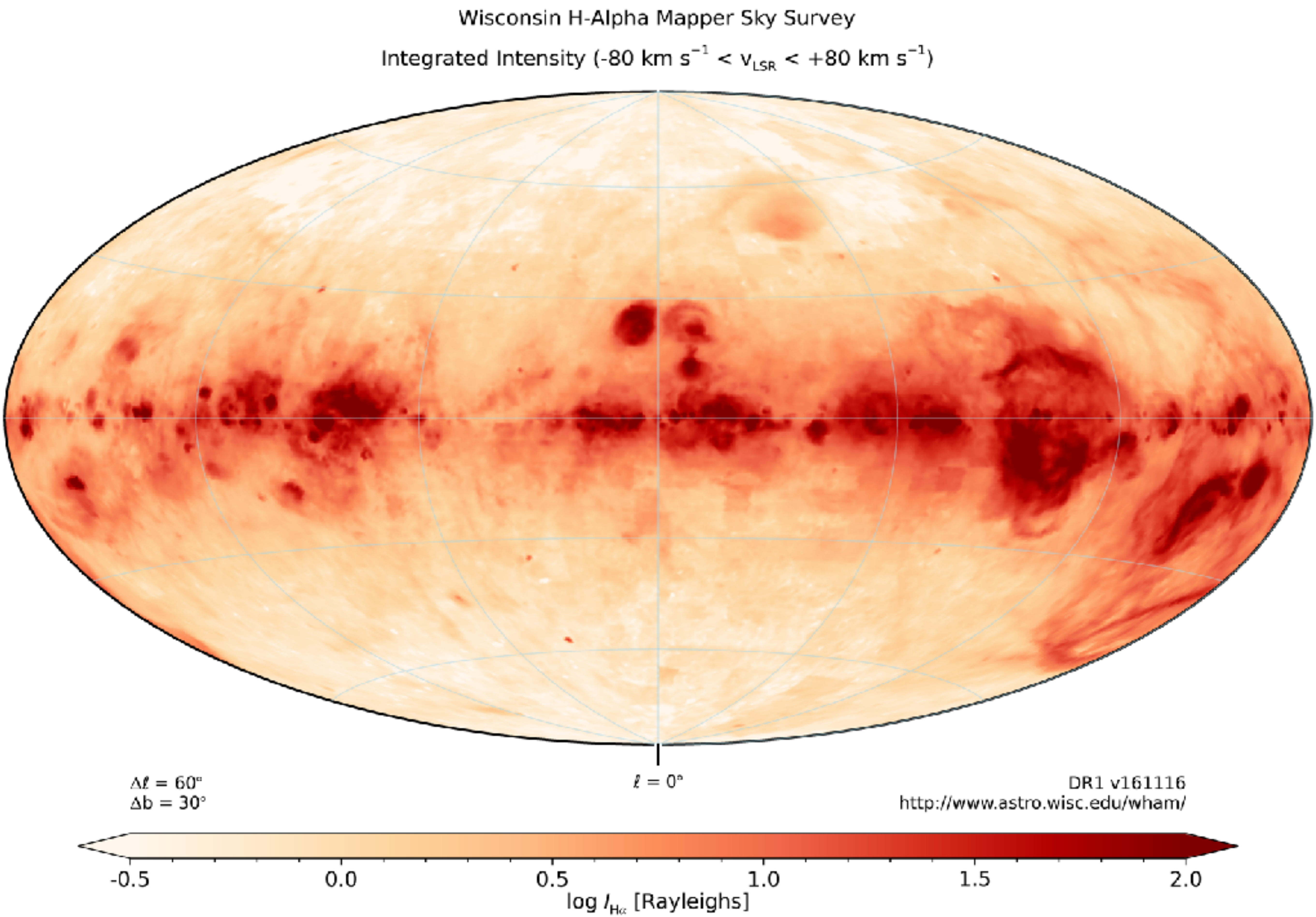
Physics 224
The Interstellar Medium

Lecture #20 - the last!


Wisconsin H-Alpha Mapper Sky Survey
Integrated Intensity (-80 km s^{-1} < v_{LSR} < +80 km s^{-1})
$\Delta\ell$ = 60°
Δb = 30°
ℓ = 0°
DR1 v161116
http://www.astro.wisc.edu/wham/
-0.5
0.0
0.5
1.0
1.5
2.0
log $I_{H\alpha}$ [Rayleighs]

Diffuse Ionized Gas

Optical Emission from Ionized Gas

$$I_\nu(\mathrm{H}\alpha) = \frac{h\nu(\mathrm{H}\alpha)}{4\pi} \int_0^L n_e n_p \alpha(\mathrm{H}\alpha) dL$$

recombination rate + fraction of recombinations that produce Hα

define "emission measure":

$$\mathrm{EM} = \int_0^L n_e n_p dL$$

if $n_e \sim n_p$ then:

$$\mathrm{EM} = \int_0^L n_e^2 dL$$

Diffuse Ionized Gas

Observed Properties of the DIG (aka warm ionized medium)

- From comparison of DM and EM along lines of sight through the galaxy:
  - $n_e \sim 0.03 - 0.08\ cm^{-3}$
  - filling fraction f ~ 0.2 - 0.4
  - almost full ionized ($H^+/H \sim 0.9$)

Diffuse Ionized Gas

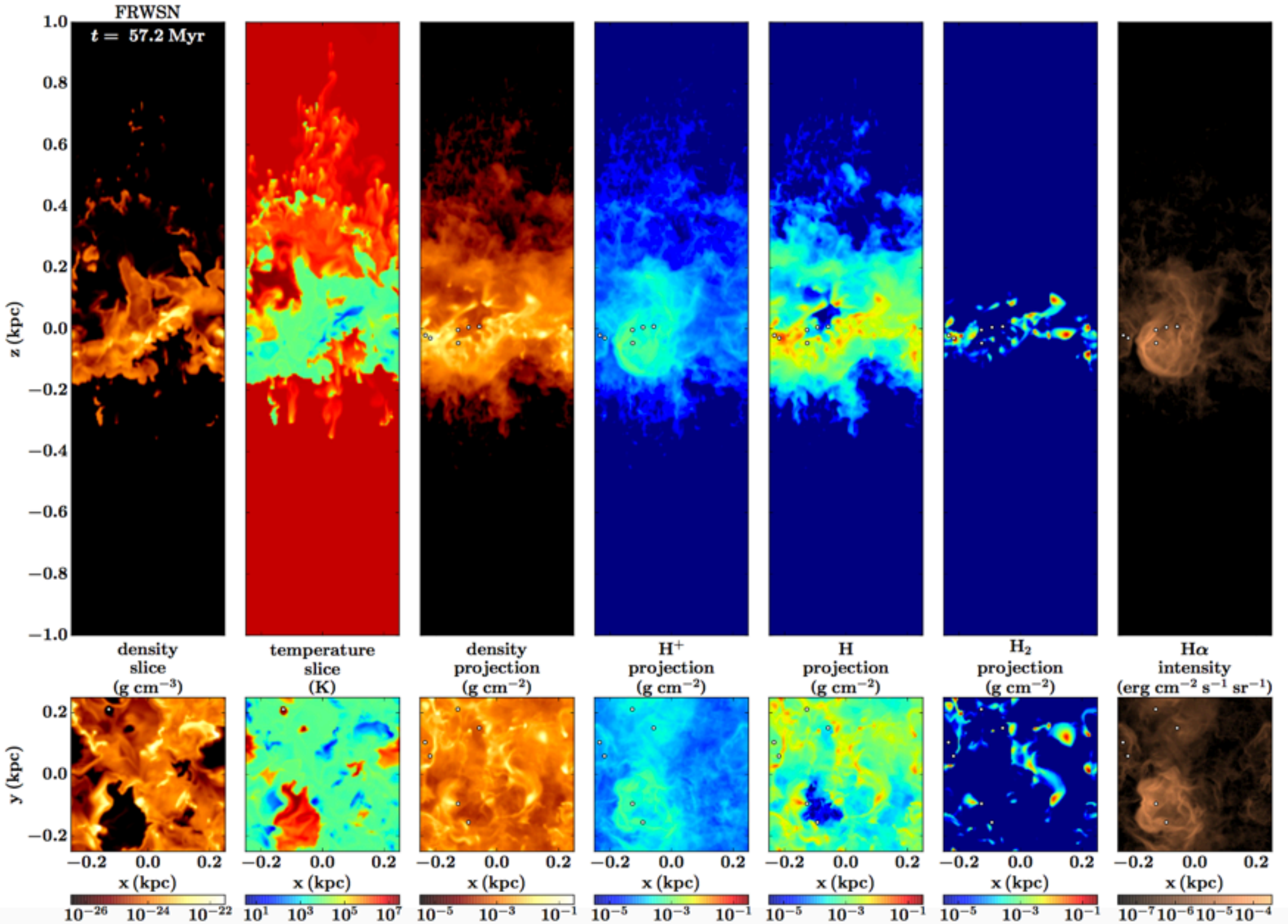
What ionizes the gas?

Need ionizing photon rate of ~ 10^{50} photons/s/kpc^2

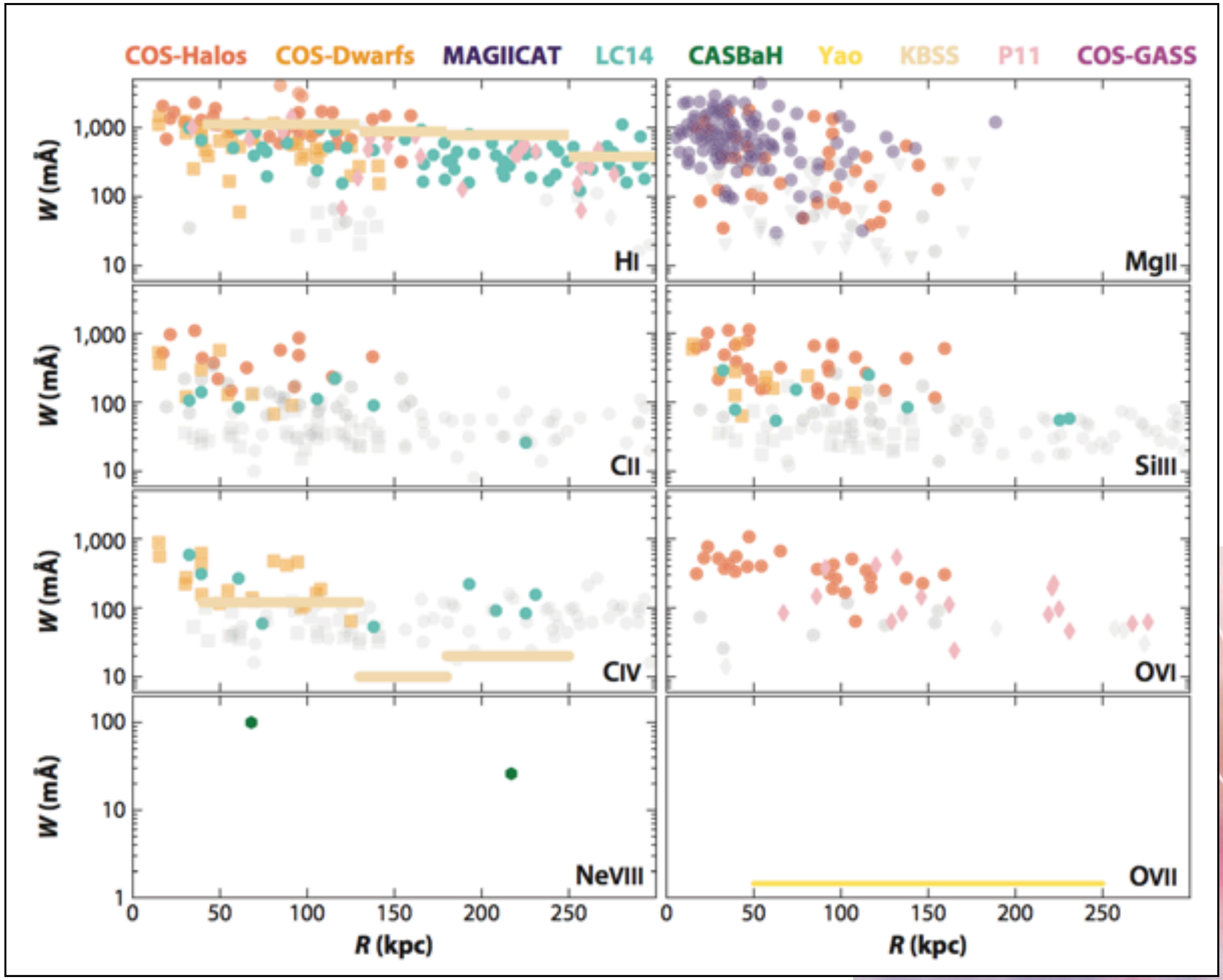
equivalent to about one O5 star (or 100 B0 stars) per kpc^2

equivalent to about 1/7 of the available ionizing photons in the kpc^2 around the Sun (Reynolds 1990)

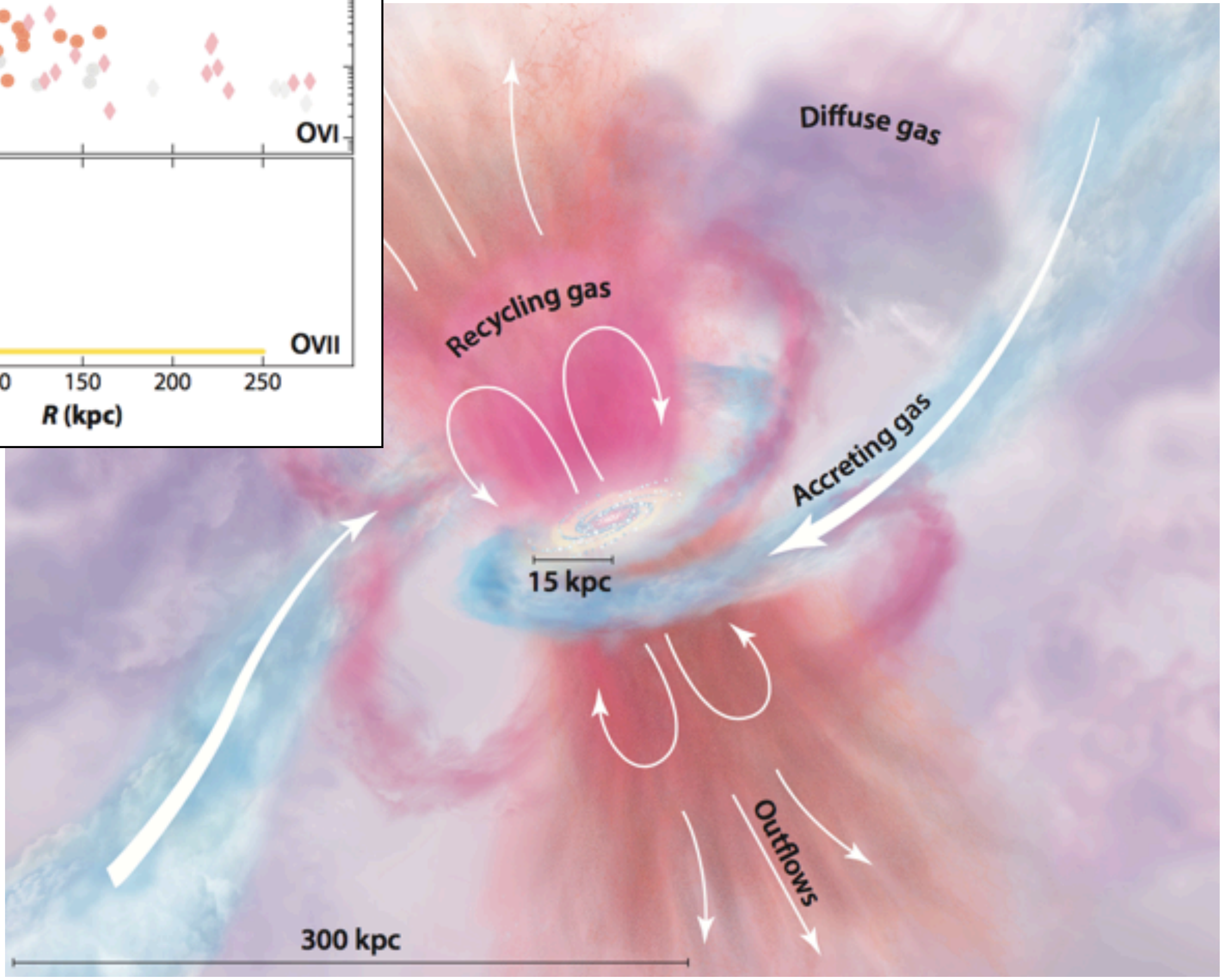
How do they get out of the Stromgren spheres though??



Supernova Driven ISM simulation - SILCC (Peters et al. 2017)



Disk-Halo connection - enriched, ionized material is being expelled from the galaxy as shown by COS-Halos measurements



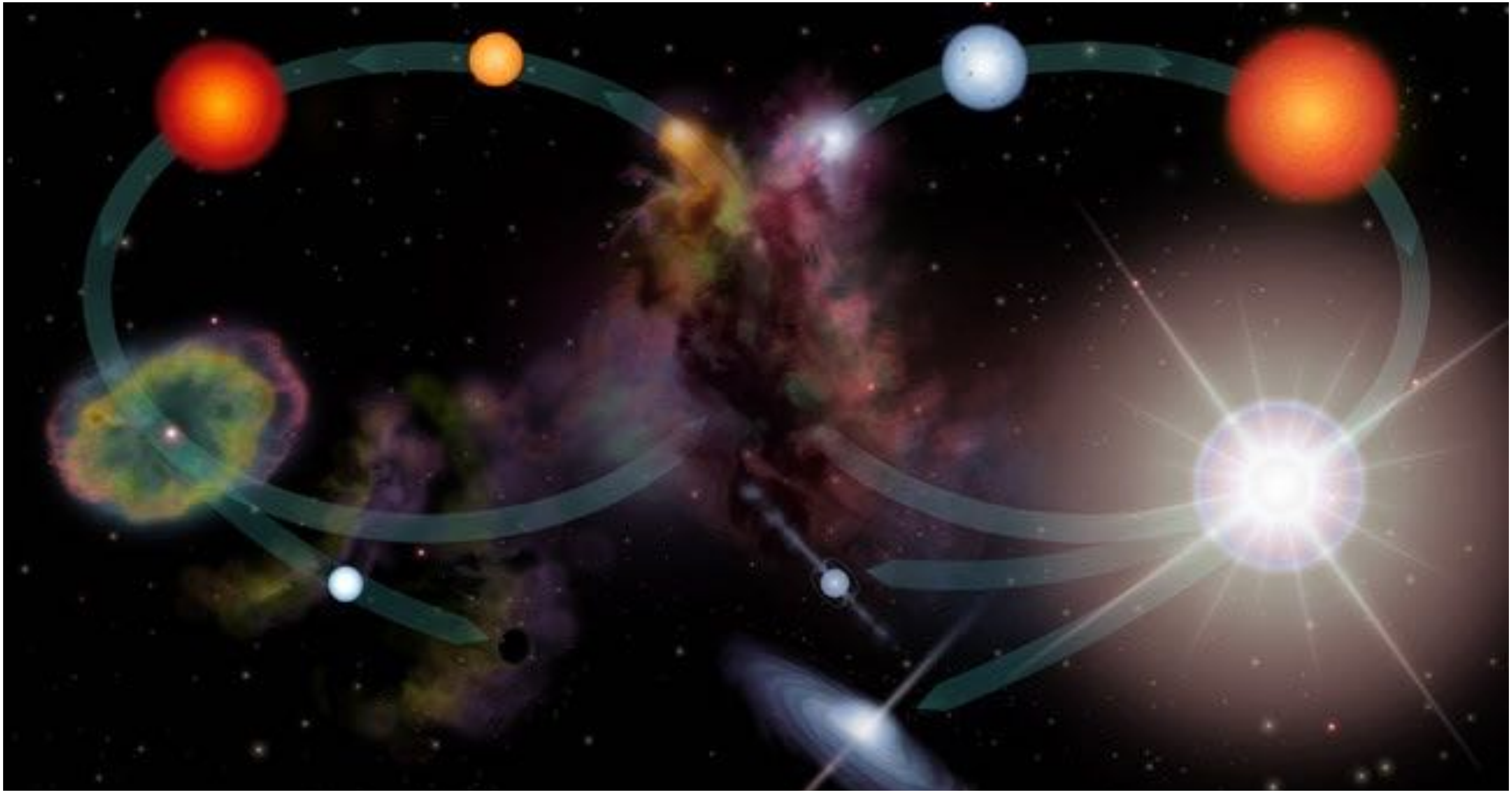
Tumlinson, Peeples & Werk 2017 ARA&A

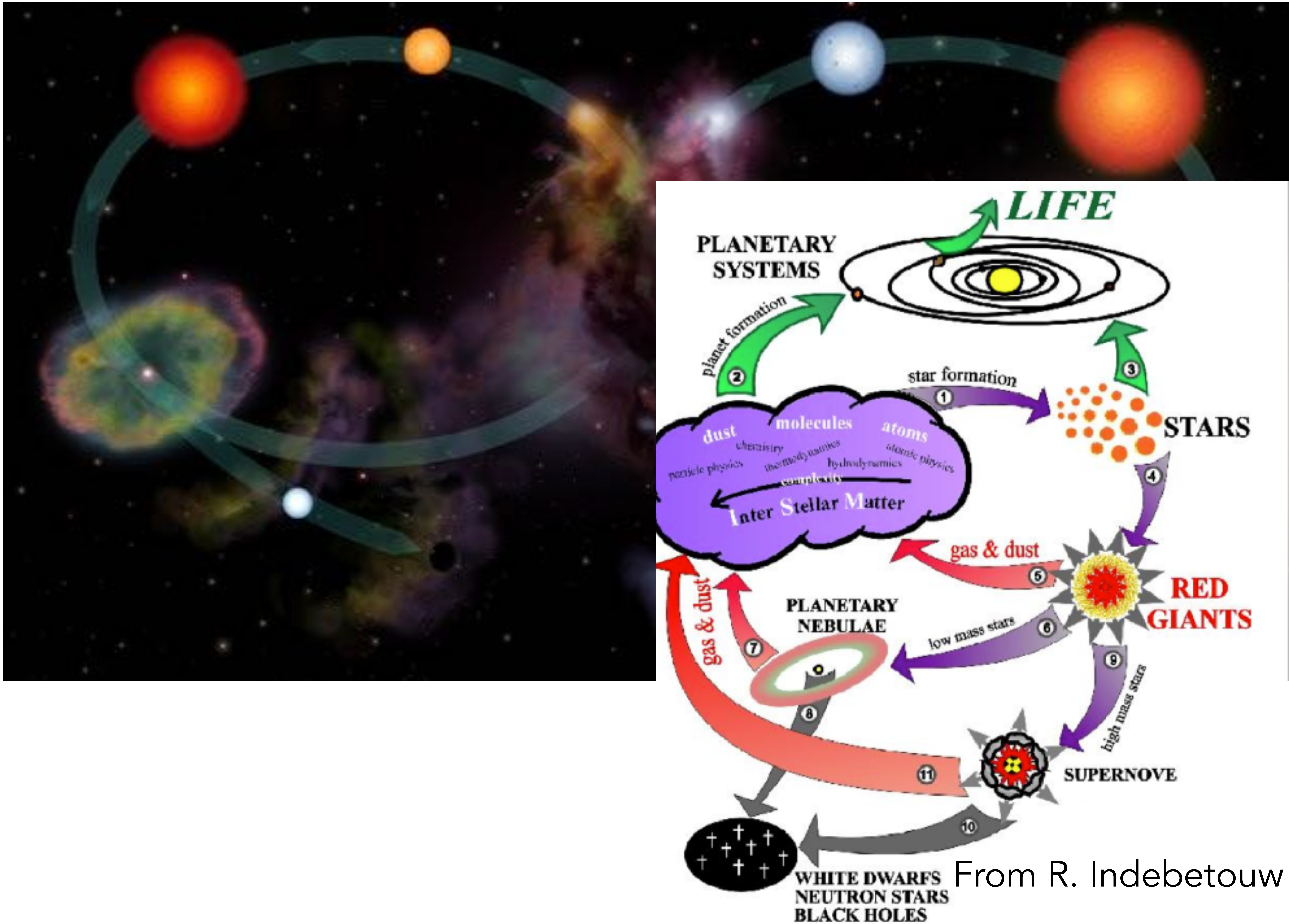
closing the loop…

ISM Energy Density

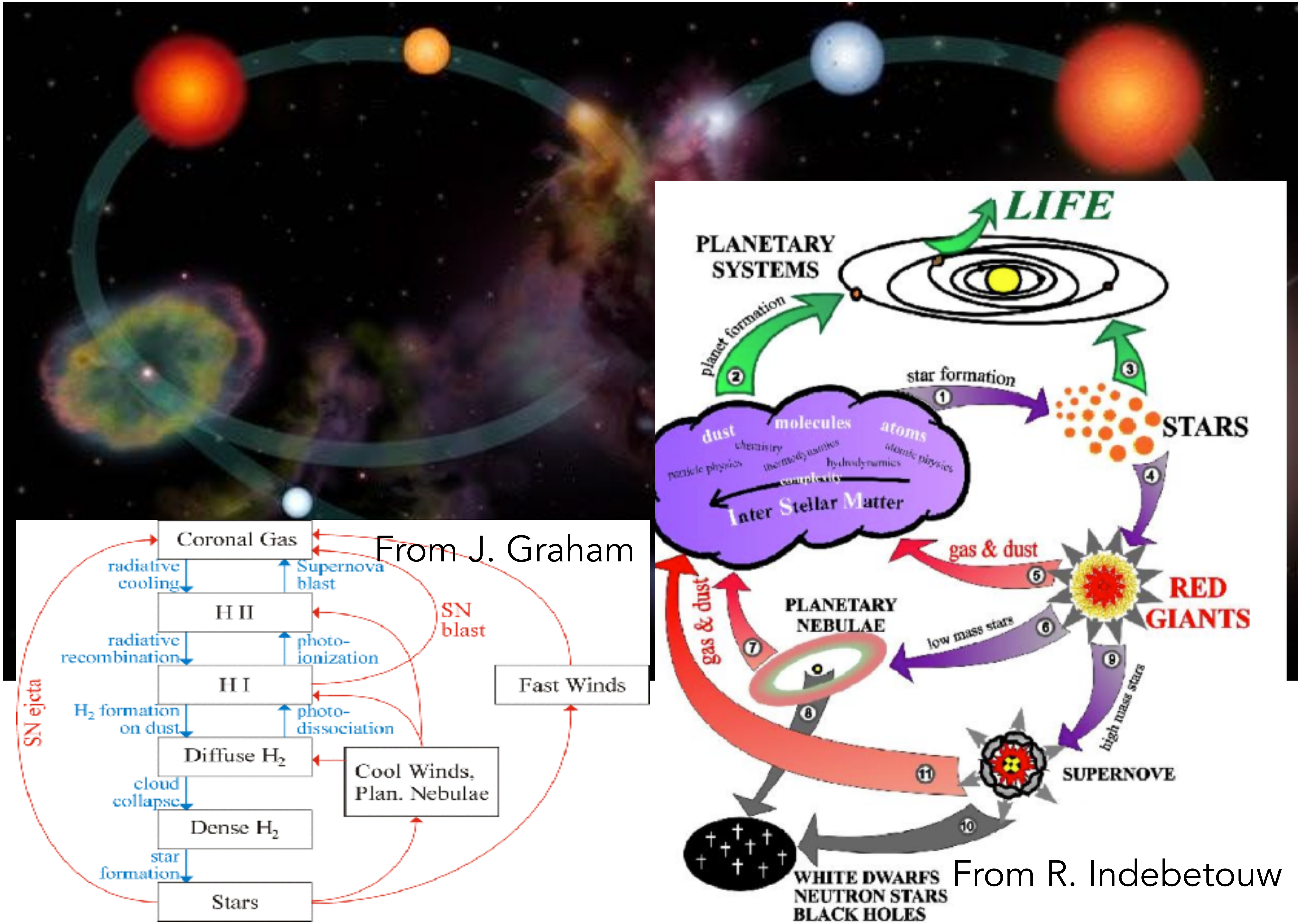
Component	*u* (eV cm^{-3})
Cosmic Microwave Background	0.25 (T_{CMB} = 2.725 K)
Gas Thermal Energy	0.49 (for nT = 3800 cm^{-3} K)
Gas Turbulent Kinetic Energy	0.22 (for n = 1 cm^{-3}, v_{turb} = 1 km/s)
B-Field	0.89 (for 6 μGauss)
Cosmic Rays	1.39 (see Draine ch 13)
Starlight	0.54 (for hν < 13.6 eV)

All the same order of magnitude!





From R. Indebetouw



From J. Graham

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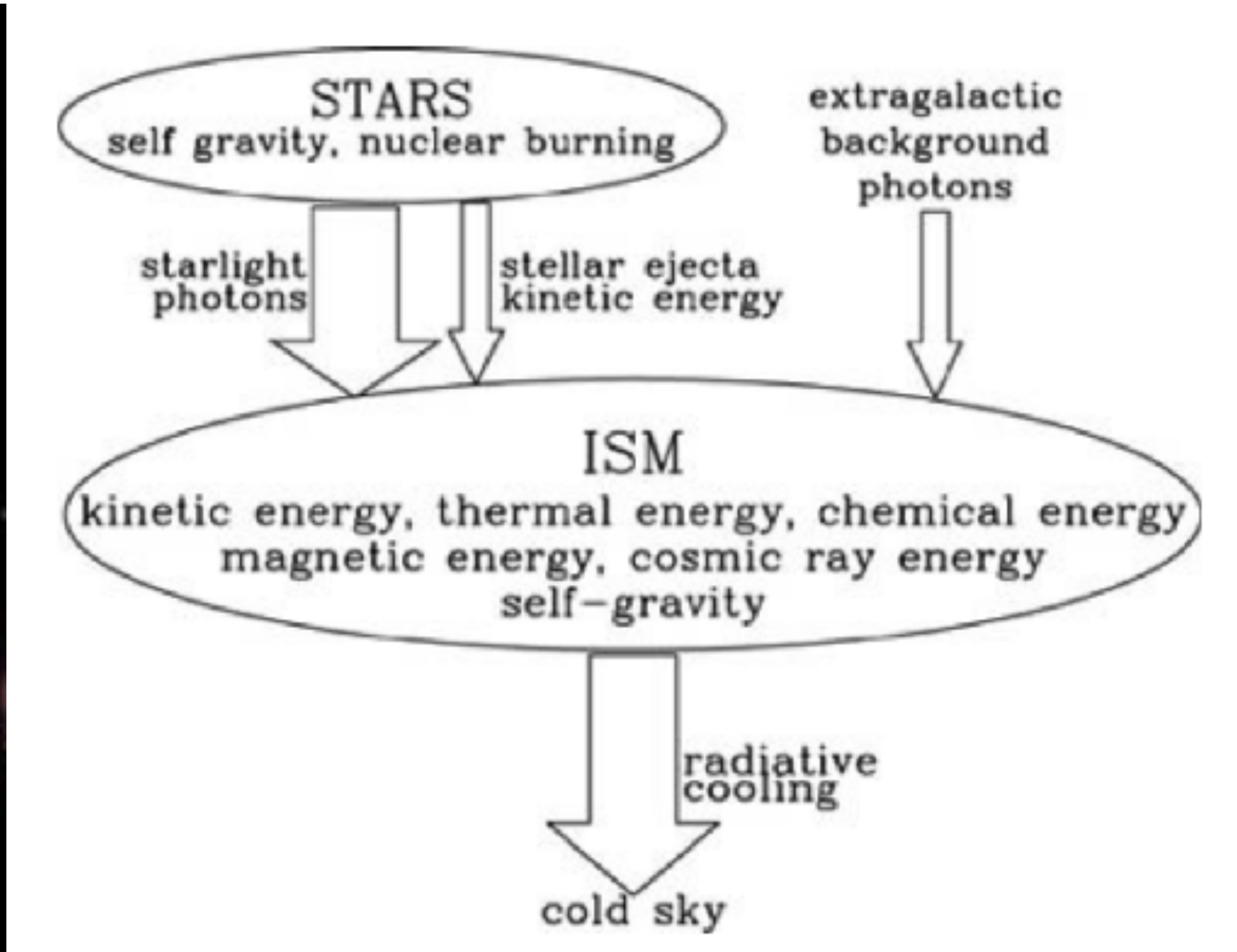

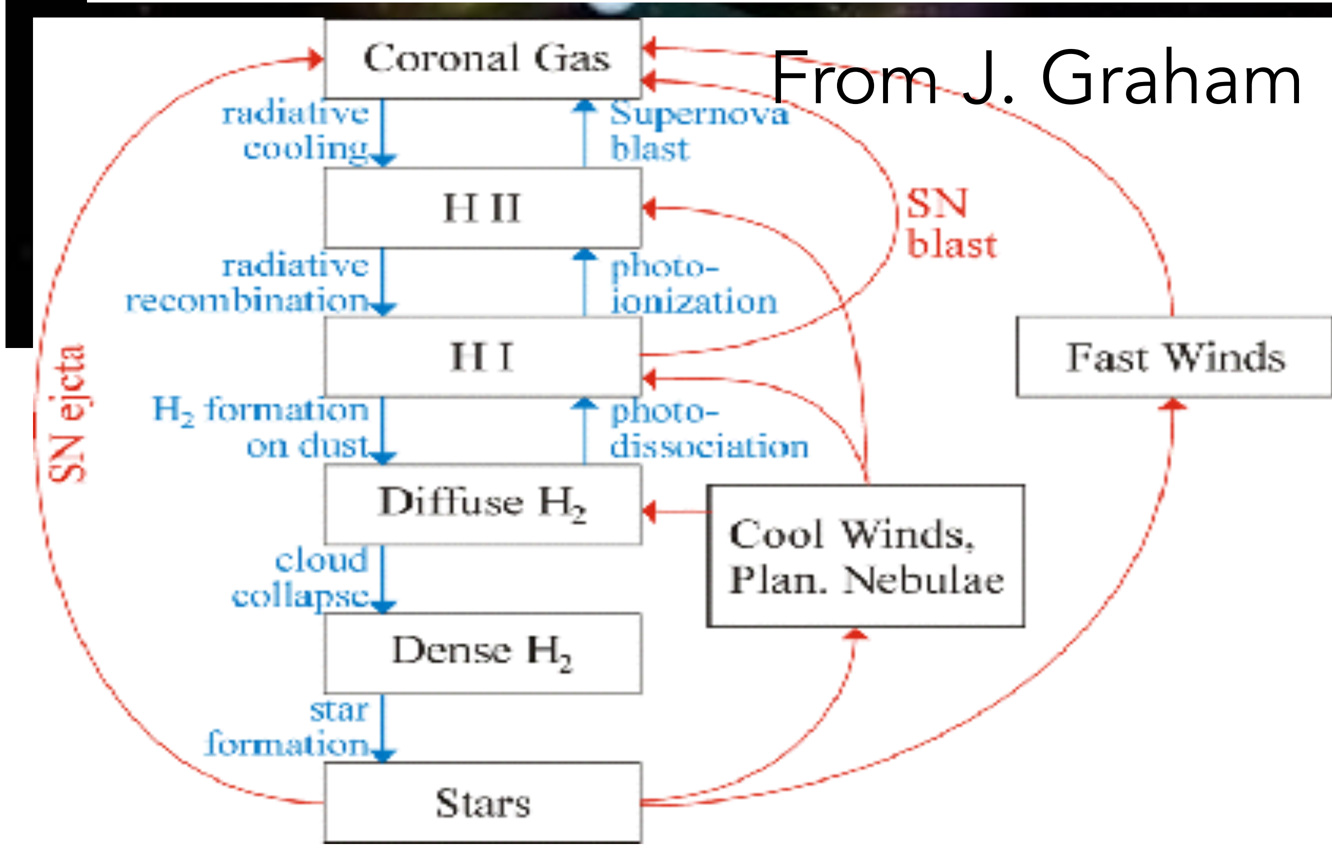

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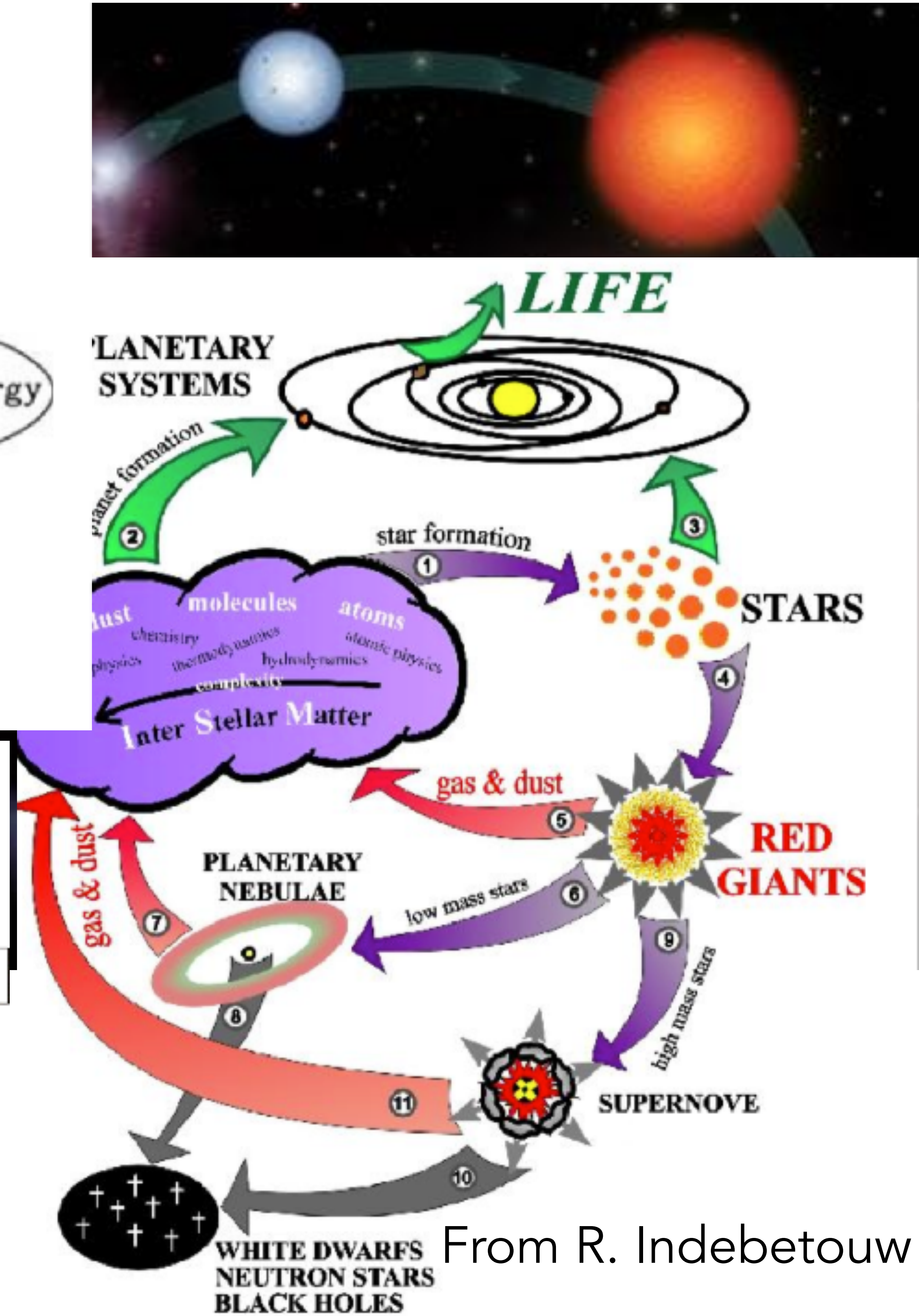

From R. Indebetouw

How does THIS affect THIS	Gravitational Potential	Gas	Dust	Radiation Field	Cosmic Rays	Magnetic Fields	Stars
Gravitational Potential	———-	hydrostatic pressure, dynamics, spiral arms, large scale gas stability	2nd order	2nd order	pressure confinement, dynamical influence (e.g. spiral arms)	gas dynamics, pressure arrange B-field	sets stellar mass distribution, 2nd order hydrostatic pressure -> SF
Gas	self-gravity in dense gas clouds	gas dynamics, collisional excitation, self gravity	dust growth in dense gas, collisional heating/cooling, charging, dust destruction in shocks	alters radiation field (H2 shielding, ionizing photons absorbed)	creation (shocks accelerate), collisions (CR + p+ -> γ ray), confinement (B-field)	dynamically, MHD turbulence, dynamos create/ amplify B-field	star formation
Dust	2nd order	heating/cooling gas, shielding, chemistry, metal abundance (grain sputtering)	grain-grain collisions, shielding small grains from UV	extinction (absorption & scattering)	2nd order	ionization of grains and gas, keeps B-field tied to gas	key role in SF
Radiation Field	2nd order	heating of gas, ionization, photoelectric effect	heating dust, charging grains (PE effect), destruction of small grains	———-	2nd order	ionization of gas, keeps B-field tied to gas	key role in SF
Cosmic Rays	2nd order	ionization in dense gas, connection to B-field	2nd order	2nd order	———-	tied closely to B-field, equipartition?	heats dense gas that forms stars
Magnetic Fields	2nd order	dynamically, MHD turbulence	grain alignment, charged grains coupled to B-field	2nd order	tied closely to B-field, equipartition?	? reconnection & dissipation	dynamically important in collapse -> SF
Stars	large part of the overall mass that sets the grav potential	SNe/winds - dynamics, nucleosynthesis (metals), radiation field generation	create & destroy dust, generate radiation field that heats dust	directly produce it	SNe shocks -> CR	2nd order	feedback shuts off SF

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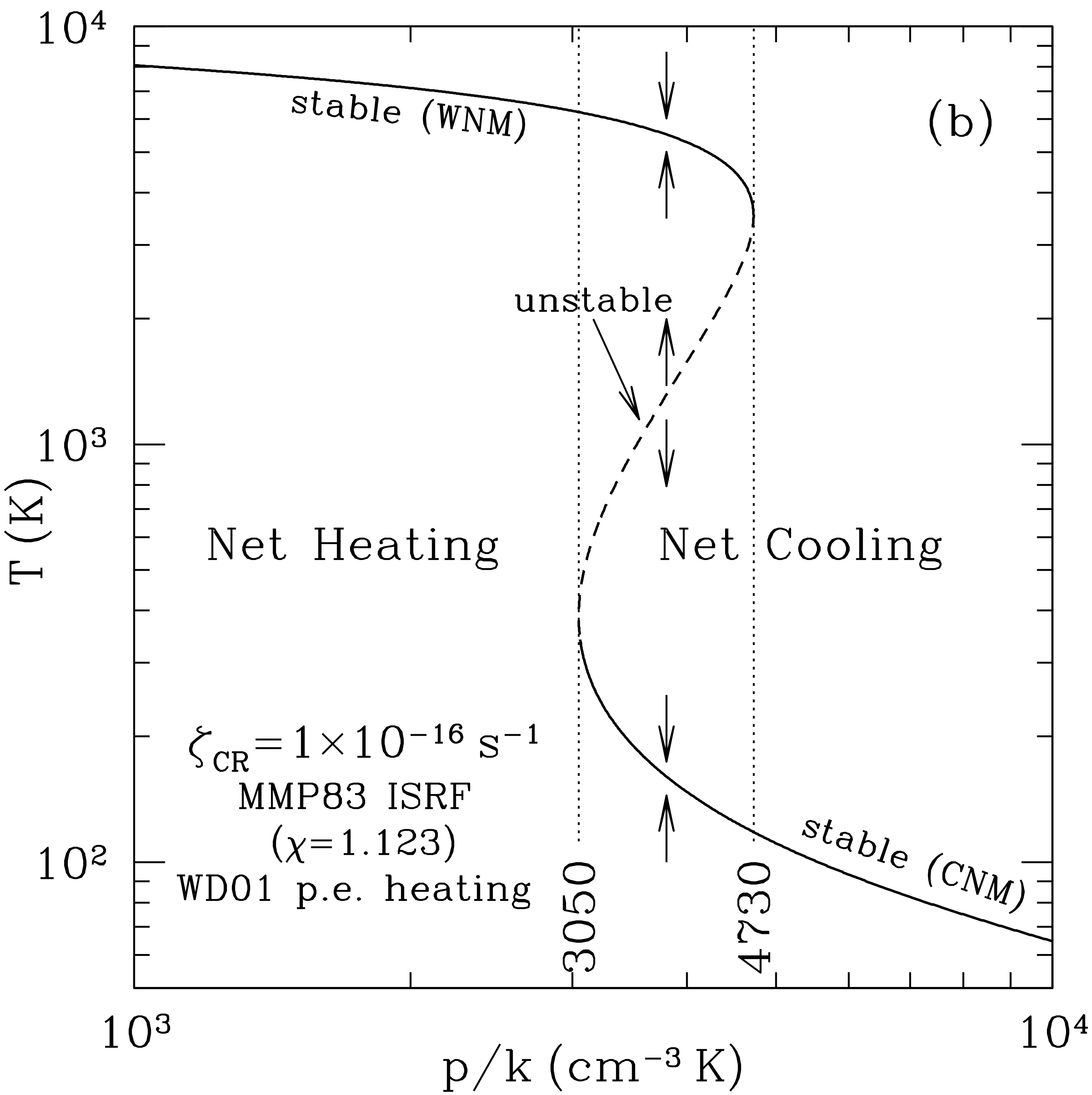
Global ISM Models

- FGH 1969 - Thermal Instability 2 phase model
- McKee & Ostriker 1977 - SNe regulated 3 phase model
- Hydrostatic Balance models - Ostriker, McKee & Leroy 2010
- Simulations of SNe regulated ISM

FGH 1969 Thermal Instability



Not a full ISM model, predicts existence of two phases in thermal equil. given heating and cooling rates and average ISM pressure.

Observational prediction:
CNM/WNM n,T,
& filling factors

Issues:
why is P what it is?

MO 1977 SNe Driven 3 Phase

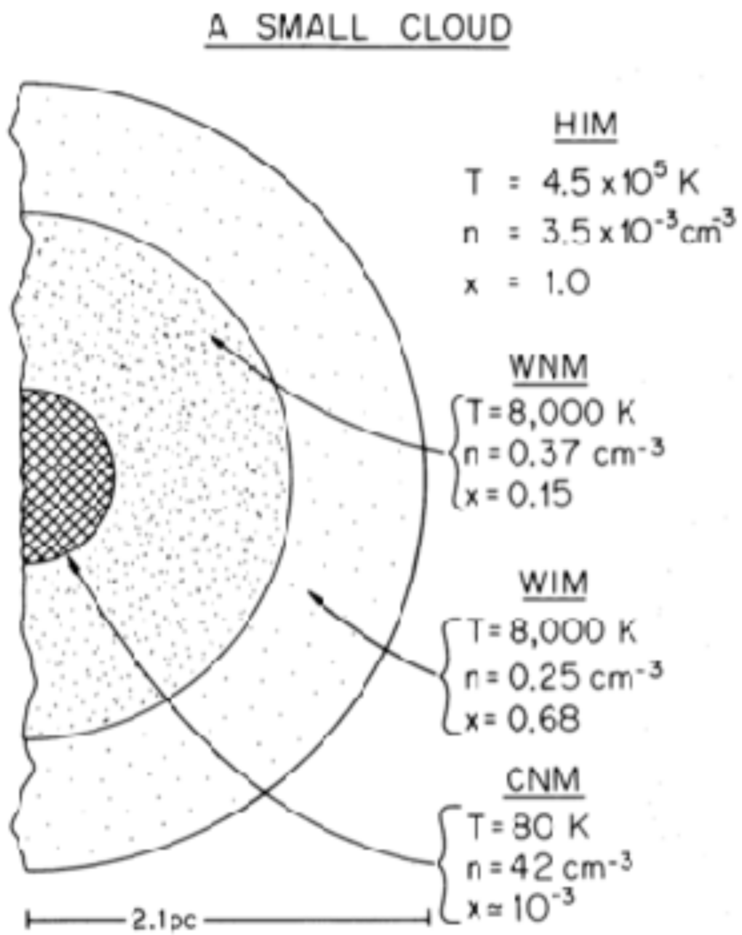


FIG. 1

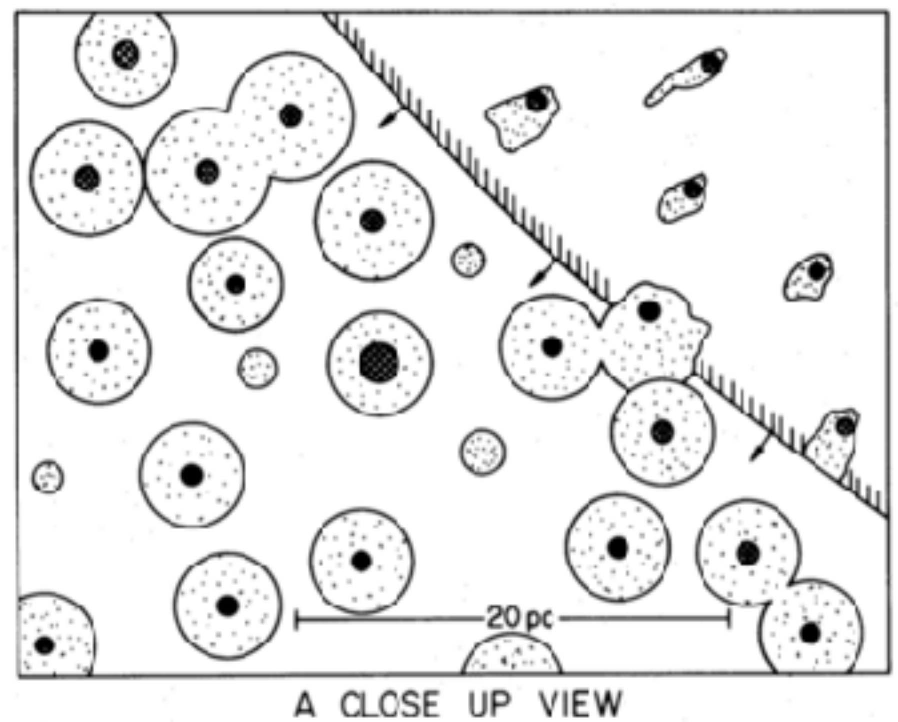


FIG. 2

SNe rate, ISM density structure, cloud evaporation combine to set radius (& therefore pressure) at which SN remnants overlap.

Observational prediction: filling factors of hot ionized gas, CNM/WNM, ISM pressure

Issues:
WNM fraction lower than observed, how does SNR pressure balance relate to hydrostatic pressure? clustered vs random SNe?

Hydrostatic Balance
Ostriker, McKee & Leroy 2010

In equlibrium:

heating from UV

$\Gamma_{diffuse} \propto SFR \propto M_{self\text{-}grav}$

balances:

cooling from far-IR lines

$\Lambda_{diffuse} \propto n \propto P_{diffuse} \propto \Sigma$

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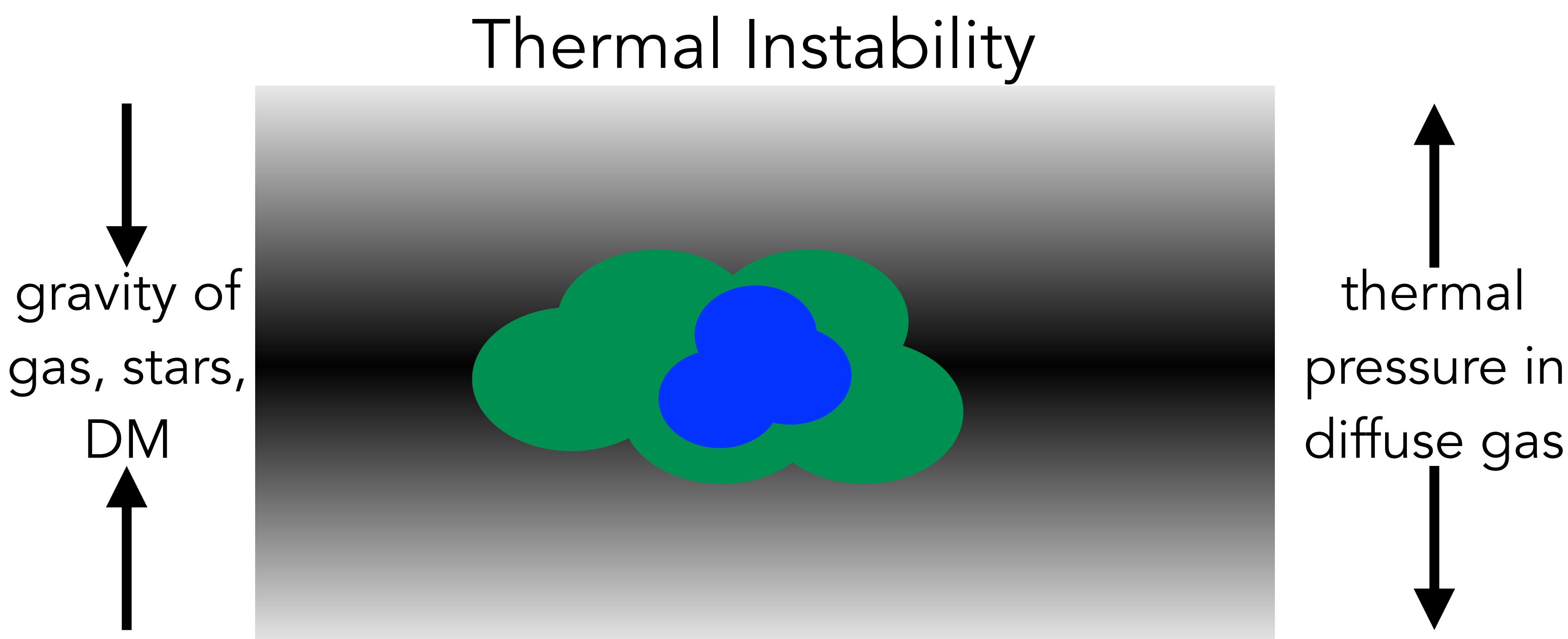

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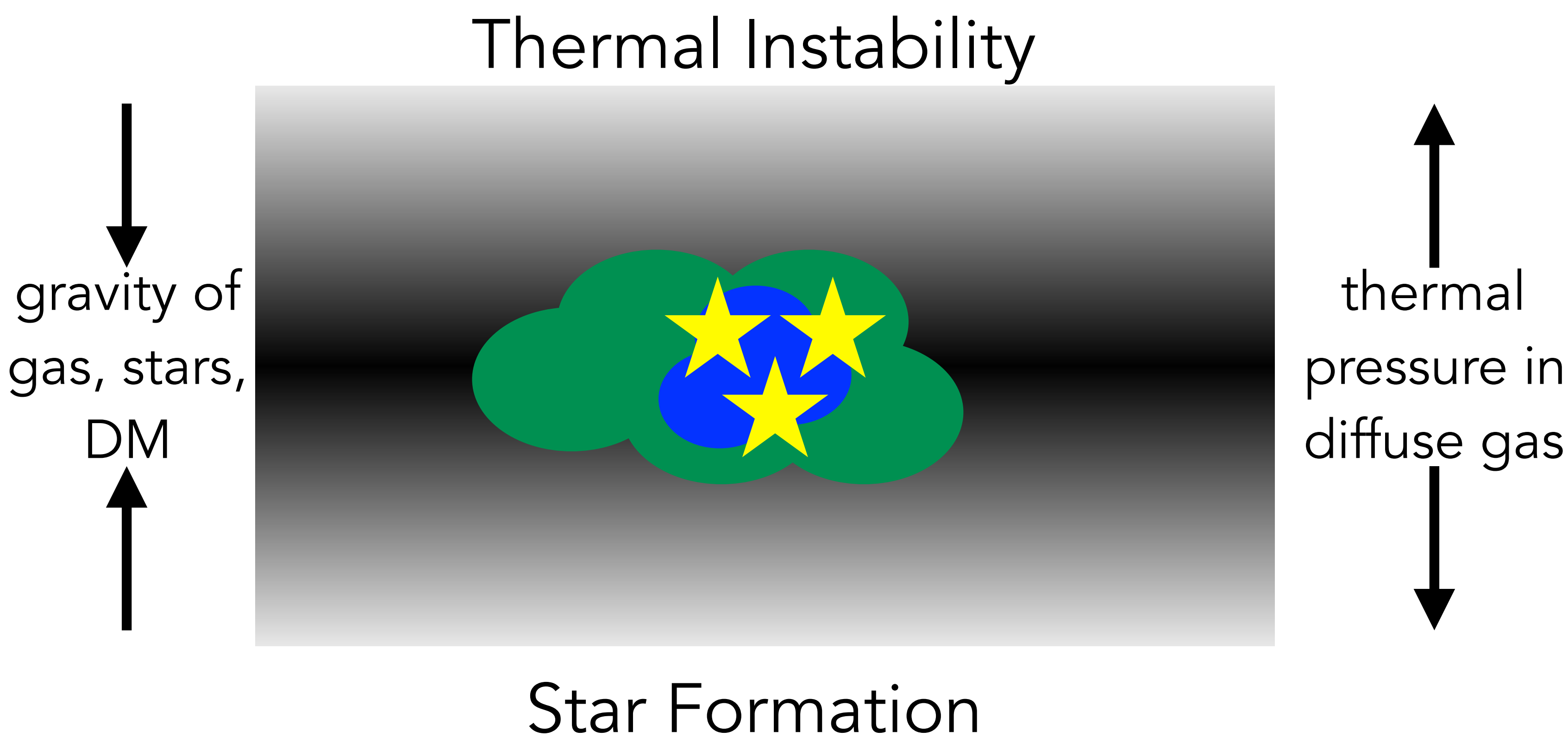

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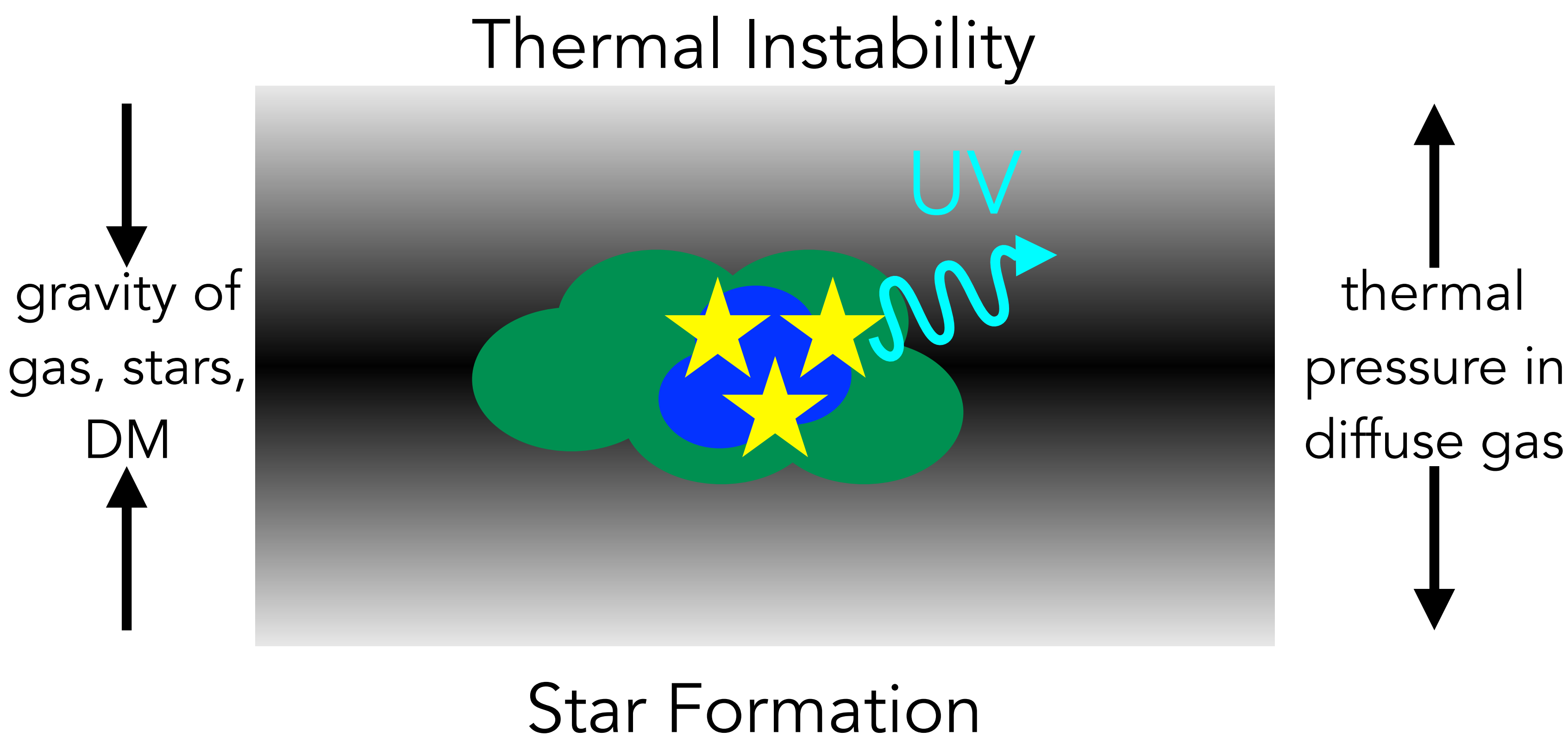

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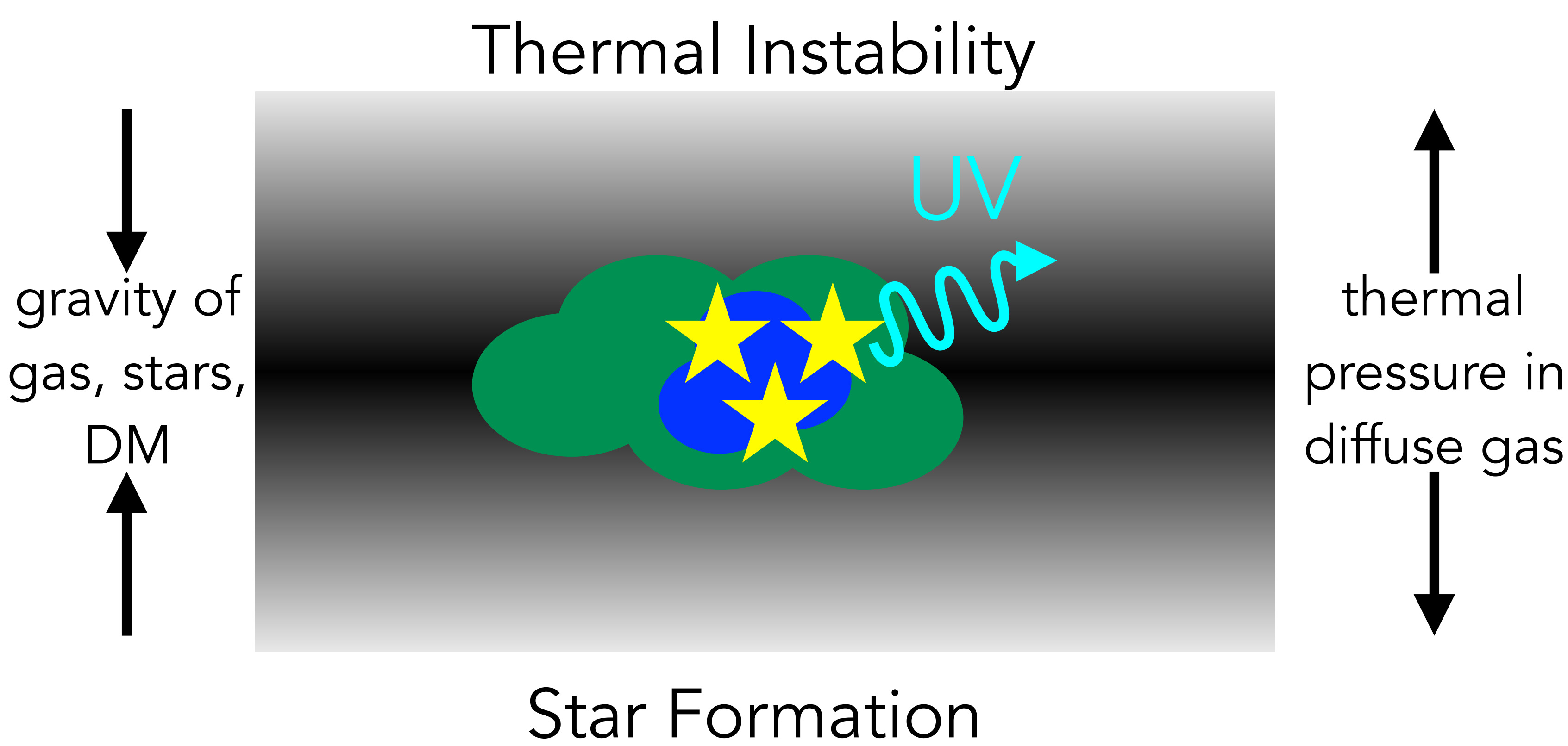

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Observational prediction:
relationship between Σ_{tot},
$\Sigma_{self\text{-}grav}$, $\Sigma_{diffuse}$

Global ISM Models

Test models with observables:

Easier:

Stellar mass surface density

Gas mass surface density

Star formation rate

Dust mass surface density (& dust-to-gas ratio)

Mass spectrum of molecular clouds

Metallicity

Gas "phase" (CNM/WNM, H_2 fraction)

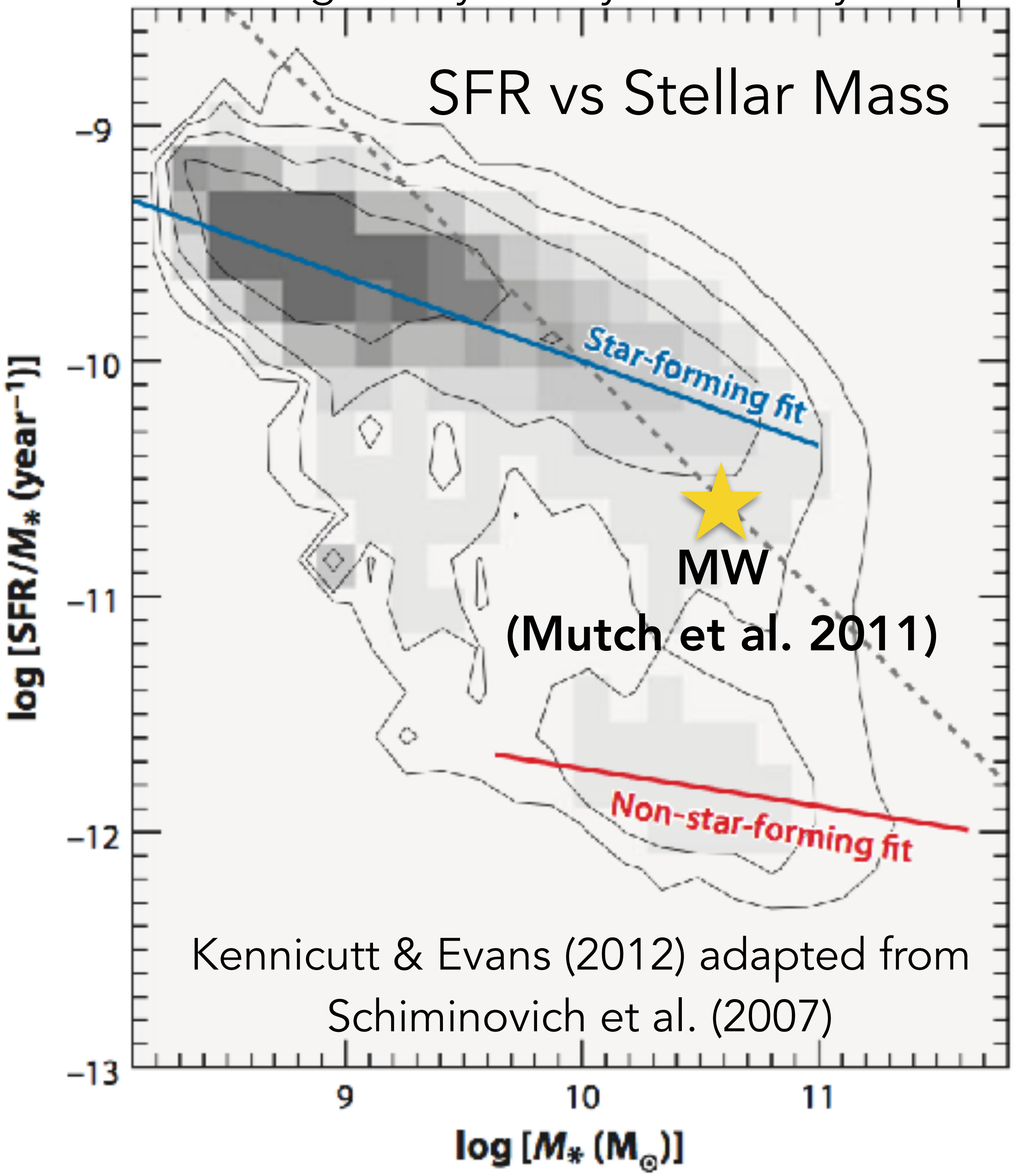
Harder:

B-field strength

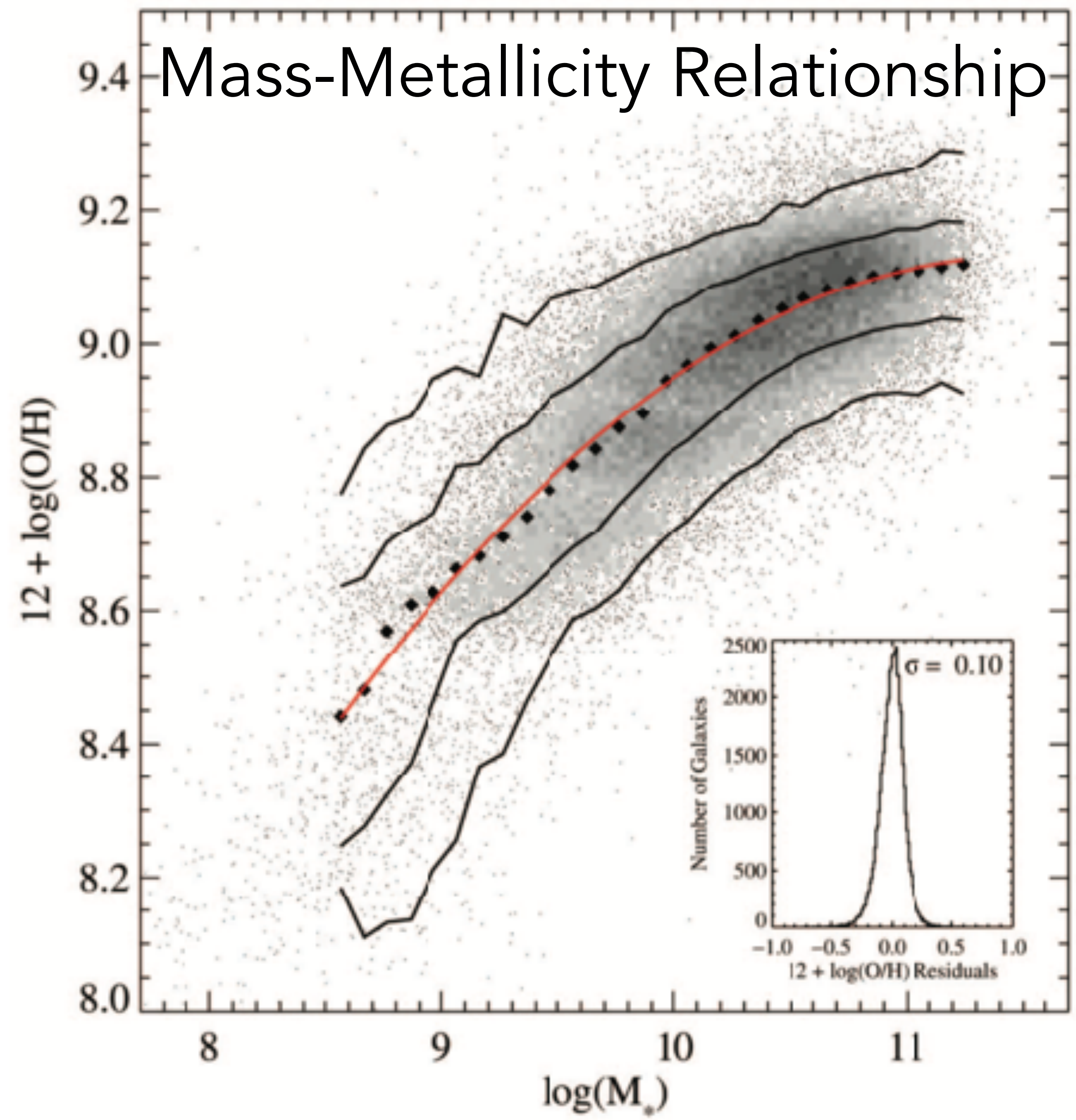
Cosmic ray flux

Beyond the Milky Way

Sloan Digital Sky Survey z~0 Galaxy Sample



Tremonti et al. (2004)



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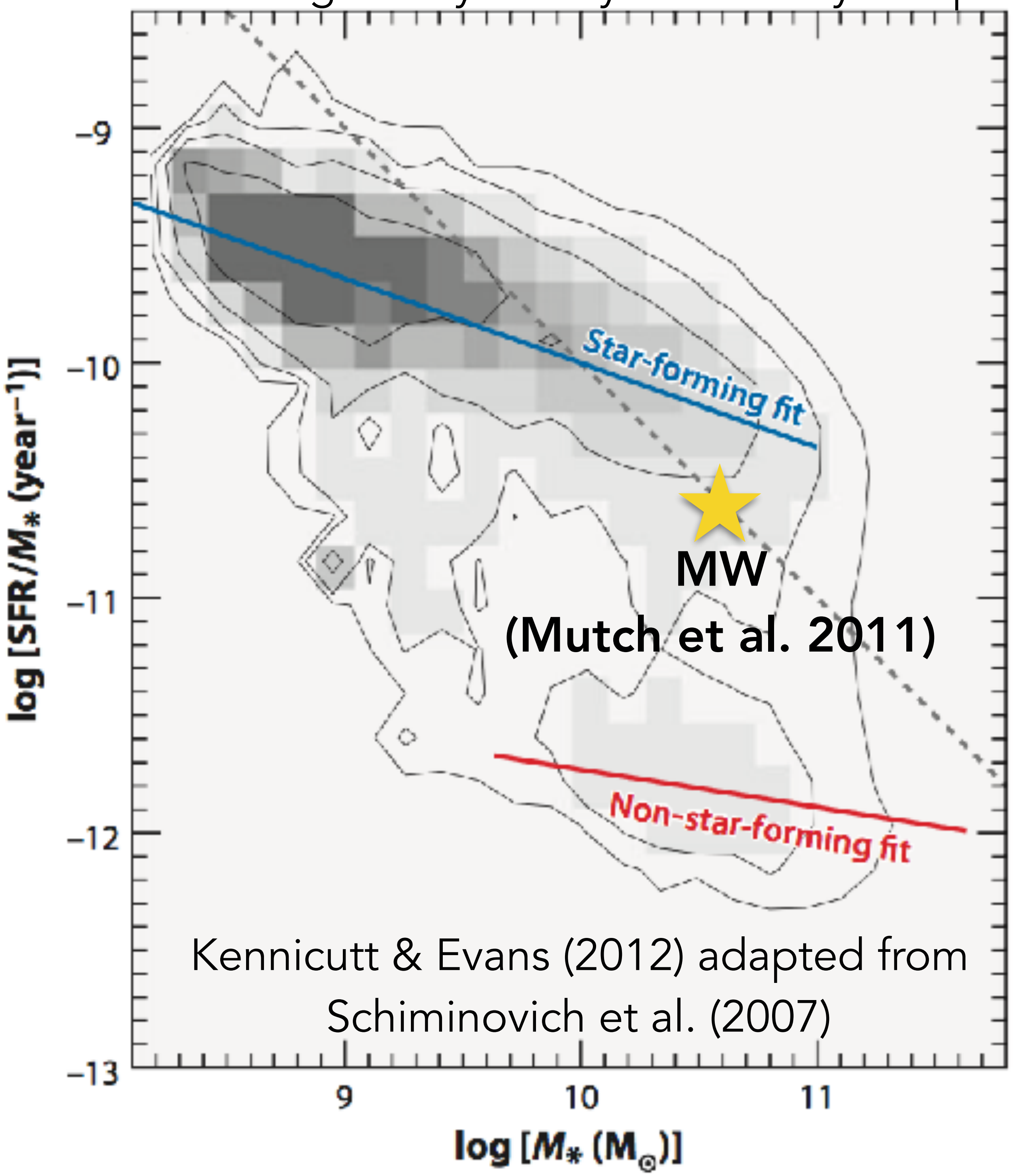


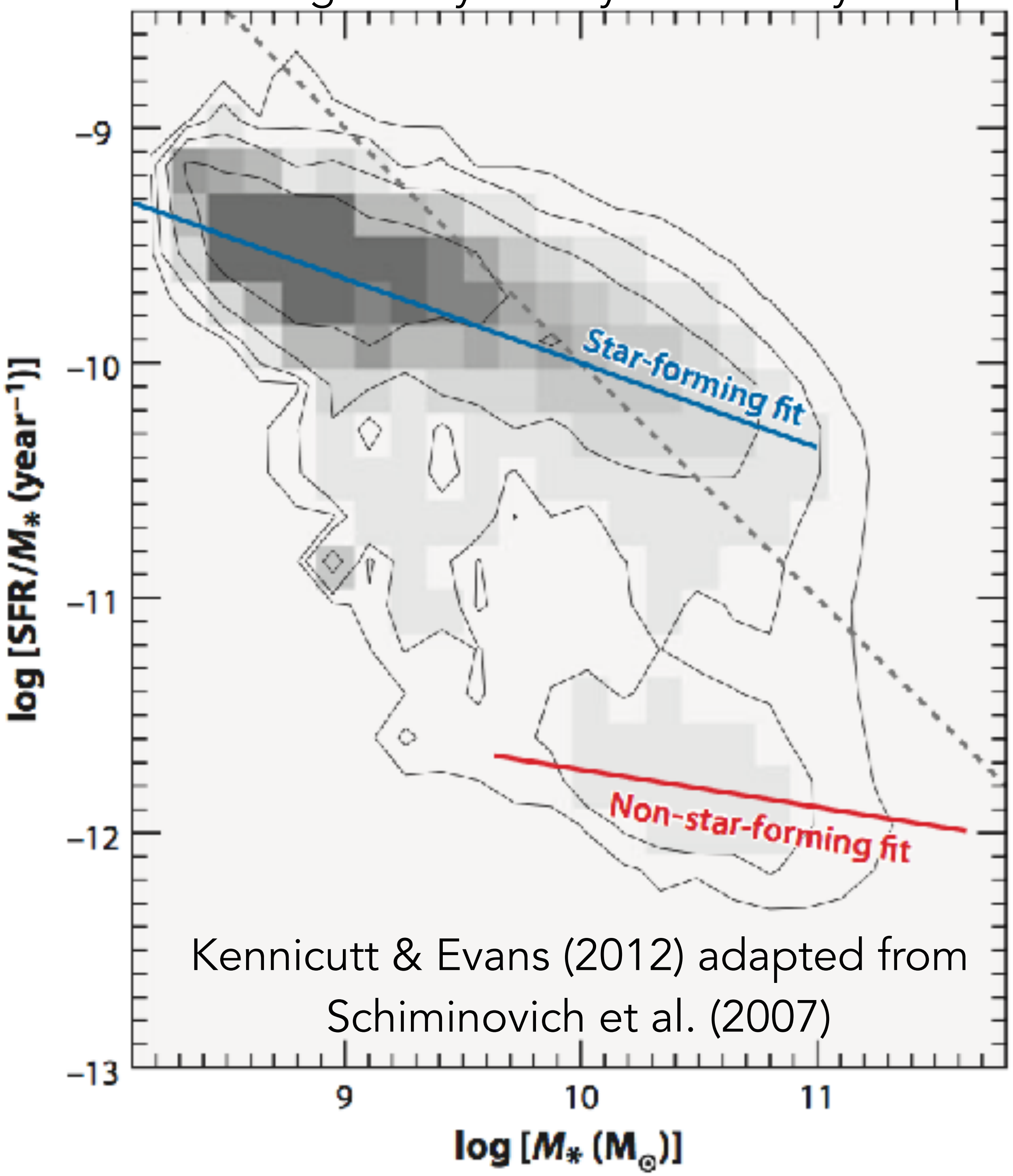
Kennicutt & Evans (2012) adapted from Schiminovich et al. (2007)

A variety of models reproduce the basic properties of the MW's ISM.

To test models need to see if they also work in conditions different from the MW, i.e. local galaxies.

Beyond the Milky Way

Sloan Digital Sky Survey z~0 Galaxy Sample

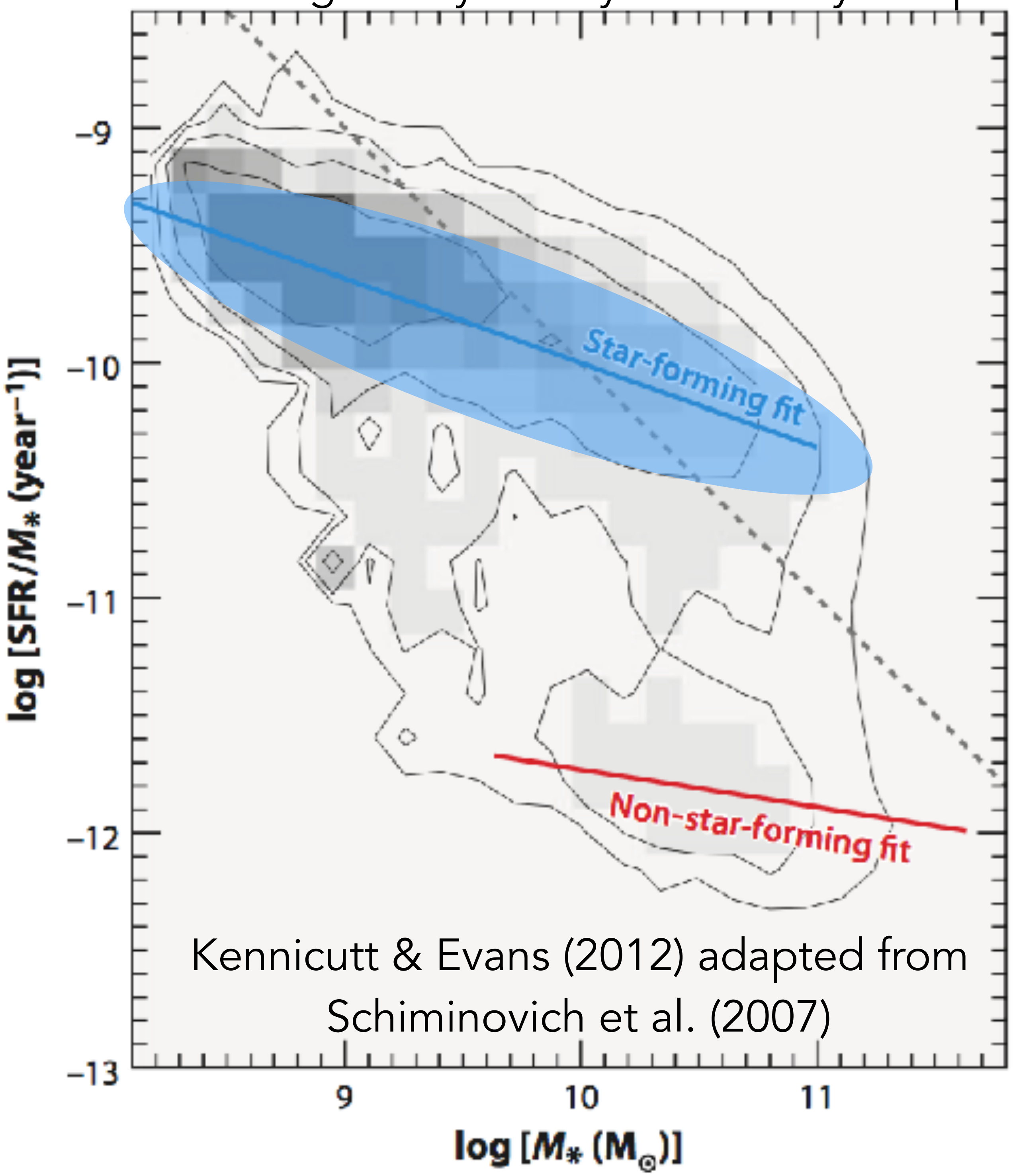


Kennicutt & Evans (2012) adapted from Schiminovich et al. (2007)

- Galaxies on the "star forming sequence"
- Quiescent galaxies
- Galaxies in the process of becoming quiescent?
- Dwarf galaxies
- Starburst galaxies

Beyond the Milky Way

Sloan Digital Sky Survey z~0 Galaxy Sample



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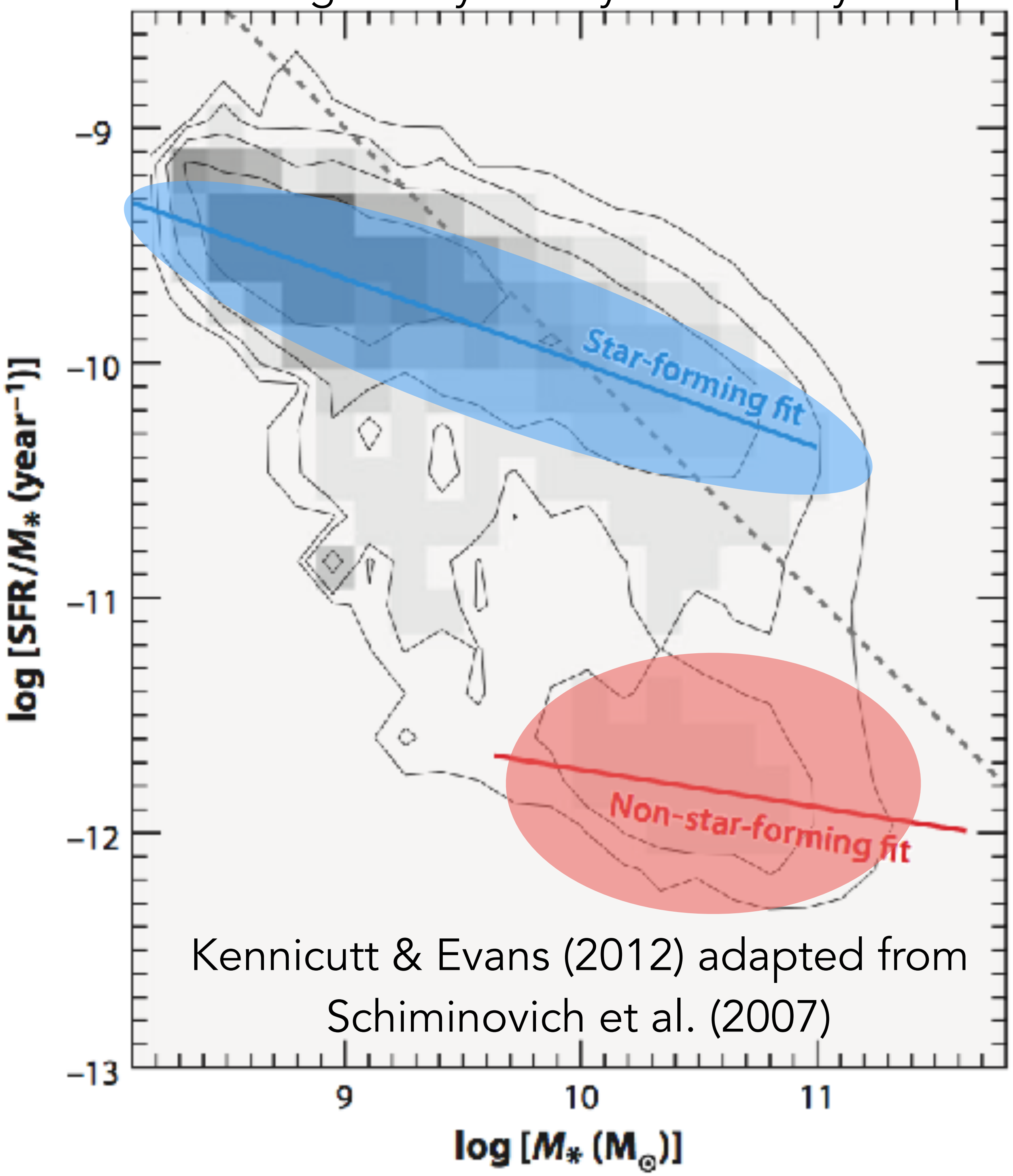

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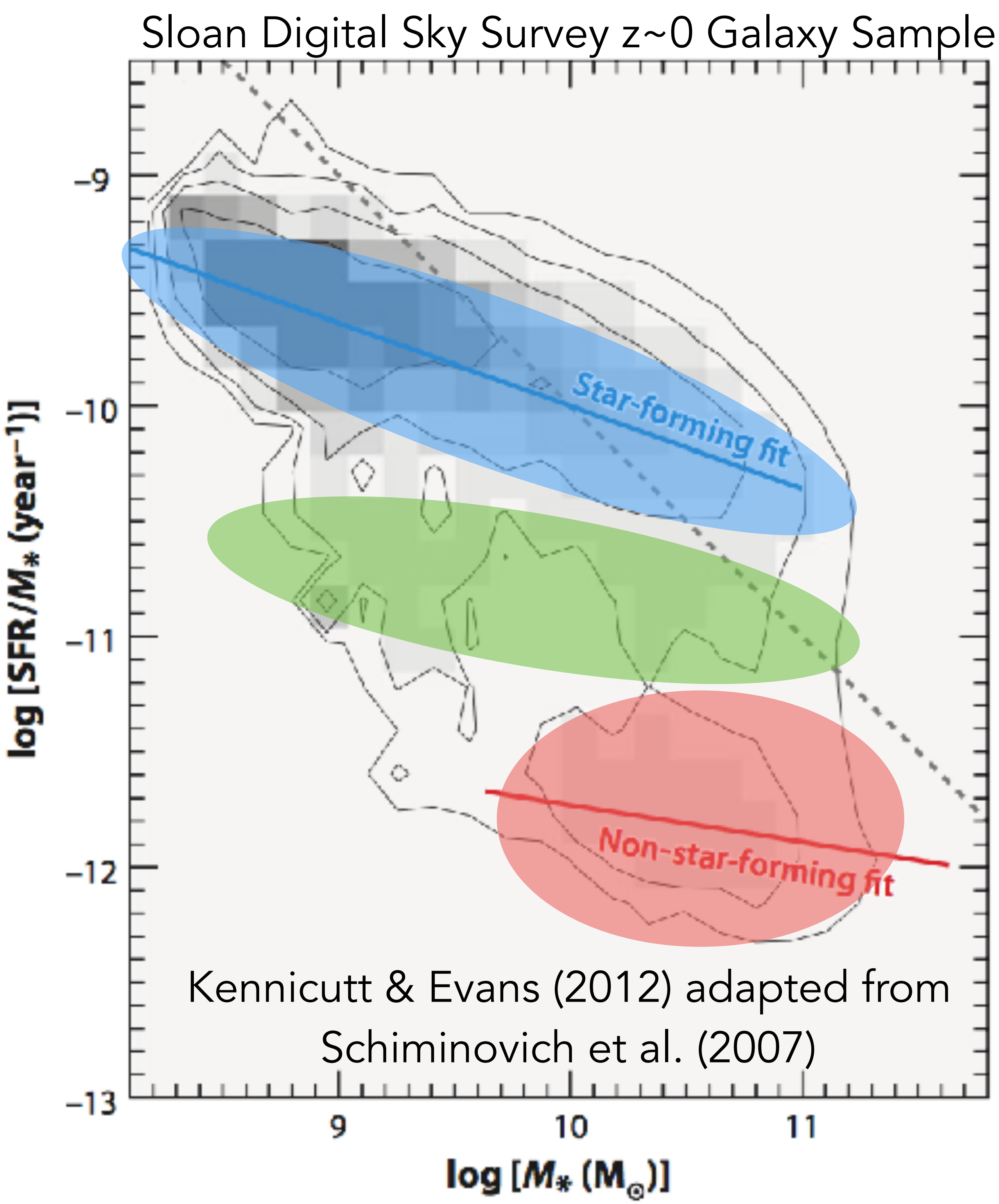

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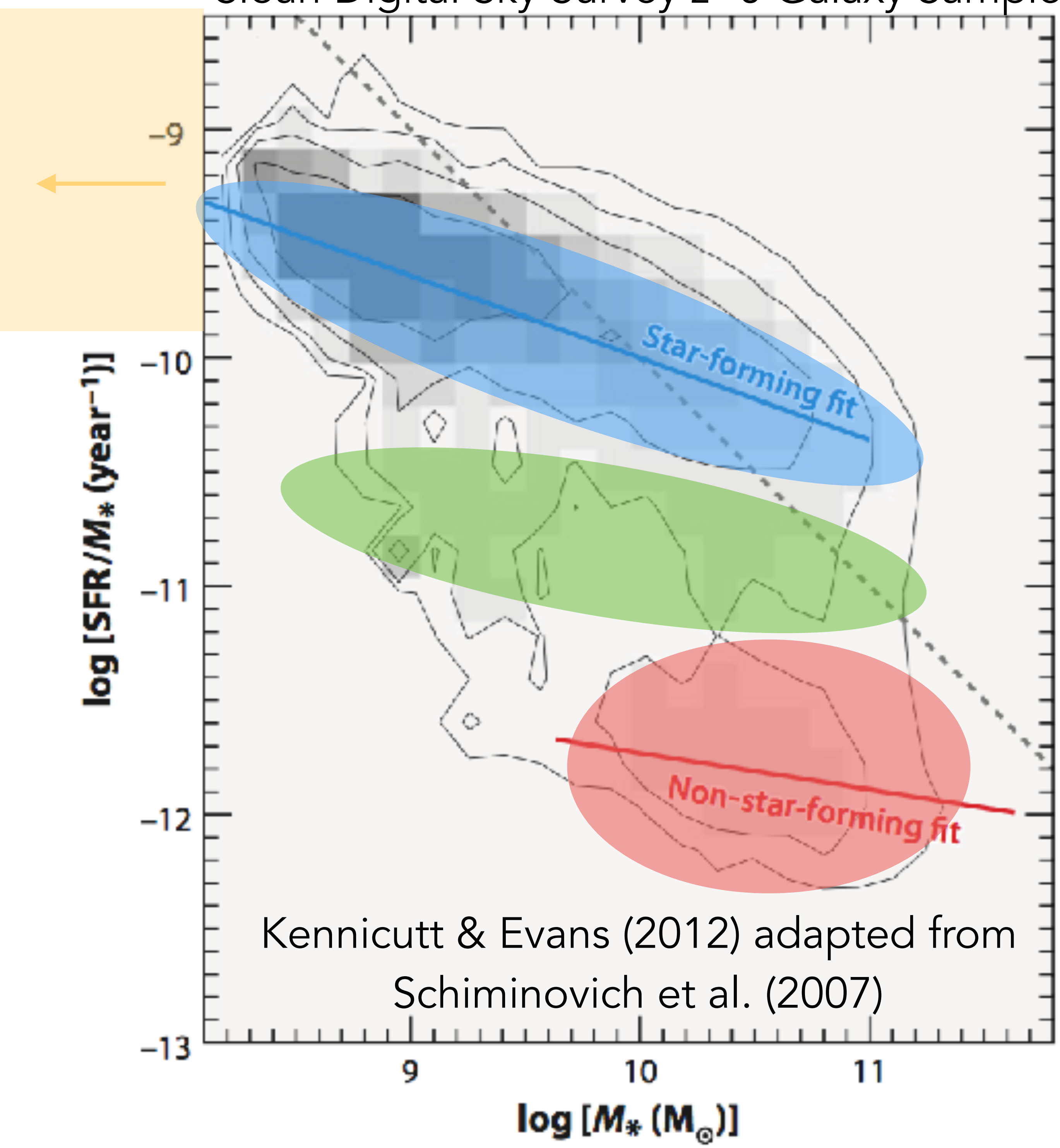

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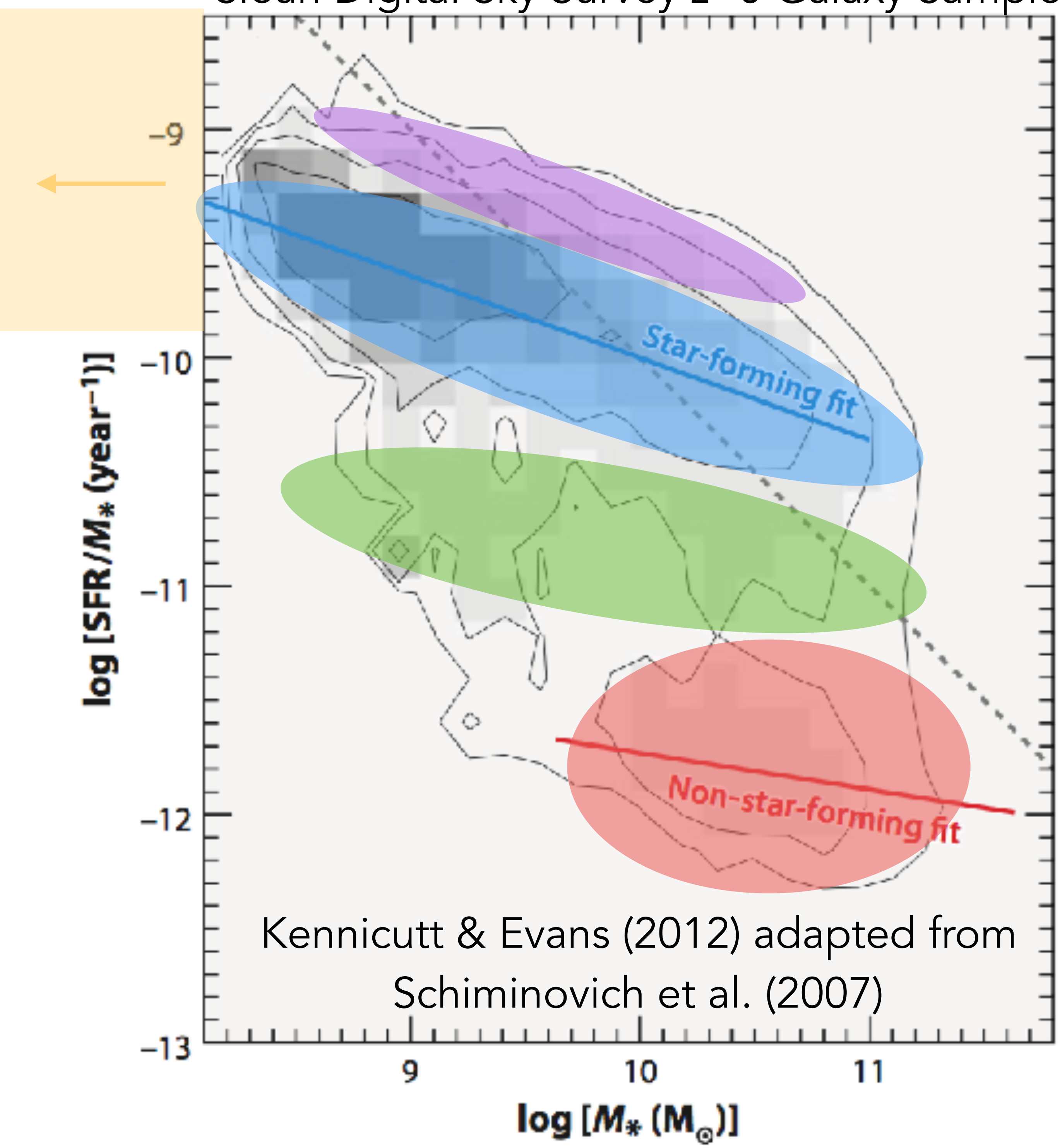

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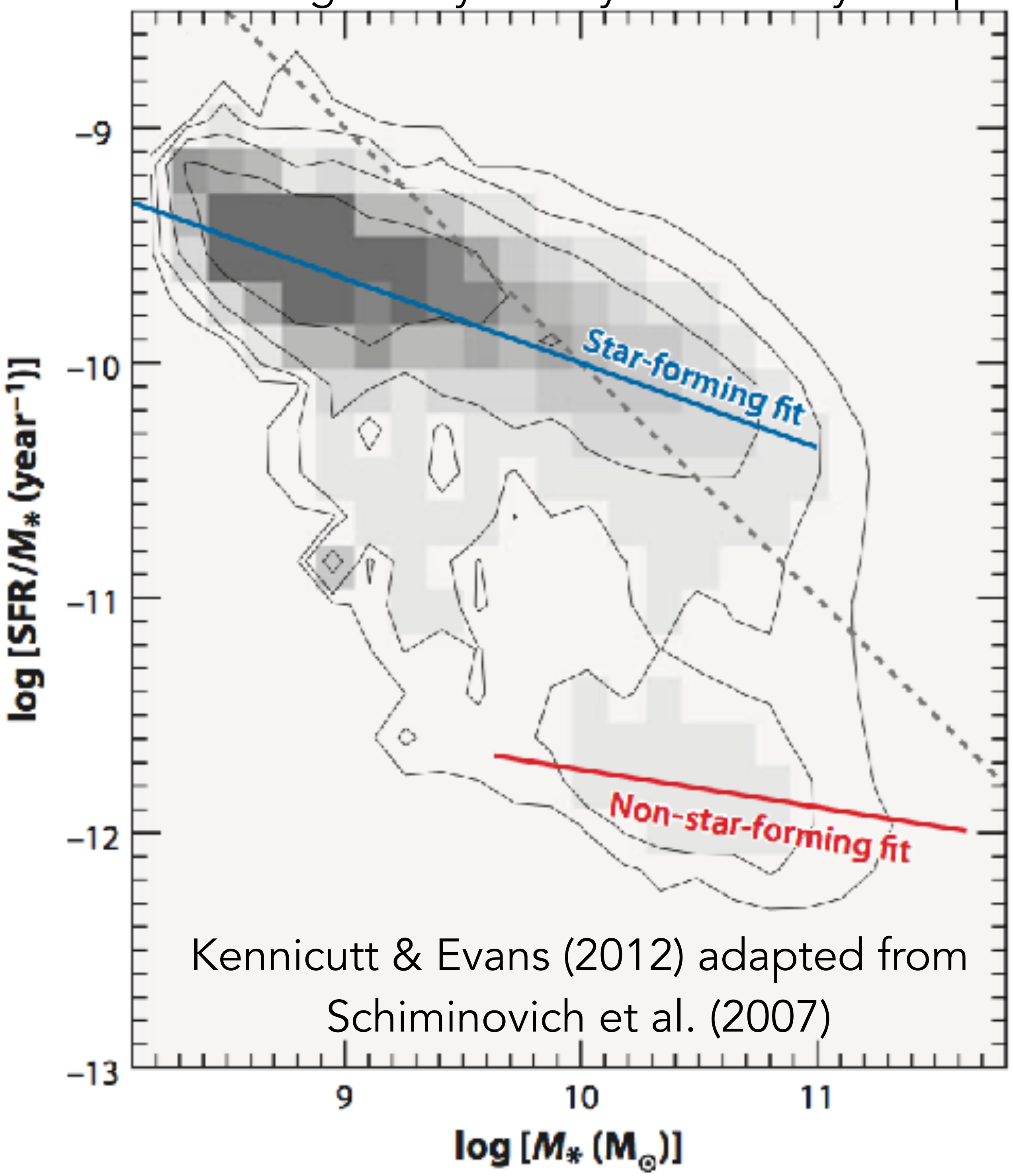

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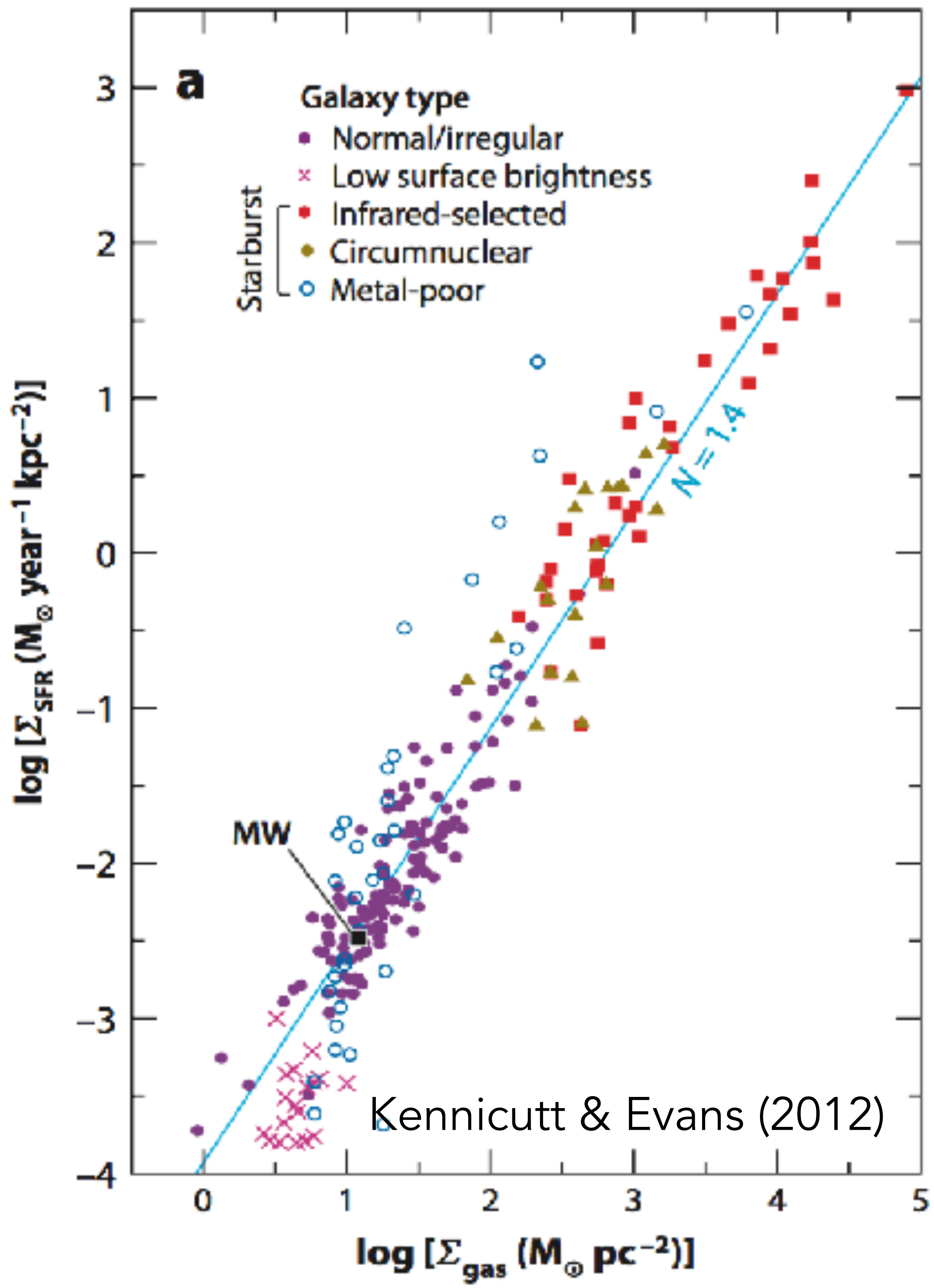
Other key properties:

- Morphology
- Galaxy environment (e.g. cluster, group, void)
- Properties of any nuclear source (e.g. AGN)
- Merger/Interaction
- REDSHIFT!

Beyond the Milky Way



Beyond the MW, don't have access to the same detailed measurements. Key observations include "scaling relations" that show how gas, SFR, stars, dust are related.

The Schmidt-Kennicutt relation is a key scaling connecting galaxy averaged SF surface density and total gas surface density.

Schmidt (1959), Kennicutt (1989, 1998)

What do we know about …
in other galaxies?

Diffuse atomic gas

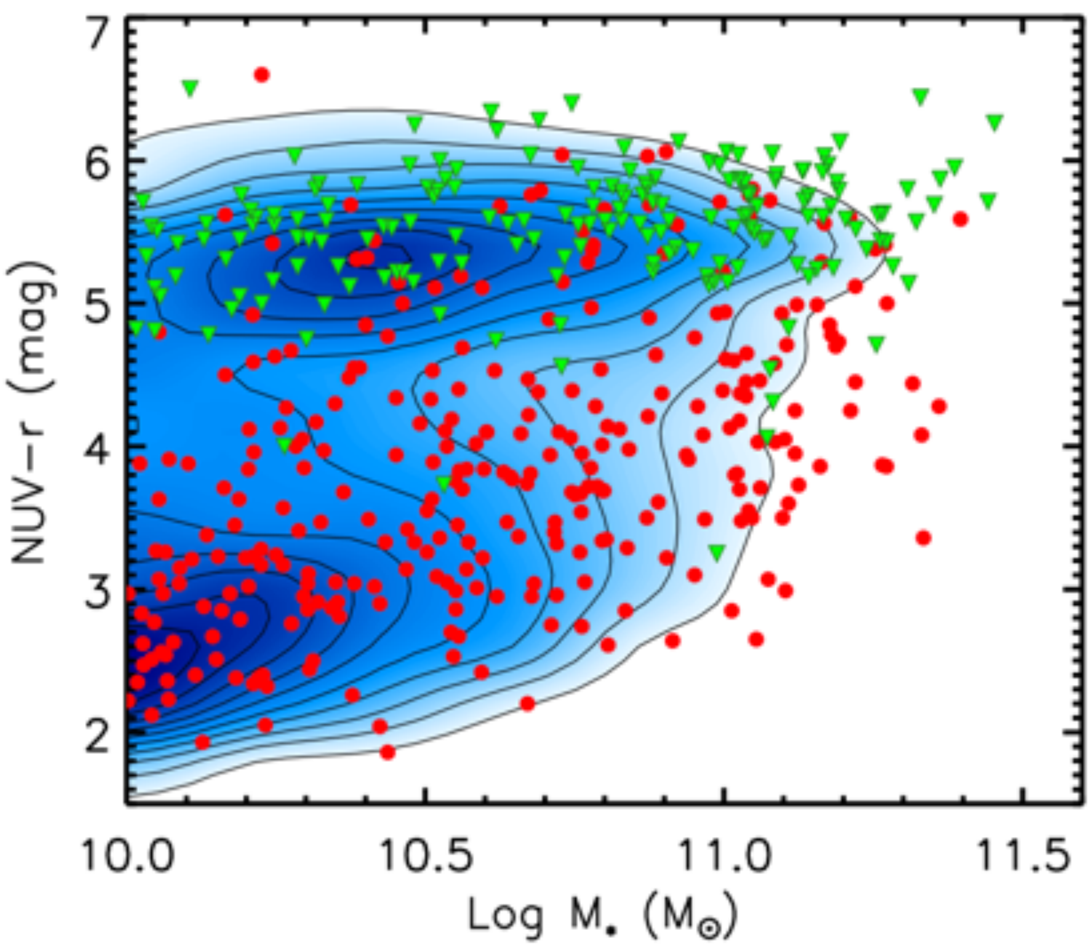
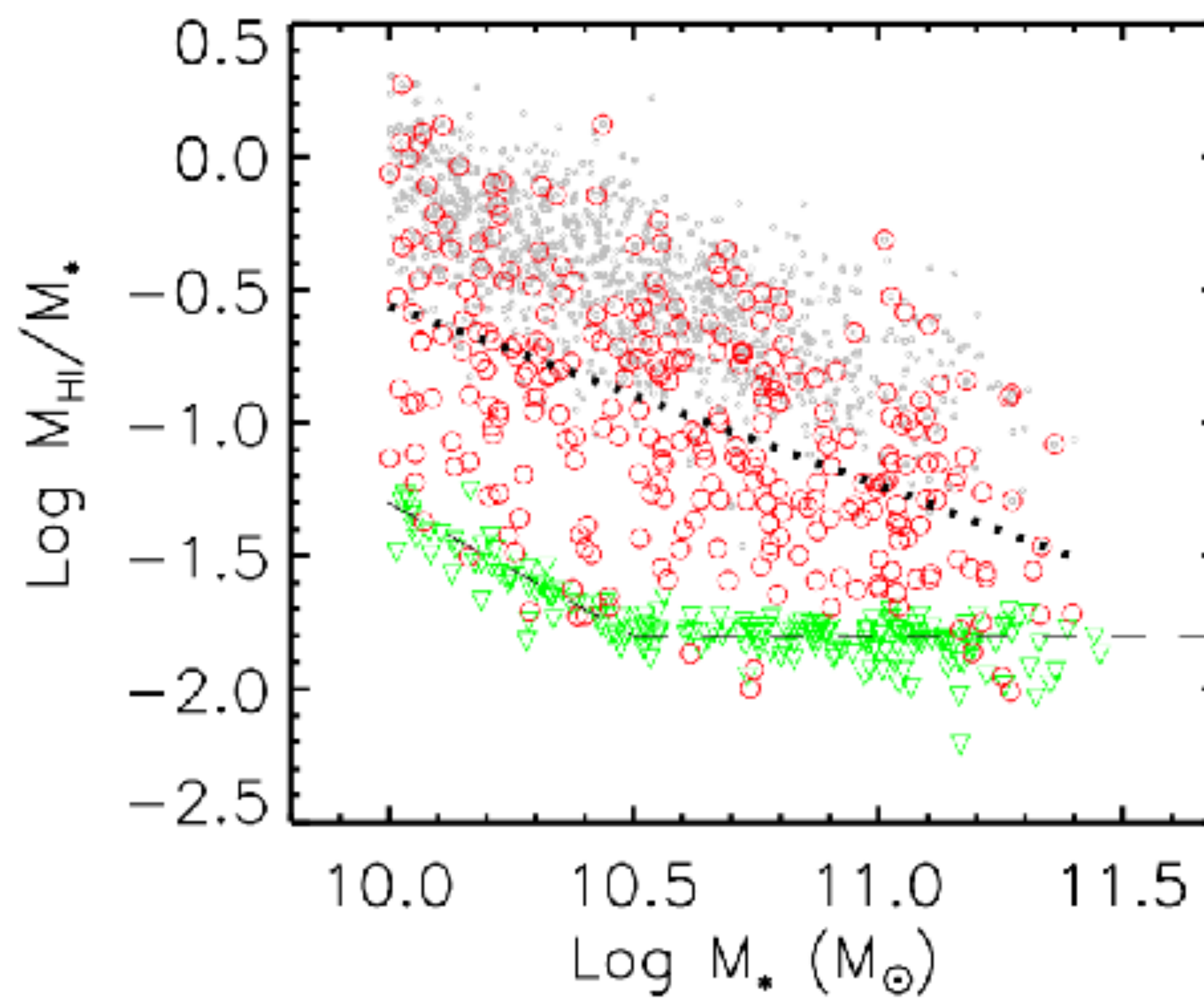


Fig. 4. Color-stellar mass diagram for the GASS *parent sample*, the super-set of ~12 000 galaxies that meet the survey criteria (grayscales). Red circles and green upside-down triangles indicate HI detections and non-detections, respectively, from the representative sample.

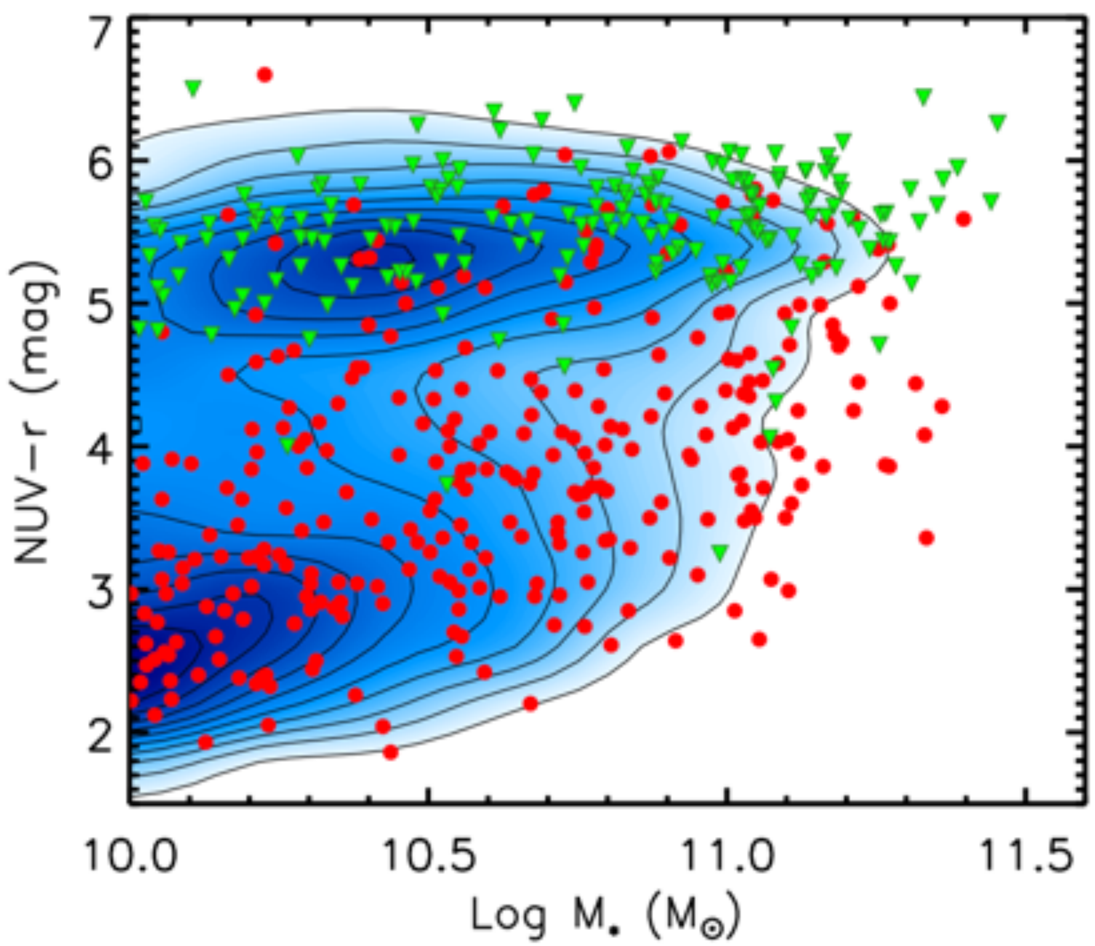
Catinella et al. 2012 (GALEX-Arecibo-SDSS survey)



HI-to-stellar mass decreases with stellar mass

What do we know about …
in other galaxies?

Diffuse atomic gas



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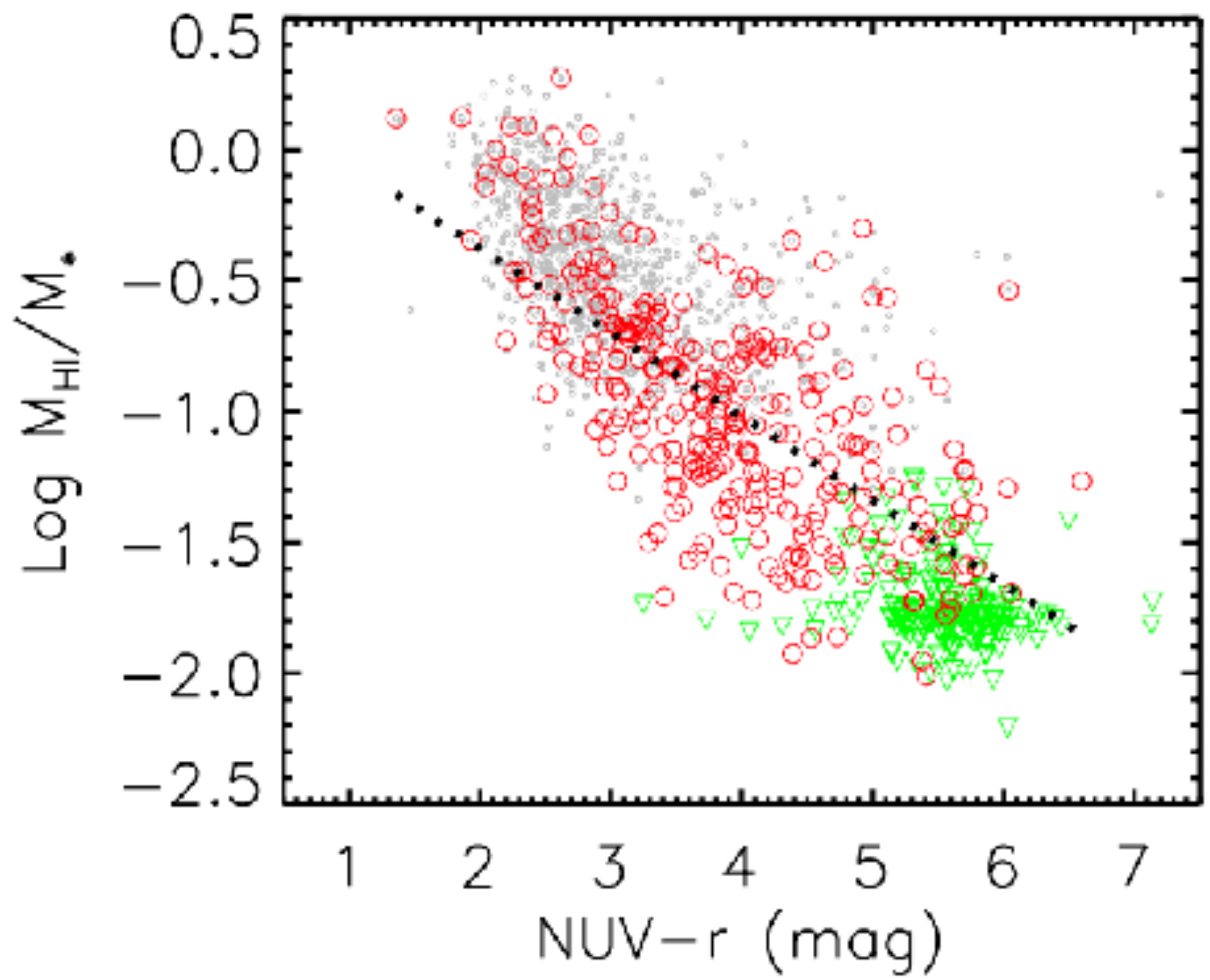
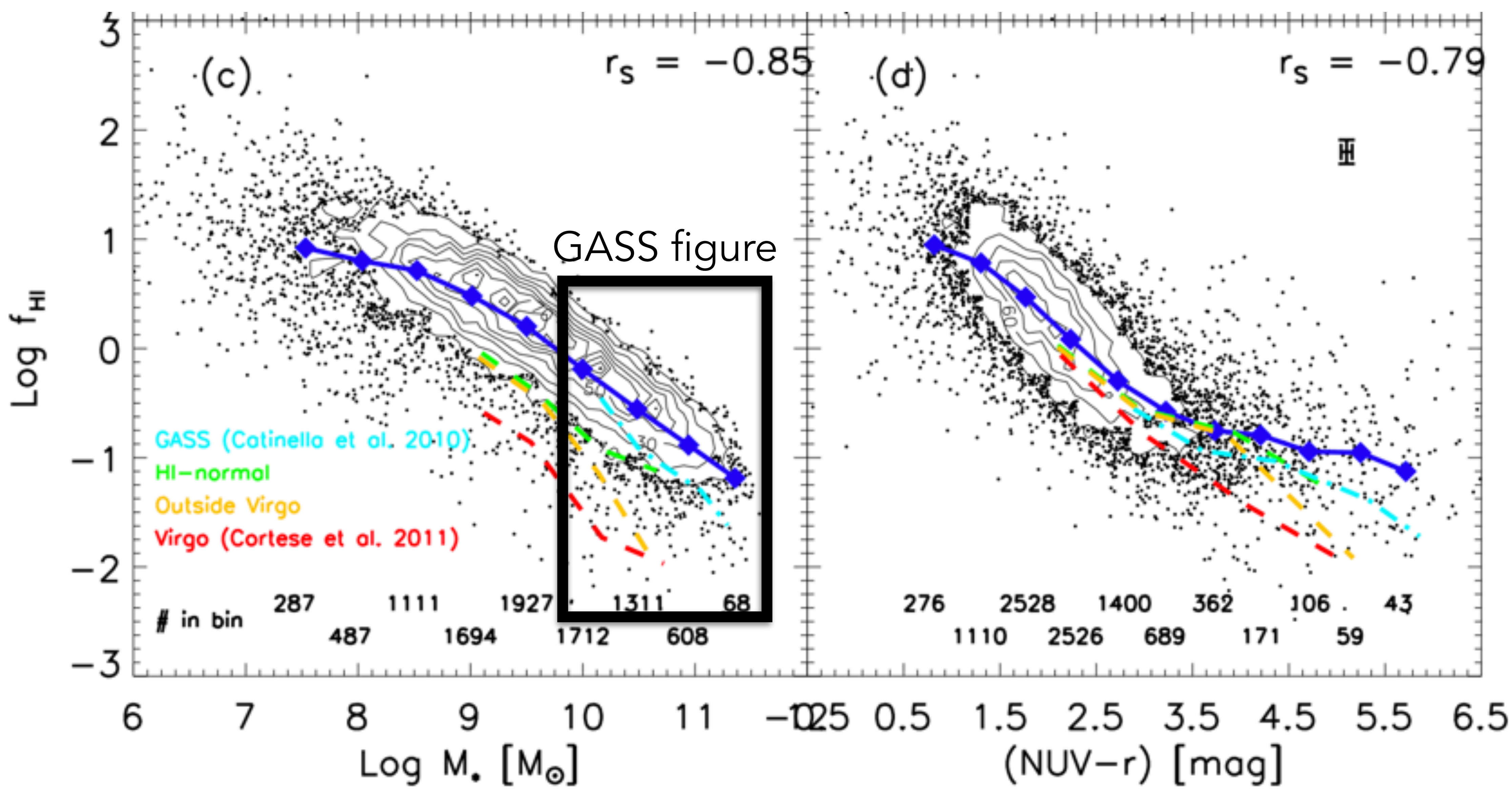


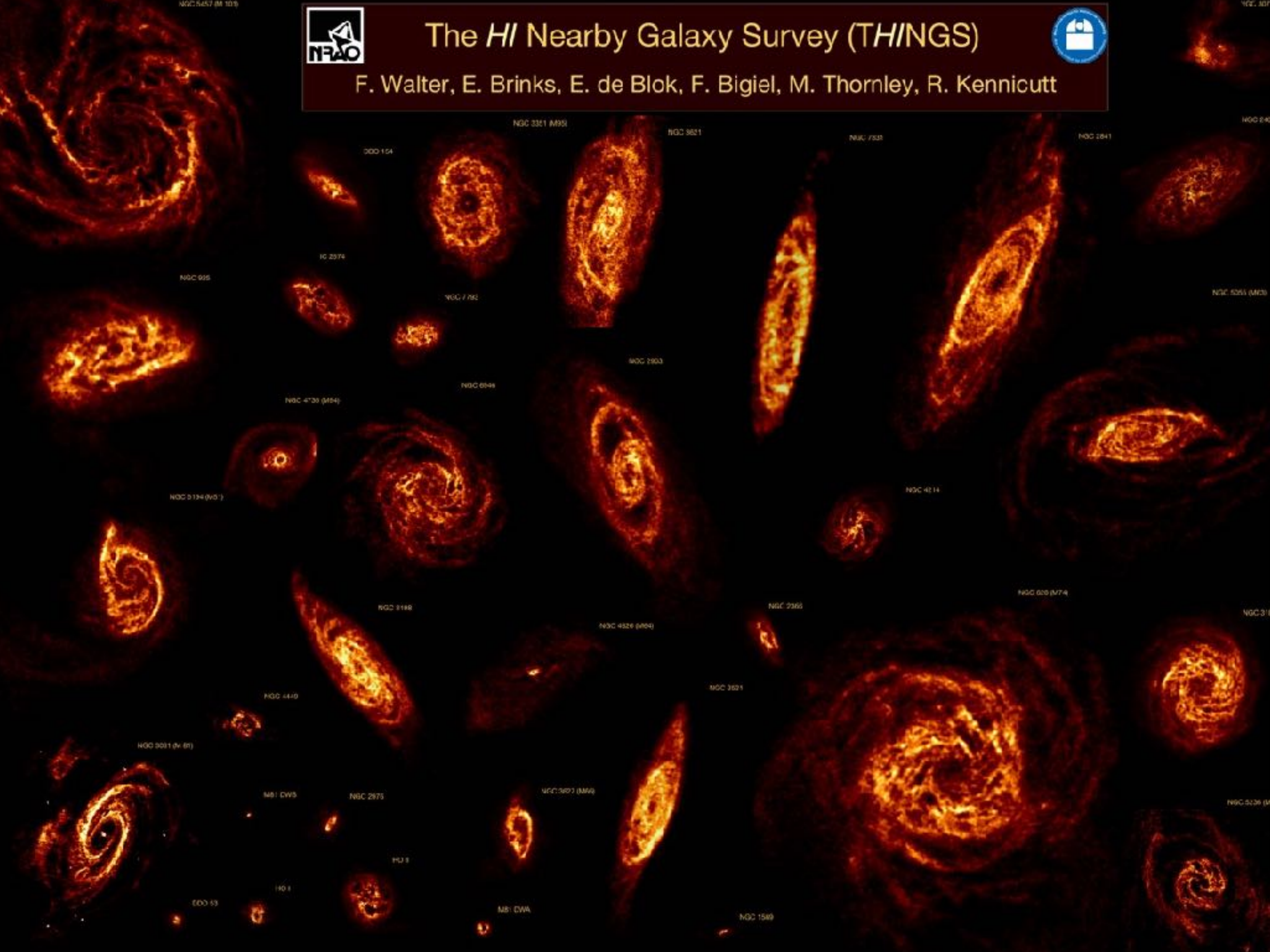
HI-to-stellar mass decreases with specific SFR

What do we know about …
in other galaxies?

Diffuse atomic gas

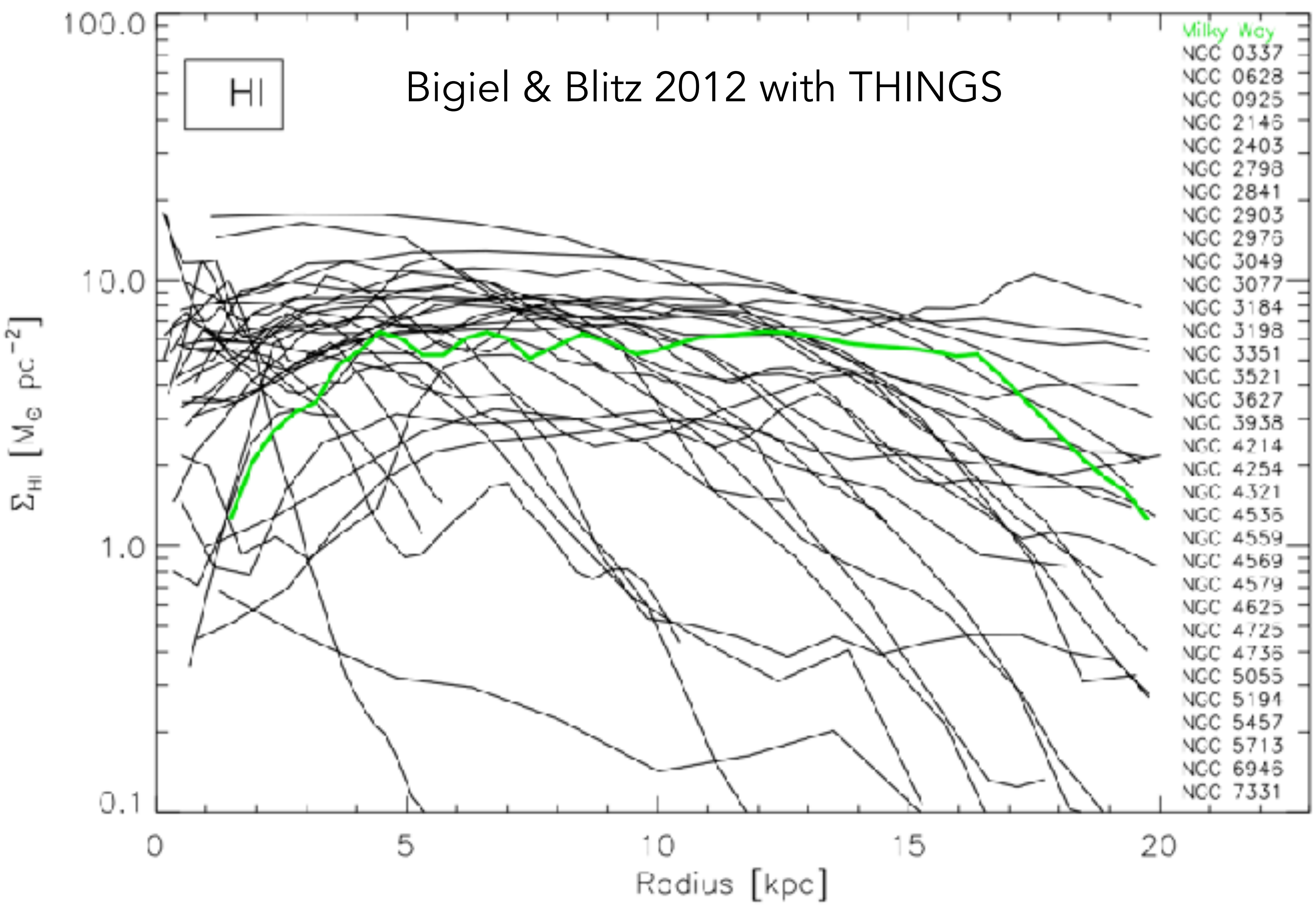


Huang et al. 2012 - compilation of HI surveys (detections only)

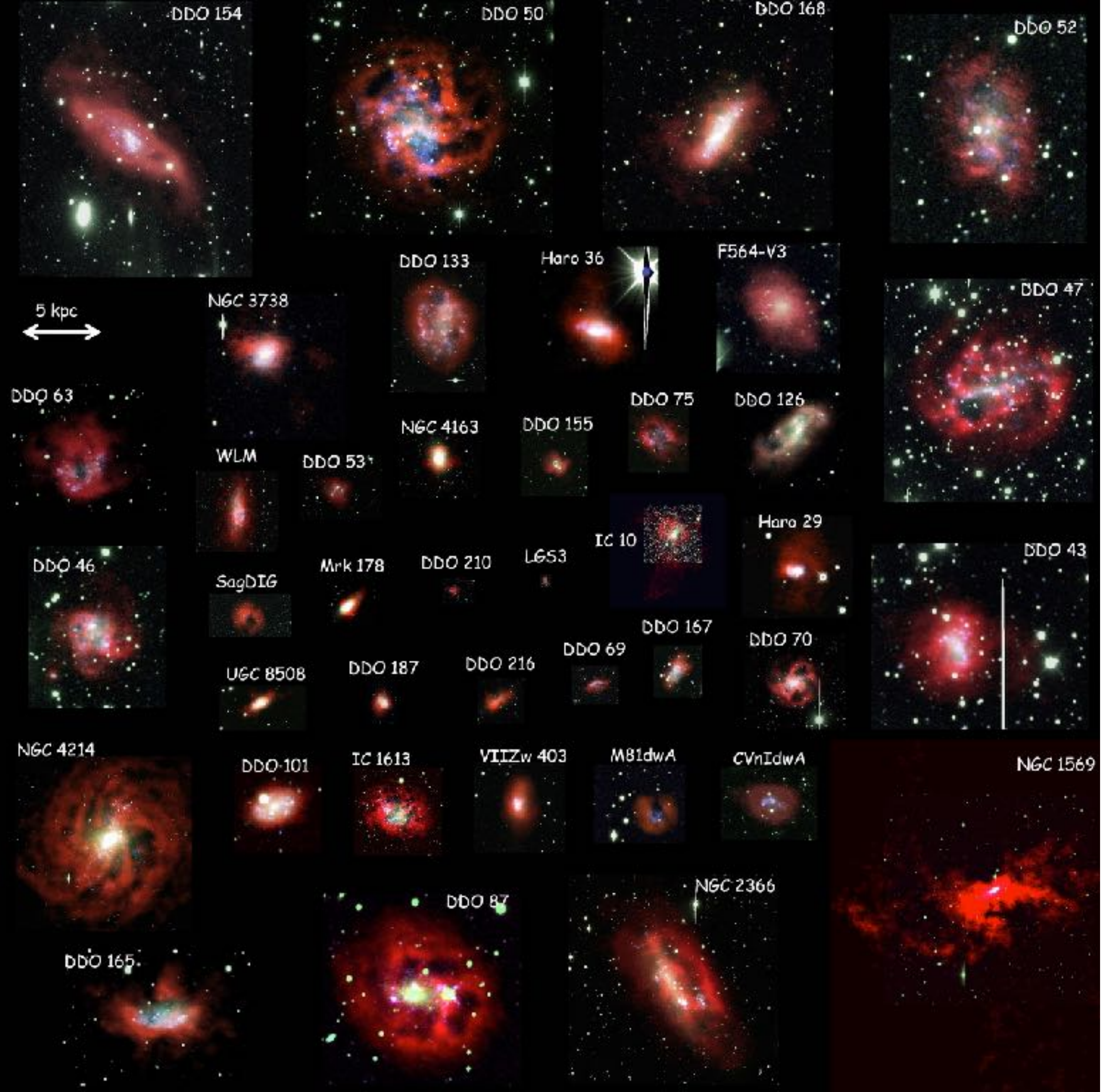

The *HI* Nearby Galaxy Survey (T*HI*NGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 2976
M81 DWA
NGC 1569

What do we know about …
in other galaxies?

Diffuse atomic gas



HI radial profiles in spiral galaxies tend to be quite flat



The LITTLE THINGS Survey

Hunter et al. 2011

What do we know about …
in other galaxies?

Diffuse atomic gas

- From galaxy integrated measurements:
    - quiescent galaxies have little HI
    - HI fraction decreases w/stellar mass for star forming galaxies
    - dwarf galaxies are very HI rich
- From galaxy resolved measurements
    - star forming spiral galaxies have somewhat flat HI radial profiles
    - dwarf galaxies have abundant, patchy HI, full of holes

What do we know about … in other galaxies?

CNM/WNM phase balance

- Need HI absorption - requires background radio sources which are scarce and limits us to BIG galaxies on the sky. This means: LMC, SMC, M31, M33 for the most part.
- Key reference for M31, M33: Dickey & Brinks 1993
    - Warm neutral medium dominates, as in the MW.
    - M31 has more CNM than MW, M33 has less
- Key reference for the SMC: Dickey et al. 2000 shows even scarcer CNM than MW or M33

What do we know about …
in other galaxies?

CNM/WNM phase balance

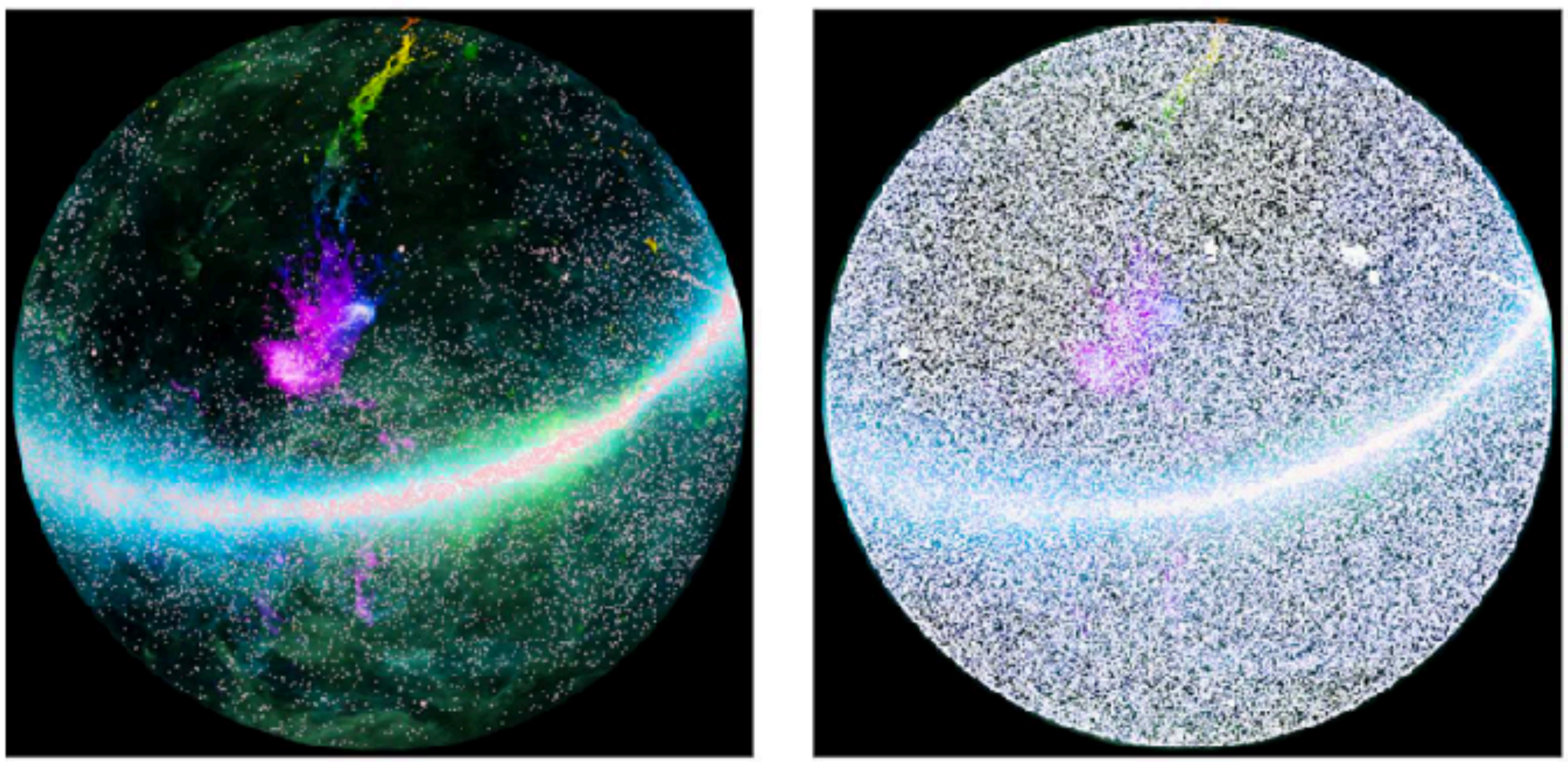
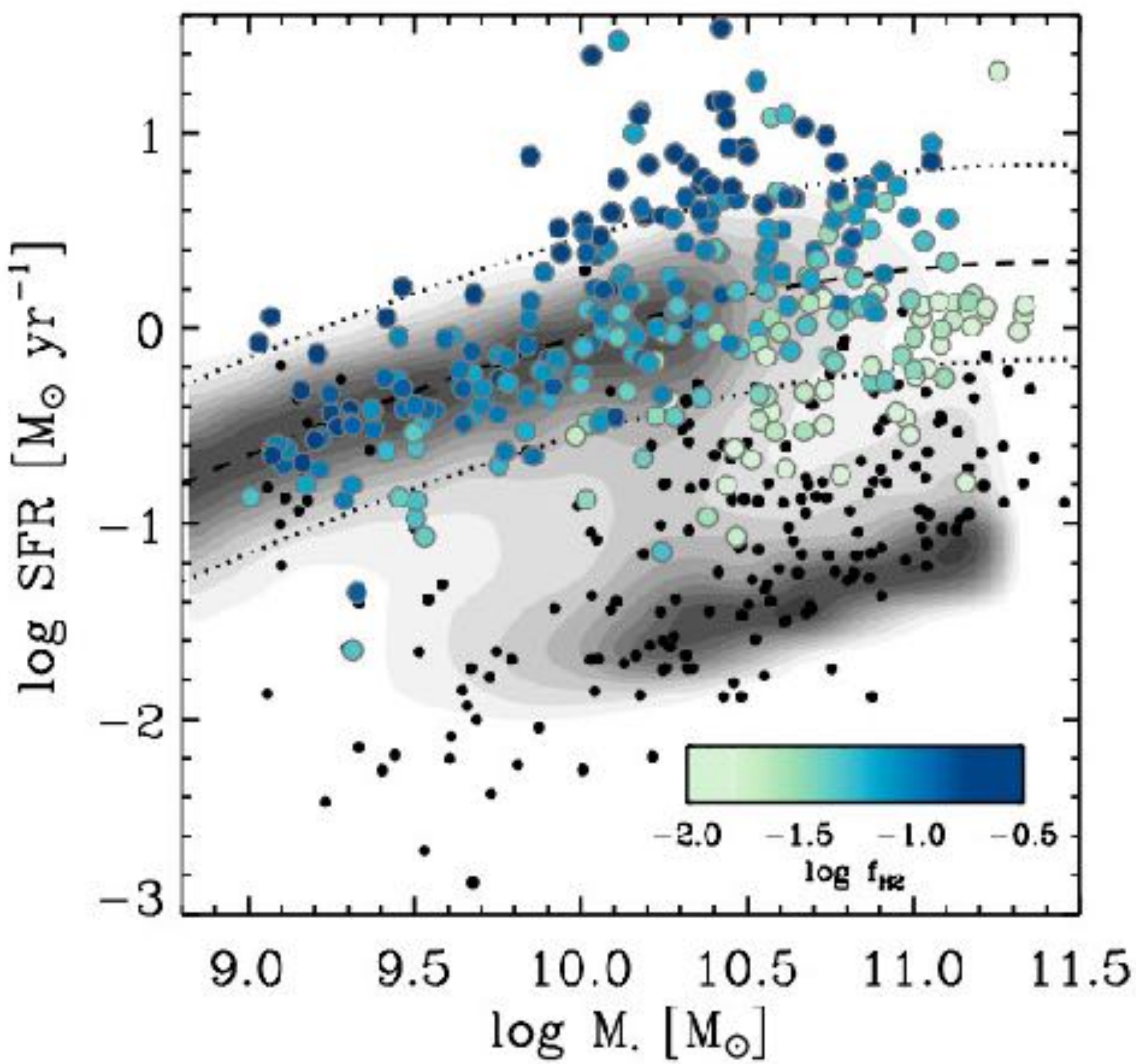


Figure 4: Source density of H I absorption measurements expected with SKA1 of the WNM (left) and the CNM (right). Each dot is an anticipated absorption measurement. The color image in the background is H I emission, where color represents velocity from the Parkes Galactic All-Sky Survey (McClure-Griffiths et al. 2009).

McClure-Griffiths et al. 2015

What do we know about …
in other galaxies?

Molecular Gas



Saintonge et al. 2017 (xCOLDGASS survey)

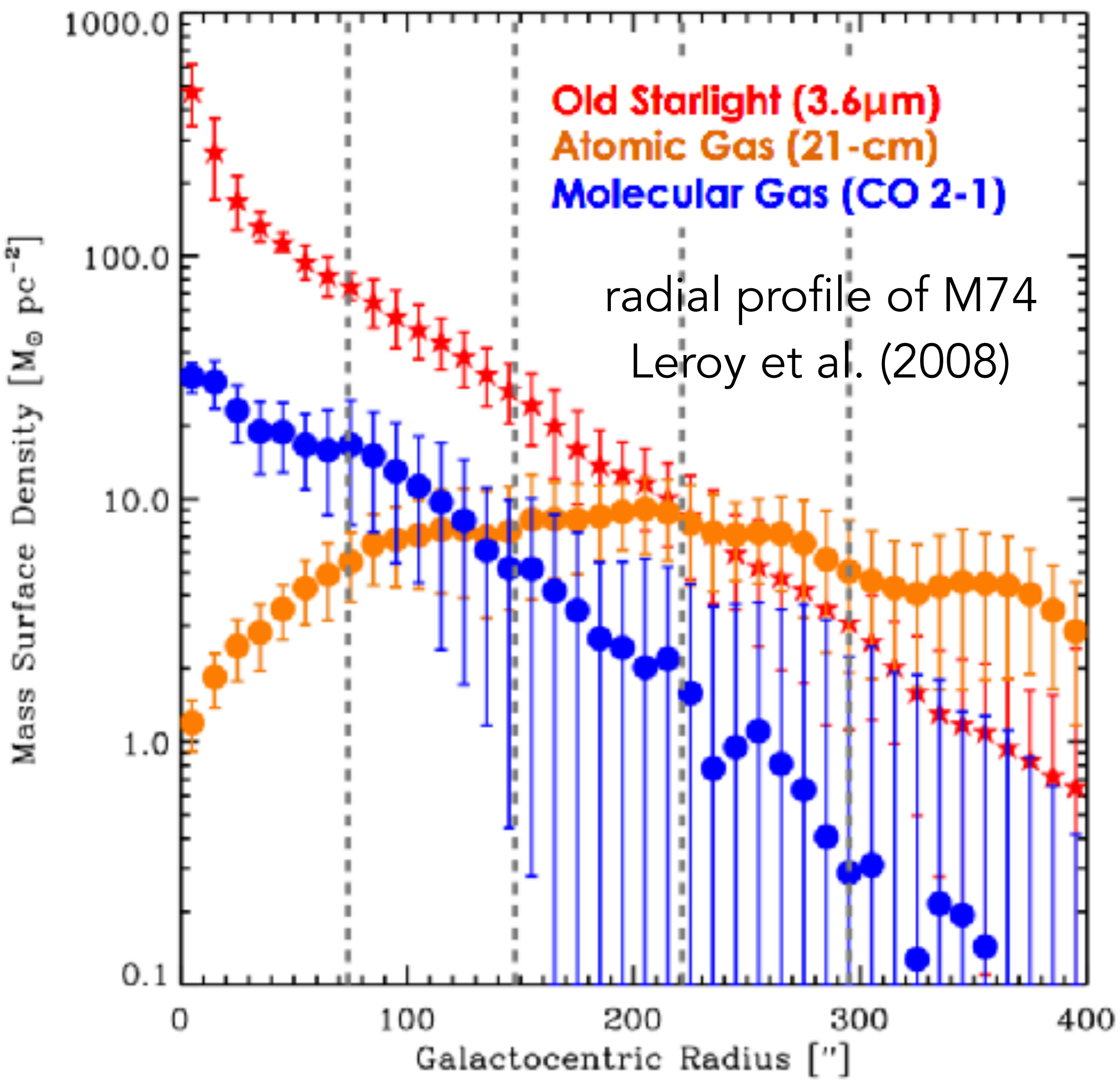
Quiescent galaxies have very low H_2 fractions.

H_2 fraction is correlated with the specific star formation rate of star-forming galaxies.

"starburst galaxies" have very high H_2 fractions.

What do we know about …
in other galaxies?

Molecular Gas

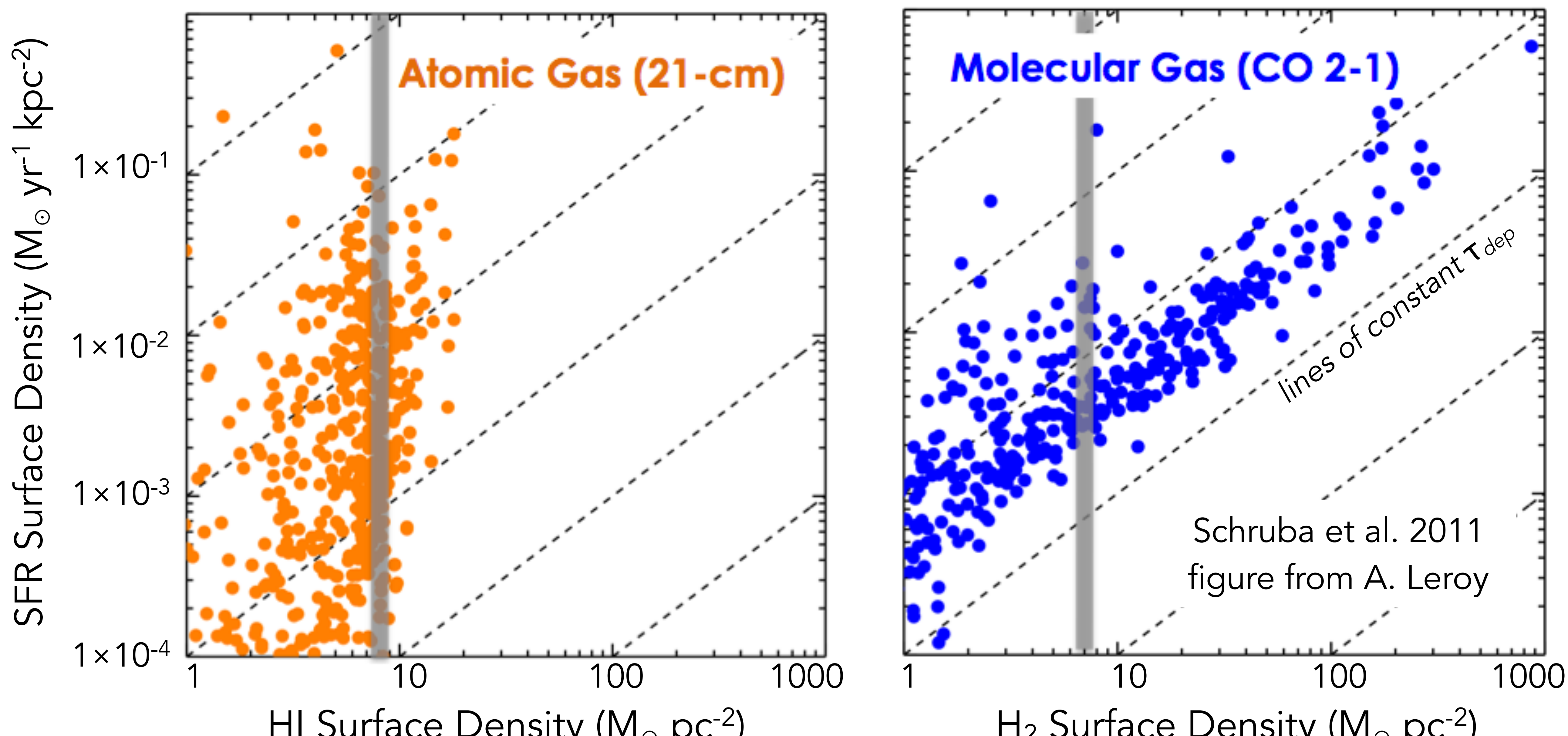


Molecular gas surface density generally tracks the stellar mass surface density profile.

Around $\Sigma \sim 10\ M_{\odot}/pc^2$ H_2 takes over as the dominant form of gas.

What do we know about …
in other galaxies?

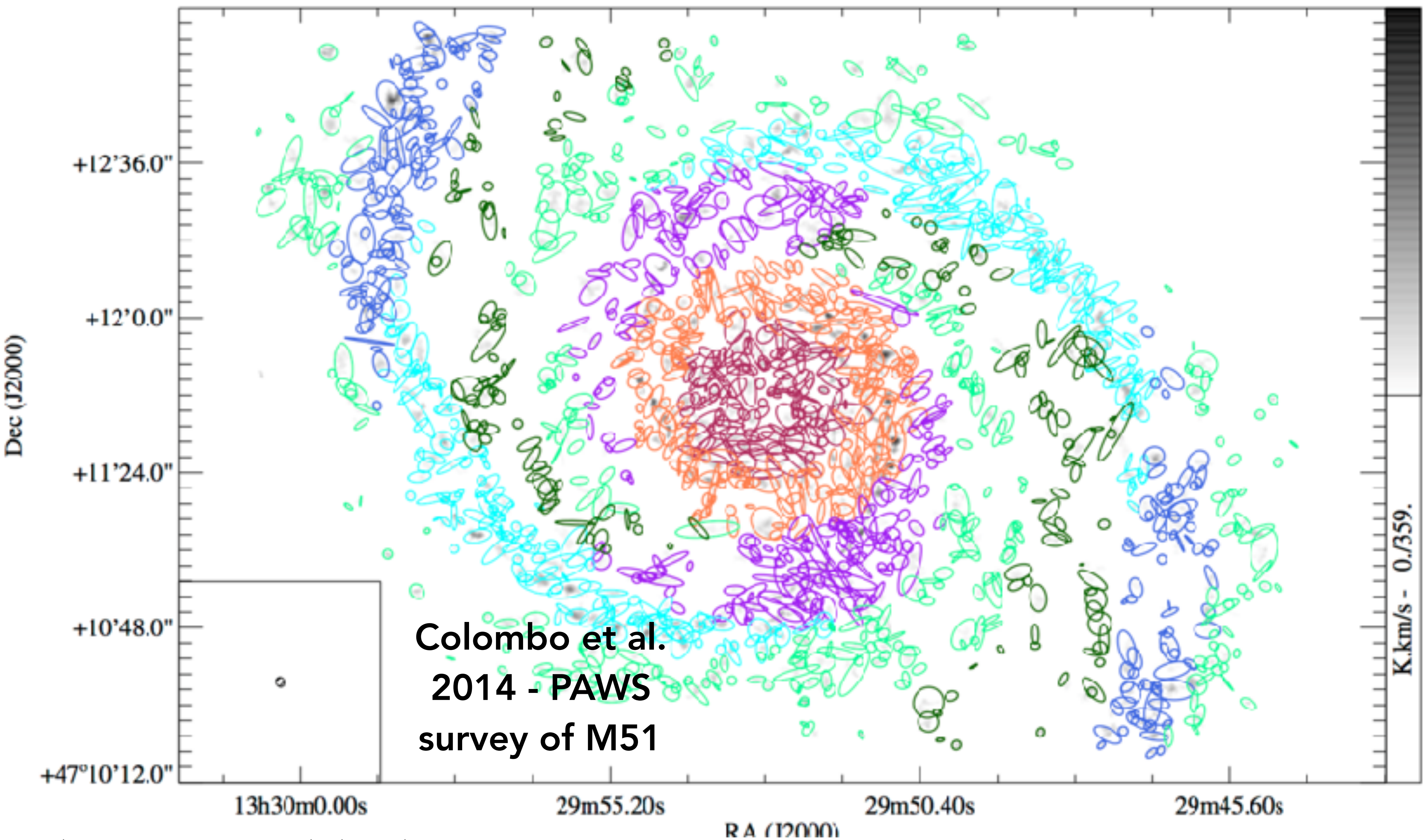
Molecular Gas



Star formation is correlated with H_2 not HI.

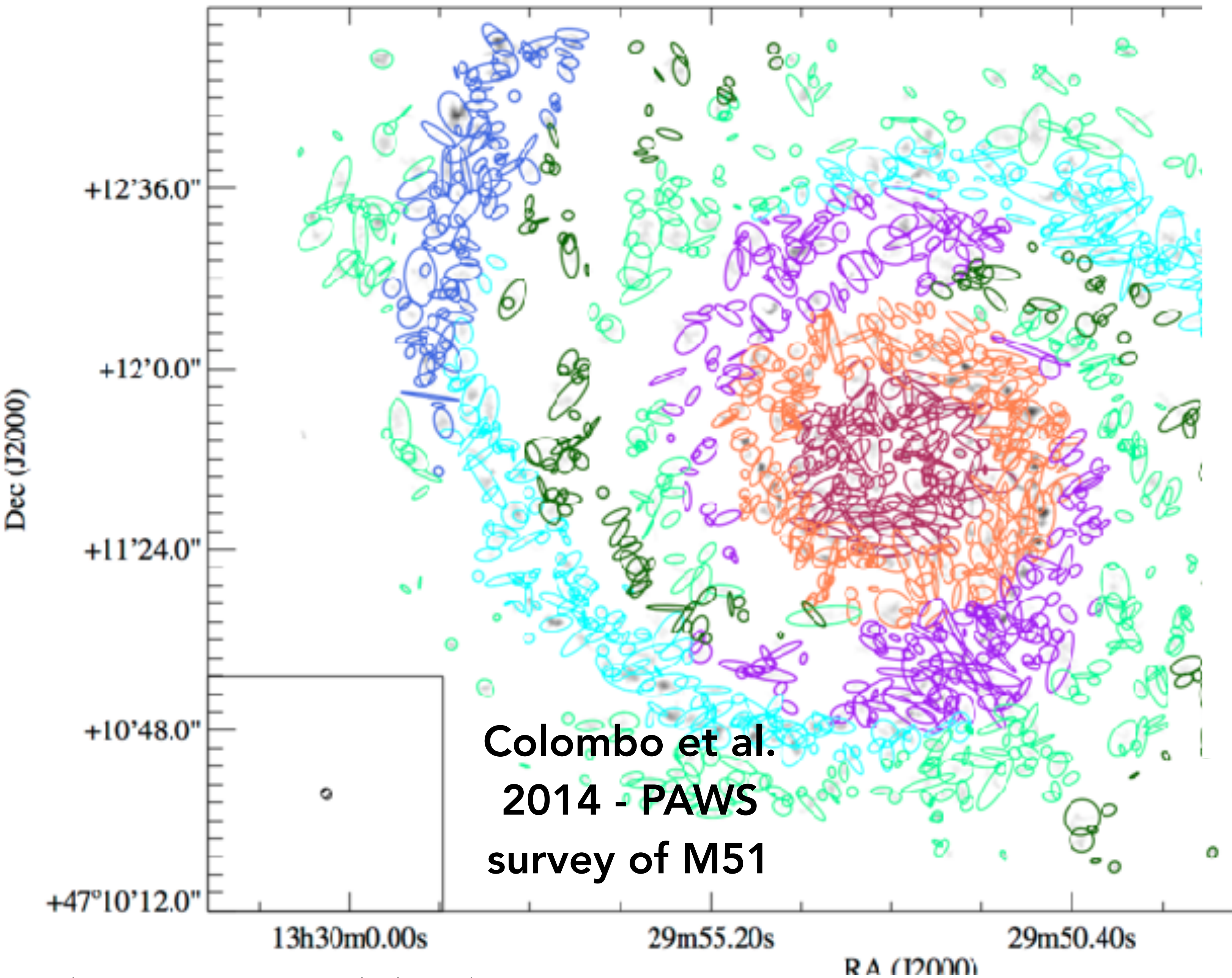
What do we know about …
in other galaxies?

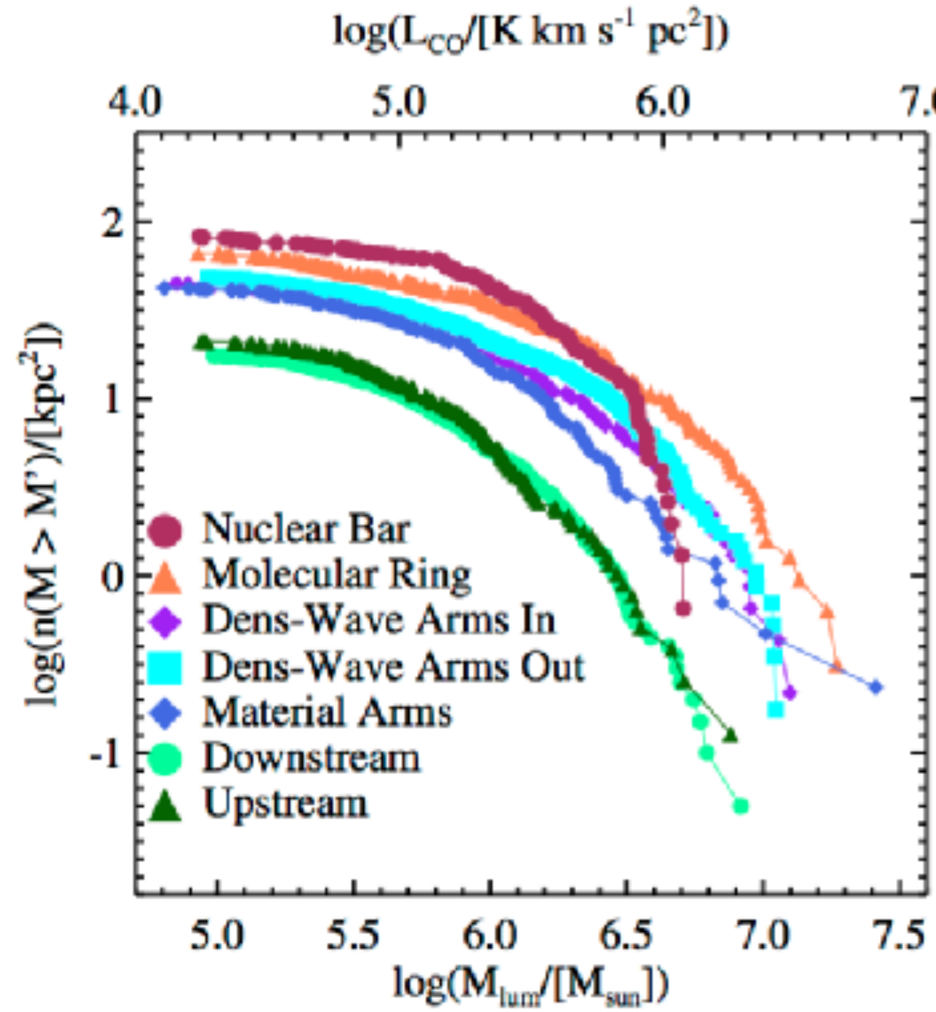
Molecular Gas



What do we know about … in other galaxies?

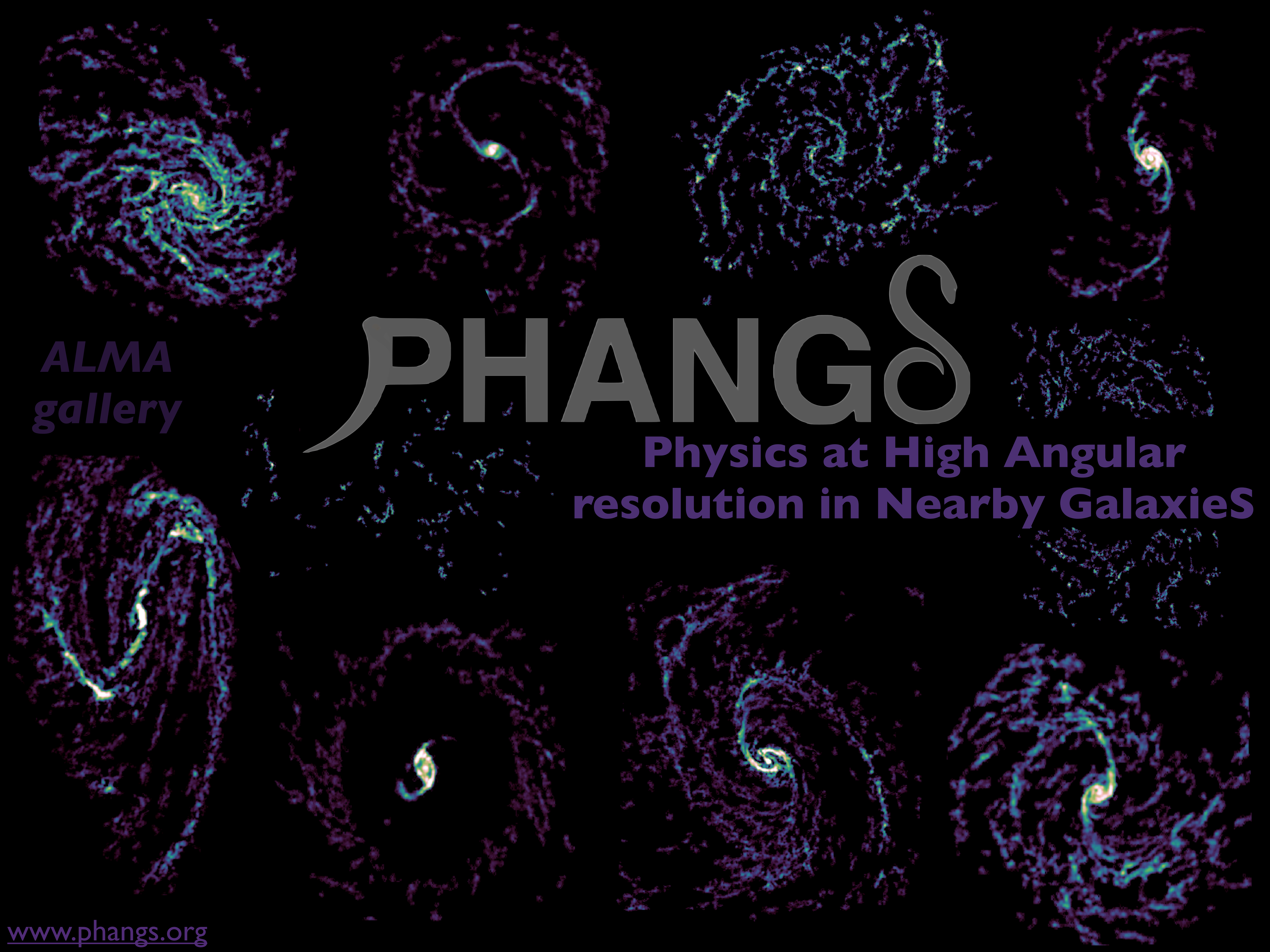
Molecular Gas





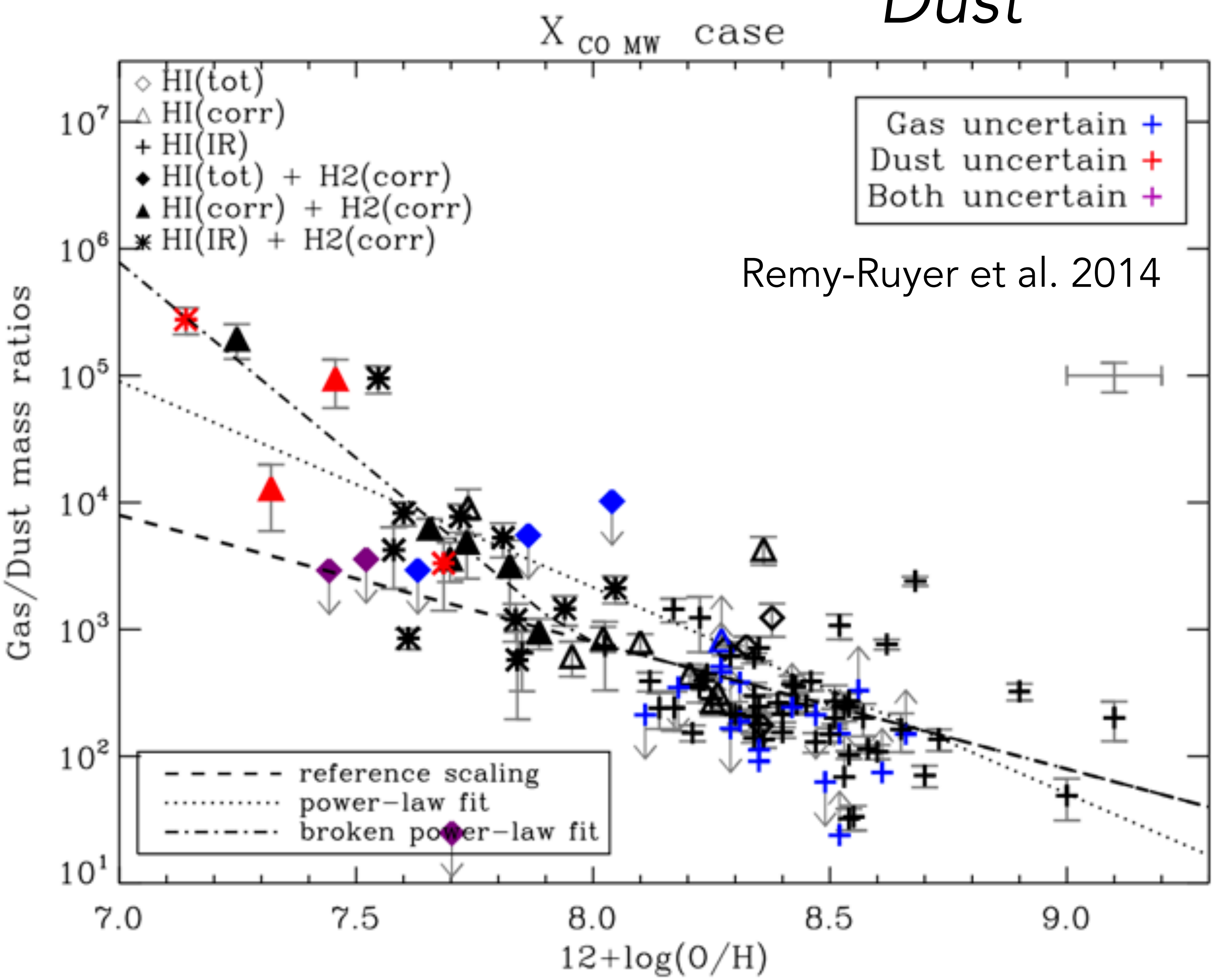
Colombo et al. 2014 - PAWS survey of M51

Image from:
https://public.nrao.edu/AlmaExtras/


ALMA gallery
PHANGS
Physics at High Angular resolution in Nearby GalaxieS
www.phangs.org

What do we know about …
in other galaxies?

Dust

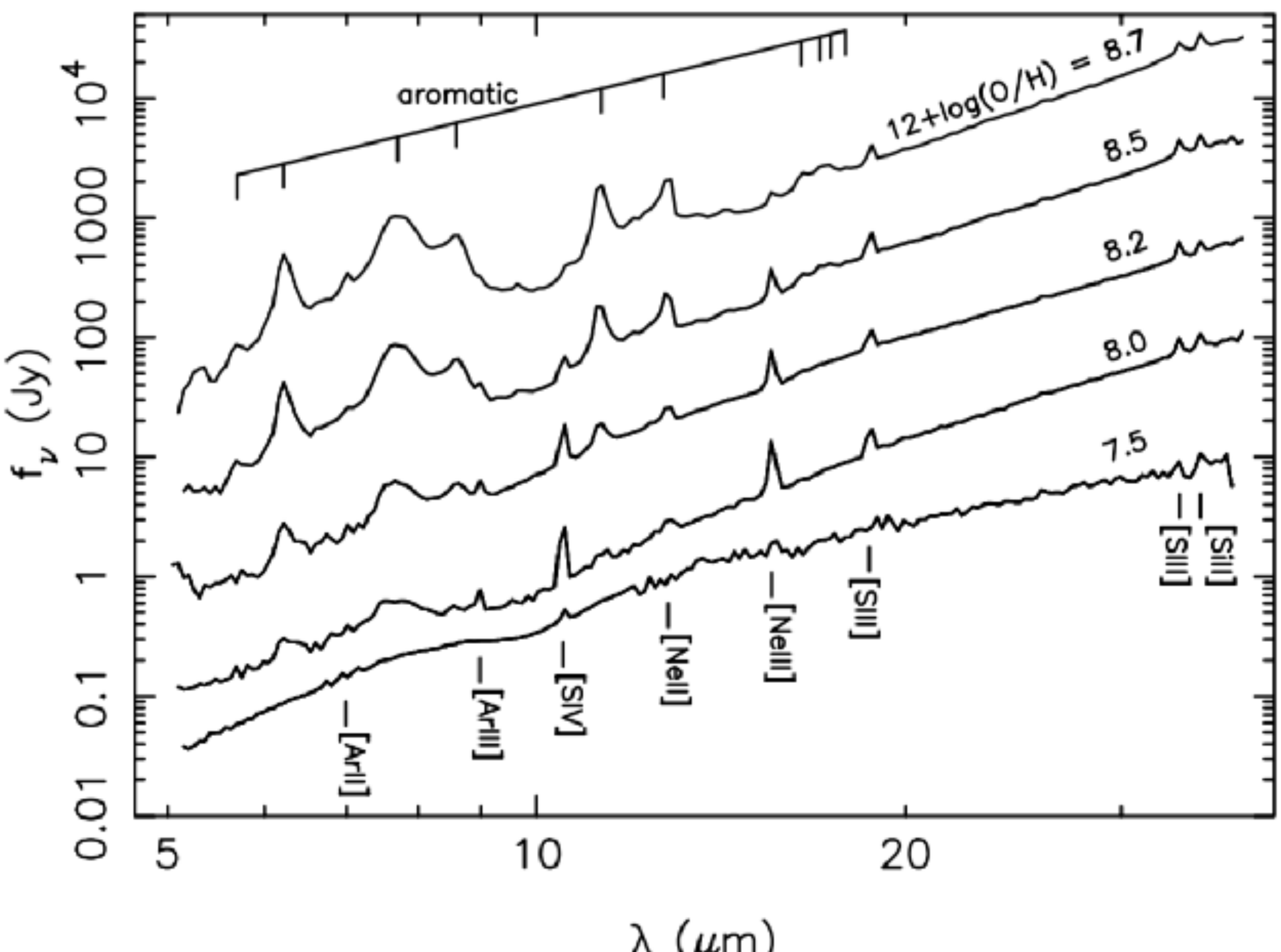


Dust-to-gas ratio tracks metallicity for high Z galaxies but becomes very non-linear at low Z.

What do we know about …
in other galaxies?

Engelbracht et al. 2008

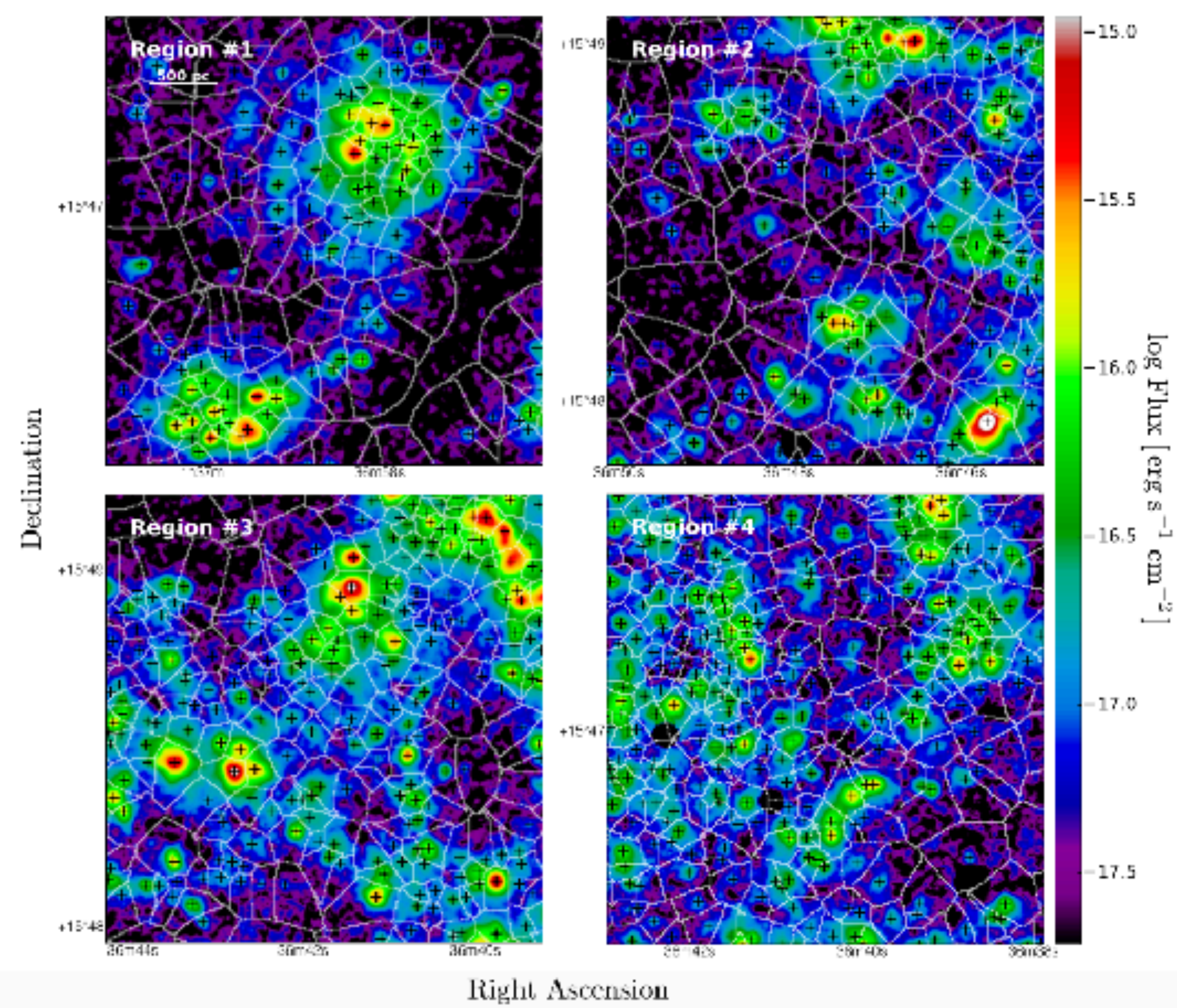
Dust



Small PAH grains disappear as the metallicity gets low.

What do we know about …
in other galaxies?

Ionized Gas



What do we know about …
in other galaxies?

Ionized Gas

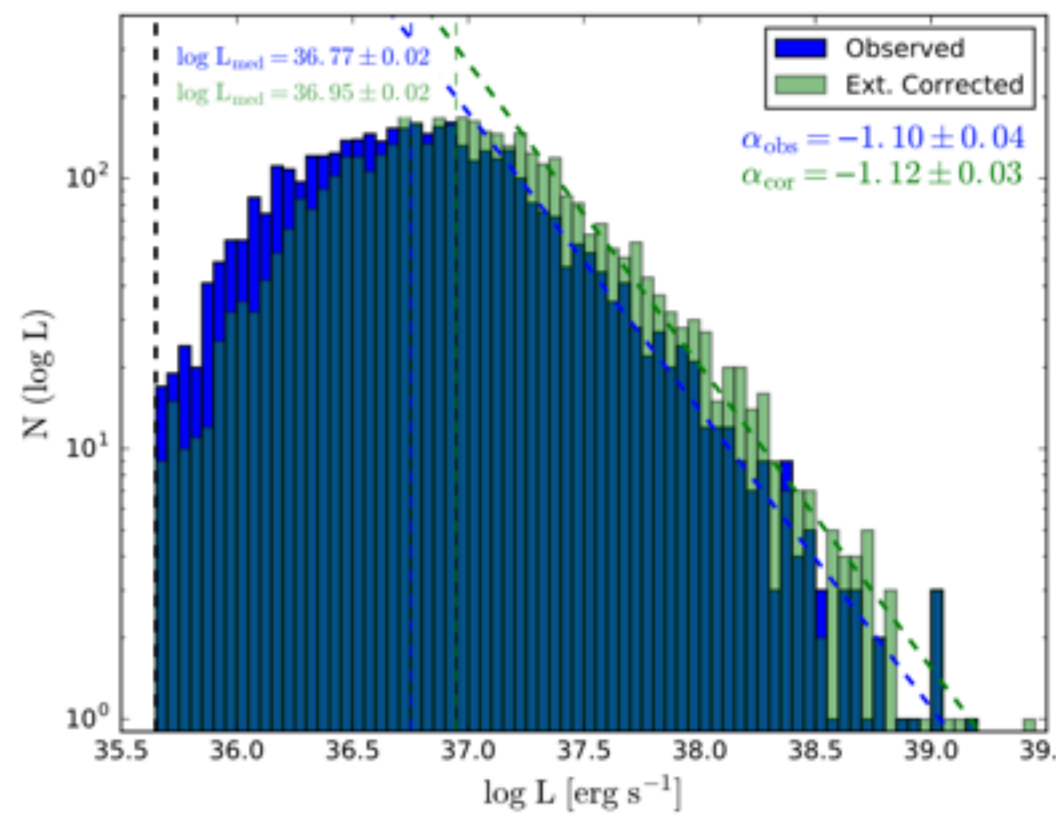


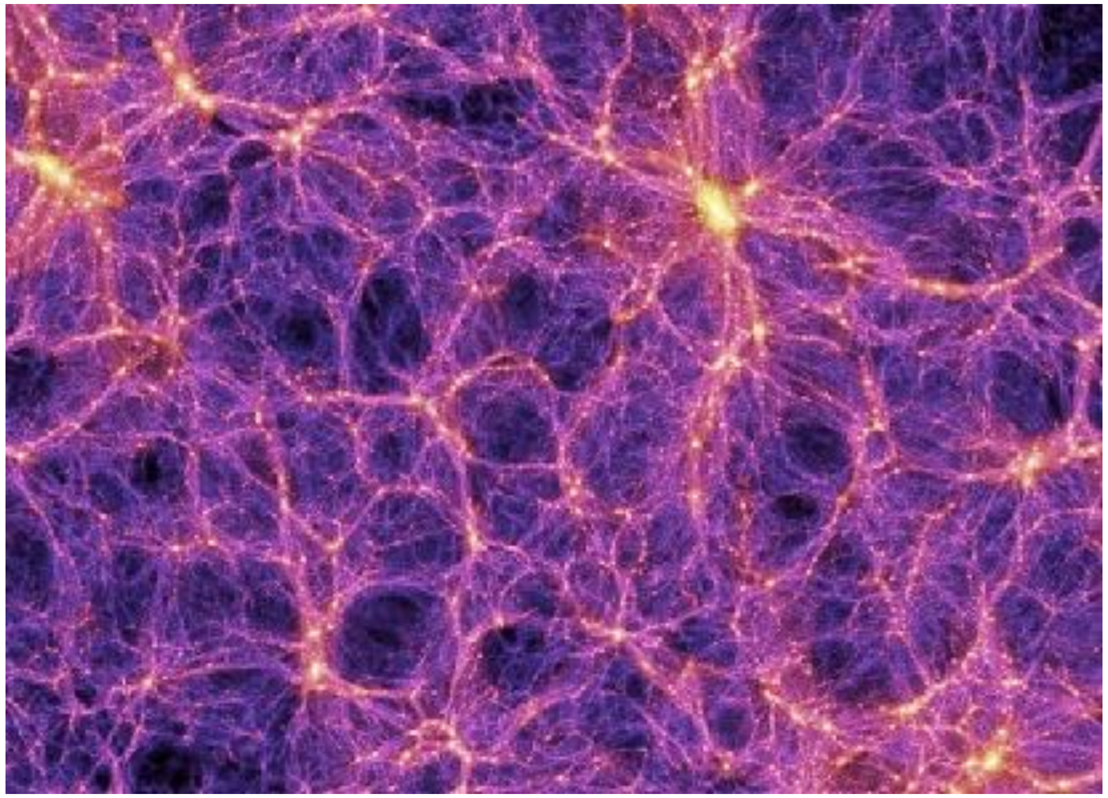
Figure 18. The Hα luminosity function of the 4158 HII region candidates before (in blue) and after (in green) the extinction correction. The slope α is evaluated in the luminosity range log(L_{med})+0.2 to 39.3 in both cases. The vertical lines in blue and green indicate the median value for each case. The vertical line in black shows the detection limit.

What do we know about …
in other galaxies?

a lot, but there is much to learn!

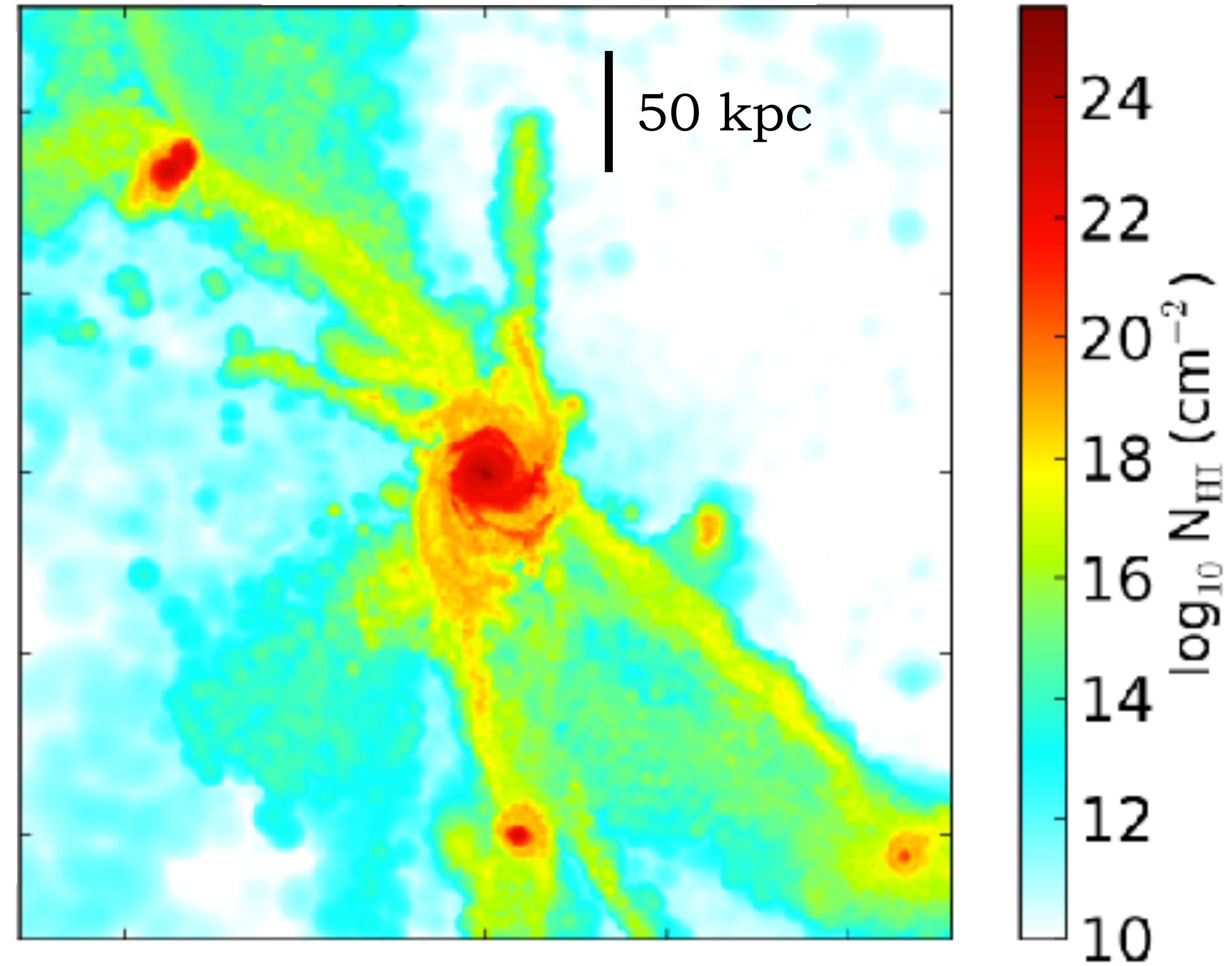
Zooming back out to the big picture…

Dark Matter & Structure Growth



Millennium Simulation (Springel et al. 2005)
cosmological dark matter only simulation

Gas Supply



HI around z=4.0 DM halo (Bird et al. 2012)
cosmological moving mesh sim, w/gas & DM

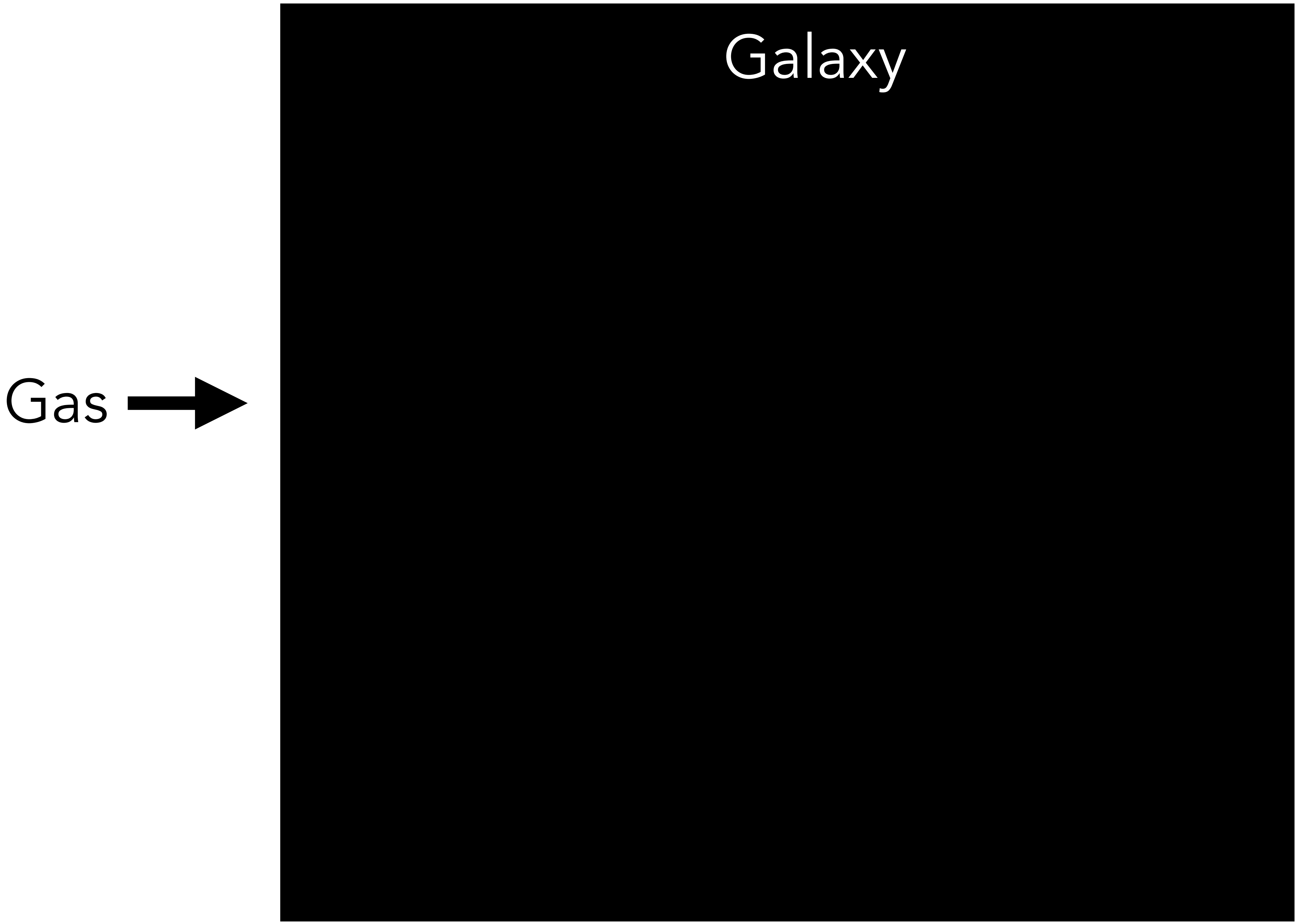
Star Formation

M51 Hubble ACS imaging
Credit: NASA/ESA/Hubble Heritage

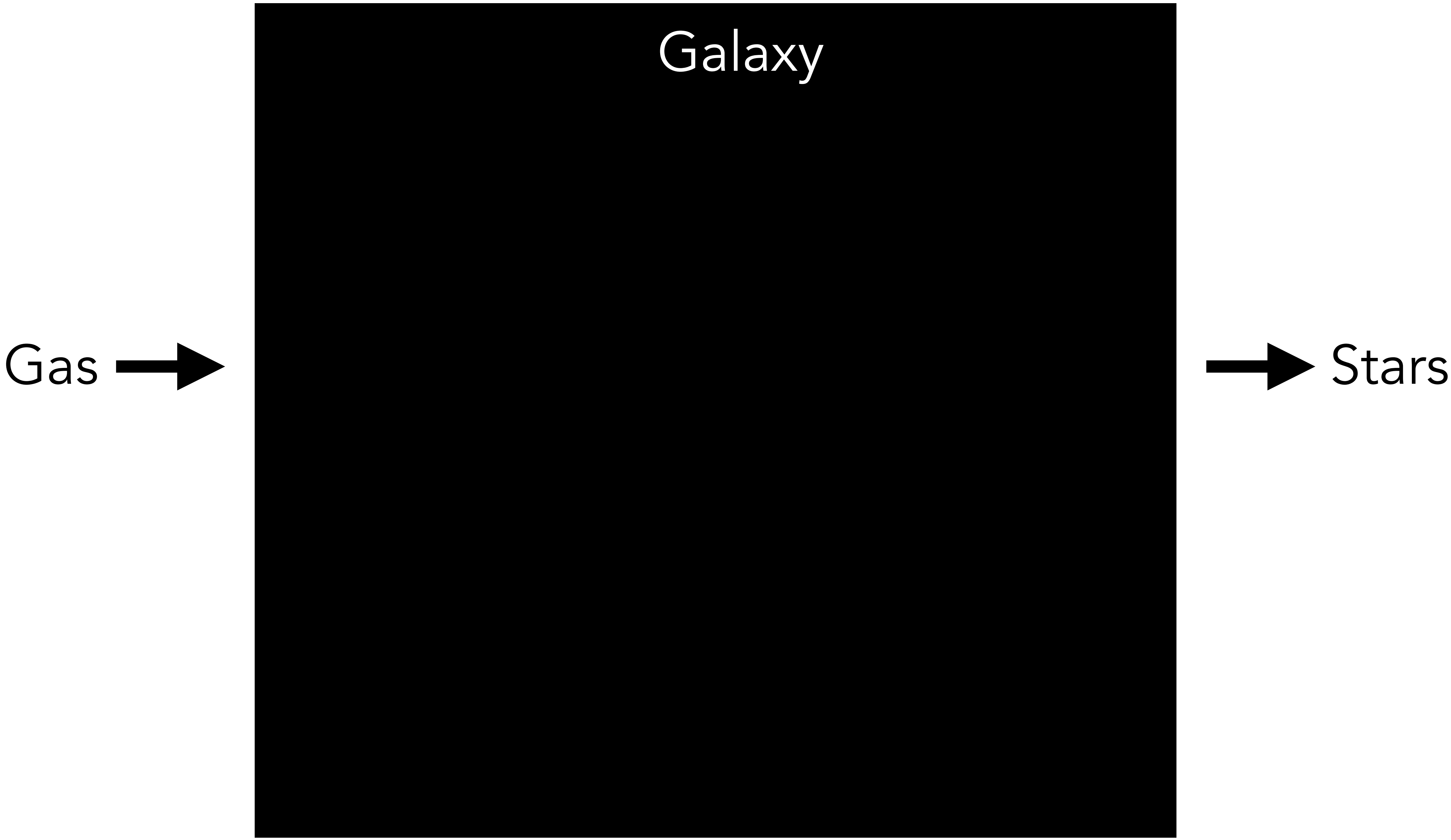
gas supply regulation includes: AGN & Feedback

Galaxy

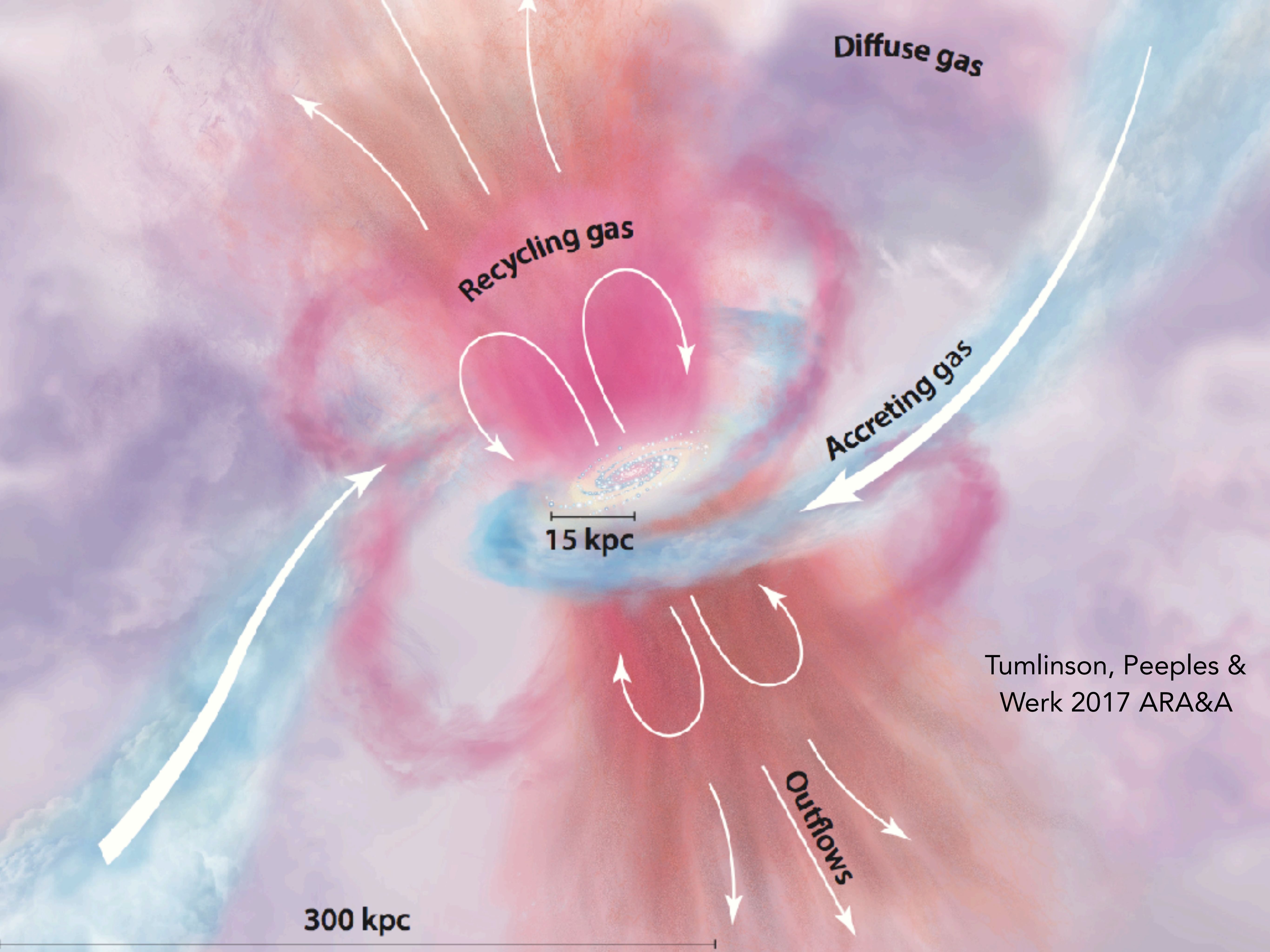
Given some amount of gas in a galaxy…



Given some amount of gas in a galaxy…



At what rate will it form stars?



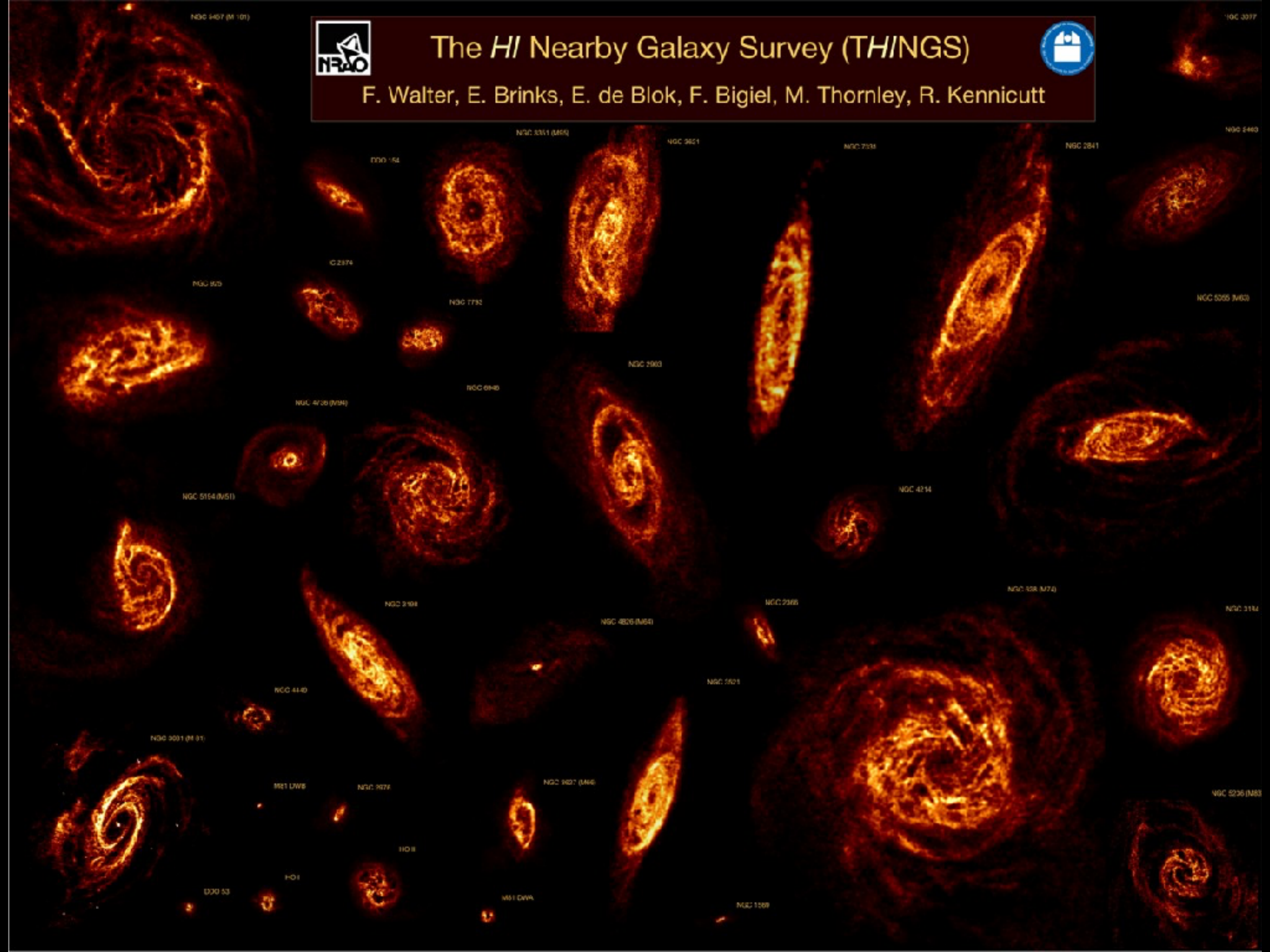
Tumlinson, Peeples &
Werk 2017 ARA&A

Gas →

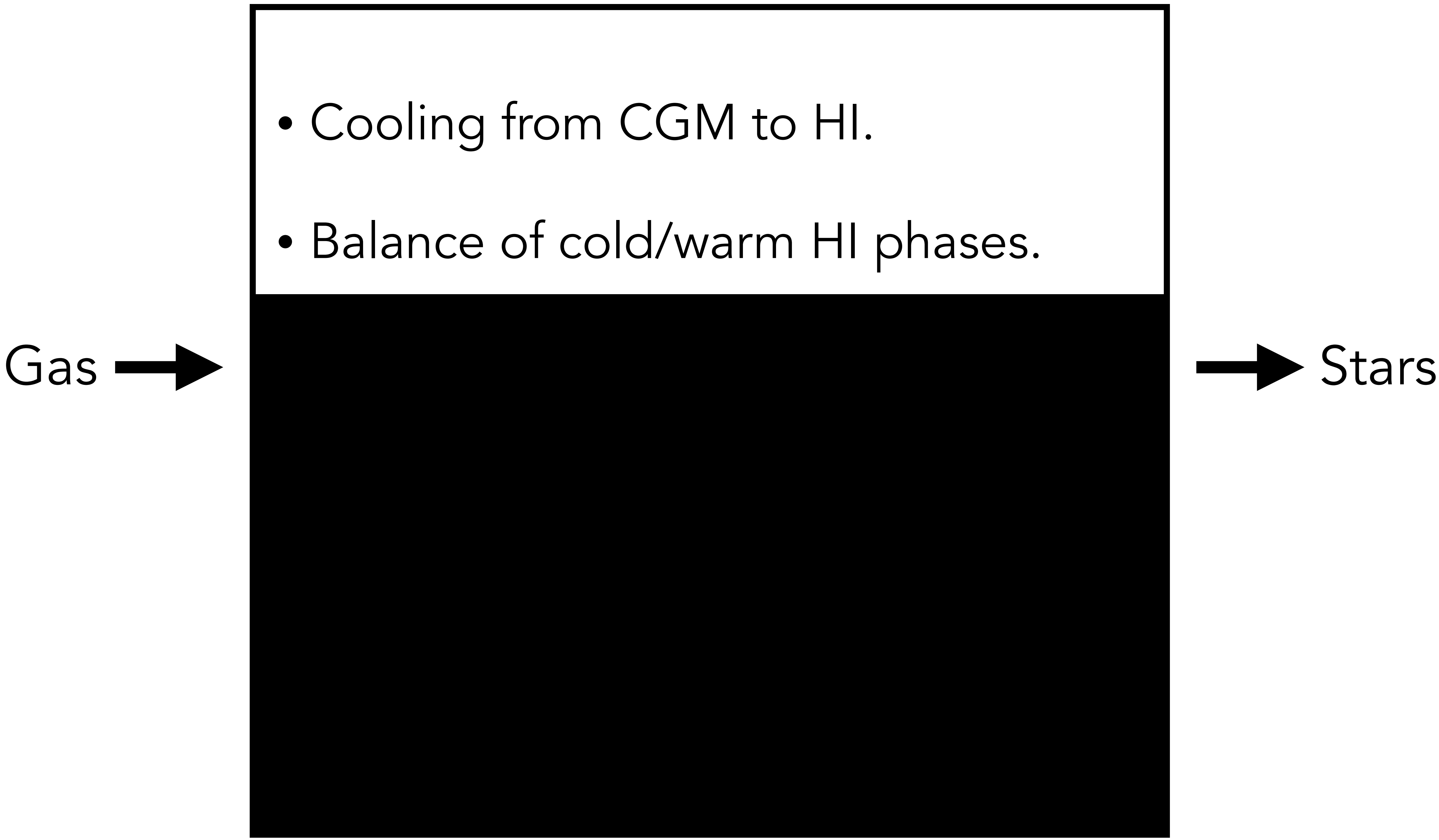
- Cooling from CGM to HI.

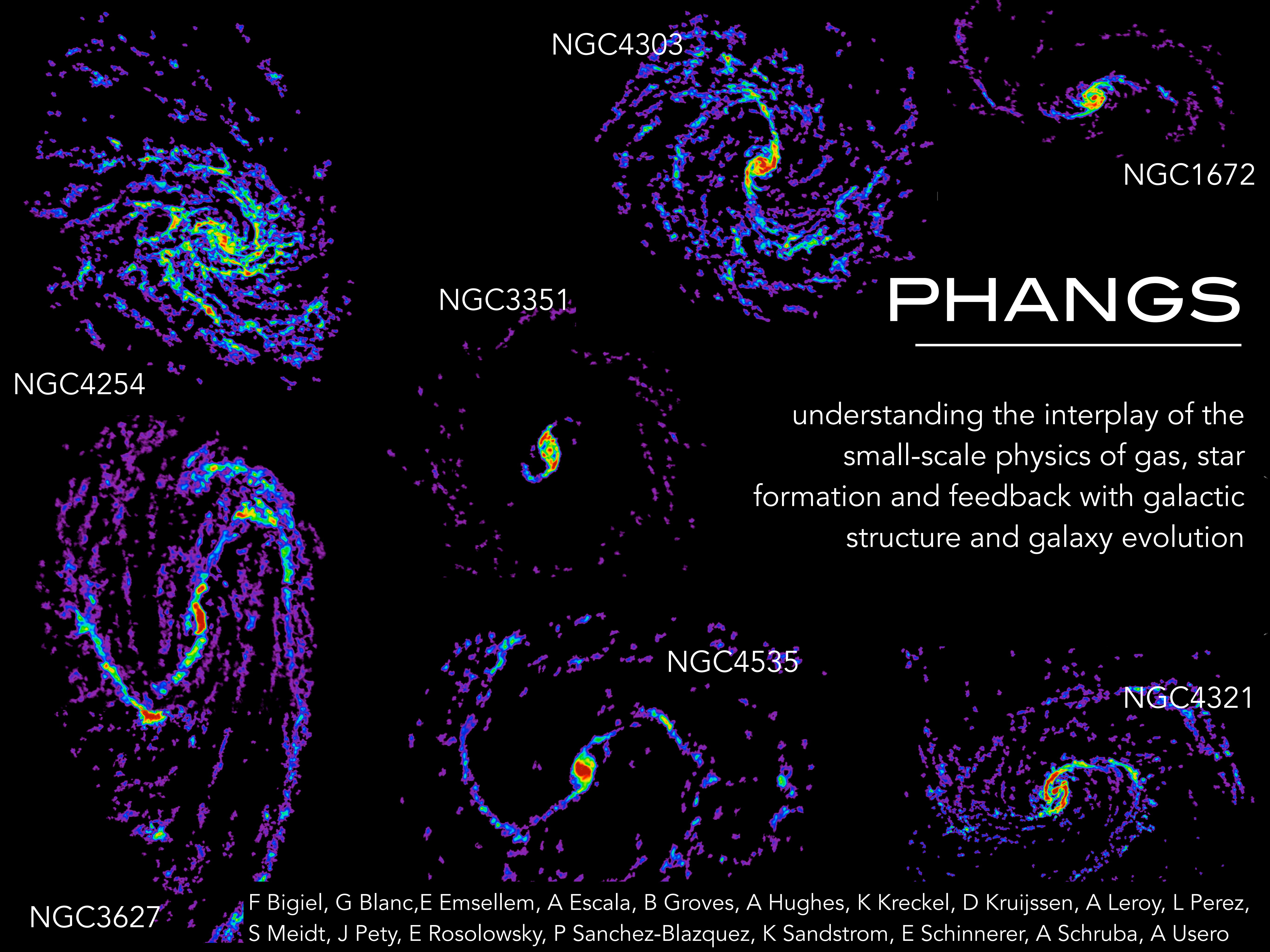
[redacted]

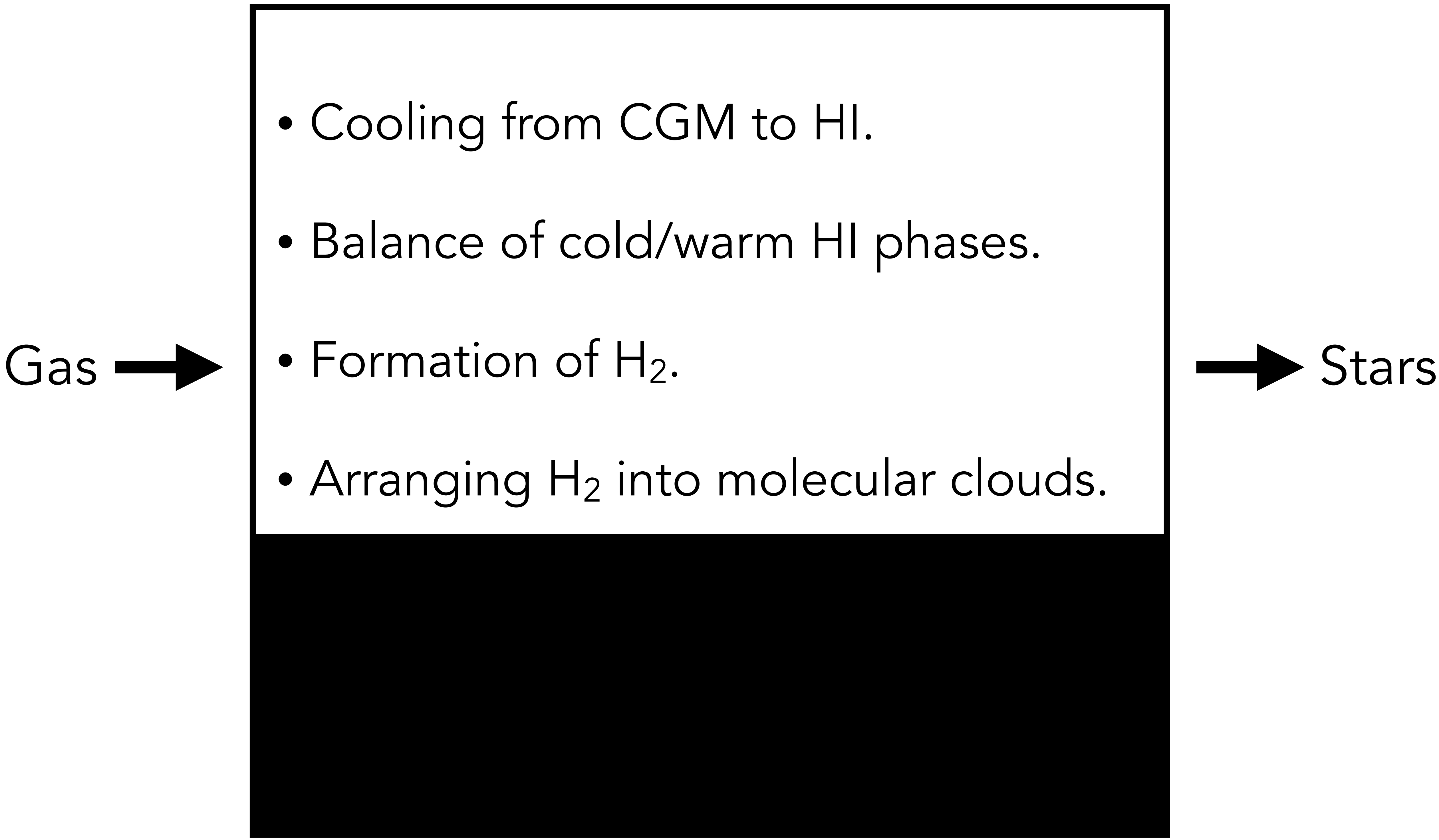
→ Stars

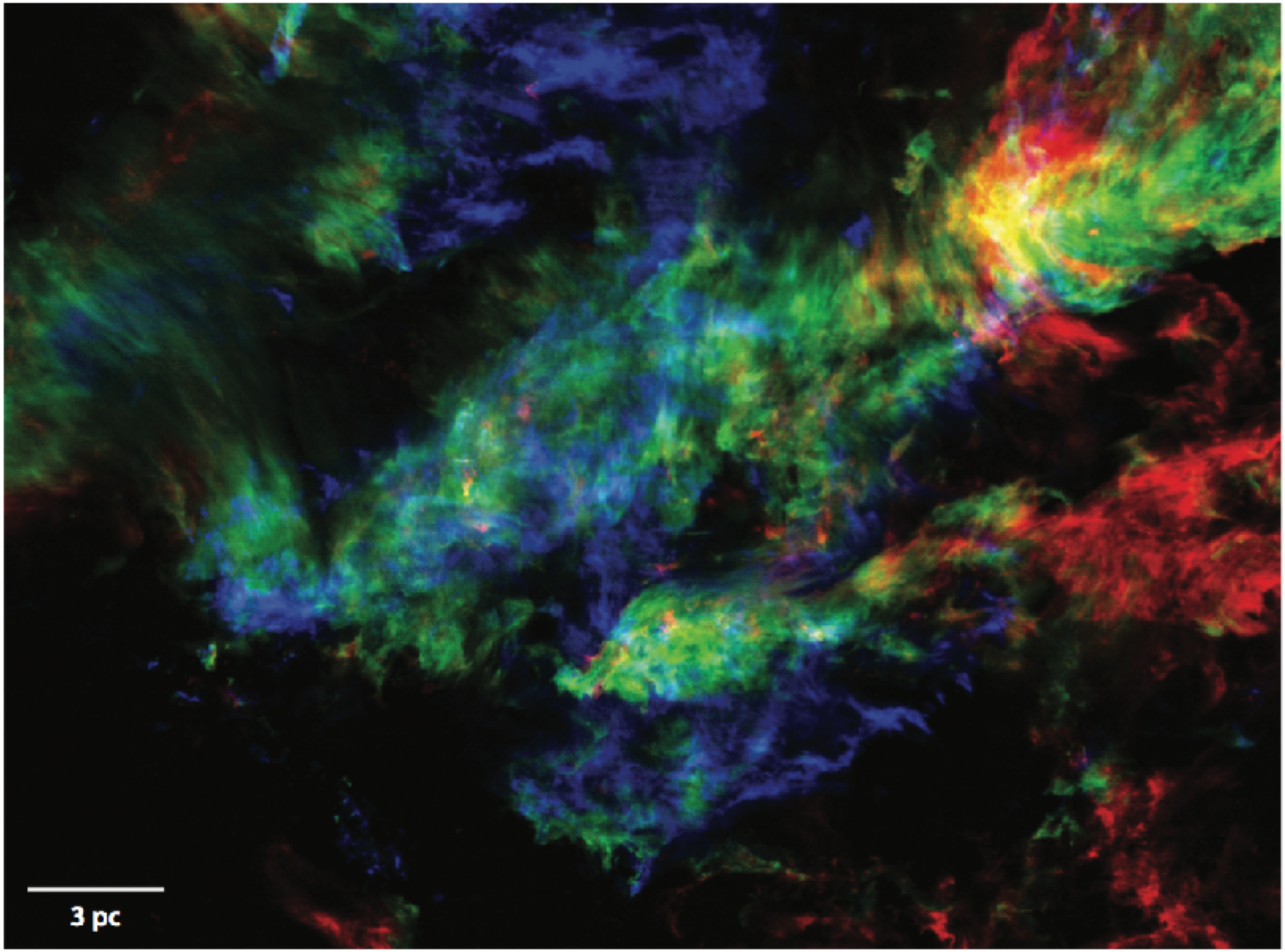


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 2841
NGC 2903
NGC 4214
NGC 7793
NGC 6946
IC 2574
NGC 2366
NGC 3184

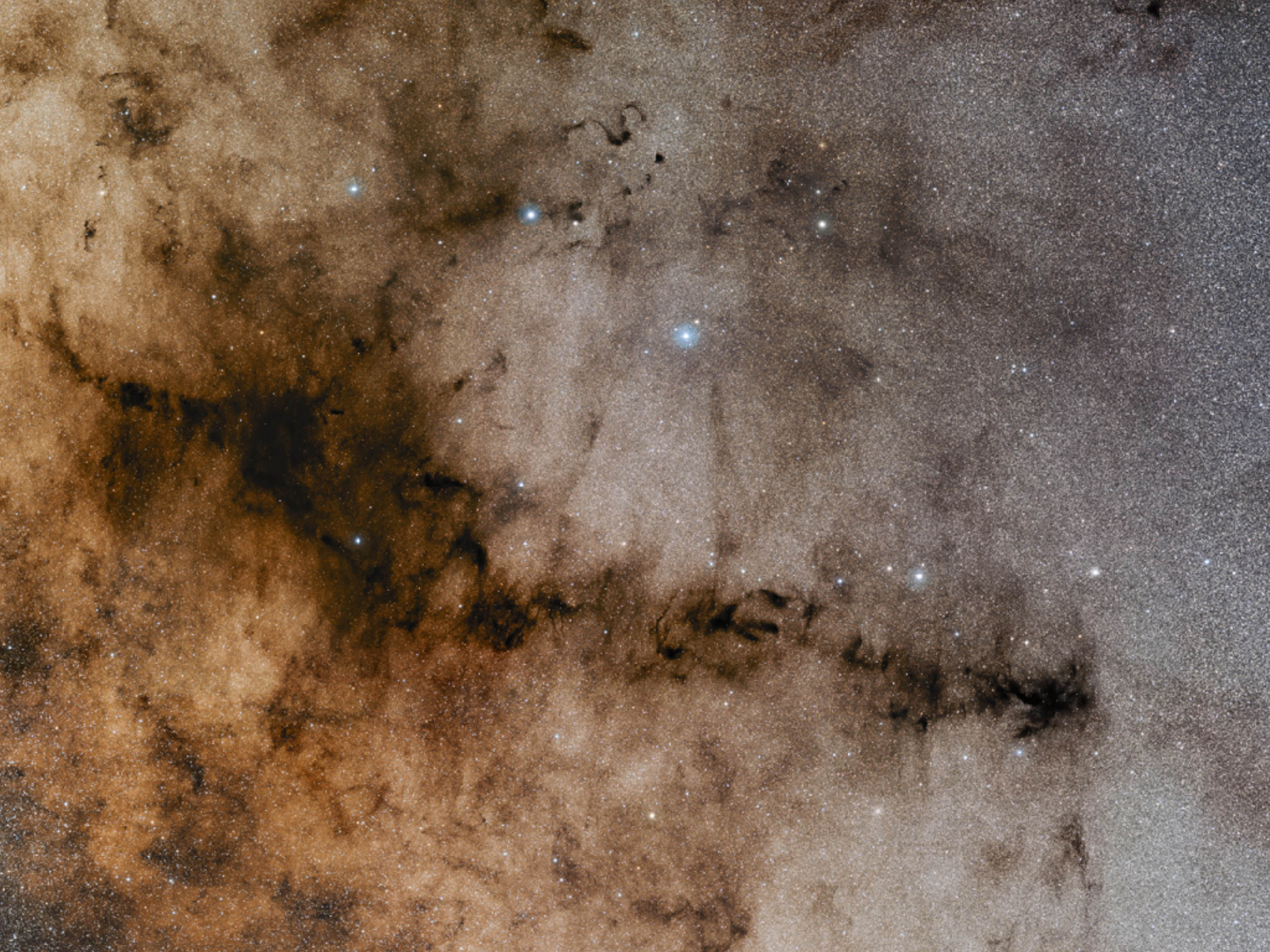

• Cooling from CGM to HI.
• Balance of cold/warm HI phases.
Gas
Stars

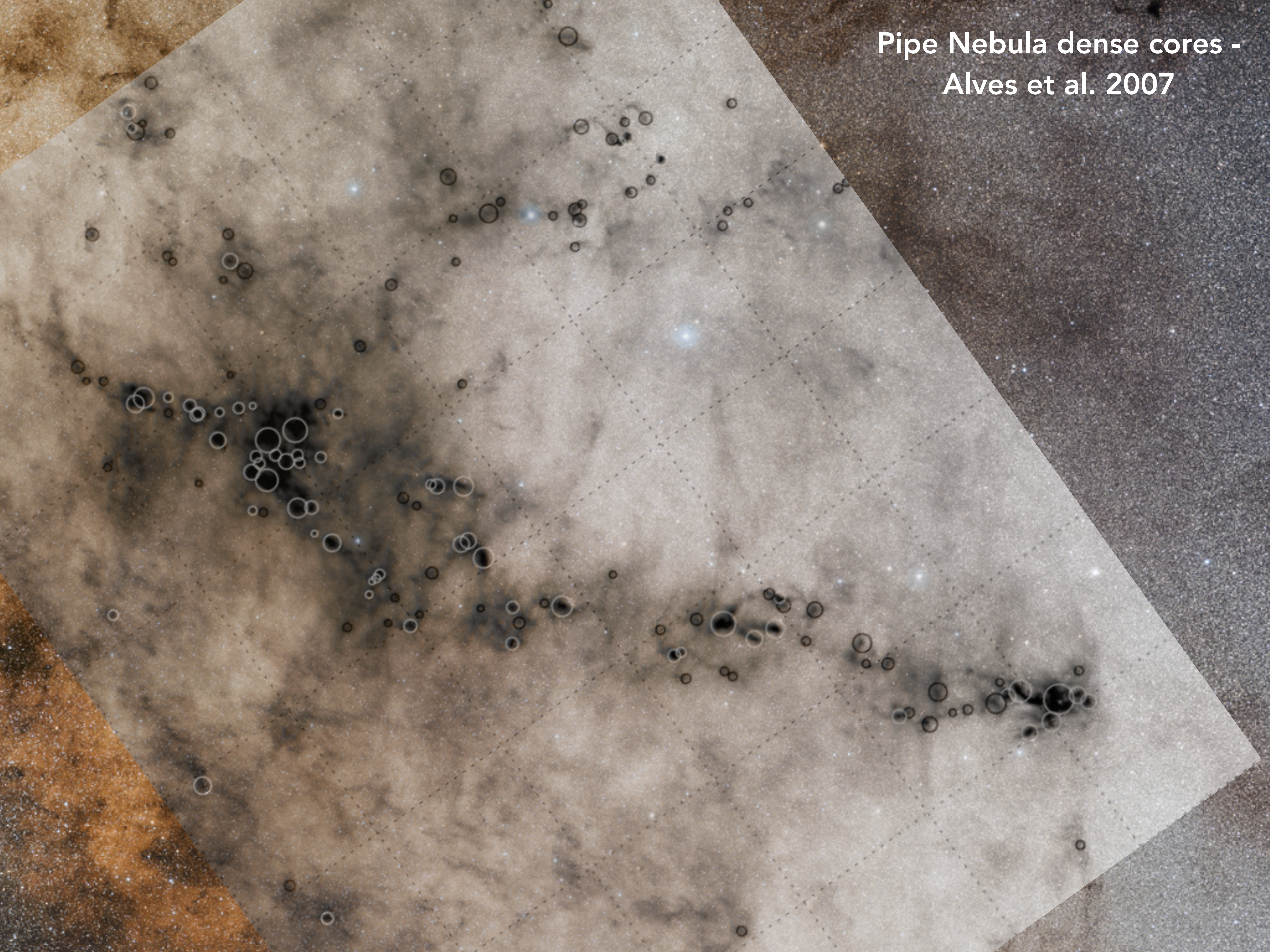

NGC4303
NGC1672
PHANGS
NGC3351
NGC4254
understanding the interplay of the small-scale physics of gas, star formation and feedback with galactic structure and galaxy evolution
NGC4535
NGC4321
NGC3627
F Bigiel, G Blanc,E Emsellem, A Escala, B Groves, A Hughes, K Kreckel, D Kruijssen, A Leroy, L Perez,
S Meidt, J Pety, E Rosolowsky, P Sanchez-Blazquez, K Sandstrom, E Schinnerer, A Schruba, A Usero

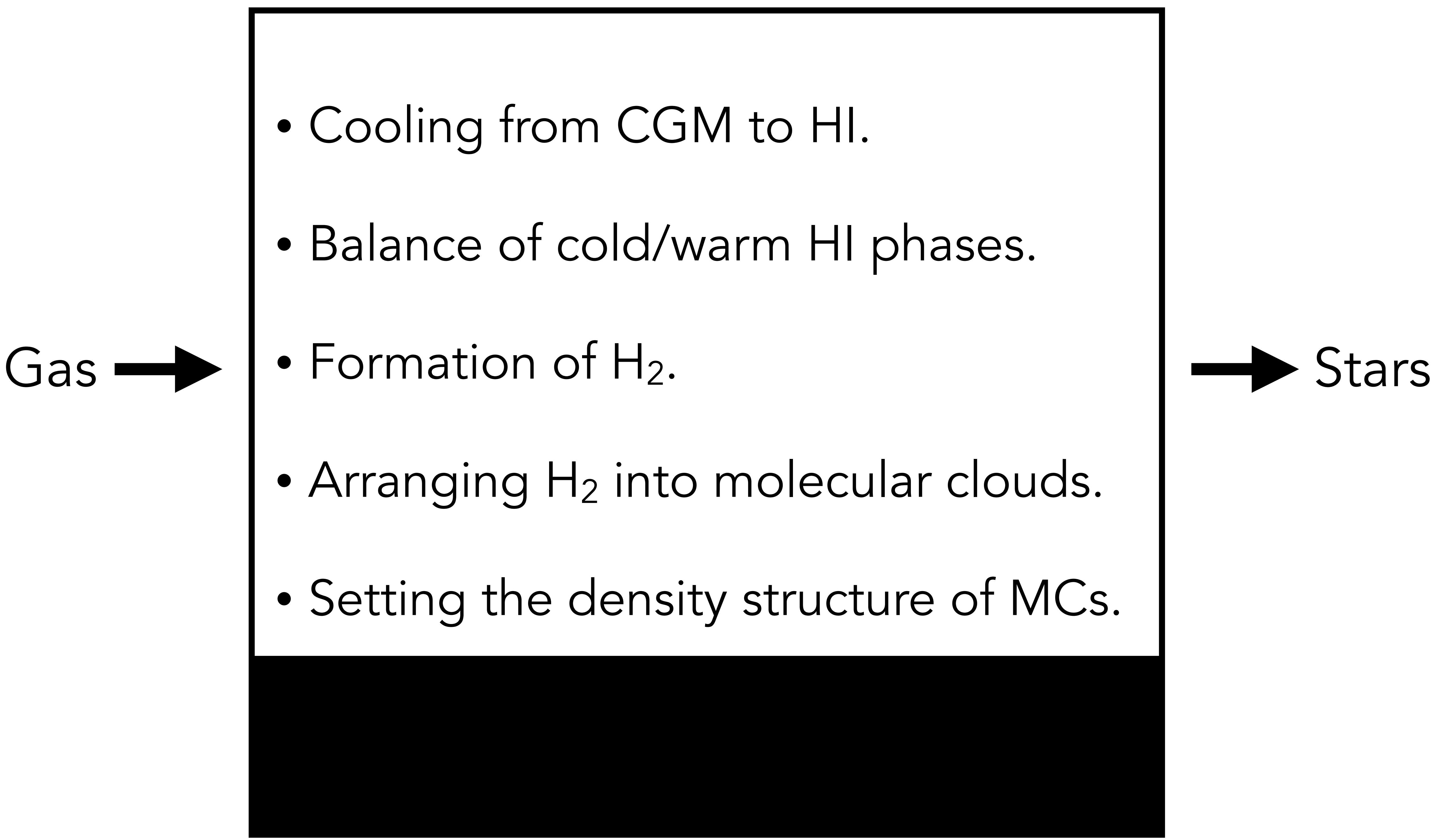

Gas
• Cooling from CGM to HI.
• Balance of cold/warm HI phases.
• Formation of H_2.
• Arranging H_2 into molecular clouds.
Stars



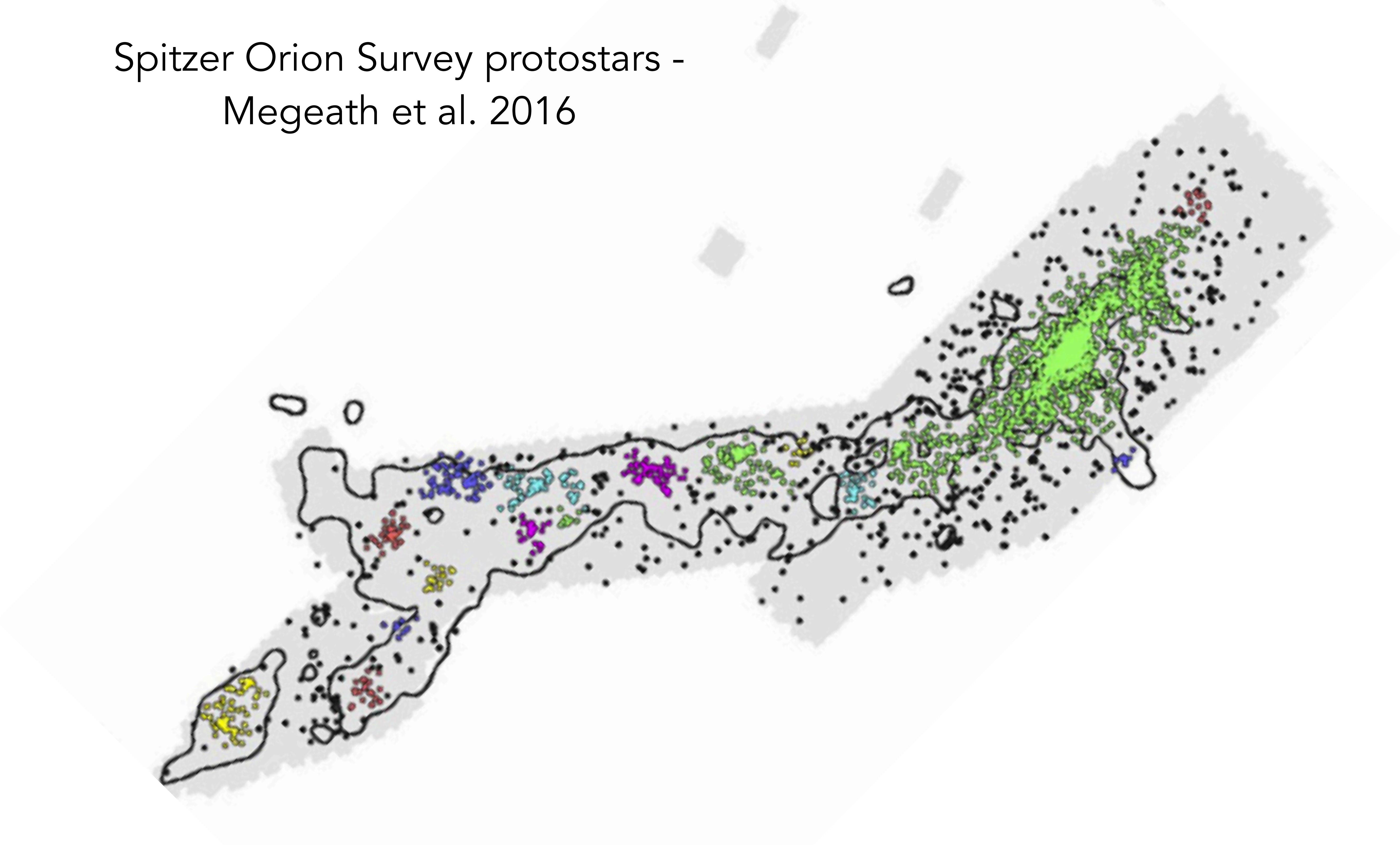
Taurus Molecular Cloud in CO - Goldsmith et al. 2008, Heyer & Dame 2015




Pipe Nebula dense cores -
Alves et al. 2007


Gas
• Cooling from CGM to HI.
• Balance of cold/warm HI phases.
• Formation of H_2.
• Arranging H_2 into molecular clouds.
• Setting the density structure of MCs.
Stars

Spitzer Orion Survey protostars - Megeath et al. 2016



Gas →

- Cooling from CGM to HI.
- Balance of cold/warm HI phases.
- Formation of H_2.
- Arranging H_2 into molecular clouds.
- Setting the density structure of MCs.
- Forming stars in dense molecular gas.

→ Stars

All of these processes depend on local environment too!