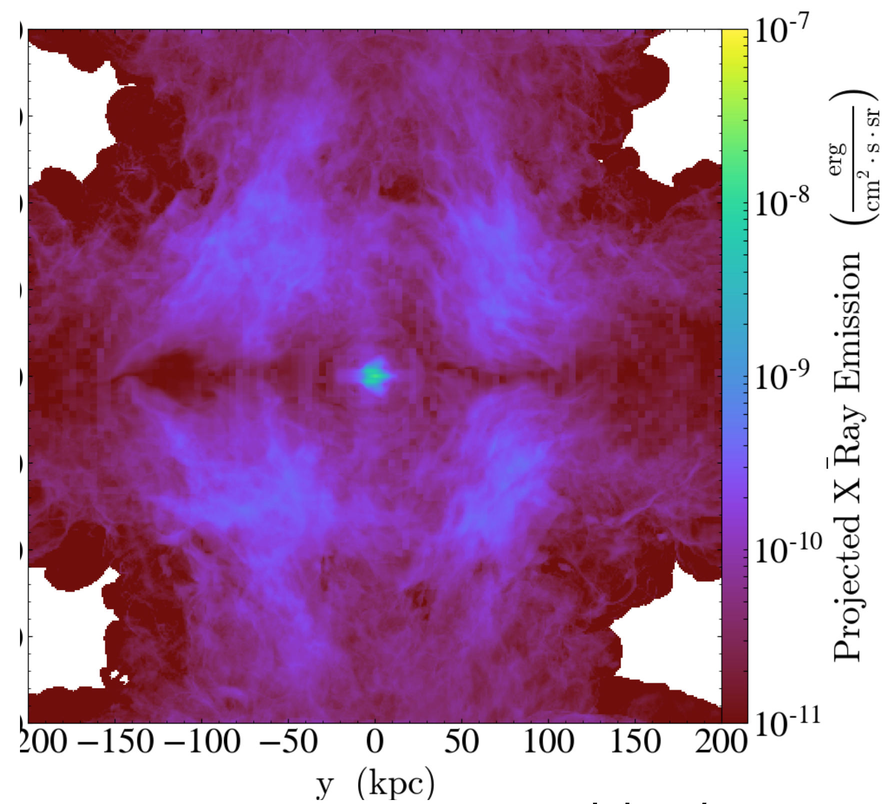
Lx = 2e39 erg/s



Breakout leads to significantly reduced Lx — inconsistent w/ obs

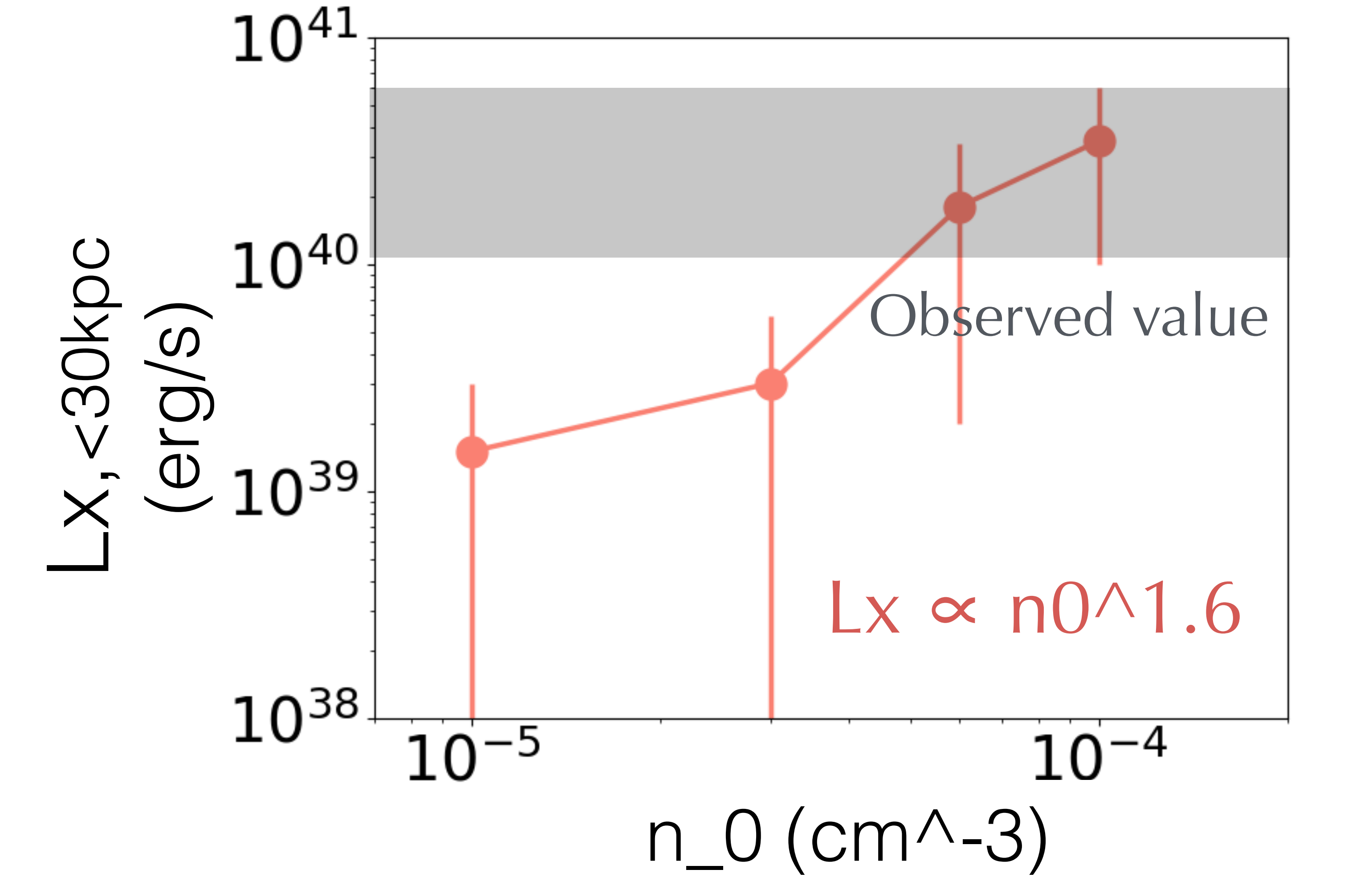
SFR = 10 Msun/yr

Lx = 5e38 erg/s



Li+ *in prep*

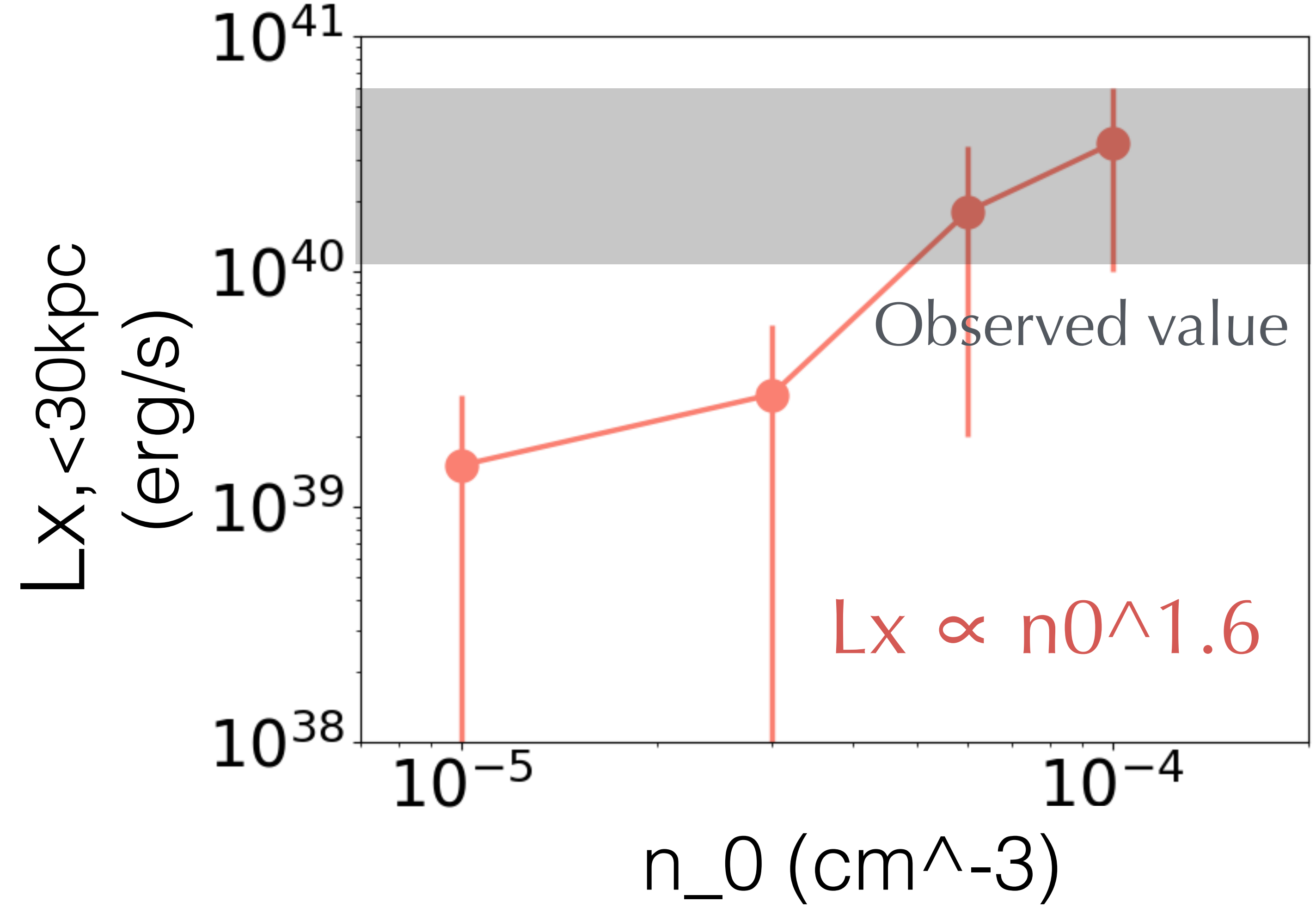
For SFR = 10 Msun/yr

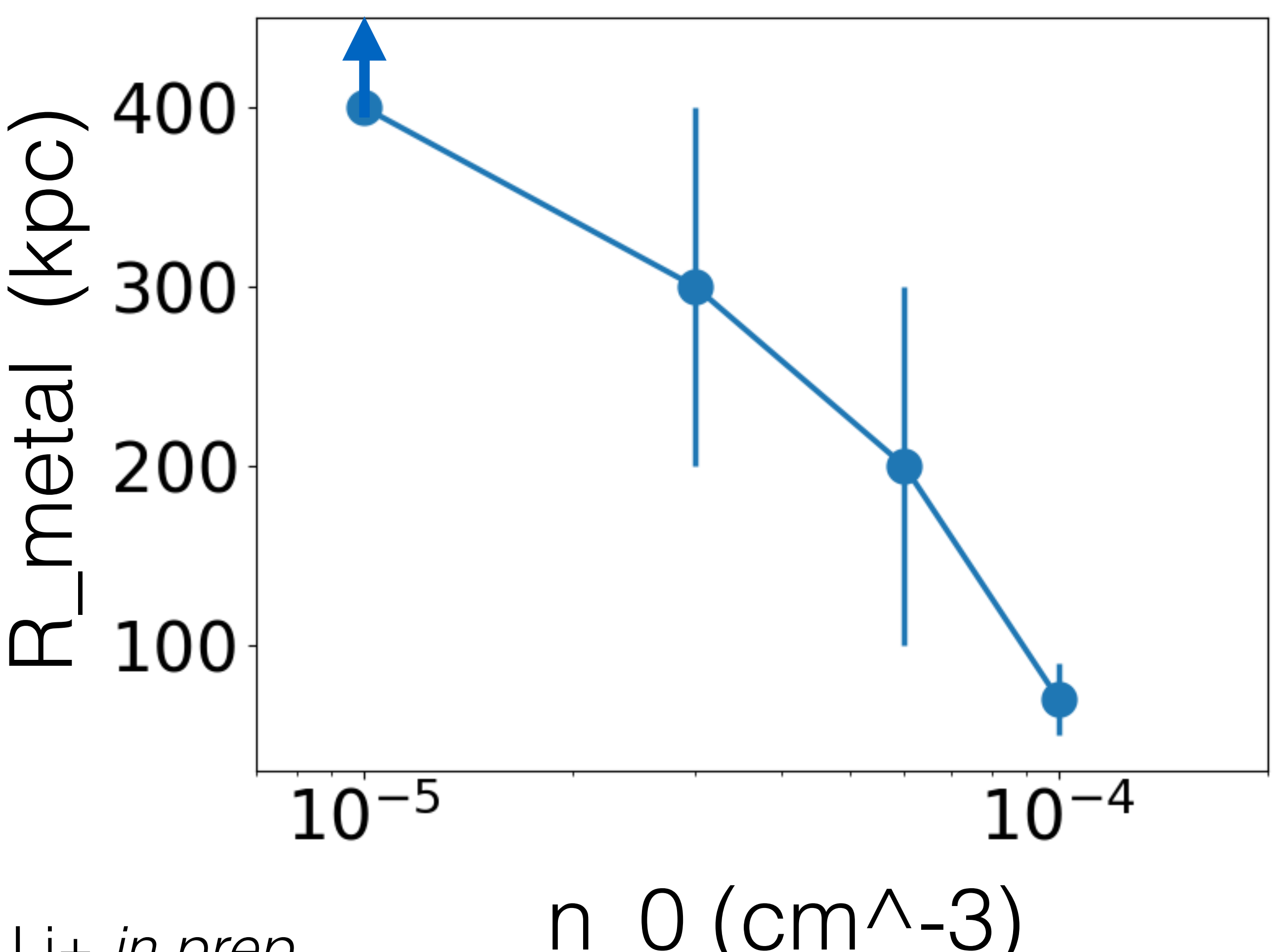


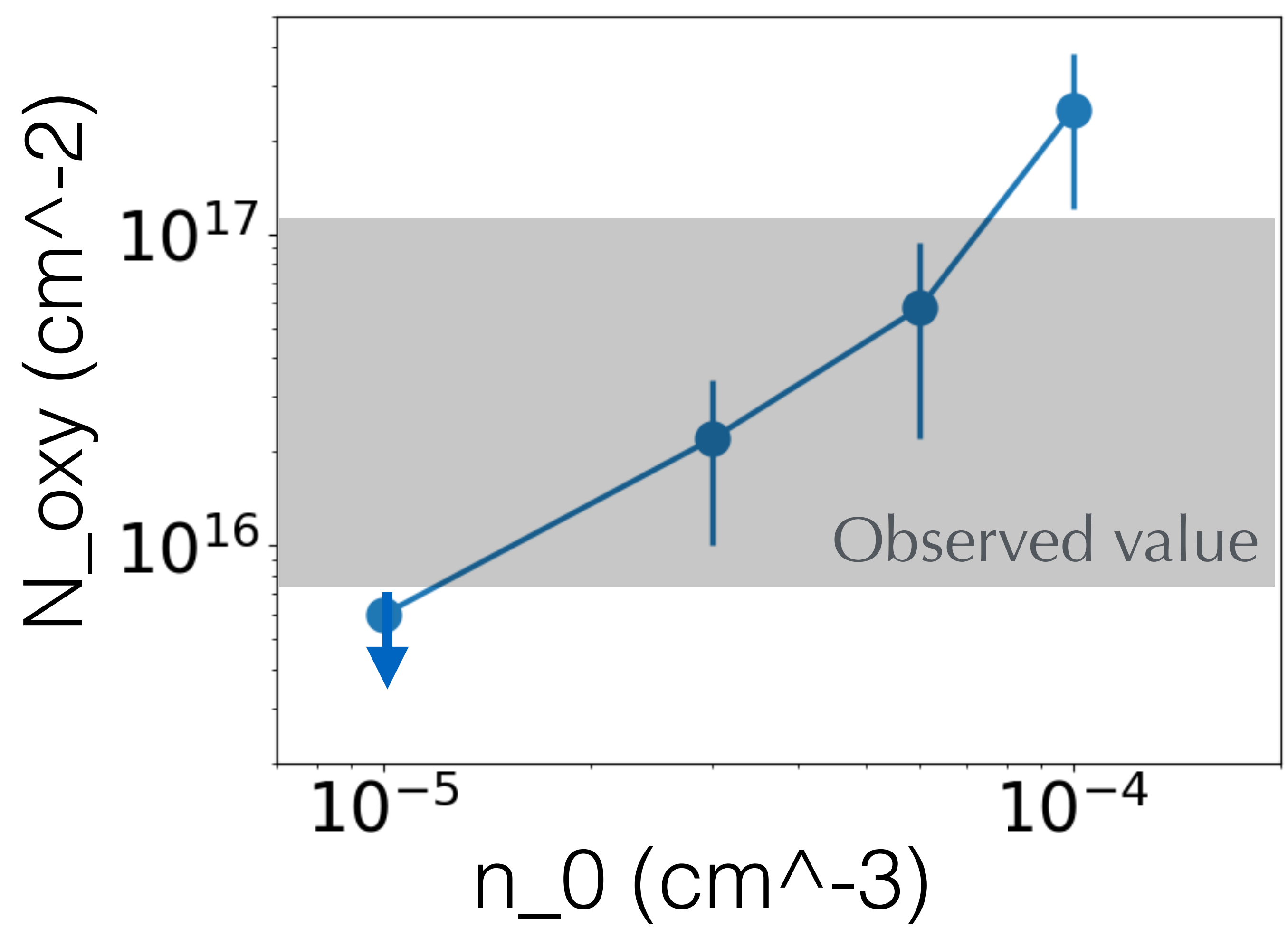
Li+ *in prep*

For SFR = 10 Msun/yr

- **Lx & N_oxy (O VII+VIII) favor n_0 ~ (5-8)x10^-5 cm^-3**



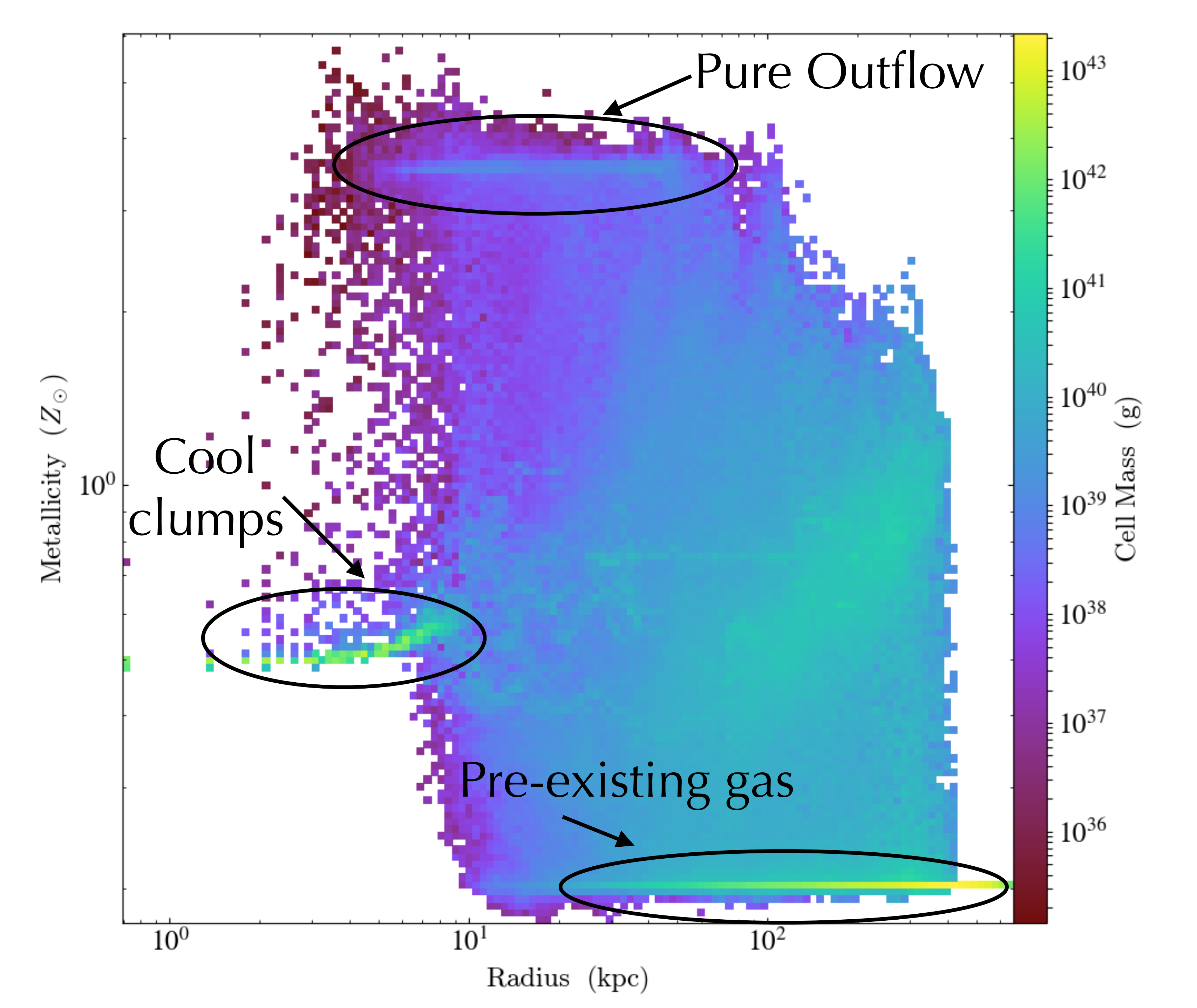




Li+ *in prep*

Halo gas: broad distribution of metallicity

- as a result of (incomplete) mixing of outflows and pre-existing gas



SFR:
10 Msun/yr
n_0 = 6e-5/cc

Li+ *in prep*

Summary

- Small-box simulations:
  - Hot outflows carry most energy and metals
  - $\eta_m = 0.8(\Sigma_{SFR}/0.008 \text{ Msun/kpc}^2\text{/yr})^{-0.44}$, $\eta_E \sim 0.3$, $\eta_{metal} \sim 0.5$
- From n(50kpc) and Lx, n_0 ~ 1-3e-5 cm^-3 is favored for current MW
  - M_CGM (T>1e5, R<200kpc) ~ 2-4e10 Msun
- For MW halo, SNe-driven hot outflows
  - Eject ~ 1e10 Msun hot gas over Hubble time —> not much mass
  - eject ~50% of metals ever produced -> lots of metals
  - Can reach >150 kpc (when SFR ~ 10 Msun/yr), and explain N_oxy,hot
- The observed Lx ∝ SFR implies n_0 ∝ SFR^0.5