RADIO SPECTRAL LINES

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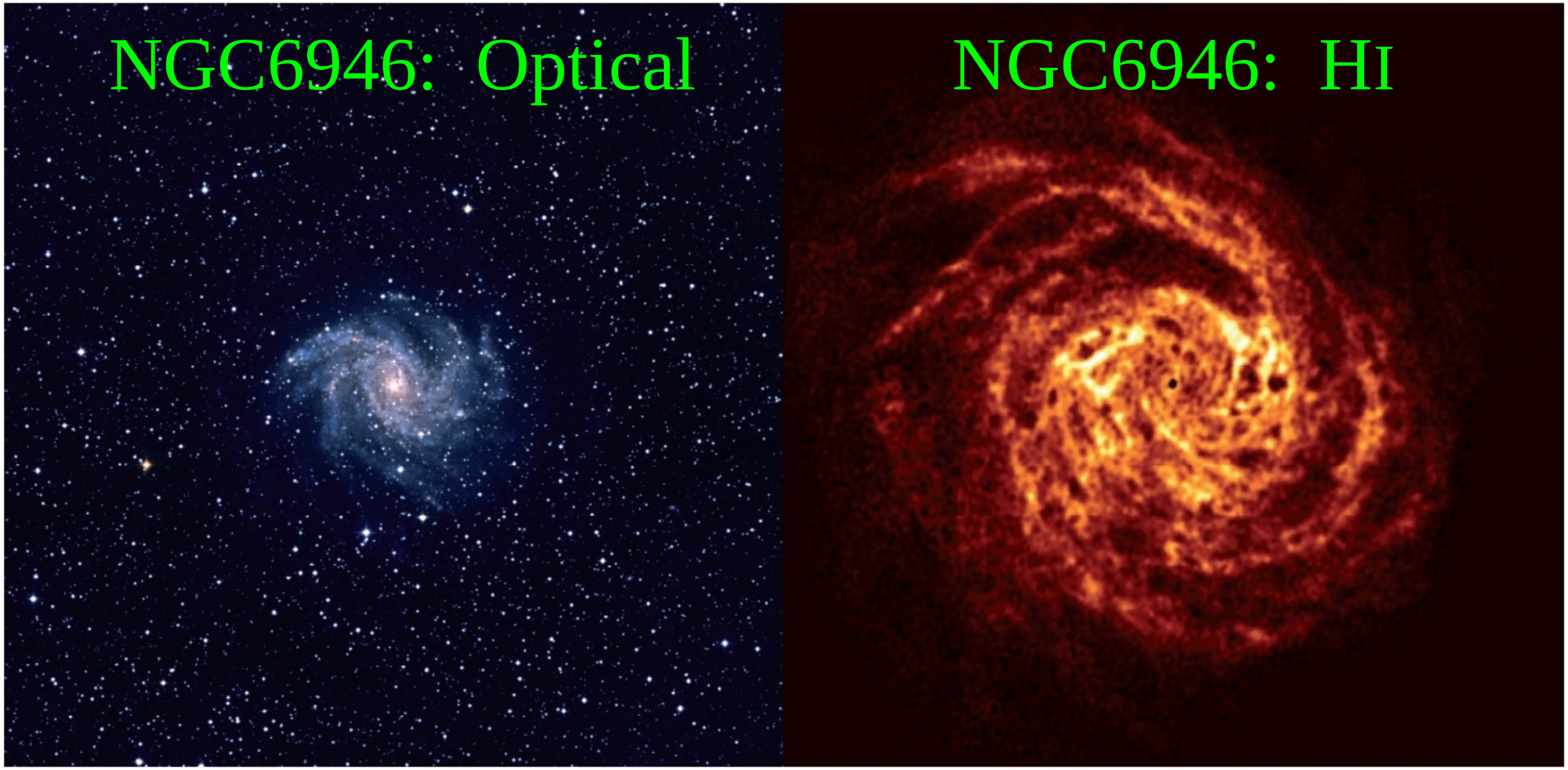
OUTLINE

- The importance of radio spectral lines.
- Equilibrium issues: “kinetic”, “excitation”, “brightness” temperatures.
- Atomic gas: The HI 21cm hyperfine line.
- Molecular gas: The CO rotational lines.
- “Ionized” gas: The CII 158μm fine structure line.
- Lambda-doublets, recombination lines, megamasers, inversion lines, …

THE IMPORTANCE OF RADIO SPECTRAL LINES

- Main constituents of galaxies: Dark matter, Stars, Gas.

- Understanding galaxies requires us to understand both stars and the interstellar medium (ISM): Galaxies look very different in stars and gas!



(Boomsma, Ph.D. thesis)

- Critical spectral lines of the ISM (e.g. the HI 21cm line, molecular rotational lines, the CII-158μm line of ionized carbon, etc., all lie at *radio* wavelengths (~ 100 MHz – 2 THz).

The ISM of the Milky Way

Species	Density cm^{-3}	Temperature K	Pressure $P/k\ cm^{-3}K$	Mass $10^9\ M_\odot$
HI (CNM)	30	80	~2500	2.8
HI (WNM)	0.3	8000	~2500	2.2
HII (WIM)	0.3	8000	~2500	1.0
H_2	>1000	10	$>10^4$	1.3
HII (HIM)	0.003	10^6	~3000	< 1 ?
Dust,PAHs	-	-	-	0.01

(e.g. Draine 2011)

- Most important phases of the ISM: Neutral atomic gas (HI), Molecular gas (H_2), ionized gas (HII).

THE IMPORTANCE OF RADIO SPECTRAL LINES

- Arise from quantum mechanical transitions at a specific frequency.
- Probe *physics* and *chemistry* in the gas phase, i.e. in the ISM.
- Measure line *velocities*! E.g. galaxy redshifts, rotation curves, etc..
- Can provide local measurements of number density, column density, temperature, magnetic field strength, gas mass, CMB temperature, …!
- Radio spectral lines: A view unbiased by dust extinction!
- Atomic gas: The HI 21cm line ⇨ The most important line in astronomy!?
- Molecular gas: Bulk of molecules in H_2, which has no electric dipole moment for rotational/vibrational lines. Also, H_2 is a light molecule, so lines at mid-IR wavelengths. $h\nu/k > 500$ K ⇨ Not seen in typical clouds. ⇨ CO rotational lines are the main *bulk* tracer of molecular gas.
- Ionized gas: Radio recombination lines, the CII-158μm fine-structure line.

EQUILIBRIUM ISSUES

- Thermodynamic equilibrium: Maxwell-Boltzmann velocity distribution Boltzmann energy levels, Planck radiation field, etc. ⇨

- Velocity distribution : $f(v) = (m/2\pi kT)^{1/2}\, e^{-mv^2/2kT}$

- Level populations : $(n_u/n_l) = (g_u/g_l)\, e^{-h\nu/kT}$

- Radiation field : $B(\nu,T) = (2h\nu^3/c^2)\,[e^{h\nu/kT} - 1]^{-1}$

  Wien limit : $B(\nu,T) = (2h\nu^3/c^2)\, e^{-h\nu/kT}$
  Rayleigh-Jeans limit: $B(\lambda,T) = (2kT/\lambda^2)$

- Critical aspect: *A single temperature!*

Species	Density cm^{-3}	Temperature K	Pressure P/k $cm^{-3}K$	Mass 10^9 $M_\odot$
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(e.g. Draine 2011)

The ISM is NOT in thermodynamic equilibrium!

EQUILIBRIUM ISSUES

- For typical ISM densities, the thermalization timescale in most phases is short ⇨ Phases *likely* to have a well-defined *kinetic* temperature, T_K.

  ⇨ Velocity distribution : $f(v) = (m/2\pi kT_K)^{1/2}\, e^{-mv^2/2kT_K}$

- But, the ISM pressure is low ⇨ Mixing of phases is very slow ⇨ Different kinetic temperatures, but pressure equilibrium!?

  (Spitzer 1956)

- Radiative timescales different from collisional timescales ⇨ Level populations may *not* be determined by the kinetic temperature.

- *Define* the *excitation* temperature, T_X, of a transition by

$$(n_u/n_l) = (g_u/g_l)\, e^{-h\nu/kT_X}$$

- T_X depends on T_K, on the local radiation field at the line frequency, and the radiation field at the frequencies of lines from the levels in question.

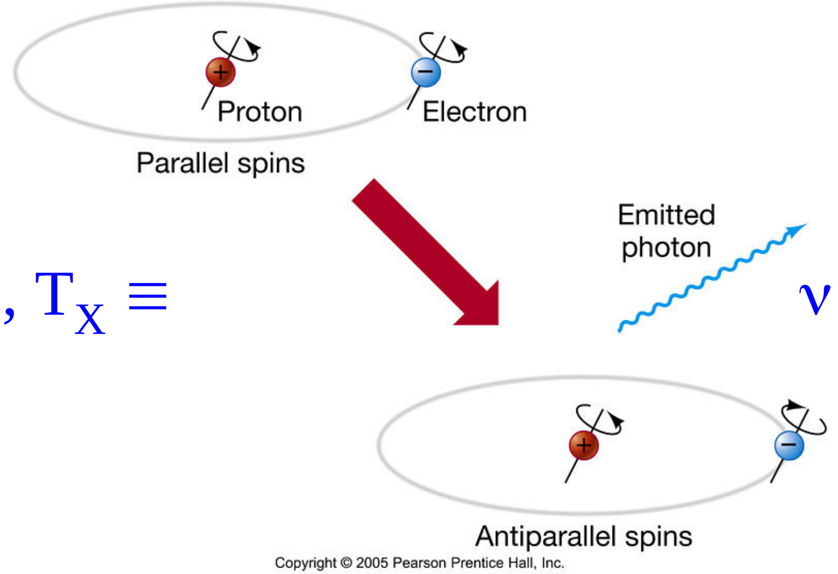
  (e.g. Wouthuysen 1952; Field 1959)

- At low (radio) frequencies, *define* the line *brightness* temperature by

$$I_\nu = (2kT_B/\lambda^2)$$

THE HI 21CM LINE

- “Spin-flip” transition: electron moves from a state with spin parallel to that of the proton, to one with anti-parallel spin.



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Excitation temperature, $T_X \equiv$ Spin temperature, T_S.

$\nu = 1420.40575$ MHz

(Courtesy: NRAO)

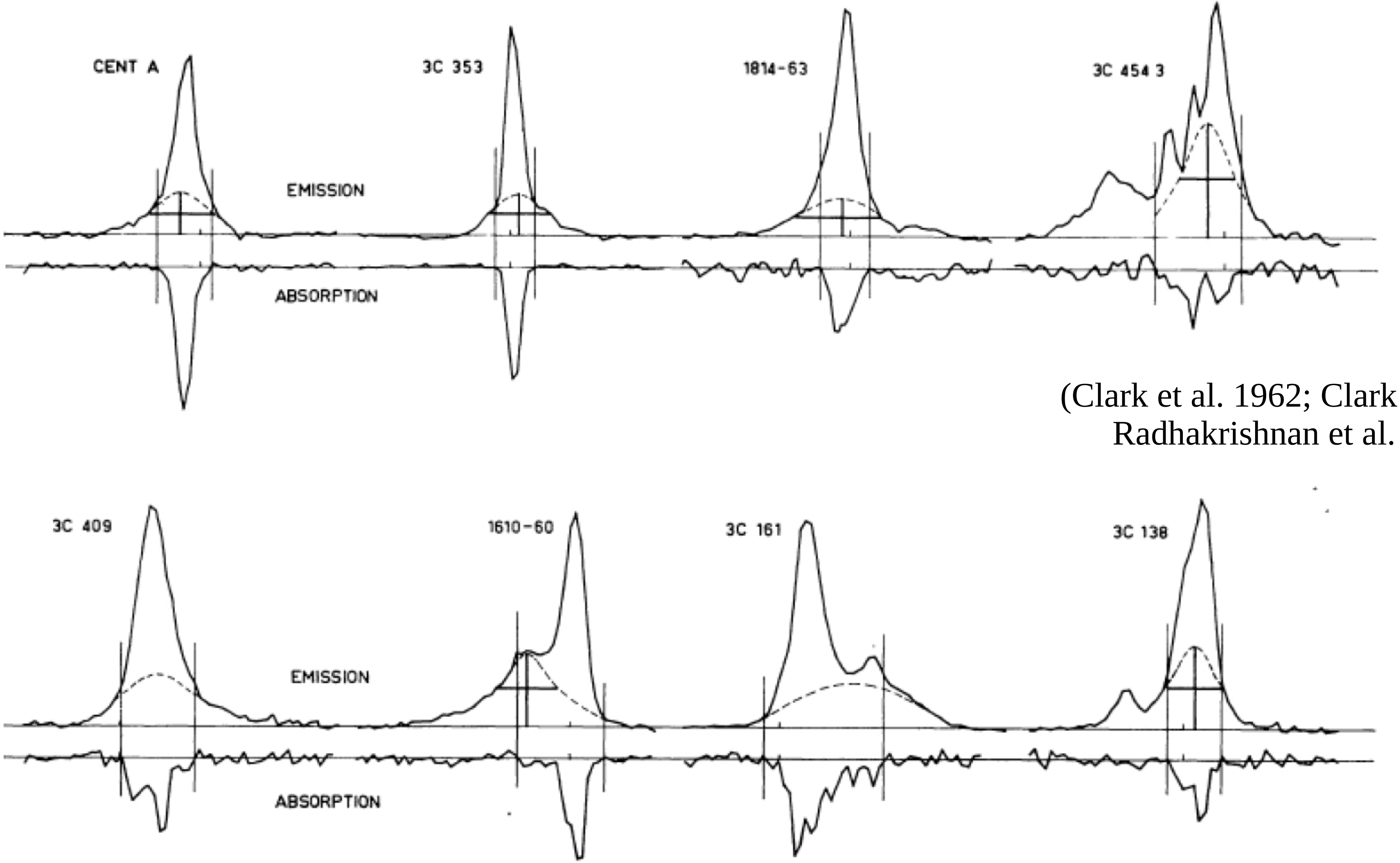
- “Forbidden” magnetic dipole transition: $A_{21cm} = 2.87 \times 10^{-15}\ s^{-1}$.
- $(h\nu/k) \sim 0.07$ K, $\ll T_S$ ⇨ Energy level ratio $(n_u/n_l) \approx (g_u/g_l) = 3$.
- General equation: HI column density, $N_{HI} = 1.8 \times 10^{18} \int T_S\, \tau_v\, dV$.
- For unresolved galaxies: HI mass, $M_{HI} = 2.35 \times 10^5\, D^2 \int S\, dV\ \ (M_\odot)$

HI 21CM STUDIES: OBSERVABLES

- Emission studies: If $\tau_v \ll 1$ ⇨ $N_{HI} = 1.8 \times 10^{18} \int T_B \, dV$
  - ⇨ Can measure N_{HI} directly from HI 21cm emission studies!
- Absorption studies: $N_{HI} = 1.8 \times 10^{18} \, \langle T_S \rangle \times \int \tau_v \, dV$; $I_v = I_0 \times \exp(-\tau_v)$.
  - ⇨ Can infer T_S if N_{HI} is known (HI 21cm emission or Ly-α absorption).
- If $\tau_v \ll 1$, line profile would be Gaussian in local thermal equilibrium.
  - ⇨ Can fit a multi-Gaussian profile to infer the kinetic temperature.
- All-sky HI 21cm emission surveys: HI-selected galaxy samples, unbiased by dust extinction! ⇨ HI mass function, cosmological HI mass density!
- External galaxies: HI mass, $M_{HI} = 2.35 \times 10^5 \, D^2 \int S \, dV \quad (M_\odot)$
  - ⇨ Gas mass, spatial distribution, velocity field, dynamical mass.
- High-z galaxies: Weak line! ⇨ “Stacking” to measure average gas mass!
- The Epoch of Reionization: HI 21cm mapping of the IGM at $z > 6$
  - ⇨ Probes the nature of the earliest galaxies and cosmological issues!

A Two-Phase Neutral Medium

Wide HI 21cm emission profiles, narrow HI 21cm absorption.

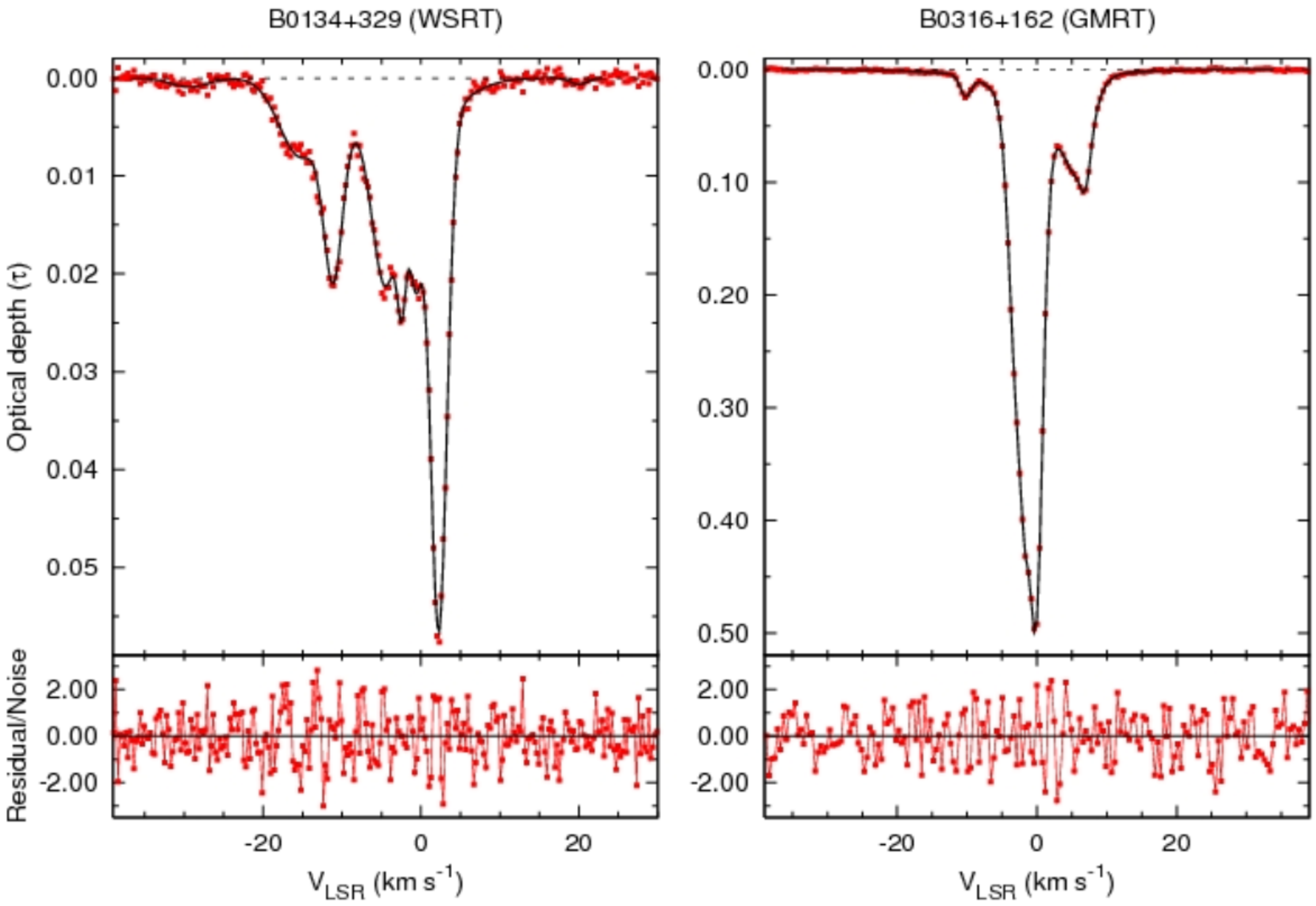


(Clark et al. 1962; Clark1965;
Radhakrishnan et al. 1972)

“Two-phase” model, with cold neutral medium and warm neutral medium!

KINETIC TEMPERATURES IN THE GALAXY

- Based on Gaussian fitting: A pinch (or a ton?) of scepticism needed!



(Roy et al. 2013)

- Cold phase kinetic temperatures ~ 20 – 200 K.

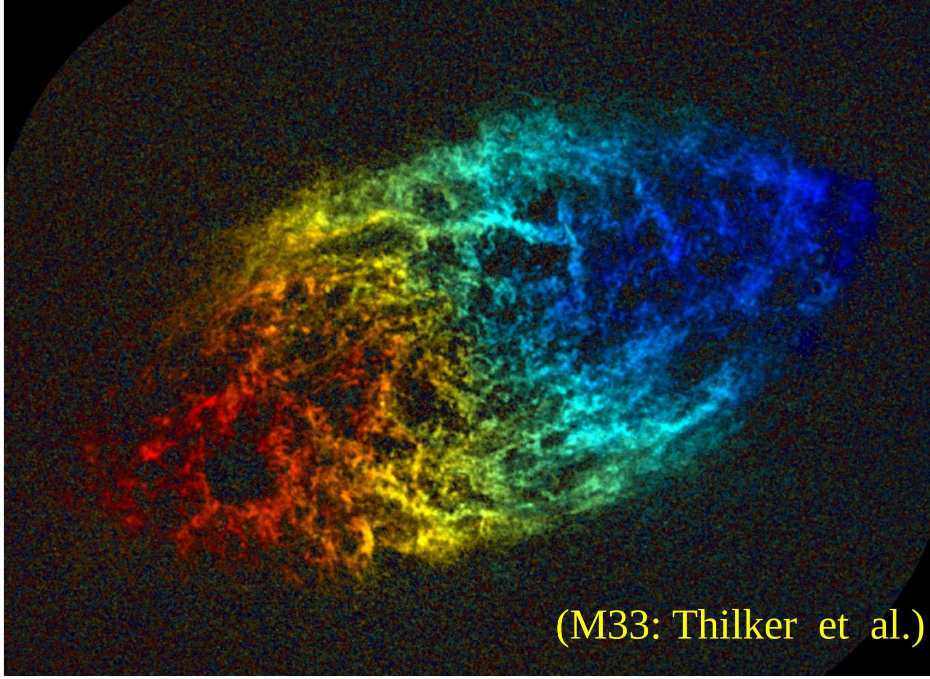
- Lots of HI in the thermally "unstable" temperature range, 500 – 5000 K. Very little detected gas in the WNM temperature range, > 5000 K.

(Heiles & Troland 2003; Roy et al. 2013)

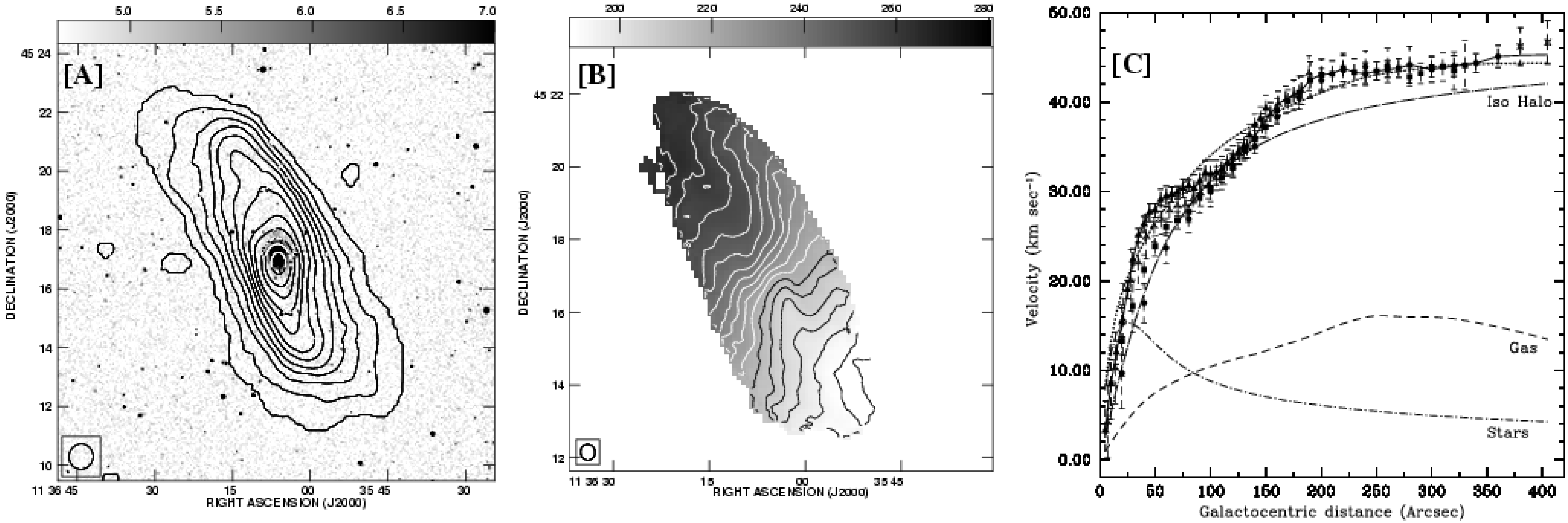
VELOCITY FIELDS

- Interferometric HI 21cm mapping studies
  ⇨ Determine velocity field of a galaxy!

- For circular orbits, $V = [GM/R]^{1/2}$.
  Should have $V \propto R^{-1/2}$ at large R,
  as most mass is in inner regions.



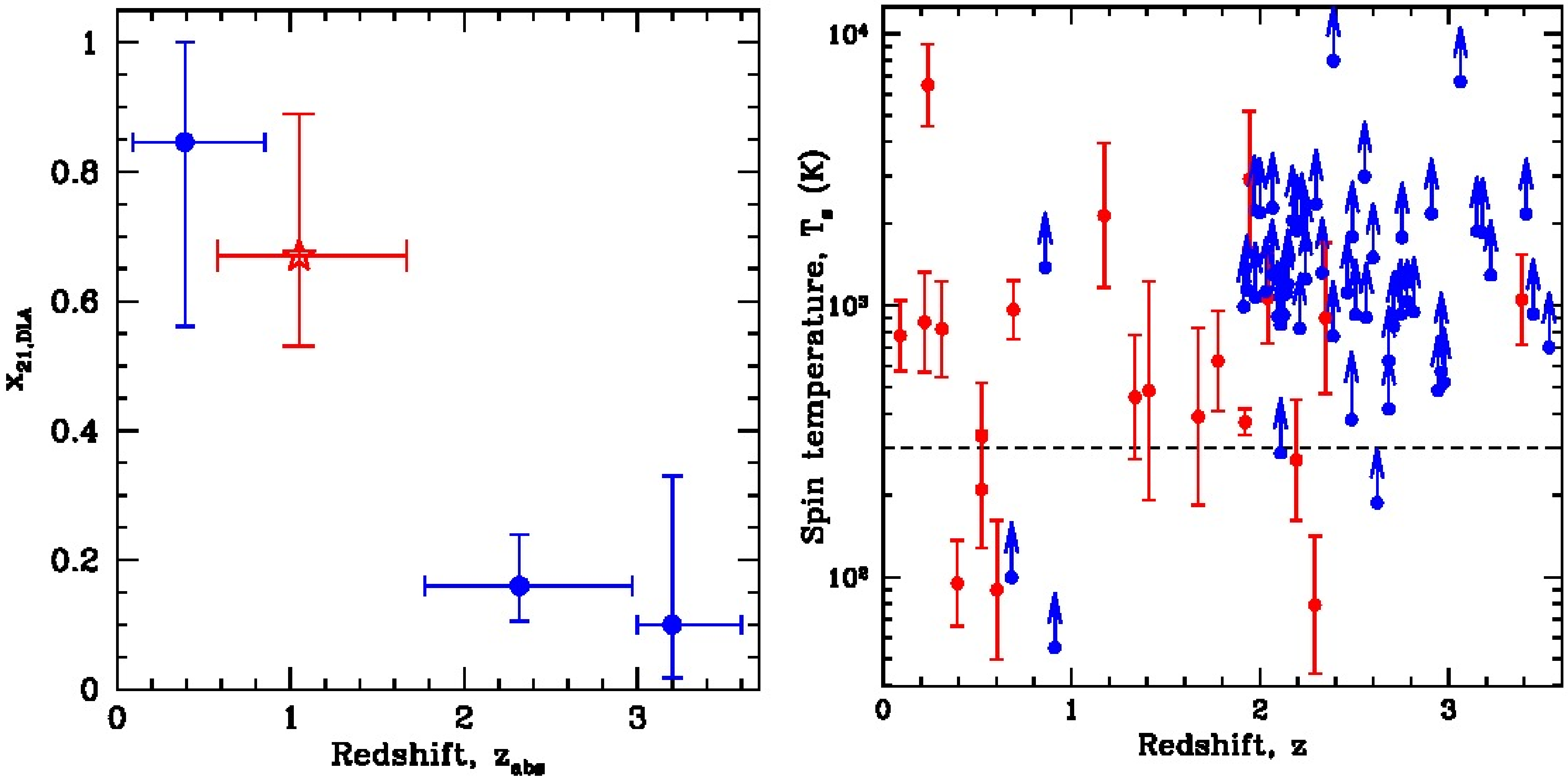
(M33: Thilker et al.)



But... Flat rotation curves ⇨ Dark Matter halos!!

(e.g. Begum et al. 2005)

HI in High-Redshift Galaxies: Absorption

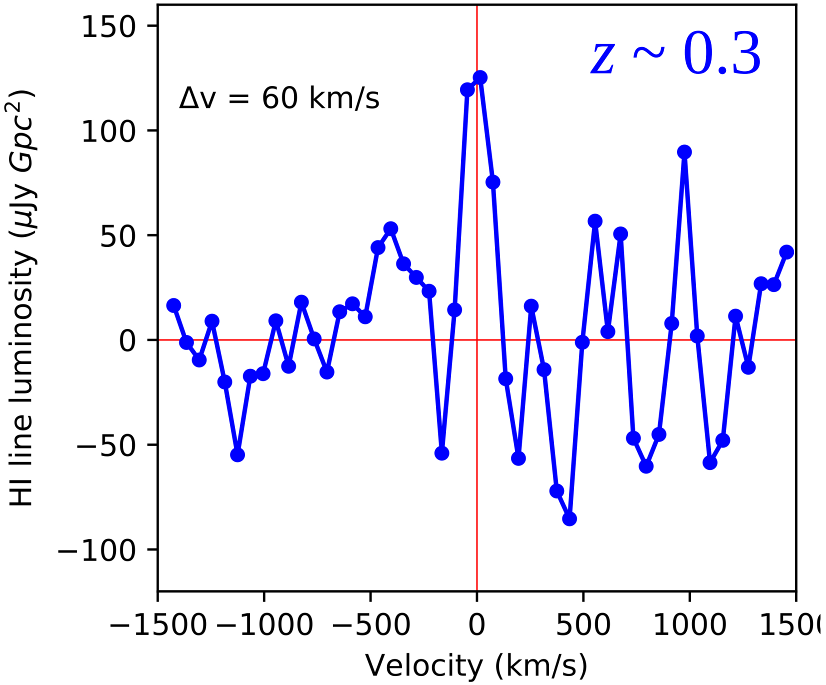


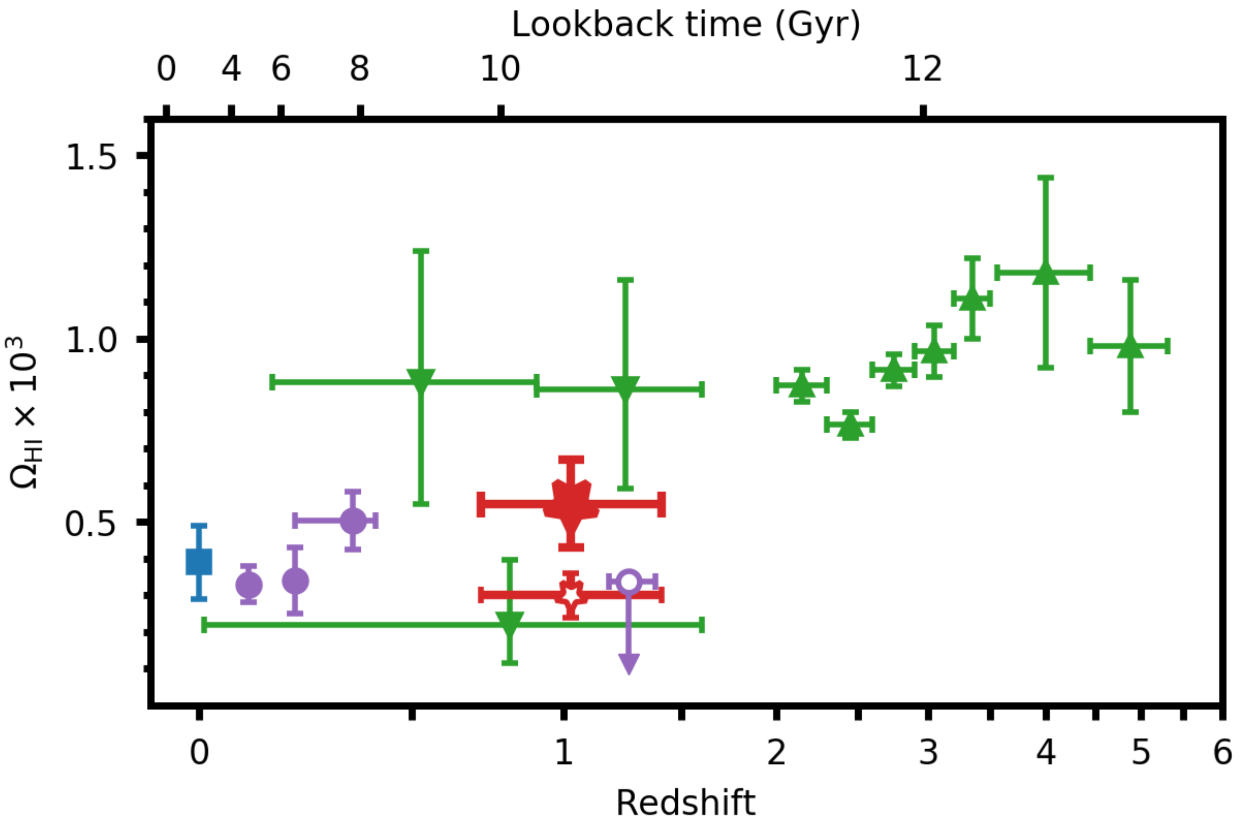
- The atomic gas in most high-z galaxies is in the warm phase.

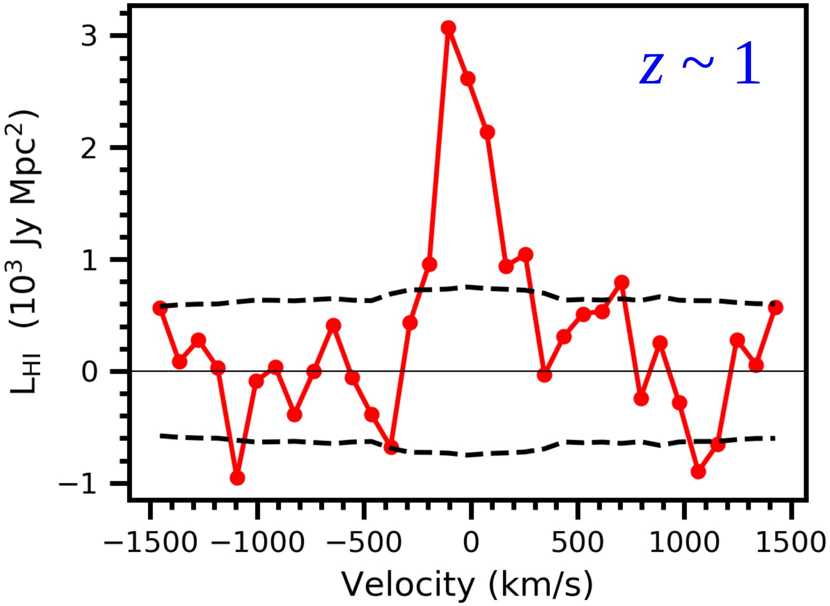
- Clear redshift evolution in the detection rate of HI 21cm absorption (i.e. the cold gas fraction), and in the spin temperature.

(NK et al. 2014; Murthy et al., in prep.)

HI in High-Redshift Galaxies: Emission







- Stacking of GMRT HI 21cm emission from star-forming galaxies with known redshifts: ⇨ Measurements of Ω_{HI} at $z \sim 0.2 – 2$!

- HI fraction & HI depletion time at $z \sim 0.3$ similar to values in the local Universe. High HI fraction and very rapid HI depletion at $z \sim 1$!

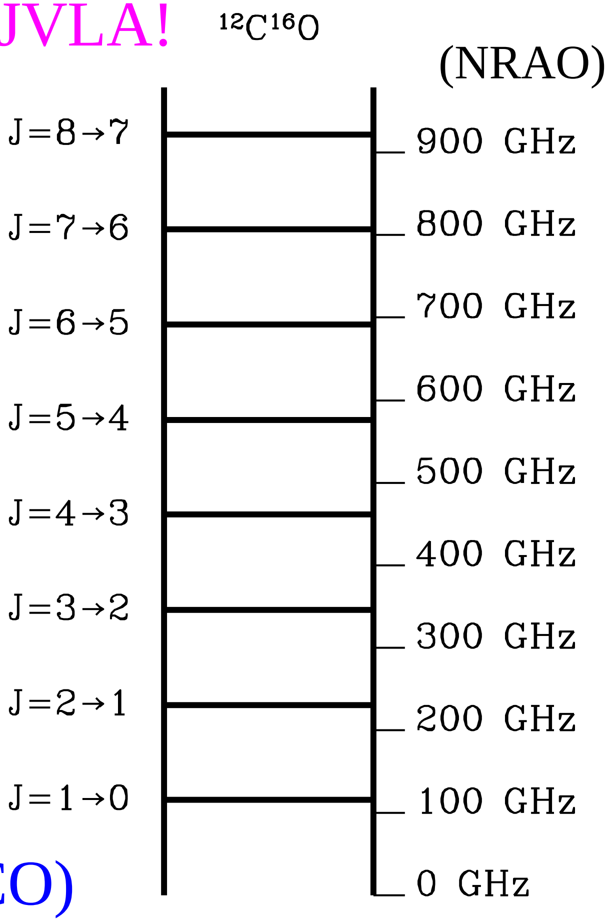
(Bera et al. 2019; Chowdhury et al., in prep.)

MOLECULAR GAS: CO ROTATIONAL LINES

- CO rotational lines are the best tracer of the bulk of the molecular gas!

(e.g. Carilli & Walter 2013)

- CO line frequencies ~ (115.271 × J) GHz ⇨ ALMA, JVLA!



(NRAO)

- "Low" Einstein A-coefficients: $A_{10} \sim 7 \times 10^{-8}\ s^{-1}$.

  $A_{ul} \propto \nu^3$ ⇨ High-J lines have higher Einstein A's.

- CO line luminosity ∝ Molecular cloud (virial) mass!

  ⇨ Measure the molecular gas mass of galaxies!!!

(e.g. Dickman 1986)

- CO "line luminosity", $L'(CO) \propto T_B(CO)$:

  $L'(CO) = 3.25 \times 10^7\ [D_L/\nu_{obs}]^2 \times \int S\ dV / (1+z)^3$

(e.g. Solomon et al. 1997)

- CO-to-H_2 conversion factor, α_{CO}: $M_{MOL} = \alpha_{CO}\ L'(CO)$

  $\alpha_{CO} \sim 4\ M_\odot\ (K\ km/s\ pc^2)^{-1}$ (Disks), $\sim 1\ M_\odot\ (K\ km/s\ pc^2)^{-1}$ (Starbursts).

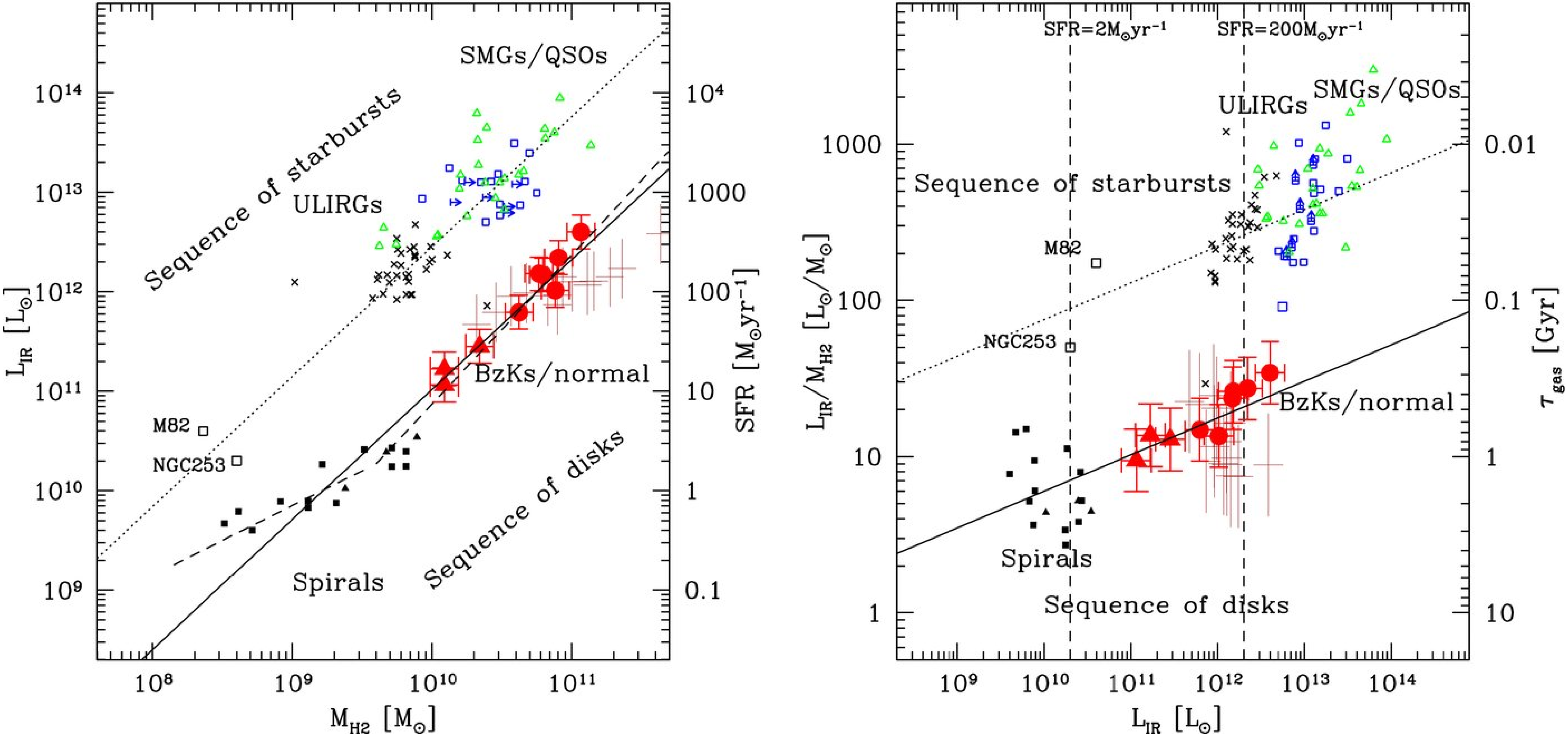
  $\alpha_{CO} > 10\ M_\odot\ (K\ km/s\ pc^2)^{-1}$ (Dwarfs)! ⇨ Strong metallicity dependence!!!

  Much easier to detect CO emission from a ULIRG than from a dwarf!

(e.g. Bolatto et al. 2013)

STAR FORMATION EFFICIENCY

(Daddi et al. 2010)



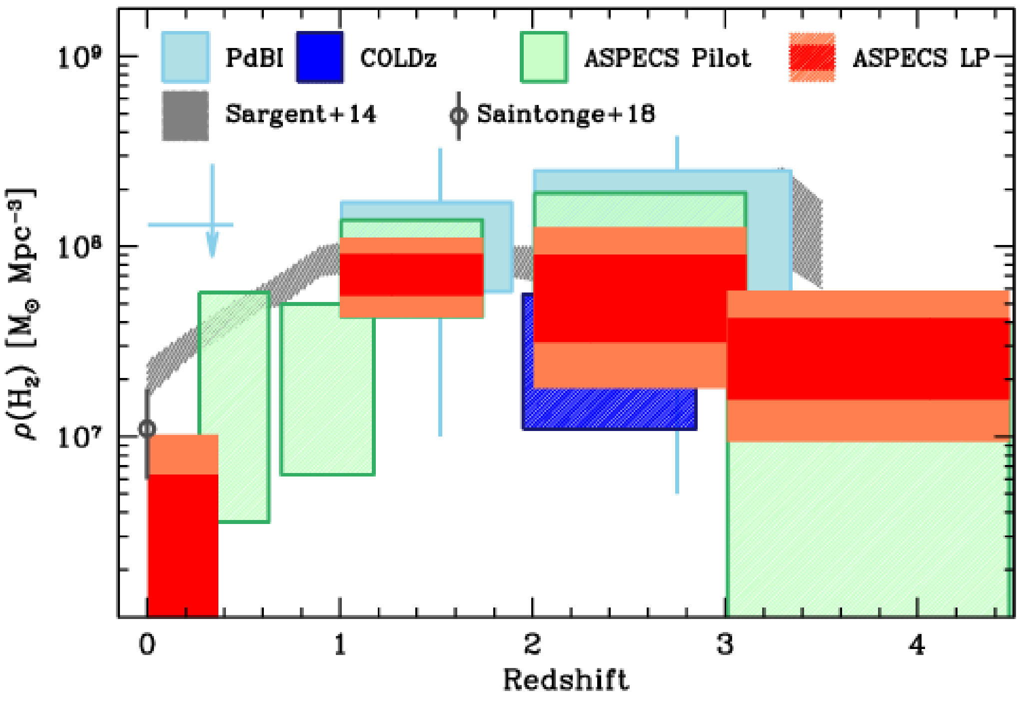
- SFRs higher by an order of magnitude, and H_2 depletion times lower by an order of magnitude in starburst galaxies (ULIRGs, SMGs) and QSOs.
- Starburst galaxies (and QSOs) are far more efficient in forming stars than disk galaxies on the main sequence!

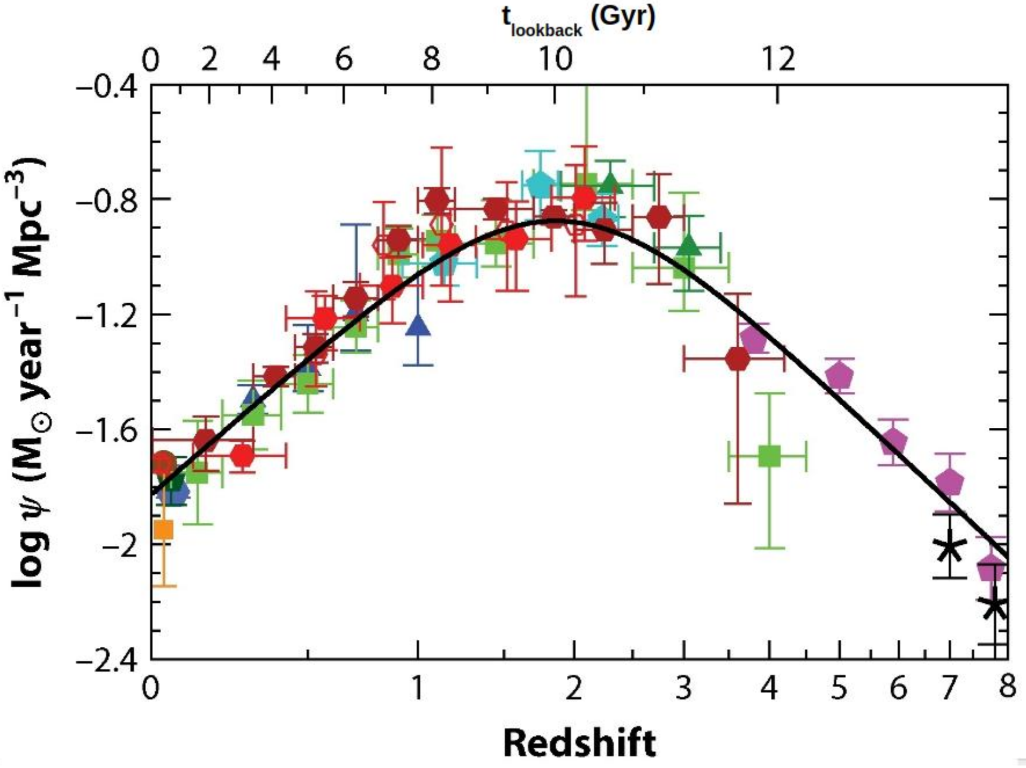
(Daddi et al. 2010; Genzel et al. 2012)

THE COSMOLOGICAL H_2 MASS DENSITY

- Unbiased ALMA & JVLA surveys for CO emission: ASPECS, ColdZ!

(Decarli et al. 2019; Riechers et al. 2019)





(Decarli et al. 2019; Madau & Dickinson 2014)

- Redshift evolution of cosmological H_2 density broadly traces SFR density!

(Decarli et al. 2019)

- CO emission still the best way of measuring redshifts for dusty galaxies (e.g. SMGs!): HDF850.1 finally detected at $z \sim 5.2$, after 15 years!

(Walter et al. 2012)

The CII-158μm Line

- Fine-structure line in the ground state of singly-ionized carbon, ~1.9 THz. "Low" Einstein A-coefficient: ~ $2.4 \times 10^{-6}\ \mathrm{s}^{-1}$.

- Strongest cooling line in most galaxies! ~ 0.5% of a galaxy's luminosity!

- Traces cold atomic gas, molecular gas, and photo-dissociation regions.

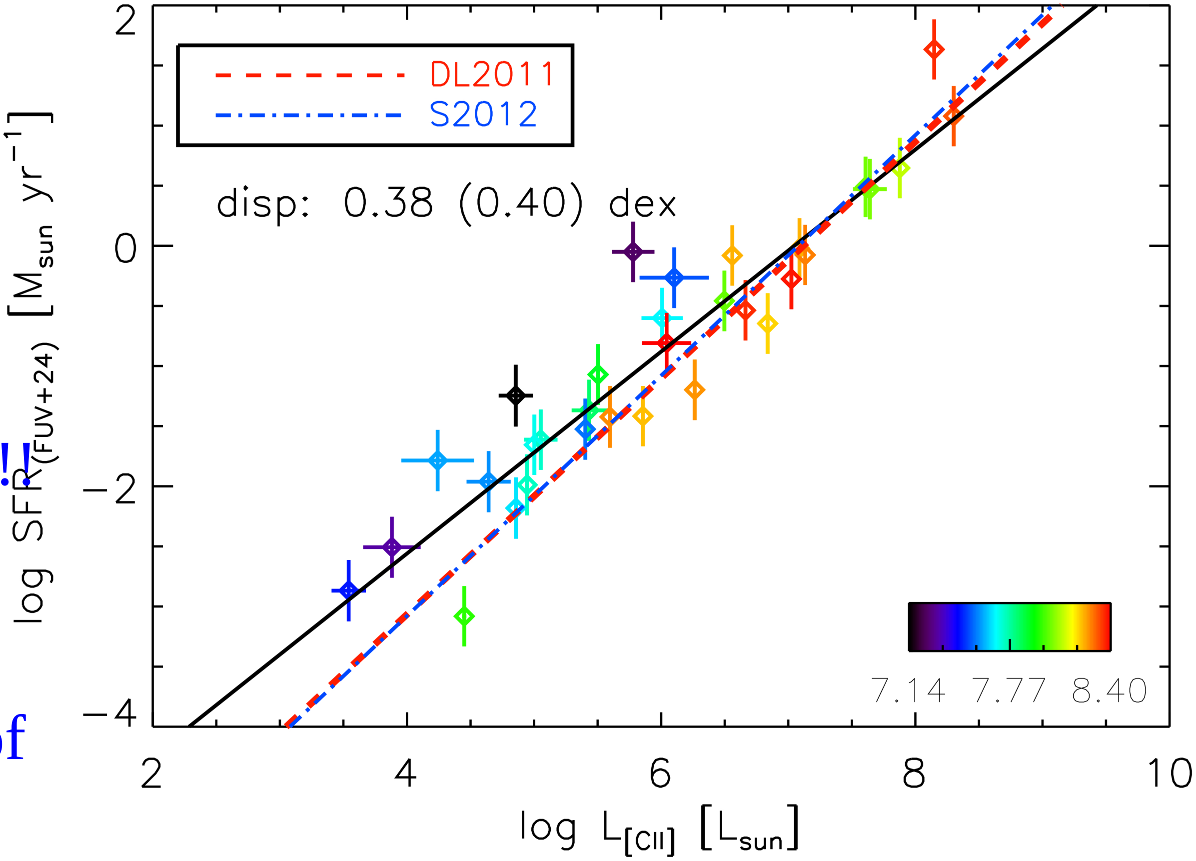
- CII line luminosity correlates with SFR in nearby galaxies.

  (e.g. de Looze et al. 2011, 2014)

- Much higher luminosity than that of CO lines, for both normal galaxies and starbursts!!!

  ⇨ Best gas tracer in high-z galaxies (ALMA!!!).

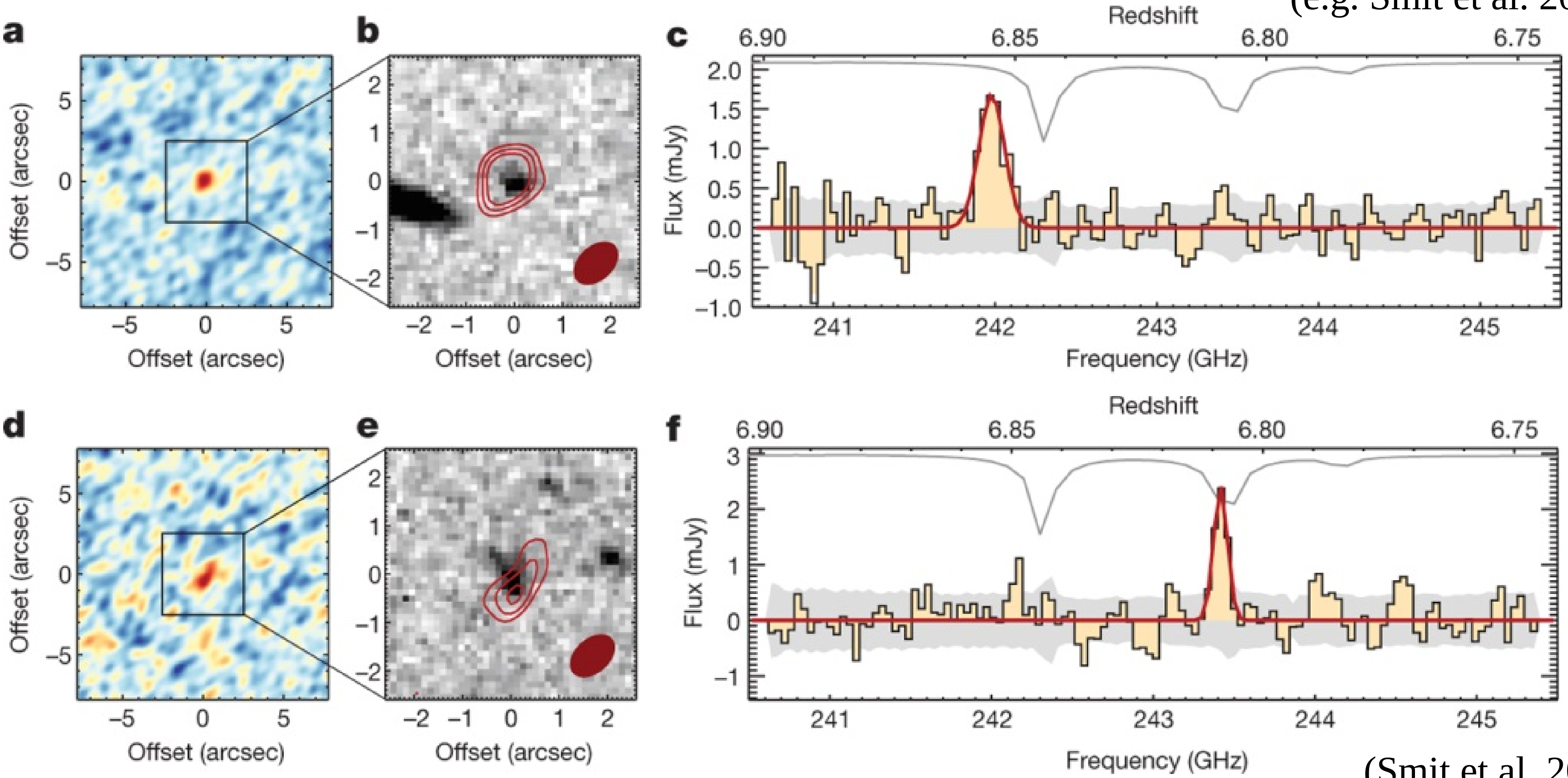
- Optically-thin, so good tracer of gas kinematics!



CII-158μm EMISSION AT HIGH REDSHIFT

- Has been used to measure redshifts of galaxies at $z \sim 7 - 8$, for objects with only photometric redshifts!

(e.g. Smit et al. 2018)



(Smit et al. 2018)

- Unbiased ALMA surveys now being carried out for CII emission at $z > 4$!

- Spectacular imaging of CII emission around $z \sim 6$ QSOs!

(e.g. Venemans et al. 2019)

OTHER RADIO LINES

- “Other” rotational lines: HCN, CS, H_2O, …: Trace higher-density gas.

  (e.g. Gao & Solomon 2004)

- H_2O 22.3 GHz megamasers: Arise in AGN accretion disks. For Keplerian orbits, can measure the AGN distance, and thence, the Hubble constant!

  (e.g. Moran et al. 1995; Reid et al. 2013, 2019)

- Physical conditions in molecular clouds: Density (e.g. HC_3N), temperature (e.g. NH_3), magnetic fields (e.g. OH, CN, CCH), …

  (e.g. Henkel et al. 2008, 2009; Heiles & Crutcher 2005)

- Radio recombination lines: Density, temperature of the WIM.

  (e.g. Gordon & Sorochenko 2009)

- OH 1667-MHz megamasers: Tracers of mergers at high redshifts.

  (e.g. Briggs 1998; Darling & Giovanelli 2001, 2004)

- Complex molecules: ~ 200 species detected in the ISM so far! Searches under way for amino acids, especially glycine (lots of heat, no light)!!!

  (e.g. Hollis et al. 2004, 2006)

- OH Lambda-doubled lines, NH_3 inversion lines, CH_3OH lines: Probe fundamental constant evolution with redshift.

  (e.g. NK 2011; NK et al. 2015, 2018)

EXTRA SLIDES

H_2O MEGAMASERS: THE DISTANCE SCALE

- 22 GHz water megamasers arise in accretion disks that rotate around the central black holes of bright active galactic nuclei.

(e.g. Claussen et al. 1984)

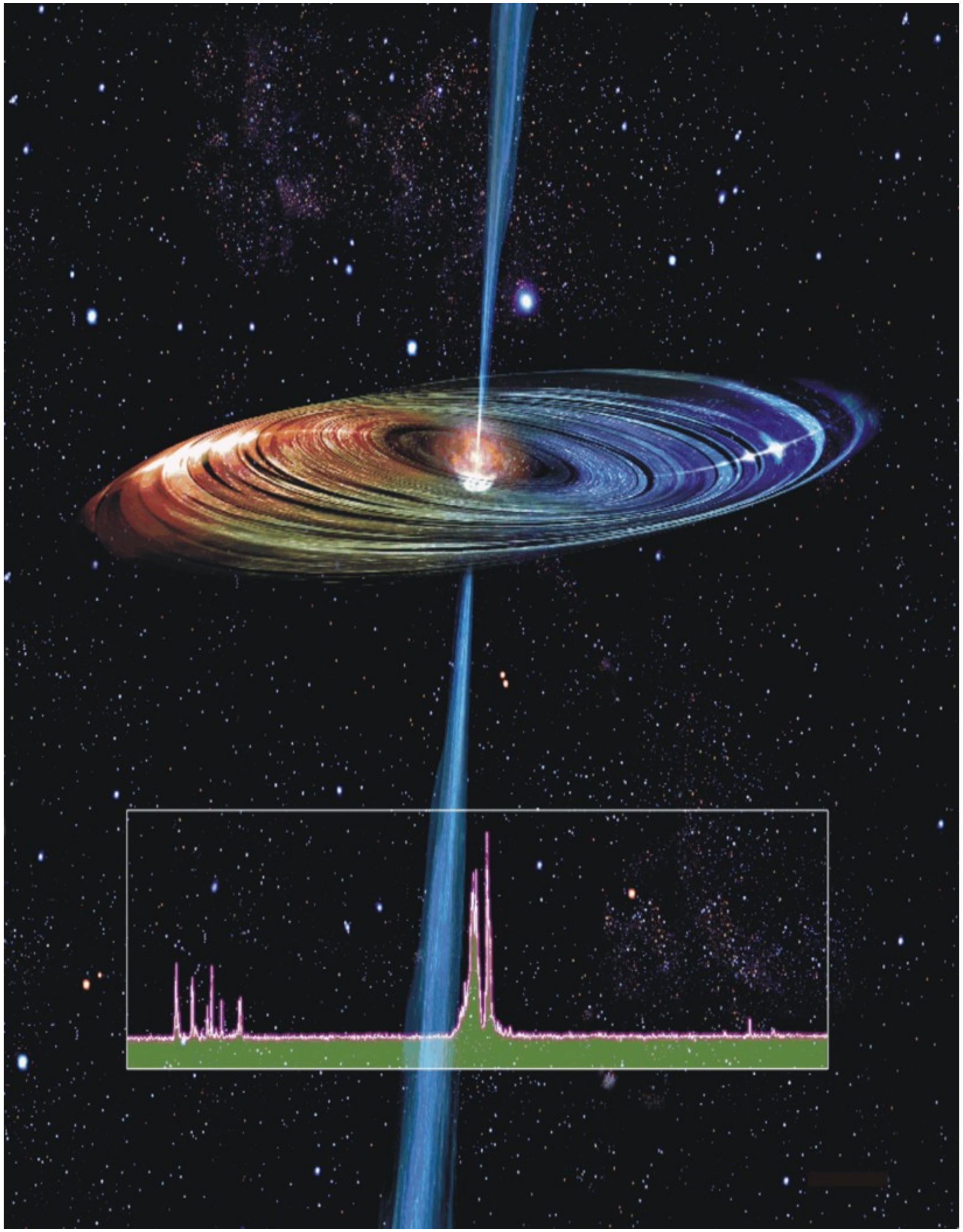
- VLBI studies: The megamaser emission consists of multiple lines, each arising from small regions (of size ~ 0.1 pc) in the disk. The line velocities trace the disk rotation!

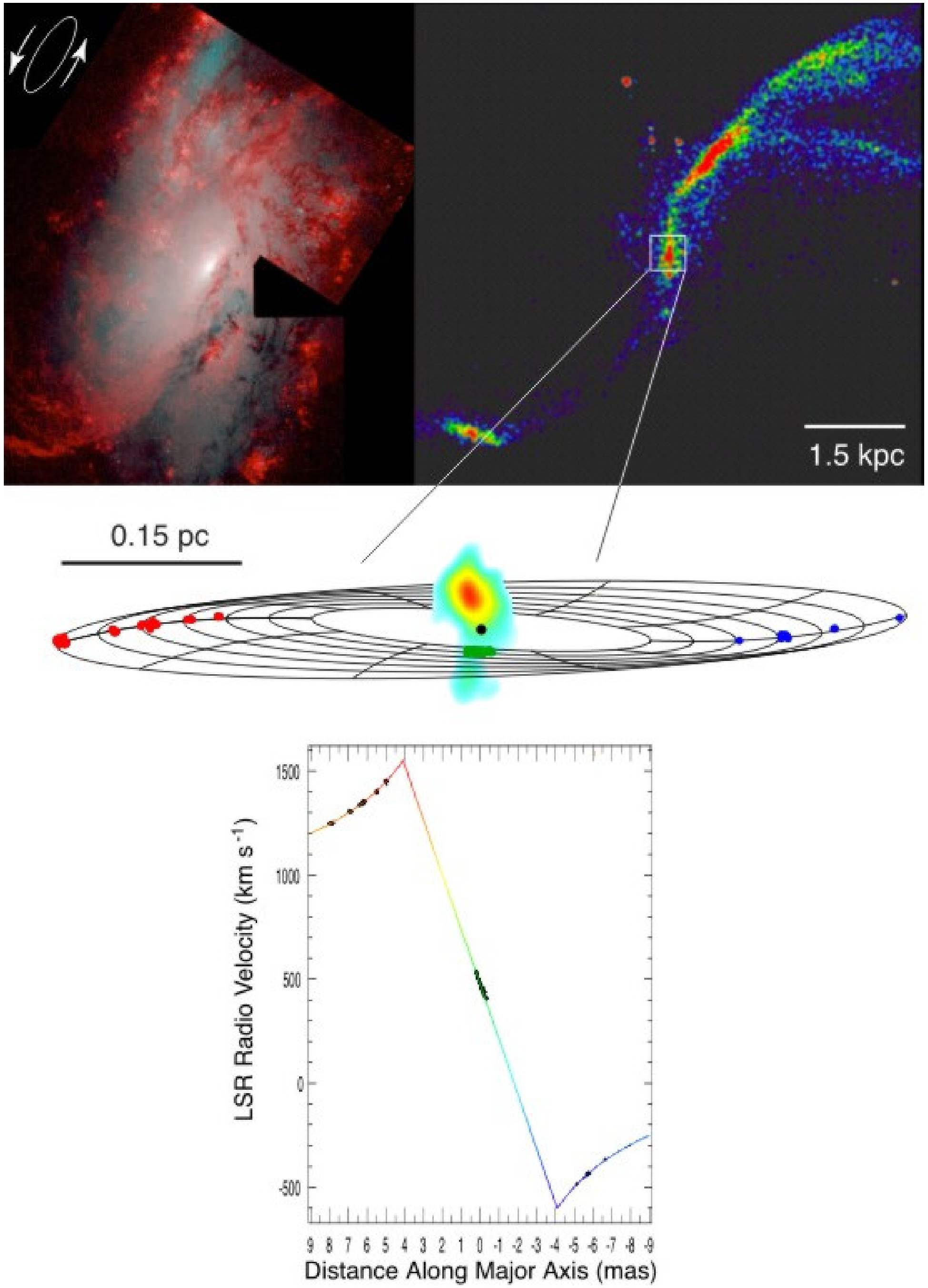
(e.g. Haschick et al. 1990)

- The H_2O megamasers in NGC4258: Lovely Keplerian rotation!!! Very slight warp in the disk!

(Moran et al. 1995)

H_2O MEGAMASERS: THE DISTANCE SCALE





(Courtesy Mark Reid and NRAO)

H_2O MEGAMASERS: THE DISTANCE SCALE

- VLBA monitoring of the H_2O megamasers in NGC4258 with angular resolution of ~ 0.2 mas, along with GBT monitoring to measure the accelerations of different lines: Map the rotation of the megamasers and determine their distance from the central black hole. From the measured angular distance, determine the distance of NGC4258:

  7.58 ± 0.08 (stat.) ± 0.08 (syst.) Mpc

  (Reid et al. 2019)

- Detect Cepheids in NGC4258: Calibrate the Cepheid scale to 3%!
  ⇨ Measure both H_0 and Type Ia supernovae distances to 3%!

  (e.g. Riess et al. 2011; Humphreys et al. 2013)

- Hubble constant, $H_0 = 72.0 \pm 1.9$ km/s/Mpc ($\sim 4\sigma$ deviant from Planck!).

  (Reid et al. 2019)

- *En passant*, measure the black hole mass: $4 \times 10^7\ M_\odot$!

  (e.g. Moran et al. 1995; Humphreys et al. 2013)

ESTIMATING THE MOLECULAR GAS MASS

- The CO line luminosity of a uniform cloud at a distance D is

$$L_{CO} = D^2 \int I_{CO}\, d\Omega \quad , \text{ where } I_{CO} = \int T_B\, dV.$$

$$\Rightarrow \quad L_{CO} \approx \pi R^2\ T_{CO}\, \Delta V \quad , \quad \Delta V \equiv \text{Line width}, \ R \equiv \text{cloud radius},$$

$$T_{CO} \equiv \text{Peak brightness temperature.}$$

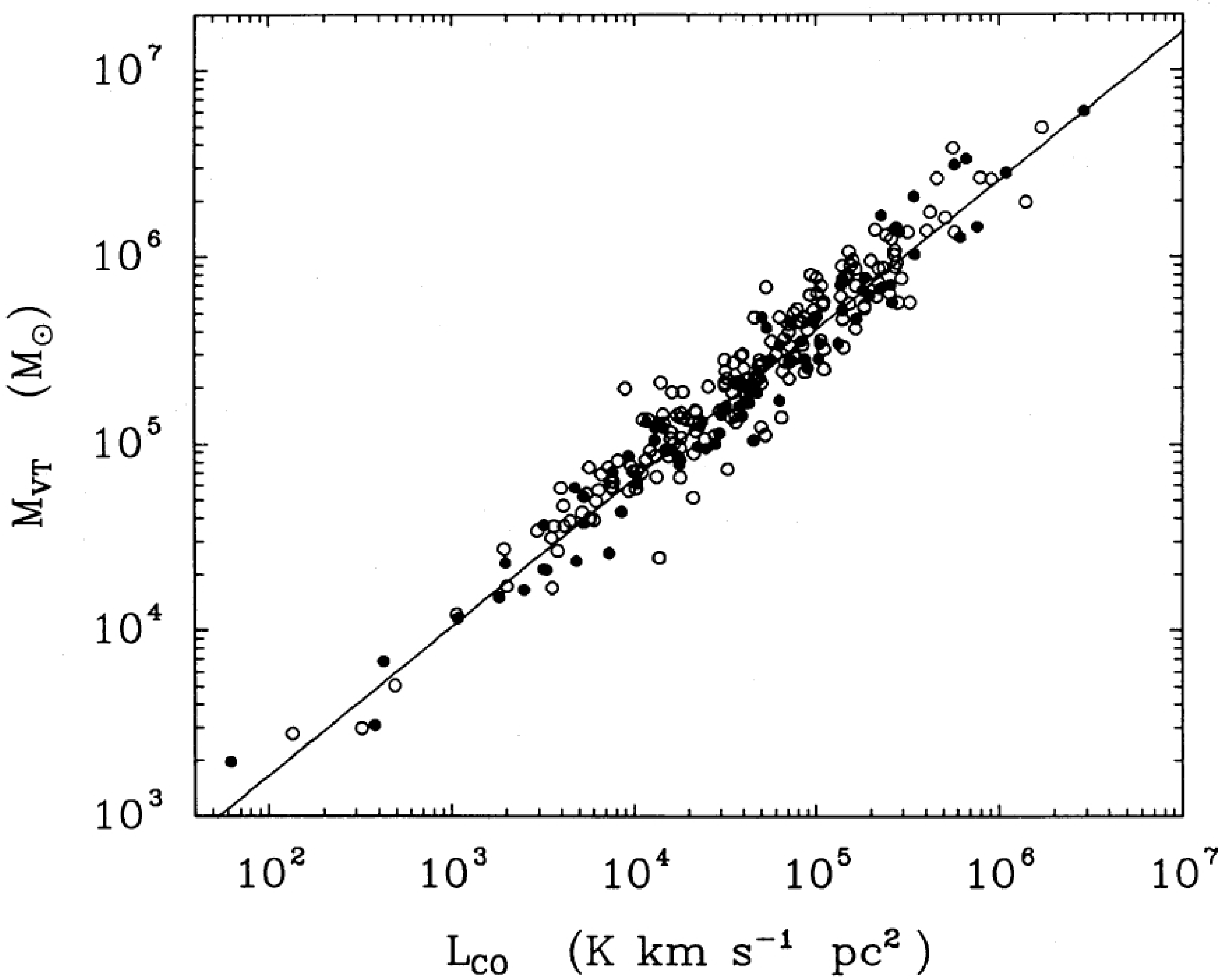
- For a spherical, virialized cloud of mass M, $\Delta V \approx (GM/R)^{1/2}$

$$\Rightarrow \quad M = L_{CO} \cdot (4\rho/3\pi G)^{1/2} \cdot (1/T_{CO})$$

- *IF* the ratio $(\rho^{1/2}/T_{CO})$ doesn't vary (on the average) from one galaxy to another, and if different clouds don't overlap in velocity, the total mass is proportional to the line luminosity!

- Test this by inferring virial masses from ^{13}CO measurements of line width and cloud size ⇨ Compare with ^{12}CO intensity.

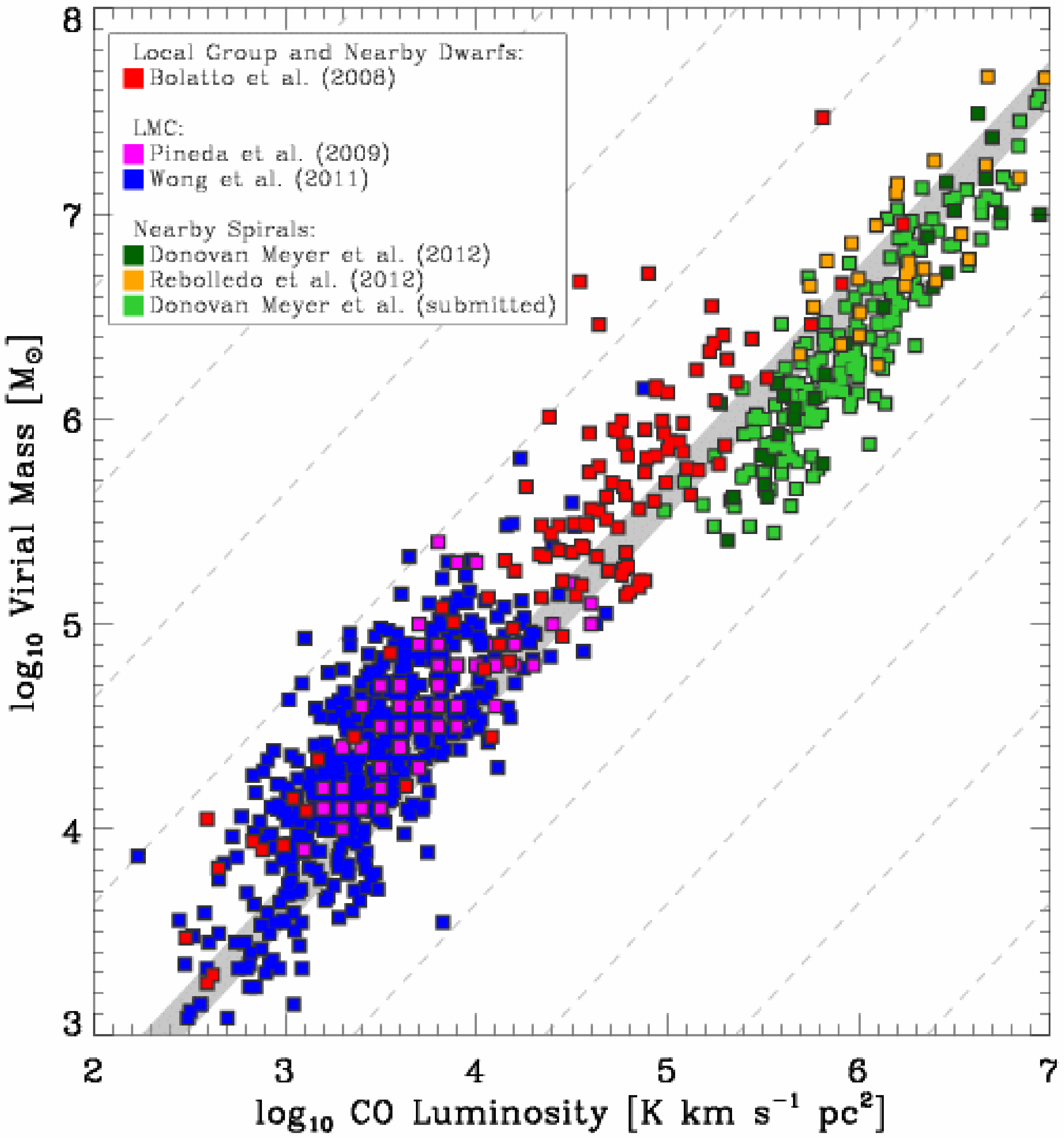
ESTIMATING THE MOLECULAR GAS MASS



Near-linear relation between CO line luminosity & virial mass!

(e.g. Solomon et al. 1987;
Scoville et al. 1987)

ESTIMATING THE MOLECULAR GAS MASS



Slope appears to depend on galaxy type.

(Bolatto et al. 2013)

AN N(HI) THRESHOLD FOR CNM FORMATION

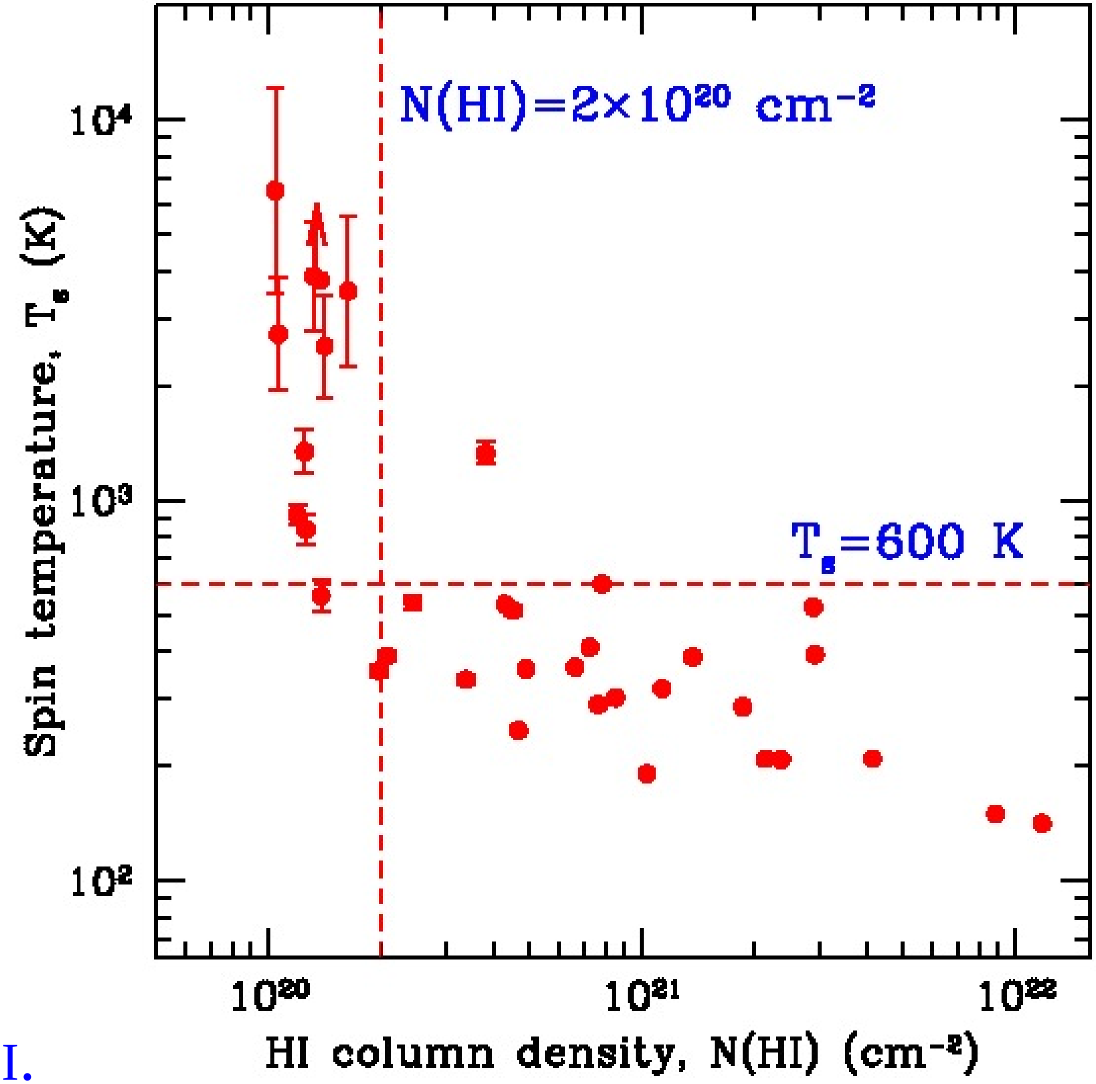
(NK et al. 2011)

- Median spin temperature:
  ~ 340 K: N(HI) $\geqslant 2 \times 10^{20}$ cm^{-2},
  ~ 2500 K: N(HI) $< 2 \times 10^{20}$ cm^{-2}.

- Sharp drop in CNM fraction for N(HI) $< 2 \times 10^{20}$ cm^{-2}.

- Inefficient self-shielding against soft X-ray / UV photons ? Or vertical dynamical equilibrium yielding WNM-only sightlines ?

(Kim et al. 2014)



- *Four* ISM phase transitions ?

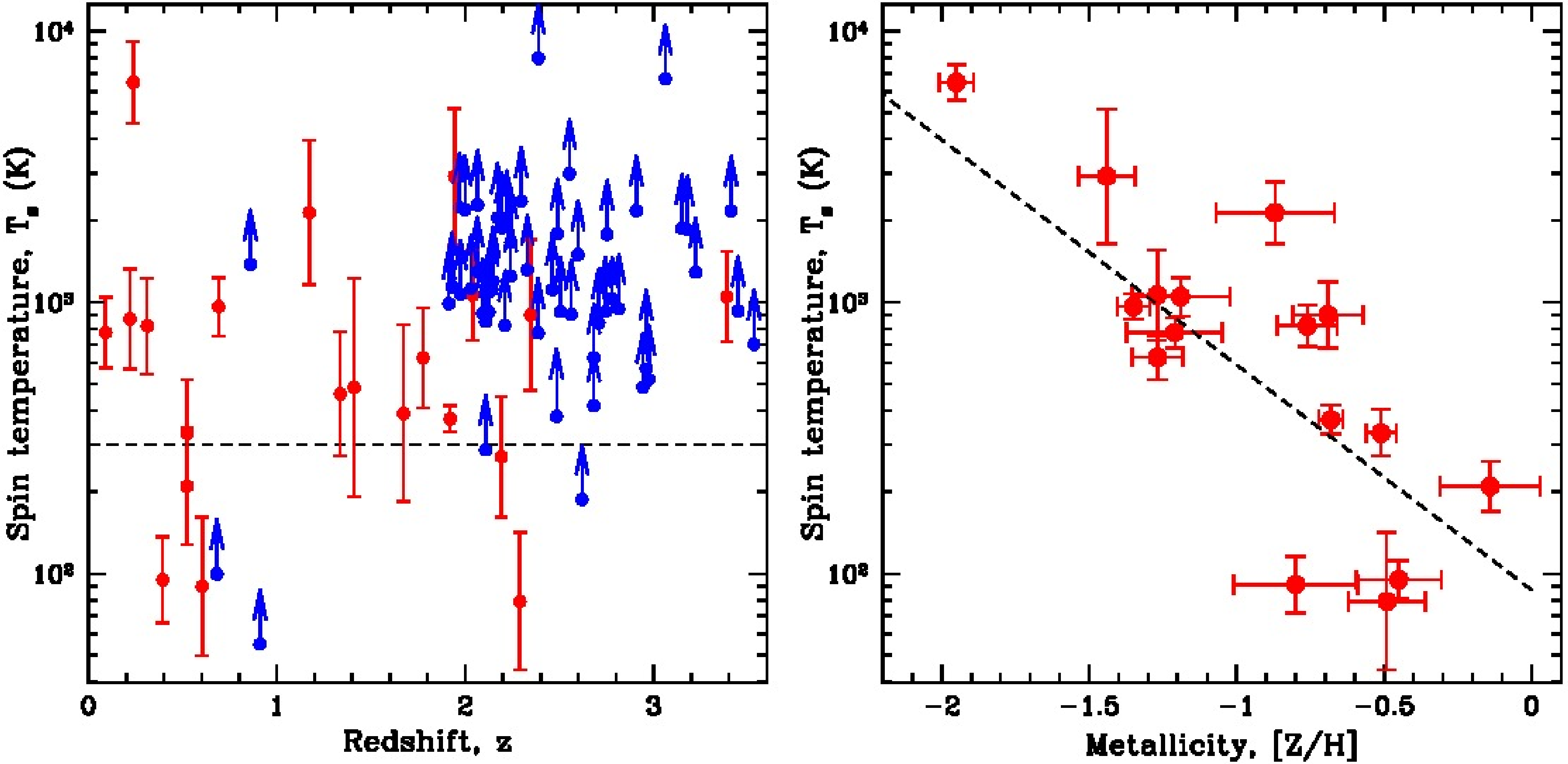
N(HI) ~ 10^{17} cm^{-2}: HII → HII + HI.
N(HI) ~ 2×10^{20} cm^{-2} : Warm HI → Warm HI + Cold HI.
N(HI) ~ 5×10^{20} cm^{-2} : HI → HI + H_2.
N(HI) ~ 10^{22} cm^{-2}: HI → H_2.

(Savage et al. 1977)

(e.g. Schaye 2001; Krumholtz et al. 2009)

Spin Temperatures in DLAs

(NK et al. 2014; Murthy et al., in prep.)



- Most high-z DLAs have high T_S, >> 300 K ⇨ Low CNM fraction, due to low metallicity in high-z DLAs: Lack of cooling routes.

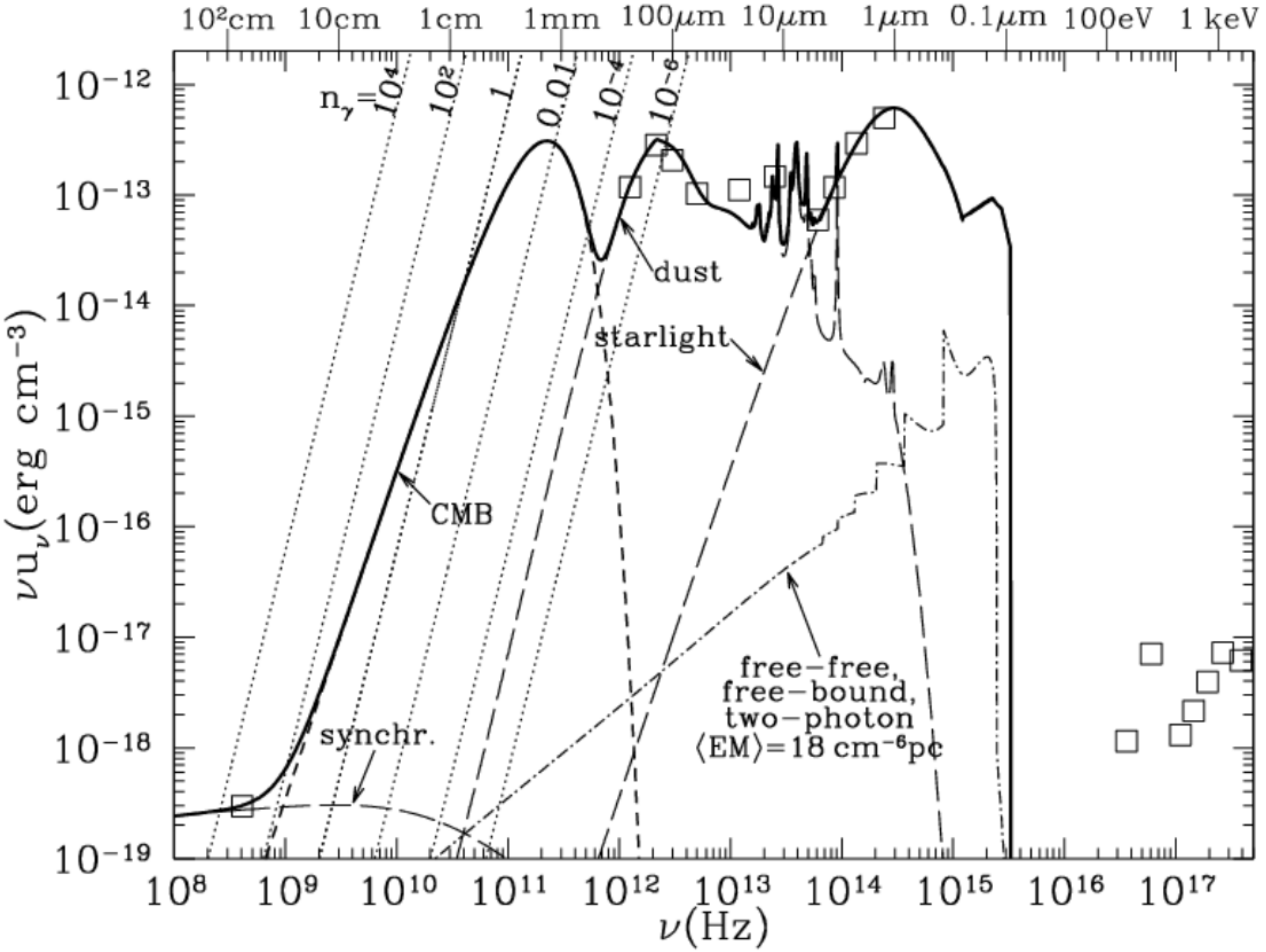
(NK & Chengalur 2001; NK et al. 2009)

- Low SFR & metallicity, high T_S: Are most high-z DLAs dwarfs ?

EQUILIBRIUM ISSUES

(Draine 2011)

- Interstellar radiation field very different from that of a black body!



- Power per unit area between ν and ν+dν, in solid angle dΩ:

$$P_\nu = I_\nu \ .\ \mathrm{Cos}\theta \ .\ d\nu .\ \ d\Omega \qquad (I_\nu \ \equiv \text{Intensity})$$

- In general, $T_B \neq T_K$. Note: T_B is *NOT* a physical temperature!

EQUILIBRIUM ISSUES

- Radiative timescales different from collisional timescales ⇨ Level populations may *not* be determined by the kinetic temperature.

- *Define* the Excitation Temperature T_X of a transition by

$$(n_u/n_l) = (g_u/g_l)\, e^{-h\nu/kT_X}$$

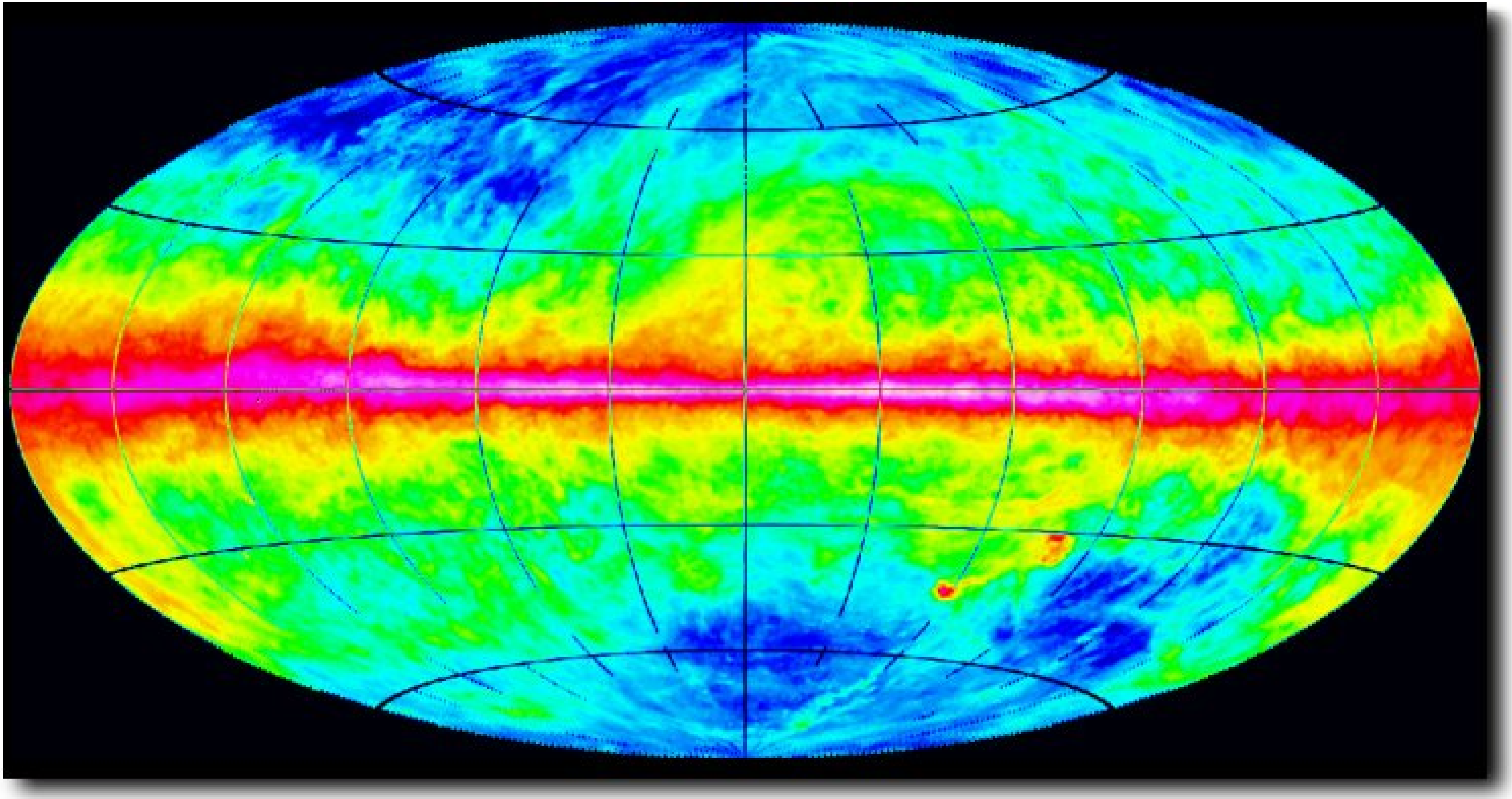
- In general, $T_X \neq T_K$, except for densities $\gg$ the critical density.

- T_X depends on the kinetic temperature, the local radiation field at the line frequency, and the radiation field at the frequencies of transitions connected to the levels in question.

- NOTE: T_X is *NOT* a physical temperature !

- For spectral lines, all three temperatures matter: the line strength depends on T_X and is quantified by T_B; the width depends on T_K.

All-Sky HI-21cm Emission Image



Leiden-Argentine-Bonn survey (Kalberla et al. 2005; Bajaja et al. 2005)

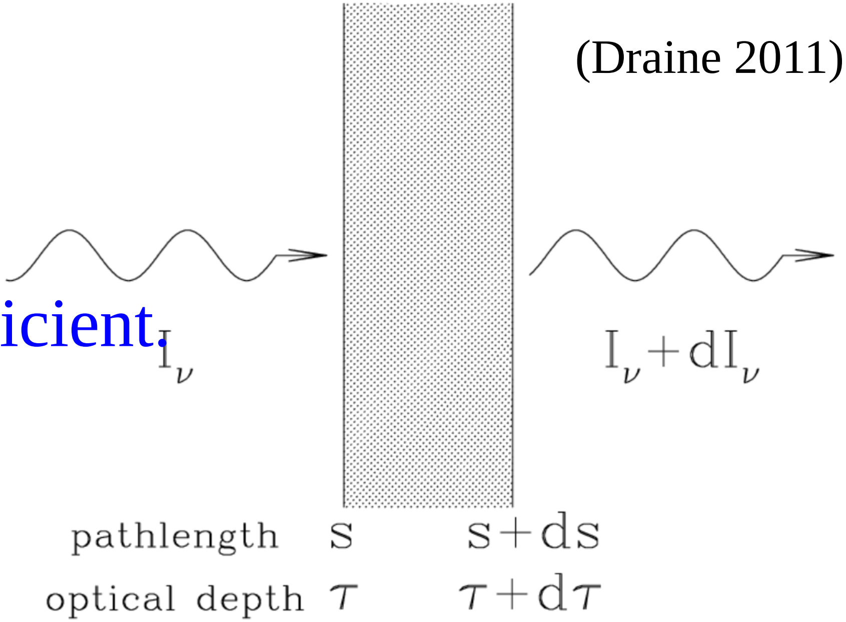
- Note: Assumed $\tau_V \ll 1$ to infer N_{HI} from the brightness temperature.
- Combine with the Galaxy's velocity field to infer the scale height!

(e.g. Heiles et al. 1985)

RADIATIVE TRANSFER

- Power per unit area between ν and ν+dν, in solid angle dΩ:

$$P_\nu = I_\nu \, d\nu \, d\Omega \qquad (I_\nu \equiv \text{Intensity})$$


(Draine 2011)

- Equation of radiative transfer:

$$dI_\nu = -I_\nu \kappa_\nu ds + j_\nu ds$$

- $j_\nu \equiv$ Emissivity, $\kappa_\nu \equiv$ Attenuation coefficient,

- Define optical depth, $d\tau_\nu = \kappa_\nu \, ds$

$$\Rightarrow \quad dI_\nu = -I_\nu \, d\tau_\nu + (j_\nu/\kappa_\nu) \, d\tau_\nu$$

- For a uniform medium, with level populations given by T_X

$$\Rightarrow \quad I_\nu = I_\nu(0) \, e^{-\tau_\nu} + B_\nu(T_X) \, (1 - e^{-\tau_\nu})$$

- At radio wavelengths, $I_\nu = (2k\nu^2 T_B/c^2)$

$$\Rightarrow \quad T_B = T_B(0) \, e^{-\tau_\nu} + (h\nu/k) \, [e^{h\nu/kT_X} - 1]^{-1} \, (1 - e^{-\tau_\nu}).$$

THE HI-21CM LINE: ABSORPTION ISSUES

- Level populations: $(n_1/n_0) = (g_1/g_0)\, e^{-h\nu/kT_S}$.
  $T_S \equiv$ “Spin temperature”; $g = (2S + 1)$; $g_1 = 3$, $g_0 = 1$.

- $h\nu/k \approx 0.07$ K, $\ll T_S \Rightarrow (n_1/n_0) \approx 3\,(1 - h\nu/kT_S) \Rightarrow n \approx 4n_0$.

- The absorption cross-section is given by

$$\sigma_{10}(\nu) = (g_1/g_0)\,(c^2/8\pi\nu^2)\,A_{21cm}\,\phi(\nu).$$

- The attenuation coefficient, $\kappa_\nu = n_0\sigma_{01}(\nu) - n_1\sigma_{10}(\nu)$.

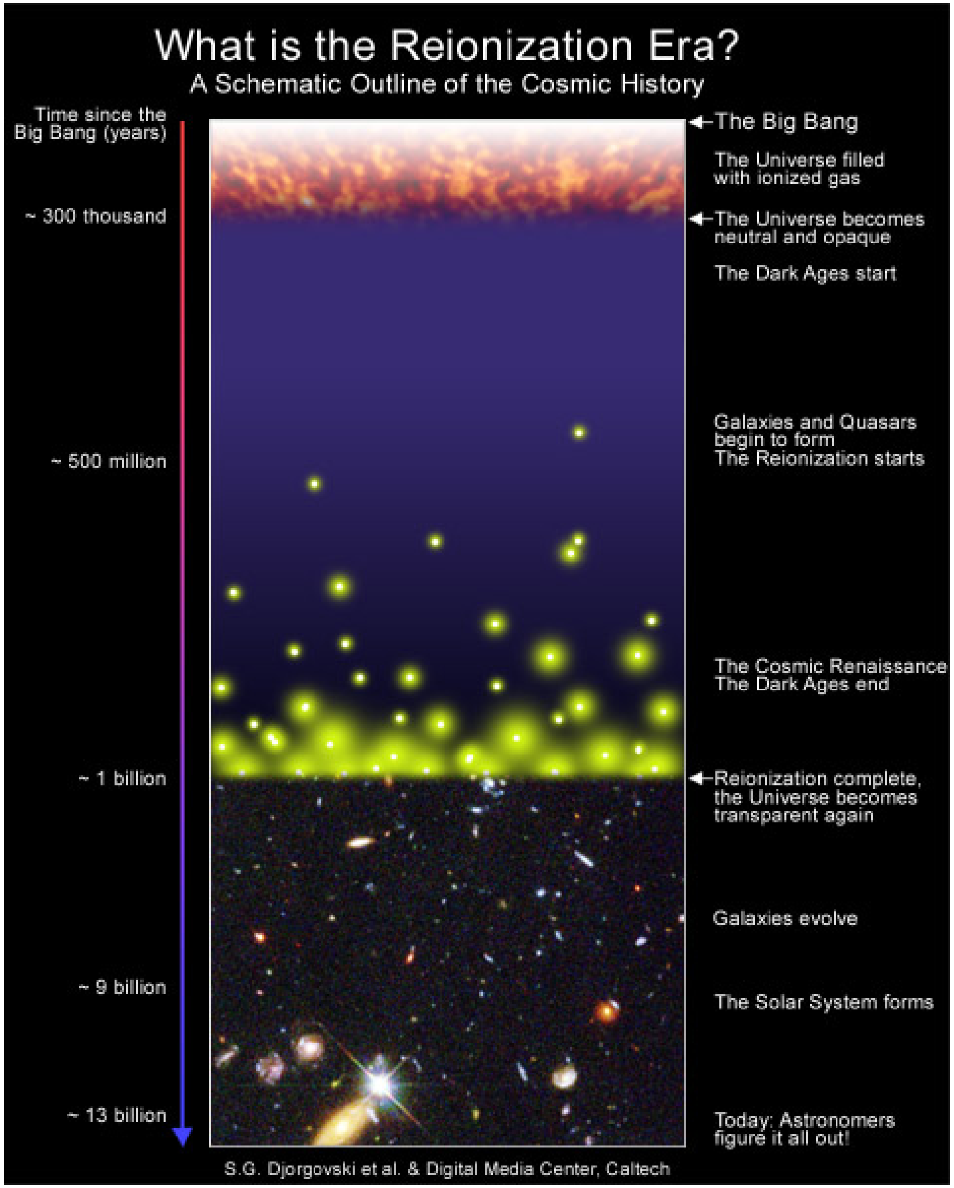
$$\Rightarrow \kappa_\nu = (c^2/8\pi\nu^2).\ 3.\ A_{21cm}\ .\ (n/4).\ \phi(\nu)\ [1 - e^{-h\nu/kT_S}\ ]$$

$$= (3c^2/32\pi\nu^2)\ .\ A_{21cm}.\ n.\ \phi(\nu)\ (h\nu/kT_S)$$

- Optical depth, $\tau_\nu = \int\kappa_\nu\, ds = (3c^2/32\pi\nu^2)\ A_{21cm}\,\phi(\nu)\ .\ (h\nu/kT_S)\ N_{HI}$

  $\Rightarrow$ Total HI column density, $N_{HI} = 1.823 \times 10^{18} \int T_S\, \tau_\nu\, dV$.

HI-21cm Emission from the EoR



(Courtesy: MIT-Haystack)

- Last phase transition in the Universe; probe of cosmology!
- HI-21cm emission from the EoR: GMRT, LOFAR, MWA, SKA...