The ISM of the First Galaxies

A theoretical perspective

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Sequence of events

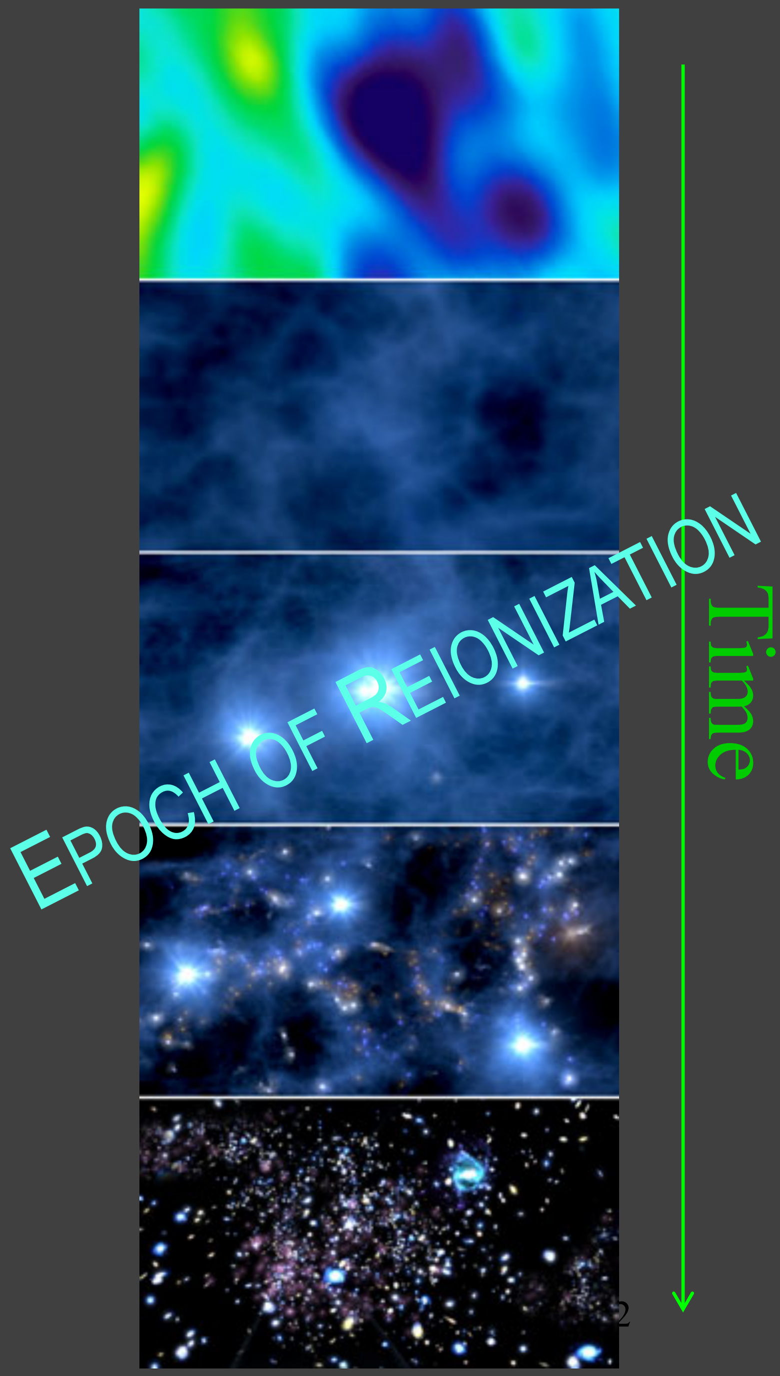
At z=1000 the Universe has cooled down to 3000 K. Hydrogen becomes neutral (“Recombination”).

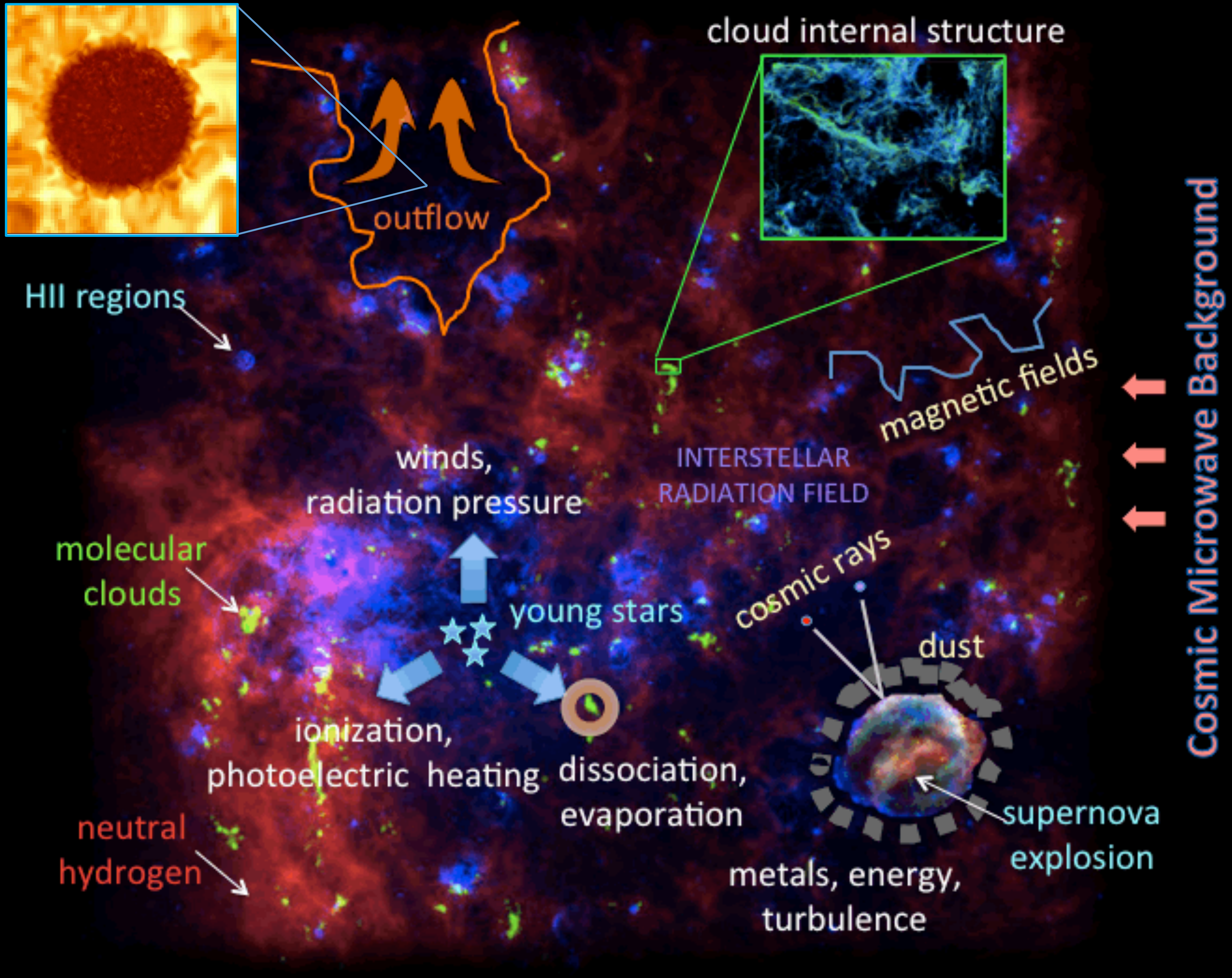
At z < 40 the first “PopIII” star (clusters)/small galaxies form.

At z ~ 6-15 these gradually photo-ionize the hydrogen in the IGM (“Reionization”).

At z<6 galaxies form most of their stars and grow by merging.

At z<1 massive galaxy clusters are assembled.





Decataldo+20

cloud internal structure

outflow

HII regions

magnetic fields

winds,
radiation pressure

INTERSTELLAR
RADIATION FIELD

molecular
clouds

young stars

cosmic rays

dust

ionization,
photoelectric heating

dissociation,
evaporation

neutral
hydrogen

supernova
explosion

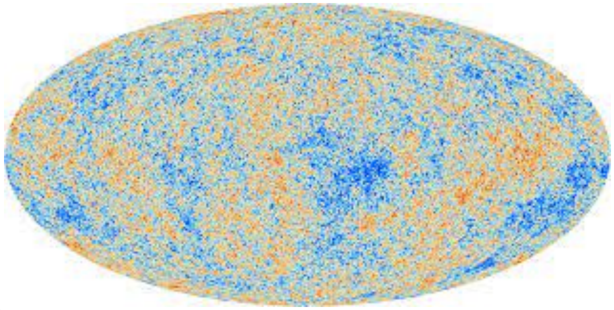
metals, energy,
turbulence

Cosmic Microwave Background

OUTLINE OF THE LECTURE

1. First galaxies in a nutshell
2. Key physical properties and physics
3. *Break point: questions*
4. Implications for their ISM
5. Phenomenology

PERTURBATION GROWTH



Initial fluctuations grow under the action of gravity force.
Define density contrast $\delta = \rho/\langle\rho\rangle \ll 1$. Work in Fourier space.

$$\frac{d^2\delta_k}{dt^2} + 2\,H(t)\frac{d\delta_k}{dt} = (4\pi G\langle\rho(t)\rangle - kc_s^2)\delta_k$$

Jeans length/mass.
Equilibrium between gravity
and pressure force.

$$\lambda_J = \frac{2\pi}{k_J} = c_s\left(\frac{\pi}{G\langle\rho\rangle}\right)^{1/2} \approx c_s\,t_{ff}$$

$$M_J = \frac{4\pi}{3}\,\langle\rho\rangle\left(\frac{\lambda_J}{2}\right)^3$$

Redshift independent during MDE

$$M_J = 1.5{\times}10^5\,(\Omega_b h^2)^{-1/2}\,M_\odot$$

NONLINEAR GROWTH: DM HALOS

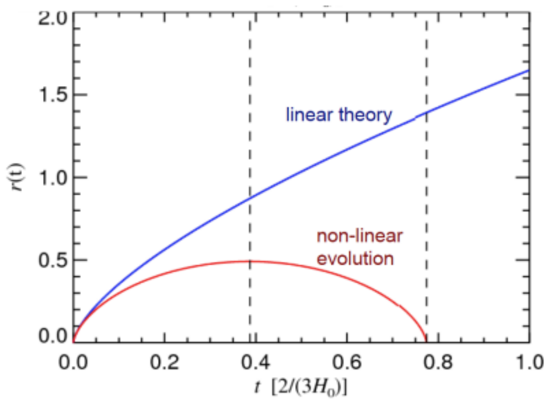
Growth becomes nonlinear.

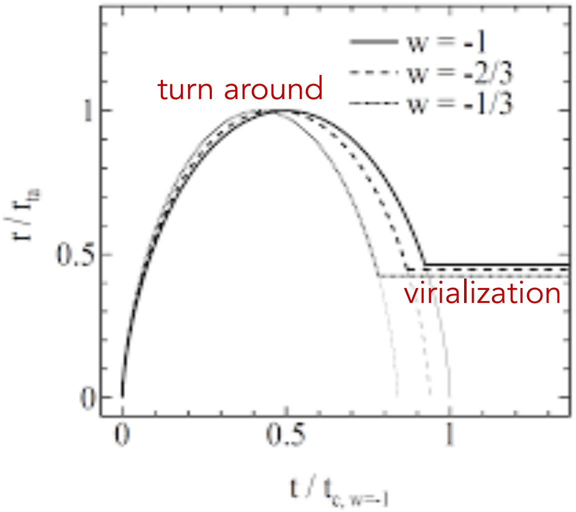
Spherical perturbation
$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 - \frac{GM}{r} = E$$

Solution
$$r \approx \frac{r_i}{2\delta_i}\,(1 - cos\vartheta);\ t \approx \frac{3}{4}\frac{t_i}{\delta_i^{3/2}}\,(\vartheta - sin\vartheta)$$

Collapse
$$\lim_{\vartheta \to 2\pi} \delta = \infty \qquad \delta_L(2\pi) = \delta_c = 1.686$$

Virialization
$$\delta(2\pi) = 18\,\pi^2 = 178$$





Virialized dark matter halos are on average ≃ 200 times denser than the cosmic mean

HALO GLOBAL PROPERTIES

radius

$$R_{vir} = 0.784\left(\frac{M_h}{10^8 h^{-1} M_\odot}\right)^{1/3}\left[\frac{\Omega_m \Delta_c}{\Omega_m^z\, 18\pi^2}\right]\left(\frac{1+z}{10}\right)^{-1} h^{-1}\mathrm{kpc}.$$

velocity

$$V_{vir} = 23.4\left(\frac{M_h}{10^8 h^{-1} M_\odot}\right)^{1/3}\left[\frac{\Omega_m \Delta_c}{\Omega_m^z\, 18\pi^2}\right]^{1/6}\left(\frac{1+z}{10}\right)^{1/2} \mathrm{km\,s^{-1}}.$$

temperature

$$T_{vir} = 1.98\times 10^4\left(\frac{\mu}{0.6}\right)\left(\frac{M_h}{10^8 h^{-1} M_\odot}\right)^{2/3}\left[\frac{\Omega_m \Delta_c}{\Omega_m^z\, 18\pi^2}\right]^{1/3}\left(\frac{1+z}{10}\right) \mathrm{K}$$

where we define:

$$\Delta_c = 18\pi^2 + 82(\Omega_m^z - 1) - 39(\Omega_m^z - 1)^2$$

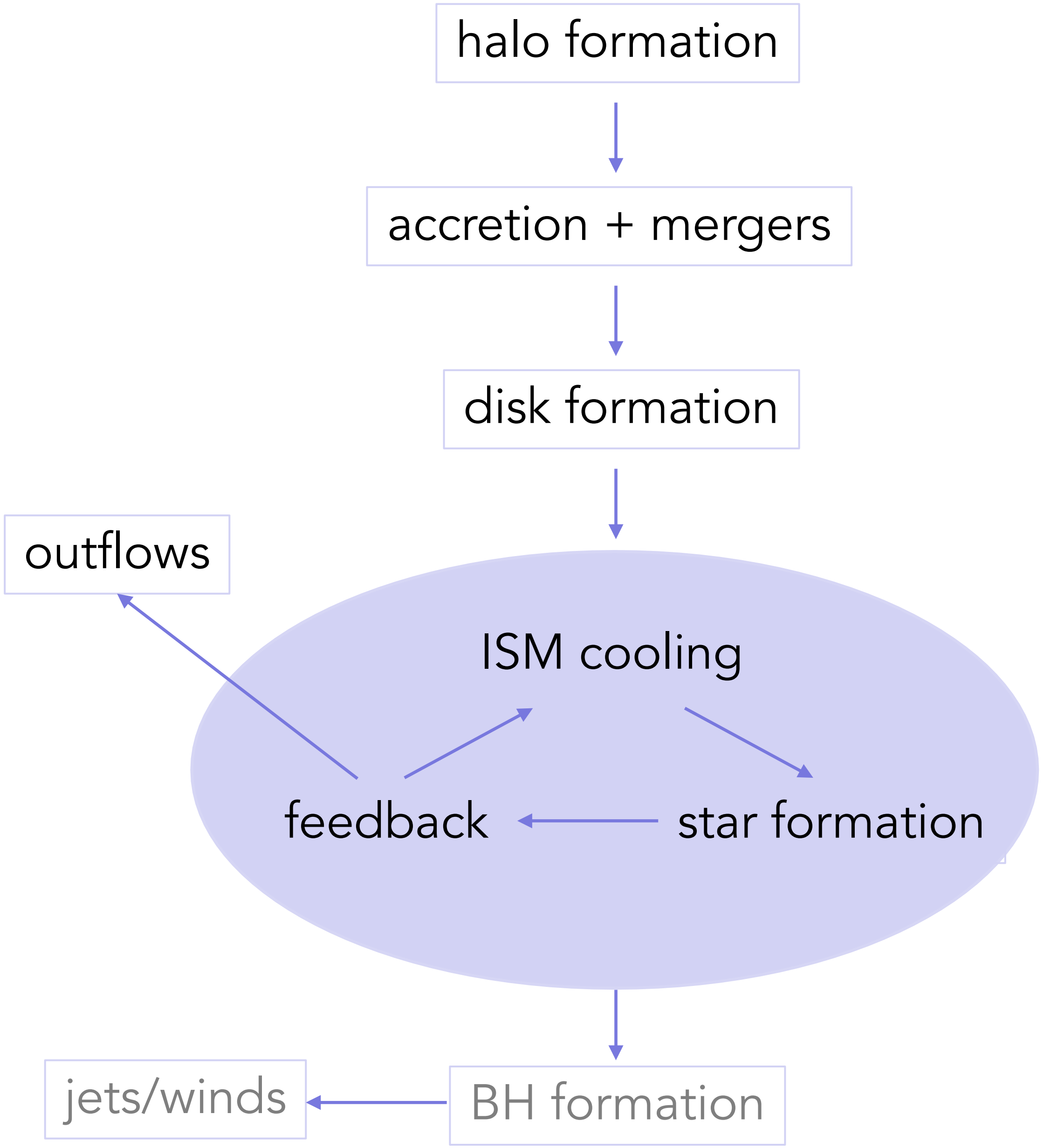
$$\Omega_m^z = \frac{\Omega_m(1+z)^3}{\Omega_m(1+z)^3 + \Omega_\Lambda},$$

At fixed halo mass, high redshift halos

- Are smaller
- Have larger circular velocities
- Have larger virial temperatures

For a Milky Way-like halo @z=7: R_{vir} = 21 kpc; V_{vir} = 450 km s^{-1} ; T_{vir} = 7×10^6 K

BARYONS



halo formation

accretion + mergers

disk formation

outflows

ISM cooling

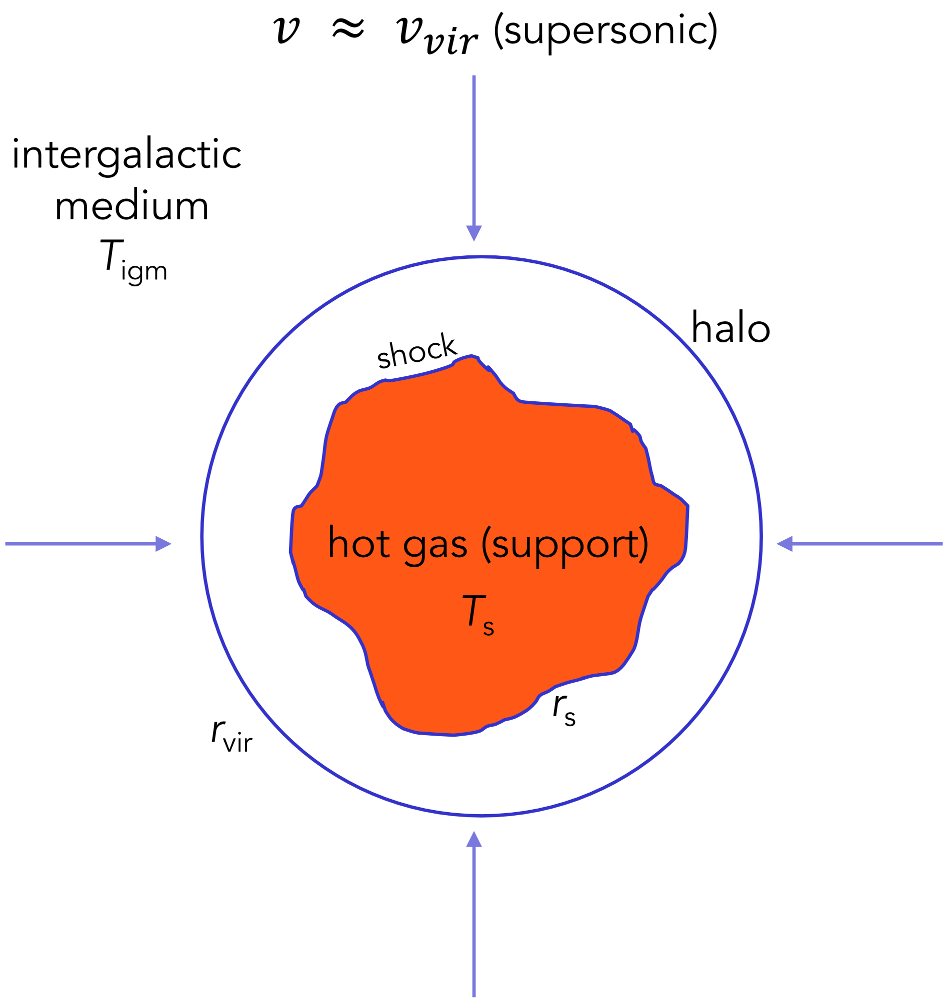
feedback

star formation

jets/winds

BH formation

ACCRETION



$v \approx v_{vir}$ (supersonic)

intergalactic
medium
T_{igm}

halo

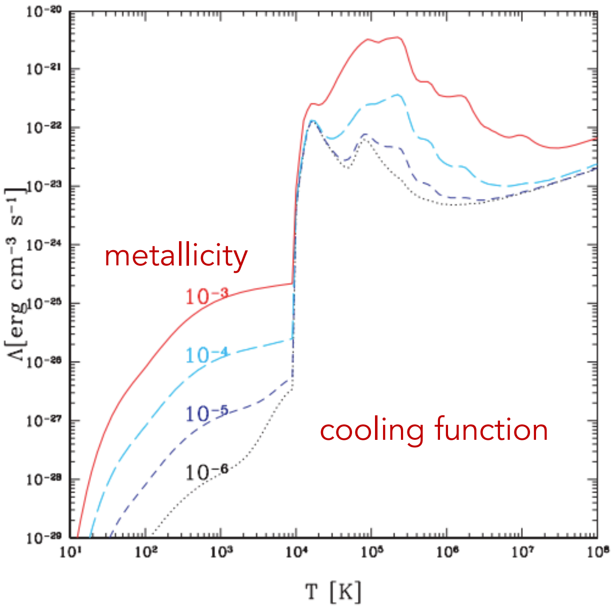
shock

hot gas (support)

T_s

r_s

r_{vir}



Cooling time $$t_{cool} = \frac{3}{2}\frac{k\,T}{n\,\Lambda(T,Z)}$$

Shock stable $$\frac{\rho\, r_s\, \Lambda(T_s,Z)}{v^3} < 0.0126$$

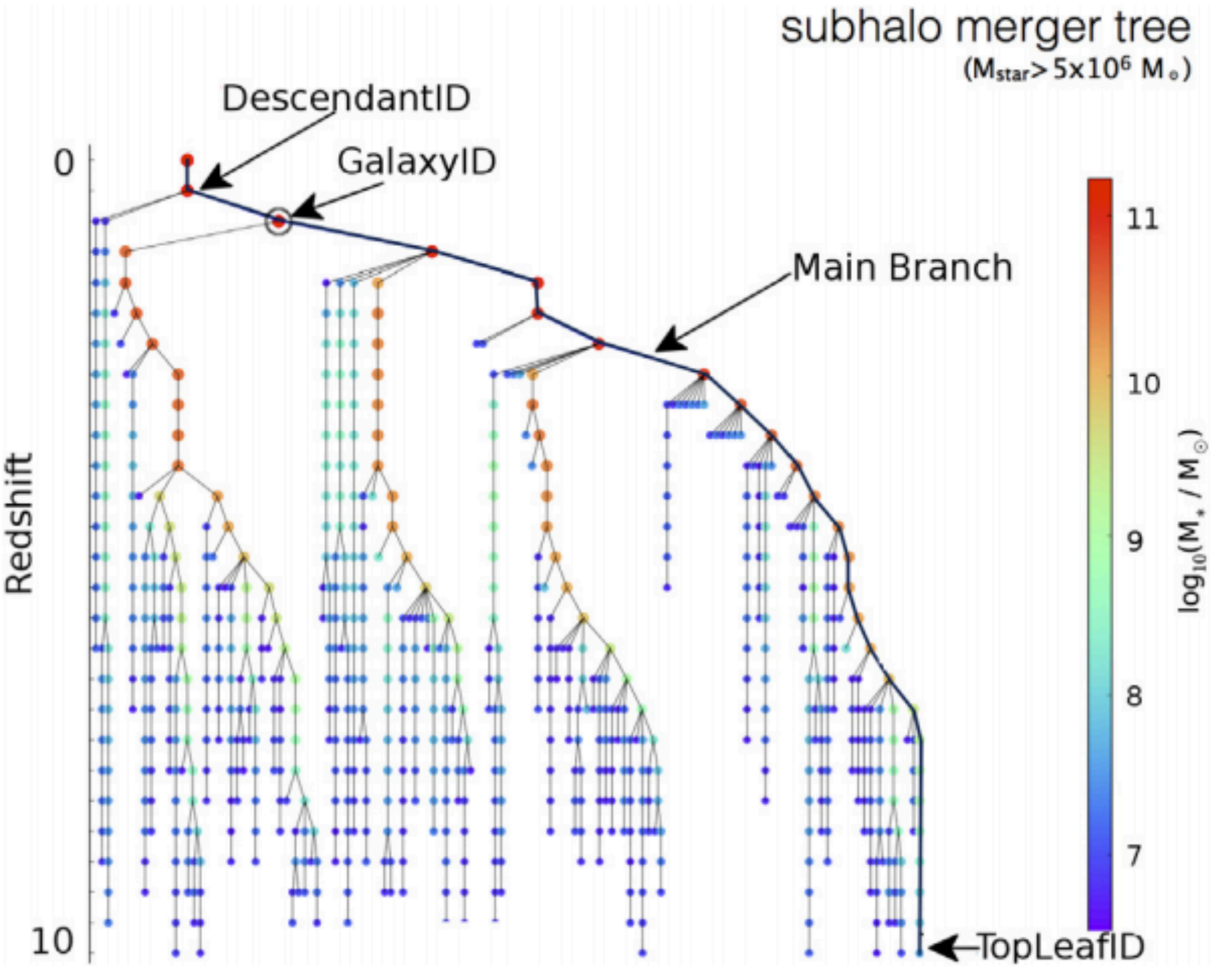
Birnboim & Dekel 2003

Weak redshift dependence: $\propto (1+z)^{1/2}$

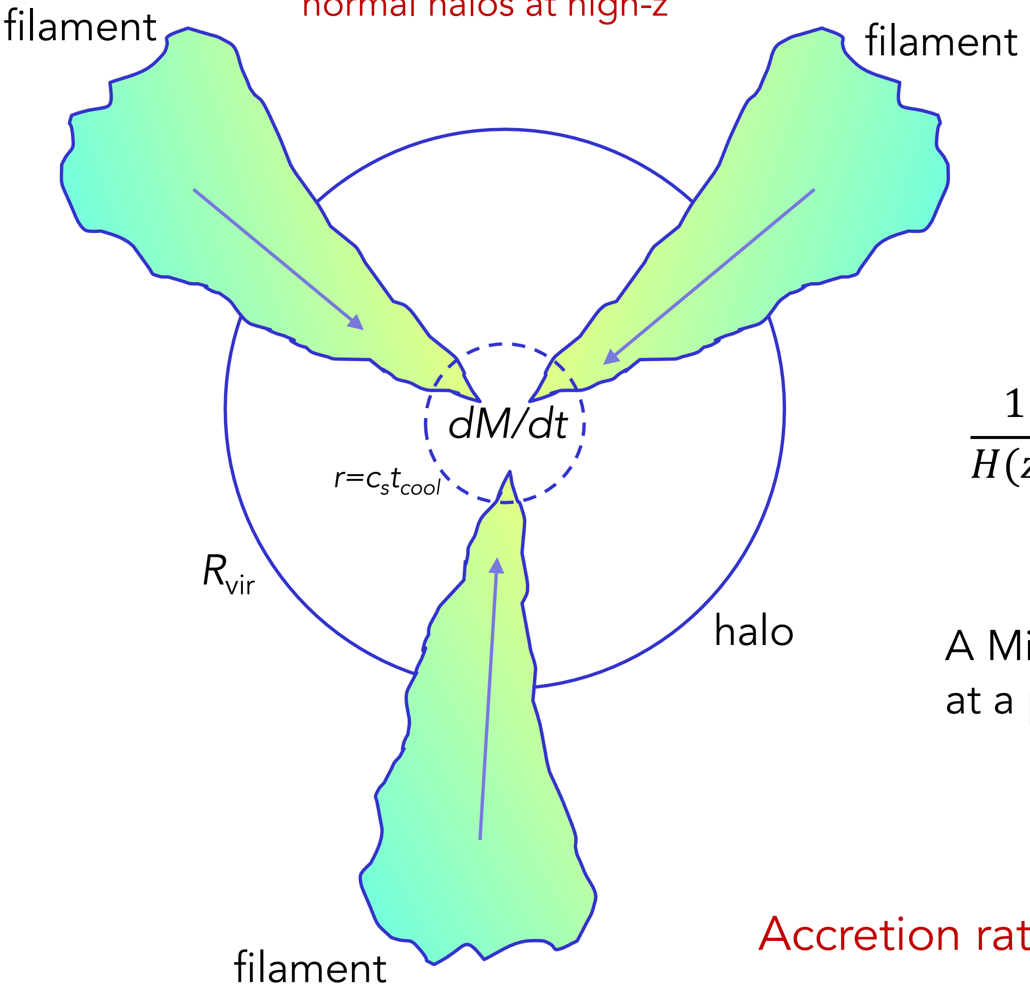
Halos with M < 10^{12} $M_\odot$: “cold accretion”, limited only by cosmological infall rate

HALO MERGERS

McAlpine+16



COLD ACCRETION



Dominant accretion mode for normal halos at high-z

Neistein+16

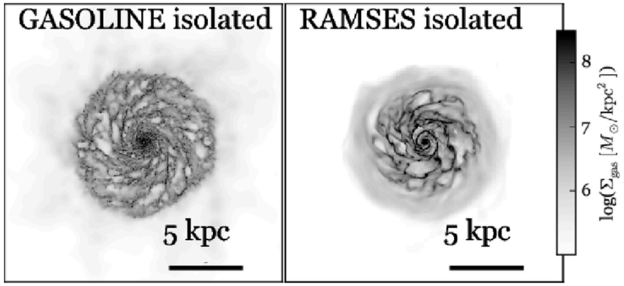
Cosmological accretion rate

$$\frac{1}{H(z)}\frac{1}{M}\frac{dM}{dt}\approx 10.6\left(\frac{M}{10^{12}\,M_\odot}\right)^{0.15}\left(\frac{1+z}{10}\right)^{0.75}$$

A Milky Way-like halo @z=7 accretes gas at a prodigious rate of $\simeq 1200\ M_\odot\ \mathrm{yr}^{1}$

Accretion rates are much more vigorous at high-z

DISK FORMATION



Halo spin parameter $\lambda \overset{\text{def}}{=} J\,|E|^{1/2}\,G^{-1}M^{-5/2}$

Assume:

- Halo rotation velocity $V_c \sim J/(M\,r_{vir})$
- Kinetic energy $|E| \sim M\,v_{vir}^2$
- Virial (breakout) velocity $v_{vir}^2 \sim G\,M/r_{vir}$

Find: $\lambda \sim V_c\,/V_{vir}$ (physical interpretation)

Disk scalelength (exp. disk) : $r_d = \frac{1}{\sqrt{2}}\left(\frac{j_d}{m_d}\right)\lambda\,r_{vir} \propto (1+z)^{-1}$

Spin parameter lognormal distributed with $\langle\lambda\rangle = 0.05$, $\sigma_\lambda = 0.5$

Galaxy disks are smaller at high redshift.

DISK STABILITY

Toomre 64

Linearized thin disk fluid equations

$$\begin{aligned} \frac{\partial \Sigma_1}{\partial t} &= -\Sigma_0 \nabla \cdot \vec{v}_1, && \text{mass} \\ \frac{\partial \vec{v}_1}{\partial t} &= -\frac{c_s^2}{\Sigma_0}\nabla\Sigma_1 - \nabla\Phi_1 - 2\vec{\Omega}\times\vec{v}_1 && \text{momentum} \\ \nabla^2\Phi_1 &= 4\pi G\Sigma_1\delta(z). && \text{Poisson} \end{aligned}$$

Look for plane wave solutions of frequency ω and wavenumber $\boldsymbol{k}$; define $\Omega = v/r$

Dispersion relation

① ② ③

$$\omega^2 = c_s^2 k^2 + 4\Omega^2 - 2\pi G\Sigma_0|k| > 0$$

(for stability)

thermal rotation gravity

Define

$$k_J = \frac{2\pi G\Sigma_0}{c_s^2}$$

③ ①

$$k_{\rm rot} = \frac{2\Omega^2}{\pi G\Sigma_0}$$

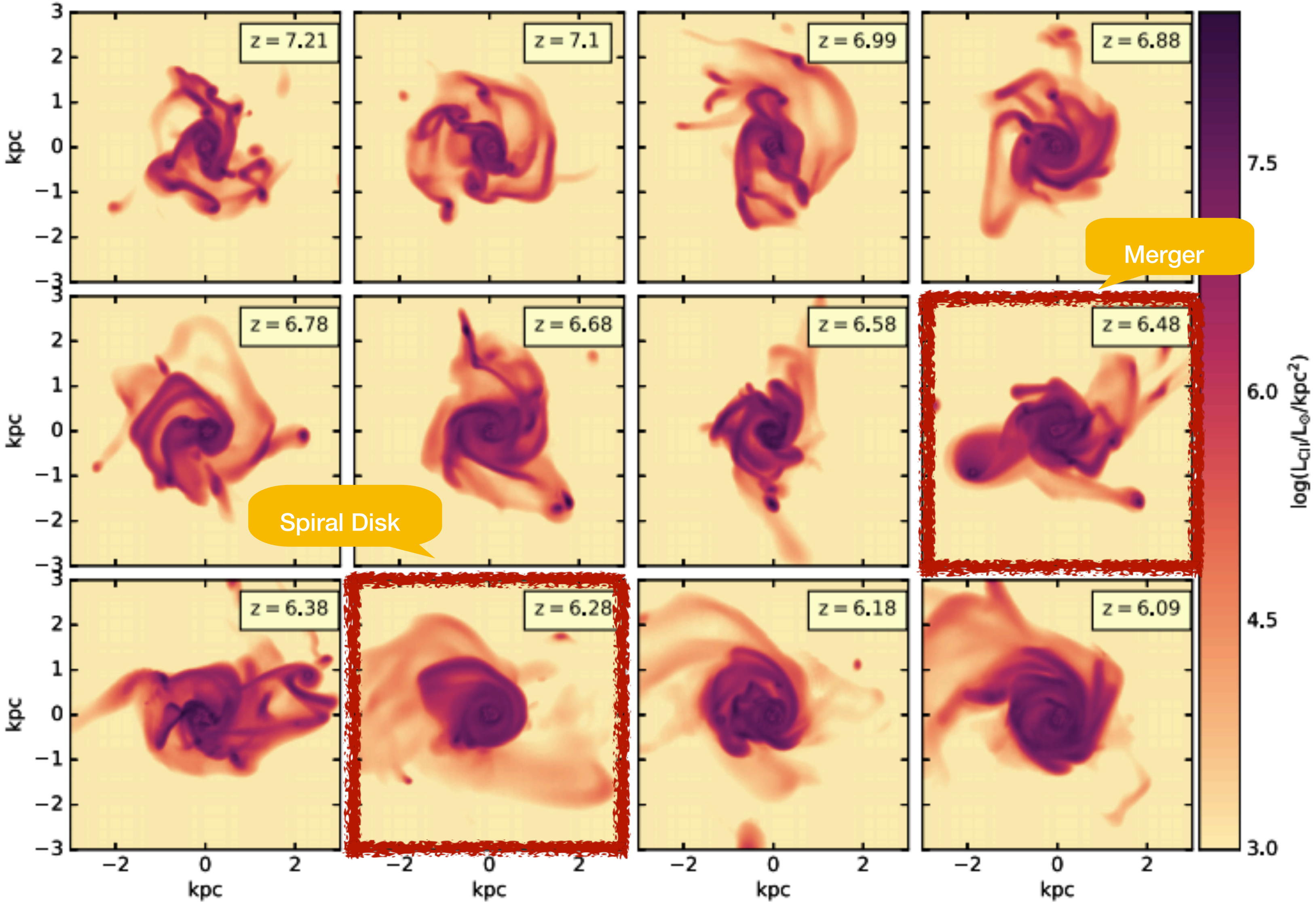
② ③

If $k_{\rm rot} > k_J$ disk is stable. Using above definitions, this is equivalent to impose

Toomre parameter $$Q \equiv \frac{\Omega c_s}{\pi G\Sigma_0} < 1$$ (disk fragments into clumps)

DISK SURVIVAL AGAINST MERGERS

Kohandel+19



Merger

Spiral Disk

GAS VELOCITY DISPERSION

Generalized
Toomre parameter

$$Q = \frac{\kappa\sigma}{\pi G\Sigma}$$

where

$$\kappa^2 = \frac{2\Omega}{r}\frac{d(\Omega r^2)}{dr}$$

$$\sigma^2 = c_s^2 + v_{nth}^2$$

Steady state disk.
Fed by accretion

$$\sigma = \frac{1}{\sqrt{2}}\left(\frac{G\dot{M}_g}{f_g}\right)^{1/3}$$

Krumholz & Burkert 10

For cosmological
accretion

$$\sigma = 120\left(\frac{M}{10^{12}\,M_\odot}\right)^{0.38}\left(\frac{1+z}{8}\right)^{3/4} f_g^{-1/3} \quad \mathrm{km\ s^{-1}}$$

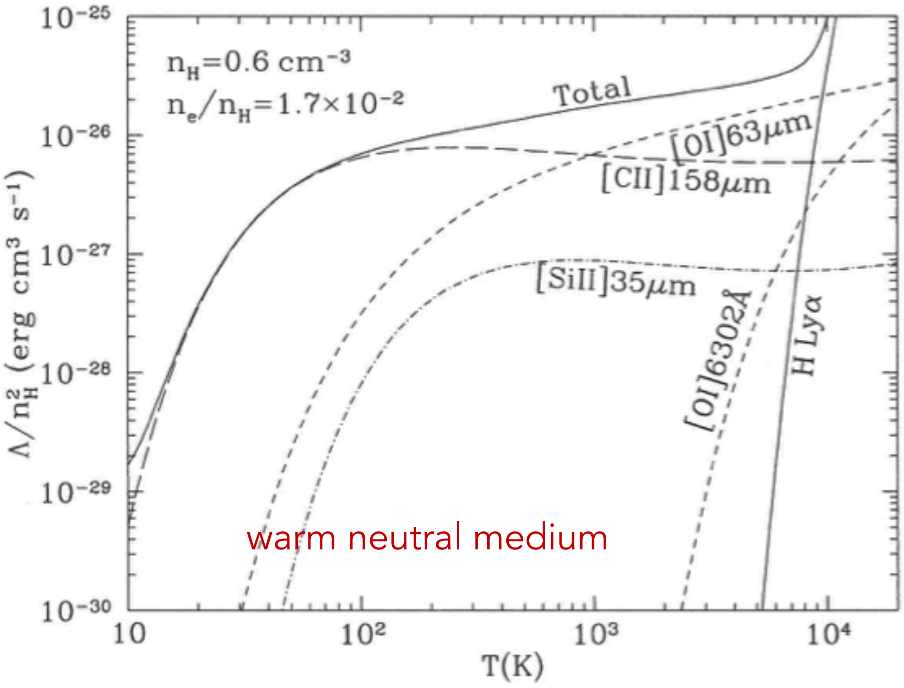
The gas velocity dispersion of a Milky Way-like galaxy @z=7 is >10× higher

ISM COOLING

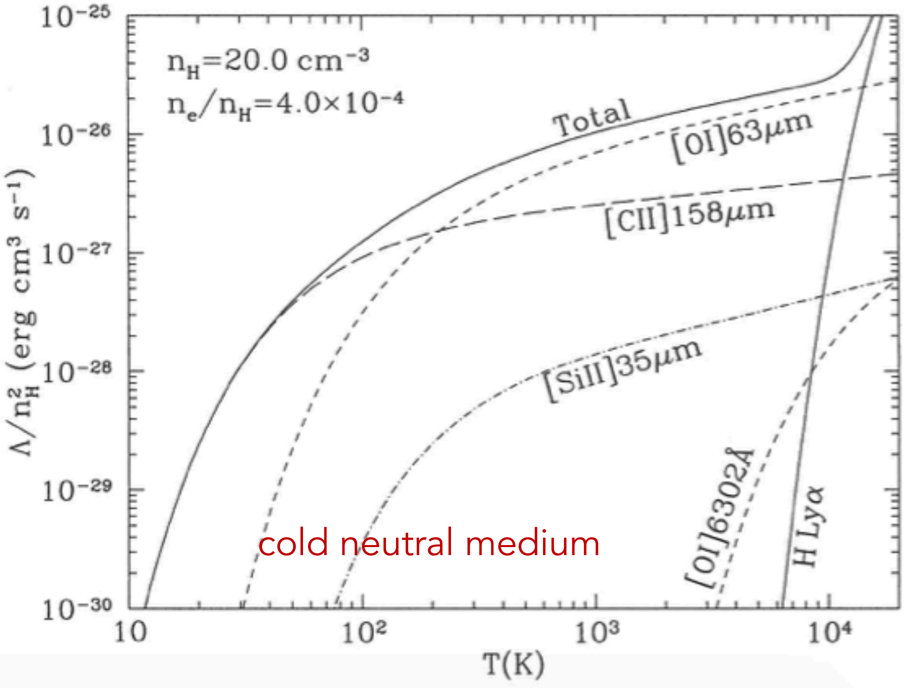
Cooling rates for neutral HI gas for two fractional ionizations and solar metallicity.

$$\left(\frac{dE}{dt}\right)_{rad} = n_H^2 \Lambda(T,Z)$$

The cooling is dominated by two fine structure lines: [CII]158μm and [OI]63μm



warm neutral medium

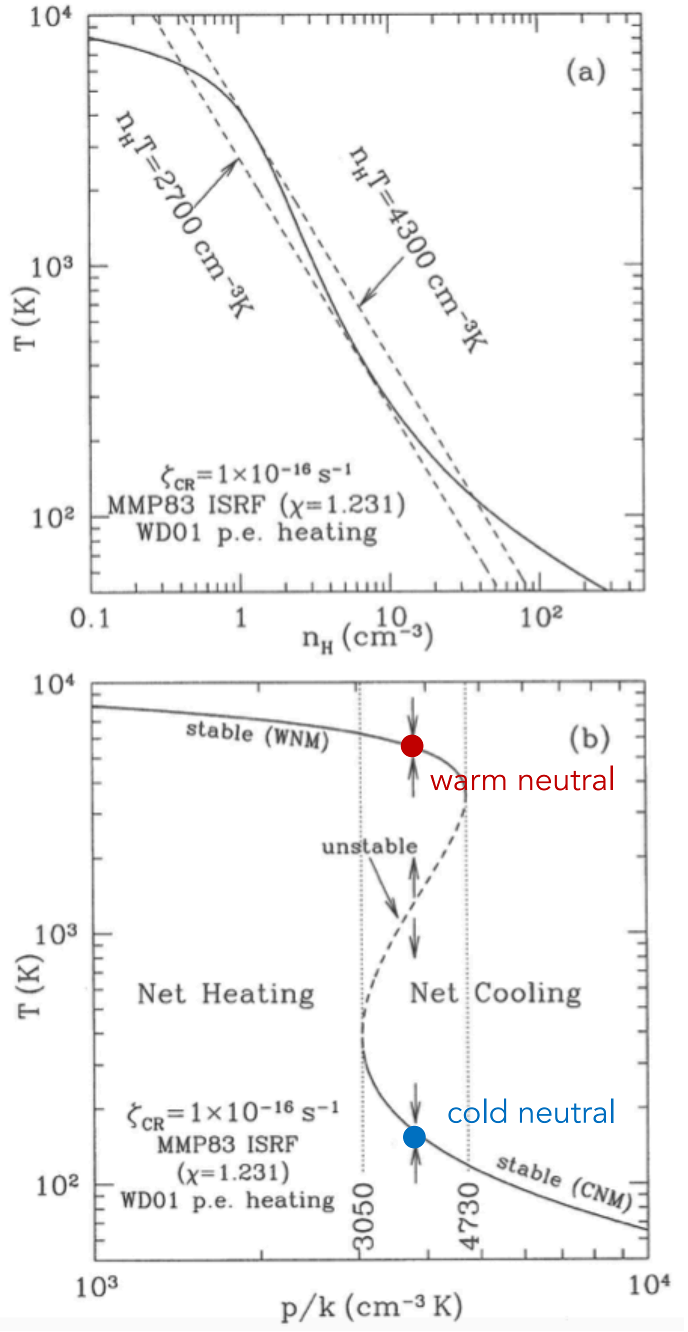


cold neutral medium

MULTIPHASE ISM

Field 65

Steady state temperature/density for gas heated by cosmic rays and photoelectric heating by dust grains

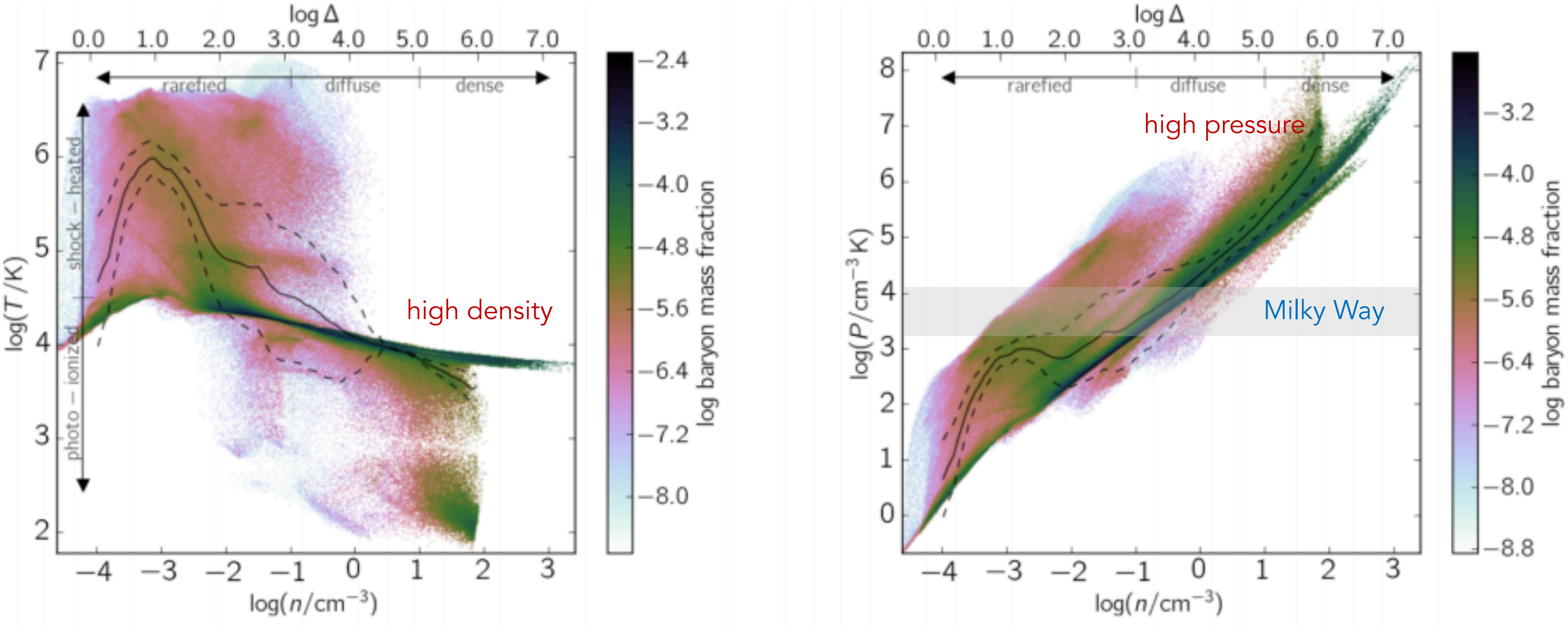


Multiphase structure of the ISM derived
From heating-cooling equilibrium curves

ISM PHASE DIAGRAMS

Pallottini+17

Simulated z=6 Lyman Break Galaxy

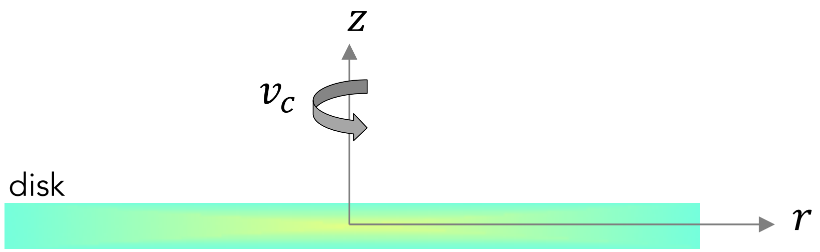


high density

high pressure

Milky Way

DISK VERTICAL EQUILIBRIUM



Hydrostatic equilibrium

$$\frac{\partial p}{\partial z} = \sigma^2 \frac{\partial \rho}{\partial z} = -\rho \frac{GM}{r^3} z$$

Dimensionally

$$\sigma^2 \approx \frac{GM}{r^3} H^2 = \frac{H^2}{r^2} v_c^2$$

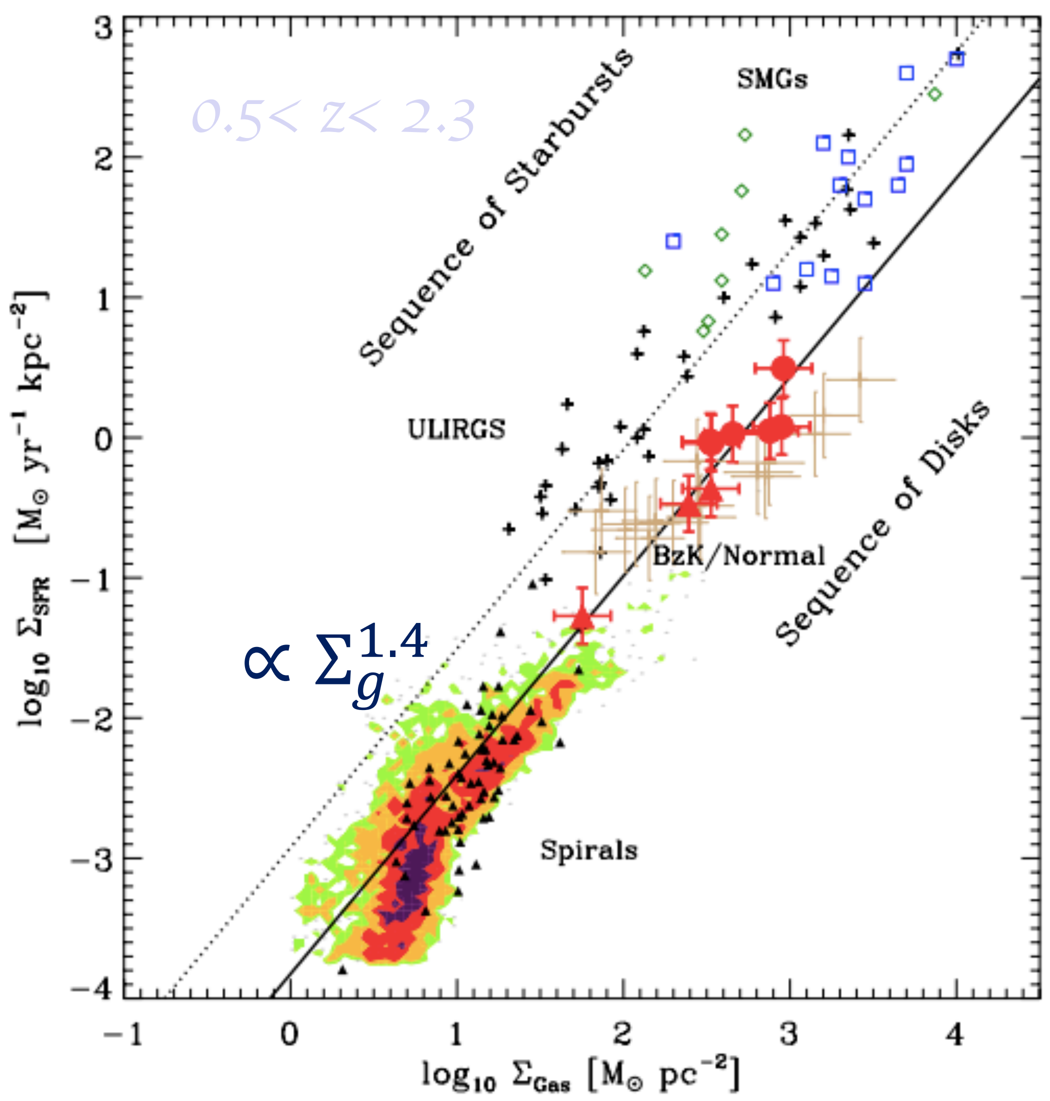
$$\sigma \approx \frac{v_c}{r} H = \Omega H$$

$$H \approx \frac{\sigma}{\Omega}$$

STAR FORMATION

Daddi+10

Kennicutt-Schmidt law



STAR FORMATION

Observations: molecular gas forms stars at a rate of $\varepsilon_{\rm ff}$ ~1% of its mass per free-fall time.

Surface star formation $$\dot{\Sigma}_* = \varepsilon_{ff}\, \Sigma_g \sqrt{G\rho}$$

Disk gas density $$\rho = \frac{\Sigma_g}{H} = \frac{\Sigma_g \Omega}{\sigma} \propto (1+z)^{11/4}$$ [at fixed halo mass]

Kennicutt-Schmidt law

theory $$\dot{\Sigma}_* = \varepsilon_{ff} \sqrt{G\Omega/\sigma}\, \Sigma_g^{3/2} \propto (1+z)^{3/8}\, \Sigma_g^{3/2}$$

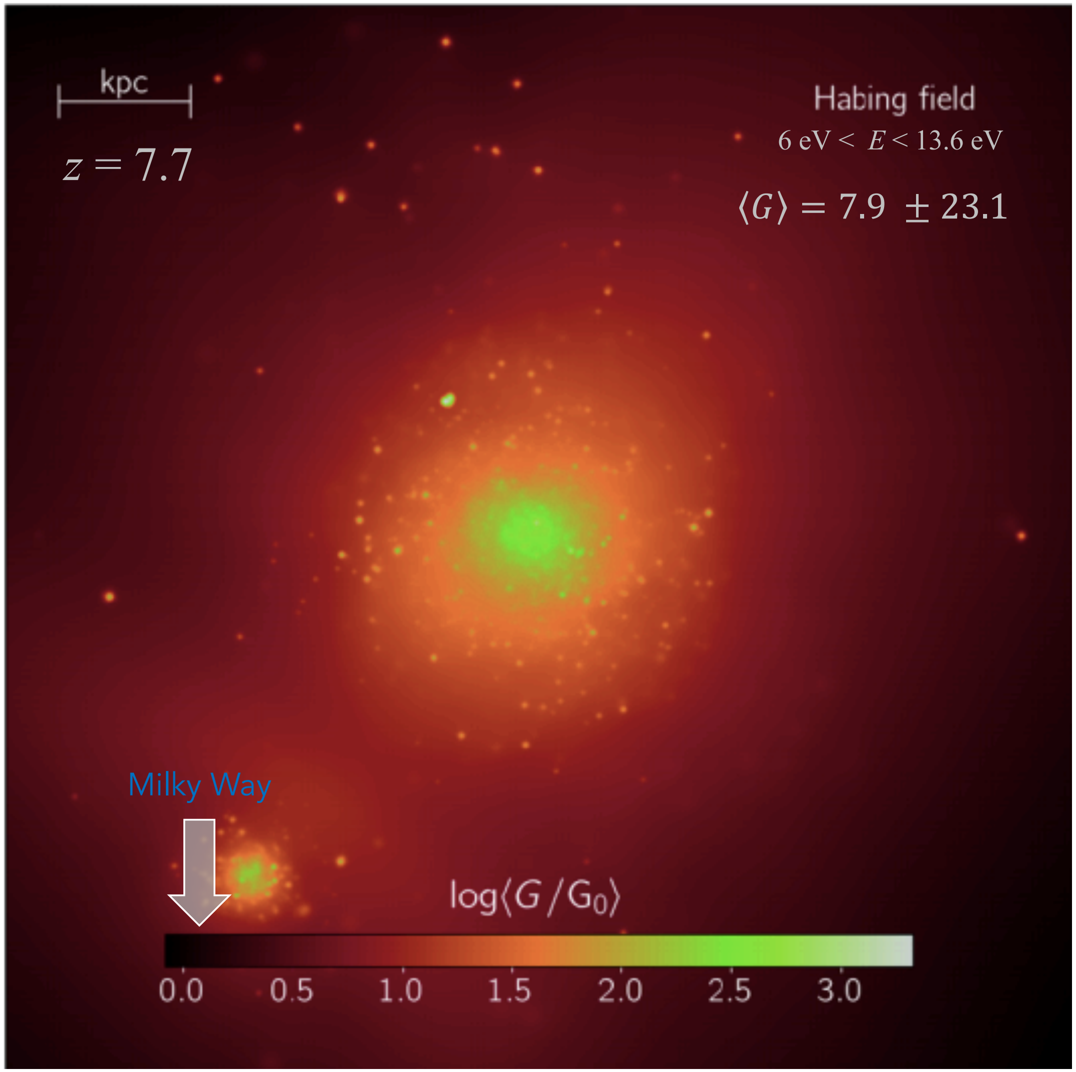
data $$\dot{\Sigma}_* = 10^{-12}\, k_s\, \Sigma_g^{1.4}$$

[excellent agreement]

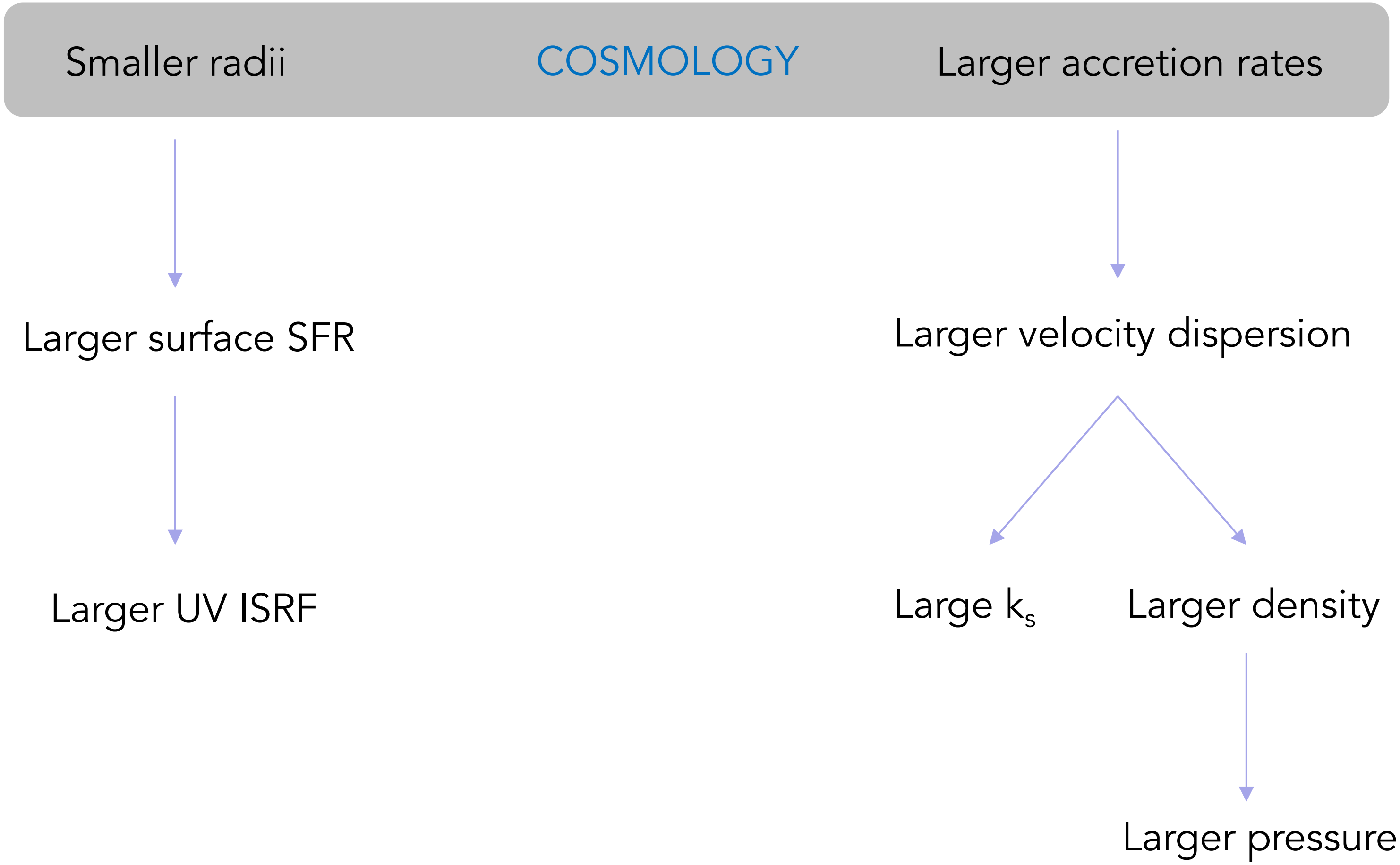
High-z galaxies are denser and are likely to be more bursty (larger k_s value)

INTERSTELLAR RADIATION FIELD

Pallottini+19



QUICK RECAP



COSMOLOGY

Smaller radii

Larger surface SFR

Larger UV ISRF

Larger accretion rates

Larger velocity dispersion

Large k_s

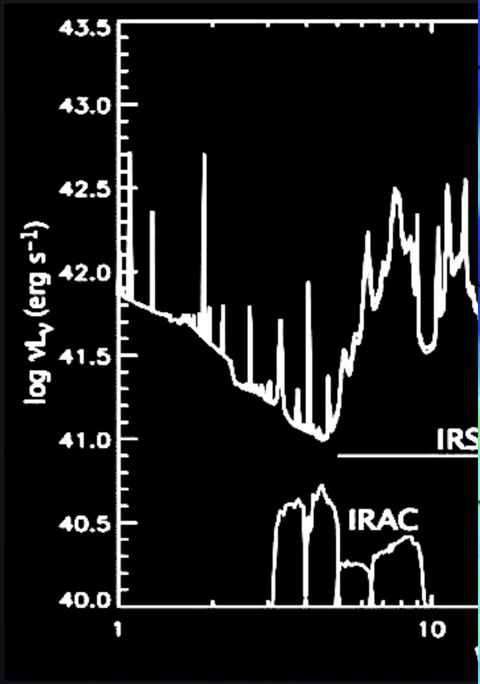
Larger density

Larger pressure

BREAK POINT

Questions

THE POWER OF FIR LINES



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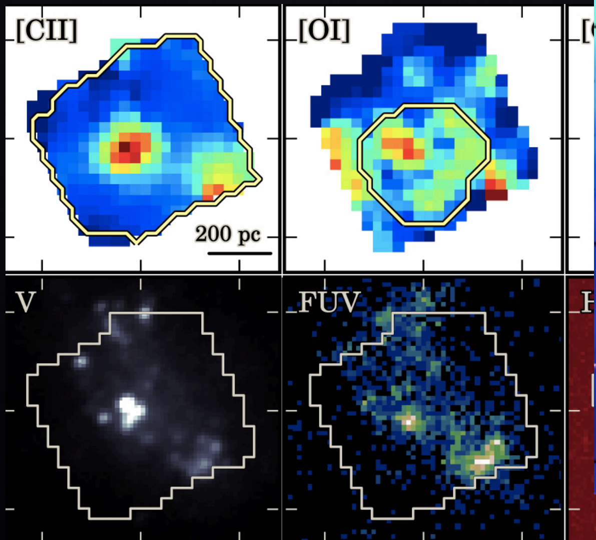
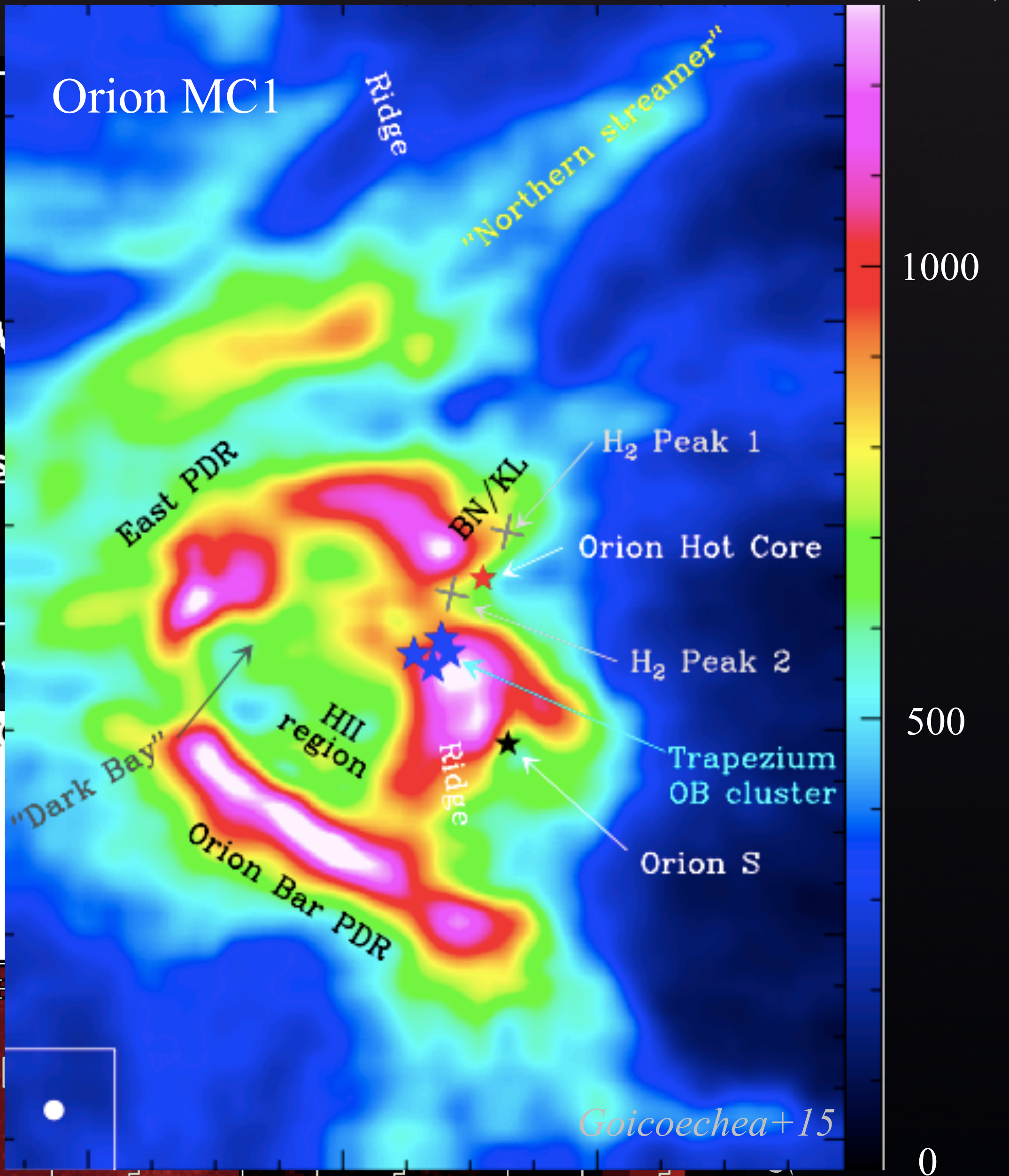


[CII] 158 µm



Goicoechea+15

[CII] – SFR RELATION: SIMPLE DERIVATION

Assume photoelectric heating balanced by [CII] line emission.

$$\Gamma_{pe} = 10^{-24}\, \epsilon_{pe}\, \tilde{G}\, n_H$$

Bakes & Tielens 94

$$\tilde{G} = G/G_0 \approx SFR/M_\odot yr^{-1} \qquad \epsilon_{pe} \approx 0.05$$

$$L_{CII} \approx \Gamma_{pe} V = 10^{-24} \epsilon_{pe}\, \tilde{G}\, \frac{\Sigma_g}{\mu m_p H}\, \pi r_d^2 H = 10^{-24} \epsilon_{pe}\, \tilde{G}\, \frac{M_g}{\mu m_p}$$

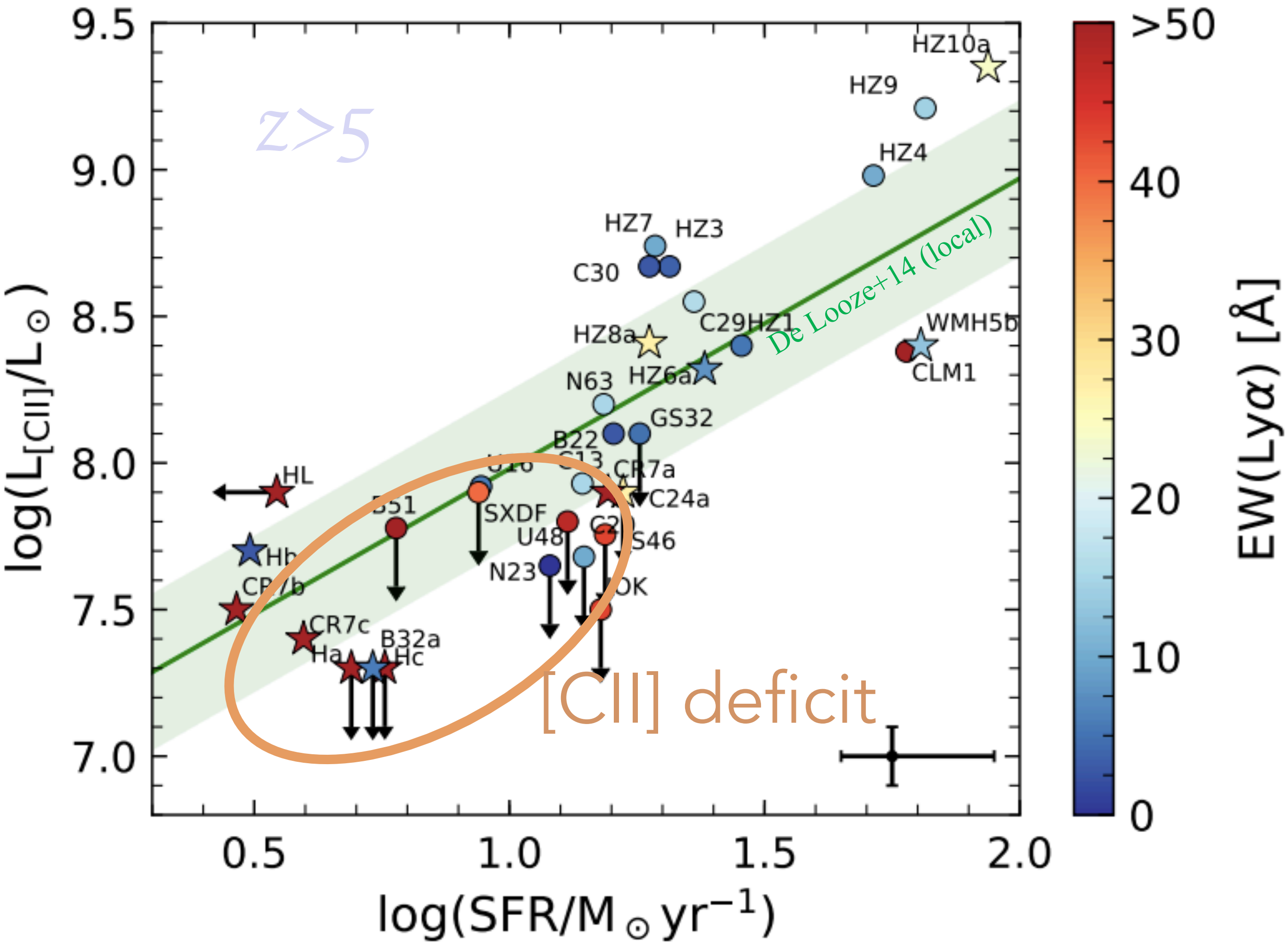
$$L_{CII} \approx 2.4\times 10^9 \left(\frac{\Omega_b/\Omega_m}{0.15}\right) f_d M_{12}\, SFR \;\; L_\odot$$

A linear relation between [CII] luminosity and SFR is expected.

[CII] – SFR RELATION: DATA

Carniani+18

$L_{CII} \approx 10^7 SFR \;\; L_\odot$ [locally] De Looze+14



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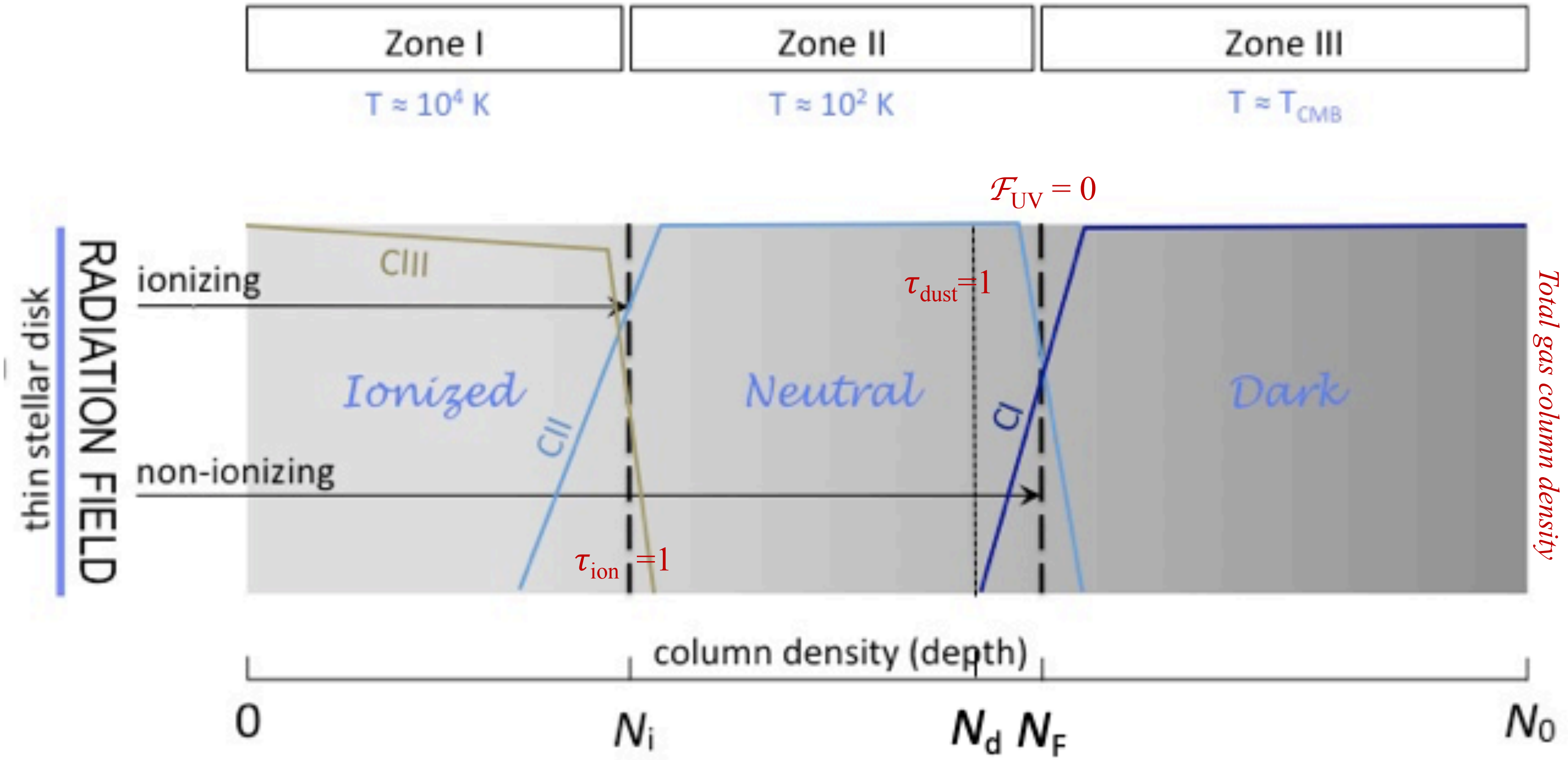
[CII] – SFR RELATION: PHYSICAL MODEL

Ferrara+19



Classical, dust free Strömgren length

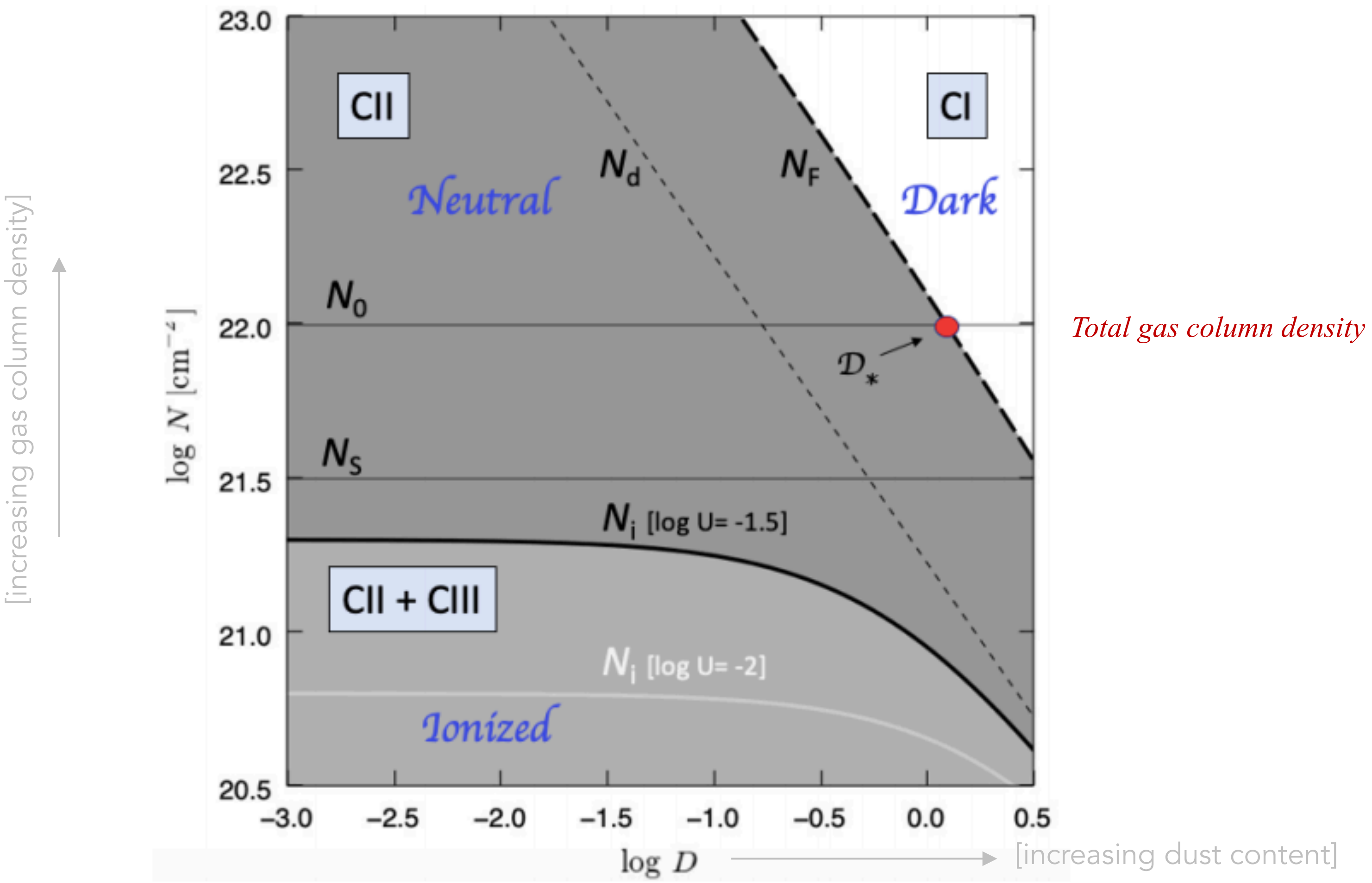
$$N_i = y_i N_S = N_d \ln\left(\frac{1+\tau_{sd}}{1+\tau_{sd}/e}\right)$$

$$N_d = 1/\bar{\sigma}_d = 1.7 \times 10^{21} \mathcal{D}^{-1}\ \mathrm{cm}^{-2}$$

$$\tau_{sd} = N_S/N_d$$

[CII] – SFR RELATION: PHYSICAL MODEL

Ferrara+19

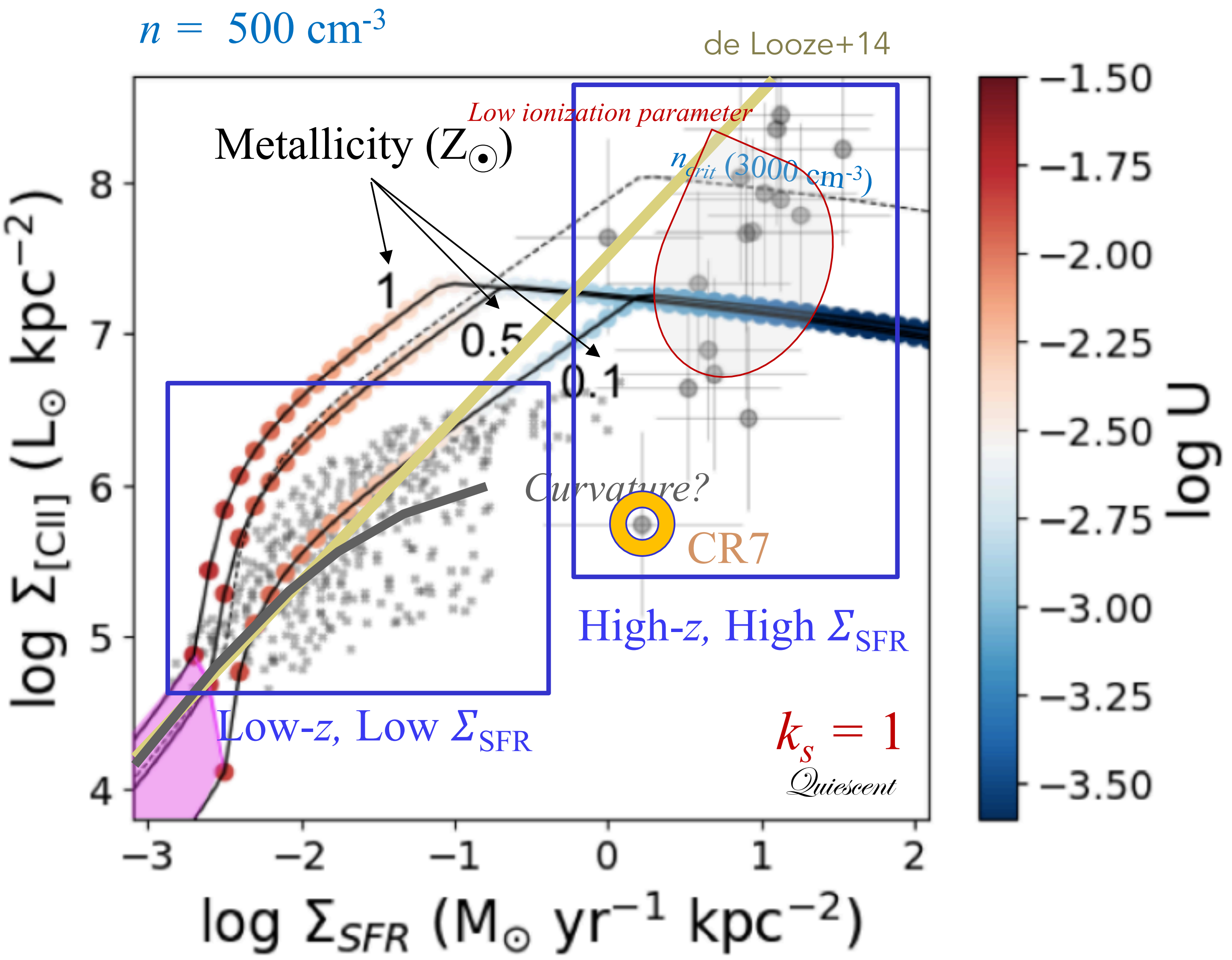


Total gas column density

$$F_{[\mathrm{CII}]} = n\mathcal{A}_C\mathcal{D}\left\{\underbrace{\Lambda^{(4)}_{[\mathrm{CII}]}N_{\mathrm{HI}}(y_i)}_{\text{IONIZED}} + \underbrace{\Lambda^{(2)}_{[\mathrm{CII}]}\left[\min(N_F, N_0) - N_i\right]}_{\text{NEUTRAL}}\right\}$$

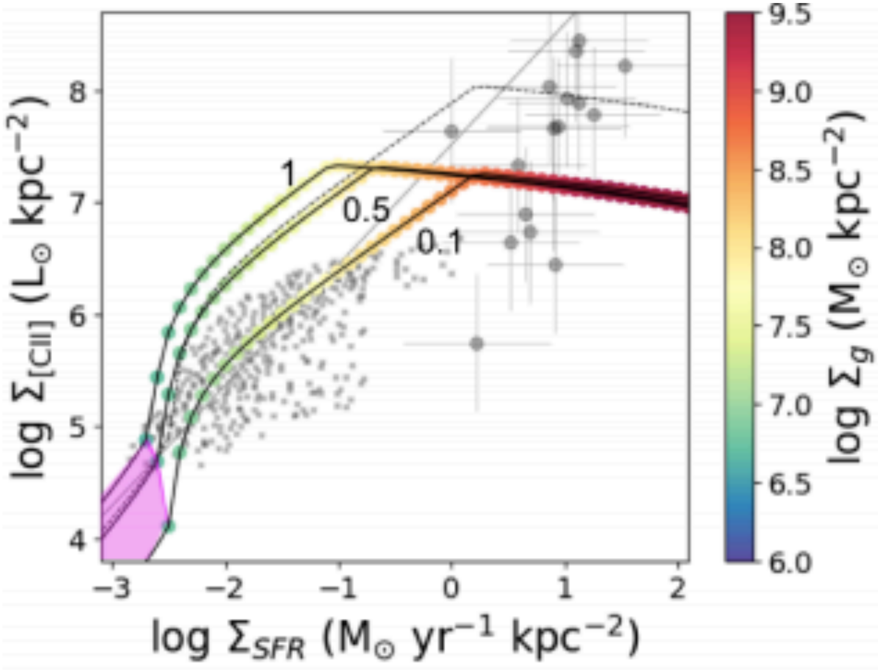
[CII] DEFICIT EXPLAINED

Ferrara+19



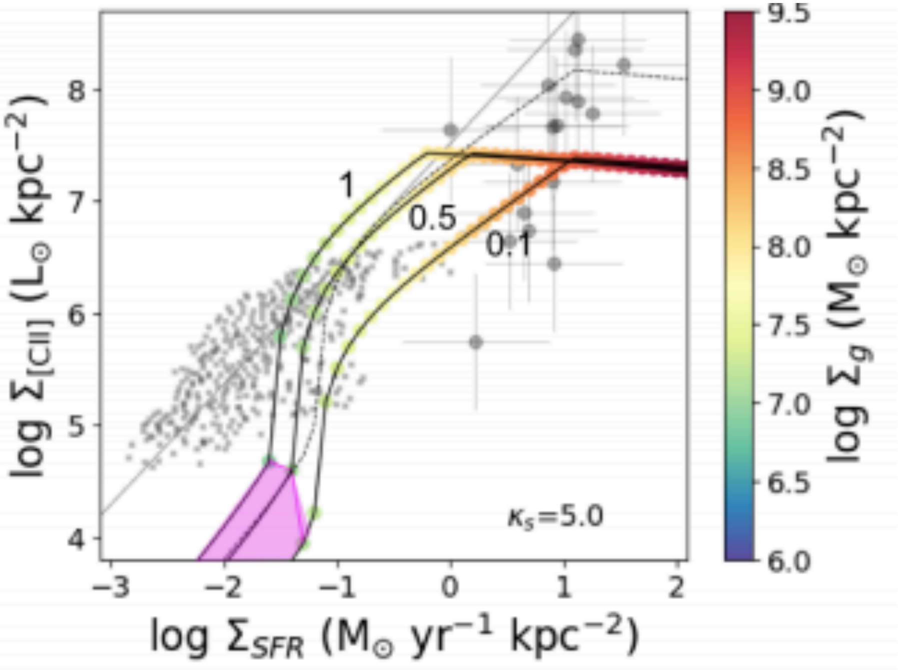
STARBURSTS ARE [CII] FAINT

Ferrara+19



$k_s = 1$

Quiescent

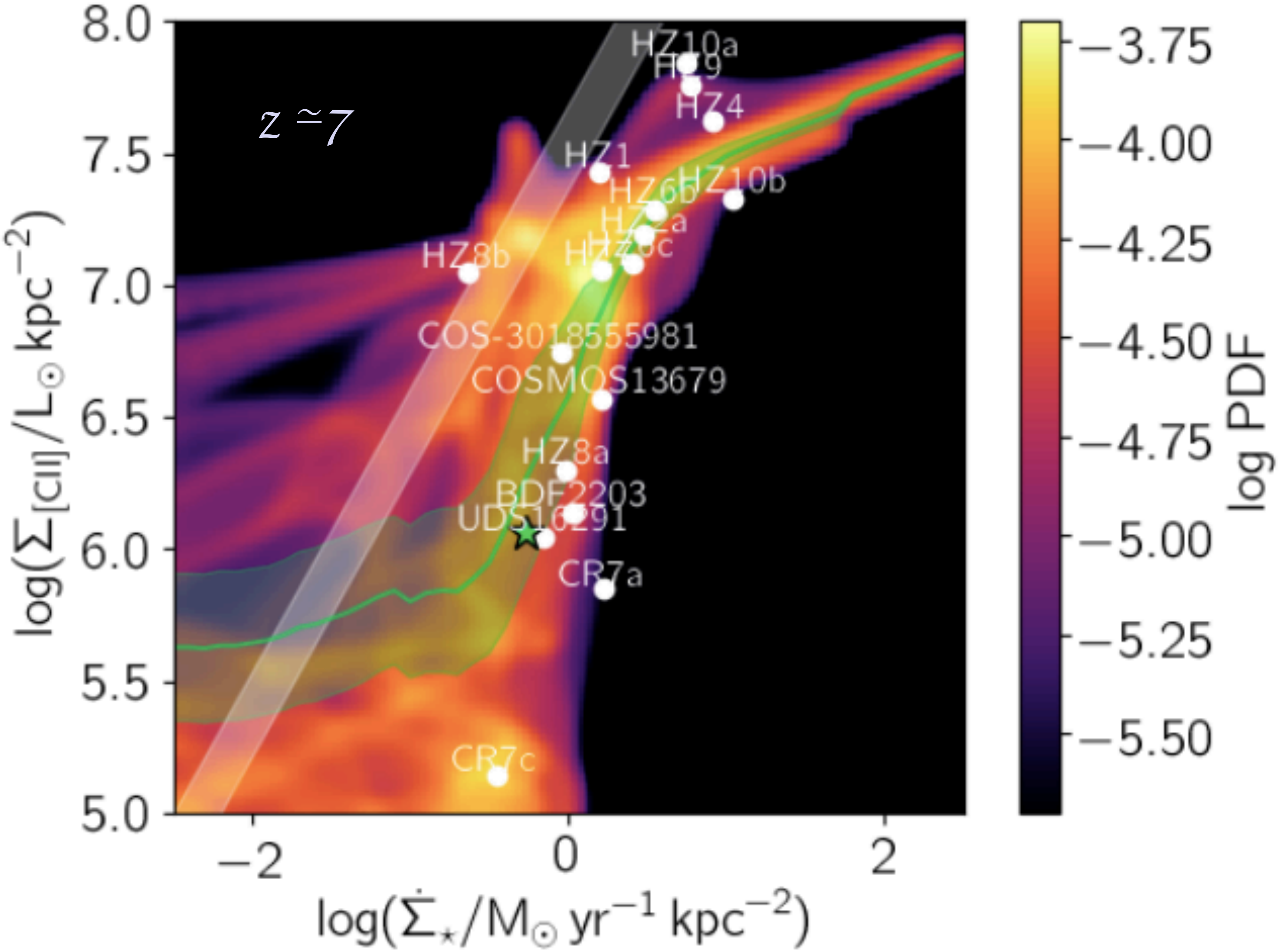


$k_s = 5$

Starburst

[CII] DEFICIT SIMULATED

Pallottini+19

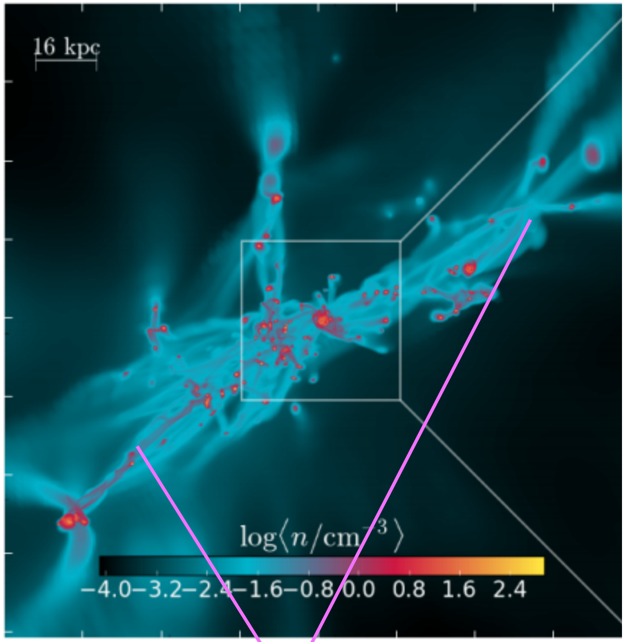


SIMULATING EARLY GALAXIES

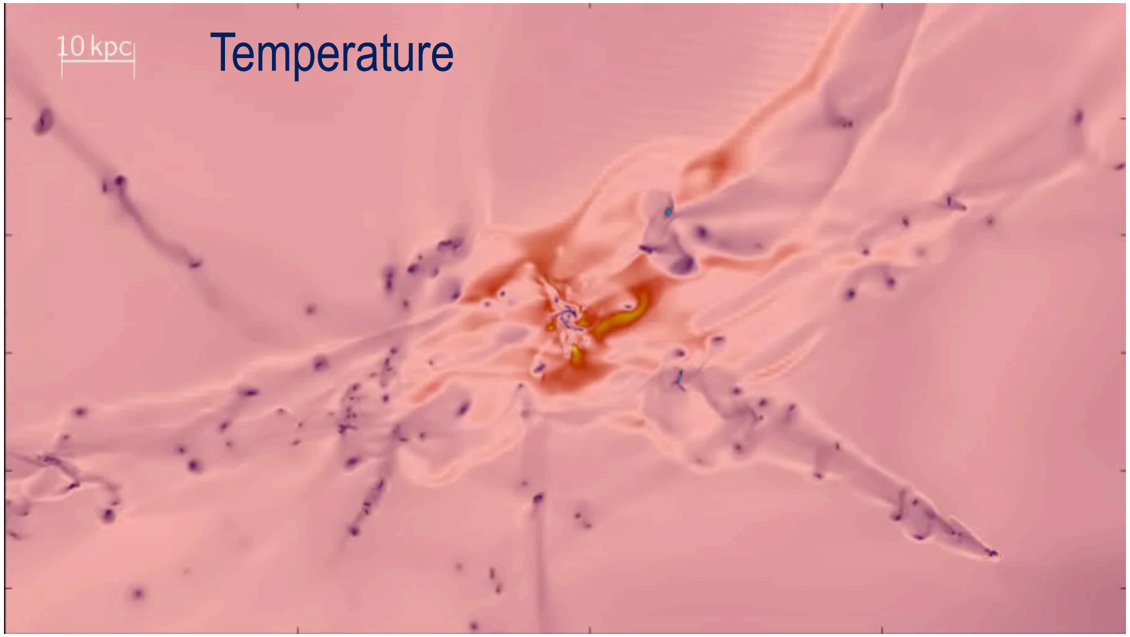
Pallottini+19

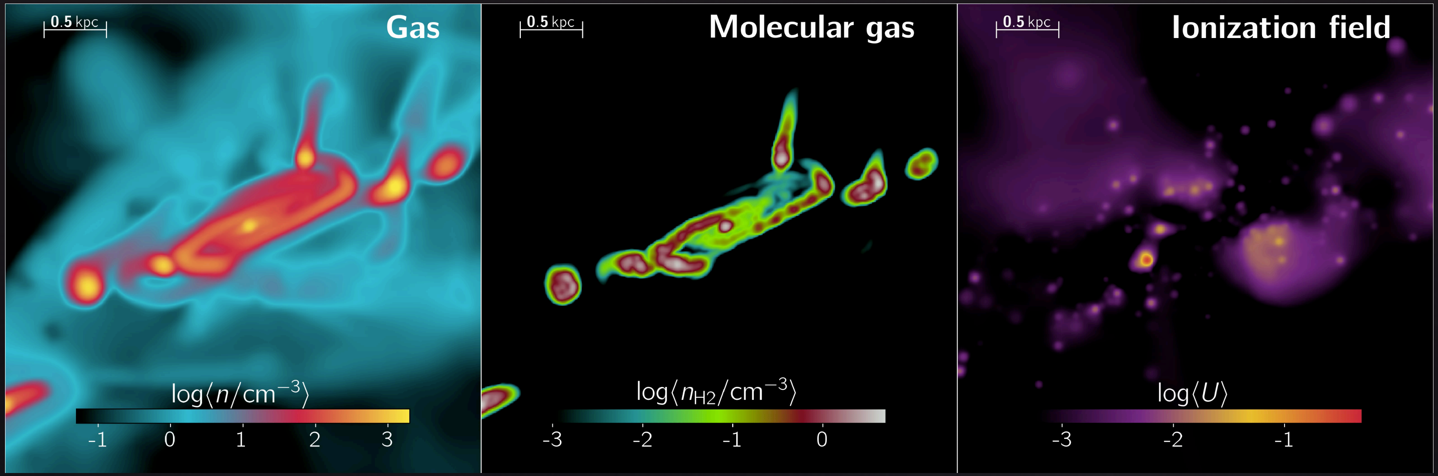
AMR zoom simulations
Spatial res = 8 pc
H_2-based SFR prescription
Non-equilibrium chemistry
Updated SN feedback model
Radiation pressure on dust
On-the-fly RT in 11 bands

serra

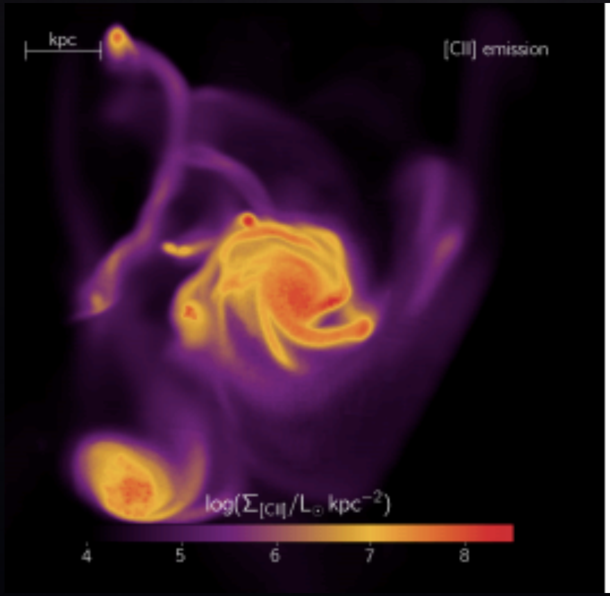


over-dense accreting filaments

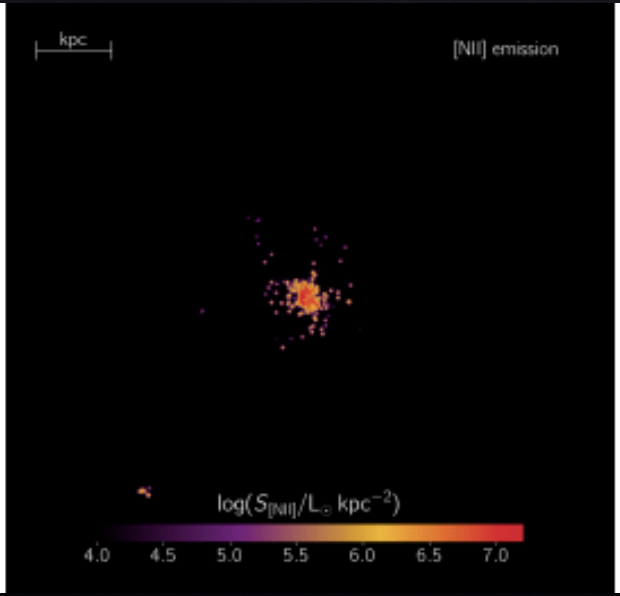




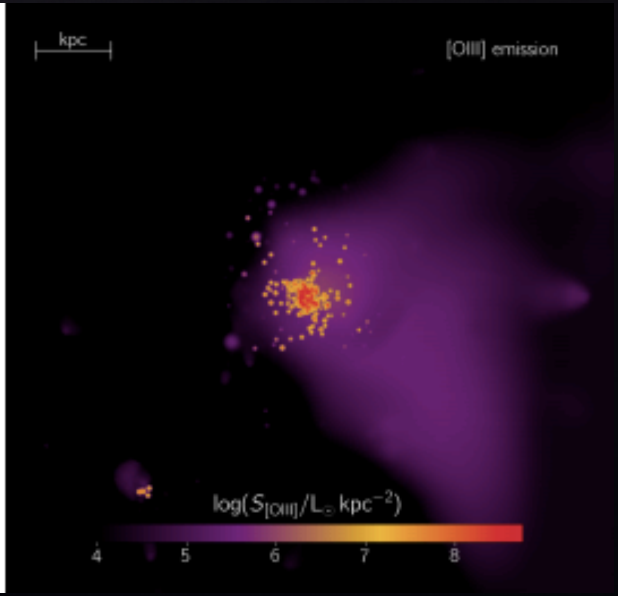
FIR LINES SURFACE BRIGHTNESS



[CII] 158 μm



[NII] 205 μm



[OIII] 88 μm

CMB EFFECTS

Gong+12; Vallini+15; Pallottini+15

ISM FIR emission is seen against the CMB

Contrast $$\Delta I_\nu = [B_\nu(T_s) - B_\nu(T_{cmb})](1 - e^{-\tau_\nu})$$

Flux ratio $$\eta = \frac{F^{obs}_{\nu/(1+z)}}{F^{int}_{\nu/(1+z)}} = 1 - \frac{B_\nu(T_{cmb})}{B_\nu(T_s)}$$

Spin temperature :: $$\frac{n_u}{n_l} = \frac{g_u}{g_l}\, e^{-T_*/T_s}$$

u: ${}^2P_{3/2}$

l: ${}^2P_{1/2}$

$g_u = 4$

$g_l = 2$

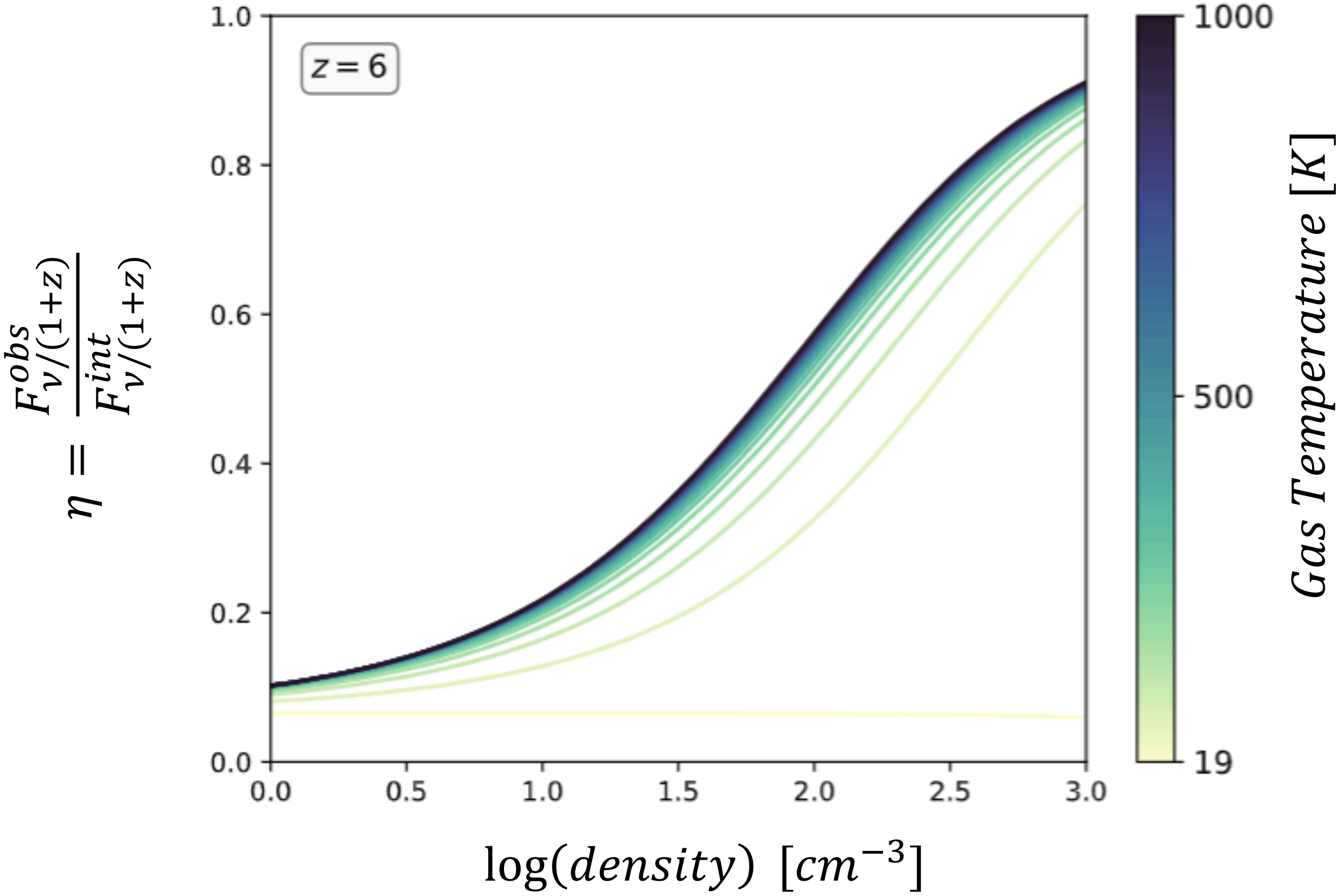
$T_* = 91.21\ K$

$$\frac{n_u}{n_l} = \frac{\overset{\text{stimulated absorption}}{\overline{B_{lu}I_\nu}} + \overset{\text{collisional excitation}}{\overline{n_e C^e_{lu} + n_{\mathrm{H}} C^{\mathrm{H}}_{lu}}}}{\underset{\text{stimulated emission}}{\underline{B_{ul}I_\nu}} + \underset{\text{spontaneous emission}}{\underline{A_{ul}}} + \underset{\text{collisional de-excitation}}{\underline{n_e C^e_{ul} + n_{\mathrm{H}} C^{\mathrm{H}}_{ul}}}}$$

CMB EFFECTS

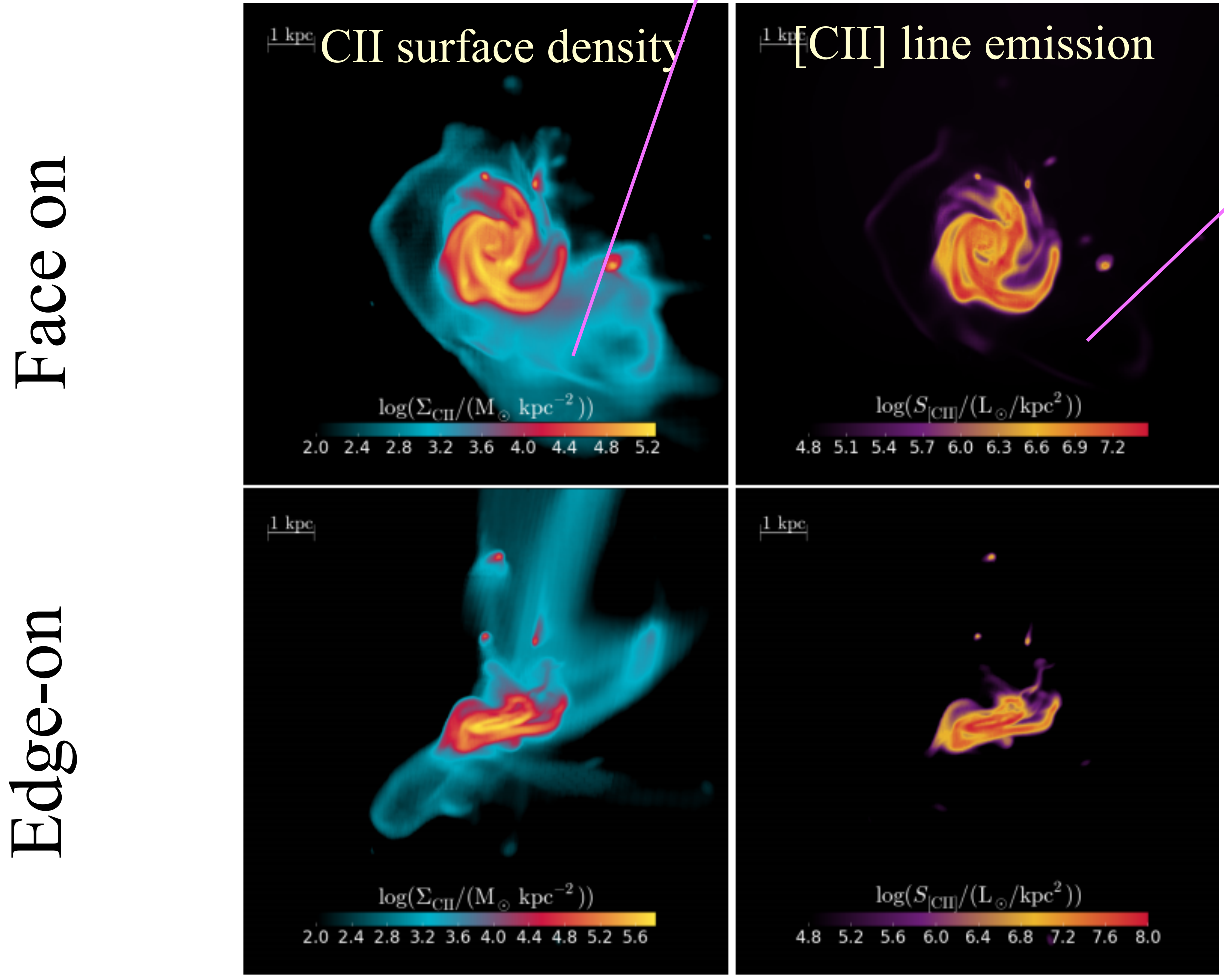
Kohandel+19

Suppression of emission by the CMB



CMB EFFECTS

⅓ of CII mass in diffuse, low-Z, weakly emitting gas (invisible due to CMB)



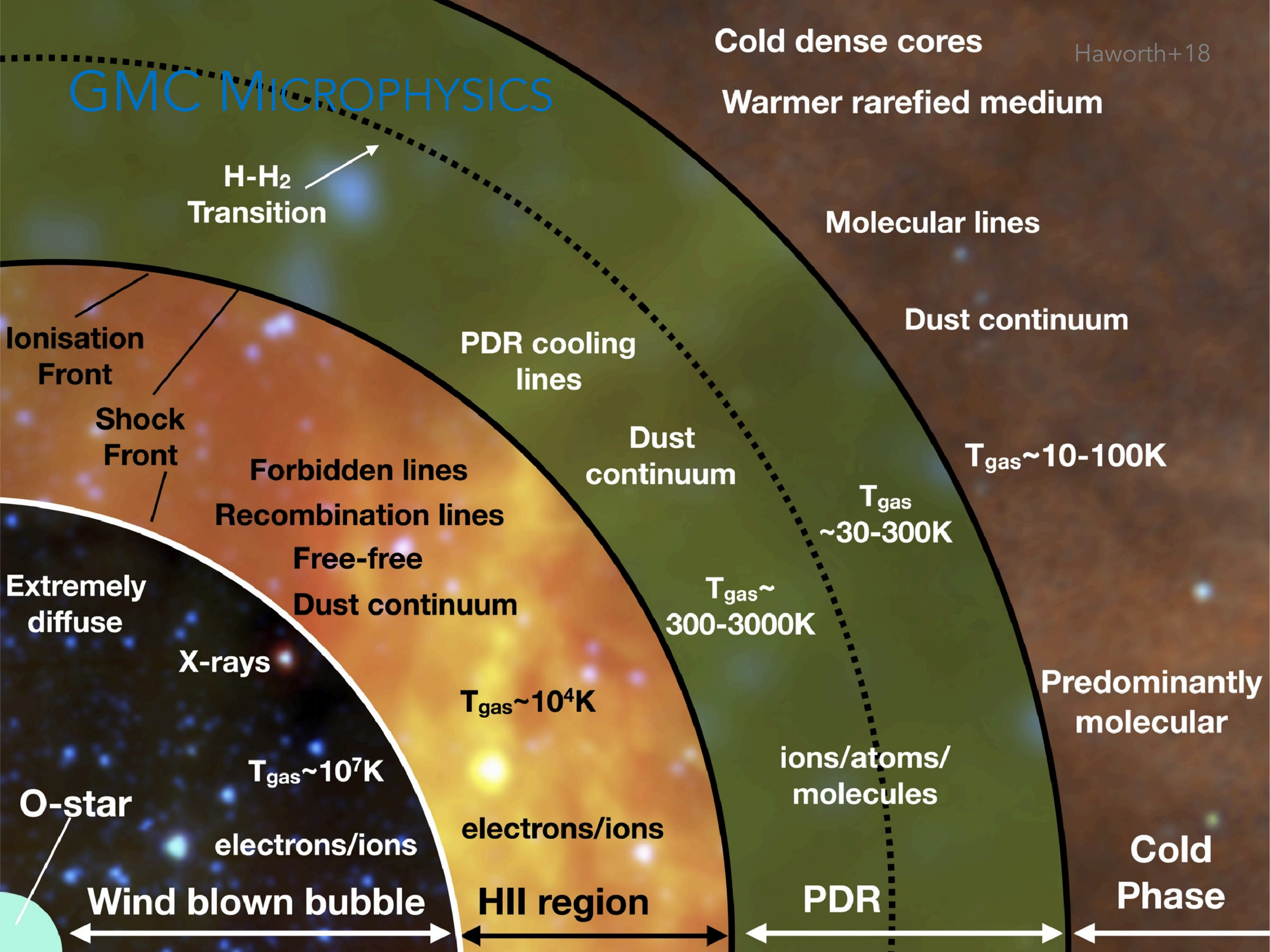
Total [CII] Luminosity
$L_{CII} = 3.5\times10^7\ L_\odot$

❖

95% of emission co-located with H_2 disk

GMC MICROPHYSICS

Haworth+18



O-star

Extremely diffuse

X-rays

T_{gas}~10^7K

electrons/ions

Wind blown bubble

Ionisation Front

Shock Front

Forbidden lines

Recombination lines

Free-free

Dust continuum

T_{gas}~10^4K

electrons/ions

HII region

H-H_2 Transition

PDR cooling lines

Dust continuum

T_{gas}~ 300-3000K

T_{gas} ~30-300K

ions/atoms/ molecules

PDR

Cold dense cores

Warmer rarefied medium

Molecular lines

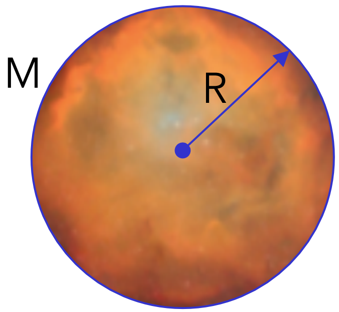
Dust continuum

T_{gas}~10-100K

Predominantly molecular

Cold Phase

MOLECULAR CLOUDS



Virial parameter $$\alpha_{vir} = \frac{5\sigma^2 R}{3GM}$$

Local observations $$\alpha_{vir} \approx \frac{5}{3}$$ Heyer+09

It follows $$M = \frac{1}{2}\frac{\sigma^4}{\sqrt{G^3 p}}$$ and $$R = \frac{1}{2}\frac{\sigma^2}{\sqrt{Gp}}$$

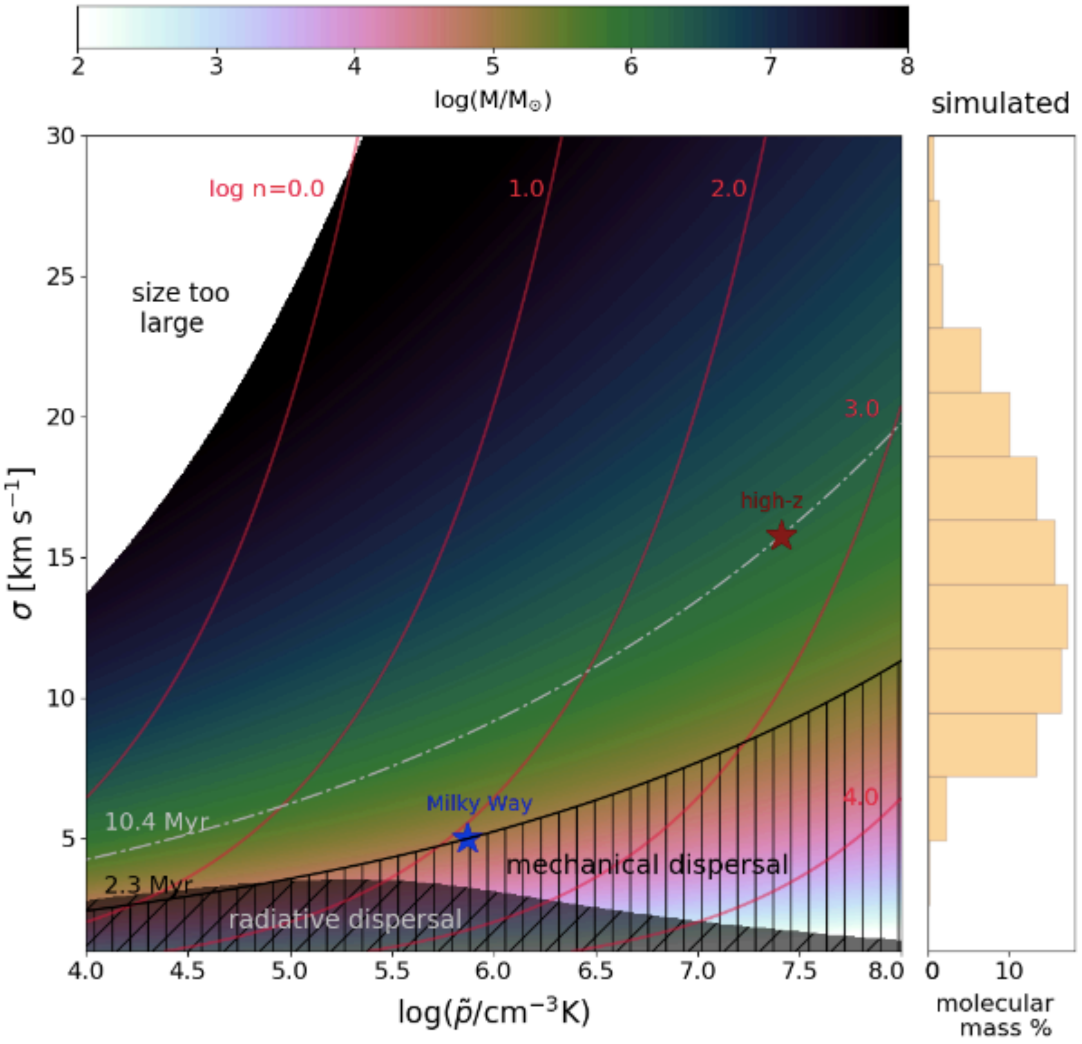
and $$SFR = \epsilon_{ff}\frac{M}{t_{ff}} = \frac{1}{2}\,\epsilon_{ff}\,\frac{\sigma^3}{G} = 10^{-5.9}\,\sigma_{kms}^3\,M_\odot\,yr^{-1}$$

Dispersal time by winds and SNe $$t_{dis} \approx 2\times10^{-3}\sigma_{kms}^3 p_8^{-1/2} Myr$$ Sommovigo+19

Efficiency $$f_* = \frac{t_{dis}}{t_{dep}} \approx 2\times10^{-4}\sigma_{kms}^2$$

MOLECULAR CLOUDS

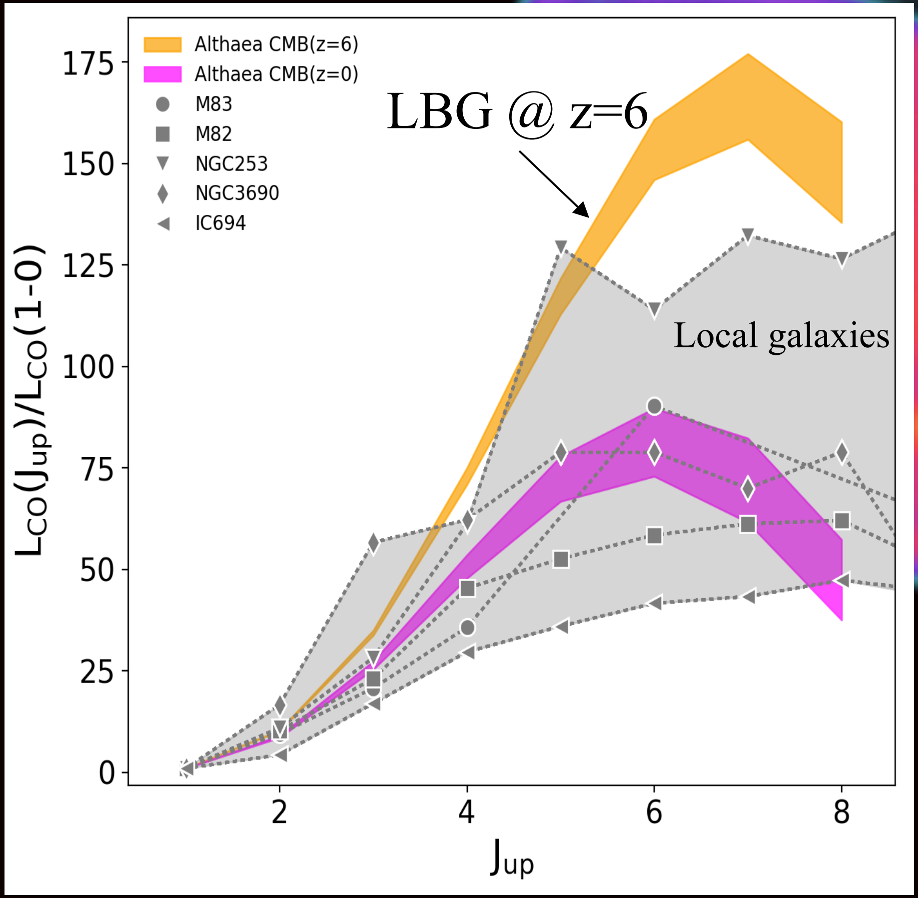
Sommovigo+19



GMC live longer ➡ SF more obscured ➡ higher IR luminosities

Next Frontier: CO

Vallini+18



High gas surface density

+

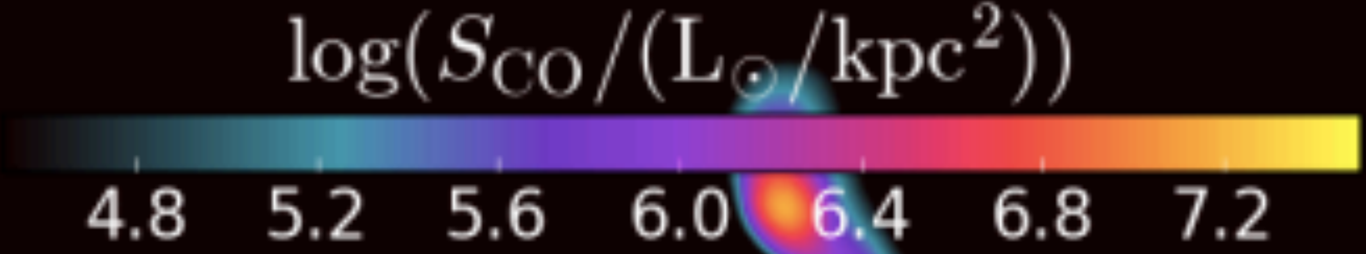
Large velocity dispersion ($\mathfrak{M} \approx 30$)

+

Warm GMCs ($T_k \approx 45K$)

⇩

- CO SLED peaks @ $J = 7$
- Low $\alpha_{CO} = ⅓\, \alpha_{CO}$(Milky Way)
- CO(7–6) line @ 5σ with ALMA detected (resolved) in 13 (38) hr



High-z GMCs

Clumpy disks
Predictions for a *z*=6 LBG
combining JWST & ALMA

[CII] more extended than stars/dust

HST/ACS F850LP

HST/WFC3 F105W

HST/WFC3 F125W

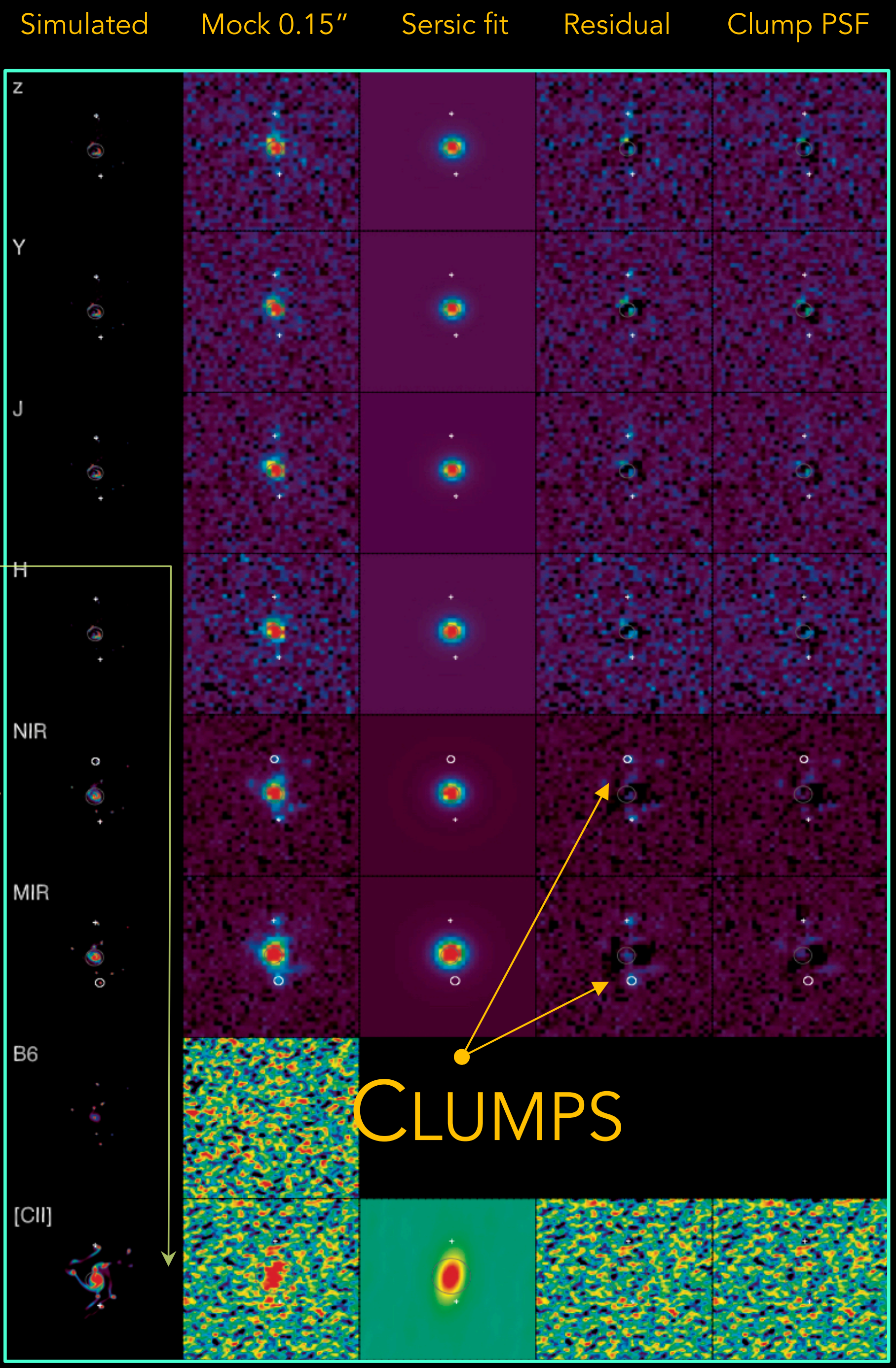
HST/WFC3 F160W

JWST/NIRCam F444W

JWST/MIRI F770W

ALMA Band 6 cont.

ALMA 158um



Pallottini+19, Zanella+20

ADDITIONAL TOPICS [NOT COVERED]

1. Metallicity effects
2. Dust formation, properties and emission
3. Cosmic rays & magnetic fields
4. Feedbacks
   1. Mechanical
   2. Radiative
   3. Chemical

Ciardi & Ferrara, 2005, Space Science Reviews, 116, 625

THE END

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