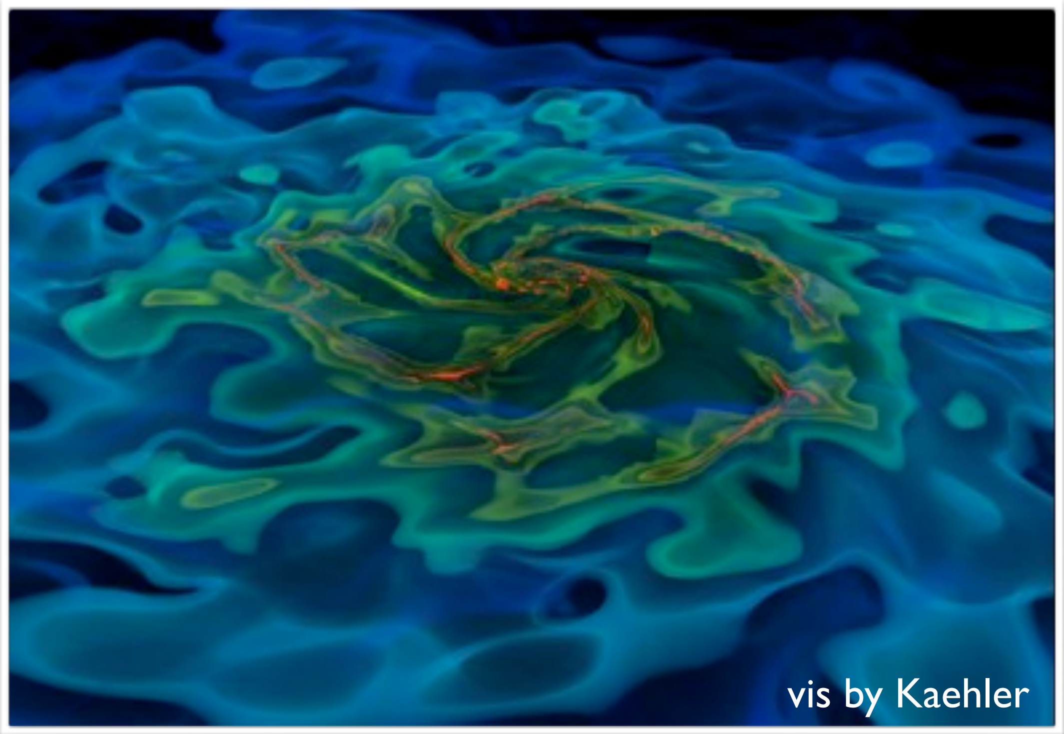
High-resolution Galaxy Formation with Radiating Molecular Cloud Particles



vis by Kaehler

M51/HST

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Thanks to: John Wise, Nathan Goldbaum, Matthew Turk, and many others

Towards An Unabridged Understanding of Galaxy Formation

- Modeling the Physics of Galaxy Formation in ~pc Resolution Era

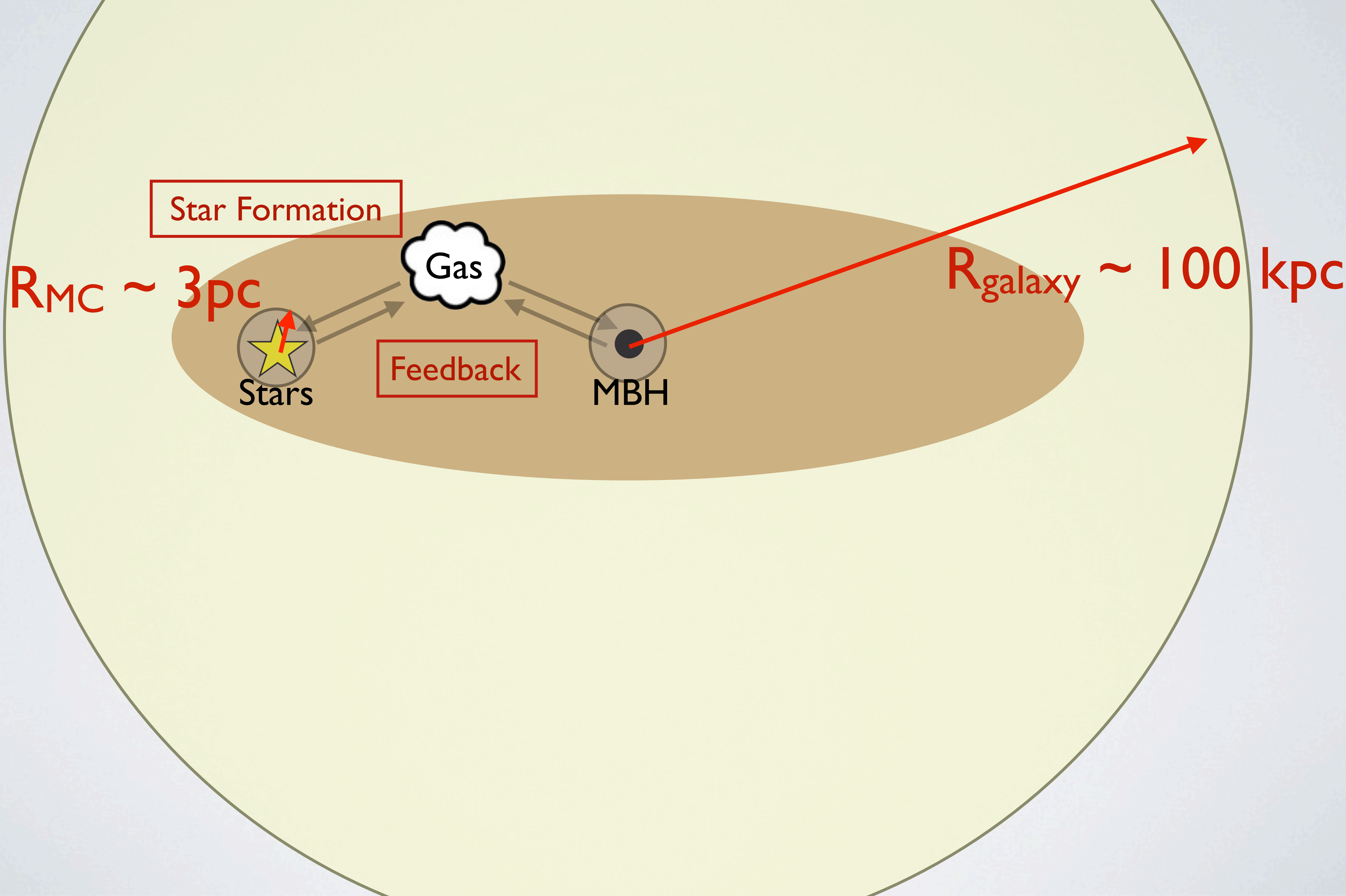
  - Radiaitng Molecular Cloud Formation and Feedback (Radiation & Supernova)

- Applications and Results

  - Dwarf Galaxies with Radiating Molecular Cloud Particles

  - Simulated Observations & UV Escape Fraction

Contemporary High-resolution Galaxy Simulations



Star Formation

Gas

$R_{MC} \sim 3$pc

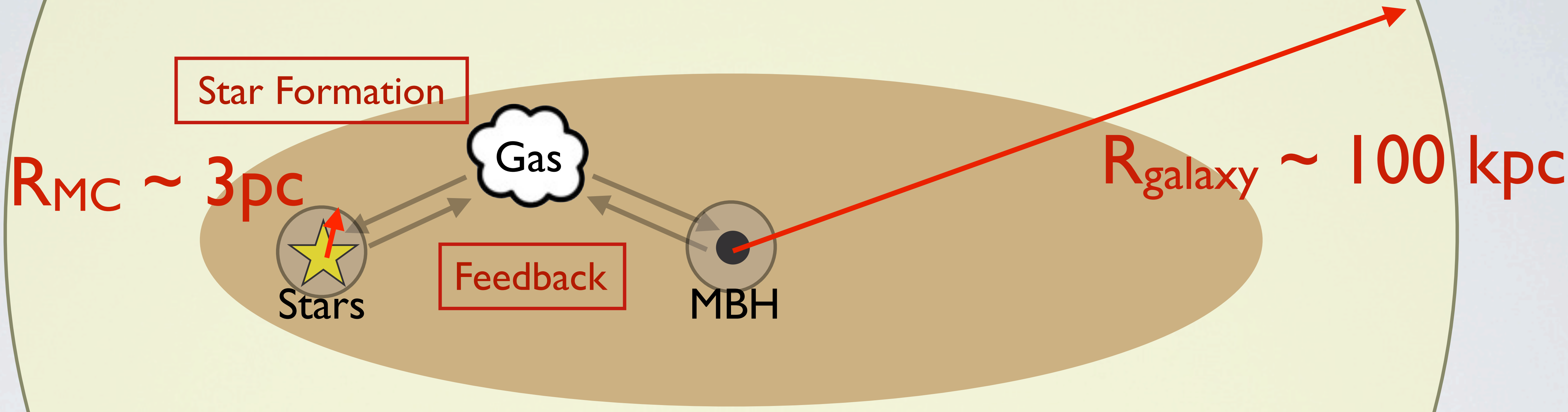
Stars

Feedback

MBH

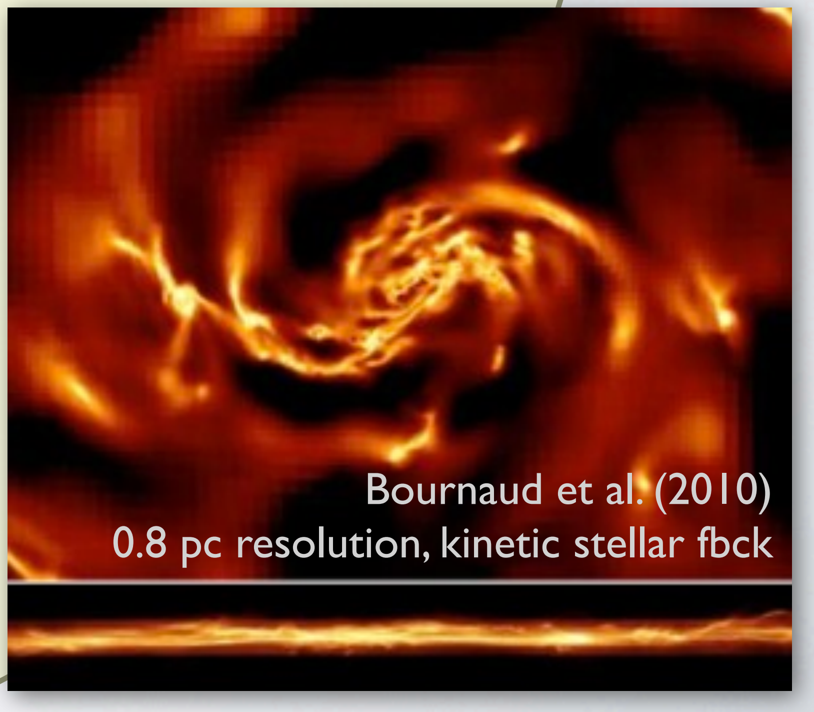
$R_{galaxy} \sim 100$ kpc

Molecular Cloud Physics in Galaxy Simulations



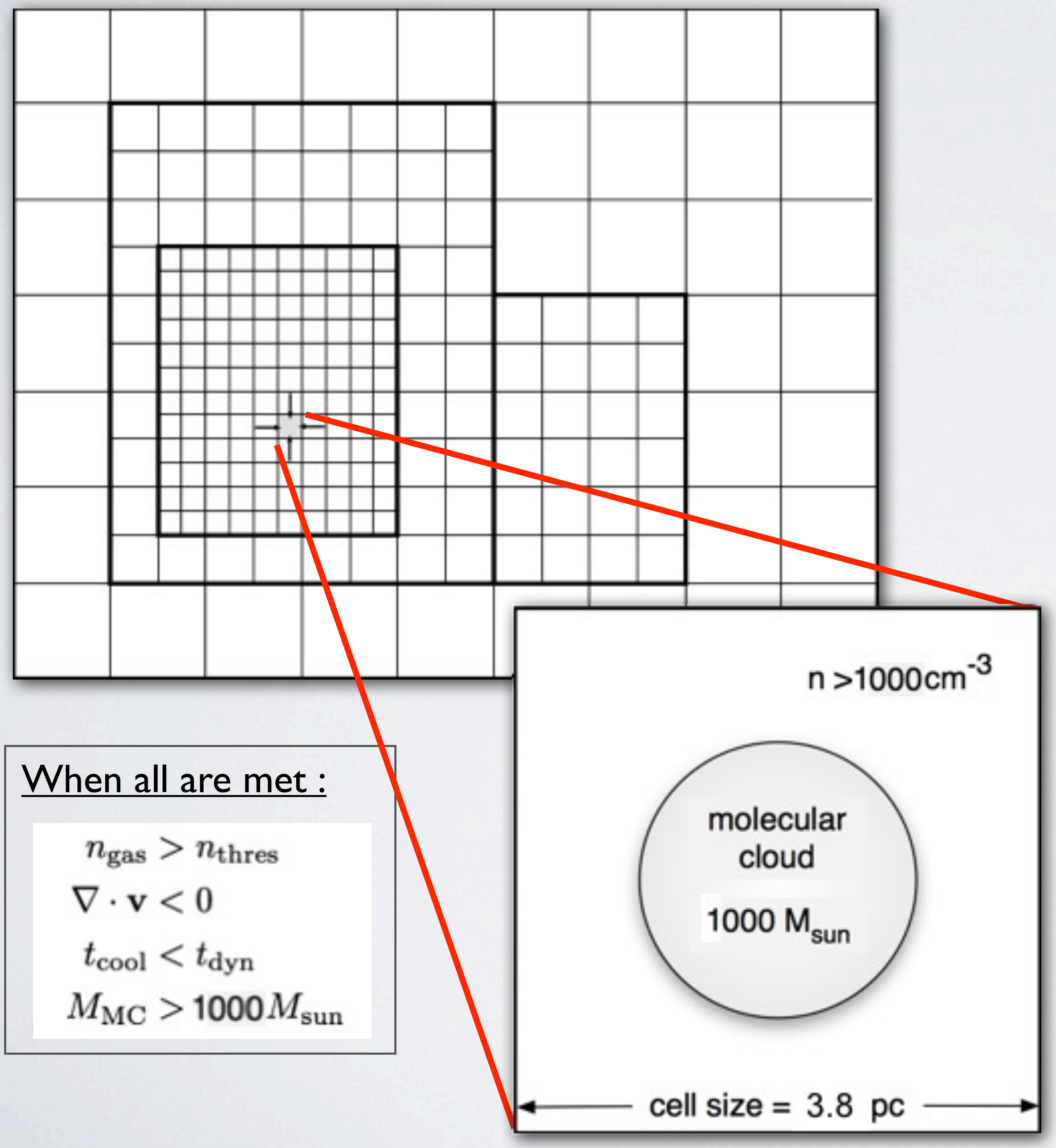
- It is crucial to include proper molecular cloud physics for $\Delta x \sim$ pc resolution simulations (corresponding $\Delta t \sim 10^4$ yrs)

→ Need transition from phenomenology (i.e. Schmidt model) to realistic physics



Bournaud et al. (2010)
0.8 pc resolution, kinetic stellar fbck

Molecular Cloud Particle - Formation



When all are met :

$$n_{\mathrm{gas}} > n_{\mathrm{thres}}$$
$$\nabla \cdot \mathbf{v} < 0$$
$$t_{\mathrm{cool}} < t_{\mathrm{dyn}}$$
$$M_{\mathrm{MC}} > 1000 M_{\mathrm{sun}}$$

- Max resolution of 3.8 pc = L_{Jeans} of molecular clouds of 1000 protons/cm^3 at ~100 K

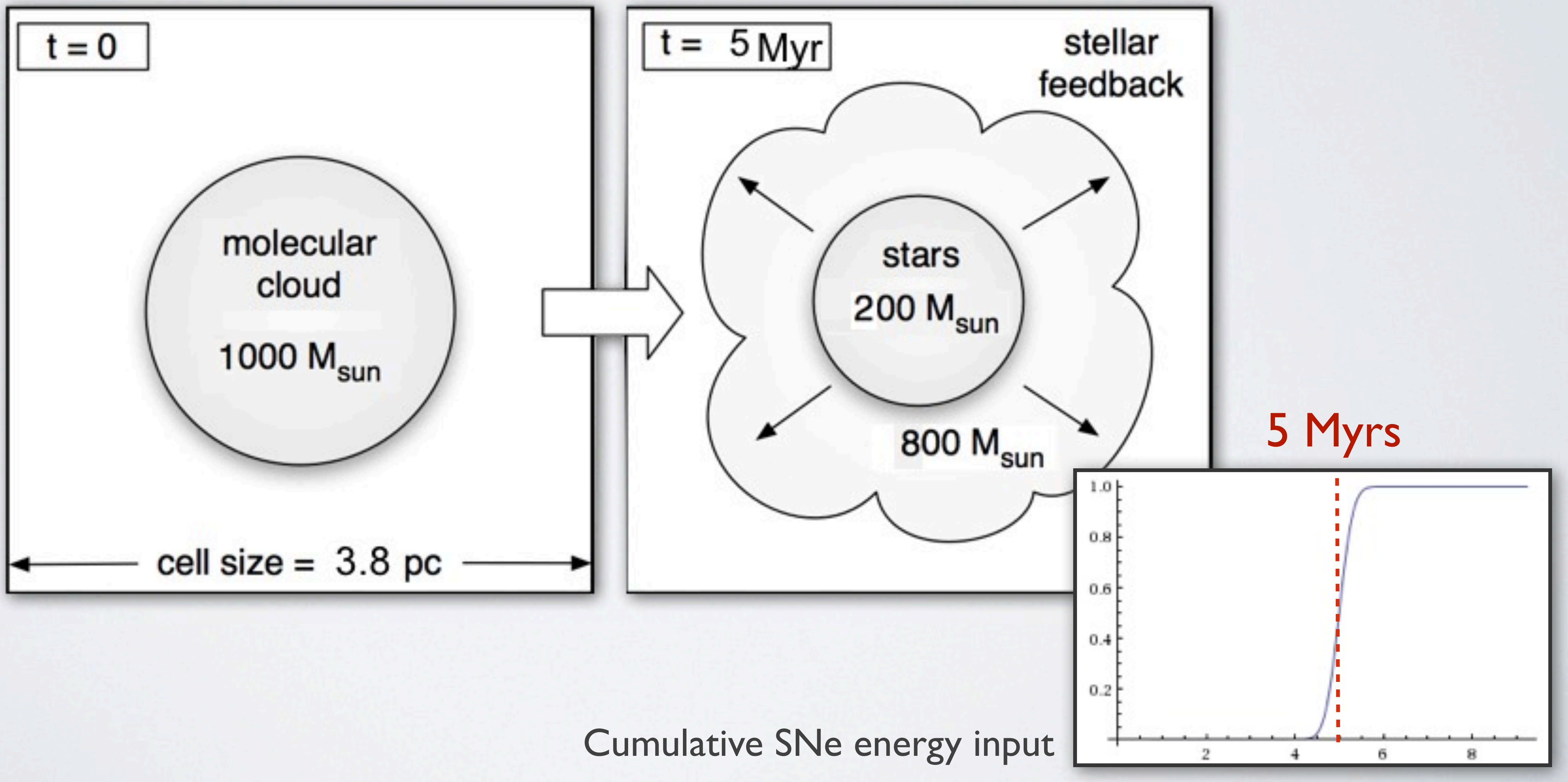
$$M_{\mathrm{MC}} = \epsilon_* \rho_{\mathrm{gas}} \Delta x^3$$

- Self-consistently deposit a particle when a cell of a typical molecular cloud size actually gets Jeans unstable, i.e. $M_{\mathrm{cell}} > M_{\mathrm{Jeans}}$

  → each particle describes a MC of 1000 $M_{\odot}$

MC Particle - Supernova Feedback

- Both mass and energy are added back to gas
  - 20% remains as “stars” after 6 Myrs + 80% returns to gas phase
  - returning mass carries the thermal energy of 10^{51} ergs per $M_{star} = 750\ M_\odot$ peaking at 5 Myrs

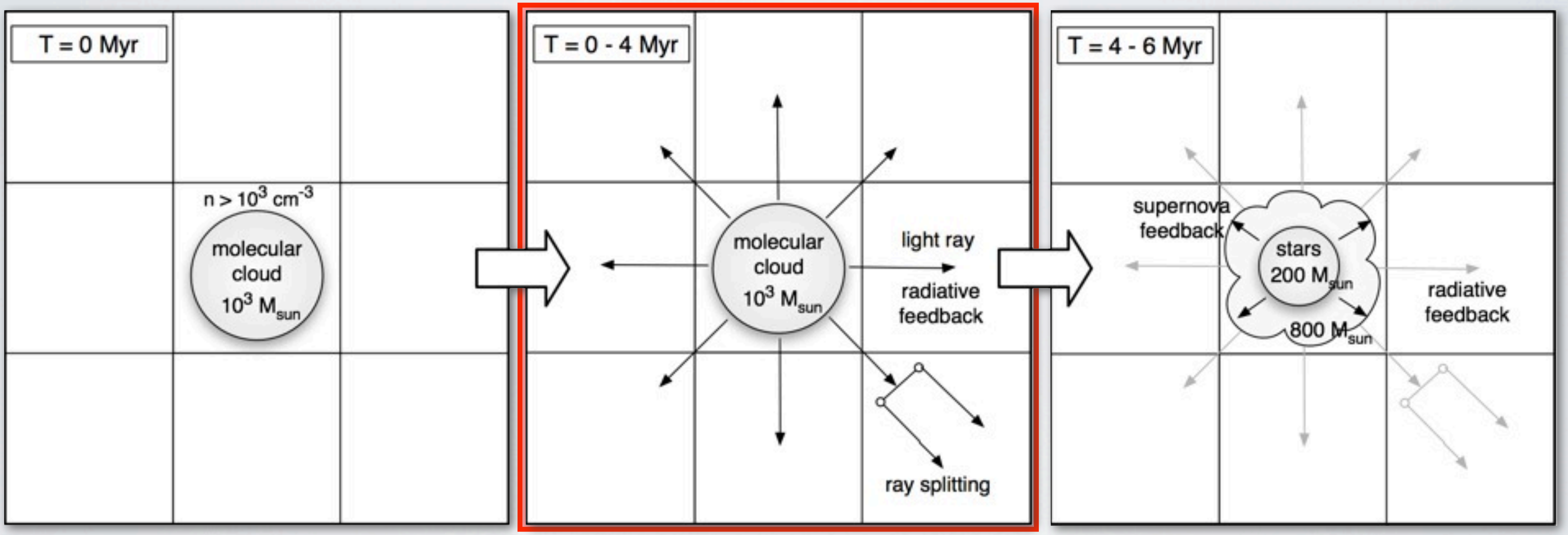


5 Myrs

Cumulative SNe energy input

MC Particle - Radiation Feedback

- UV photons from MCs traced so its energy is added to ISM
  - 16.0 eV photon interact with H by photo-ionization and heating



- Photoionization + Photoheating + Radiation pressure (no τ_{IR})
- E_{ph} = 16.0 eV (Whalen et al. 2004, 2006)
- $L_{MC} = 6.3\times10^{46}\, M_{MC} E_{ph}$ eV/s (Murray & Rahman 2010)
- Early stellar fbck important (Hopkins et al., Stinson et al.)

Test on An Isolated Dwarf Galaxy

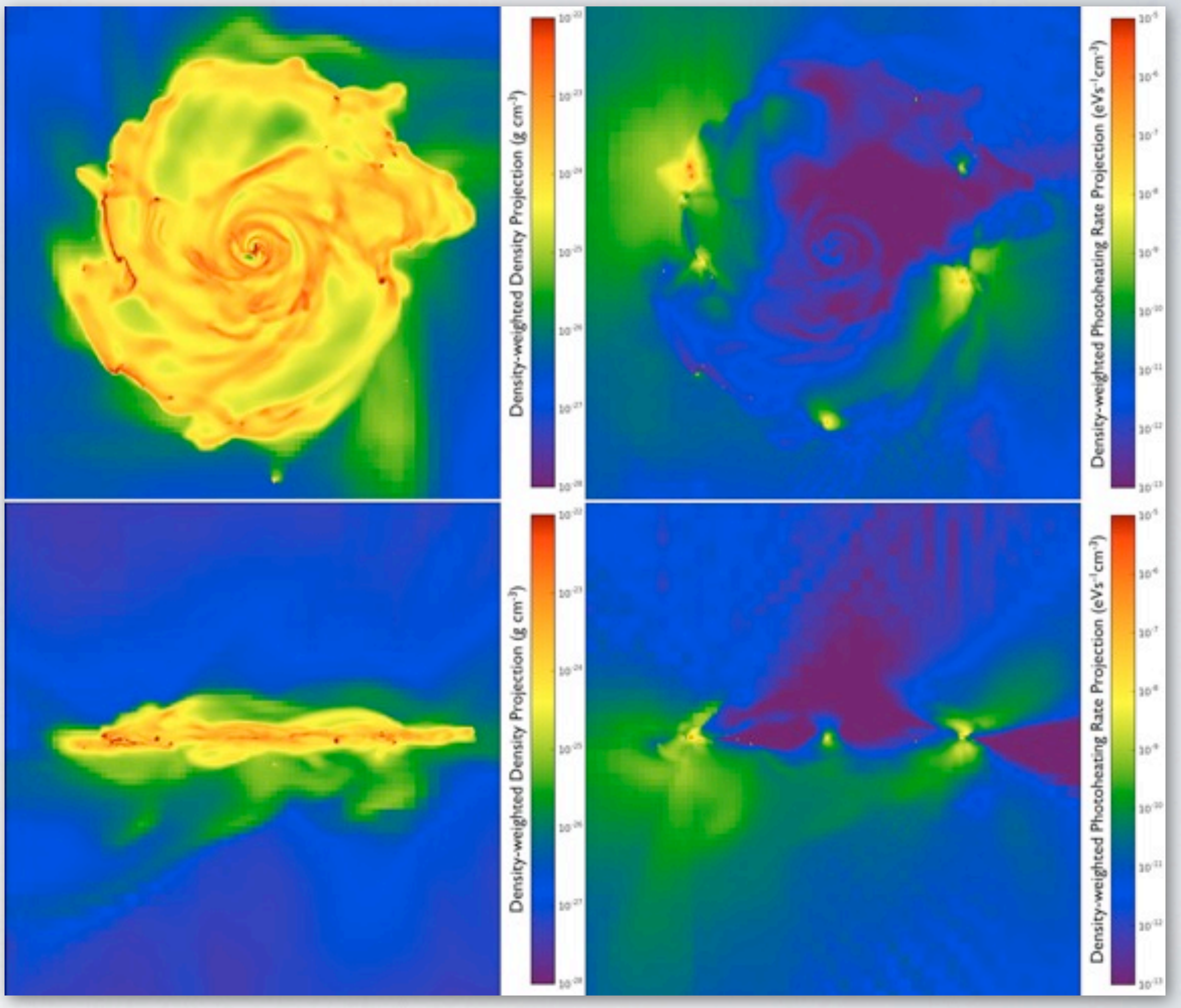
- $2.3\times10^{11}\ M_\odot$ halo hosts $<10^4$ radiating MCs (excluding galactic center)

  - 3.8 pc resolution with Enzo on a well-defined dwarf galaxy

  - SF suppressed by 22.4% in 20 Myrs when compared to SN fbck only case

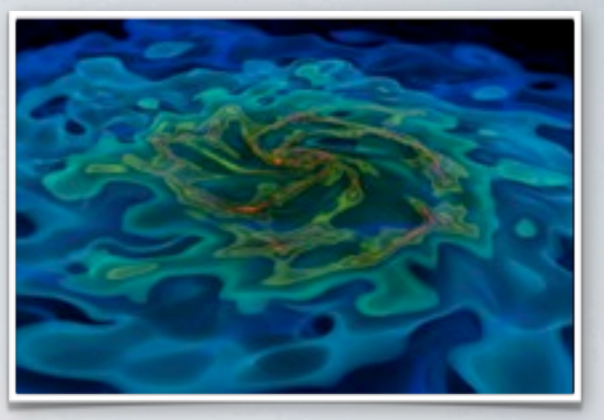
- Simulated observation possible because of
  - radiation physics
  - spatial+temporal resolution
  - post-processing with *yt*

Analysis tool *yt* by Matthew Turk; his talk tomorrow!



Projected Density (Density-weighted, $\#/\mathrm{cm}^3$)

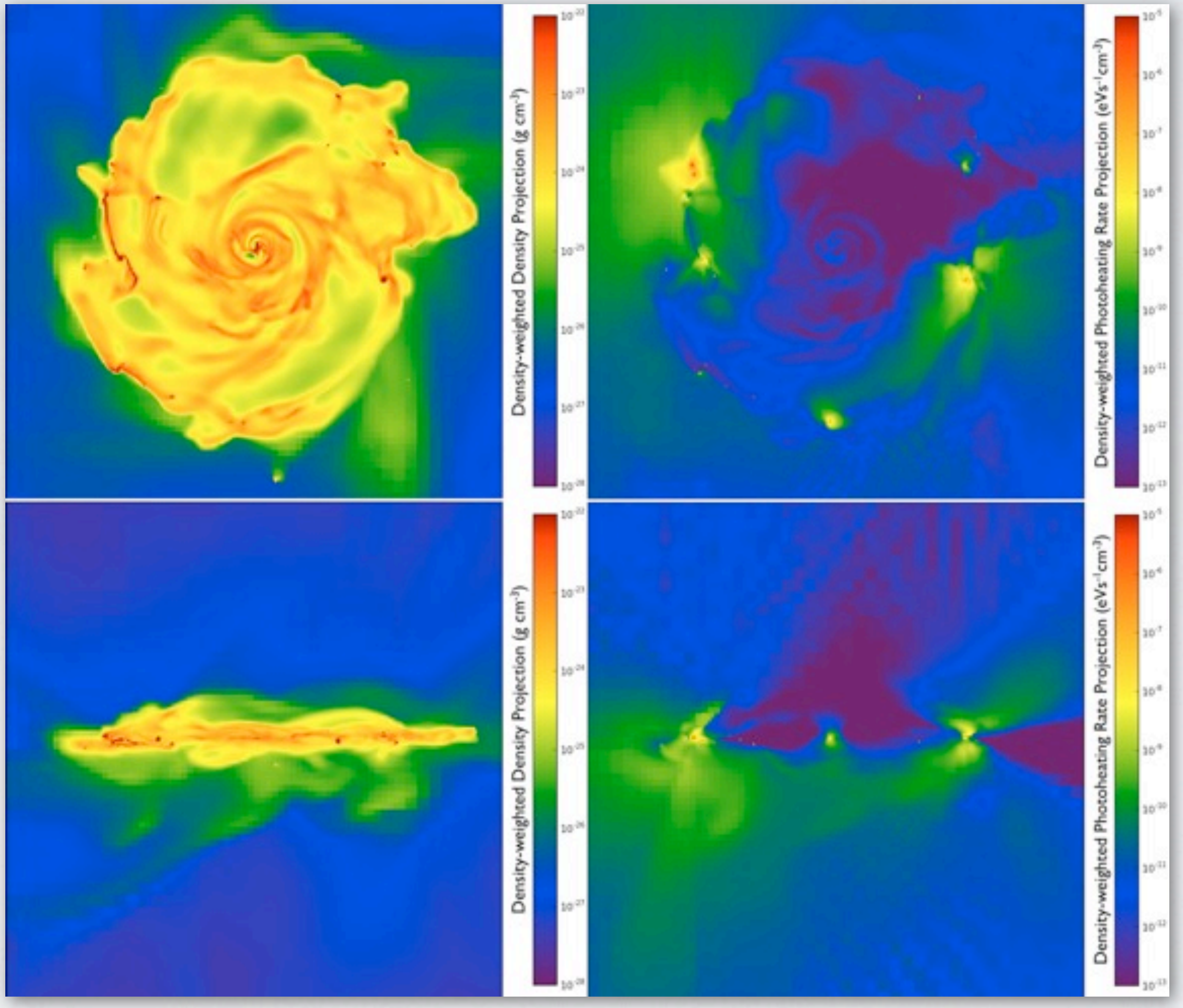
Projected Photoheating Rate (Density-weighted, $\mathrm{eV/s/cm}^3$)



I. Escape of Ionizing Photons

Beyond Integrated Radiation Fields

- Integrated fields are interesting, but let's move to the next stage



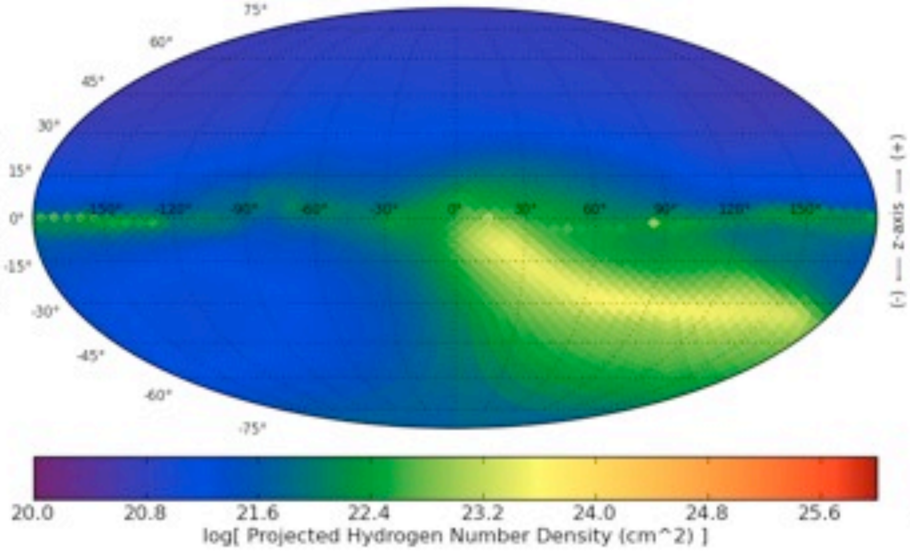
Face-on

Edge-on

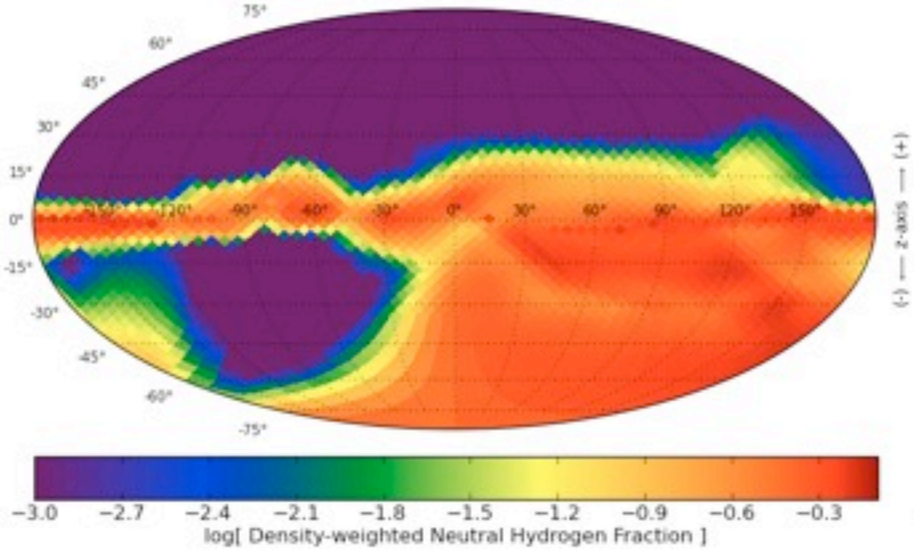
Projected Density
(Density-weighted, #/cm^3)

Projected Photoheating Rate
(Density-weighted, eV/s/cm^3)

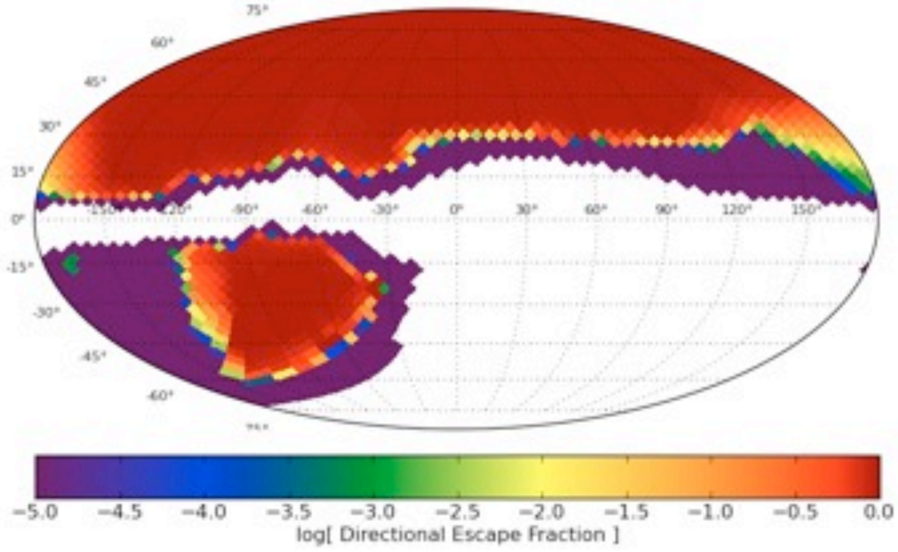
Escaped Photons From An Individual MC



Projected HI Number Density
(#/cm2)



Projected HI Fraction
(Density-weighted)



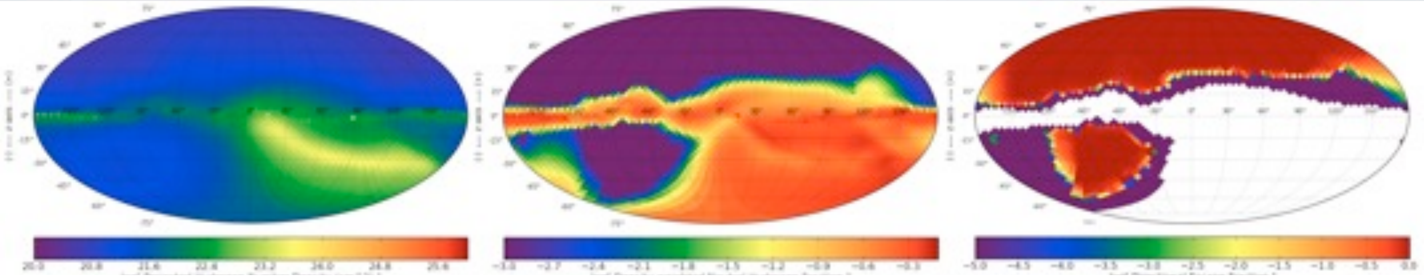
Directional Escape Fraction
(at 100 kpc)

- From each MC, directional escape fraction can be easily calculated

Total Escaped Photons at R=100 kpc

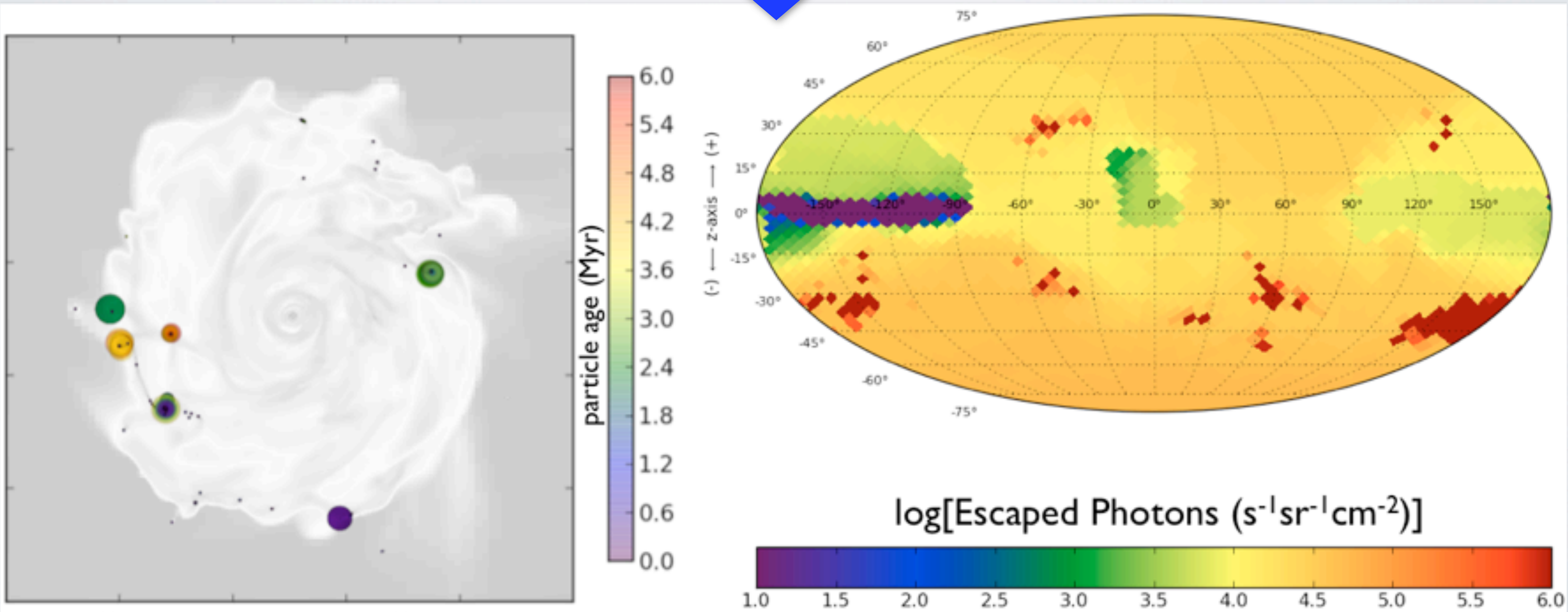
- From $f_{esc}(i)$ of an individual MC to f_{esc} of the entire galaxy

(1) Individual MC:



Projected HI Number Density   Projected HI Fraction   Directional Escape Fraction

(2) For Entire Galaxy:

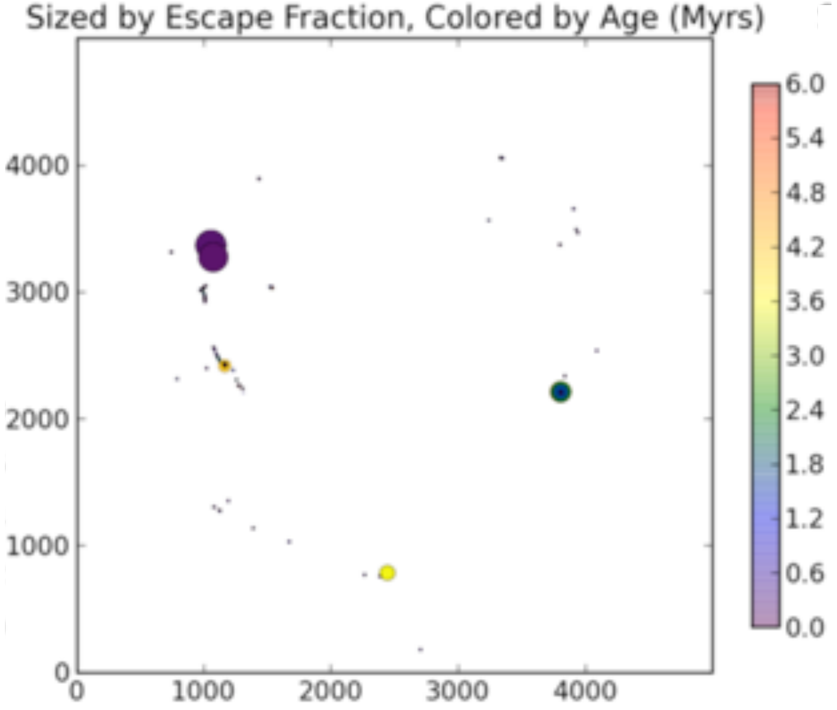


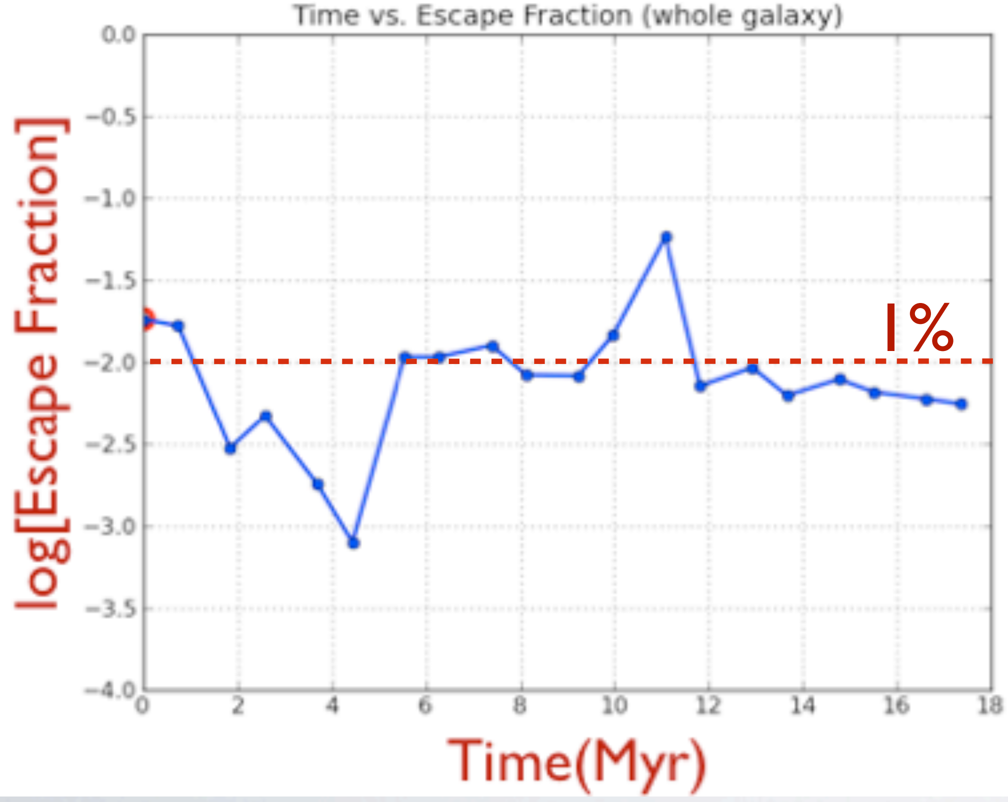
High $f_{esc}(i)$ clumps: size by $f_{esc}(i)$, color by age

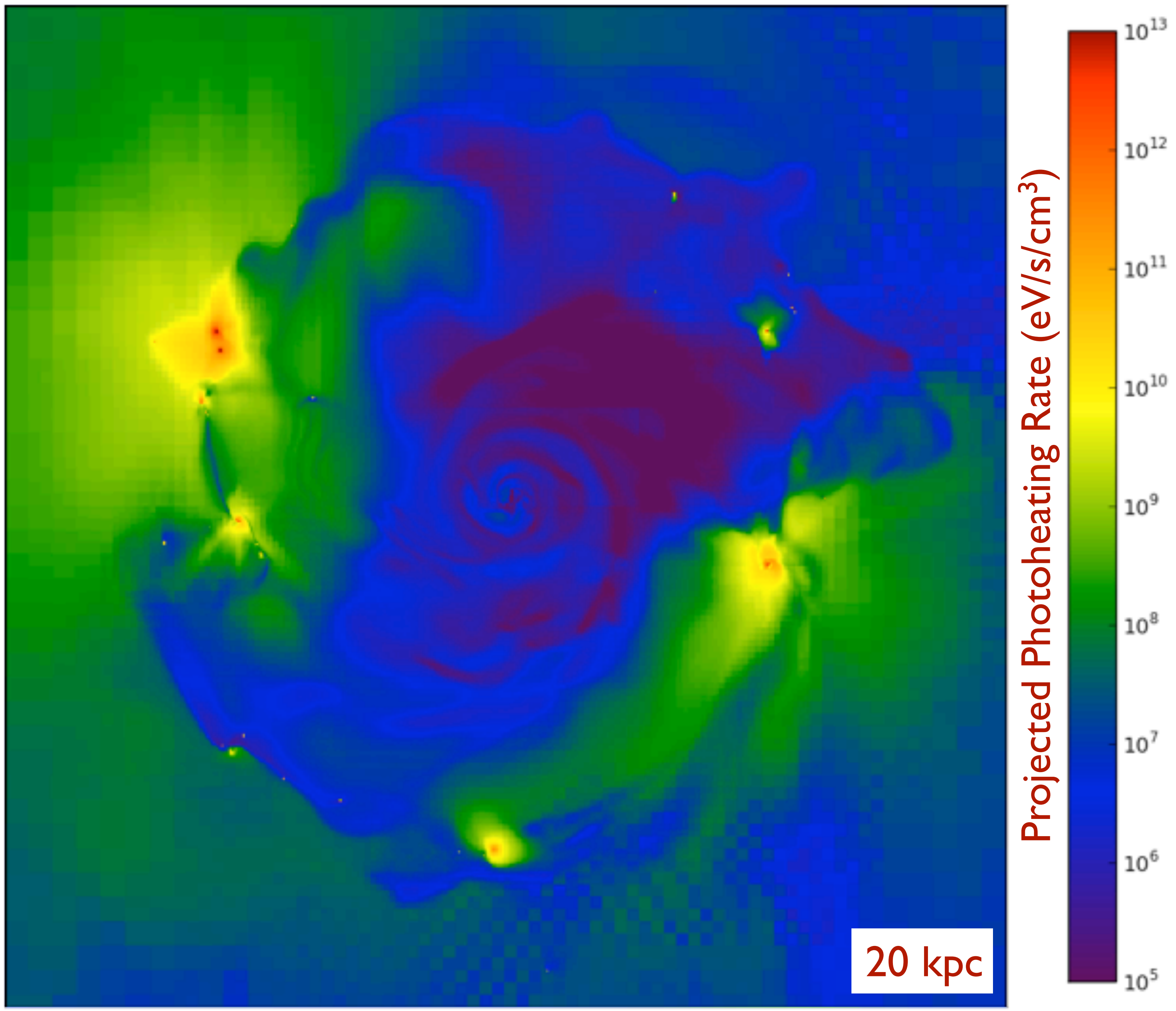
Only A Few Clumps Have High f_{esc}(i)

- Overall galactic f_{esc} stays at around 1% during 20 Myrs

High f_{esc}(i) clumps: size by f_{esc}(i), color by age

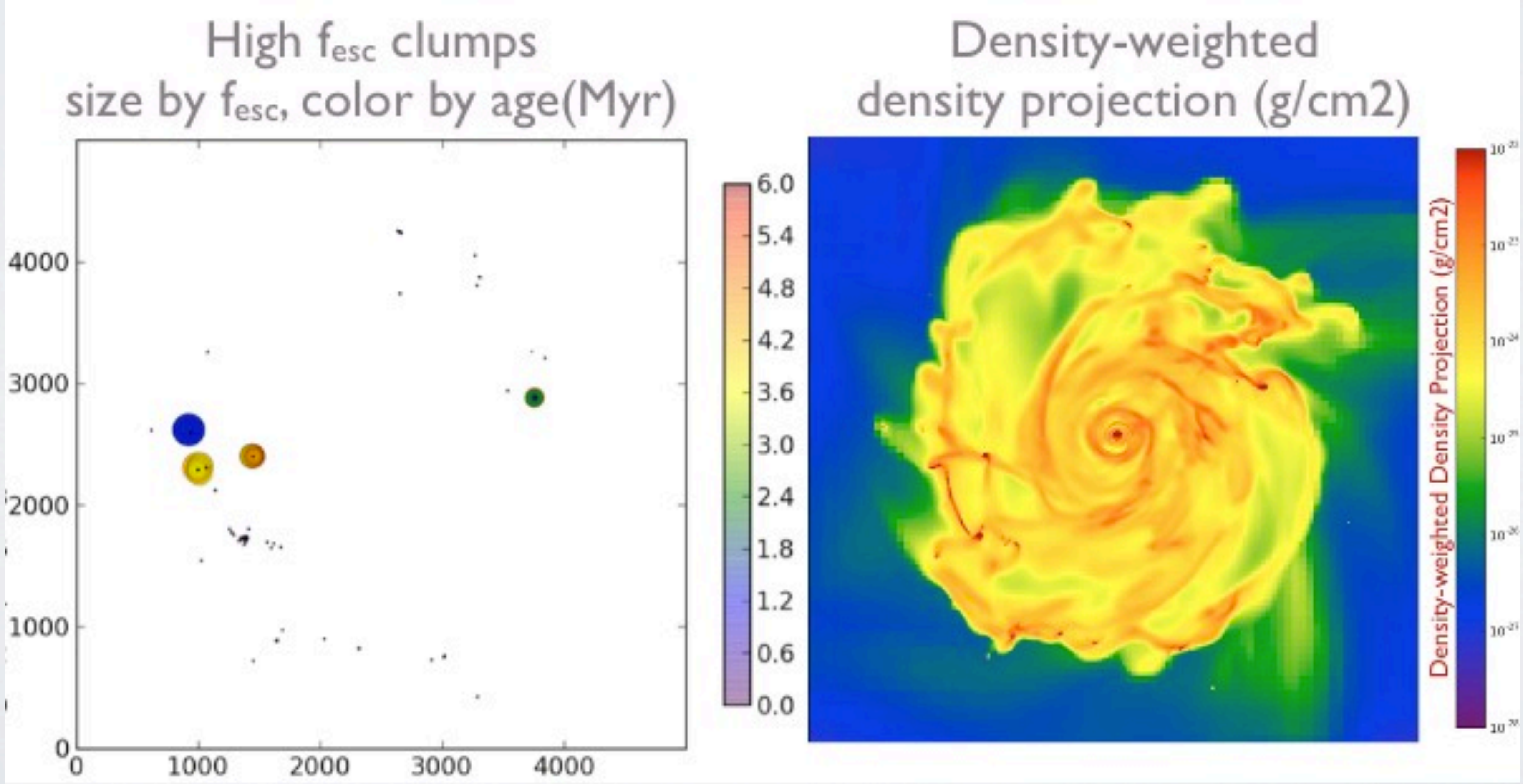






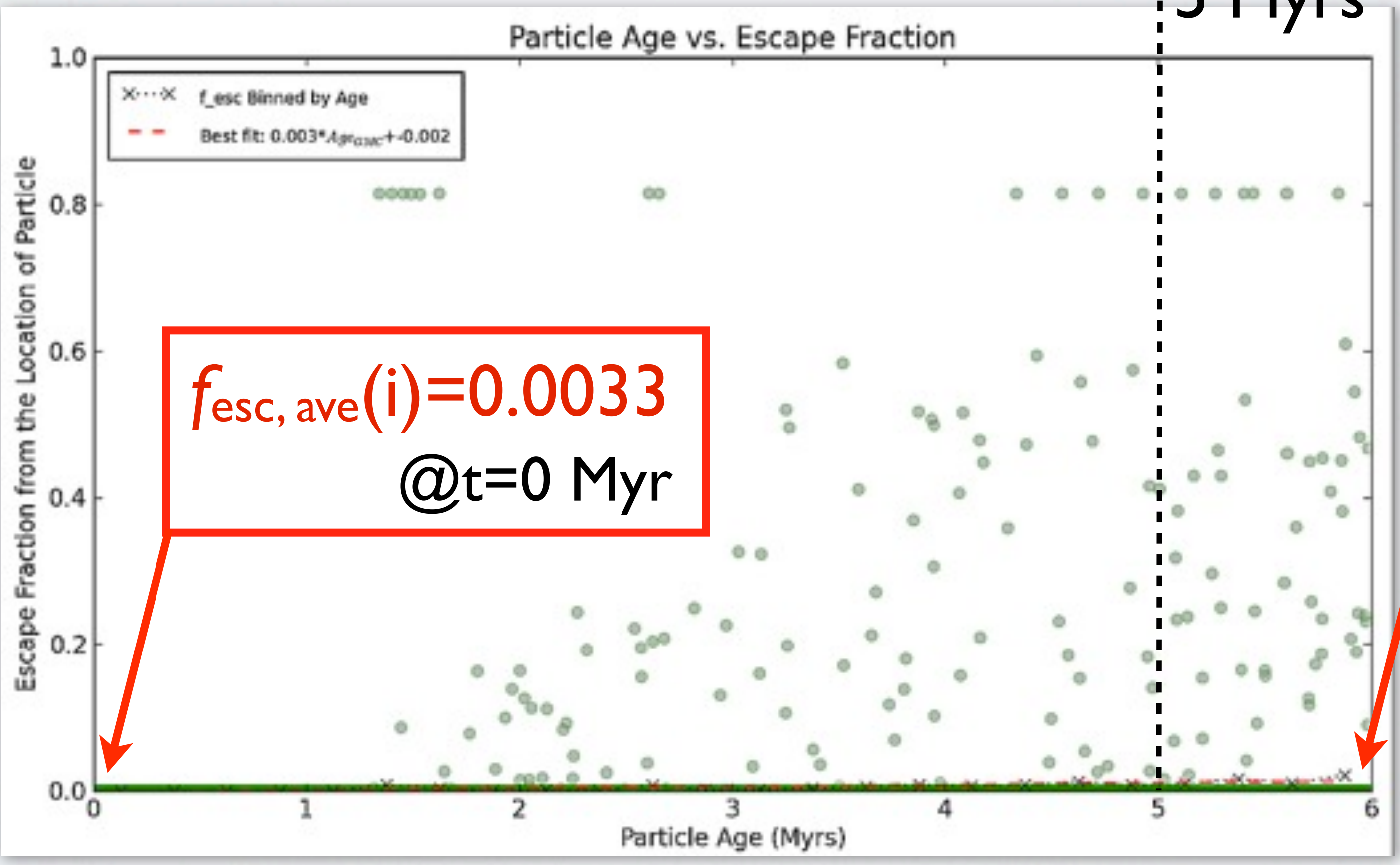
Galactic f_{esc} Dominated by A Few Clumps

- A small number of MCs with high escape fraction dominates the overall galactic escaped ionizing photons
  - e.g. galactic $f_{esc} = 0.01$ → 1% of particles with $f_{esc}(i) = 1.00$
    rather than
    100% of particles with $f_{esc}(i) = 0.01$



High f_{esc}(i) Clumps Tend To Be Old

- Young MCs still buried in cold gas
- Old MCs tend to have higher f_{esc}(i) and contribute equally to the total escaped photons
  - MC drifts from dense clump + aided by SN peaking at 5 Myr
  - $f_{esc}(i) = 0.0031 \times (age)_{MC} + 0.0033$



5 Myrs

Escape fraction →

$f_{esc, ave}(i)=0.0033$
@t=0 Myr

$f_{esc, ave}(i)=0.0219$
@t=6 Myr

molecular cloud particle age →

High f_{esc}(i) Clumps Tend To Be Old

- Young MCs still buried in cold gas
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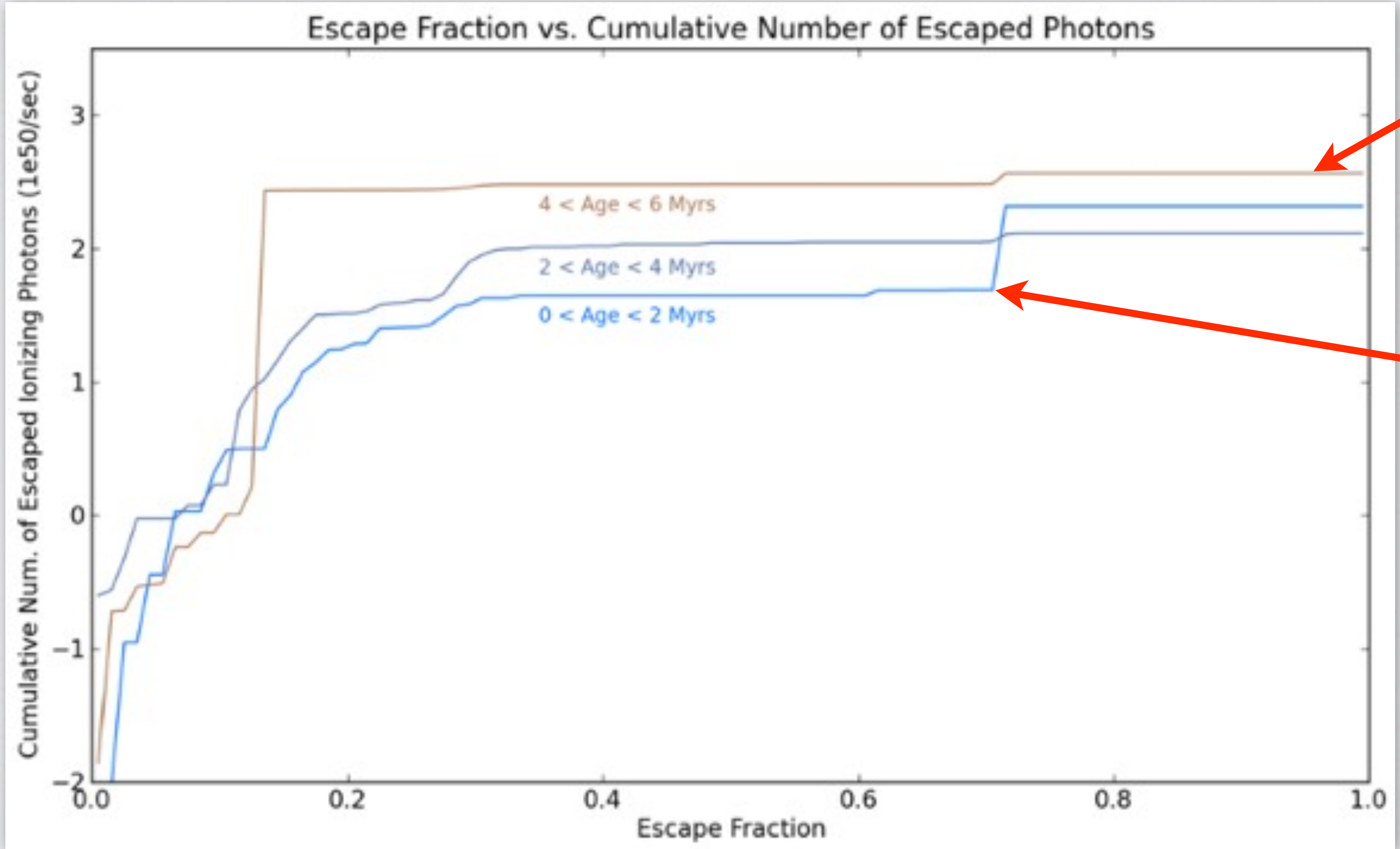
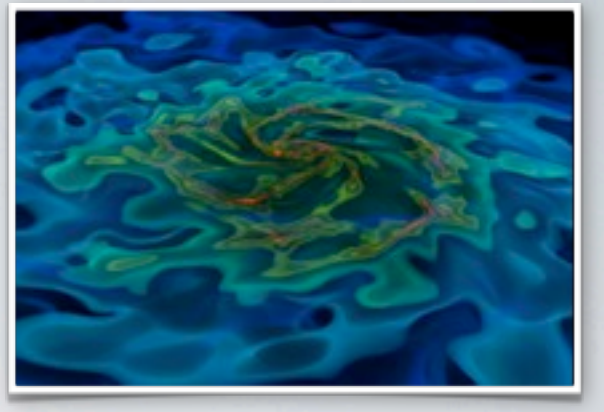


age = 4-6 Myrs

age = 0-2 Myrs

Cumulative number of escaped photon (10^{50}/sec) →

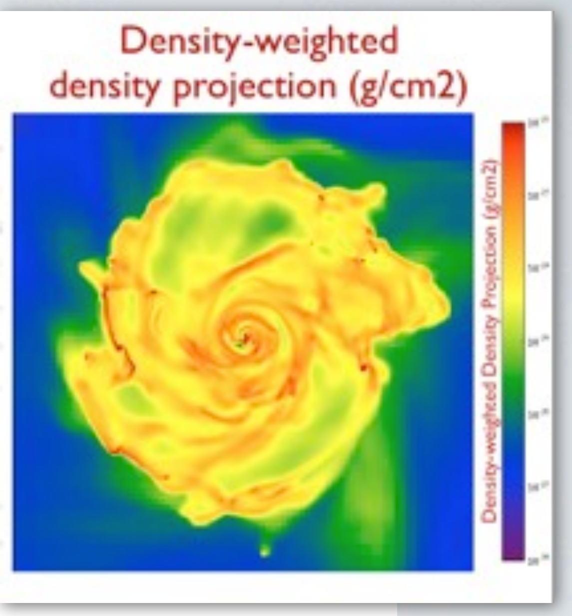
Escape fraction →

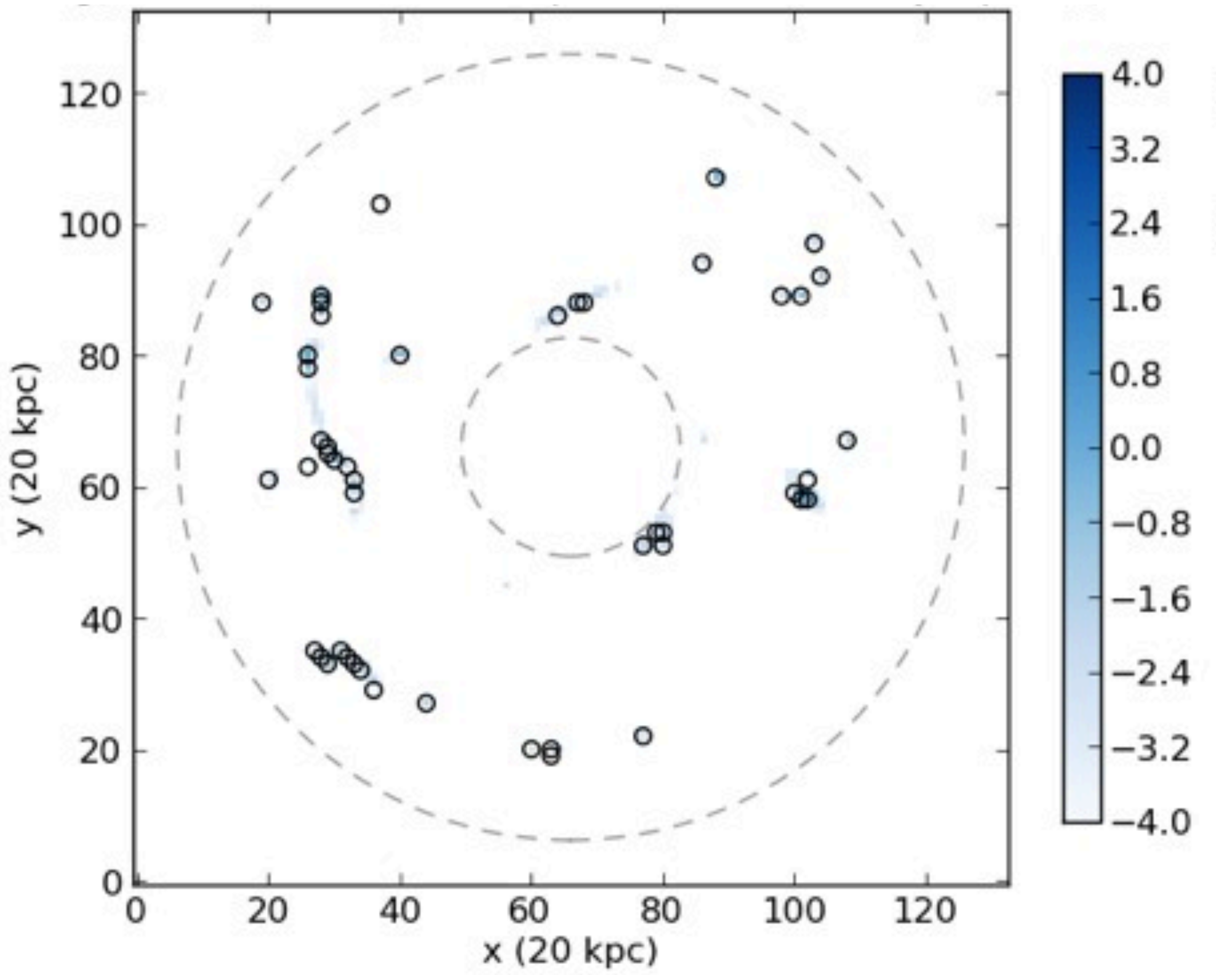


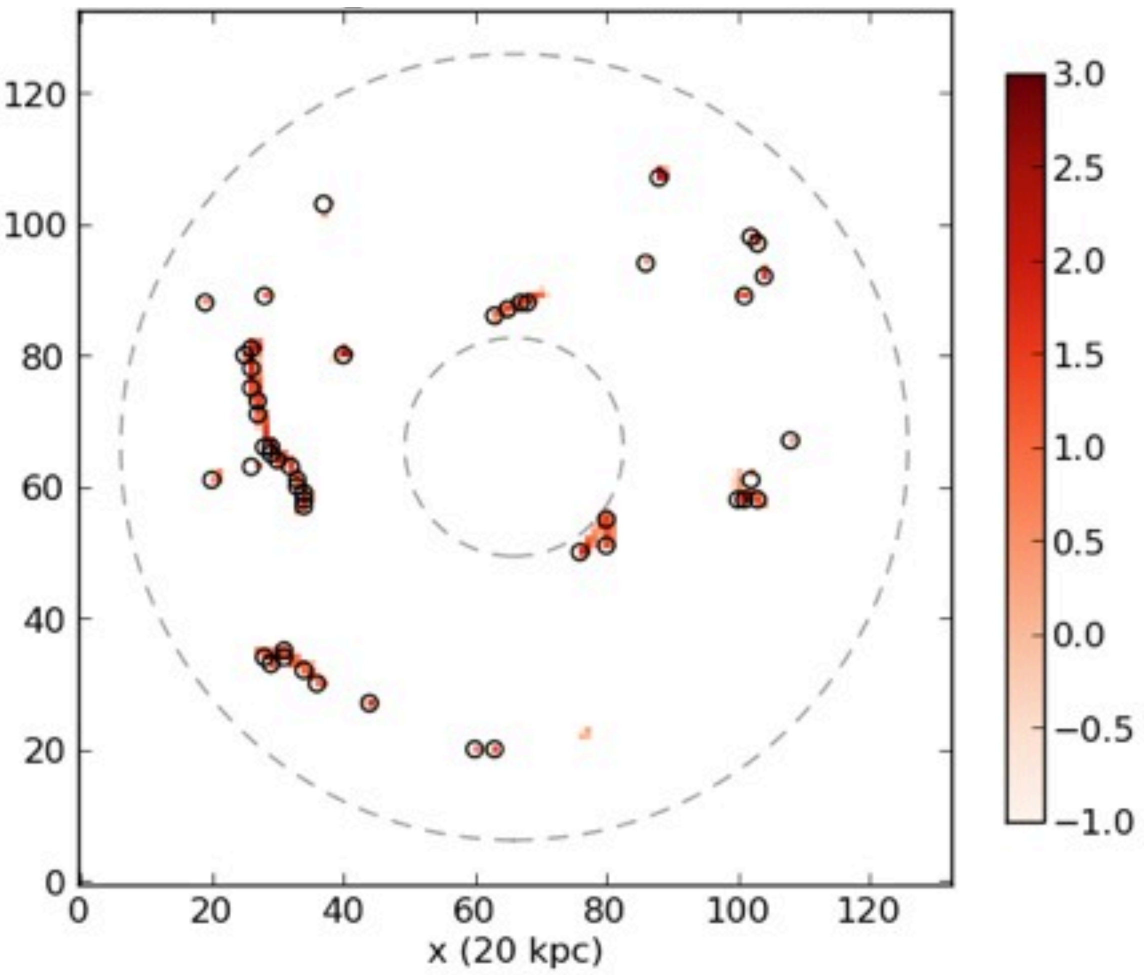
II. Star Formation Relation via Simulated Observation

Mock Observation in Simulations

- Simulated observations
  - Estimate SFR by Hα: Dong & Draine (2011) + Schruba et al. (2010)
  - Estimate H_2 by f_{H_2}: Krumholz et al. (2009) + Kuhlen et al. (2011)

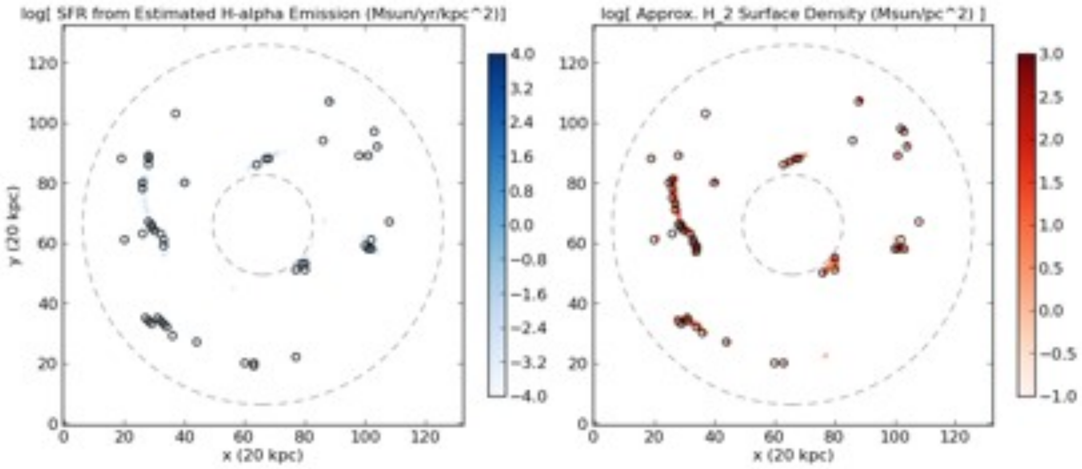


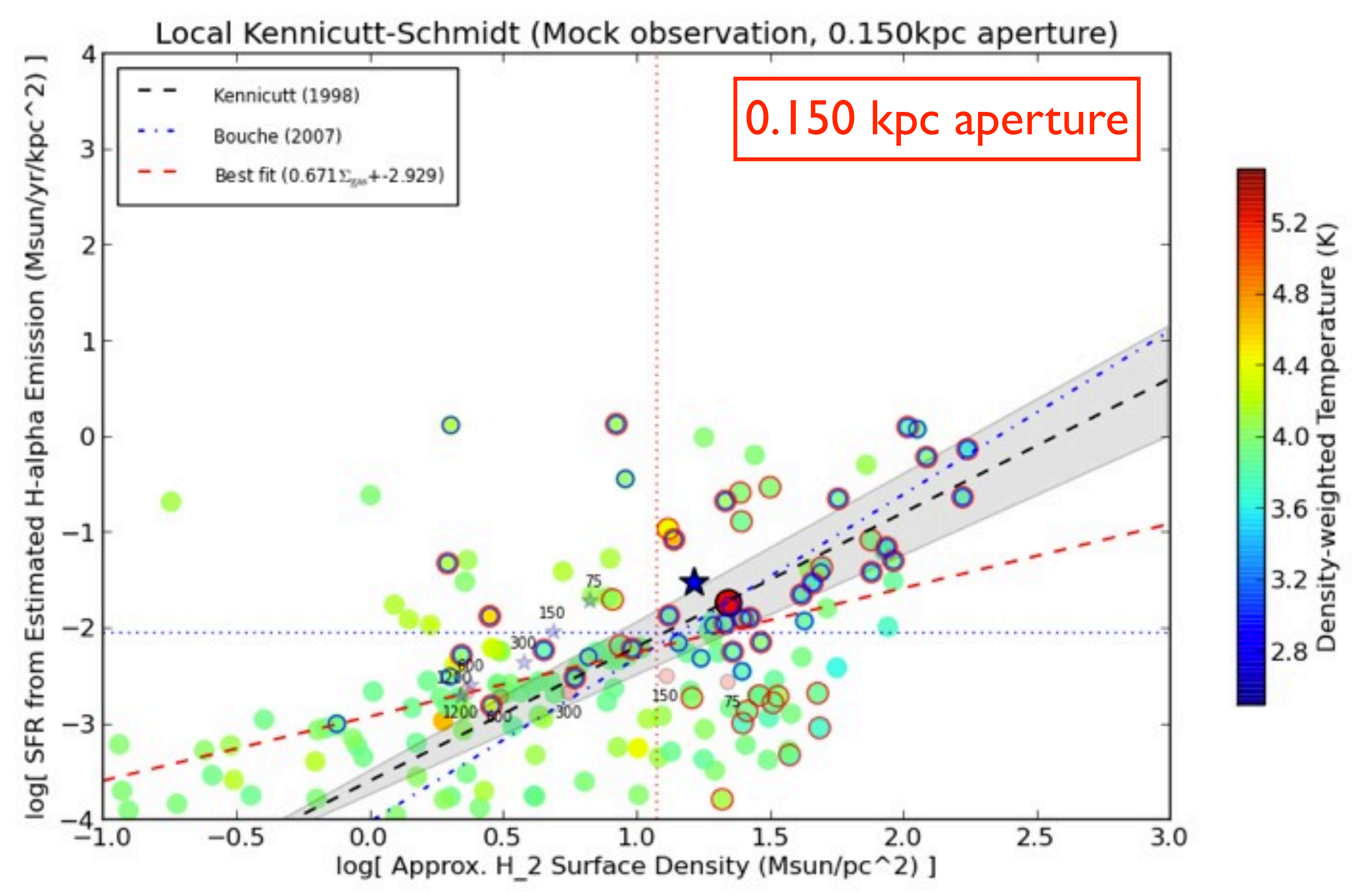

SFR estimated by Hα luminosity
$(M_\odot/\mathrm{yr}/\mathrm{kpc}^2)$


Approximate H_2 surface density
$(M_\odot/\mathrm{kpc}^2)$

Star Formation Laws via Simulated Obs.

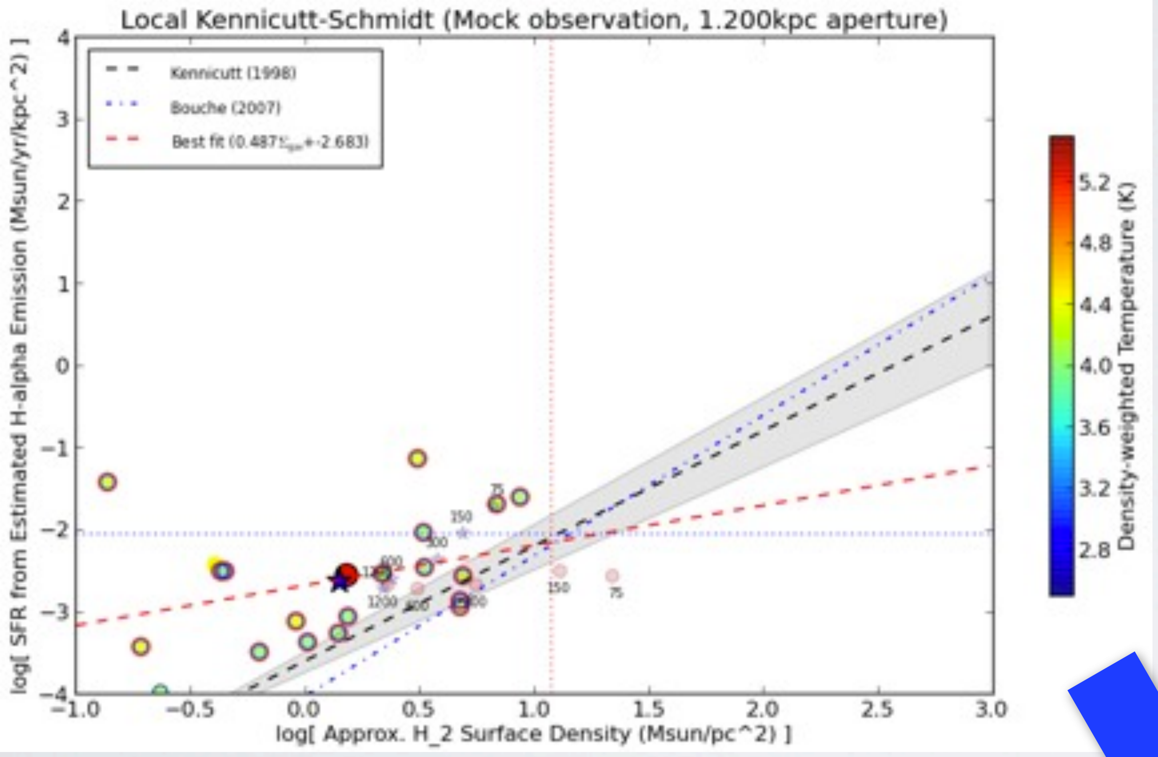
- Kennicutt-Schmidt plane with estimated SFR and H_2 densities



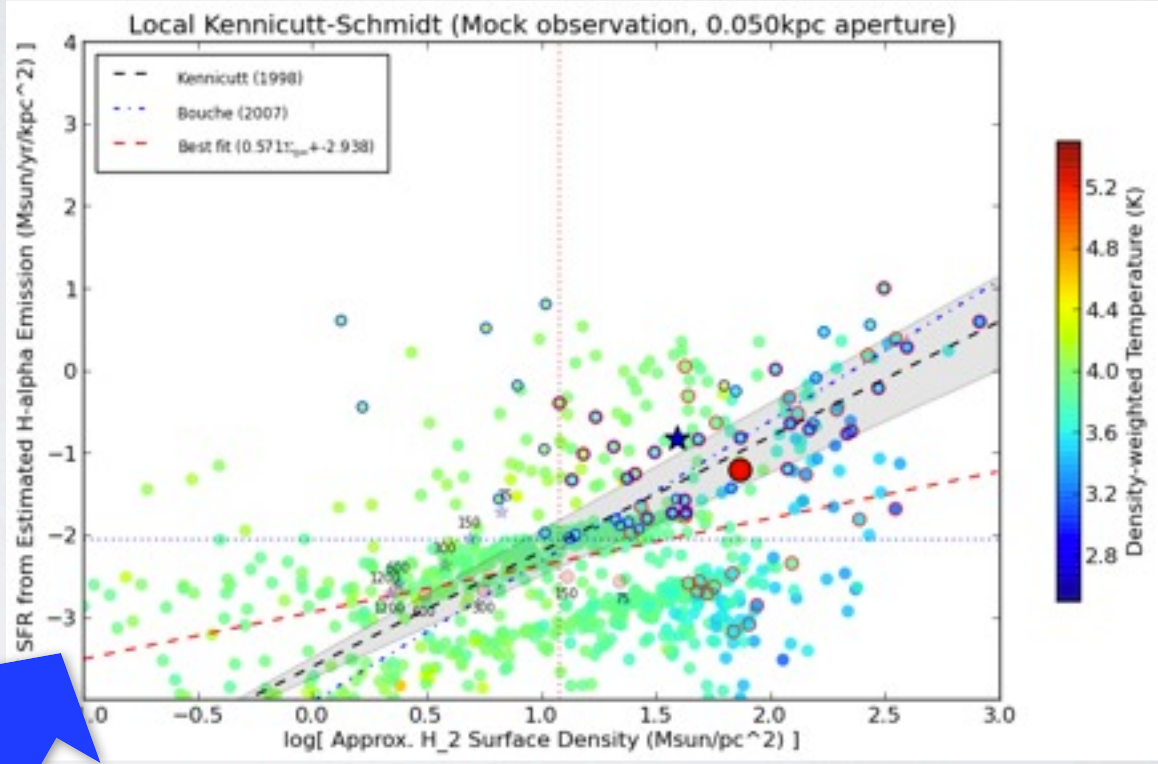


0.150 kpc aperture

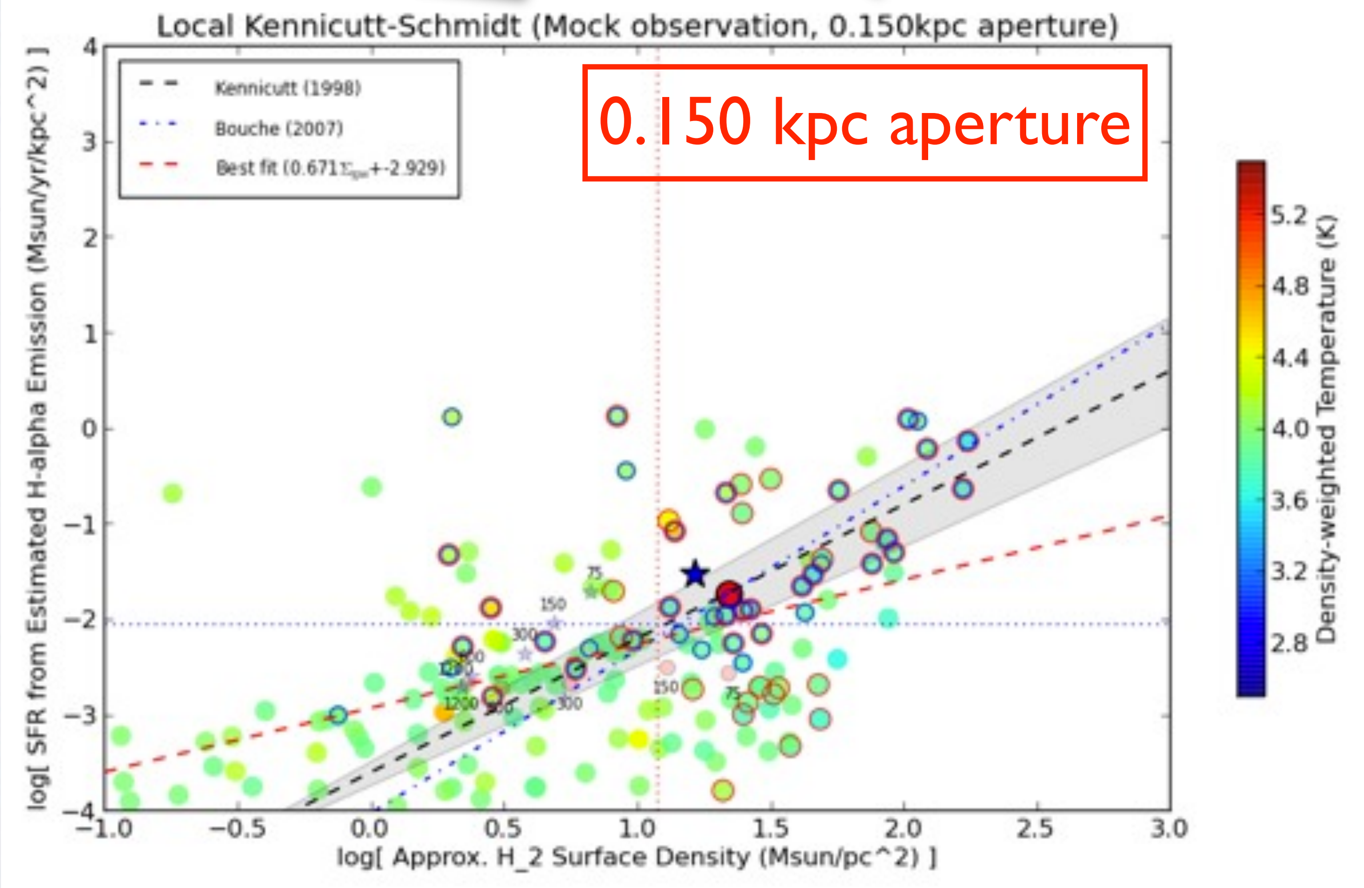
Using Different Aperture Sizes



1.200 kpc aperture



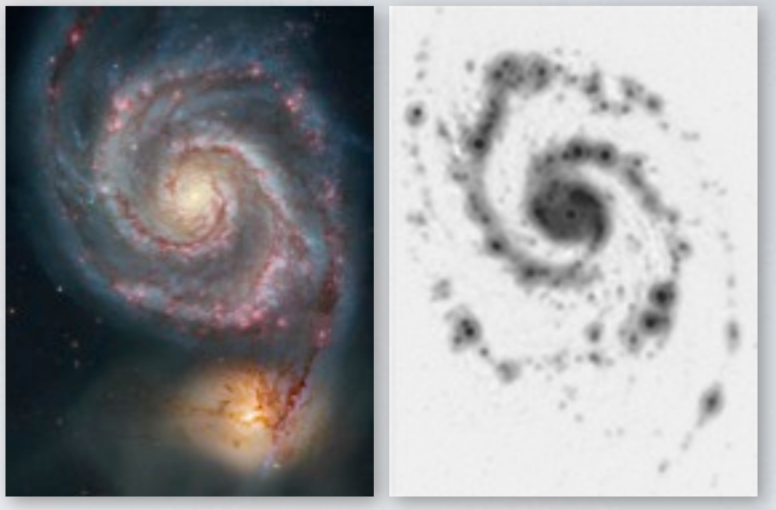
0.050 kpc aperture



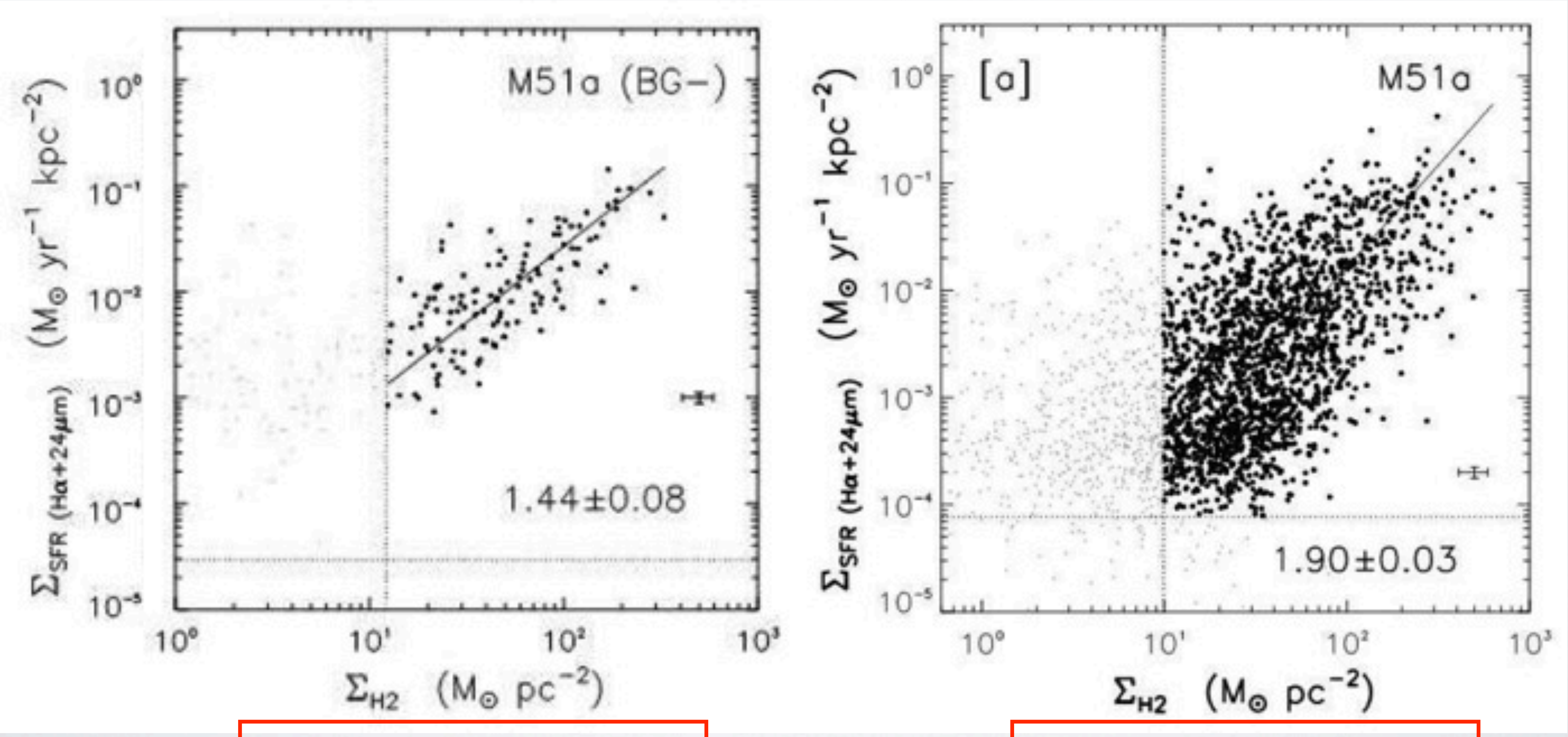
0.150 kpc aperture

Observation with Different Apertures

- Smaller aperture → more scatter



M51, Liu et al. (2011)

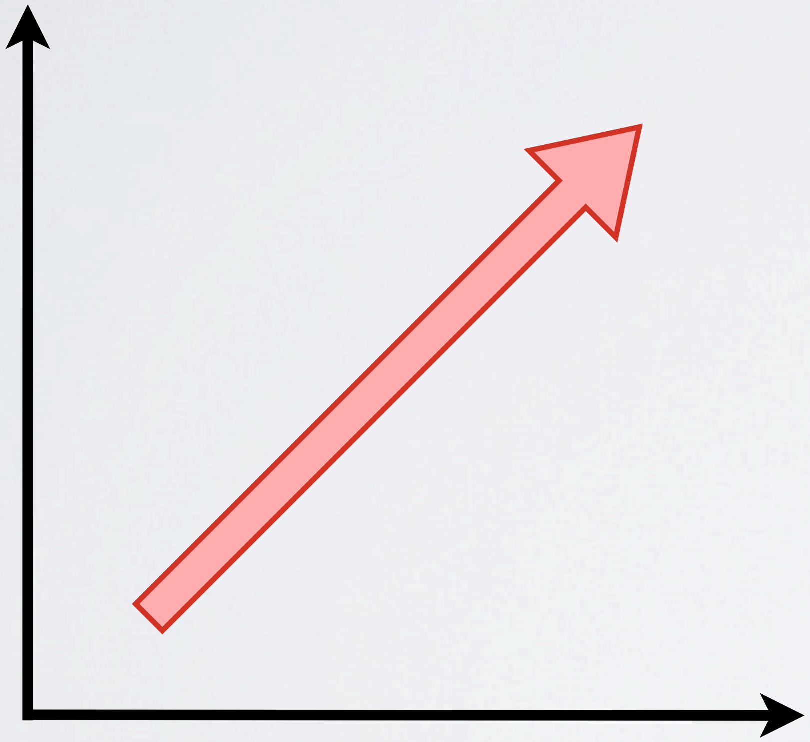


0.750 kpc aperture

0.230 kpc aperture

Kennicutt-Schmidt Plane

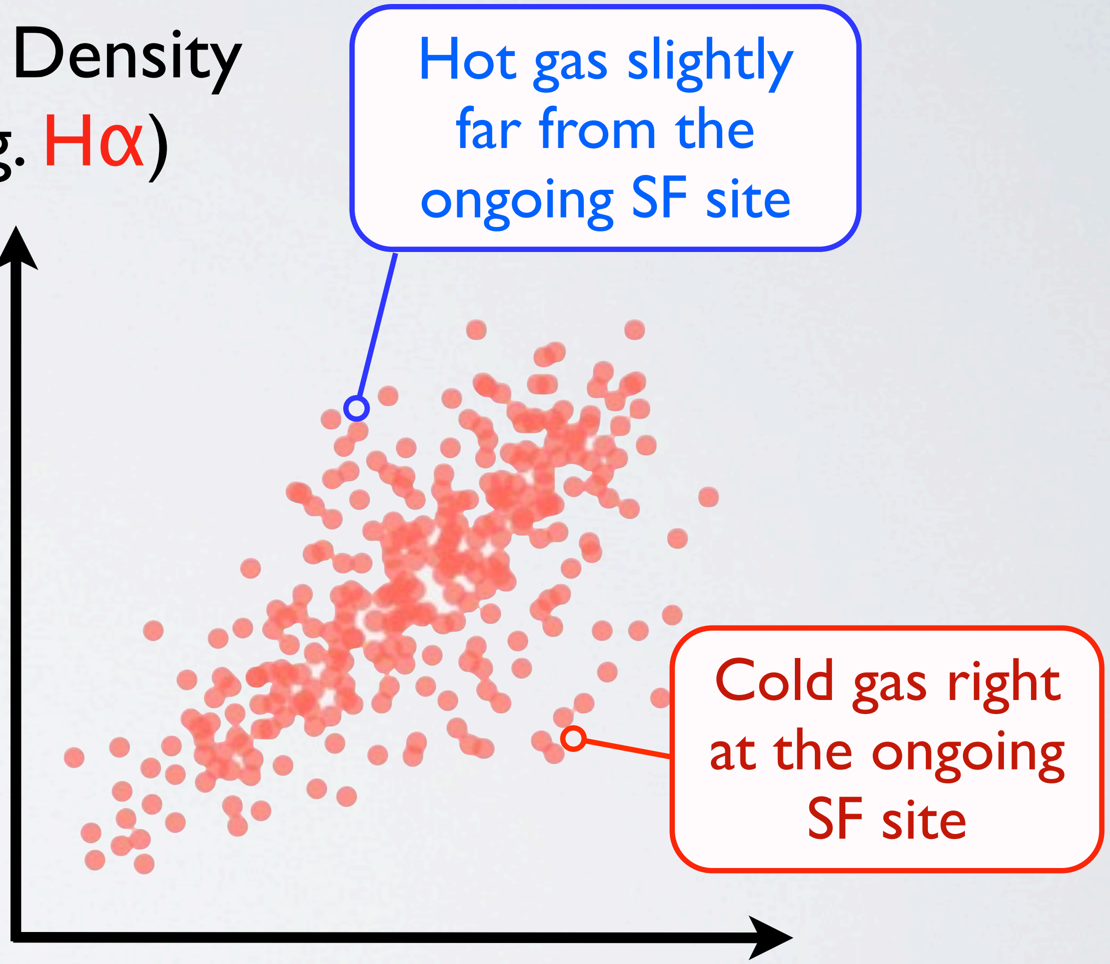
Ideal World



SFR Surface Density

Molecular Hydrogen
Surface Density

Real World



SFR Surface Density
Proxy (e.g. Hα)

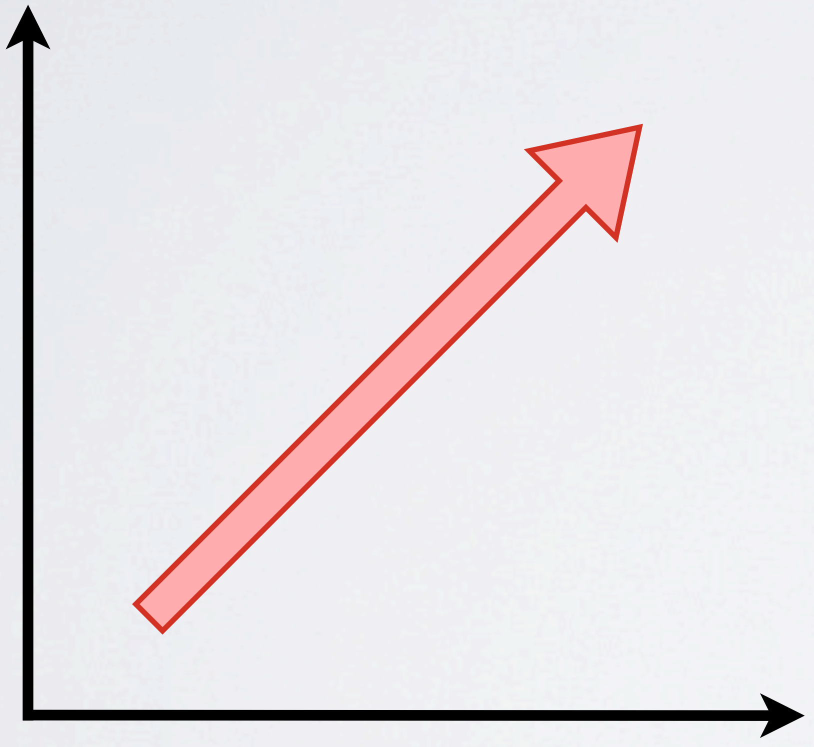
Hot gas slightly far from the ongoing SF site

Cold gas right at the ongoing SF site

Molecular Hydrogen
Surface Density Proxy
(e.g. CO)

Which Peaks to Choose: H_2 or Hα?

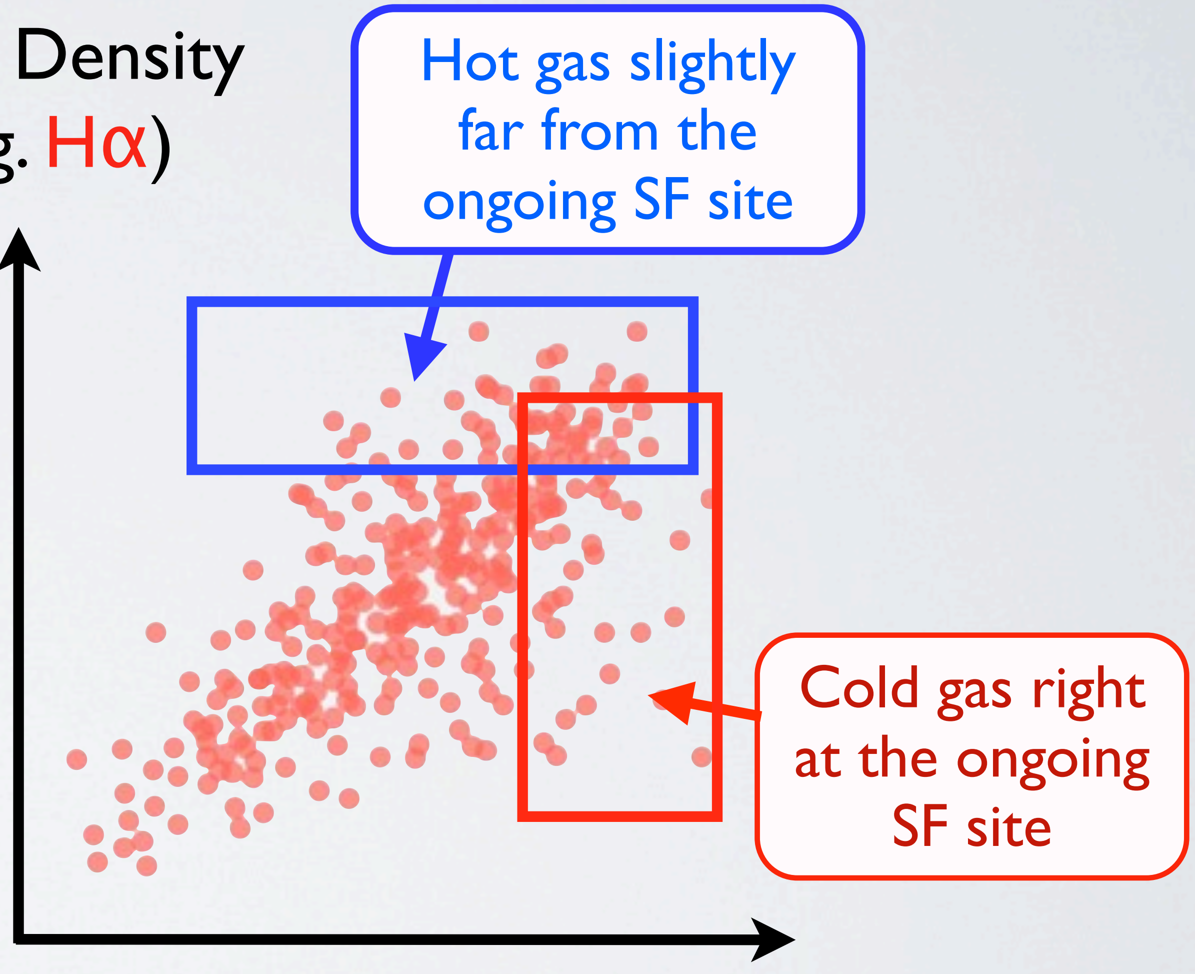
Ideal World



SFR Surface Density

Molecular Hydrogen
Surface Density

Real World



SFR Surface Density
Proxy (e.g. Hα)

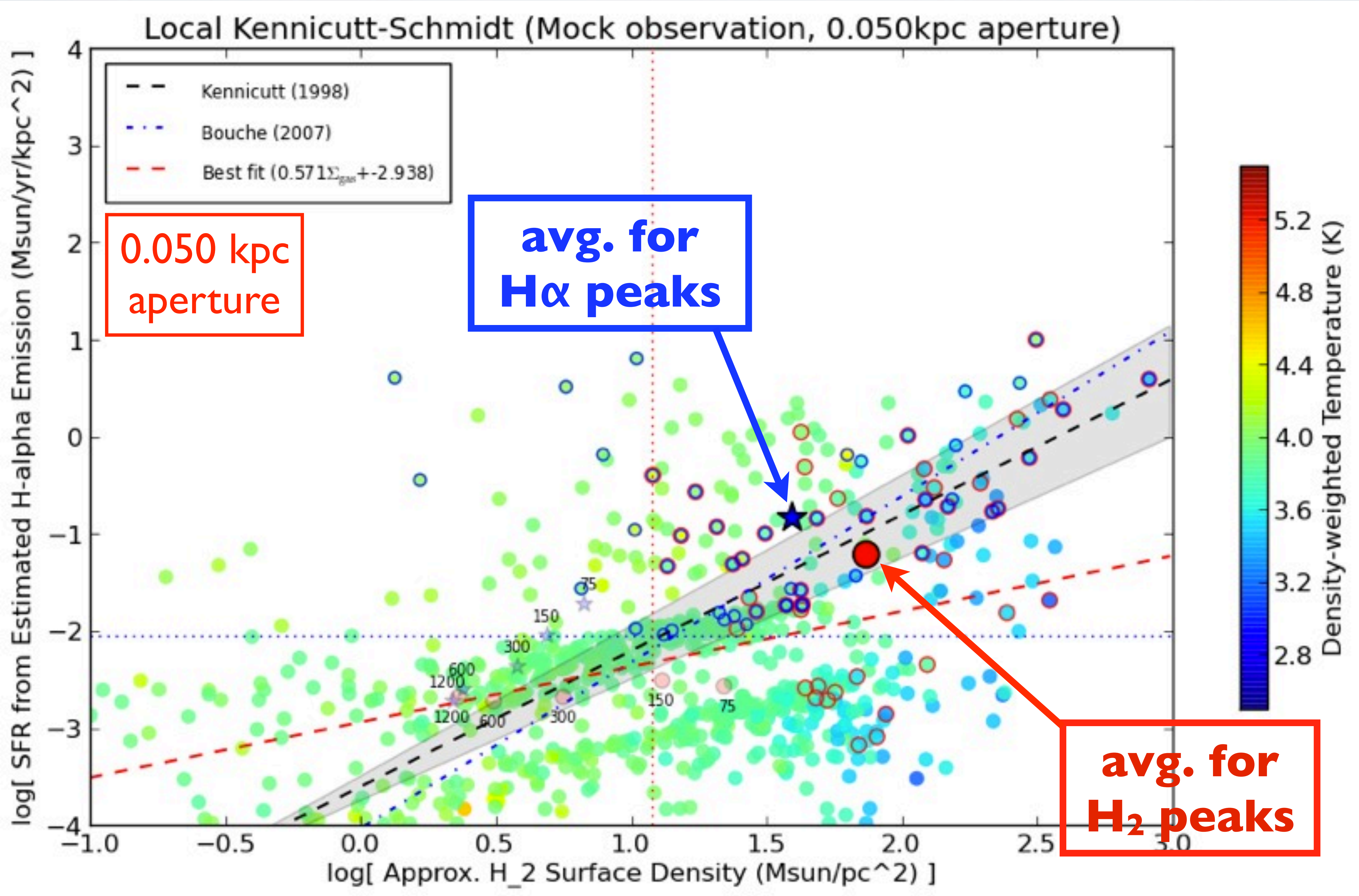
Hot gas slightly
far from the
ongoing SF site

Cold gas right
at the ongoing
SF site

Molecular Hydrogen
Surface Density Proxy
(e.g. CO)

Averages for H_2 or Hα Peaks

- Average depletion time depends on which peaks you choose



0.050 kpc aperture

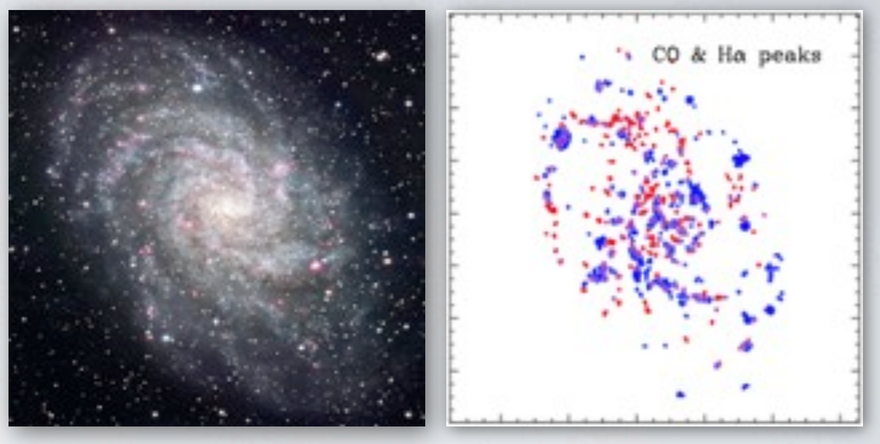
avg. for Hα peaks

avg. for H_2 peaks

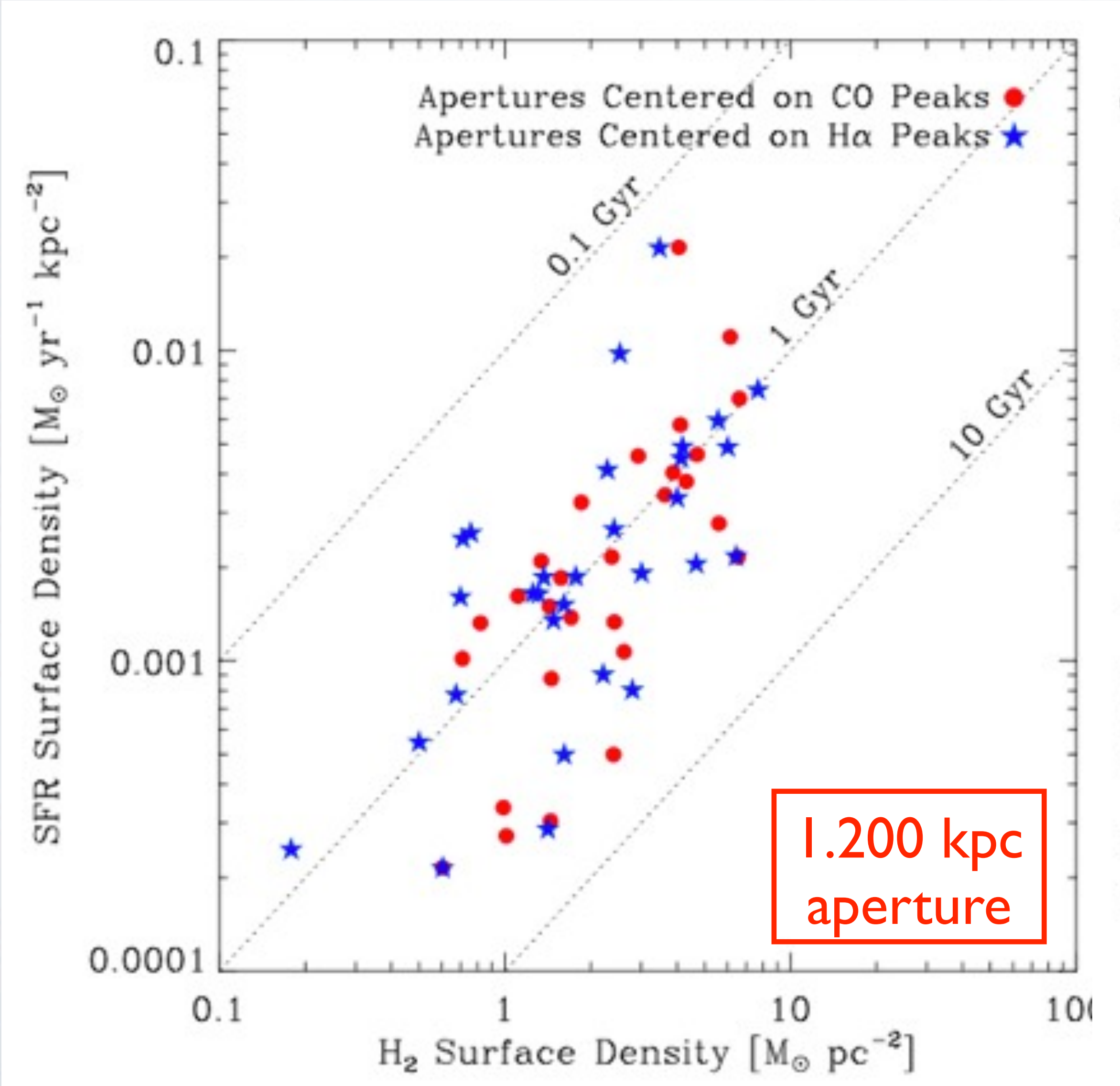
Averages for H_2 or Hα Peaks

- Average for H_2 → relatively **recent** SF

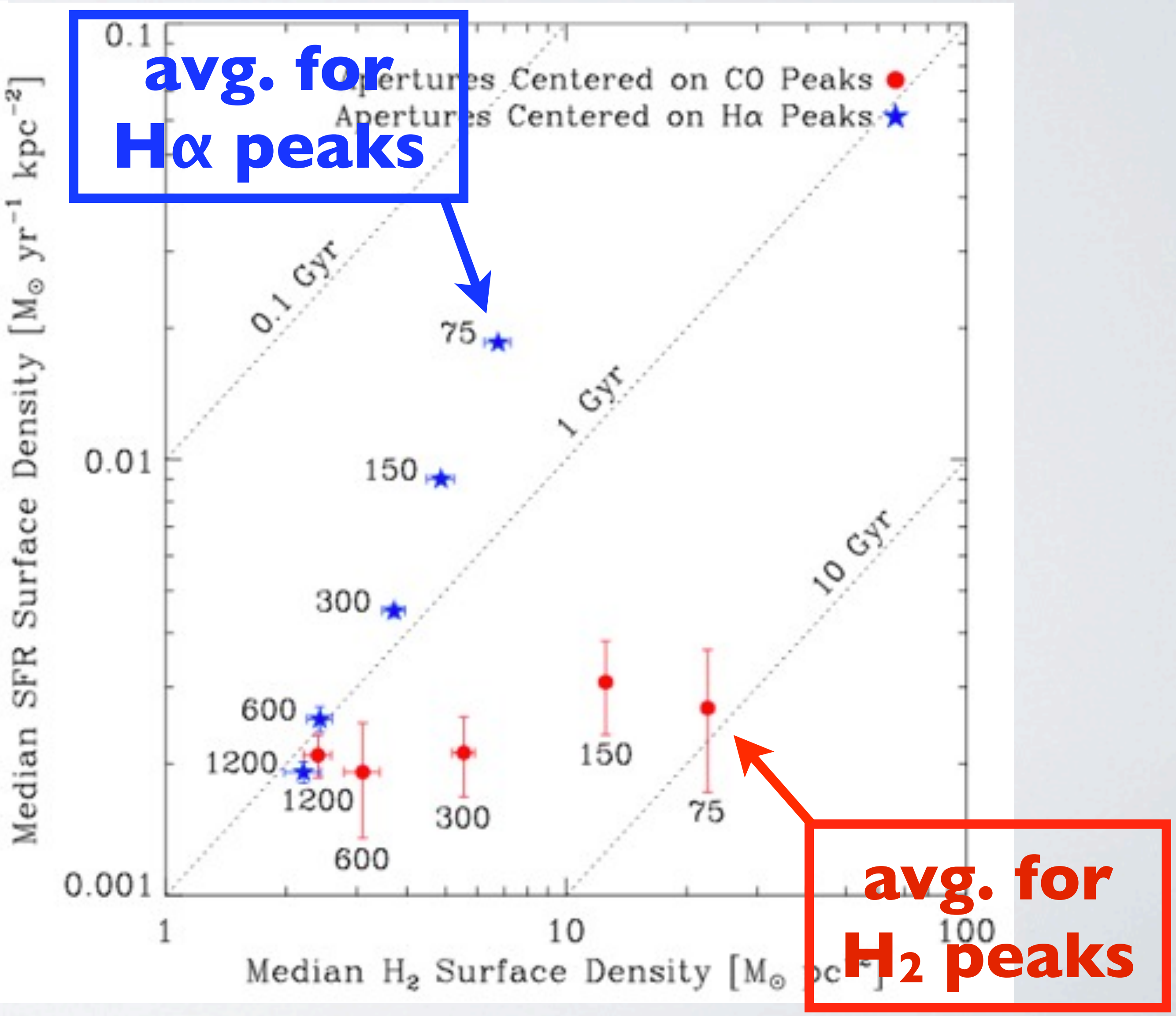
  Average for Hα → relatively **old** SF sites



M33, Schruba et al. (2010)



1.200 kpc aperture



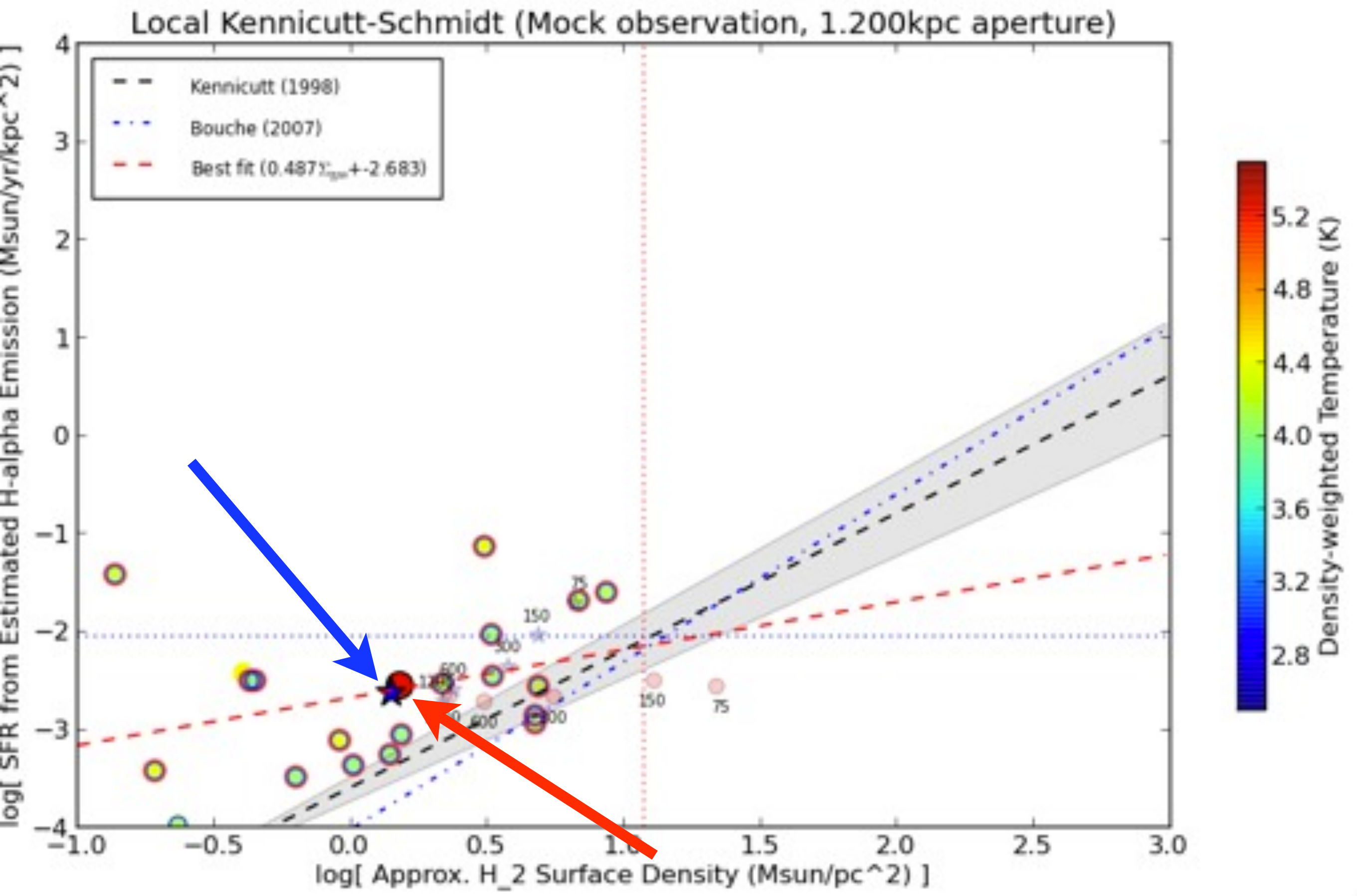
avg. for Hα peaks

avg. for H_2 peaks

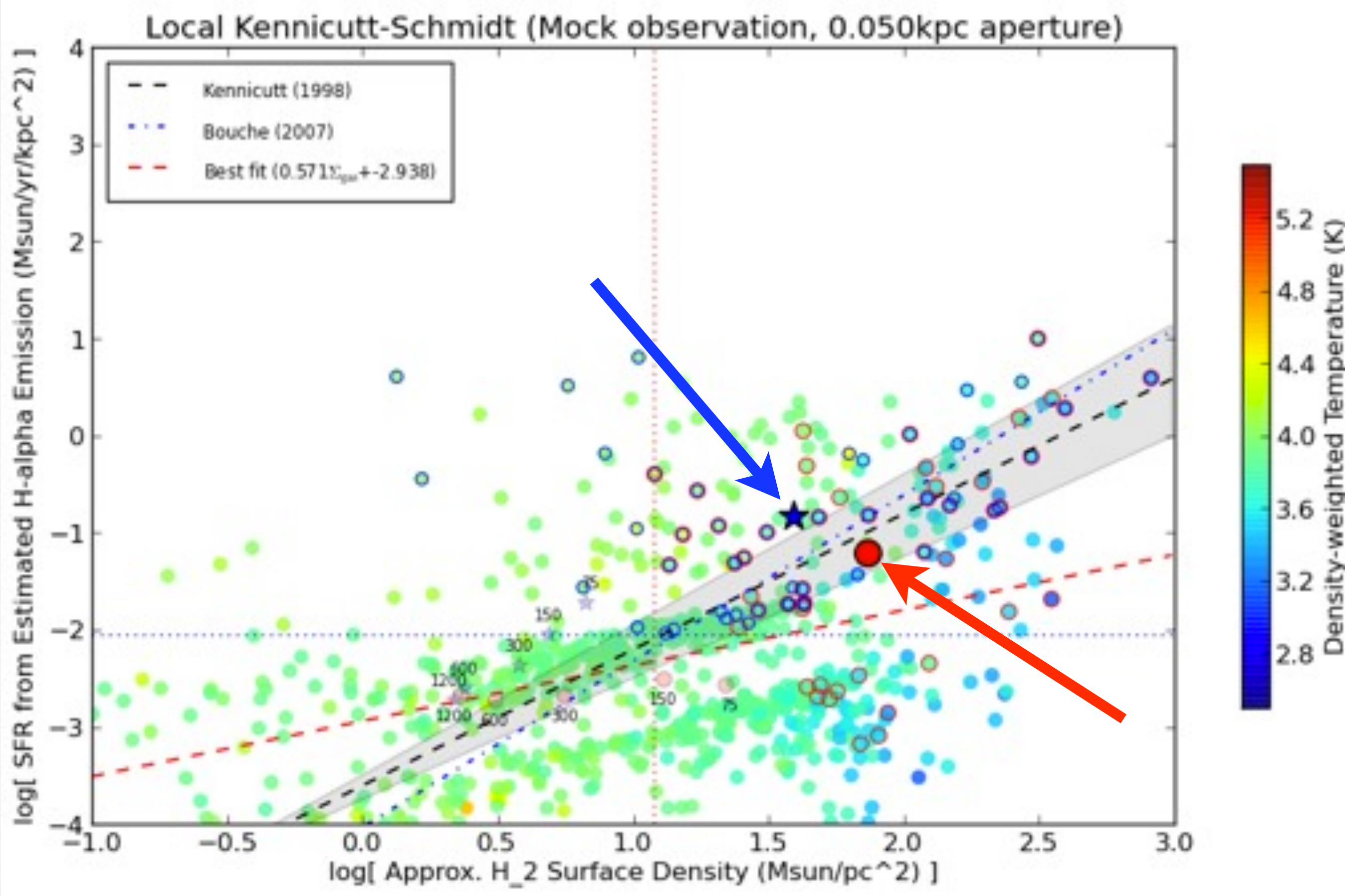
Scale Dependence of SF Relation

- Kennicutt-Schmidt law holds well with large aperture size

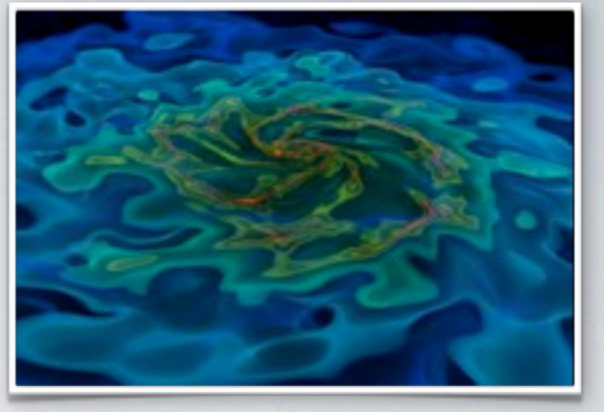
  → may break down at <0.300 kpc where each datapoint no longer averages over many different evolutionary states



1.200 kpc aperture



0.050 kpc aperture



Conclusions

Towards An "*Unabridged*" Understanding of Galaxy Formation

- We are at a critical junction in numerical study of galaxies

- Realistic treatments of stellar feedback from molecular cloud particles is a key in ~pc resolution galactic simulations

- Radiation feedback of molecular cloud particles combined with a versatile post-processing tool enables us to make intriguing mock observations