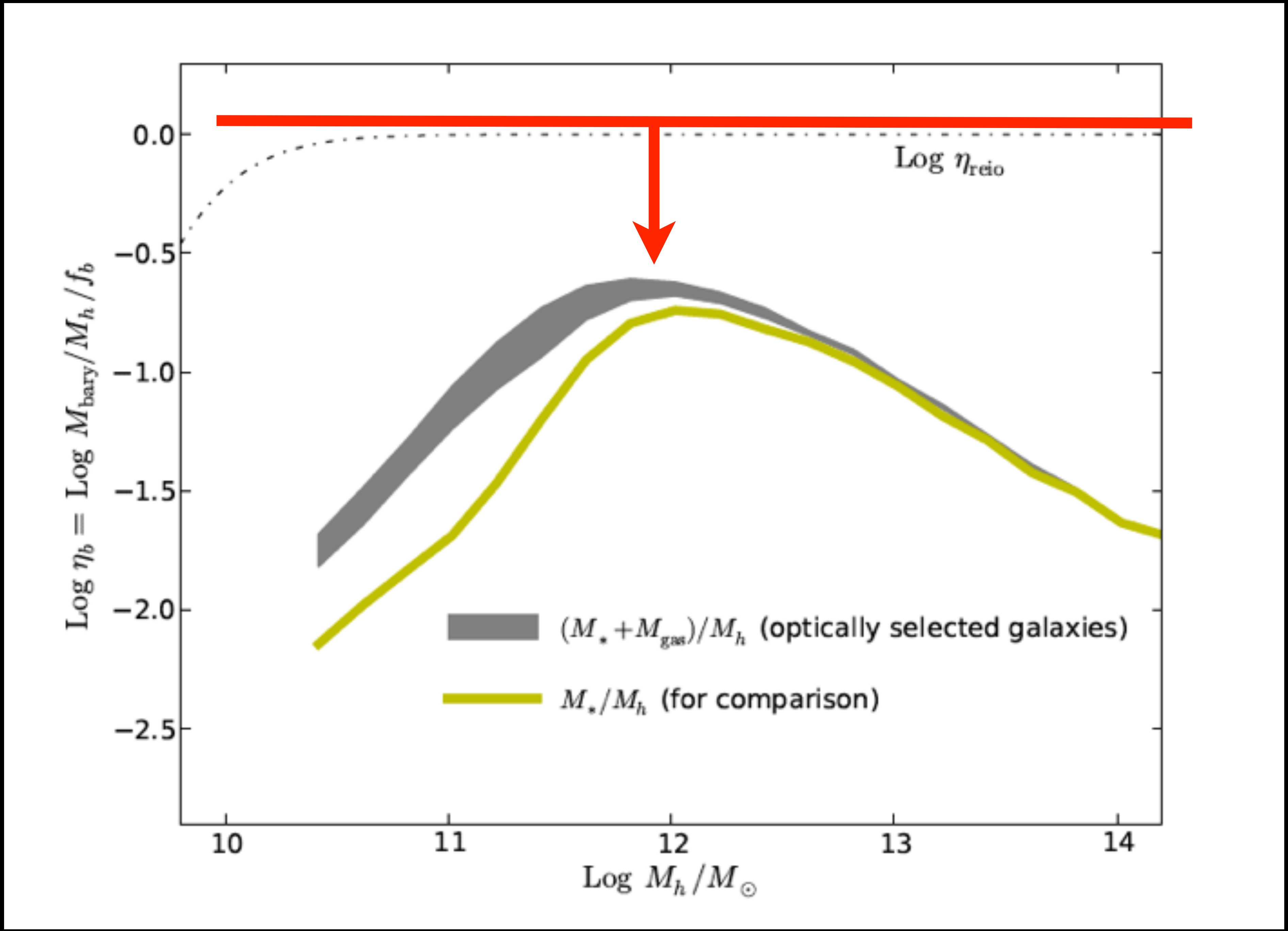
How Do Galaxies Get Their Gas?

- The Intergalactic Medium (IGM)
  - Evolution & ionization history
- Tracing the IGM with absorption lines
  - Ly alpha forest (lowest column density)
  - Damped Lyman Alpha Systems
  - Metal Line Systems (highest column density)
  - The Circumgalactic Medium
- How does gas get to the center of galaxies?
  - Shocks+cooling (hot mode) vs Filaments (cold mode)
- Overview of the warm & cool ISM

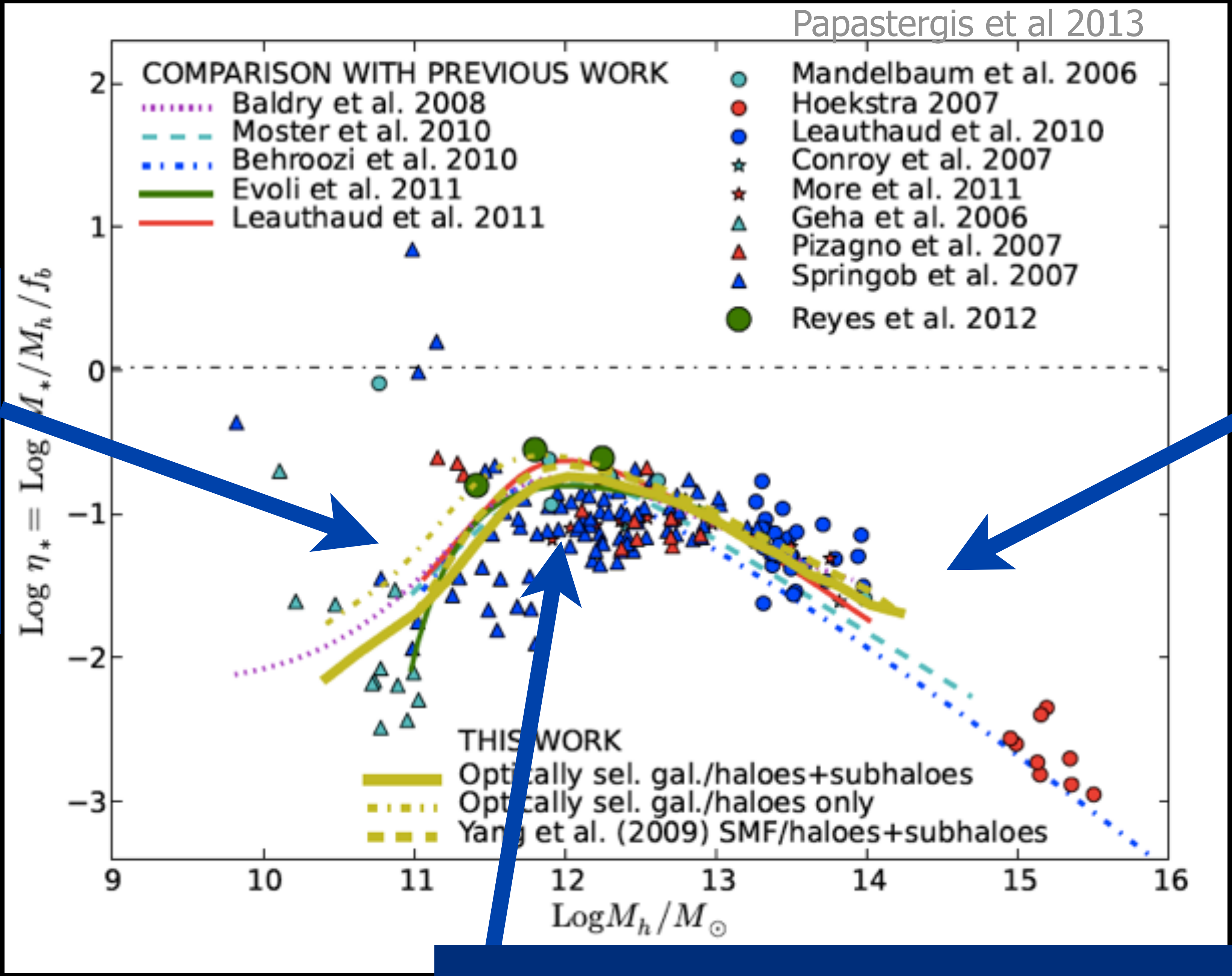
Global issue w/ Gas

The baryon fraction of galaxies is below the cosmic mean ($f_b = \Omega_b/\Omega_m \approx 0.16$)



Papastergis et al 2012

Baryon fractions ≲20% of global f_b



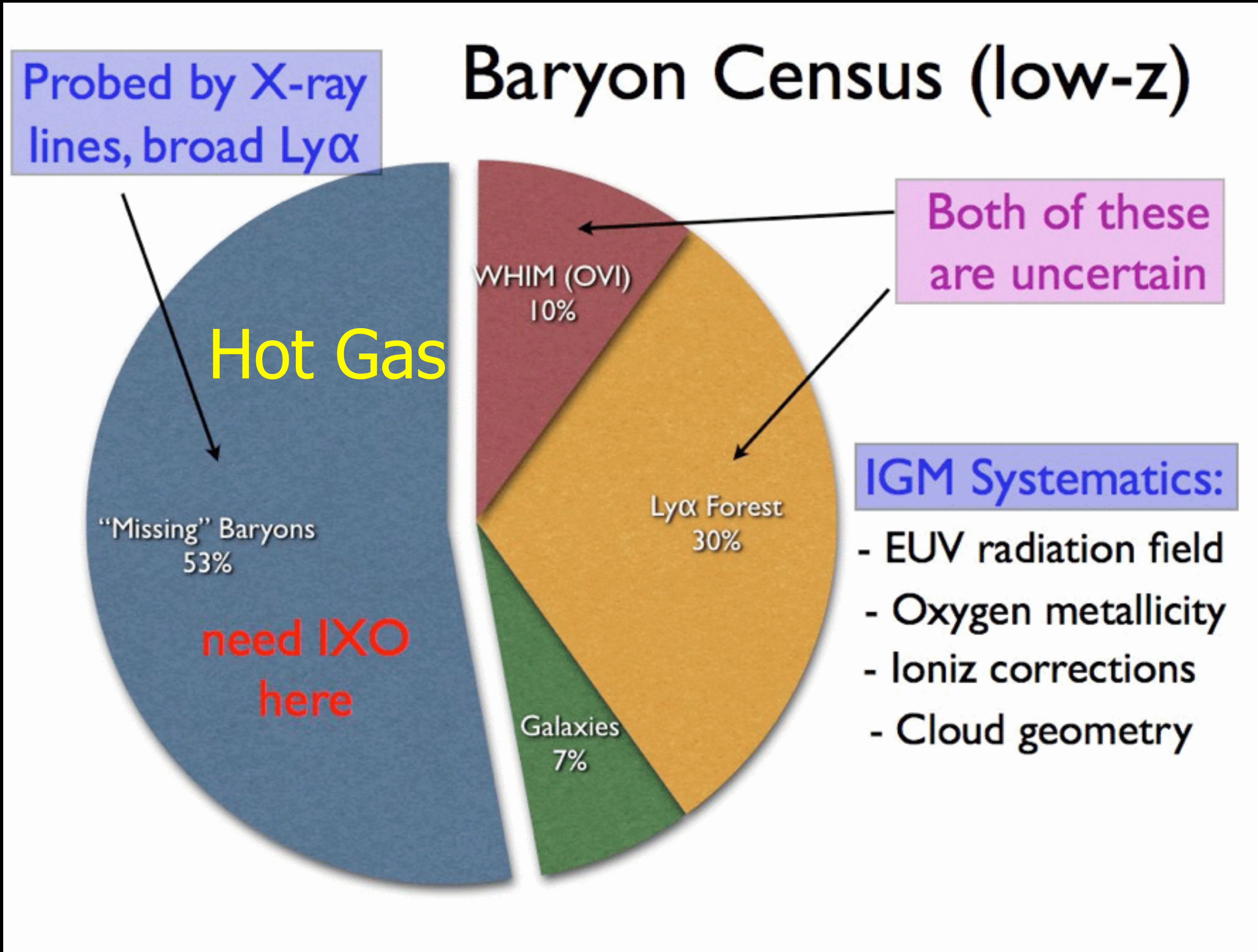
Missing in small galaxies

Missing in big galaxies

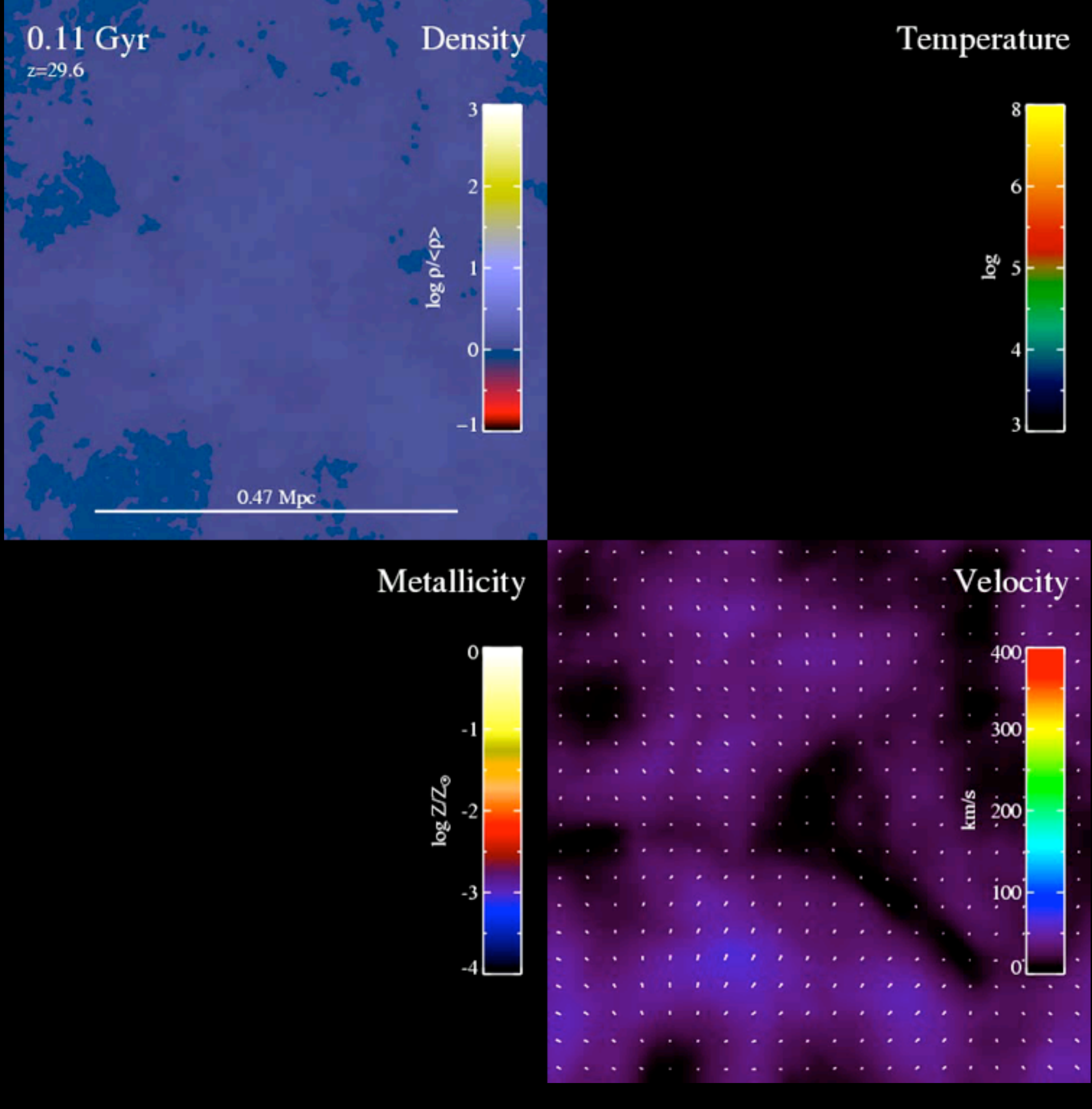
Clear peak at MW-ish scale

Either the baryons never came in, or they came in and went out....

Most low-z baryons probably in IGM



The Inter-galactic Medium (IGM)



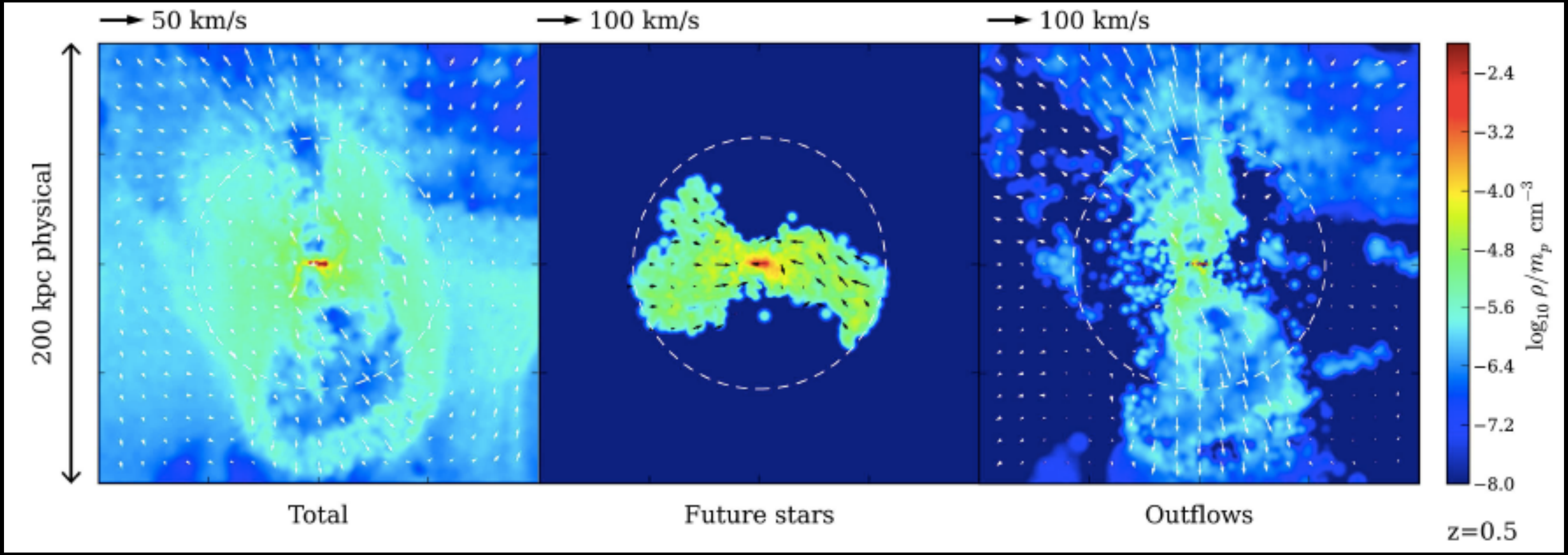
B. Oppenheimer

Structure grows, gas shock heats, feedback pollutes metals.

https://vimeo.com/72220338

Processes Driving IGM Evolution

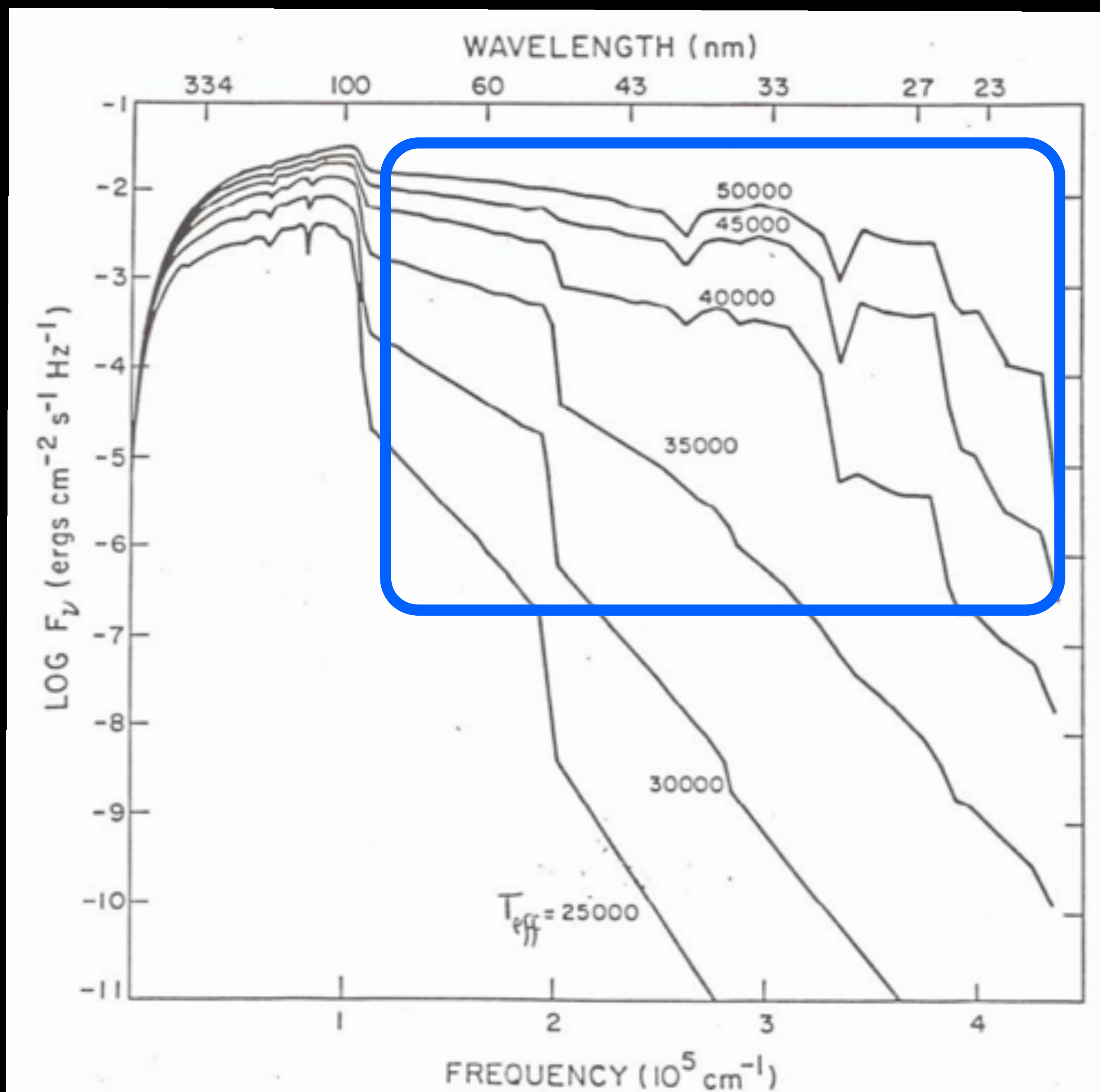
1. Outflows from galaxies & AGN

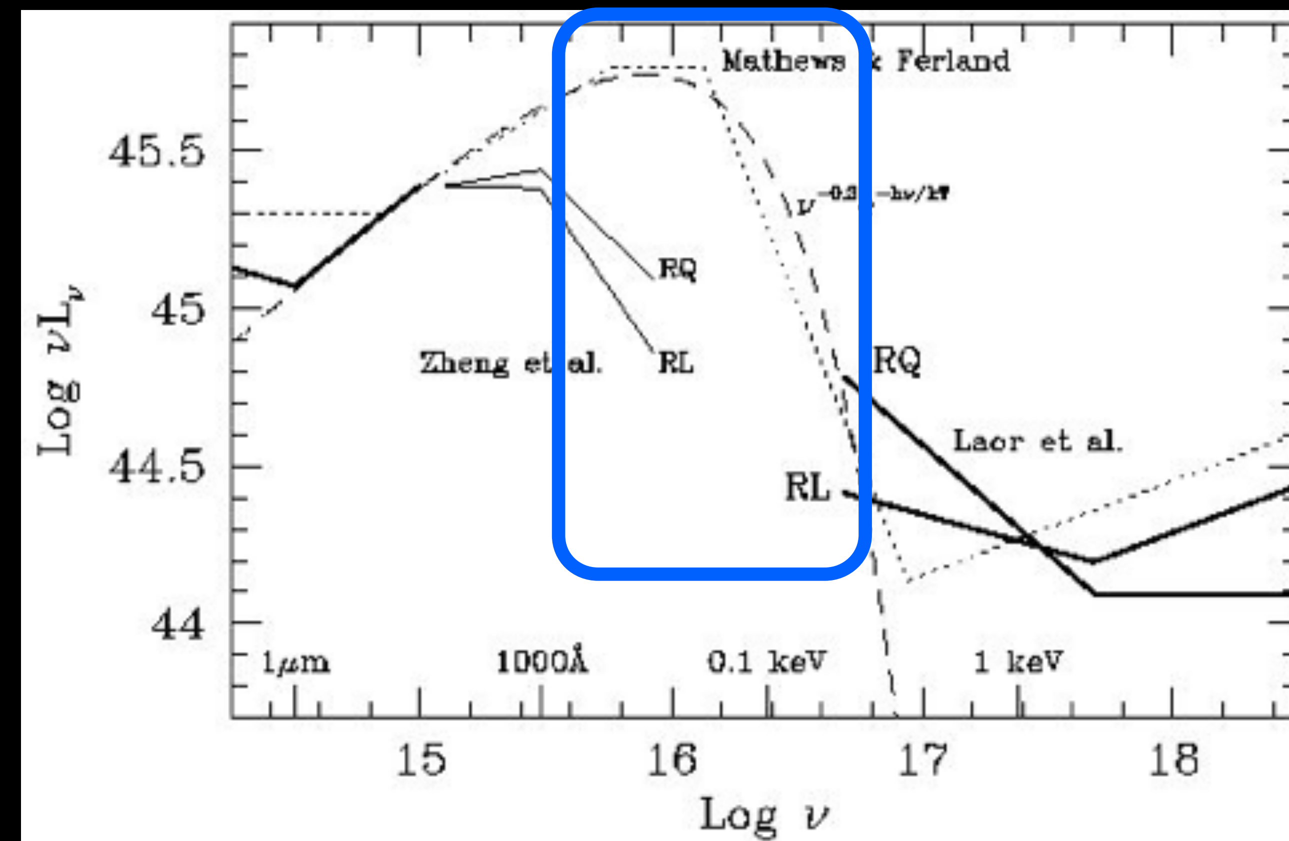


Shock Heating + Metal Enrichment

Processes Driving IGM Evolution

2. Ionization from galaxies & AGN

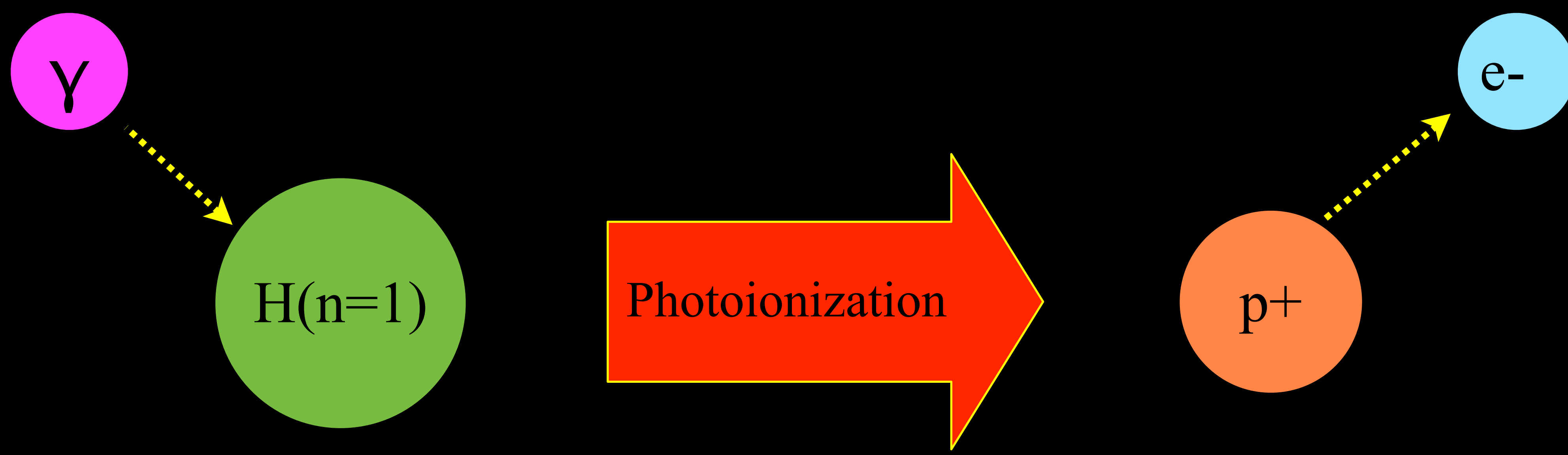




Laor et al 1997

Hot Massive Stars + AGN Continuum

Physics of Photoionization

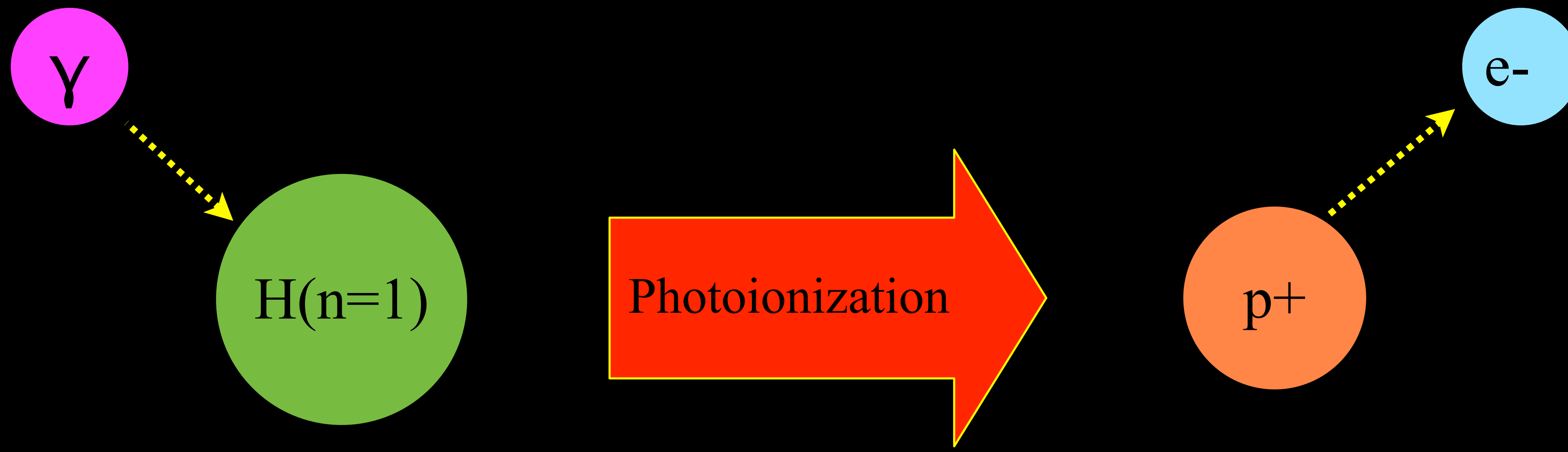


$$\boxed{H + h\nu \rightleftarrows H^{+} + e-}$$

Ionization rate per atom, per volume = *Density of photons* x *Cross section for ionization* x *Speed of photons*

(Shown for Hydrogen, but applies to any atom with bound electrons)

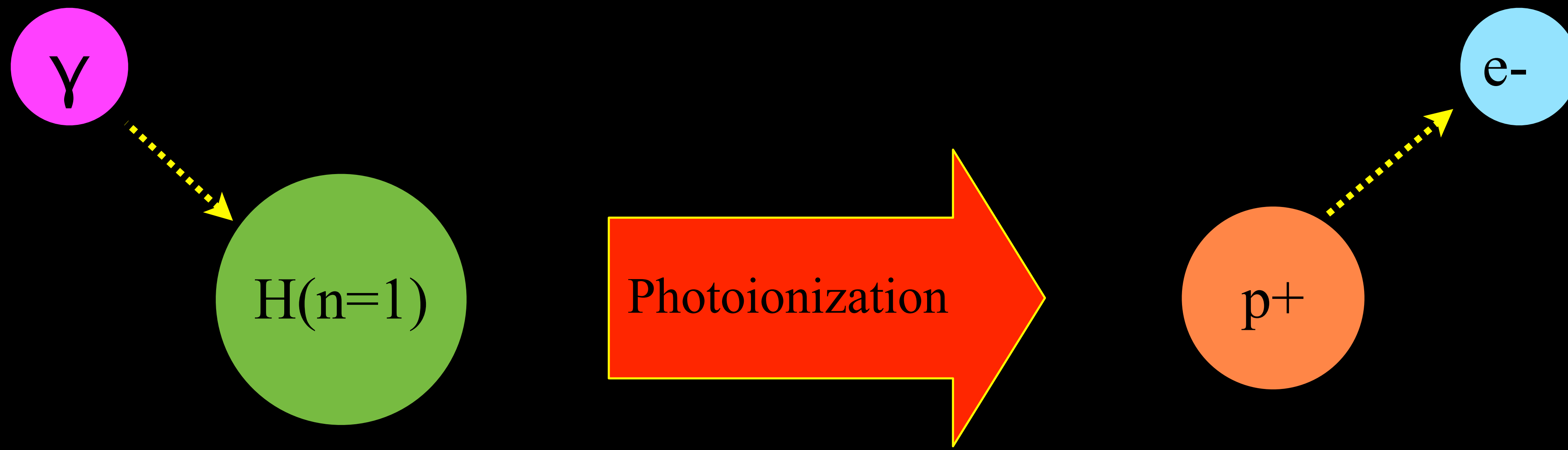
Physics of Photoionization



Evolves due to expansion of universe, AGN(t), SFR(t)

Ionization rate per atom, per volume = *Density of photons*
x *Cross section for ionization*
x *Speed of photons*

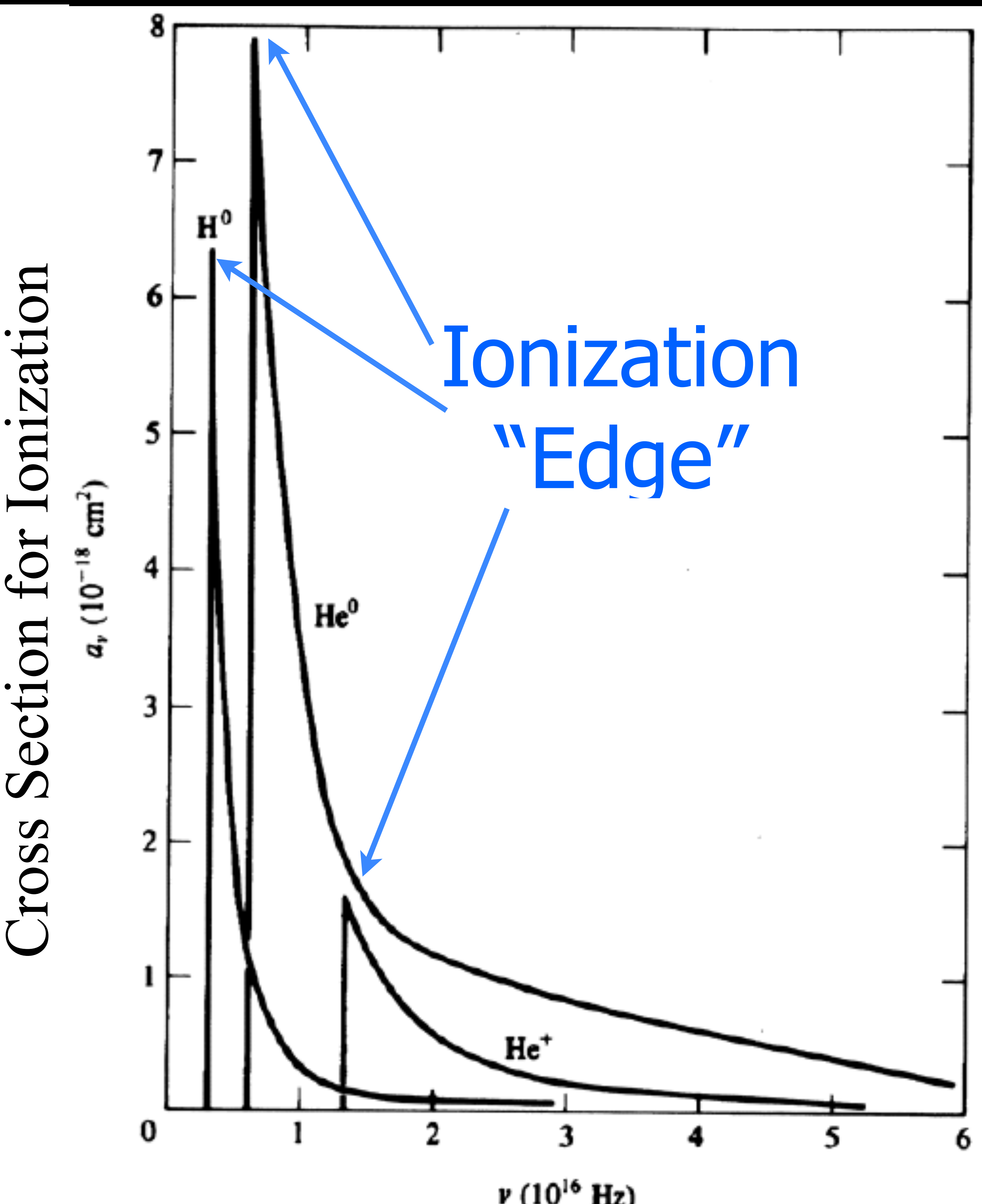
Physics of Photoionization



Depends on atom/ion being considered, photon wavelength

Ionization rate per atom, per volume = *Density of photons* x *Cross section for ionization* x *Speed of photons*

Photoionization Cross Sections



- Peak at energies well matched to the ionization energy.
- Falls off like ν^{-3}
- Ionization edge occurs at higher energies for higher Z, and for more ionized atoms (less shielding) usually

Harder to strip off each successive electron!

Photoionization Cross Sections

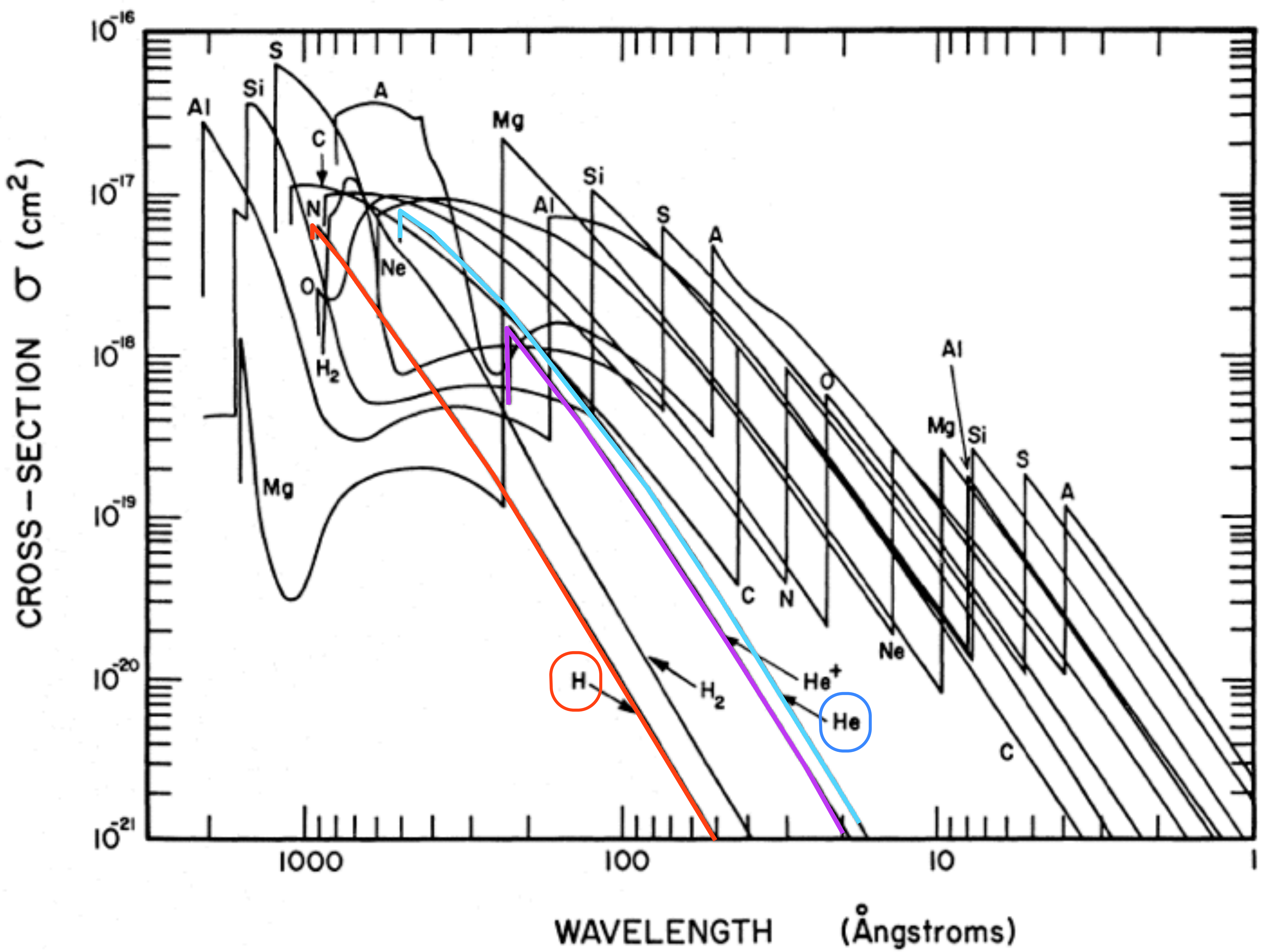


FIG. 1.—Photoabsorption cross-sections of the abundant elements in the interstellar medium as a function of wavelength

Cruddace et al 1974

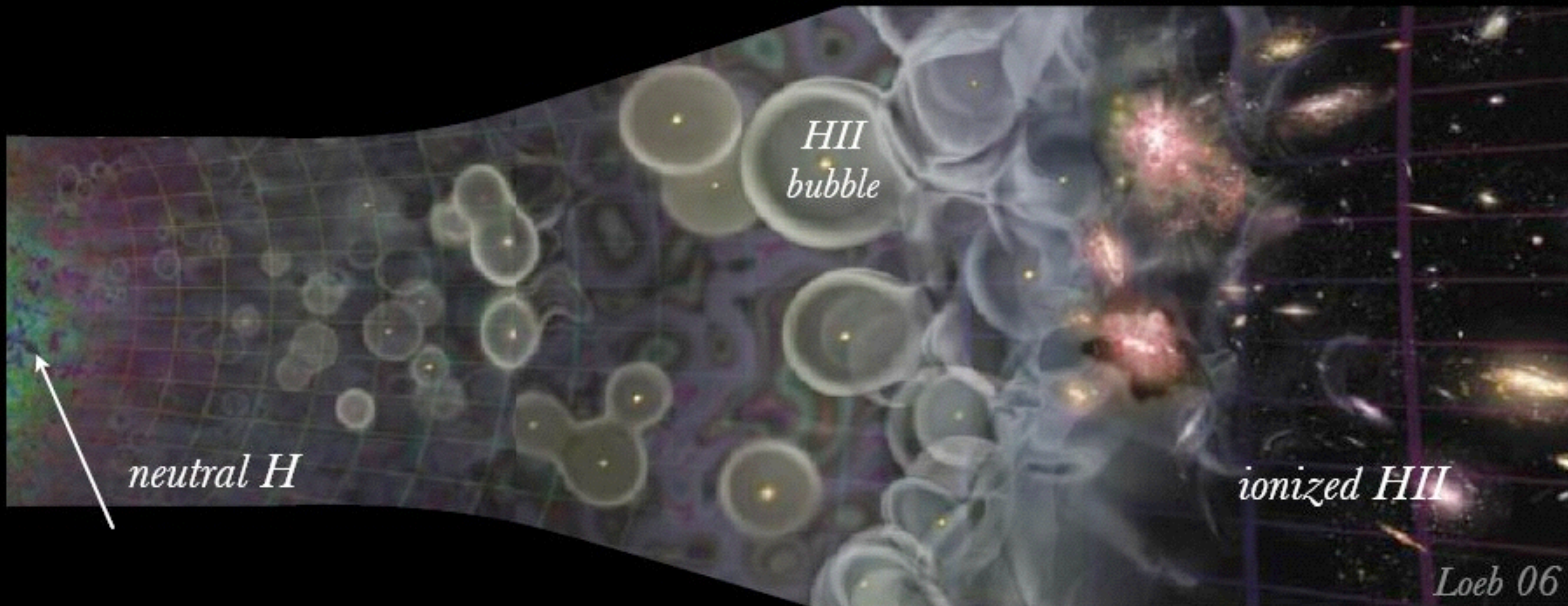
Common Ionization Potentials

Ionization Potentials

HI – HII : 13.6eV	HeI – HeII : 24.6eV	HeII – HeIII : 54.4eV
OI – OII : 13.6 eV	OII – OIII : 35.1 eV	OIII – OIV : 54.9 eV
CI – CII : 11.3 eV	CII – CIII : 24.4 eV	CIII – CIV : 47.9 eV
NI – NII : 14.5 eV	NII – NIII : 29.6eV	NIII – NIV : 47.4 eV
SI – SII : 10.4 eV	SII – SIII : 23.3 eV	SIII – SIV : 34.8 eV
	NeI – NeII : 21.6 eV	NeII – Ne III : 41.0 eV

Other sources of ionization (collisions in shocks) often needed to produce highest ionization states

Photoionization drives “reionization”



Increasing time

Mostly neutral after recombination

Mostly ionized after reionization

“Reionization”

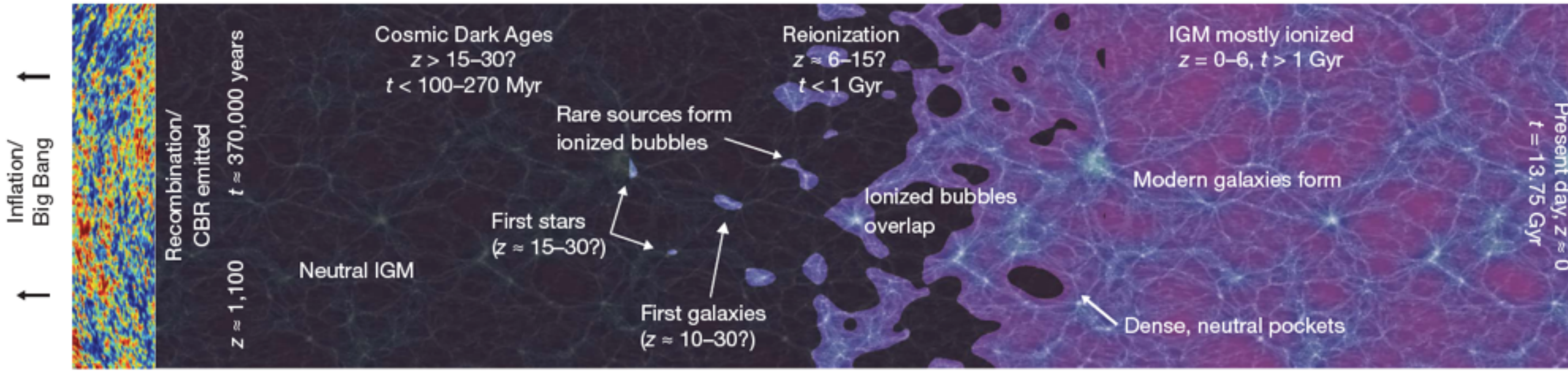
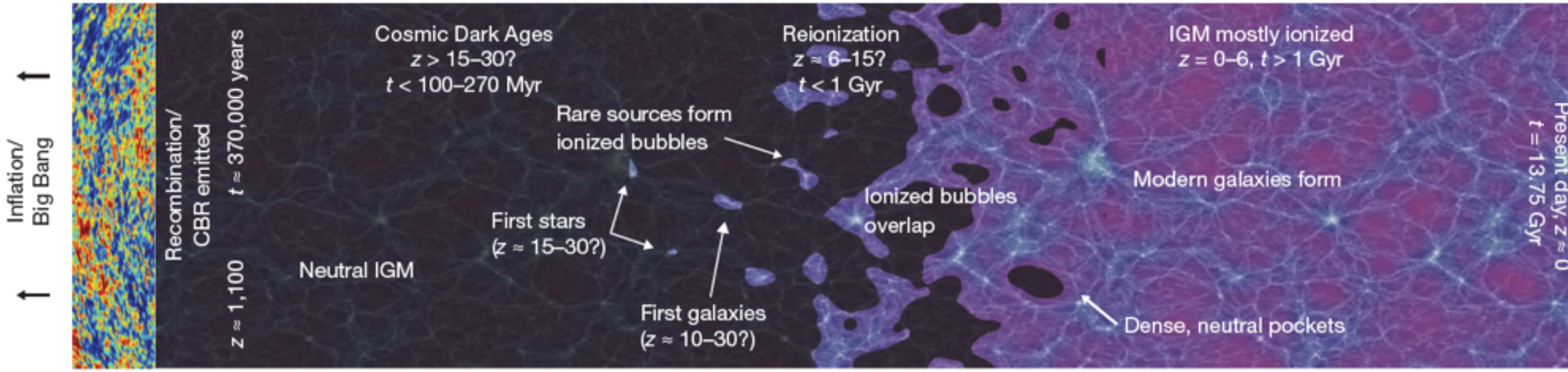


Figure 1 | Cosmic reionization. The transition from the neutral IGM left after the Universe recombined, at $z \approx 1{,}100$, to the fully ionized IGM observed today is termed cosmic reionization. After recombination, when the CMB radiation was released, hydrogen in the IGM remained neutral until the first stars and galaxies[2,4] formed, at $z \approx 15$–30. These primordial systems released energetic ultraviolet photons capable of ionizing local bubbles of hydrogen gas. As the abundance of these early galaxies increased, the bubbles increasingly overlapped and progressively larger volumes became ionized. This reionization process ended at $z \approx 6$–8, ~1 Gyr after the Big Bang. At lower redshifts, the IGM remains highly ionized by radiation provided by star-forming galaxies and the gas accretion onto supermassive black holes that powers quasars.

- Transition from mostly neutral to mostly ionized
- Ends early (z~6, probably starting z>10)
- Doesn’t happen uniformly

Nice explanations in Robertson et al 2010

“Reionization”: Issues



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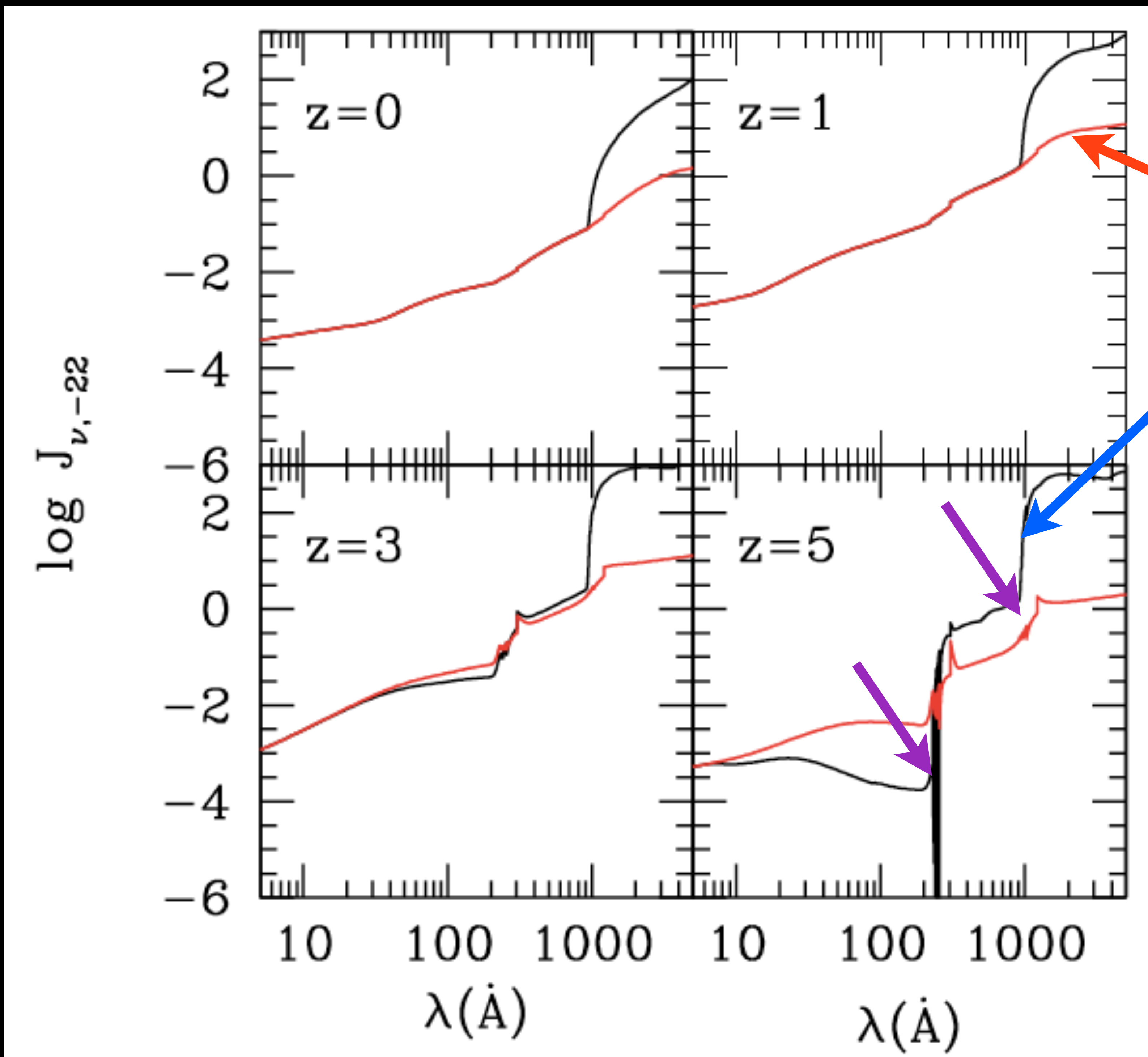
- What sources provide the ionizing radiation?
- How much UV flux escapes from galaxies/AGN?
- How “hard” is the escaping spectrum?
- When did it occur?

Nice explanations in Robertson et al 2010

Evolution of ionization background



The intensity J_ν is expressed in units of 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}

- Matches observed evolution in H absorbers w/ z.
- Assumes observed QSO and galaxy luminosity functions

Note ionization edges from HI and HeII

Models from Haardt & Madau 2011

Evolution of ionization background

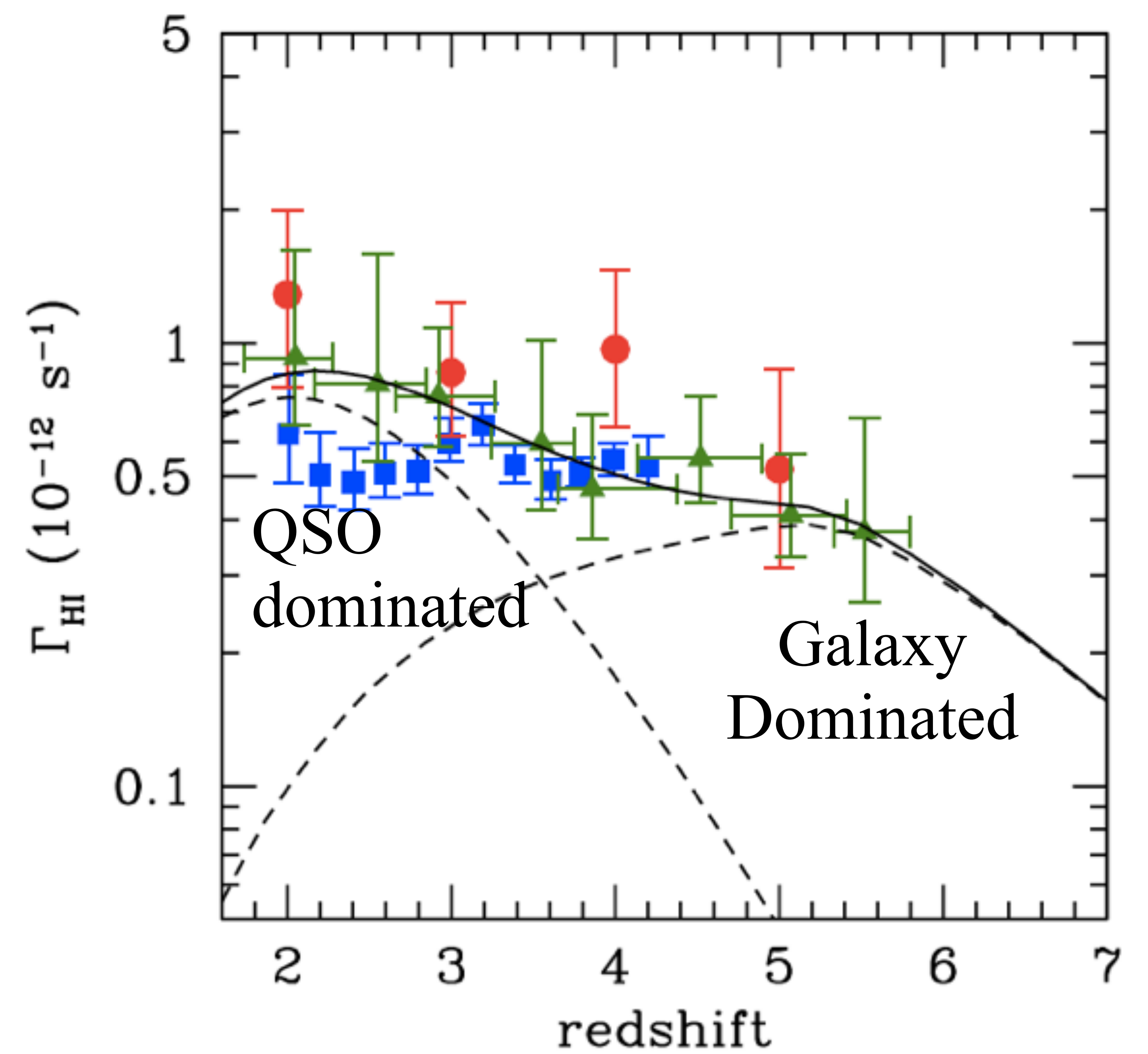
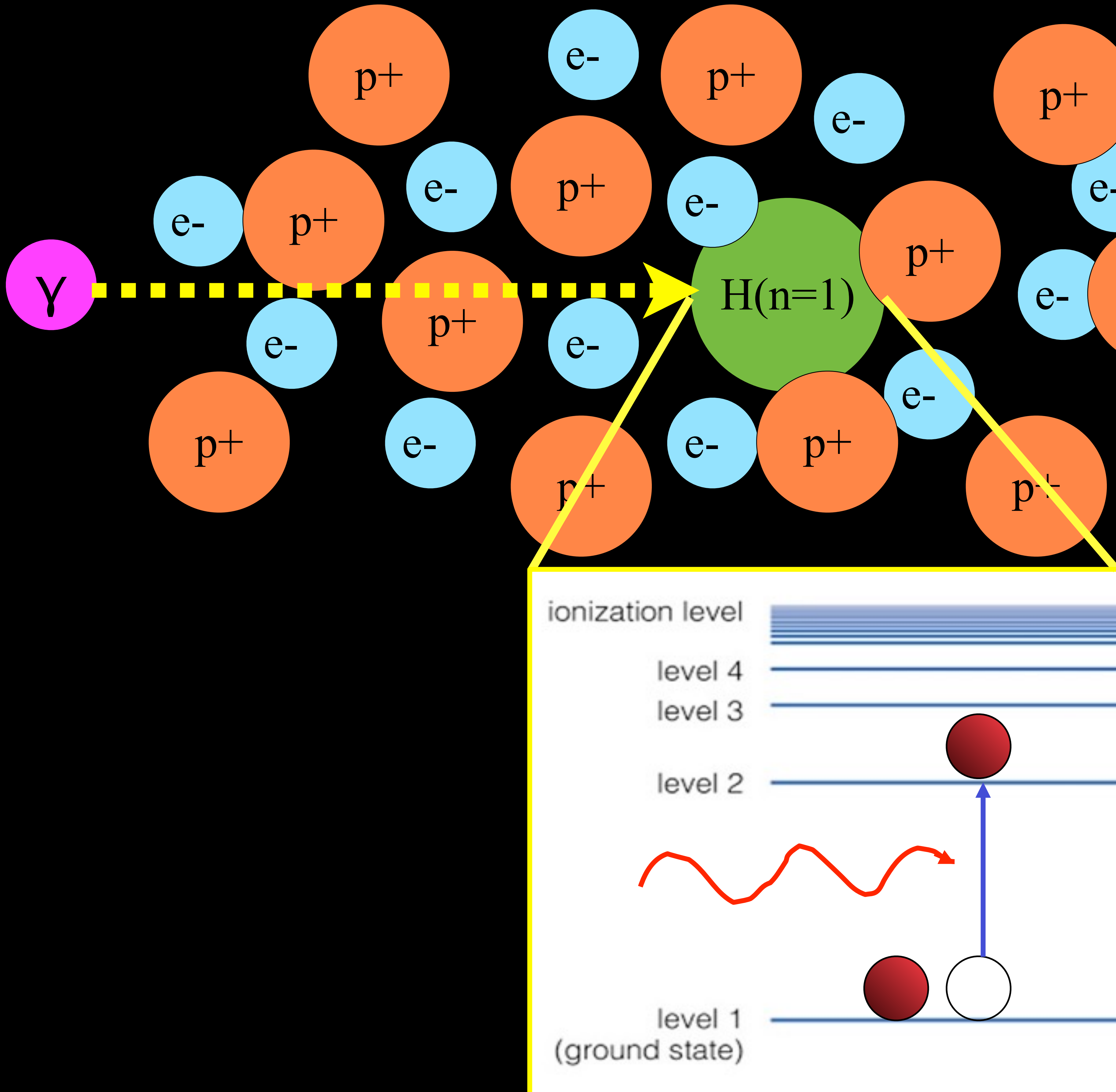


Figure 3: Hydrogen photoionization rate as a function of redshift. *Solid curve:* our full model. *Dashed curves:* separate contributions from quasars (leftmost curve) and galaxies (rightmost curve). Different data points refer to various empirical measurements from the Lyα forest effective opacity (see Haardt & Madau 2011 for full references).

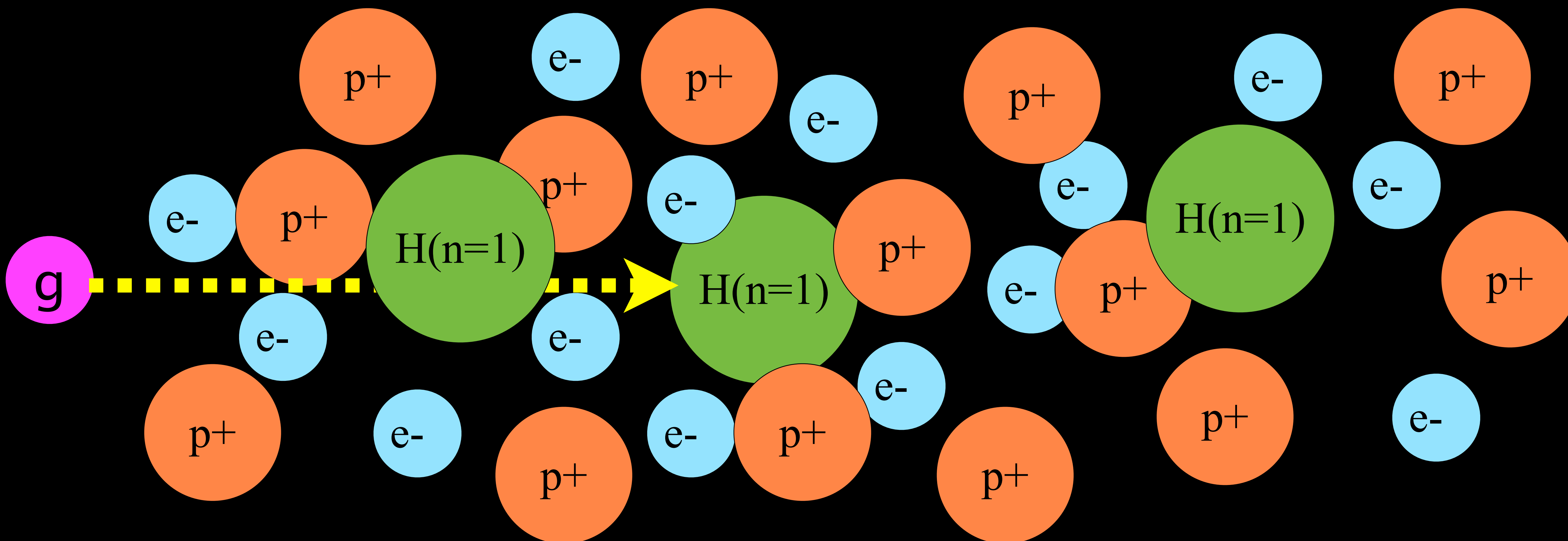
- Ionization of hydrogen dominated by galaxies at z>3.5
- Dominated by QSO's more recently

How do we track IGM & photoionization?



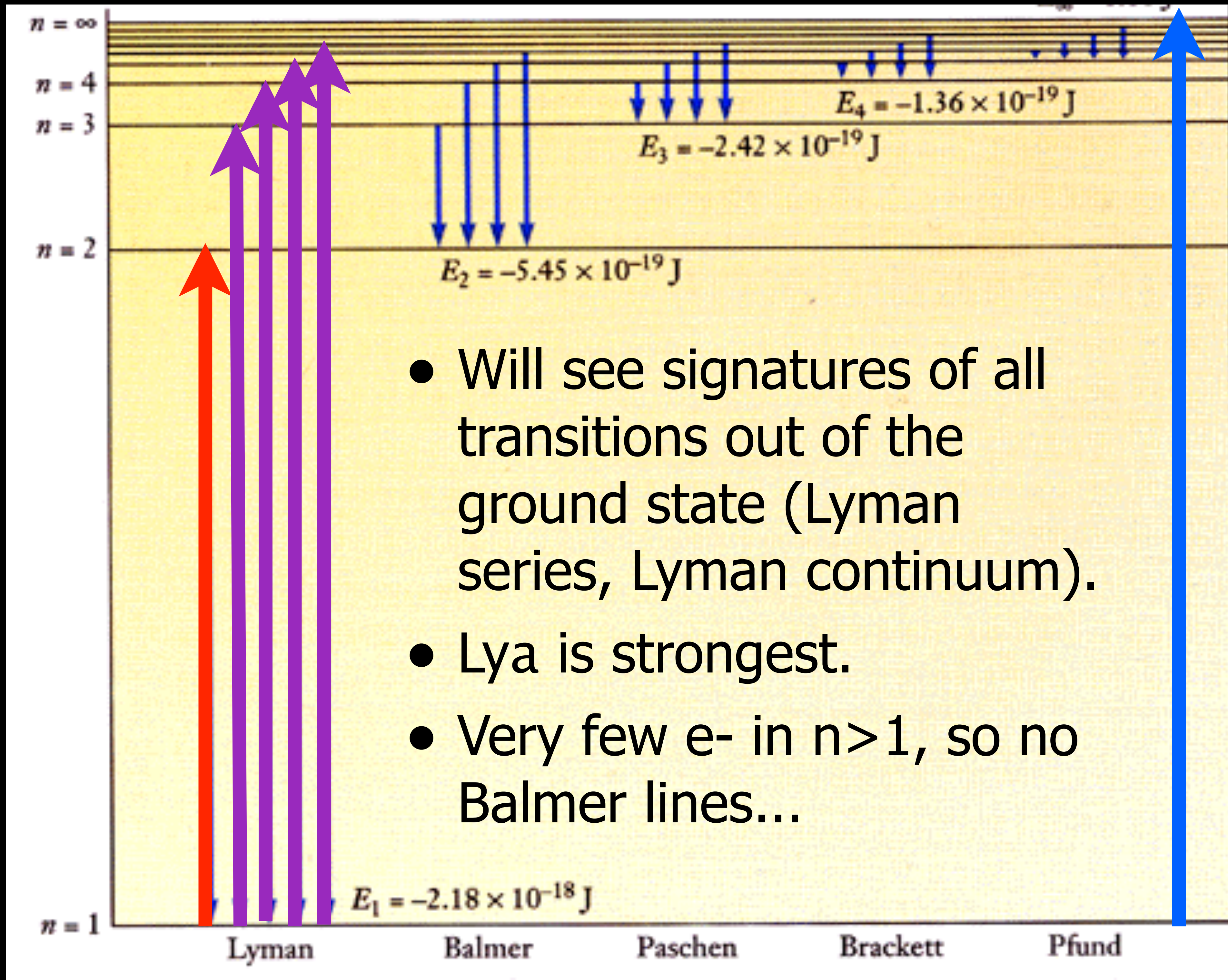
- Photons with the proper rest frame λ are absorbed by ground state e- in H

How do we track IGM & photoionization?



- The larger the fraction of neutral hydrogen, the more frequent the absorption
- Total column density of hydrogen requires significant corrections for small neutral fraction

Absorption seen for ground state transitions



- Will see signatures of all transitions out of the ground state (Lyman series, Lyman continuum).
- Lya is strongest.
- Very few e- in n>1, so no Balmer lines...

Lyα (1216Å)

Ionization="Ly limit" (912Å)

Measuring the photoionizing background:

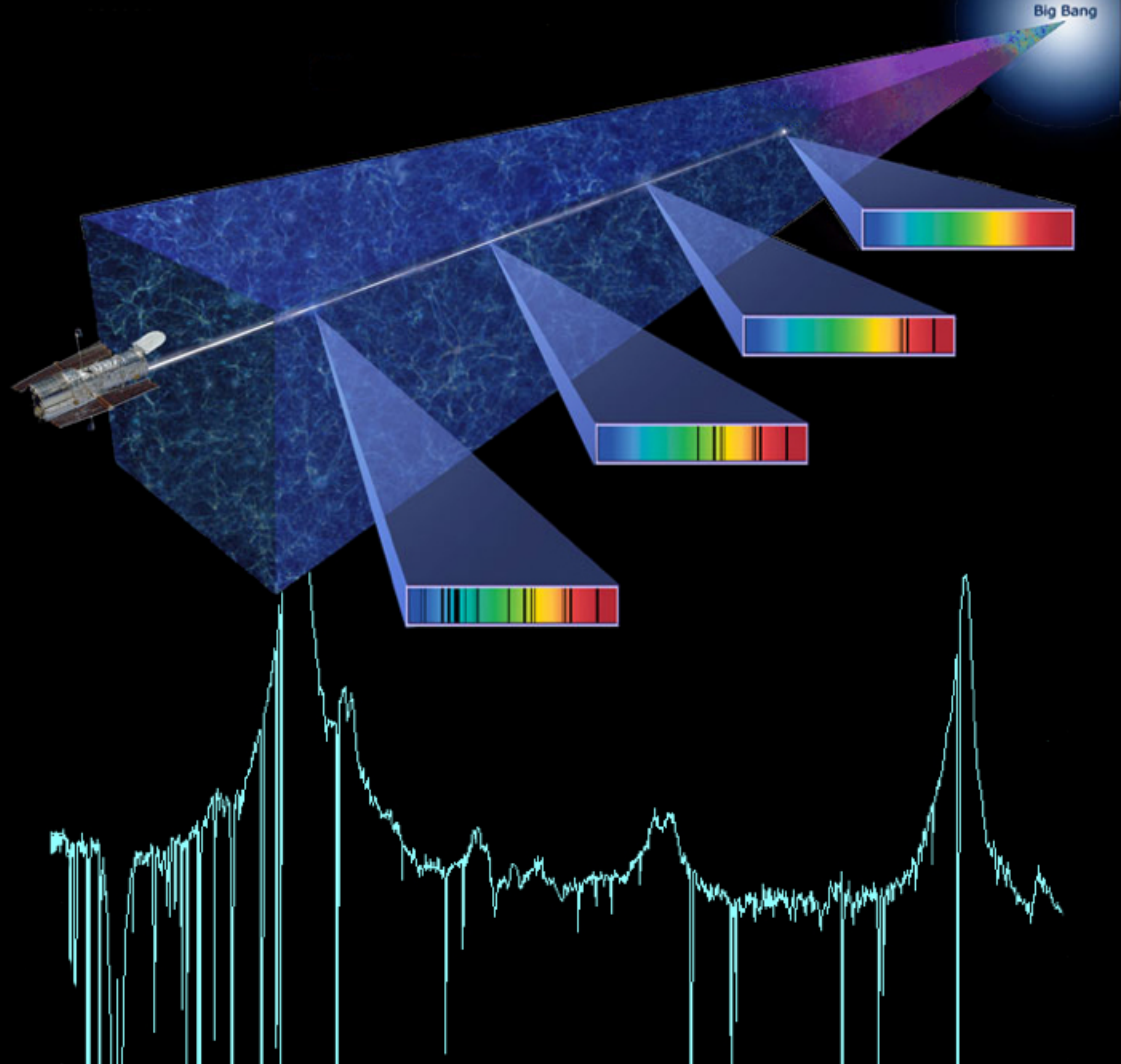
- "Proximity Effect"
  - Relative lack of Lyα absorption close to the ionizing source in QSO spectra (i.e., fewer lines near QSO rest-frame Lya, due to QSO ionizing local IGM)

http://ned.ipac.caltech.edu/level5/Sept01/Rauch/Rauch2_2.html

- Hα emission beyond edge of HI disks
- "Flux Decrement"
  - The mean fraction of QSO light observed by the Lyα forest (the "Gunn Peterson (1965) Effect"). Higher neutral fraction implies more obscuration from Lyα forest.

QSO/GRB Absorption lines

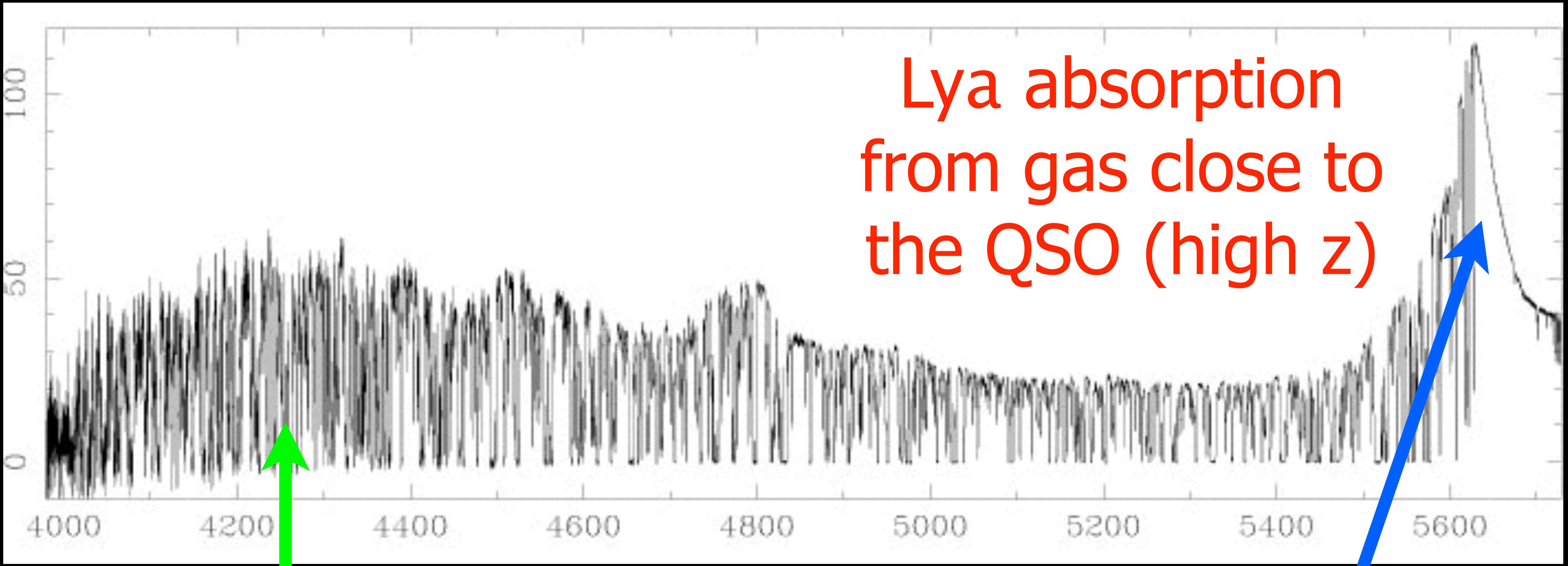
Produced by intervening gas clouds



Gas clouds not primarily neutral, especially at low column density

Absorption occurs primarily at rest frame UV (1216 for Lya). Lines appear at longer wavelengths for gas at high z.

The Lyman-alpha Forest



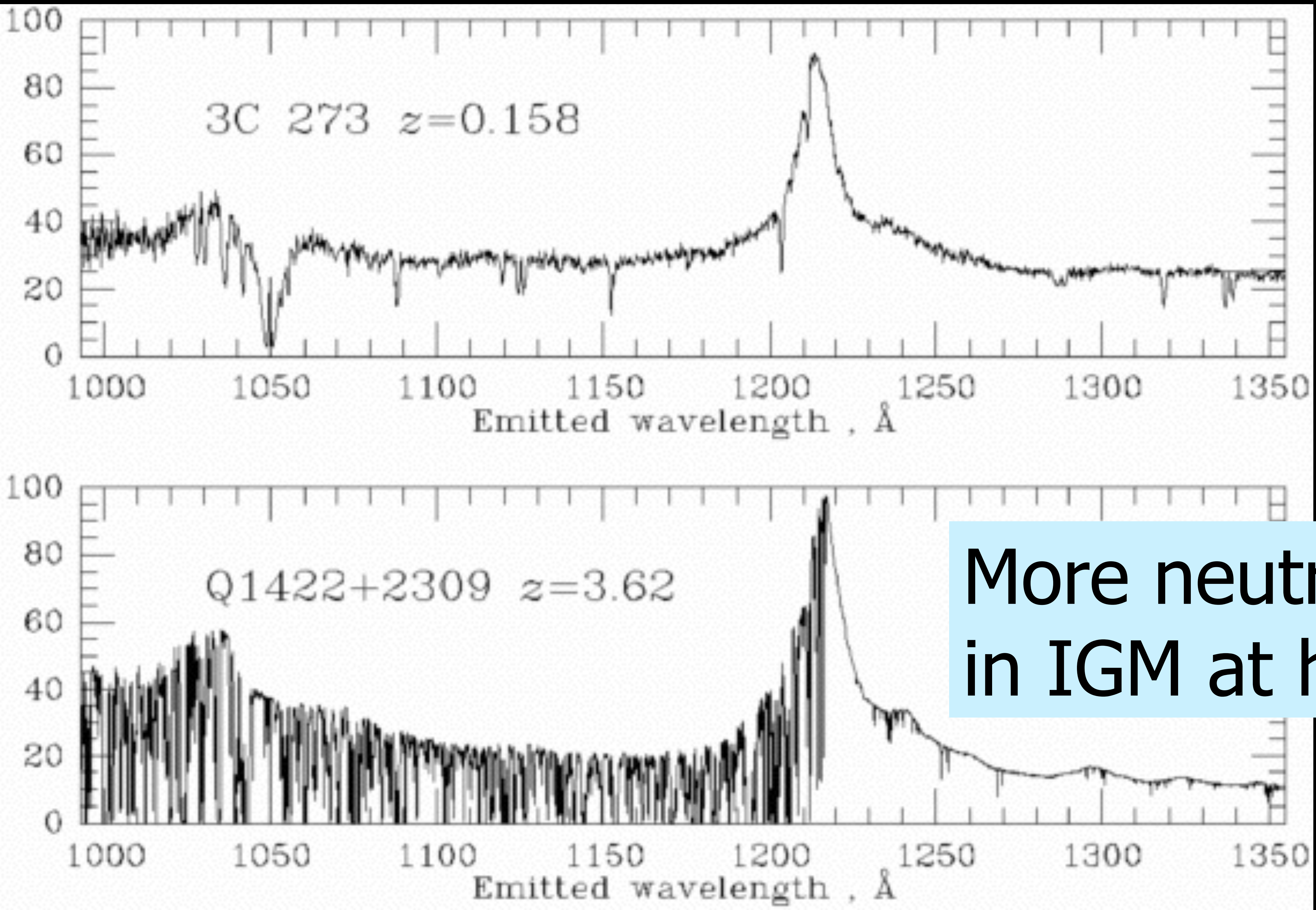
Lya absorption from gas close to the QSO (high z)

Lyα absorption from lower redshift gas

Lyα emission line from the QSO itself

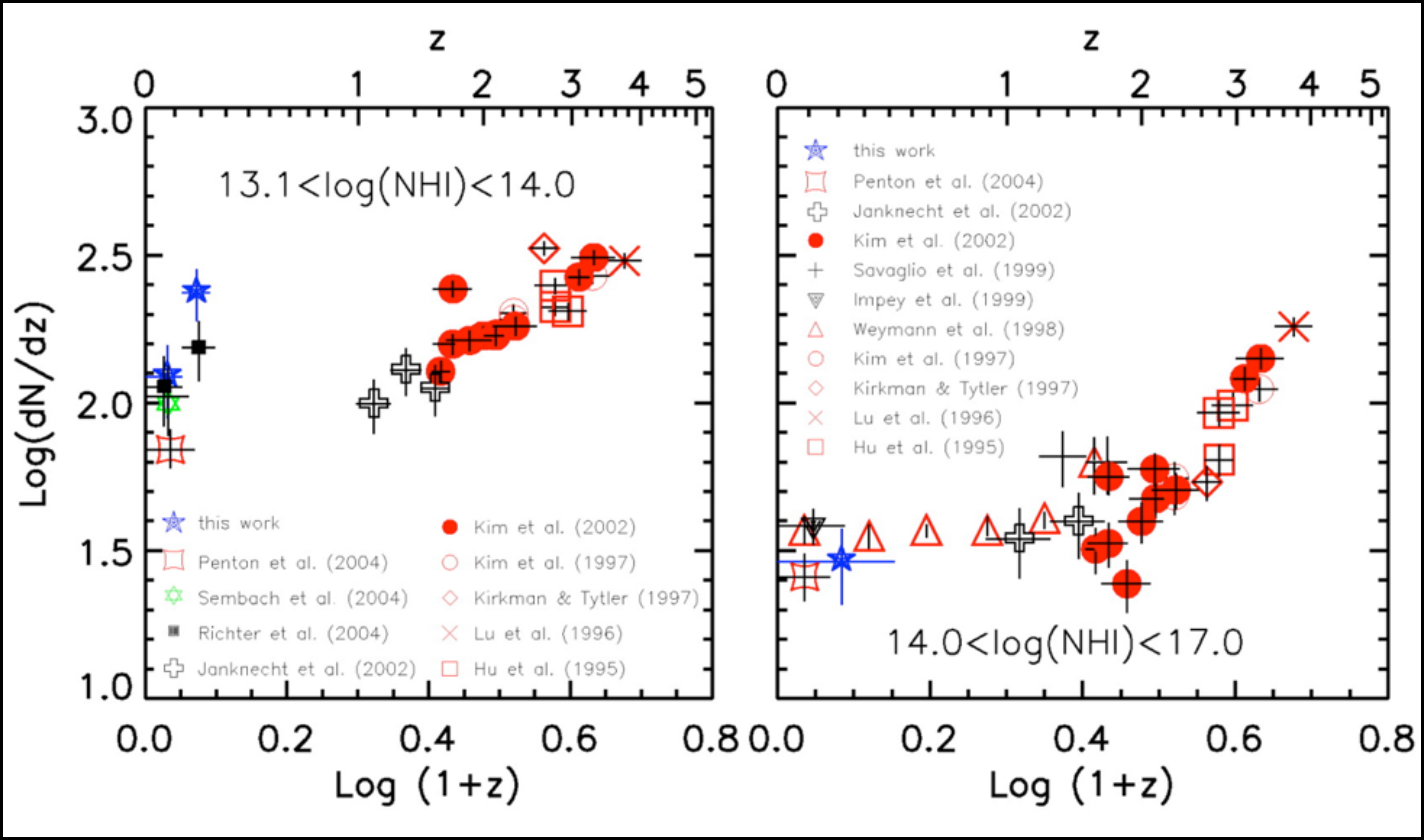
Note: Absorption due to neutral gas, but likely just a trace of HI in a highly ionized larger cloud

Amount of absorption varies with redshift



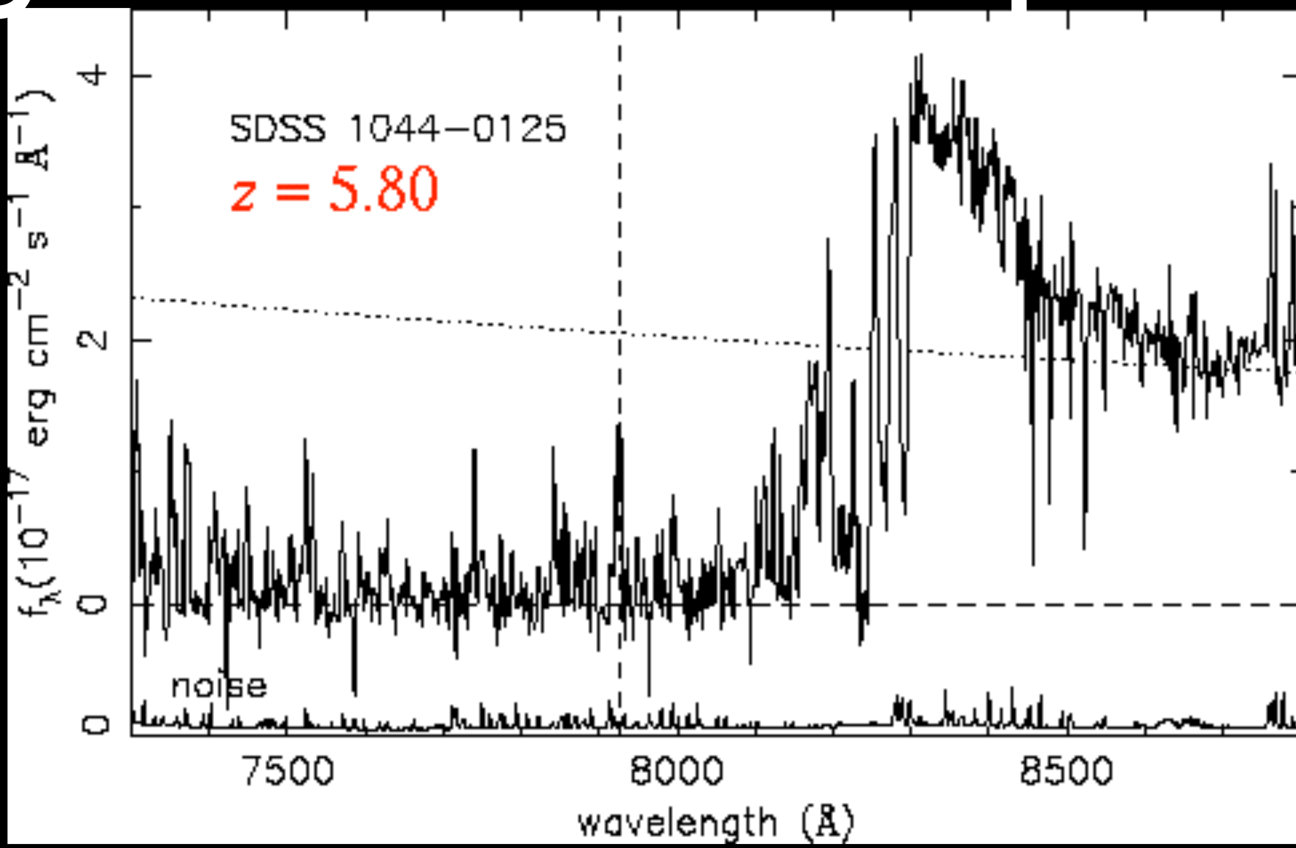
More neutral gas in IGM at high z.

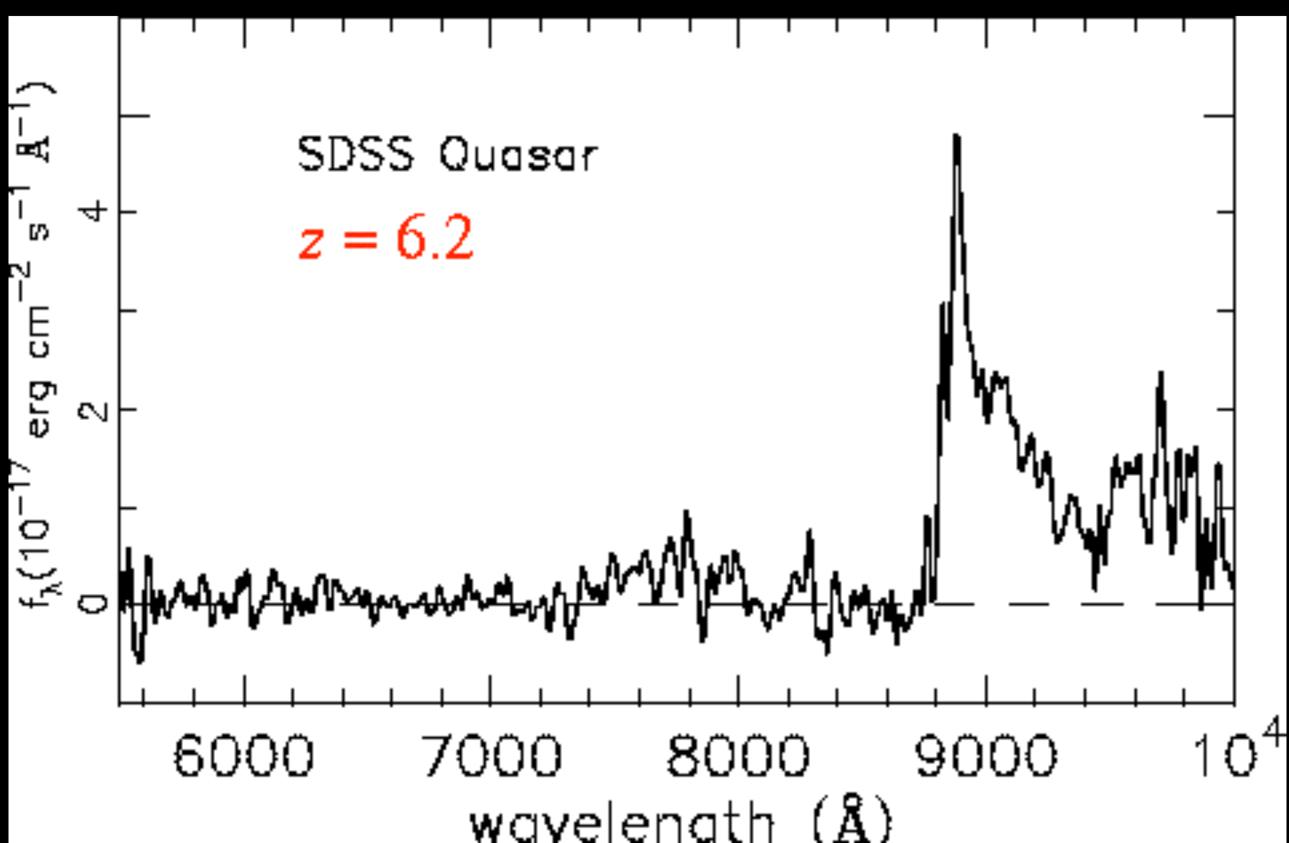
Number of absorbers shoots up at z>1



Williger et al 2006

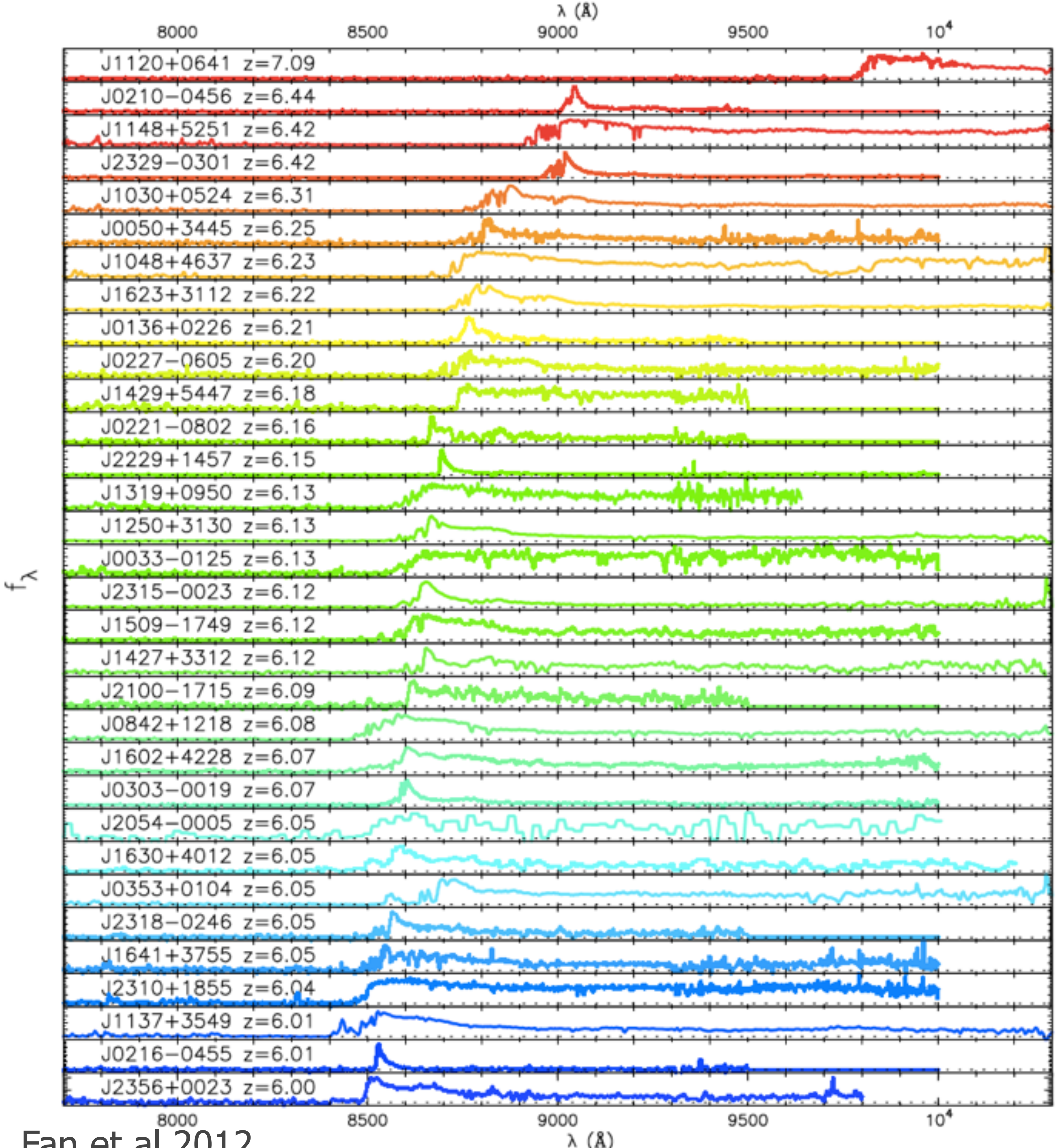
At verrry high-z, so much neutral gas that absorption blocks all flux.





Tracing the epoch of reionization?

- When?
- Uniform in time?
- Uniform in space?
- How neutral?



Fan et al 2012

Tracing reionization z=6-7

(0.77-0.94 Gyr old!)

- Continuum above Lya is increasingly dark
- But, not uniformly dark
- Suggests not uniformly neutral in space or time

Reionization complete at z~7, but likely started much earlier (CMB fits)

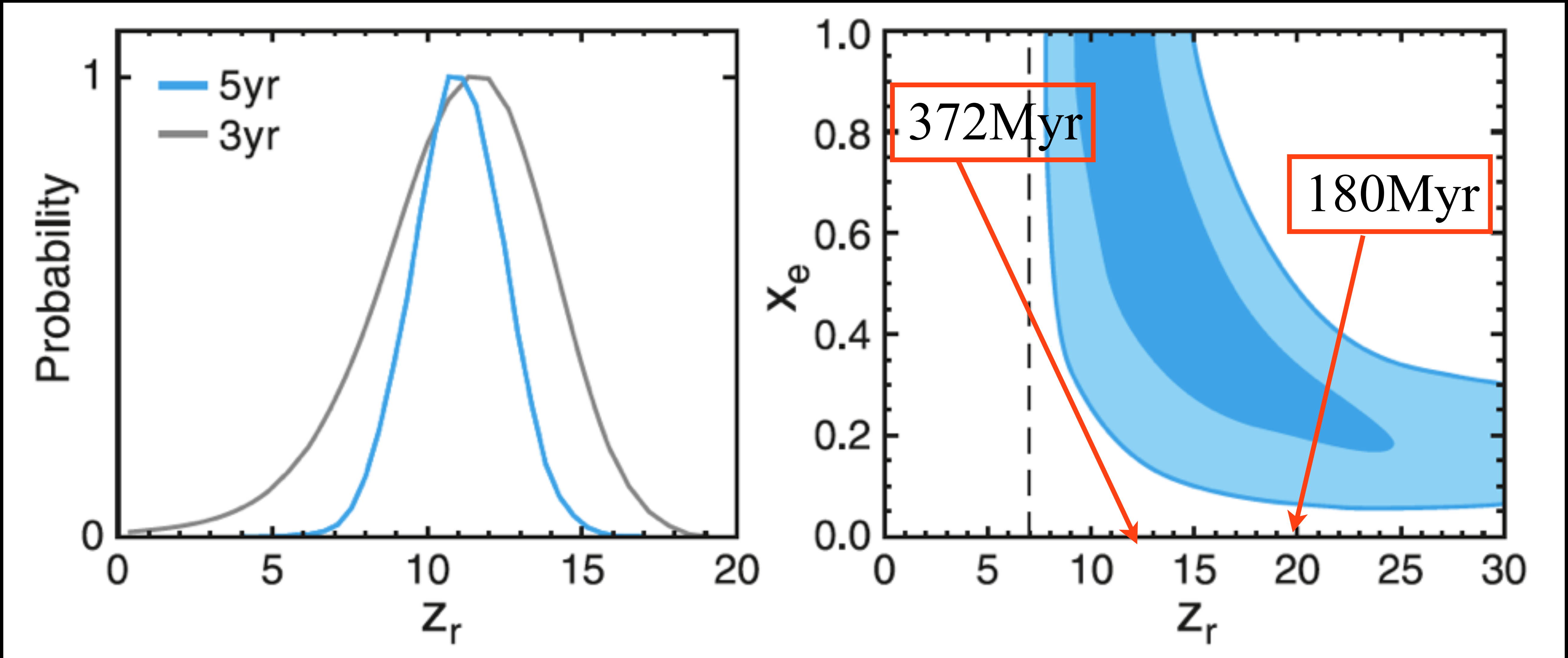
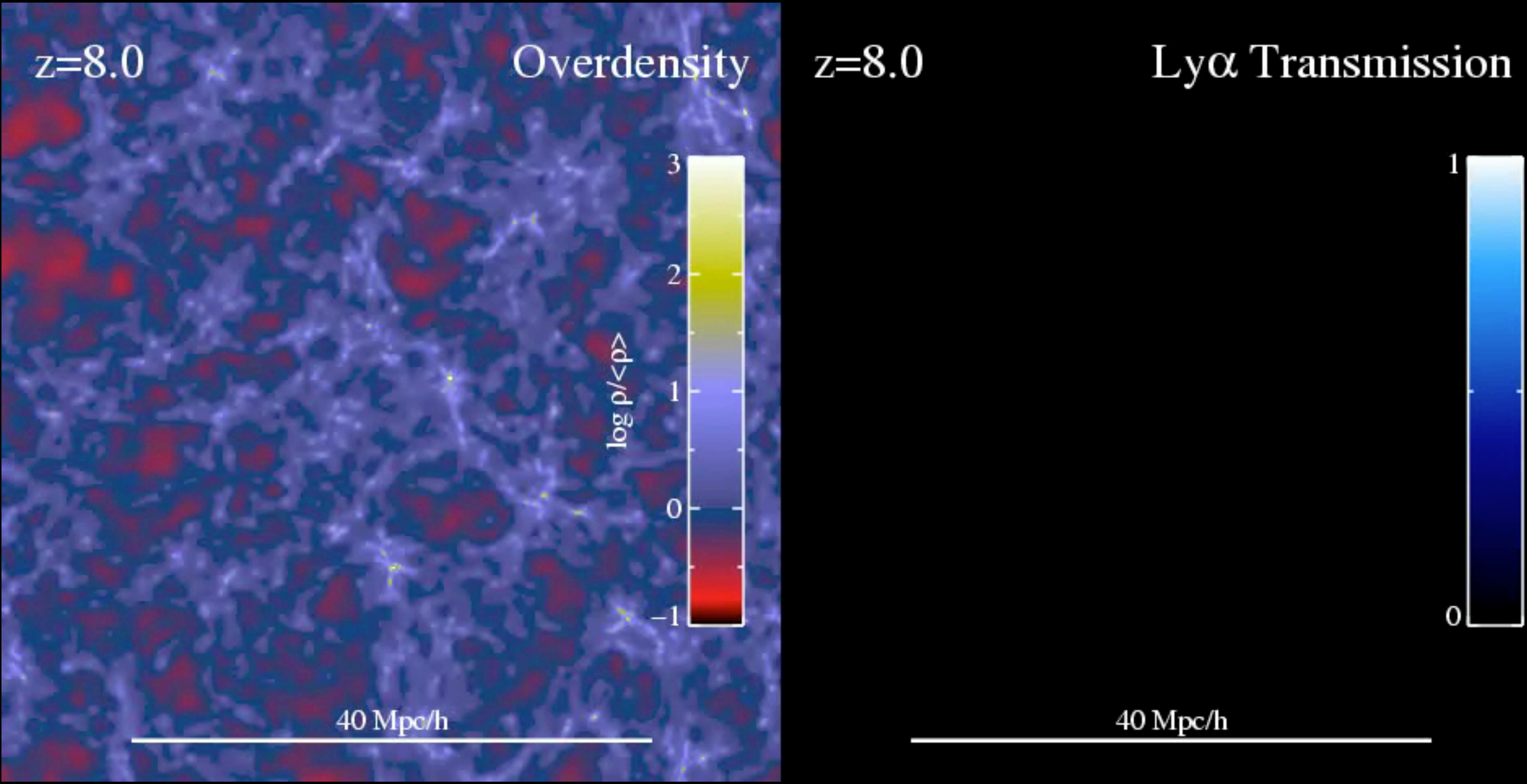


Fig. 14 *Left*: Marginalized probability distribution for $z_{\rm reion}$ in the standard model with instantaneous reionization. Sudden reionization at $z = 6$ is ruled out at a high level of significance, suggesting that reionization was a gradual process. *Right*: in a model with two steps of reionization (with ionization fraction x_e at redshift z_r, followed by full ionization at $z = 7$), the WMAP data are consistent with an extended reionization process. Adapted from Dunkley et al. (2009).

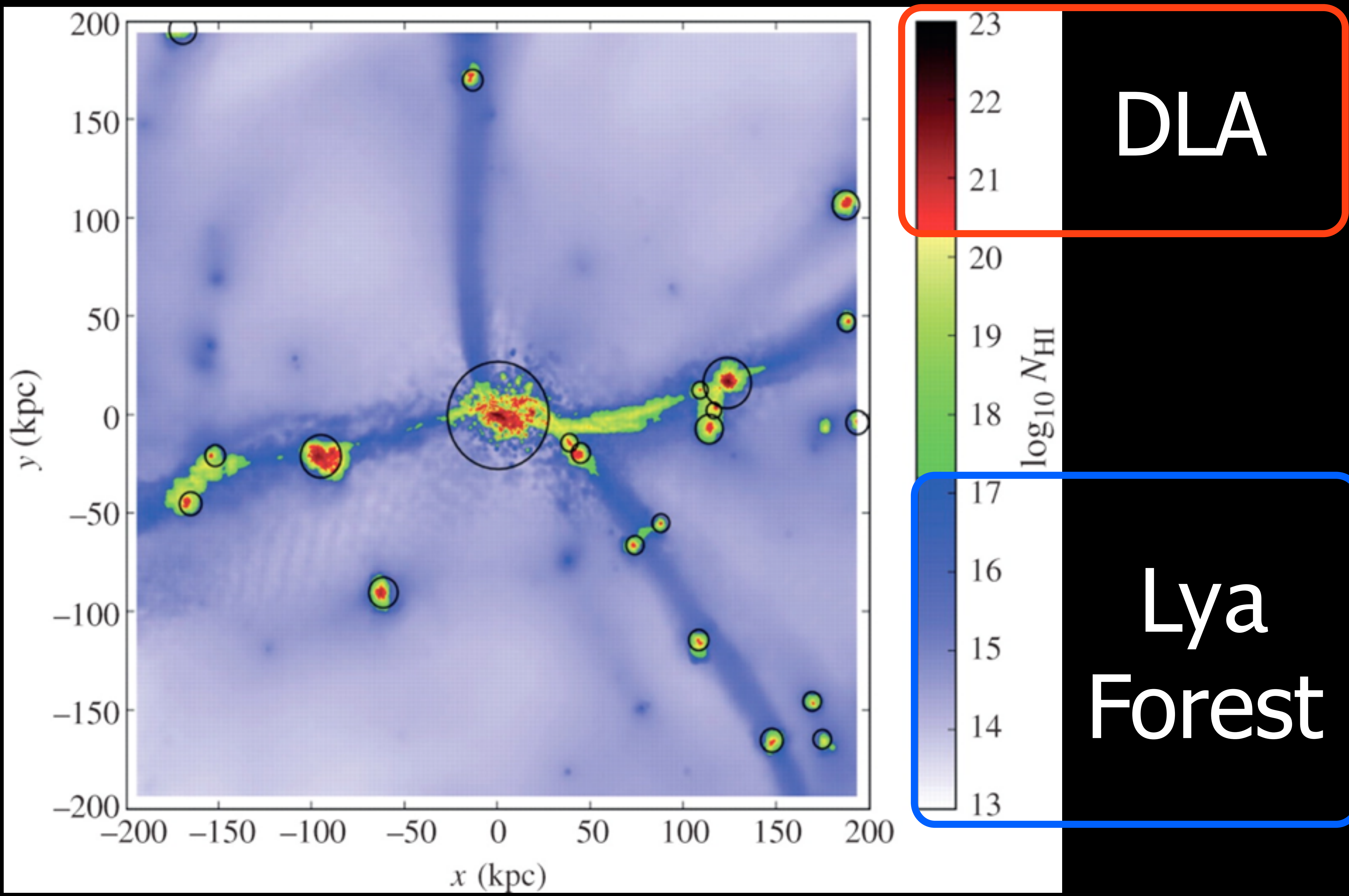
Absorption lines trace "Cosmic Web"



- Opaque before reionization (all neutral).
- After, high opacity traces densest structures

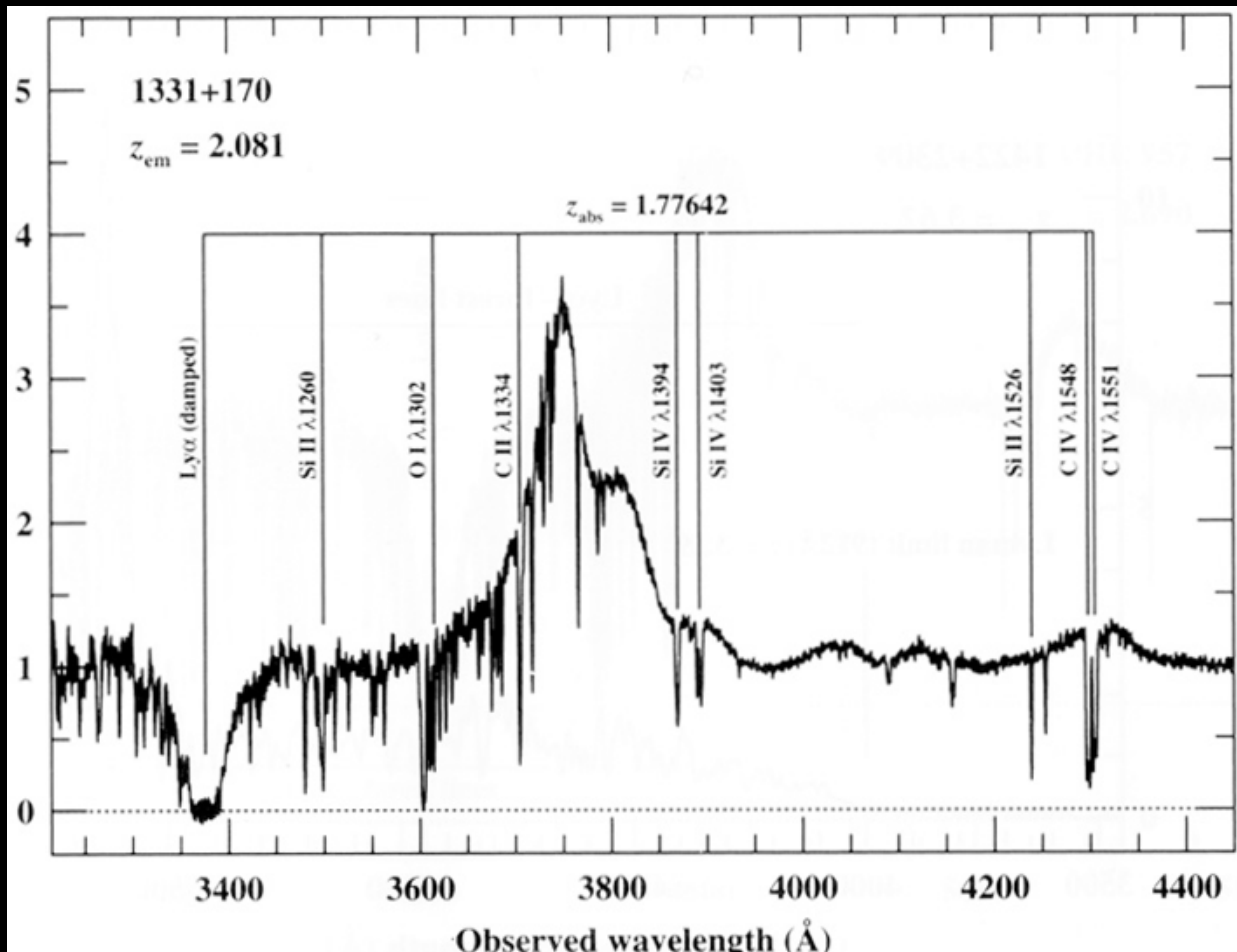
[most of IGM ionized, so little neutral gas left]

DLA: Closely associated w/ galaxies



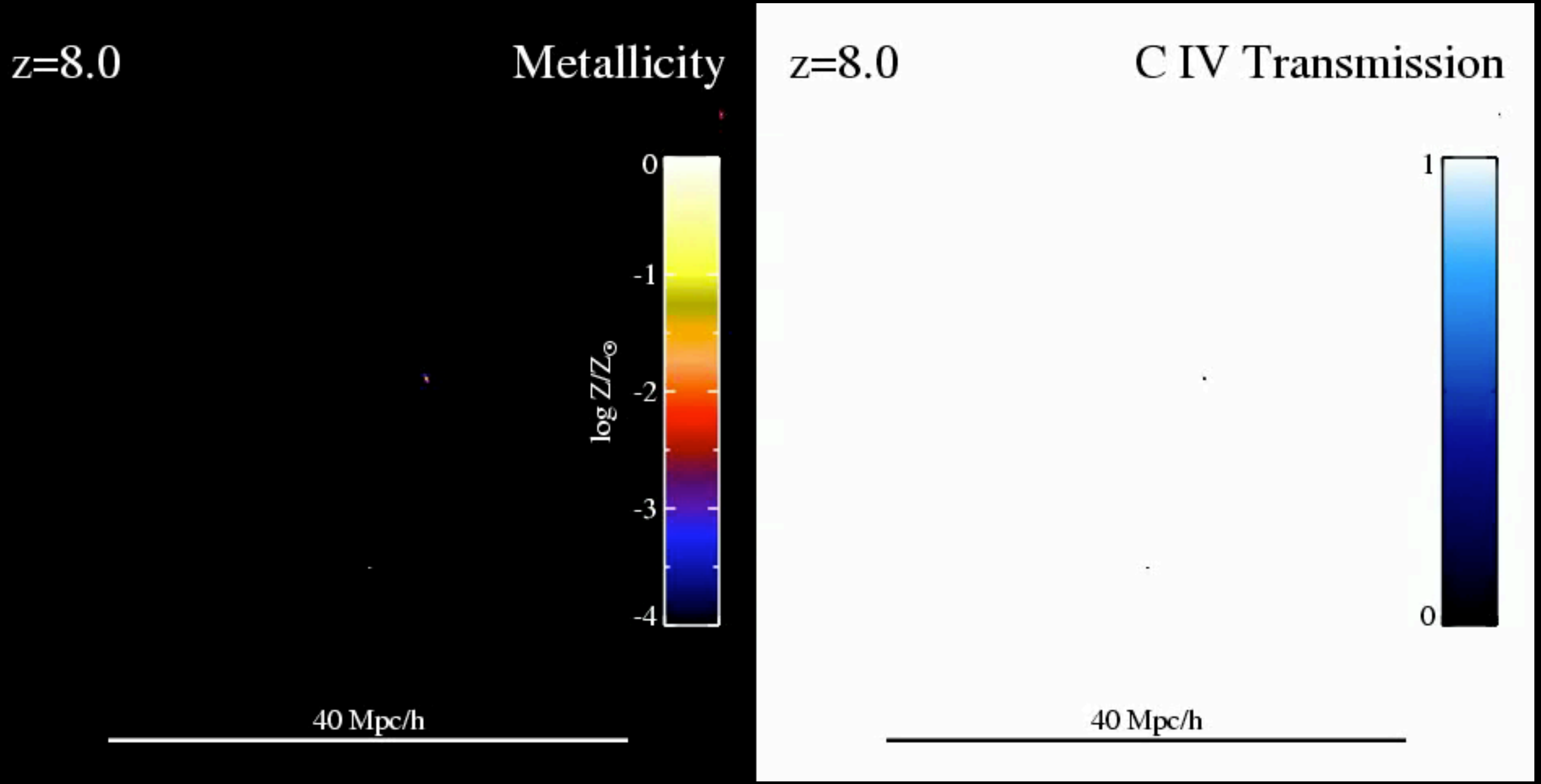
Pontzen et al 2008

Even higher column densities: Metal Line Systems



Lines at same redshift as high N_{HI} systems

Absorption lines trace "Cosmic Web"

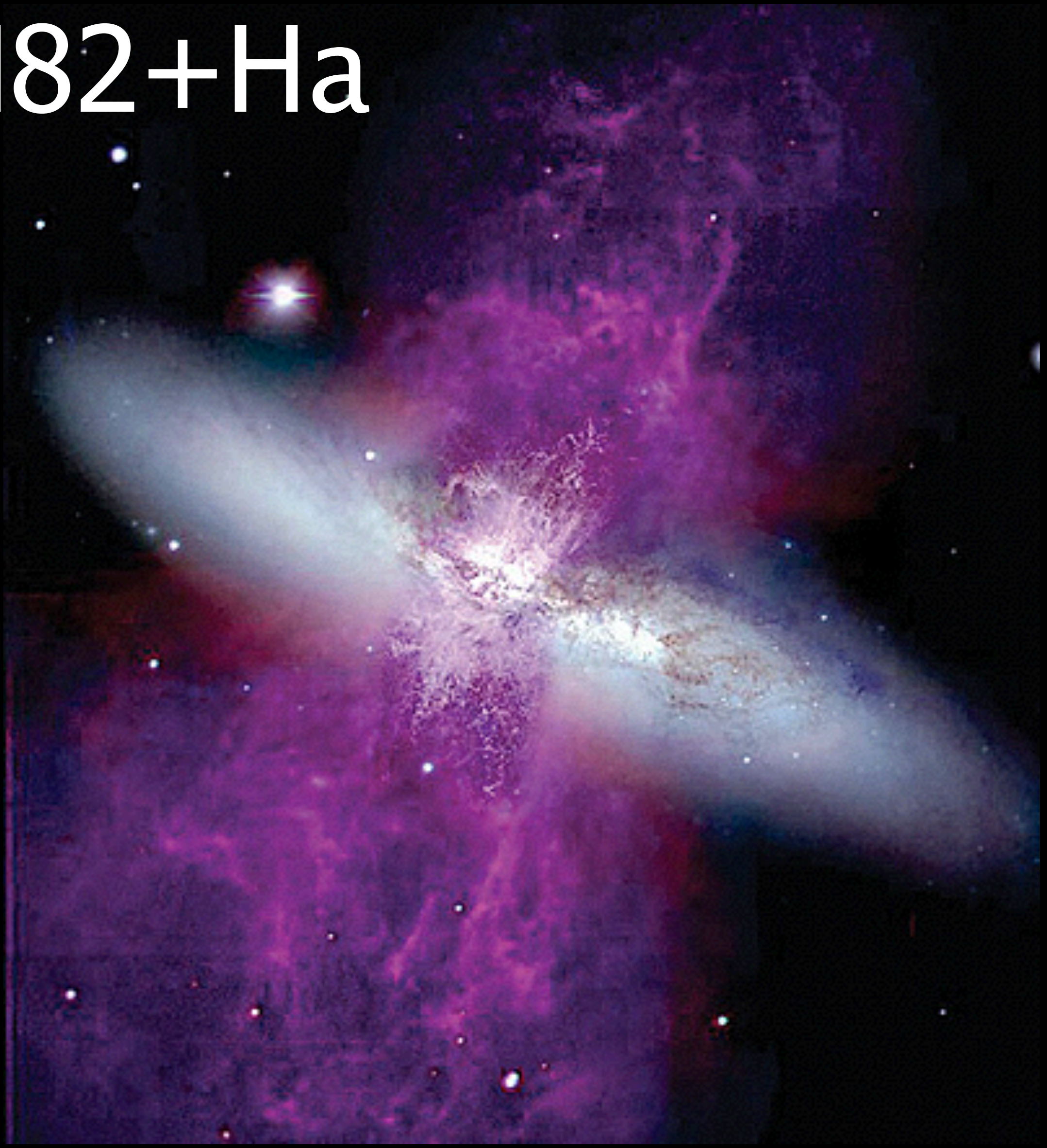


- Metal-line absorption traces even higher density structures.

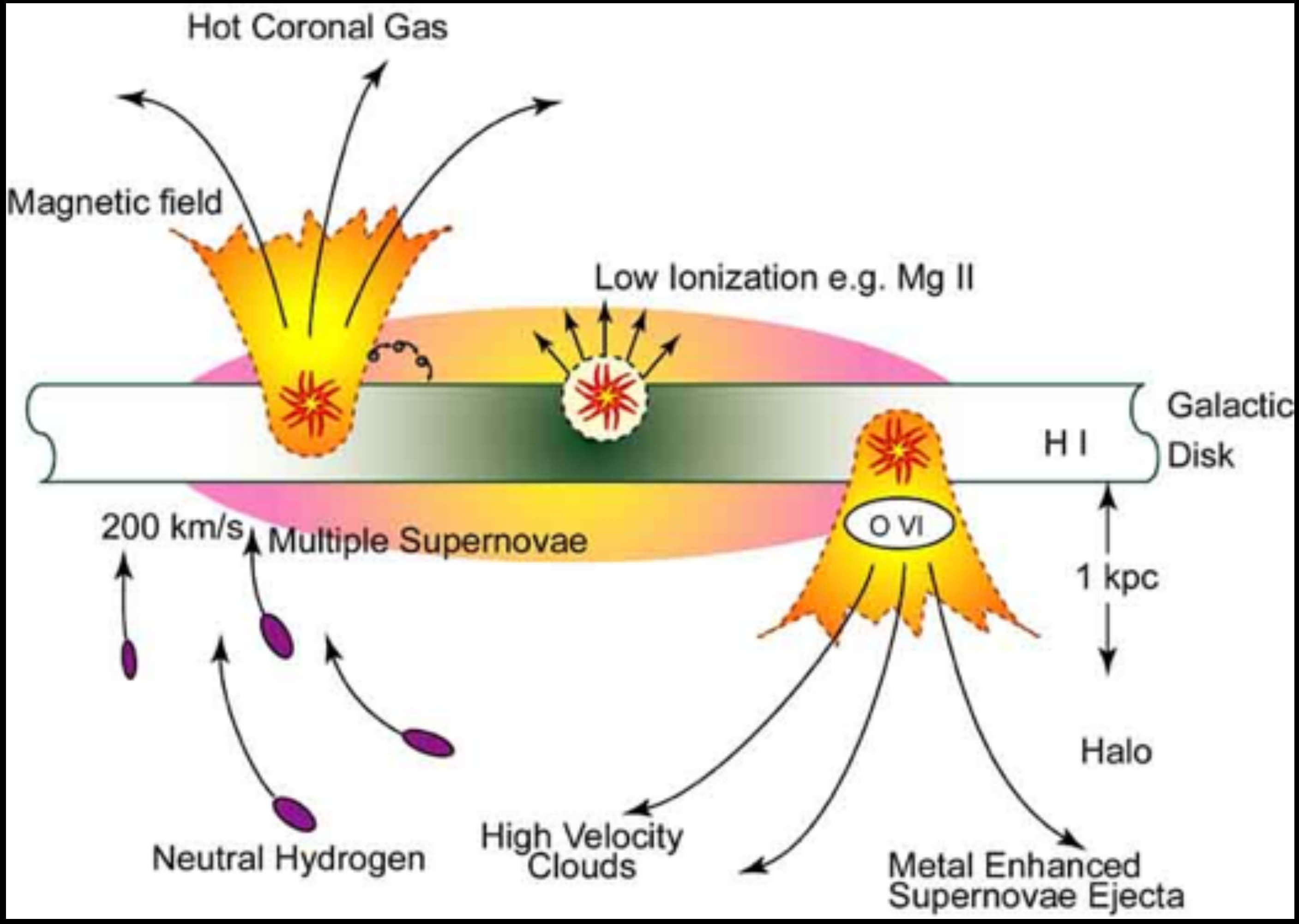
"Circum-Galactic Medium" (CGM)

Near galaxies, hot/warm gas has likely been processed through the galaxy

M82+Ha



"outflows" or "feedback"



"galactic fountain"

Need different lines to probe these hotter phases: UV+Xray spectroscopy

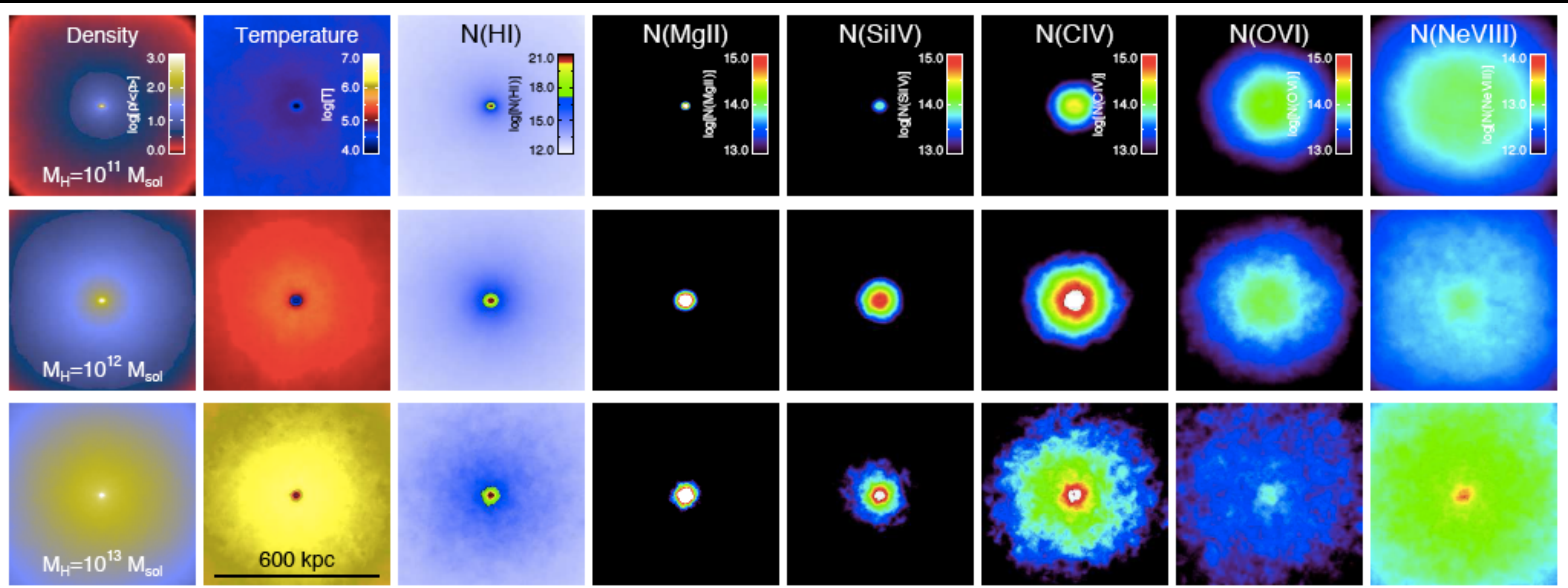
Table 1 Key Baryonic Diagnostic Lines and Features

Line	Phase	T (K)	λ_{rest} (Å)	$\lambda_{z=1}$ (Å)	$\lambda_{z=3}$ (Å)	$\lambda_{z=9}$ (μm)
Lyman-Werner	Molecular gas	10–100	~1000	2000	4000	1
21cm	Atomic gas	100–1000	21cm	0.7 Ghz	0.4 Ghz	140 MHz
Lyα	Atomic+Ionized gas	100–40000	1216	2400	4800	1.2
Hα	Ionized gas	10000–40000	6560	13000	26000	65000
Lyman limit	Ionized gas	10000–40000	912	1800	3600	0.9
HeII	Ionized gas	10000–40000	304	450	912	0.2
CIV	Ionized Gas	20000–40000	1550	3000	6000	1.5
OVI	Warm/Hot Gas	20000–10^6	1030	2000	4000	1
OVII,OVIII	Hot Gas	10^6–10^8	21.6,18.9	40	8	200
NeVIII	Hot Gas	10^7	775	1550	3100	7750

(At high enough temperatures, hydrogen 100% ionized, so can only reliably use metals)

Prochaska & Tumlinson 2008

CGM: trace w/ metal-rich ionized gas



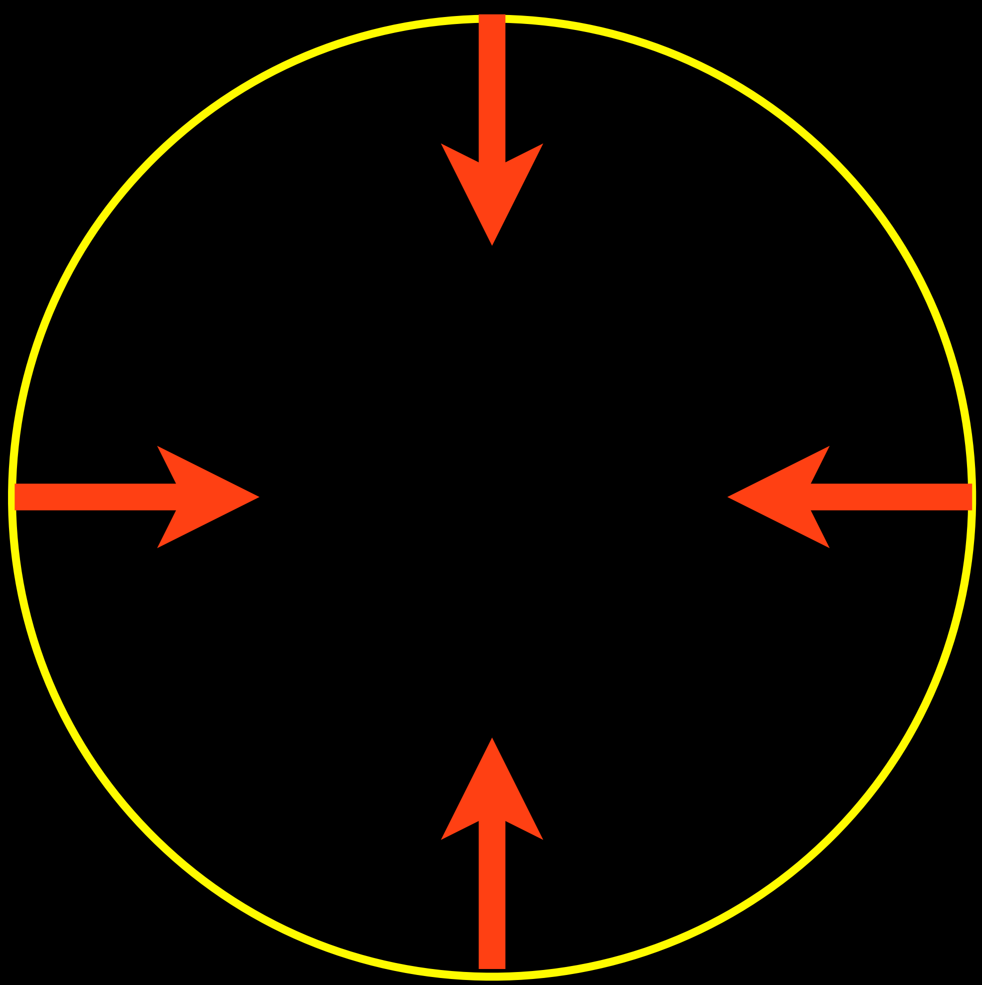
Numerical simulations z~0.25: Ford et al 2013

Note: Depends critically on galactic winds. If "feedback" (i.e., winds) are turned off, little halo

How does gas get into galaxies?

- General smooth accretion
- Effects of UV background
- Hot mode vs Cold mode accretion

Old School: Collapse + Cooling



Classic papers: White & Rees 1978, Rees & Ostriker 1977

- Gravity pulls gas into dark matter overdensities
- Kinetic energy quickly "thermalizes" via shocks, heating the gas to high temps
- If gas can cool faster than collapse time, dissipates into center

What are characteristic temperatures?

Gravitational equilibrium:

$$\frac{GM}{r^2} 4\pi r^2 \rho(r) dr = \left(-\frac{dp}{dr} dr \right) 4\pi r^2$$

Where the pressure is:

$$p = \frac{\rho k_B T}{\mu m_p}$$

Which leads to:

$$T = \left(\frac{\mu m_p}{2k_B} \right) v_{\rm circ}^2$$

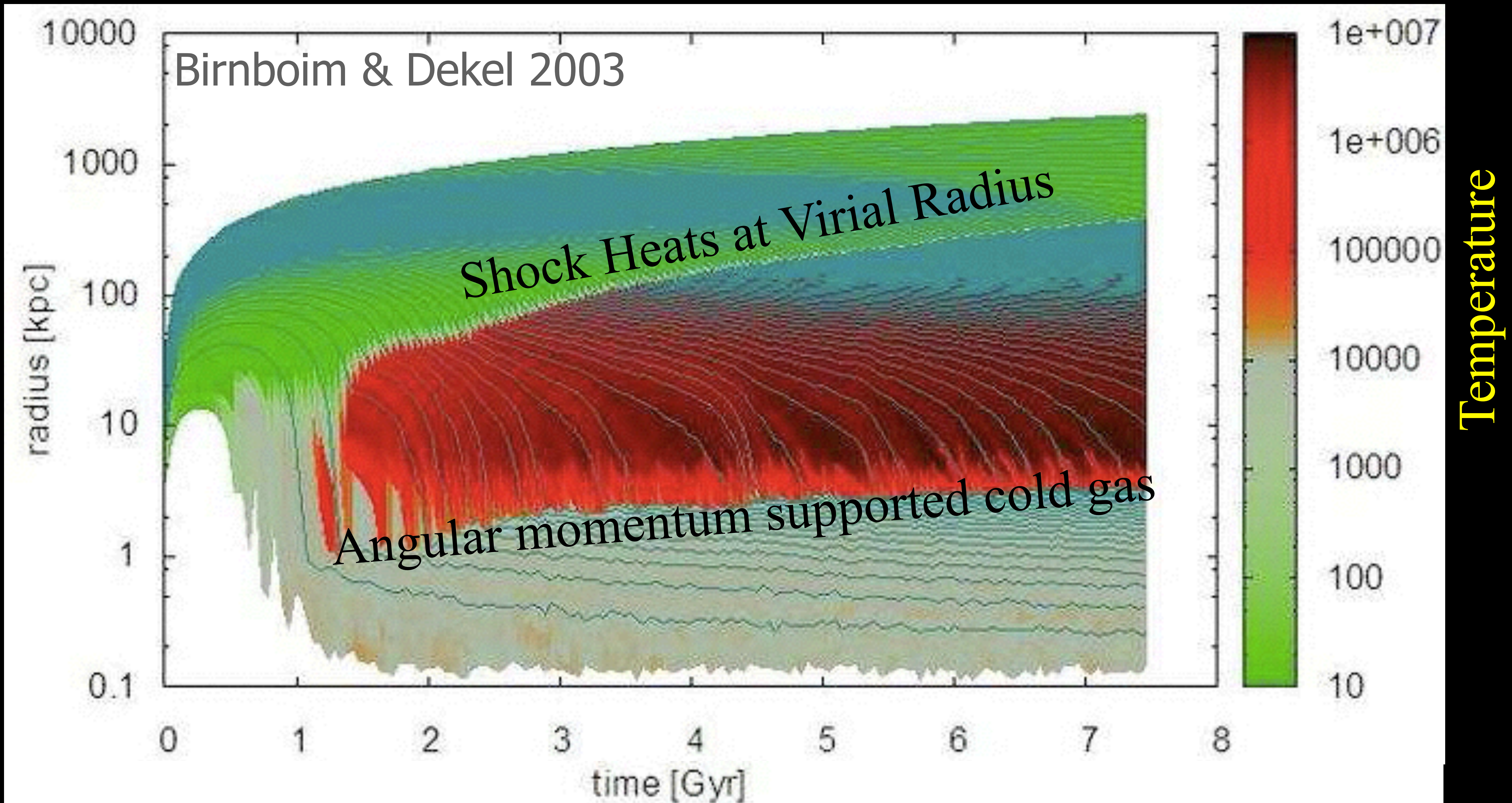
$$= 5.95 \times 10^5 \text{ K} \left(\frac{\mu}{0.6} \right) \left(\frac{v_{\rm circ}}{128 \text{ km s}^{-1}} \right)^2$$

Very Hot

Highly ionized

Thoul & Weinberg 1996

Simulation of massive galaxy gas infall



Massive Galaxy: $M_{final} \sim 10^{13}$ M_{sun}

Collapse largely unaffected by UV background, for massive galaxies

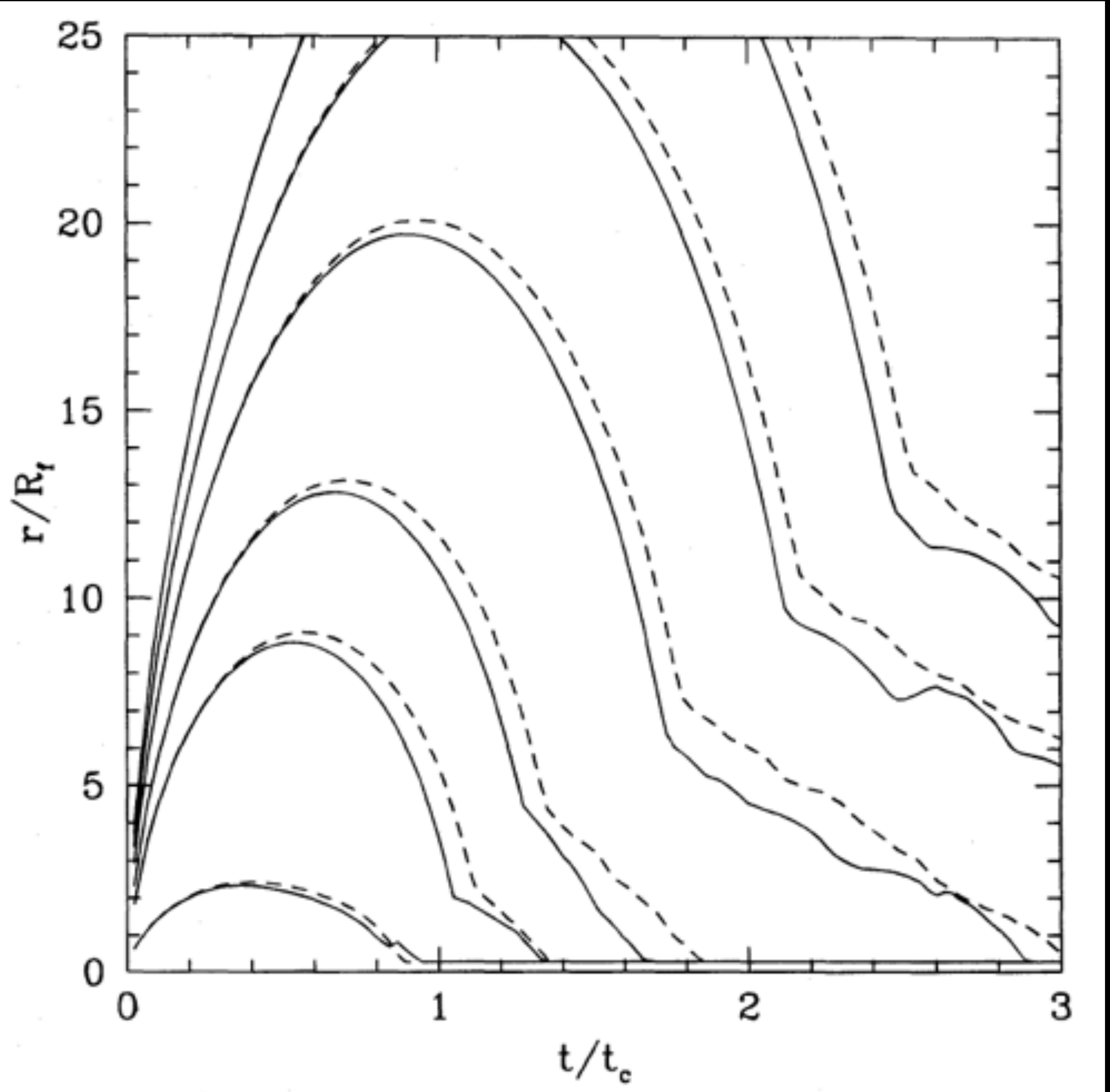


FIG. 3.—Gas shell trajectories in high-mass collapses ($M_f = 1 \times 10^{11}$ $M_\odot$, $z_c = 2$, $v_{circ} = 128$ km s^{-1}) with (*dashed lines*) and without (*solid lines*) a UV background. The time and radii are scaled with respect to the collapse time t_c and the filter radius R_f.

Thoul & Weinberg 1996

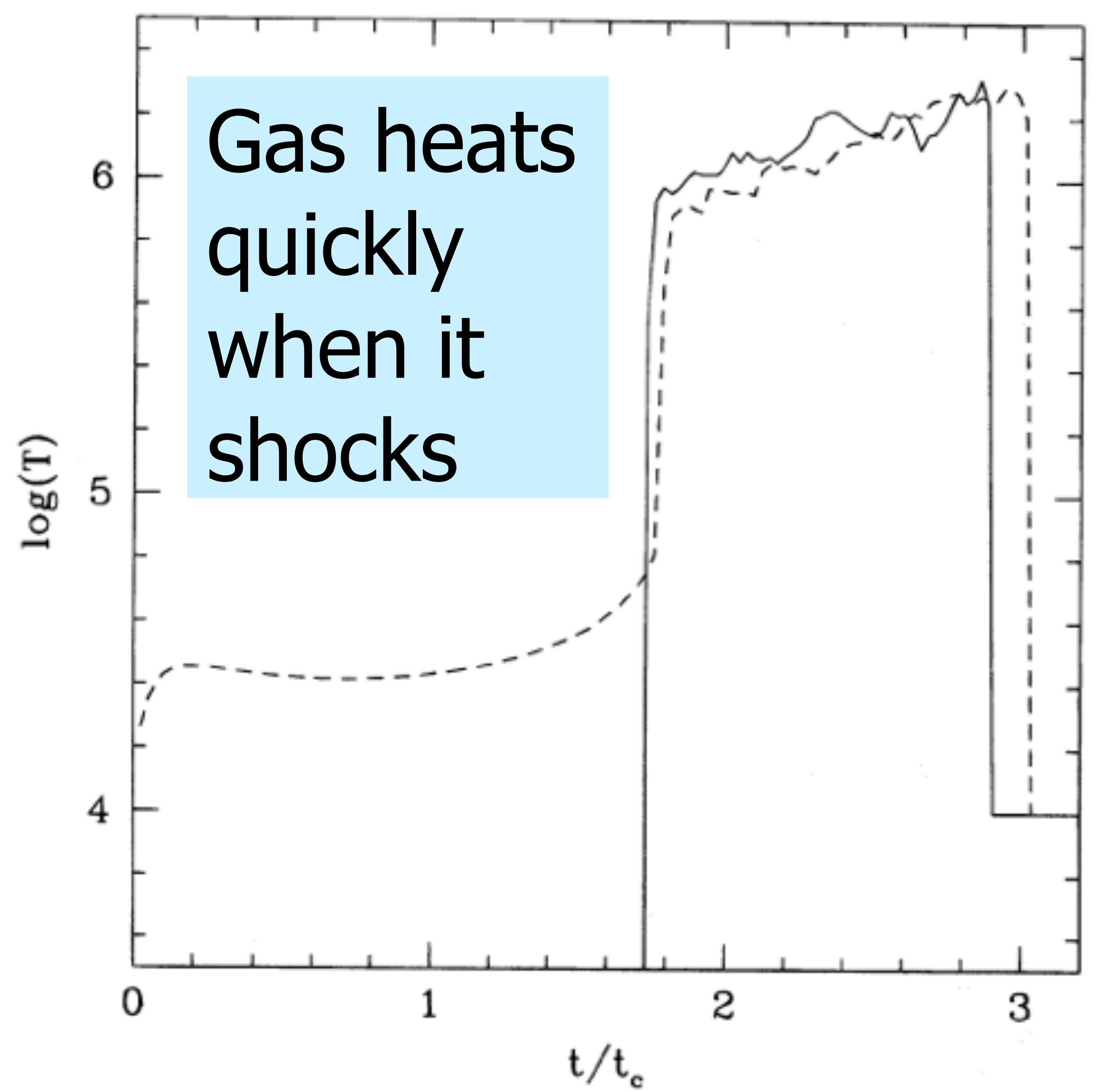


FIG. 4.—Time evolution of the temperature of a typical gas shell in the high-mass collapses of Fig. 3, with (*dashed line*) and without (*solid line*) a UV background.

Solid: No UV background   Dashed: UV on

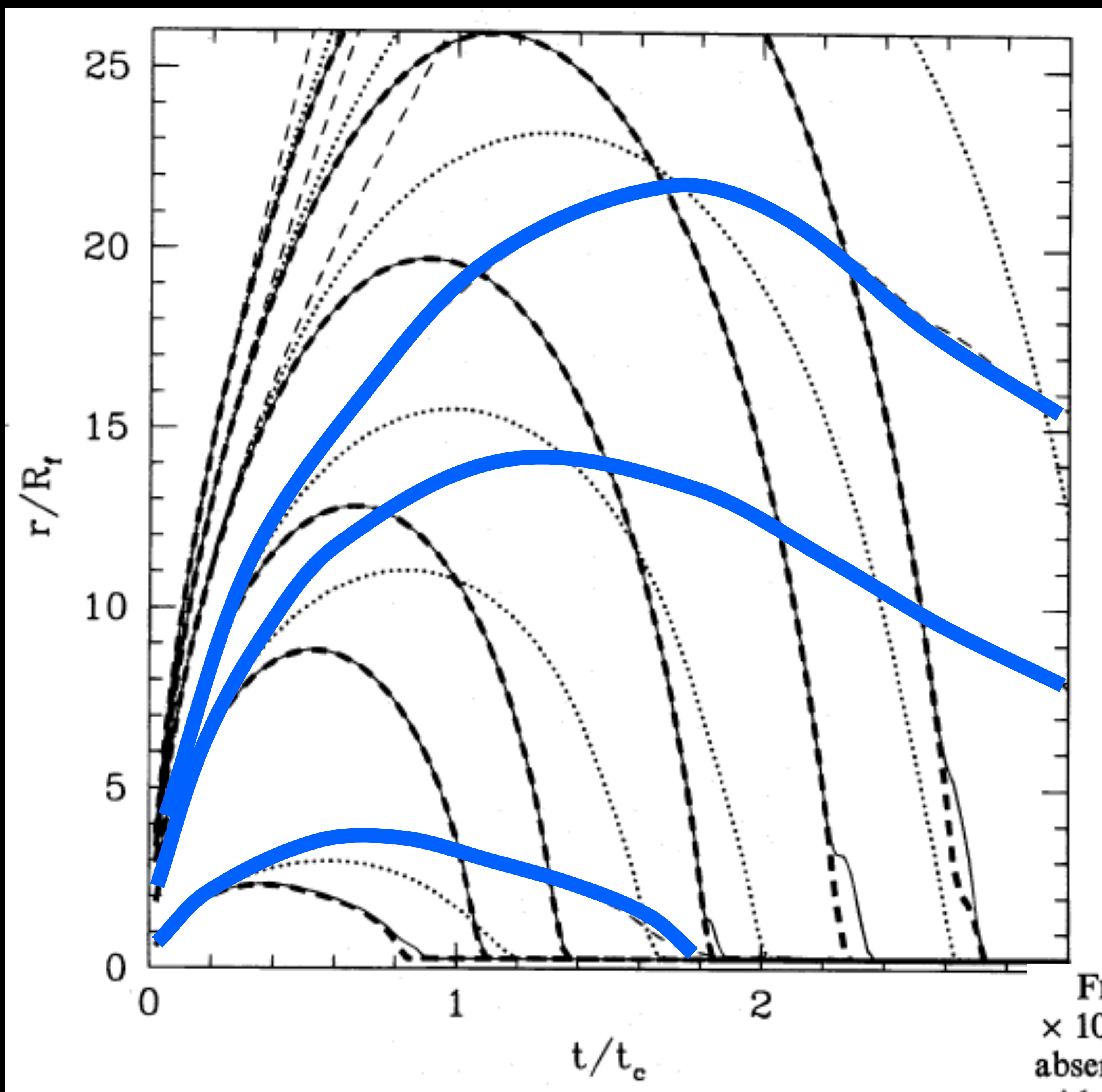
Very different for low mass galaxies

$$T = \left(\frac{\mu m_p}{2k_B}\right) v_{\rm circ}^2$$

$$= 5.95 \times 10^5\ \mathrm{K} \left(\frac{\mu}{0.6}\right)\left(\frac{\boxed{v_{\rm circ}}}{128\ \mathrm{km\ s^{-1}}}\right)^2$$

- UV background sets temperature of IGM gas.
- If this temperature is hotter than the characteristic temp needed to keep gas pressure supported in a halo, no collapse.

After reionization, hard to get gas to cool into low mass halos



- Reduces gas fraction in low mass halos
- Can keep very low mass halos entirely “dark”

FIG. 5.—Gas shell trajectories in a low-mass collapse ($M_f = 0.02 \times 10^{11}\ M_\odot$, $z_c = 2$, $v_{\rm circ} = 35\ {\rm km\ s^{-1}}$). The solid lines are obtained in the absence of a UV background ($J_{-21} = 0$). The dashed lines are obtained with $J_{-21} = 1$ and $\alpha = 1$. The dotted lines are obtained with $J_{-21} = 1$ and $\alpha = 5$. The thick dashed lines are obtained with $J_{-21} = 1$ and $\alpha = 1$, but neglecting heating terms. The time and radii are scaled with respect to the collapse time t_c and the filter radius R_f.

Thoul & Weinberg 1996

Effects most important at V_c<30 km/s

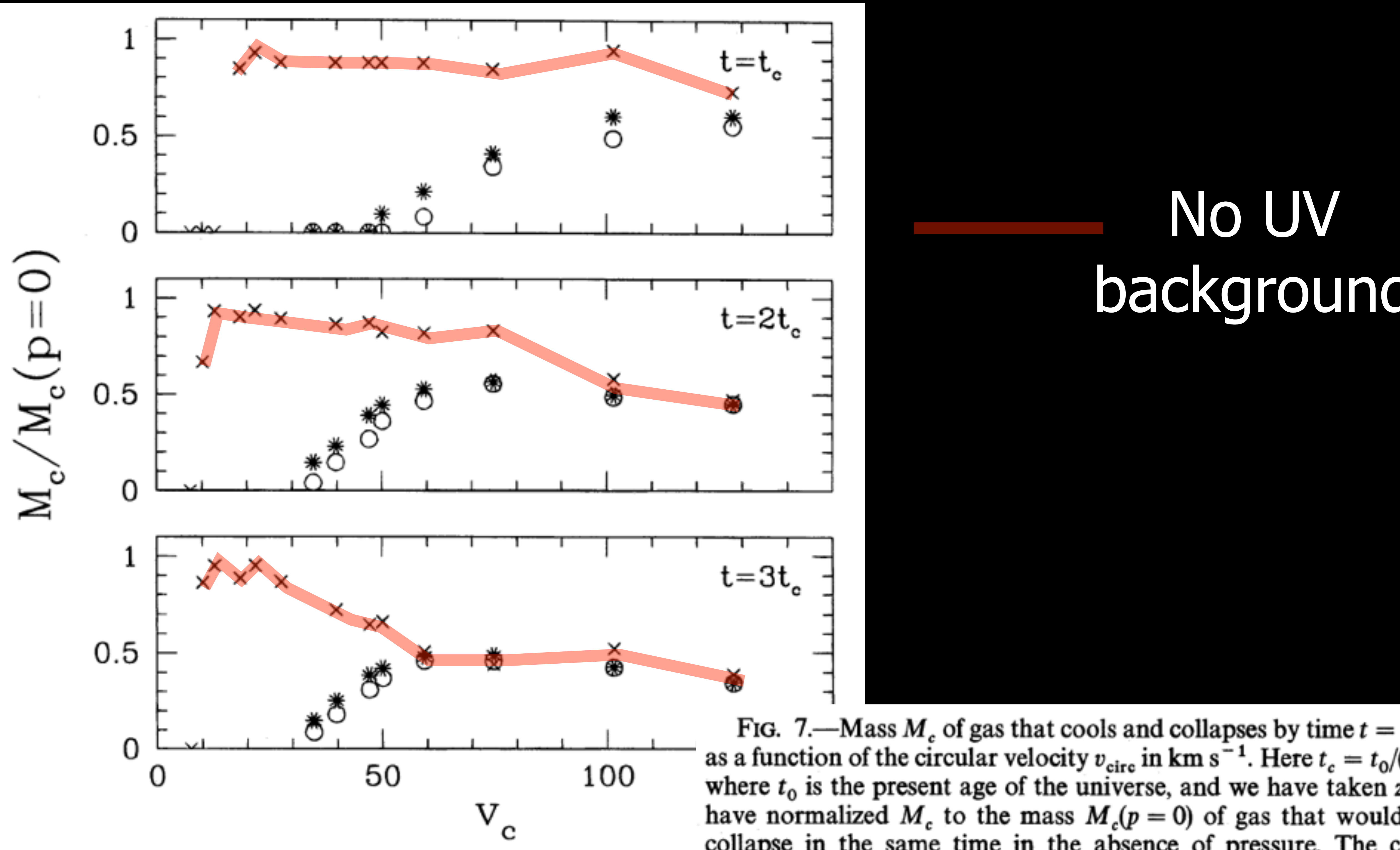


FIG. 7.—Mass M_c of gas that cools and collapses by time $t = t_c, 2t_c, 3t_c$, as a function of the circular velocity $v_{\rm circ}$ in km s^{-1}. Here $t_c = t_0/(1 + z_c)^{3/2}$, where t_0 is the present age of the universe, and we have taken $z_c = 2$. We have normalized M_c to the mass $M_c(p = 0)$ of gas that would cool and collapse in the same time in the absence of pressure. The crosses are obtained in the absence of a UV background; the circles are obtained in the presence of the photoionizing flux defined by eqs. (1) and (2), with $J_{-21} = 1$ and $\alpha = 1$; the asterisks are obtained for $J_{-21} = 0.3$ and $\alpha = 1$.

Thoul & Weinberg 1996

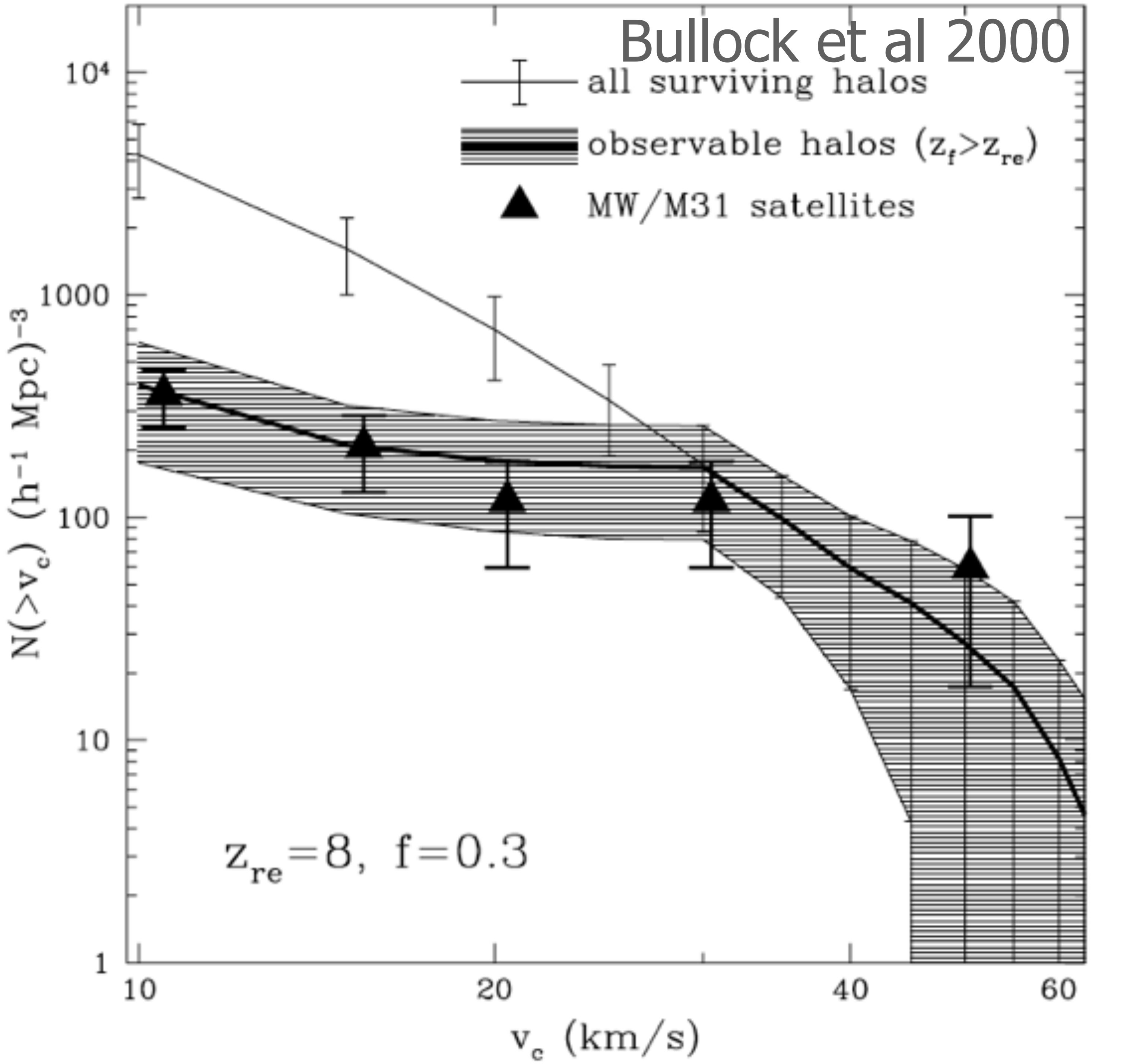
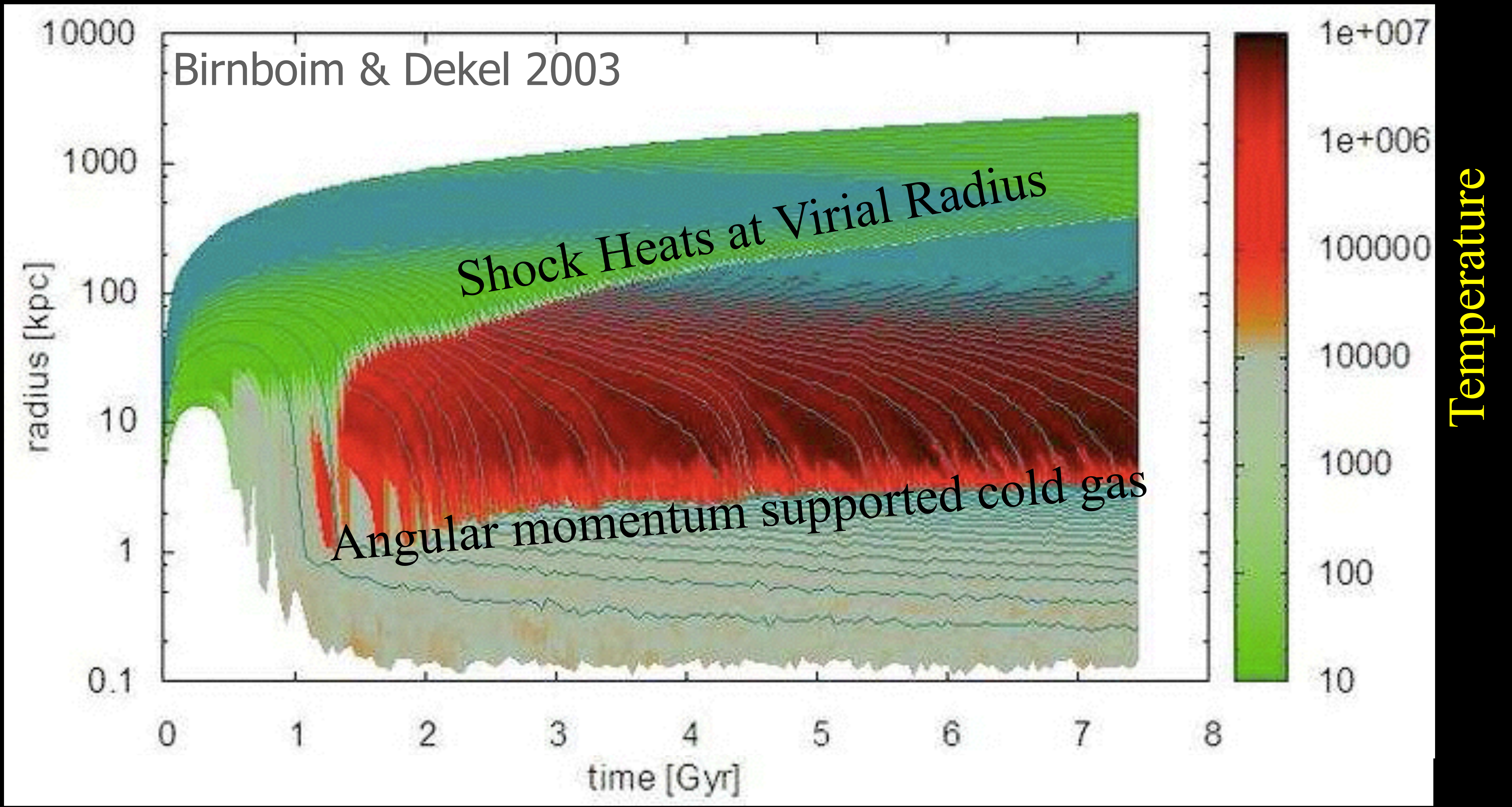


FIG. 2.— Cumulative velocity function of all dark matter subhalos surviving at $z = 0$ (*thin solid line*) and "observable" halos ($z_f > z_{re}$) (*thick solid line with shading*), for the specific choice of $z_{re} = 8$ and $f = 0.3$. The velocity function represents the average over 300 merger histories for halos of mass $M_{vir}(z = 0) = 1.1 \times 10^{12} h^{-1}\ M_\odot$. The errorbars and shading show the dispersion measured from different merger histories. The observed velocity function of satellite galaxies around the Milky Way and M31 is shown by triangles.

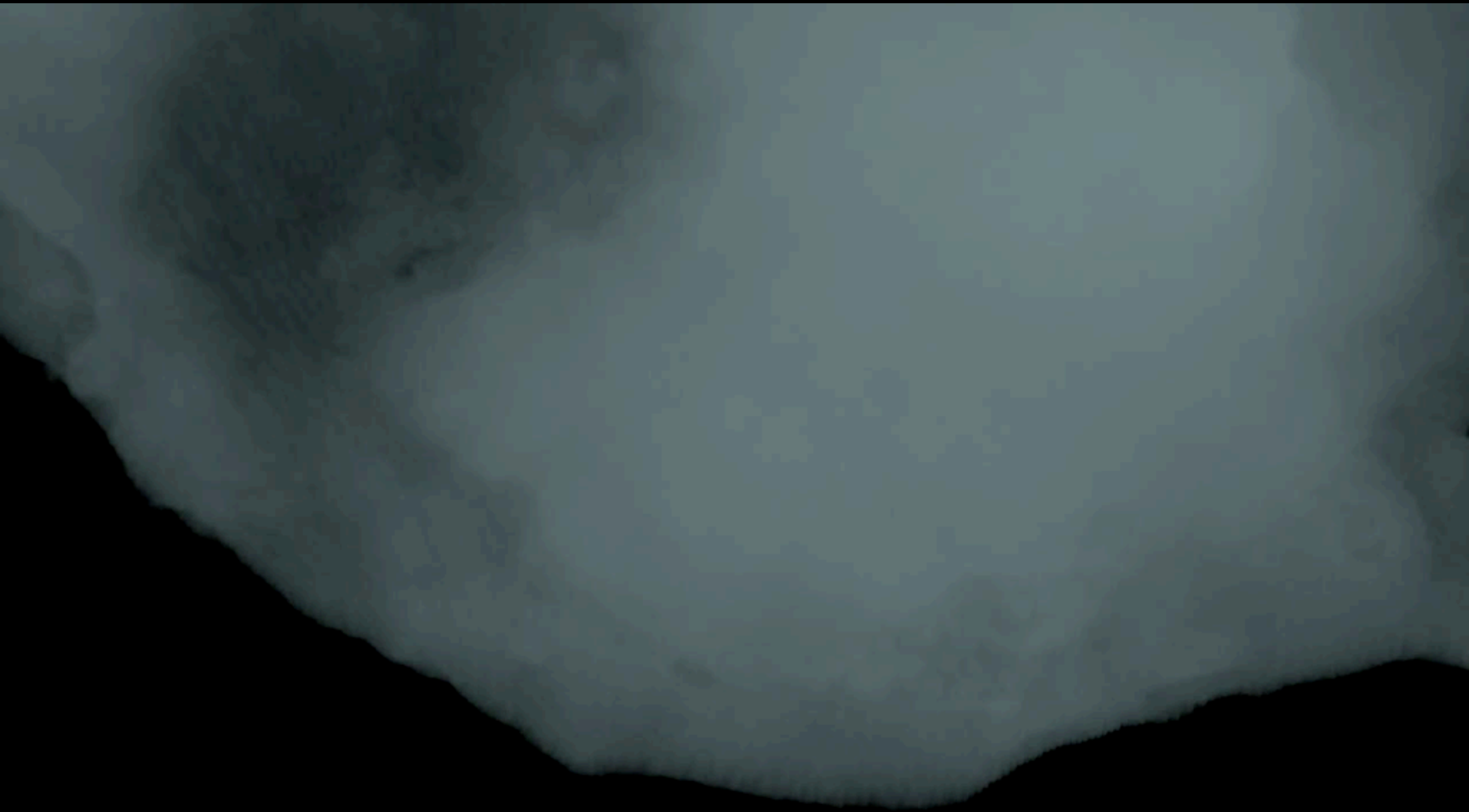
UV background + tidal stripping: partial reason for paucity of low mass galaxies in Local Group

Predicts visible dwarfs are those that accreted gas before reionization

Actual gas accretion more complicated than classical shocked, virialized, cooling halo

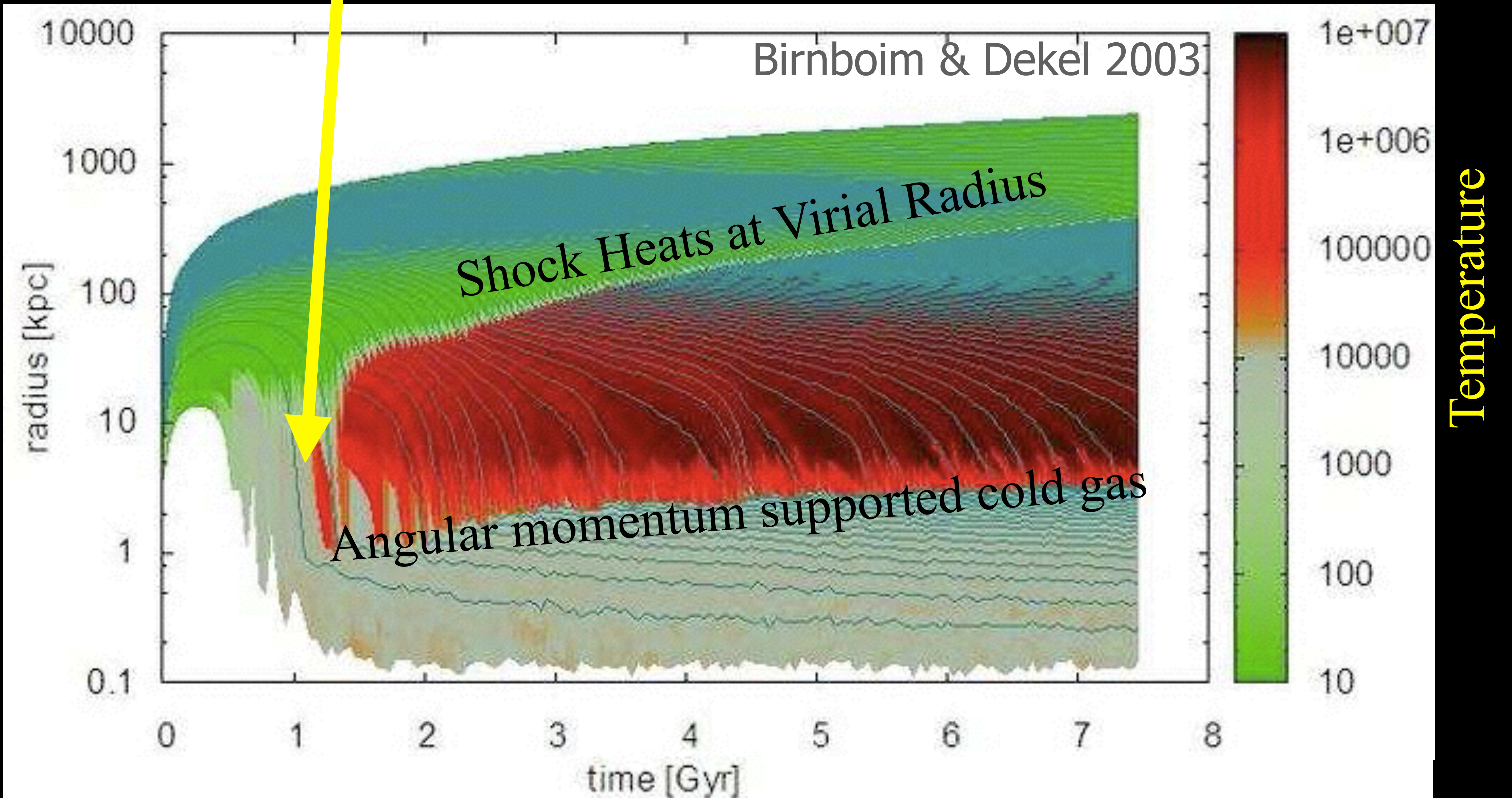


Some cold gas comes in through galaxy accretion & mergers

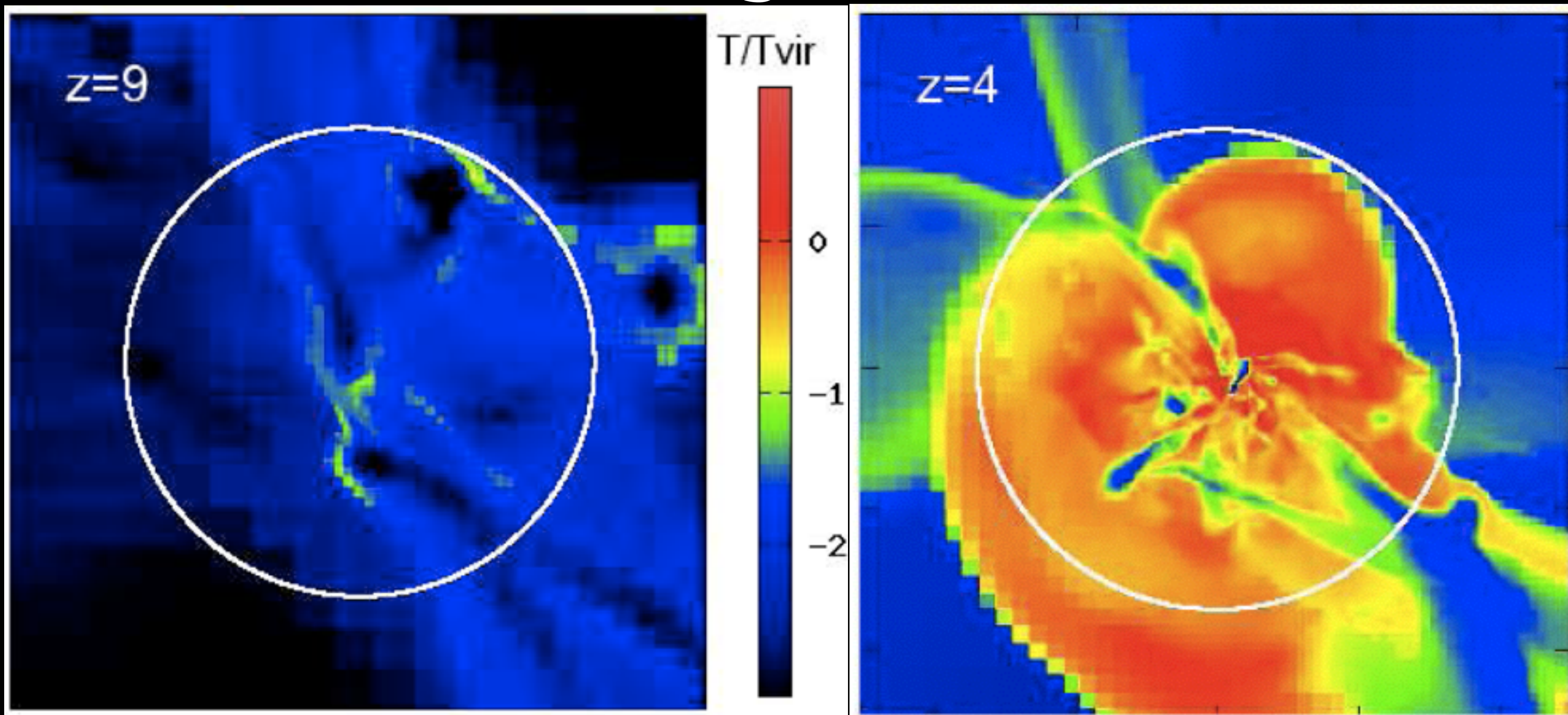


http://www.physics.rutgers.edu/~abrooks/videos.html

Some gas comes in directly, without passing through shock



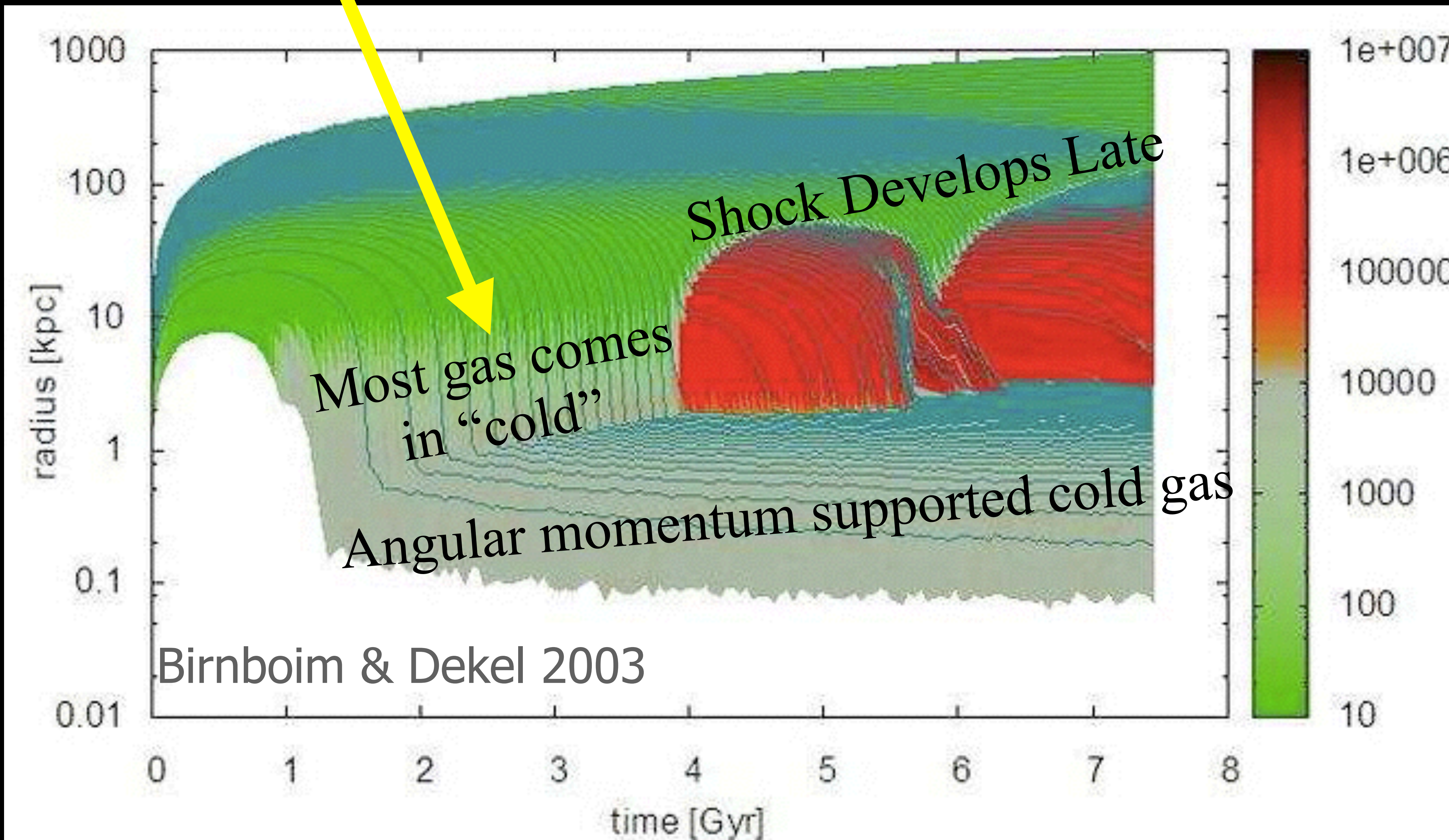
"Cold" and "Hot Mode" Accretion of IGM onto galaxies



Early Times:
Mass still low, gas doesn't shock and comes in cold.

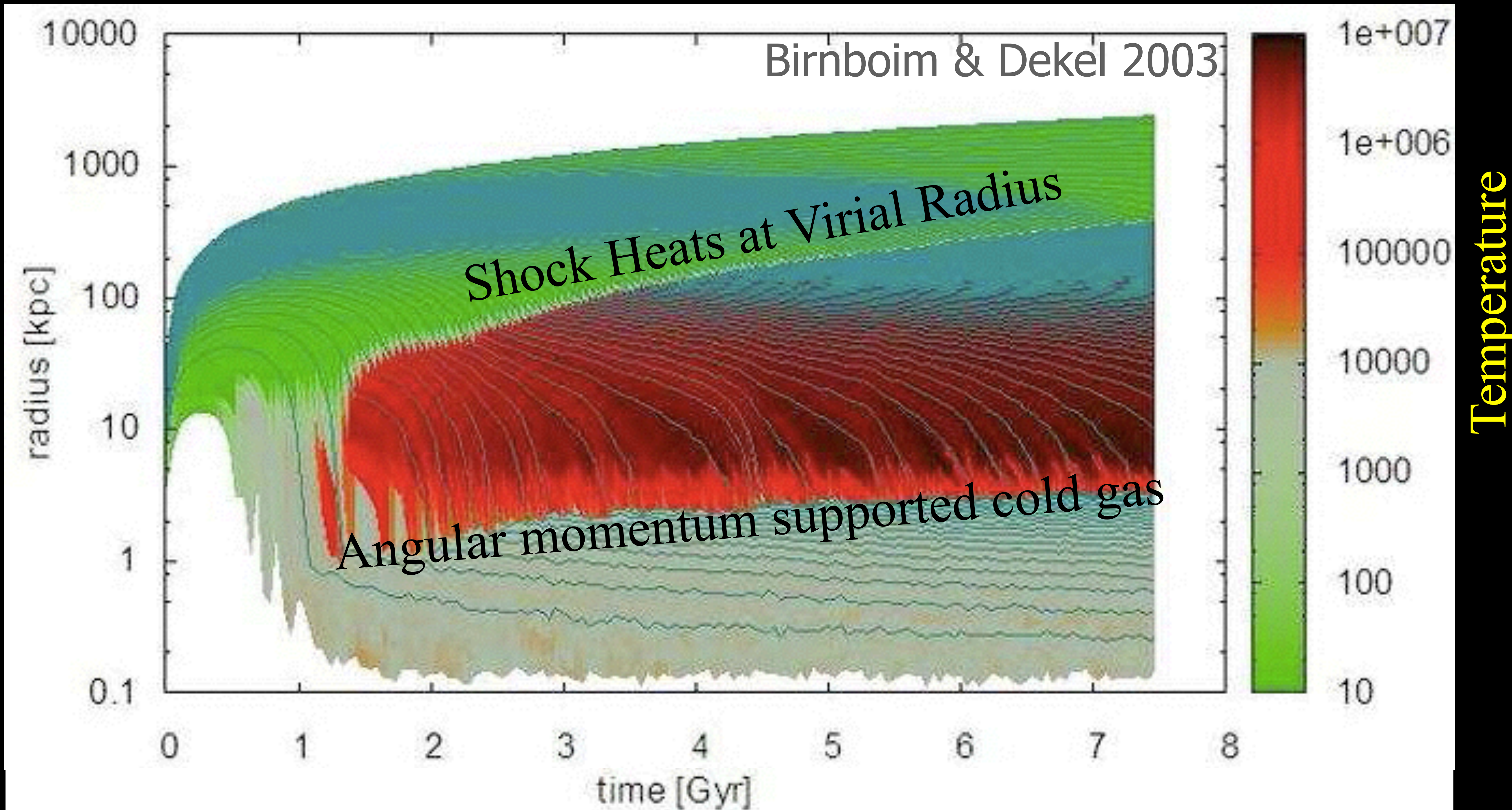
Late Times:
Mass higher, gas shock heats, some cold streams/ filaments still penetrate.

Cold Mode: Dominates for low mass?



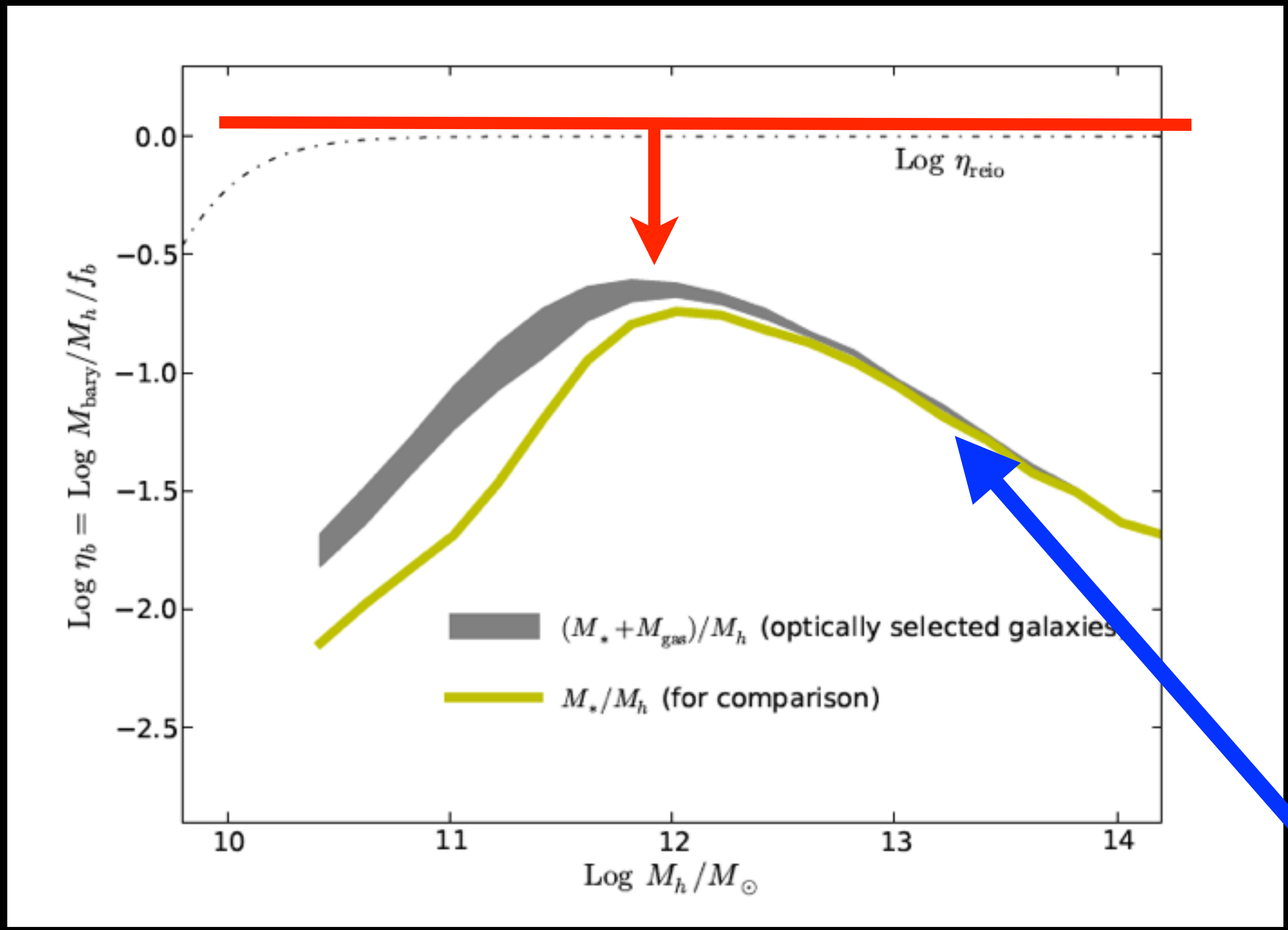
Lower Mass Galaxy: $M_{final} \sim 10^{12}\ M_{sun}$

Hot mode accretion onto main galaxy limited by cooling times, which are long for diffuse gas



Cool gas can build up faster through cold mode

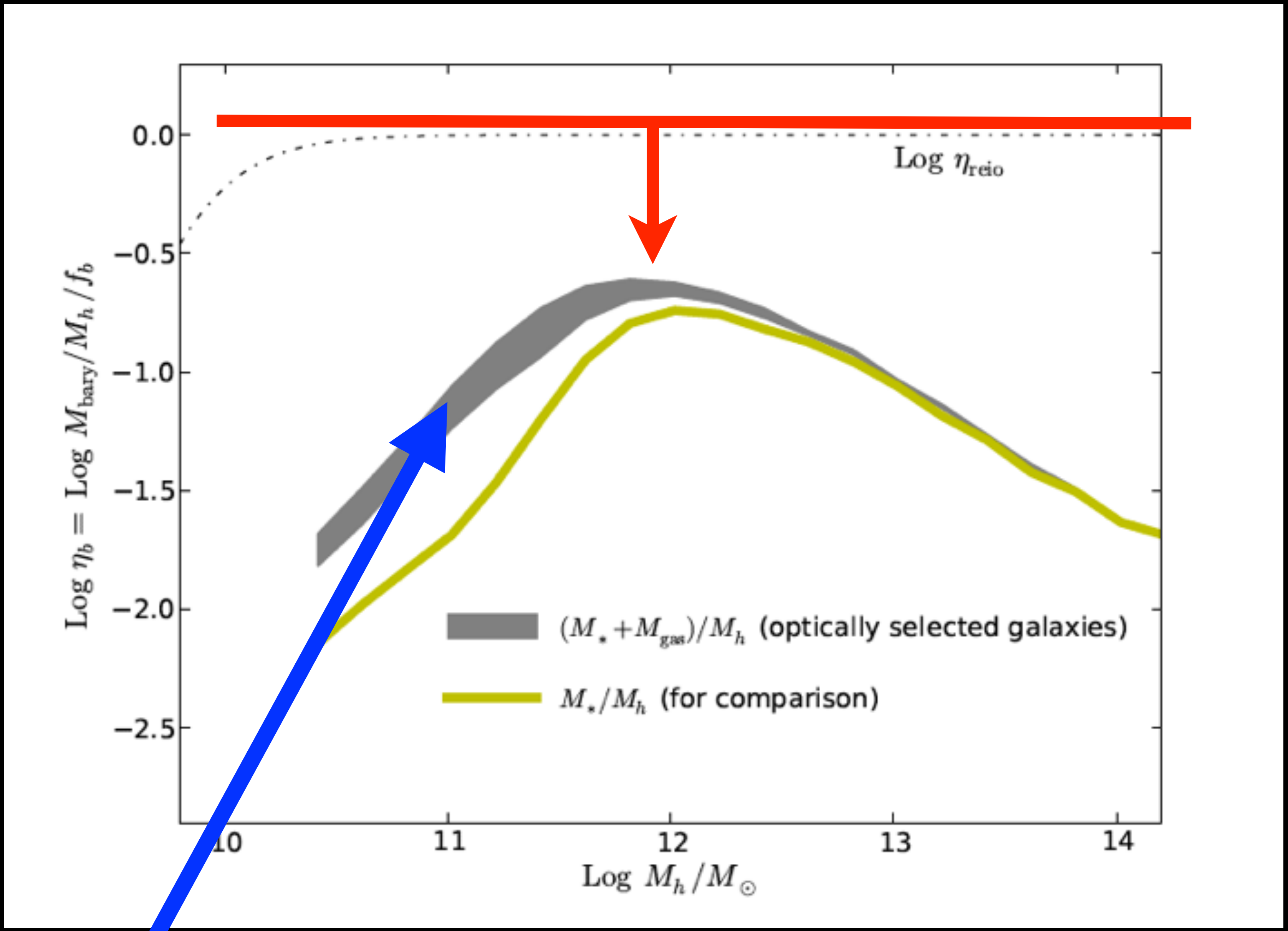
Returning to baryon fractions…



Possible suppression due to shocked halos w/ long cooling times?

Papastergis et al 2012

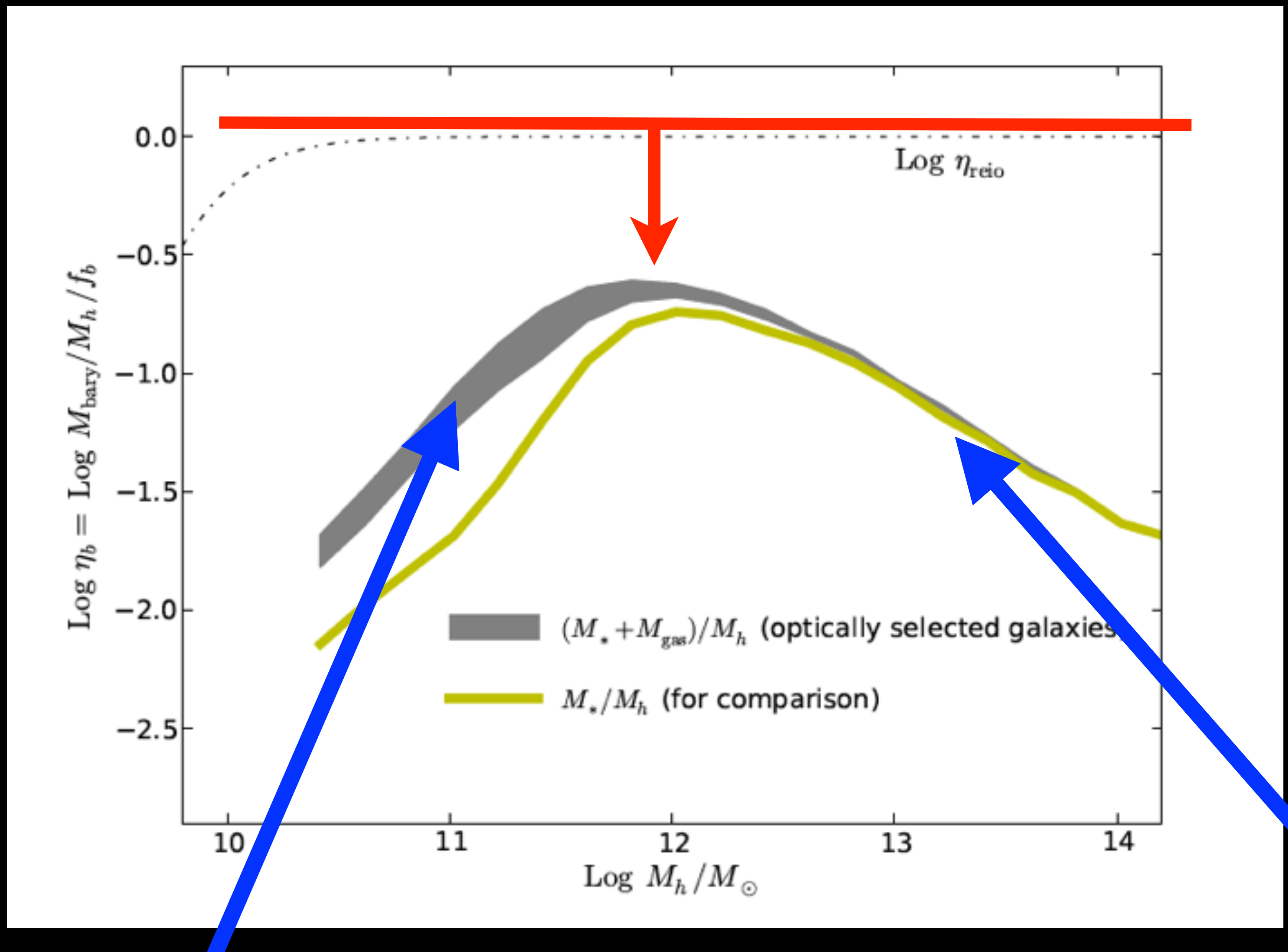
Returning to baryon fractions…



Some suppression due to photoionizing background keeping gas too hot to collapse

Papastergis et al 2012

Feedback also likely to be essential



SN feedback, which is more effective in shallower potential wells

AGN feedback, which may scale w/ BH mass

Papastergis et al 2012

ISM in Galaxies: Overview

- Major constituents
- Multi-wavelength tracers of emission
- Relative distributions
  - Radially
  - Vertically

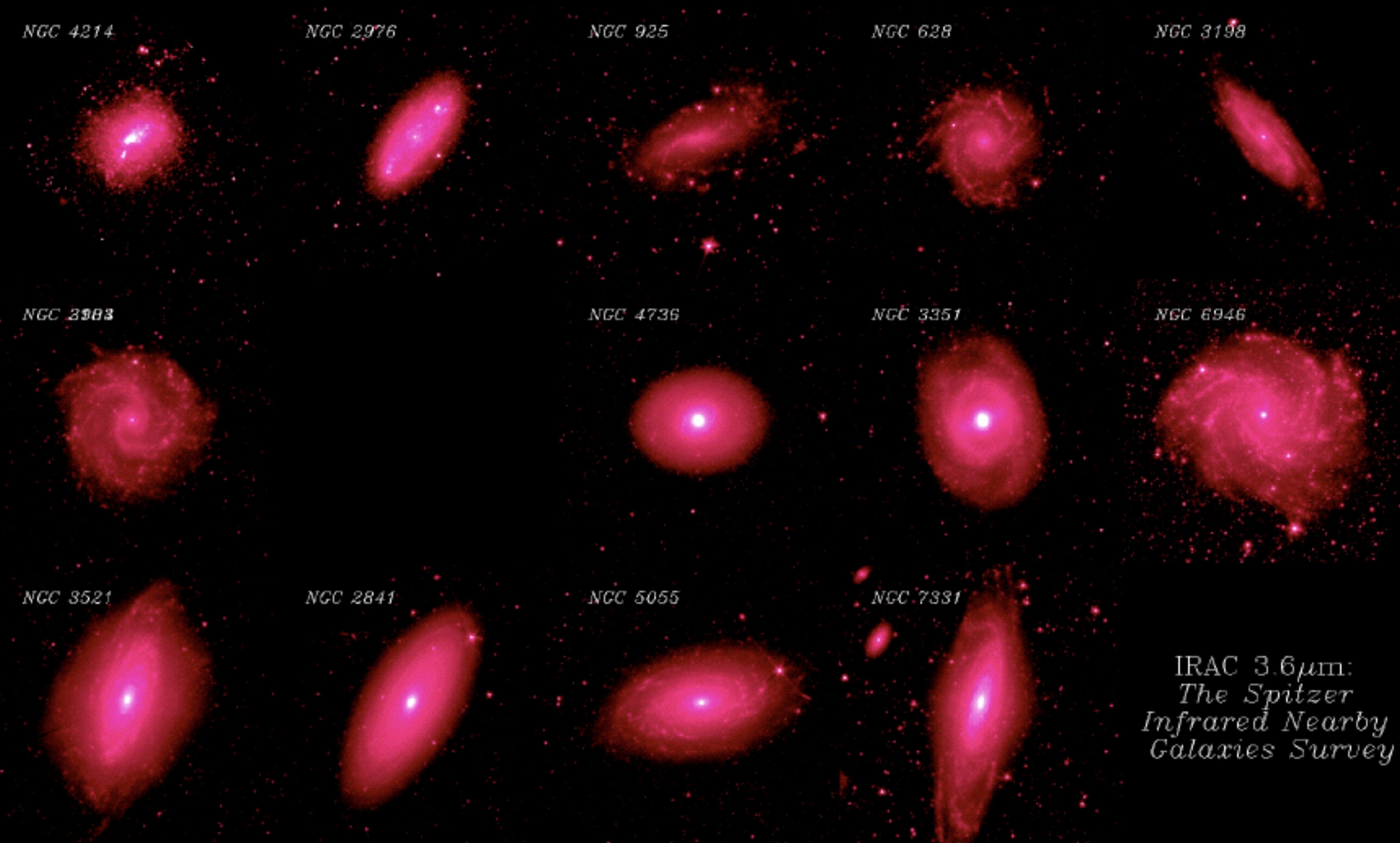
The Interstellar Medium in the Milky Way

Name	T (K)	Ionization	frac of volume	density (cm^{-3})	P ~ nT (cm^{-3} K)
hot ionized medium	10^6	H^+	0.5(?)	0.004	4000
ionized gas (HII & WIM)	10^4	H^+	0.1	$0.2-10^4$	$2000 - 10^8$
warm neutral medium	5000	H^0	0.4	0.6	3000
cold neutral medium	100	H^0	0.01	30	3000
diffuse molecular	50	H_2	0.001	100	5000
dense molecular	10-50	H_2	10^{-4}	10^3-10^6	$10^5 - 10^7$

Pressure equilibrium

Courtesy Karin Sandstrom

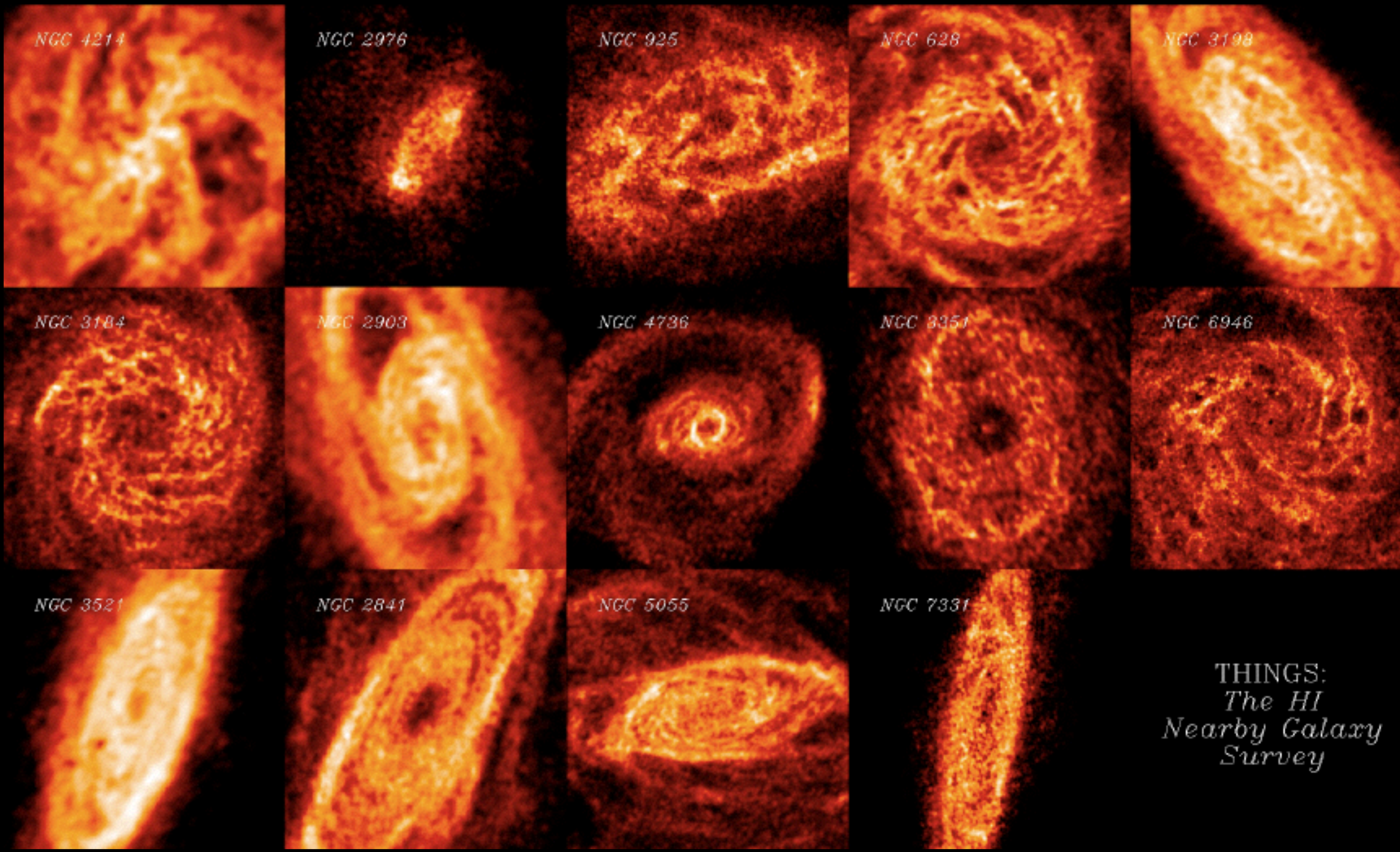
NIR traces (oldish) RGB/AGB stars



Approximate map of stellar mass

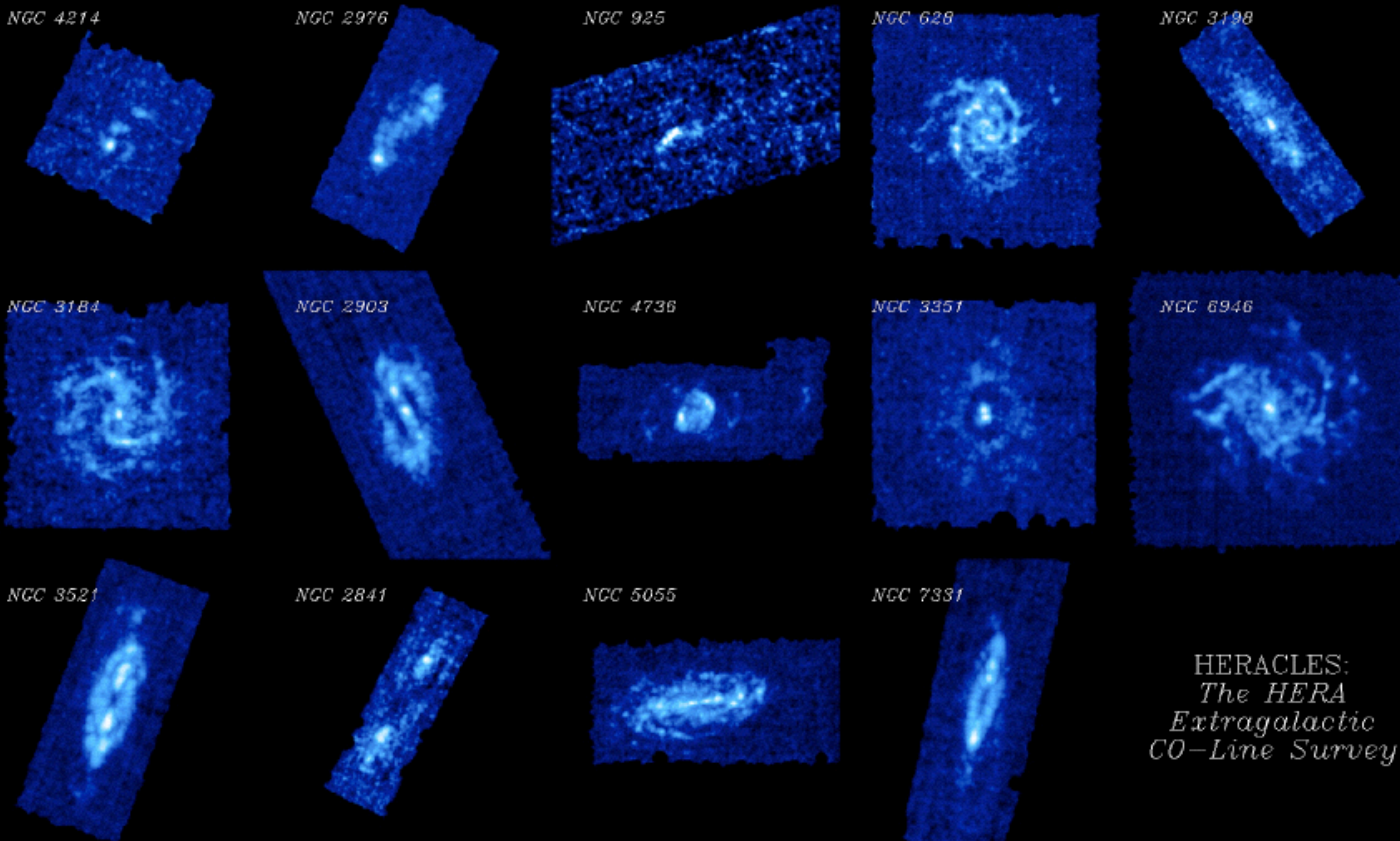
Slides from A. Leroy

HI is Structured & Extended



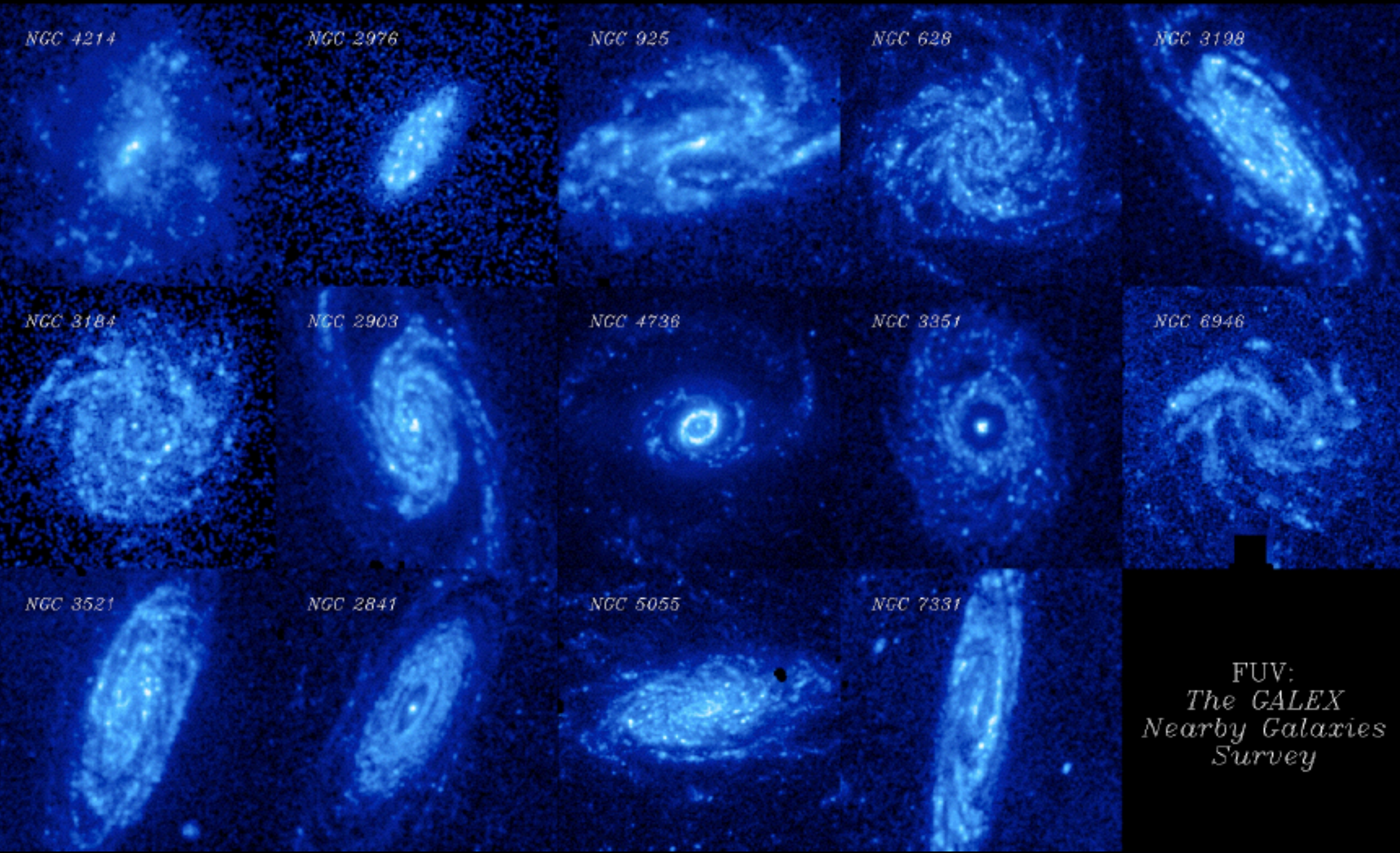
 Frothy -- SNe driven bubbles? HI depressed in center, often

Molecular gas is centrally concentrated



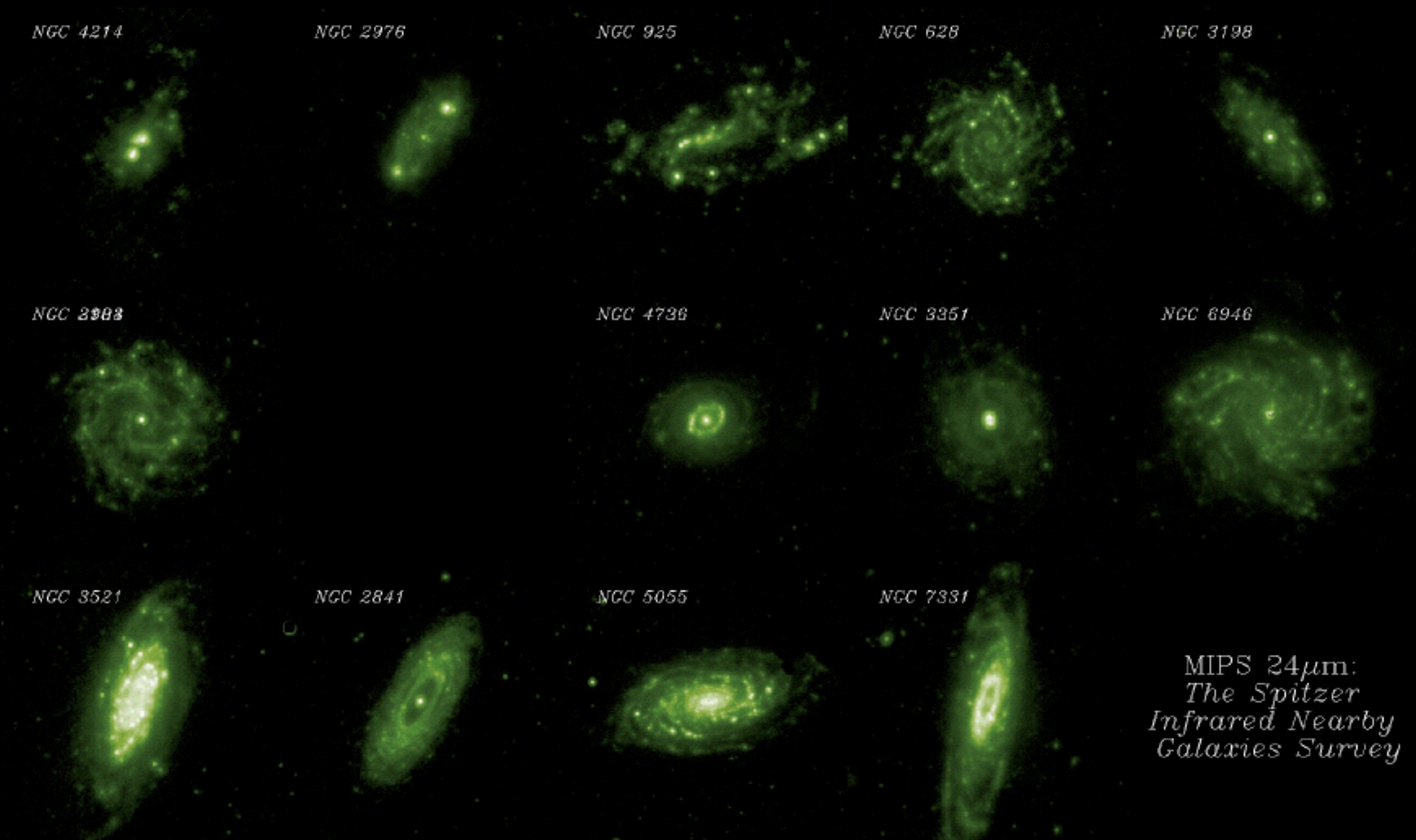
 Largely confined to spiral arms & centers. Note: CO, not H_2!

Far UV emission from young O-stars



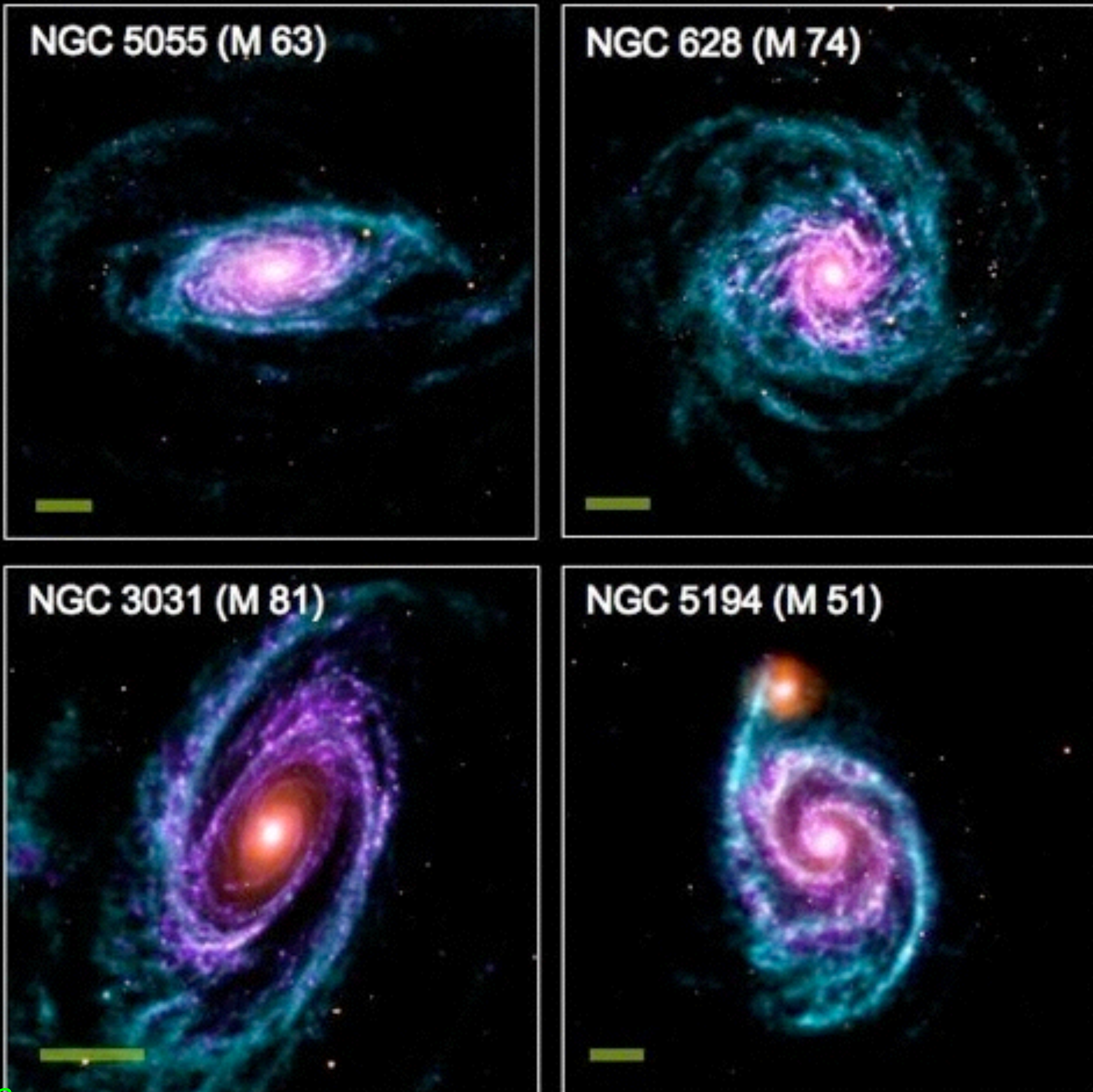
Traces only unobscured stars, whose light is unblocked by surrounding molecular cloud

24μm traces dust heated by stars



BB emission from warm dust, presumedly in MCs near SF

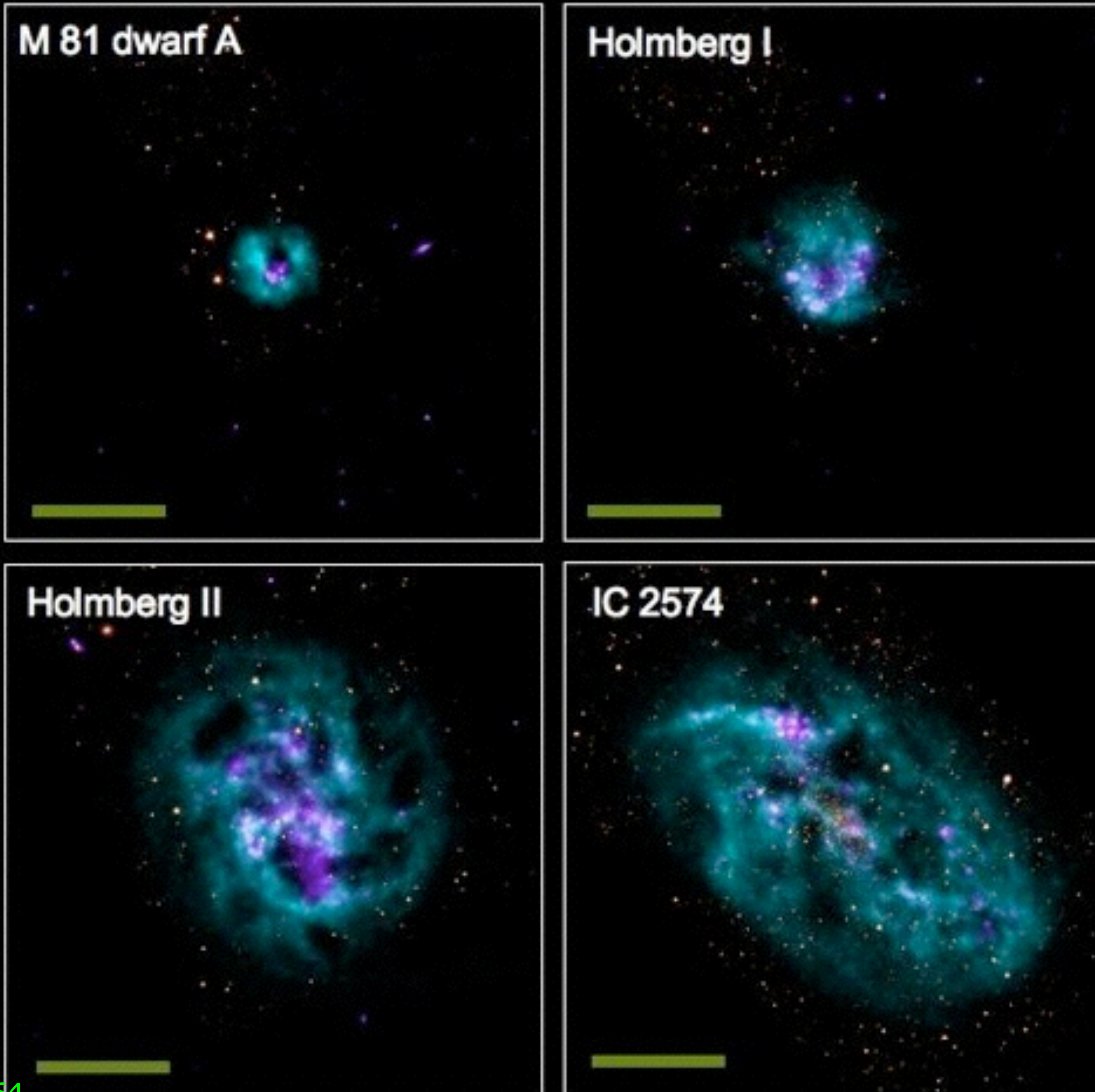
Spiral Galaxies in THINGS — The HI Nearby Galaxy Survey



color coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)

scale:
15,000 light years

Dwarf Galaxies in THINGS — The HI Nearby Galaxy Survey

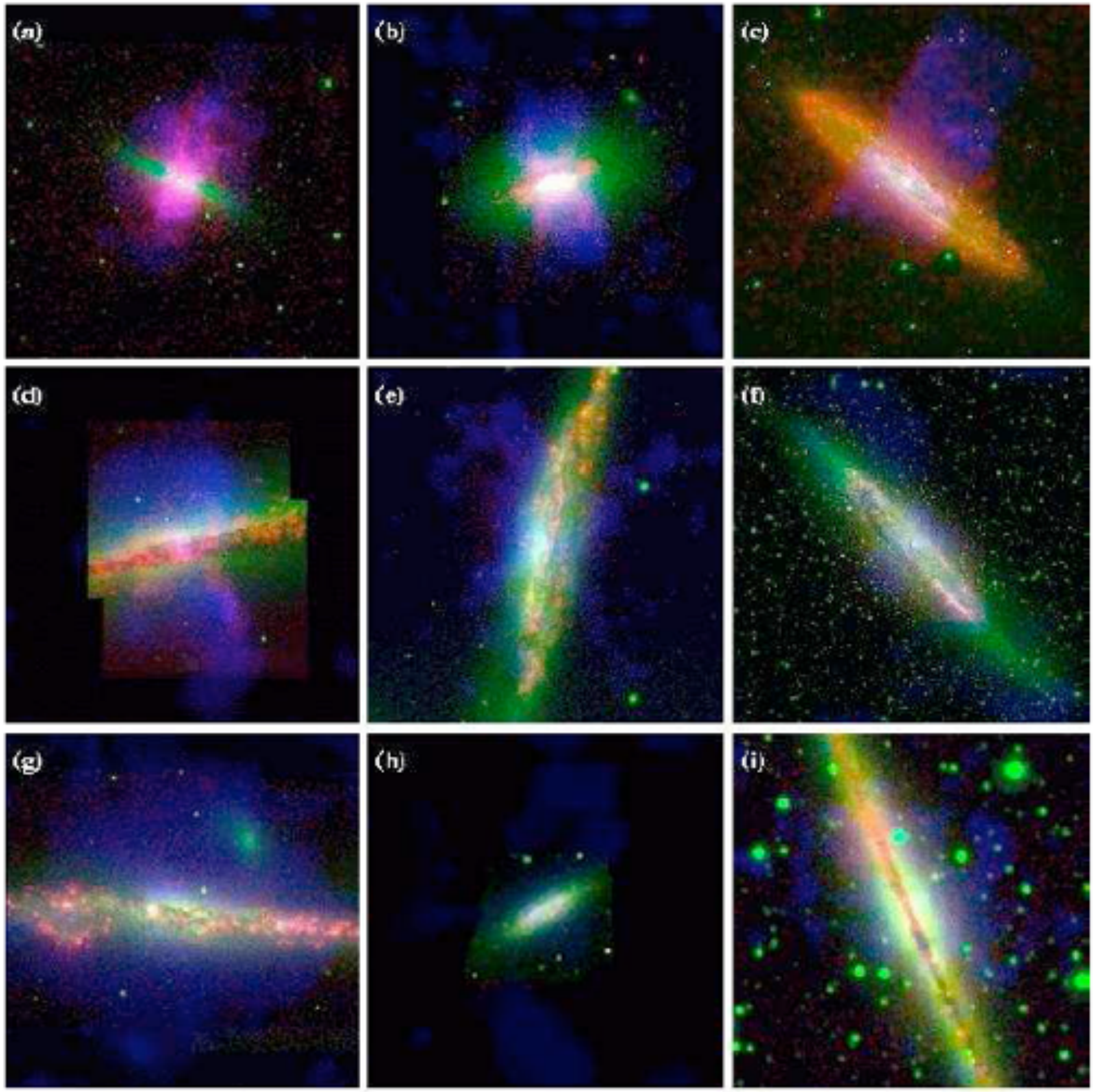


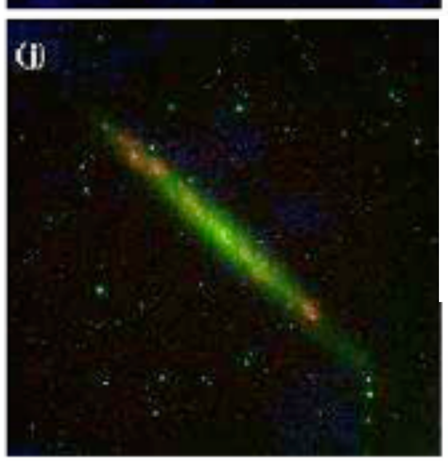
color coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)

scale:
15,000 light years

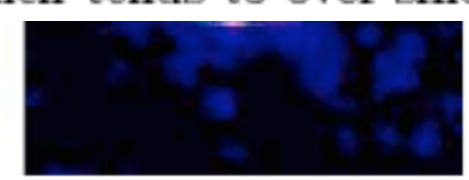
Hot gas: Detected readily in actively SF galaxies as an X-ray halo.

Stronger in more actively SF galaxies.





891 (h) and NGC 6503 (i). Hα emission is shown in red, optical R-band in green and 0.3–2.0 keV energy band soft X-ray emission is shown in blue. The X-ray emission is the point-source subtracted diffuse emission which has been adaptively smoothed to achieve a local S/N of 3, which tends to over-smooth structure in the X-ray emission. All images are

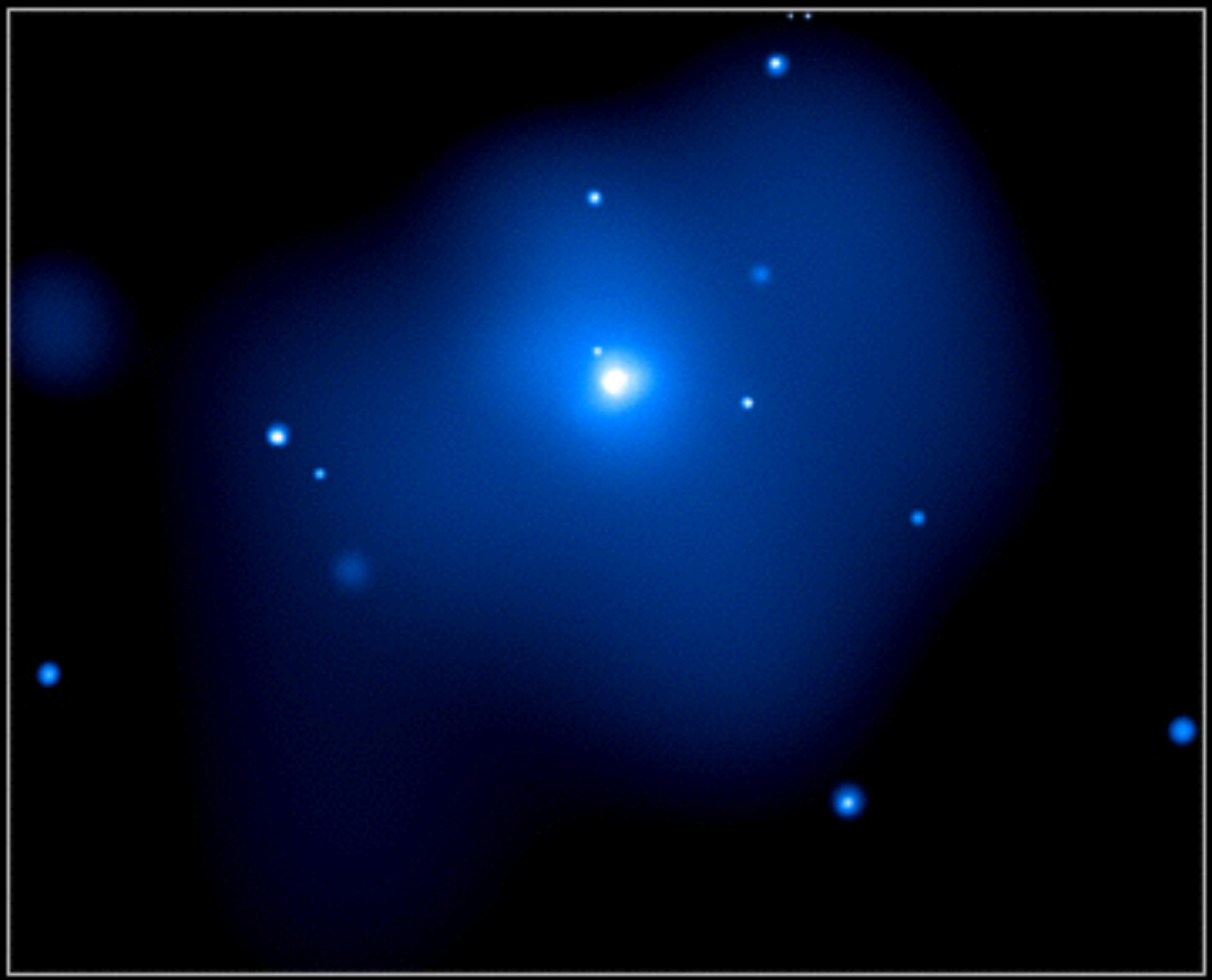


Sometimes also detected in absorption, via OV,OVI line

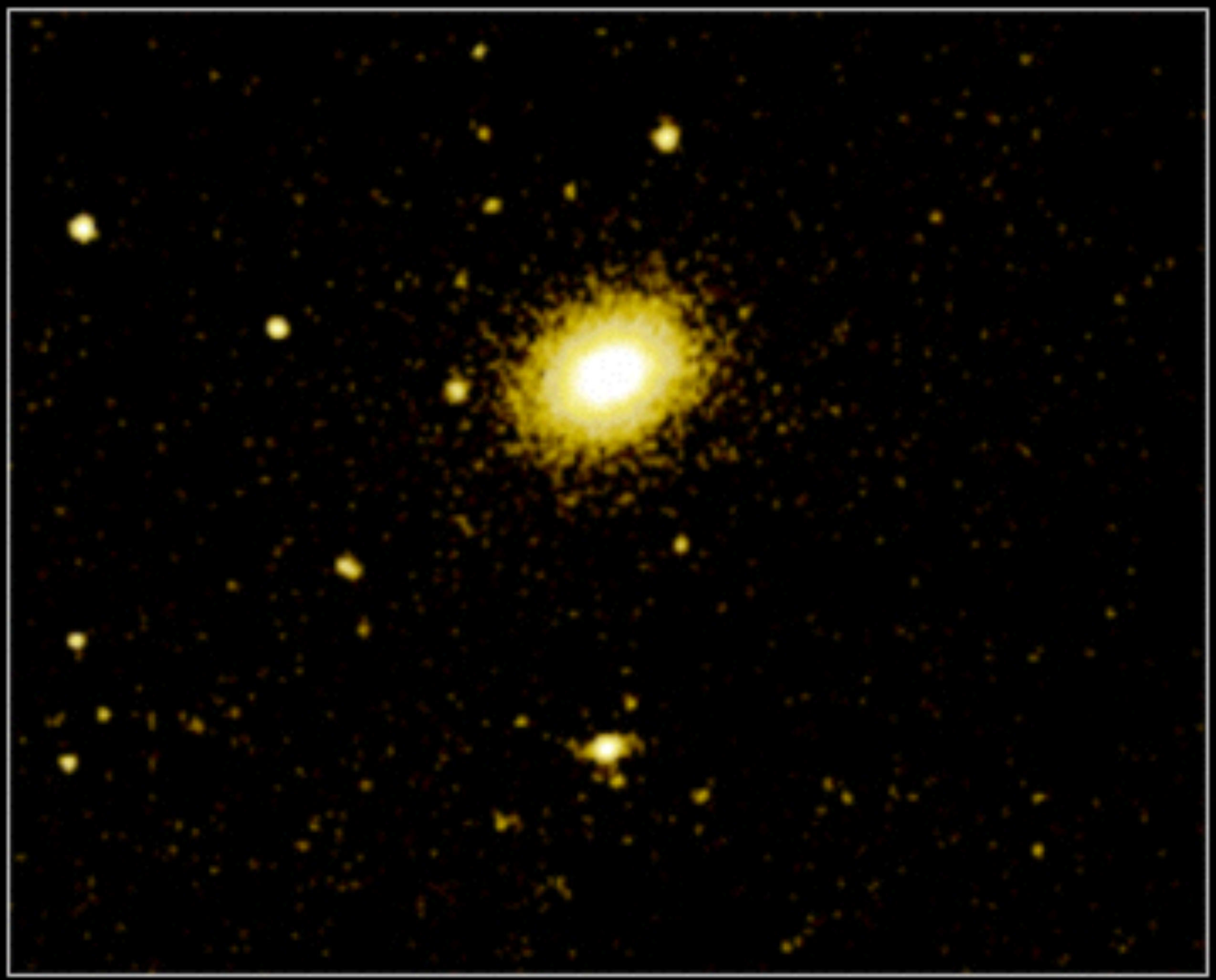
Fig. 2.— As Fig. 1, except that panels (a) through (j) now show 20 kpc by 20 kpc boxes, while in panel (k) the region is 40 kpc by 40 kpc. The galaxies are M82 (a), NGC 1482 (b), NGC 253 (c), NGC 3628 (d), NGC 3079 (e and k), NGC 4945 (f), NGC 4631 (g), NGC 6503 (h), NGC 891 (i), NGC 6503 (j), and NGC 3079 (k).

Strickland et al 2004

Hot gas around isolated elliptical



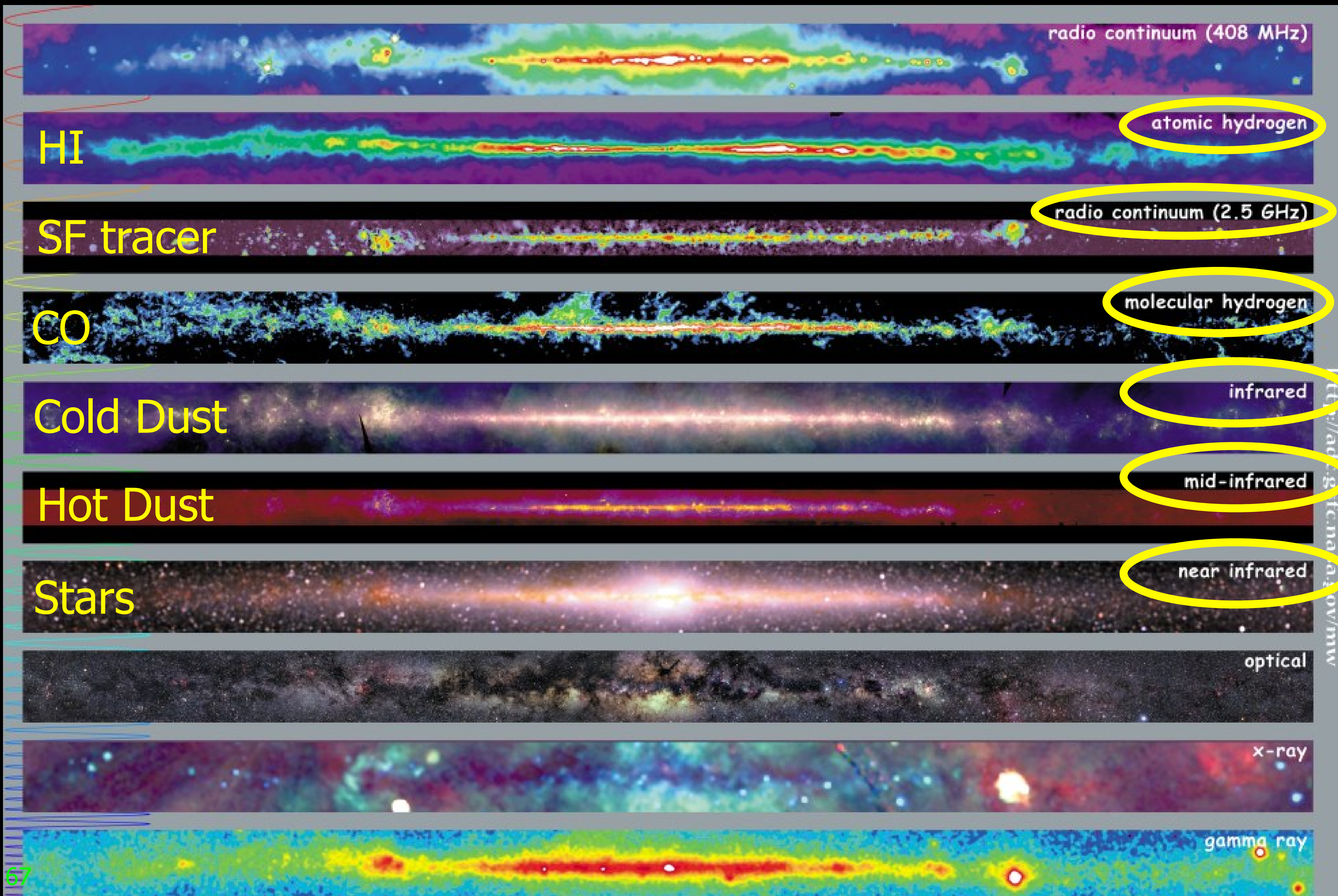
CHANDRA X-RAY



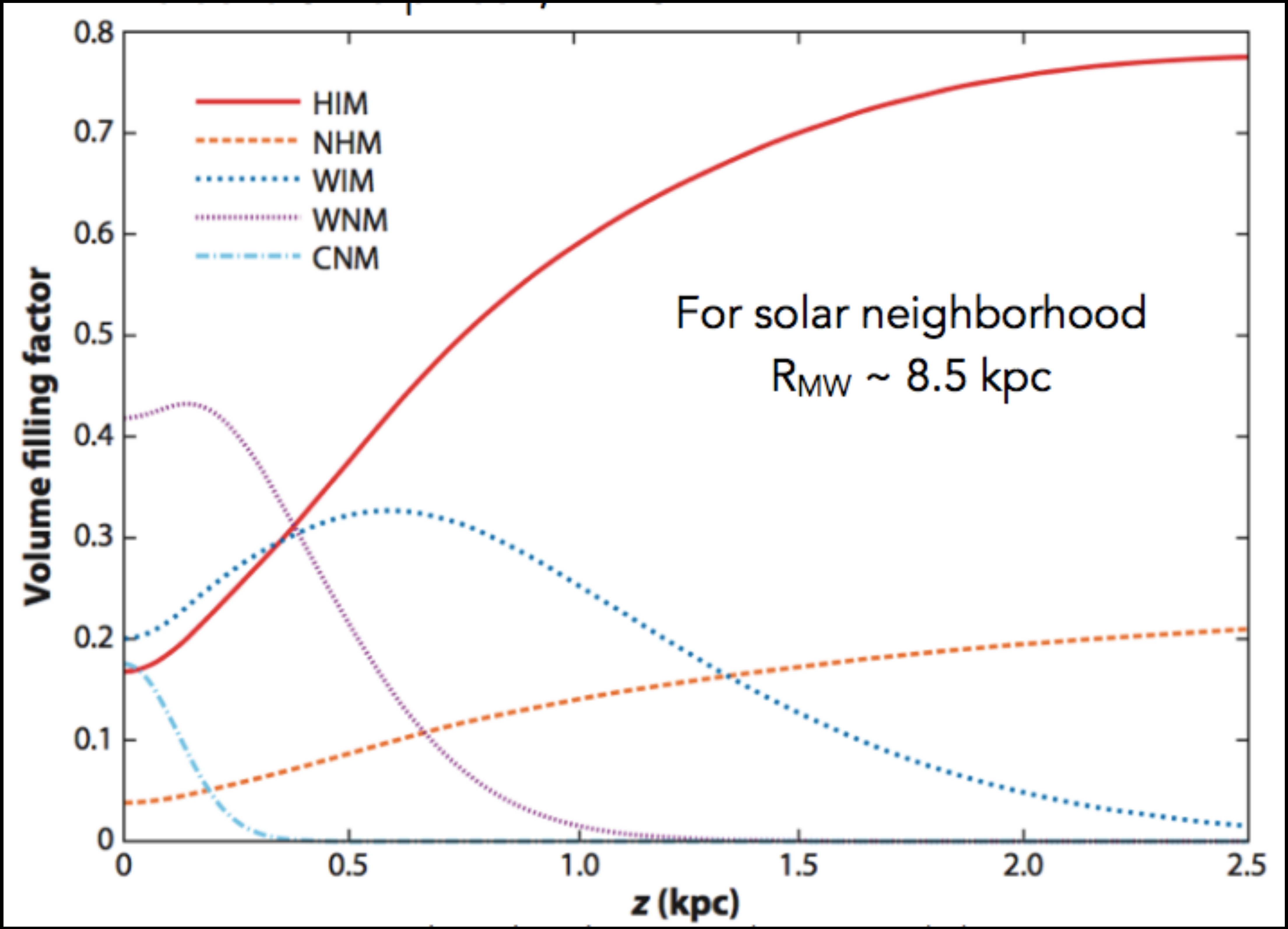
DSS OPTICAL

- Shock heated when falling into potential well?
- Ejected by SNe/AGN winds from the galaxy?

Vertical Structure varies w/ Component



ISM scale heights in the Milky Way

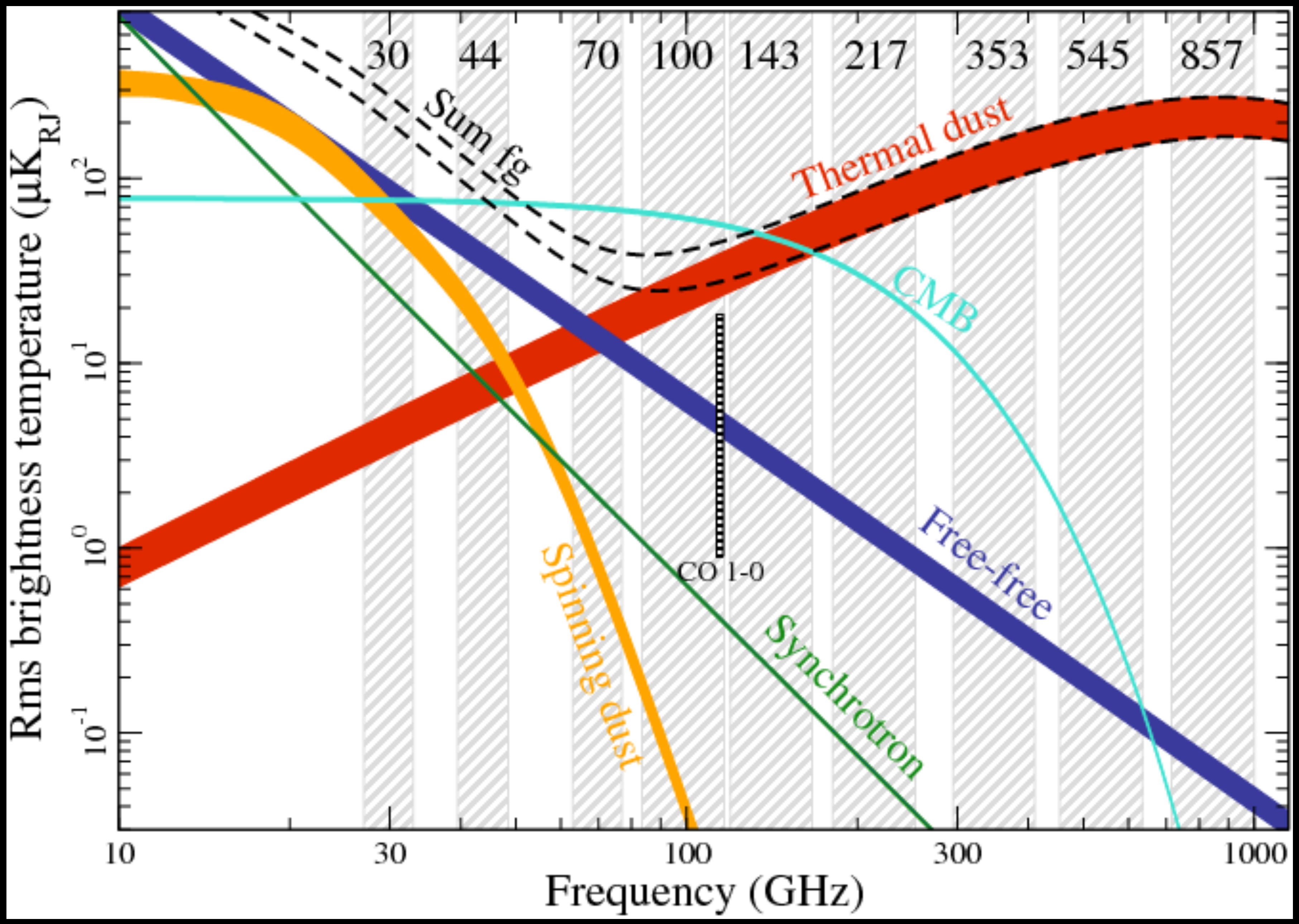


HIM: Hot ionized medium, NHM: Neutral halo medium,
WIM=Warm ionized medium

Kalberla & Kerp 2009 ARA&A

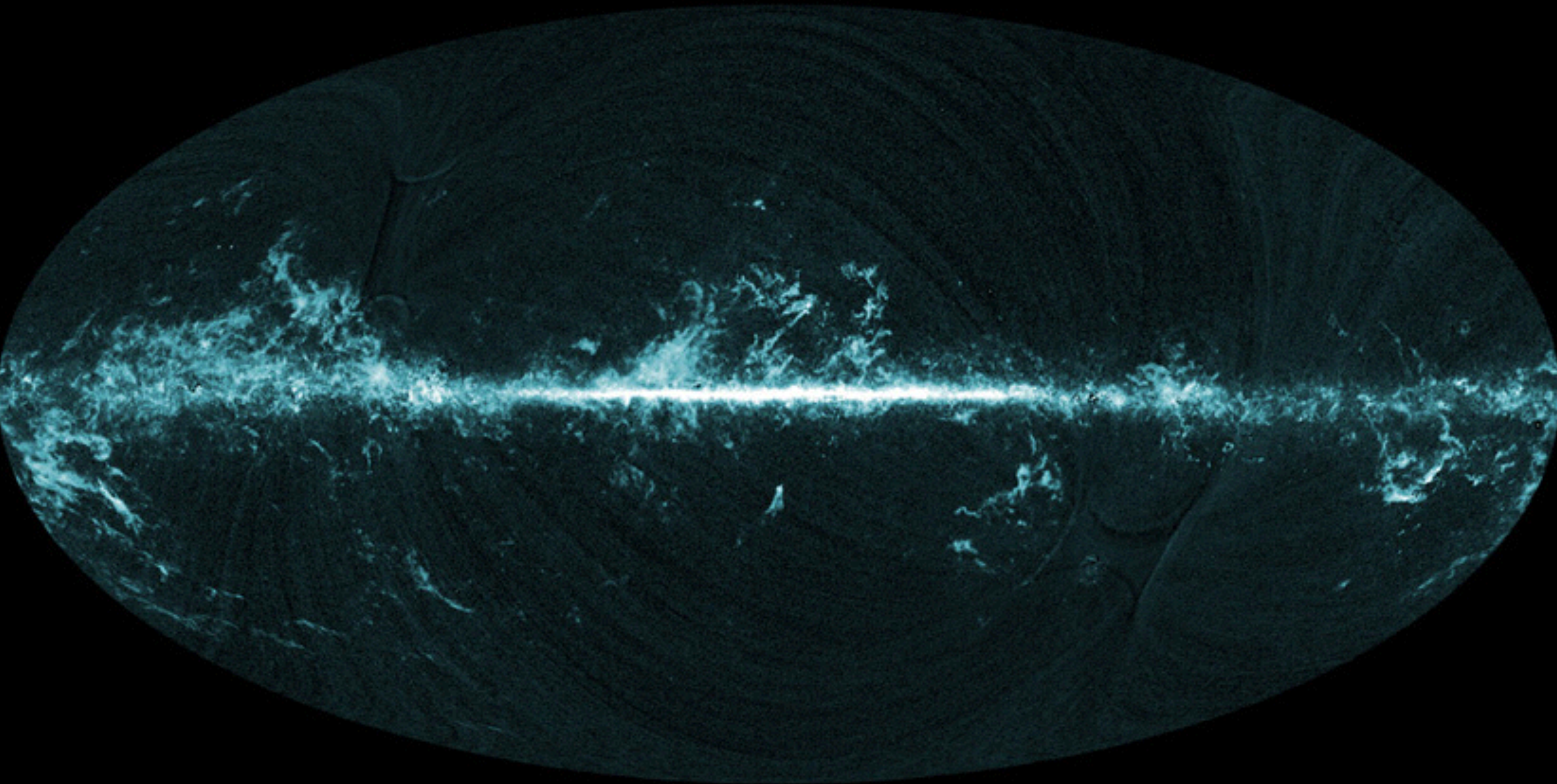
All sky maps of key ISM components

- Direct mapping of emission
- Inference from multi-frequency spectral fitting w/ Planck



http://adsabs.harvard.edu/abs/2016A%26A...594A...1P

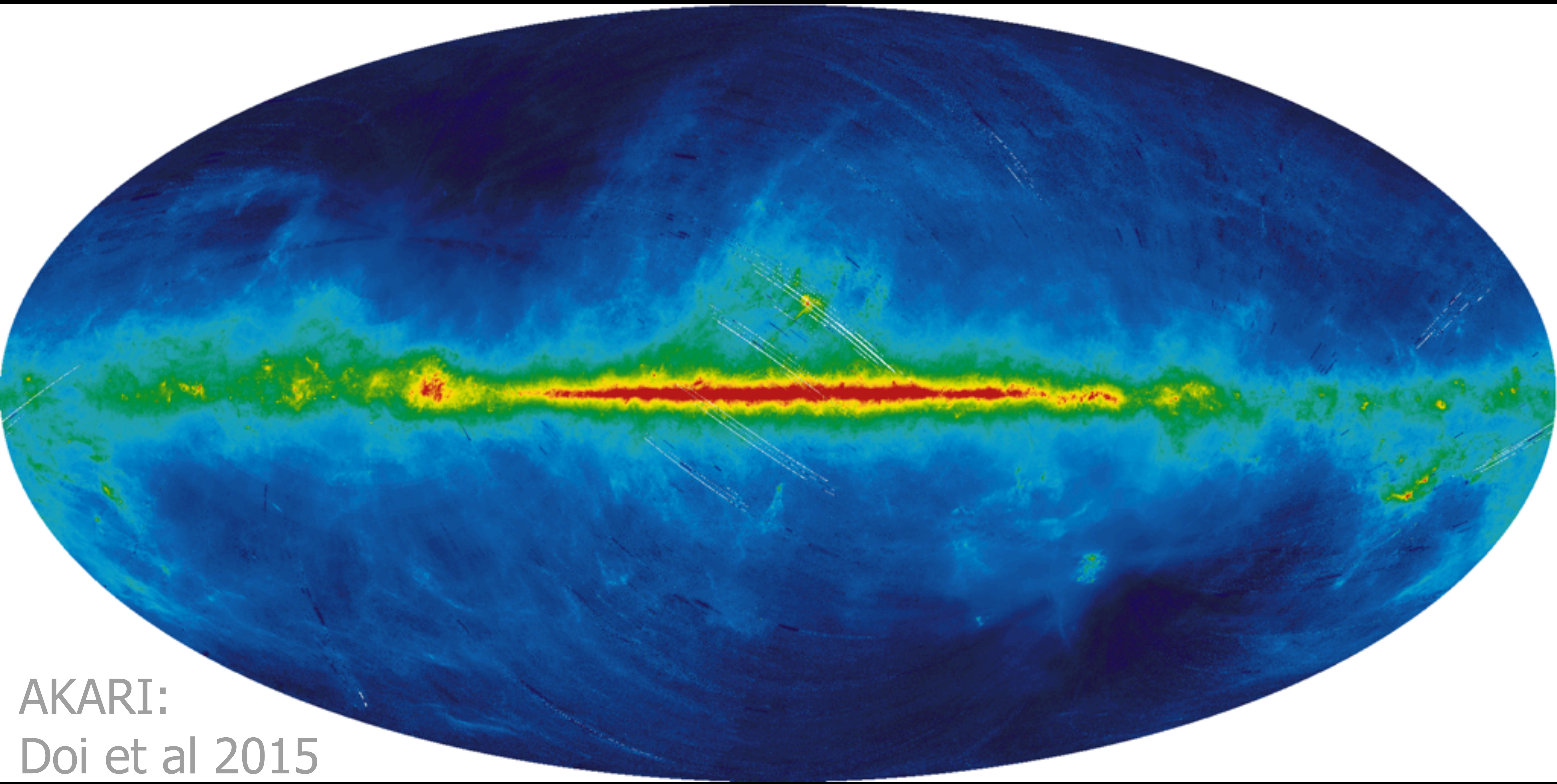
Molecular Gas



CO map from Planck

http://sci.esa.int/planck/50004-new-planck-maps-reveal-unseen-details-across-the-milky-way/

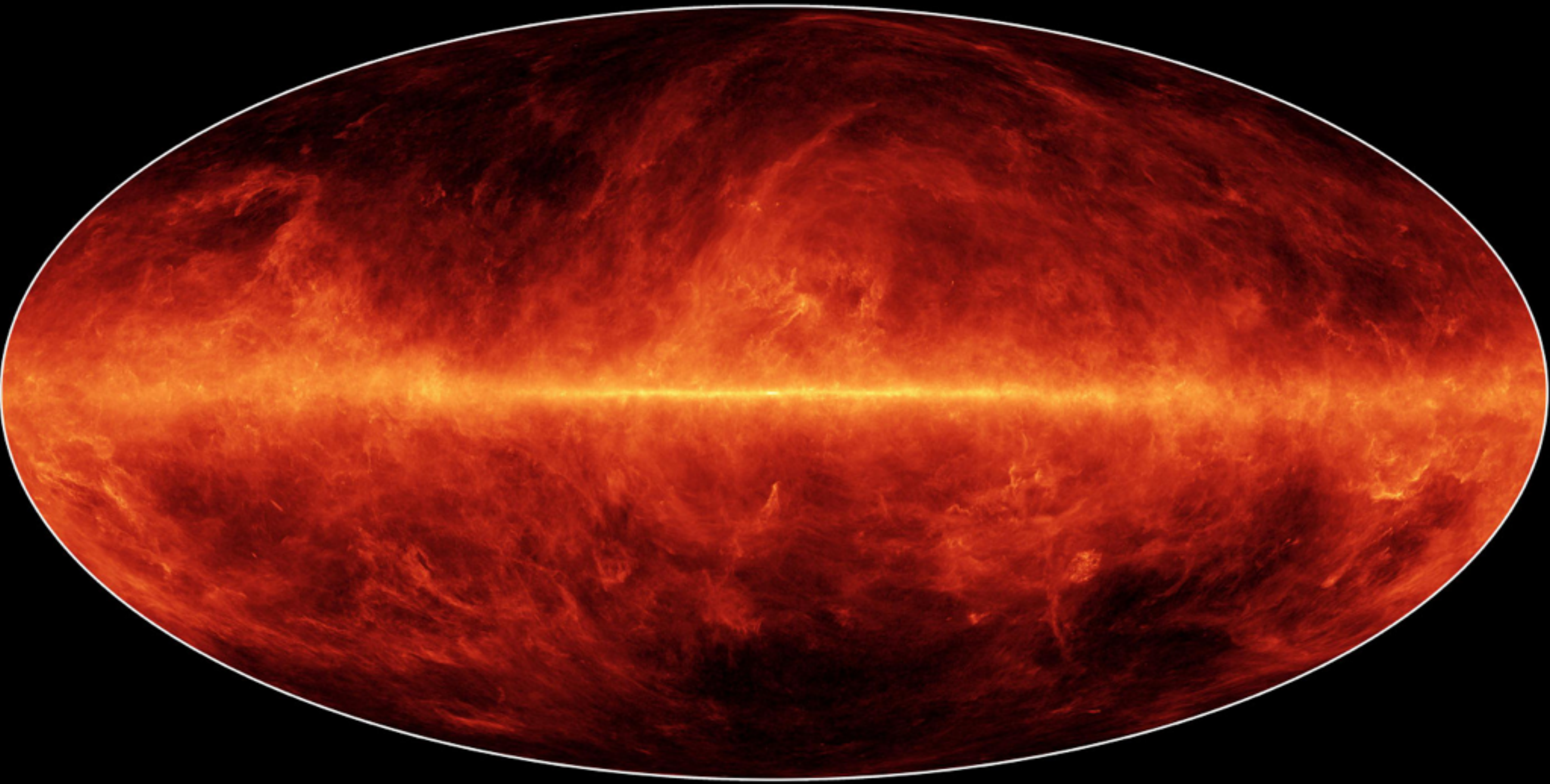
160μm Dust Emission



Note correspondence w/ CO structure

https://lambda.gsfc.nasa.gov/product/foreground/f_images.cfm

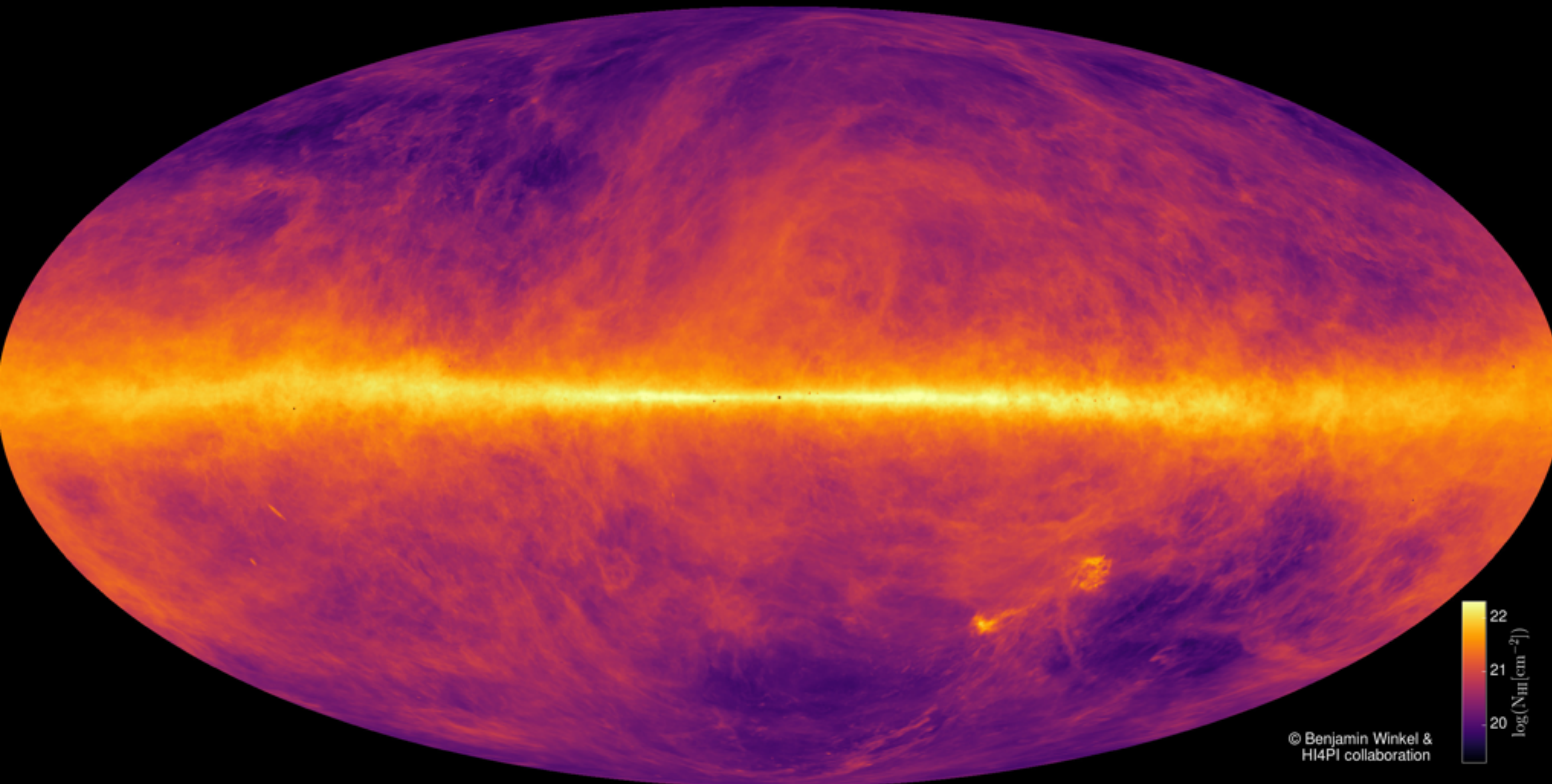
Longer-wavelength Dust Emission



545 GHz, corresponding to ~20K dust: Planck Collaboration 2015

https://astronomynow.com/2015/02/06/planck-reveals-first-stars-

Atomic Hydrogen

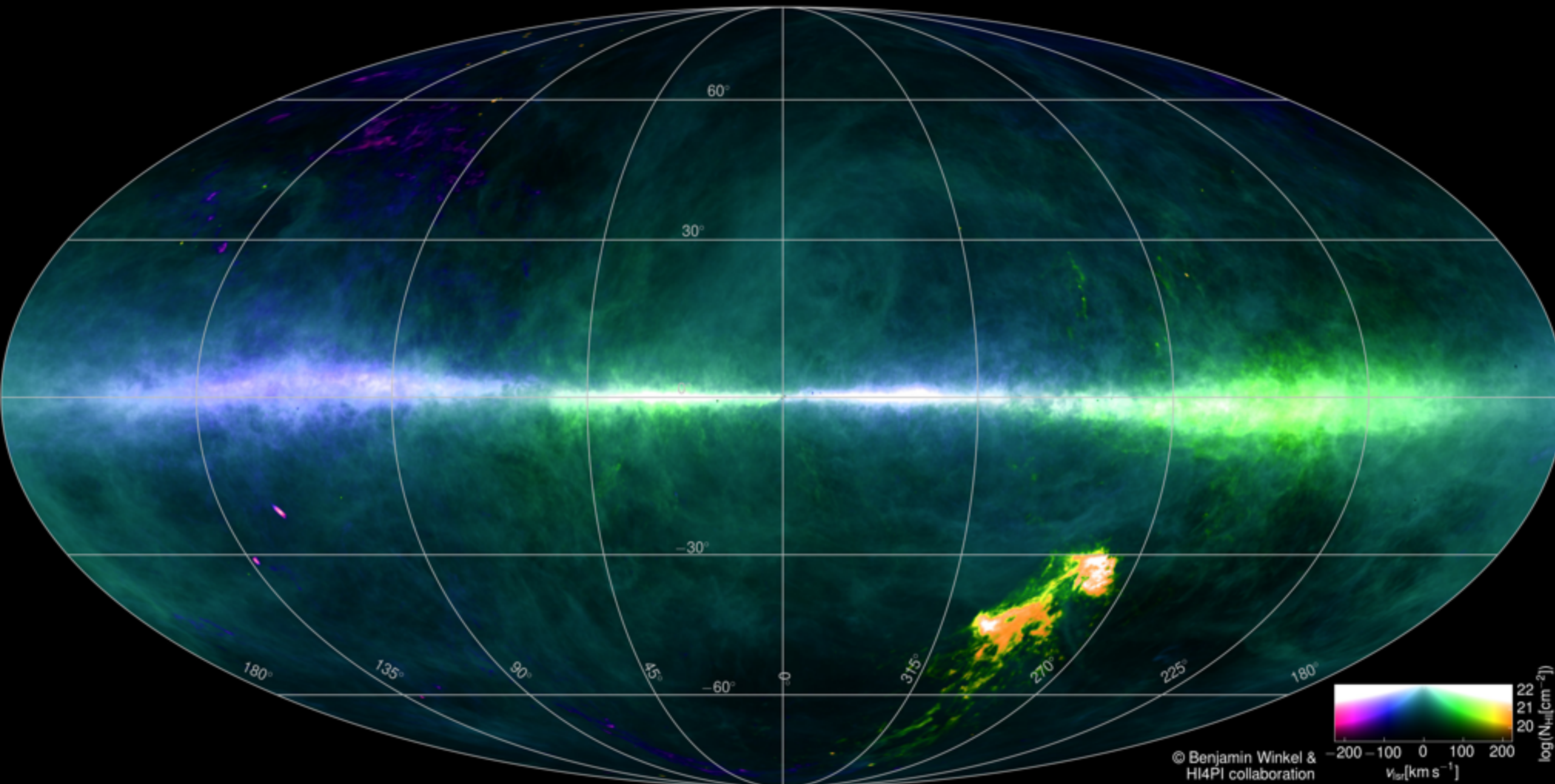


Note correspondence w/ cold dust

Effelsberg-Bonn HI Survey
Winkel et al 2016

https://astro.uni-bonn.de/~bwinkel/research.html

Velocity structure of HI



https://www.youtube.com/watch?v=Q2mgpsTFuV8

Effelsberg-Bonn HI Survey
Winkel et al 2016

https://astro.uni-bonn.de/~bwinkel/research.html

Velocity structure of HI

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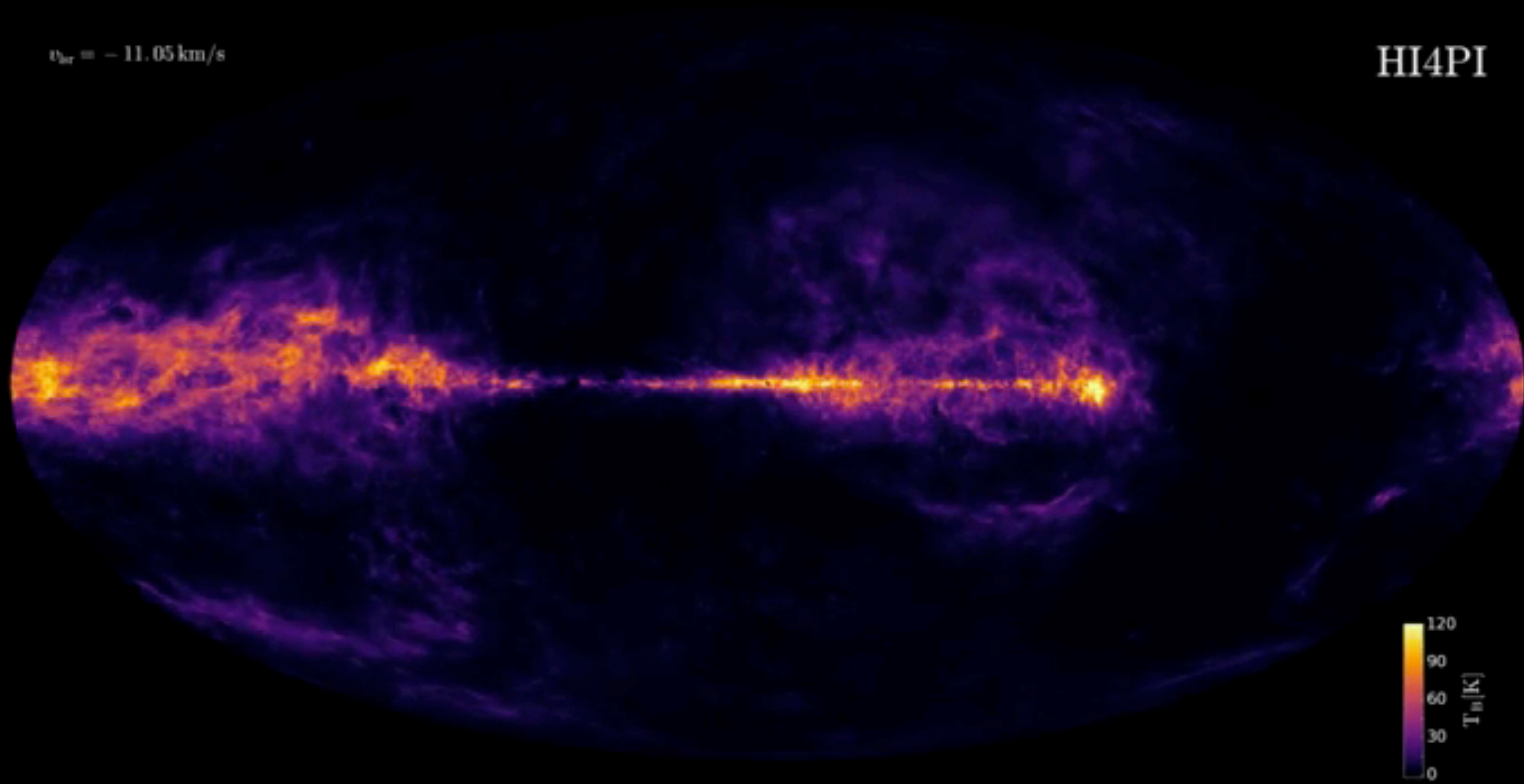
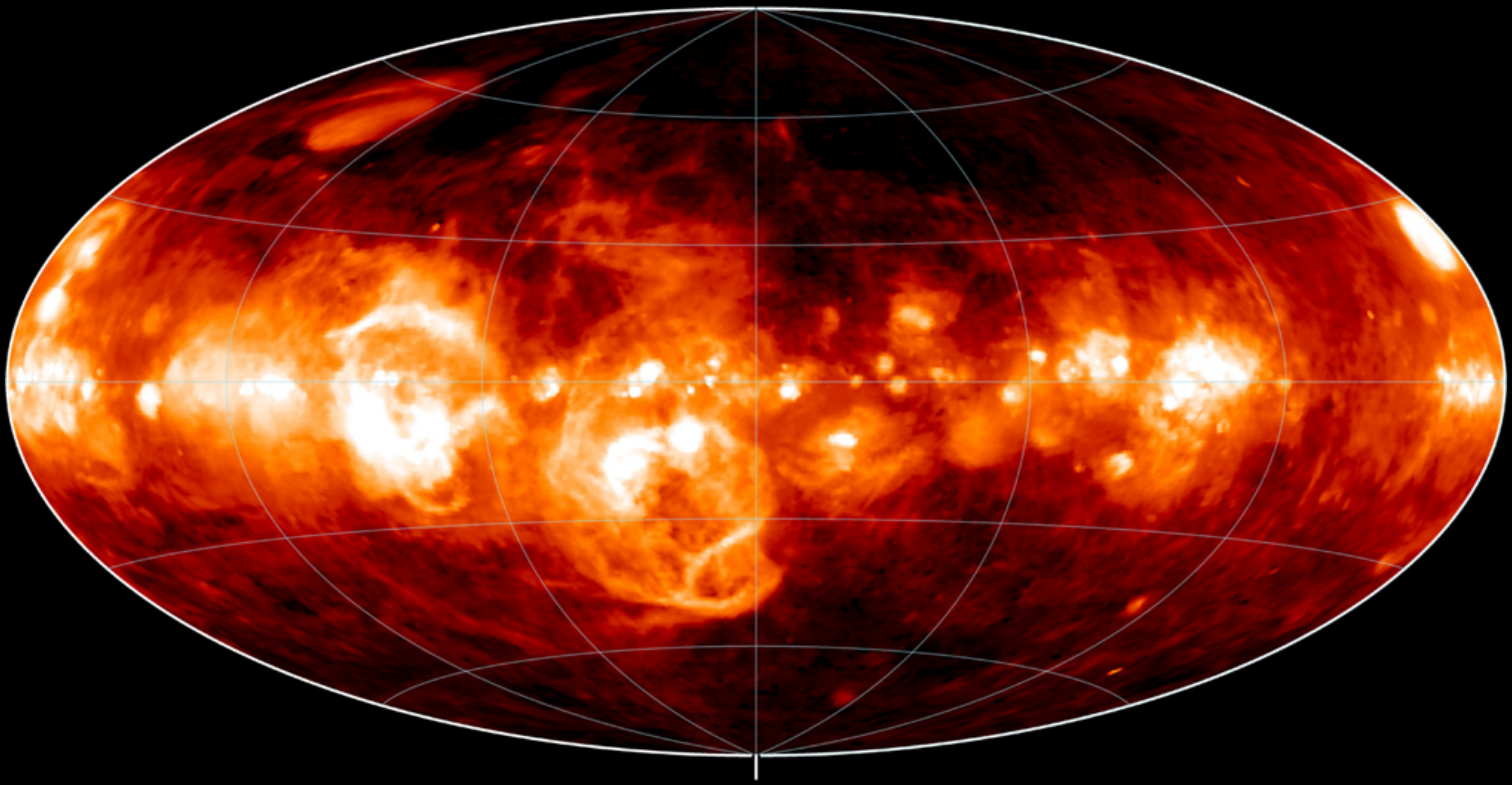


https://astro.uni-bonn.de/~bwinkel/research.html

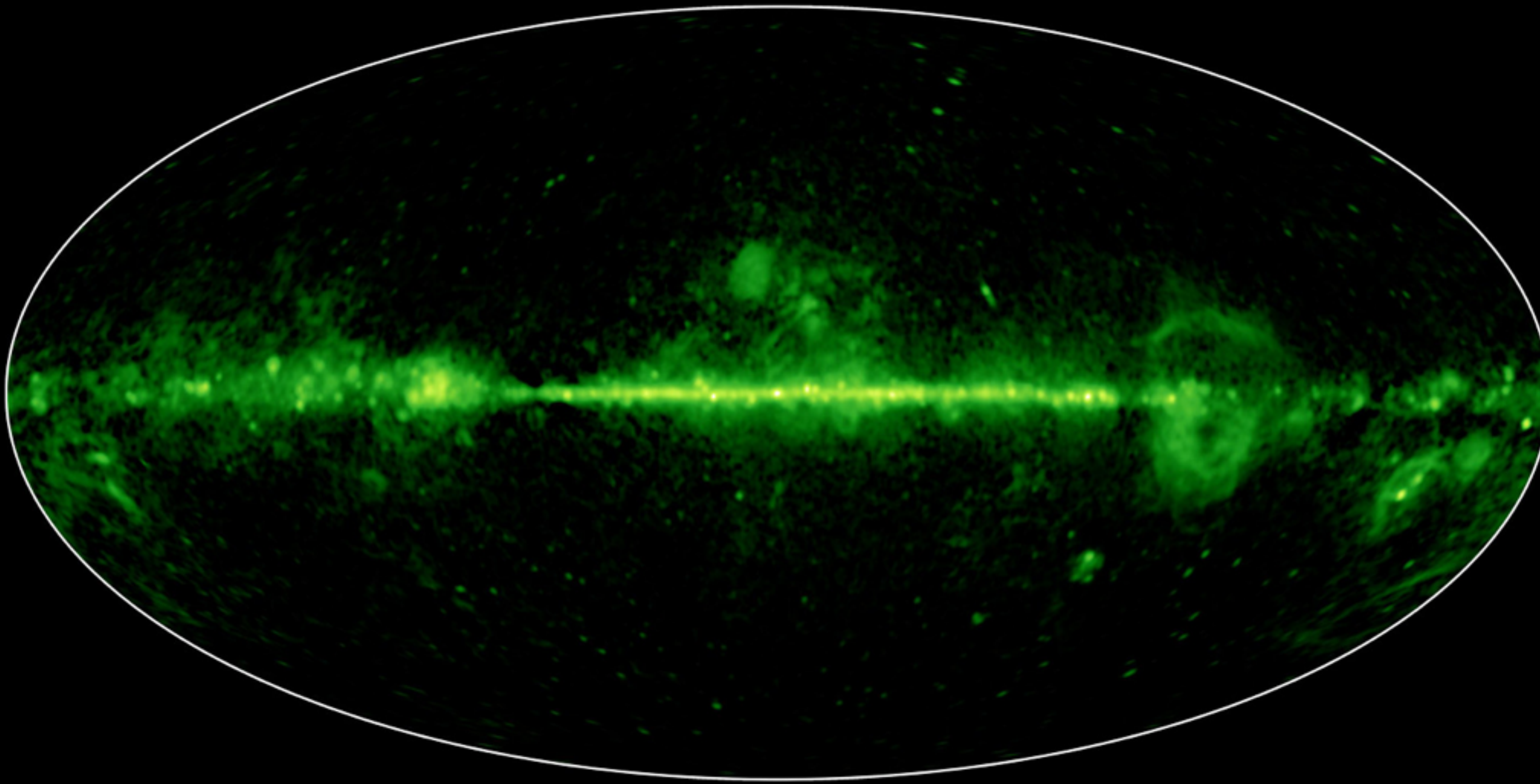
Hα Map of Milky Way



WHAM: Wisconsin H-Alpha Mapper
Haffner et al 2017

http://news.wisc.edu/uw-project-brings-milky-ways-ionized-hydrogen-into-focus/

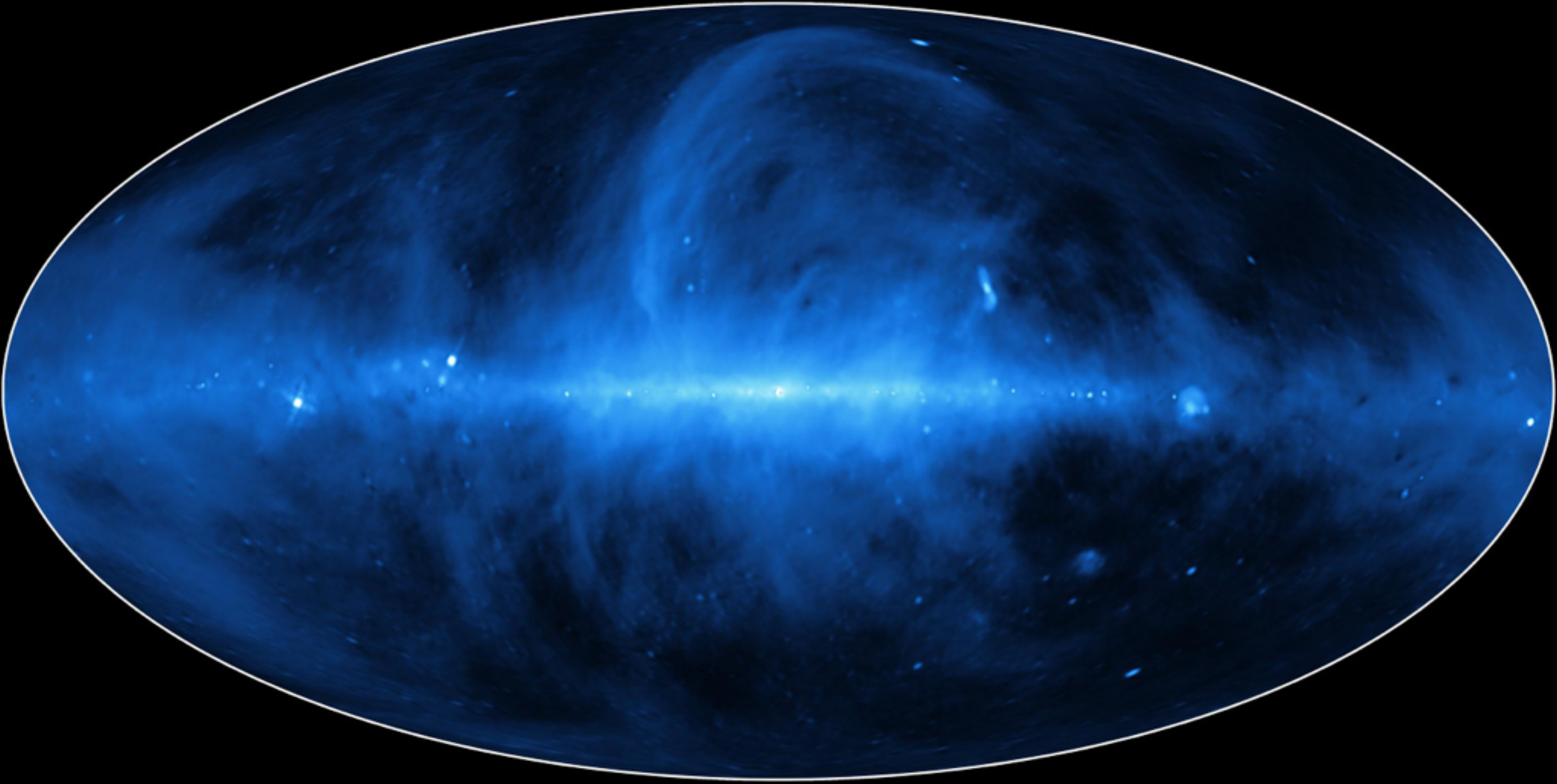
Free-free emission



Planck Collaboration 2015

https://astronomynow.com/2015/02/06/planck-reveals-first-stars-were-born-later/

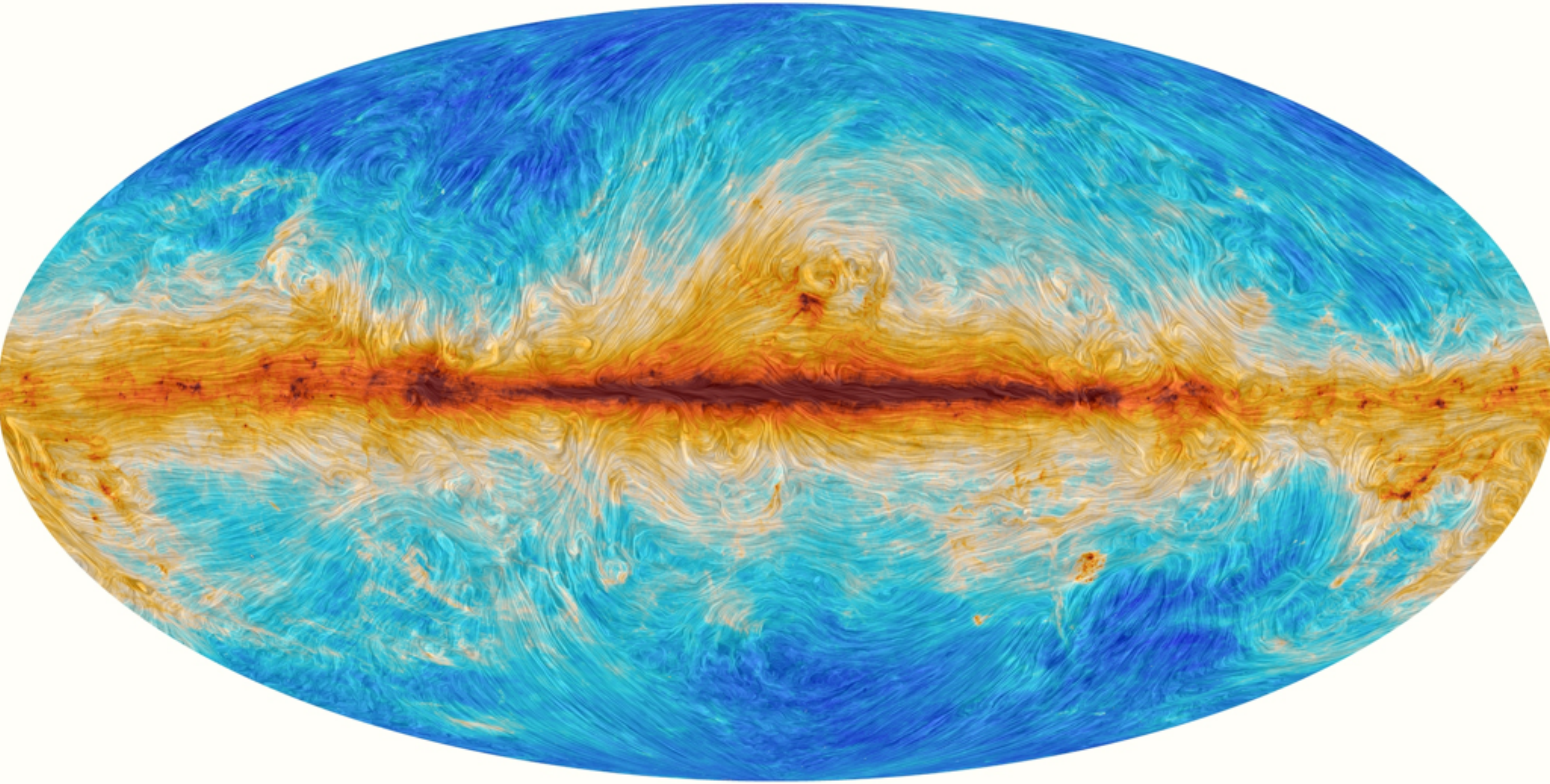
Magnetic fields play a role



Synchrotron emission; Planck collaboration 2015

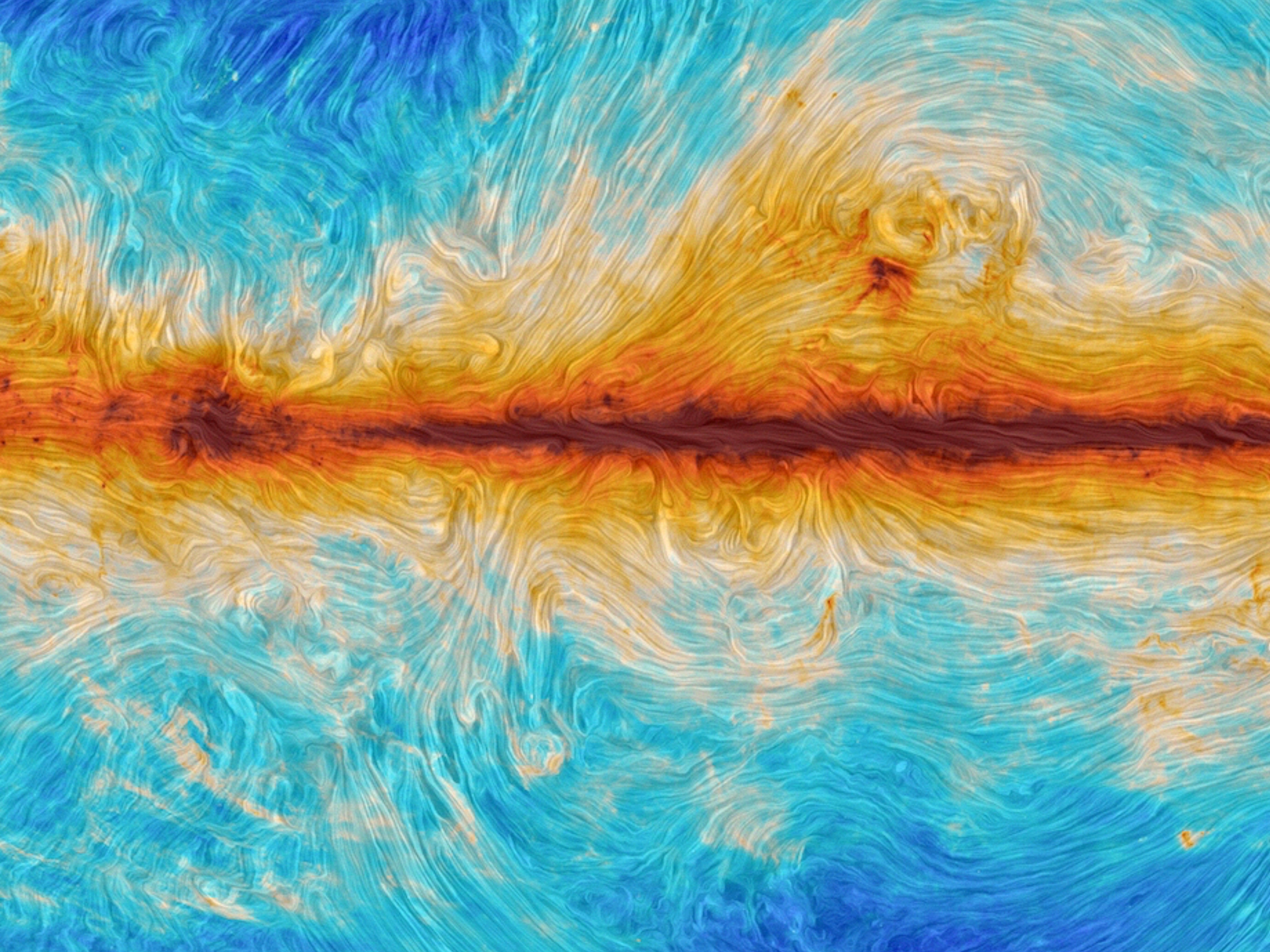
 https://astronomynow.com/2015/02/06/planck-reveals-first-stars-were-born-later/

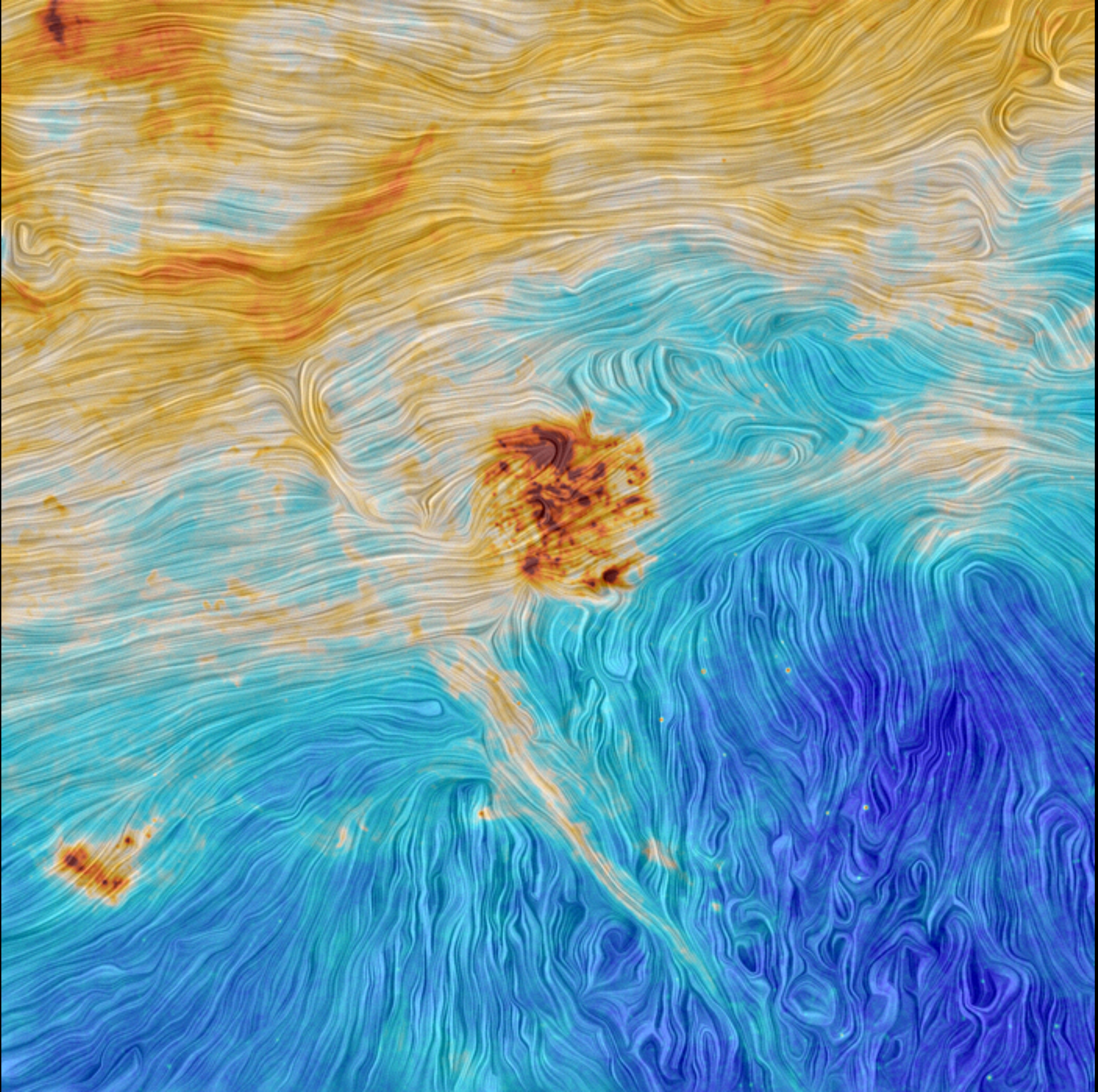
Magnetic fields play a role



Planck collaboration https://arxiv.org/abs/1405.0871
Polarization of thermal dust emission, due to alignment of dust grains w/ magnetic fields

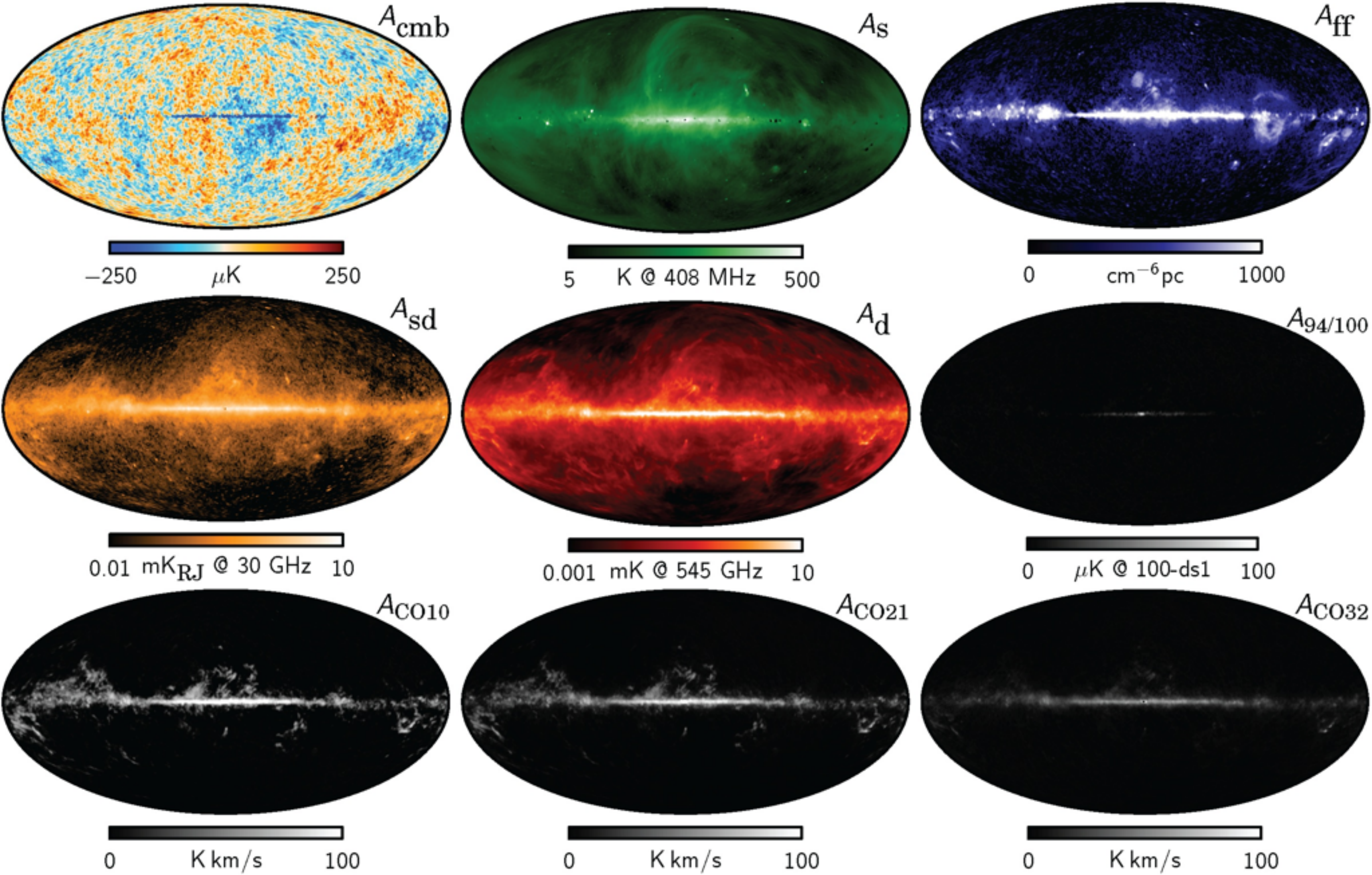
http://www.esa.int/spaceinimages/Images/2015/02/Polarised_emission_from_Milky_Way_dust





Magellanic Clouds

http://www.esa.int/spaceinimages/Images/2015/09/The_Magellanic_Clouds_and_an_interstellar_filament


A_{cmb}
−250 μK 250
A_s
5 K @ 408 MHz 500
A_{ff}
0 cm^{-6}pc 1000
A_{sd}
0.01 mK$_{RJ}$ @ 30 GHz 10
A_d
0.001 mK @ 545 GHz 10
$A_{94/100}$
0 μK @ 100-ds1 100
A_{CO10}
0 K km/s 100
A_{CO21}
0 K km/s 100
A_{CO32}
0 K km/s 100